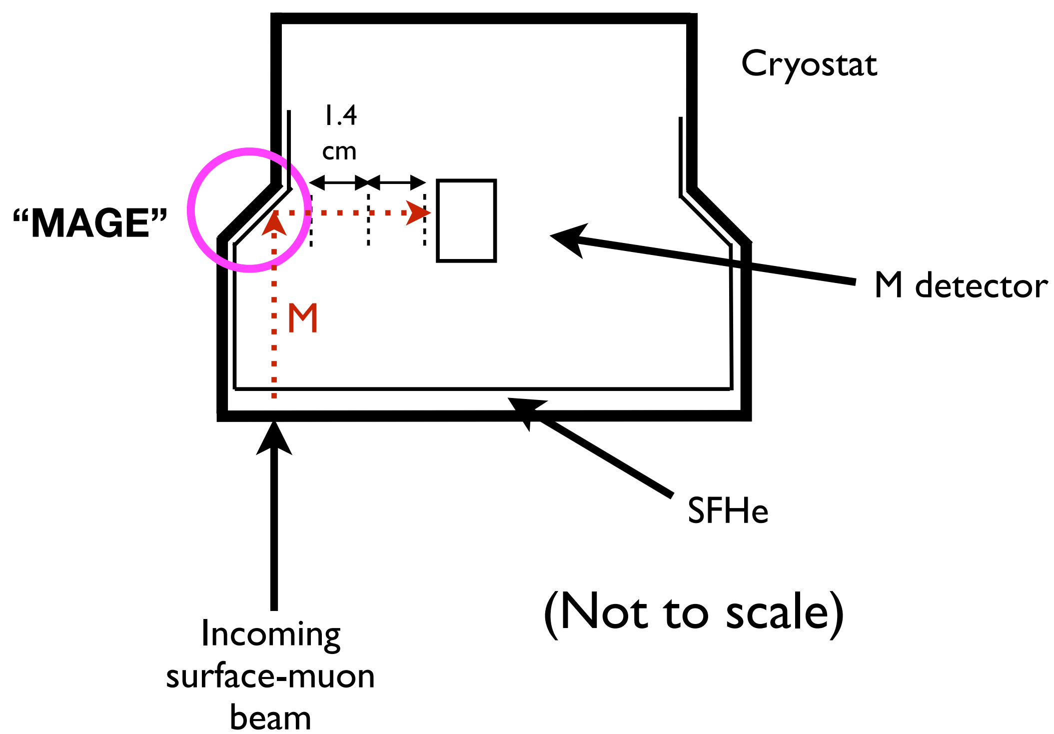
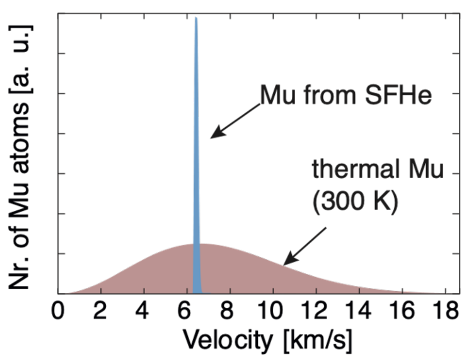
Muonium-Antimuonium Experiments

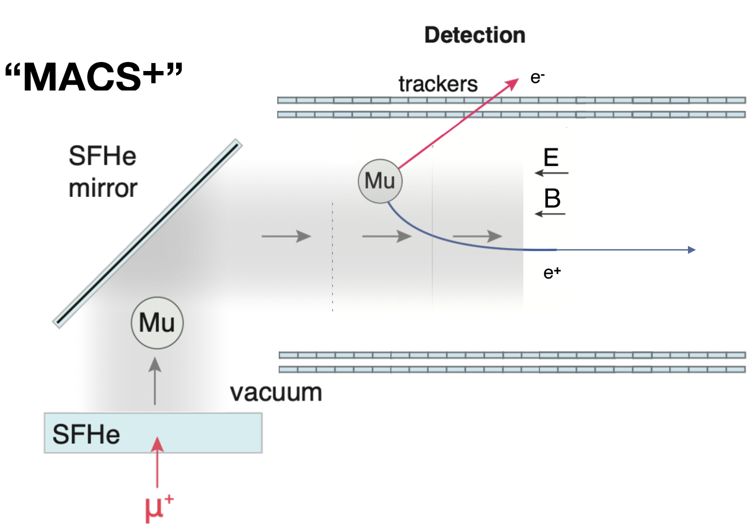


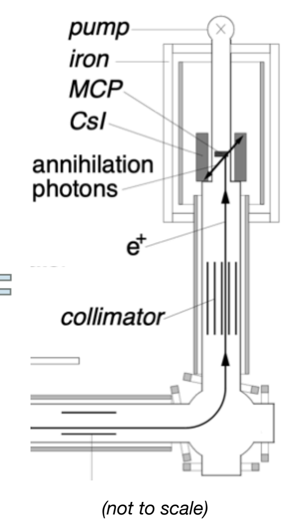
(See Workshop on Low-Energy Muonium and Muon Physics at Fermilab,
14 July 2022, https://indico.fnal.gov/event/55117/)

Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY







"Snowmass" Community Summer Study
Univ. of Washington
22 July 2022

Outline

- Motivation
- Muonium
  - oscillation search
  - precision spectroscopy
  - gravity
- Fermilab advantages
- Conclusions

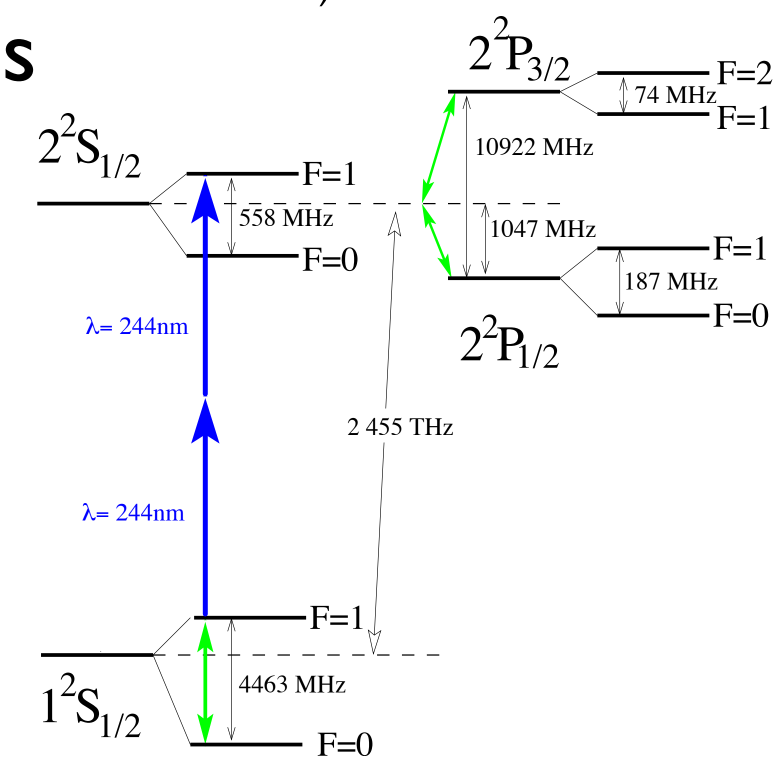
Why Muonium?

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

    [V. W. Hughes et al., "Formation of Muonium and Observation of its Larmor Precession," Phys. Rev. Lett. 5, 63 (1960)]

  - decays to e^+ (fast) + e^- (slow), $\tau_M = \tau_\mu = 2.2$ μs (bound-state correction ~10^{-10})
  - readily produced when μ^+ stop in matter
  - chemically, almost identical to hydrogen
  - atomic spectroscopy well studied
  - "ideal testbed" for QED, the search for new forces, precision measurement of muon properties, etc.
  - also useful for materials science

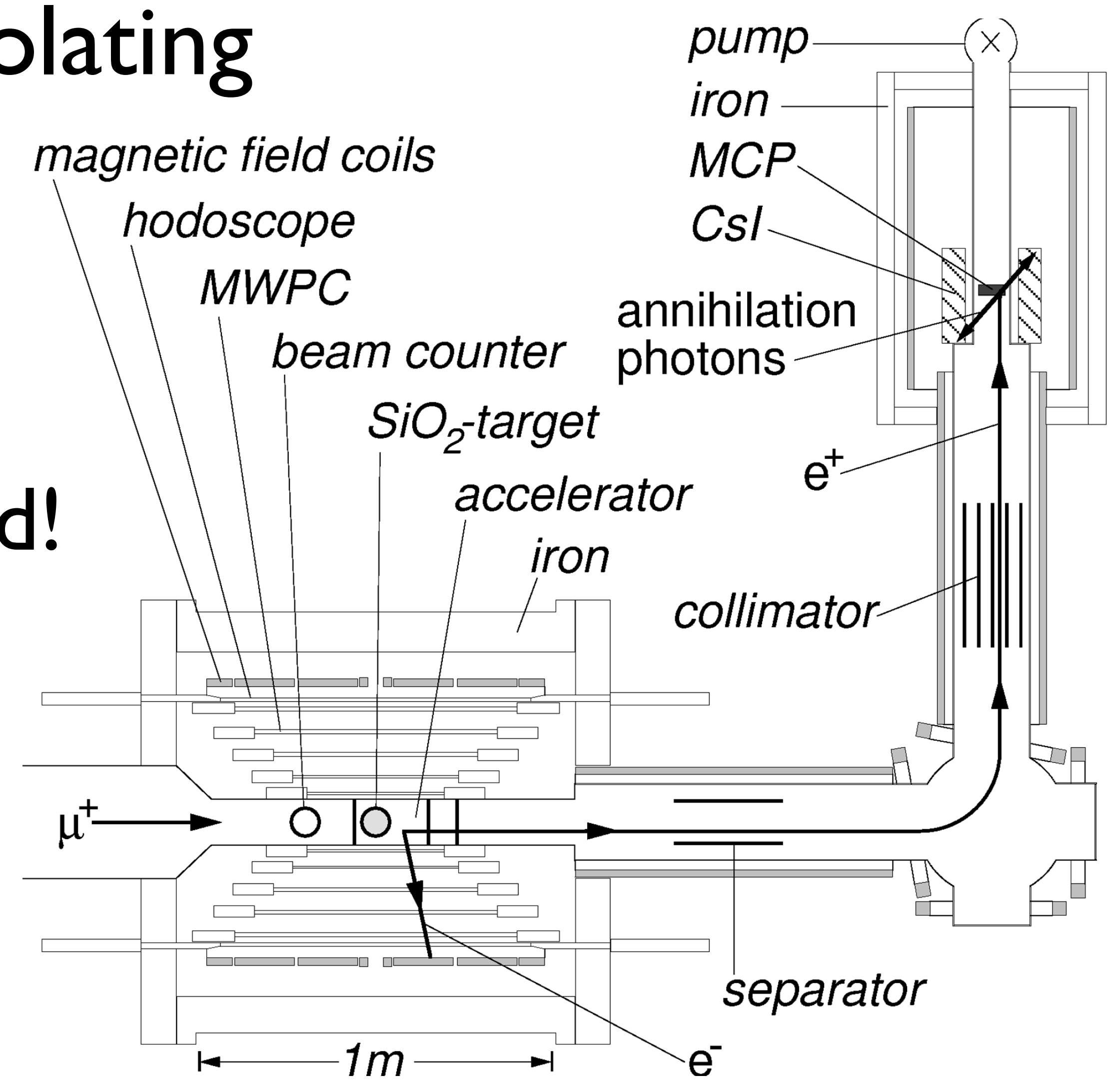
    (world μSR facilities: ISIS@RAL, J-PARC, PSI, RCNP@Osaka, TRIUMF)



Muonium Double CLFV?

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

- Muonium-antimuonium (M-$\bar{\text{M}}$) oscillation would be doubly charged-lepton-flavor violating
- Nothing forbids it *except* lepton-flavor conservation
  - which we know (ν mixing) is violated!
    - but M $\leftrightarrow$ $\bar{\text{M}}$ via virtual ν mixing negligible
    - background-free search for new physics!



- Current limit set by MACS (1999) at PSI: $P_{M\bar{M}} \leq 8.3 \times 10^{-11}$ (90% C.L.) in 0.1 T field

Willmann talk

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

Muonium Double CLFV?

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

Phillips talk

Muonium Spectroscopy

49 Page 2 of 9 Hyperfine Interact (2018)

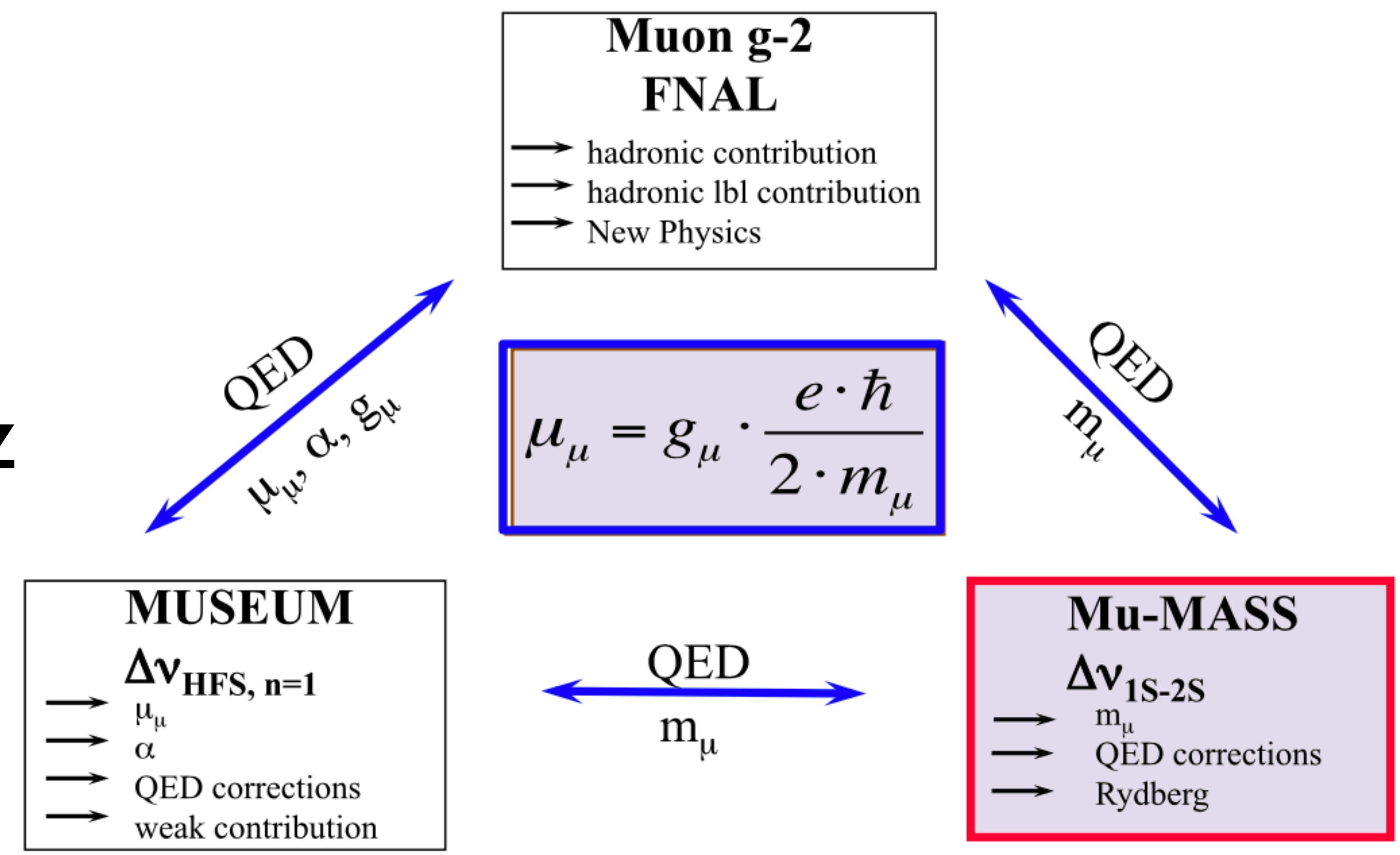


Fig. 1 Fundamental constants in the muon sector and related experiments (adapted from [42])

