# The Muonium Antimatter Gravity Experiment

## Testing to see if something is the **Matter** with **Gravity**

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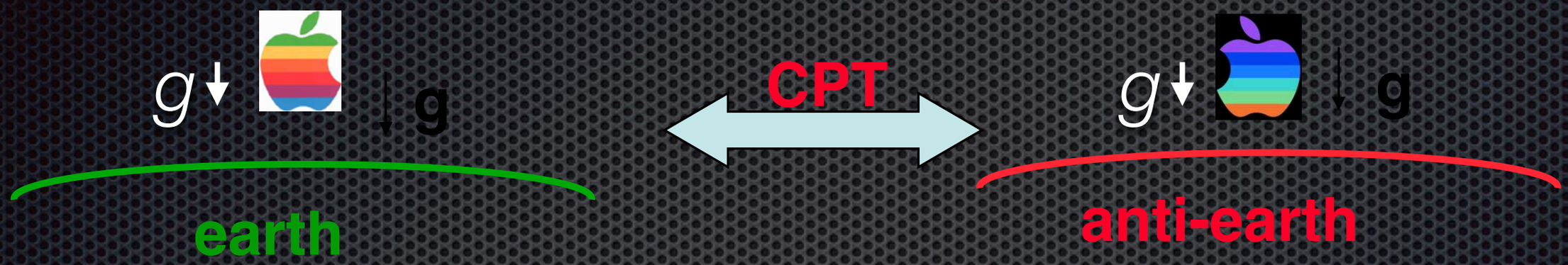
# Outline

1. Motivation: What if we are wrong about antimatter gravity?
2. Why Muonium to measure gravity?
3. How to measure gravity in 10μs
4. Muonium: How to make a beam

# Antimatter & Gravity





$\bar{g}$ (the acceleration of antimatter towards the earth)

has never been directly measured!

(only broad limits)

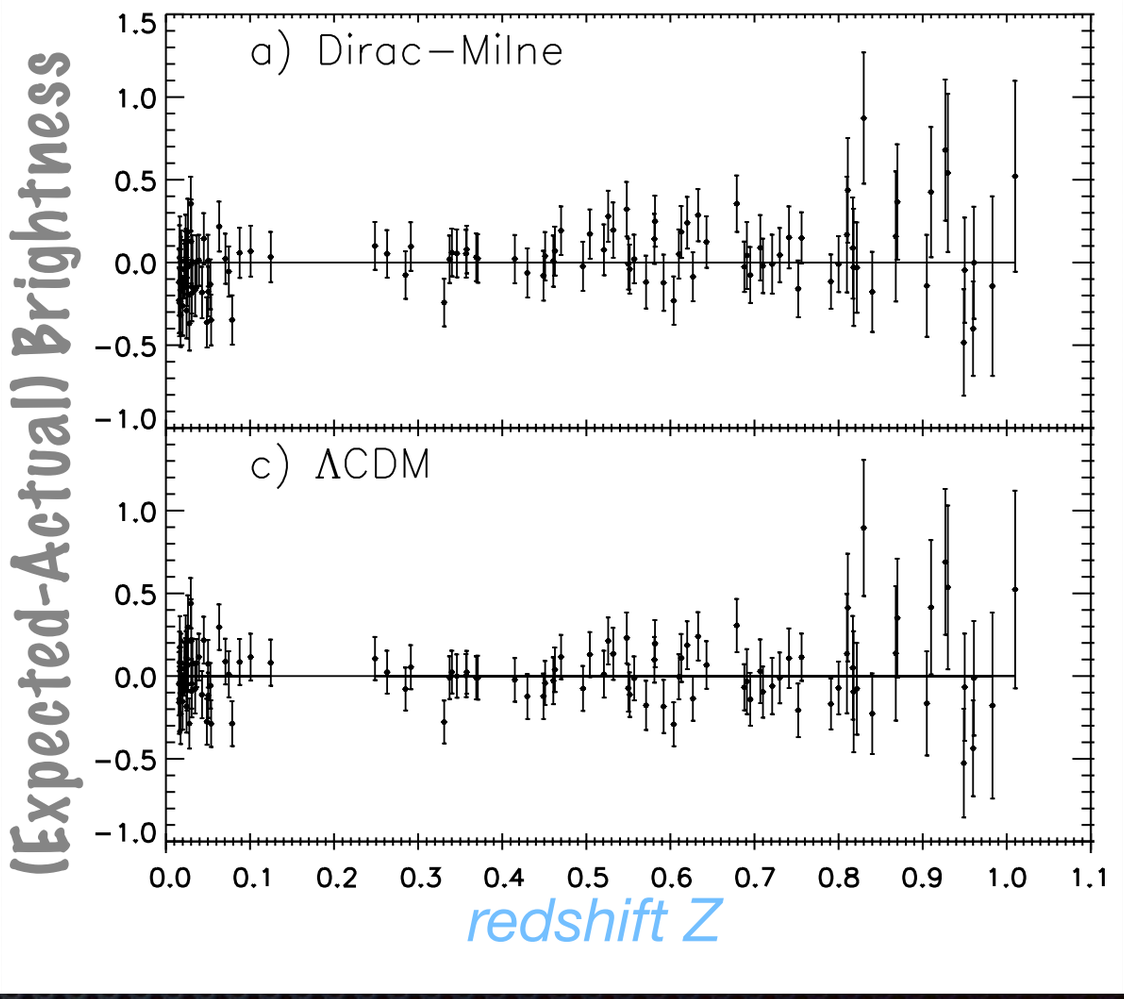
# Dirac-Milne Cosmology

Dirac-Milne cosmology assumes equal amounts of matter and antimatter; antimatter has negative gravitational charge.

➡ **no missing antimatter!**

- fits supernova data without dark energy
  ➡ **no dark energy needed!**
- slower early expansion allows causal connection throughout visible universe
  ➡ **no inflation needed!**
  ➡**(also solves the Age problem)**
- Note! Dirac-Milne cosmology is a work in progress; not fully developed yet!

