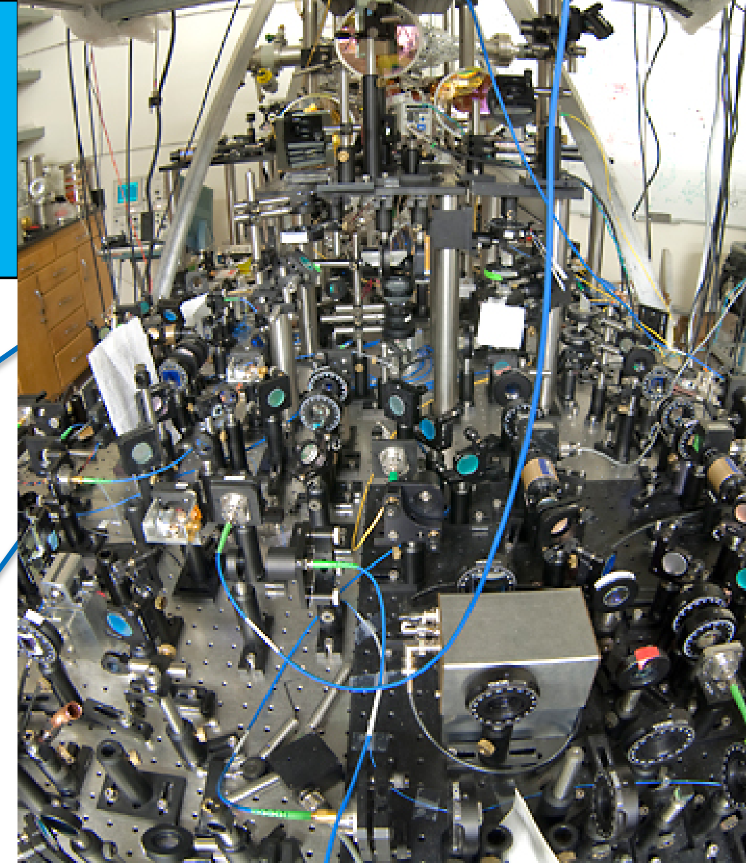
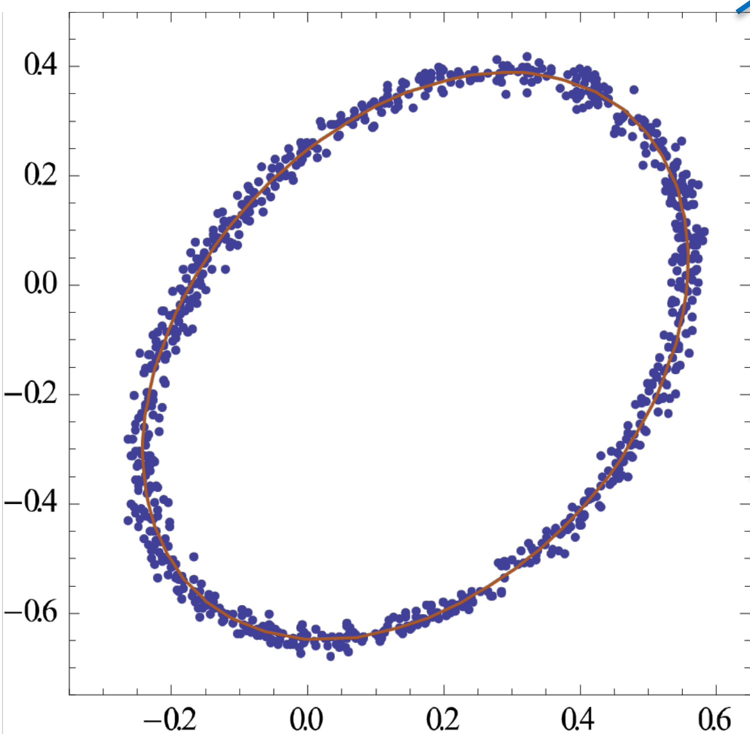
Measurement of the fine-structure constant as a test of the Standard Model





Richard Parker

Testing QED with Alpha

$$\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137.035999139(31)} \quad (0.23\text{ppb})$$

2014 CODATA

Neutral Atom

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

Rydberg Constant
0.006 ppb

Electron mass in amu
0.02 ppb

Cs mass in amu
0.03 ppb

Recoil frequency measurement
0.38 ppb

Penning Trap

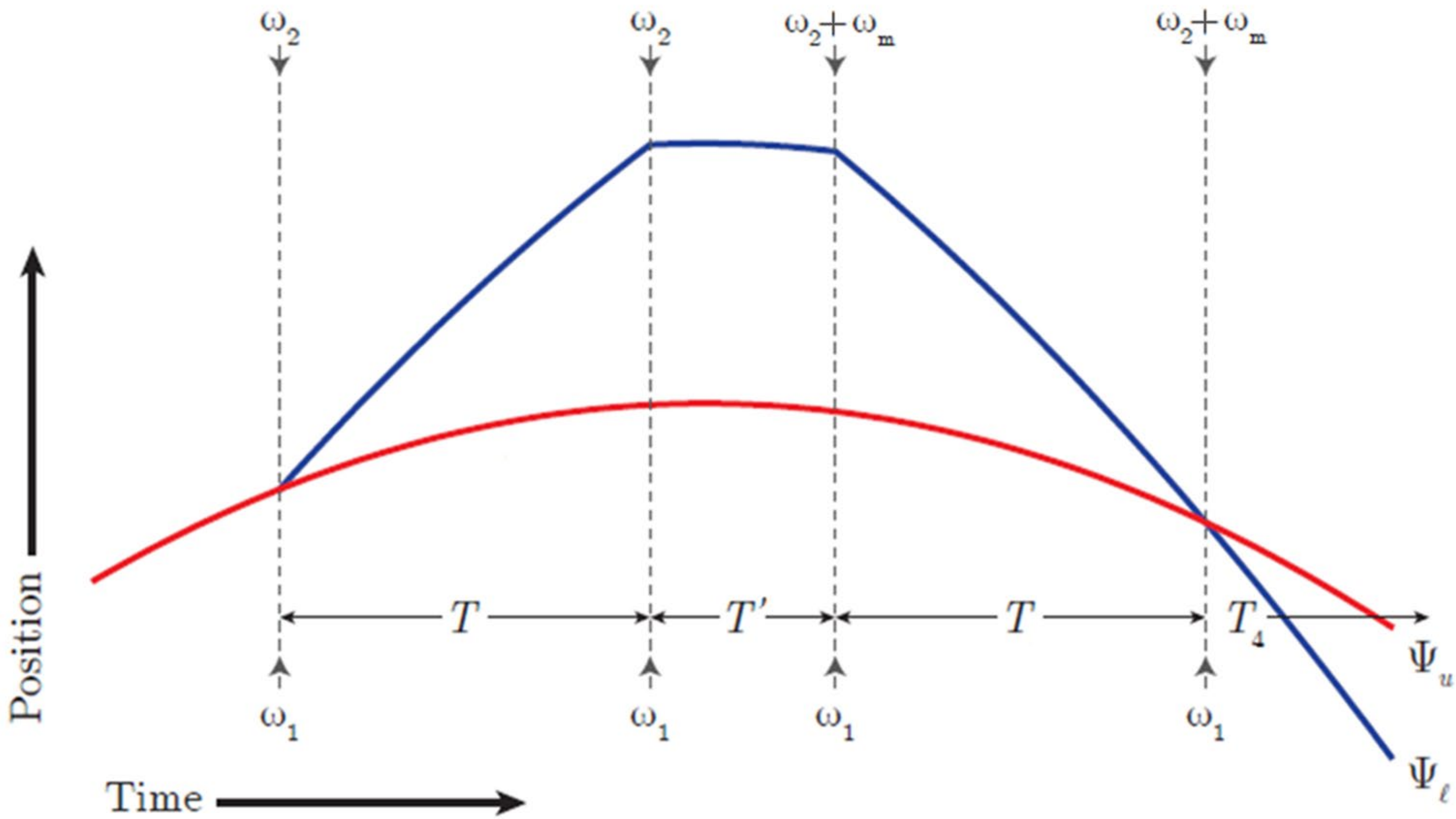
$$g - 2 = \sum_{n=1} \left(\frac{\alpha}{\pi}\right)^n a_n + a_{weak} + a_{QCD}$$