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

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

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

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

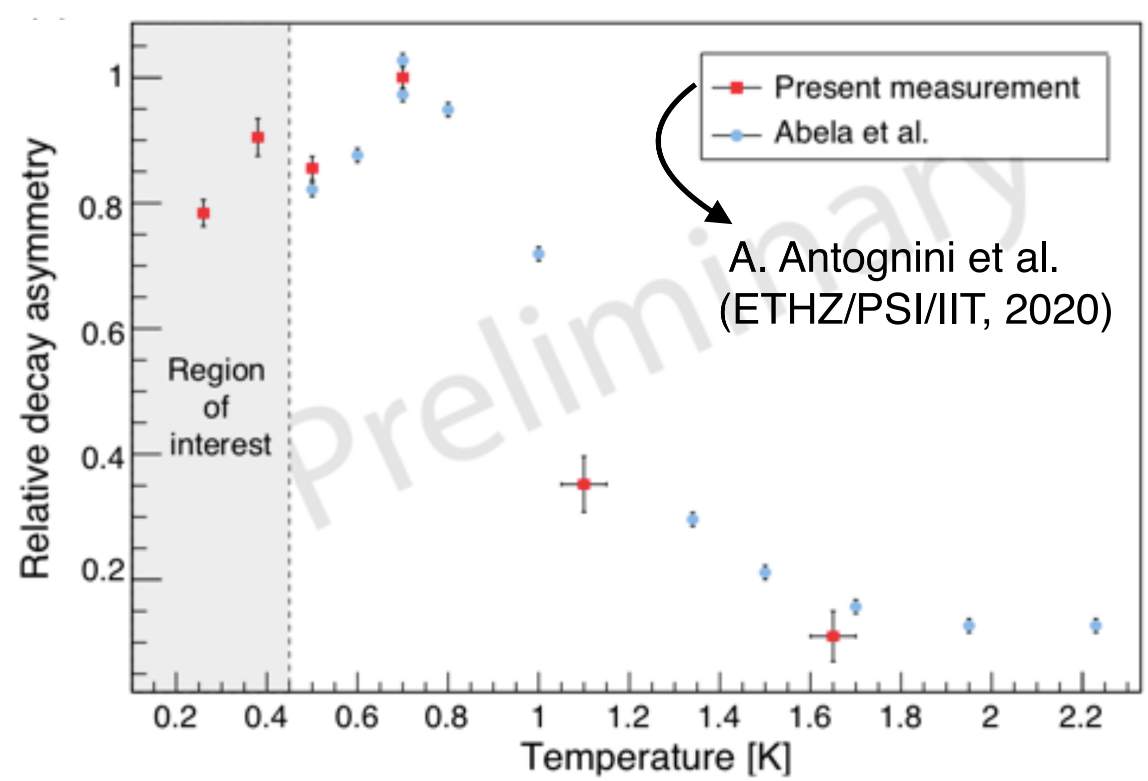
Muonium Spectroscopy

- New 1S-2S experiment, Mu-MASS, now in R&D/commissioning stage at PSI
  - goal: improve sensitivity x1000 (<10 kHz), 4 ppt
  - systematics expected to dominate
    - PIP-II muon rate (~3 orders higher than current PSI) would help
      - 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 – ∃ nowhere

- Proposals by D. Taqqu of Paul Scherrer Institute (Swiss national laboratory ≠ CERN):
  - stop slow (keV) muons in ~ μm-thick layer of superfluid He (SFHe)
    - or (T. Phillips, IIT) use ~ 100 μm SFHe layer for ~ 10^2 ↑ intensity?



  - R&D in progress @ PSI & proposed @ Fermilab

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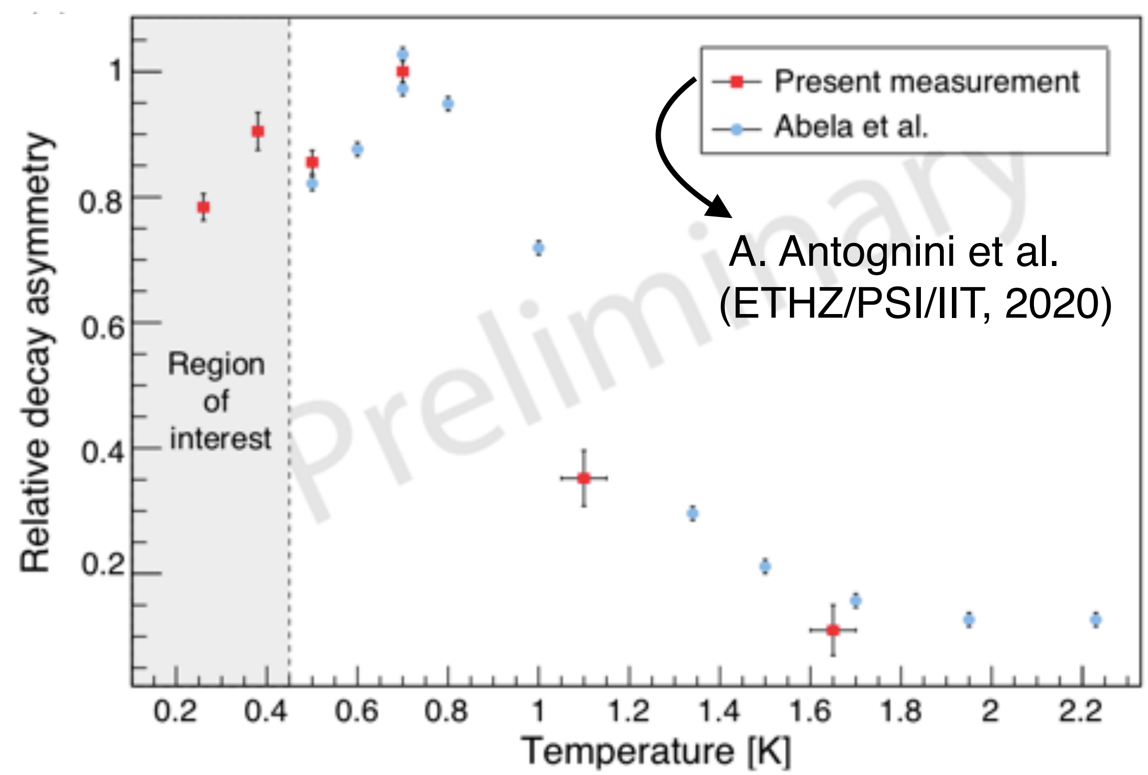
H *immiscible* in SFHe ⇒ μM should expel M atoms at 6,300 m/s, ⊥ to SFHe surface



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

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

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

We formed the first "atomic-optics" beam of electron-spin-polarized hydrogen atoms using a 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.

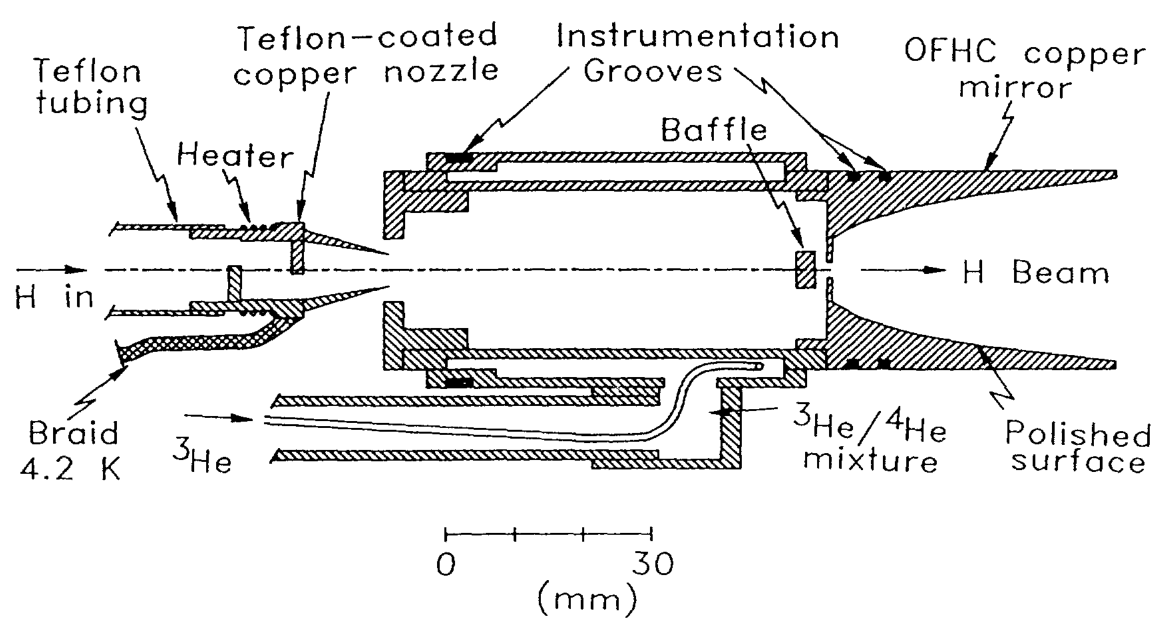


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

muCool @ PSI

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

Editors' Suggestion

Demonstration of Muon-Beam Transverse Phase-Space Compression

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

(muCool Collaboration)

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

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

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

DOI: 10.1103/PhysRevLett.125.164802

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Make M beam suitable for stopping in ~μm SFHe layer

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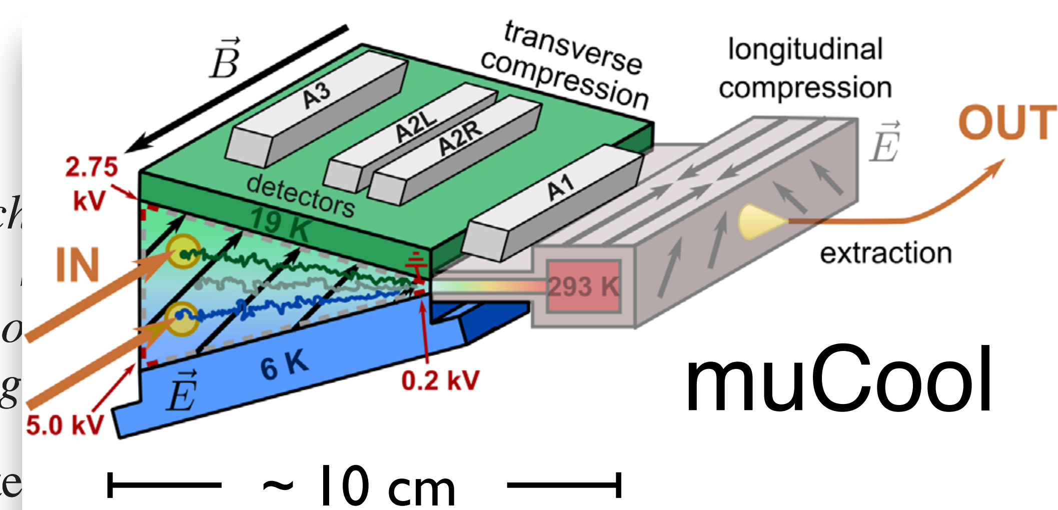

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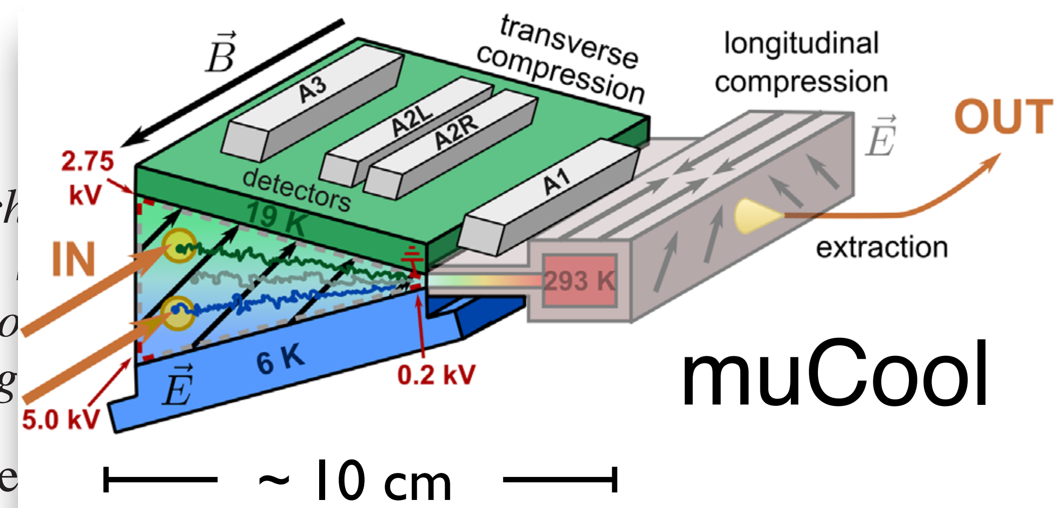

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Can photo-ionize for unique slow-μ^+ beam