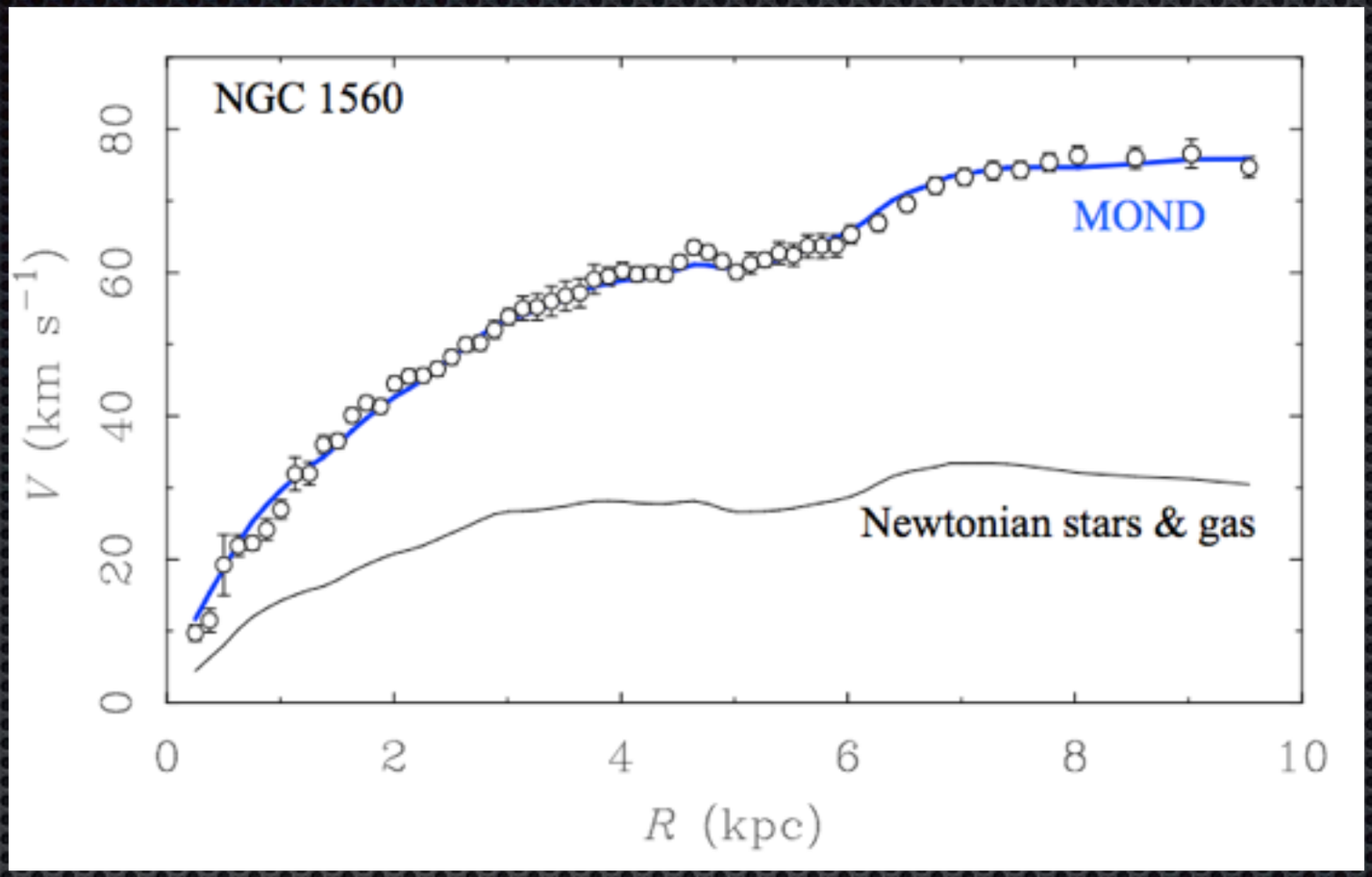
Type Ia supernovæ data




*Benoit-Levy & Chardin, A&A 537, A78 (2012)*

High-redshift data slightly favor Dirac-Milne
Low-redshift data favor $\Lambda$CDM ($1.5\,\sigma$ systematic)

# No Dark Matter Needed




- Modified Newtonian Dynamics (MOND)
  - ➡ Fits rotation curves without Dark Matter
  - ➡ “Kepler’s law” for galaxies
- Gravitational vacuum polarization
  - ➡ physical mechanism for MOND

*Blanchet, Class. Quant. Gray. 24,3529 (2007)*
*Hajdukovic, Astrophys. Space Sci. 334, 215 (2011)*

# How to Measure Antimatter Gravity?

For gravity to dominate, antimatter must be

**Neutral**

& **Cold**

Charged antimatter? E&M forces dominate

Neutral antimatter?

antineutrons Annihilate before cooling

Solution: cool charged antimatter, neutralize, cool more

Options: antiprotons, positrons, antimuons

## Antiprotons+Positrons -> Antihydrogen

stable

annihilates on contact with normal matter
-> hard to cool

Mass dominated by:
strong binding energy

*direct cosmological implications if $\overline{g}$=-g*

## Antimuons+Electrons -> Muonium

easy to make cold

very short lived

Mass dominated by:
2nd generation antilepton
(sensitive to a 5th force)

# MAGE: The Muonium Antimatter Gravity Experiment

MAGE is still an informal Collaboration based upon the muCool Collaboration:

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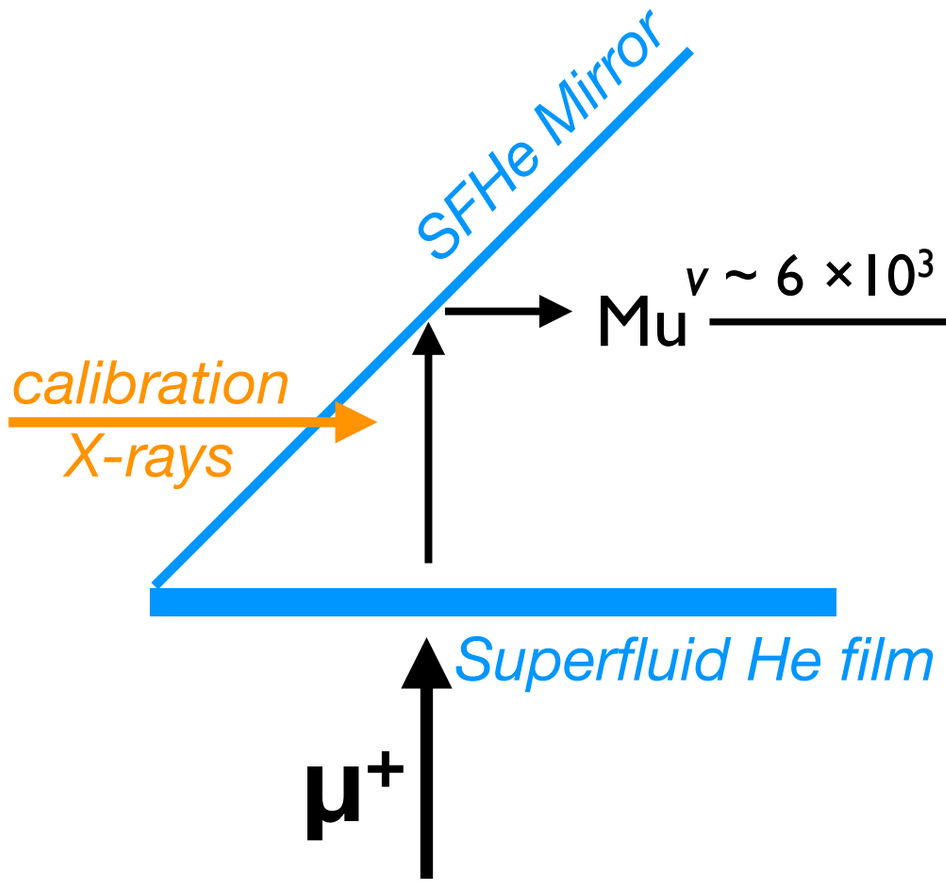
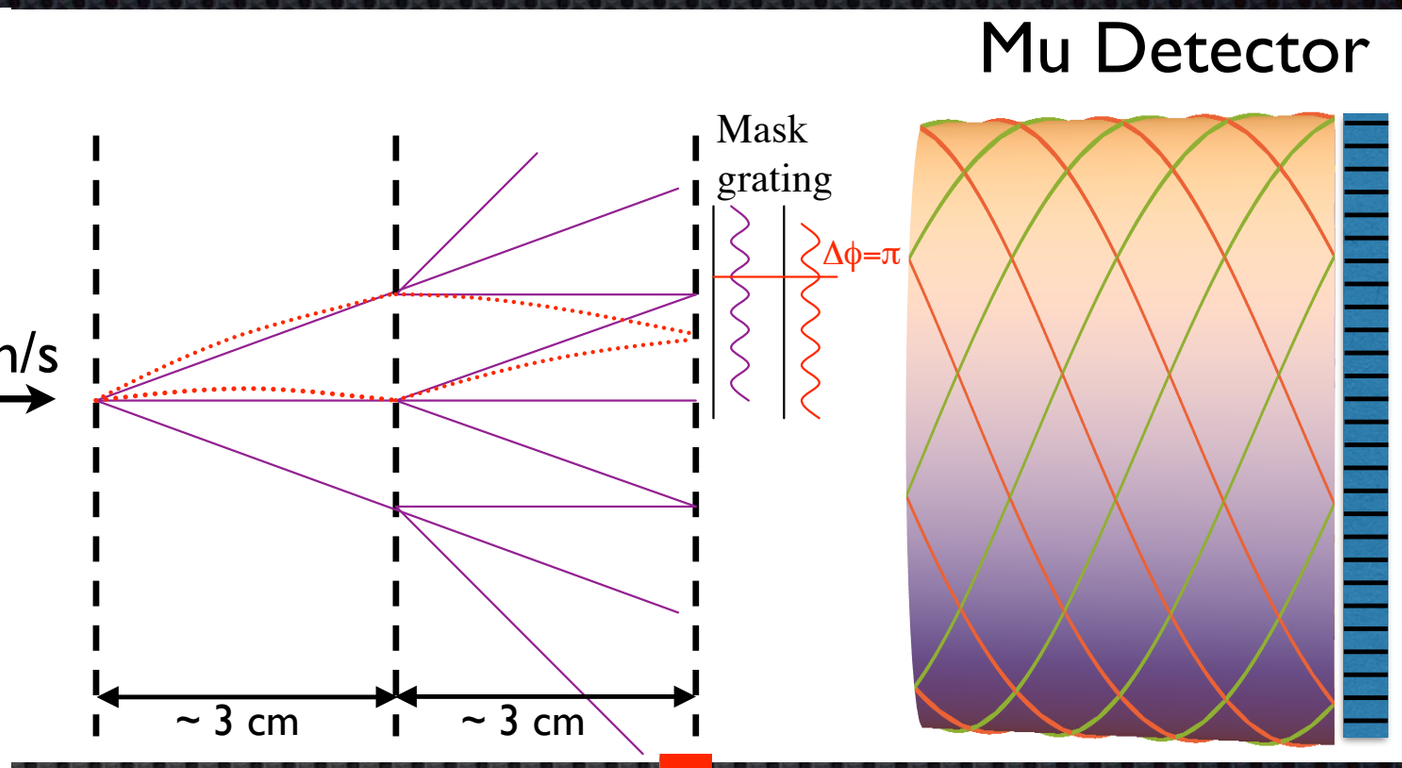
D.M. Kaplan, T.J. Phillips

