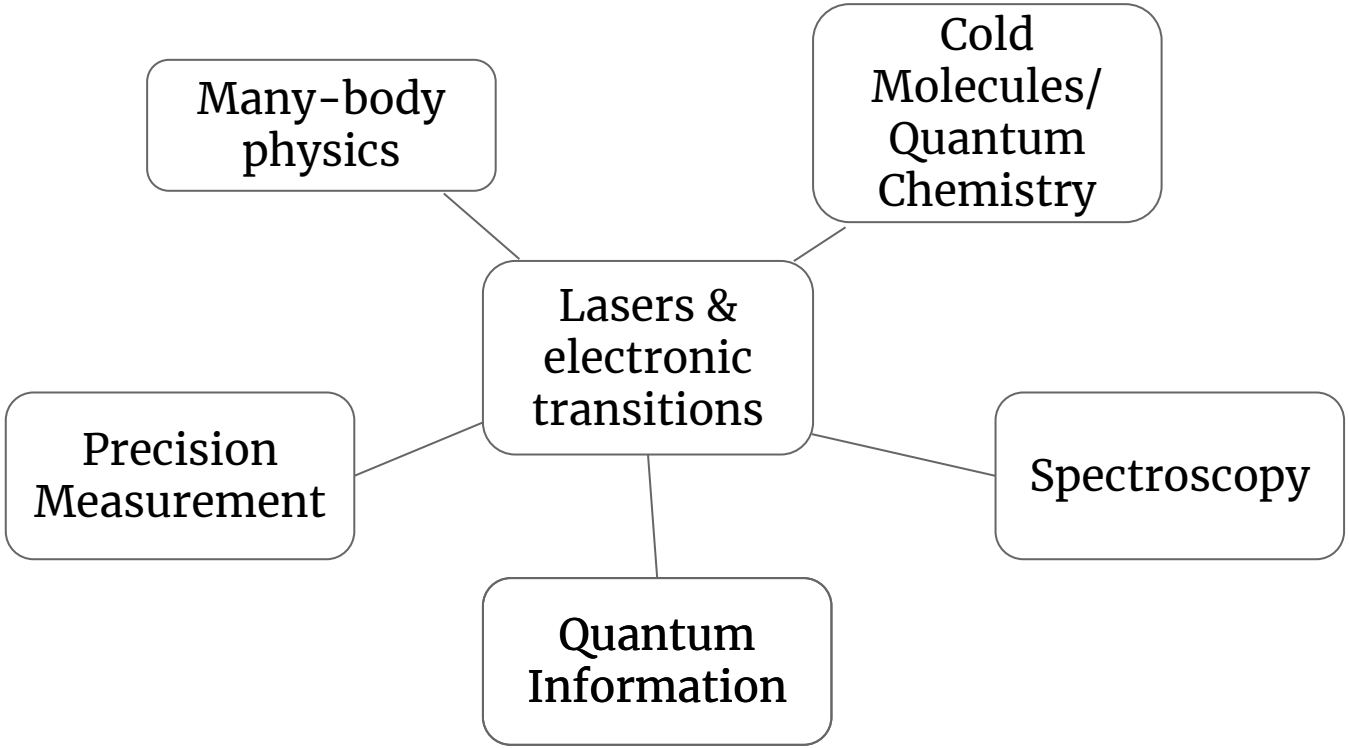
# Measuring the Fine Structure Constant with Atom Interferometry

Zachary Pagel
Holger Müller Group
University of California, Berkeley

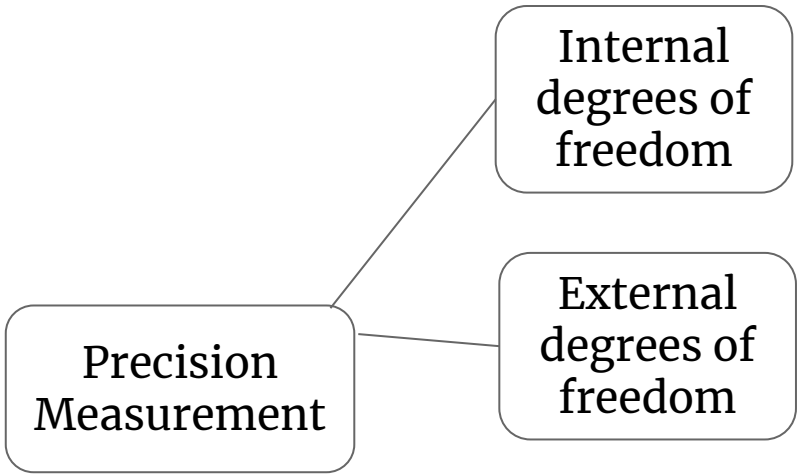
# Introduction: atomic physics



# Introduction: atomic physics

Precision Measurement

# Introduction: atomic physics



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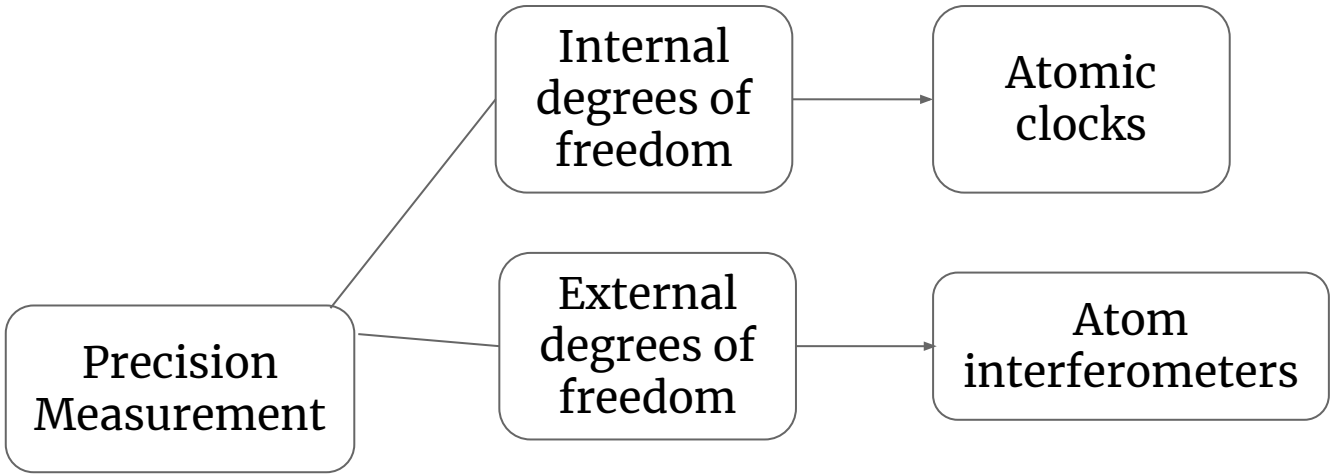
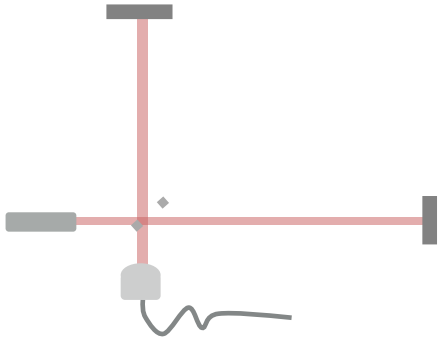


# Introduction: light pulse atom interferometry

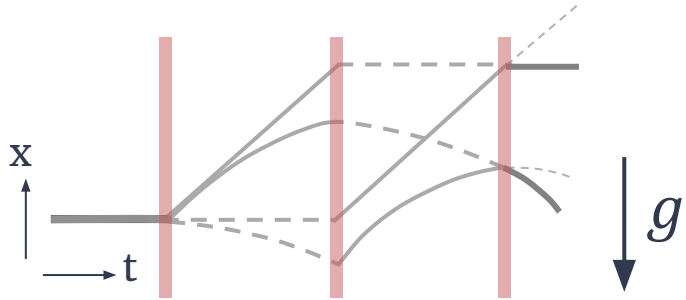
**Laser interferometer (e.g., LIGO):**

- *Coherent source* = laser
- *Manipulation* = Optics
  - Beam-splitters, mirrors



