Measuring Antimatter Gravity with Muonium

Daniel M. Kaplan,[1] Klaus Kirch,[2,*] Derrick Mancini,[1,3] James D. Phillips, Thomas J. Phillips,[1] Thomas J. Roberts,[1] Jeff Terry[1]
[1]*Physics Dept., Illinois Institute of Technology, Chicago, IL, USA* [2]*Paul Scherrer Institute, Villigen and ETH, Zürich, Switzerland*
[3]*Argonne National Laboratory, Argonne, IL, USA* **Swiss partners supported by SNF grant 200020_146902*

- Indirect tests imply stringent limits on gravitational acceleration of antimatter:

$$\left|\bar{g}/g - 1\right| < 10^{-7}$$

[Alves, Jankowiak, Saraswat, arXiv:0907.4110]

(unclear to what extent this applies to muonium)

- But no *direct* test has yet achieved significance. Best direct limit, on antihydrogen:

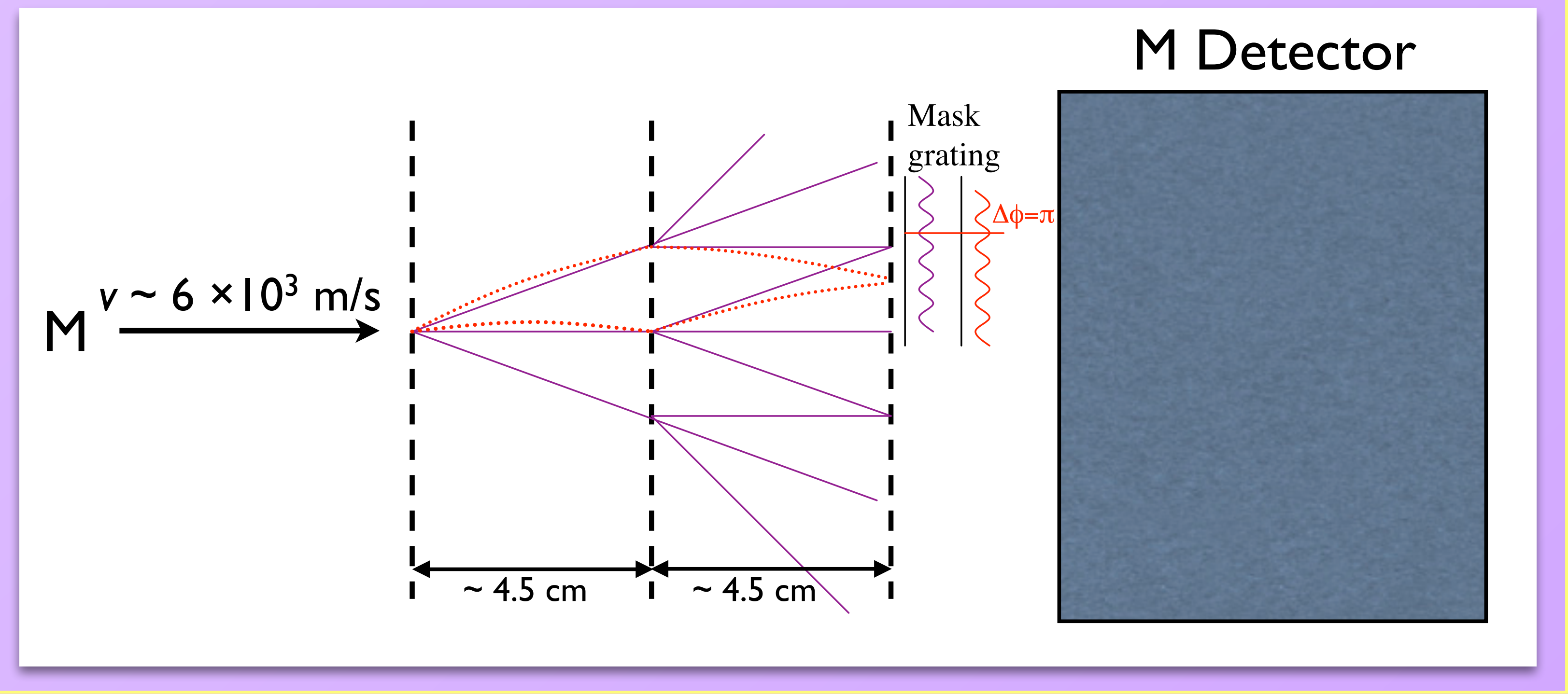
$$-65 < \bar{g}/g < 110$$

[Amole *et al.* (ALPHA collaboration), Nature Commun. 4 (2013) 1785]