*Illinois Institute of Technology, Chicago, IL 60616, USA*

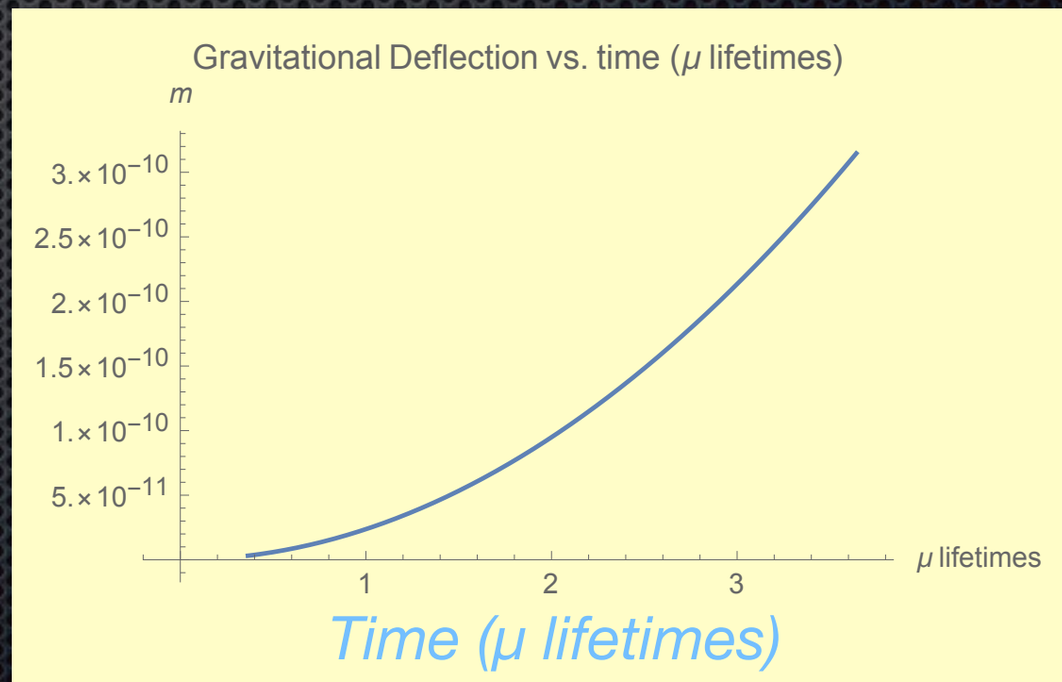
plus additional IIT Collaborators:

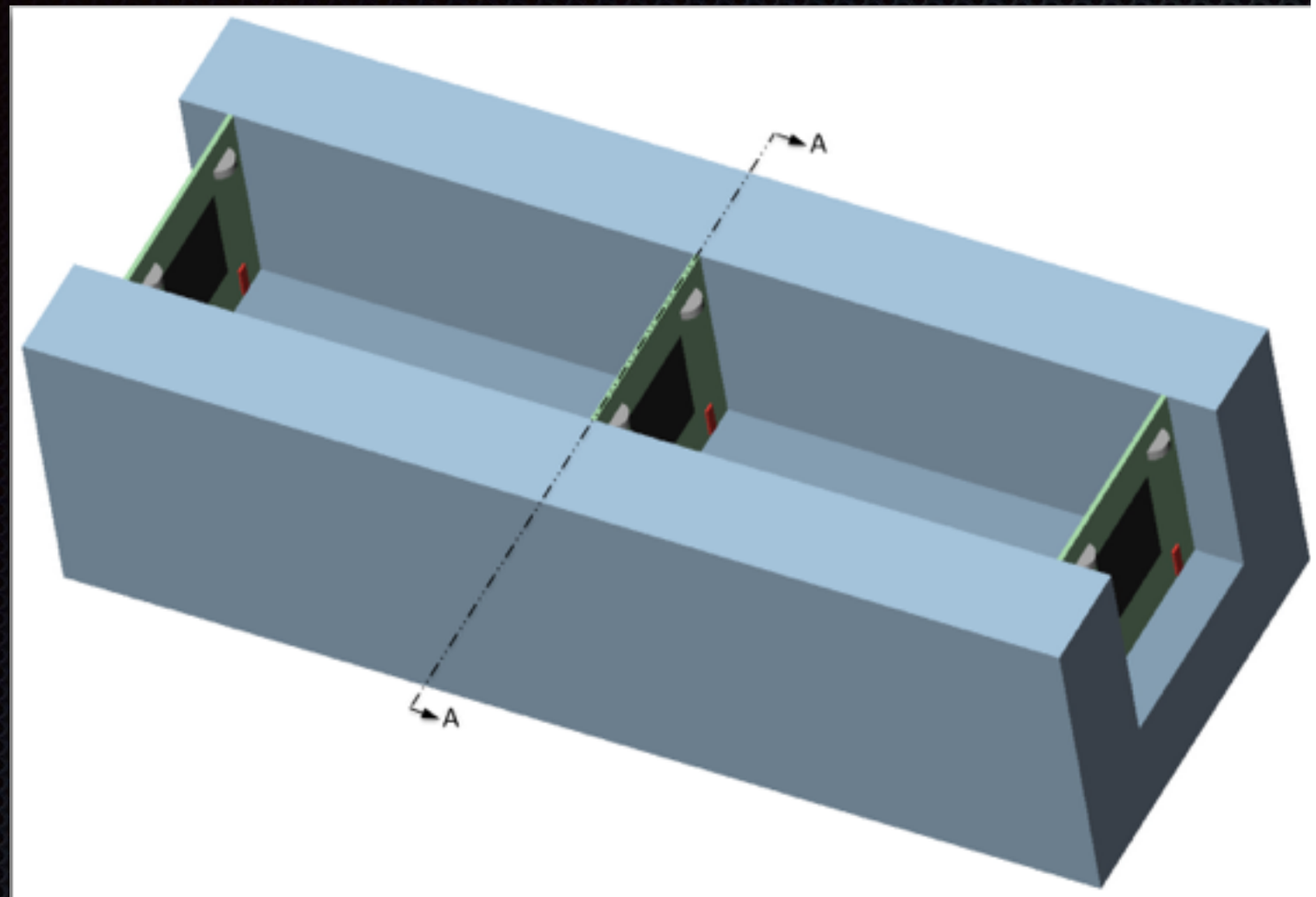
D.C. Mancini, J.D. Phillips, R.D. Reasenberg, T.J. Roberts, J. Terry