**Atom interferometer (e.g., us):**

- *Coherent source* = matter-waves
- *Manipulation* = Diffraction gratings



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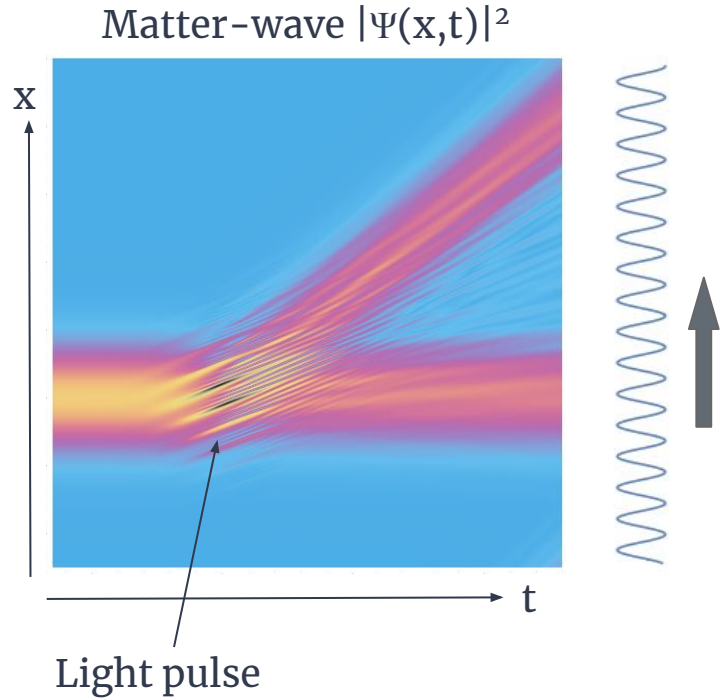
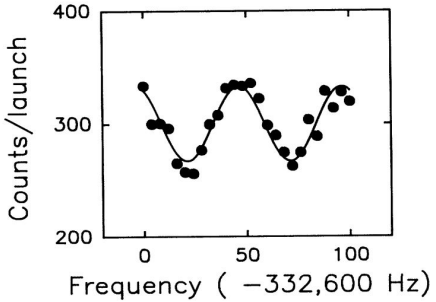


# Introduction: light pulse atom interferometry

**Atomic Interferometry Using Stimulated Raman Transitions**

Mark Kasevich and Steven Chu

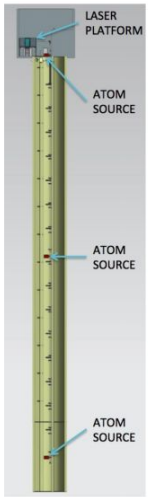



T~10 msec
(1991)

10m Atomic Fountains

T~2 s
(2010)

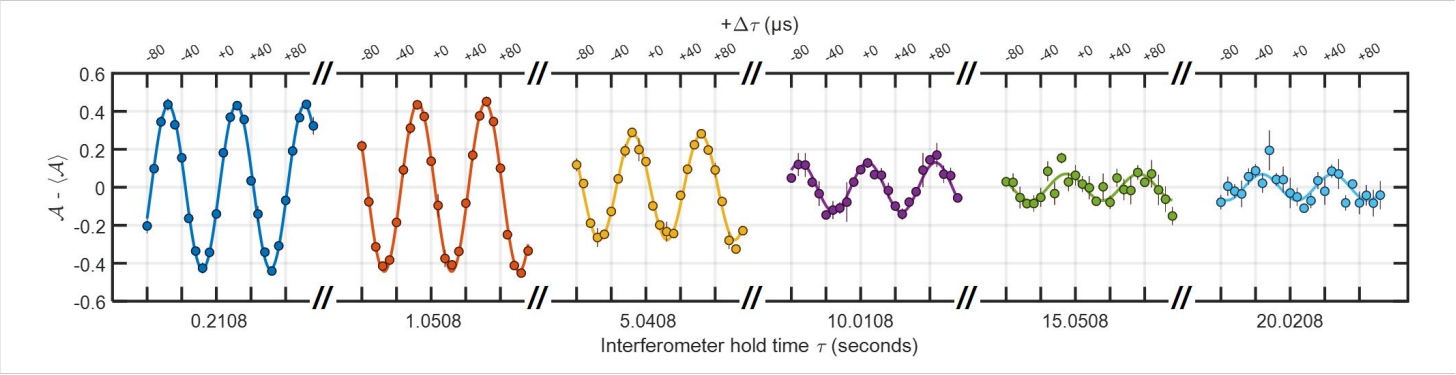
100m GW Detector
“MAGIS100”




T ≤ 10 s
(2020?)

# Introduction: light pulse atom interferometry

20 second atom interferometer in an optical cavity [2]



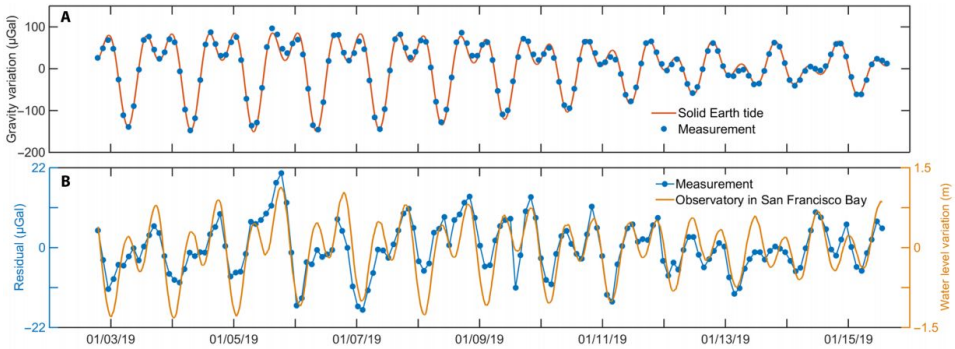

$\Delta\varphi_{free}$ ~ 1.6 Mrad

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

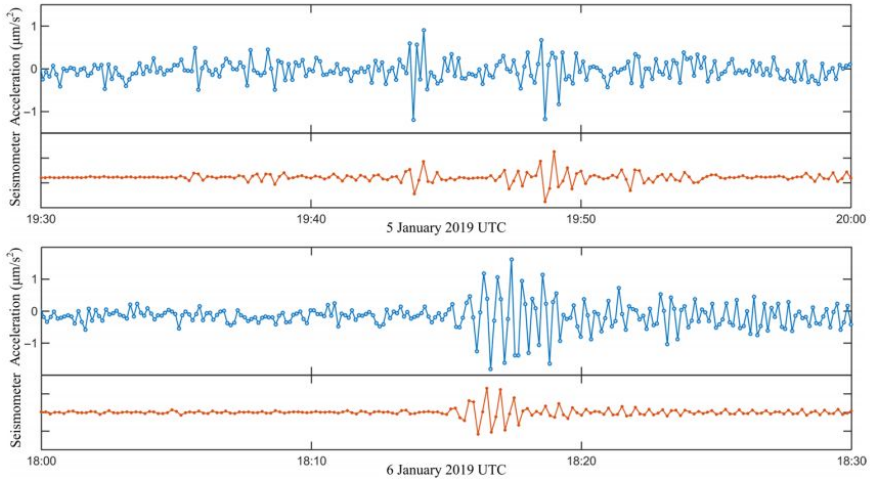
# Introduction: light pulse atom interferometry

## Precision Gravimetry [1]

### Measuring water level in SF Bay




### Seismic waves from earthquakes in Brazil and Indonesia



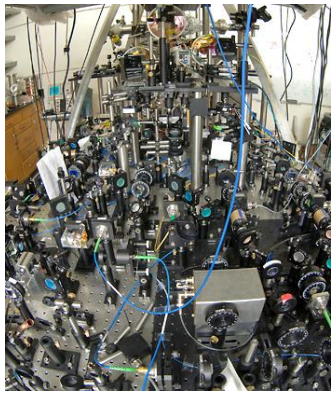

[1] X. Wu et. al 2019, Science Advances 5

# Probing physics with alpha

## Fine structure constant

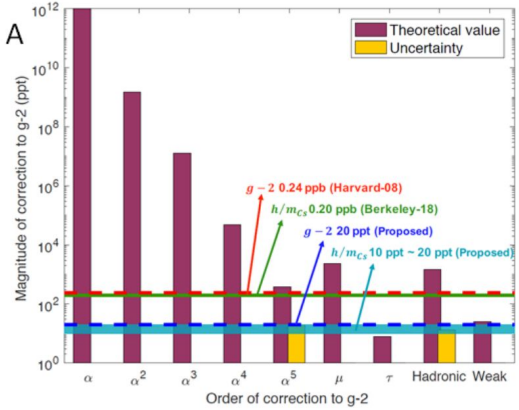
$$hcR_\infty = \frac{1}{2} m_e c^2 \alpha^2$$