$(\hbar/m_{Rb}) \longrightarrow$ 0.62 ppb vs. 0.24 ppb

$(\hbar/m_{Cs}) \longrightarrow$ 0.20 ppb

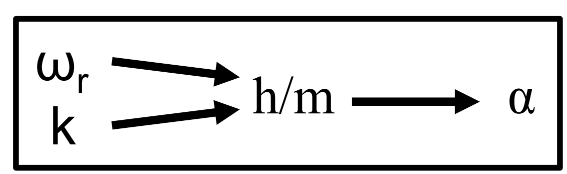
Atom-interferometer measurement of α

Ramsey-Bordé Interferometer

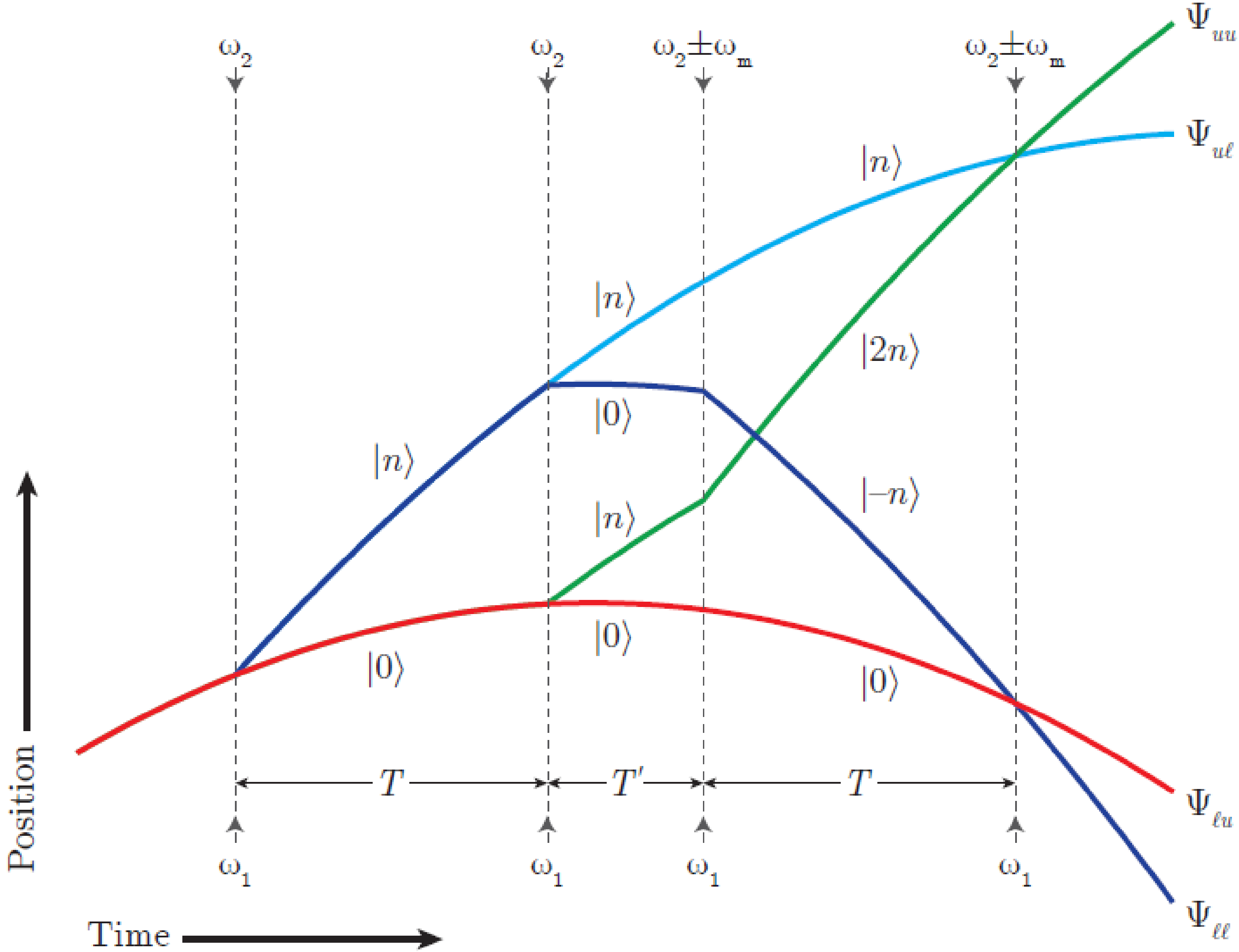


$$\Phi_{RB} = 8n^2\omega_r T - 2nkg(T + T')T - n\omega_m T$$

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



Simultaneous Conjugate Interferometers

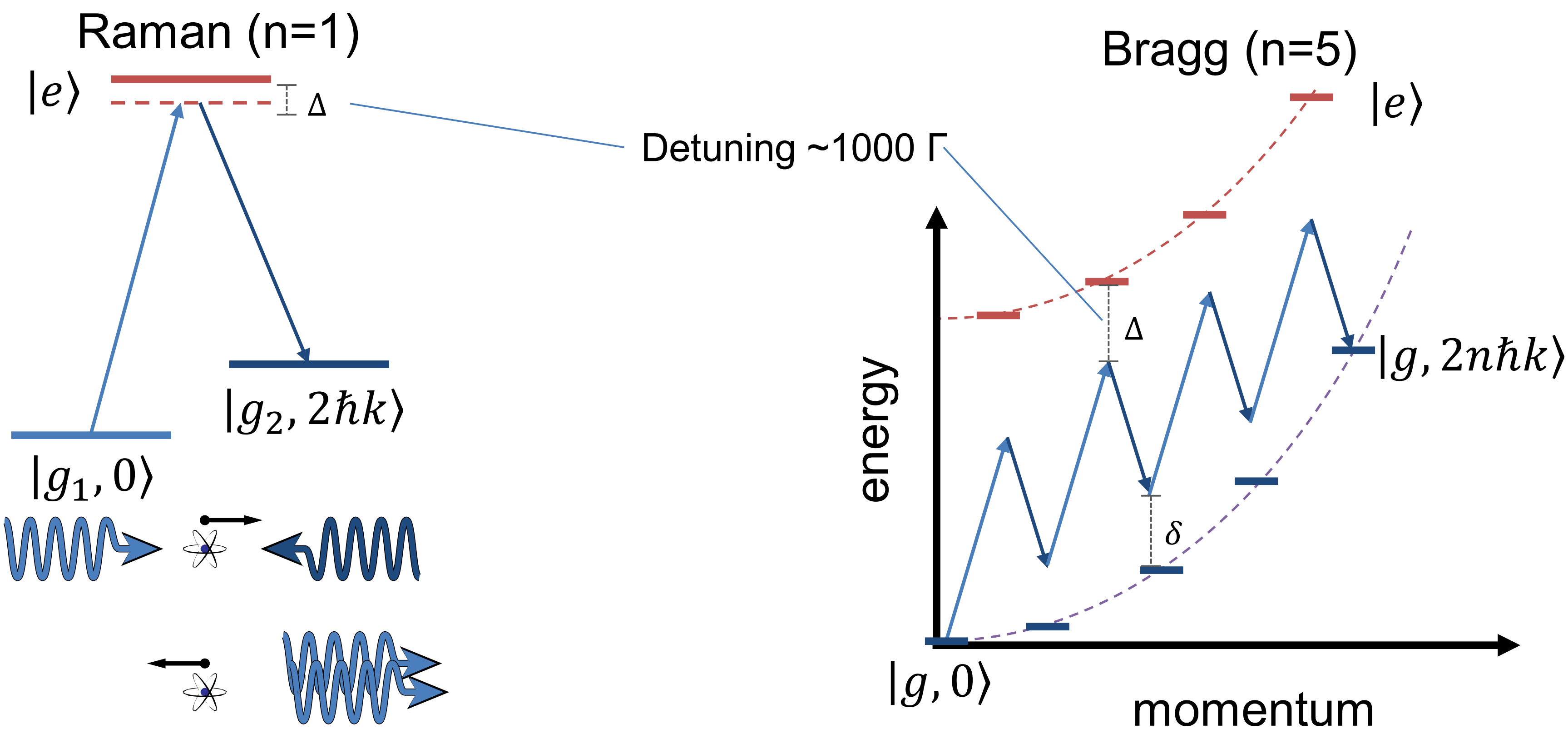


$$\Phi_{RB} = \pm 8n^2\omega_r T \pm n\omega_m T + 2nkg(T + T')T$$

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

Multi-Photon Bragg Diffraction

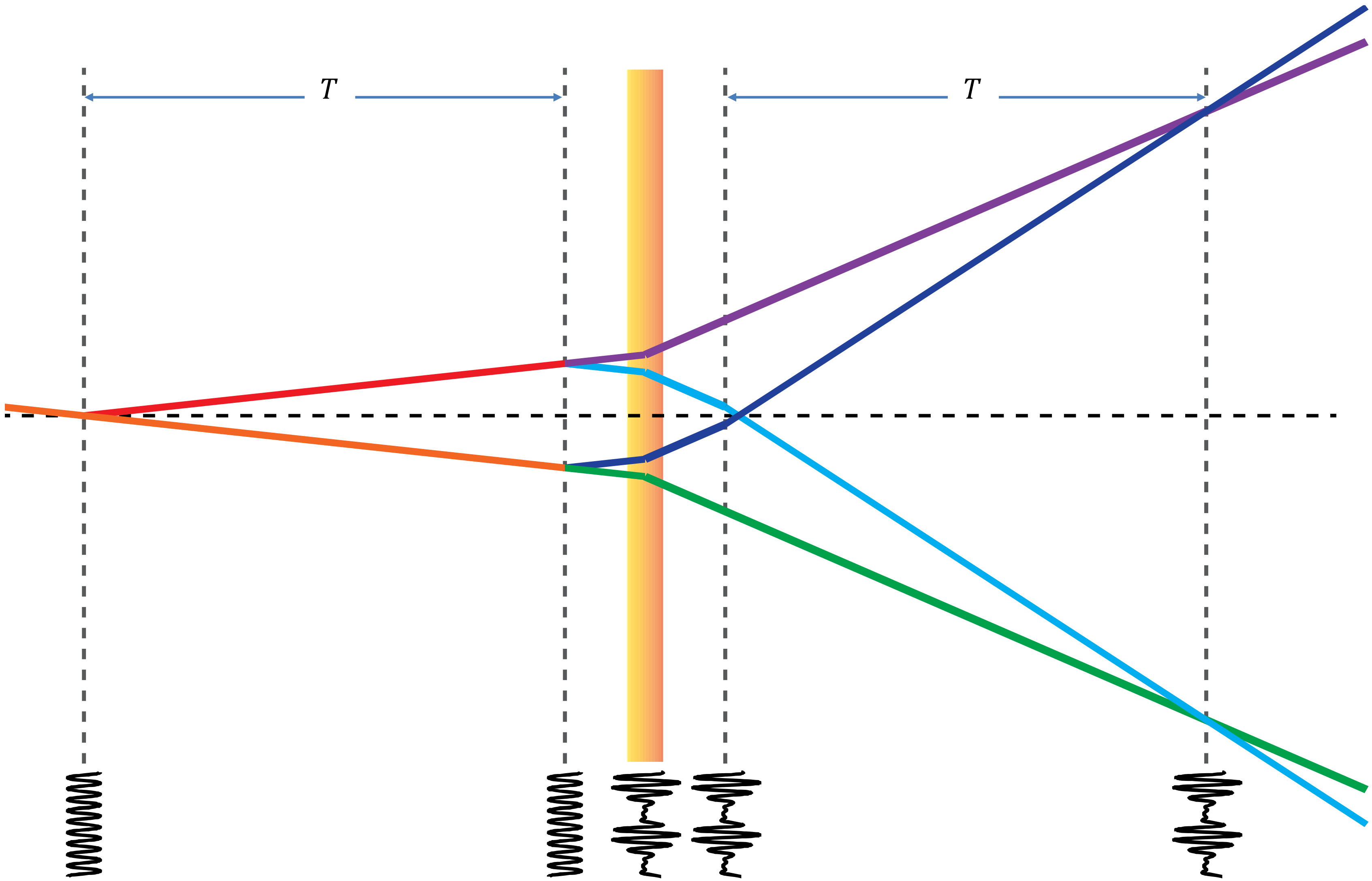
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$



<u>Bragg gives you:</u>

- More photons transferred per pulse (higher sensitivity)
- Atoms stay in same internal state (Zeeman, AC Stark systematics suppressed)
- But…
- Higher power needed
- Complicated phase shift between output ports

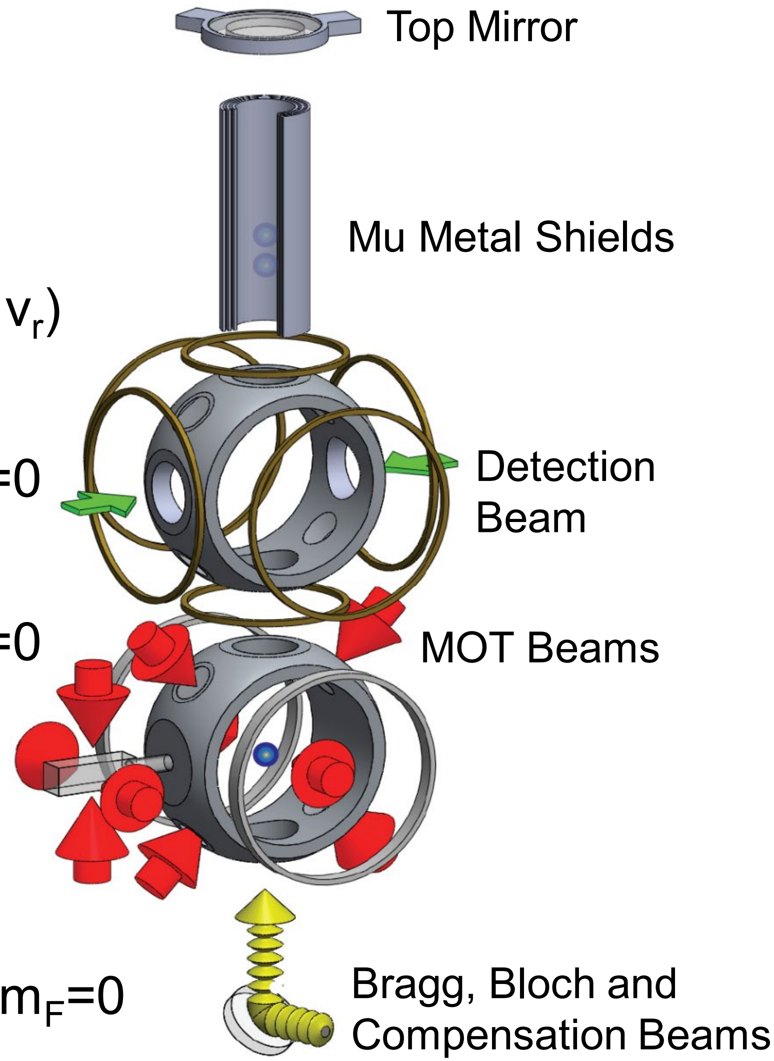
Bloch Oscillations



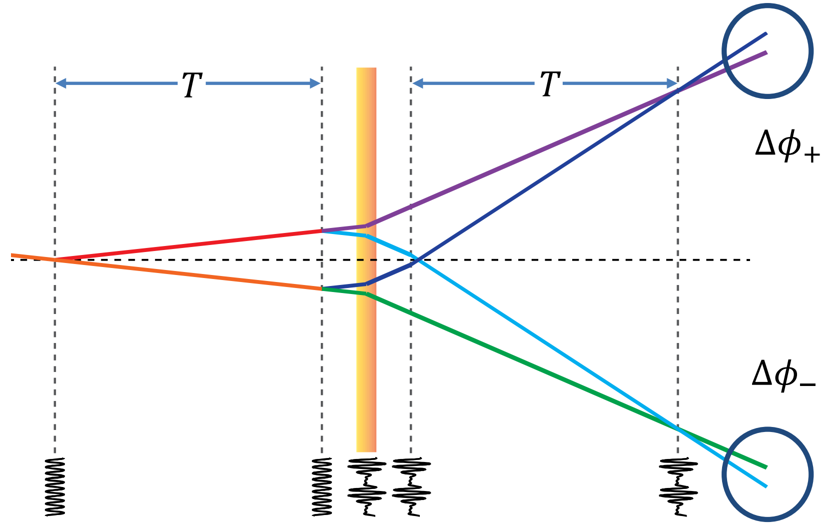
$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T$$

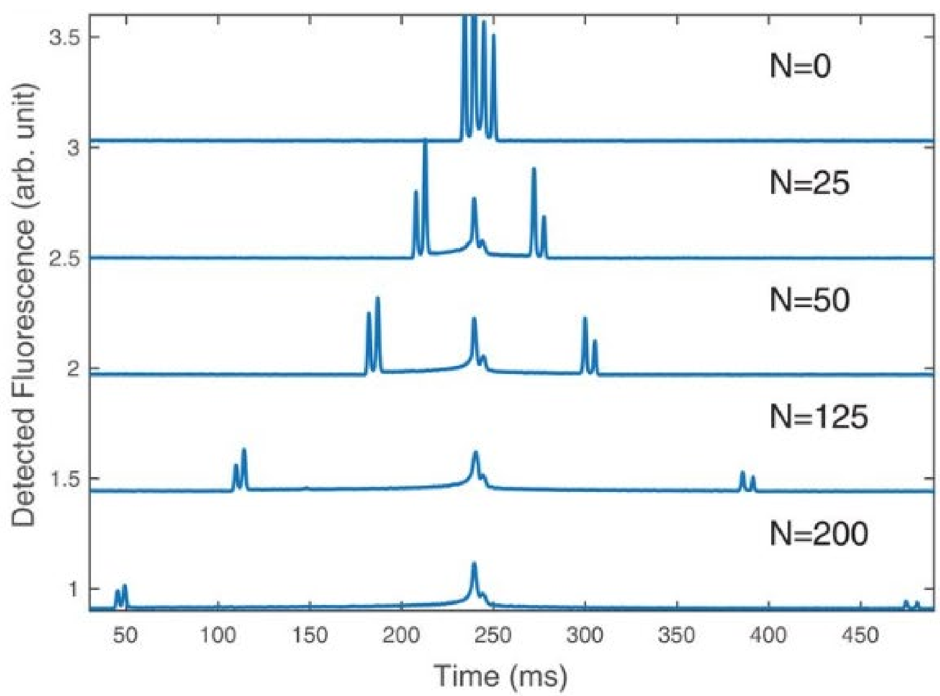
Experimental Sequence

Atomic Fountain	10^8 atoms/sec → 4 m/s
↓	
Polarization Gradient Cooling	1 μK
↓	
Raman Sideband Cooling	300 nK (~$1v_r$)
↓	
Rapid Adiabatic Passage	→F=4, m_F=0
↓	
State Selection	→F=3, m_F=0
↓	
Velocity Selection x2	~0.1 v_r
↓	
Interferometer Sequence	All in F=3, m_F=0
↓	
Fluorescence Detection	

