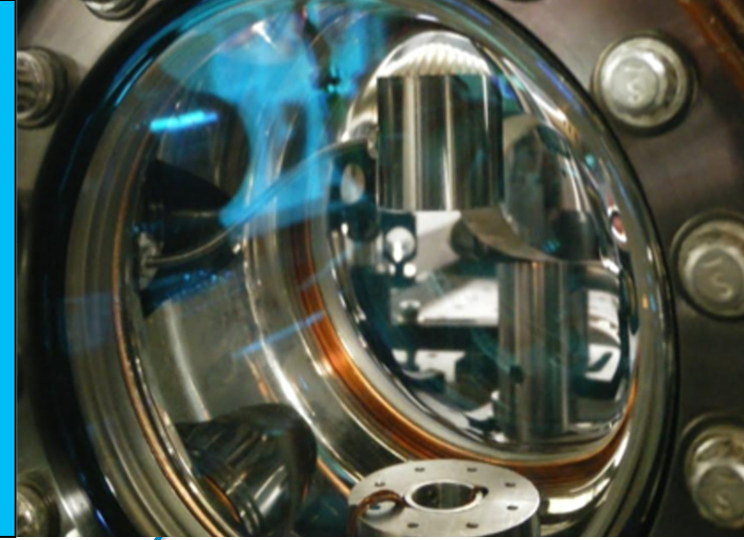
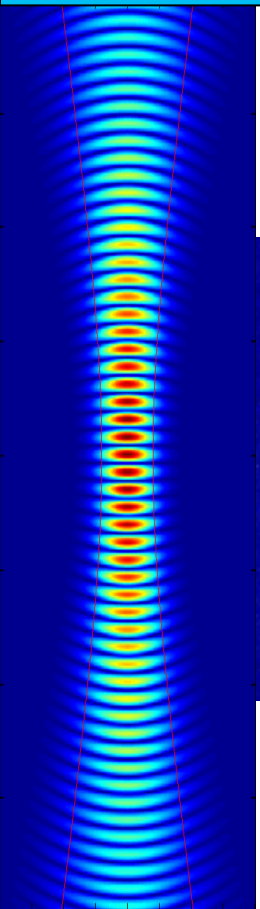
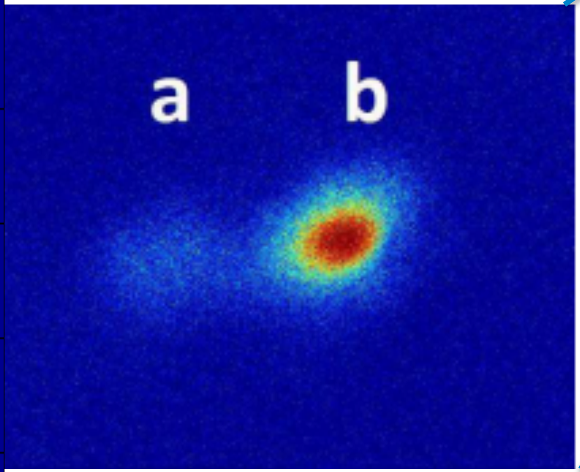
Blind analyses in precision measurements







Holger Müller

Contents

Motivation

CP violation

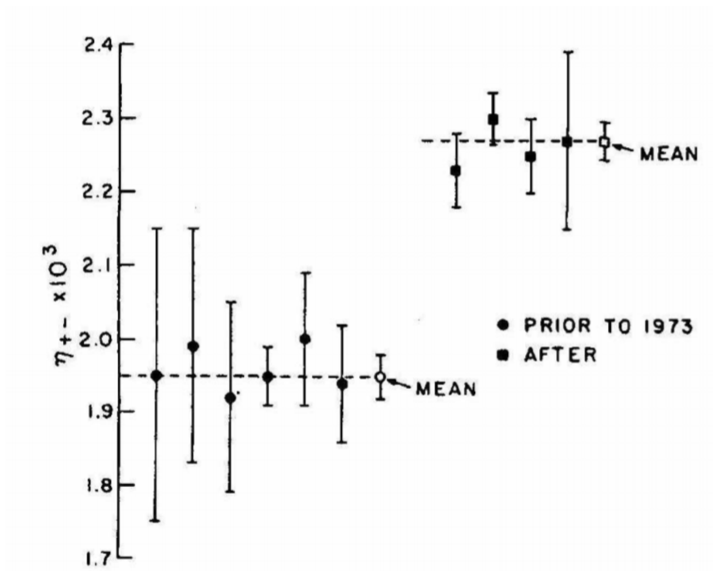
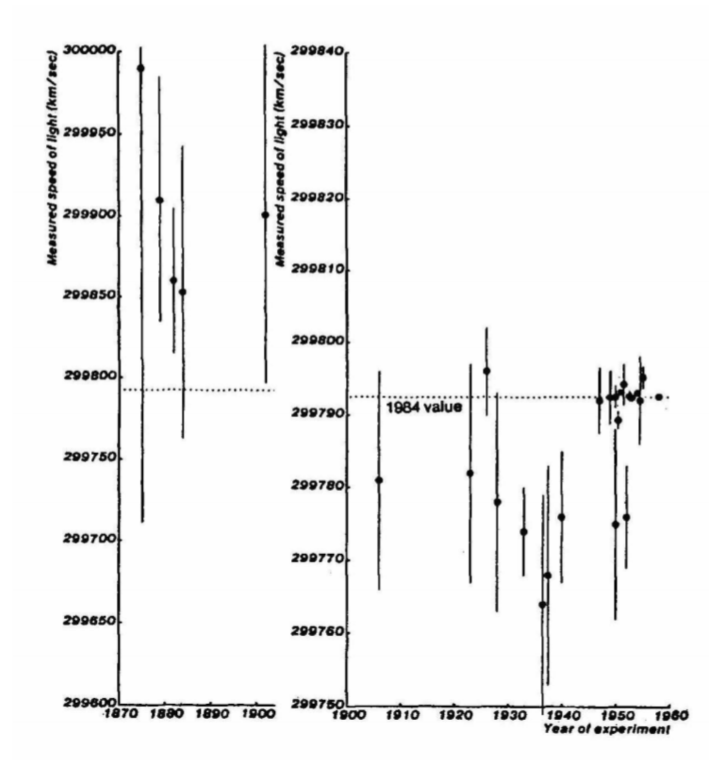


FIG. 1: Measurements of $|\eta_{+-}|$ in order of their year of publication. Reprinted with permission from A. Franklin, "Forging, cooking, trimming, and riding on the bandwagon," Am. J. Phys. **52**, 786-793 (1984), copyright 1984, American Asso-

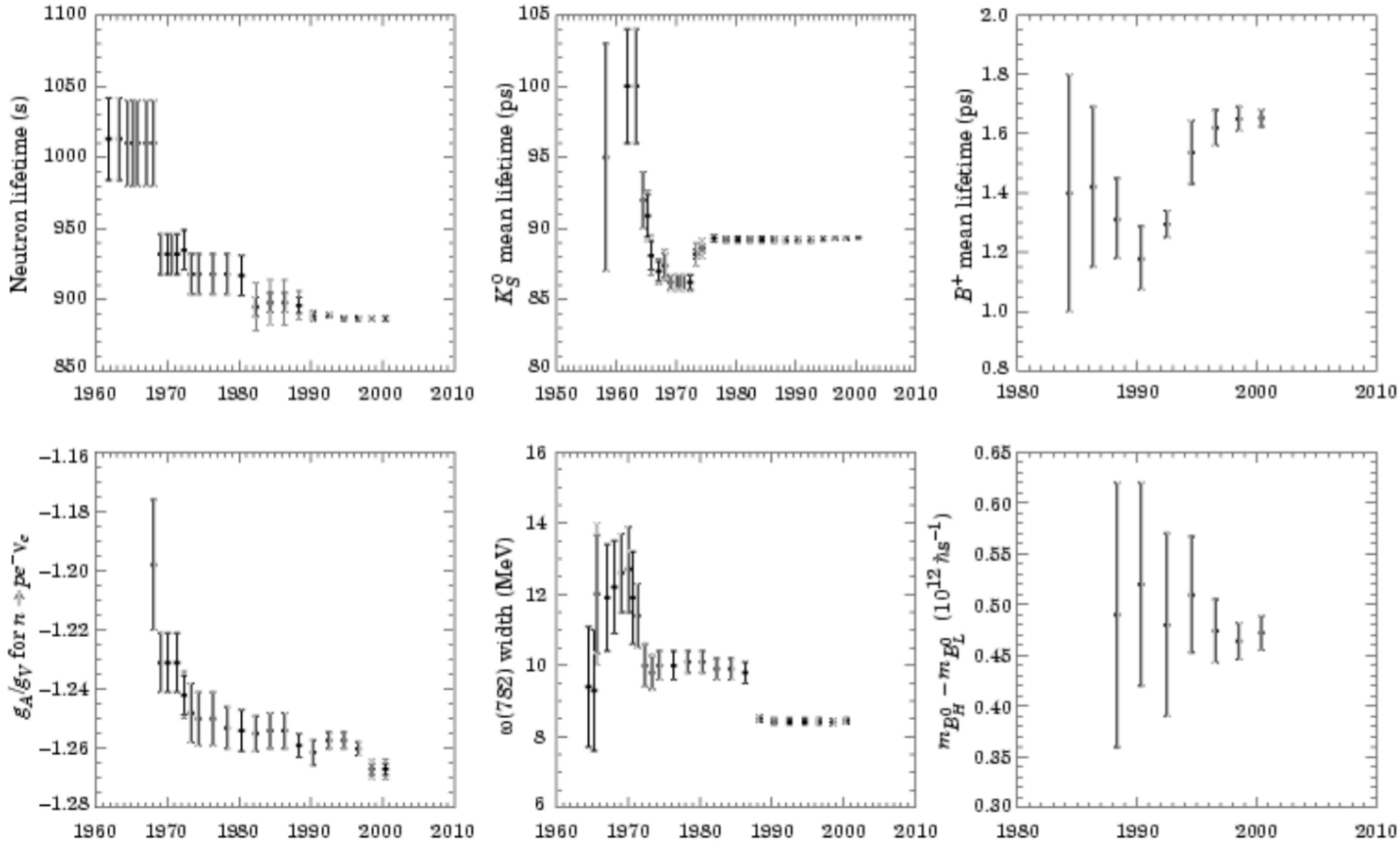
Speed of light



Jeng, arXiv:0508199 (2005)

Motivation

Neutron lifetime | Kaon lifetime | B+ lifetime



P.F. Harrison

Accuracy versus precision

Low accuracy
Low precision

Low accuracy
High precision

High accuracy
High precision

Millikan oil drop experiment

Millikan measured the charge on an electron by an experiment with falling oil drops, and got an answer which we now know not to be quite right. It's a little bit off because he had the incorrect value for the viscosity of air. It's interesting to look at the history of measurements of the charge of an electron, after Millikan. If you plot them as a function of time, you find that one is a little bit bigger than Millikan's, and the next one's a little bit bigger than that, and the next one's a little bit bigger than that, until finally they settle down to a number which is higher.

