Proposed Muonium R&D/ Physics Program at the MTA

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Muons, Inc.

for the collaboration:

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Fermilab PAC Meeting
19 Jan. 2023

“Nutshell” Summary

- Muonium–antimuonium oscillations complementary to Mu2e — differently sensitive to CLFV new physics
- Muonium gravity measurement sensitive to possible 5th force (in which *g* – 2, leptonic *B*, & *W*-mass anomalies have stimulated renewed interest)
- New cryogenic muonium-production method could make Fermilab 400 MeV Linac competitive with PSI
  - also enables muonium gravity measurement & other low-*E* μ^+ applications
- With PIP-II, Fermilab potential muonium world leader (~ 10^2 x PSI)
- R&D can start now, with newly installed MTA low-energy muon beamline, giving muonium at PIP-II a running start
  - about a day of installation remains to be done (target + instrumentation)
- Mu@MTA collaboration formed, seeks approval & funding
  - cost-effective, few M$ project includes R&D and initial gravity experiment

Outline

- Motivation:
  - Muonium
    - oscillation search
    - precision spectroscopy
    - gravity
- Fermilab & PIP-II advantages
- Summary & Conclusions

NOTE: references in this format are to talks at https://indico.fnal.gov/event/55117/

Motivation

Why Muonium?

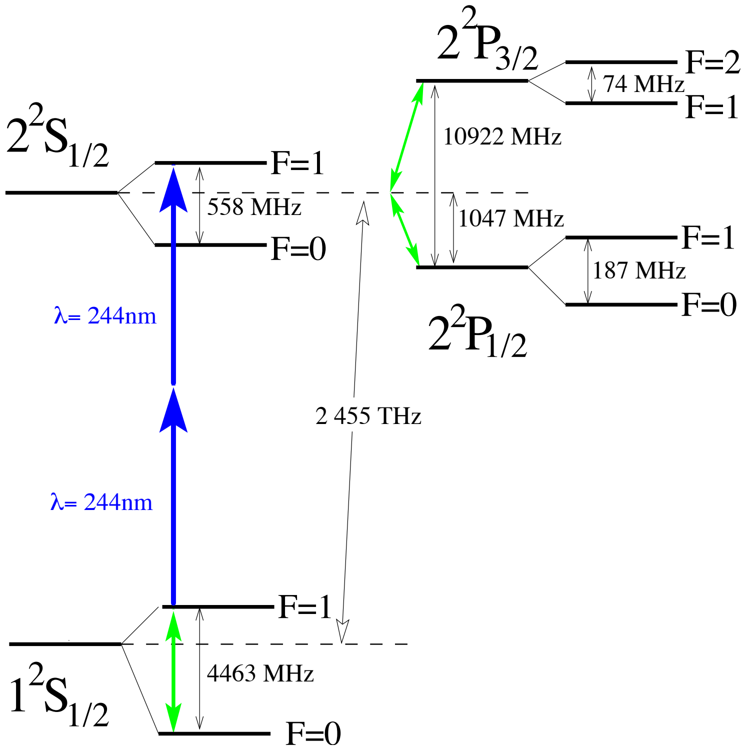
- Much known about muonium… (AKA M, or Mu)
  - a *purely leptonic atom*, discovered 1960

[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 ~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)

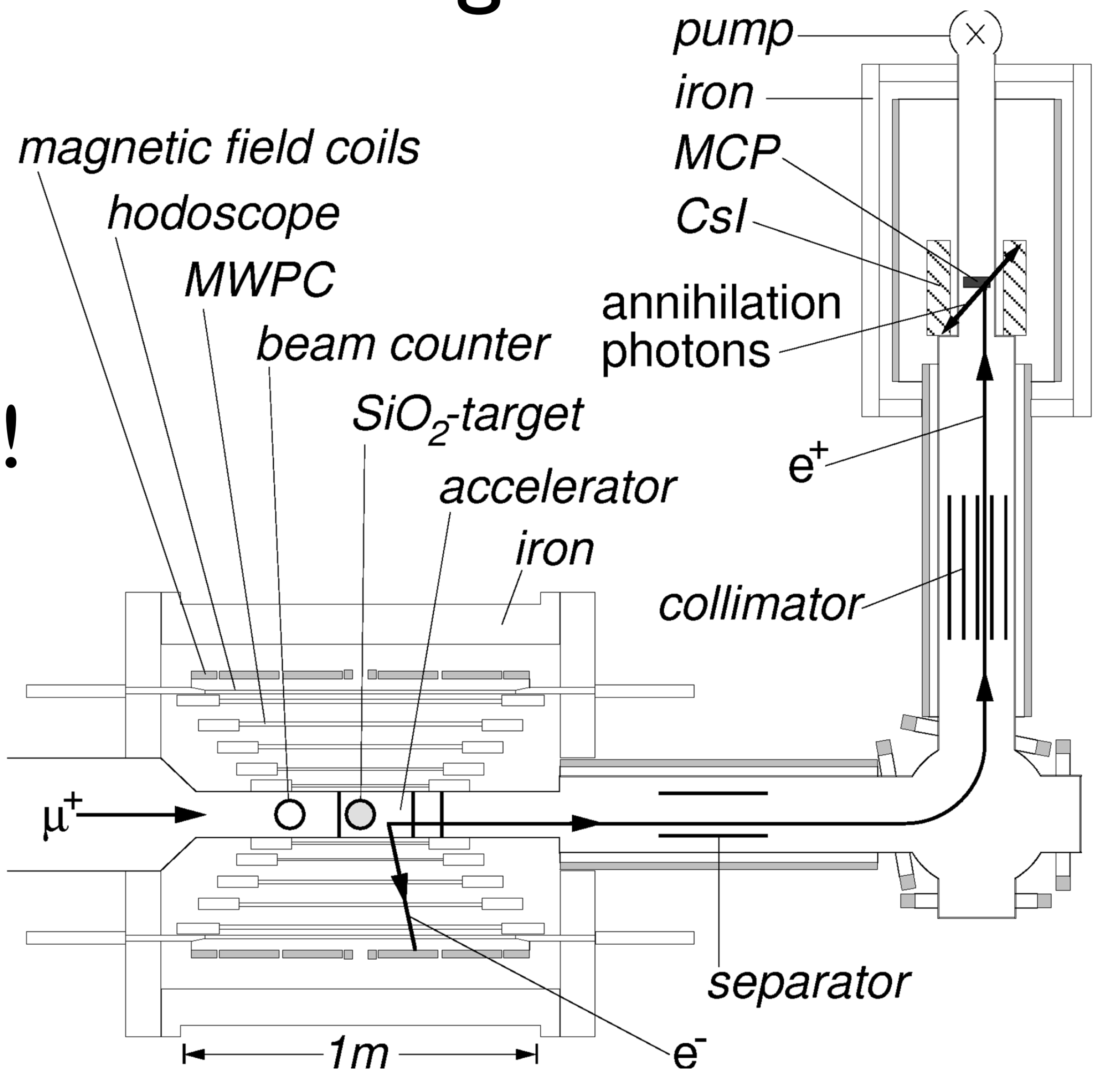


Muonium Double CLFV?

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

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

- 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!
    - in some models, more likely than $\mu N \to eN$
- Current limit set by MACS (1999) at PSI: $P_{\text{M}\overline{\text{M}}} \leq 8.3 \times 10^{-11}$ (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

- 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

49 Page 2 of 9 Hyperfine Interact (2018)

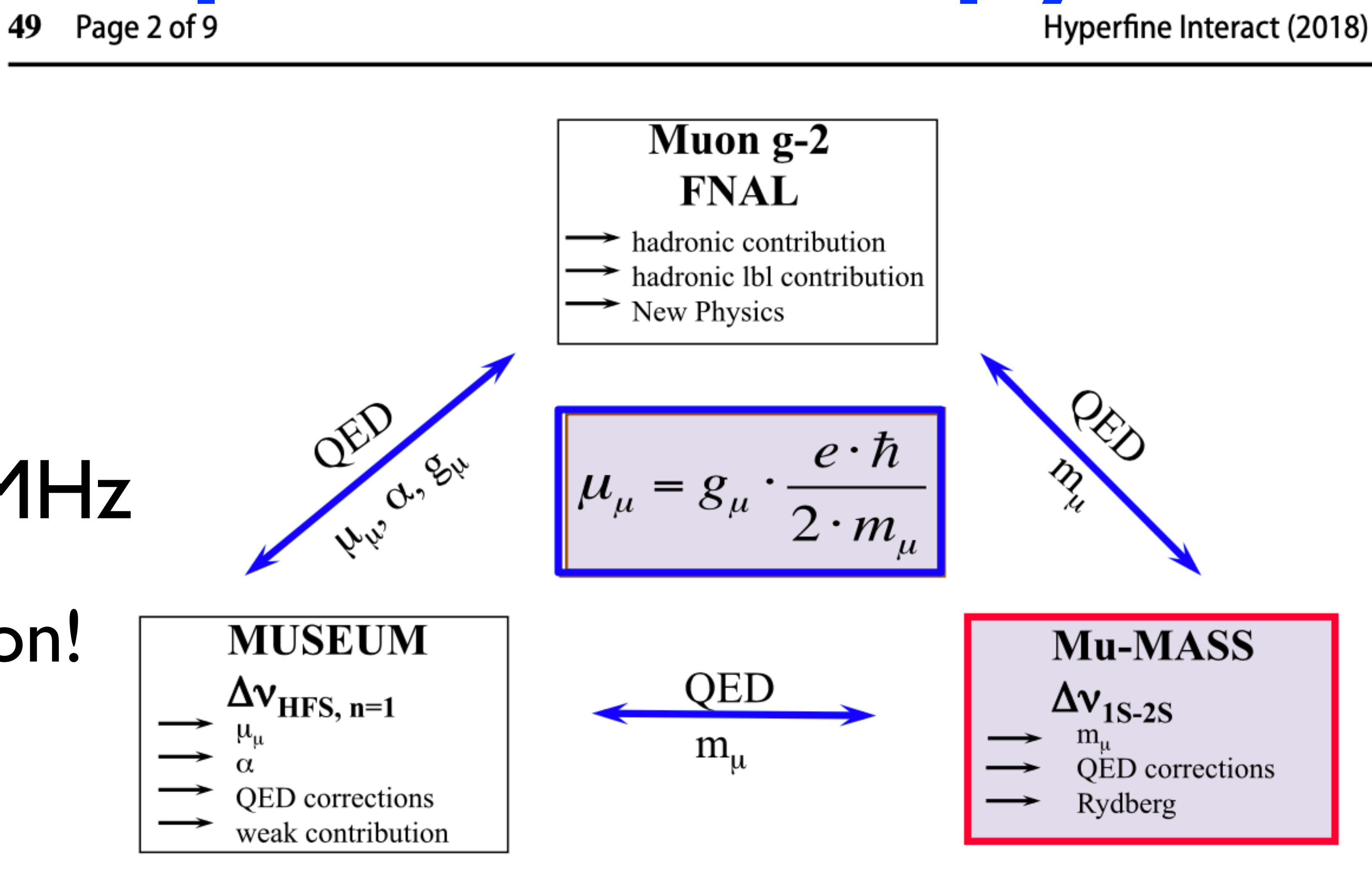


Fig. 1 Fundamental constants in the muon sector and related experiments (adapted from [42])

[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

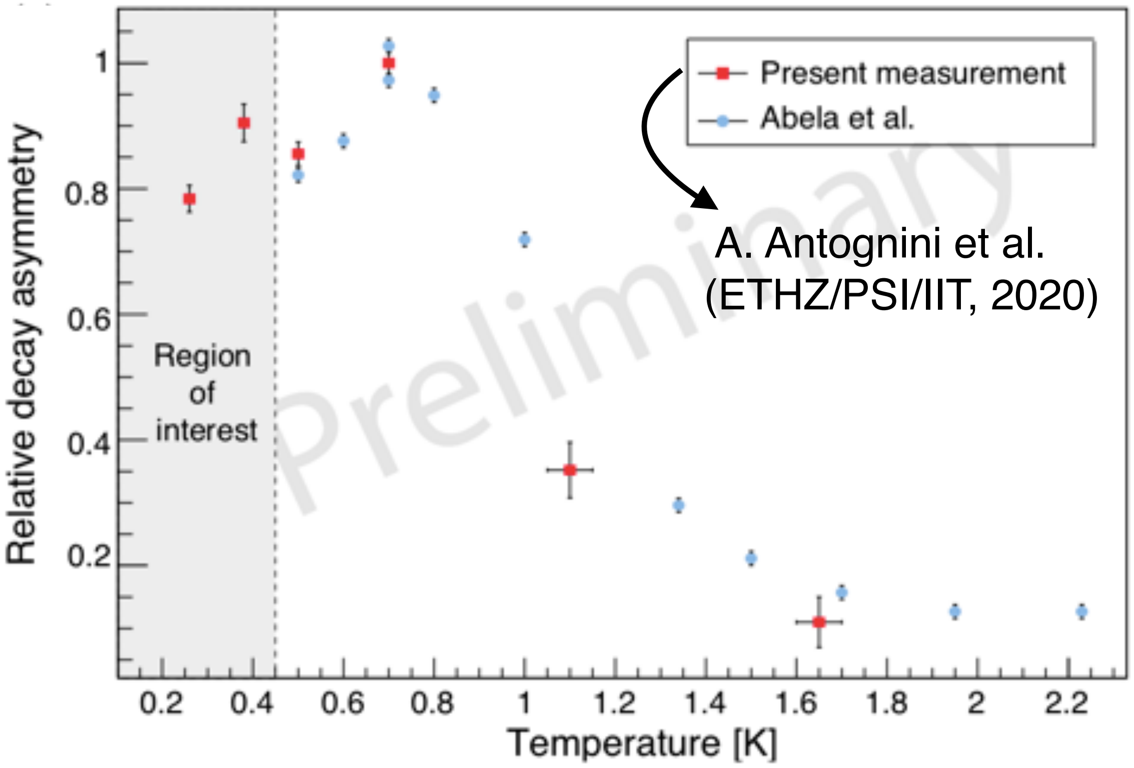
- New 1S-2S experiment, Mu-MASS, now in R&D/commissioning stage at PSI
  - goal: improve sensitivity x1000 (<10 kHz), 4 ppt
  - systematics expected to dominate
    - PIP-II muon rate (~2 orders higher than current PSI) would help
      - will allow better handle on systematics (per Crivelli)
- Also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

