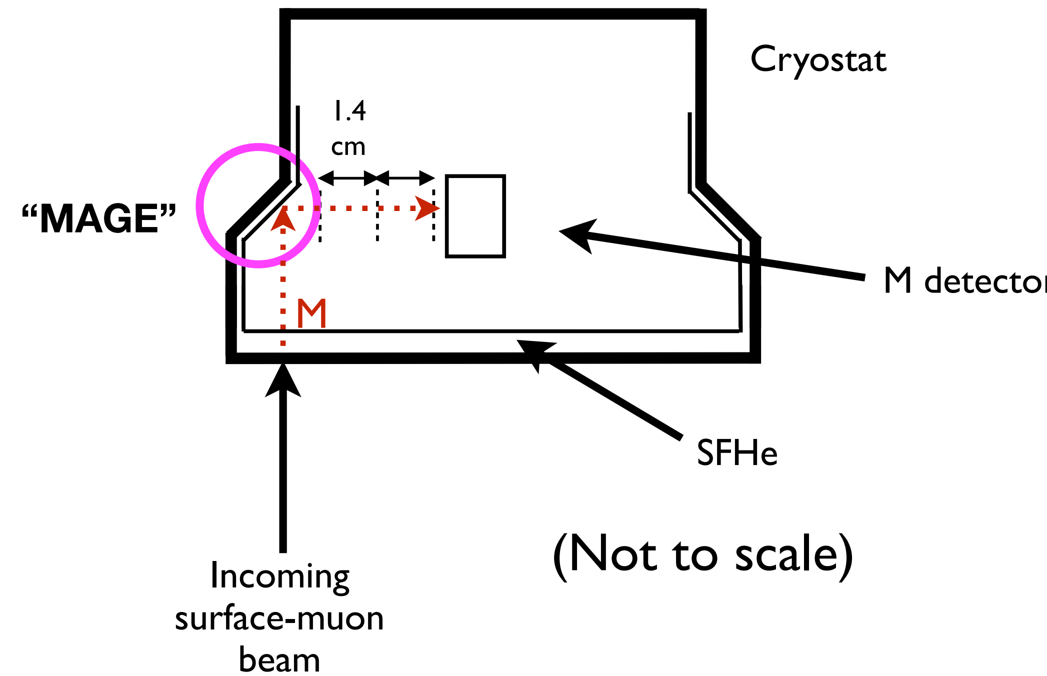
Muonium Gravity Experiment (MAGE)



Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

Muons, Inc.

Workshop on Future Muon Program at Fermilab
Caltech
28 March 2023

Outline

- Muonium antimatter gravity motivation
- Experimental approach
- R&D issues
- Conclusions

Muonium Gravity: Motivation I

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

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

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

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

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

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

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

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

…]

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

Muonium Gravity: Motivation 2

- 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 ($\Delta g_{H\text{-}\bar{H}}/g \lesssim 10^{-7}$): torsion pendulum ("Eöt-Wash") & lunar laser ranging [D.S.M. Alves, M. Jankowiak, P. Saraswat, "Experimental constraints on the free fall acceleration of antimatter," arXiv:0907.4110 [hep-ph] (2009)]
  - relies on assumed contribution of virtual antimatter to nuclear binding energy – untested assumption
  - inapplicable to M
- M provides *only way* to observe 2nd-generation gravity

"Crisis in Cosmology"

- All large-scale GR predictions wrong:
  - missing mass, accelerating expansion, homogeneous microwave-background temp., age of universe…
- ΛCDM cosmology model developed in response
  - includes Dark Matter, Dark Energy, Inflation
  - despite lack of direct evidence
- Could there be a simpler explanation?

Antigravity?

- What if matter and antimatter repel gravitationally?
  - leads to universe with separated matter and antimatter regions (and 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 the expansion rate of the universe
    - possible explanation of 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 early universe causally connected

      [A. Benoit-Lévy and G. Chardin, *ibid.*]
  - virtual gravitational dipoles can modify gravity at long distances
    - possible explanation of rotation curves – *without* dark matter

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

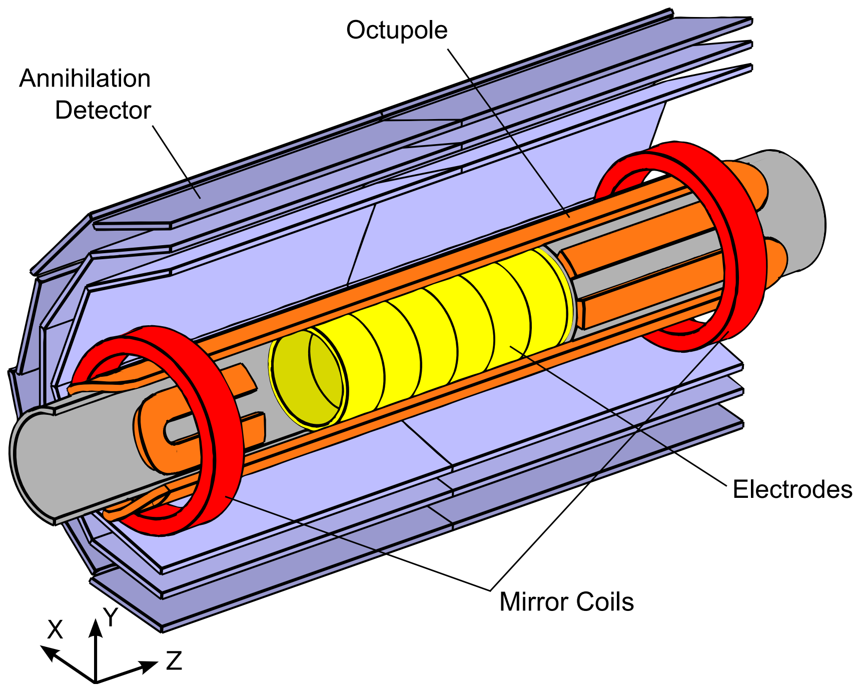
Studying Antimatter Gravity

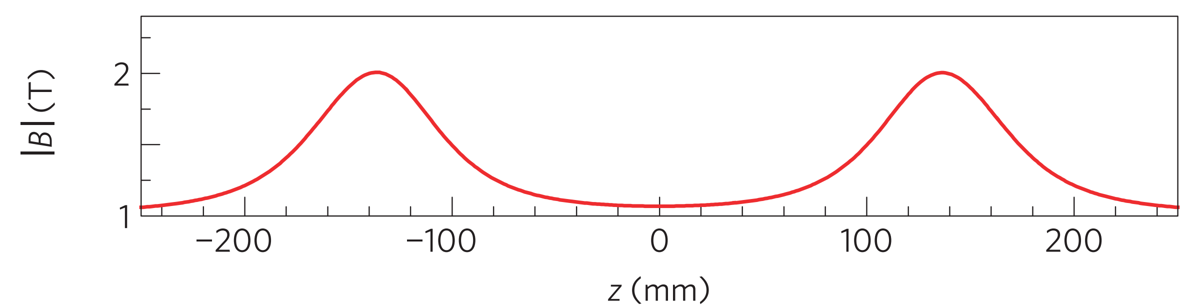
- World leader: ALPHA* at CERN Antiproton Decelerator

Aarhus Univ, Simon Fraser Univ, Berkeley, Swansea Univ, CERN, Univ Federal do Rio de Janeiro, Univ of Calgary, TRIUMF, Univ of British Columbia, Univ of Tokyo, Stockholm Univ, York Univ, Univ of Liverpool, Univ of Victoria, Auburn Univ, NRCN-Nuclear Research Center Negev, RIKEN

* Antihydrogen Laser Physics Apparatus

- They make antihydrogen from $\bar{p}$ and e^+ in a Penning trap and trap it with an octupole winding,





[G. B. Andresen et al., "Confinement of antihydrogen for 1,000 seconds," Nature Phys. **7** (2011) 558]

- then shut off the magnet currents & see whether more $\bar{\mathrm{H}}$ annihilate on the top or on the bottom

[C. Amole et al., "Description and first application of a new technique to measure the gravitational mass of antihydrogen," Nature Comm. **4** (2013) 1785]

Studying Antimatter Gravity

- The first published limit:
- Let $F = m_{grav.}/m_{inert.}$ of $\bar{\mathrm{H}}$
- Then

  $-65 \le F \le 110$ @ 90% C.L.

  [ALPHA Collaboration, 2013]
- They propose improving sensitivity to $\Delta F \sim 0.5$
- May take another ~year...?