Why didn't they discover the new number was higher right away? It's a thing that scientists are ashamed of—this history—because it's apparent that people did things like this: When they got a number that was too high above Millikan's, they thought something must be wrong—and they would look for and find a reason why something might be wrong. When they got a number close to Millikan's value they didn't look so hard. And so they eliminated the numbers that were too far off, and did other things like that ...[10][11]

Die atomaren Konstanten e, e/m_0 und h *).

Von U. Stille in Braunschweig.

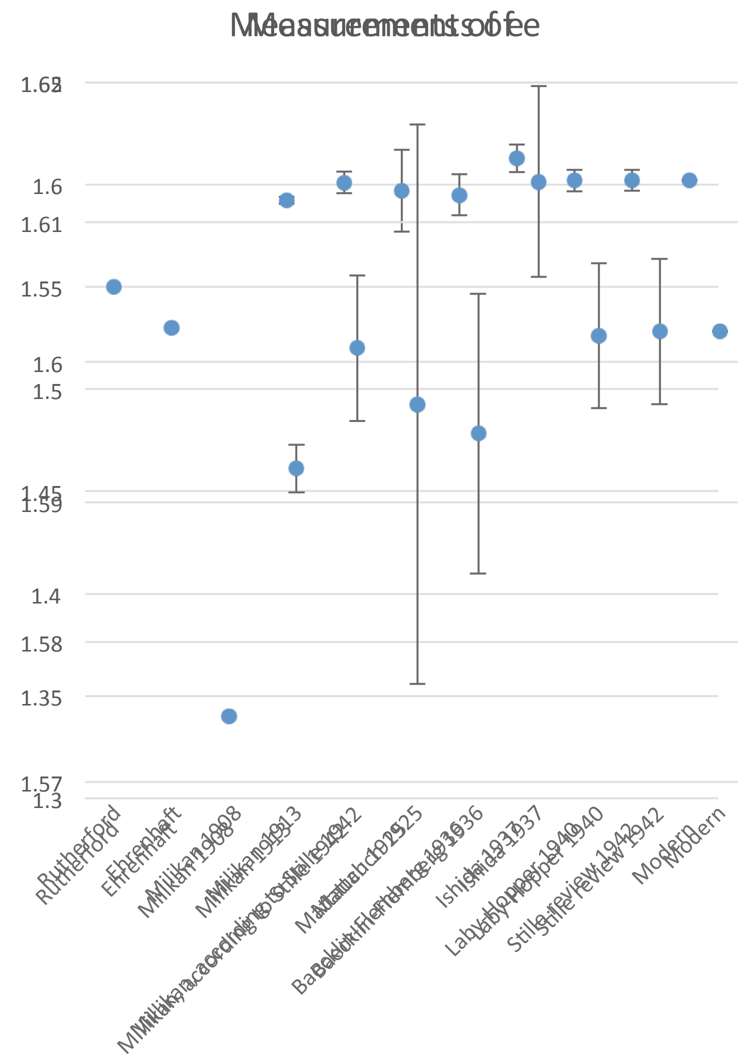
Mit 1 Abbildung. (Eingegangen am 1. Dezember 1942.)

Entsprechend den in einer früheren Veröffentlichung aufgestellten allgemeinen Gesichtspunkten werden die zur Bestimmung der Atomkonstanten verfügbaren experimentellen Daten neu zusammengestellt und diskutiert. In einem I. Teil sind die hierfür erforderlichen Hilfsgrößen zusammengefaßt. Die Zahlenwerte für die elektrischen Umrechnungsfaktoren werden dabei einer weiteren Veröffentlichung entnommen, die dieses Thema gesondert behandelt. Als zur Zeit experimentell gesicherte Werte sind für die Vakuumlichtgeschwindigkeit c_0, die Induktionskonstante μ_0, die Influenzkonstante ε_0, die spezifische Molekülzahl N_L und die spezifische Ionenladung F folgende anzunehmen: $c_0 = (2{,}997\,77 \pm 0{,}000\,20) \cdot 10^8$ m/sec, $\mu_0 = (1{,}25602 \pm 0{,}00002) \cdot 10^{-6}$ Volt · sec/Amp · m, $\varepsilon_0 = (8{,}8594 \pm 0{,}0014) \cdot 10^{-12}$ Amp · sec/Volt · m, $N_L = (6{,}0243 \pm 0{,}0048) \cdot 10^{26}$ Kilomol^{-1} und $F = (9{,}6520_3 \pm 0{,}0006) \cdot 10^7$ Amp · sec/Kiloäquivalent, wobei die beiden letzten Zahlenwerte auf die physikalische Atomgewichtsskala bezogen sind. Im Teil II werden auf Grund des vorliegenden experimentellen Materials Zahlenwerte für die drei atomaren Konstanten abgeleitet. Es ergeben sich für die Elementarladung e, die spezifische Elektronenladung e/m_0 und das Plancksche Wirkungsquantum h: $e = (1{,}6022 \pm 0{,}0014) \cdot 10^{-19}$ Amp · sec, $e/m_0 = (1{,}759_3 \pm 0{,}002) \cdot 10^{11}$ Amp · sec/kg und $h/e = (4{,}1312 \pm 0{,}0026)$ 10^{-15} Volt · sec bzw. hieraus $h = (6{,}619 \pm 0{,}010) \cdot 10^{-34}$ Watt · sec². Der aus den Messungen nach der Öltröpfchenmethode folgende e-Wert stimmt mit dem oben angegebenen, aus F und N_L folgenden innerhalb dessen Fehlergrenze

Z. Phys. **121**, 133 (1942)

Millikan oil drop experiment

- There may never have been a long-lasting problem with the elementary charge.
- Controversy with Ehrenhaft (claimed “subelectrons”
- 1942 review notes and corrects error
- Inexplicably, Millikan keeps defending his original value
- The problem isn’t that the community keeps following false previous measurements, but that the authority figures don’t like being corrected.
- Error 2% -> 0.5% [Franklin, A. (1997), *The Chemical Educator*. **2** (1): 1–14]



Frank Dunnigton 1932 e/m measurement

- Two previous measurements disagree
- Electrons on circle must pass slits S during period 2π/ω of rf drive
- Angle unknown to experiementer
- Phys. Rev 42, 734 (1932)

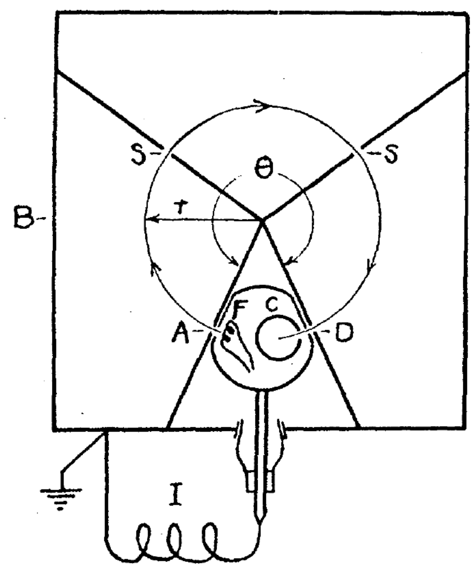


Fig. 1.

