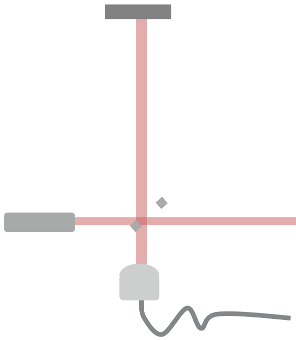
Measuring the Fine Structure Constant with Atom Interferometry

Zachary Pagel
Holger Müller Group
University of California, Berkeley

Introduction: light pulse atom interferometry

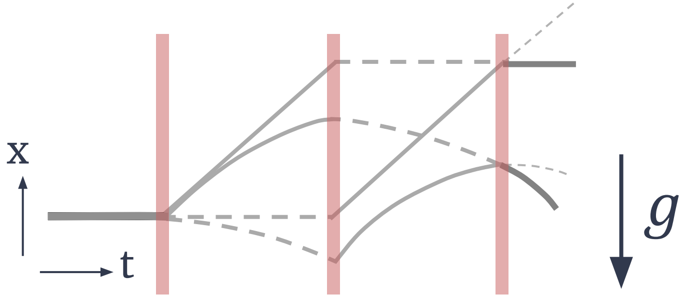
Laser interferometer (e.g., LIGO):

- *Coherent source* = Laser
- *Manipulation* = Material objects
  - Beam-splitters, mirrors



Atom interferometer (e.g., us):

- *Coherent source* = Matter-waves
- *Manipulation* = Laser diffraction gratings



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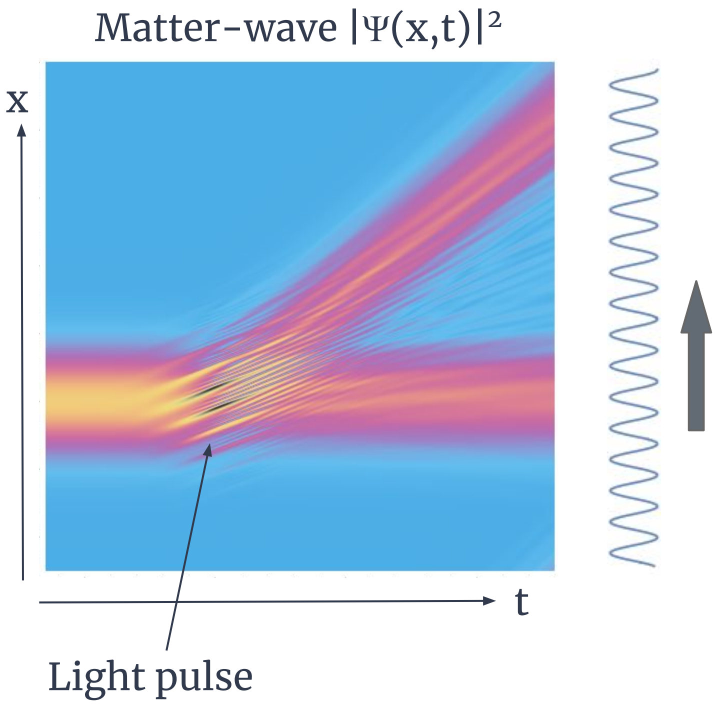
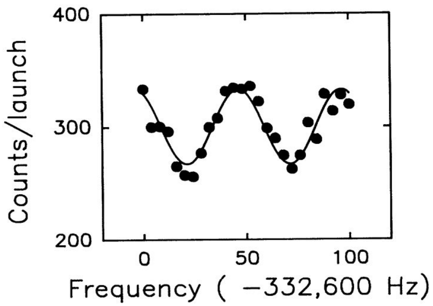


Introduction: light pulse atom interferometry

Atomic Interferometry Using Stimulated Raman Transitions

Mark Kasevich and Steven Chu

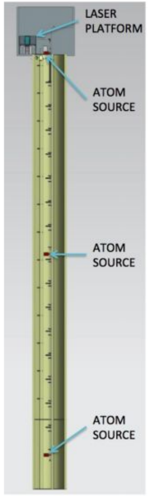


T~10 msec
(1991)

10m Atomic Fountains

T~2 s
(2010)

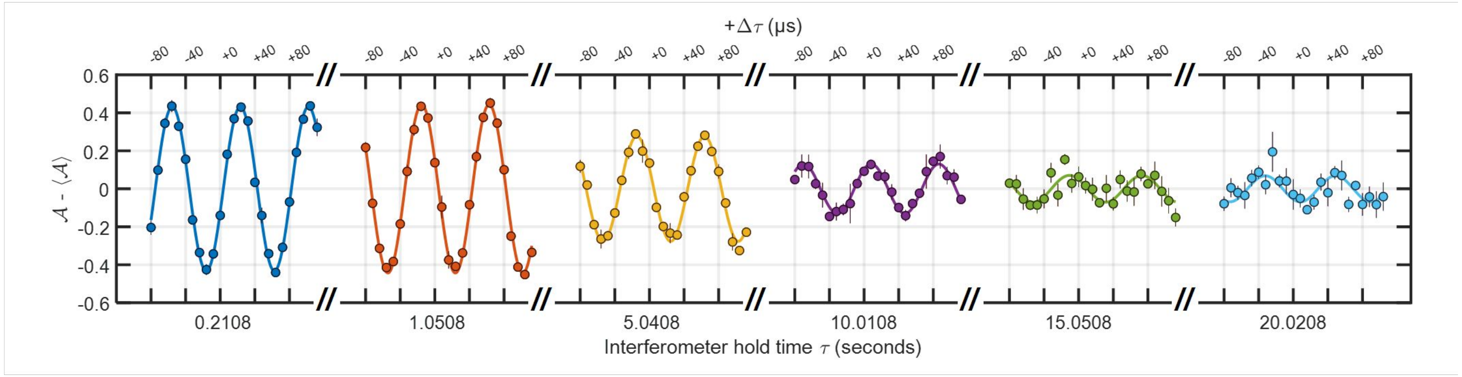
100m GW Detector
“MAGIS100”



T ≤ 10 s
(2020?)

Introduction: light pulse atom interferometry

20 second atom interferometer in an optical cavity [2]



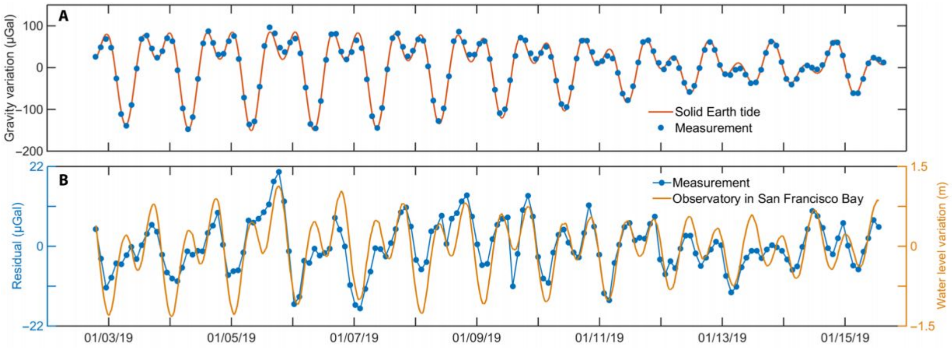
$\Delta\varphi_{free}$ ~ 1.6 Mrad

[2] V. Xu et. al 2019, arxiv:1907.03054v1

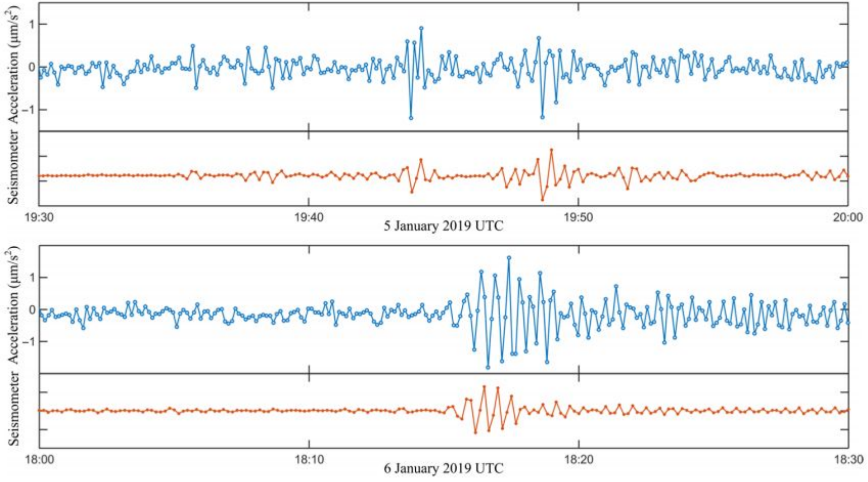
Introduction: light pulse atom interferometry