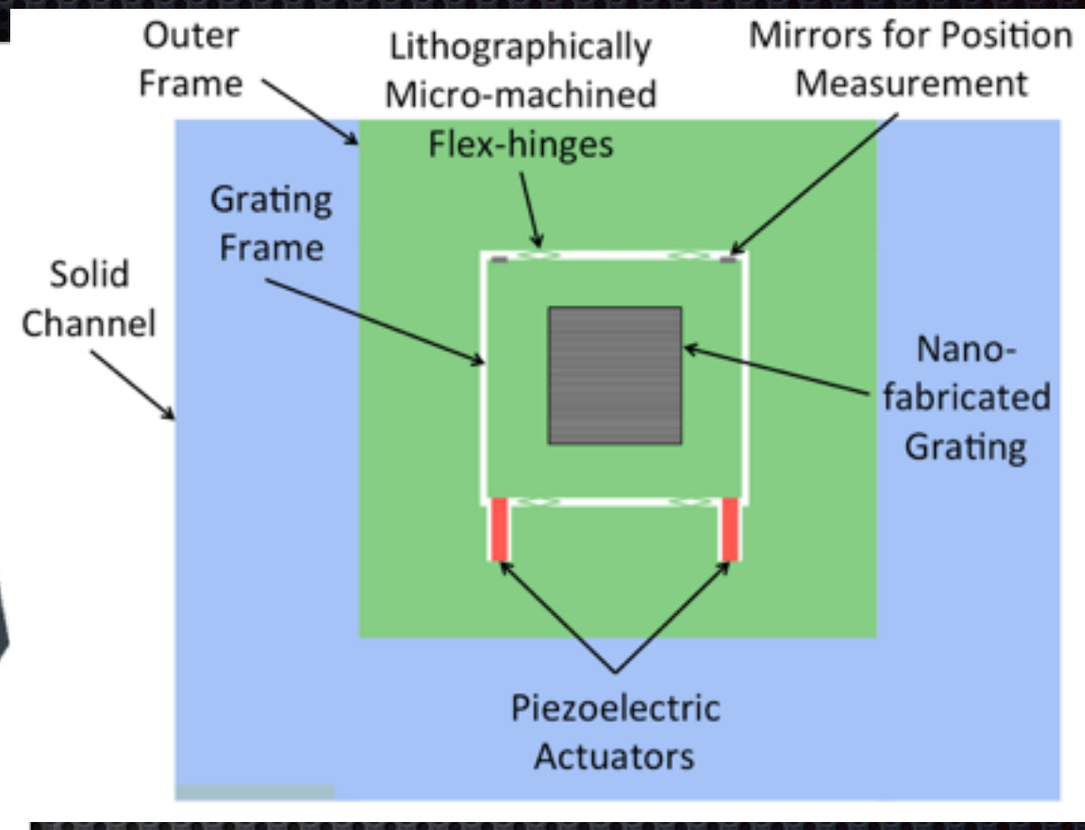


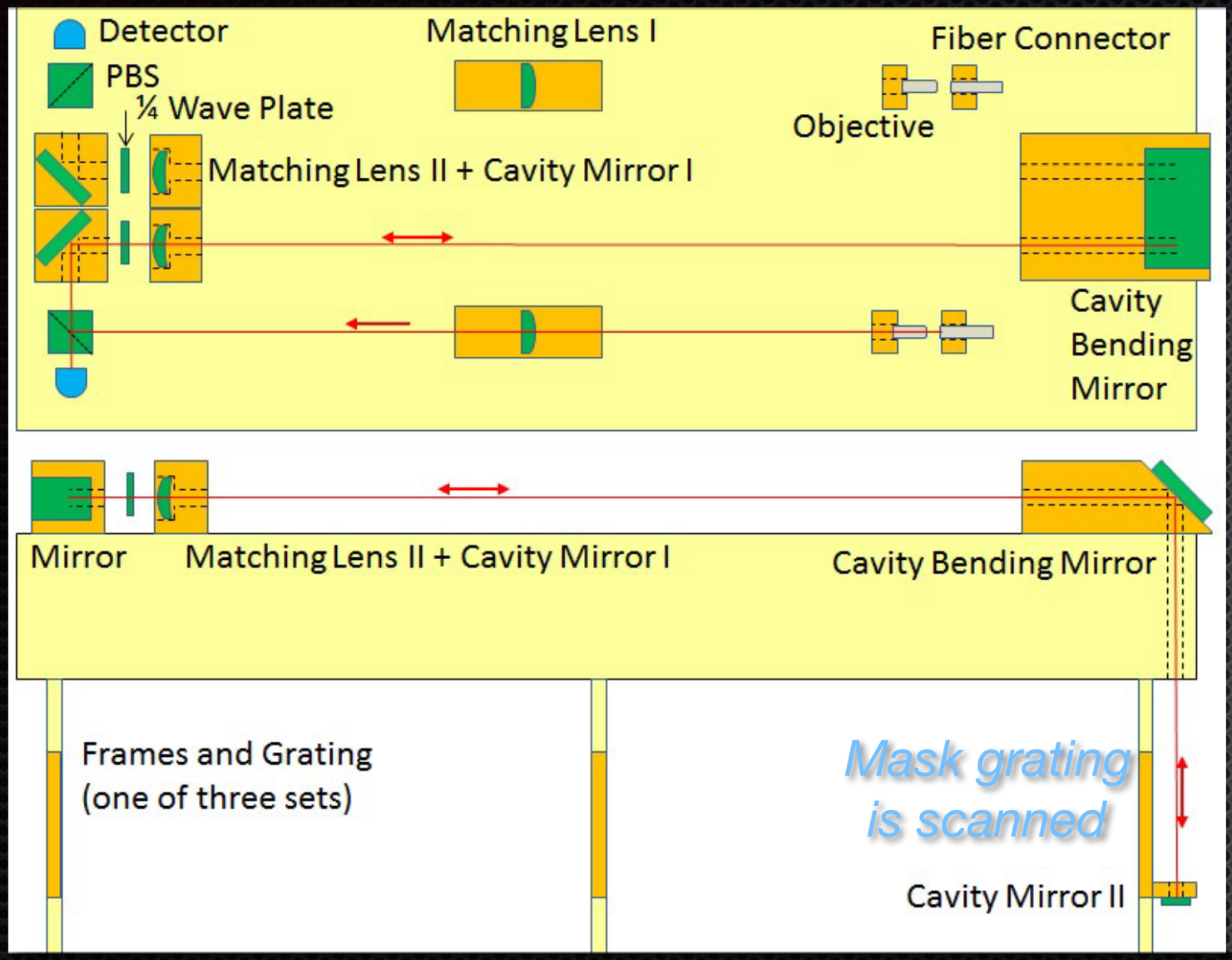

# MAGE Concept






# MAGE Interferometer




Color key:

Orange and yellow: silicon

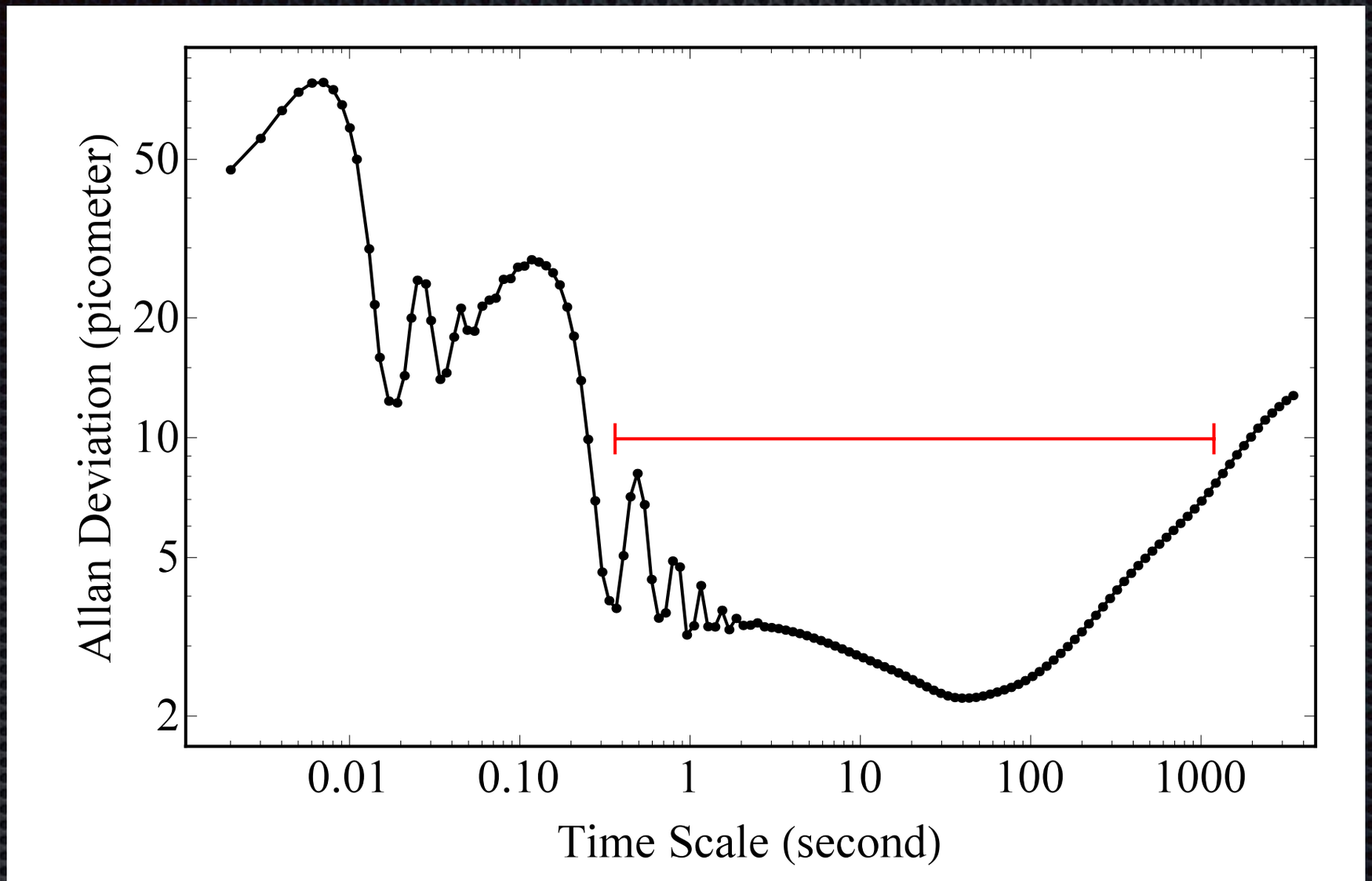
Green: glass

Blue: detector

Red: laser light path (one TFG only)

# Picometer-scale Measurements

using SL-TFGs (Semiconductor-Laser Tracking Frequency Gauges) to track the position of the Mask (3rd) grating



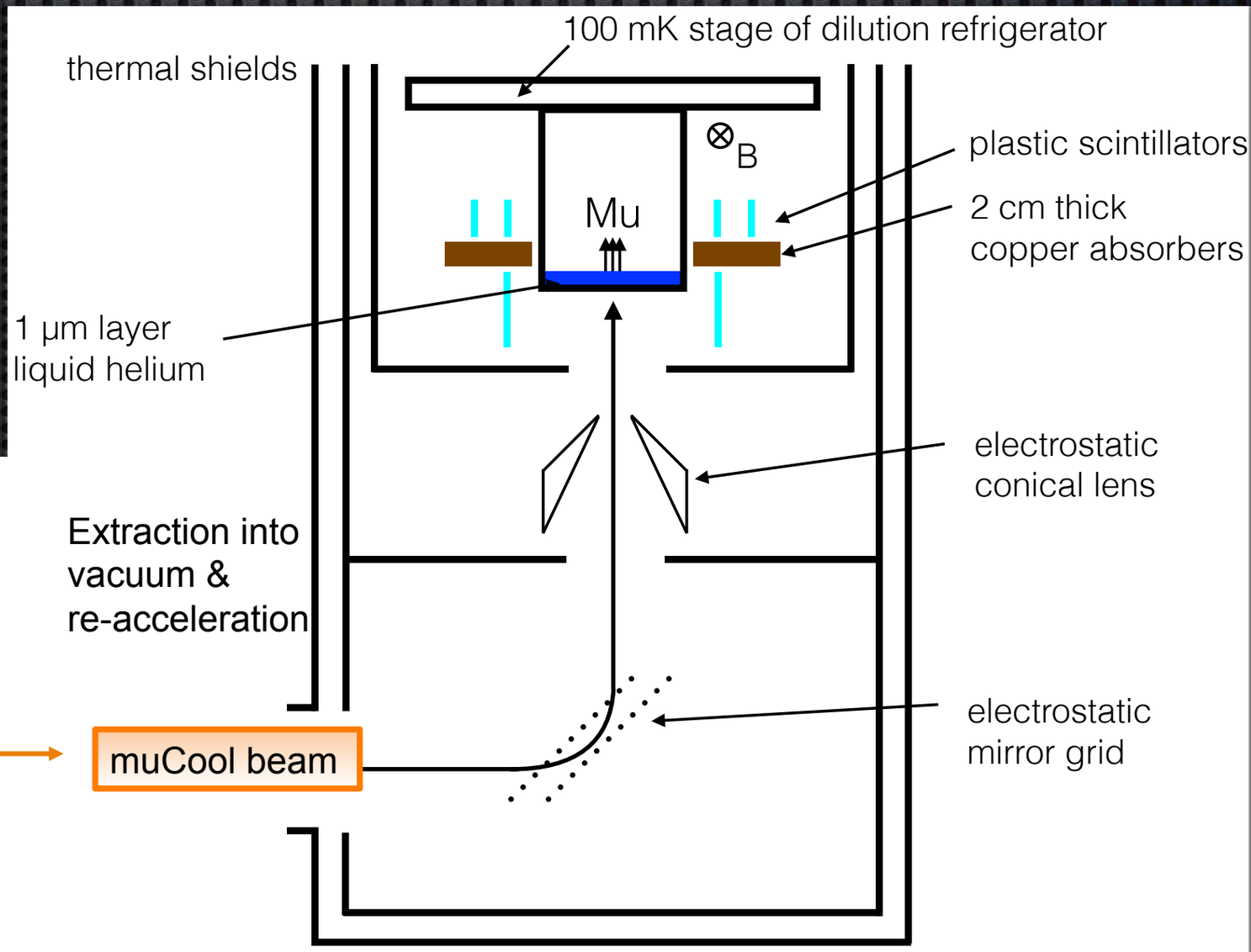

# Current SL-TFG Performance

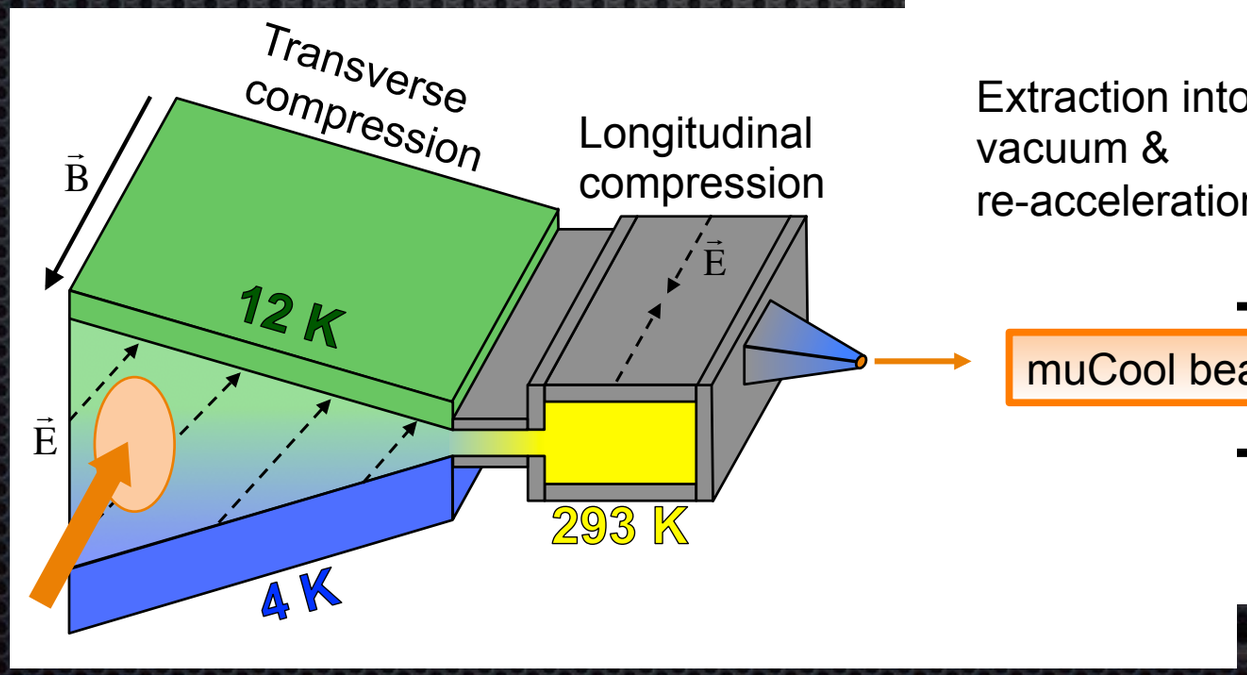
# Making Cold Muonium


- $\mu^+$ stop in SFHe and thermalize
- $\mu^+$ combine with free electron to form muonium
- muonium which diffuses to surface is ejected
  - negative affinity -> high velocity, perpendicular