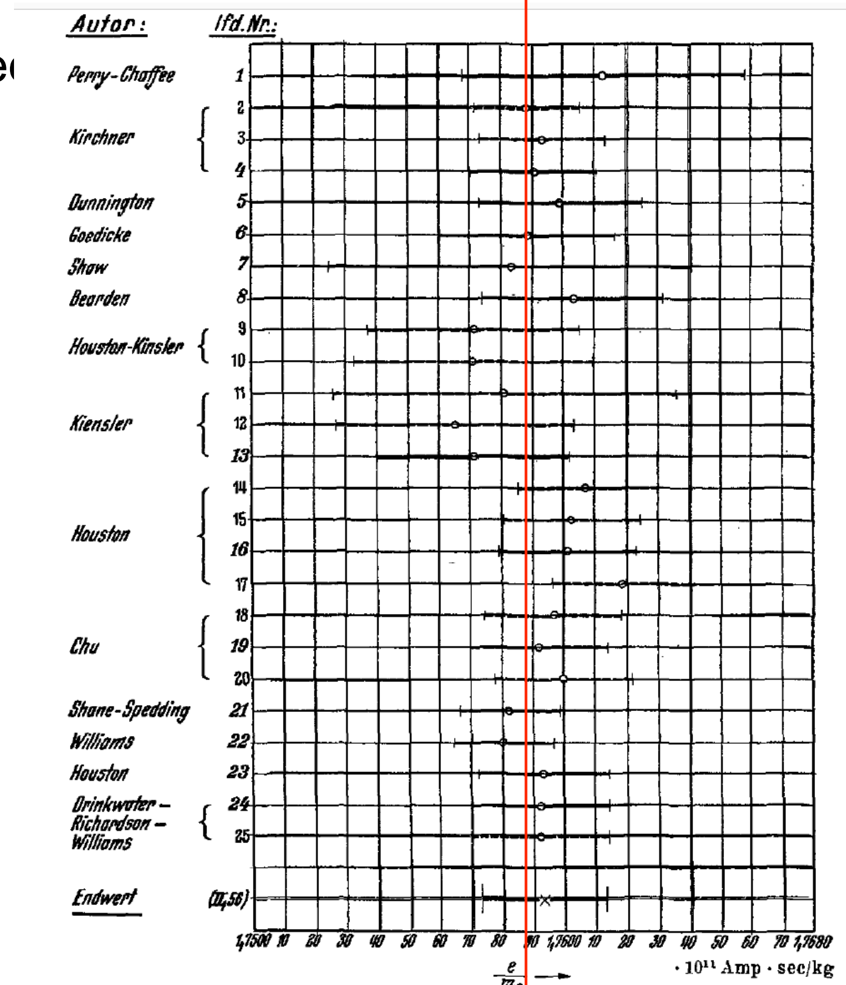
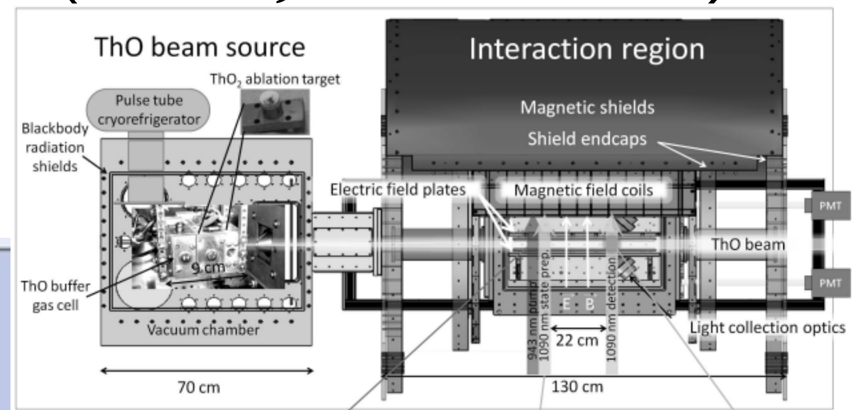
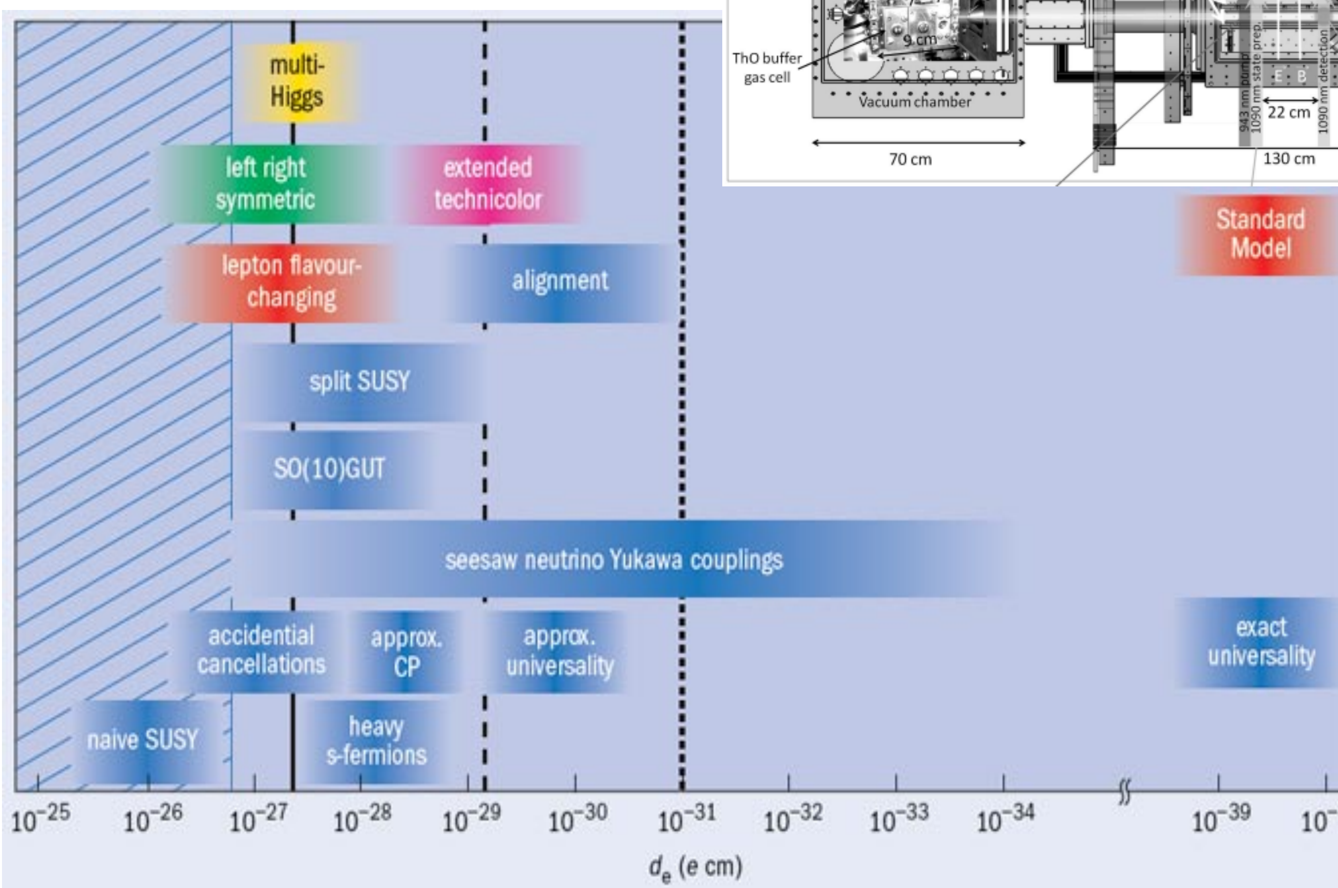


Fig. 1. Zusammenstellung der experimentell bestimmten e/m_0-Werte.

Advanced Cold Molecule Edm experiment (Yale, Harvard)