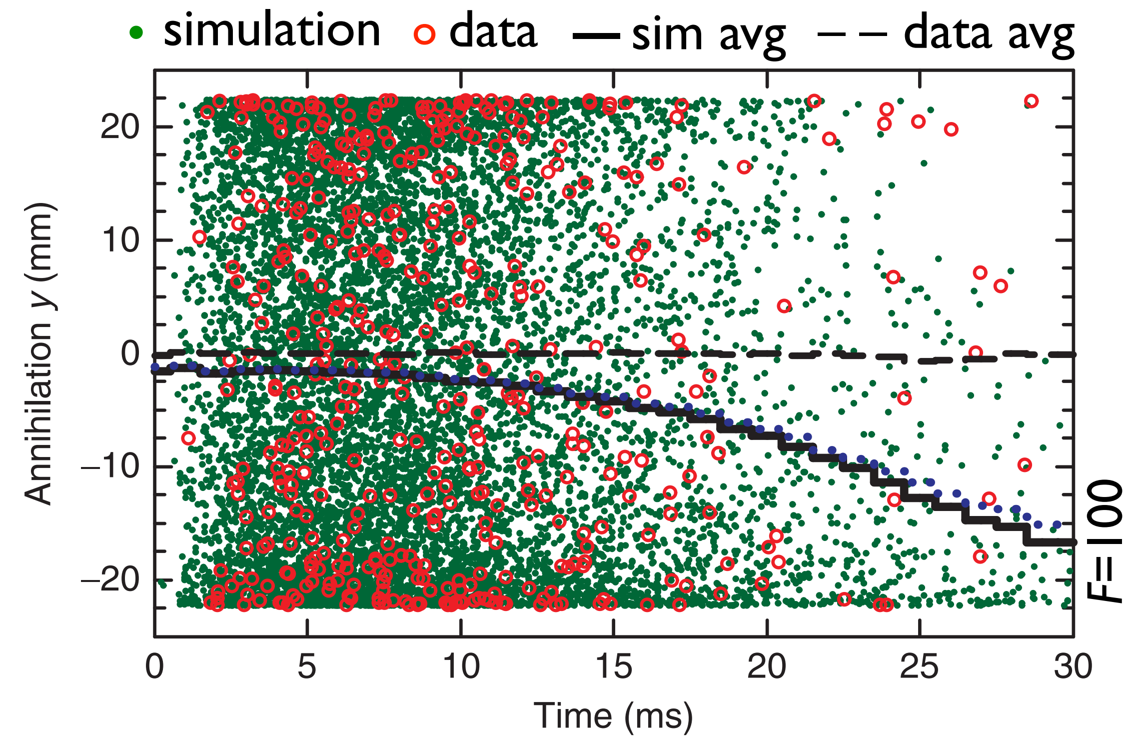
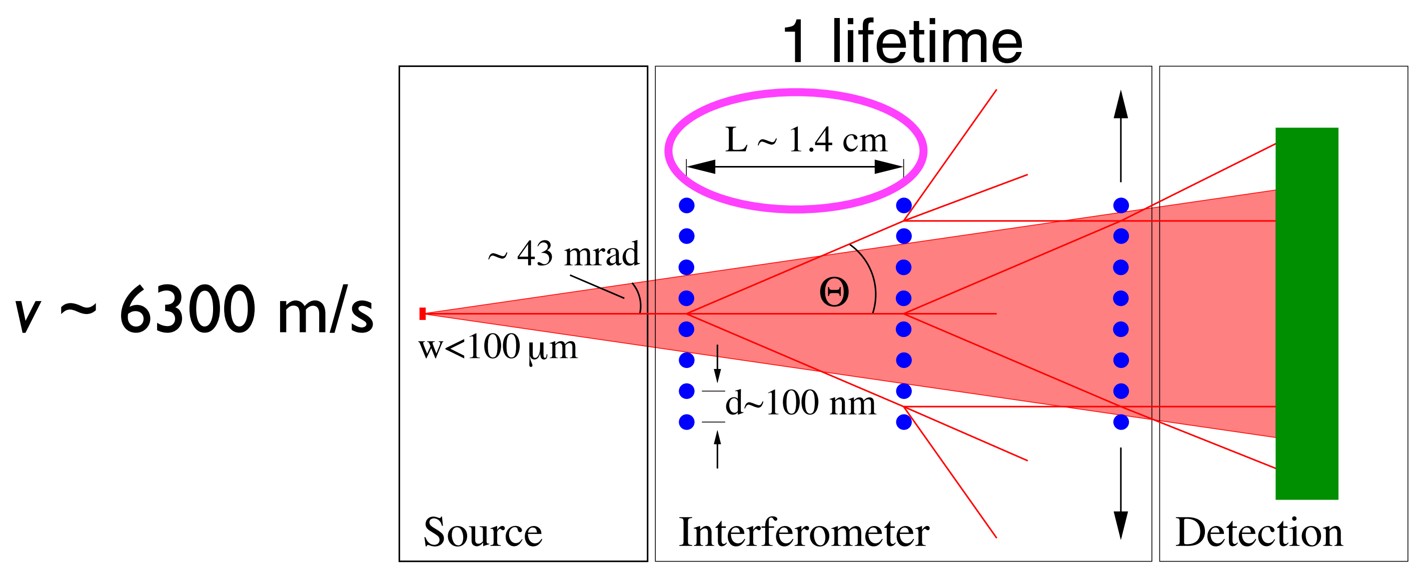


Figure 2 | Annihilation locations. The times and vertical (y) annihilation locations (green dots) of 10,000 simulated antihydrogen atoms in the decaying magnetic fields, as found by simulations of equation 1 with $F = 100$. Because $F = 100$ in this simulation, there is a tendency for the anti-atoms to annihilate in the bottom half ($y < 0$) of the trap, as shown by the black solid line, which plots the average annihilation locations binned in 1 ms intervals. The average was taken by simulating approximately 900,000 anti-atoms; the green points are the annihilation locations of a sub-sample of these simulated anti-atoms. The blue dotted line includes the effects of detector azimuthal smearing on the average; the smearing reduces the effect of gravity observed in the data. The red circles are the annihilation times and locations for 434 real anti-atoms, as measured by our particle detector. Also shown (black dashed line) is the average annihilation location for ~840,000 simulated anti-atoms for $F = 1$.

[C. Amole et al., "Description and first application of a new technique to measure the gravitational mass of antihydrogen," Nature Comm. **4** (2013) 1785]

Studying Muonium Gravity

- M atom-beam interferometer: [K. Kirch, arXiv:physics/0702143 [physics.atom-ph]]



- Adaptation of T. Phillips' $\bar{H}$ interferometry proposal to an anti-atom with a 2.2 μs lifetime! [T. Phillips, Hyp. Int. **109** (1997) 357]
- Need low-divergence source of slow muonium traveling in vacuum

Studying Muonium Gravity

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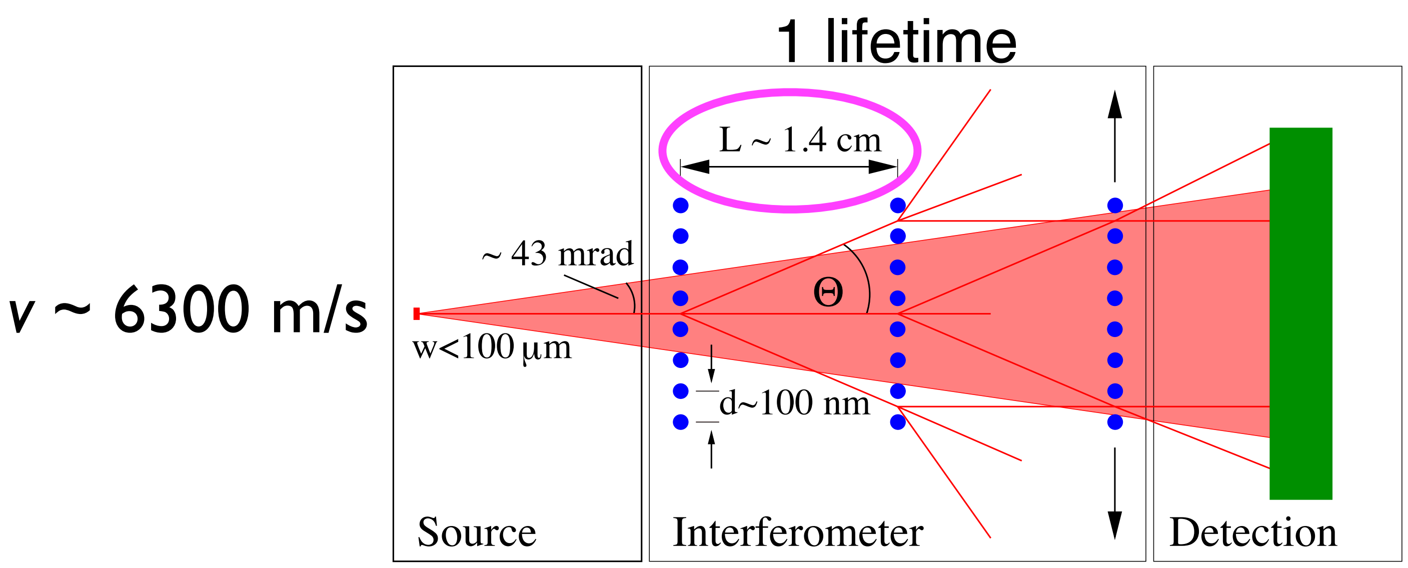

$\Delta y = \frac{1}{2} g t^2 = 24$ pm!