Novel Cryogenic M Source

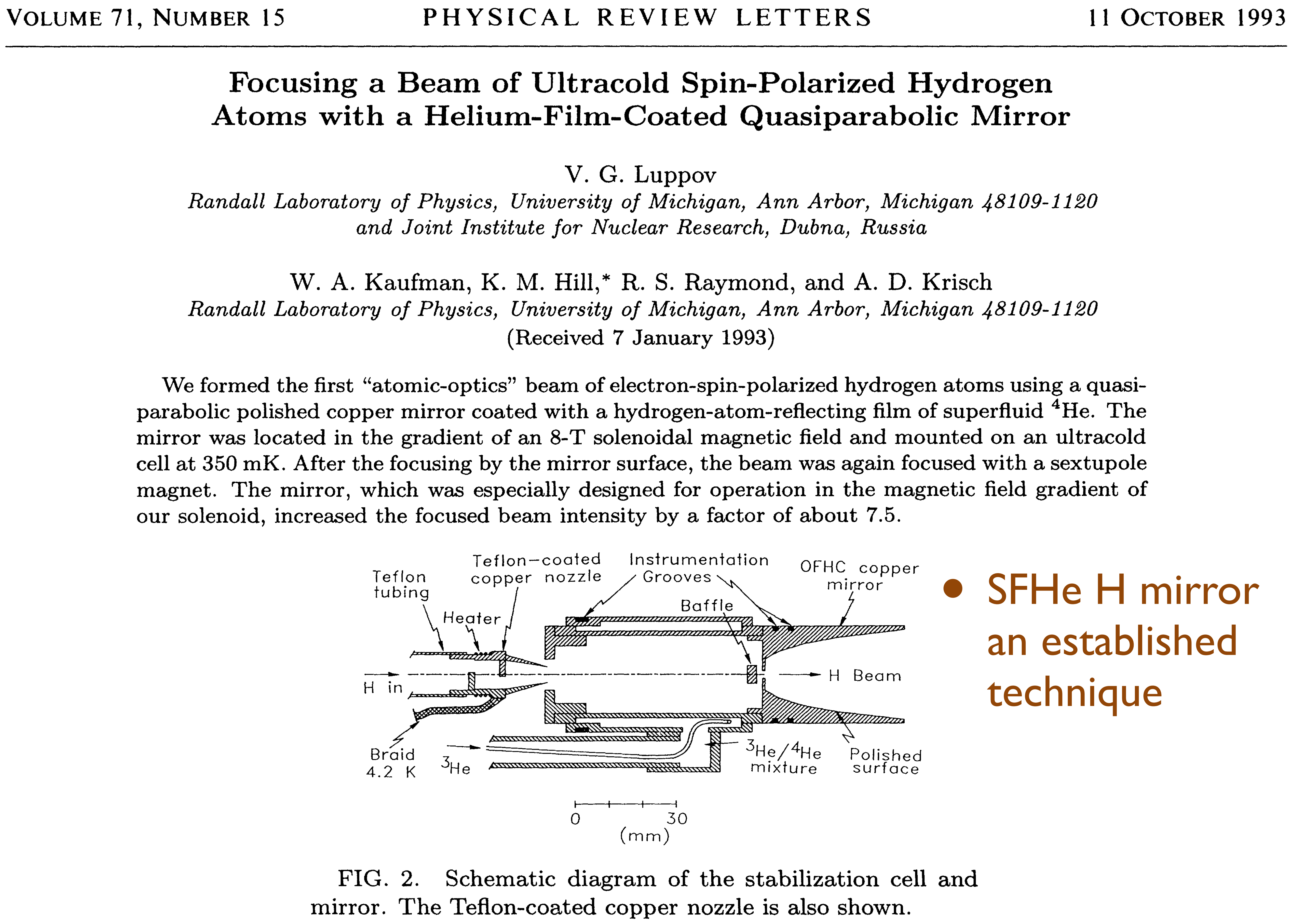
- Want low-divergence beam of slow muonium traveling in vacuum – no such beam anywhere

- 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

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



A. Antognini et al. (ETHZ/PSI/IIT, 2020)



VOLUME 71, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1993

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 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)

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[2]*Paul Scherrer Institute, 5232 Villigen-PSI,*
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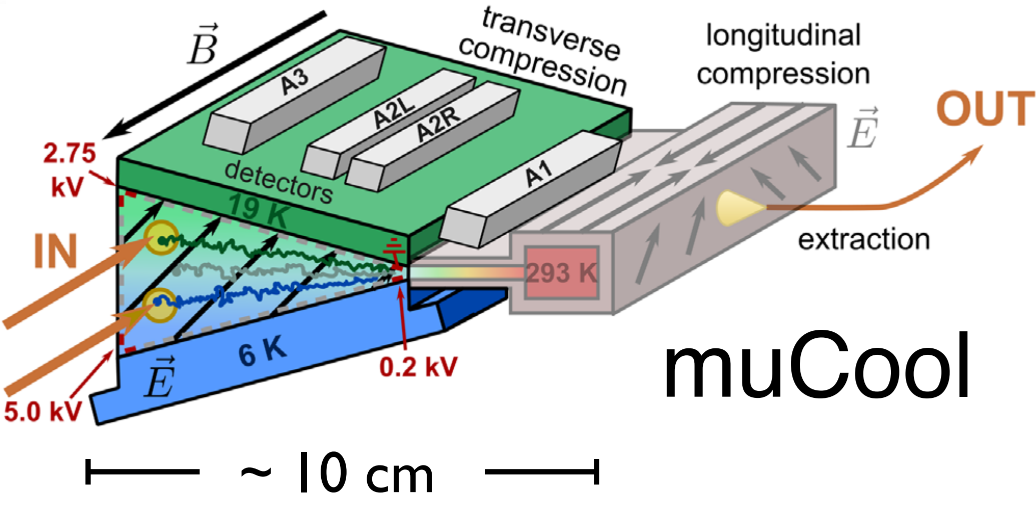
[4]*Dipartimento di Fisica, Università di Pisa and INFN sez. Pisa, Larg*



(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

[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);

…]

- Observable via M gravity?
  - what $\bar{g}$ sensitivity required? no theor. prediction available
- 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:

  ⟹ 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

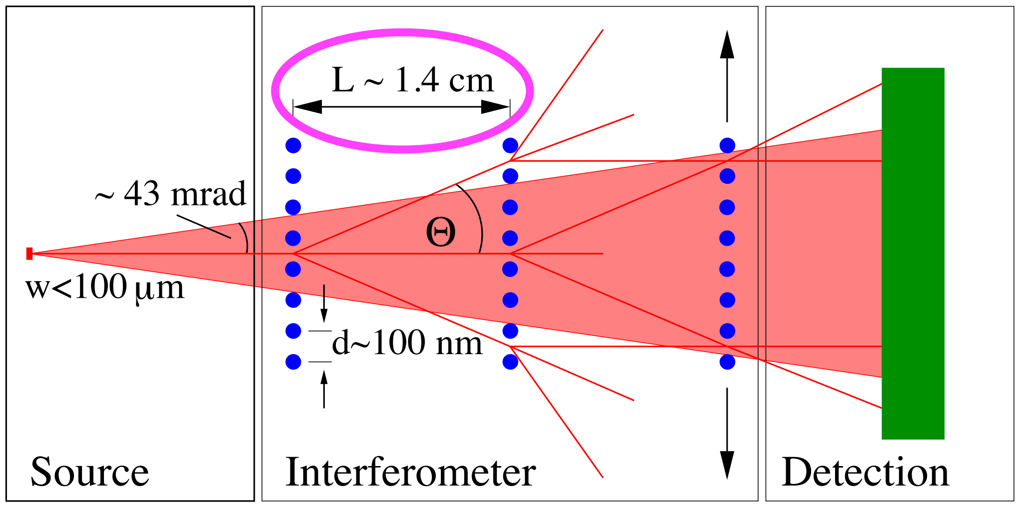
K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland
(Dated: February 2, 2008)

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

v_M ~ 6300 m/s

M beam

1 lifetime



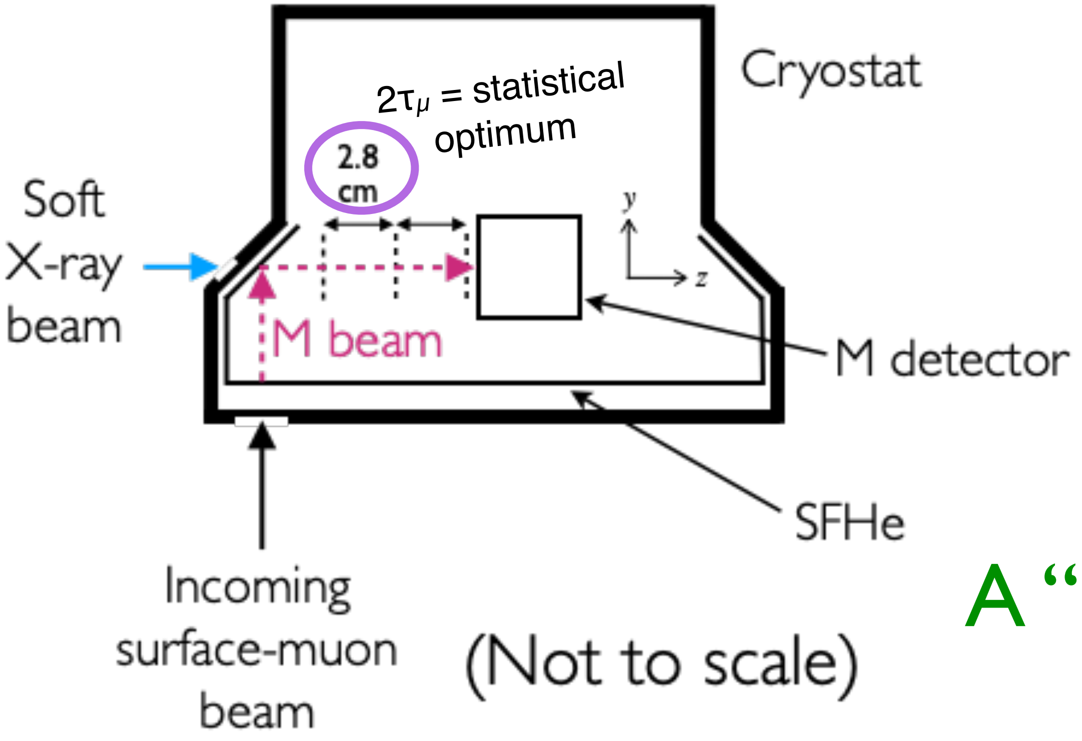
½ gt^2 = 24 pm!