Portable Precision Gravimetry [1]

Measuring water level in SF Bay



Seismic waves from earthquakes in Brazil and Indonesia



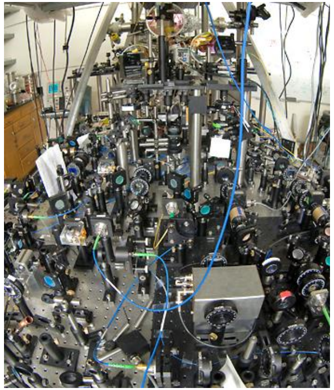
[1] X. Wu et. al 2019, Science Advances 5

Probing physics with alpha

Fine structure constant

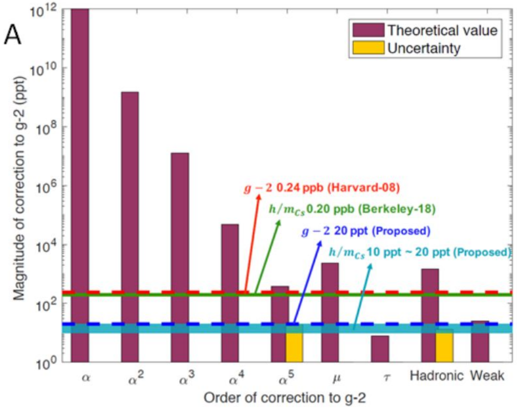
$$hcR_\infty = \frac{1}{2} m_e c^2 \alpha^2$$

$$\alpha = \left[2 \frac{R_\infty}{c} \frac{u}{m_e} \frac{M}{u} \frac{h}{M} \right]^{1/2}$$

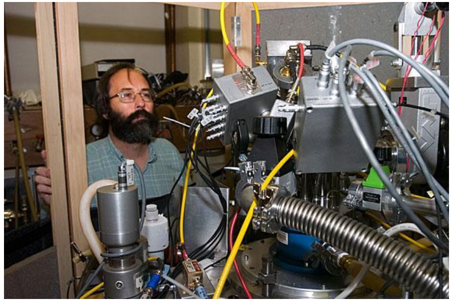


Theory

$$g - 2 = \sum_{n=1} \left(\frac{\alpha}{\pi}\right)^n a_n + a_{weak} + a_{QCD}$$



Electron gyromagnetic moment



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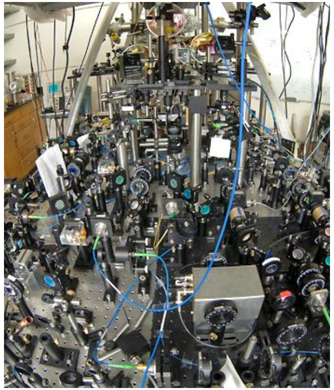

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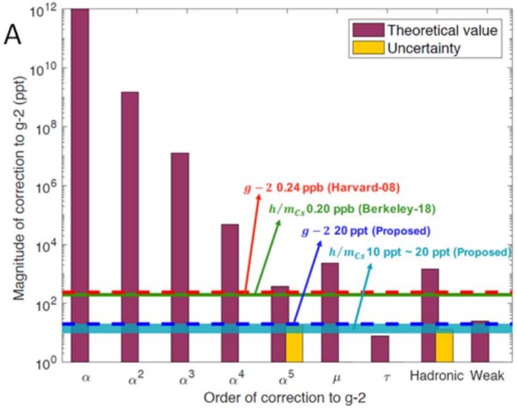

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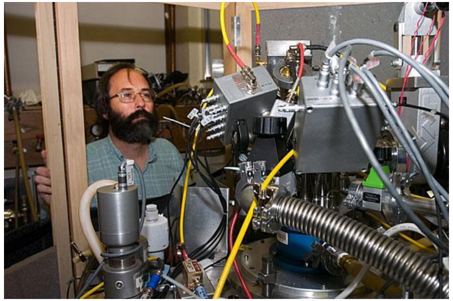

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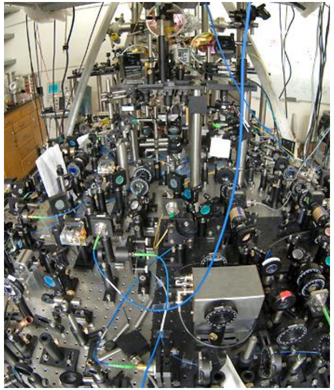

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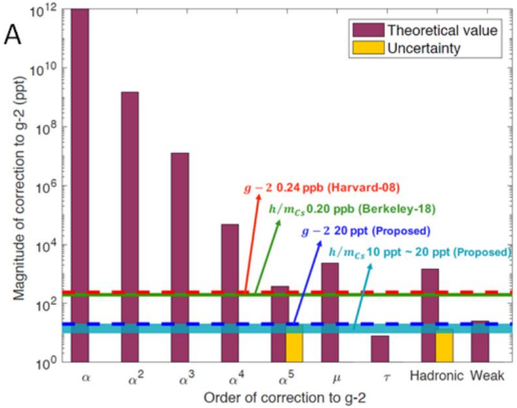
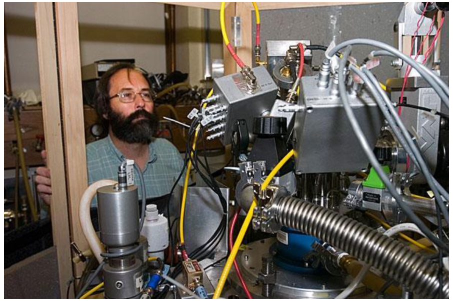


Electron gyromagnetic moment

BSM physics can shift magnetic moment versus fine structure constant



Alpha in atom recoil frequency

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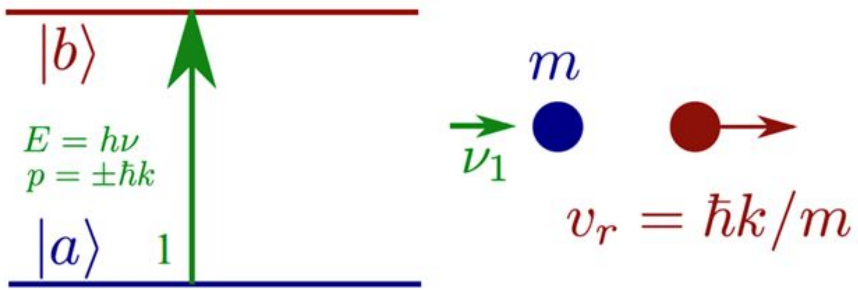
Determined by atom recoil frequency

$$\frac{h}{M} = \frac{4\pi c^2 \omega_r}{\omega^2}$$

Recoil measurement

- Cs D2 transition ~ 352 THz
- ω_r ~ 2 kHz, want 10^{-10} accuracy
- Need to pinpoint resonance to 0.2 μHz or $6x10^{-22}$