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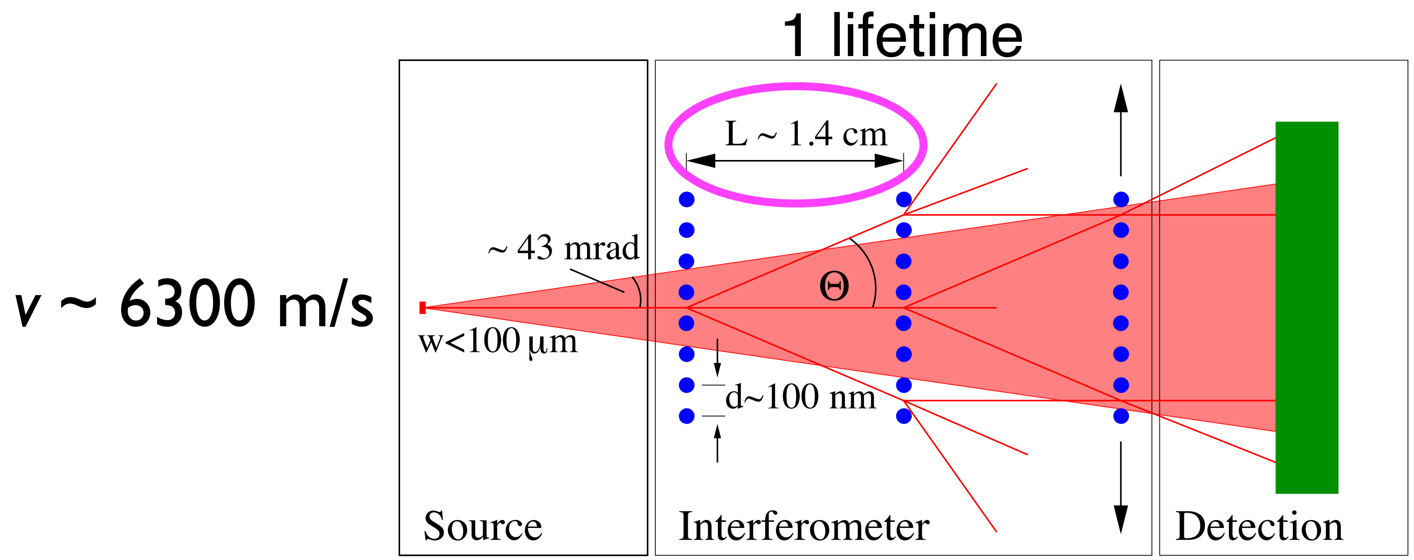

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but grows as $t^2 \Rightarrow$ easier with *old* muonium

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Studying Muonium Gravity

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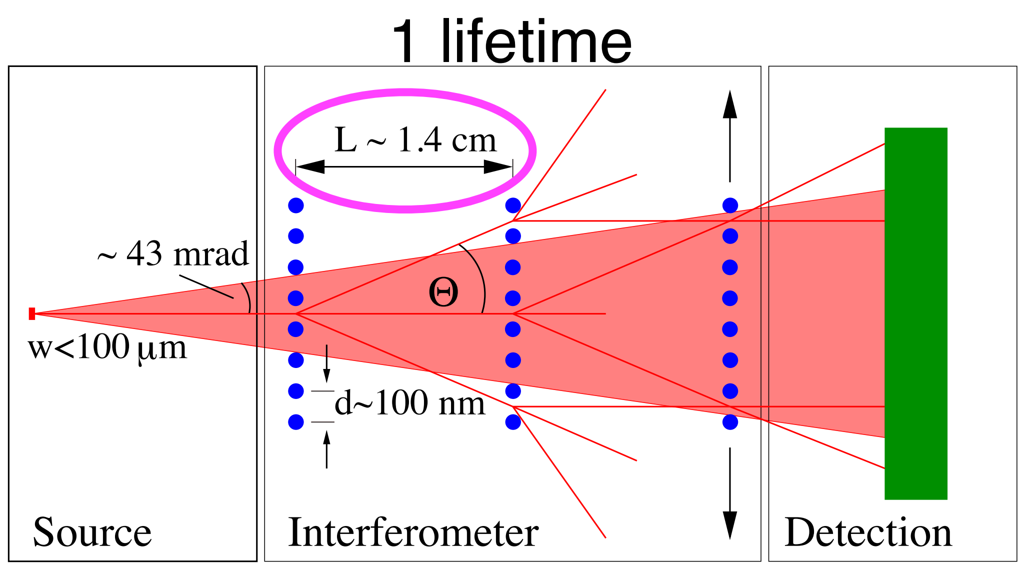
v ~ 6300 m/s



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

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

Statistical optimum: 2 lifetimes ≈ 3 cm → $\Delta y \approx 100$ pm

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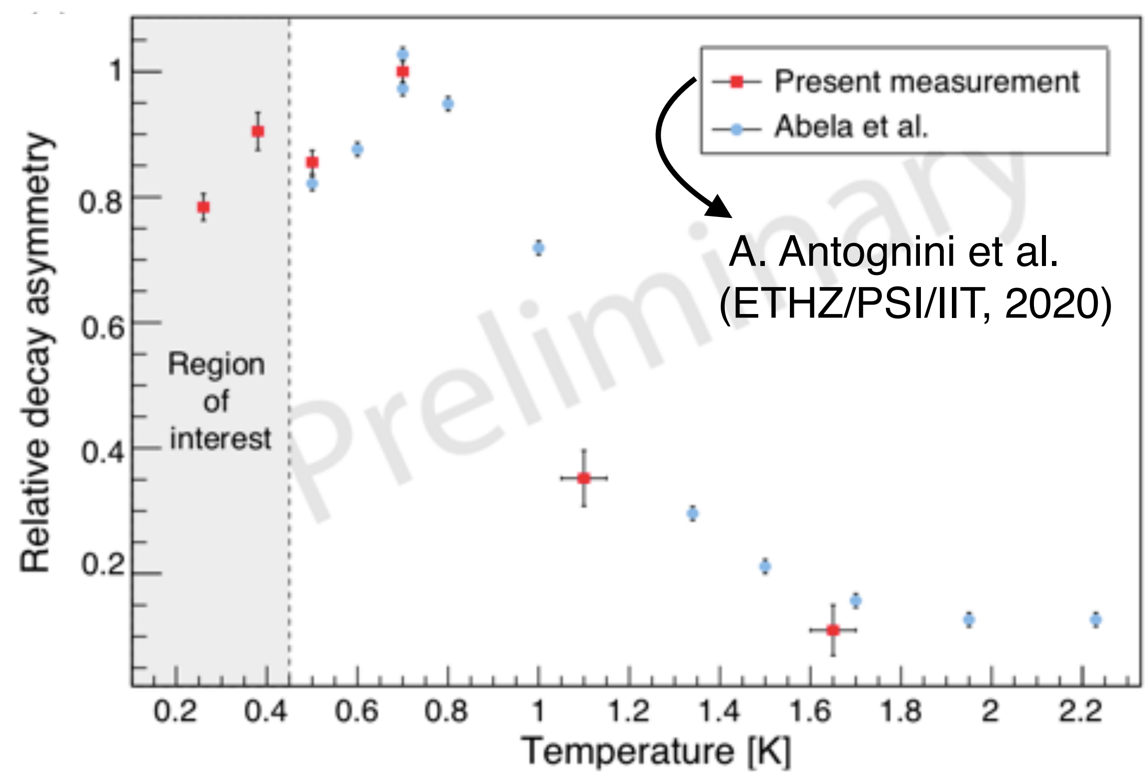
- Need low-divergence source of slow muonium traveling in vacuum

Novel Cryogenic M Source

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



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

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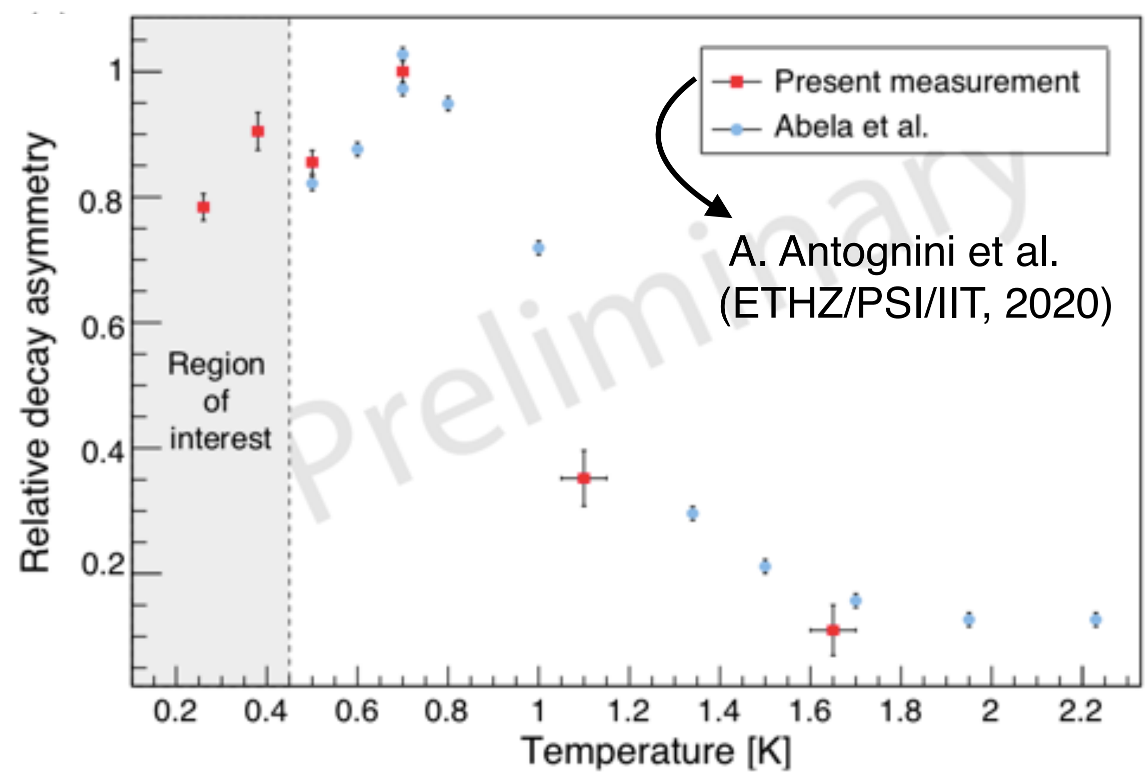
H immiscible in SFHe ⇒ μM should expel M atoms at 6,300 m/s, ⊥ to SFHe surface



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.