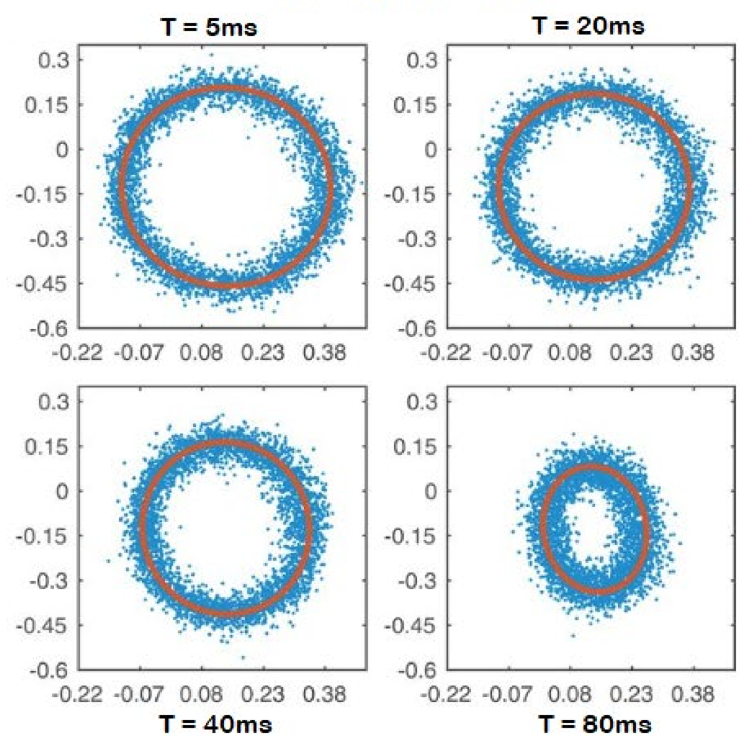


Phase Extraction



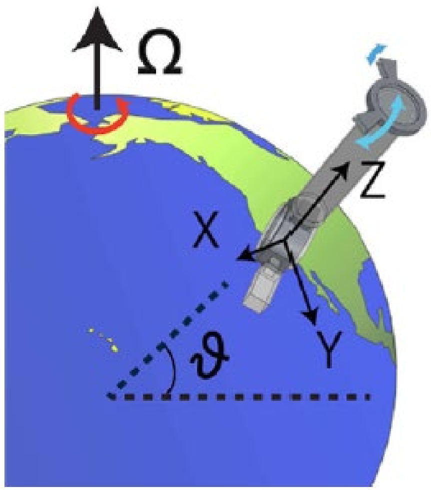


n = 5, N = 125

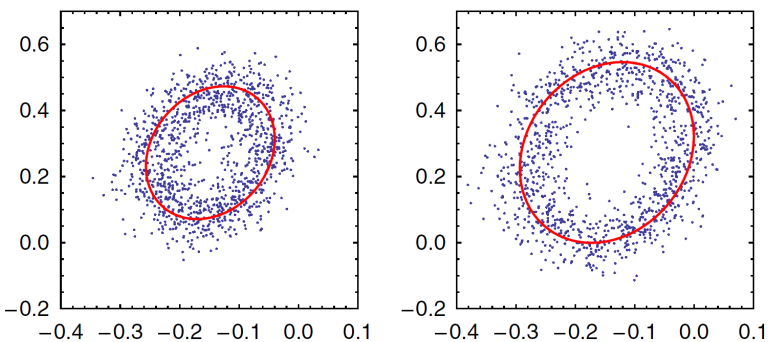


Tricks for Increased Sensitivity

Coriolis Compensation



$10\hbar k, T = 180ms$

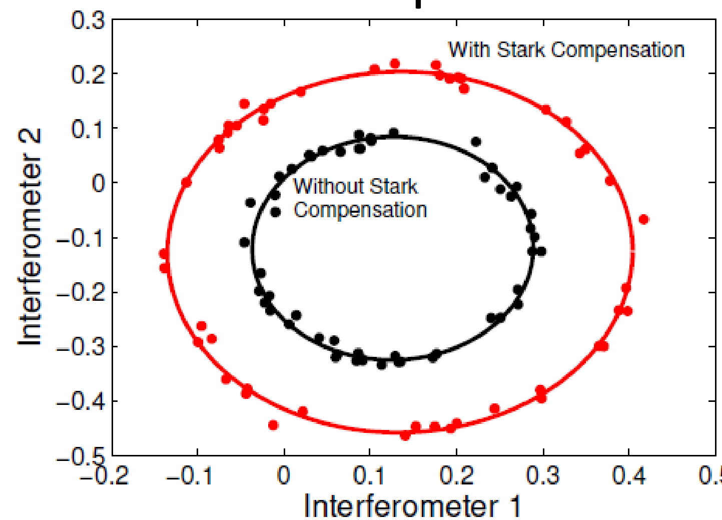


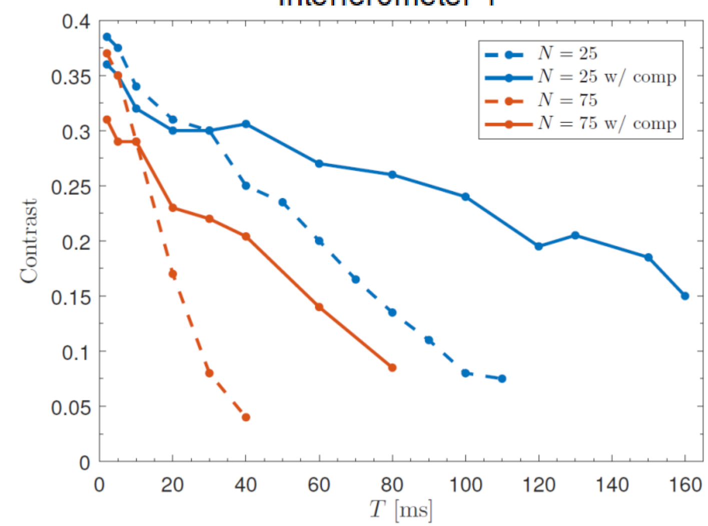
Without compensation

With compensation

x3.5 contrast gain

Stark Compensation



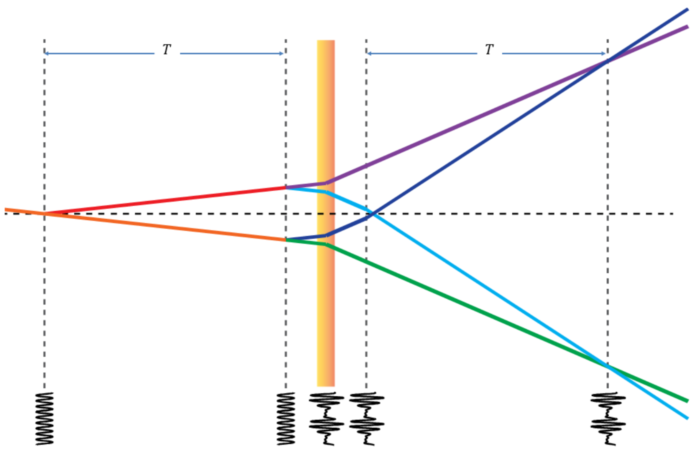


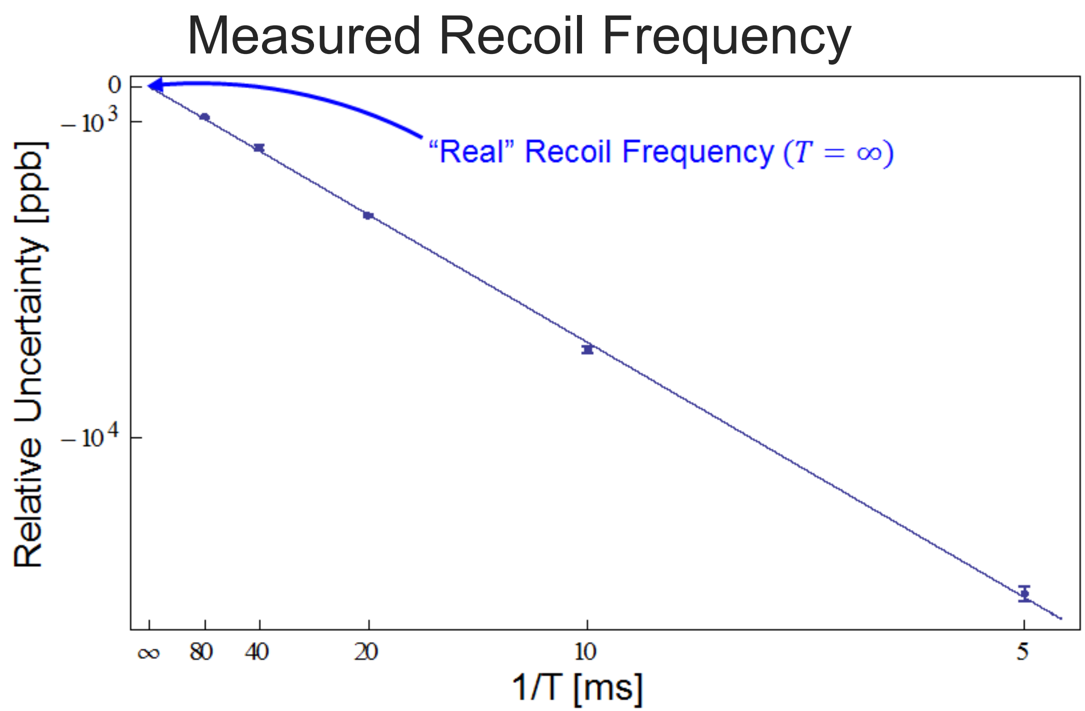
Up to N=200

>12Mrad phase diff. measurable!

Diffraction Phase

$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T + \Phi_0$$





Recoil Frequency

Diffraction Phase

Measured Frequency

$$\omega_m = 8(n+N)\omega_r + \frac{\Phi_0}{2nT}$$

Systematics

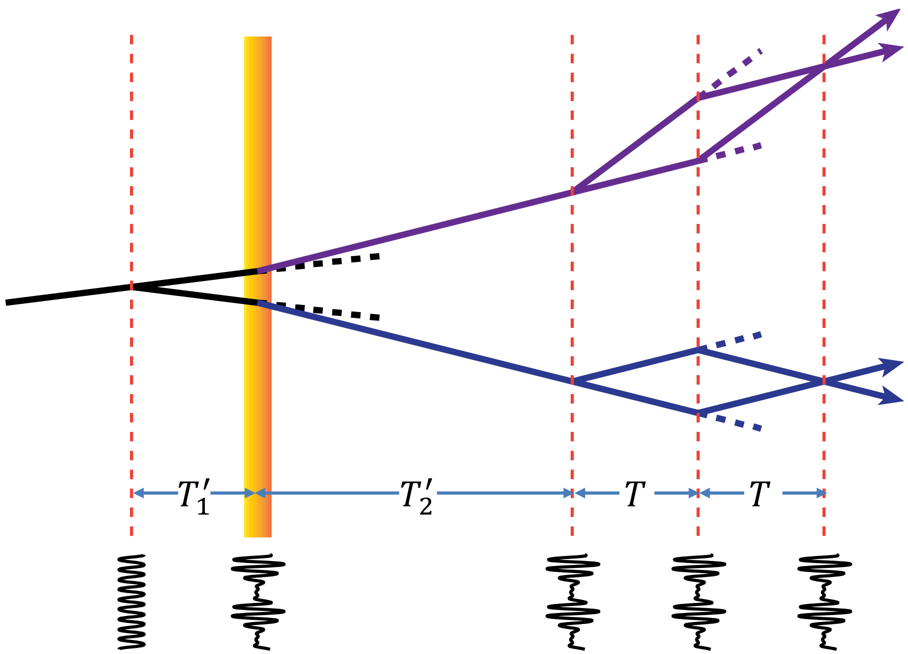
Effect	$\delta\alpha/\alpha$ (ppb)
Laser Frequency	-0.24 ± 0.03
Acceleration Gradient	-1.79 ± 0.02
Gouy Phase	-2.60 ± 0.03
Beam Alignment	0.05 ± 0.03
BO Light Shift	0 ± 0.002
Density Shift	0 ± 0.003
Index of Refraction	0 ± 0.03
Speckle Phase	0 ± 0.04
Sagnac Effect	0 ± 0.001
Mod. Frequency Wavenumber	0 ± 0.001
Thermal Motion of Atoms	0 ± 0.08
Non-Gaussian Waveform	0 ± 0.03
Parasitic Interferometers	0 ± 0.03
Total Systematic Effects	$\mathbf{-4.58 \pm 0.12}$
Total Statistical Uncertainty	$\mathbf{\pm 0.16}$

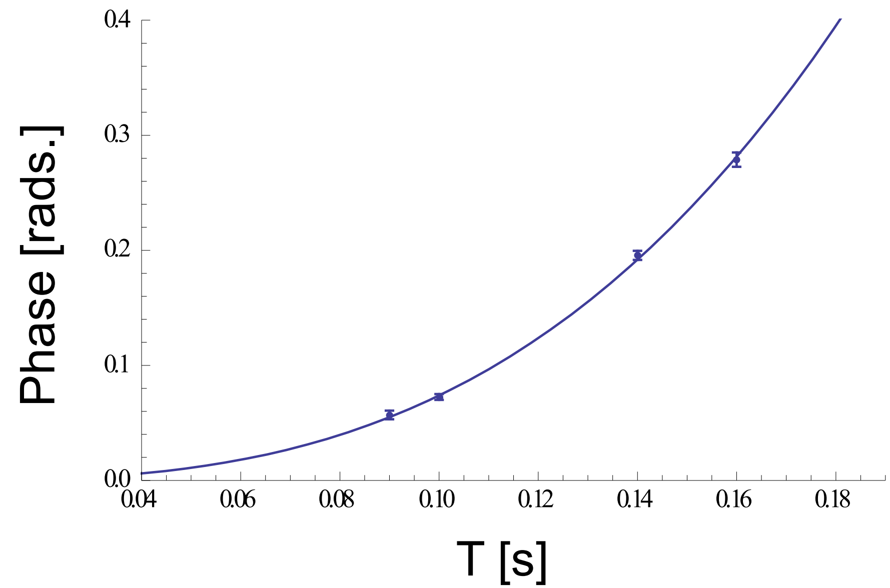
Big

‘New’

Gravity Gradient

$$\Delta\Phi = 16n(n+N)\omega_r T - 2n\omega_m T + \frac{4}{3}n\omega_r\gamma T\left[n\left(2T^2 + 3T(T_1' + T_2') + 3(T_1' + T_2')^2\right) + N\left(2T^2 + 6TT_2' + 6T_2'^2\right)\right]$$



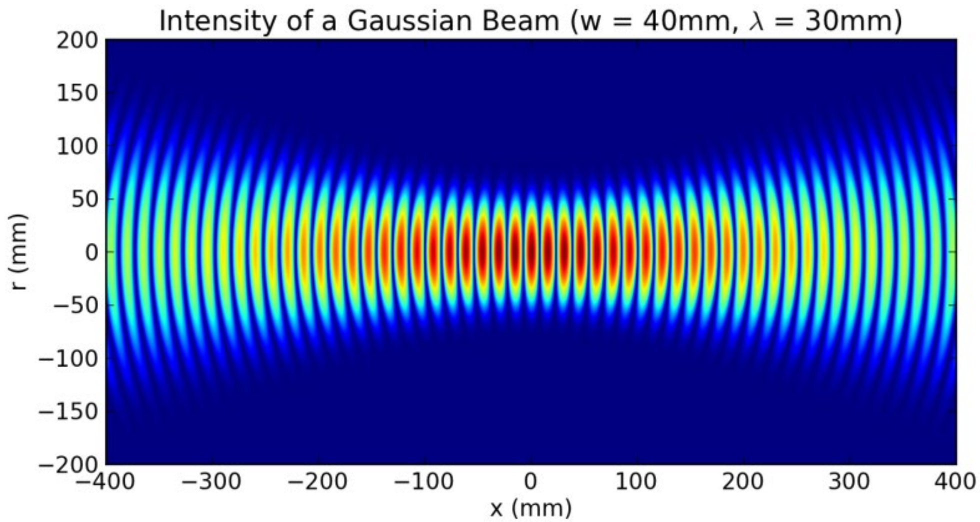


$$\Delta\phi = 2\gamma n\omega_r T^2\left(2N(2T + T_2') + n(2T + T_1' + T_2')\right)$$

$$\gamma = 1.295(32) \times 10^{-6}\,\frac{m}{s^2}\frac{1}{m}$$

Shift in alpha = -1.41 +/- 0.02 ppb

Gouy Phase Systematic



$$E(r,z) = E_0 \frac{w_0}{w(z)} e^{-\frac{r^2}{w(z)^2}} e^{-ik(z-z_0) - \frac{ikr^2}{2R(z-z_0)} + i\zeta(z-z_0)} \qquad z_R = \frac{\pi {w_0}^2}{\lambda} \sim 50 \text{ m}$$