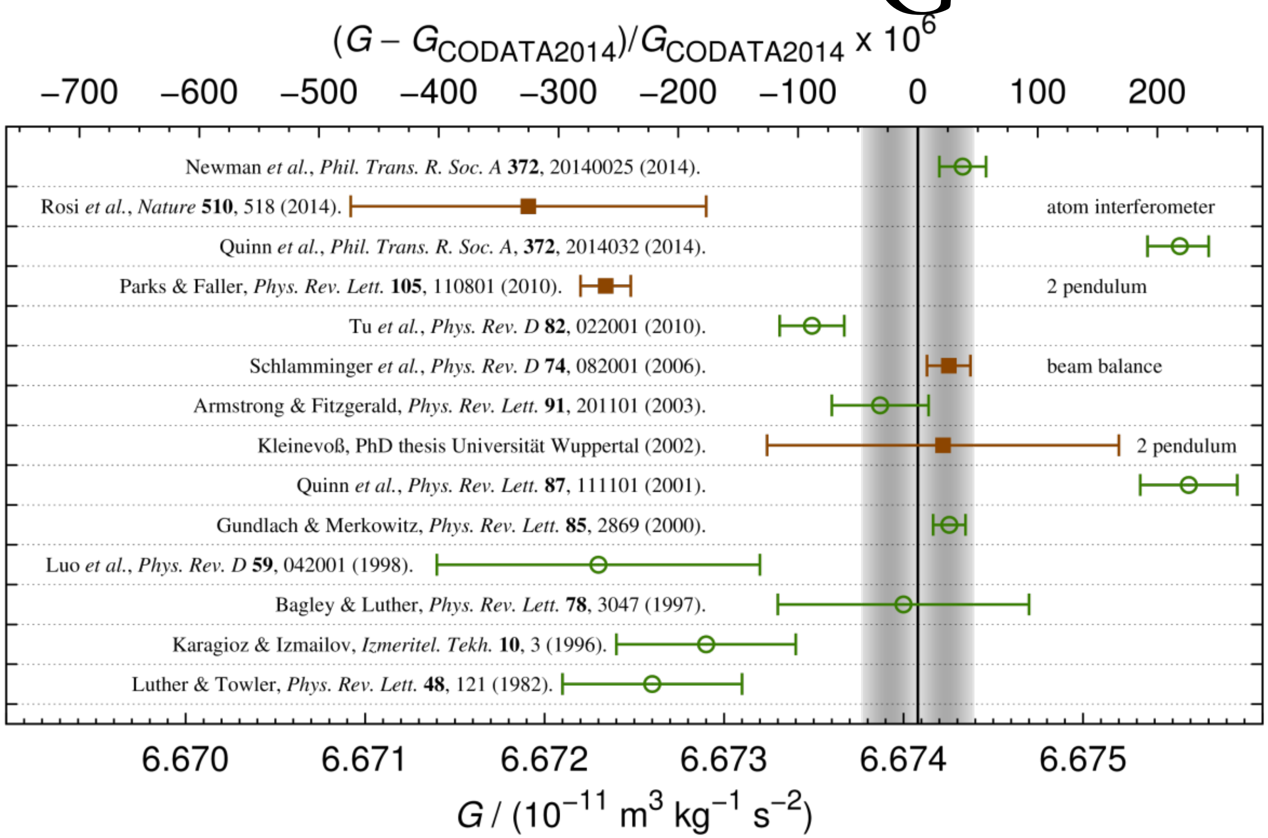


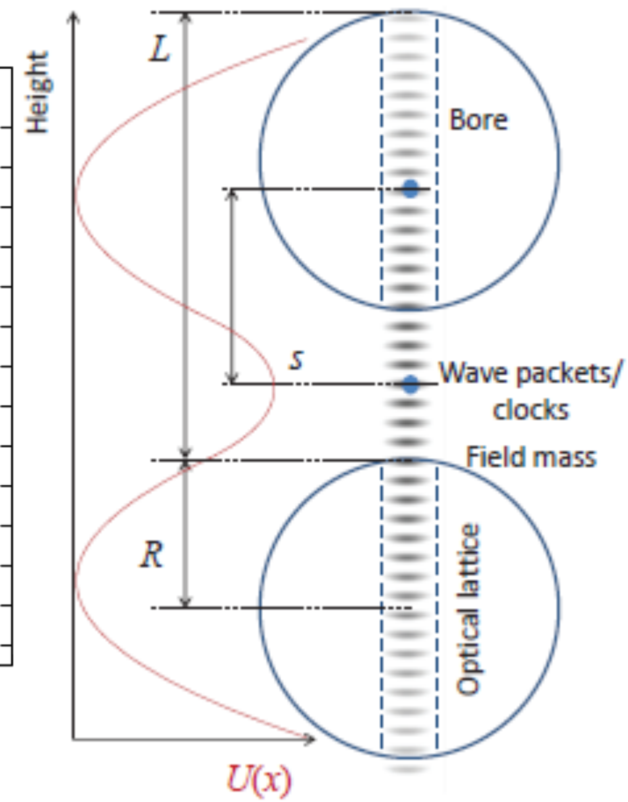


Advanced cold molecule EDM

- Blind analysis has become the norm in EDM searches.
- 199Hg EDM from Blayne Heckel & Norval Fortson's group. The Seattle group was the first EDM experiment to use blind analysis, to my knowledge.
- Hinds EDM blind
- Unknown offset added until after we had determined uncertainty and were resolved to publish the result

G





- Live unblinding

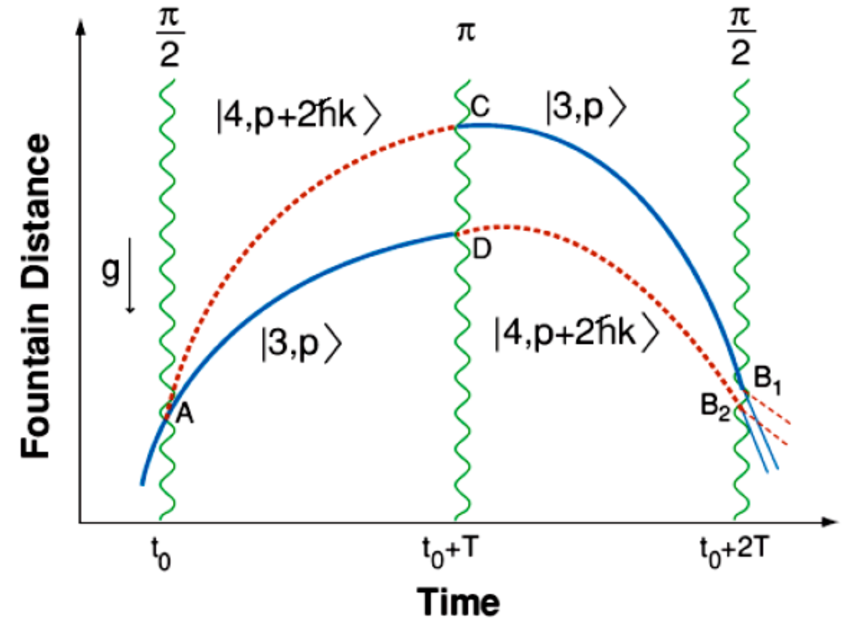
Prl 108, 230404 2013

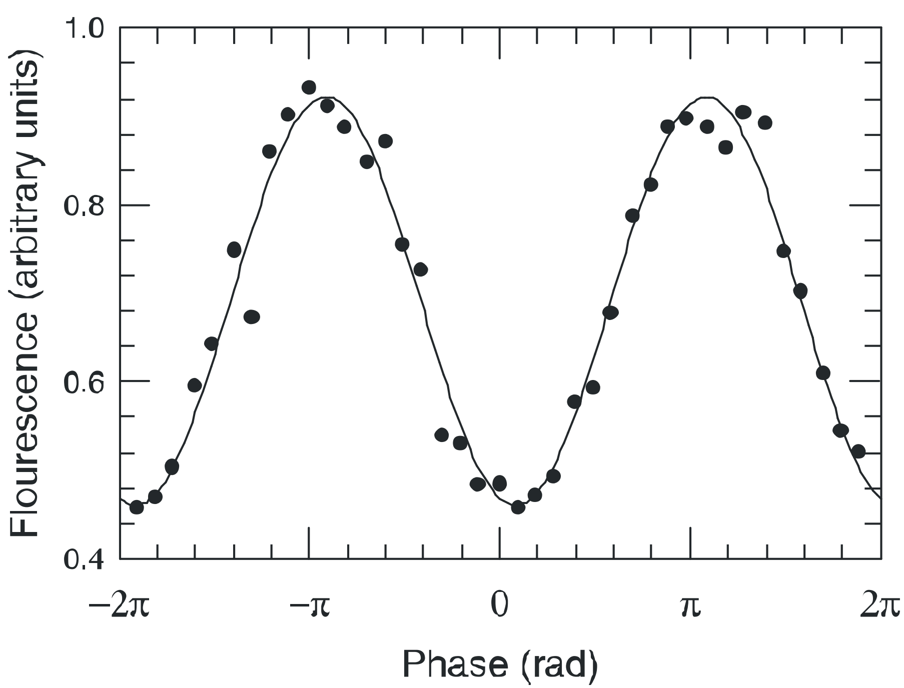
Light pulse atom interferometer

$$\Delta\varphi = -\frac{1}{\hbar}\oint L dt + \Delta\varphi_{\mathrm{laser}}$$

$$= 2T^2\vec{\Omega}\cdot[\vec{k}\times(\vec{v}_0 + \vec{a}T)] + \vec{k}\vec{a}T^2$$

$$+ O(1/c^4)$$



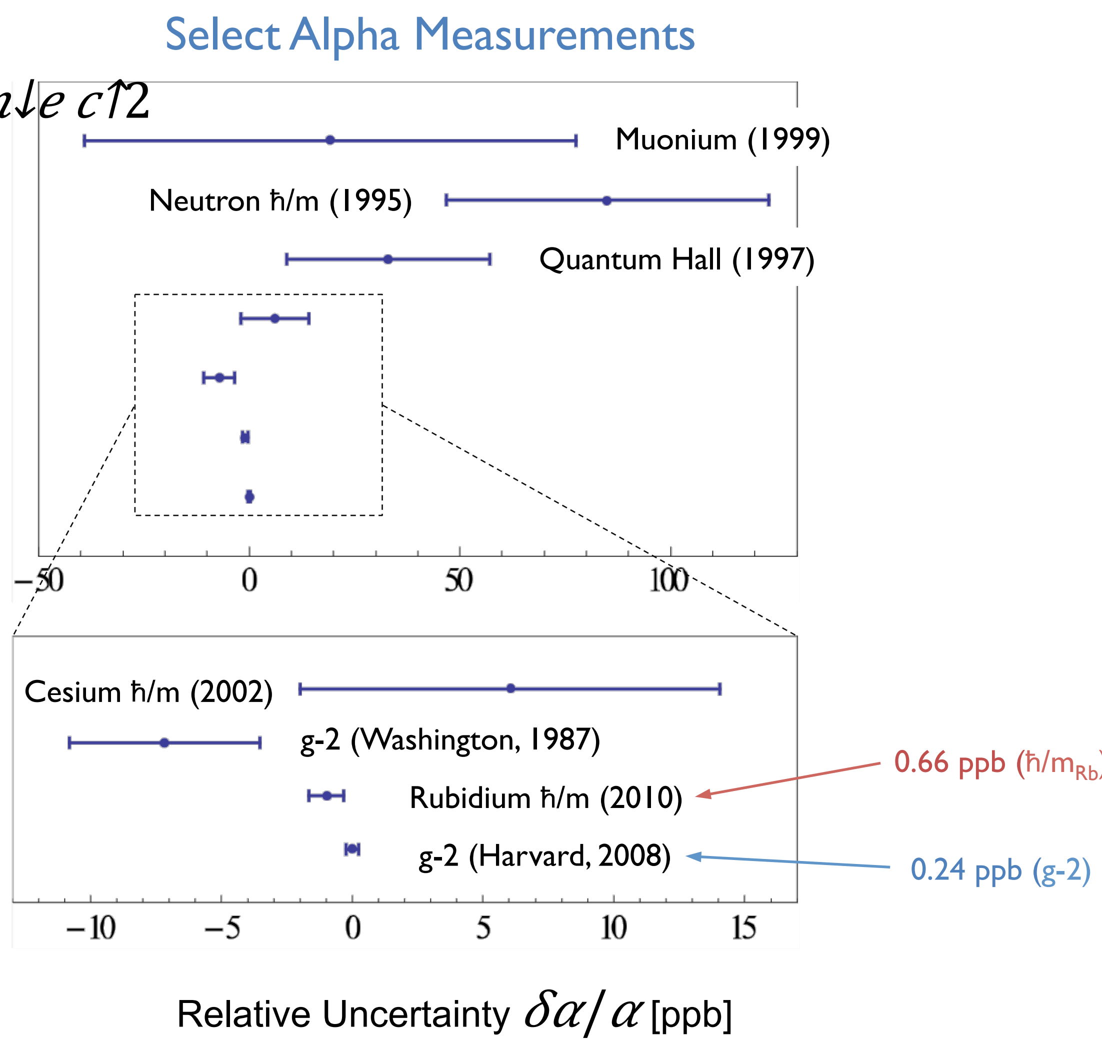


Each data point is from a single launch, determines g to 1.3ng =>11ng/sqrt(Hz)