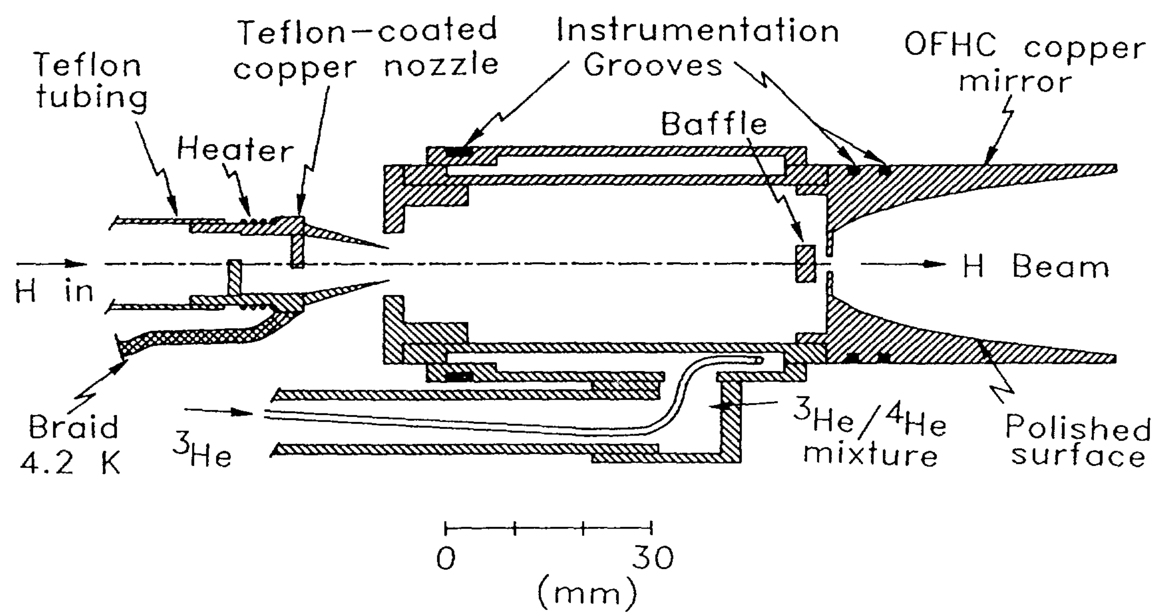
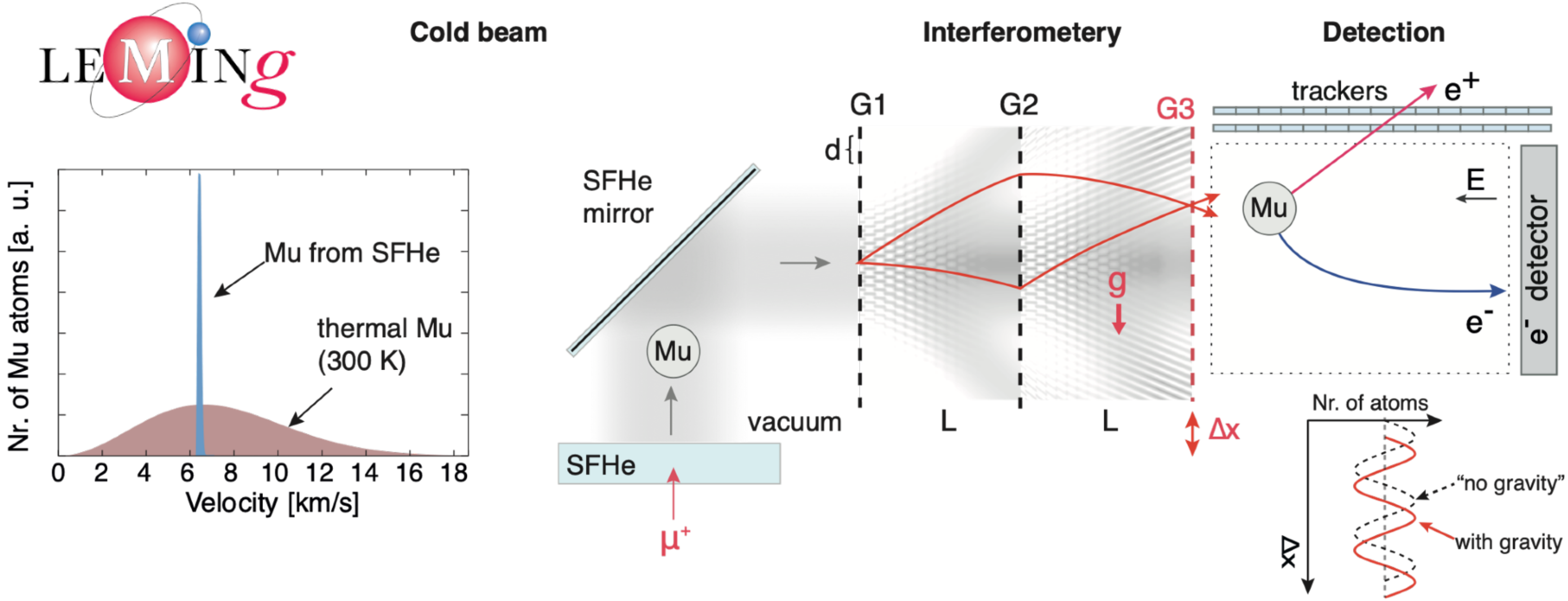


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

The LEMING experiment at PSI, Switzerland

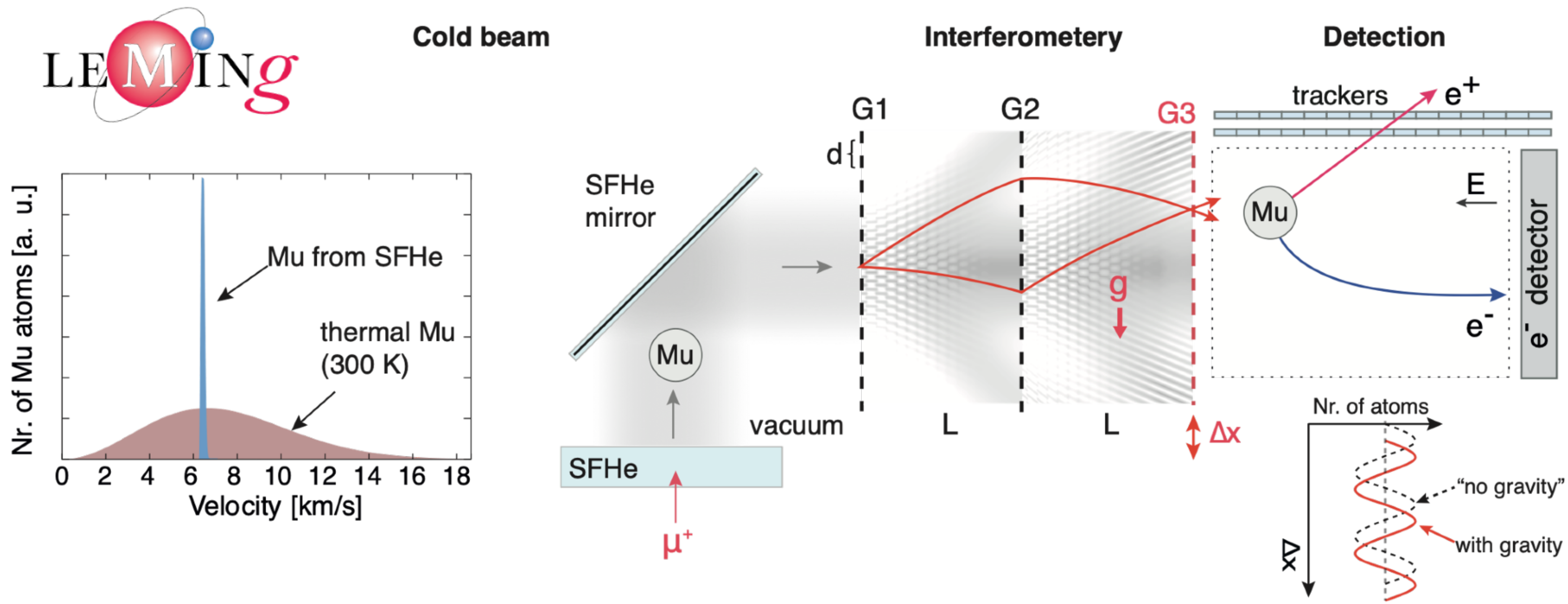


- **LEMING**: **LE**ptons in **M**uonium **IN**teracting with **G**ravity
- Approved at the Paul Scherrer Institute (PSI) in 2022 January, taking advantage of the world's highest intensity cw muon source.
- A novel, ultracold muonium beam development for next generation laser spectroscopy and atom interferometry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