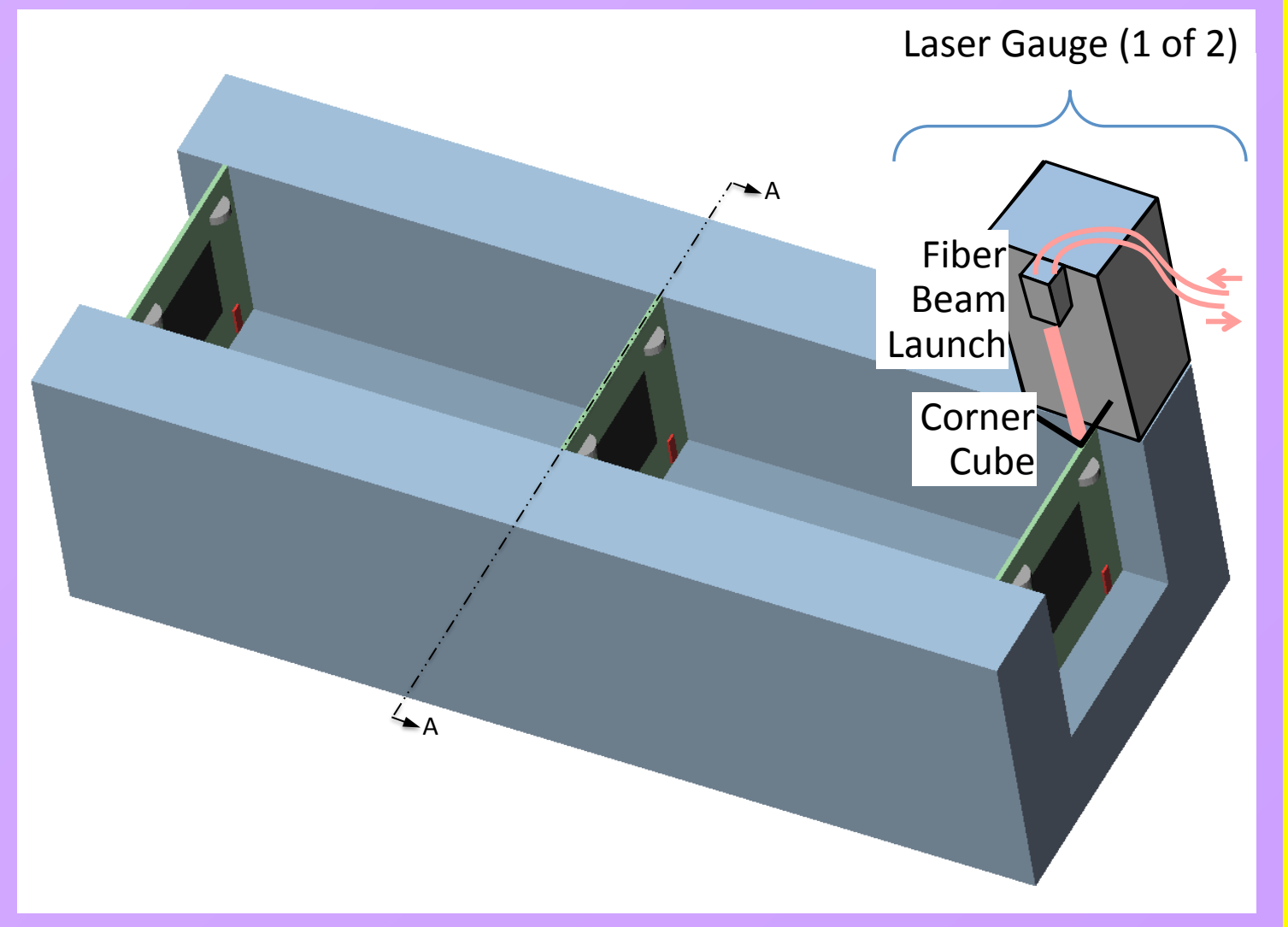
- Besides antihydrogen, only one other experimental approach is practical:

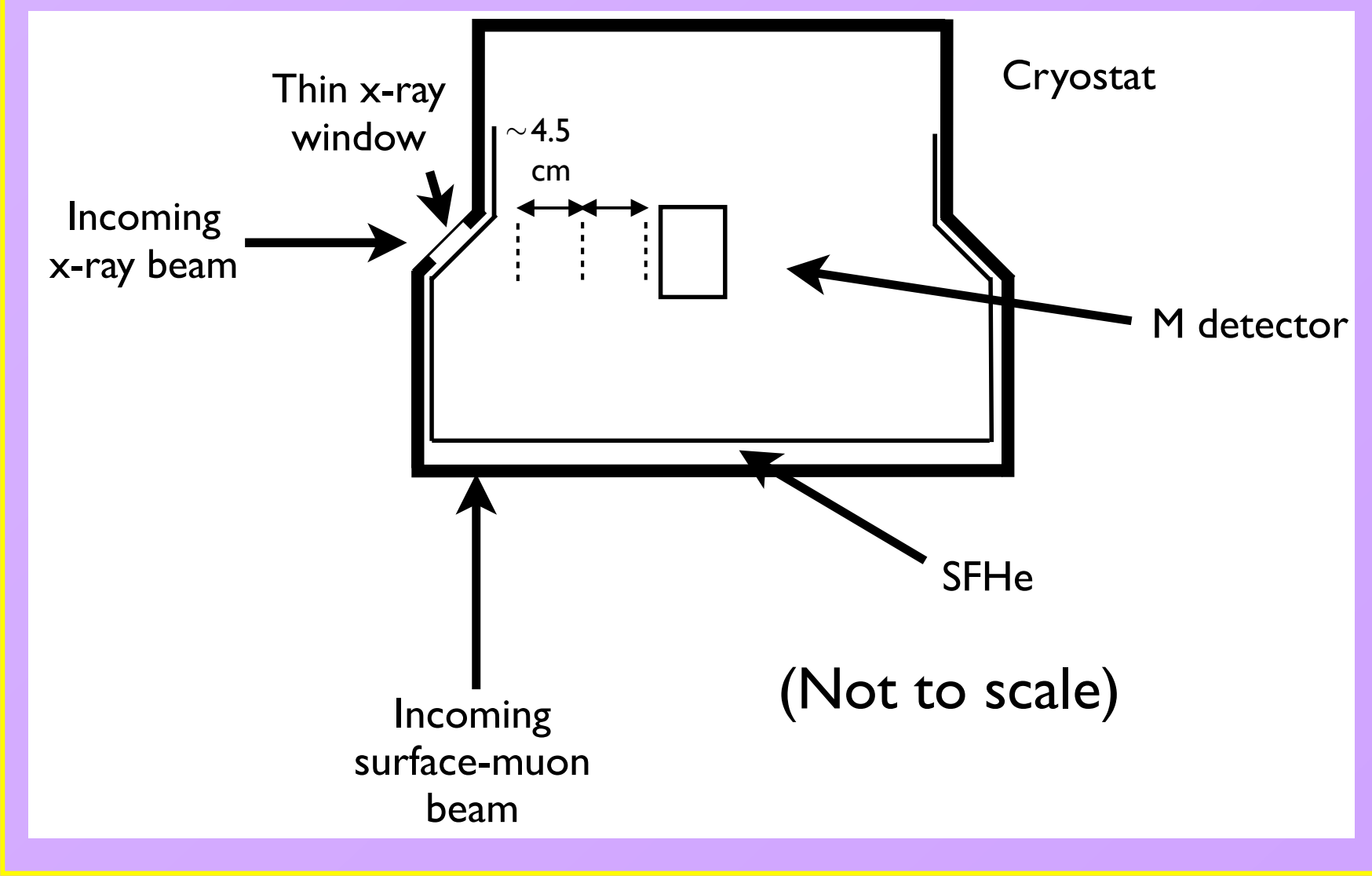
Muonium ($\mu^+ e^-$ atom, M)