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

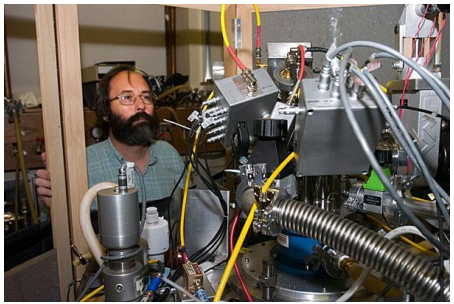


## Theory

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




## Electron gyromagnetic moment



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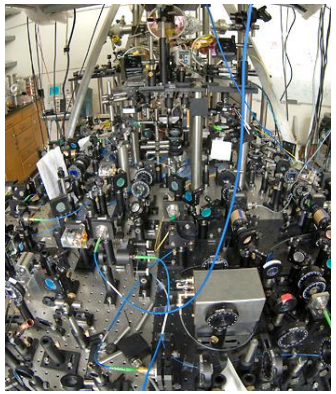

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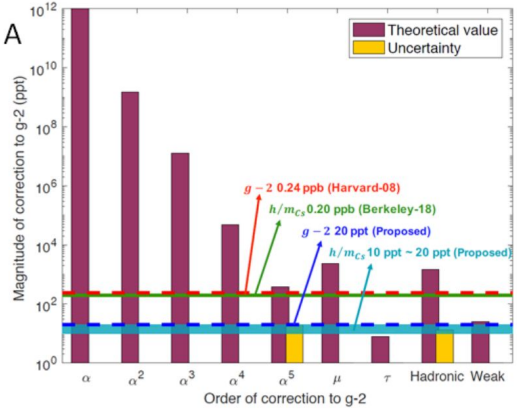


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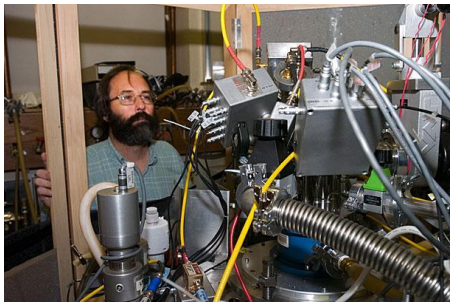

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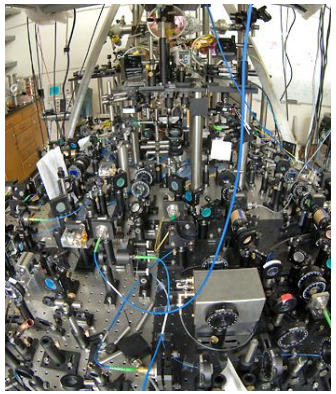
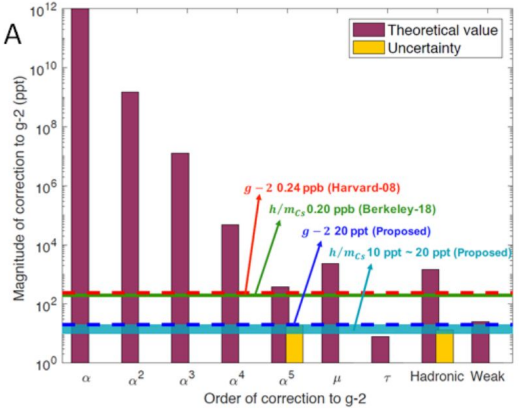
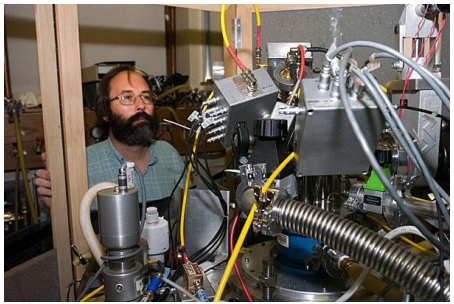
## Electron gyromagnetic moment

BSM physics can shift magnetic moment versus fine structure constant





# Alpha in atom recoil frequency

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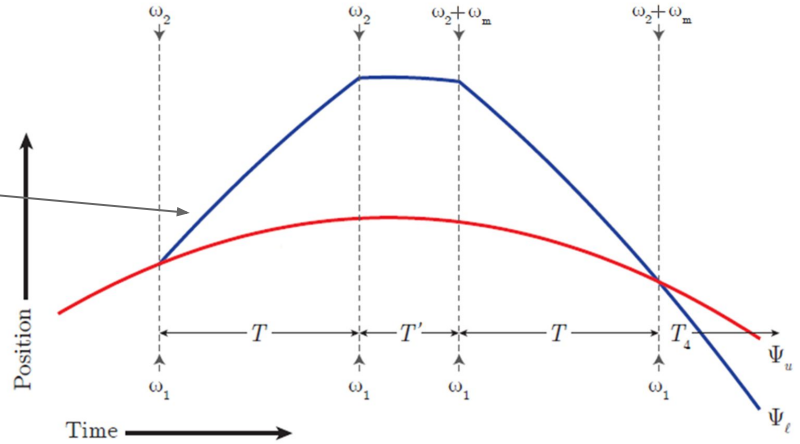
## Determined by atom recoil frequency