doi: 10.21468/SciPostPhysProc.5.031

Anna Soter, ETH Zurich

The LEMING experiment at PSI, Switzerland



In R&D phase

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Anna Soter, ETH Zurich

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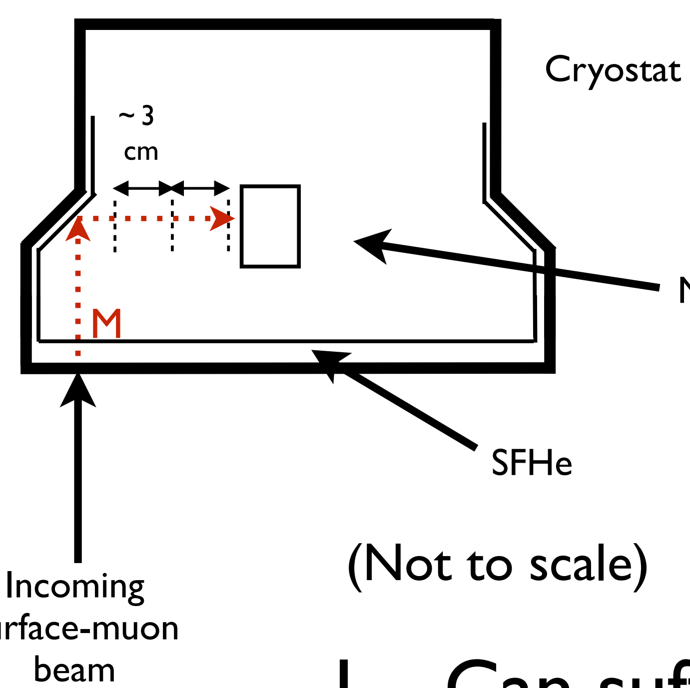
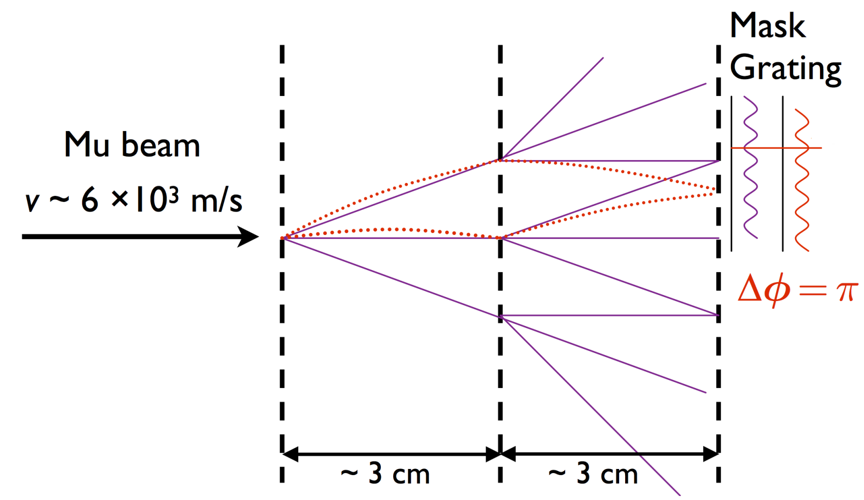
Muonium Gravity Experiment

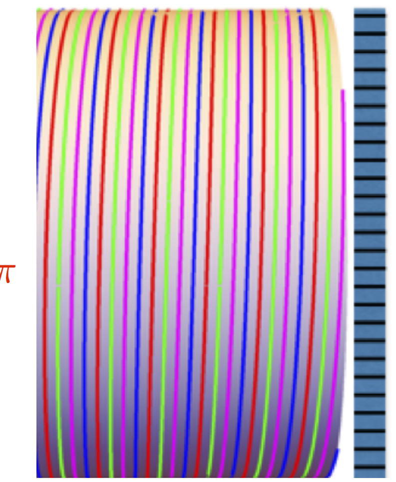
- Some important feasibility questions:



(Not to scale)

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 SFHe M production 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
   - we are operating a TFG at IIT for NASA space-telescope R&D

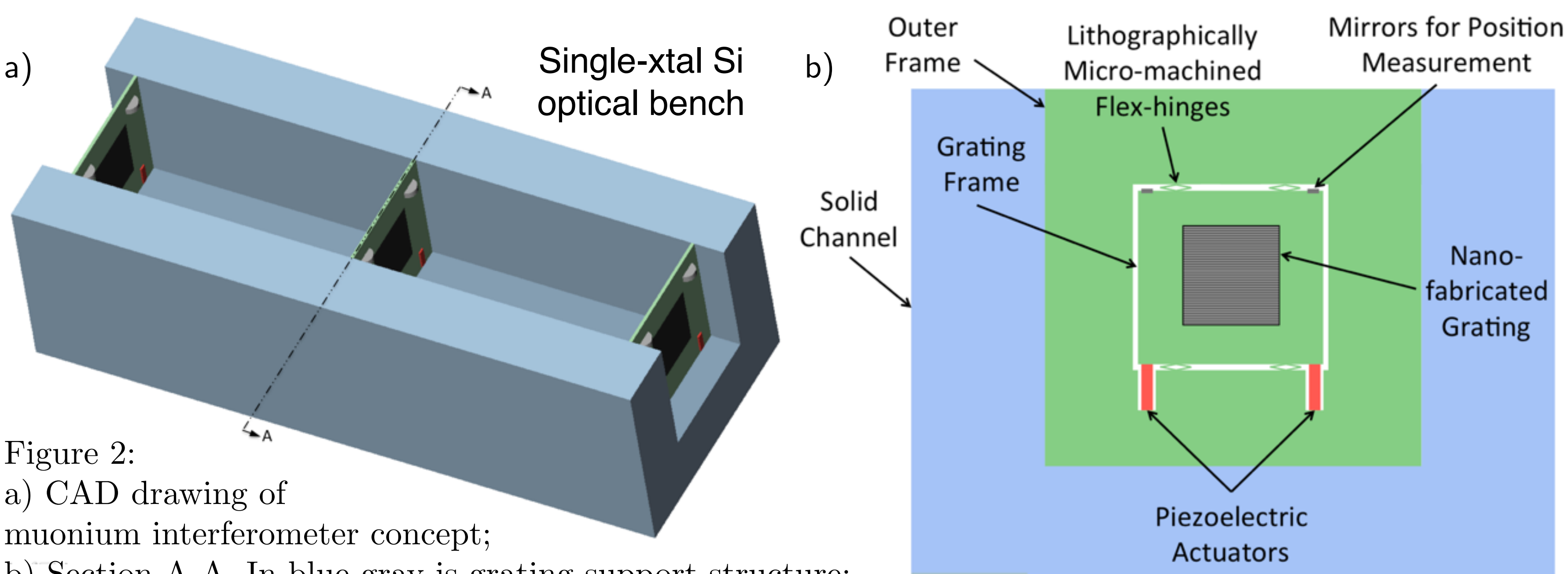


Figure 2:
a) CAD drawing of muonium interferometer concept;
b) Section A-A. In blue-gray is grating support structure: a U-channel machined out of a single-crystal silicon block. Each grating is mounted in a silicon frame connected to an outer frame by flex-hinges; piezo-actuator pair permits small rotations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

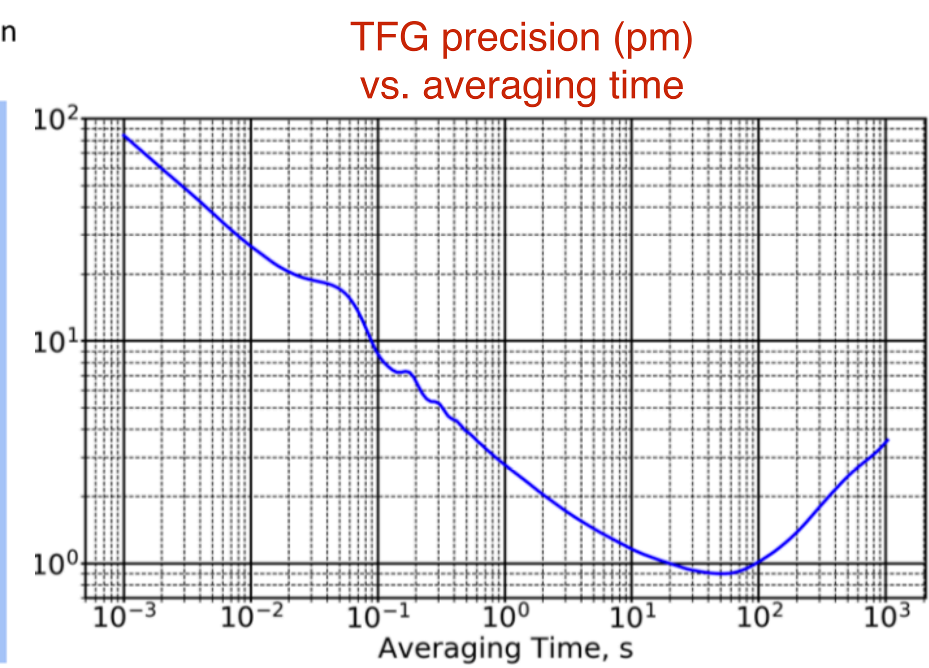


Figure 3. Allan deviation indicating TFG incremental-distance precision vs averaging time.