- We are developing a precision, 3-grating muonium atom-beam interferometer to measure $\bar{g}$.
- Unique test of leptonic and 2nd-generation gravitation



- Need ~ 10 pm precision interferometer alignment, and precision zero-degree reference
- Feasible by means of
  - ✦ Pound-Drever-Hall (PDH) -locked laser tracking frequency gauge:
  - ✦ And continual calibration with soft X rays:





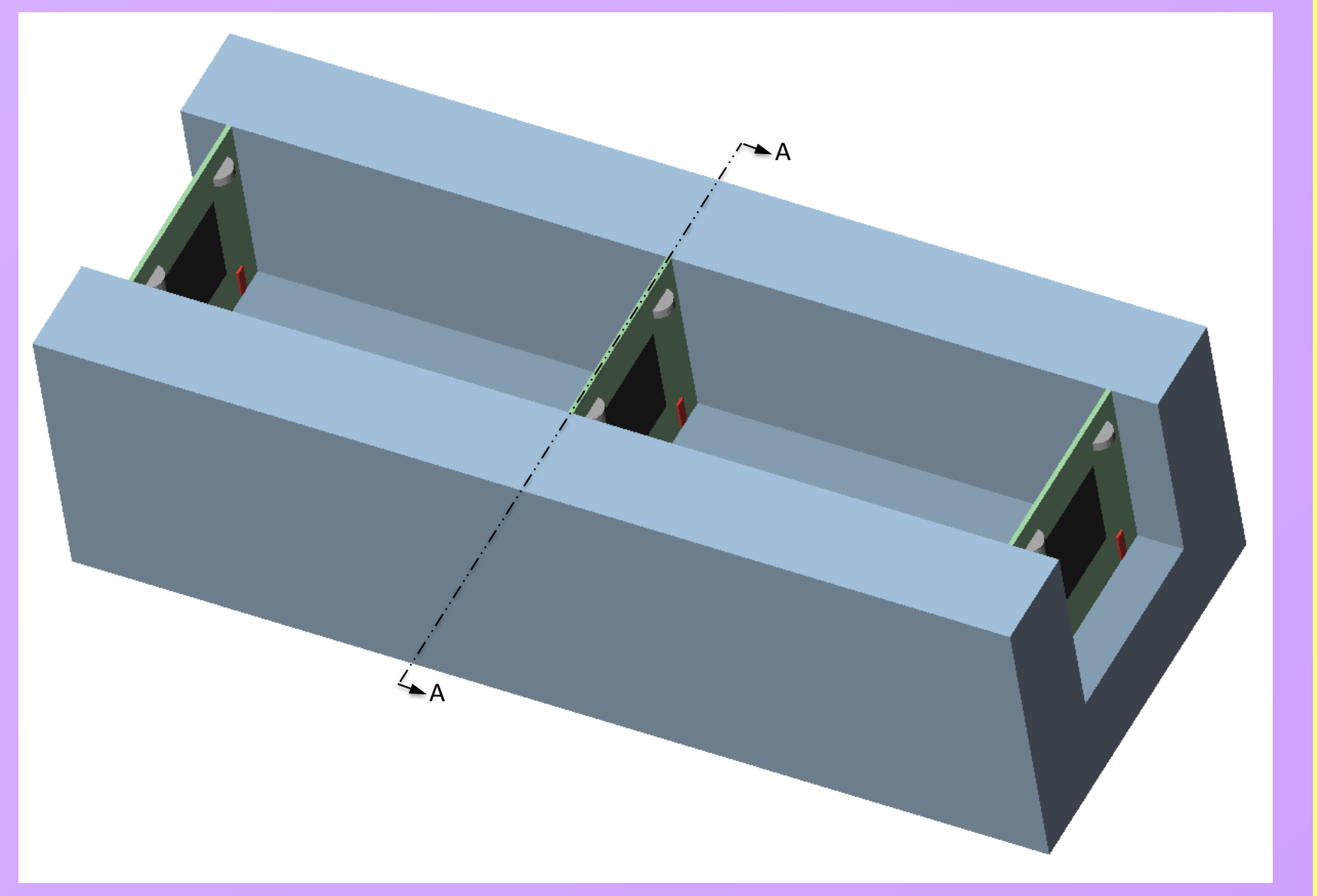
(Not to scale)

Currently, unknown even whether antimatter falls up or down!
We aim to find out!

