

Low-Energy Muon Physics – Experiment

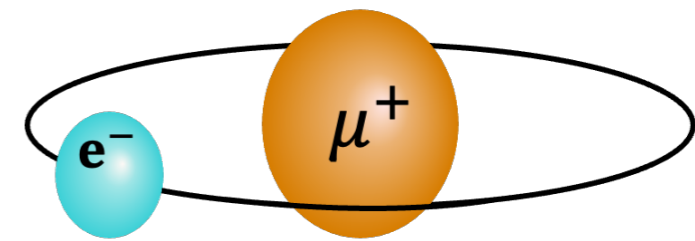
Daniel M. Kaplan



New Science and Applications at the SNS
Oak Ridge National Laboratory
10–12 June 2026

Outline

- Charged-lepton flavor violation
- Fundamental muon physics
- Muonium physics
- Cryogenic muonium source
- SNS vs. FNAL vs. PSI
- Conclusions



Charged-Lepton Flavor Violation

- Lepton-family number conserved? – **not understood!**
- Violations (CLFV) sought since soon after muon discovery!

$$\mu \rightarrow e\gamma, \mu^\pm \rightarrow e^\pm e^+ e^-, \mu \rightarrow e\gamma, \mu N \rightarrow eN$$

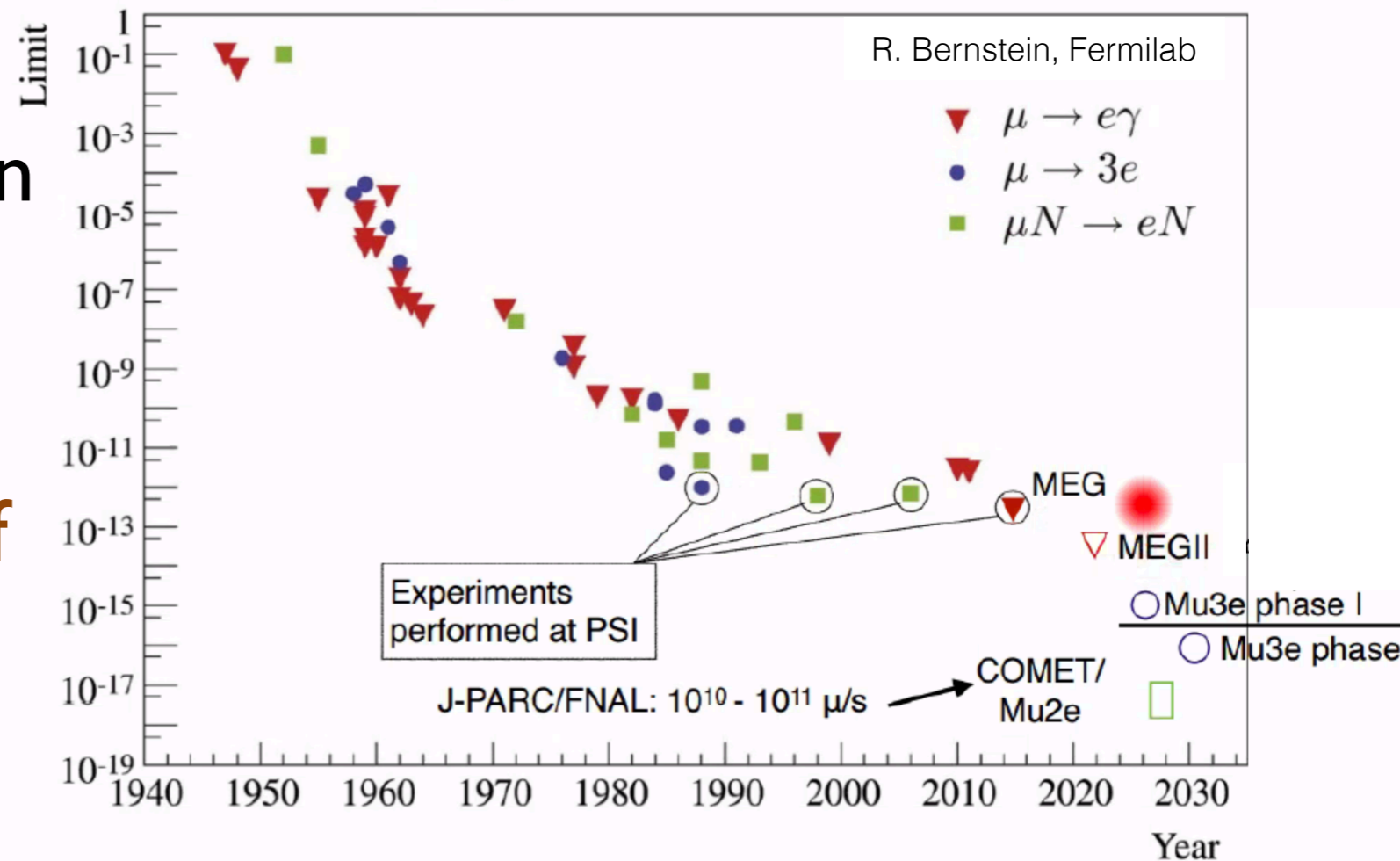
– no signal yet observed

- YET: neutrino oscillation (NLFV, e.g., $\nu_\mu \rightarrow \nu_e$) now well established

- Underlying symmetry of nature prevents CLFV?

– or accidental effect?

History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$



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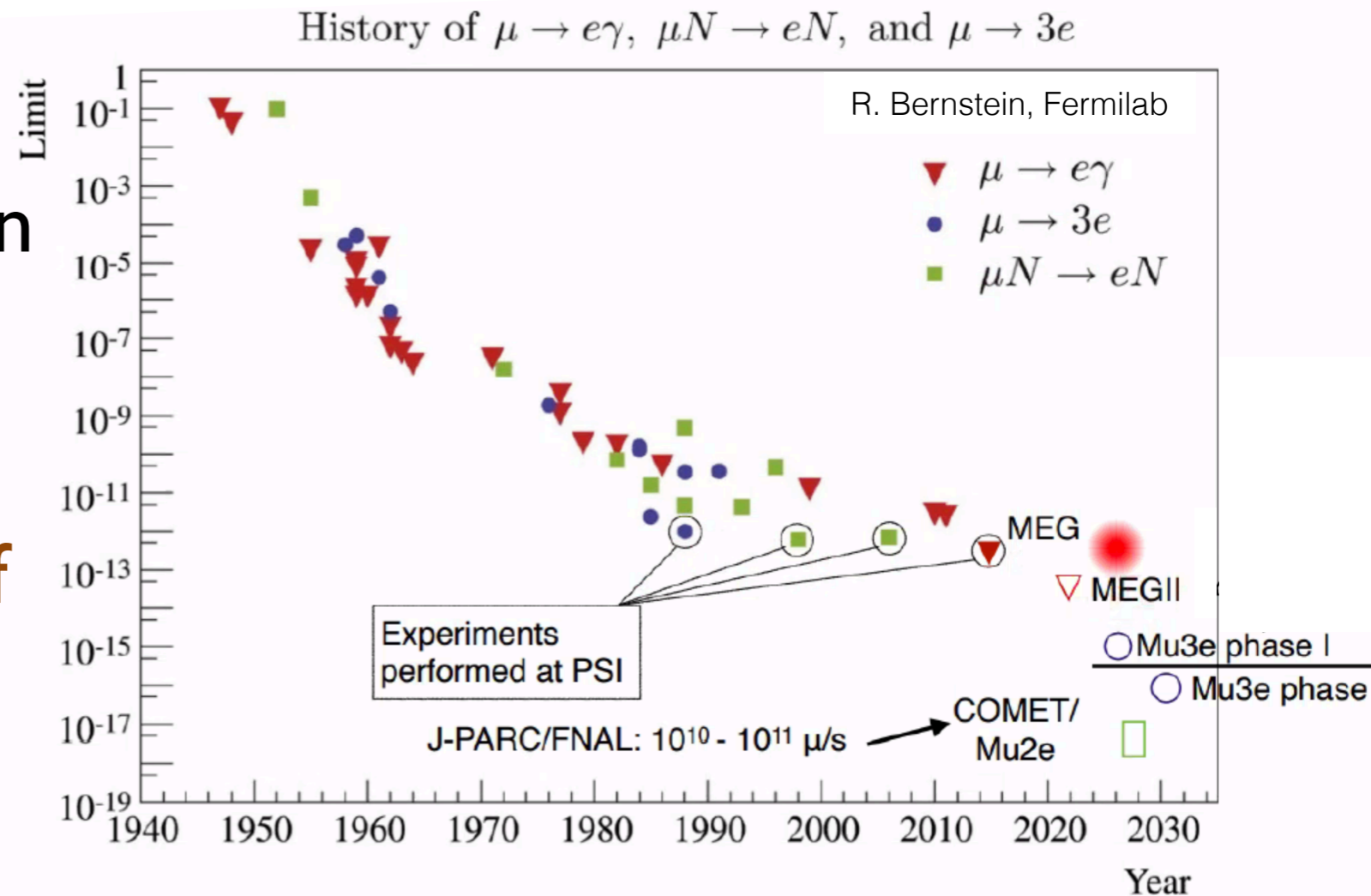
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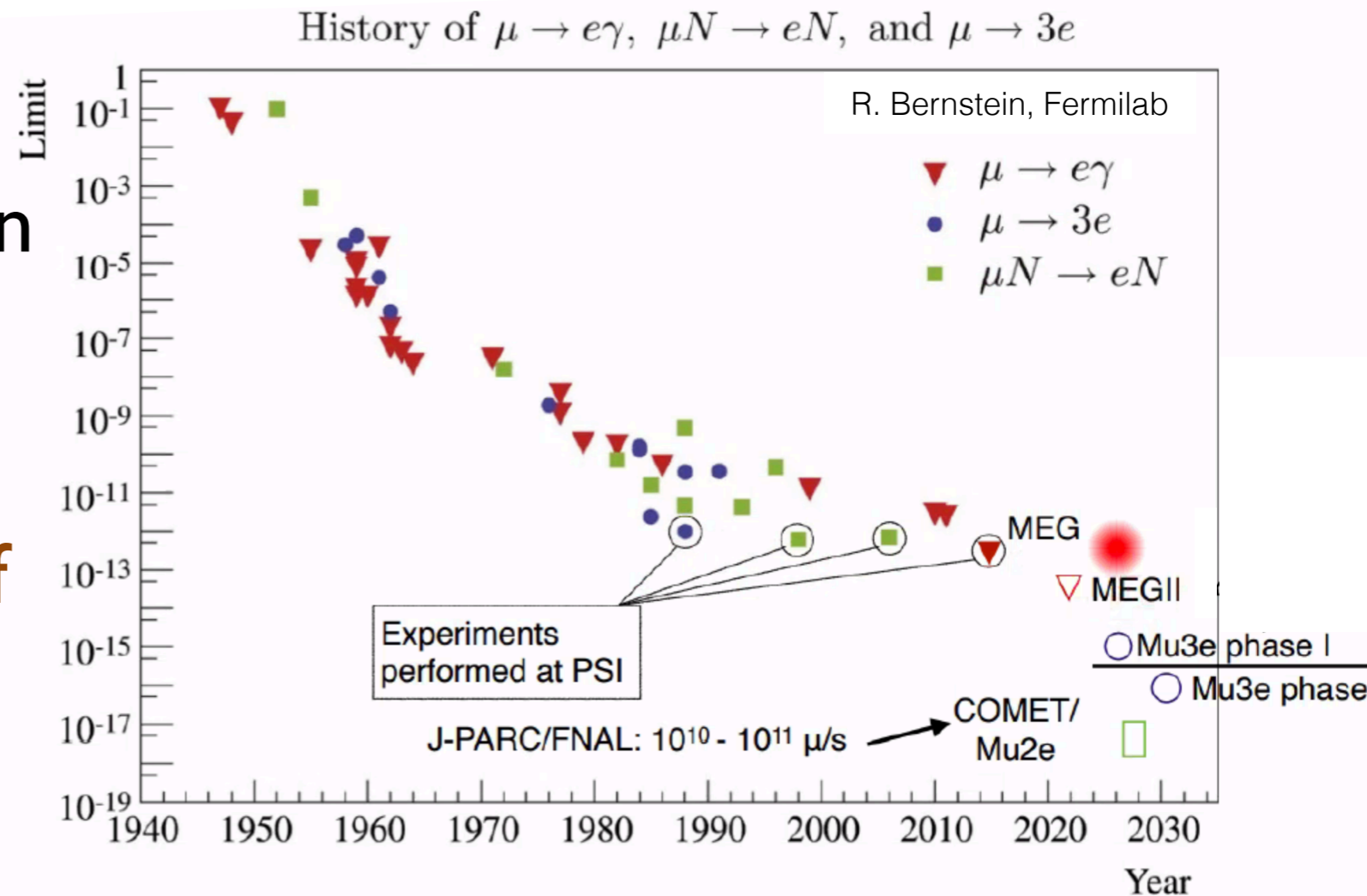
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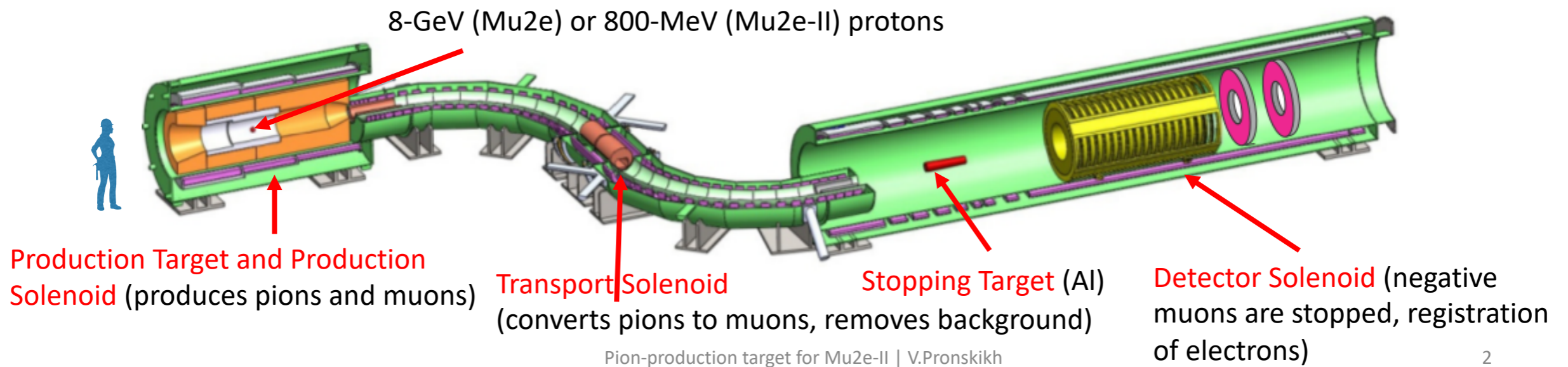
- Seeing *any* example would be very instructive!

→ muonium (M) → antimuonium (\bar{M})



Mu2e @ Fermilab

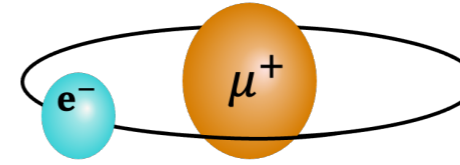
- The Mu2e experiment at Fermilab will search for evidence of charged-lepton flavor violation by observing the conversion of a negative muon into an electron in the Coulomb field of a nucleus without emission of neutrinos



- Status: installation & commissioning – aiming for 1st data in 2027
- Also COMET in Japan – on similar schedule

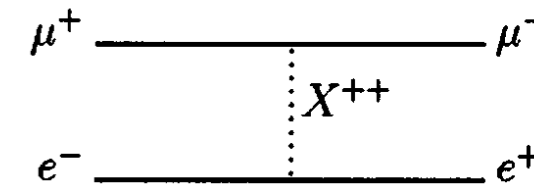
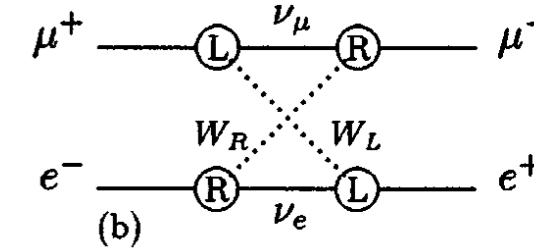
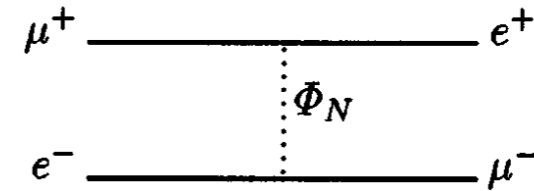
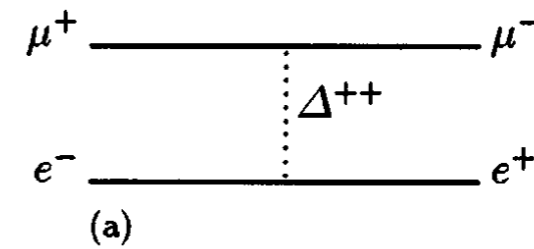
Key Muonium Measurements

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



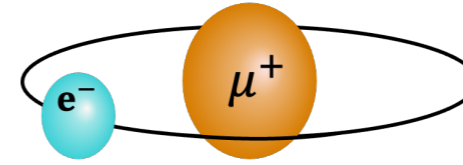
1. **Muonium-antimuonium ($M-\bar{M}$) oscillations:** complementary to $Mu2e$ — *differently* sensitive to CLFV new physics

- *both* should be sought as sensitively as possible

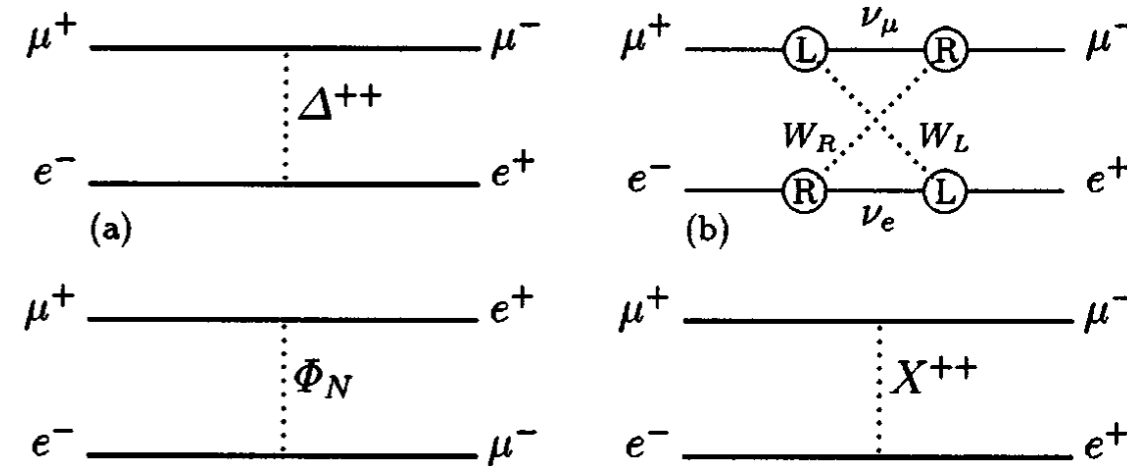


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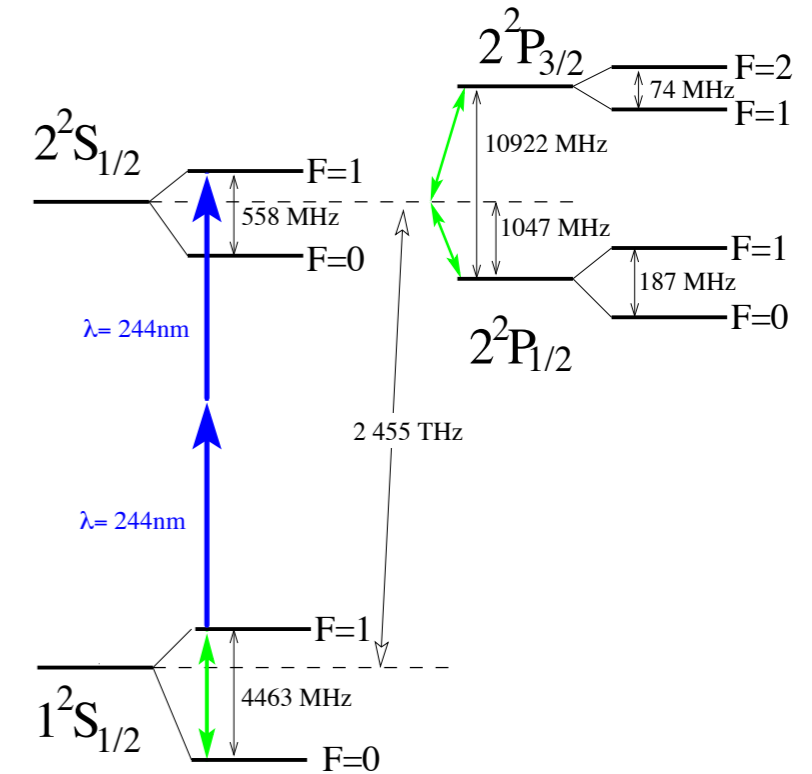


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2. **Muonium spectroscopy:**

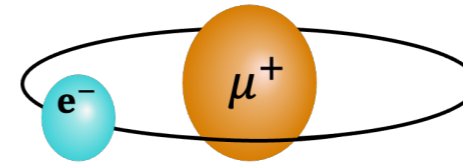
atomic levels exquisitely predicted by QED (neither strong nor finite-size corrections)