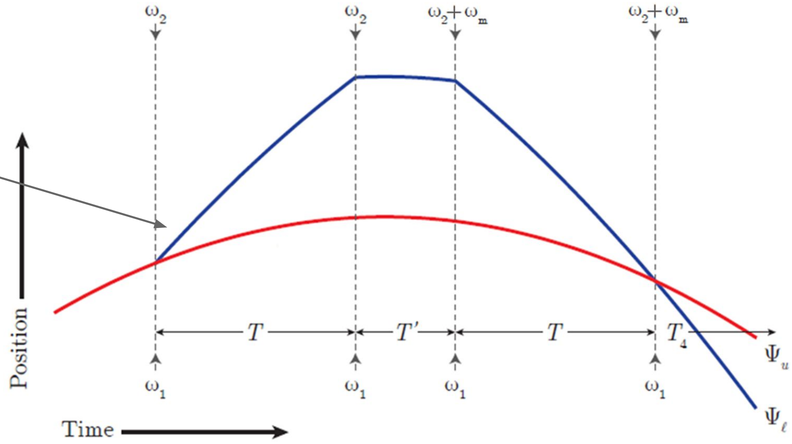


Interferometer geometry

Want to measure recoil kinetic energy

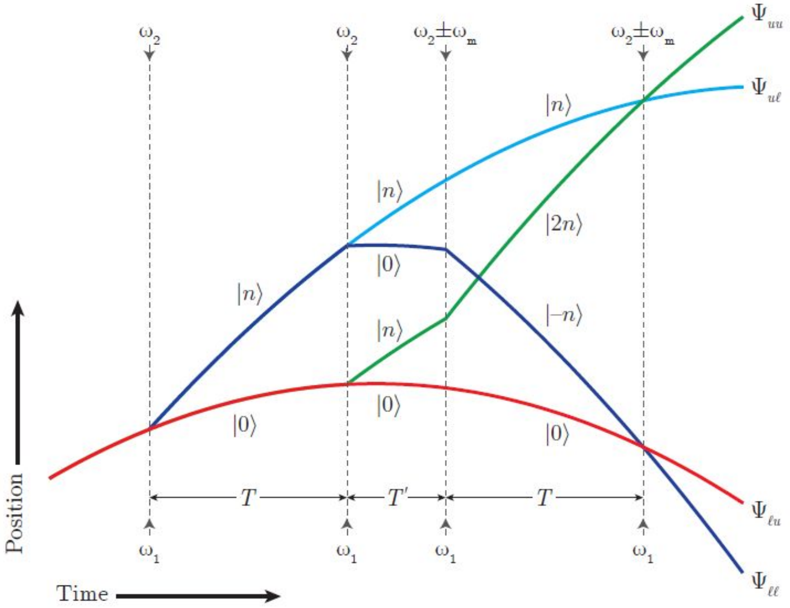
$$\phi(t) = \int_0^t E(t')\,dt'$$

$$\frac{1}{2}mv_r^2 = \hbar\left(\frac{\hbar k^2}{2m}\right) = \hbar\omega_r$$



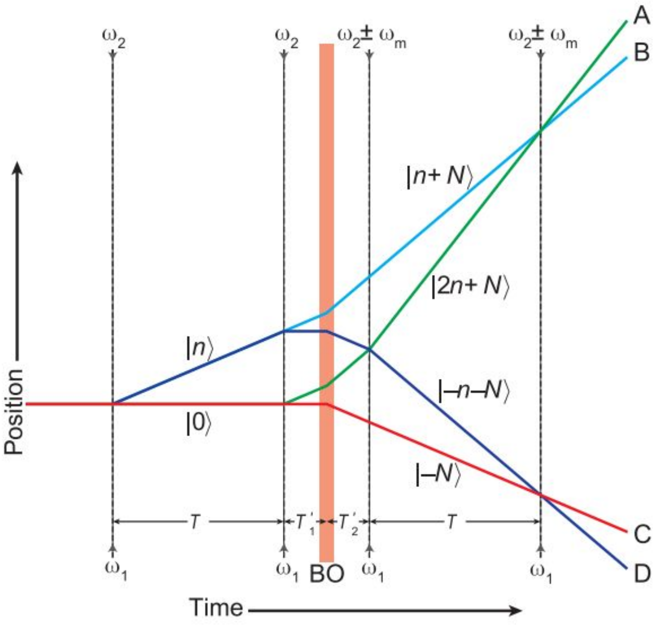
$$\Phi_{RB} = 8n^2\omega_r T - 2nkg(T+T')T - n\omega_m T$$

Interferometer geometry



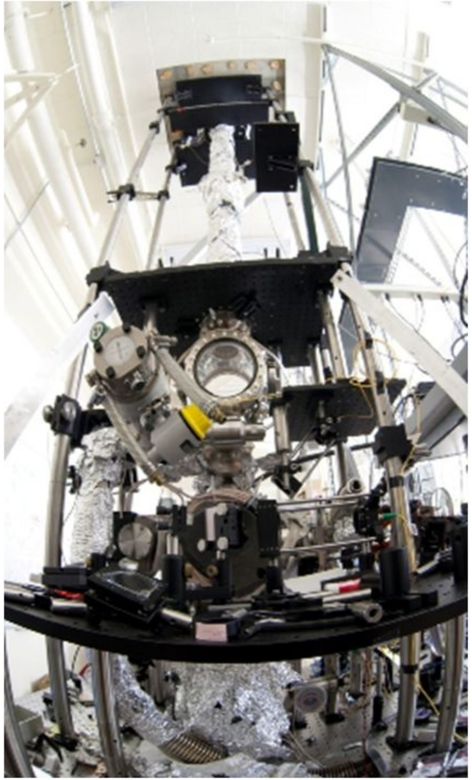
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$