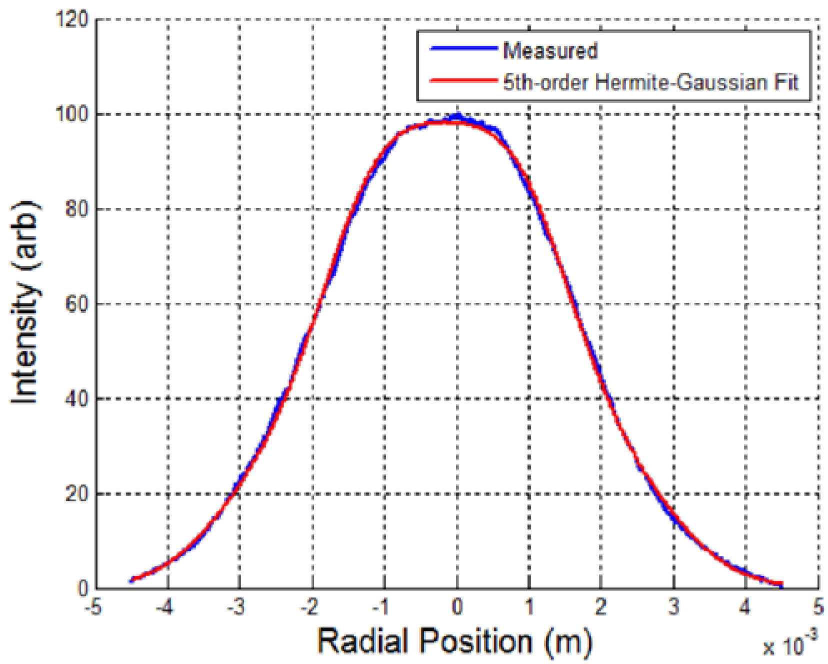
$$\zeta(z) = \tan^{-1}\left(\frac{z}{z_R}\right) \qquad w(z) = w_0\sqrt{1+\frac{z^2}{z_R^2}} \qquad R(z) = z\left(1+\frac{{z_R}^2}{z^2}\right)$$

$$k_{eff} = k - \frac{1}{z_R} + \frac{z_0^2}{z_R^3} + \frac{kr^2}{2z_R^2} + \mathcal{O}(\frac{z_0^2}{z_R^2})$$

Revised Gouy Phase

$$\frac{\delta k_{\text{eff}}}{k_{\text{eff}}} = -\frac{\lambda^2}{2\pi^2 w_0^{\ 2}}\left(1 - \frac{z_0^{\ 2}}{z_R^{\ 2}} - \frac{r^2}{w_0^{\ 2}}\right)$$

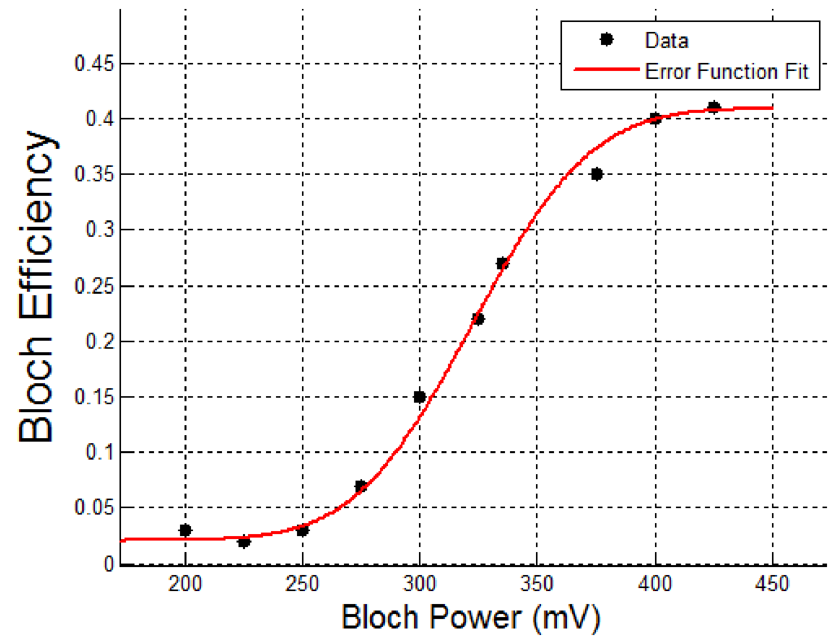
- Previously used knife-edge measurements to verify beam was Gaussian (within error)
- Suspected not Gaussian, based on 3D propagation
- With Scanning-slit/CCD, determined not Gaussian
- Use Monte Carlo to determine on-axis and wavefront-curvature corrections



French Effect

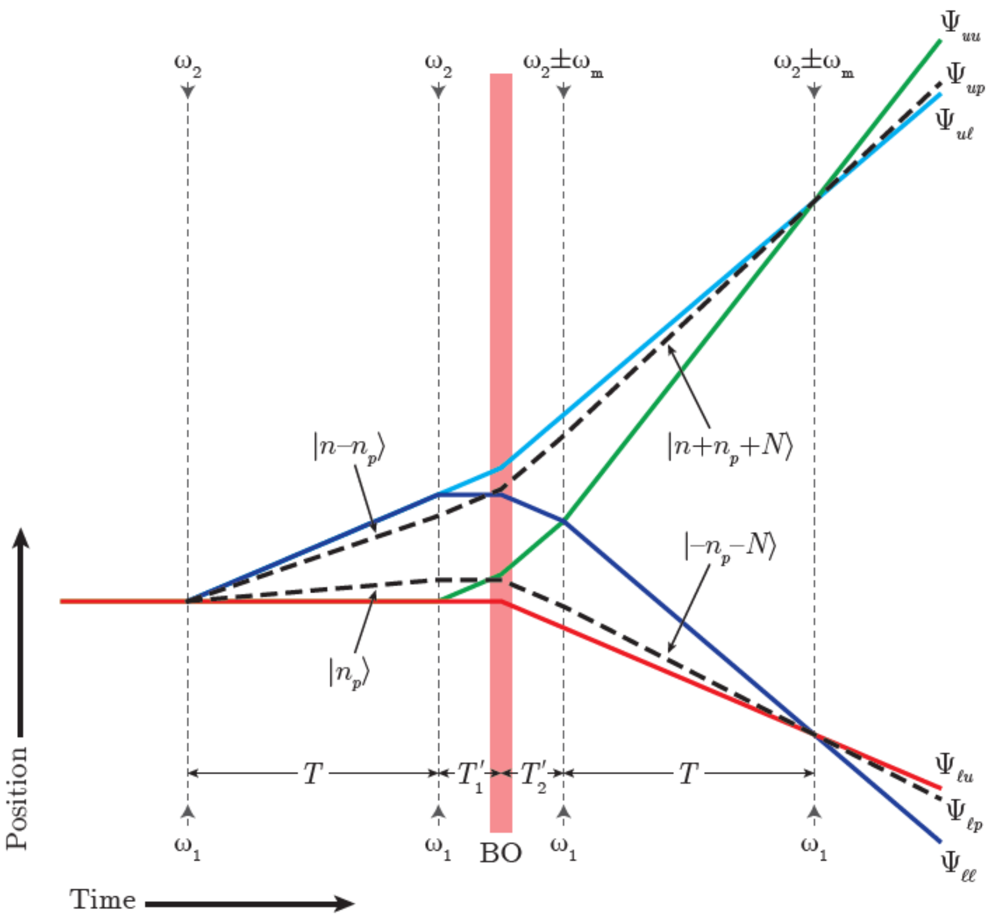
$$\frac{\delta k}{k} = \frac{1}{2k^2} \frac{\nabla_\perp^2 E}{E}$$

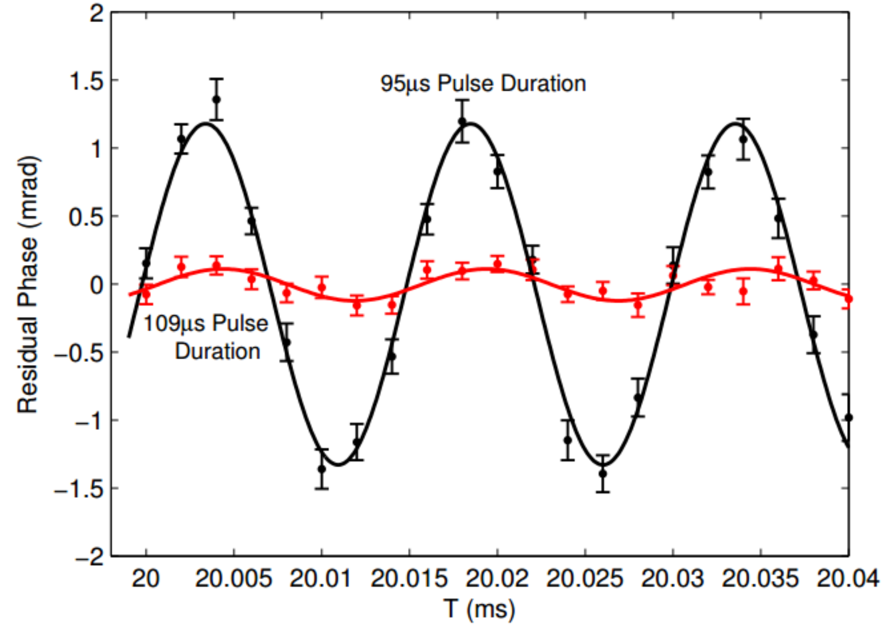
- Small-scale intensity variations can lead to dramatic changes in Gouy phase
- Doesn't average out!
- Can be >10ppb
- Use 3D Monte Carlo, CCD images, and Bloch Efficiency data to estimate effect
- <0.1 ppb for us

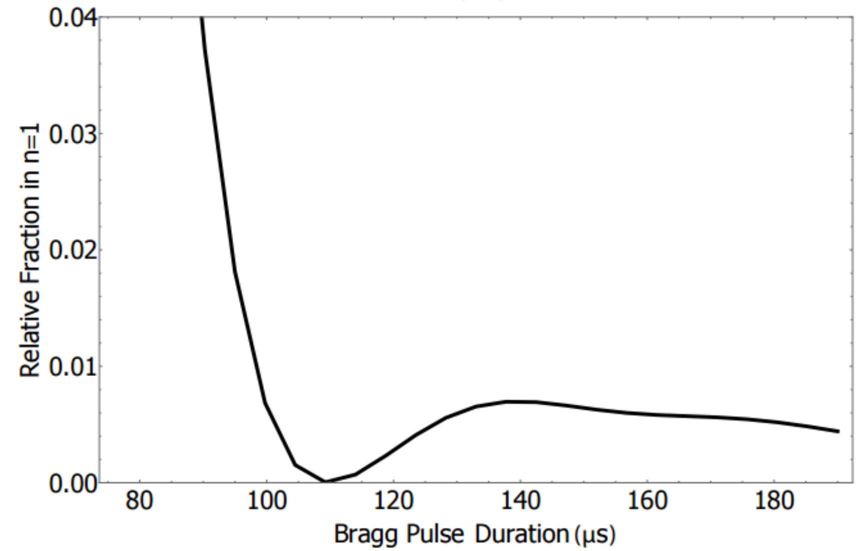


Parasitic Interferometers

$$\phi_p = \pm 8 n_p (n_p + N)\omega_r T \pm n_p \omega_m T + \phi_c(n_p)$$



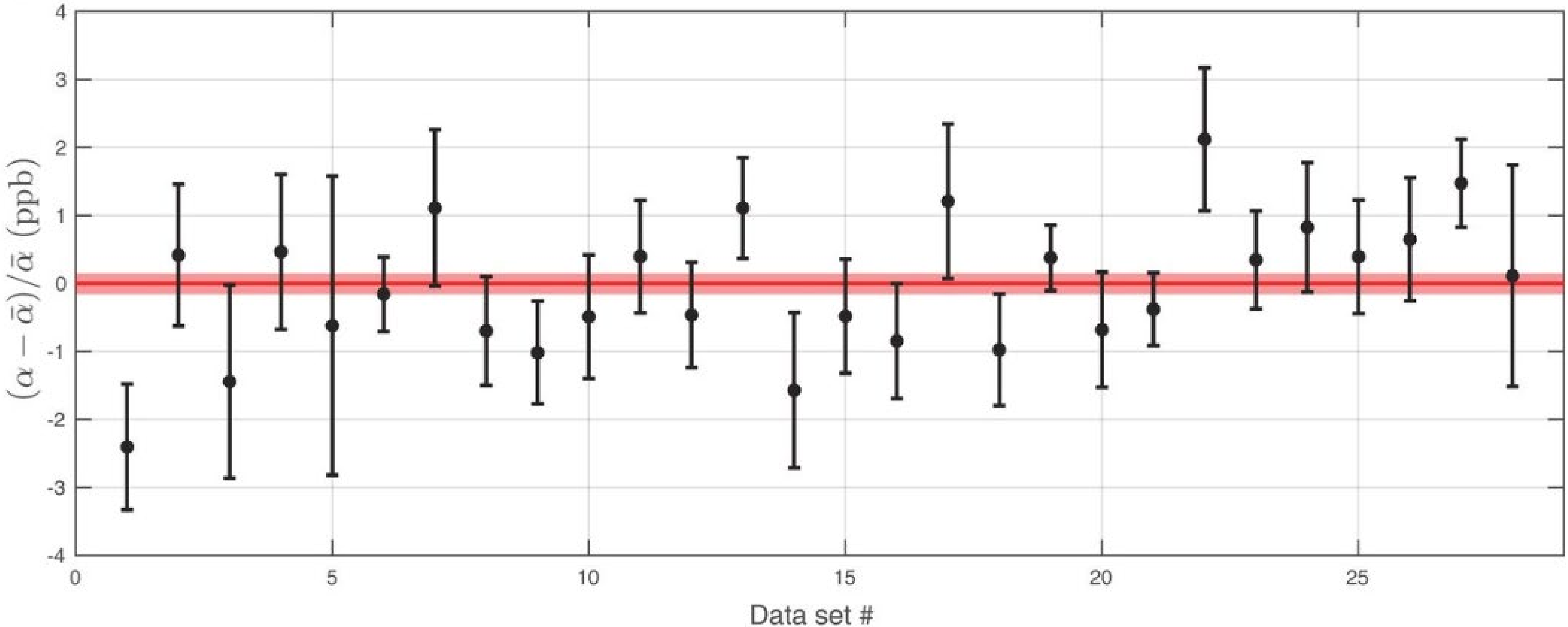




Data

Data taken from December 2016 to June 2017

0.16 ppb statistical uncertainty.