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:



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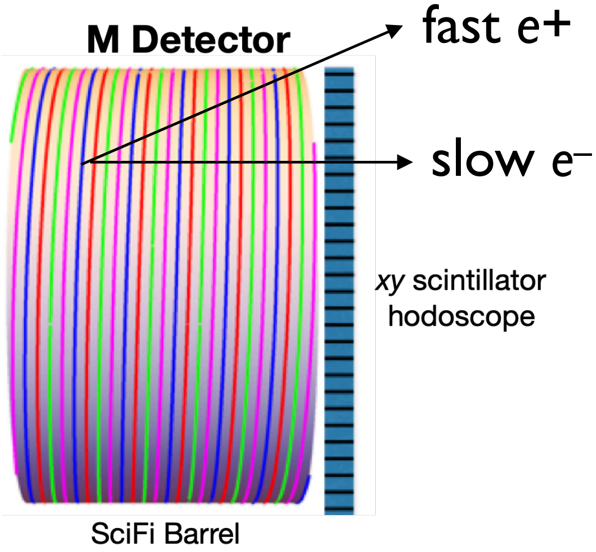
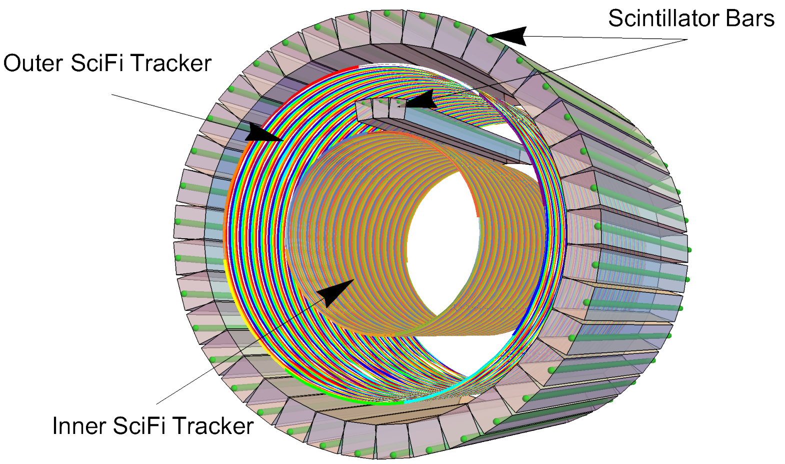




A "ship in a bottle!"

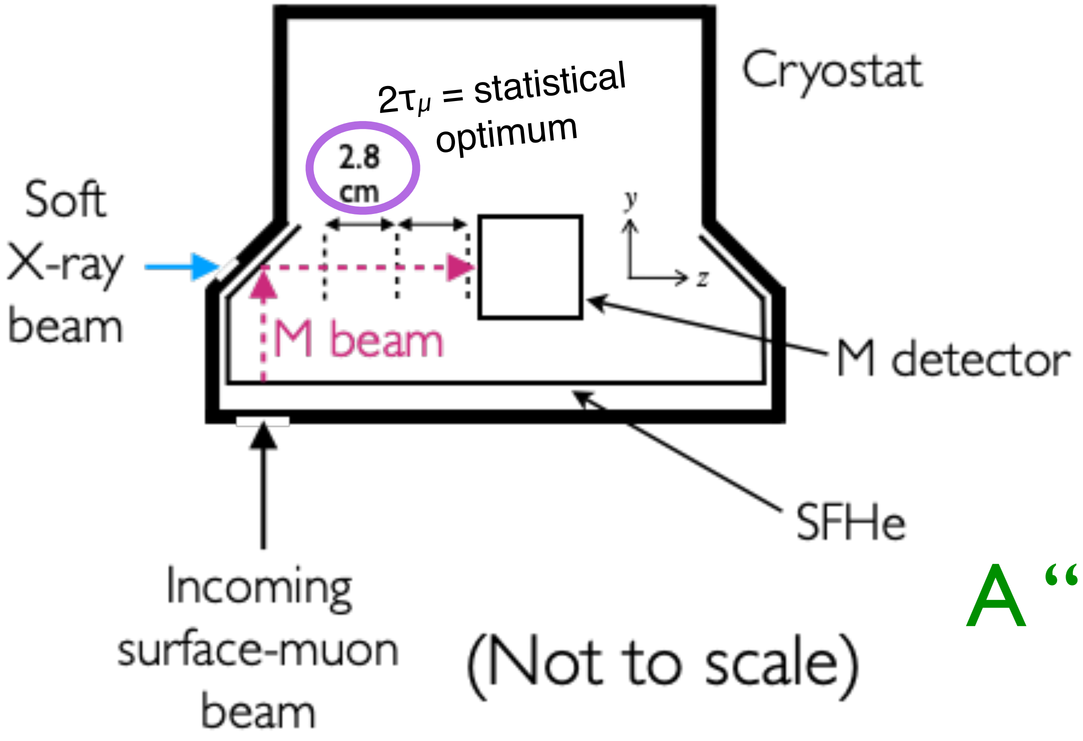
Sensitivity estimate @ 100 kHz:

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

  - 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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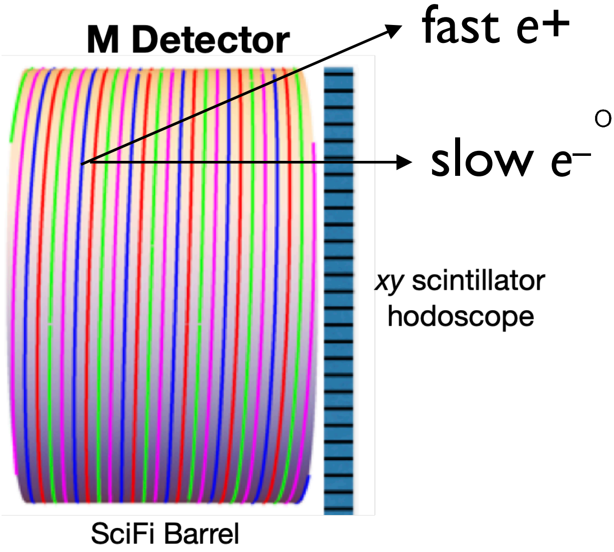

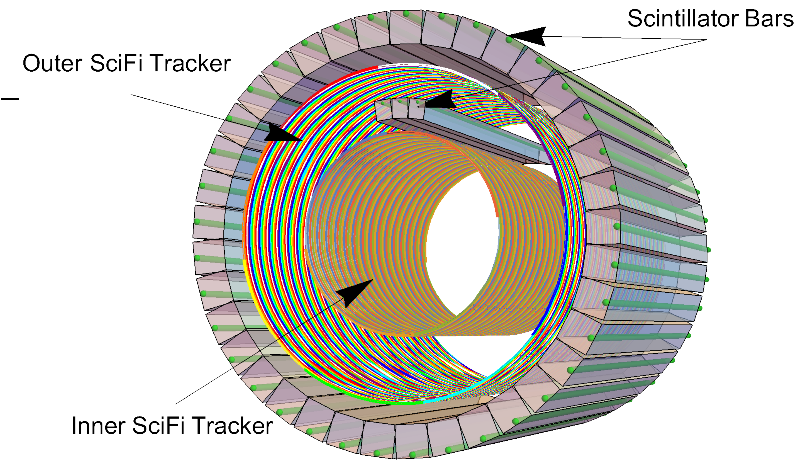

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$$\approx 0.3\,\mathrm{g}\ \mathrm{per}\ \sqrt{\#\mathrm{days}}$$

sign of $\bar{g}$ with 1 day’s data

where

C = 0.3 (est. contrast)

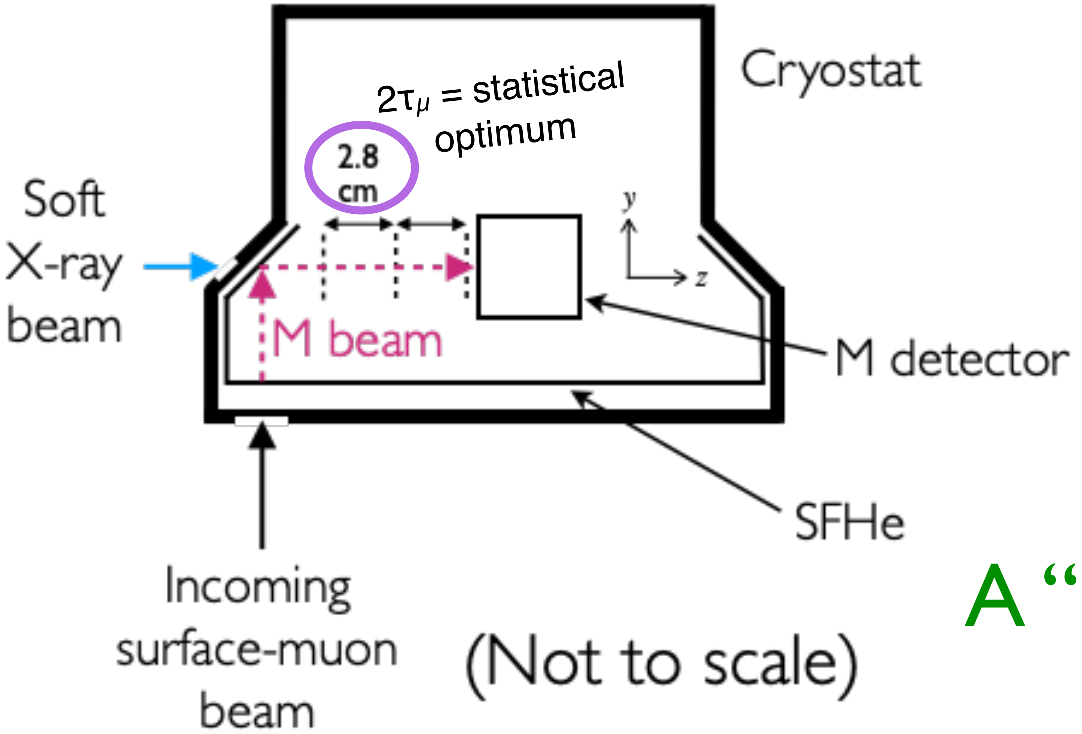
N_0 = # of events

d = 100 nm (grating pitch)

τ = inter-grating time

Muonium Gravity Experiment

- Conceptual sketch:



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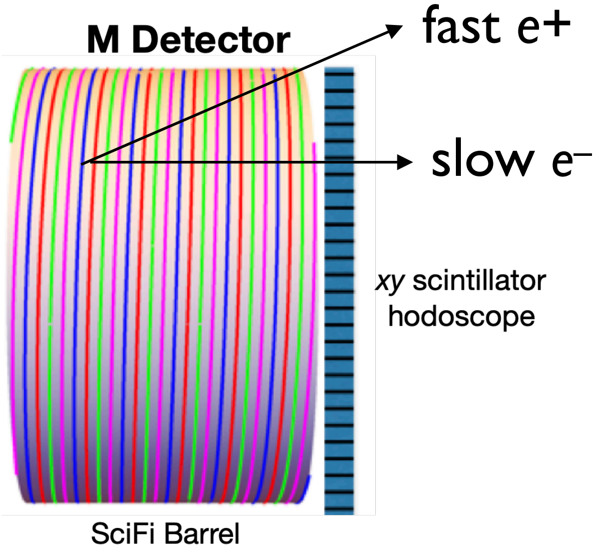