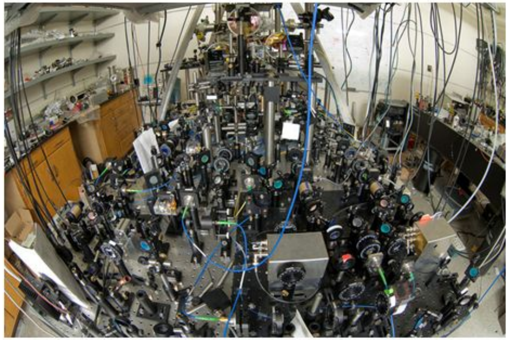
Interferometer geometry

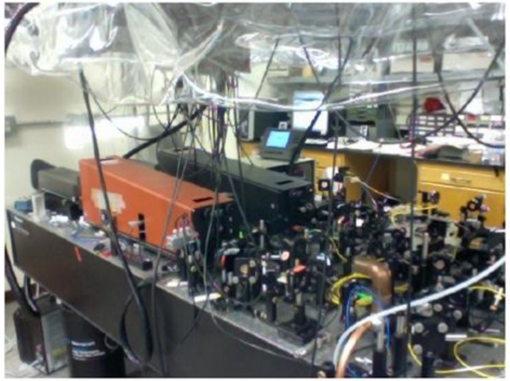


$$\Delta\Phi_{tot} = 16n(n+N)\omega_r T - 2n\omega_m T$$

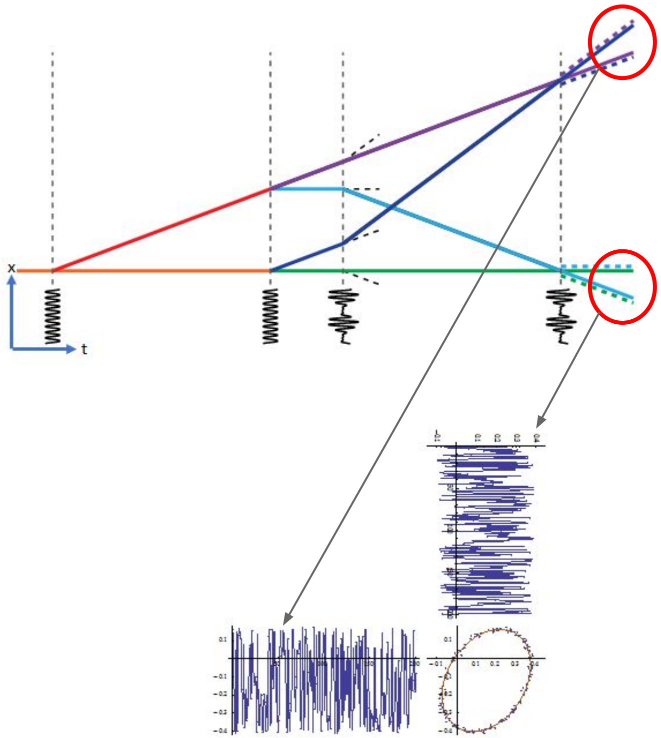
Experimental apparatus

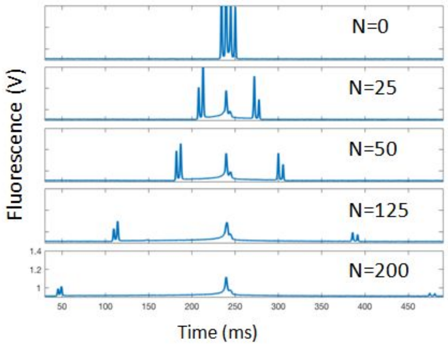


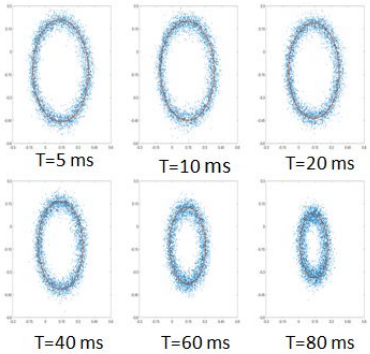


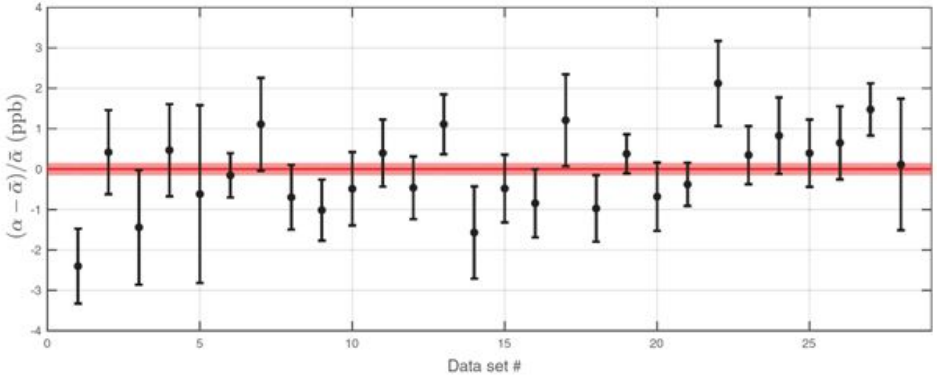


Extracting signal

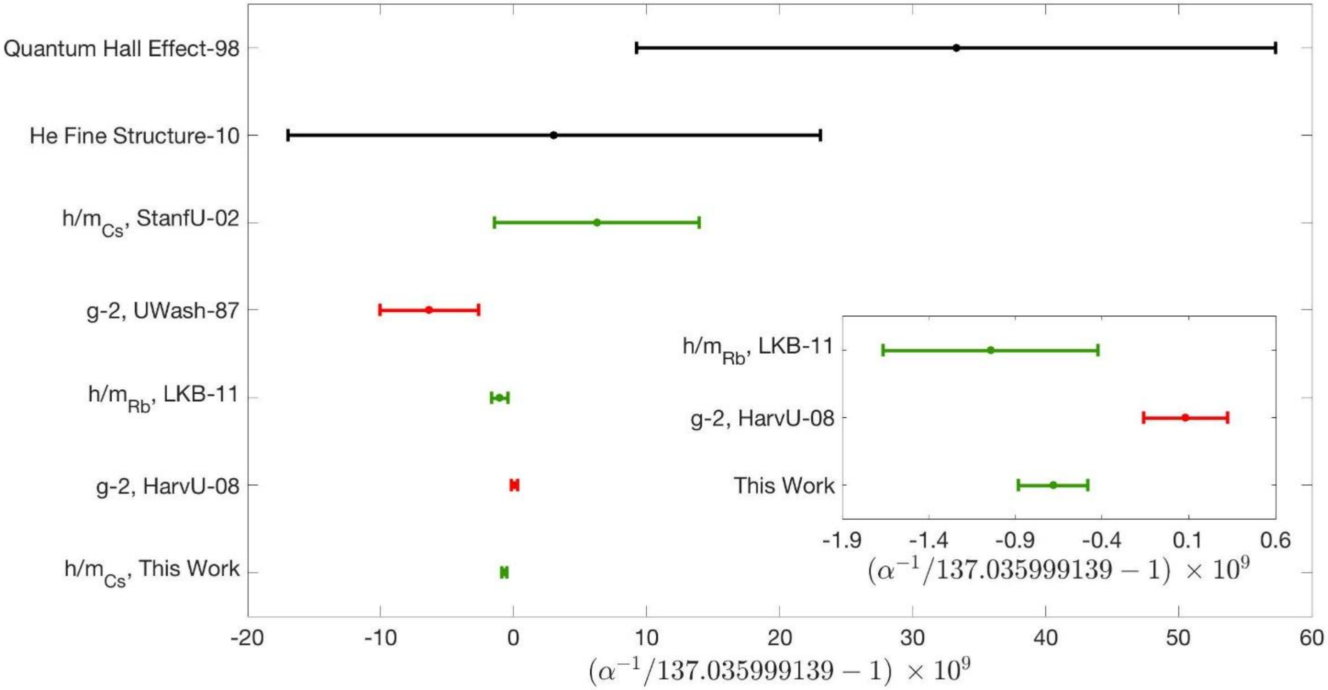








Unblinding Alpha (2018)



[4] R. Parker et. al 2018, Science 360, 6385

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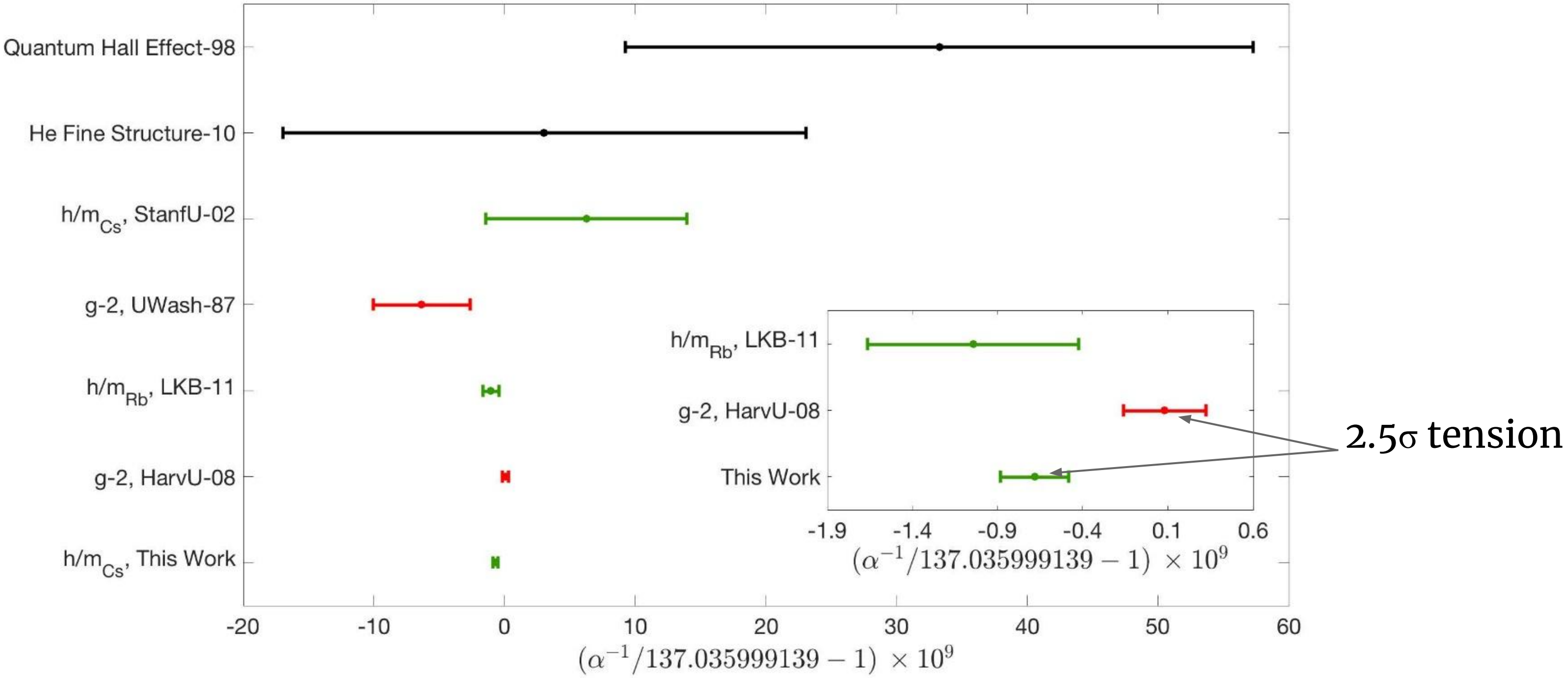

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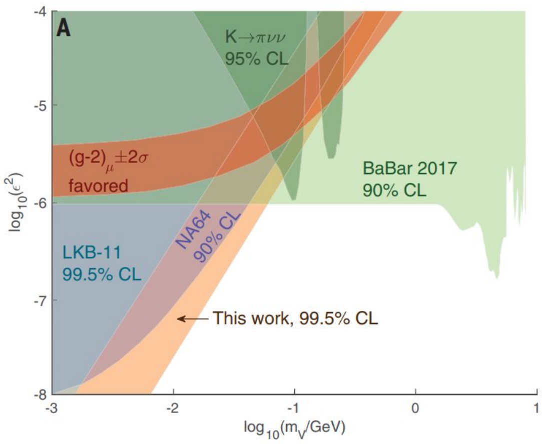
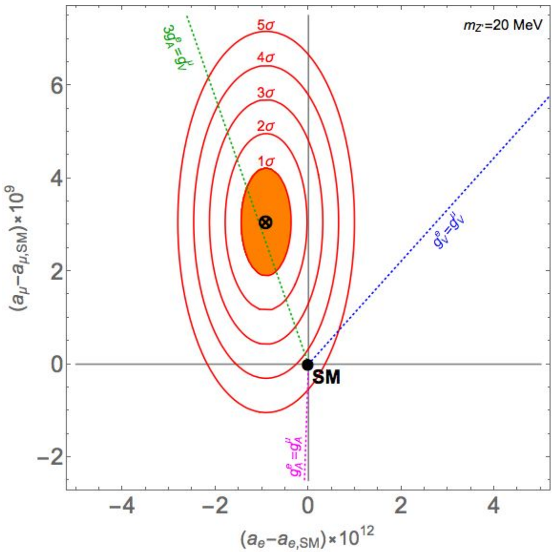
Constraining BSM Physics