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Muonium Gravity: Motivation

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

Studying Antimatter Gravity

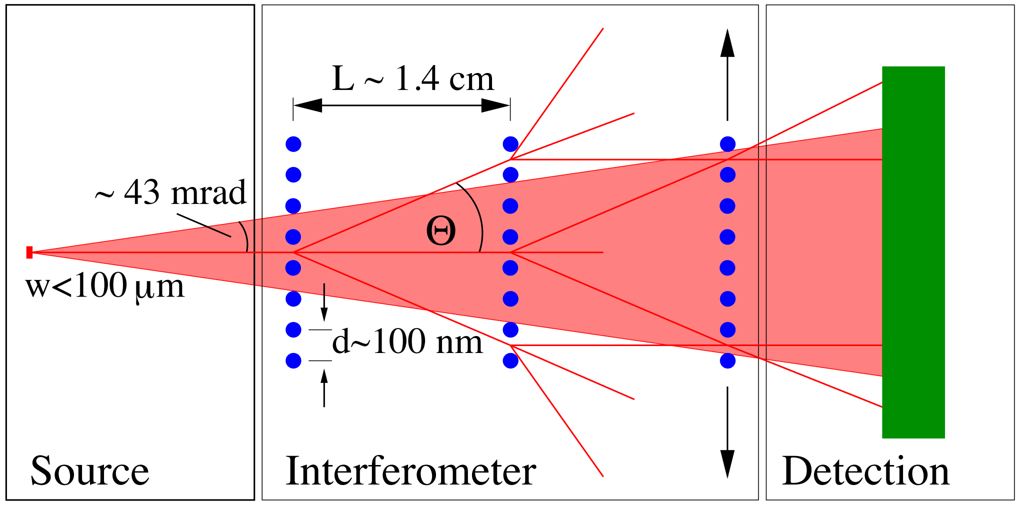
- *Many* $\overline{\text{H}}$ efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)
- All require antiprotons, so possible only at CERN Antiproton Decelerator
  - and measurements on *composite* particle ($\bar{p}$ made of quarks + gluons) theoretically complex
- BUT – another approach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

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 ~ 6300 m/s



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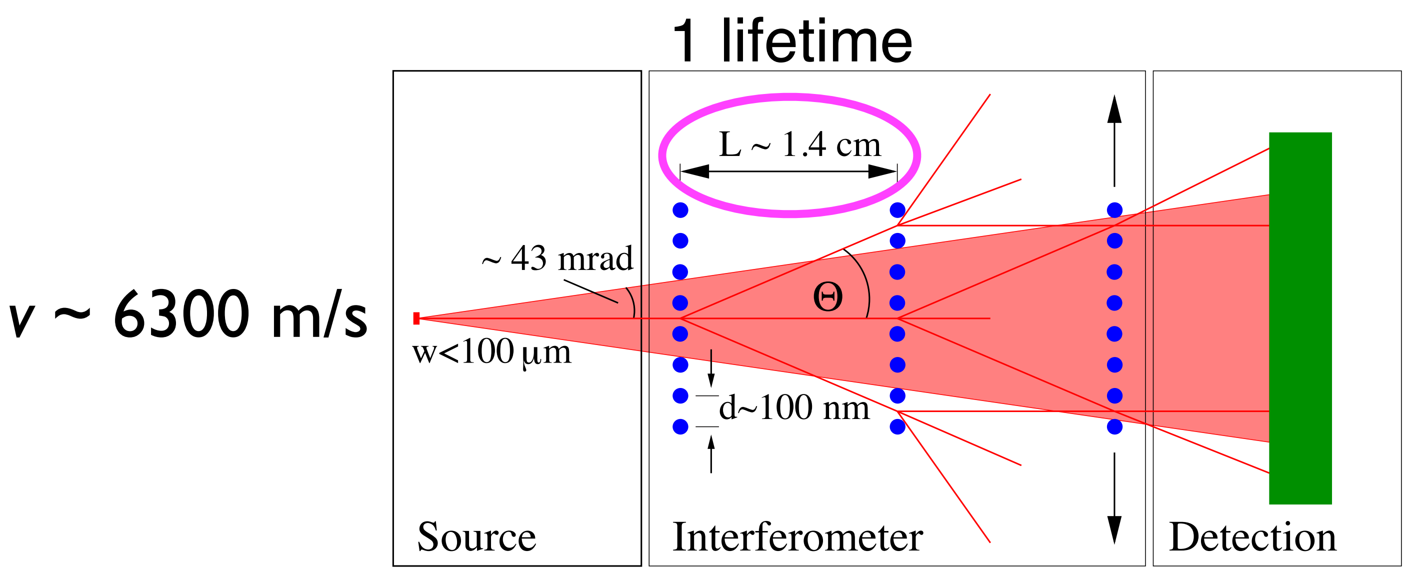

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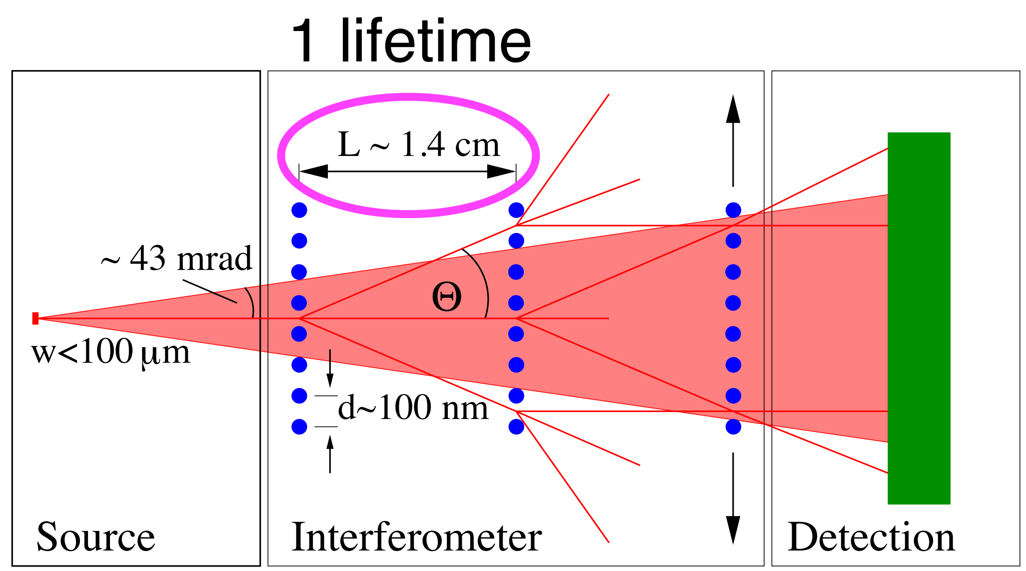

$\frac{1}{2} gt^2 = 24$ pm!

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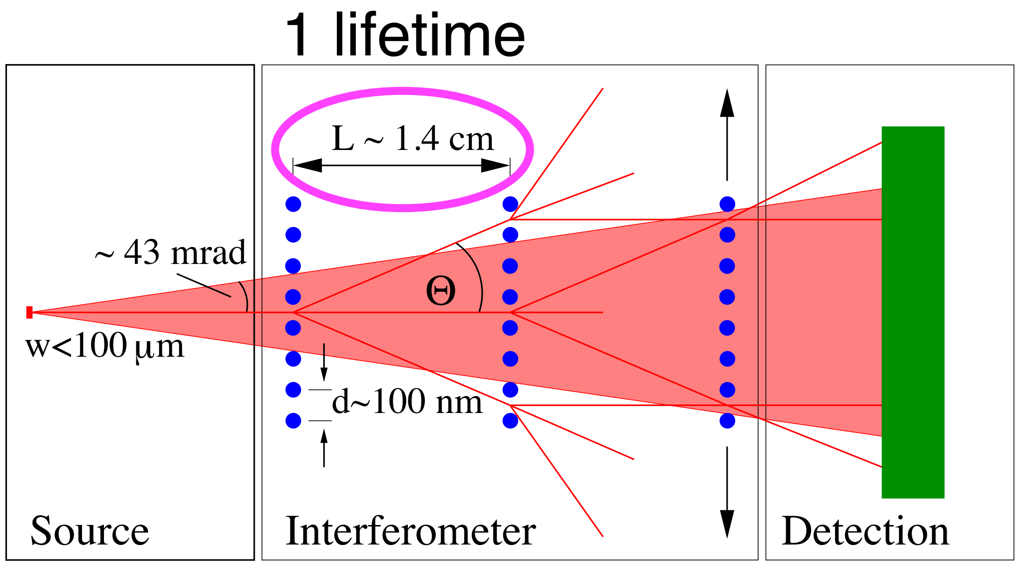

½ gt^2 = 24 pm!

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

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1 lifetime

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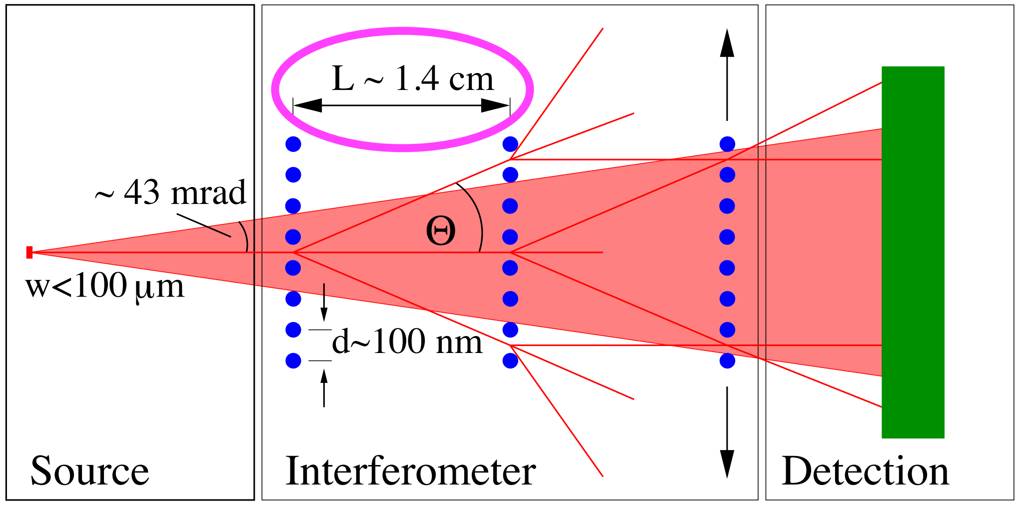

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- Need

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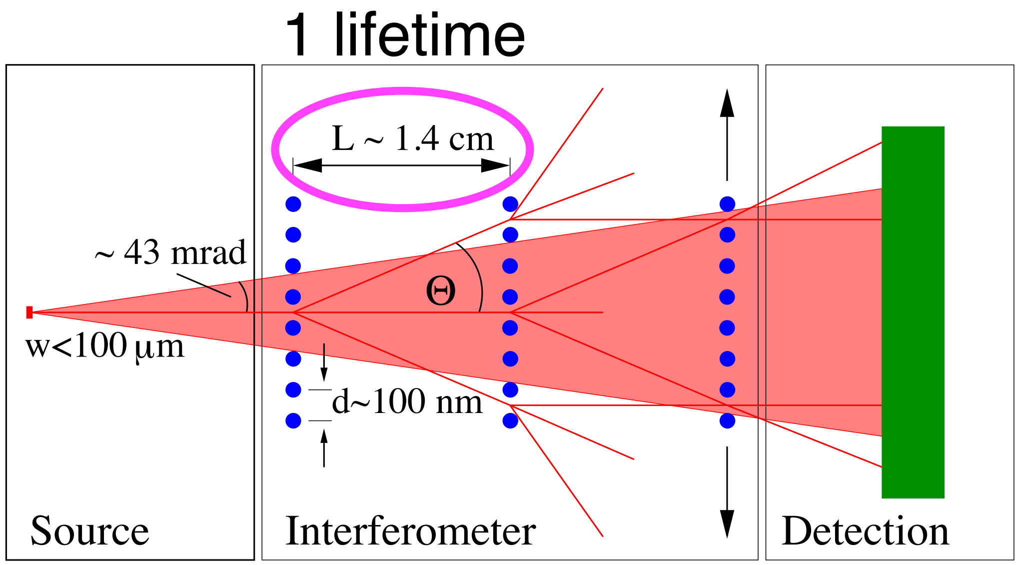

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- Need
  - very precise atom interferometer

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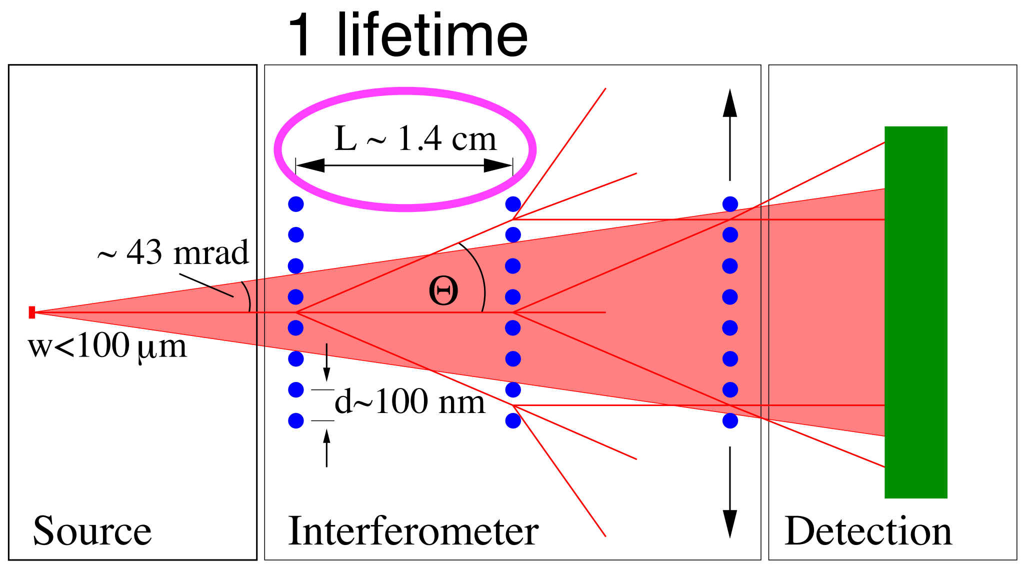


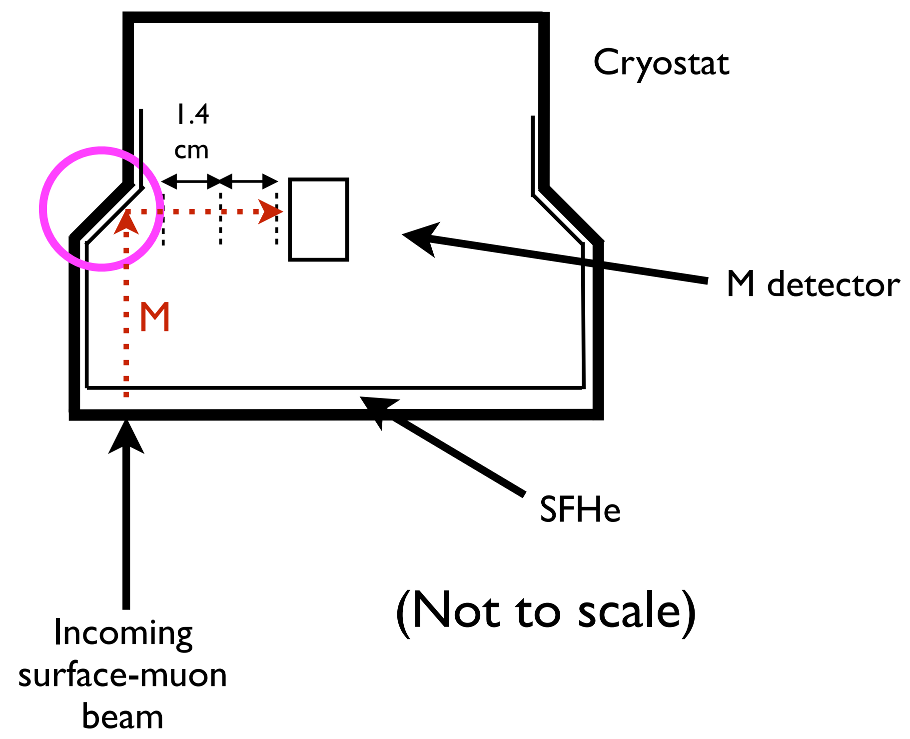
½ gt^2 = 24 pm!