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

# Interferometer geometry

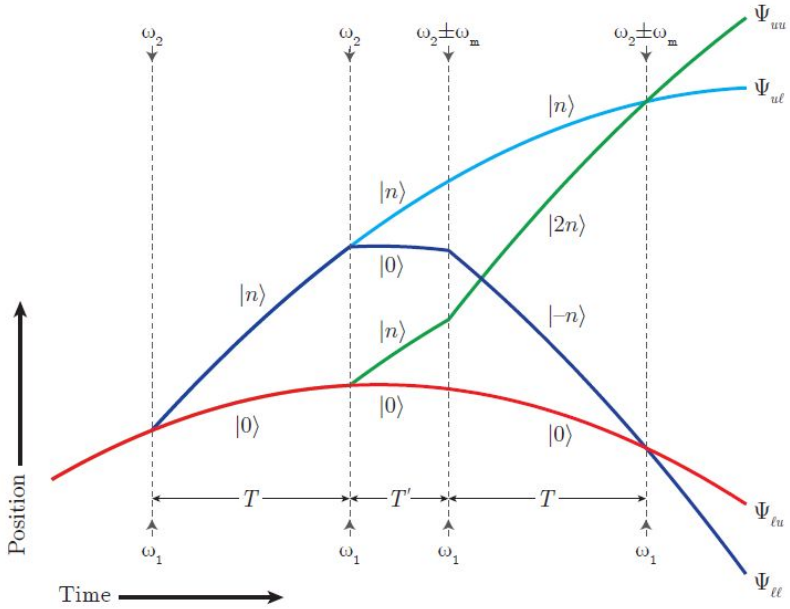
Want to measure recoil kinetic energy

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



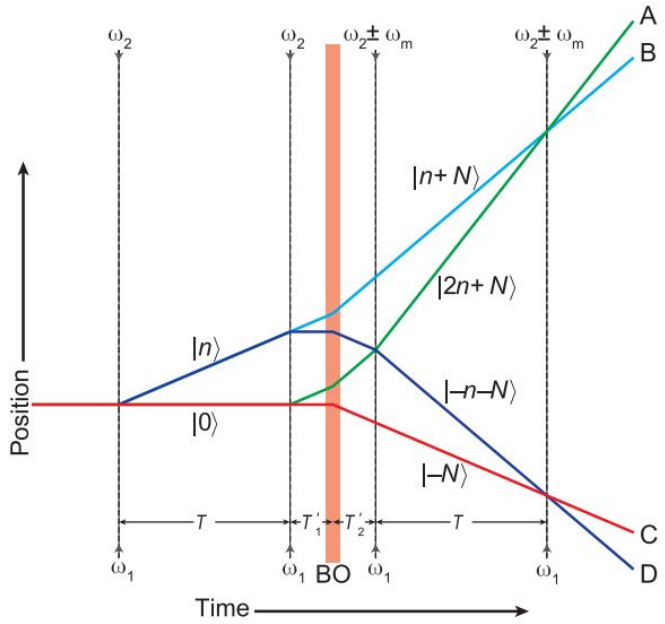

$$\Phi_{RB} = 8n^2\omega_r T - 2nkg(T + T')T - n\omega_m T$$

# Interferometer geometry



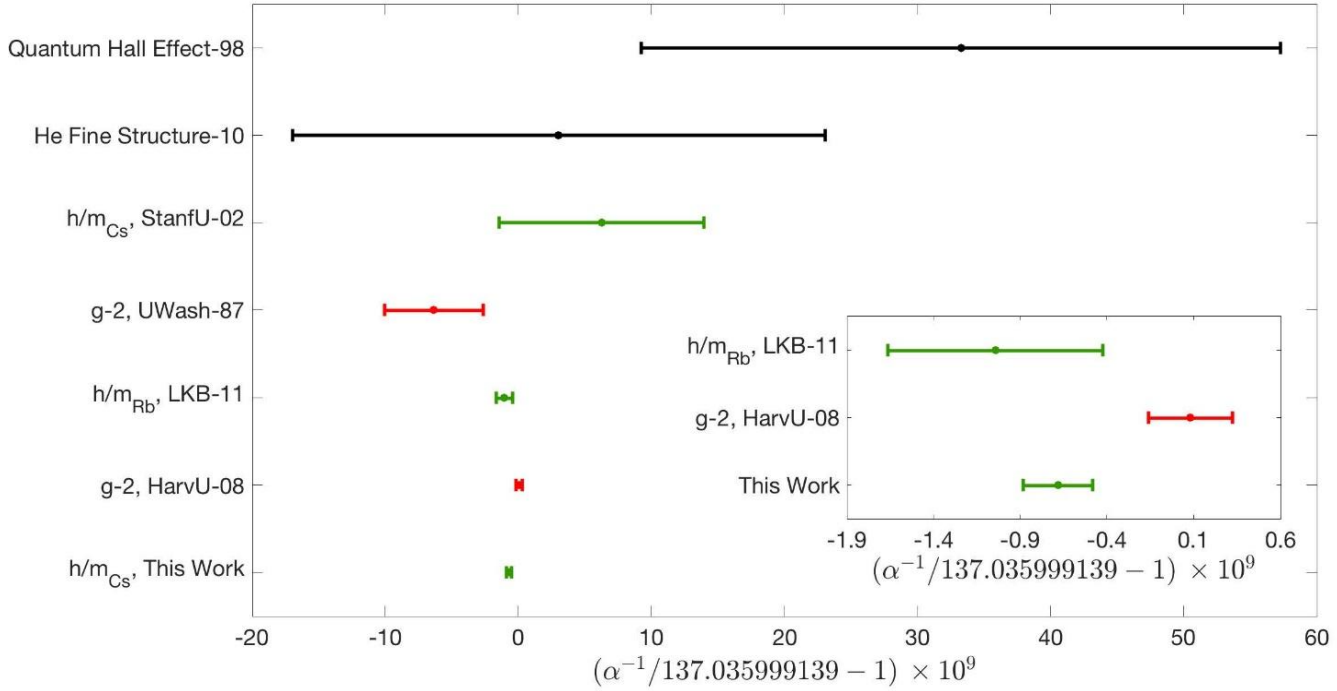

$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$

# Interferometer geometry




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

# Unblinding Alpha (2018)




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

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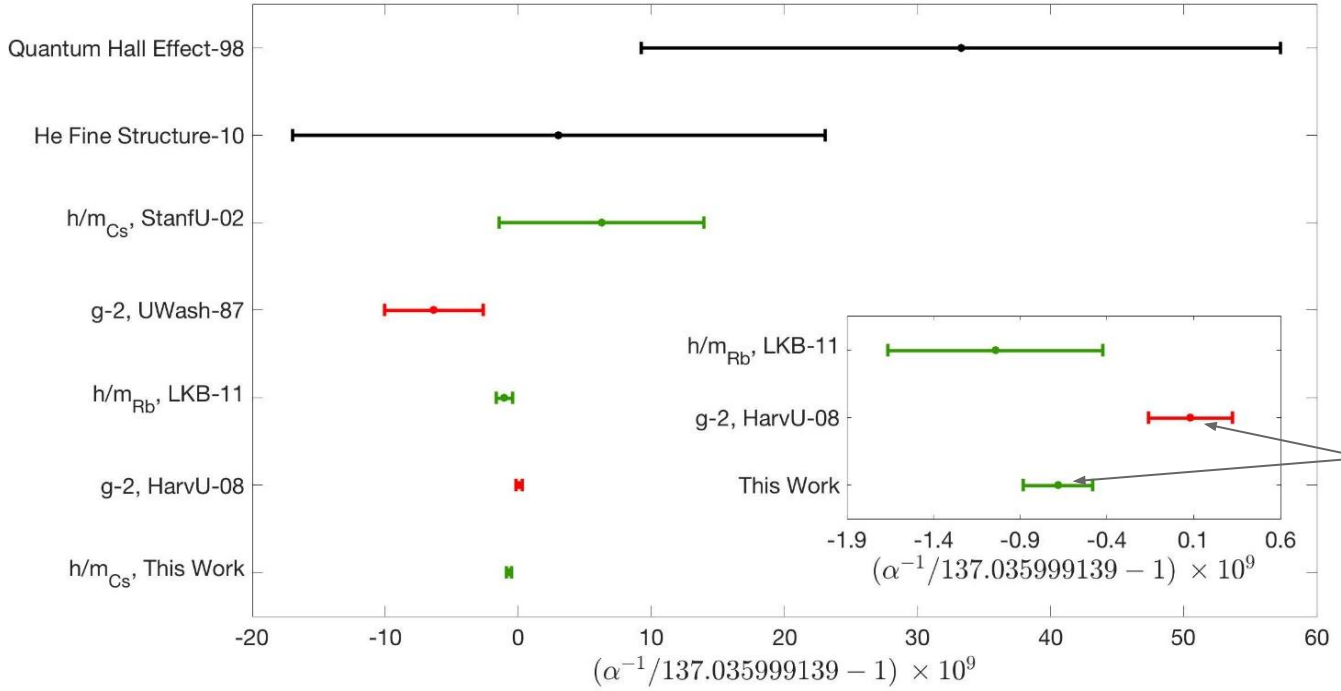