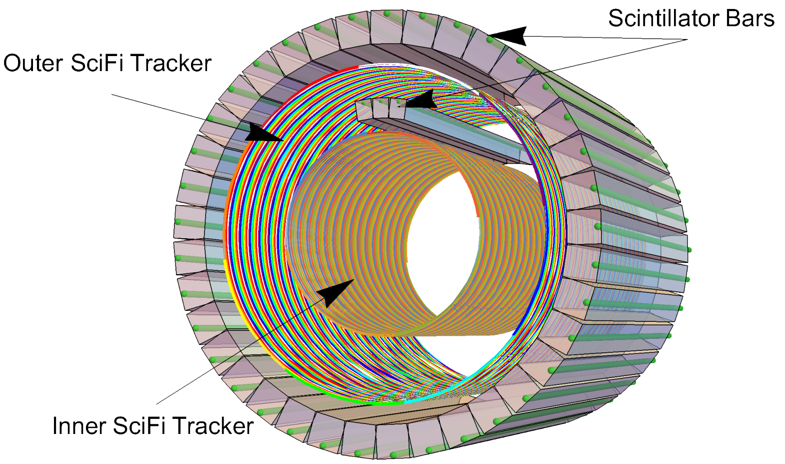

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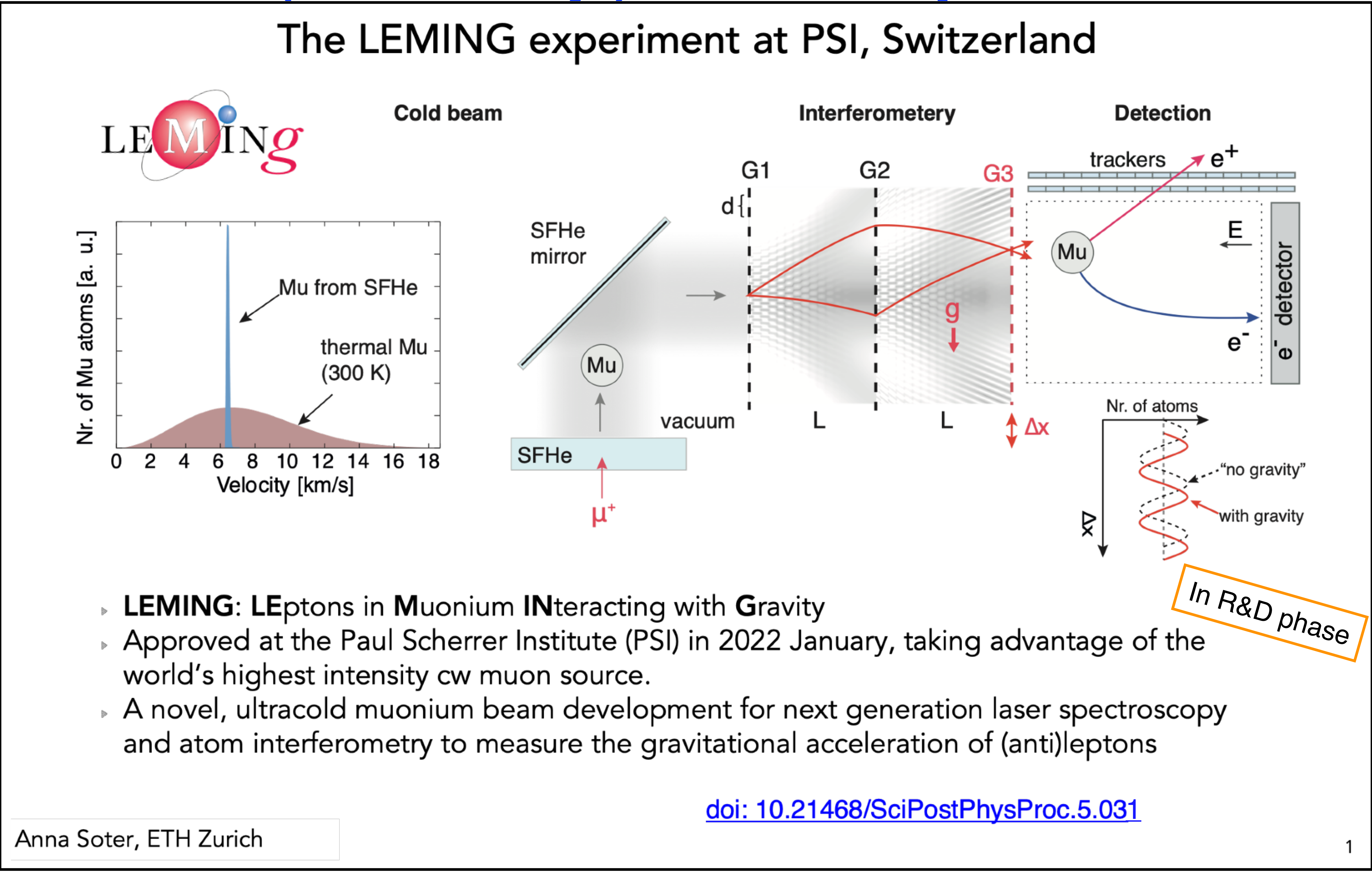
➡ Muonium Antimatter Gravity Experiment (MAGE)

The (friendly) "Competition"



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

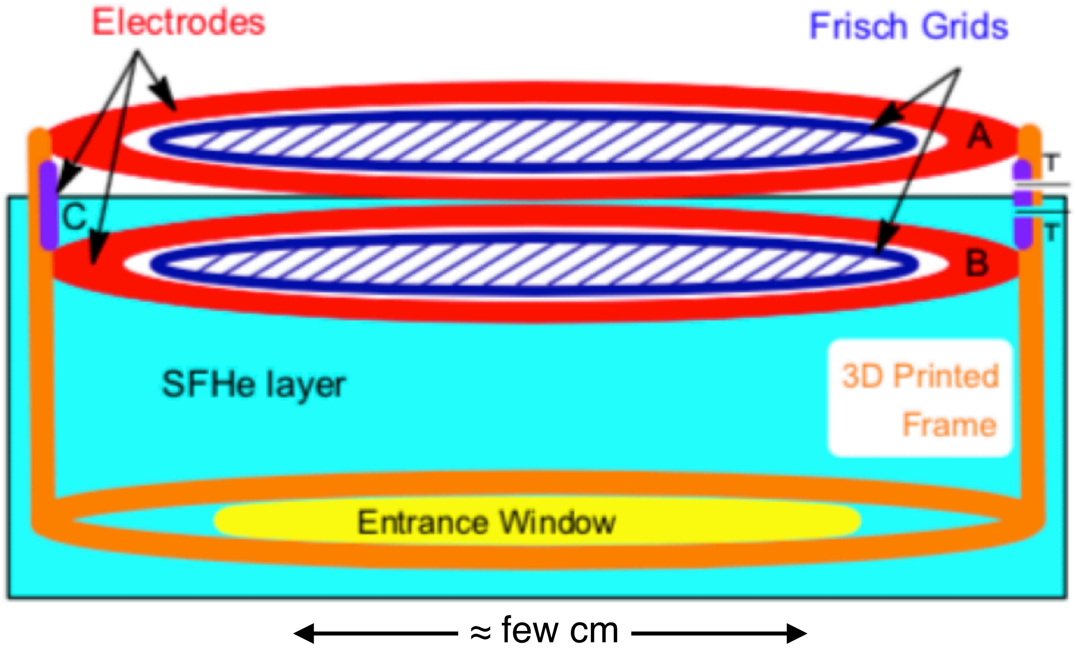
1

Thick- vs. Thin-film SFHe

Thick-film:

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

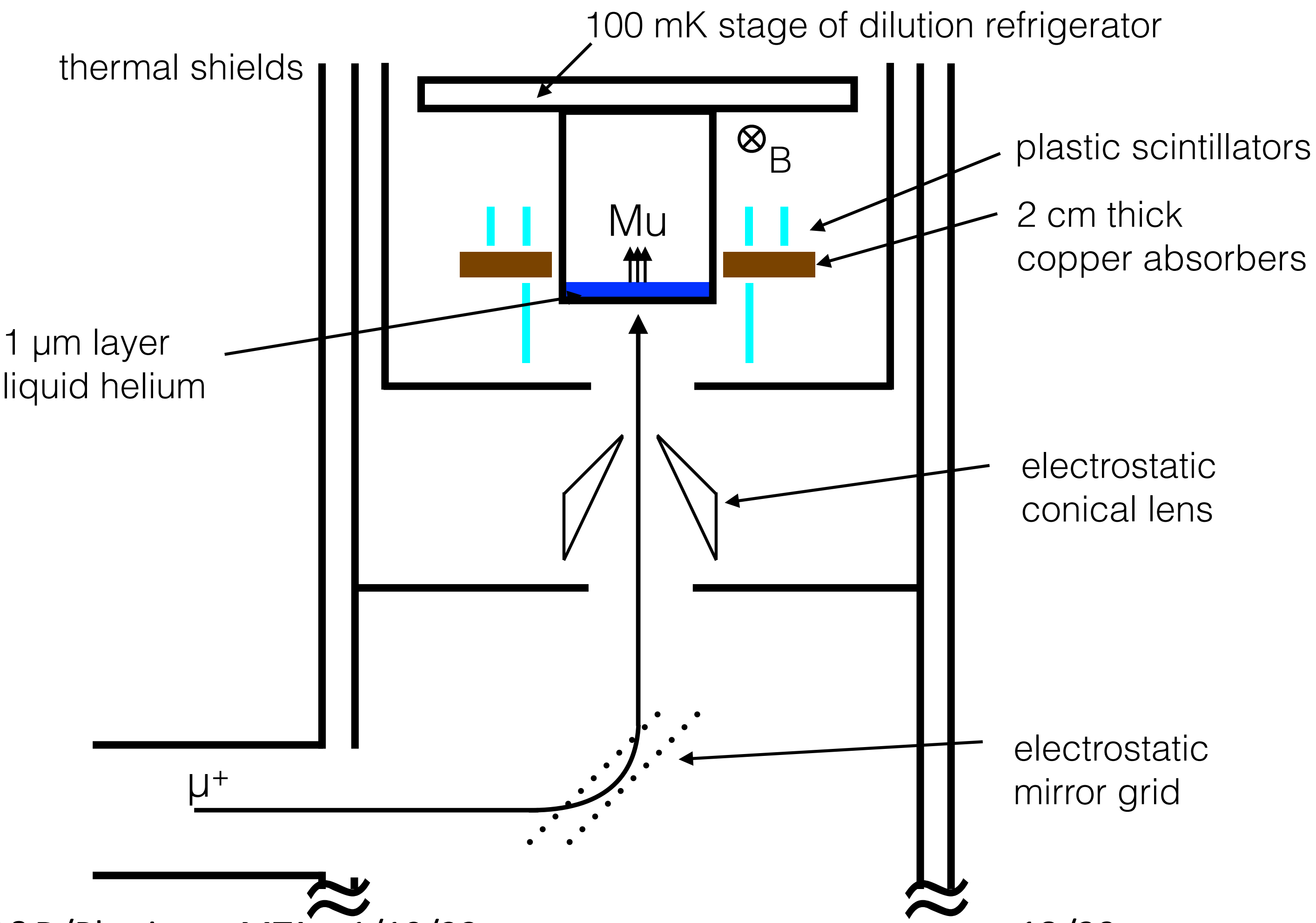
*under exploration at e.g. U of C as potential qbit system (D. I. Schuster *et al.*)



(R&D concept sketches)

Thin-film:

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



Fermilab Advantages

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]

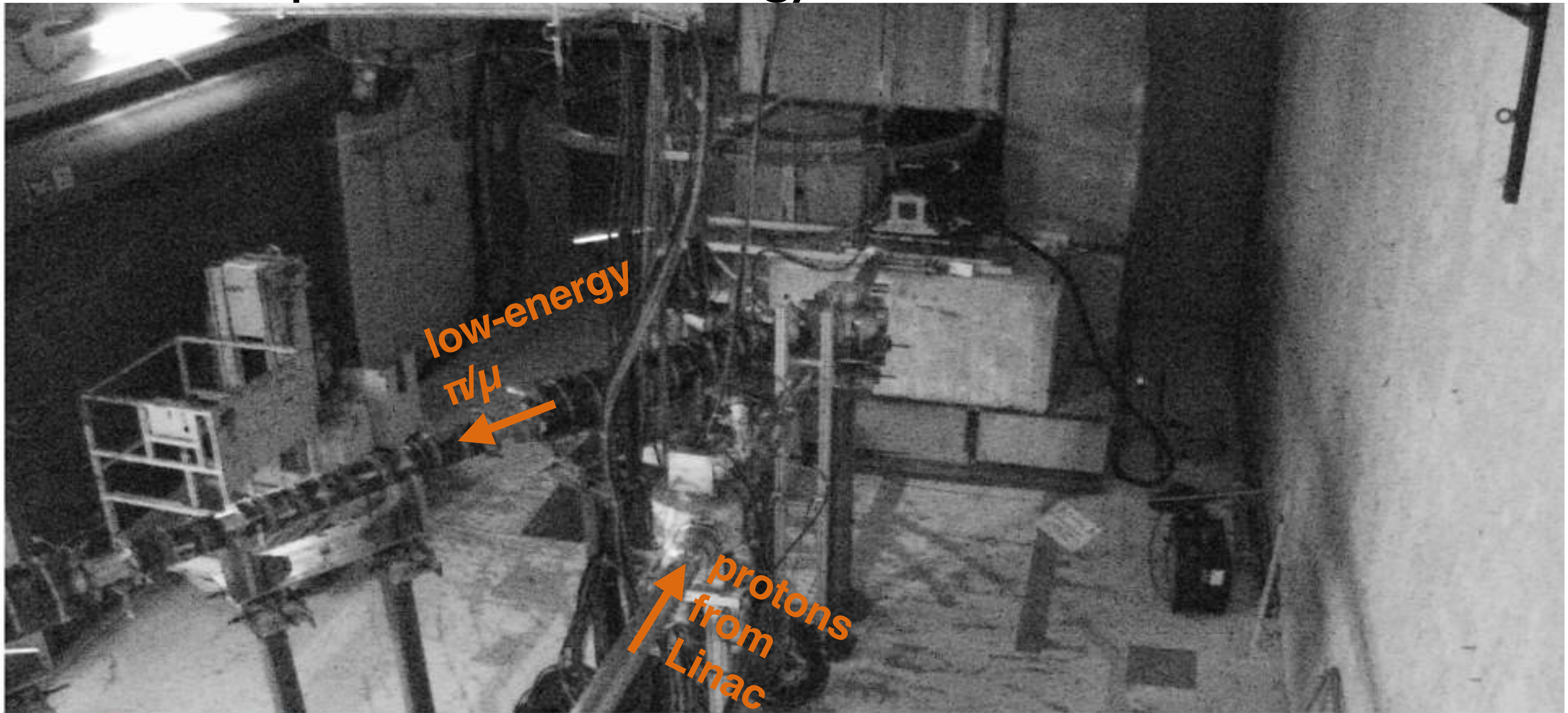
- Used for fundamental physics, μSR (MatSci, chemistry), μCF R&D…
- Oversubscribed, until now none in U.S.
- PSI: current world leader
  - x10 upgrade ("HIMB") in the works

- PIP-II could surpass HIMB (by ~ x10^2 ?)
- 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.)