but grows as $t^2 \Rightarrow$ 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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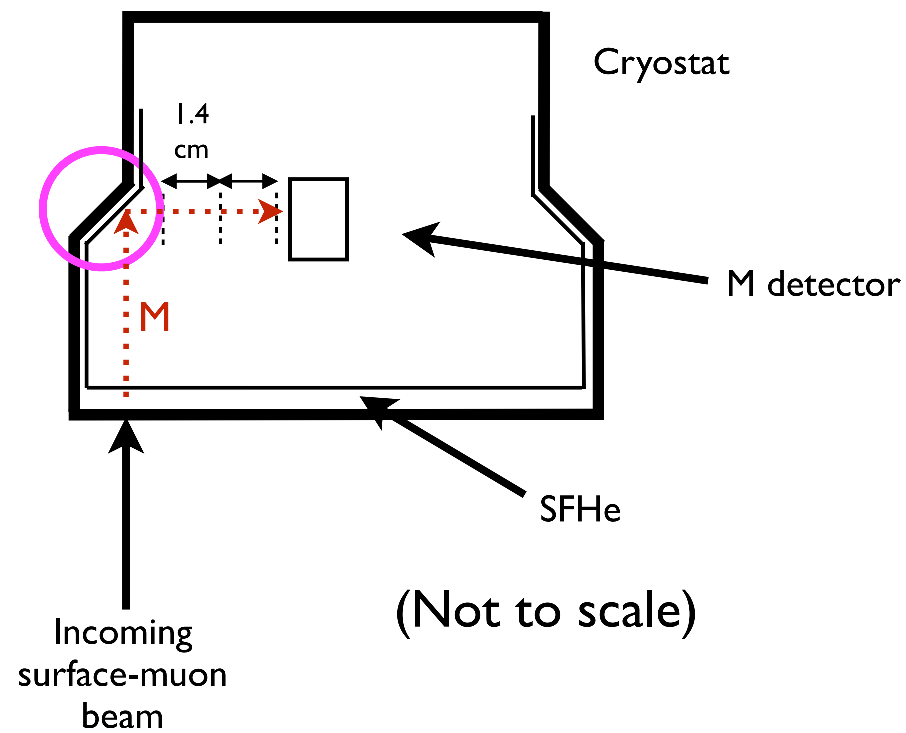

  - well-known property of SFHe to coat surface of its container
  - 45° section of cryostat reflects vertical M beam emerging from SFHe surface into the horizontal

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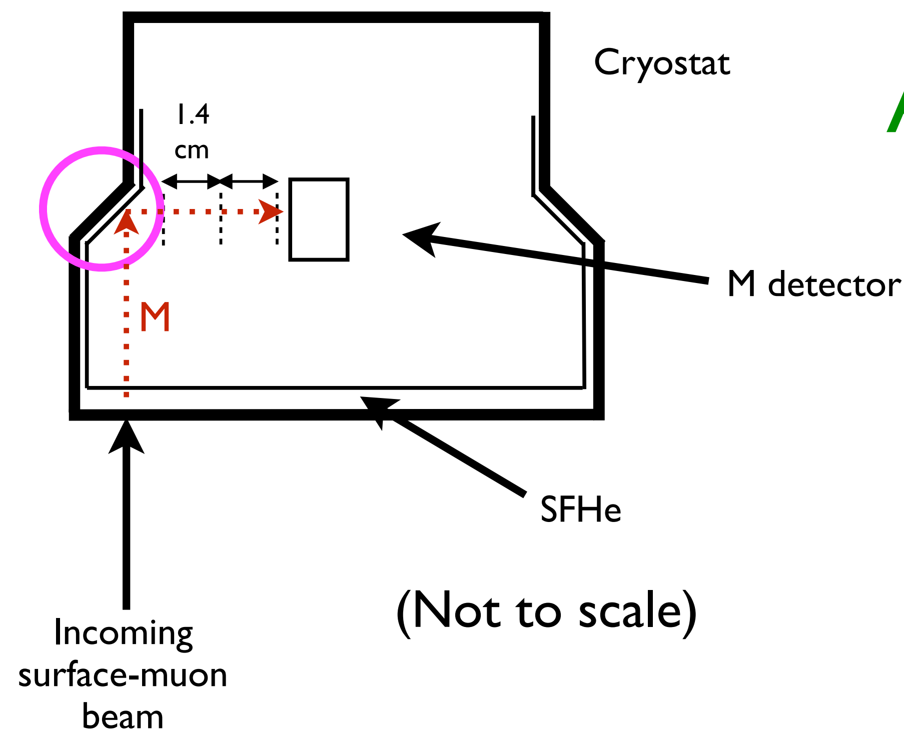

A "ship in a bottle!"

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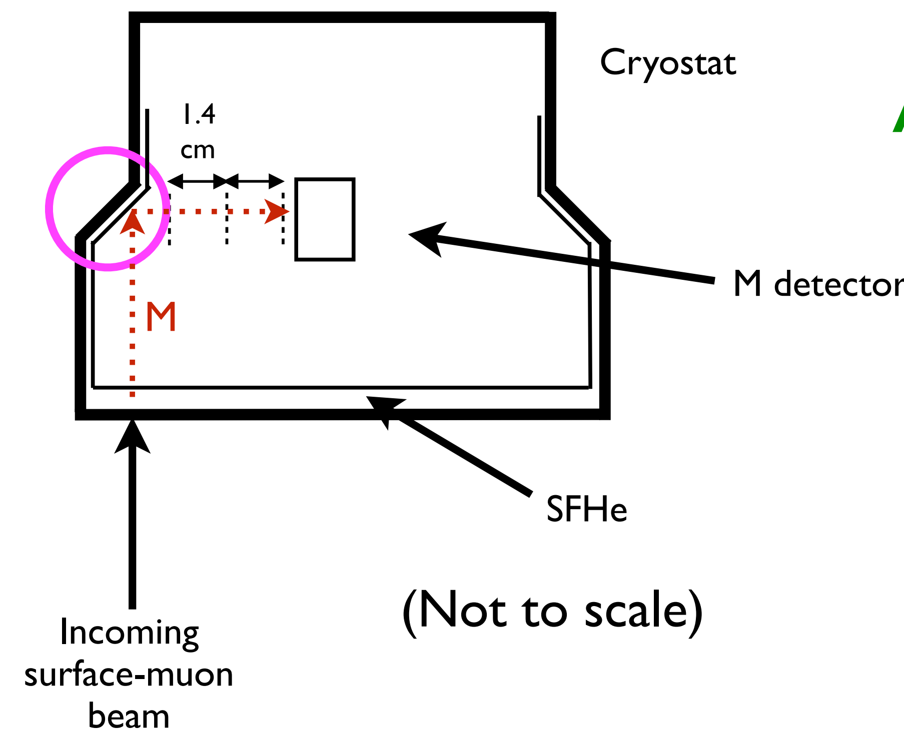

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Sensitivity estimate @ 100 kHz:

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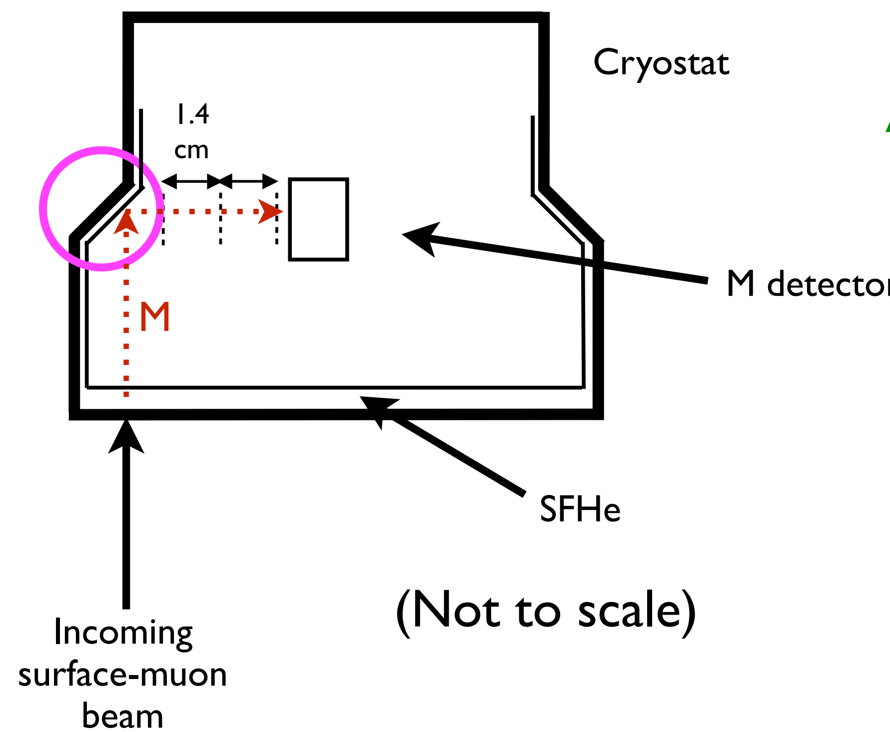

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Sensitivity estimate @ 100 kHz:

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

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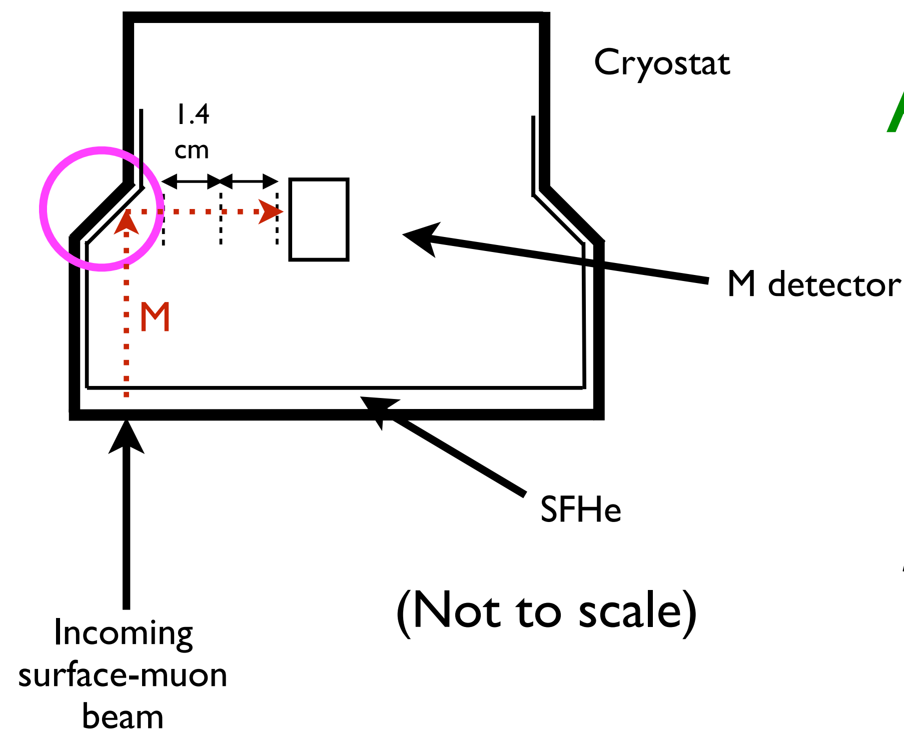

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where

C = 0.3 (est. contrast)

N_0 = # of events

d = 100 nm (grating pitch)

τ = M lifetime

Muonium Gravity Experiment

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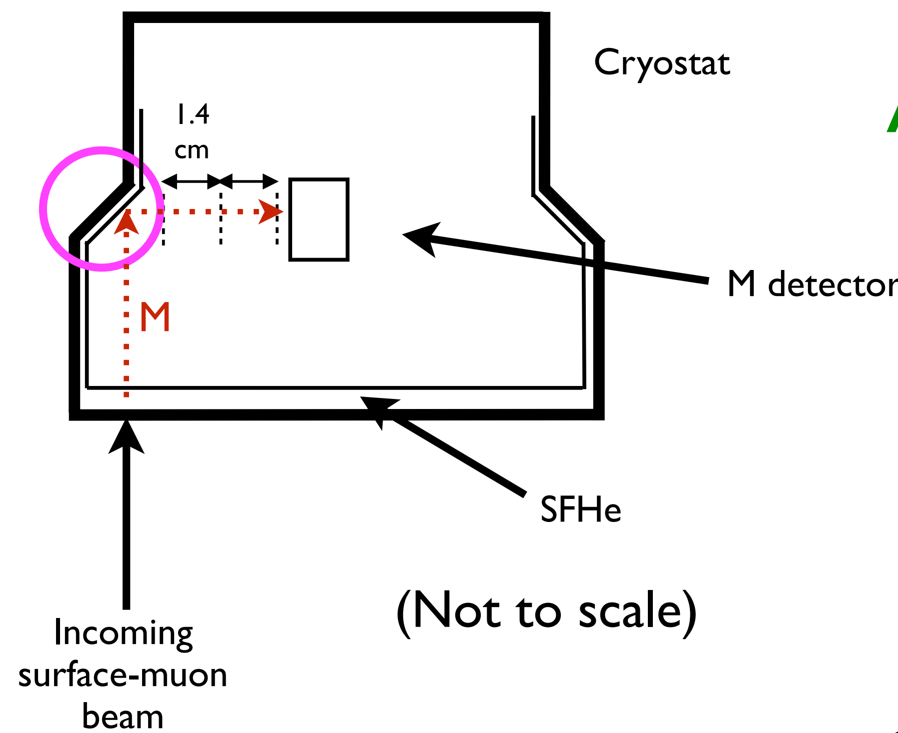

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sign of $\bar{g}$ with 1 day's data

where

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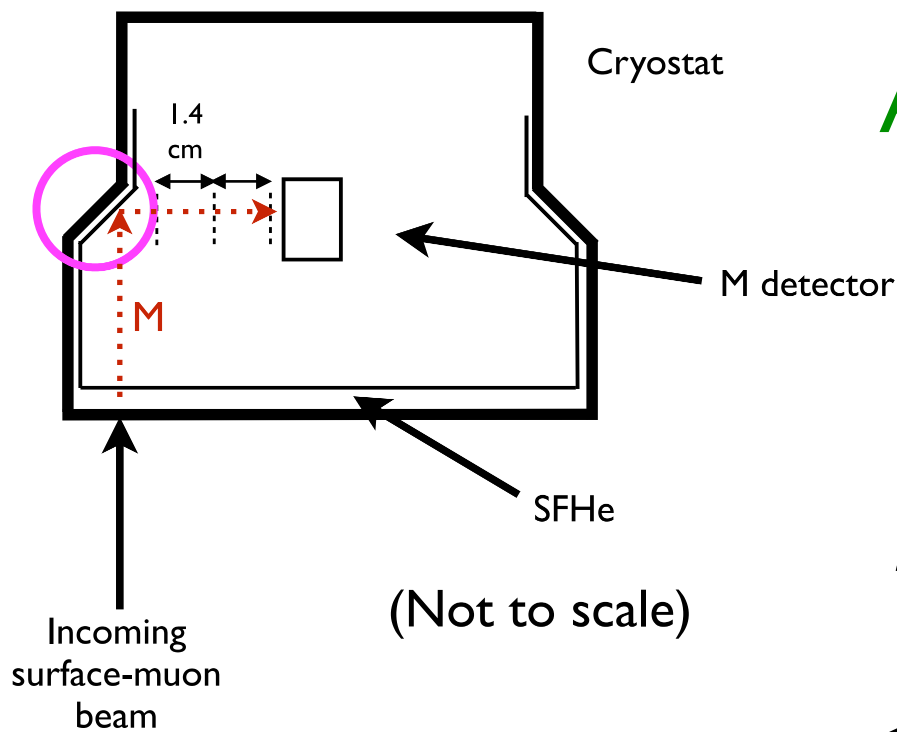


A "ship in a bottle!"