→ clear windows for new physics

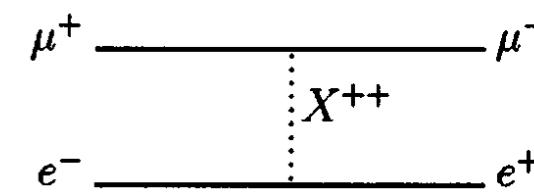
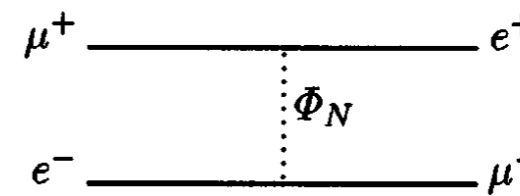
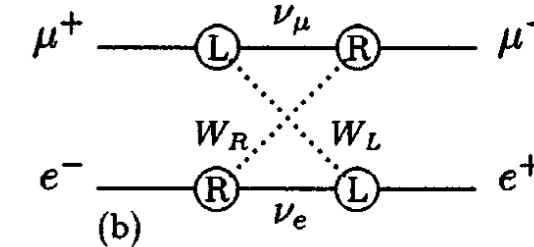
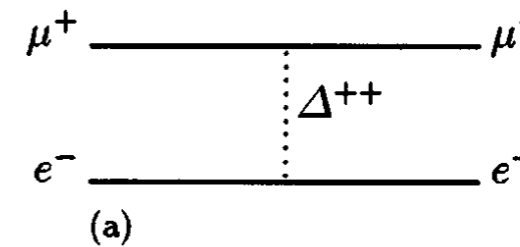


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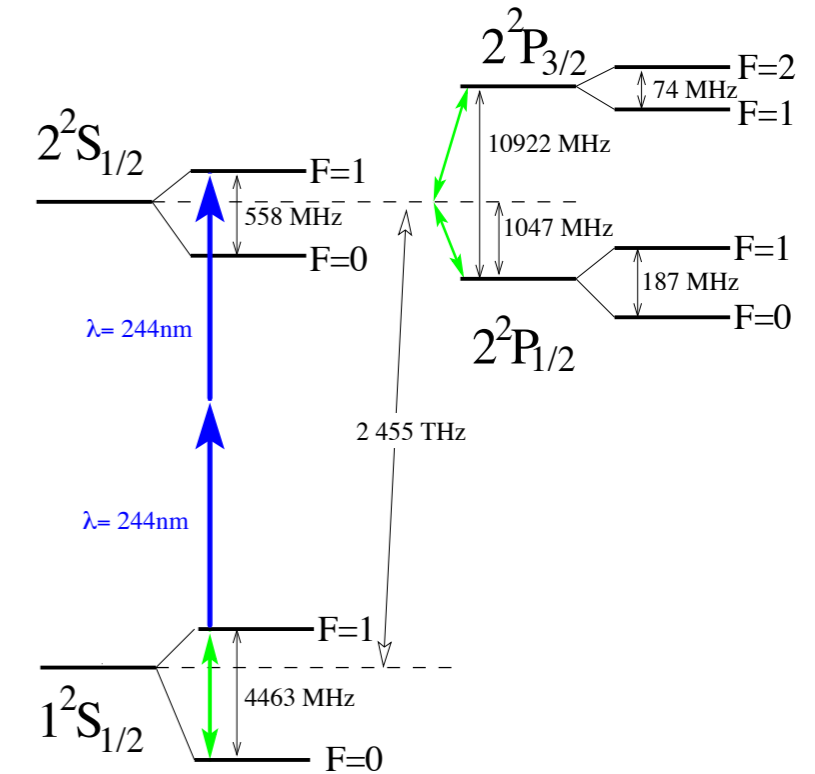
3. **Muonium gravity:** “tabletop” experiment sensitive to possible 5th force

- $g-2$, leptonic B , & W -mass anomalies → renewed interest

- now know antihydrogen falls down!

ALPHA-G: $\bar{g}/g = 0.75 \pm 0.13$ (stat. + syst.) ± 0.16 (sim) *

- *only* way to test 2nd generation's, and leptons', gravitational couplings



* E. K. Anderson *et al.*, Nature **621** (Sept. 2023) 716

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]

- decays to e^+ (fast) + e^- (slow), $\tau_M = \tau_\mu = 2.2 \mu\text{s}$ (bound-state correction $\sim 10^{-10}$)

[A. Czarnecki, G. P. Lepage, W. Marciano, Phys. Rev. D **61** (2000) 073001]

- readily produced when μ^+ stop in matter

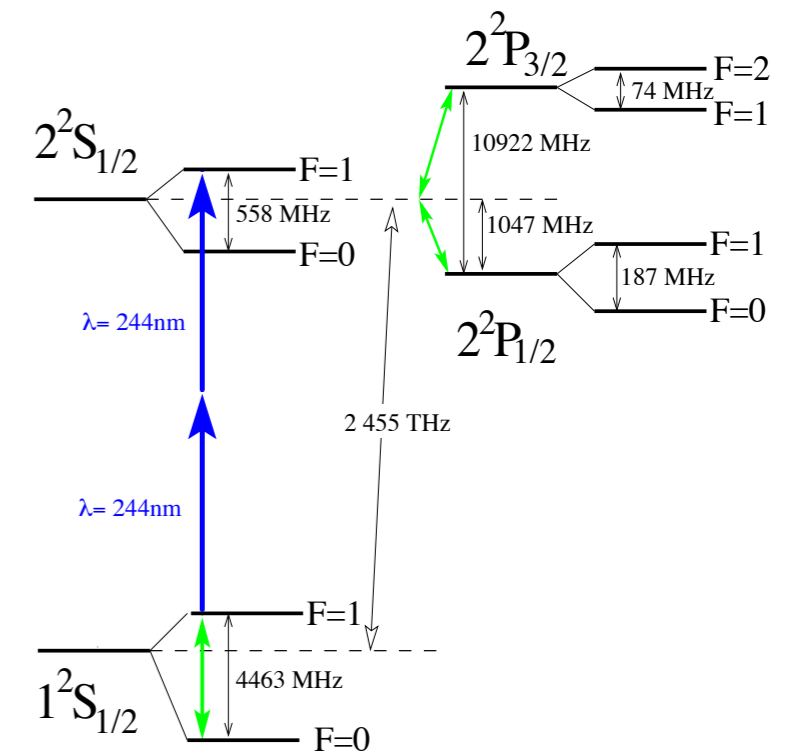
- chemically, almost identical to hydrogen

- atomic spectroscopy well studied

- free of hadronic & finite-size effects
 \Rightarrow "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

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

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

- Nothing forbids it *except* lepton-flavor conservation

— which we know (ν mixing) is violated!

▶ but $M \leftrightarrow \bar{M}$ via virtual ν mixing negligible

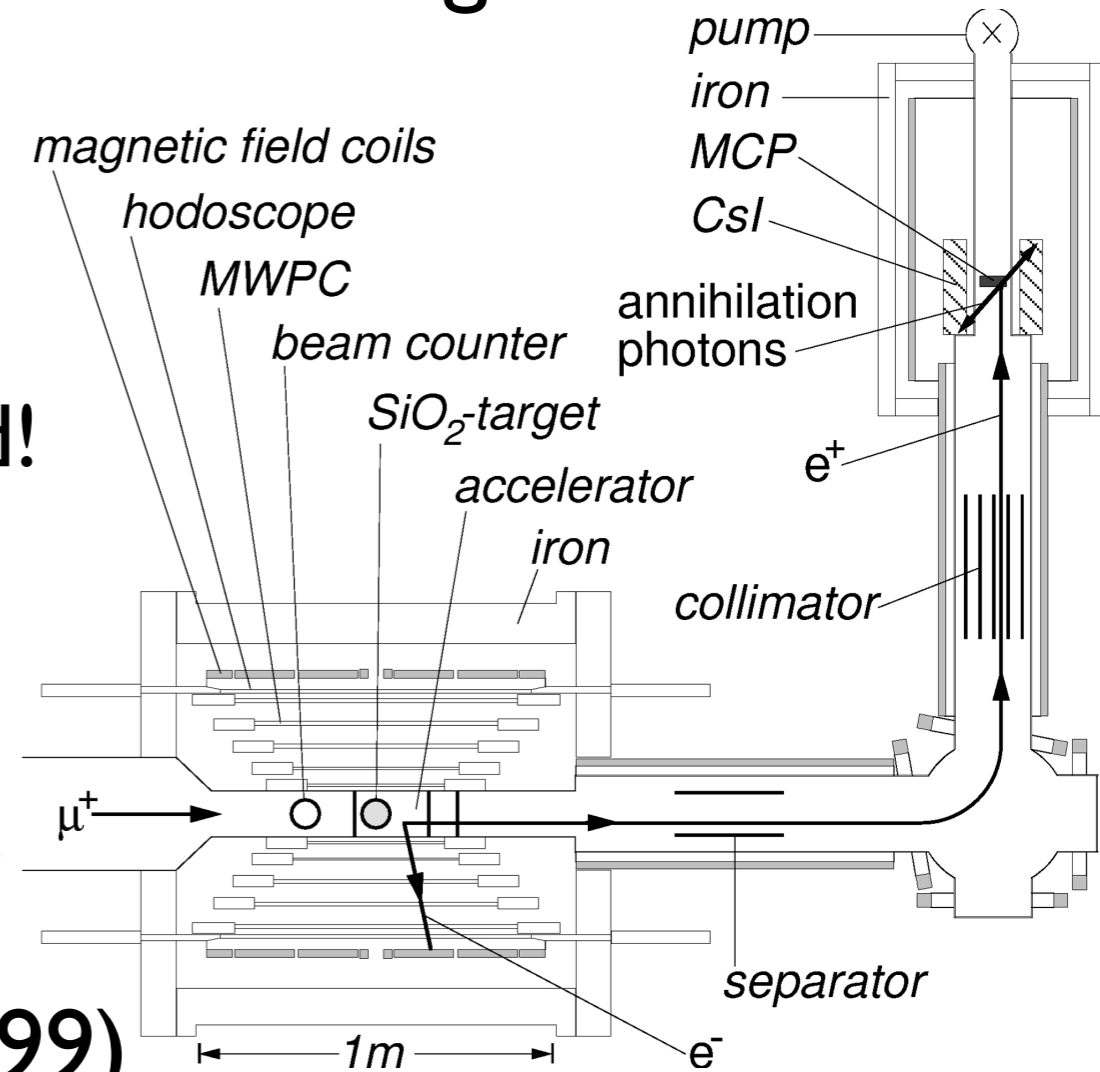
▶ \approx background-free search for new physics!

▶ in some models, more likely than $\mu N \rightarrow e N$

- Best limit to date set by MACS (1999)

at PSI: $P_{M\bar{M}} \leq 8.3 \times 10^{-11}$ (90% C.L.)

in 0.1 T field



[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
- ... (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

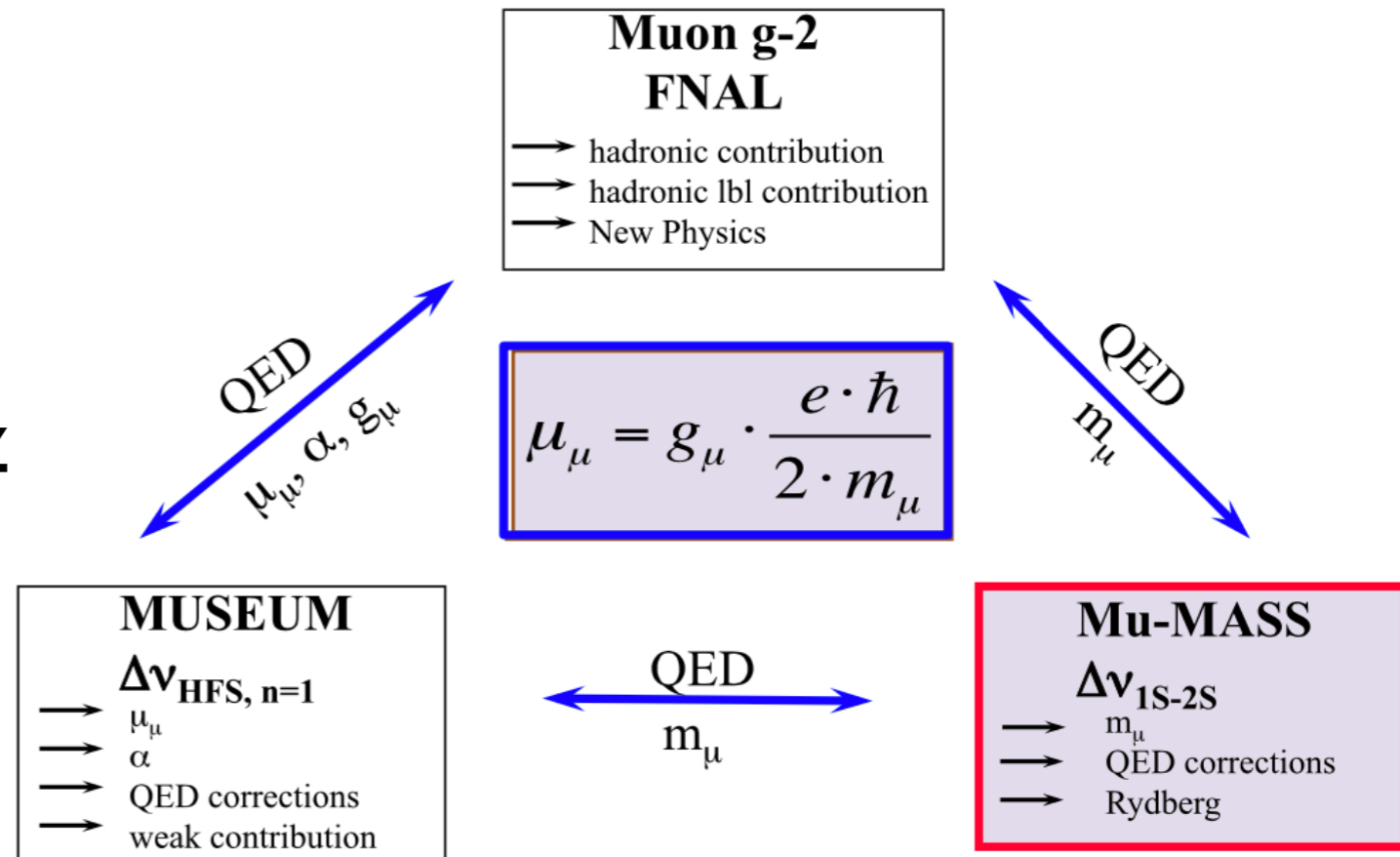


Fig. 1 Fundamental constants in the muon sector and related experiments (adapted from [42])

▶ hadronic & finite-size corrections negligible

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

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

[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)]

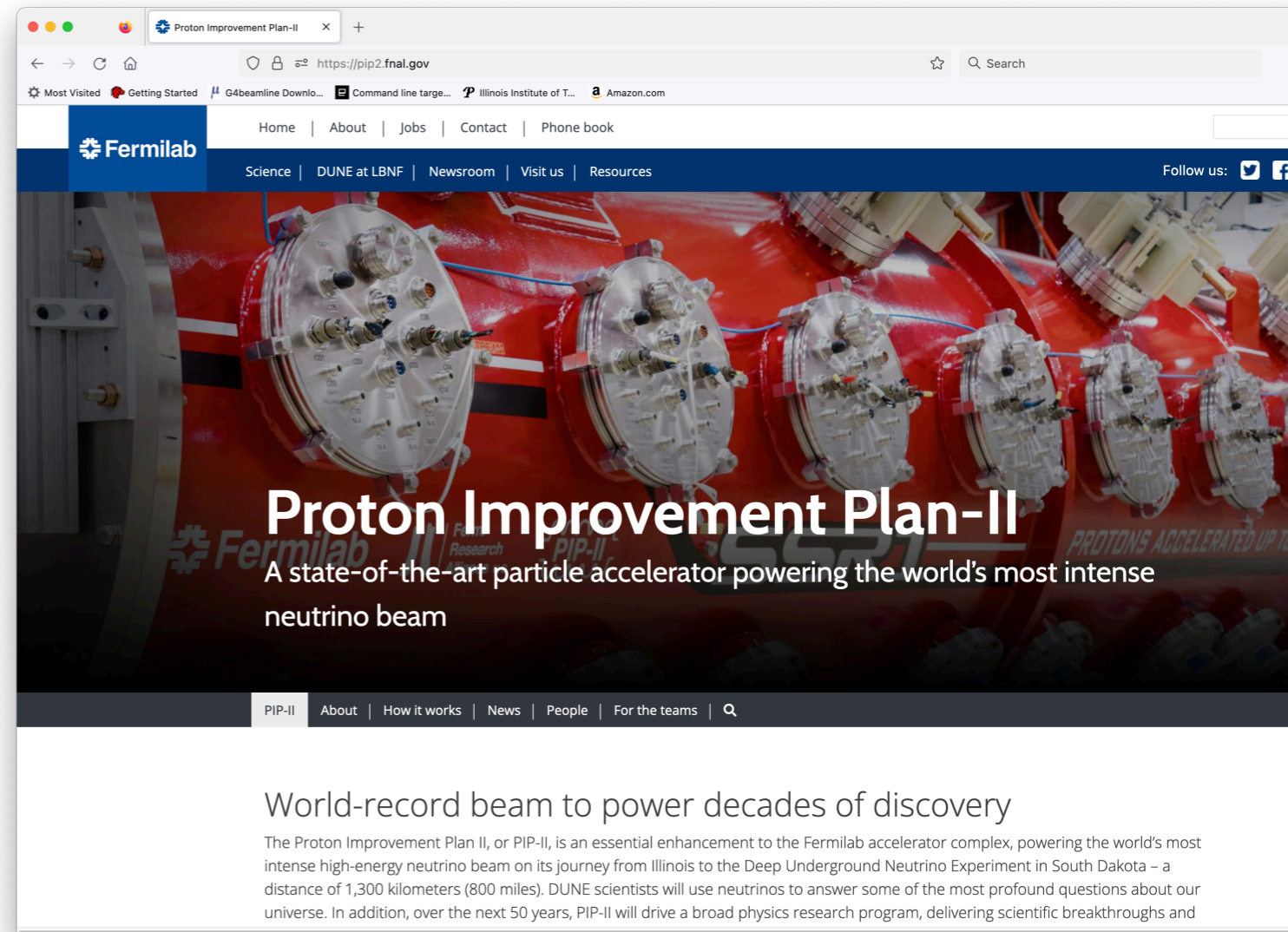
Muonium Spectroscopy

- New IS-2S experiment, Mu-MASS, now in R&D/commissioning stage at PSI

PIP-II: 800 MeV SC proton linac

- goal: improve sensitivity $\times 1000$ (< 10 kHz), 4 ppt
- systematics dominated
 - PIP-II muon rate (~ 2 orders higher than current PSI) would help!