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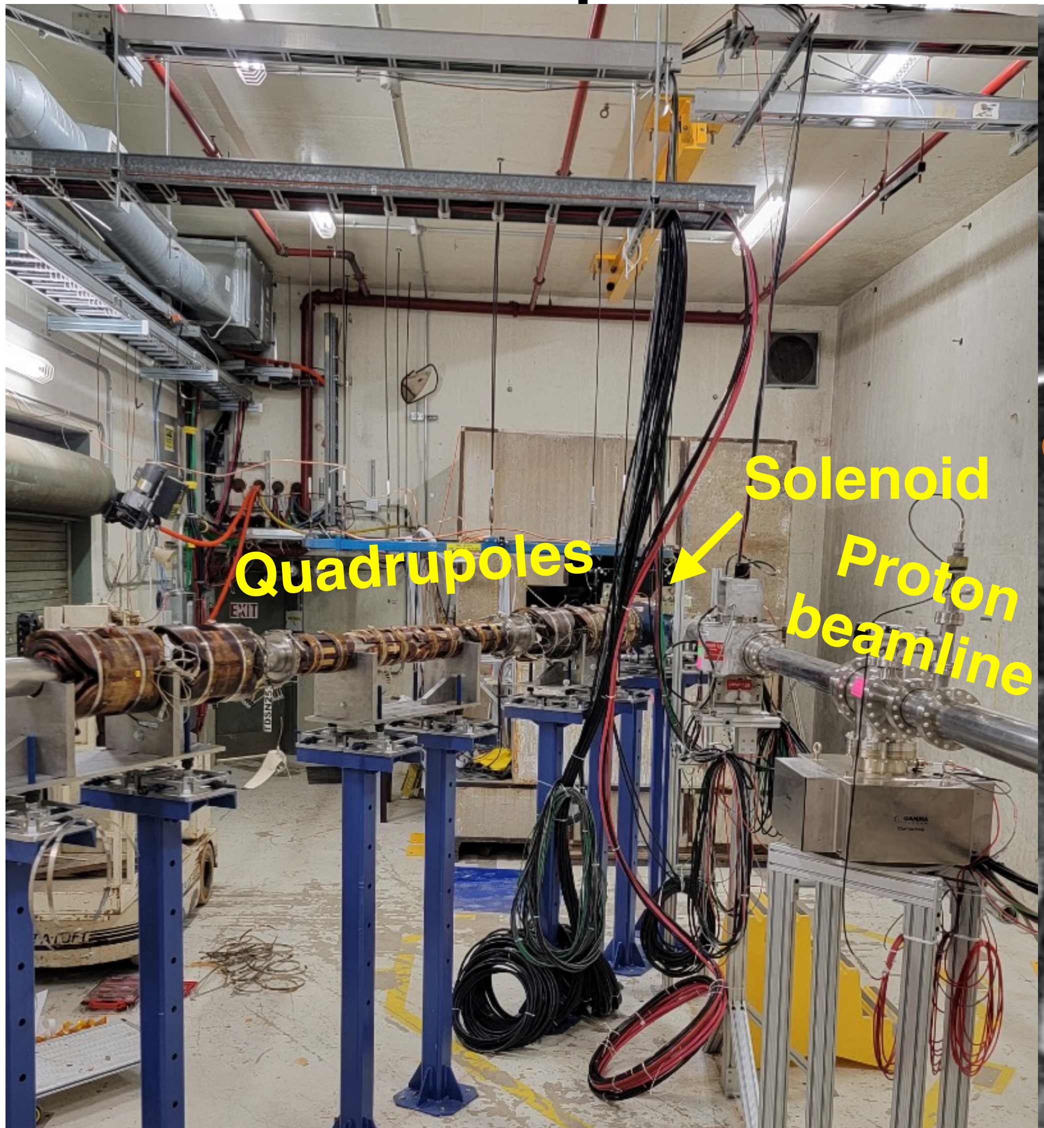

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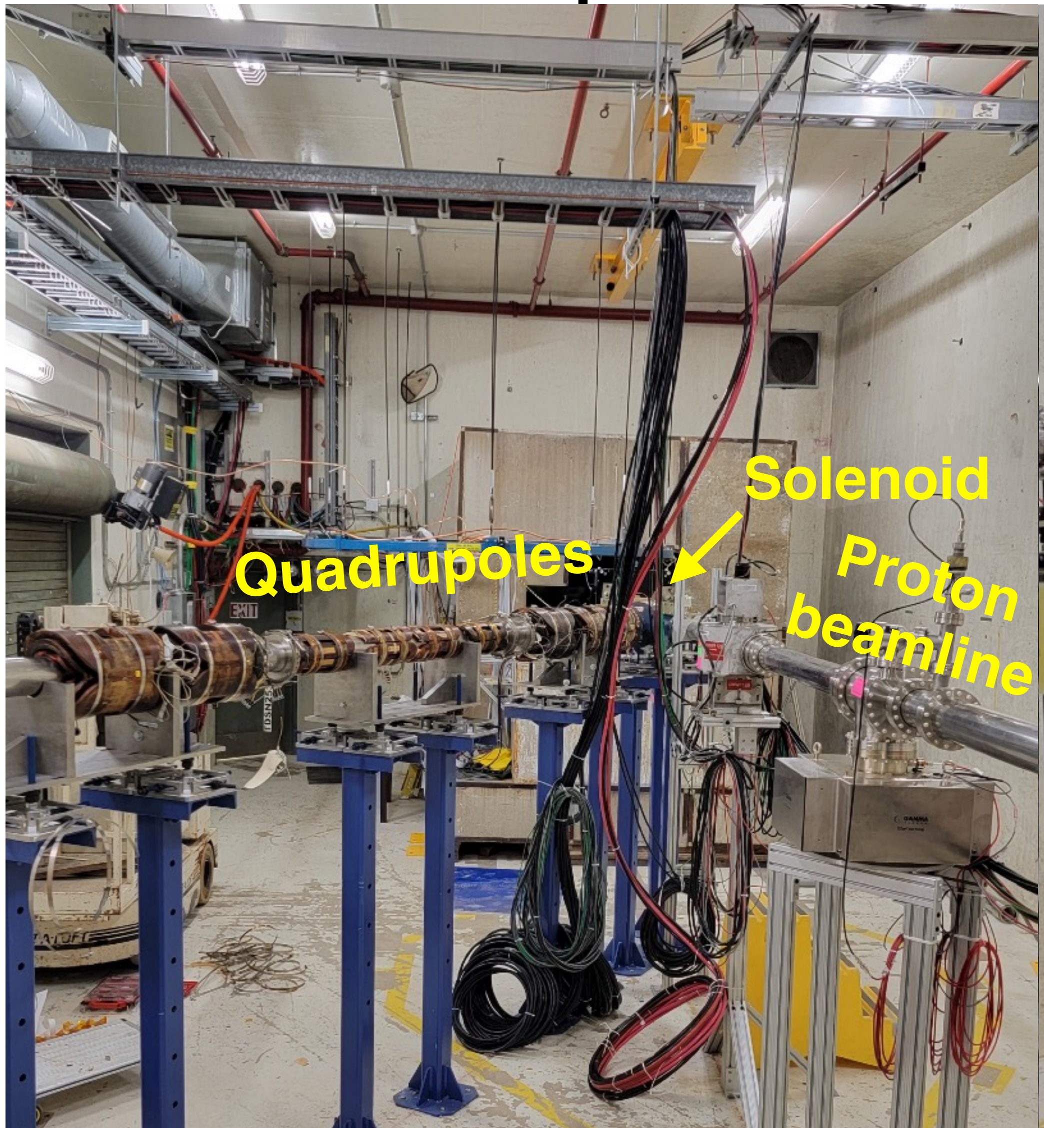
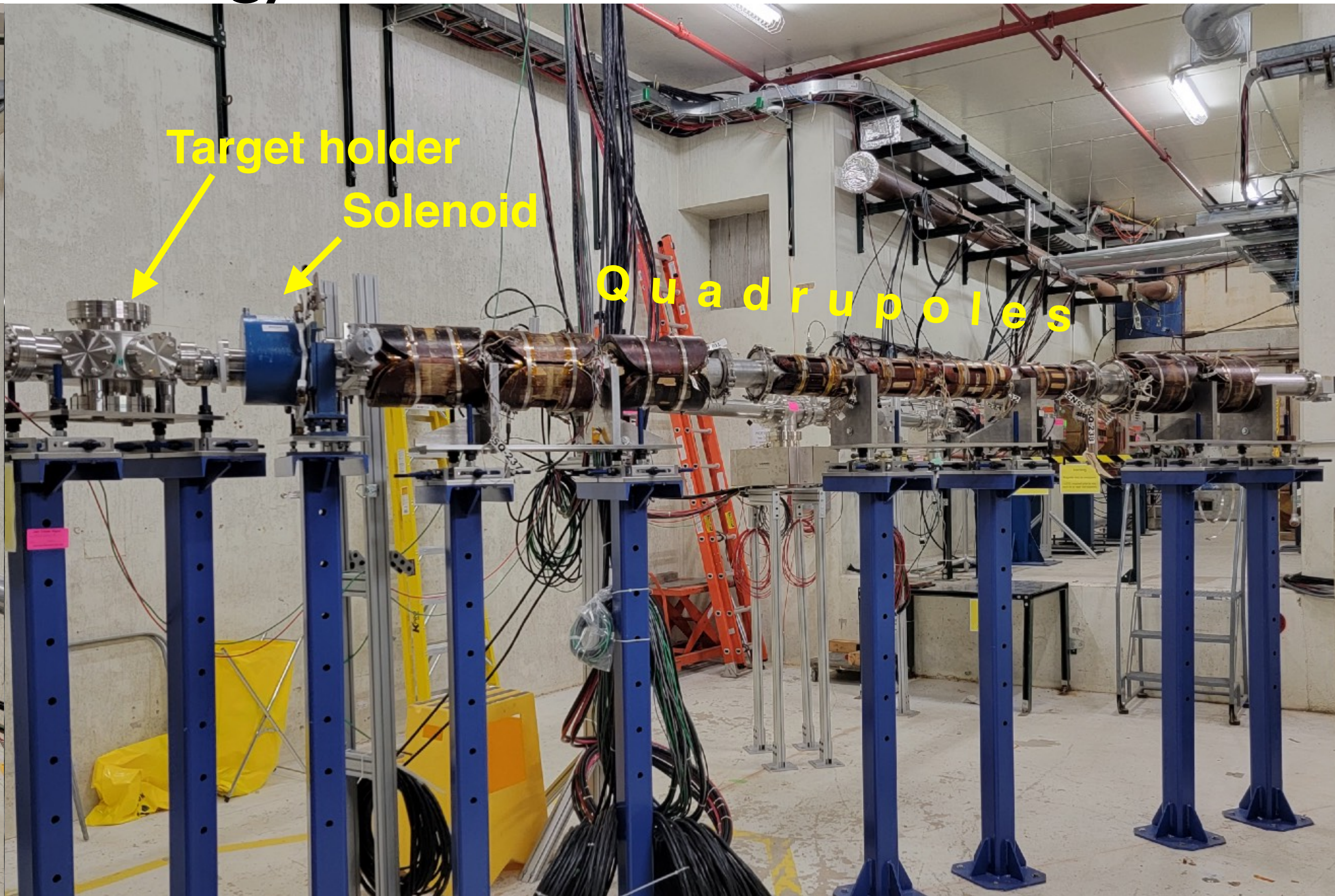
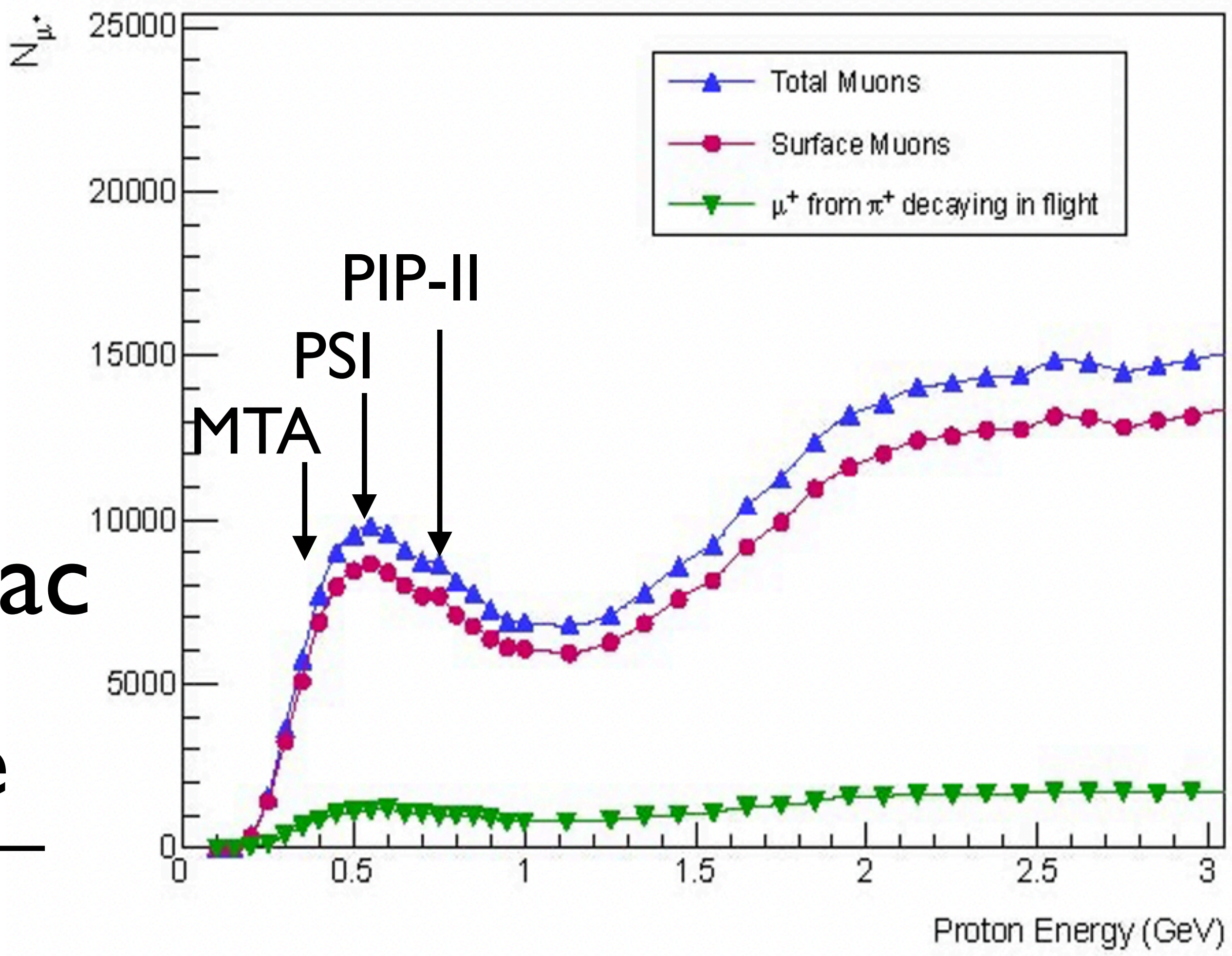