Sensitivity estimate @ 100 kHz:

$$S = \frac{1}{C\sqrt{N_0}} \frac{d}{2\pi} \frac{1}{\tau^2}$$

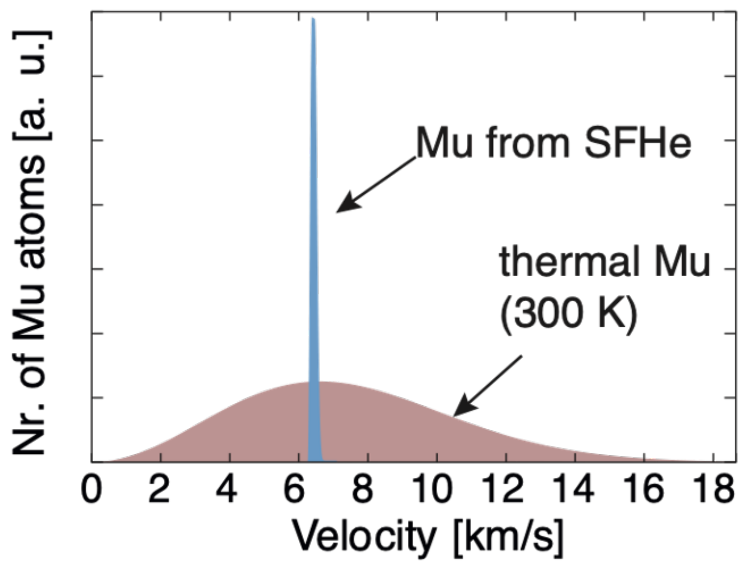
$$\approx 0.3\,\mathrm{g}\ \ \mathrm{per}\ \sqrt{\#\mathrm{days}}$$

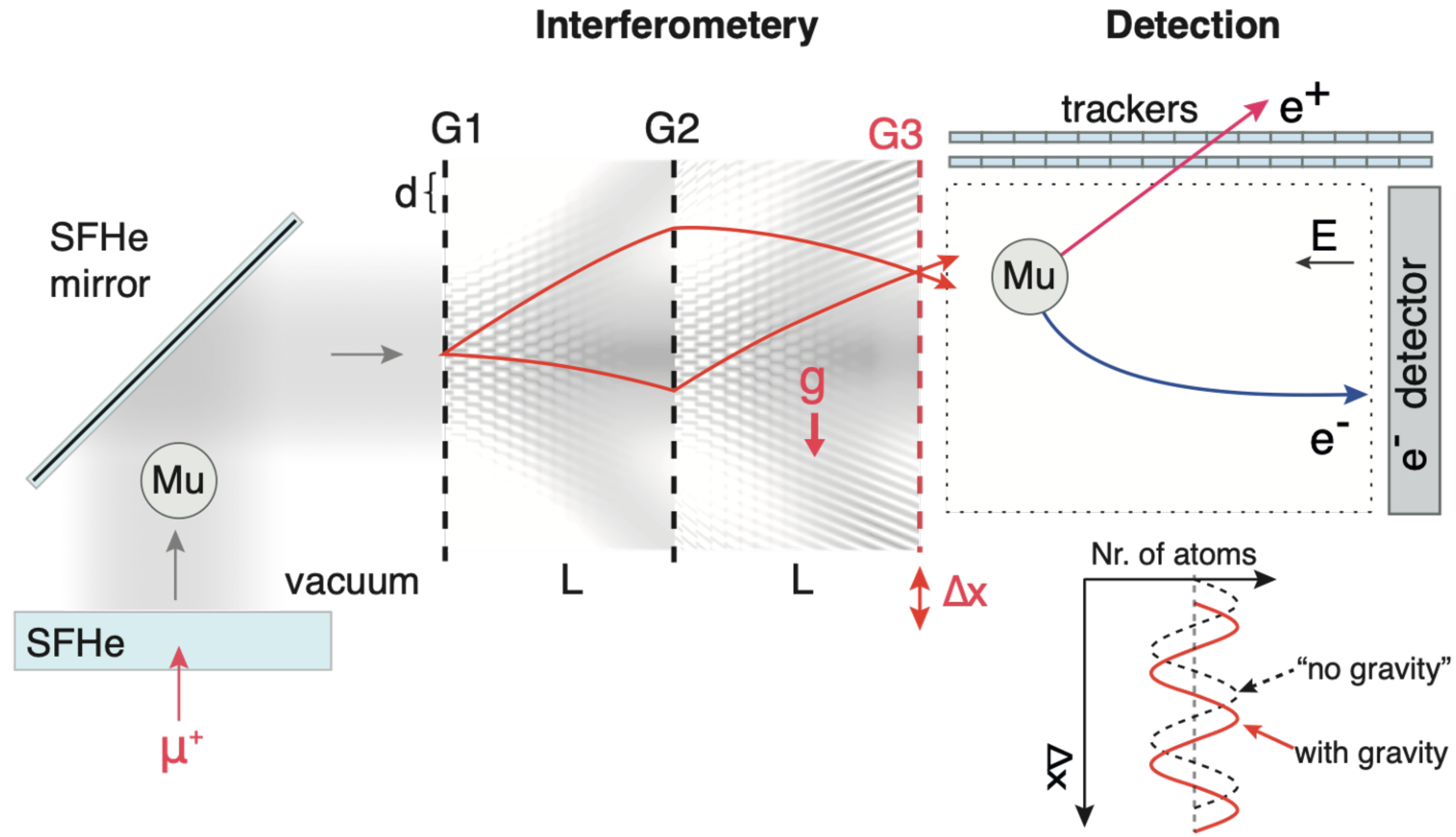
sign of $\bar{g}$ with 1 day's data

where
C = 0.3 (est. contrast)
N_0 = # of events
d = 100 nm (grating pitch)
τ = M lifetime

➡ Muonium Antimatter Gravity Experiment (MAGE)

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

World Low-Energy μ Beams

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See Johnstone & Mazzacane talks

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- Built ~20 years ago for muon collider R&D
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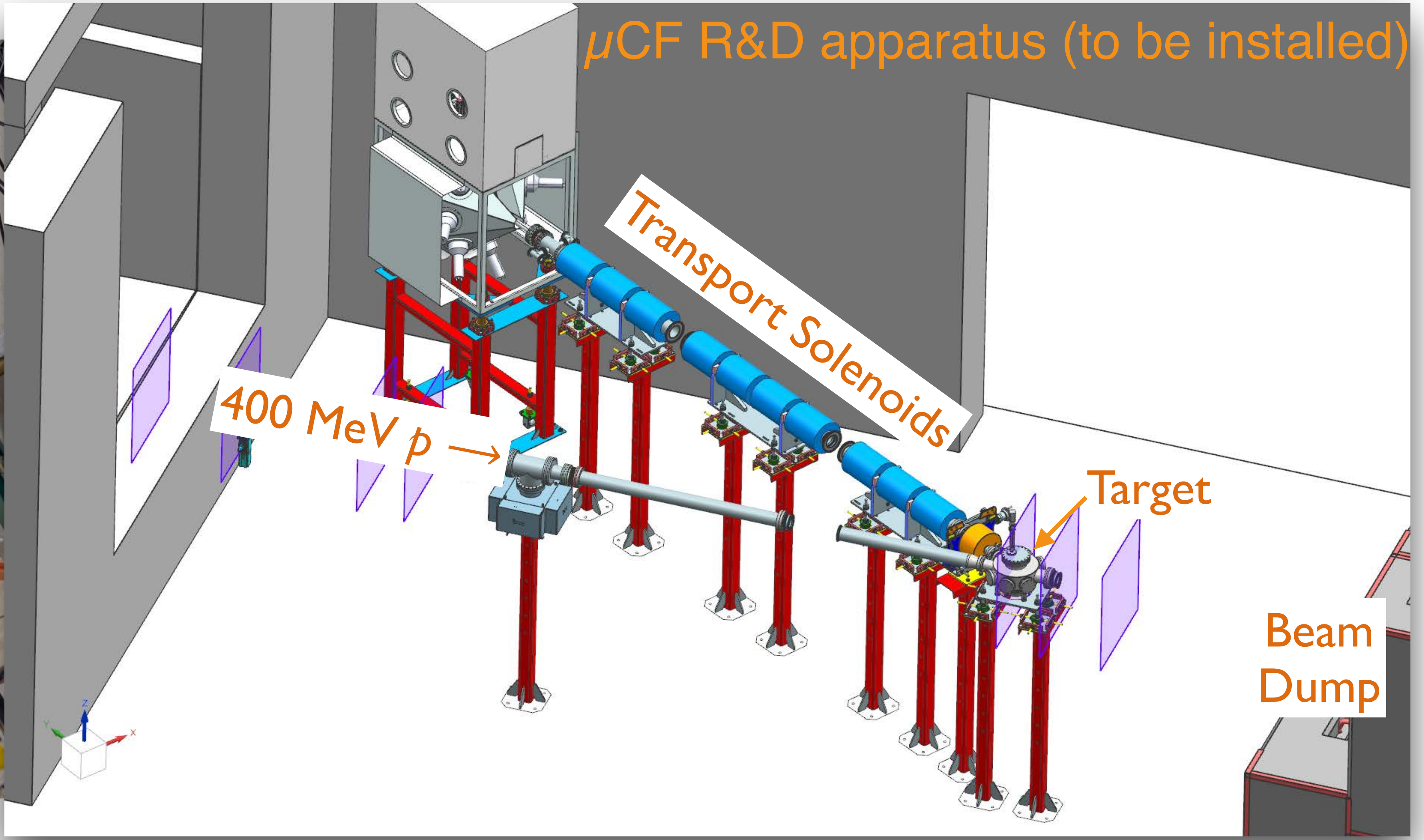

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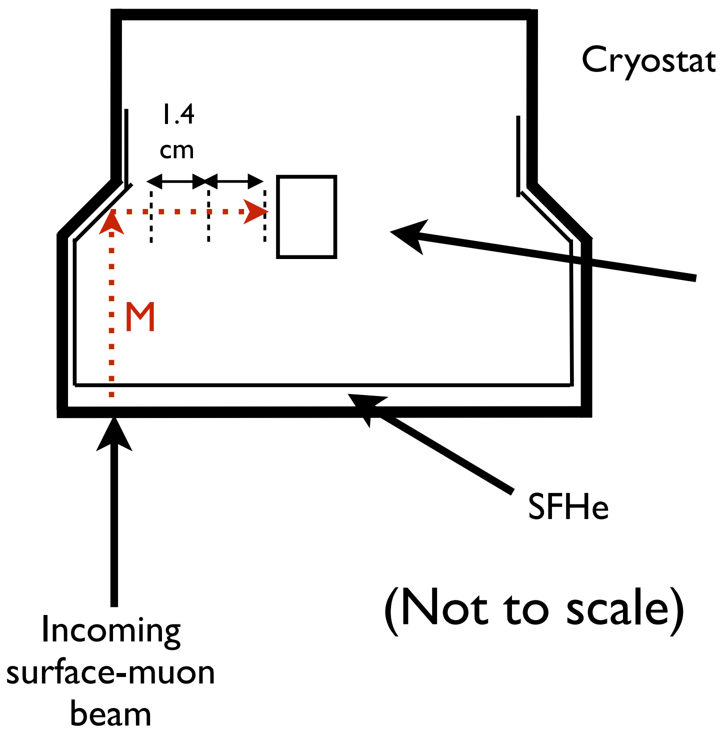
➡ Let's work towards a world-leading Fermilab muonium program!