- Precision goal requires extremely rigid, temperature-stable mounting scheme.

➡ Use single-crystal silicon, both for mount and for gratings

- ✦ 100 nm grating pitch
- ✦ 1 cm² grating area
- ✦ several-pm grating fidelity

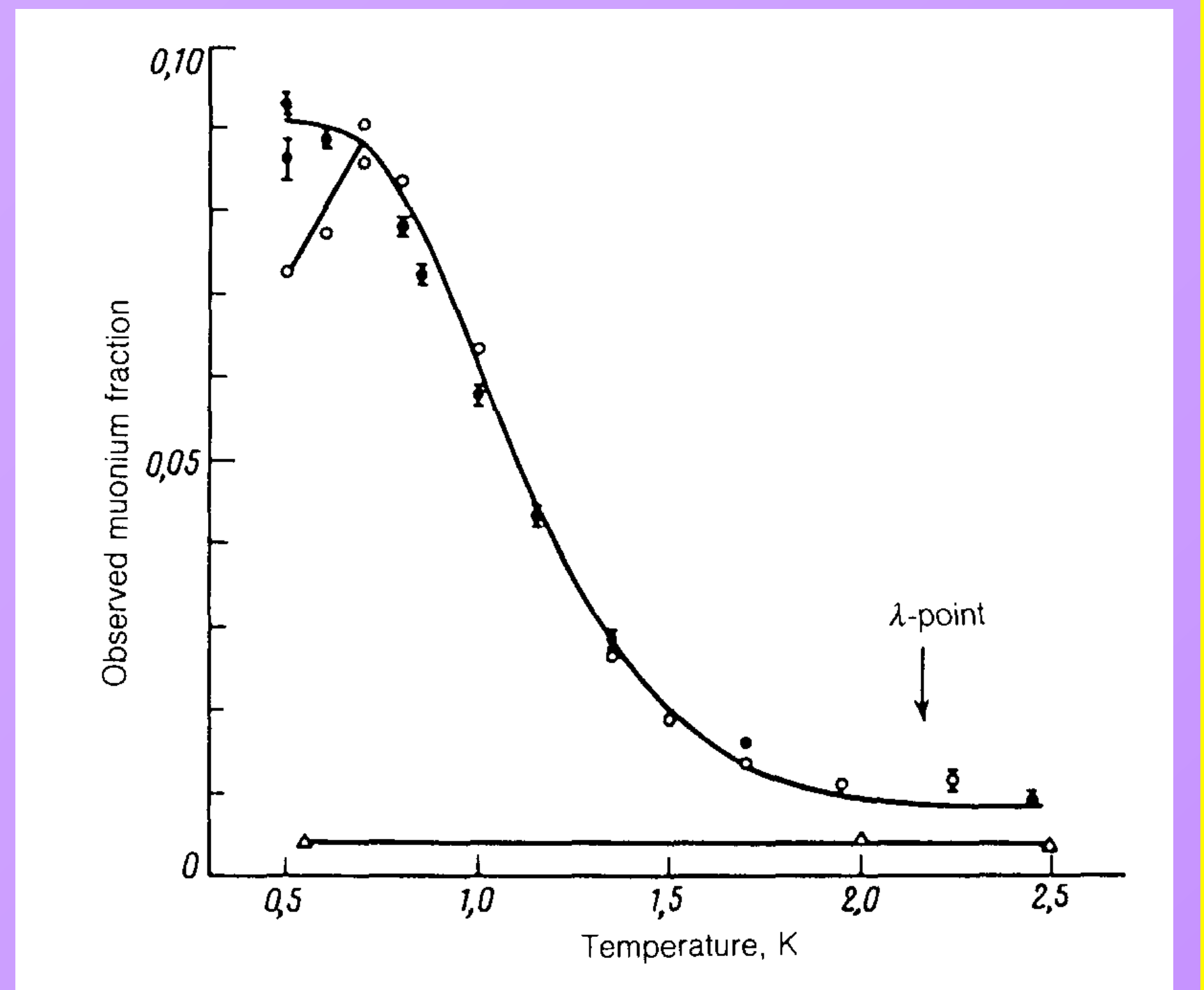


➡ Fabrication feasible at Argonne National Lab Center for Nanoscale Materials

- ✦ using Si_3N_4 film on Si substrate, *e*-beam and optical lithography, and reactive-ion (RIE) and wet etching

- Need monoenergetic muonium source.
  - ✦ Proposed via stopping muons in superfluid LHe.
  - ✦ Produces monoenergetic beam due to large, positive chemical potential (270 K) of M in LHe.
  - ✦ M is thus ejected normal to LHe surface at

$v \approx 6{,}300$ m/s



R. Abela et al., JETP Lett. 57 (1993) 157.

- Need extreme precision, $\lesssim 10$ pm:
- In one (2.2 μs) lifetime, M atom falls by

$$\Delta y = \frac{1}{2}\bar{g}\tau^2 = 24\,\text{pm} \quad \text{if} \quad \bar{g} = g\,.$$

- Statistical optimum is to measure after 4 lifetimes; then $\Delta y = 380$ pm. (Longer measurement interval may be optimal once systematics accounted for.)
- Then 10^5 monoenergetic M/s → precision ~ $0.3\,g/\sqrt{\#\text{ days}}$

COSMOLOGICAL SIDEBAR

Theories in which antimatter repels matter (so-called “antigravity”) offer simple explanations of several key cosmological puzzles:

Cosmic Baryon Asymmetry
Galactic rotation curves
Binding of galaxy clusters
Cosmic acceleration
Horizon and Flatness problems

Self-gravitating clusters of matter and antimatter form randomly interspersed matter and antimatter galaxies or galactic clusters

Thus there is no Baryon Asymmetry.