Fermilab vs. PSI

- **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

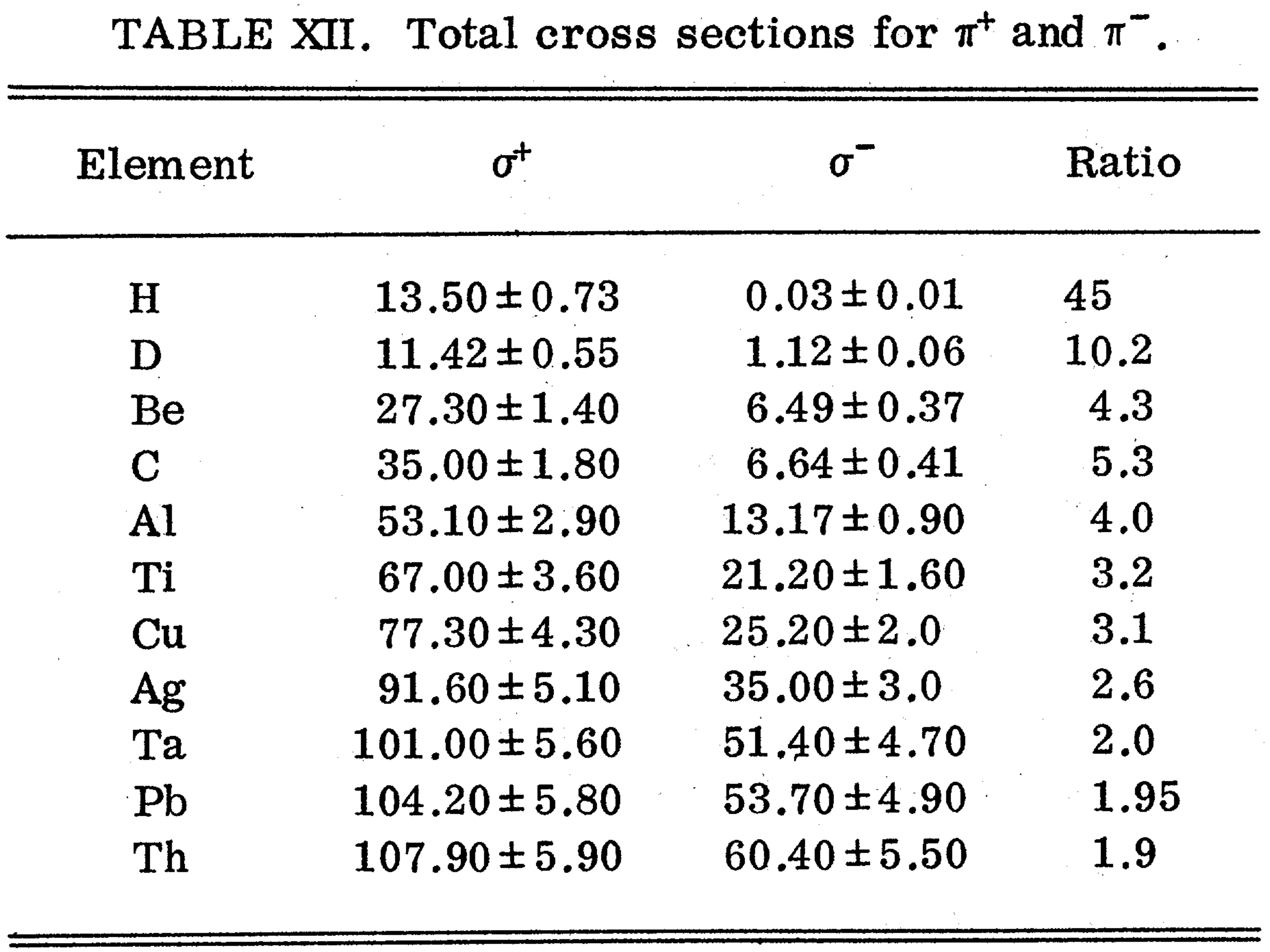


TABLE XII. Total cross sections for π^+ and π^-.

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
$\mu^+ \rightarrow$ M conversion	≈ 0.5	≈ 0.1	0.2
Net			≈10(?)

- Further improvement possible (e.g., multiple target slices, optics & target optimization)
  - current simulations see ≈ 10^{-9} surface μ/POT
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≈ x200 SFHe thick-film advantage – needs R&D to confirm

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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}	$\approx 3 \times 10^{11}$	$\gtrsim 20(?)$

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

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

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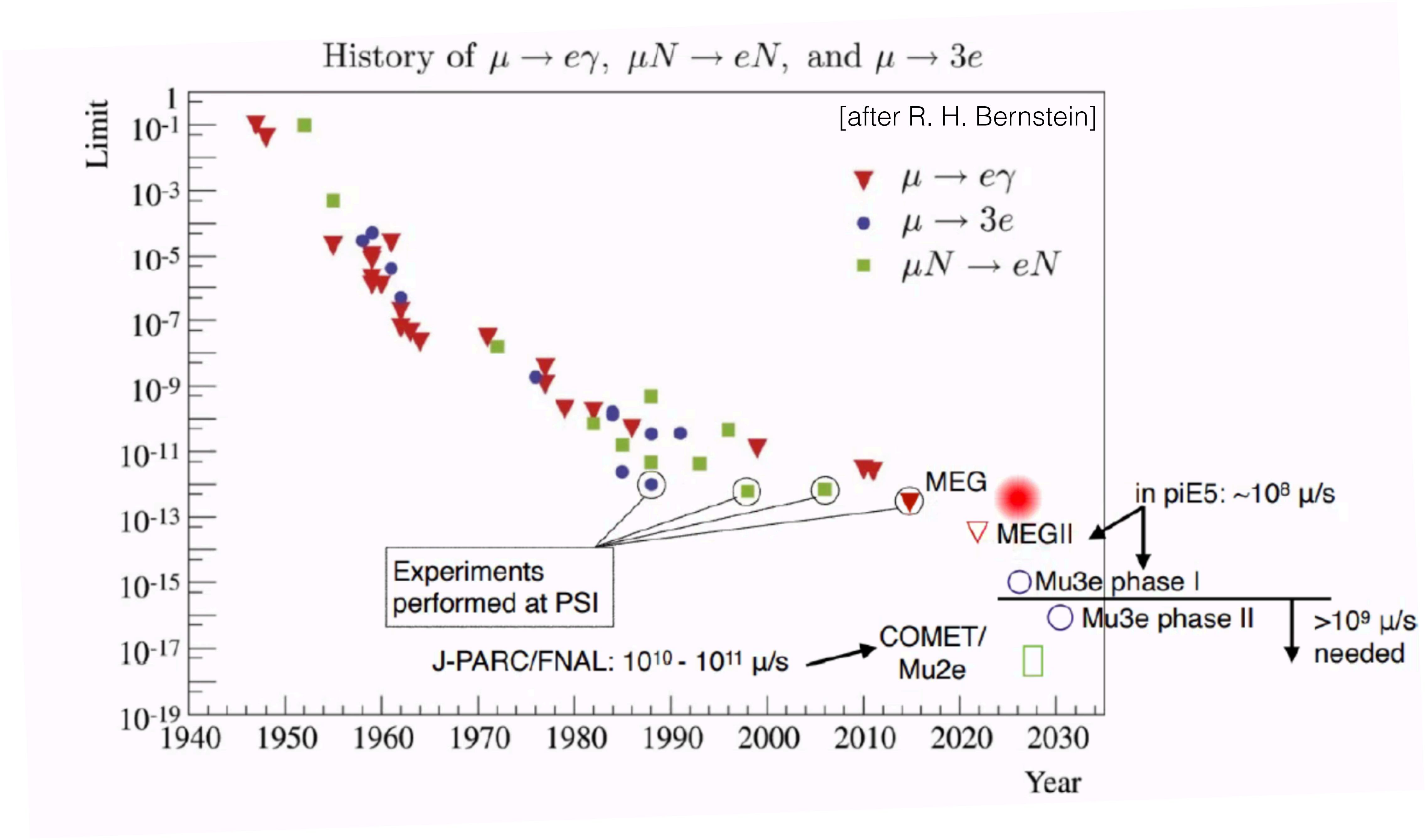
PIP-II Muonium Potential



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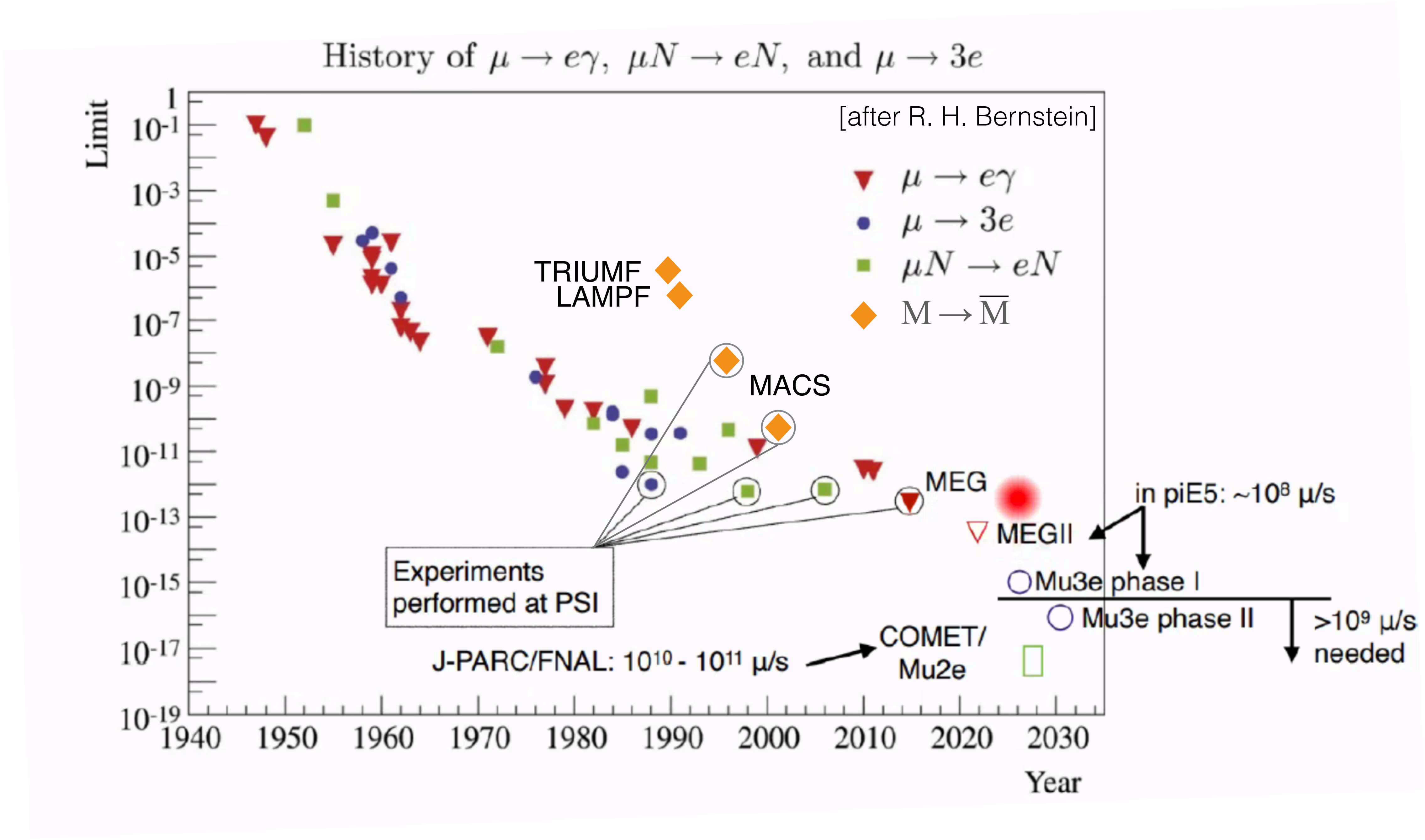