# Thin SFHe Film Mu Source

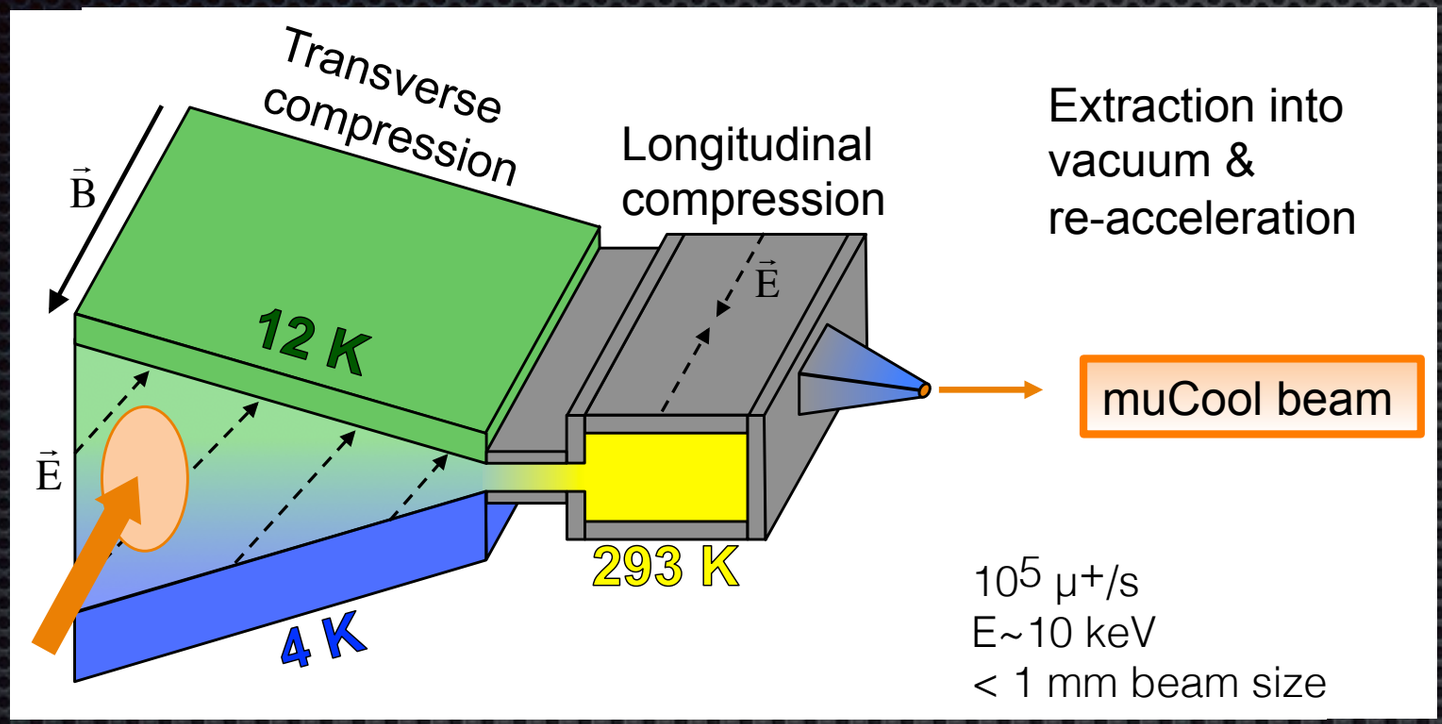
Requires cold $\mu^+$ beam (muCool) to efficiently stop in thin film. ~50% of Mu diffuse to upper surface and are ejected into vacuum at 6.3 mm/μs.