Backup Slides

Muonium Gravity Experiment



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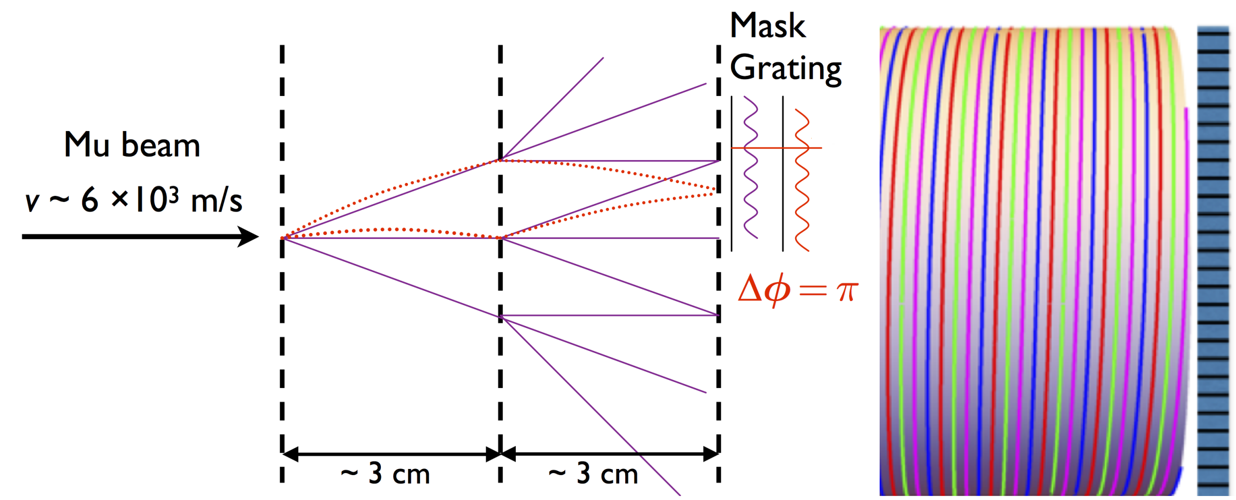

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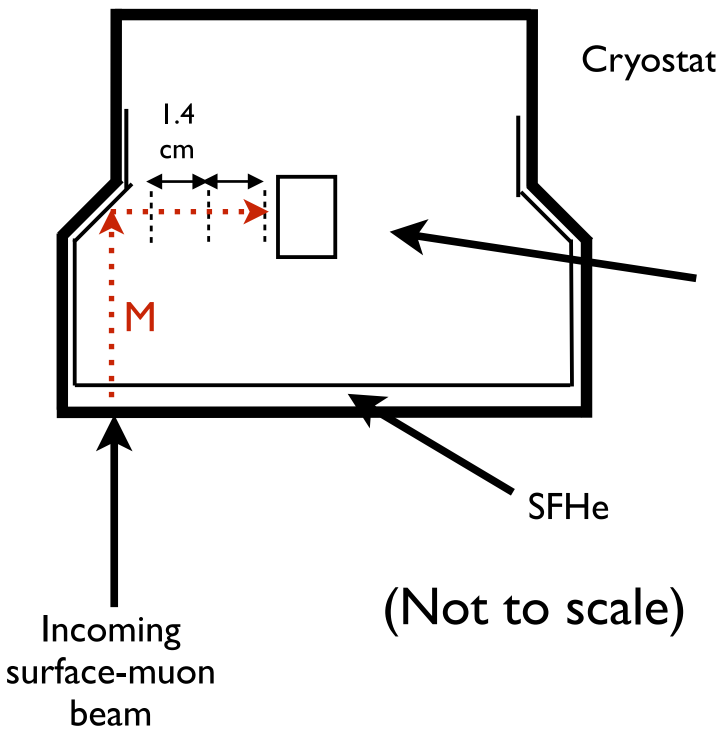

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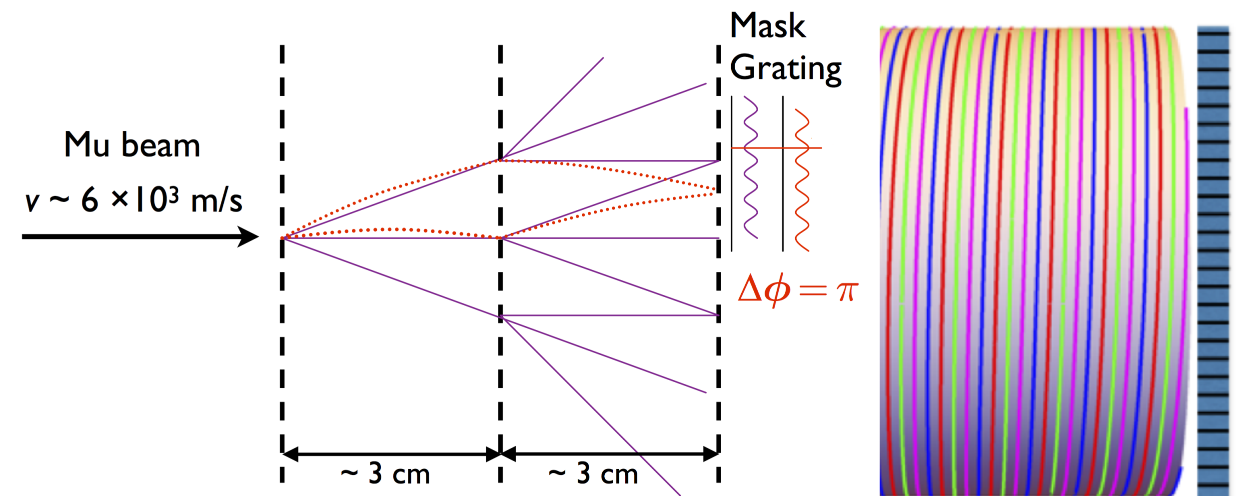

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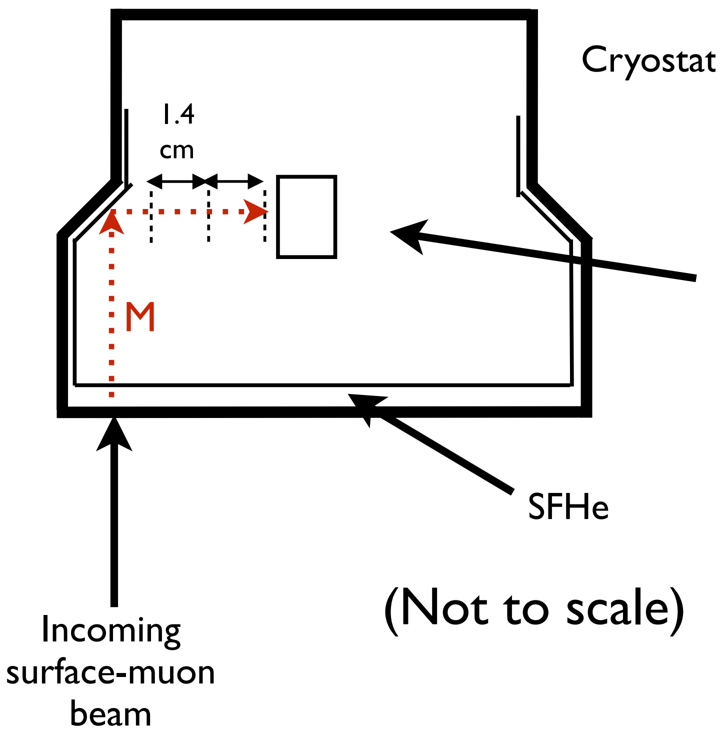

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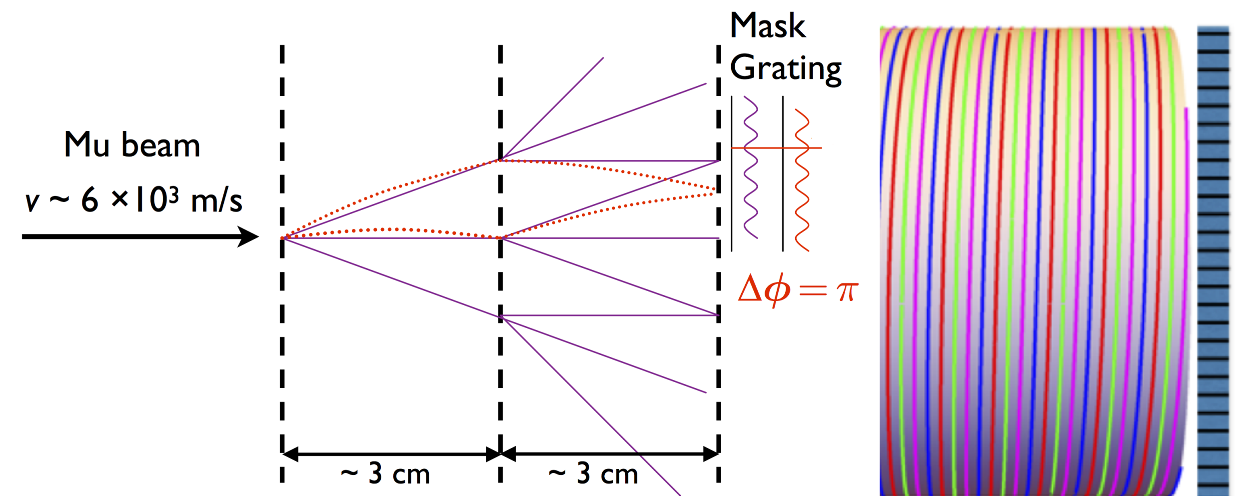

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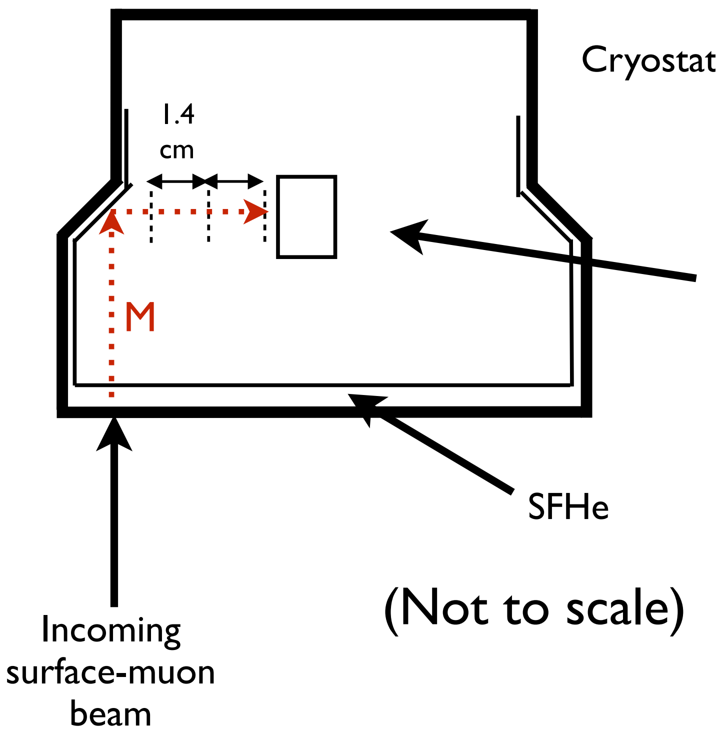

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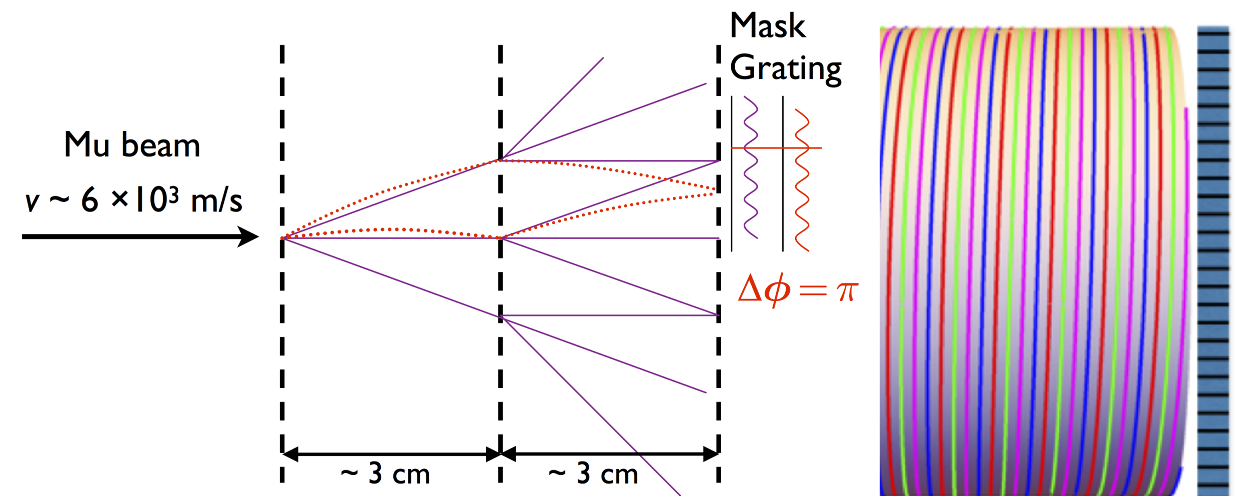

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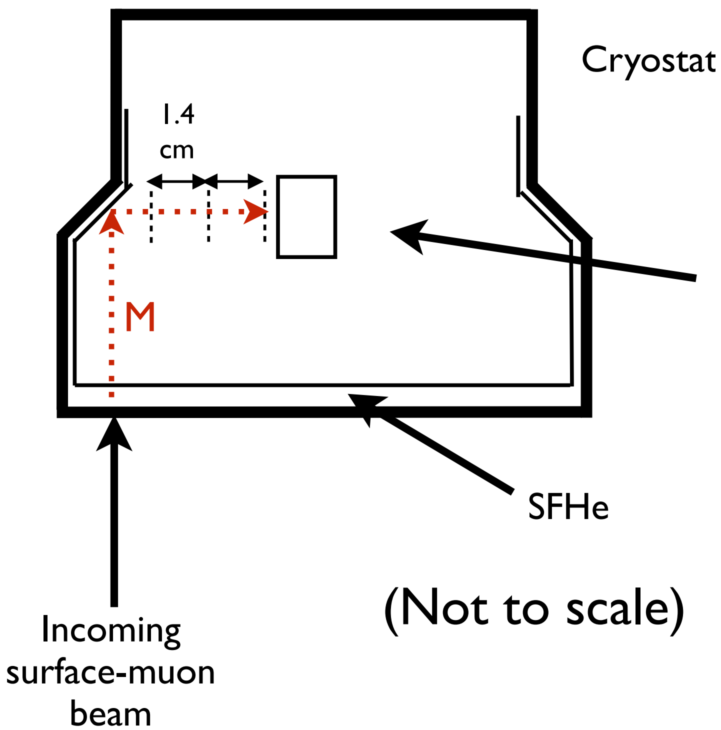

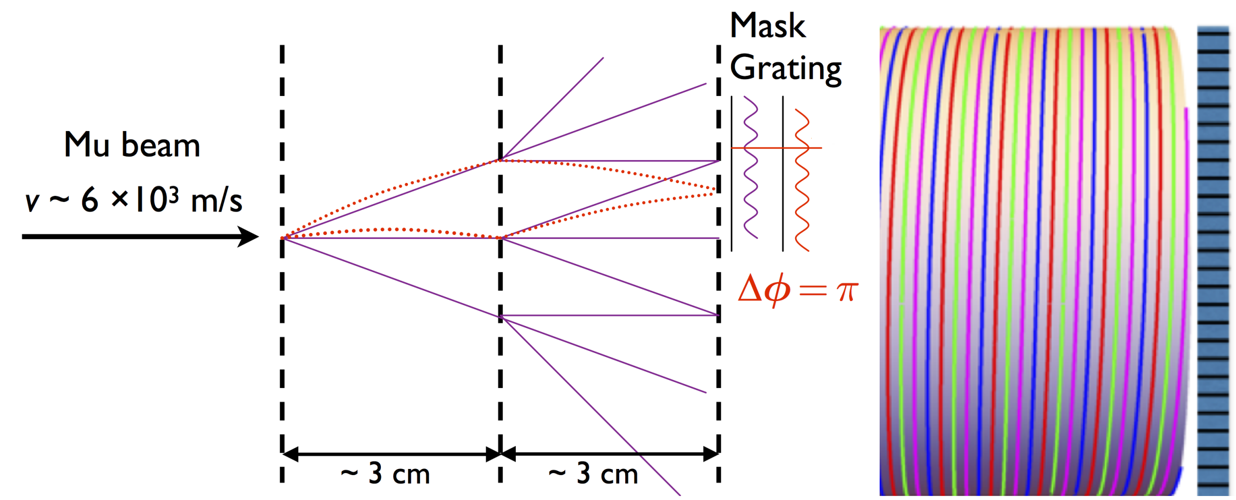

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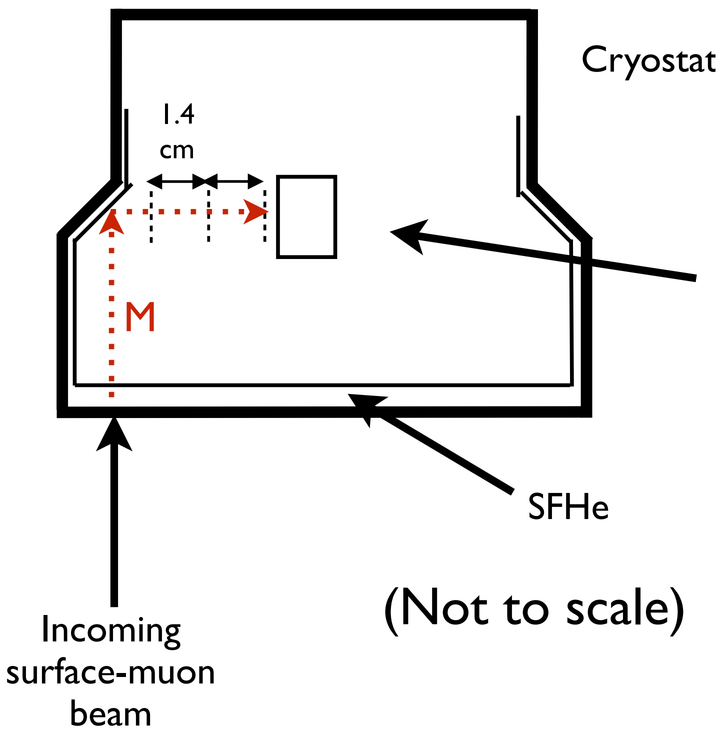