2.5σ tension

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

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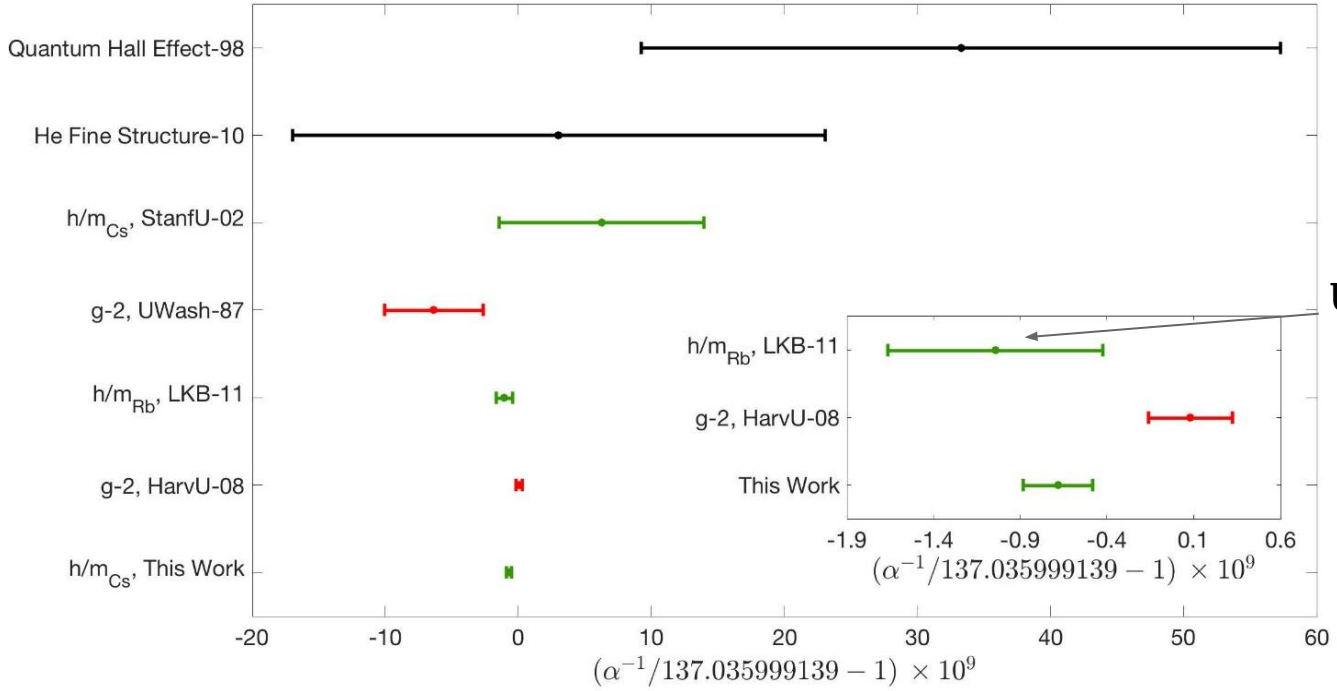
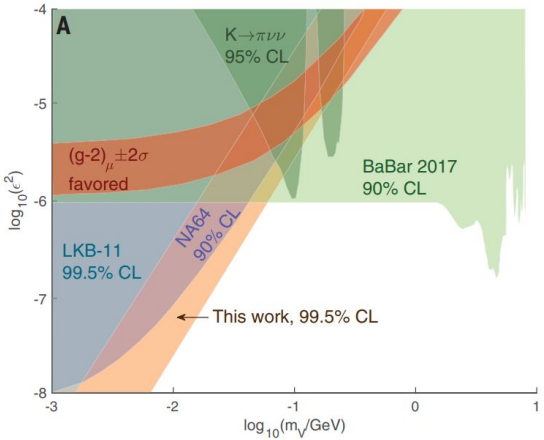



Update from LKB next!

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

# Constraining BSM Physics

Dark photons



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135 citations so far...

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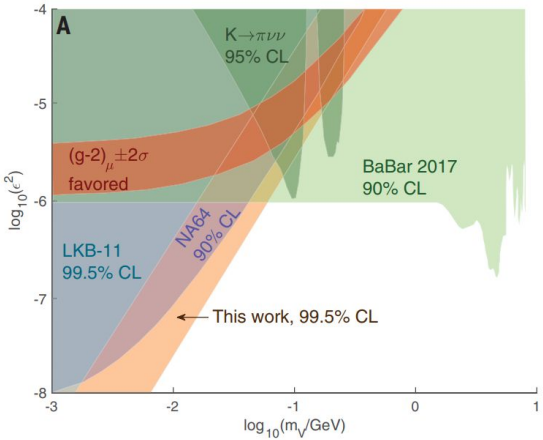

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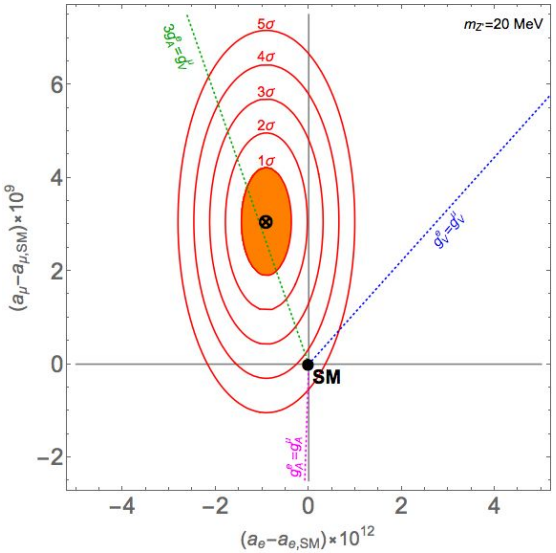
Combine with $g_\mu - 2$

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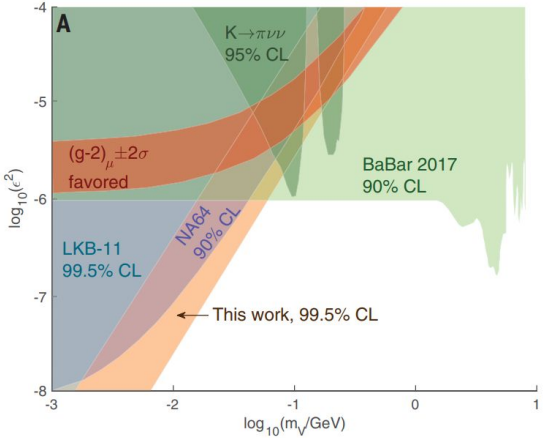

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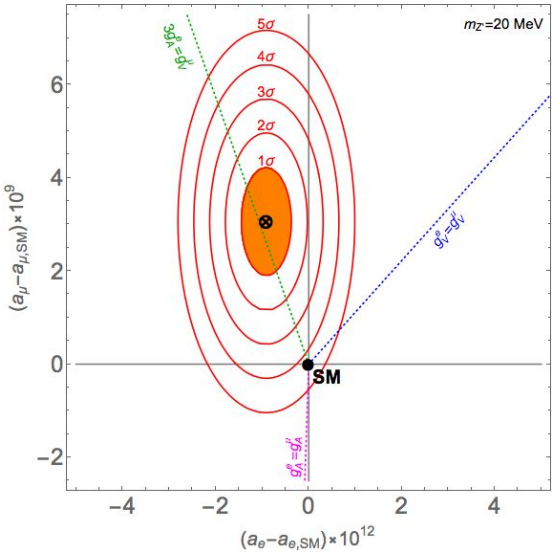


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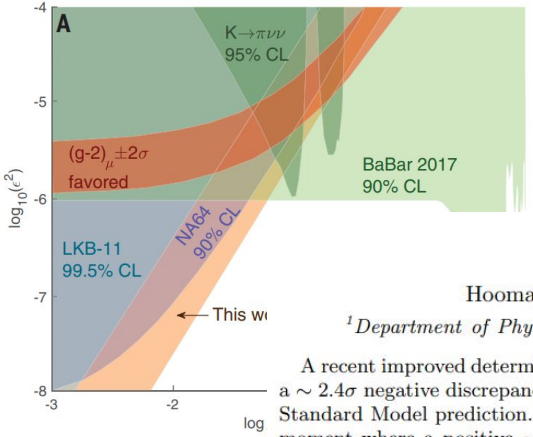



**A Tale of Two Anomalies**


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

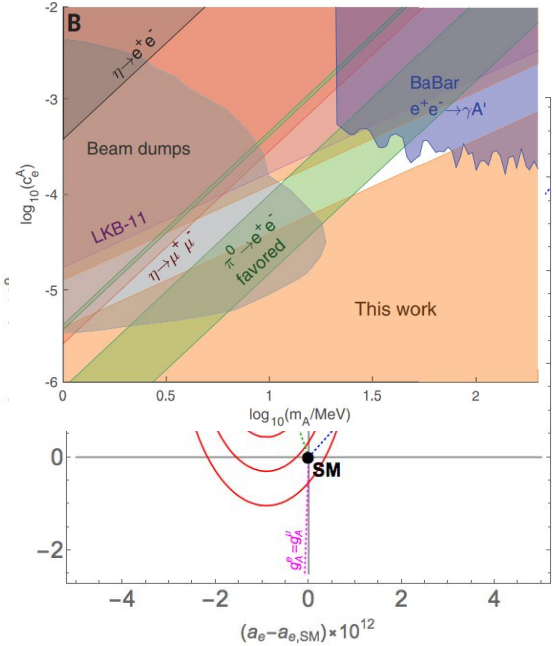
[1] *Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*



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.