➔ better systematics handle



- MUSEUM hyperfine experiment, in progress at J-PARC

- goal: improve hyperfine sensitivity $\times 10$ (1 ppb)

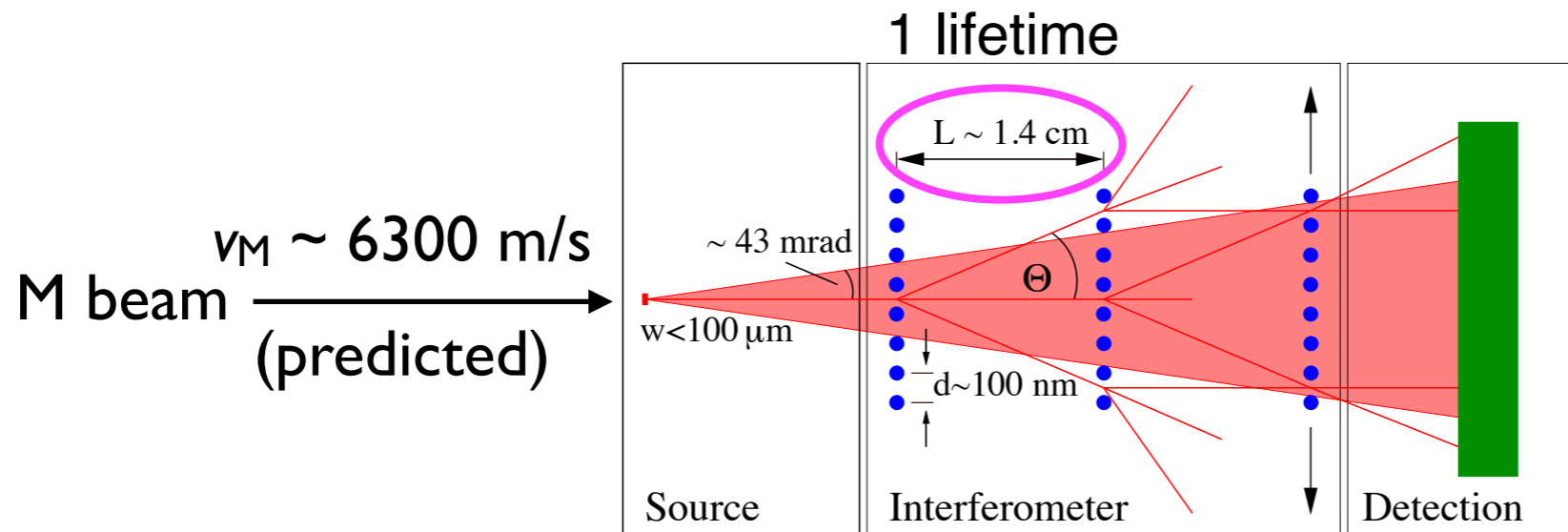
Testing Gravity with Muonium

K. Kirch*

Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland

(Dated: February 2, 2008)

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



$$\frac{1}{2} g t^2 = 24 \text{ pm!}$$

but grows as $t^2 \Rightarrow$
easier problem with
old muonium

- Inspiration: T. Phillips' proposed $\bar{\text{H}}$ gravitational interferometer

- Need

[T.J. Phillips, "Antimatter gravity studies with interferometry," *Hyp. Int.* **109** (1997) 357]

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

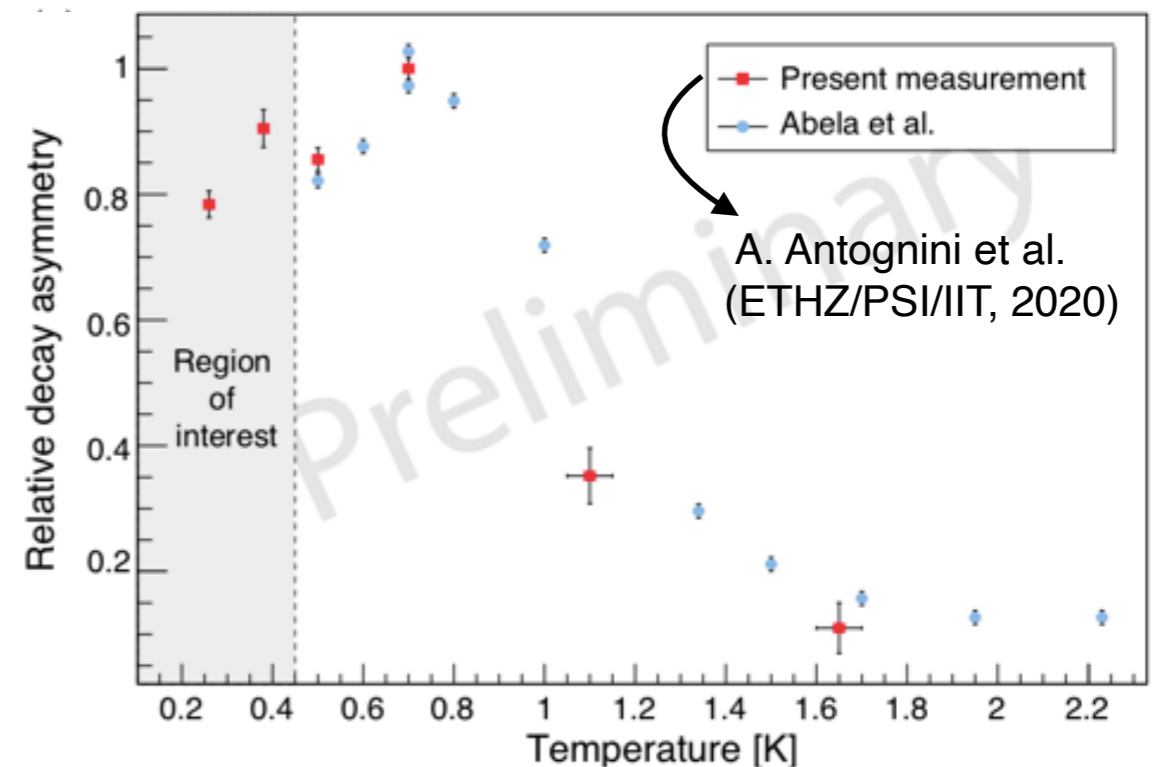
Novel Cryogenic M Source

- 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 $\sim \mu\text{m}$ -thick layer of superfluid He (SFHe)
 - or (T. Phillips, IIT/Muons) use $\sim 100 \mu\text{m}$ SFHe layer for $\sim 10^2 \uparrow$ intensity?

H immiscible in SFHe $\Rightarrow \mu\text{M}$ should expel M atoms at 6,300 m/s, \perp to SFHe surface

- R&D in progress @ PSI
- essential for M gravity, potential game-changer for others



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

V. G. Luppov

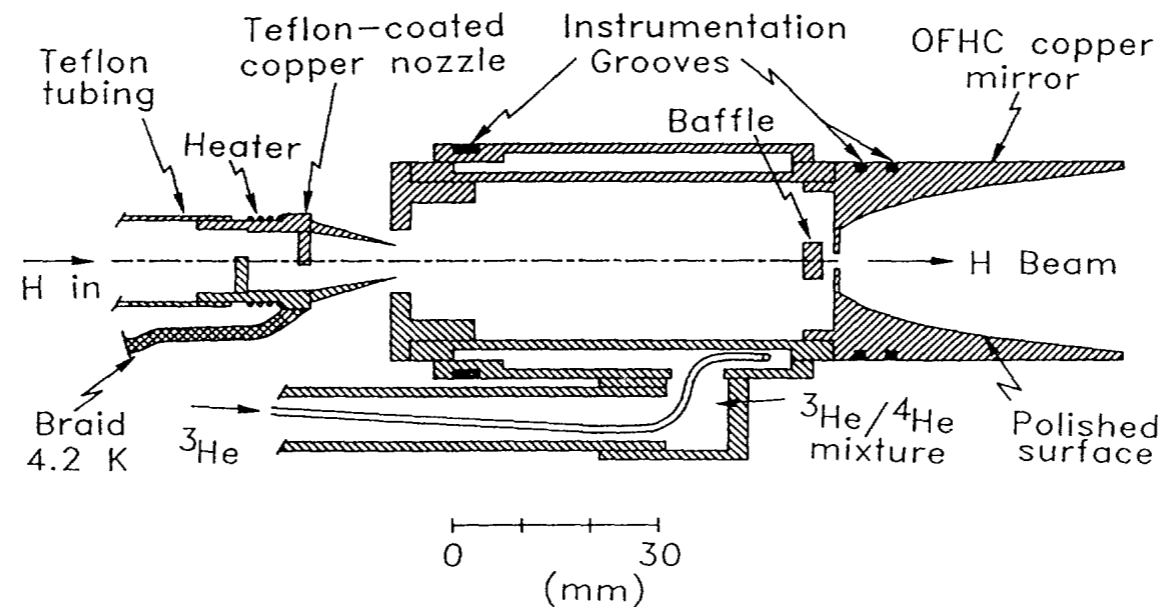
*Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
and Joint Institute for Nuclear Research, Dubna, Russia*

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 ^4He . 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.



- SFHe H mirror an established technique

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

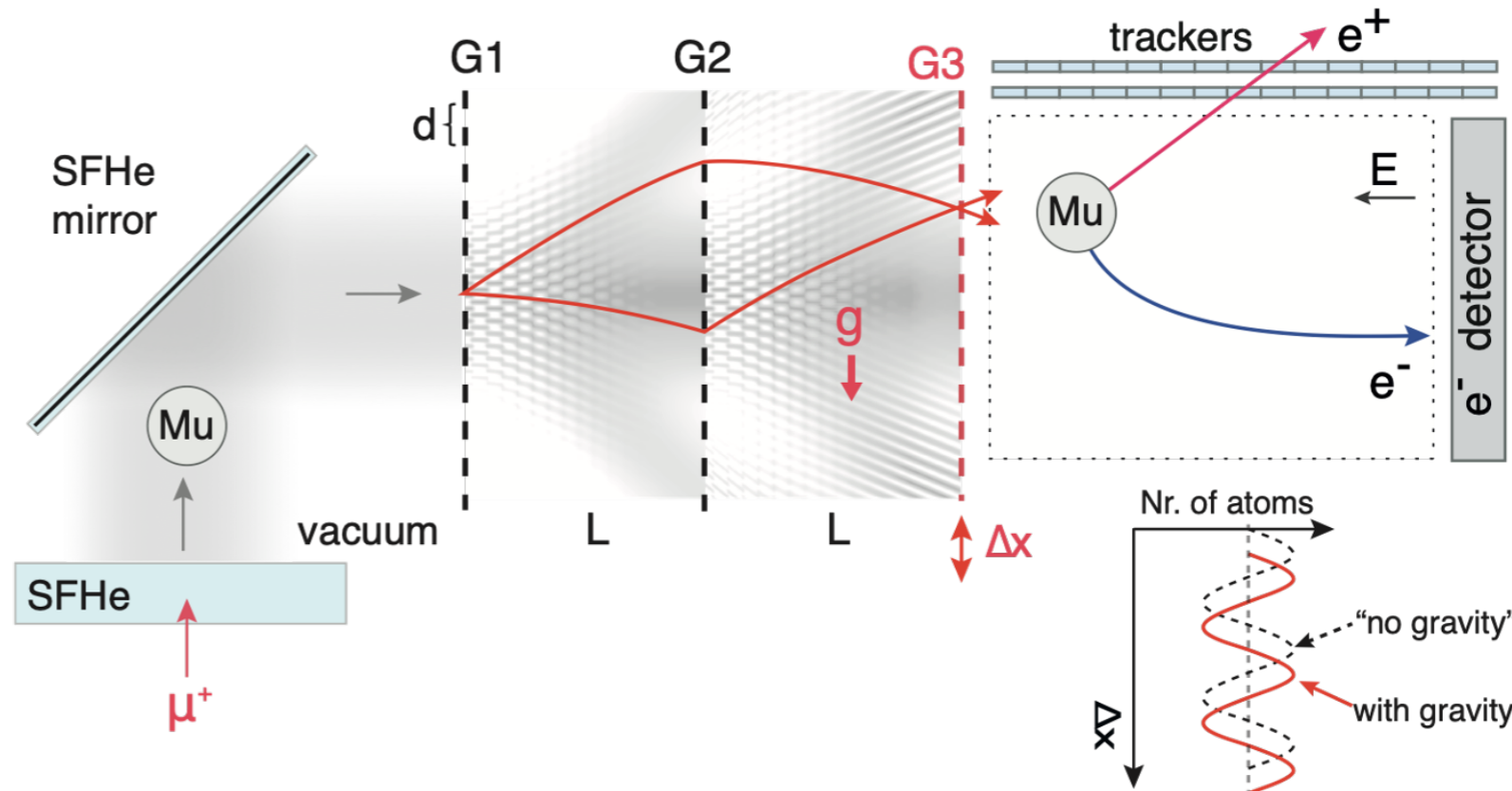
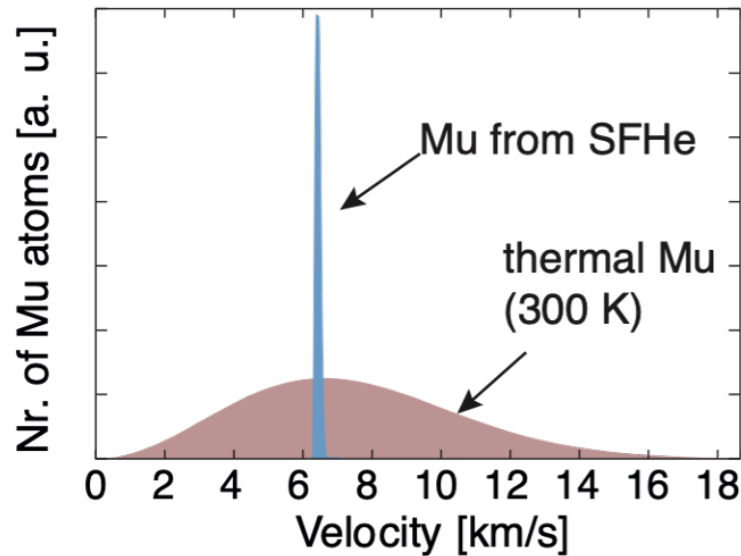
The LEMING experiment at PSI, Switzerland



Cold beam

Interferometry

Detection



- ▶ **LEMING: LE**ptons in **MU**onium **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

In R&D phase

[doi: 10.21468/SciPostPhysProc.5.031](https://doi.org/10.21468/SciPostPhysProc.5.031)

Anna Soter, ETH Zurich

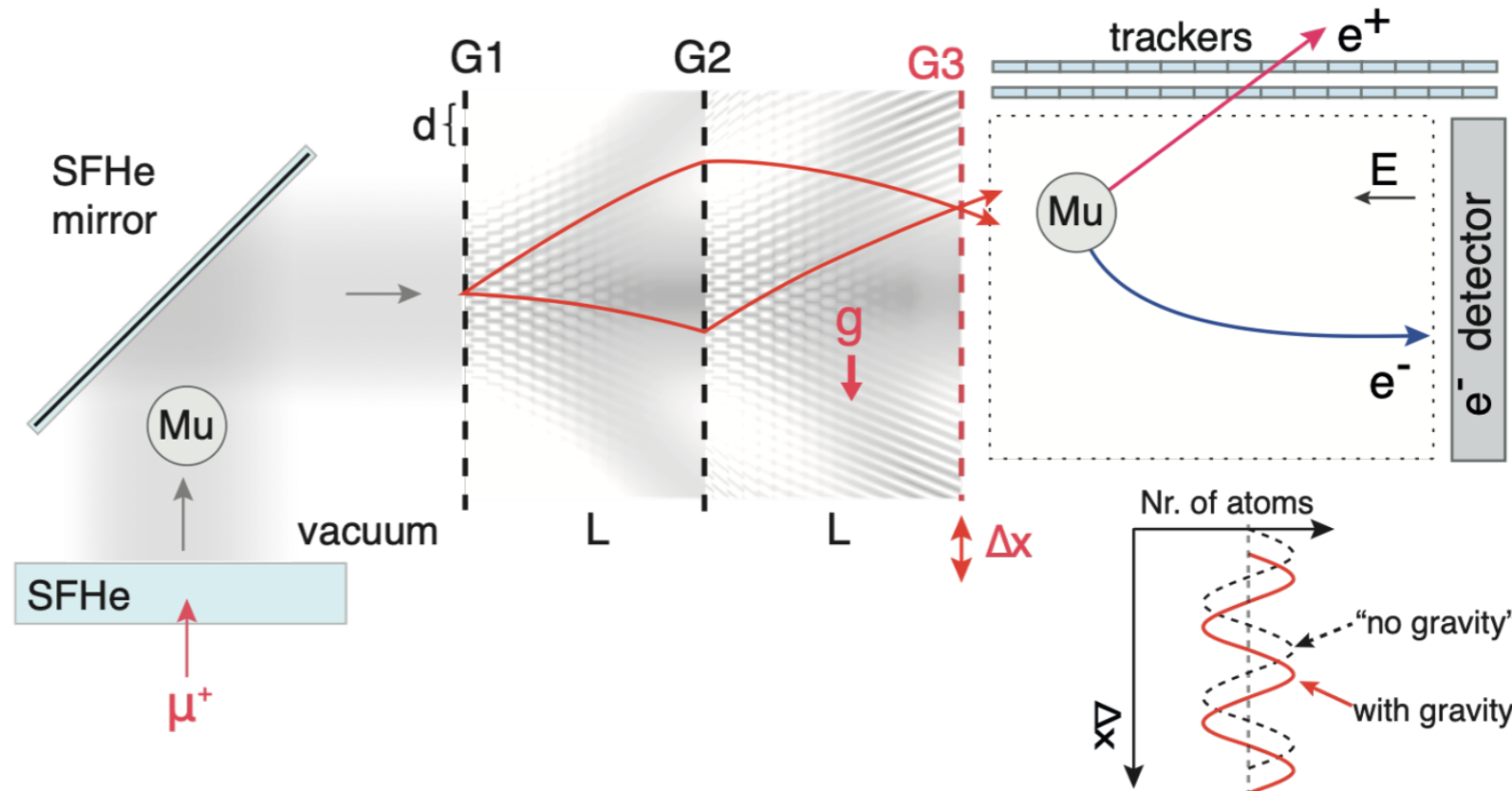
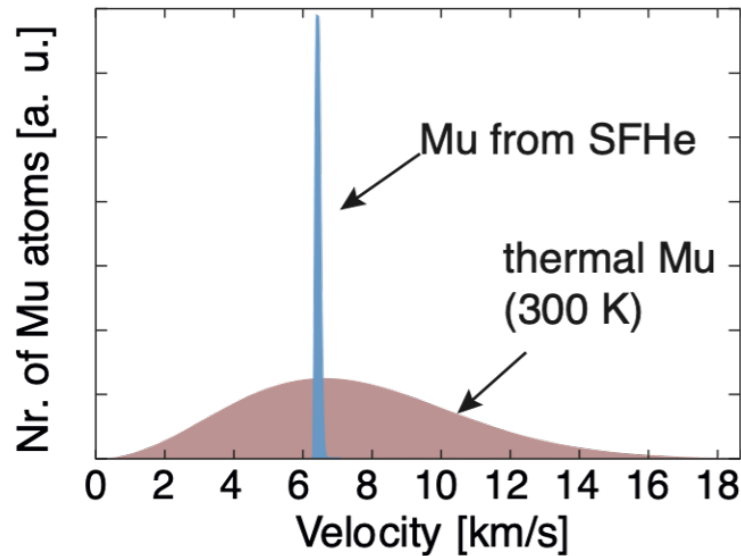
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Anna Soter, ETH Zurich

Latest: J. Zhang et al., arXiv:2512.19923: $\langle v_M \rangle \approx 2180$ m/s?



Editors' Suggestion

Make M beam stoppable in $\sim \mu\text{m}$ -thick SFHe layer

Demonstration of Muon-Beam Transverse Phase-Space Compression

A. Antognini^{1,2,*}, N. J. Ayres¹, I. Belosevic^{1,†}, V. Bondar¹, A. Eggenberger¹, M. Hildebrandt², R. Iwai¹,
 D. M. Kaplan³, K. S. Khaw^{1,‡}, K. Kirch^{1,2}, A. Knecht², A. Papa^{2,4}, C. Petitjean², T. J. Phillips³,
 F. M. Piegsa^{1,§}, N. Ritjoho², A. Stoykov², D. Taqqu¹ and G. Wichmann^{1,||}

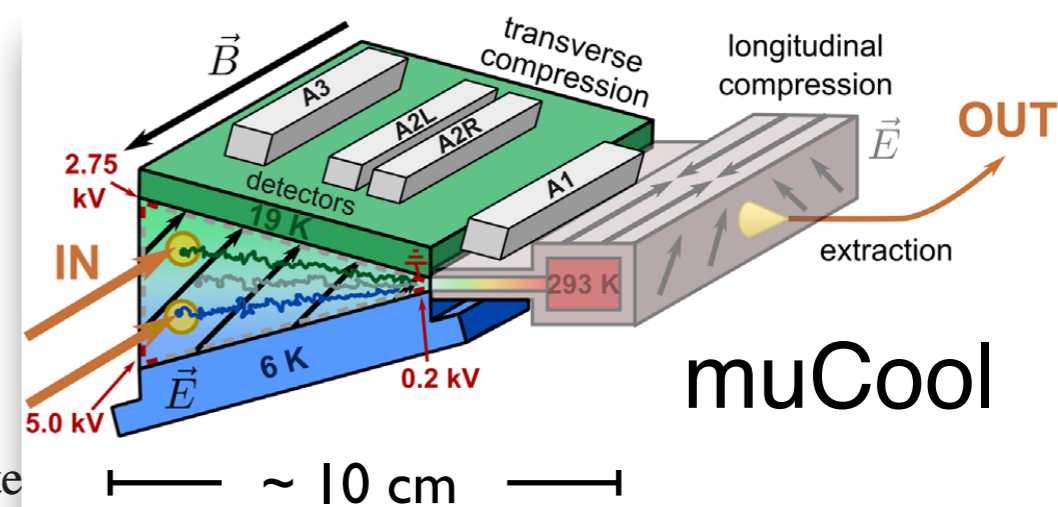
(muCool Collaboration)

¹Institute for Particle Physics and Astrophysics, ETH Zürich

²Paul Scherrer Institute, 5232 Villigen-PS

³Illinois Institute of Technology, Chicago, Ill

⁴Dipartimento di Fisica, Università di Pisa and INFN sez. Pisa, La



muCool

(Received 5 April 2020; revised 17 August 2020; accepted 15 September 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 ($\mu^+ \leftrightarrow \text{muonium}$) 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 \rightarrow gateway to J-PARC $g-2$ expt

muCool @ PSI

SciPost

SciPost Phys. Core 8, 071 (2025)

Make M beam stoppable in $\sim \mu\text{m}$ -thick SFHe layer

Phase space compression of a positive muon beam in two spatial dimensions

A. Antognini^{1,2*}, N. J. Ayres¹, I. Belosevic¹, V. Bondar¹, A. Eggenberger¹,
M. Hildebrandt², R. Iwai^{1†}, K. Kirch^{1,2}, A. Knecht², G. Lospalluto¹, J. Nuber²,
A. Papa^{2,3}, M. Sakurai¹, I. Solovyev^{1,4}, D. Taqqu² and T. Yan^{1,4}

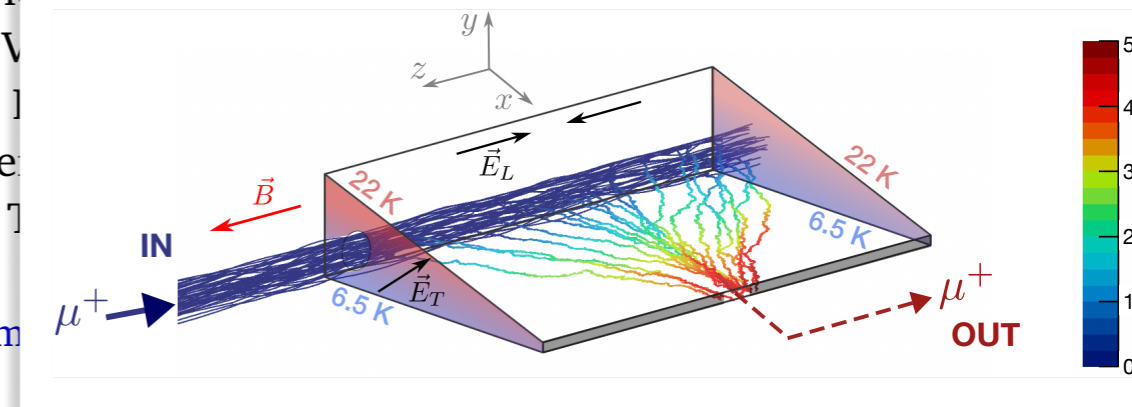
1 Institute for Particle Physics and Astrophysics, ETH Zurich