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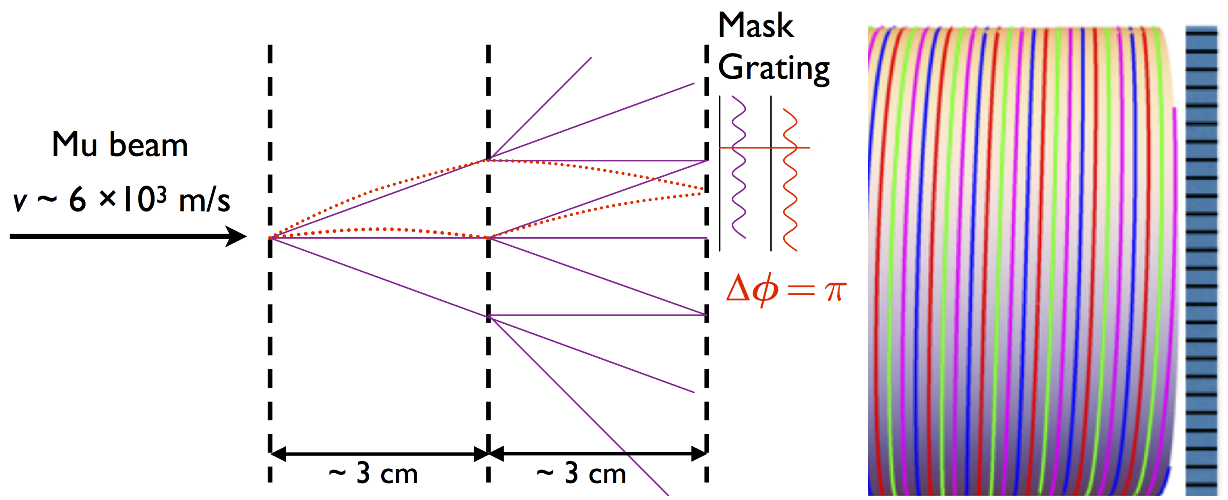

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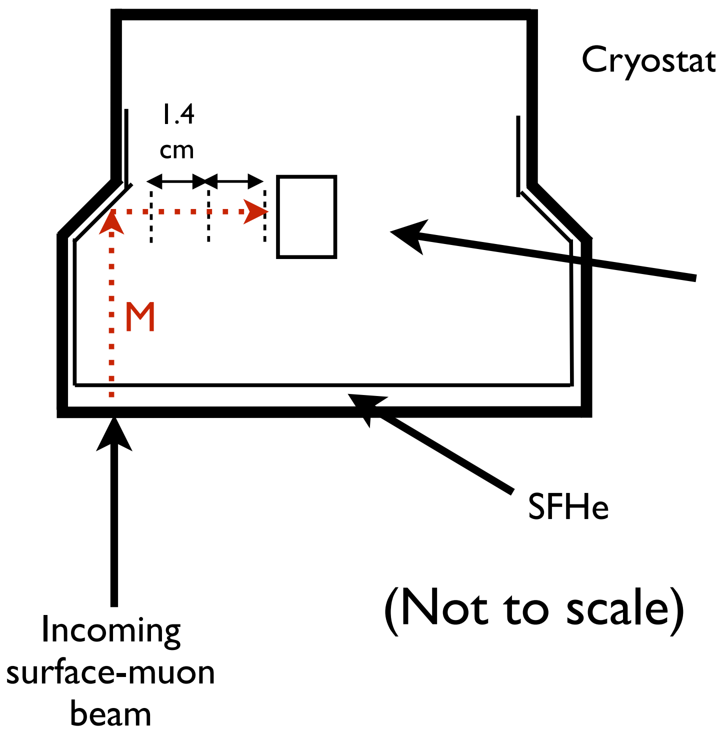

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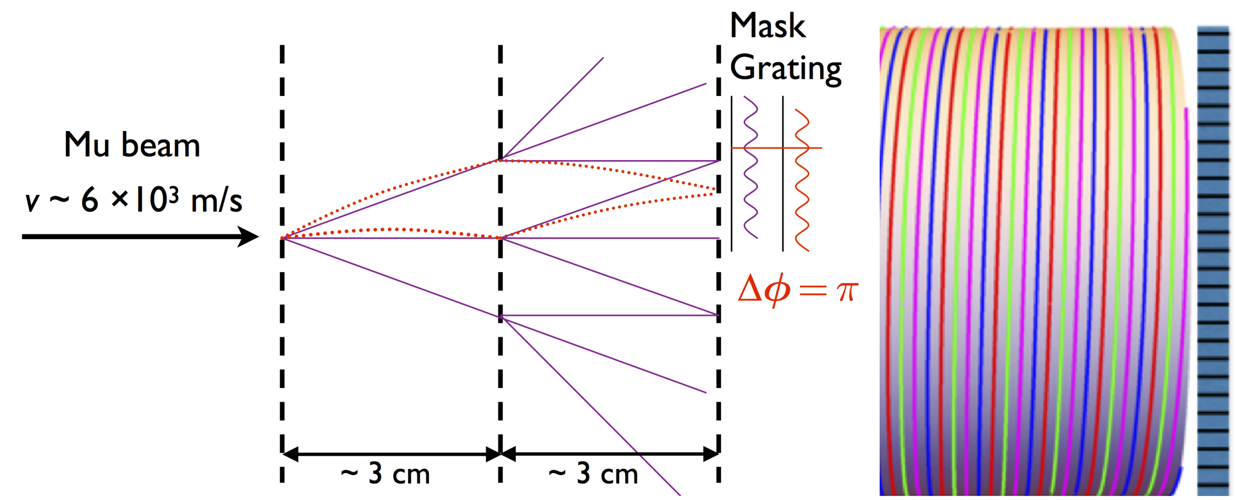

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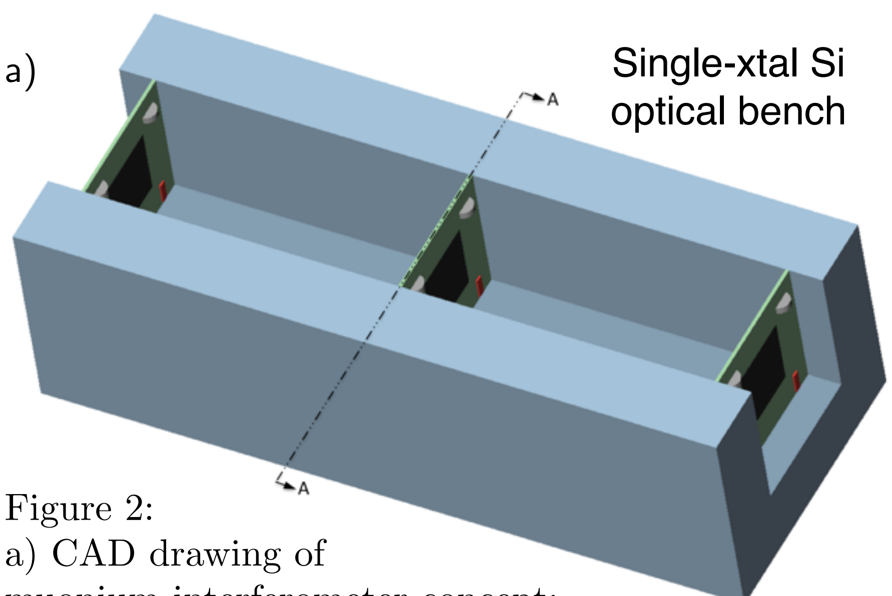

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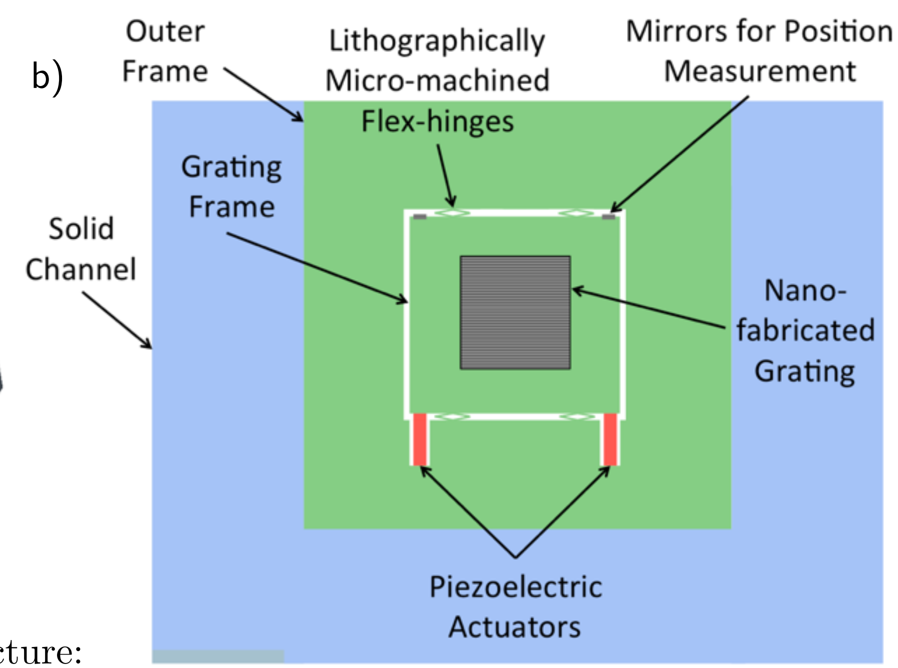

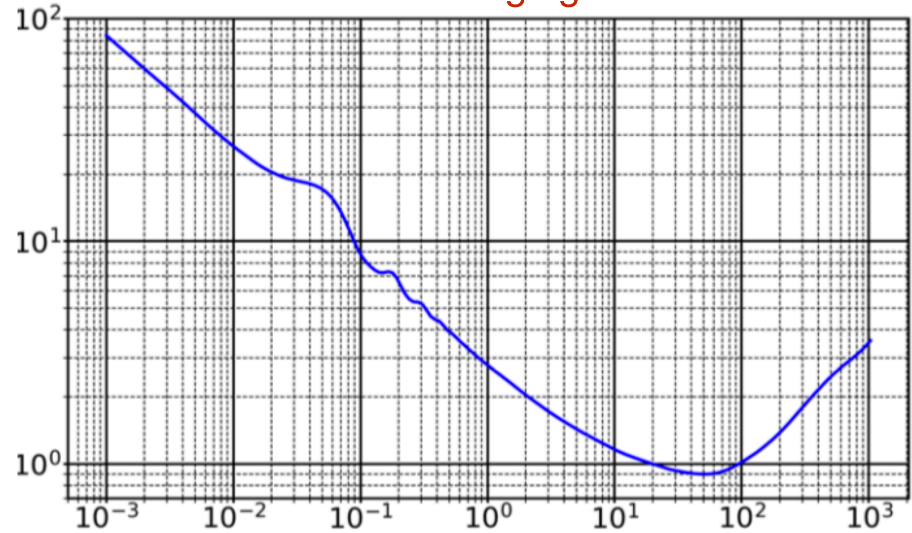

Figure 2:
a) CAD drawing of muonium interferometer concept;
b) Section A-A. In blue-gray is grating support structure: a U-channel machined out of a single-crystal silicon block. Each grating is mounted in a silicon frame connected to an outer frame by flex-hinges; piezo-actuator pair permits small rotations to align the gratings precisely in parallel, as well as scanning of grating 3. Grating frames have mirrors or corner-cube 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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   - 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
   - we are operating a TFG at IIT for NASA space-telescope R&D
3. Can interferometer and detector be operated at cryogenic temperature?
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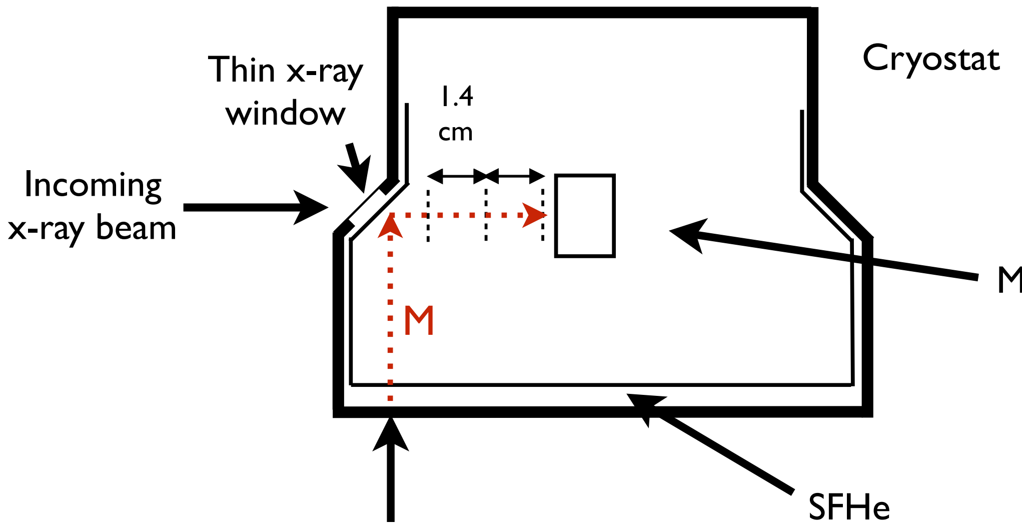