# Constraining BSM Physics

## Dark axial vectors

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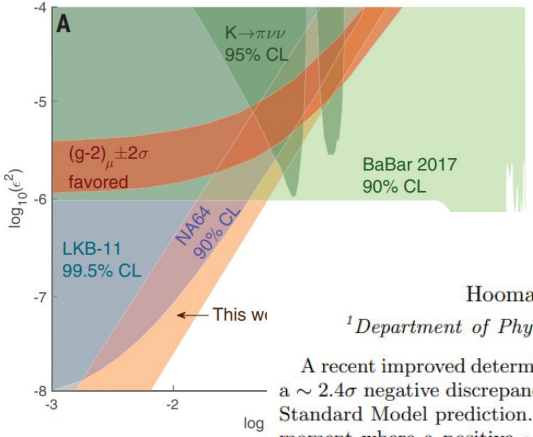


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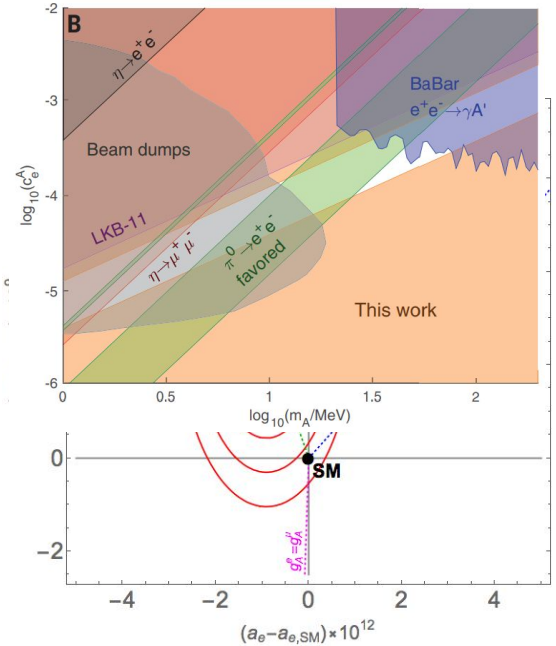


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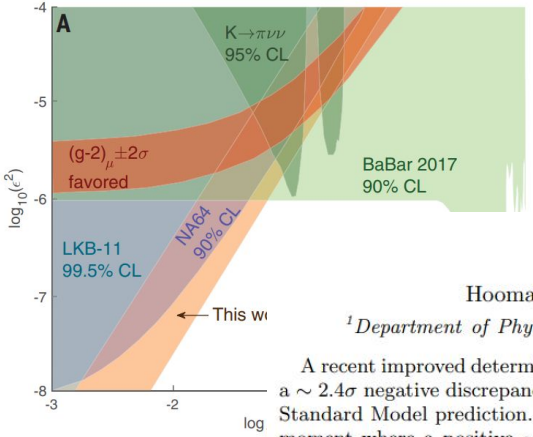


"The biggest worry is that, if the accuracy improves by another two orders of magnitude, we will need to calculate six loop QED corrections..."

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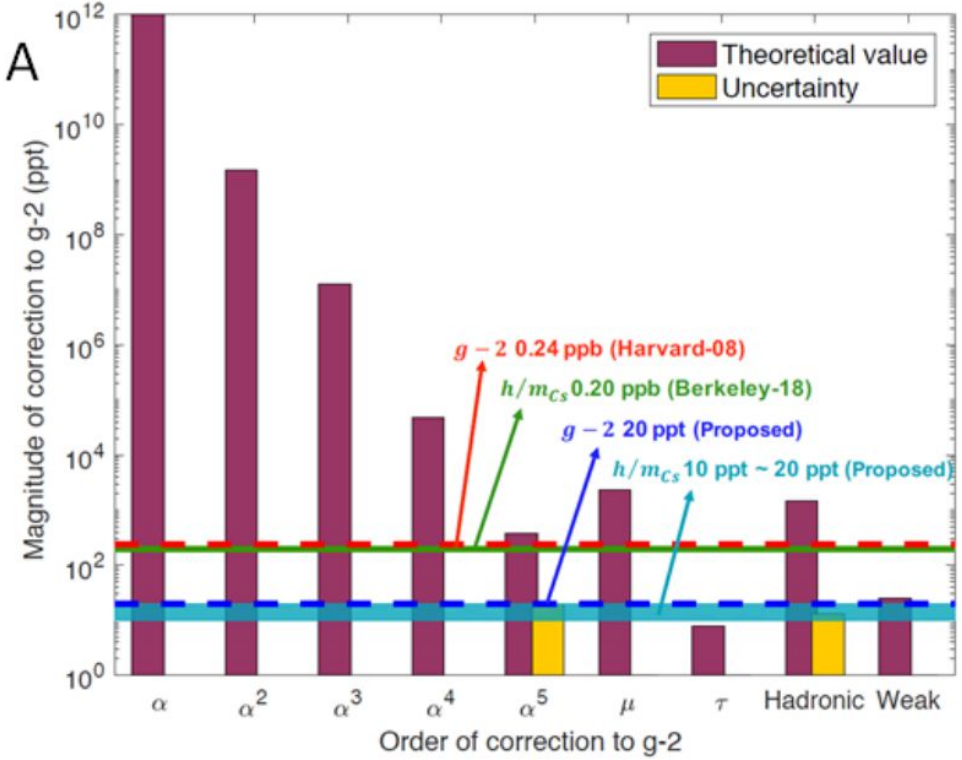
# Testing Standard Model

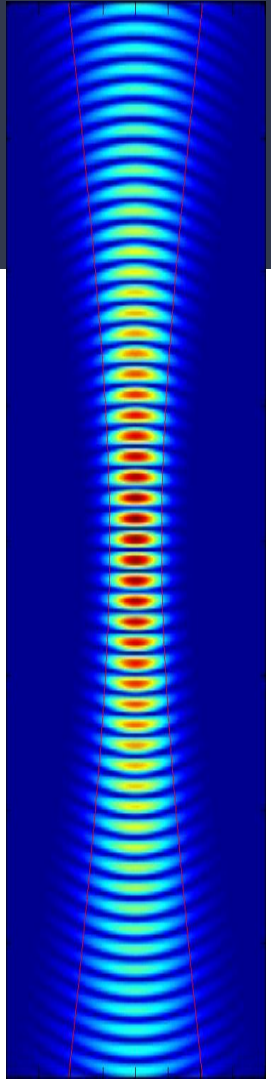


# Systematic errors

| Effect | Value | δα/α (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’



# Looking forward…

| Effect | Value | δα/α (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 |
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Larger, cleaner laser beam

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Better measurement/ characterization

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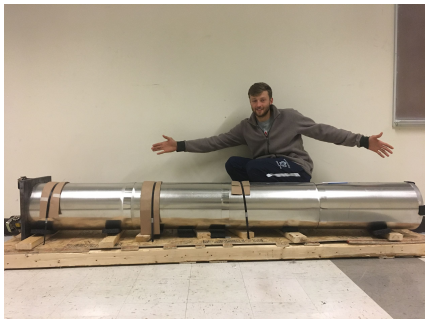
Larger, cleaner laser beam

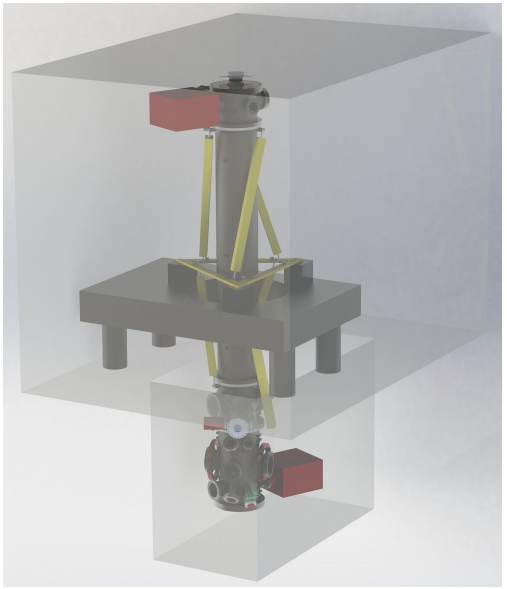
Better measurement/ characterization

Ready for an order of magnitude improvement

# Next generation

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





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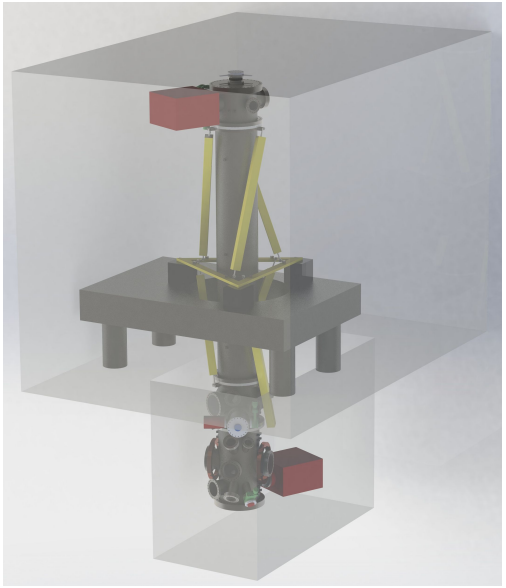