Dark photons



Constraining BSM Physics

Combine with $g_\mu - 2$



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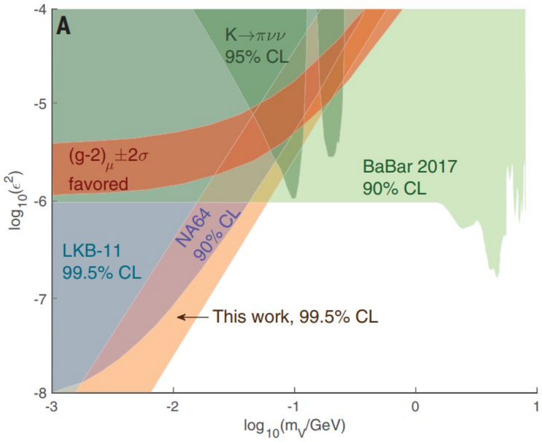

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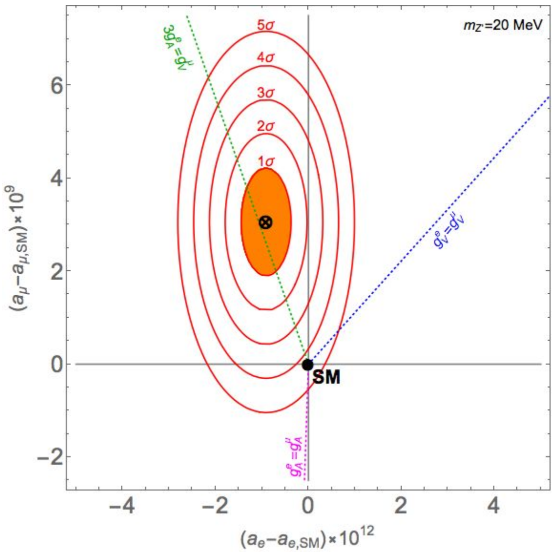

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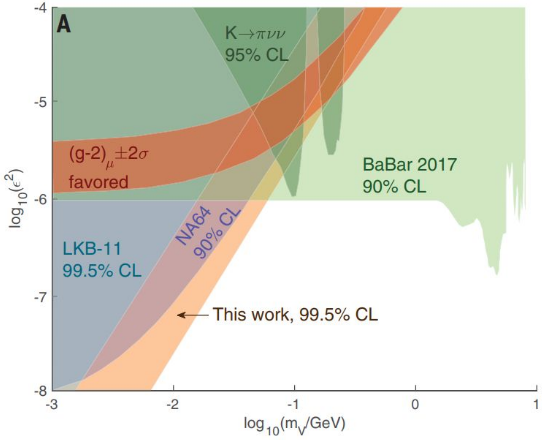
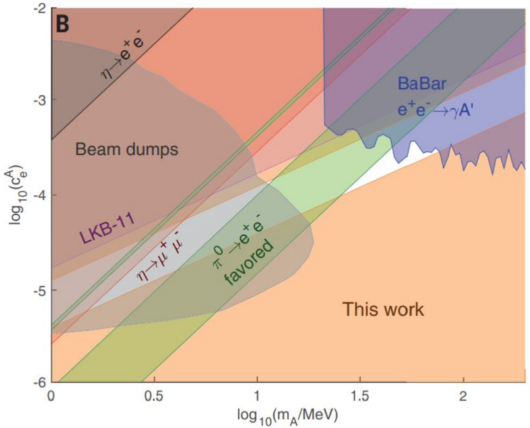


Dark axial vectors



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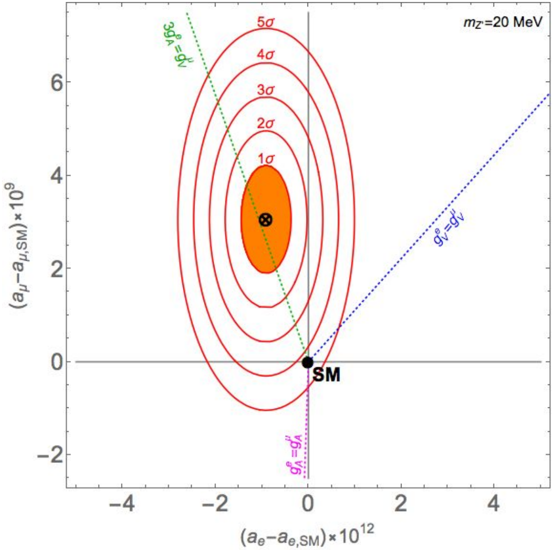
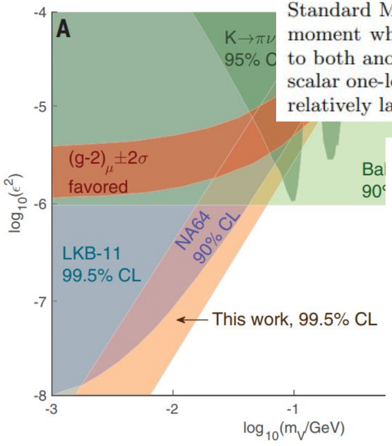


Dark p



A Tale of Two Anomalies

Hooman Davoudiasl *[1] and William J. Marciano †[1]

[1] *Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*

A recent improved determination of the fine structure constant, $\alpha = 1/137.035999046(27)$, leads to a $\sim 2.4\sigma$ negative discrepancy between the measured electron anomalous magnetic moment and the Standard Model prediction. That situation is to be compared with the muon anomalous magnetic moment where a positive $\sim 3.7\sigma$ discrepancy has existed for some time. A single scalar solution to both anomalies is shown to be possible if the two-loop electron Barr-Zee diagrams dominate the scalar one-loop electron anomaly effect and the scalar couplings to the electron and two photons are relatively large. We also briefly discuss the implications of that scenario.

A light complex scalar for the electron and muon anomalous magnetic moments

Jia Liu,[1] Carlos E.M. Wagner,[1,2,3] and Xiao-Ping Wang[2]

[1] *Physics Department and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*

[2] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439*

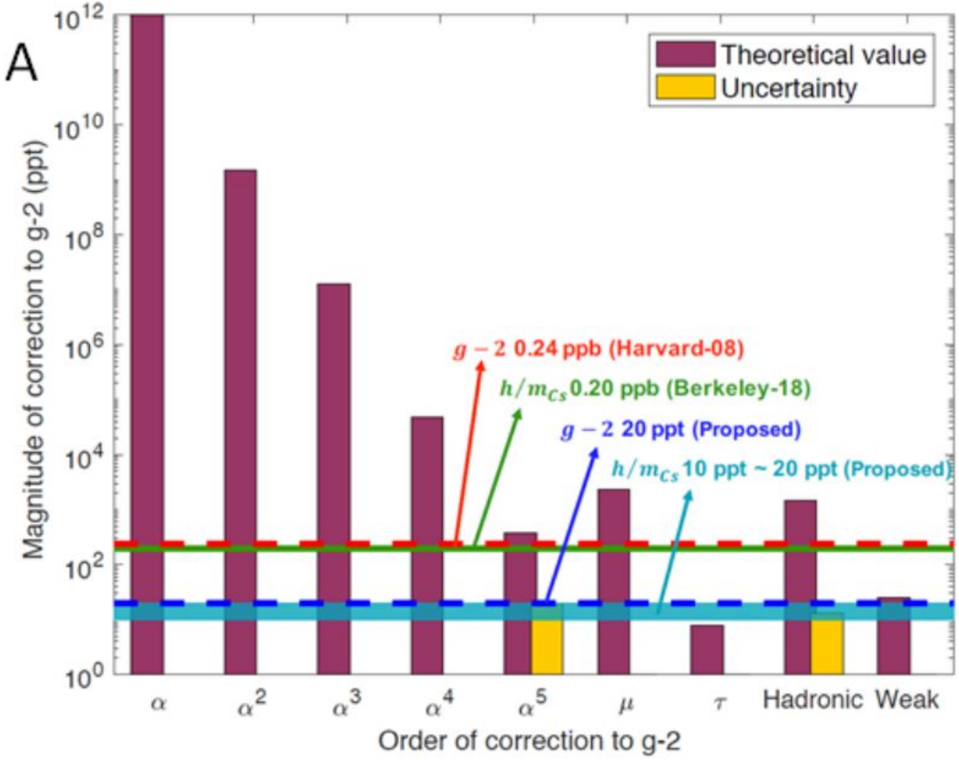
[3] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637*