Explanation relies on properties of virtual gravitational dipoles (matter–antimatter pairs). Unlike the EM case, these are repulsive, giving *anti*-shielding and *strengthening* force of gravity at large distances.

Thus there is no need for Dark Matter.

Interspersed, repulsive, matter and antimatter counteract gravitational deceleration of Universe expansion, leading to constant rate of recession. This is consistent with supernova data.

Thus there is no need for Dark Energy.

Slower expansion of early Universe means all parts are causally connected.

Thus there is no need for Inflation.

SOME USEFUL REFERENCES:

1. M. M. Nieto and T. Goldman, “The Arguments Against ‘Antigravity’ and the Gravitational Acceleration of Antimatter,” Phys. Rep. **205** (1991) 221
2. D. S. M. Alves, M. Jankowiak, and P. Saraswat, “Experimental constraints on the free fall acceleration of antimatter,” arXiv:0907.4110
3. A. Benoit-Lévy and G. Chardin, “Introducing the Dirac-Milne universe,” Astron. & Astrophys. **537**, A78 (2012)
4. T. J. Phillips, “Antimatter gravity studies with interferometry,” Hyp. Int. **109** (1997) 357
5. K. Kirch, “Testing Gravity with Muonium,” arXiv:physics/0702143
6. D. M. Kaplan *et al.*, “Measuring Antimatter Gravity with Muonium,” arXiv:1308.0878
7. T. J. Phillips, “ANTIMATTER: Out of the darkness,” Nature Phys. **10**, 473 (July 2014)
8. D. Taqqu, “Ultraslow Muonium for a Muon beam of ultra high quality,” Phys. Procedia **17** (2011) 216
9. R. Thapa, J. D. Phillips, E. Rocco, R. D. Reasenberg, “Subpicometer length measurement using semiconductor laser tracking frequency gauge,” Optics Lett. **36**, 3759 (2011)
10. Y. Bao *et al.*, “Muon Cooling: Longitudinal Compression,” Phys. Rev. Lett. **112**, 24801 (2014)