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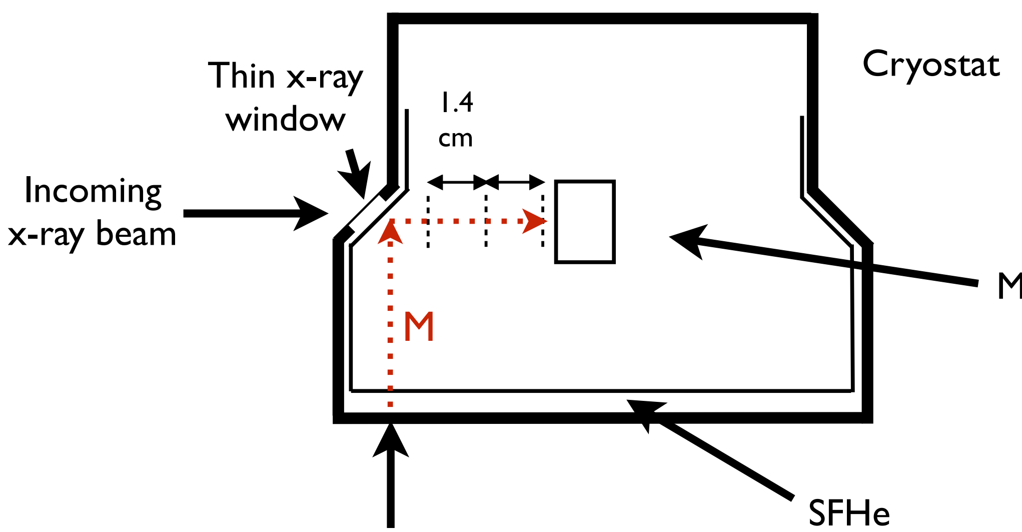

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5. Does Taqqu's scheme work?
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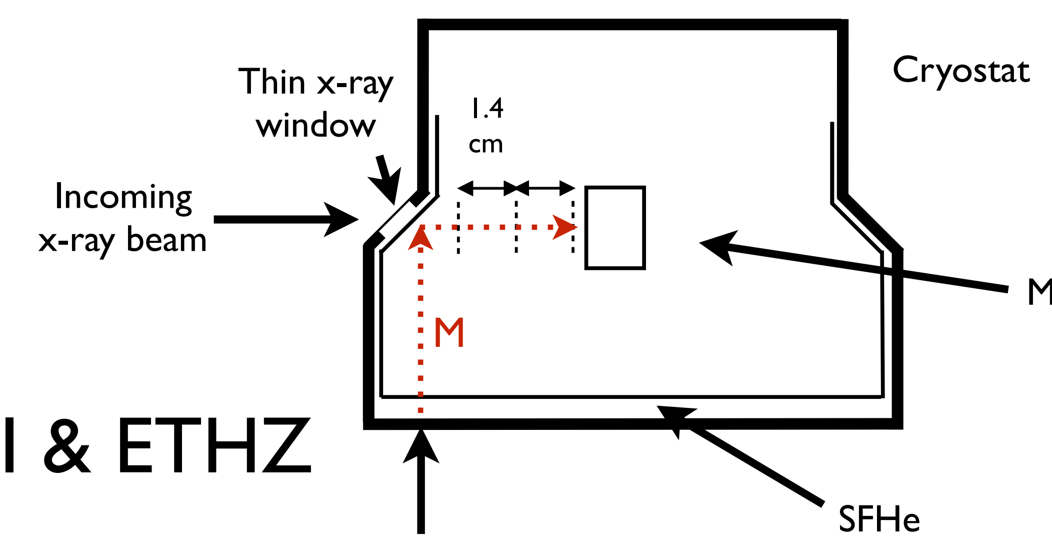
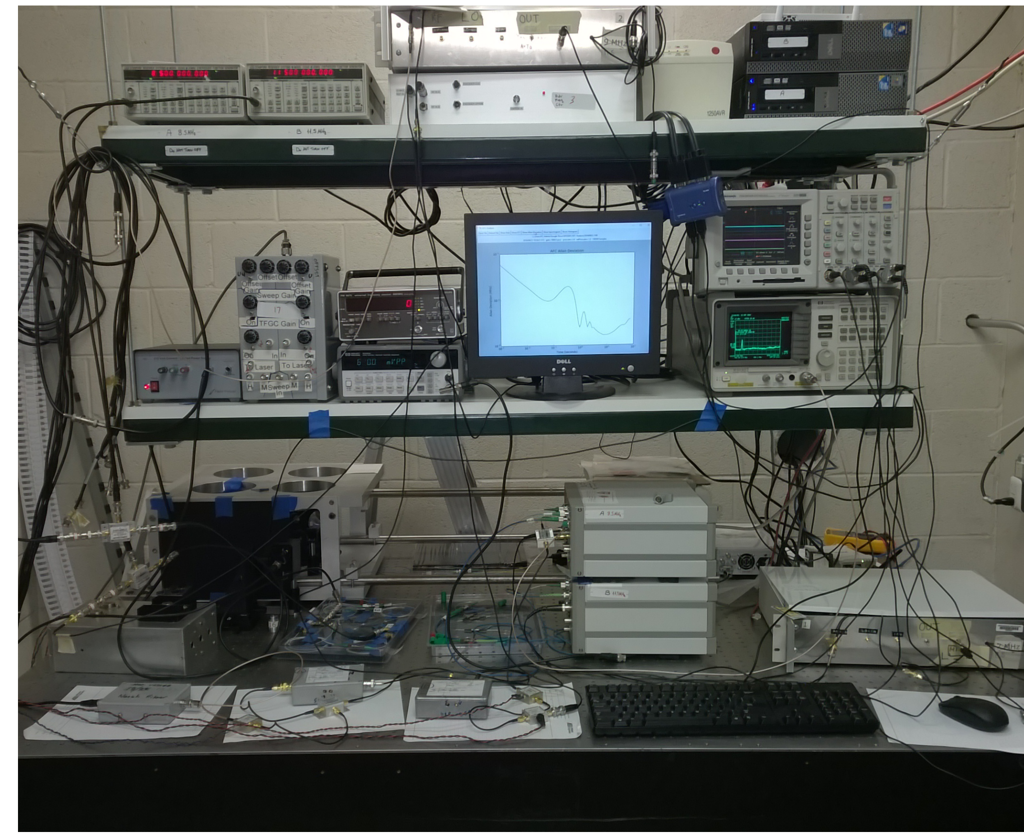


How do we measure TFG performance?

- 2-TFG common-path test



  - merge both laser beams onto one fiber
    - modulated at different frequencies ⇒ distinguishable
  - launch as free-space beam into Michelson
  - tune lasers n fringes apart (typically $n = 1$)
  - count beat frequency in msec time bins

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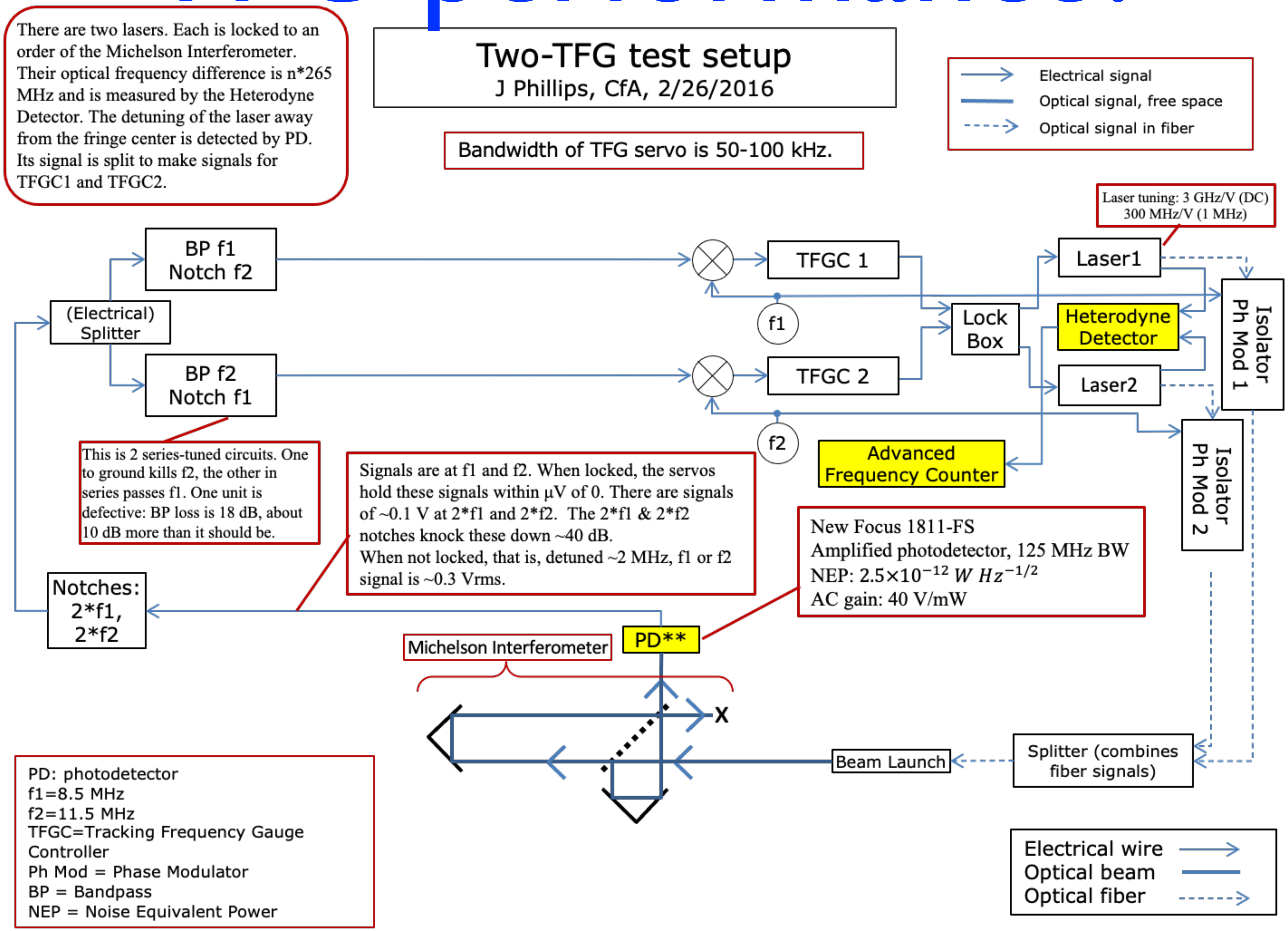
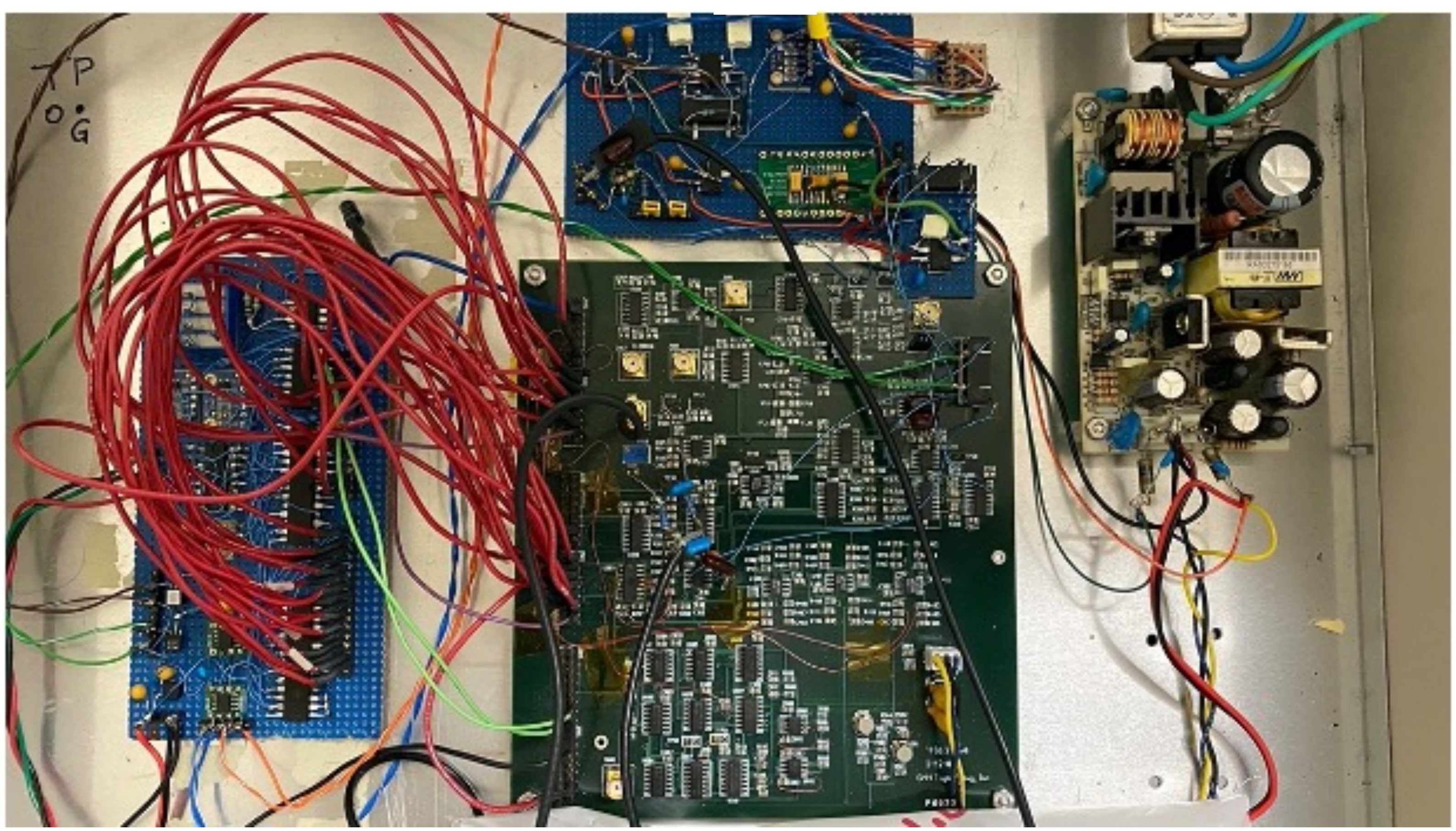


Recent TFG Progress

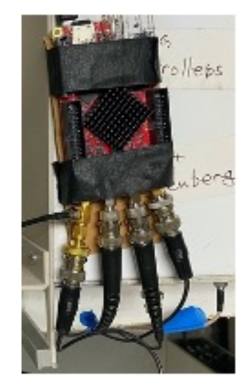
- NASA subcontract-funded R&D (NASA contract → Lockheed Martin Space → UF → IIT)
  - replace analog TFG controller with digital (Phase 1: Red Pitaya; Phase 2: Smartfusion FPGA; Phase 3: RTG4)

One Analog TFG Controller

17"



One Red Pitaya Digital TFG Controller



Red Pitaya Close-Up