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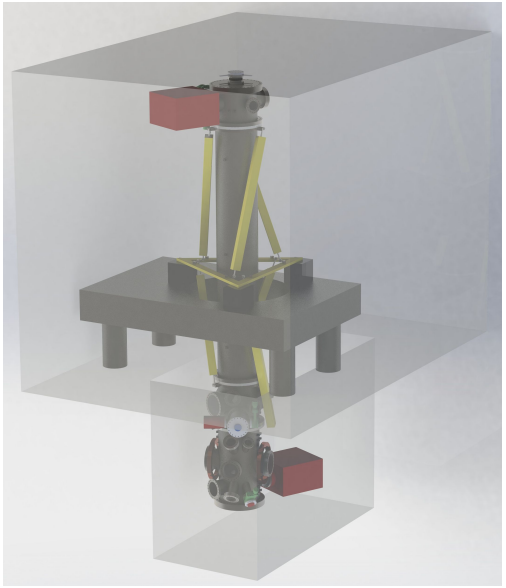
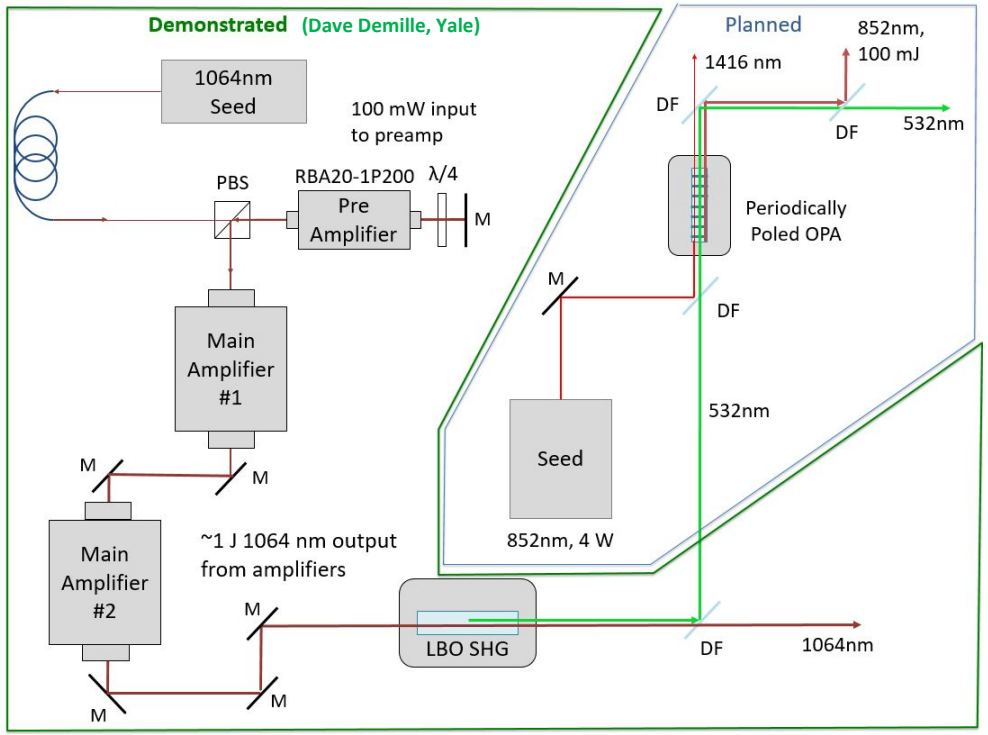
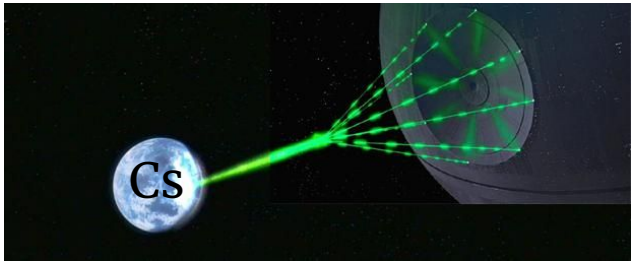
- Collaborating with Lawrence Berkeley National Lab
  - High power fiber experts
  - High-quality CCD imaging
  - Improved Monte Carlo simulations
  - Mechanical engineering



# “Death Star” pulsed laser system




Hundreds of watts peak power to atoms



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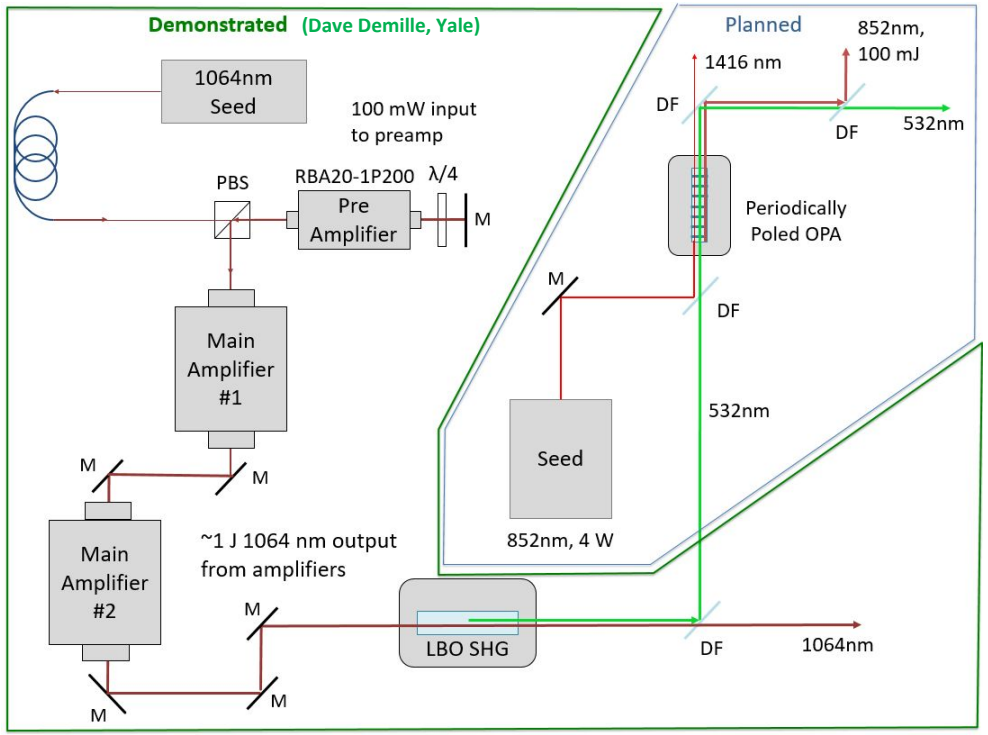
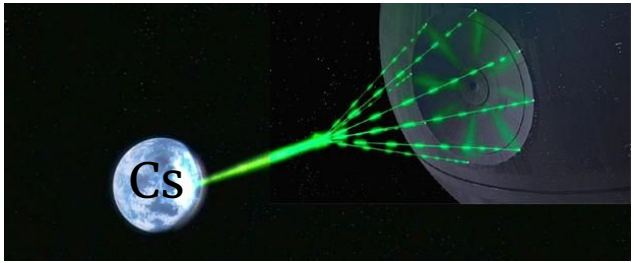