2 PSI Center for Neutron and Muon Sciences, 5232 V

3 University of Pisa and INFN, 56126 I

4 School of Physics and Center for Excellence in High Energy Physics, Suranaree University of Technology, Thailand

* aldo@phys.ethz.ch, † iwai@frib.msu.edu



Abstract

We present the first demonstration of simultaneous phase space compression in two spatial dimensions of a positive muon beam, the first stage of the novel high-brightness muon beam under development by the muCool collaboration at the Paul Scherrer Institute. The keV-energy, sub-mm size beam would enable a **factor 10^5 improvement in brightness** for precision μSR , and atomic and particle physics measurements with positive muons. This compression is achieved within a cryogenic helium gas target with a strong density gradient, placed in a homogeneous magnetic field, under the influence of a complex electric field. In the next phase, the muon beam will be extracted into vacuum.

muCool @ PSI

SciPost

SciPost Phys. Core 8, 071 (2025)

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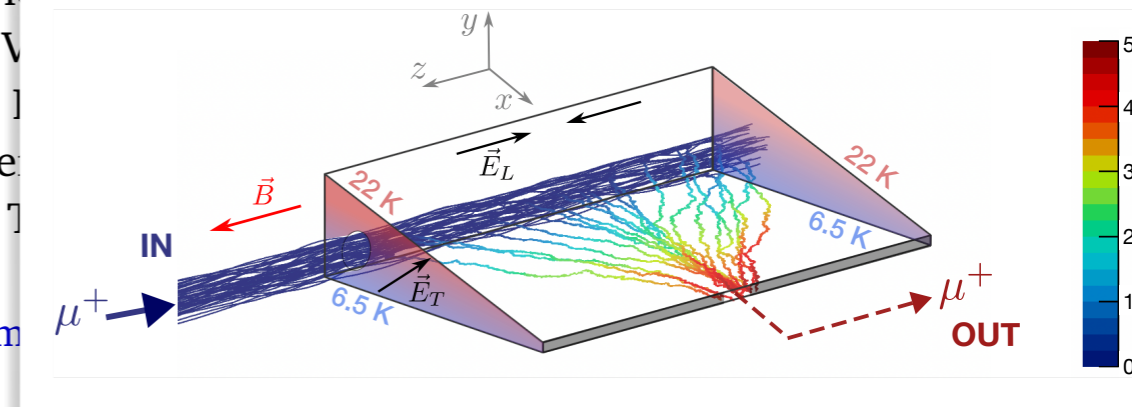
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4 School of Physics and Center for Excellence in High Energy Physics, Suranaree University of Technology, T

* aldo@phys.ethz.ch, † iwai@frib.m



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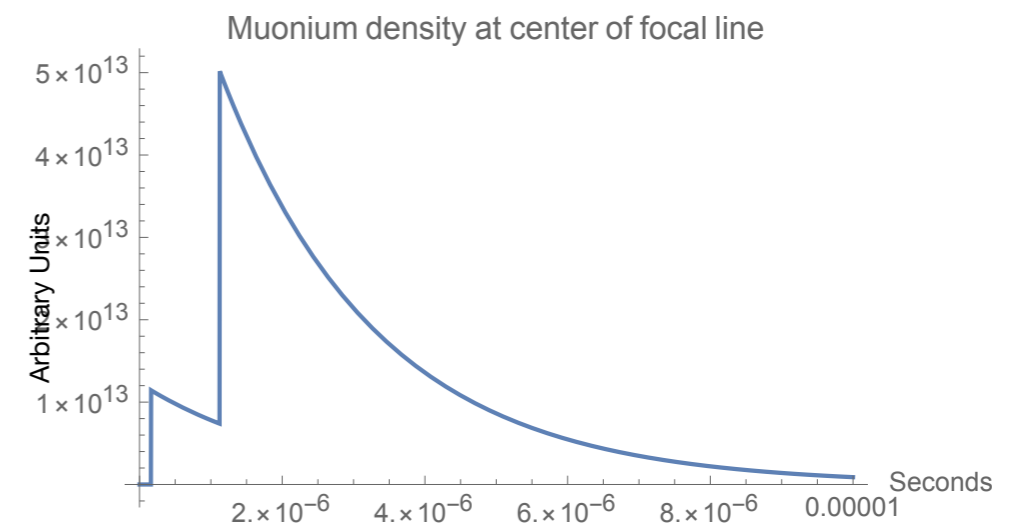
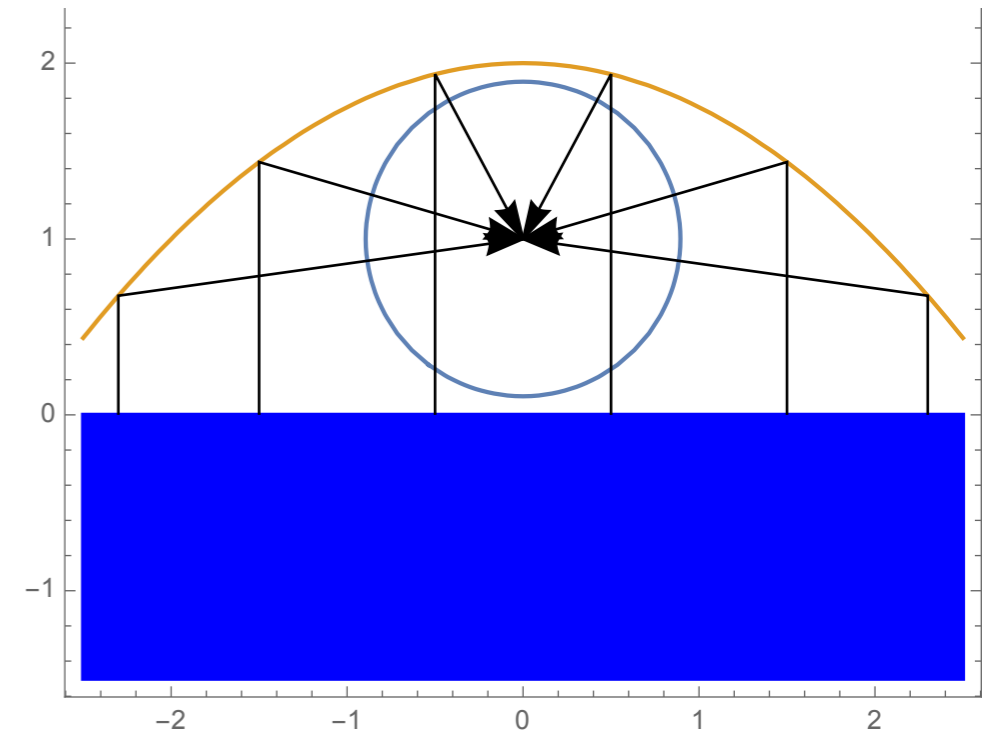
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10^9 compression,
 10^{-4} efficiency

Making Cold μ^+ from M

T. Phillips

- 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 $\approx 5X$ (dep. on beam size & concentrator height)



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: $p_\mu \approx 40 \text{ MeV}/c$
Mu2e with PIP-II	10^{12}	pulsed	Not surface muons: $p_\mu \approx 40 \text{ MeV}/c$

[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**, μ SR (MatSci, chemistry), μ CF R&D...
- **Oversubscribed, none in U.S.**
- **PSI: current world leader**
 - **> x10 upgrade ("HIMB") in the works**
- **PIP-II could surpass HIMB (by $\sim \times 10^2$?)**
- **Is SNS Linac potentially competitive with PSI/HIMB???**
 - **at minimum, invaluable near-term R&D opportunity**

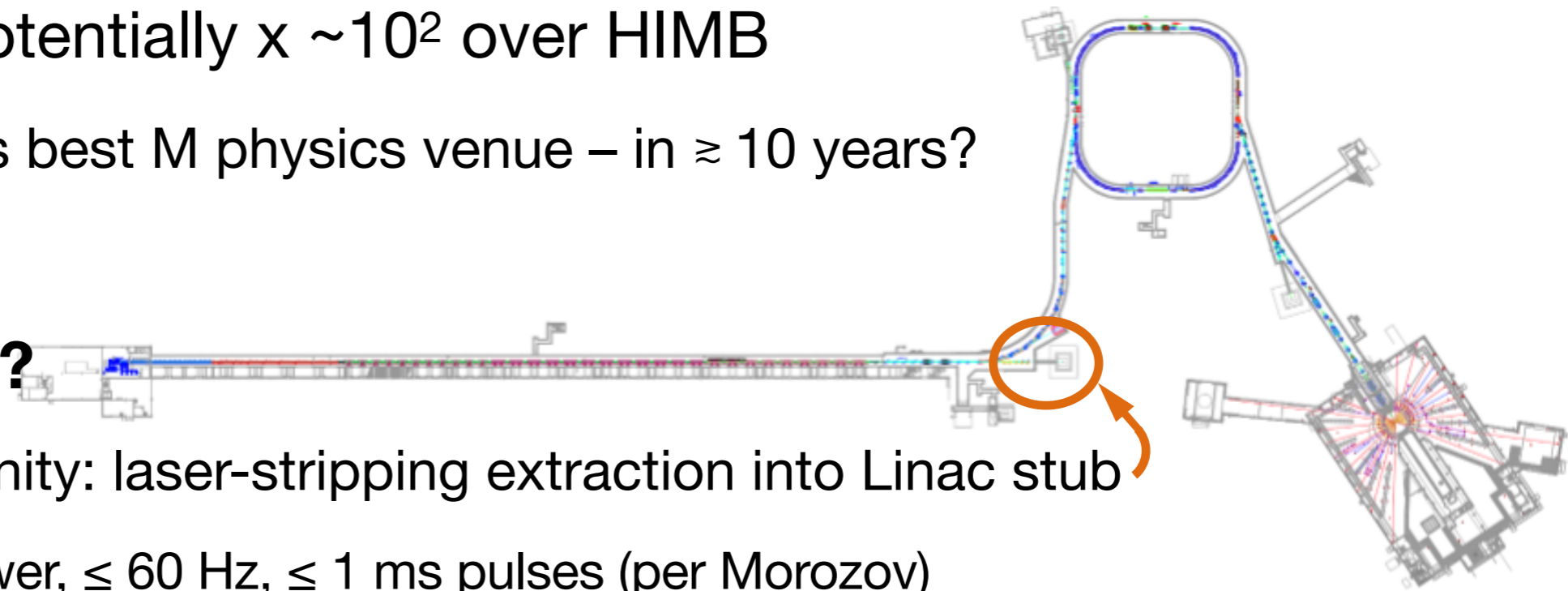
Competitive Landscape

- **PSI**: world's most intense surface-muon beams
- **HIMB** (PSI upgrade): goal $x \approx 30$ rate increase
- **PIP-II** ("AMF"): potentially $x \sim 10^2$ over HIMB
 - ➔ Fermilab world's best M physics venue – in ≈ 10 years?



- **SNS competitive?**

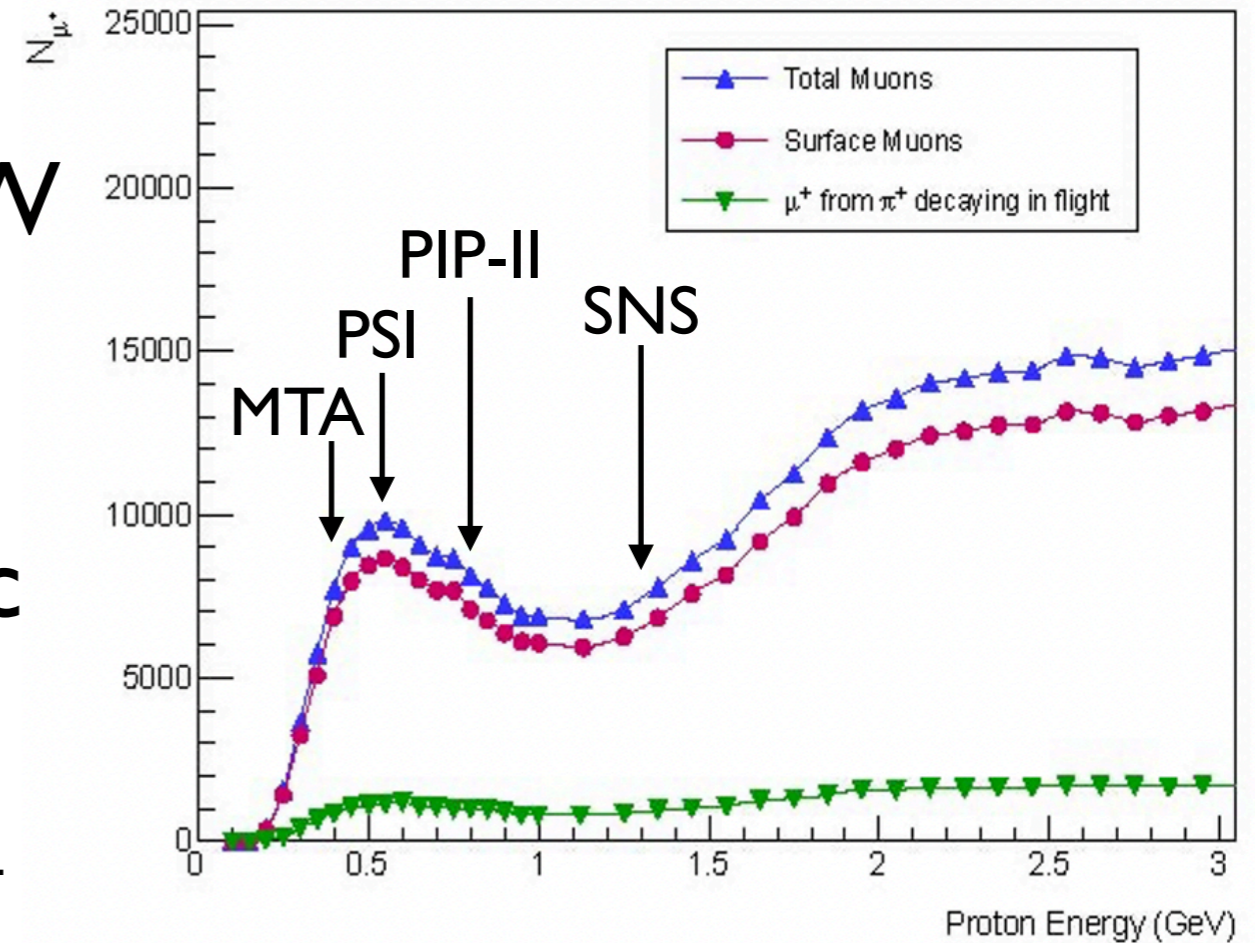
- Early R&D opportunity: laser-stripping extraction into Linac stub
 - ≤ 7 kW beam power, ≤ 60 Hz, ≤ 1 ms pulses (per Morozov)
 - potential beneficial spinoff: first/only U.S. μ SR facility
- Longer term: 100–300 W potentially available (Morozov)



SNS vs. PSI

- **PSI:** 590 MeV sector-focused p cyclotron, 1.3 MW
- **MTA:** 400 MeV H^- linac
- **PIP-II:** 800 MeV SC H^- linac
- **SNS:** 1 GeV SC H^- linac

$\approx 30\%$ PSI advantage



Variation of μ^+ yield with incident proton energy for muons with momenta $\leq 30 \text{ MeV}/c$; 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 \Rightarrow thin, low- Z target ($\approx 6\text{--}40 \text{ mm C}$)
 - SNS: can use thick, high- Z target, e.g., 3 cm W ($\div n_{\text{slices}}$)

Benefits of High-Z Target

- Ta ($Z = 73$) target increases π^+ (hence μ^+) yield by factor 2.9 over graphite (and factor ≈ 8 for π^-)

- expect similar factor for W ($Z = 74$) since π^+ yield $\sim Z^{1/3}$
- (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)]

Conclusions



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\Rightarrow **Dedicated simulation study needed**

Backup Slides



Muonium Gravity: Motivation

- Possibility of “fifth force”?

- $g - 2$, B -decay and W -mass anomalies: possible $e\mu$ nonuniversality?

- o stimulated extensive work

- 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

- o sensible to start with 10% and proceed step by step

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

Buttazzo, Greljo, 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. Algueró 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, $(g - 2)_{e,\mu}$ 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);

...]

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

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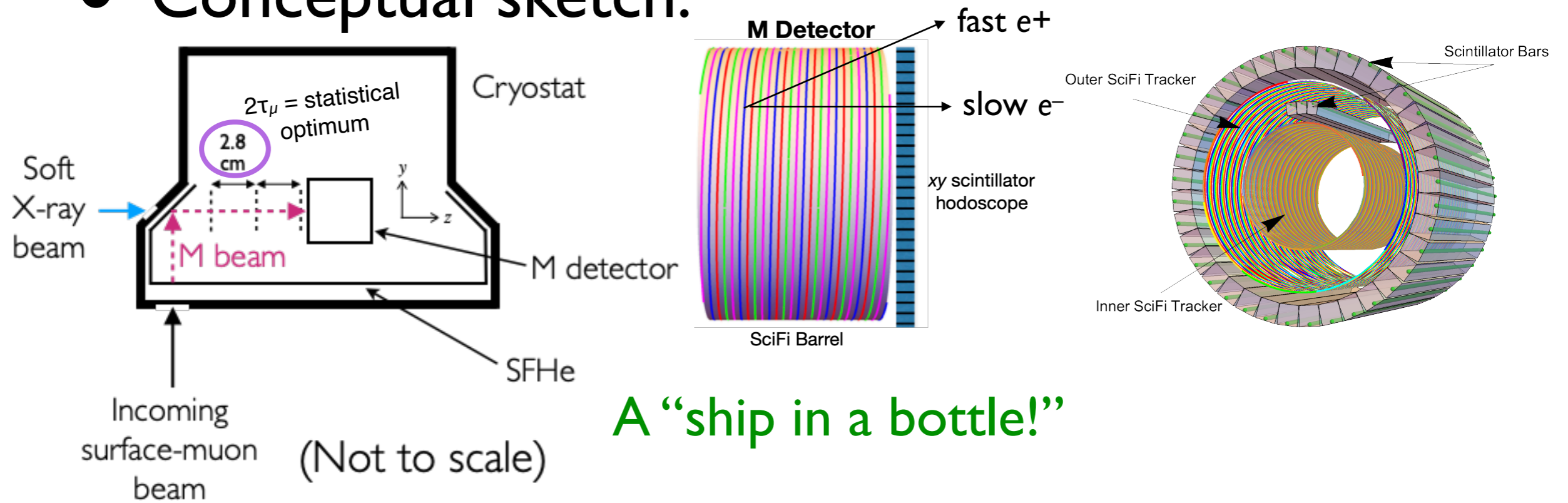
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Muonium Gravity Experiment

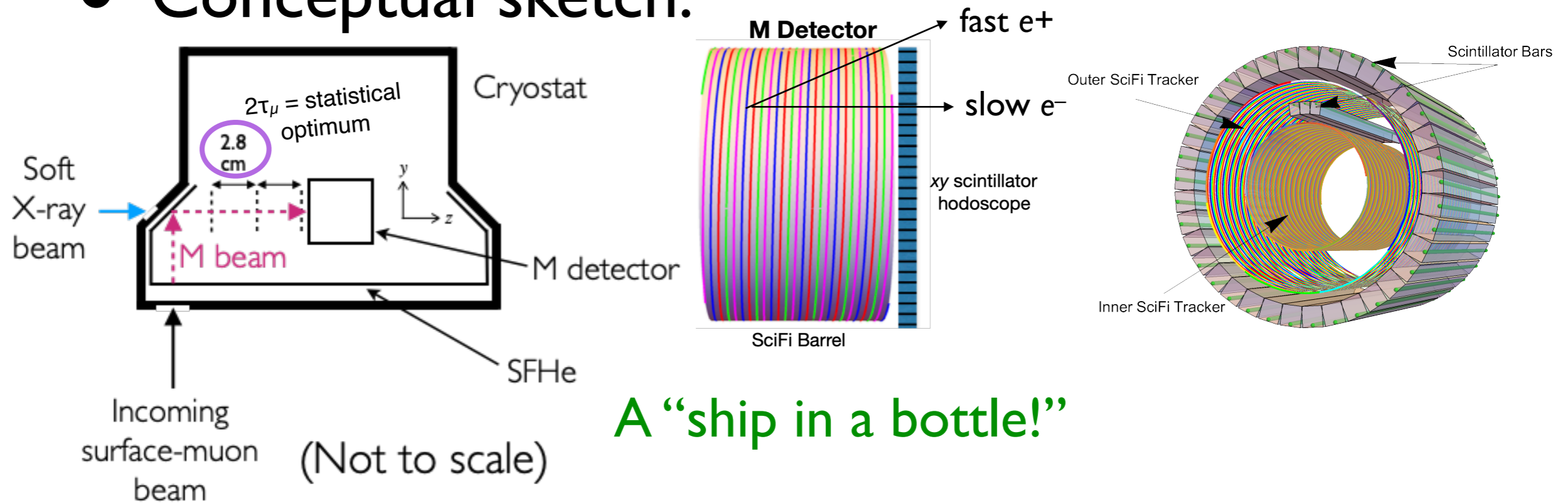
- Conceptual sketch:



A “ship in a bottle!”