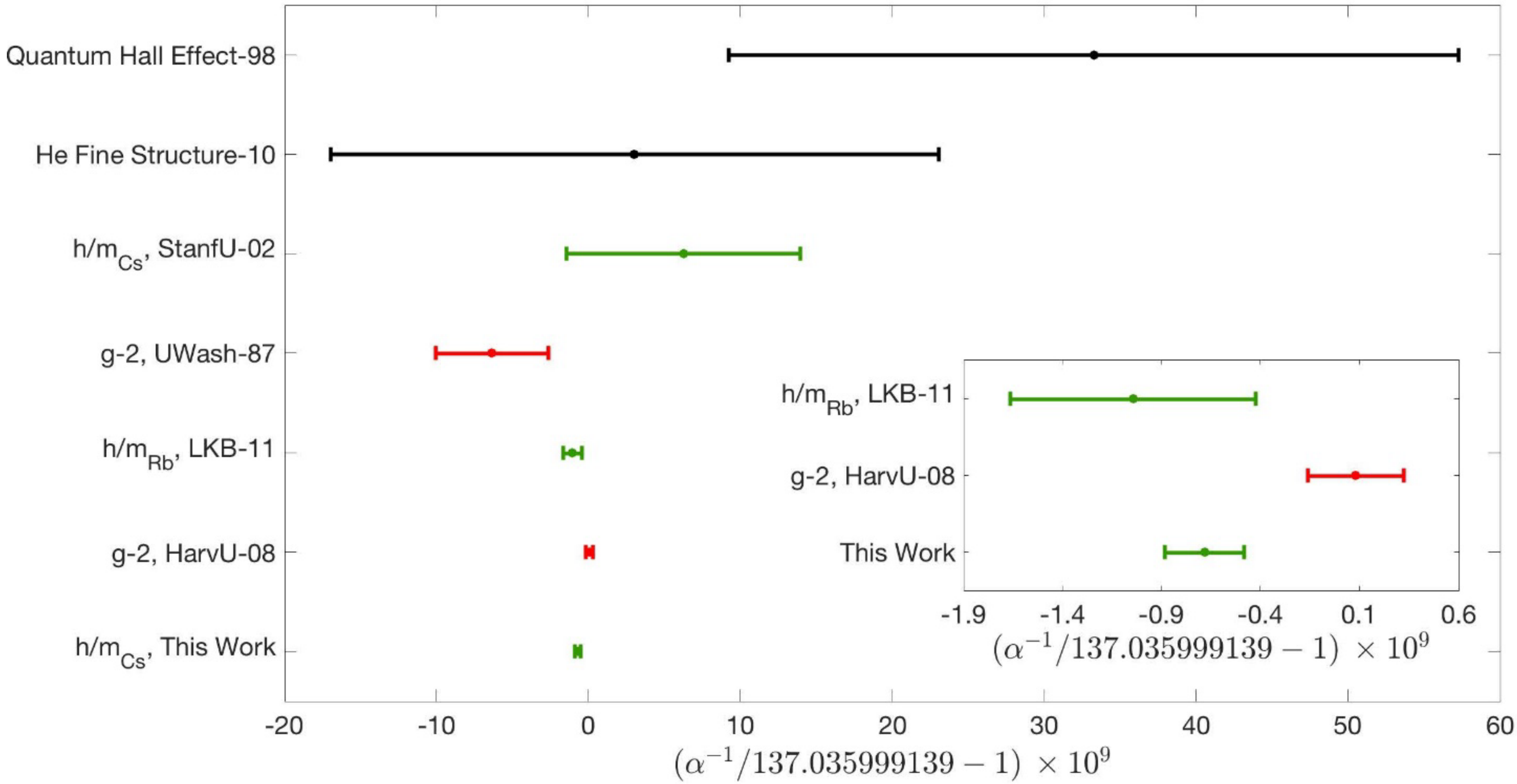


Systematic Checks

- Variation of alpha w.r.t.:
  - Beam Waist
  - Bloch order
  - Bloch power
  - Contrast
  - Detection region
  - ω_m mixing (RF)
  - ω_m mixing (optics)
  - Intensity balance between pulses
  - Delay of interferometer sequence
  - Bias B-field
  - Single-photon detuning
  - Data Analysis parameters (cuts, fitting, etc.)

The Fine Structure Constant

$\alpha = 1/137.035999046(27)$

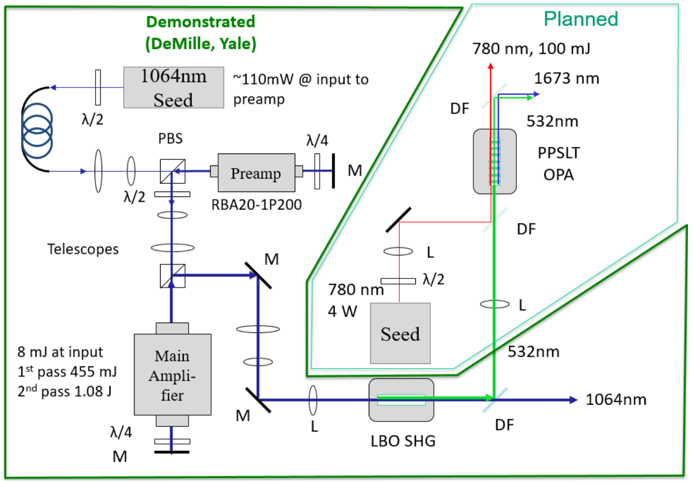


A 2.5σ tension:

$$\delta a = a_{Penning\ Trap} - a_{SM}(\alpha_{Cs}) = -0.88(0.36) \times 10^{-12}$$

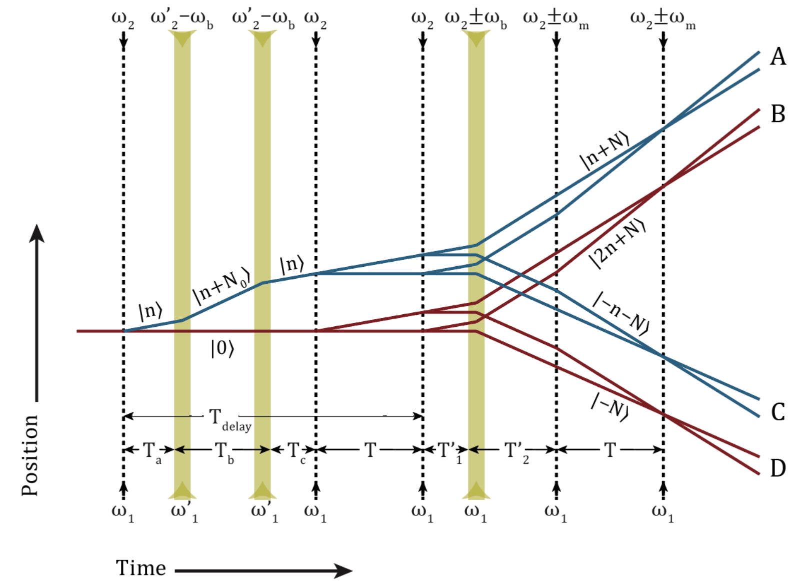
Future Upgrades

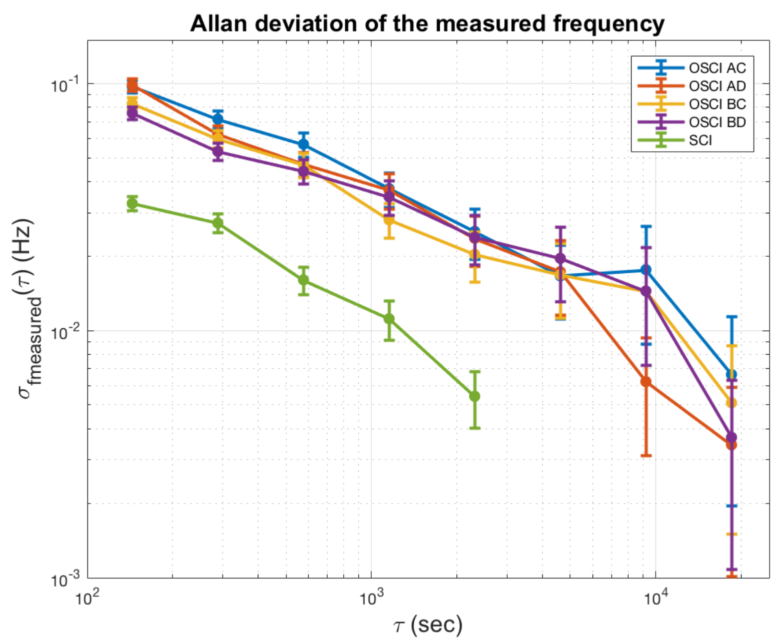
- Big Vacuum System
  - x20 waist → x400 supp.
- Pulsed Laser
  - x1000 eff. power
- EM/Acoustic Shielded Room



Future Upgrades

- Offset Simultaneous Conjugate Interferometers (OSCI)
- Multichannel AI
- One channel: insensitive to gravity gradient.
- Don't need to know gravity gradient
- But…reduced statistics
- Increase n and N to compensate?





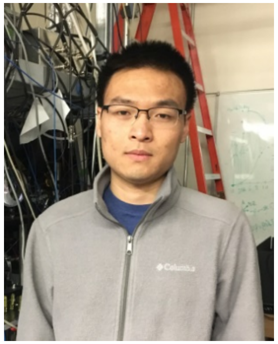
Thank you!