HM *et al.*, PRL **100,** 031101 (2008); PRD **80,** 016002 (2009)

Fine Structure Constant α

- $hcR_\infty = \frac{1}{2}\alpha^2 m_e c^2$

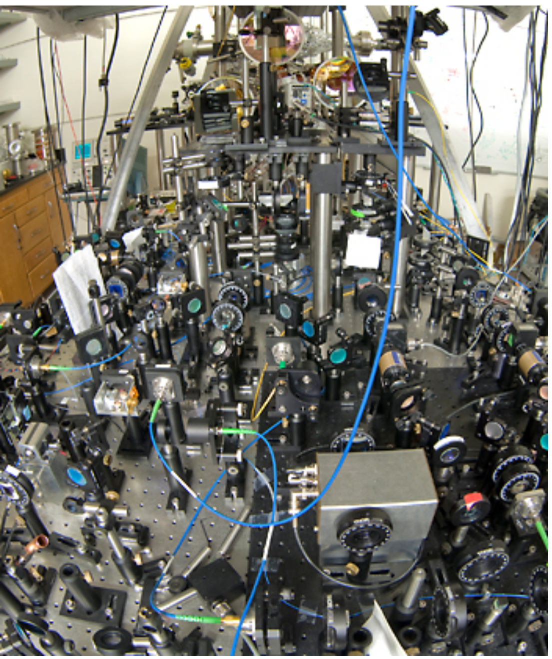


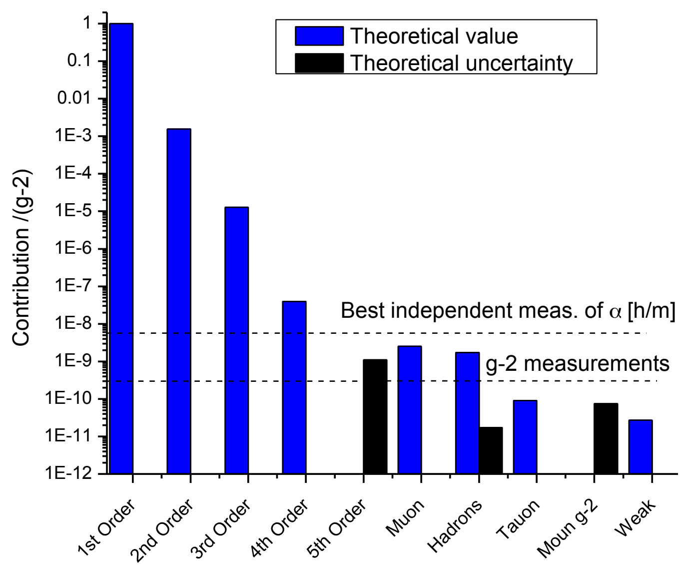
Rev. Mod. Phys. 84, 1527 (**2012**)

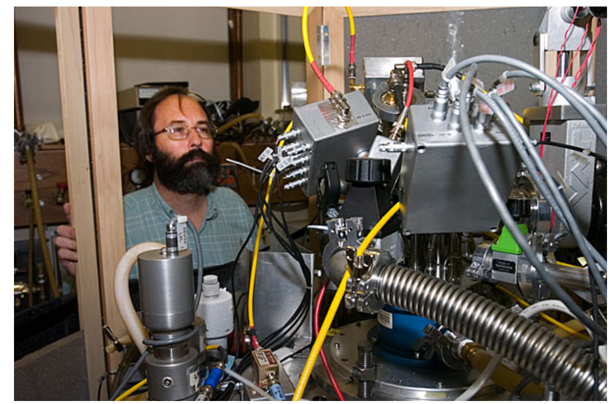
The most precise theory/experiment comparison in science

Fine structure constant

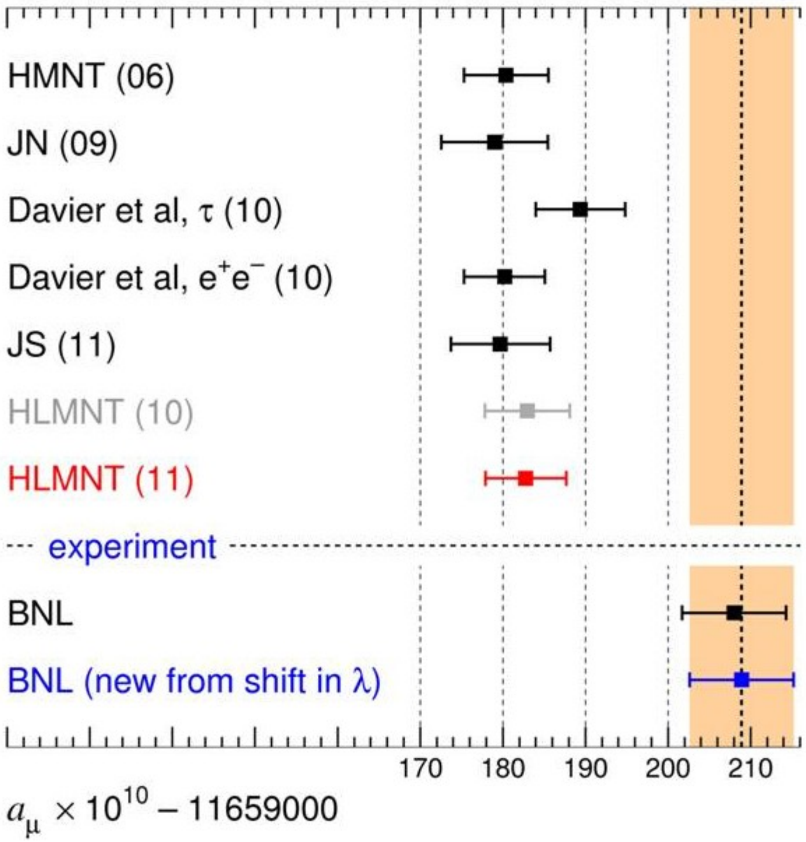
Electron gyromagnetic moment







g-2 and α



Muon g-2 campus at Fermilab

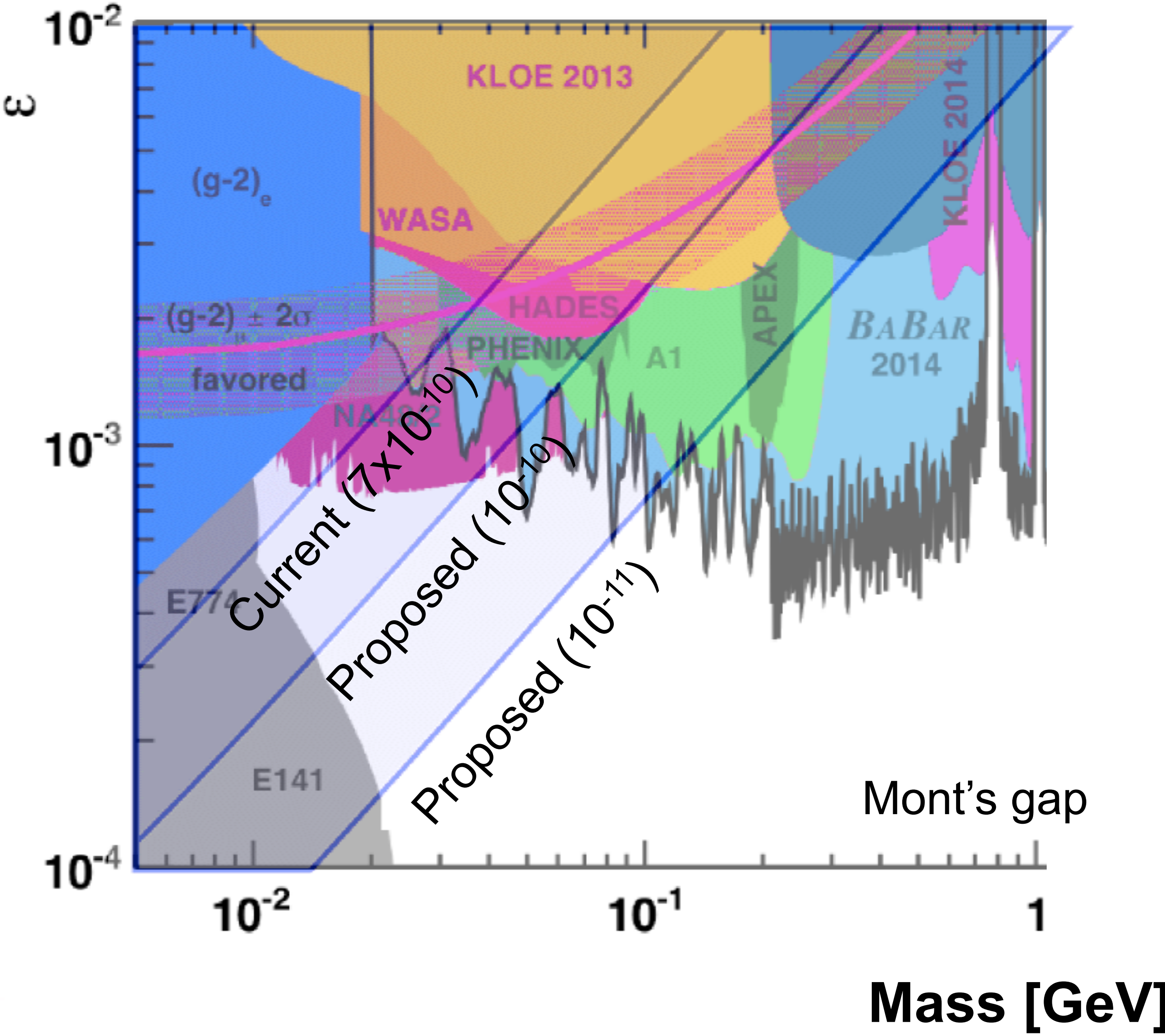
$$3\times10^{-6}\times\left(\frac{m_e}{m_\mu}\right)^2 = 0.07\text{ppb}$$