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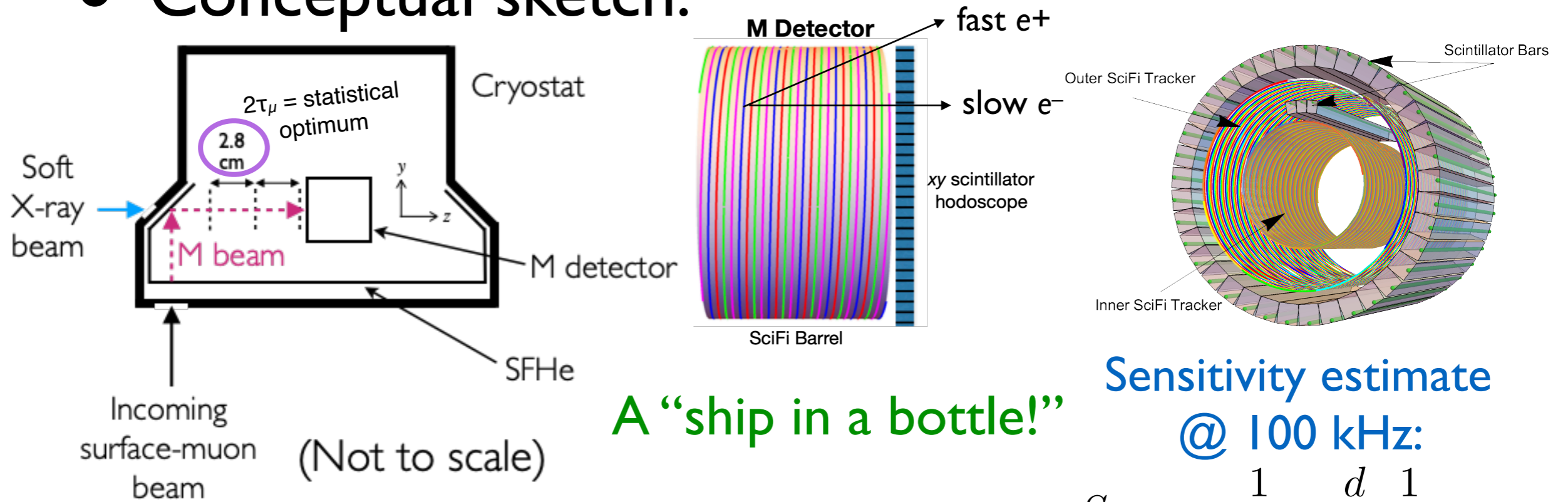


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@ 100 kHz:

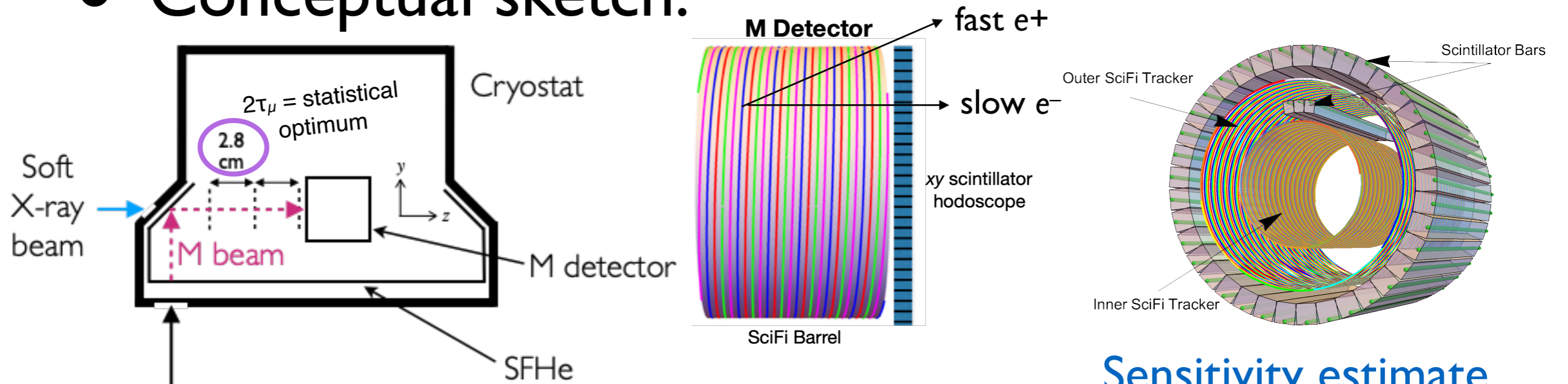
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sign of \bar{g} with 1 day's data

where

$C = 0.3$ (est. contrast)

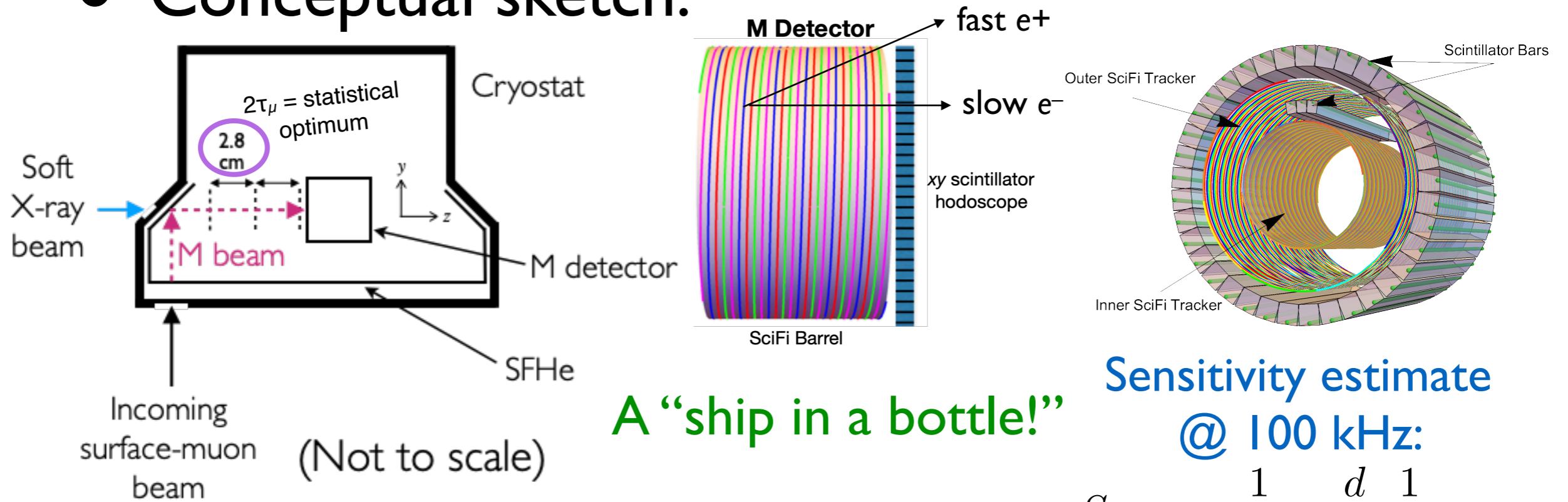
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➔ Muonium Antimatter

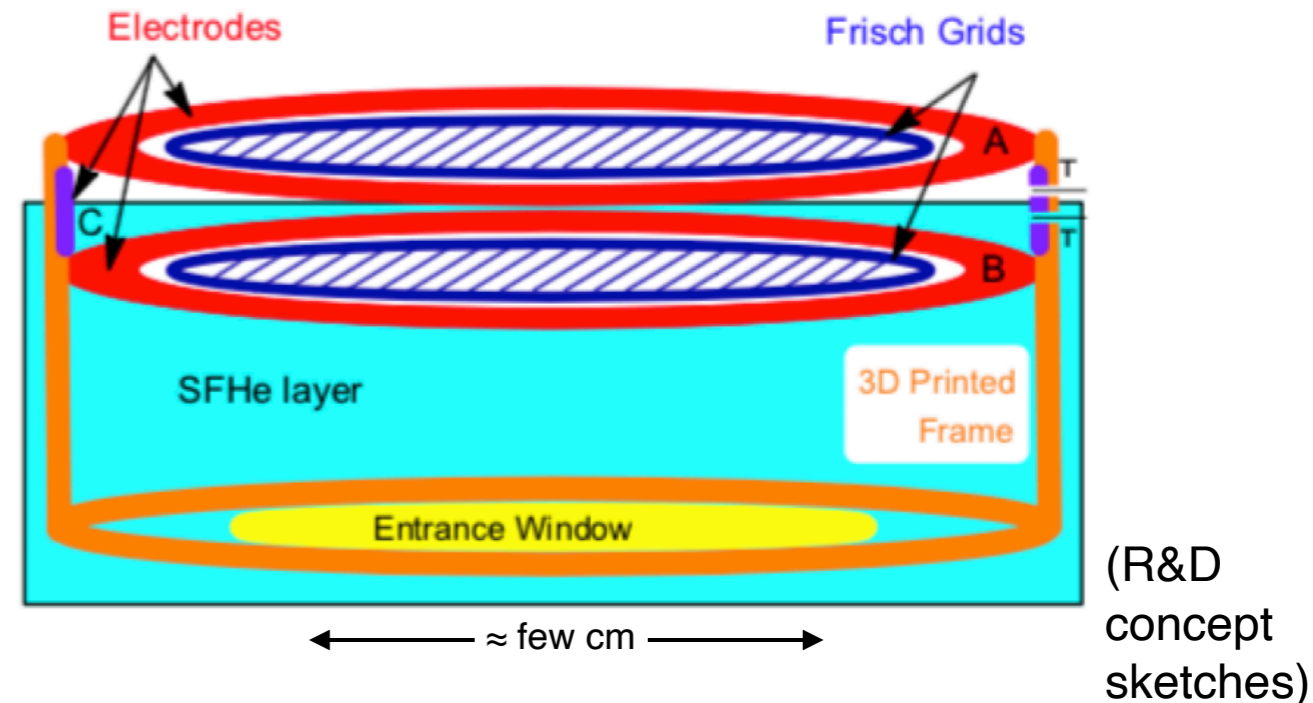
Gravity Experiment (MAGE)

Thick- vs. Thin-film SFHe

Thick-film:

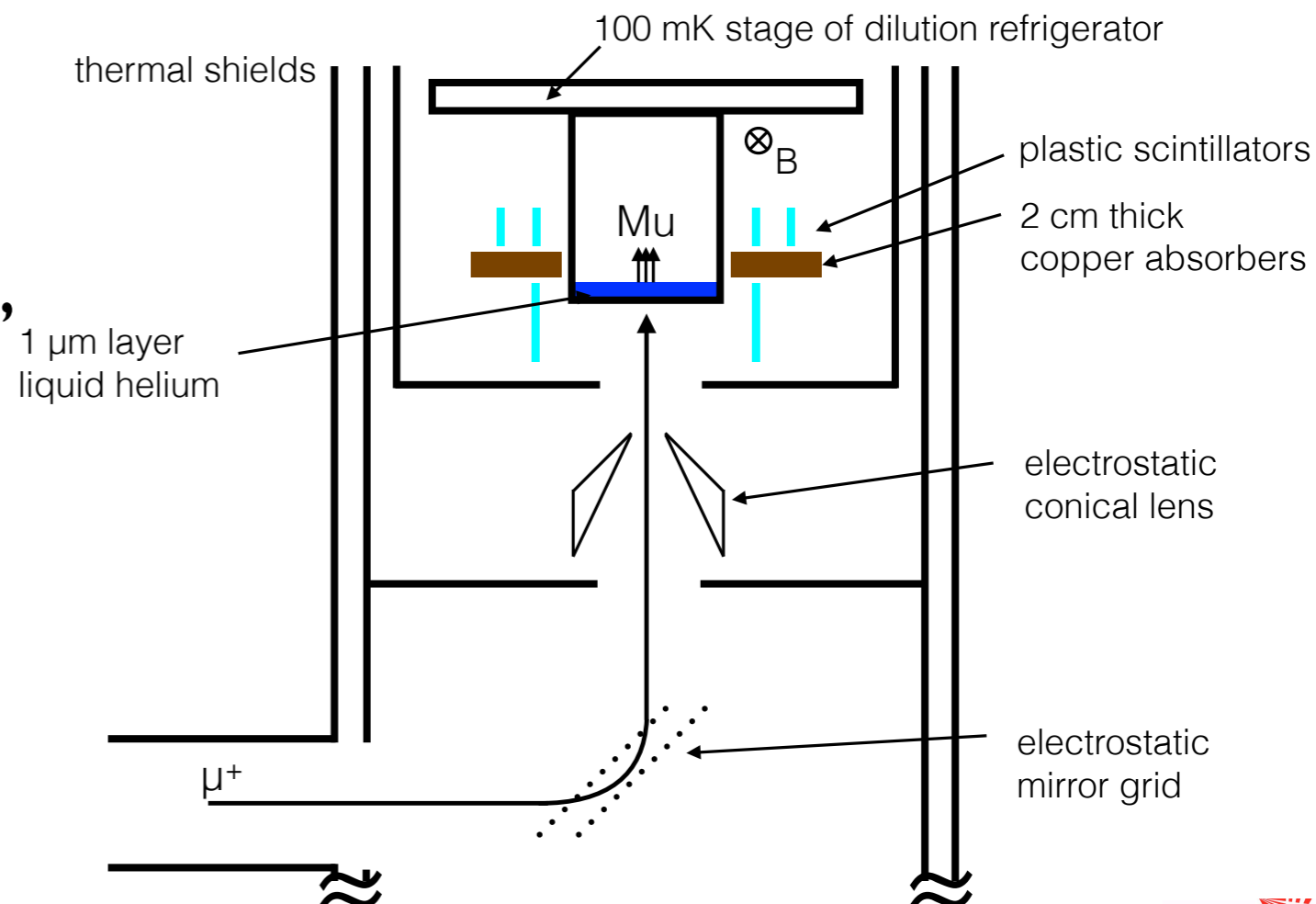
- $\approx 100 \mu\text{m}$ SFHe layer
- surface e^- pool* creates E field:
 - drifts μ^+ to surface, where M formed & expelled to vacuum

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



Thin-film:

- Under development @ PSI
- $\sim 1 \mu\text{m}$ SFHe layer, no drift field, requires tiny μ^+ ΔE :
 - μ^+ form M within SFHe & diffuse at random
 - $\approx 1/2$ reach upper surface & expelled to vacuum



Fermilab “MuCool Test Area”

- Built ~20 years ago for muon collider R&D
 - served by 400 MeV H⁻ Linac
- Now being repurposed as Irradiation Test Area (ITA)
- Can also house low-energy π/μ beam (Carol Johnstone)