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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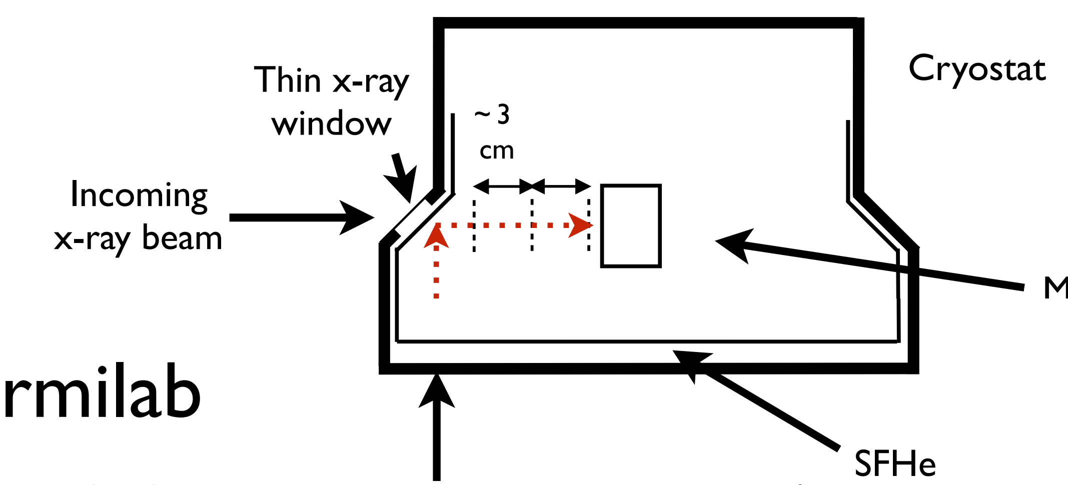
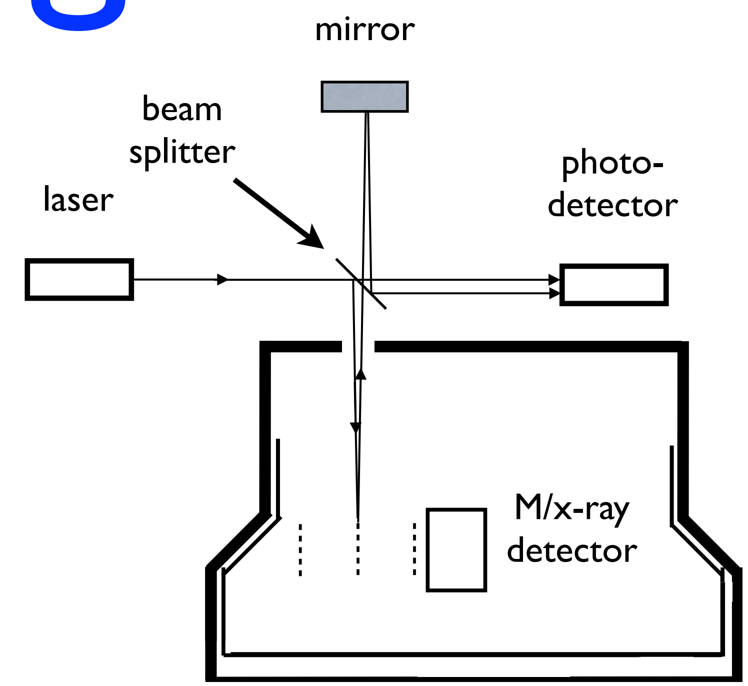
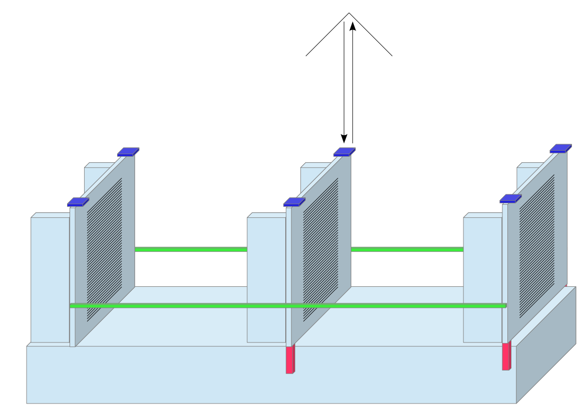
   - we are operating a TFG at IIT for NASA space-telescope R&D
3. Can interferometer and detector be operated at cryogenic temperature?
   - needs R&D; at least piezos OK; material properties favorable
4. How determine zero-degree phase?
   - use cotemporal soft X-ray beam
5. Does SFHe M production work?
   - R&D in progress @ PSI, proposed at Fermilab



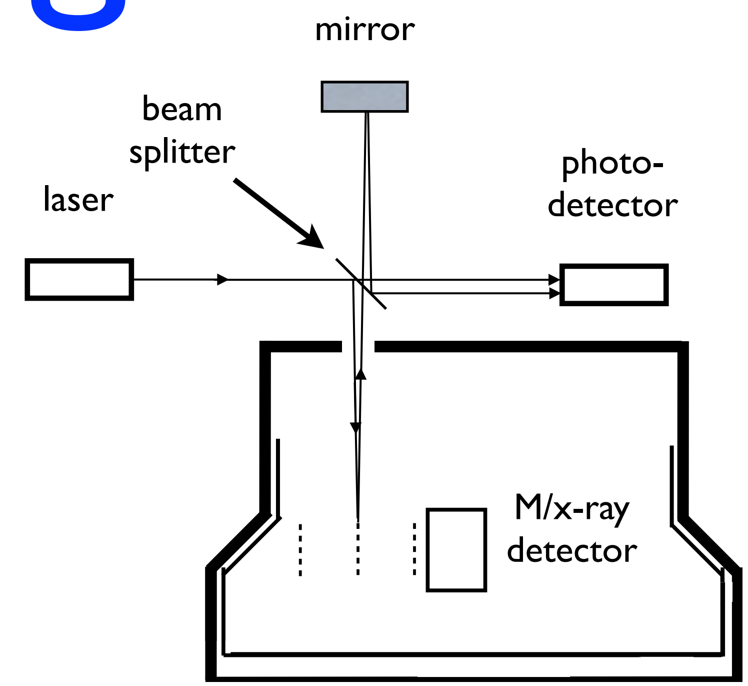
Interferometer Alignment



- Use 2 laser interferometers per grating
  - send laser beams in fiber through cryostat lid
    - keeps instrumentation & heat external to cryostat & M detection path open
  - "natural" sensitivity ~ λ/2 ~ 800 nm; need ~ 10 pm ⇒ 10^{-5} enhancement
    - achieved via Pound–Driver–Hall locking at a zero of the intensity



Interferometer Alignment



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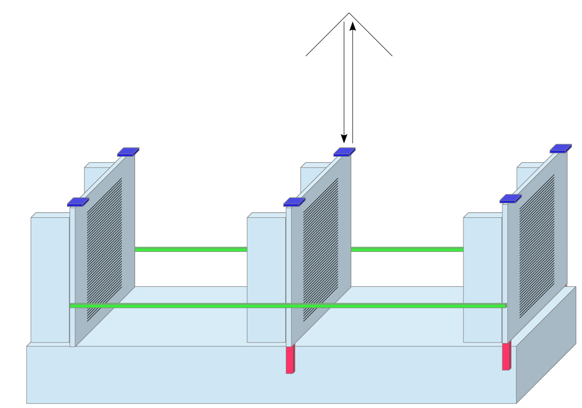

[R. Thapa et al., "Subpicometer length measurement using semiconductor laser tracking frequency gauge," Opt. Lett. **36**, 3759 (2011)]

Interferometer Alignment

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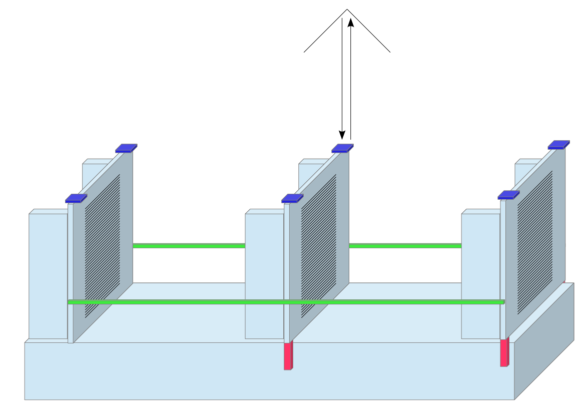