PI: Holger Müller

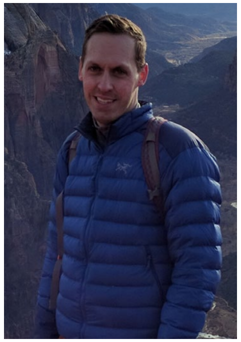
Postdoc: R. Parker

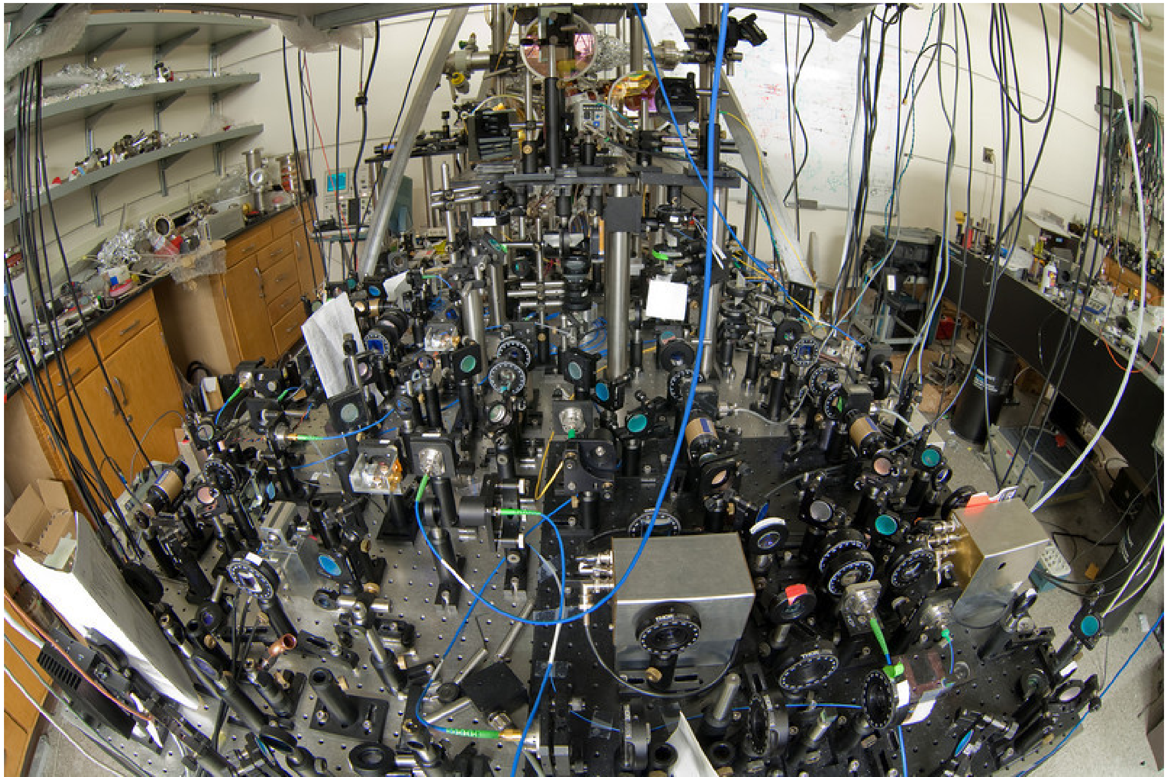
Grad: Chenghui Yu

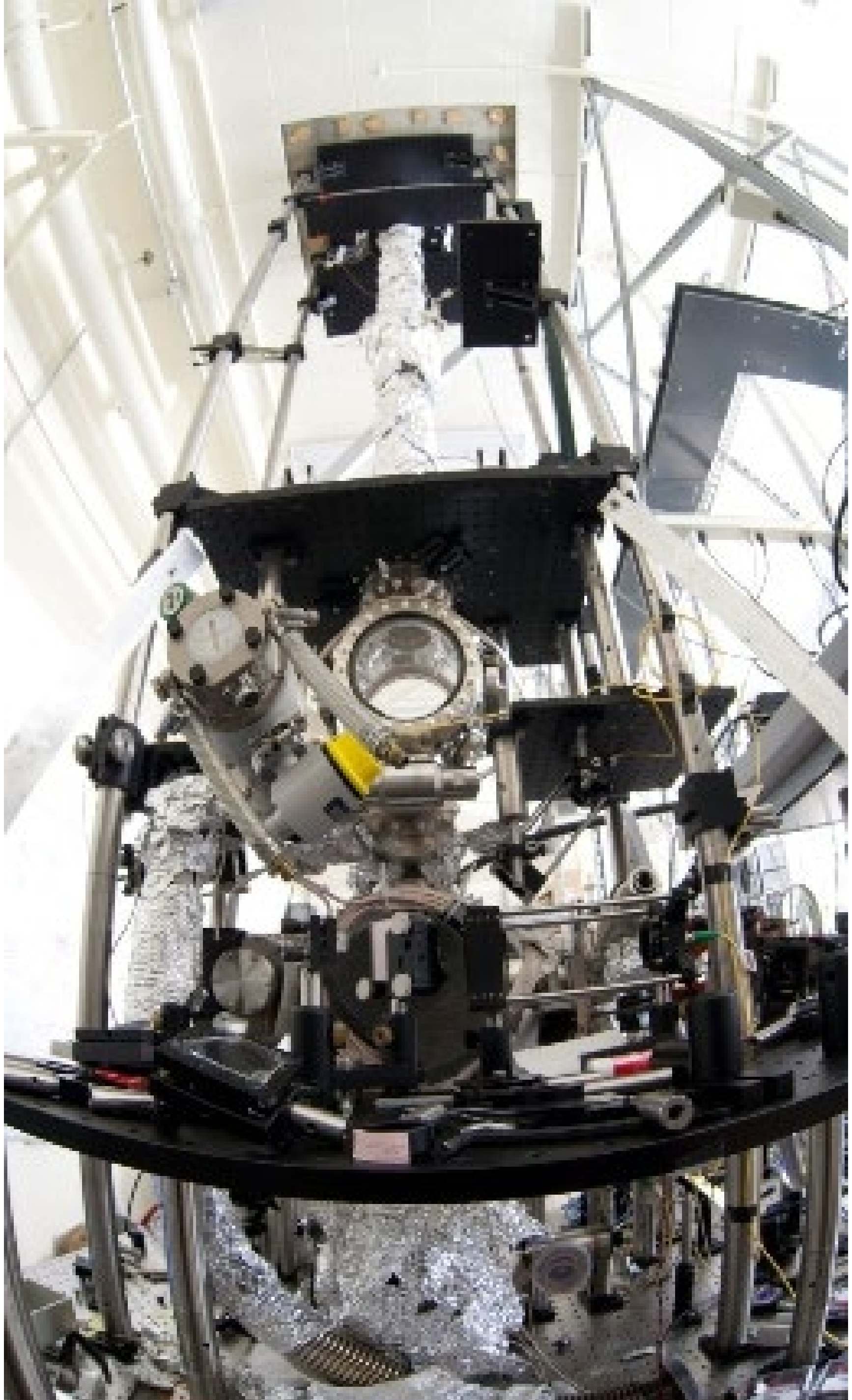
Grad: Weicheng Zhong

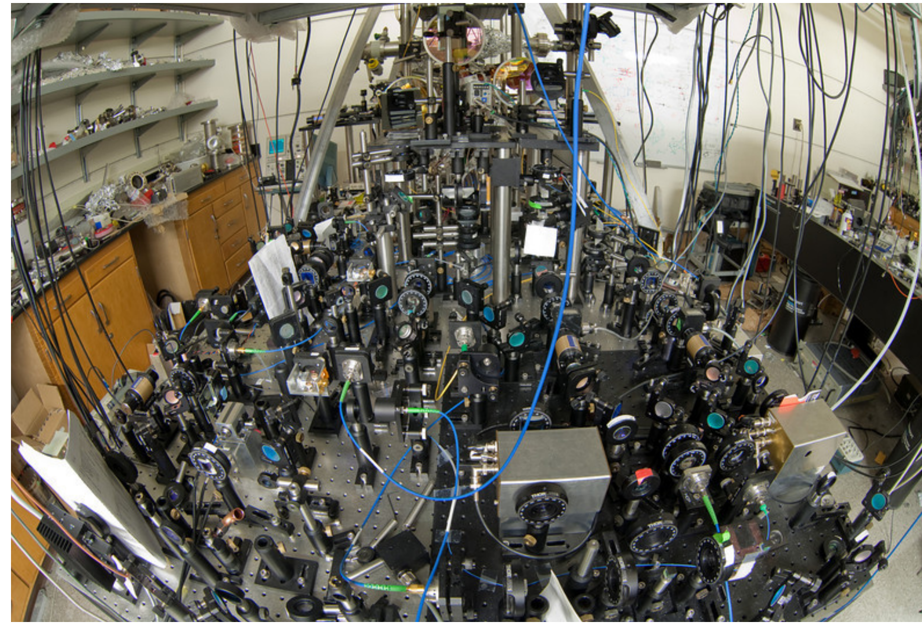


Former Grad: Brian Estey

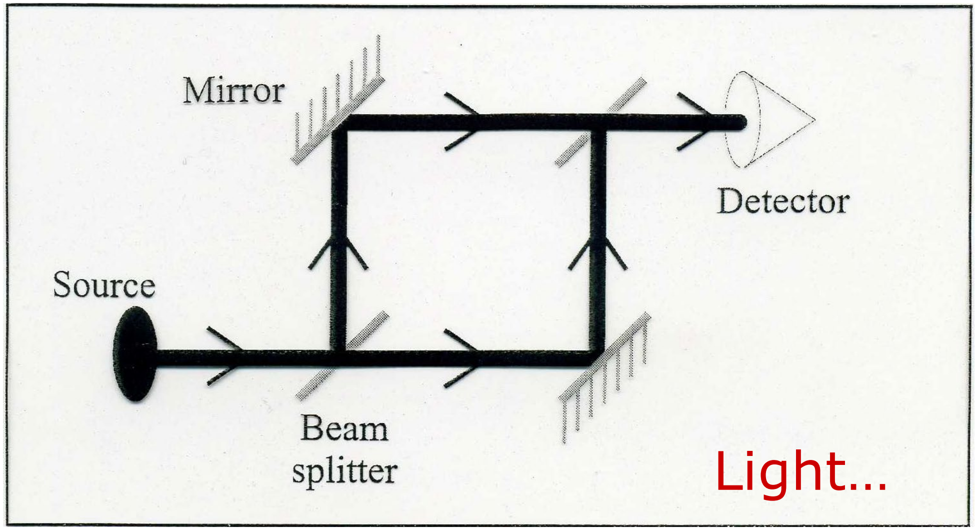


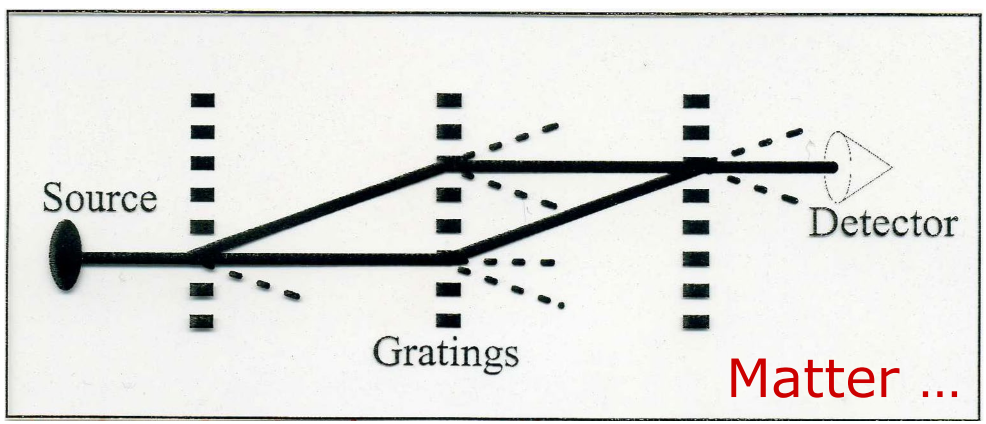






Matter Wave Interferometry

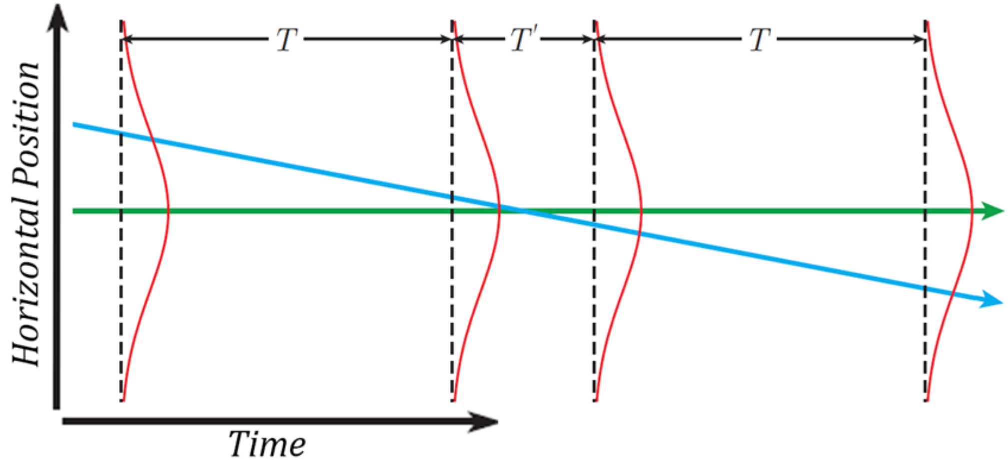


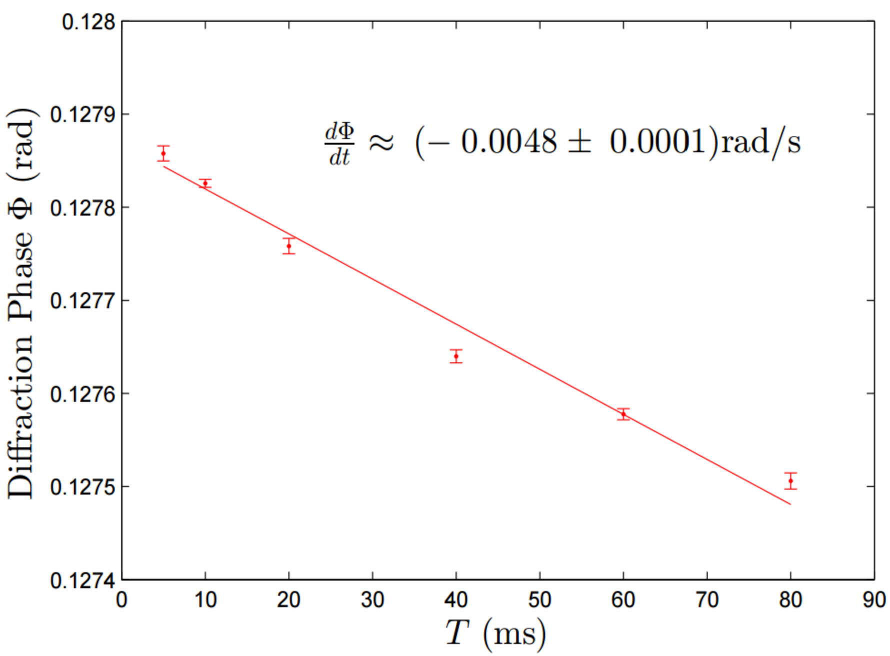


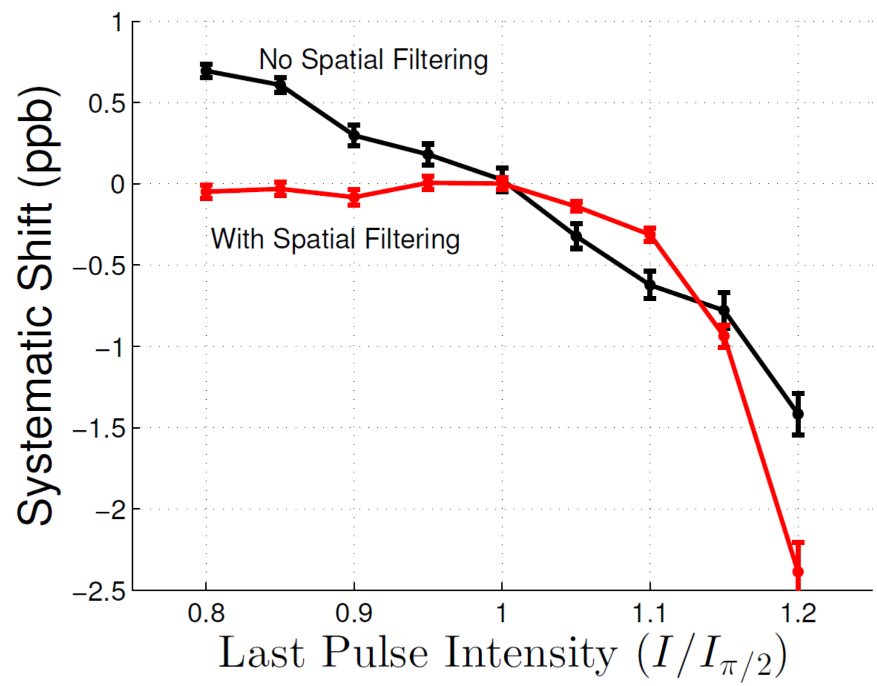
Clipping Phase

$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T + \Phi_0 + \eta T + \ldots$$

- Atom Motion → T-dependent diffraction phase
- Sensitive to pulse intensities, detection volume, …
- 2-point Spatial Filtering
  - Reduce VS waist
  - Reduce detection volume