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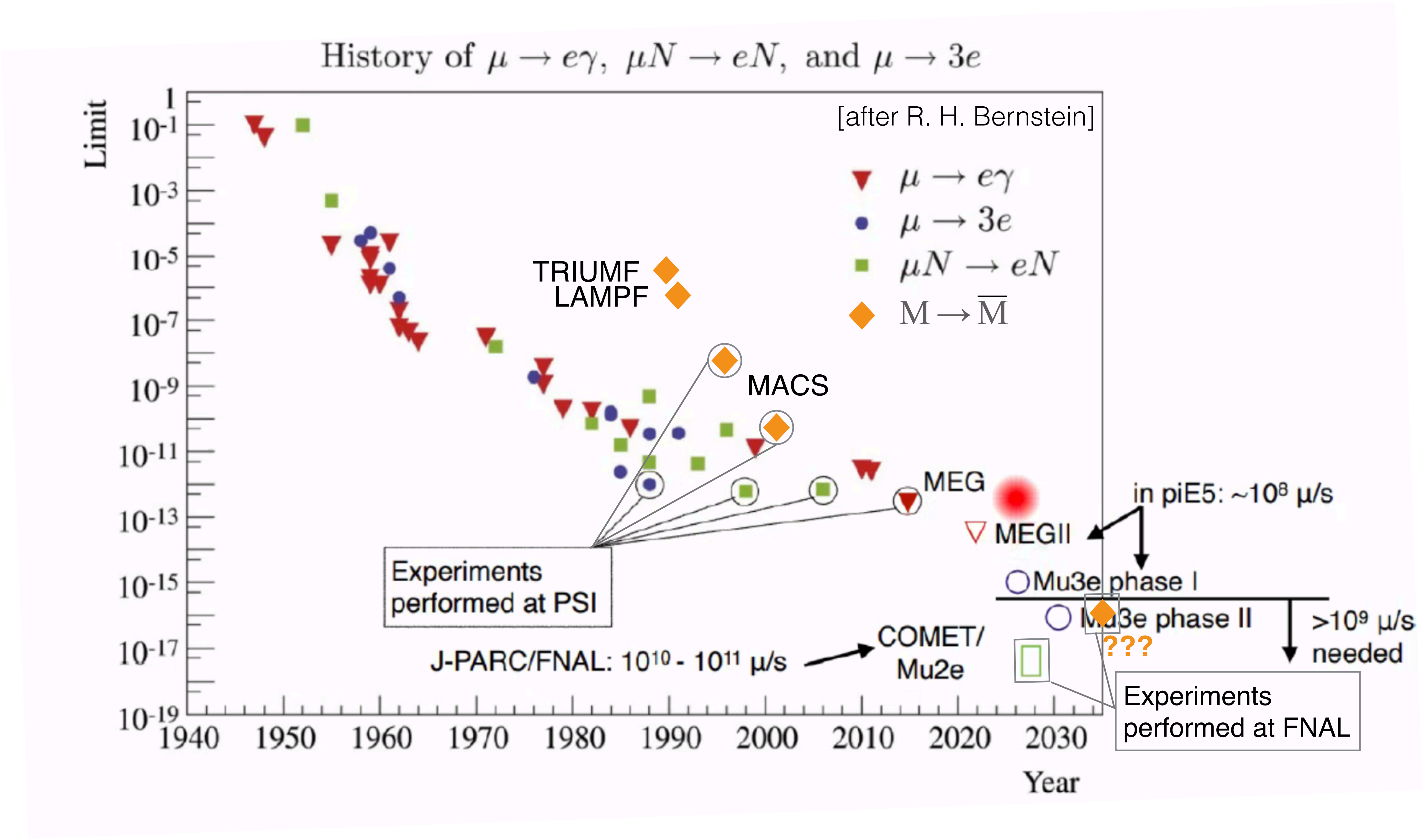

Brief R&D Goal Summary

- Determine and optimize MTA μ^+ yield
- Determine and optimize conditions to maintain drift field in SFHe ($\sim 10^8$ 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

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Would also enable μSR at MTA

Backup Slides

Examples of models possibly favoring M→$\overline{\text{M}}$

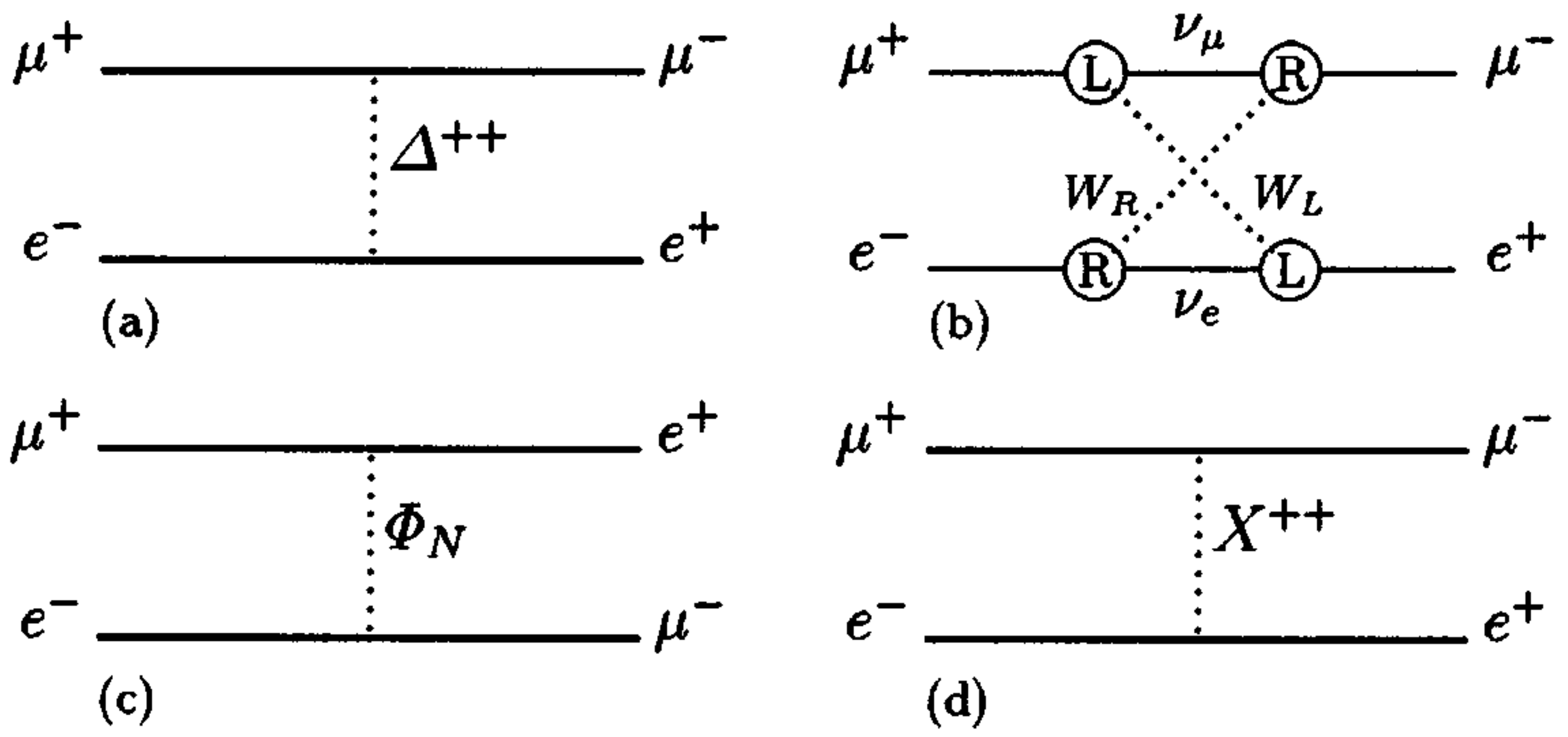


FIG. 1. Muonium-antimuonium conversion in theories beyond the standard model. The interaction could be mediated, e.g., by (a) doubly charged Higgs boson Δ^{++} [3,4], (b) heavy Majorana neutrinos [3], (c) a neutral scalar Φ_N [5], e.g., a supersymmetric τ-sneutrino $\tilde{\nu}_\tau$ [6,7], or (d) a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

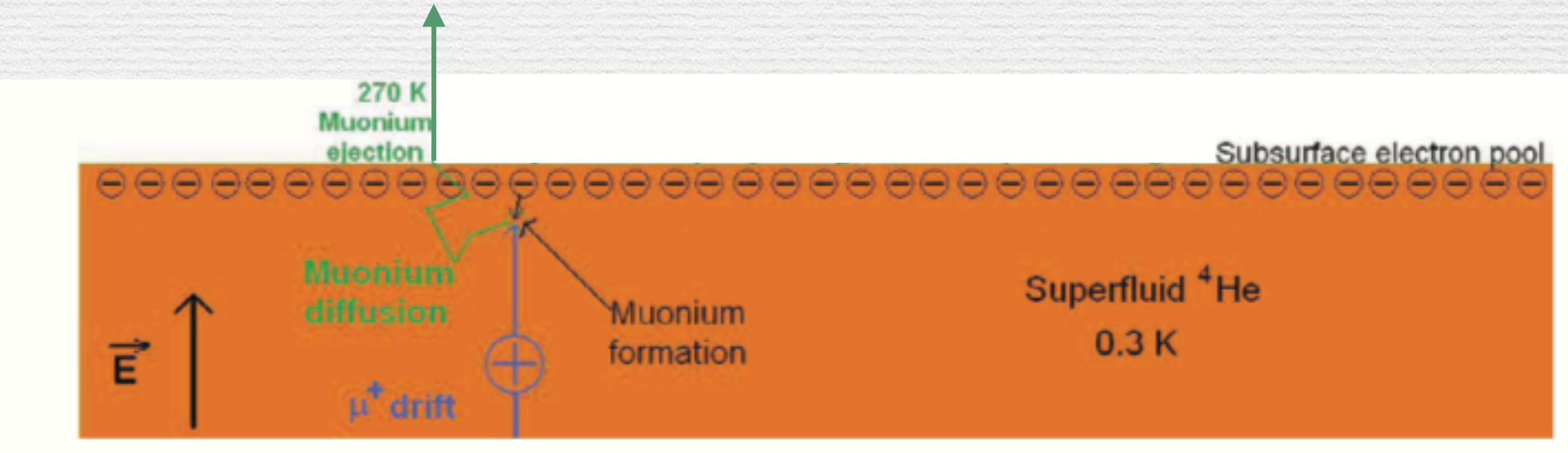
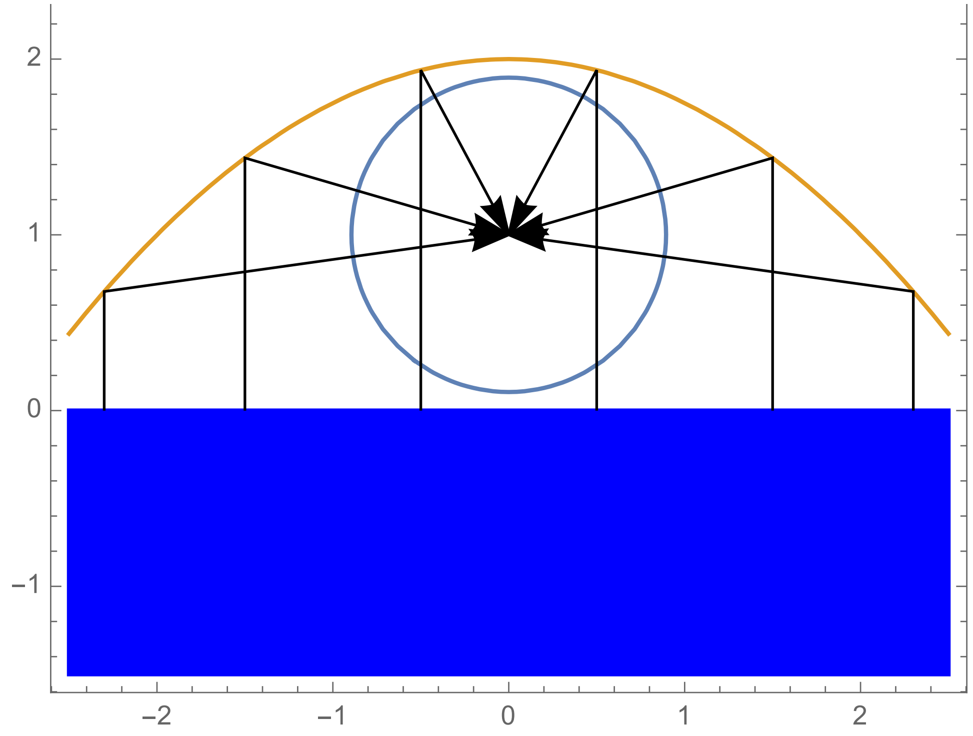