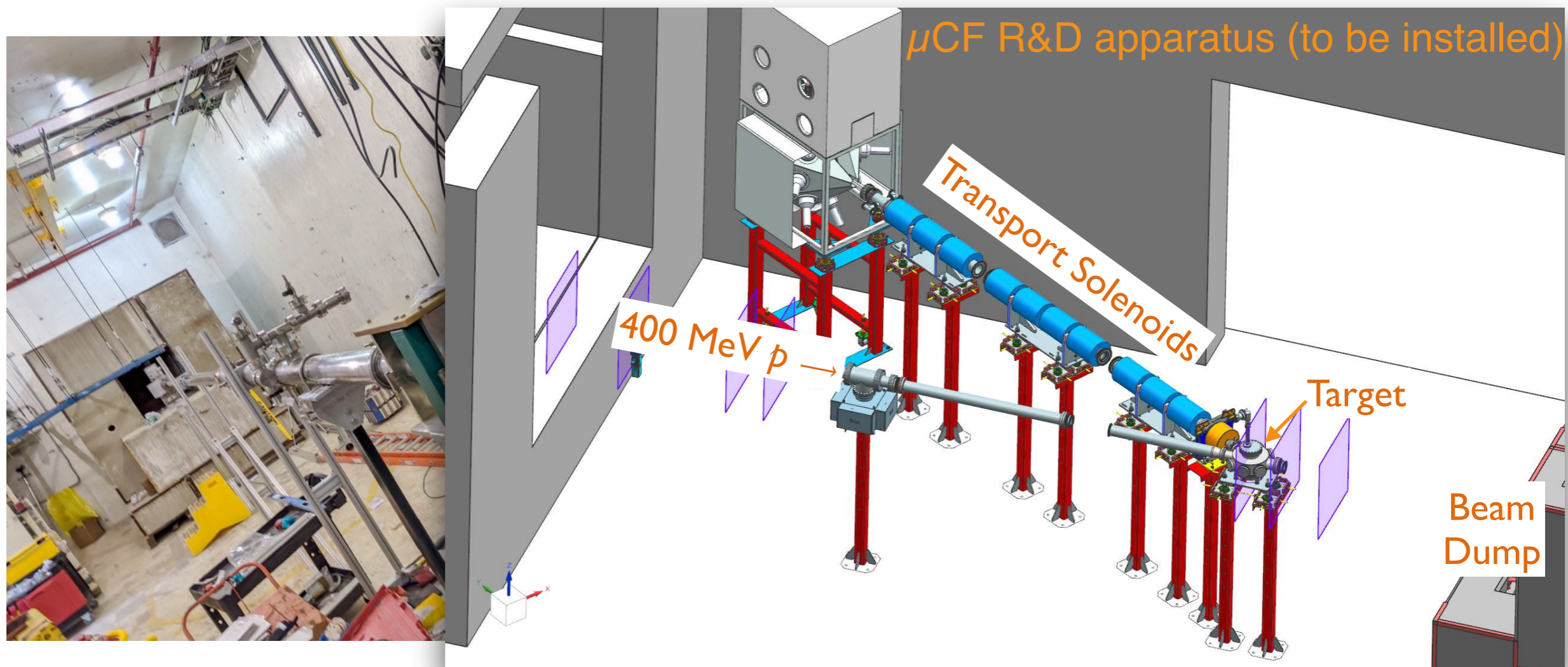
See Johnstone & Mazzacane talks



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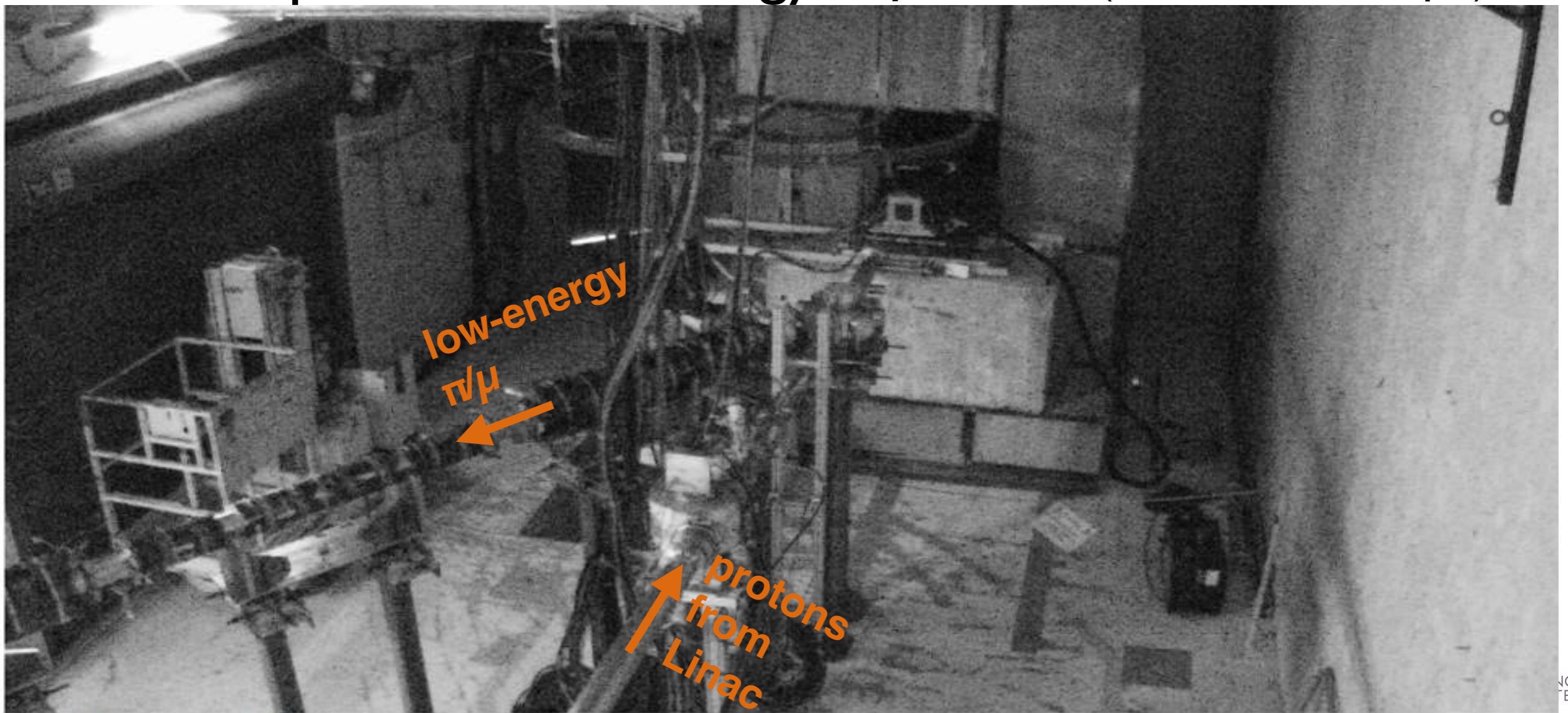
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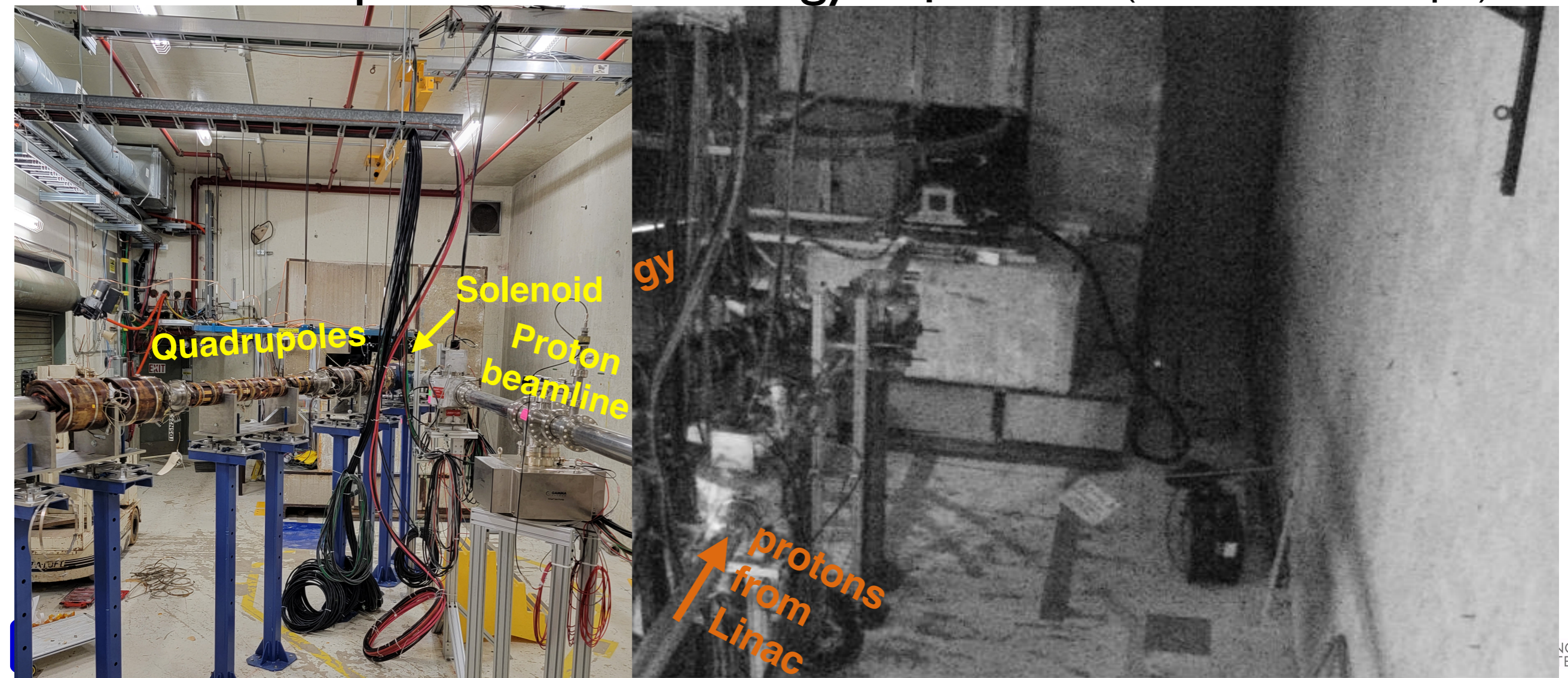
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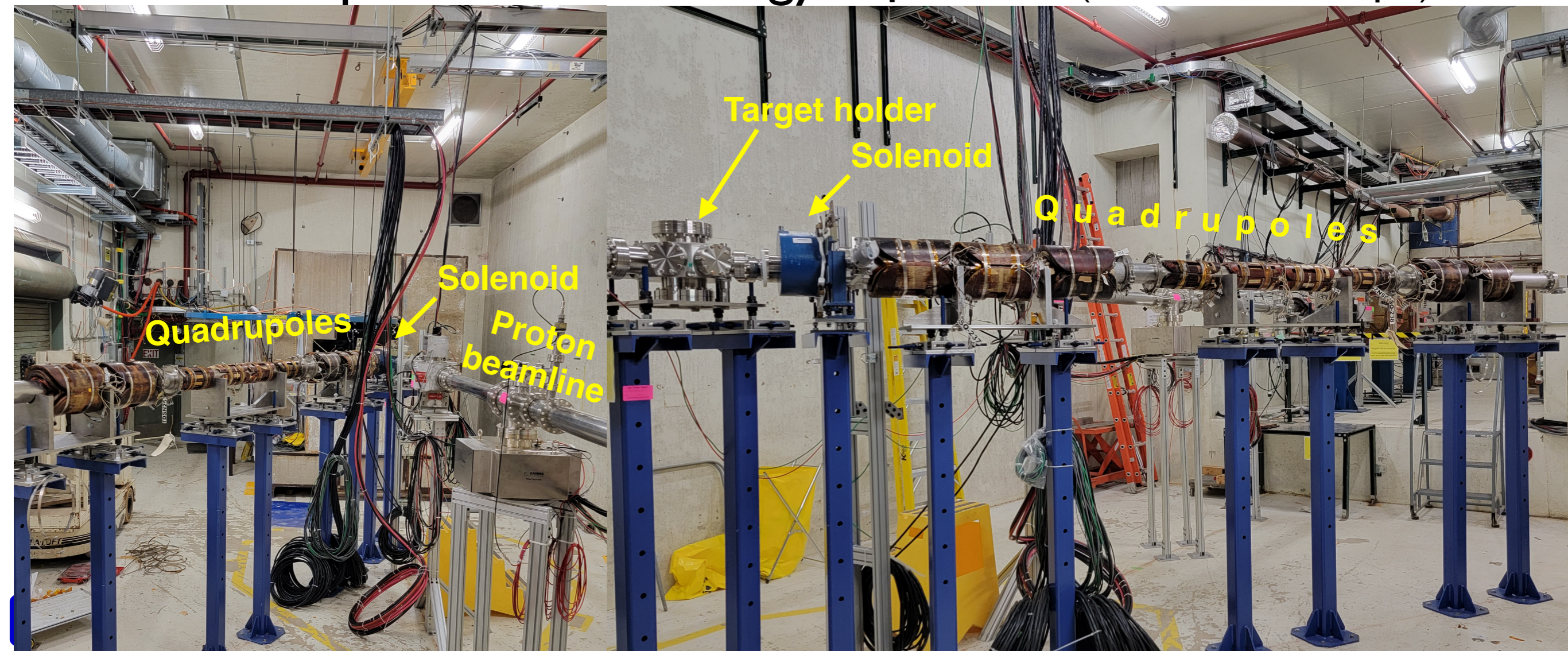
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Comparing MTA and PSI

- Relative rate estimates:

	PSI	MTA	MTA/PSI
Proton Beam Power (MW)	1.2	0.008*	0.0067
Target	40 mm C = 0.103 λ_l	30 mm W = 0.302 λ_l	2.9
σ_{π^+} (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 $\approx 10^{-9}$ surface μ /POT
 - need full simulation study (in progress)

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— additional $\approx \times 200$ if HIMB thin-film SFHe and PIP-II thick

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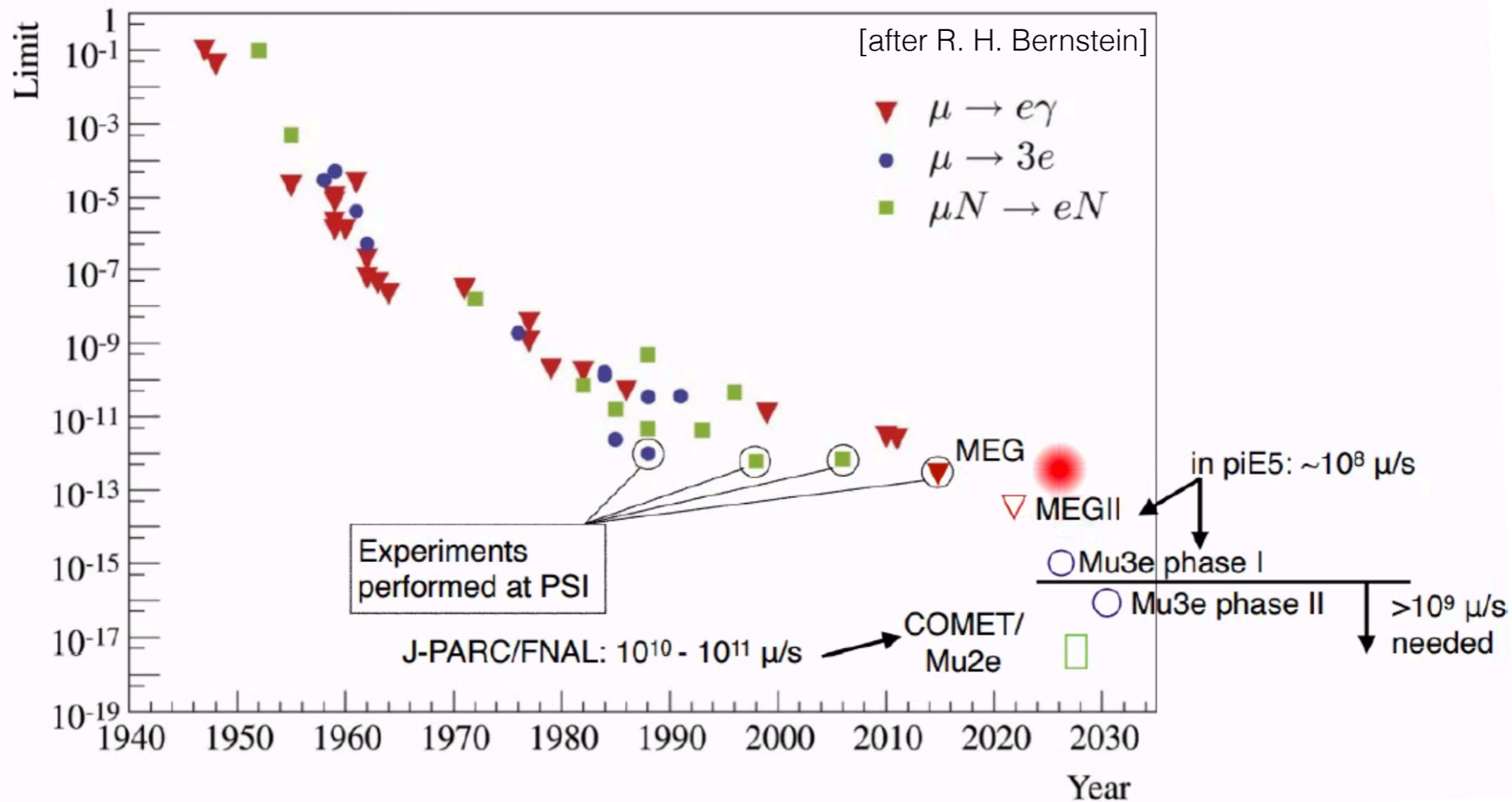
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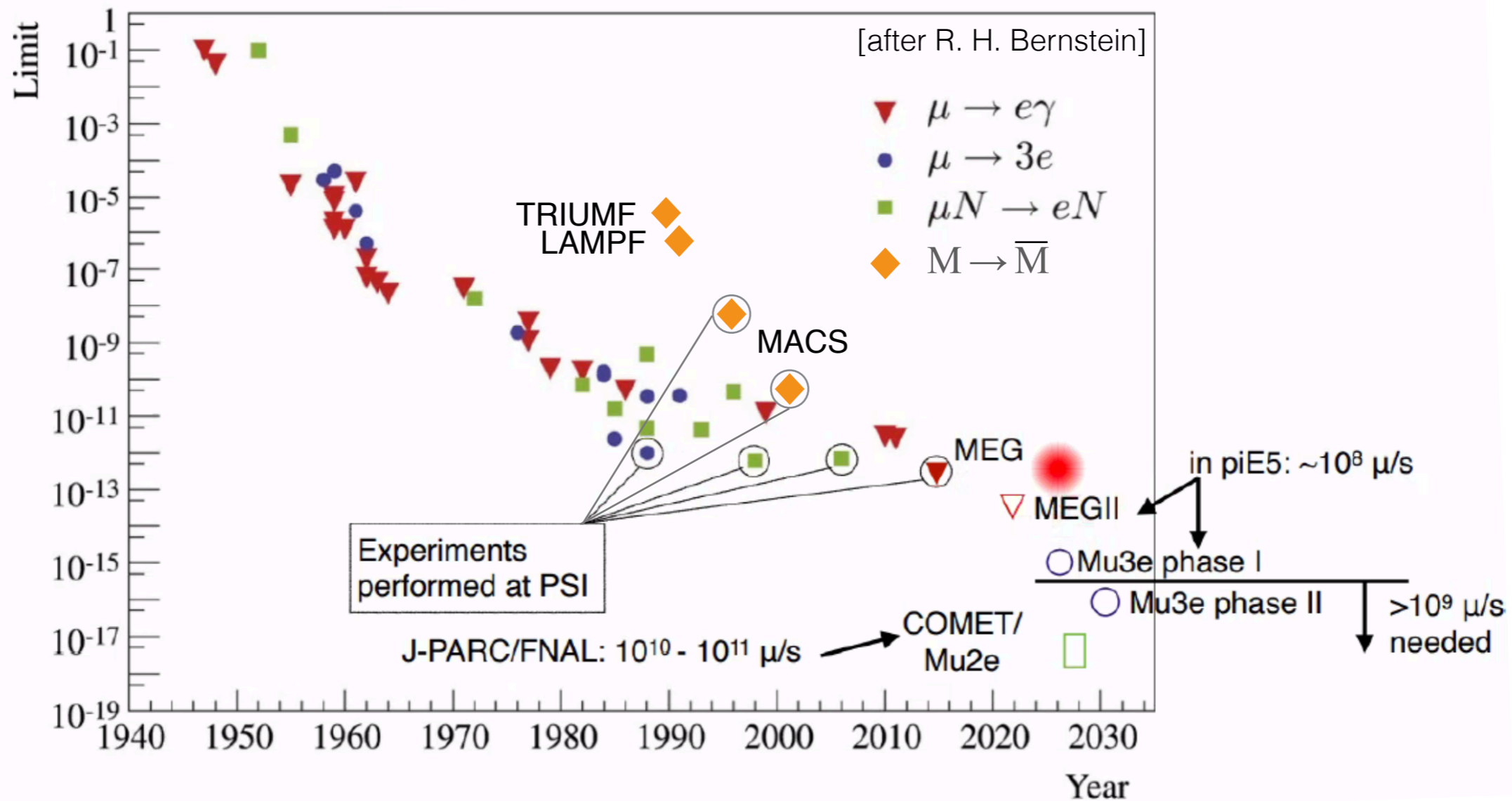
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History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$



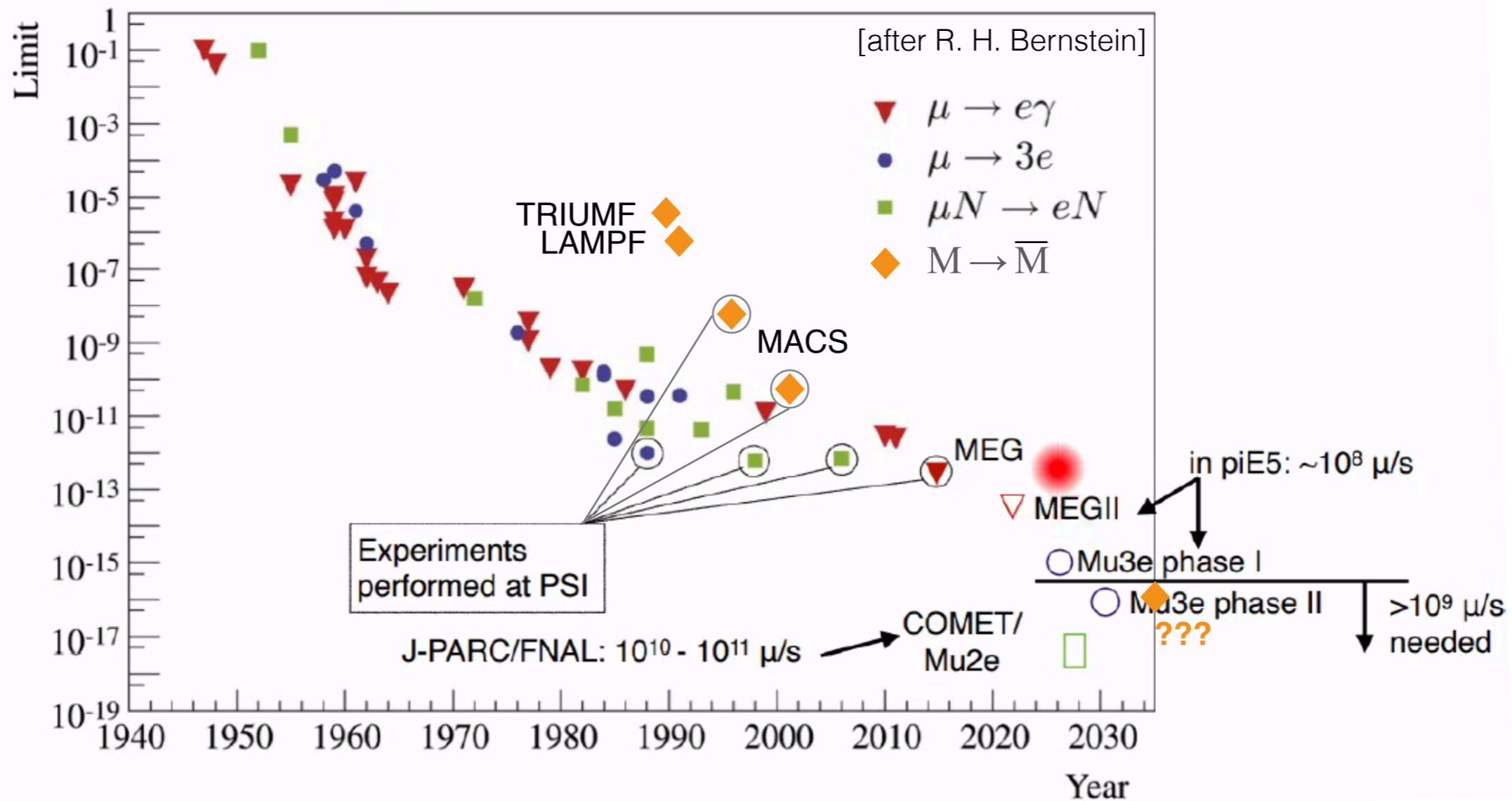
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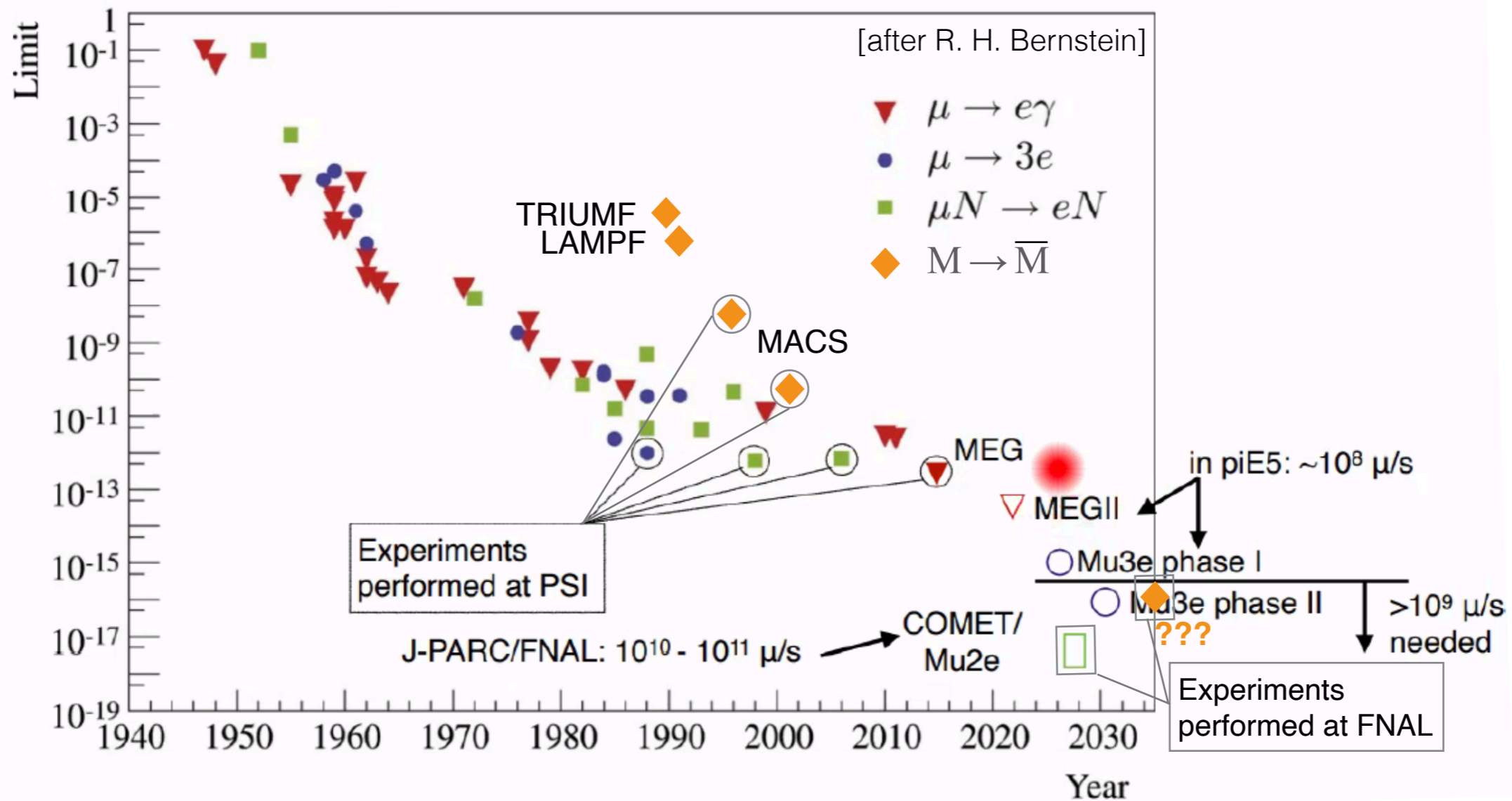
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History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$



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PIP-II Muonium Potential

- Is $M-\bar{M}$ sensitivity $>$ order of magnitude worse than $\text{Mu}2e$ sensitivity worth pursuing?