State-of-the-art
~5W

Hundreds of watts
peak power to atoms



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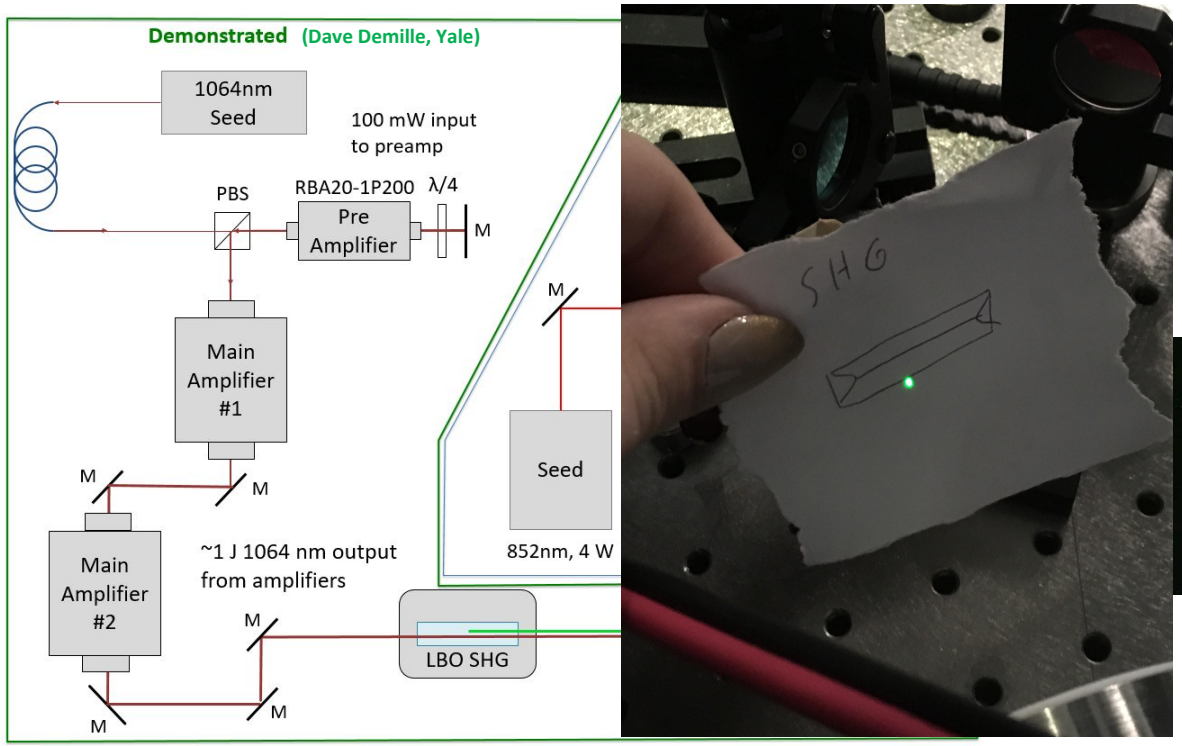





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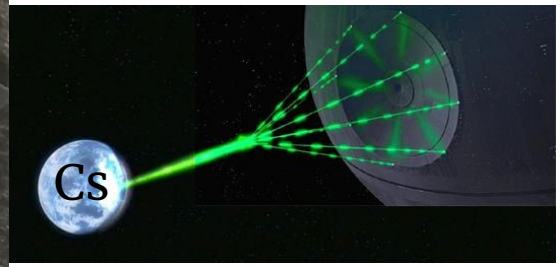
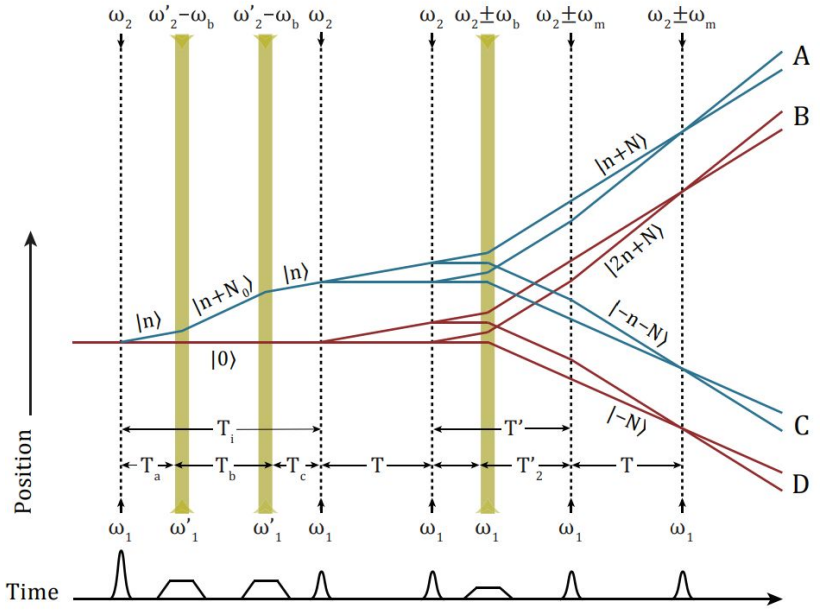


# New ideas

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

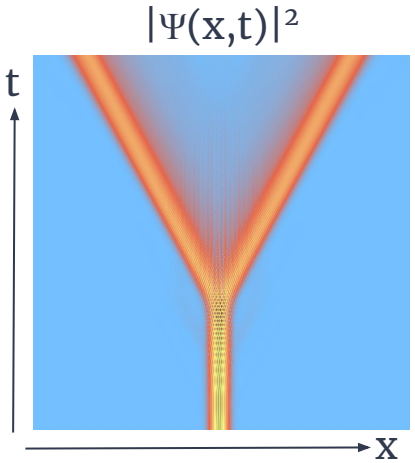


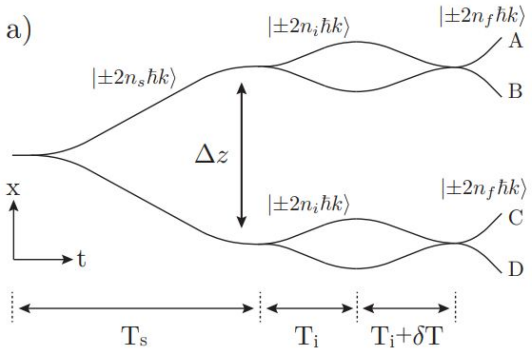

[4] W. Zhong et al 2019, arXiv:1901.03487

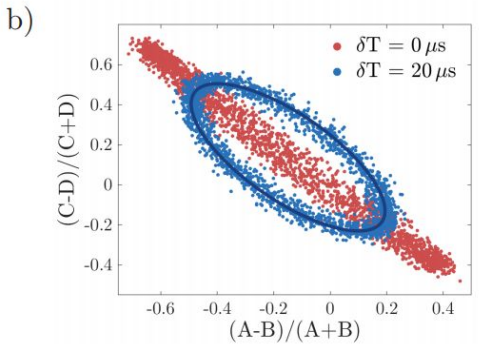
# New ideas

Symmetric “Bloch beamsplitter” [4]

- Eliminates diffraction phase
- Demonstrated 240ħk momentum transfer



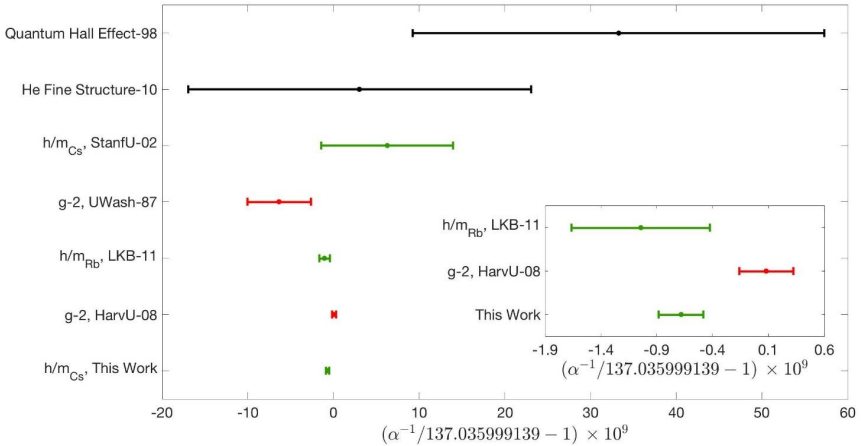




[3] Z. Pagel et al 2019, arXiv:1907.05994

# 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!

**Team alpha:**

**PI**: Holger Mueller

**Grads**: Weicheng Zhong and Zachary Pagel

**LBNL and UCB collaborators**: David Brown, Azriel Goldschmidt, Joseph H. Silber, Russell B. Wilcox, Ian Hinchliffe, Dan M. Stamper-Kurn, Roger W. Falcone

**Visiting Student**: Eric Planz

**Undergrads**: Philipp Sonnenschein, Aini Xu, Andrew Neely, Spencer Kofford

**Old members**: Richard Parker, Chenghui Yu, Brian Estey, Pei-Chen Kuan, Shau-Yu Lan