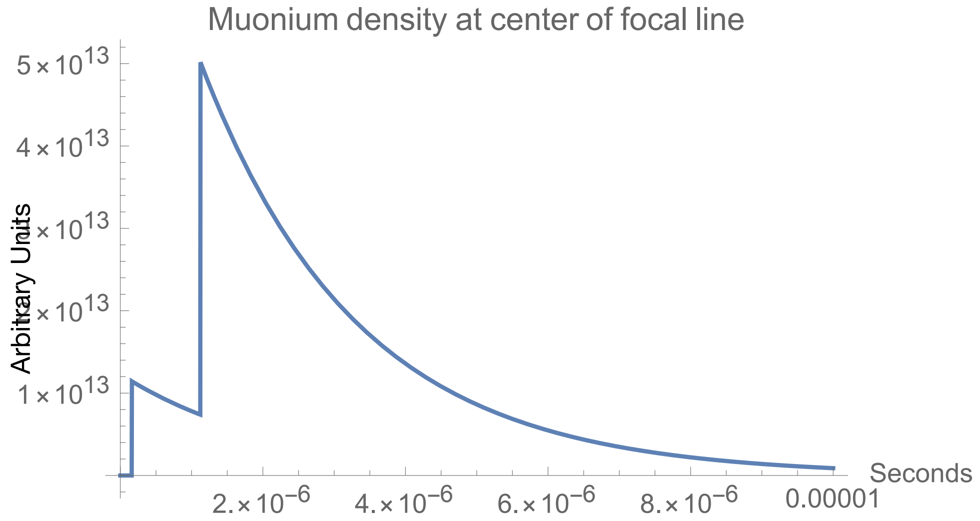
Figure after *D. Taqqu / Physics Procedia 17 (2011) 216-223*

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

$\Rightarrow$ would need additional dilution fridge to pursue both

Muonium Gravity Experiment

- Important feasibility questions:

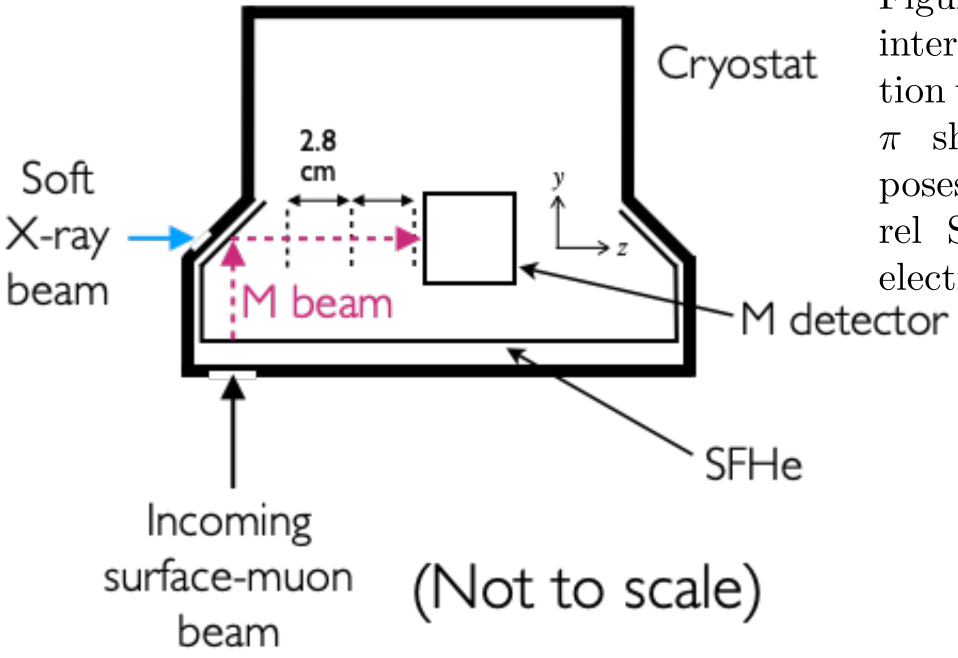
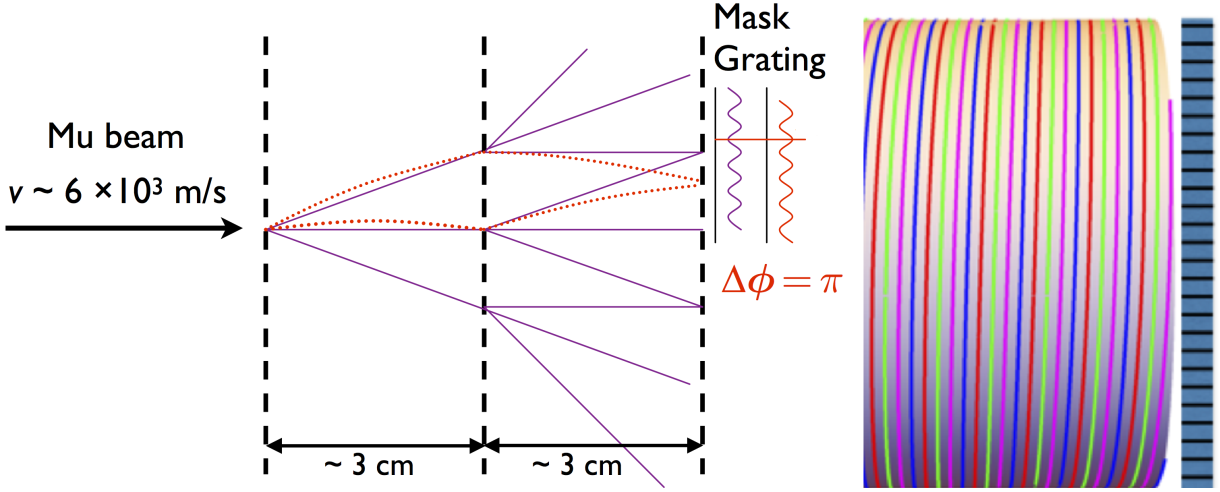


Figure 1: Principle of muonium interferometer, shown in elevation view (phase difference $\Delta\phi = \pi$ shown for illustrative purposes); Mu-decay detectors (barrel SciFi positron tracker and electron MCP) shown at right.



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

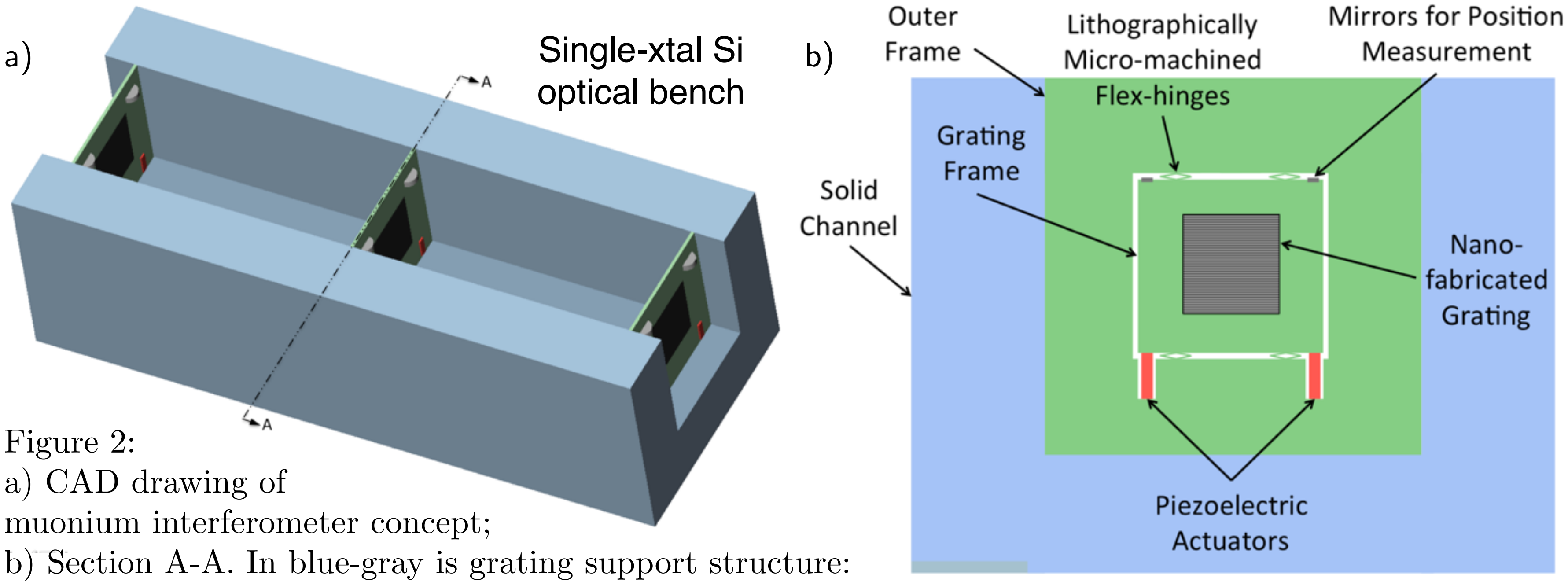


Figure 2:
a) CAD drawing of muonium interferometer concept;
b) Section A-A. In blue-gray is grating support structure: a U-channel machined out of a single-crystal silicon block. Each grating is mounted in a silicon frame connected to an outer frame by flex-hinges; piezo-actuator pair permits small rotations 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.

TFG precision (pm) vs. averaging time

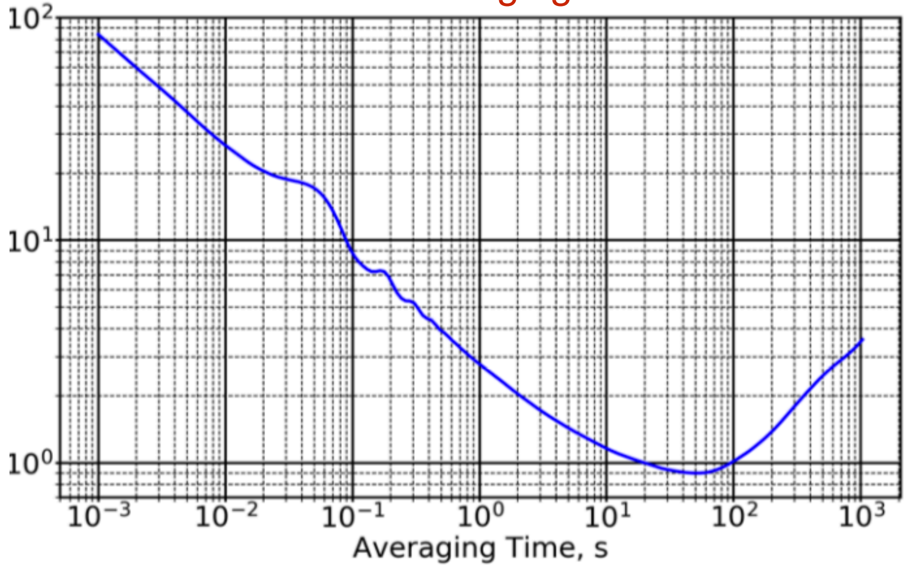


Figure 3. Allan deviation indicating TFG incremental-distance precision vs averaging time.

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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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