Surface $\mu^+$ beam

# muCool Concept




~50% conversion to Mu with thin-film SFHe

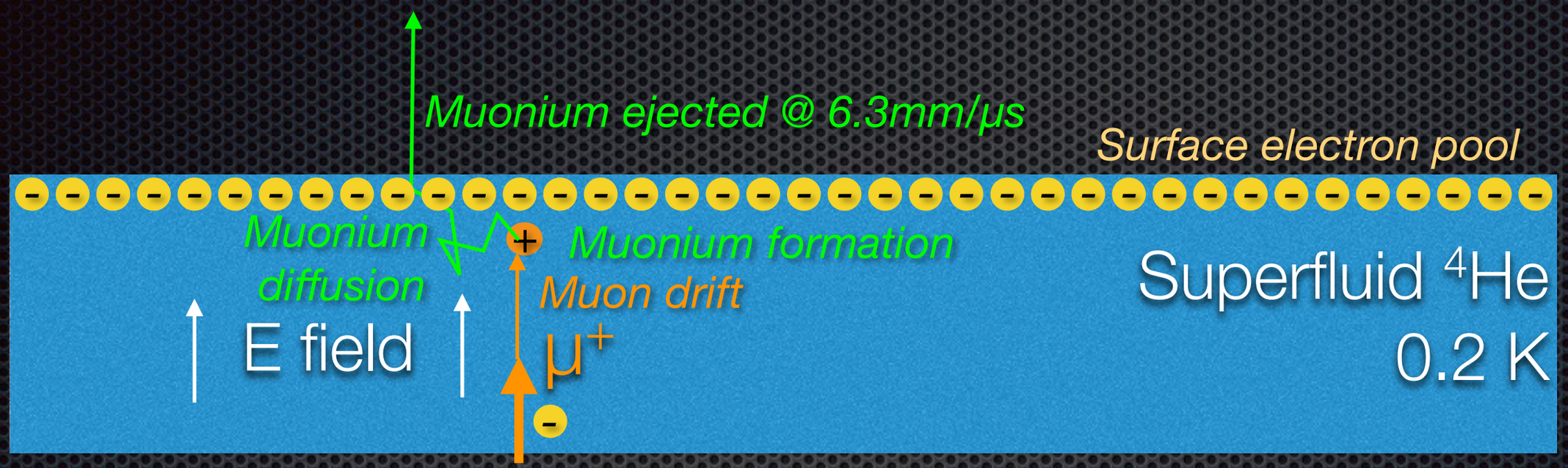
100% acceptance in interferometer

$10^{10}$ phase space compression

$10^{-3}$ efficiency

*Taqqu, PRL 97, 194801 (2006)*

# Thick SFHe Film Mu Source

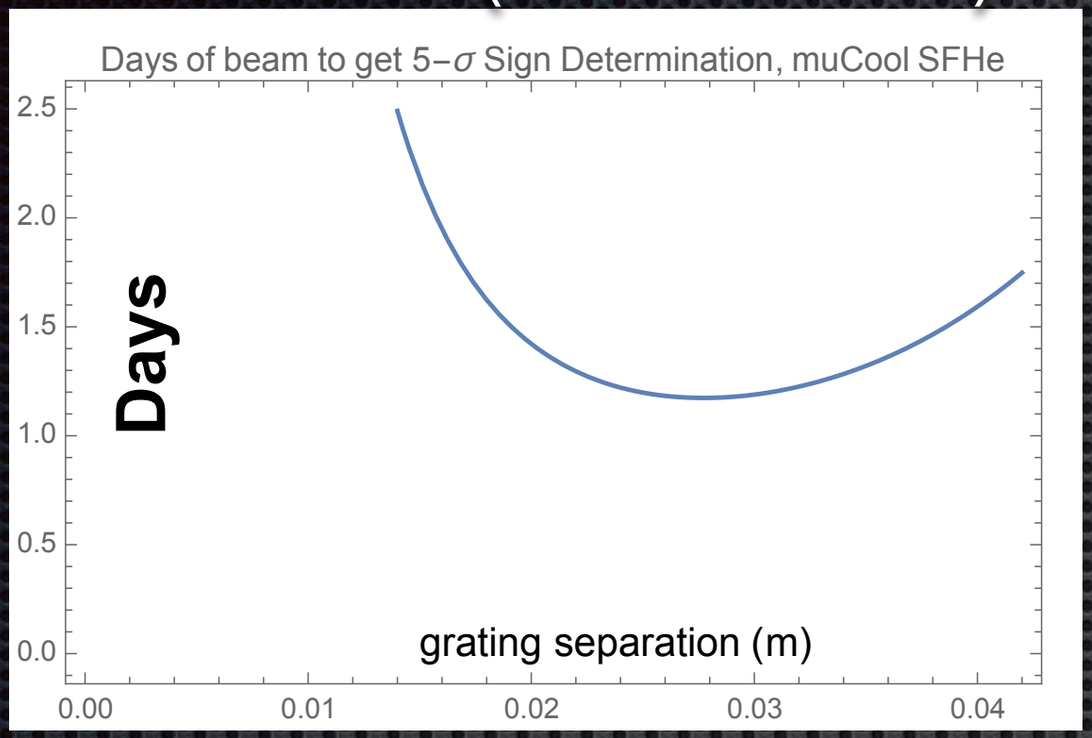



- Surface electron pool creates an electric field
- field draws 80% of $\mu^+$ from ionization trail; $\mu^+$ drift to surface
- muonium is formed near the surface
- Preliminary estimates:
  - ~5% of a surface muon beam can be converted to Mu
    - ➡~100x more Mu produced
  - ~25% of Mu accepted in interferometer