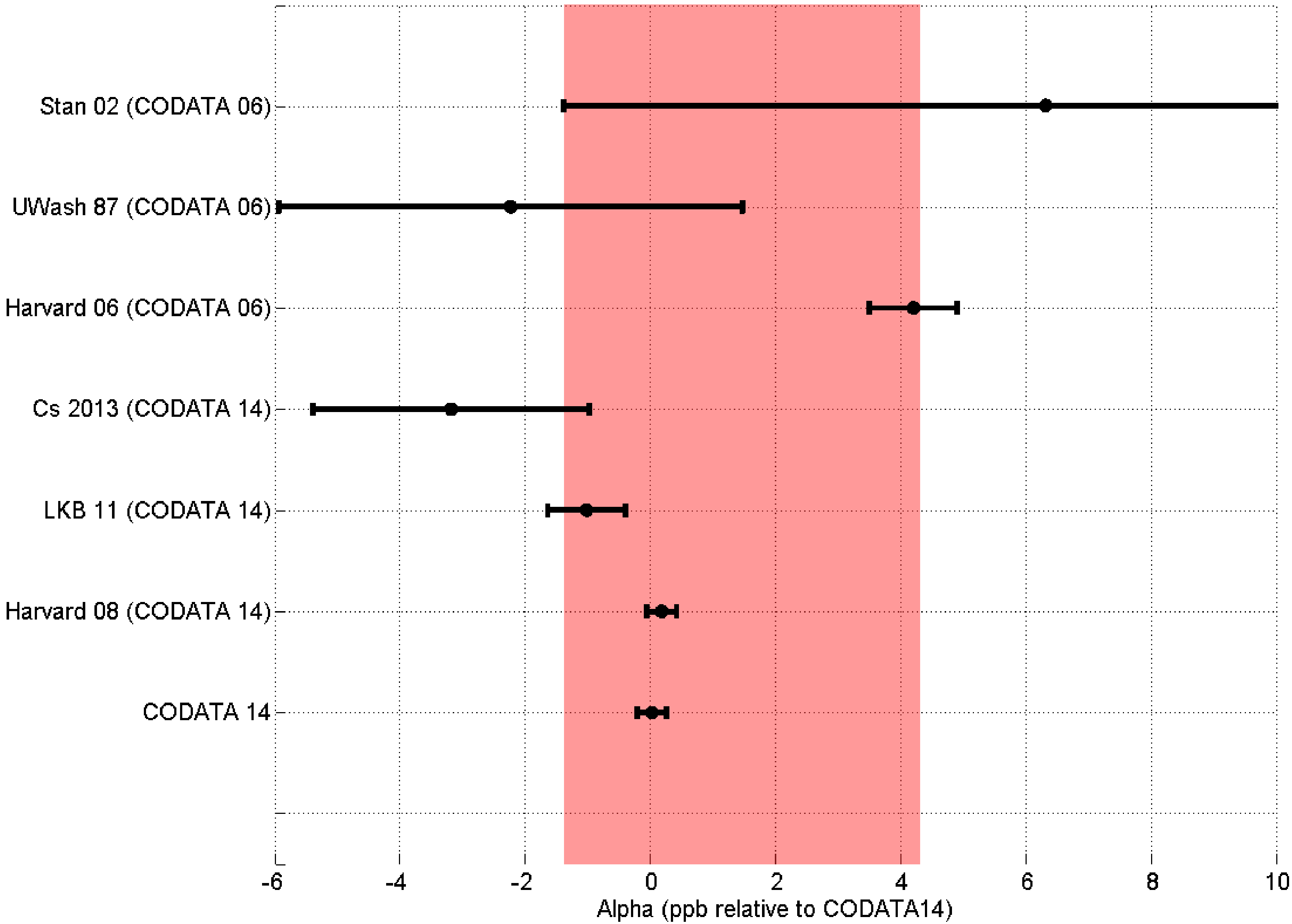




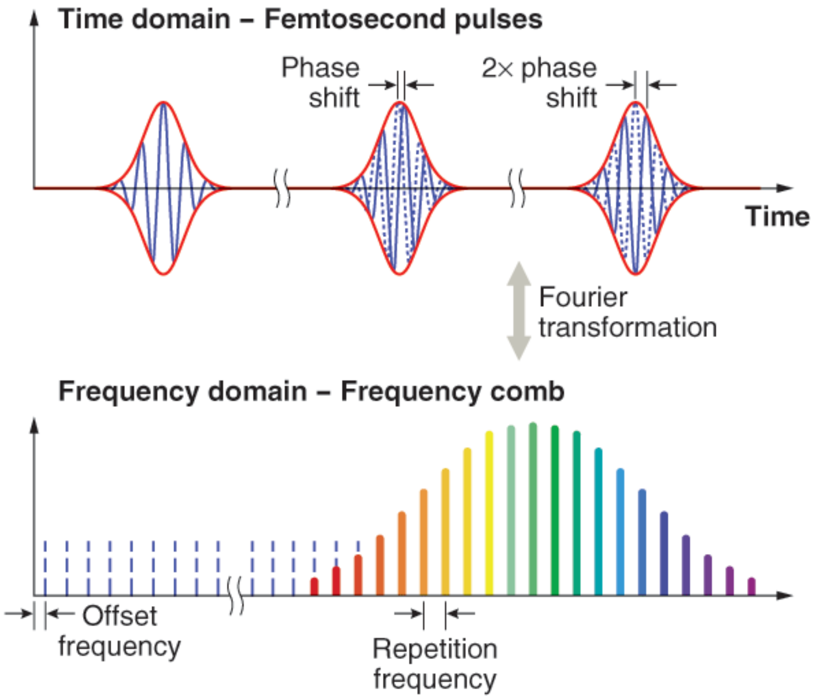


Estey, PRL 2015; Parker, PRA 2016

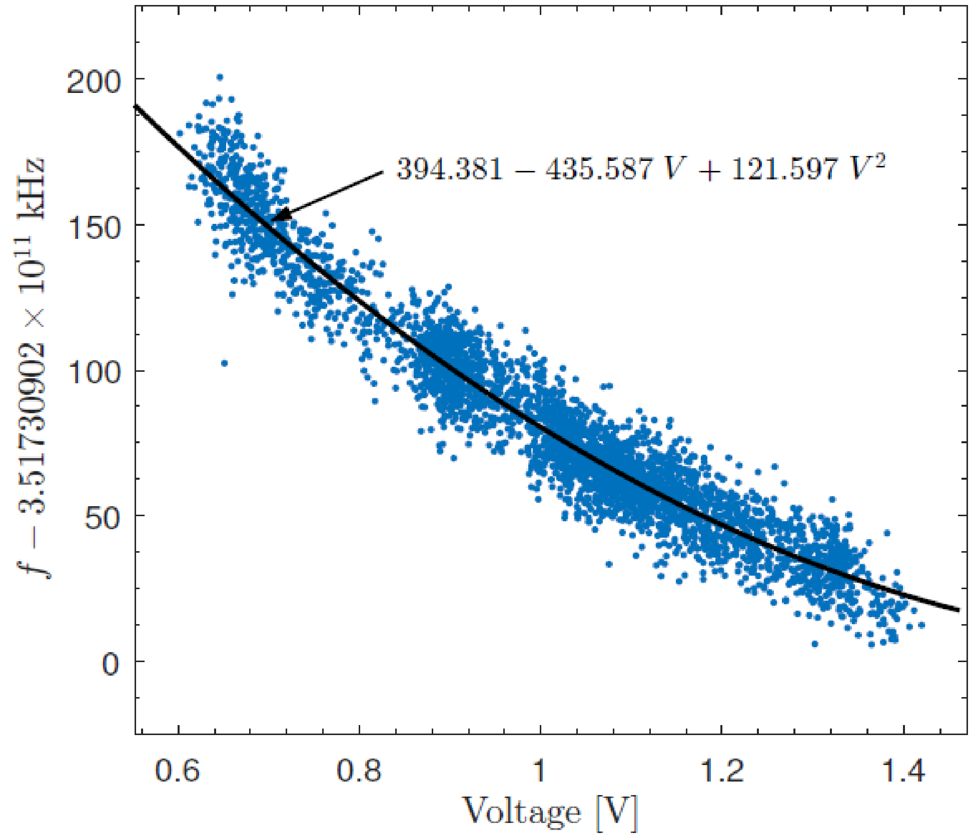
Partial Unblinding



Laser Frequency



$$f_n = nf_r + f_{offset}$$

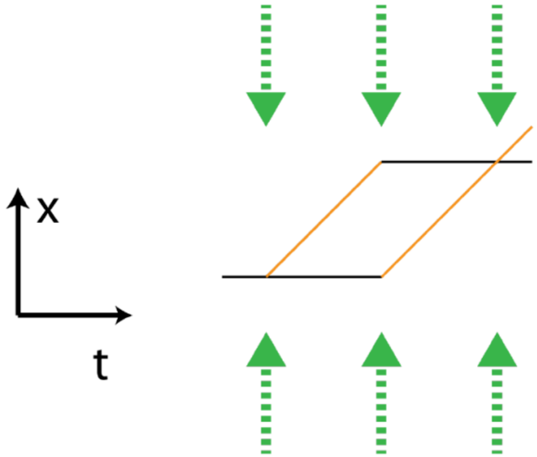


Laser frequency as a function of power send into the spectroscopy

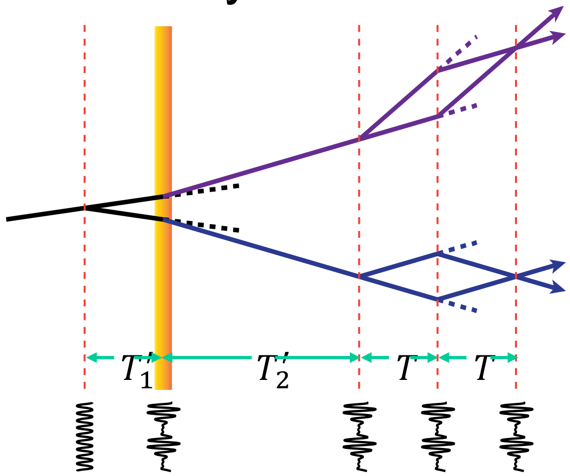
Frequency residual = 10 kHz → 0.03 ppb

Matter Wave Interferometry

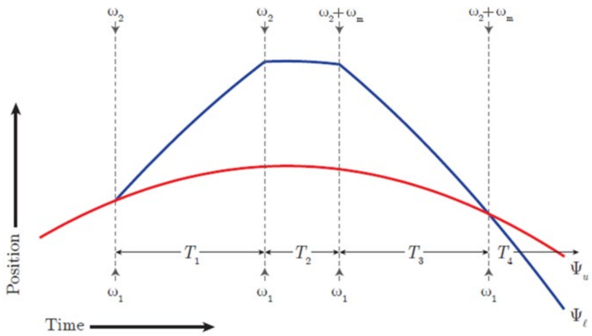
Local Gravity



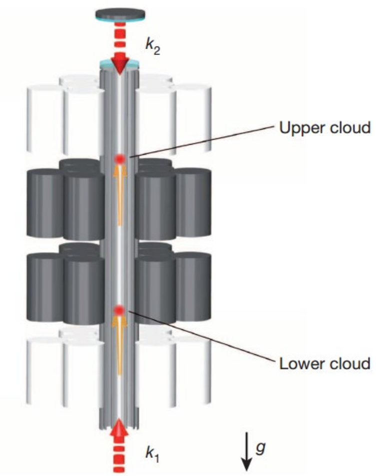
Gravity Gradients



Recoil Frequency

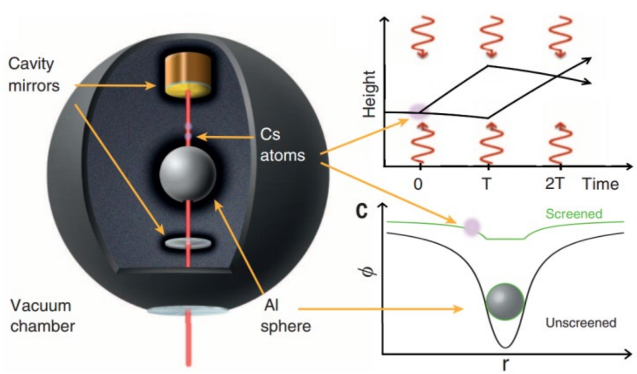


Newton's G



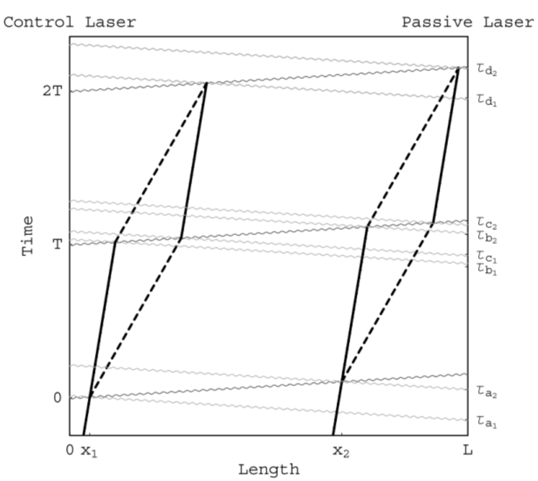
Nature, 510, 518 (2014)

Dark Energy



Science, 349, 849 (2015)

Gravitational Waves



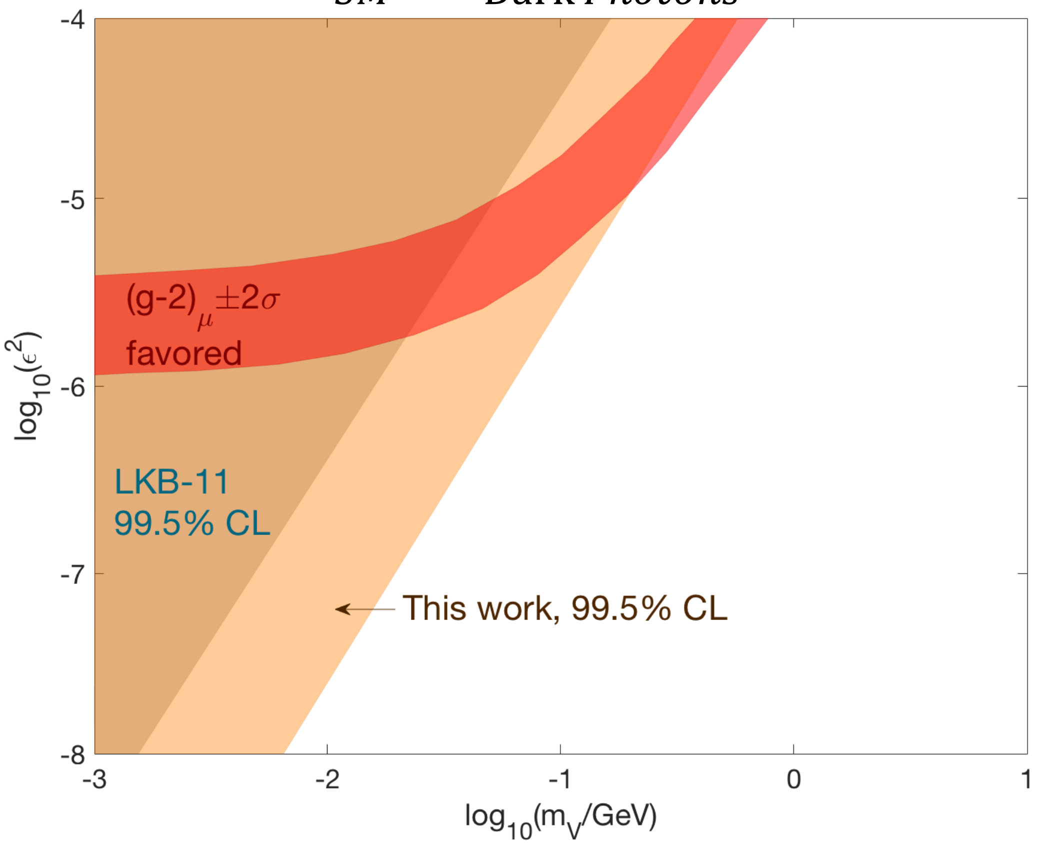
Phys. Lett. B, 678, 1 (2009)

Could it be Dark Photons?

One explanation for the 3.4σ discrepancy in the muon $g_\mu - 2$

$$\mathcal{L}_{Dark\ Photon} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{m_V^2}{2}A'_\mu A'^\mu - \epsilon e\bar{\psi}A'_\mu\gamma^\mu\,\psi \rightarrow \delta a > 0$$

$a_{SM} + a_{\mathrm{Dark}\ Photons}$?



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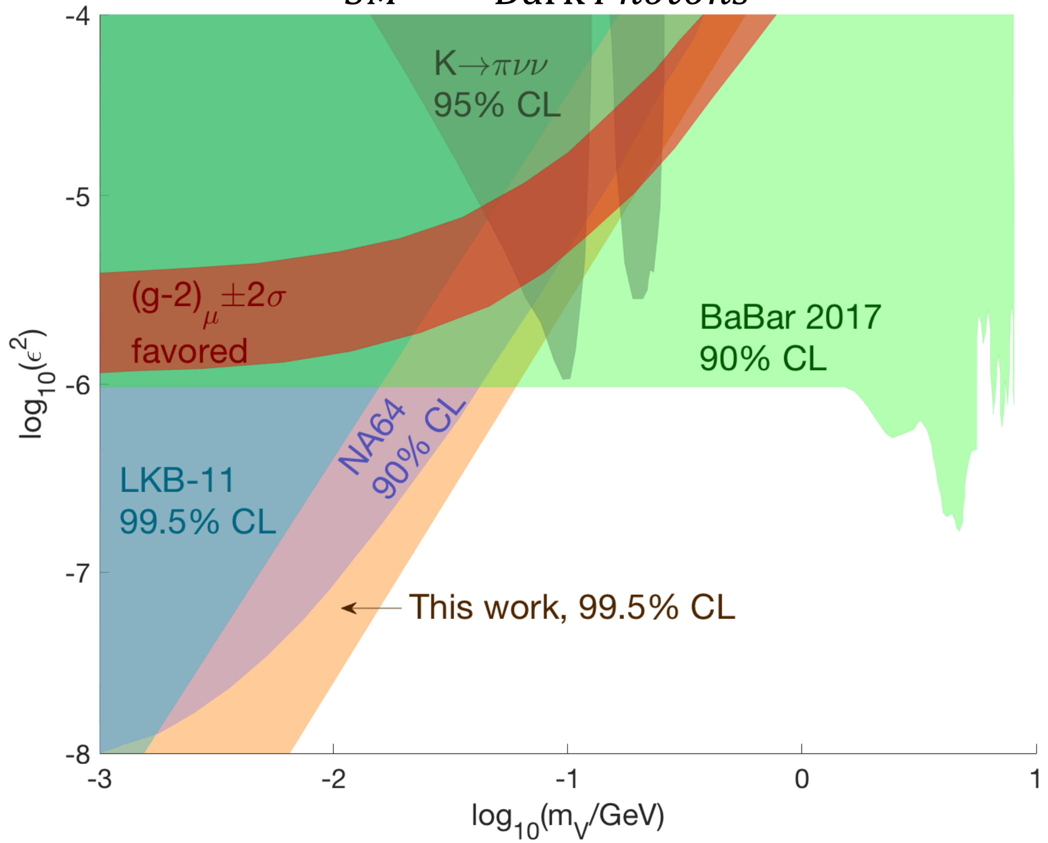
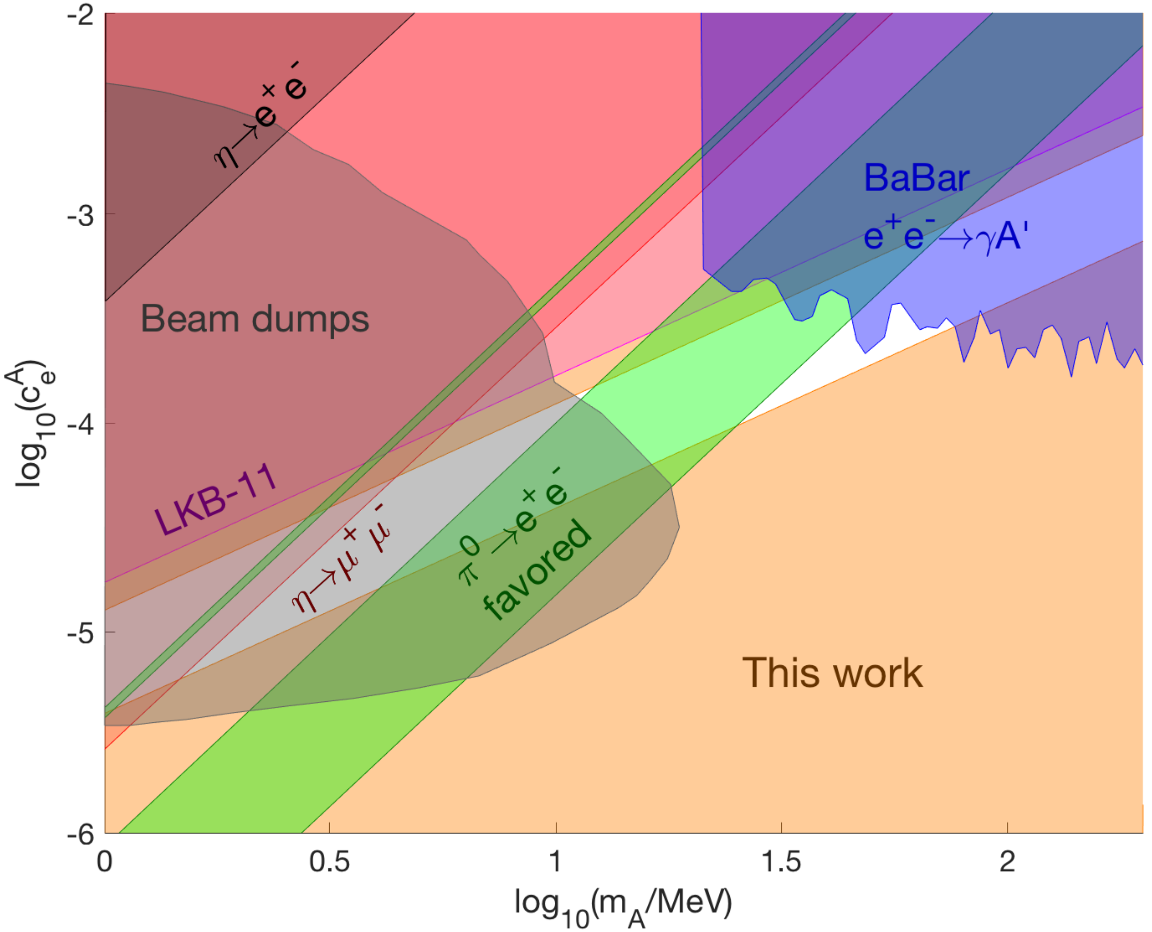
$a_{SM} + a_{\text{Dark}\,Photons}$?