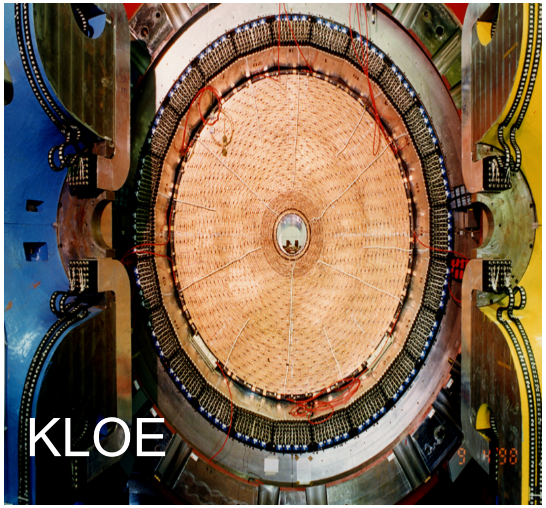
Can be tested in next-generation measurement of α and g_e-2

Dark matter candidatess such as dark photons

Sensitive up to energy scales m~ $[m_e/(10^{-10})]^{1/2}$~100 GeV

Dark photon searches

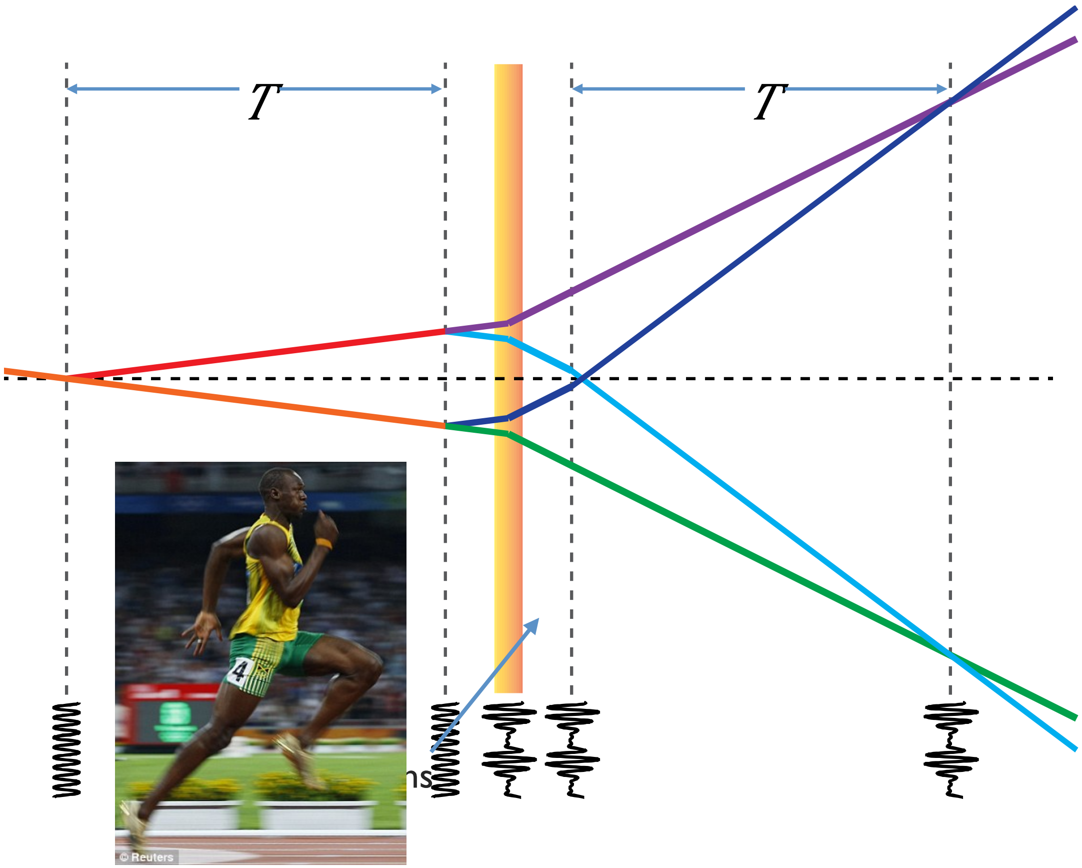


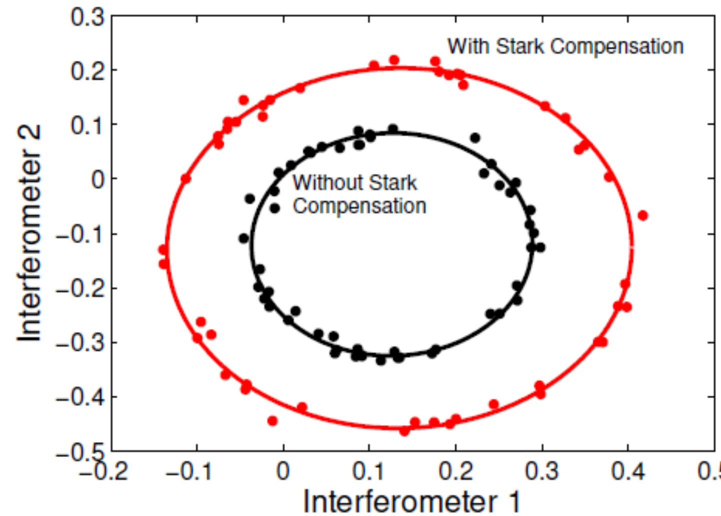


Atom-interferometer measurement of α

$$\Delta\phi = 16n(n+N)(\hbar k^2/2m)T$$

$$hcR_\infty = \frac{1}{2}\alpha^2 m_e c^2$$

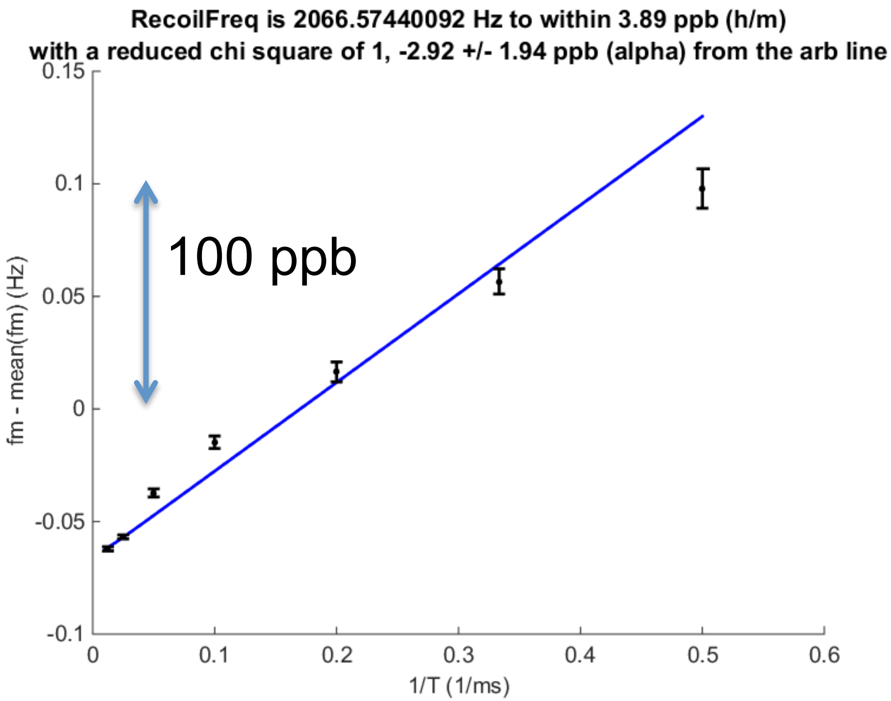




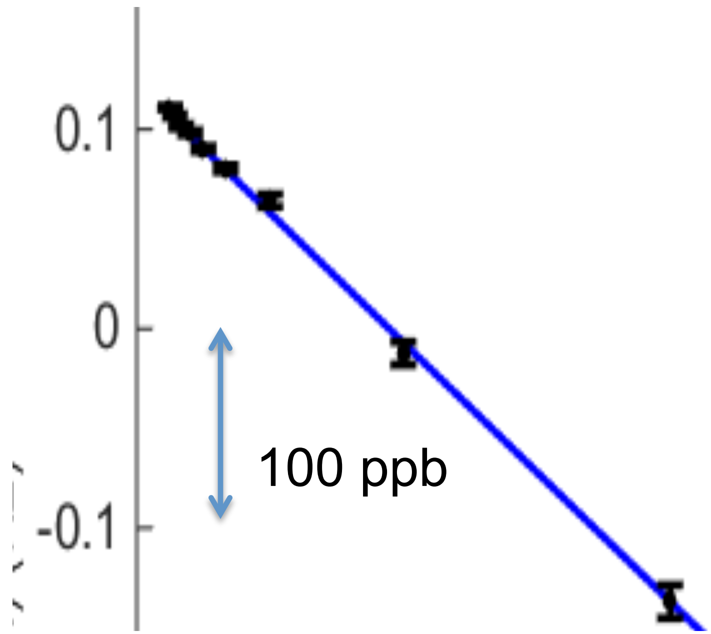
Now >800 photon kicks

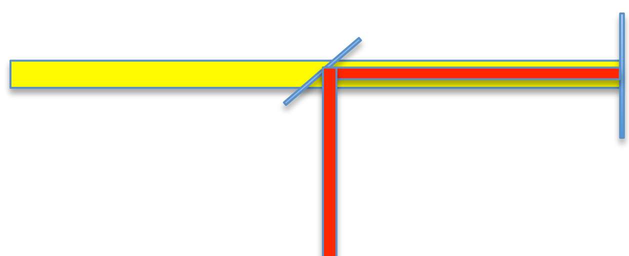
Controlling systematics at 10^{-10}

Before filtering



With spatial filtering

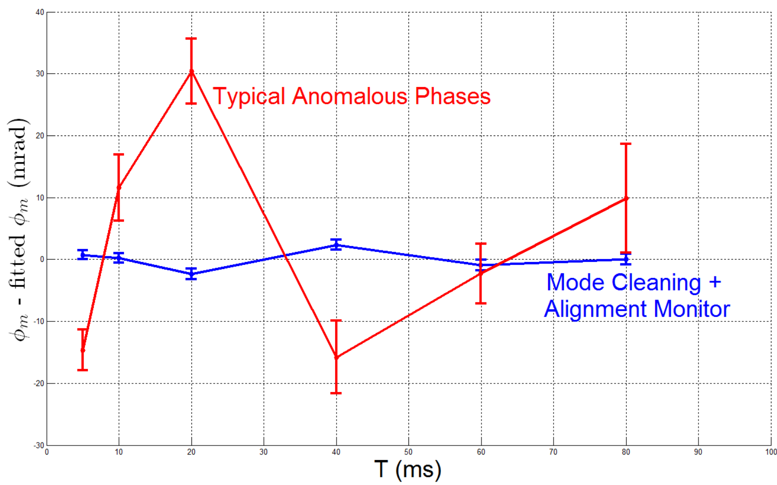




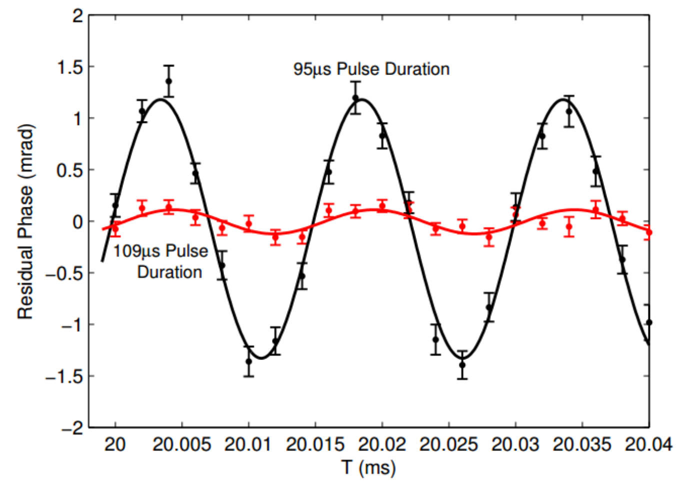
Spatial Filtering Beam

Estey et al, PRL (2015)