(Dated: February 26, 2019)

Abstract

The anomalous magnetic moments of the electron and the muon are interesting observables, since they can be measured with great precision and their values can be computed with excellent accuracy within the Standard Model (SM). The current experimental measurement of this quantities show

Testing Standard Model



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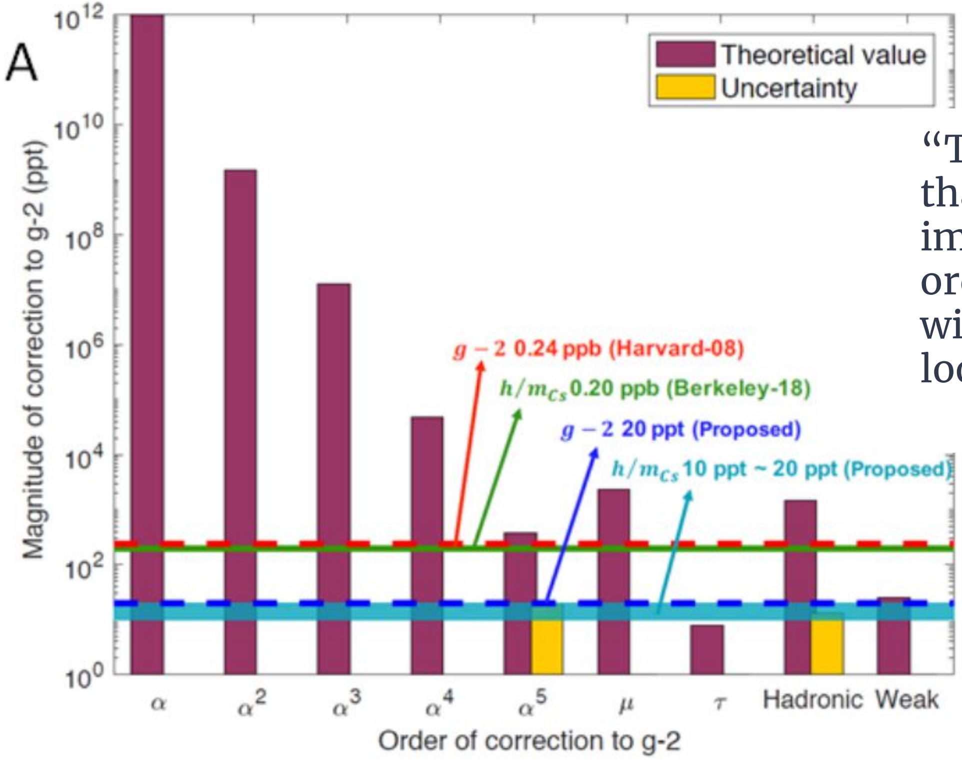


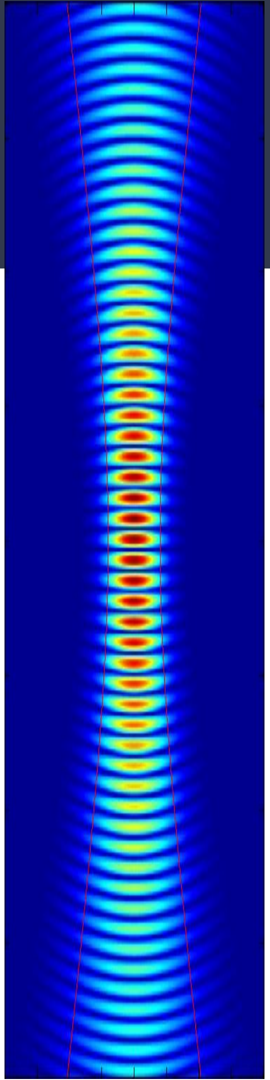
"The biggest worry is that, if the accuracy improves by another two orders of magnitude, we will need to calculate six loop QED corrections…"

Systematic errors

Effect	Value	$\delta\alpha/\alpha$ (ppb)
Laser Frequency	N/A	-0.24 ± 0.03
Acceleration Gradient	$\gamma=(2.13 \pm 0.01)\times10^{-6}/s^2$	-1.69 ± 0.02
Gouy phase	$w_0=3.21\pm0.008$ mm, $z_0=0.5\pm1.0$ m	-3.60± 0.03
Wavefront Curvature	$\langle r^2\rangle^{1/2}=0.58$ mm	0.15 ± 0.03
Beam Alignment	N/A	0.05 ± 0.03
Index of Refraction	$n_{cloud}-1=30\times10^{-12}$	0 ± 0.03
Speckle Phase Shift	N/A	0 ± 0.04
Thermal Motion of Atoms	N/A	0 ± 0.08
Non-Gaussian Waveform	N/A	0 ± 0.03
Parasitic Interferometers	N/A	0 ± 0.03
Total Systematic Error		-5.33 ± 0.12
Total Statistical Error		± 0.16
Electron Mass (18)	$5.48579909067\times10^{-4}$ u	± 0.02
Cesium Mass (4,17)	132.9054519615 u	± 0.03

‘Big’

‘New’



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Larger, cleaner laser beam

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Better measurement/ characterization

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Laser Frequency	N/A	-0.24 ± 0.03
Acceleration Gradient	$\gamma=(2.13 \pm 0.01)\times10^{-6}/s^2$	-1.69 ± 0.02
Gouy phase	$w_0=3.21\pm0.008$ mm, $z_0=0.5\pm1.0$ m	-3.60± 0.03
Wavefront Curvature	$\langle r^2\rangle^{1/2}=0.58$ mm	0.15 ± 0.03
Beam Alignment	N/A	0.05 ± 0.03
Index of Refraction	$n_{cloud}-1=30\times10^{-12}$	0 ± 0.03
Speckle Phase Shift	N/A	0 ± 0.04
Thermal Motion of Atoms	N/A	0 ± 0.08
Non-Gaussian Waveform	N/A	0 ± 0.03
Parasitic Interferometers	N/A	0 ± 0.03
Total Systematic Error		-5.33 ± 0.12
Total Statistical Error		± 0.16
Electron Mass (18)	$5.48579909067\times10^{-4}$ u	± 0.02
Cesium Mass (4,17)	132.9054519615 u	± 0.03

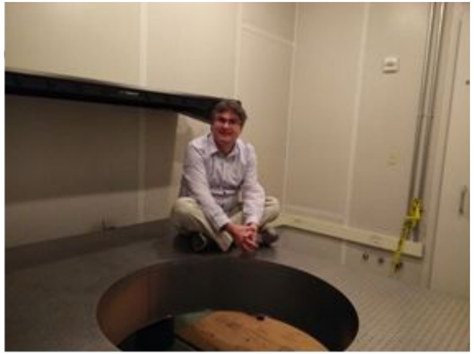
Larger, cleaner laser beam

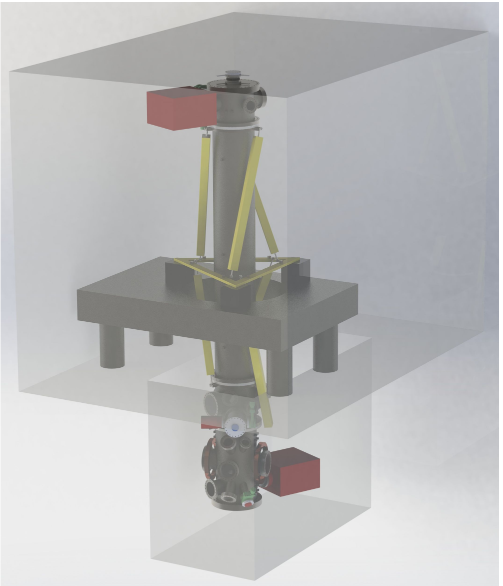
Better measurement/ characterization

Ready for an order of magnitude improvement

Next generation

- New vacuum system
  - 25x larger cross section
  - Simplified fountain alignment
  - Vibration isolation