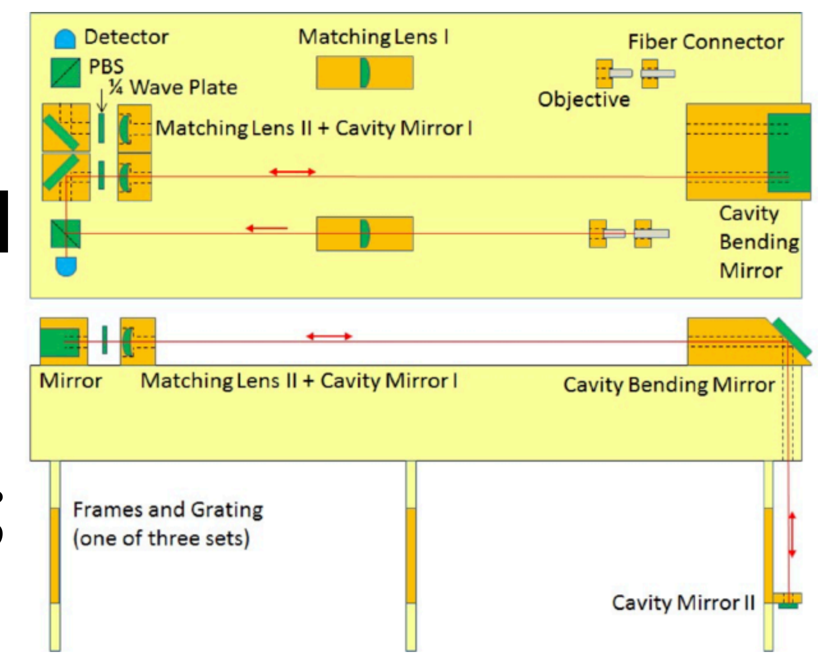

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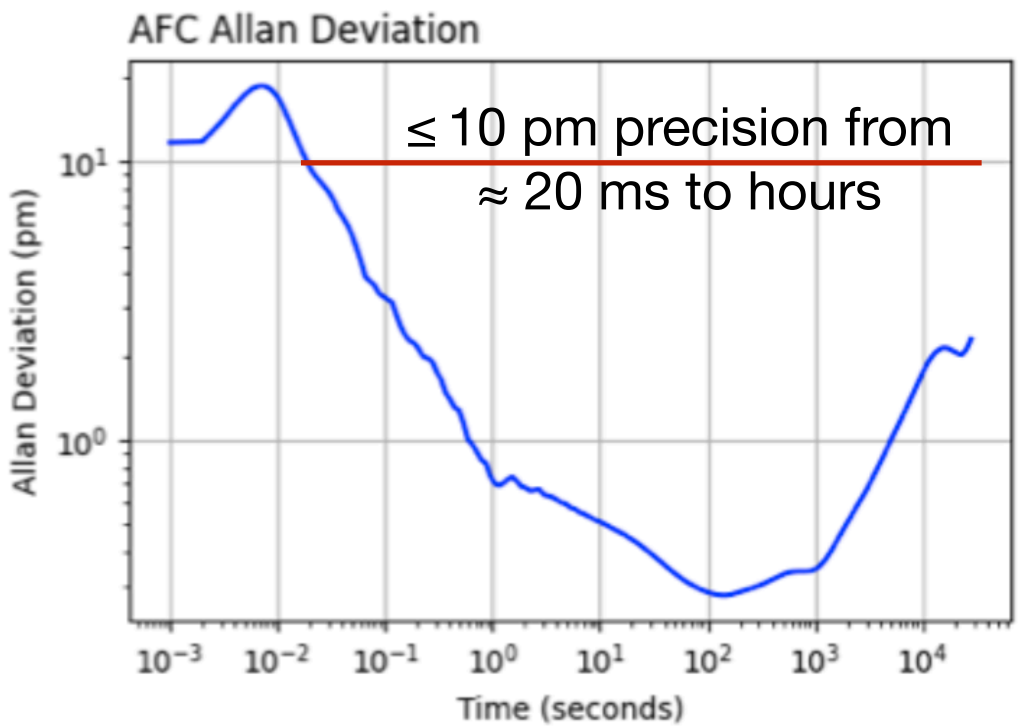
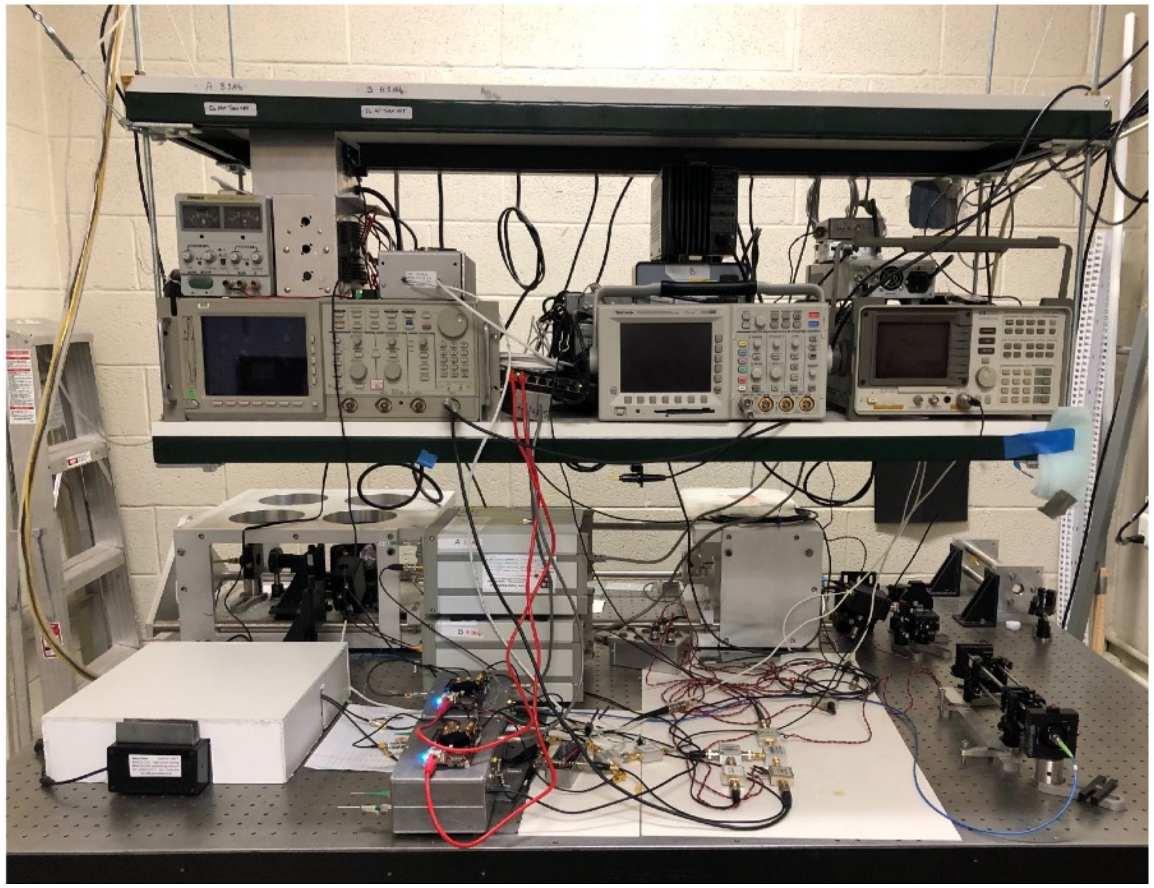
TFG performance

- 2-TFG common-path test:





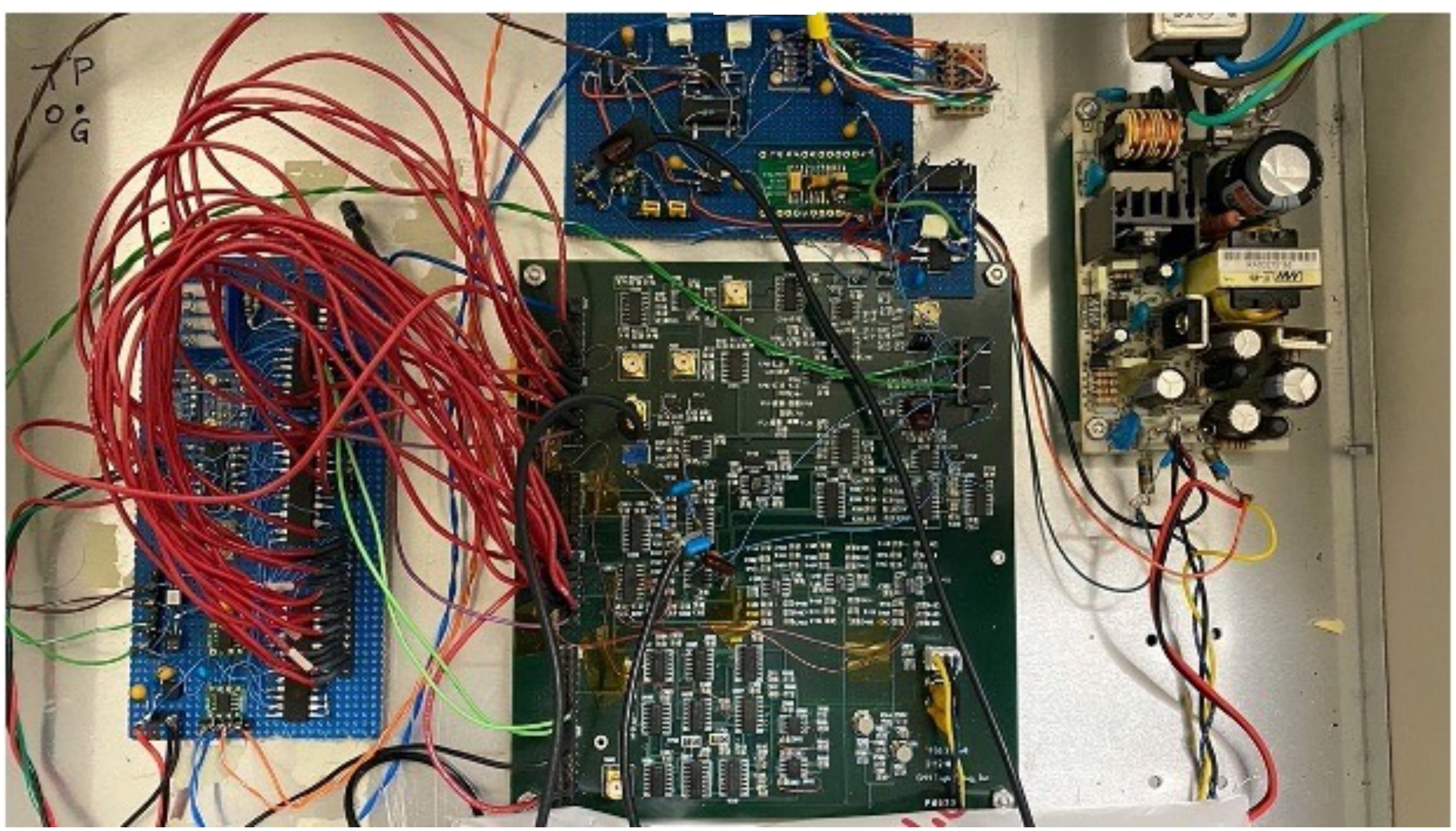
  - merge both laser beams onto one fiber
    - modulated at different frequencies ⇒ distinguishable
  - launch as free-space beam into interferometer
  - tune lasers *n* fringes apart (typically $n = 1$)
  - count beat frequency in msec time bins

Recent TFG Progress

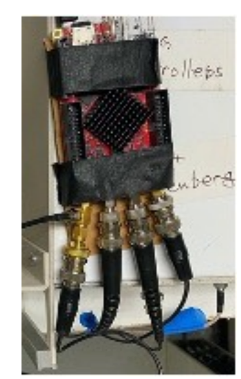
- NASA subcontract-funded R&D (NASA contract → Lockheed Martin Space → UF → IIT)
  - replace analog TFG controller with digital (Phase 1: Red Pitaya; Phase 2: Smartfusion FPGA; Phase 3: RTG4)

One Analog TFG Controller

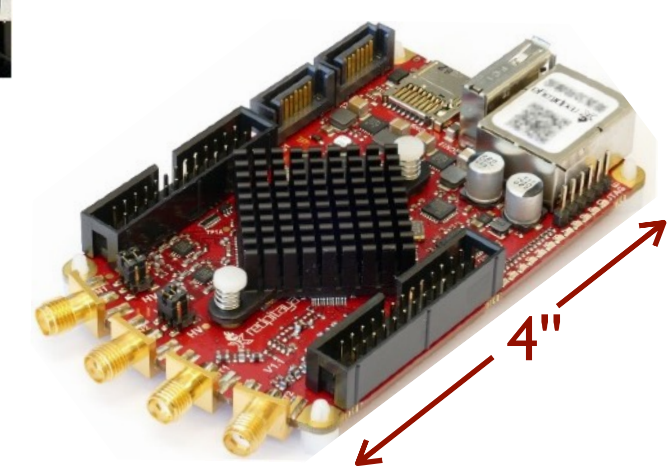
17"



One Red Pitaya Digital TFG Controller



Red Pitaya Close-Up



Sensitivity Guesstimate

$\overline{g}$ sensitivity estimate @ 100 kHz M rate:

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

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

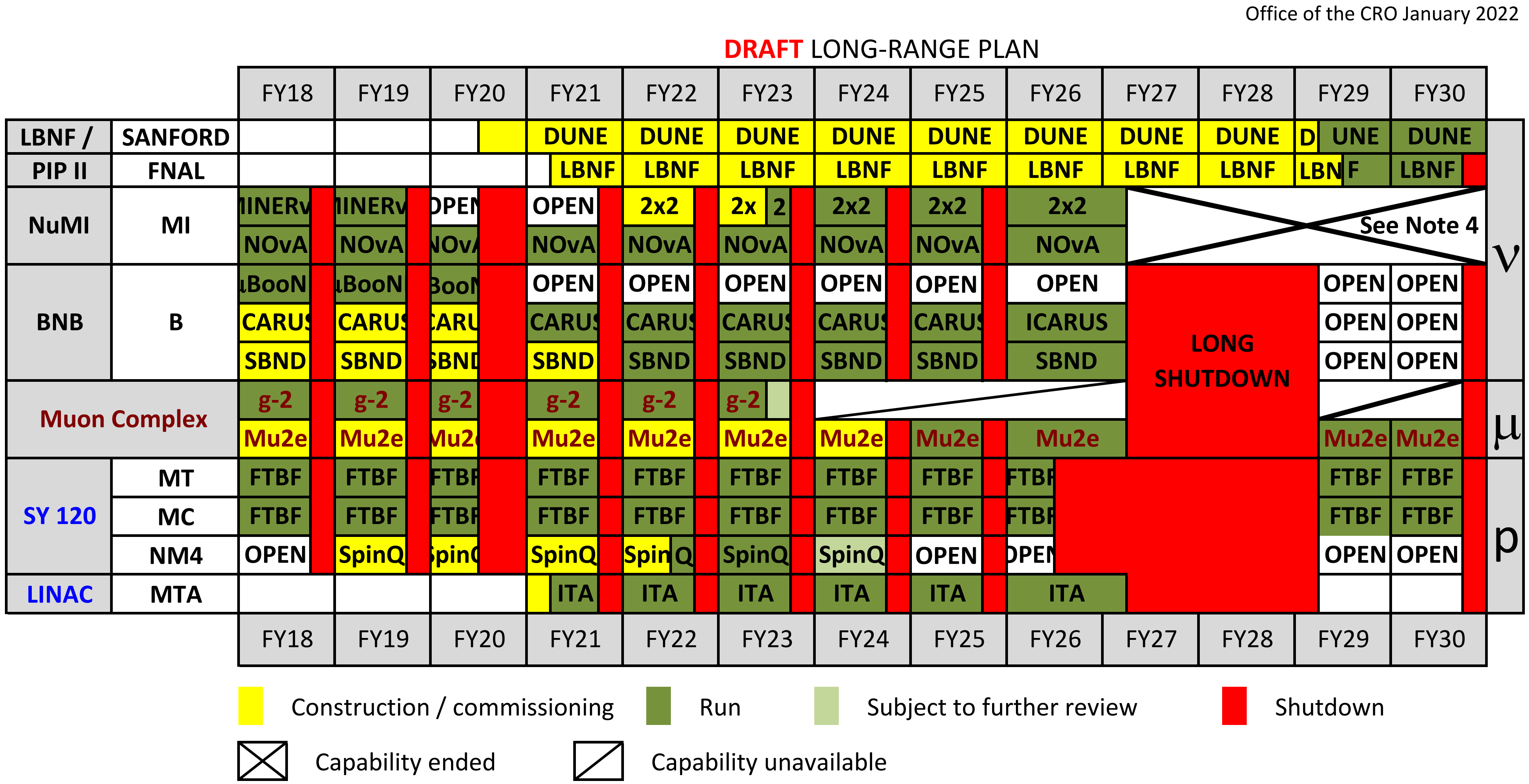
- MTA: $\leq 3 \times 10^{14}$ *p*/s × ~10^{-8} surface-μ/POT × $\lesssim$ 0.05 M/surface-μ $\lesssim$ 150 kHz?

  ⇒ $\overline{g}$ sign ($\sigma_{\overline{g}}$ = 0.4) @ MTA with a few days of beam

  ⇒ 10% $\overline{g}$ measurement possible with sufficient run time

- Higher stat. precision (1% or better) at PIP-II AMF
  - presumes sub-1% systematics (TBD)

Timeline



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

R&D Needs

- SFHe test stand (eventually incl. dilution fridge)
  - to be moved into MTA prior to M beam studies
- MTA beam studies & optimization (incl. shielding assessment)
- Several months' beam time (intermittent)
- M interferometer & detector development & fabrication

Discussion Questions

- Is SFHe M beam advantageous for M-$\overline{\text{M}}$? spectroscopy?
- Are there additional compelling M applications?
- What else?