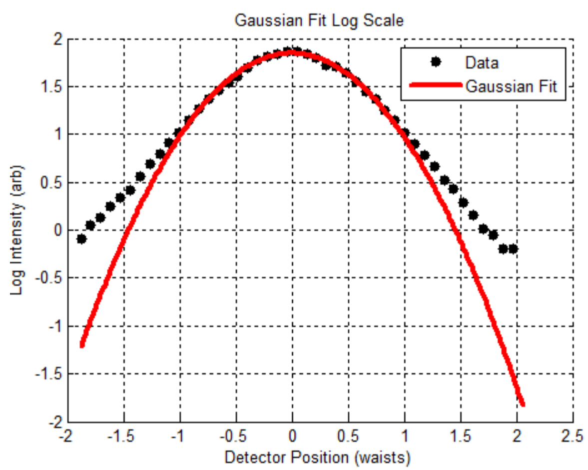
Control of systematic errors



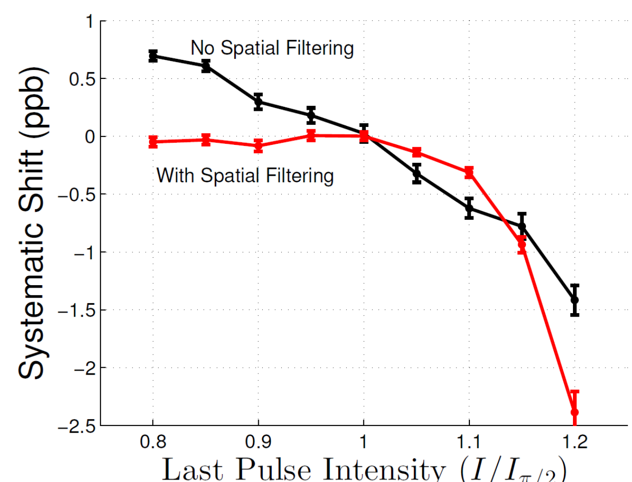
Shifts from beam distortions



Parasitic interferometers

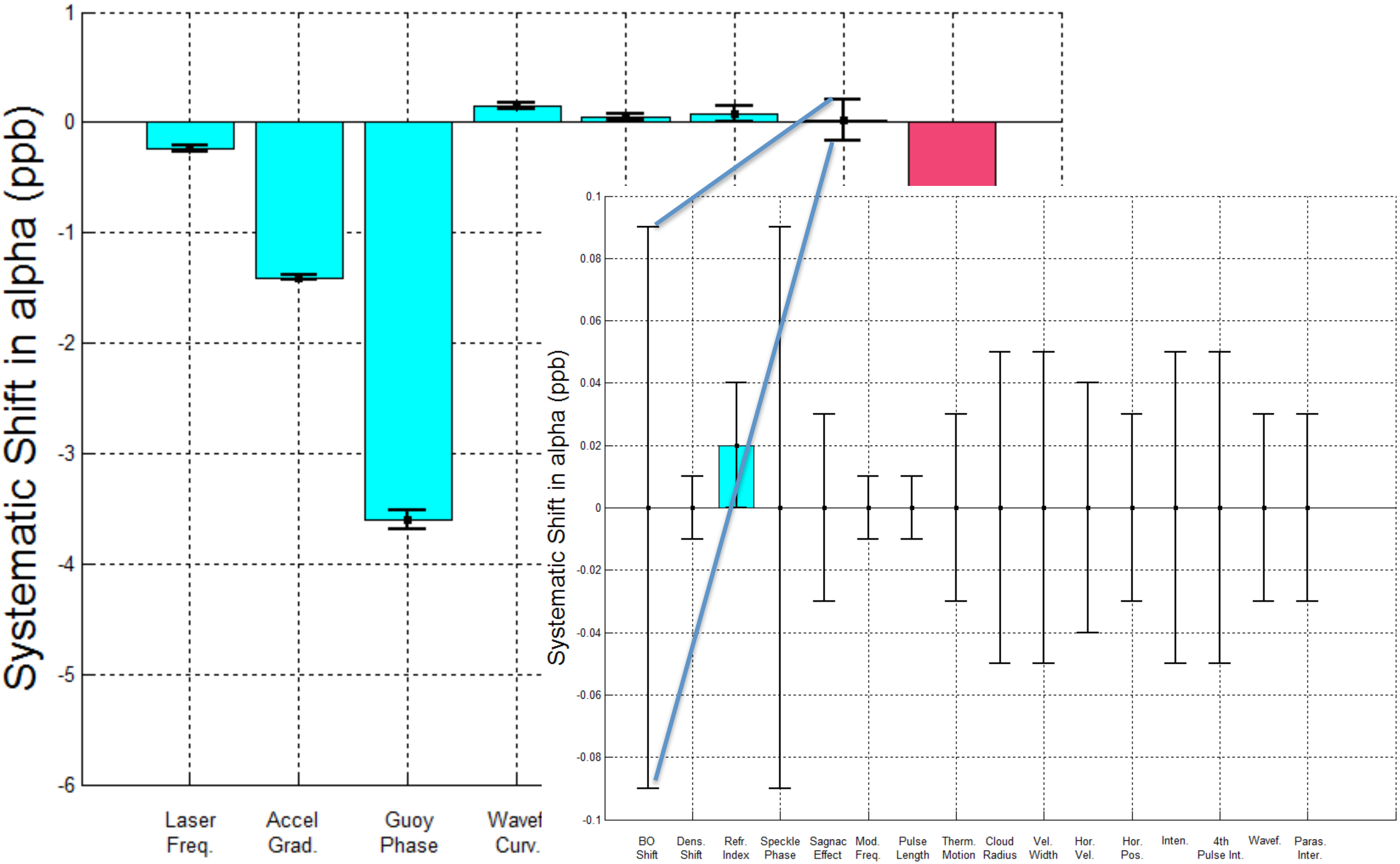


Beam distortions



Cloud size

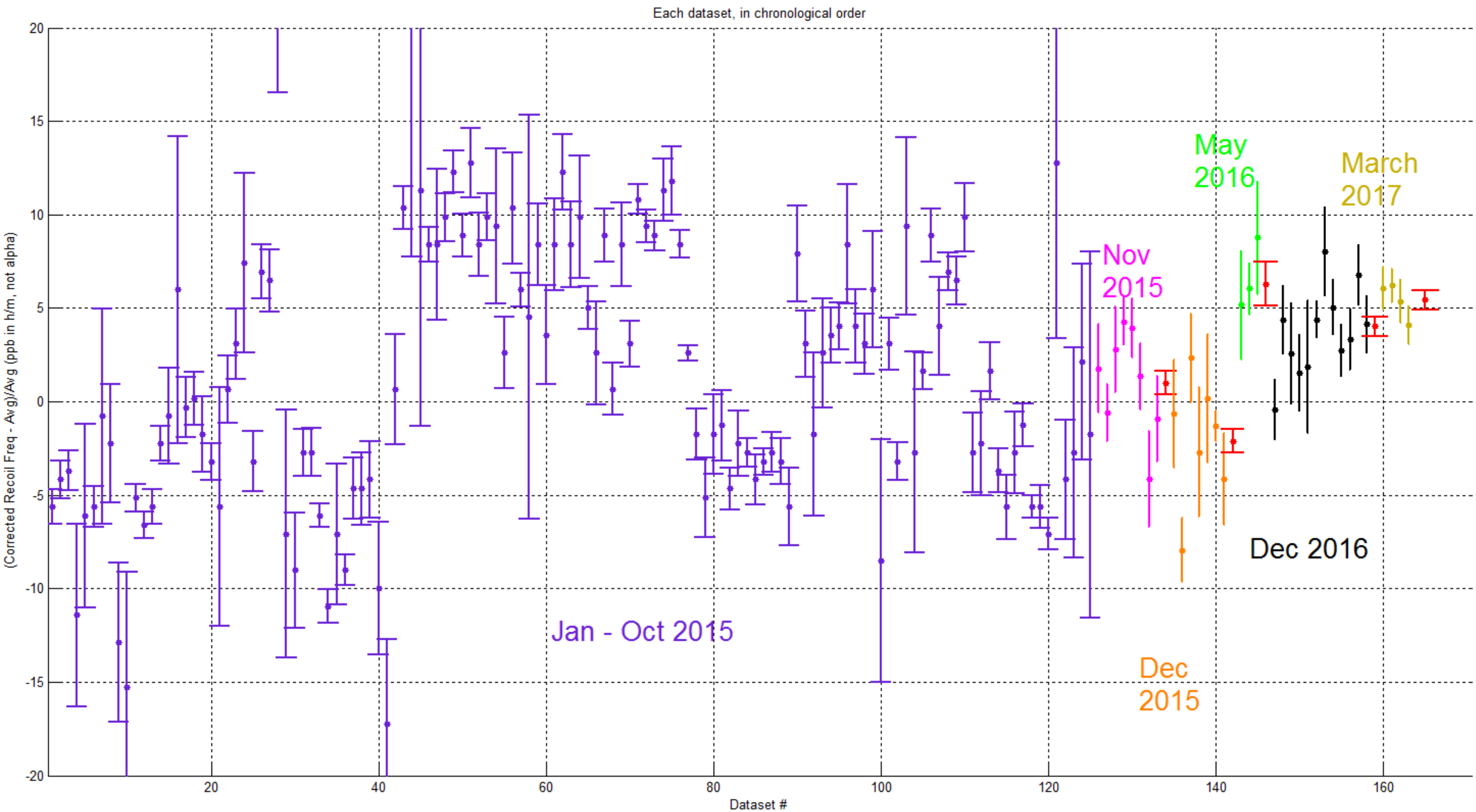
0.15 ppb error budget



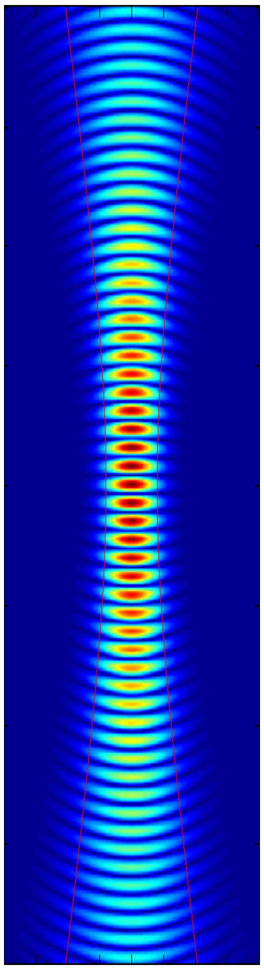
Blinding strategy

- Laser frequency: actual value hidden
- Default value used instead
- Three numerical codes will be created that should yield equal results

Overview of blinded data



A more nearly perfect laser beam



- Infinite plane wave: λ=c/v, uniform intensity
- Wavelength errors ~$(\lambda/\text{radius})^2$
- Beam splitter losses ~$(\lambda/\text{radius})^4$
- 20x radius =>
  - 400-fold lower errors: higher accuracy
  - 160,000-fold lower losses: higher momentum transfer, and thus sensitivity

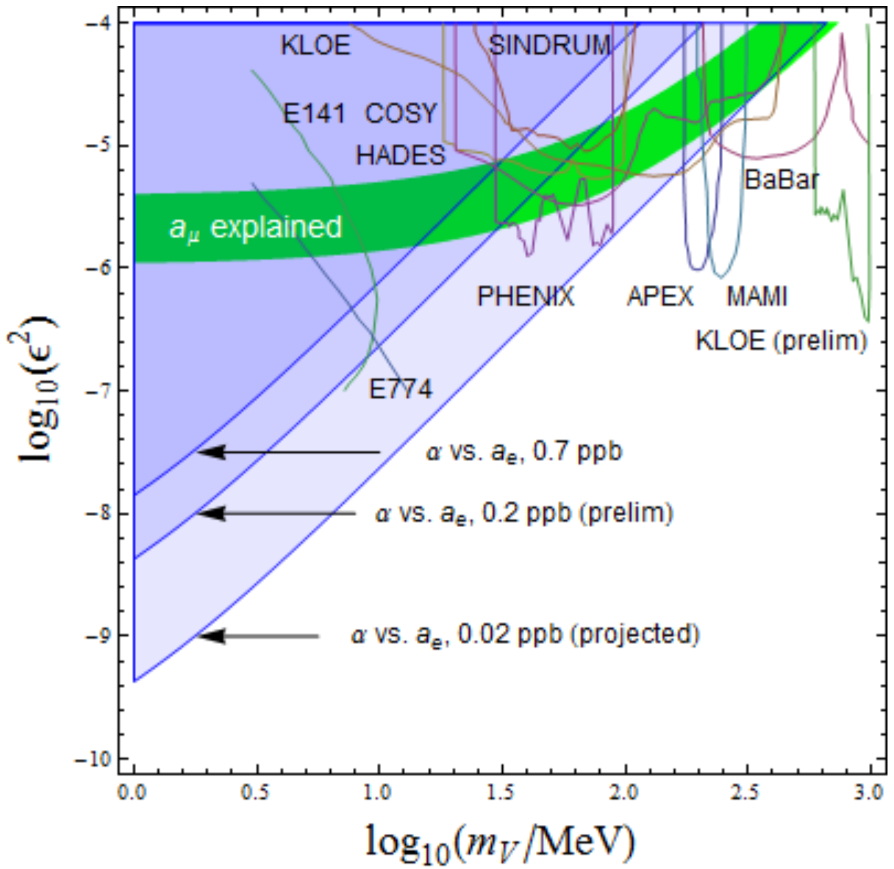
Summary

- Intellectual phase lock may be less widespread
- Other problems: politics, egos, vanity
- Blind analysis forces you to take data seriously
- Questions: how to unblind?

- Overarching goal should be to avoid errors

- Precision measurements are long-term projects.

- Culture of Care required



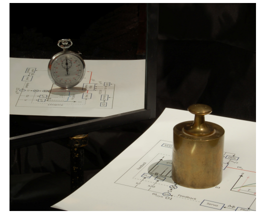
Thanks