Next generation

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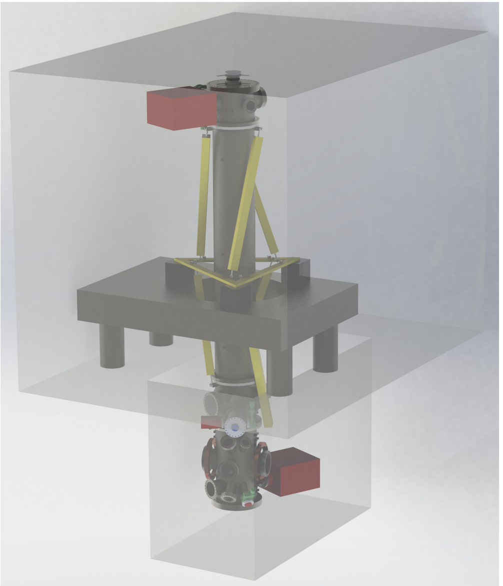
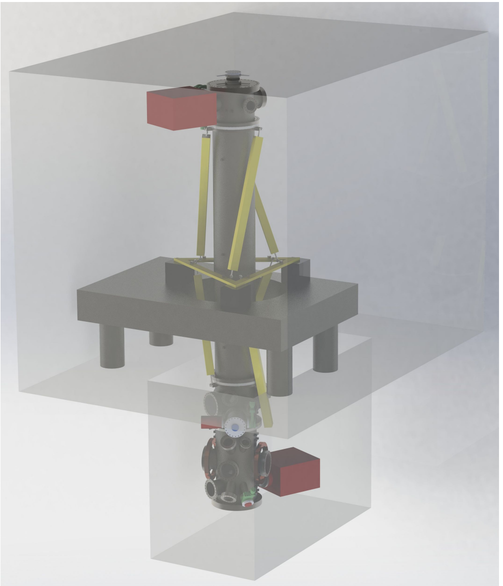


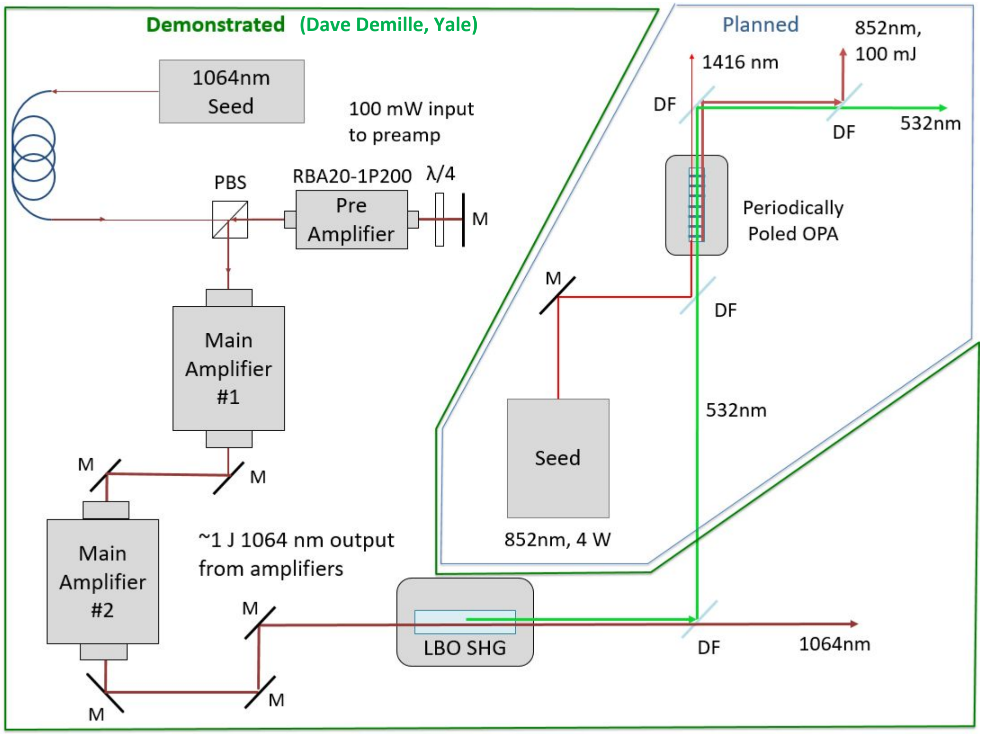
Next generation

- New vacuum system
  - 25x larger cross section
  - Simplified fountain alignment
  - Vibration isolation

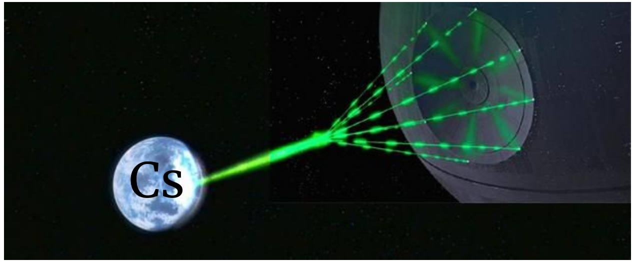
- Collaborating with Lawrence Berkeley National Lab
  - High power fiber experts
  - High-quality CCD imaging
  - Improved Monte Carlo simulations
  - Mechanical engineering