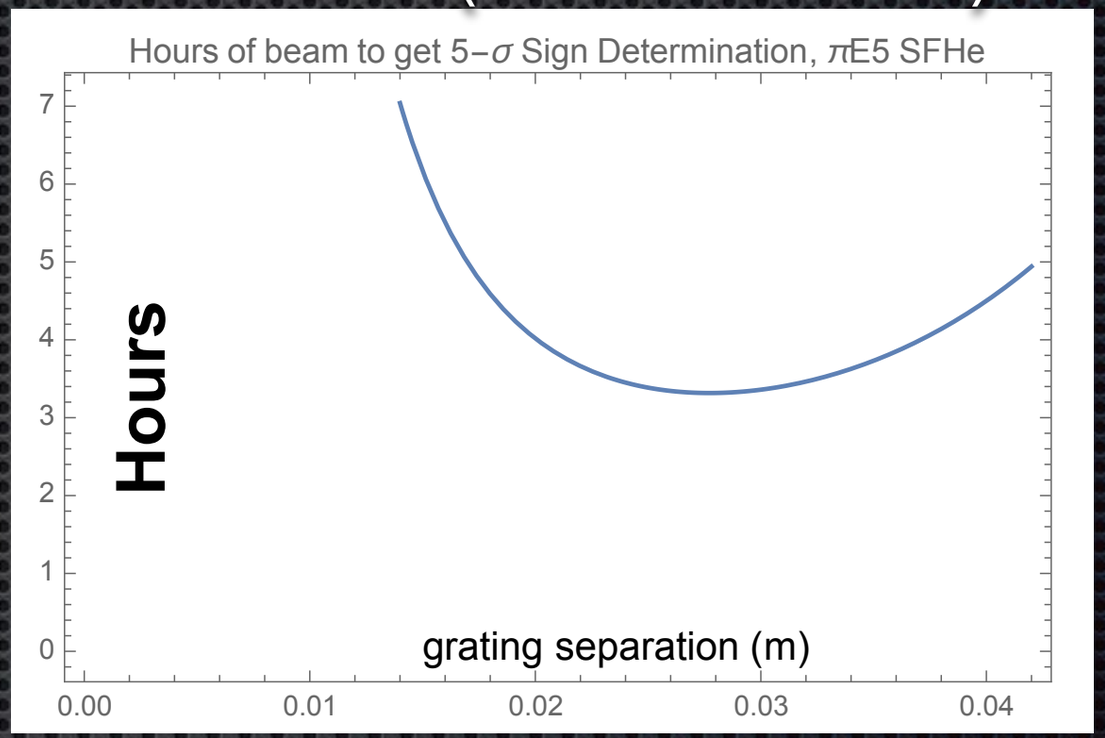
*Taqqu, Phys. Proc. 17, 216 (2011)*

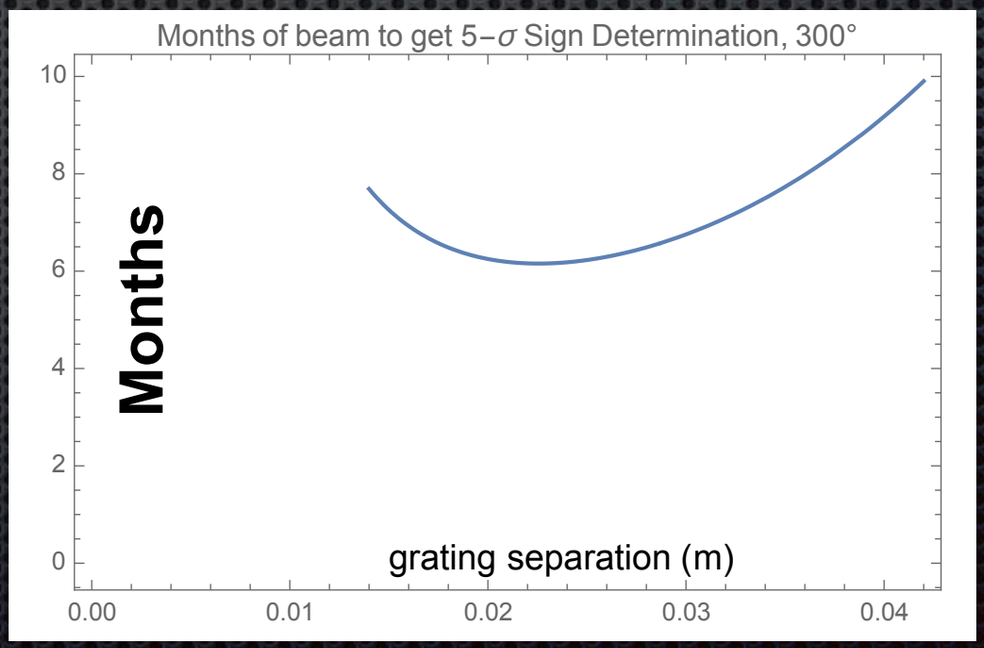
# Beam Time for 5-σ $\bar{g}$ Sign

## muCool (Thin SFHe)



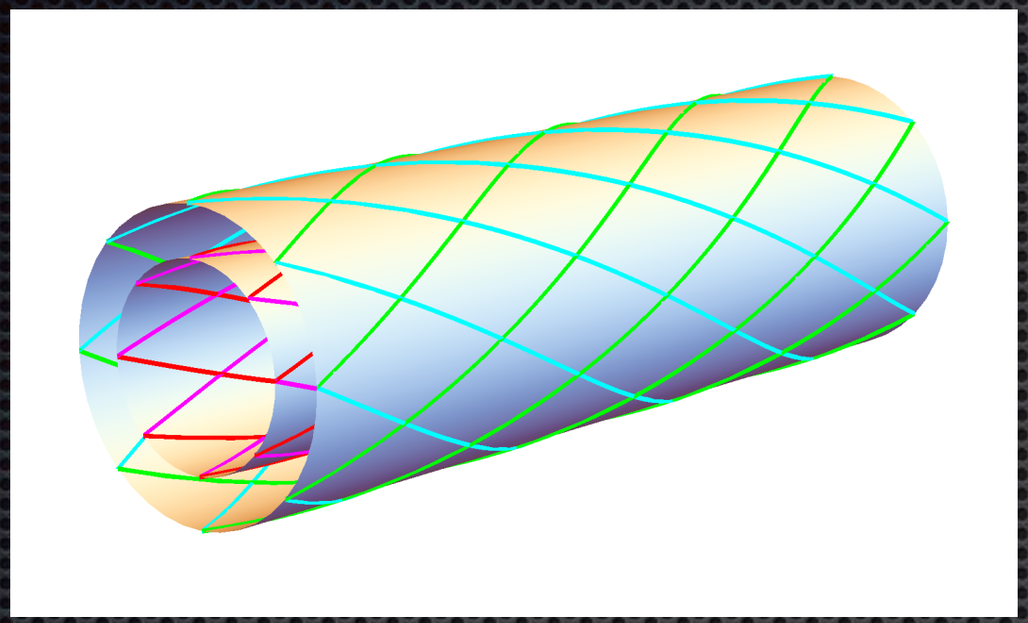

## E-Field (thick SFHe)

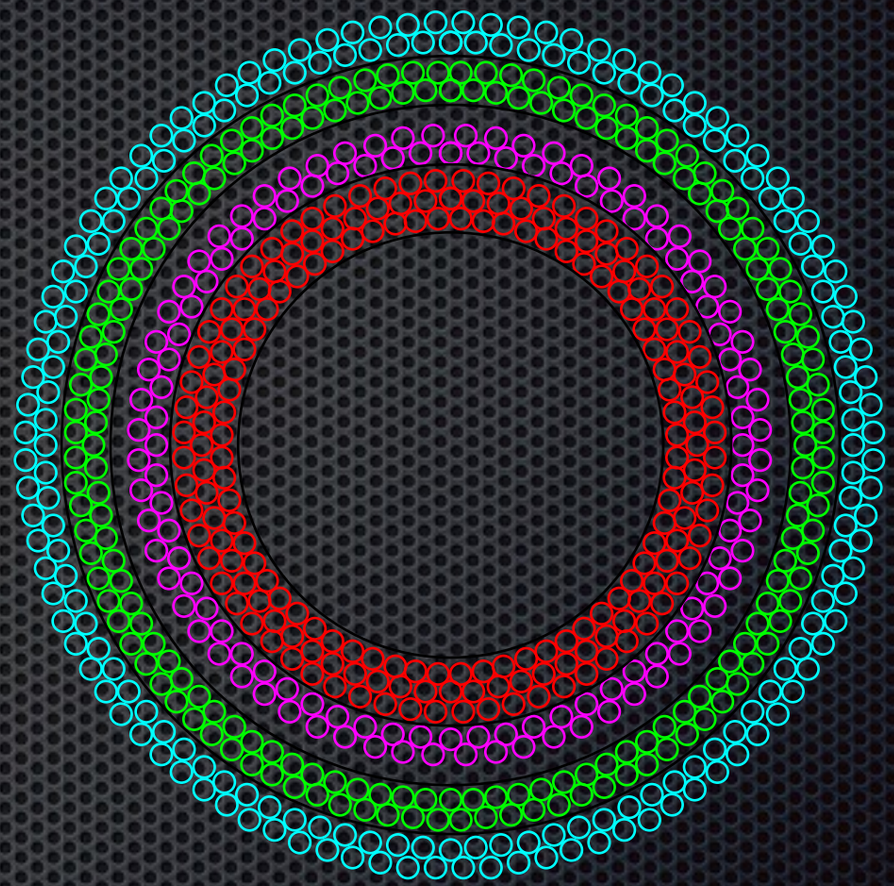



thermal Mu

# Muonium Detector Concept





UV layers cross exactly once

2cm ID
704 1mm fibers

**multichannel plate at end to detect the electron and calibration X-rays**

# MAGE Status

- Steady progress on muCool at PSI
  - next beam test this fall
  - Robust Swiss support
  - see Ivana Belosovic's talk for details
- Preliminary work on interferometer at IIT
  - SL-TFG work at IIT
  - grating development at the Center for Nanoscale Materials at Argonne National Lab
  - No NSF funding yet

# New Muonium Source Potential Applications

- Gravity
- ($g$-2) (J-PARC method)
- Mu hyperfine measurement
- Mu 1s – 2s transition energy
- muonium-antimuonium conversion

# Conclusions

- Antimatter gravity is an important experimental question (may already have evidence that it is repulsive)
- MAGE collaboration is working towards this measurement using muonium

➡ also sensitive to possible 5th forces

➡ beam development at PSI

➡ interferometer development at IIT

➡ seeking funding to conduct the experiment

xkcd

*A webcomic of romance, sarcasm, math, and language.*

xkcd updates every Monday, Wednesday, and Friday.

## Fundamental Forces

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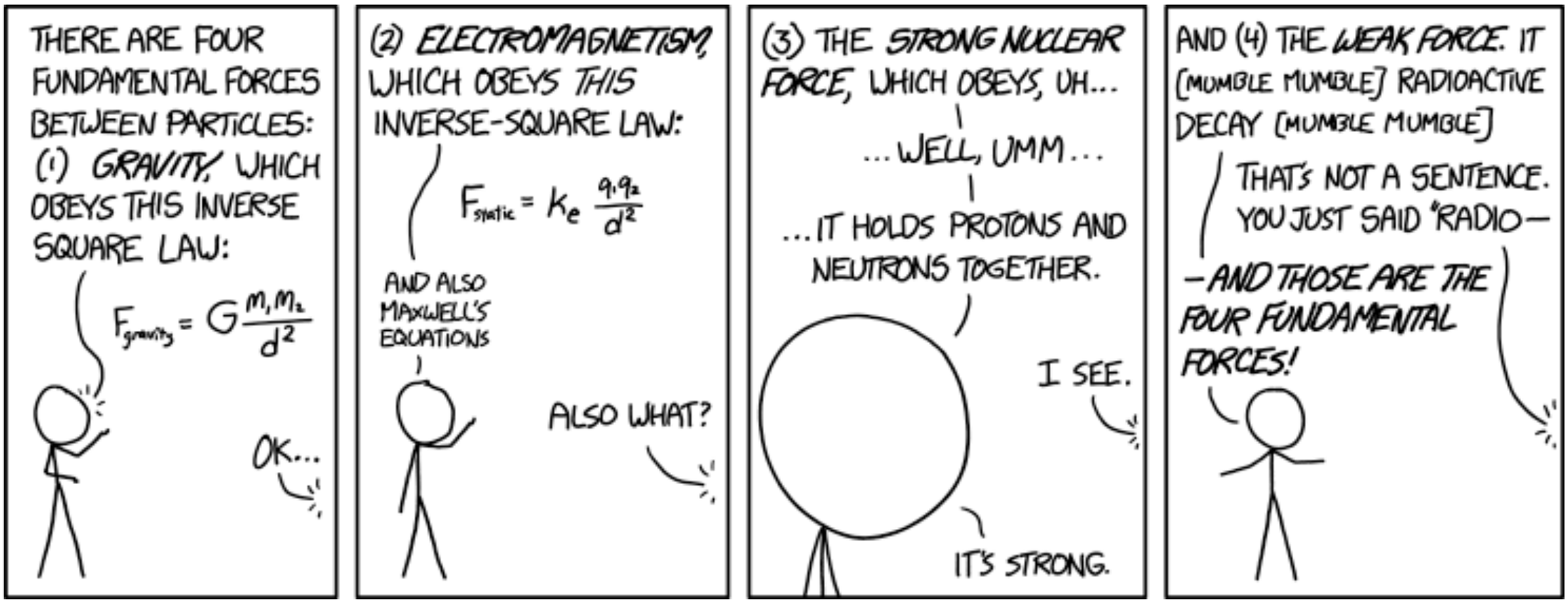


Mouseover:

"Of these four forces, there's one we don't really understand." "Is it the weak force or the strong—" "It's gravity."