- Patrichia Burchardt
- Steve Chu
- Dave DeMille
- Gerald Gabrielse
- Richard Parker
- Steve Quake

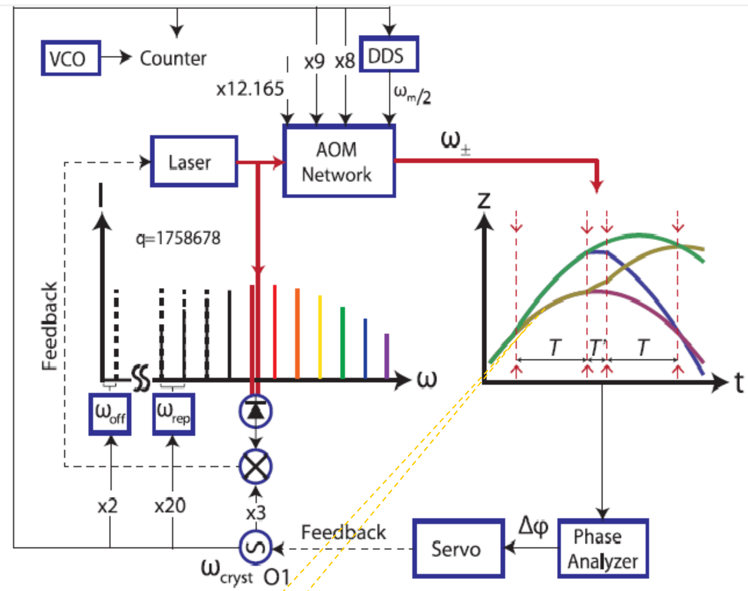
REPORTS

Science AAAS

A Clock Directly Linking Time to a Particle's Mass



Lan et al., Science **339,** 554 (2013)



$$\omega = \frac{1}{2nN^2}\frac{mc^2}{\hbar}$$

Key insight / innovation

- Feedback over atom interferometer using frequency comb
- Comb multiplies by N
- n-photon momentum transfer
- Clock frequency ~100 kHz= $(mc^2/h)/(2nN^2)$, exactly

Technology impact

- A single particle is useful as a time/frequency reference
- Cesium atom used as approximation of a point mass
- 4 ppb accuracy demonstrated, < 1 ppb feasible

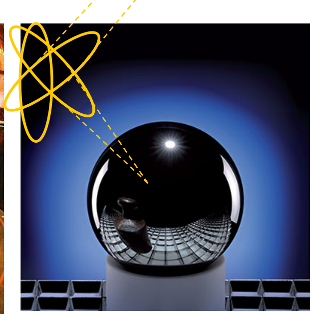
Application

- Mass standard in new SI where h and c are defined, kg measured
- With elementary (anti-) particles => equivalence principle with antimatter
- Light nanomechanical objects => mesoscopic mass standard

Watt balance

- 33 ppb for amu
- 33 ppb for kg
- Moving parts, gravity, standard resistors…
- Americans and Europeans disagree

Atom interferometer+counting



- 4 ppb for amu
- 30 ppb for kg
- No moving parts, gravity, standard resistors…
- Agrees with European versions
- <1 ppb in the future

Independent methods realize the same definition ☺