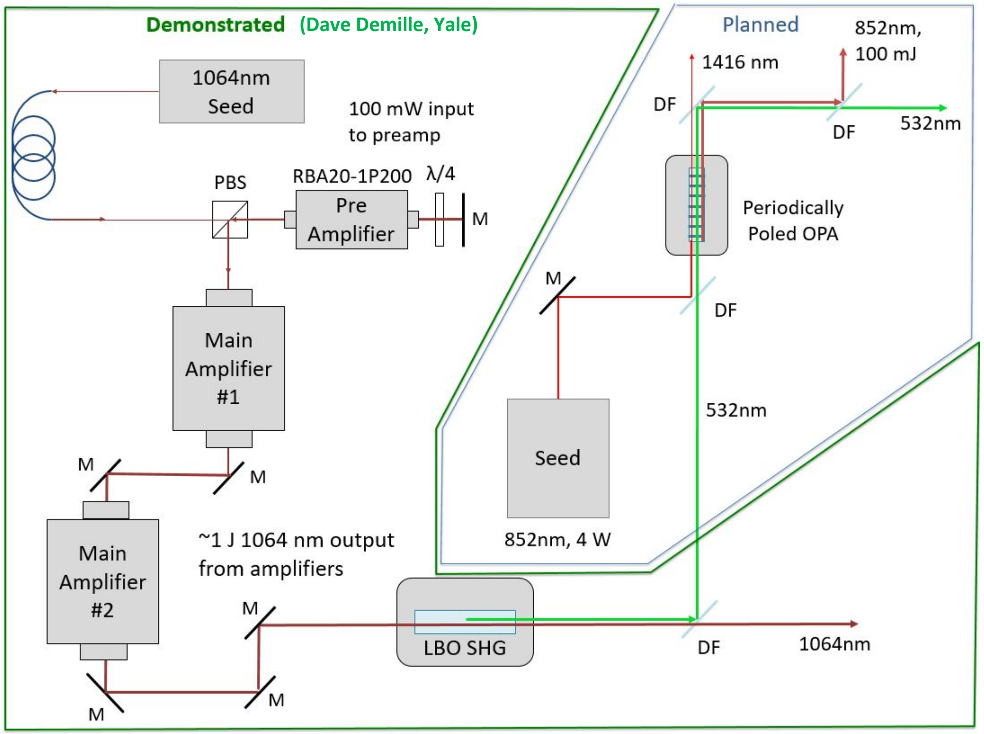
“Death Star” pulsed laser system



Hundreds of watts
peak power to atoms

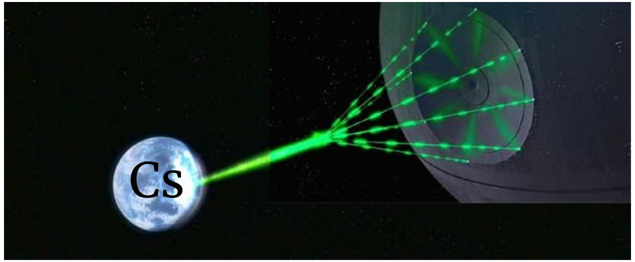


“Death Star” pulsed laser system



State-of-the-art
~5W

Hundreds of watts
peak power to atoms



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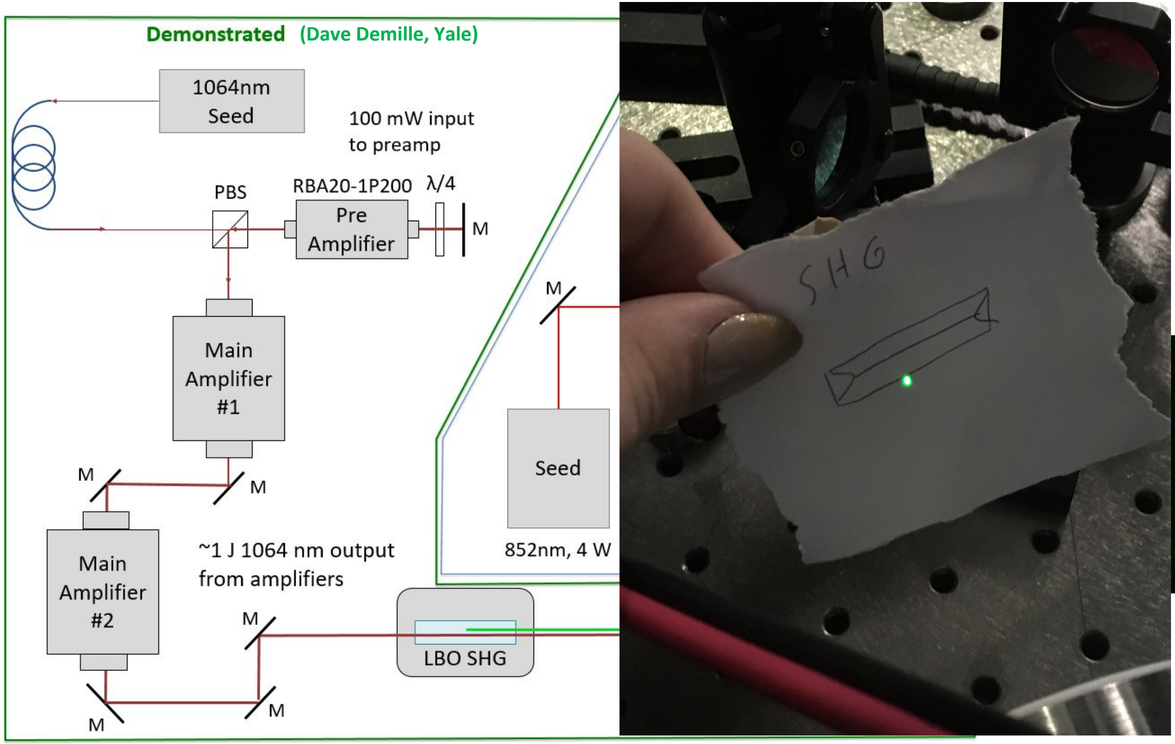

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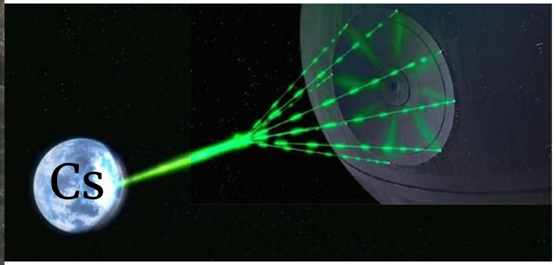
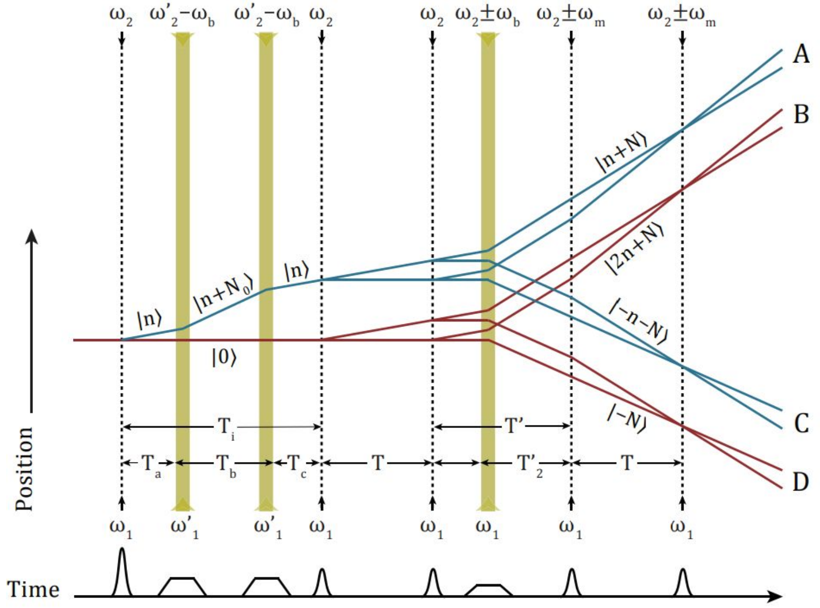


New ideas

Offset interferometers to cancel gravity gradient phase

- GG is one of the largest corrections to our measurement
- GG phase ~ T^3, which limits T of the interferometer

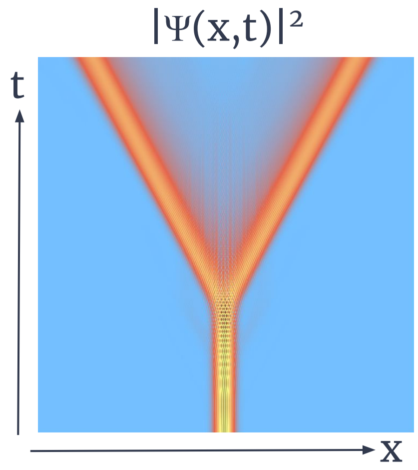


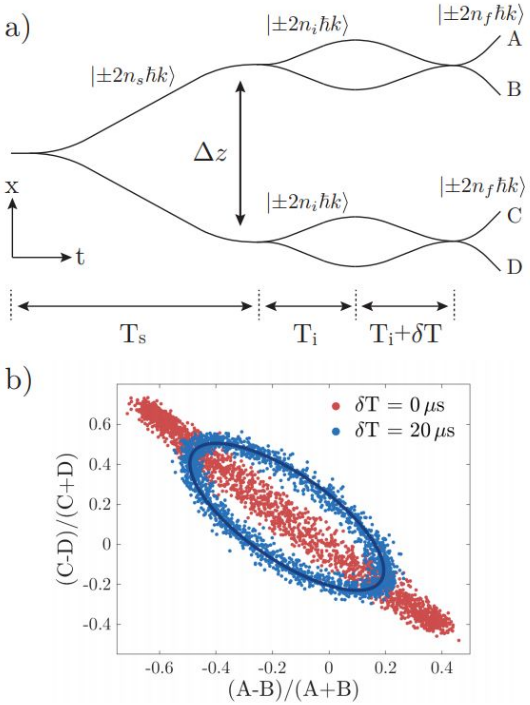
[4] W. Zhong et al 2019, arXiv:1901.03487

New ideas

Symmetric “Bloch beamsplitter” [4]

- Eliminates diffraction phase
- Demonstrated 240ħk momentum transfer

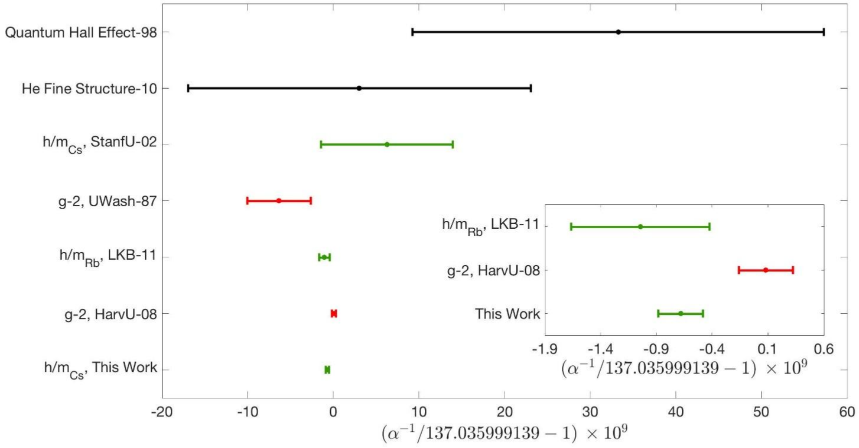




[3] Z. Pagel et al 2019, arXiv:1907.05994

Conclusions

- 2018 measurement at 0.2 ppb level
- Moving forward with next generation measurement
    - "We're not reinventing the wheel"
    - Improved laser beam quality
    - Higher power pulsed laser
    - Simplified fountain alignment
    - Collaboration with LBNL
- New ideas for cancelling gravity gradient, improving sensitivity



Thanks!

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