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/cm²)*
 - 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 ⁴He,” J. Phys. C: Solid State Phys. **19** (1986) 1135; <http://stacks.iop.org/0022-3719/19/i=8/a=012>

Resource Needs

- Modest, \approx 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

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

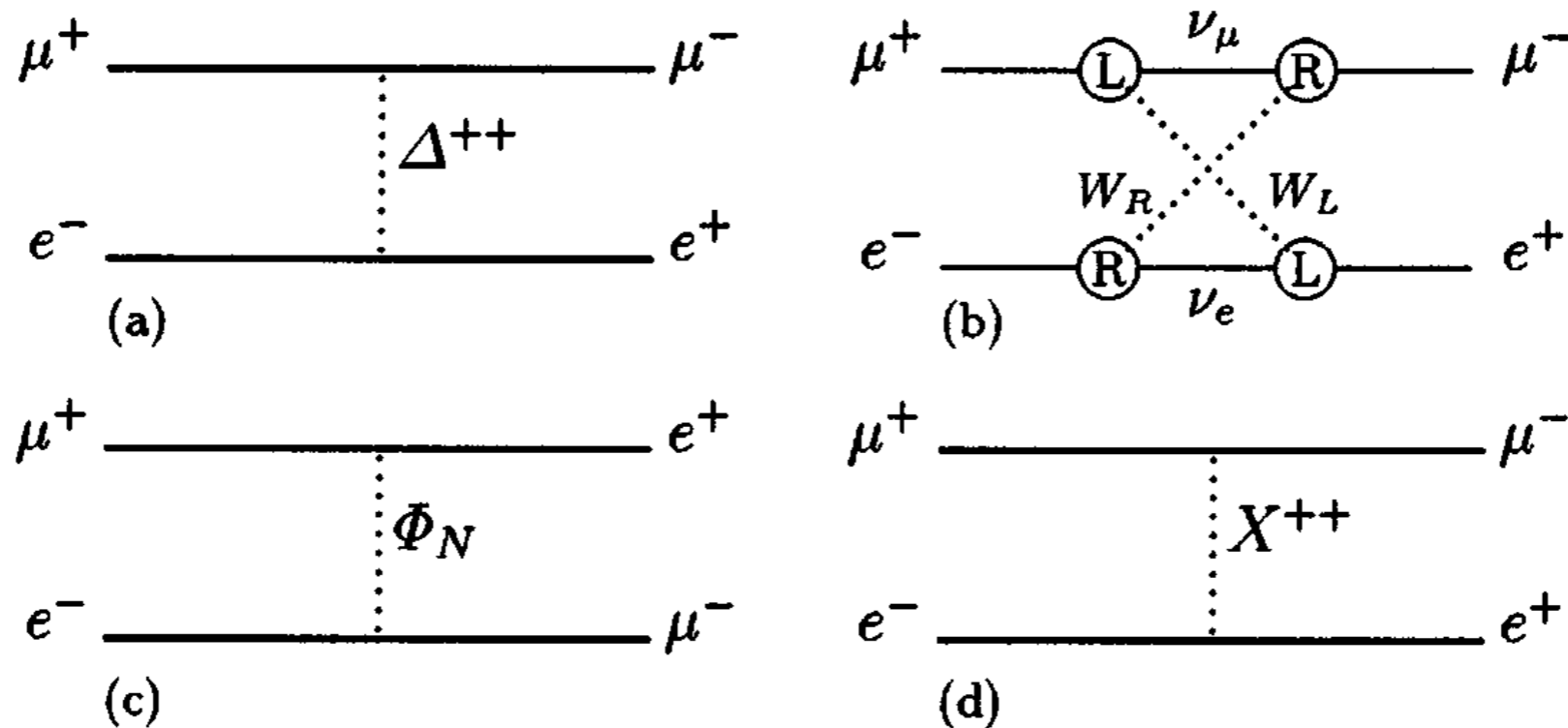


FIG. 1. Muonium-antimuonium conversion in theories beyond the standard model. The interaction could be mediated, e.g., by (a) doubly charged Higgs boson Δ^{++} [3,4], (b) heavy Majorana neutrinos [3], (c) a neutral scalar Φ_N [5], e.g., a supersymmetric τ -sneutrino $\tilde{\nu}_\tau$ [6,7], or (d) a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

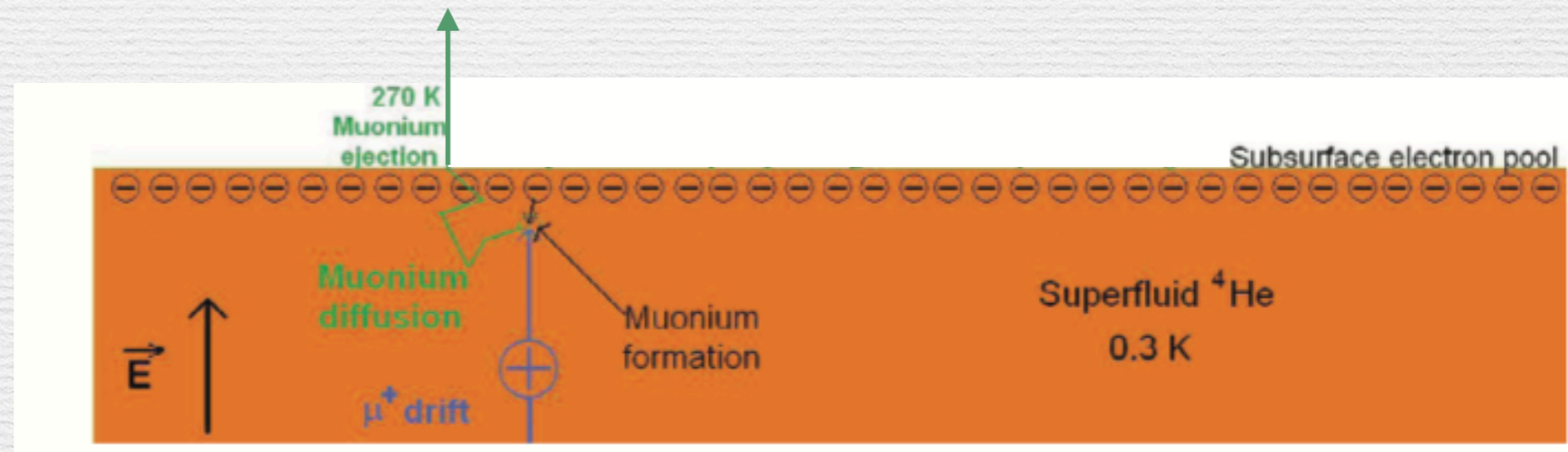
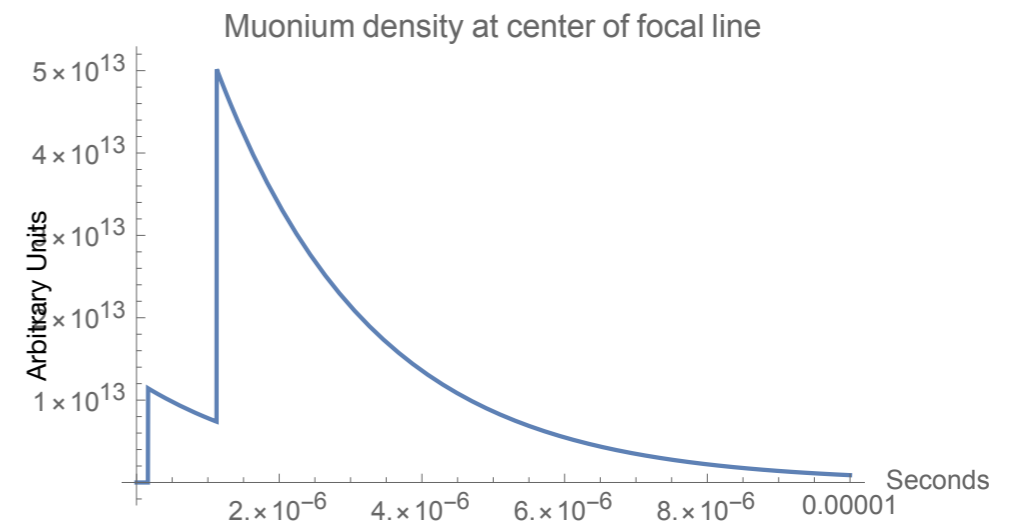
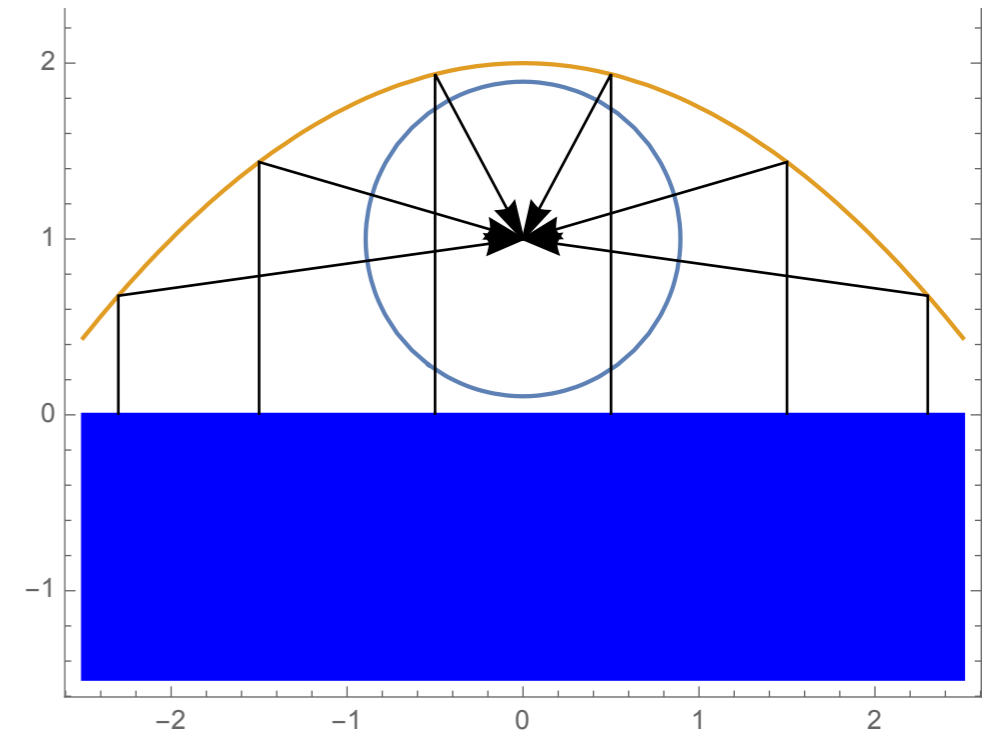


Figure after D. Taqqu / *Physics Procedia* 17 (2011) 216-223

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 $\approx 5X$ (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

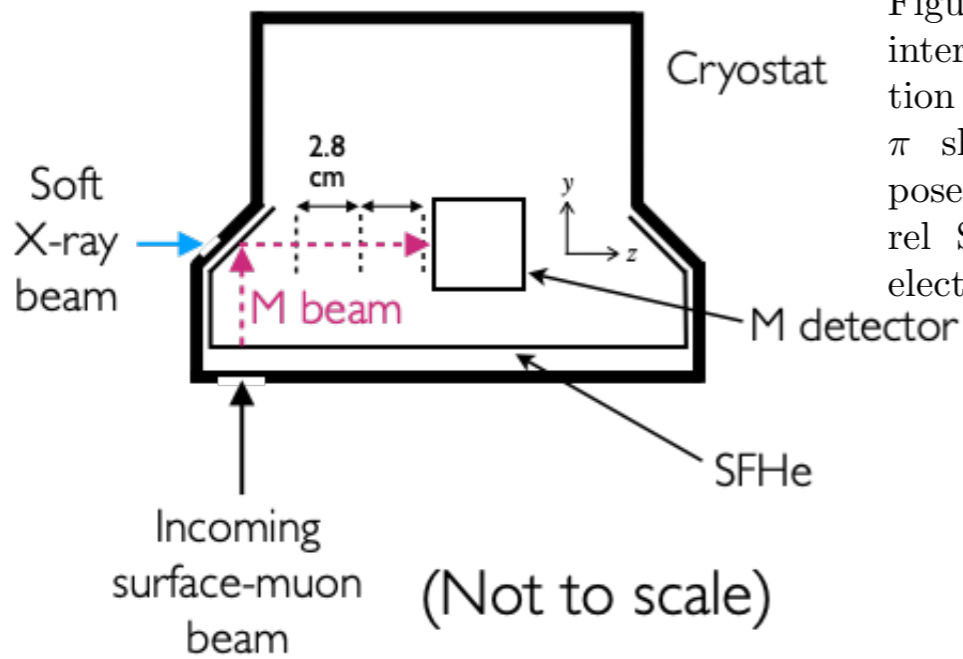
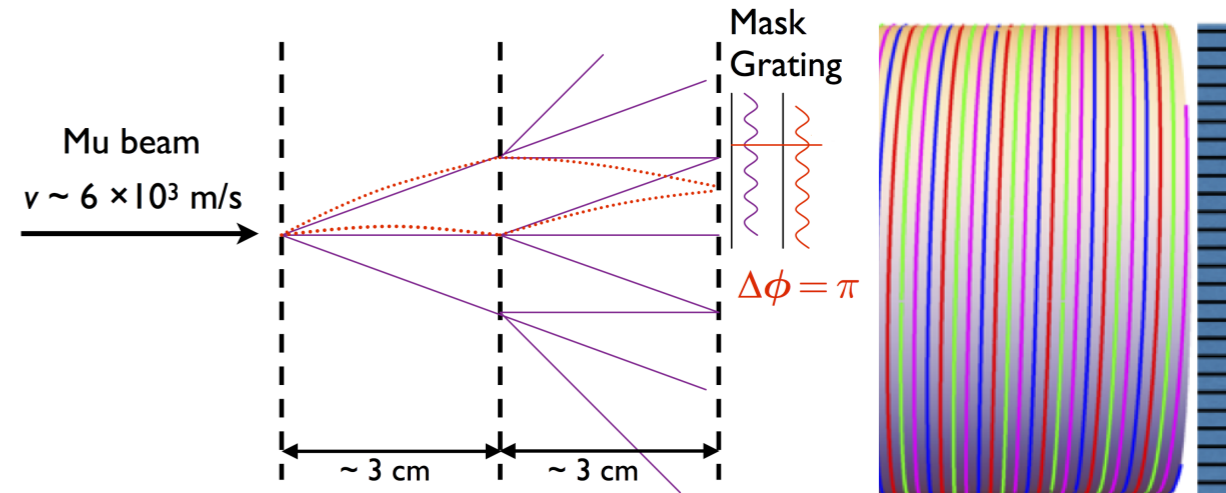


Figure 1: Principle of muonium interferometer, shown in elevation view (phase difference $\Delta\phi = \pi$ shown for illustrative purposes); Mu-decay detectors (barrel SciFi positron tracker and electron MCP) shown at right.



Muonium Gravity Experiment

- Important feasibility questions:

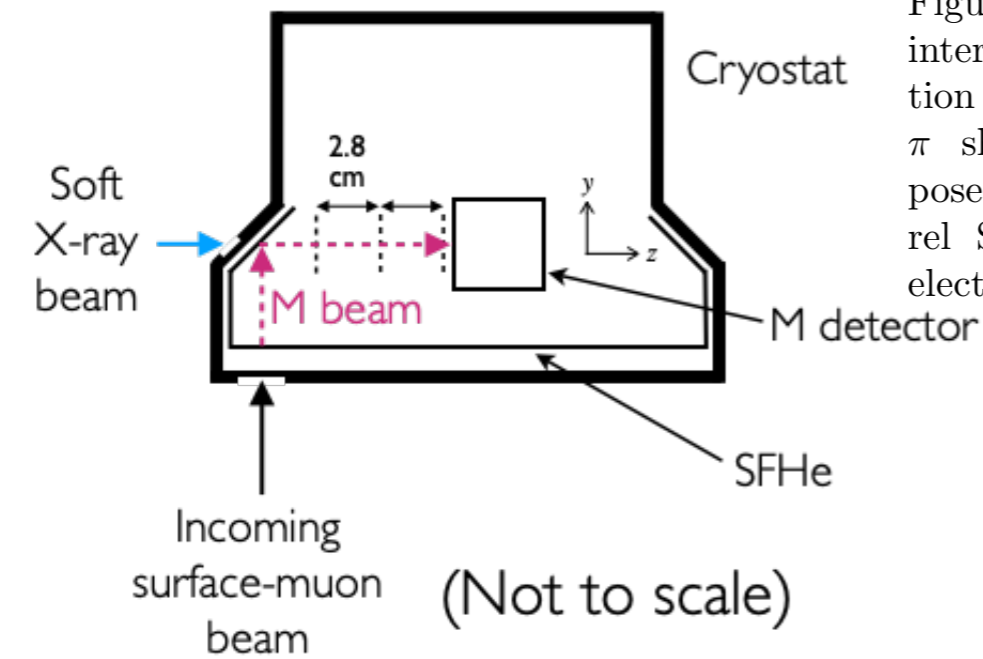
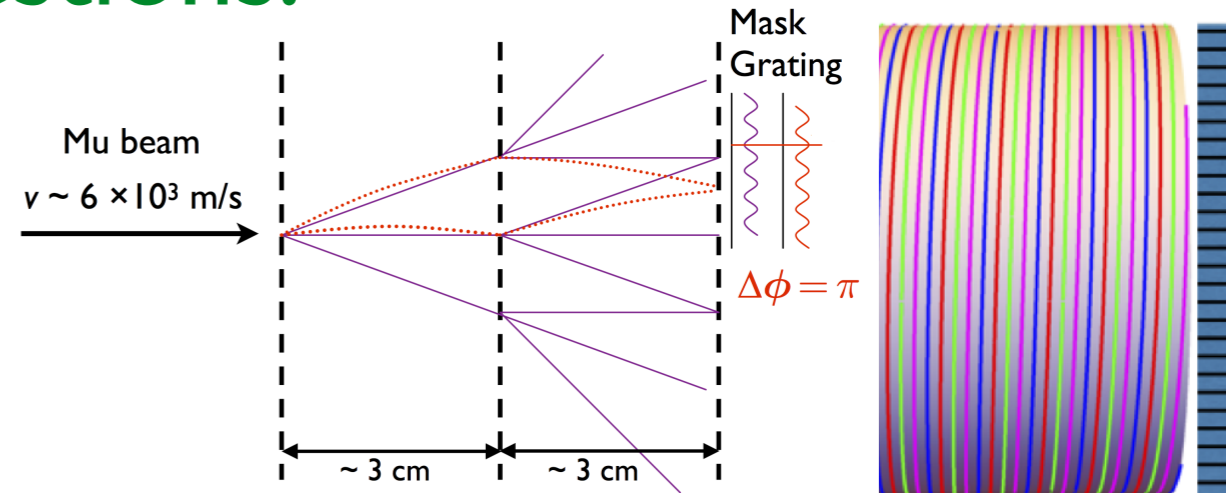


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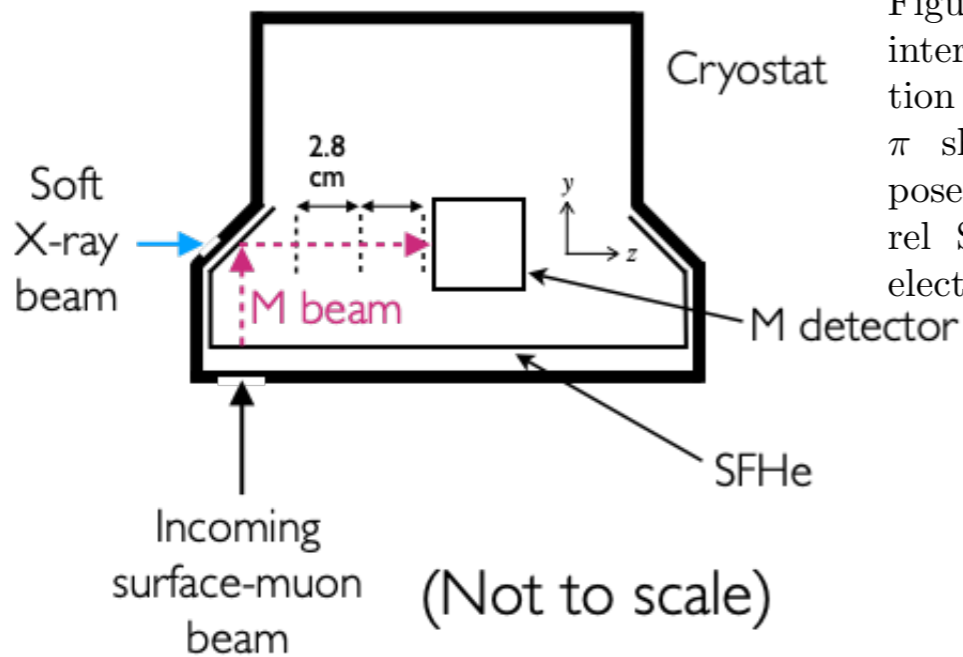
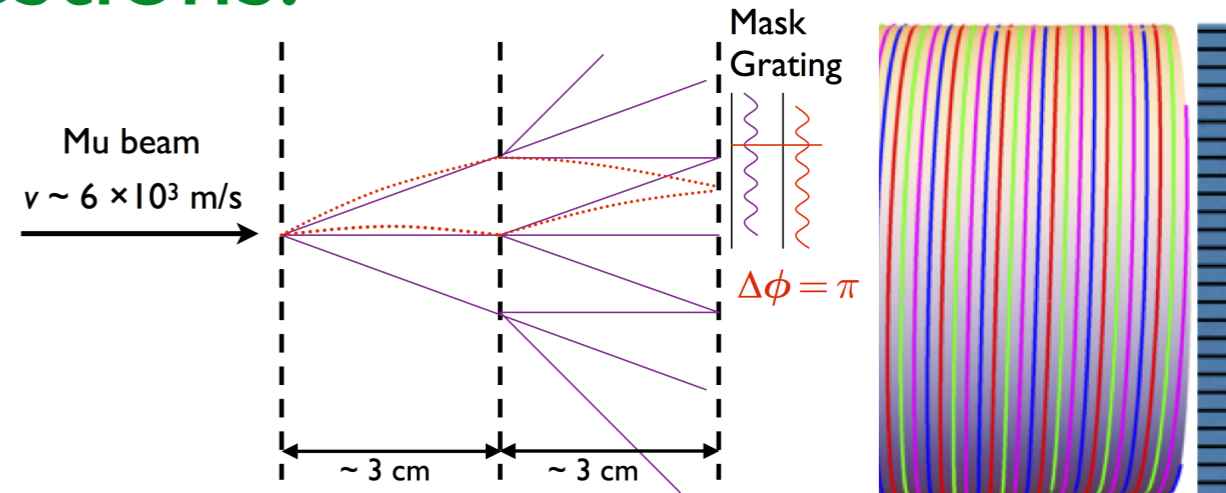


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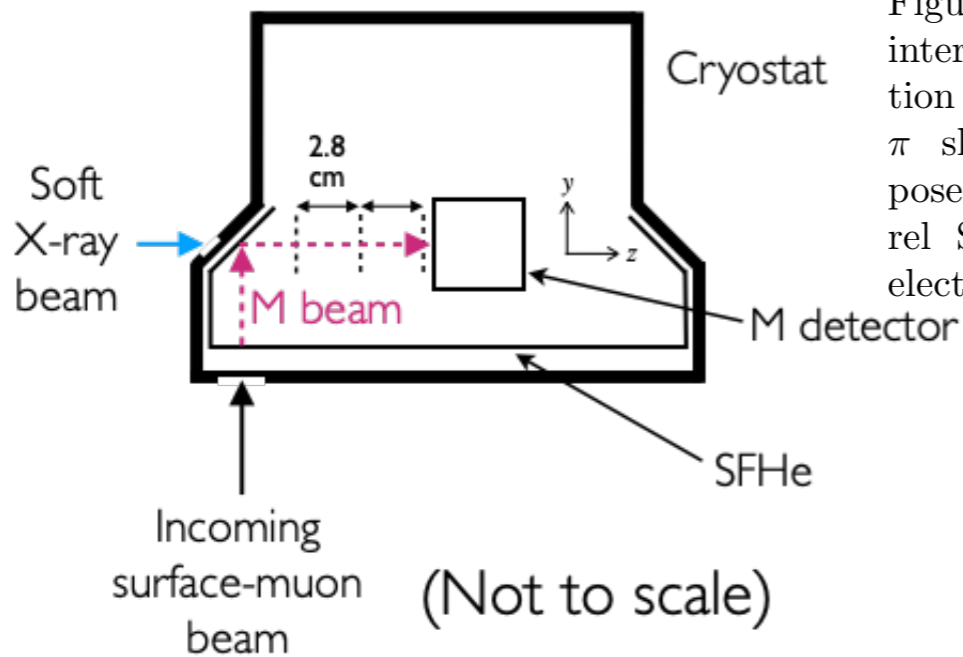
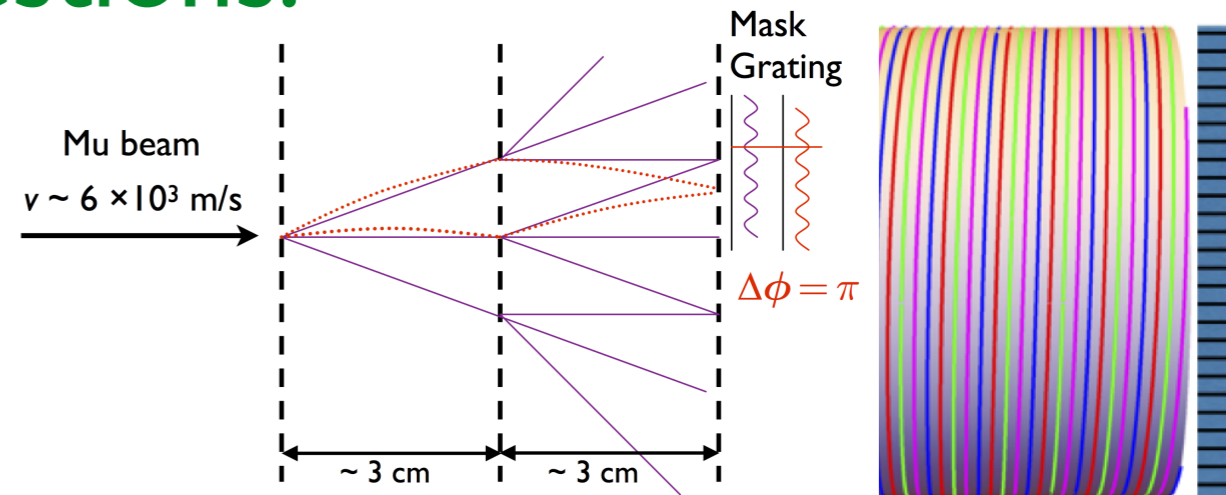


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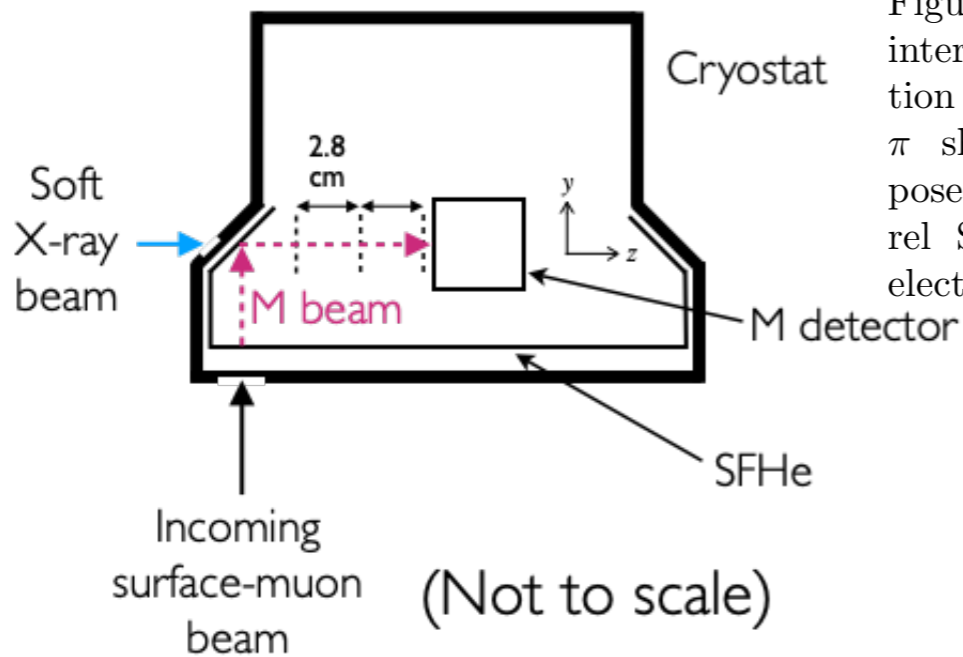
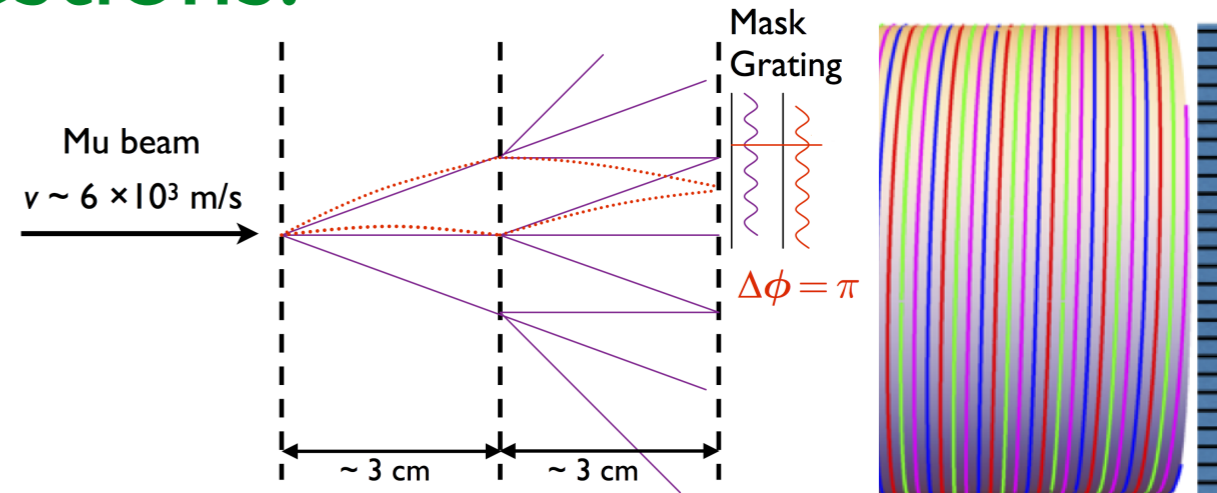


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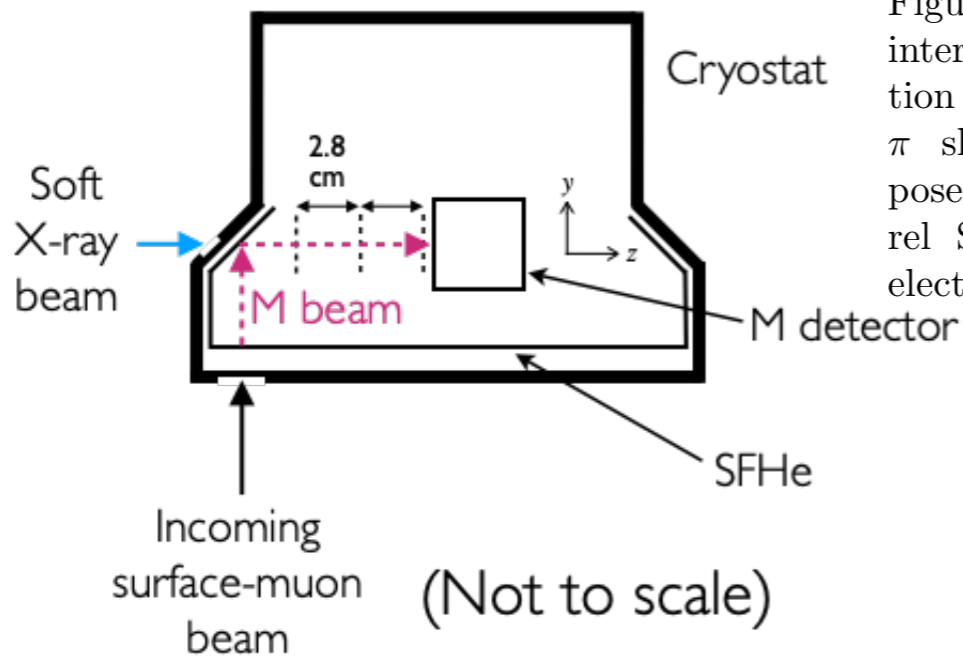
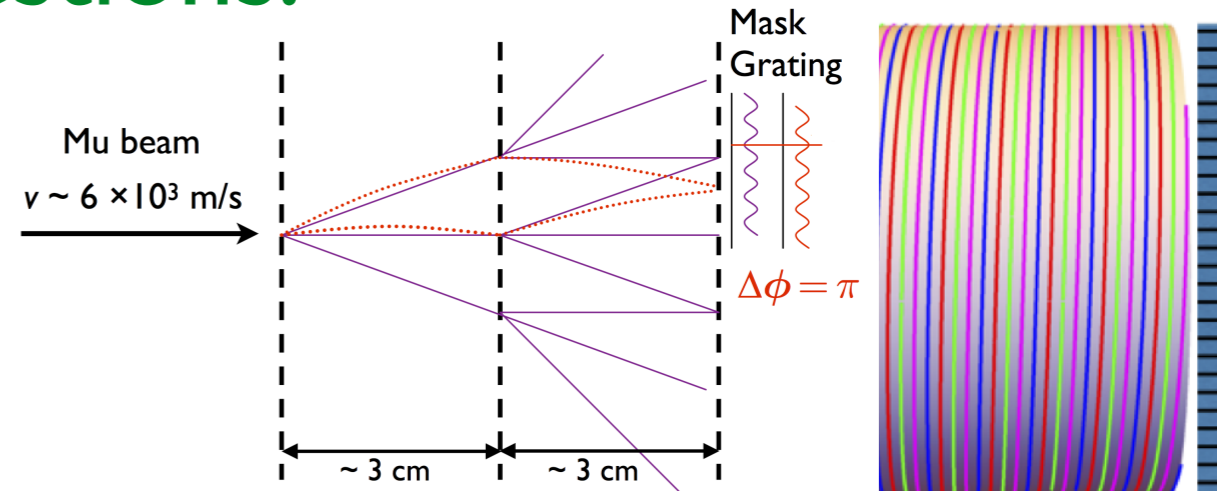


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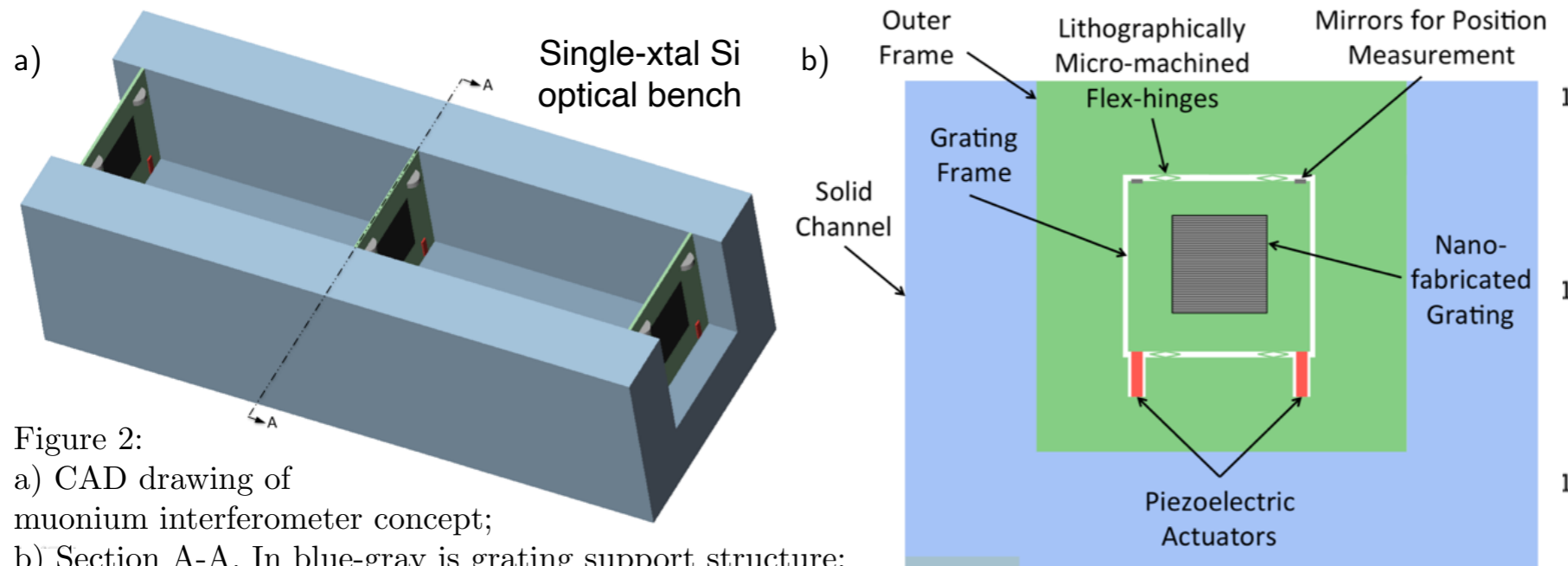


Figure 2:
a) CAD drawing of muonium interferometer concept;
b) Section A-A. In blue-gray is grating support structure: a U-channel machined out of a single-crystal silicon block. Each grating is mounted in a silicon frame connected to an outer frame by flex-hinges; piezo-actuator pair permits small rotations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

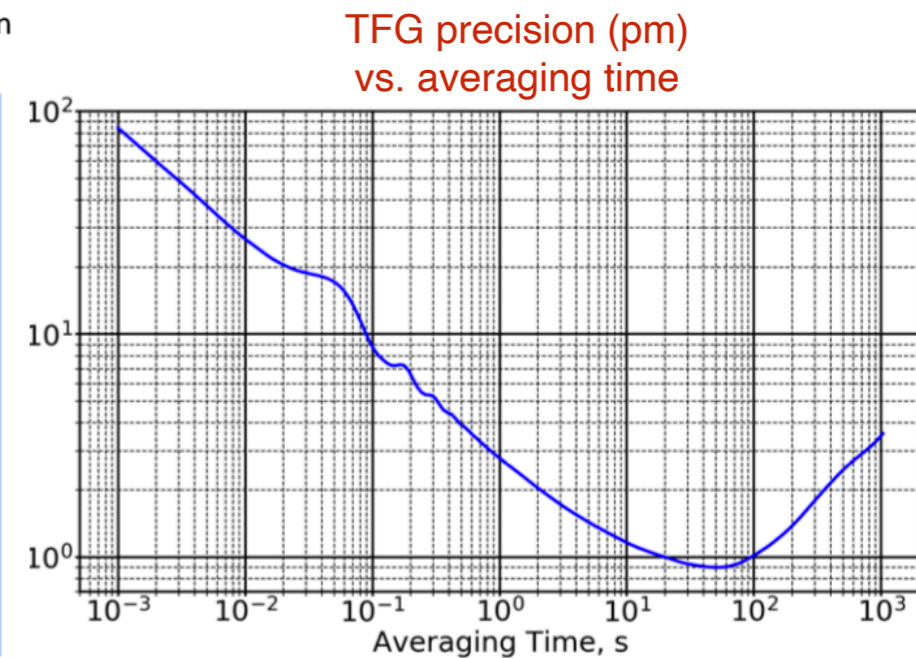


Figure 3. Allan deviation indicating TFG incremental-distance precision vs averaging time. From Kaplan, D.M.; Roberts, T.J.; Phillips, J.D.; Reasenberg, R.D. Improved performance of semiconductor laser tracking frequency gauge. *J. Instrum.* **2018**, *13*, P03008.

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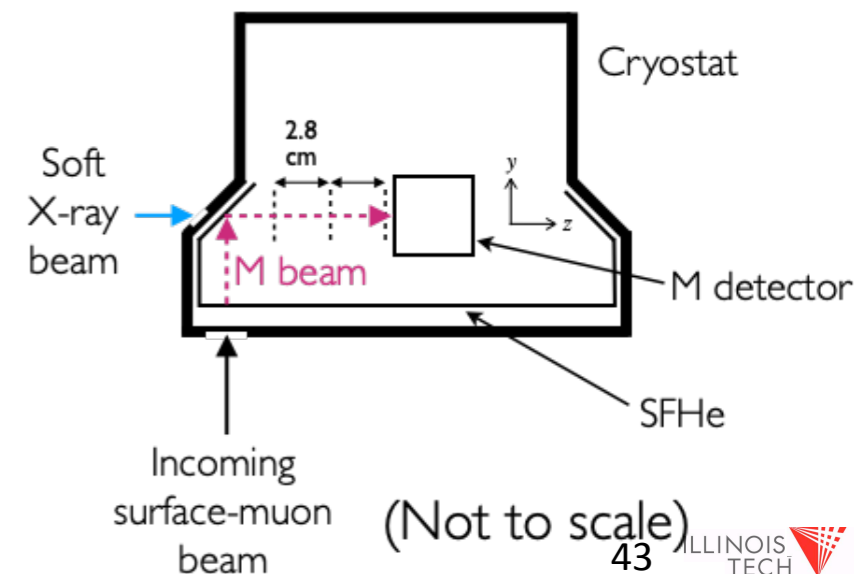
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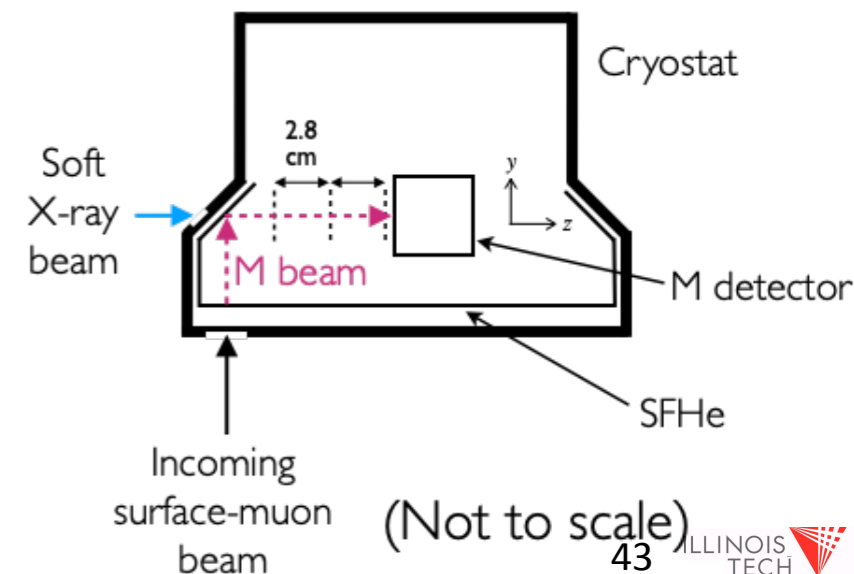
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