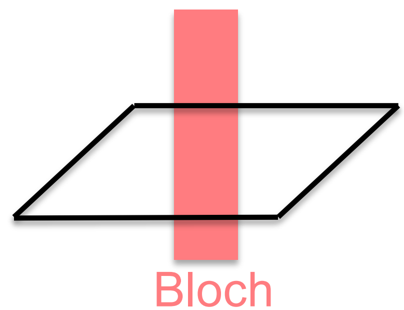
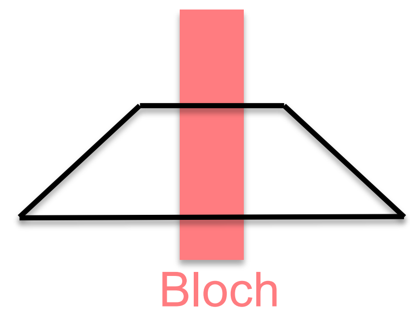


Axial-Vectors?

$a_{SM} + a_{\text{Dark } Axial\ Vectors}$?



Comparing LKB and Berkeley

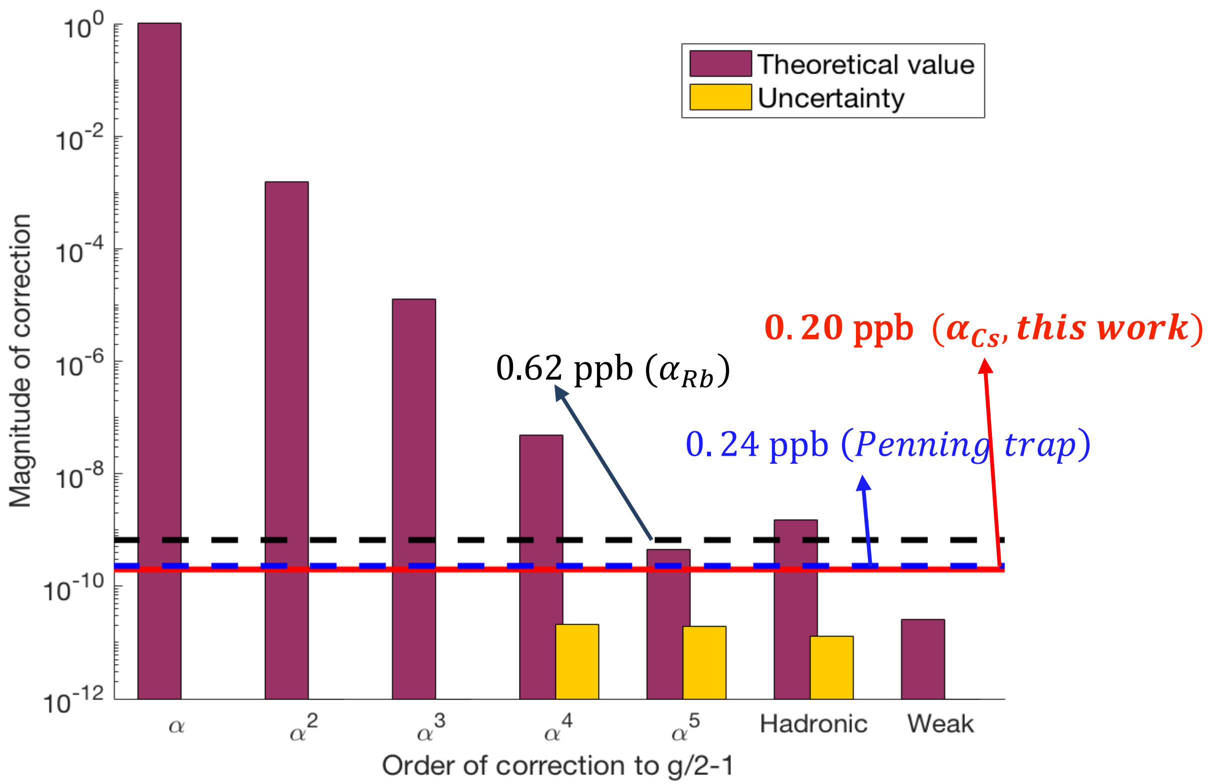
	LKB	Berkeley
Beamsplitter Type	Raman	Bragg
Momentum Splitting	$2\hbar k$	$10\hbar k$
Recoil Frequency	3.7 kHz	2.1 kHz
Interferometer Geometry		
Phase Scaling	$\phi \sim nN\omega_r T$	$\phi \sim n(n+N)\omega_r T$
Dual Interferometers?	No	Yes
N_{max}	500	200
T_{max}	10 ms	80 ms
Future Upgrades	BEC	Large Beam

Testing QED with Alpha

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

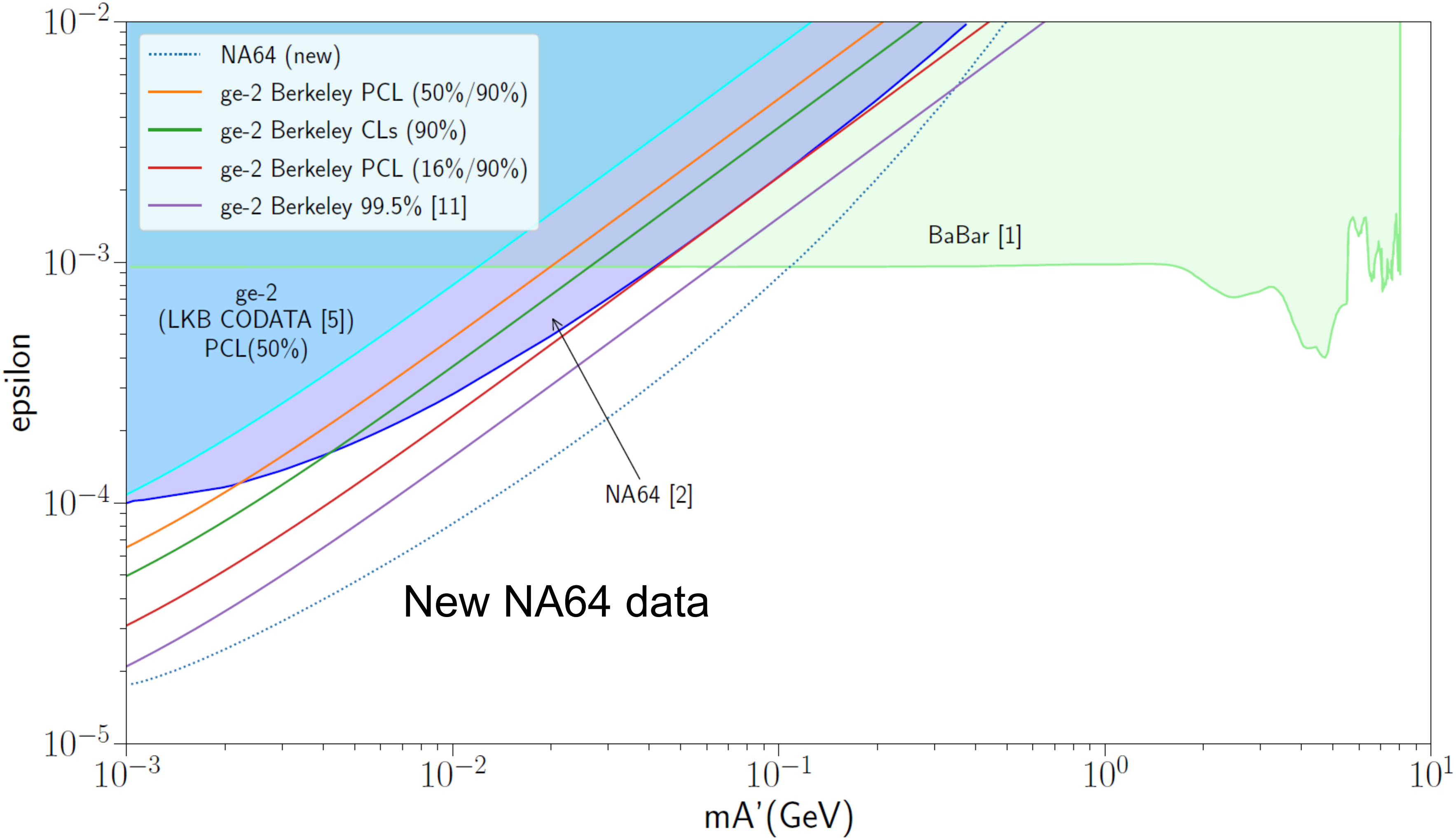
QED

$$a_{SM}(\alpha_{Cs}) = 0.00115965218161(23)$$



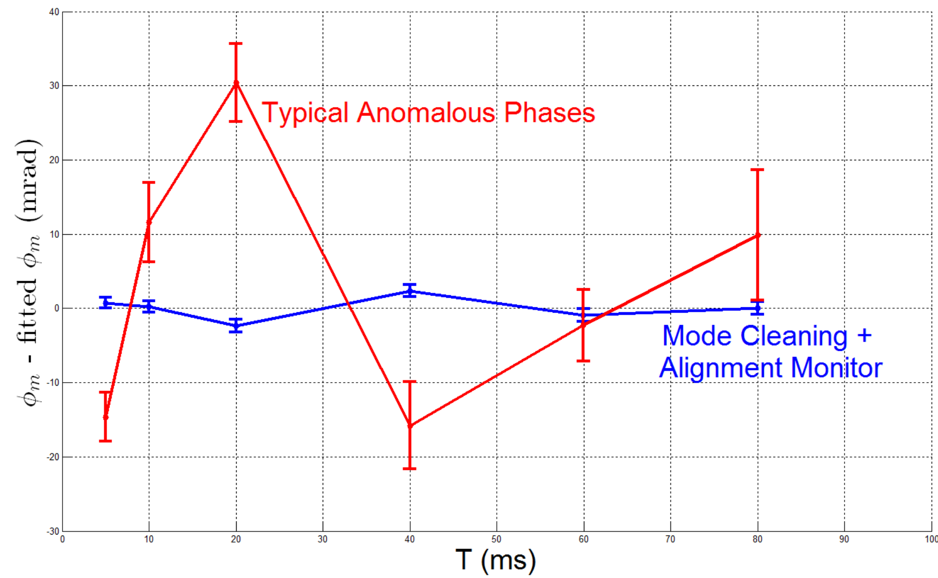
PRL 109, 111807 (2012)

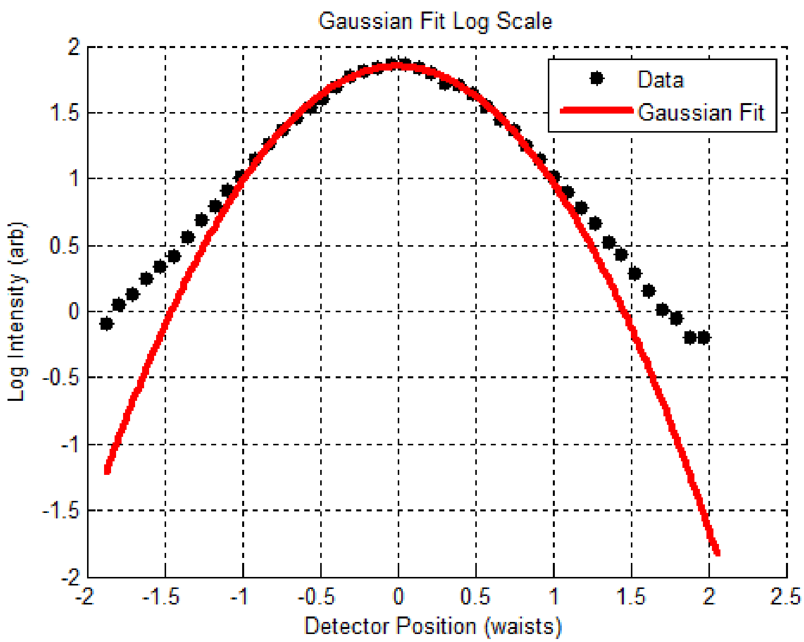
Dark photon Limits



Speckle Phase

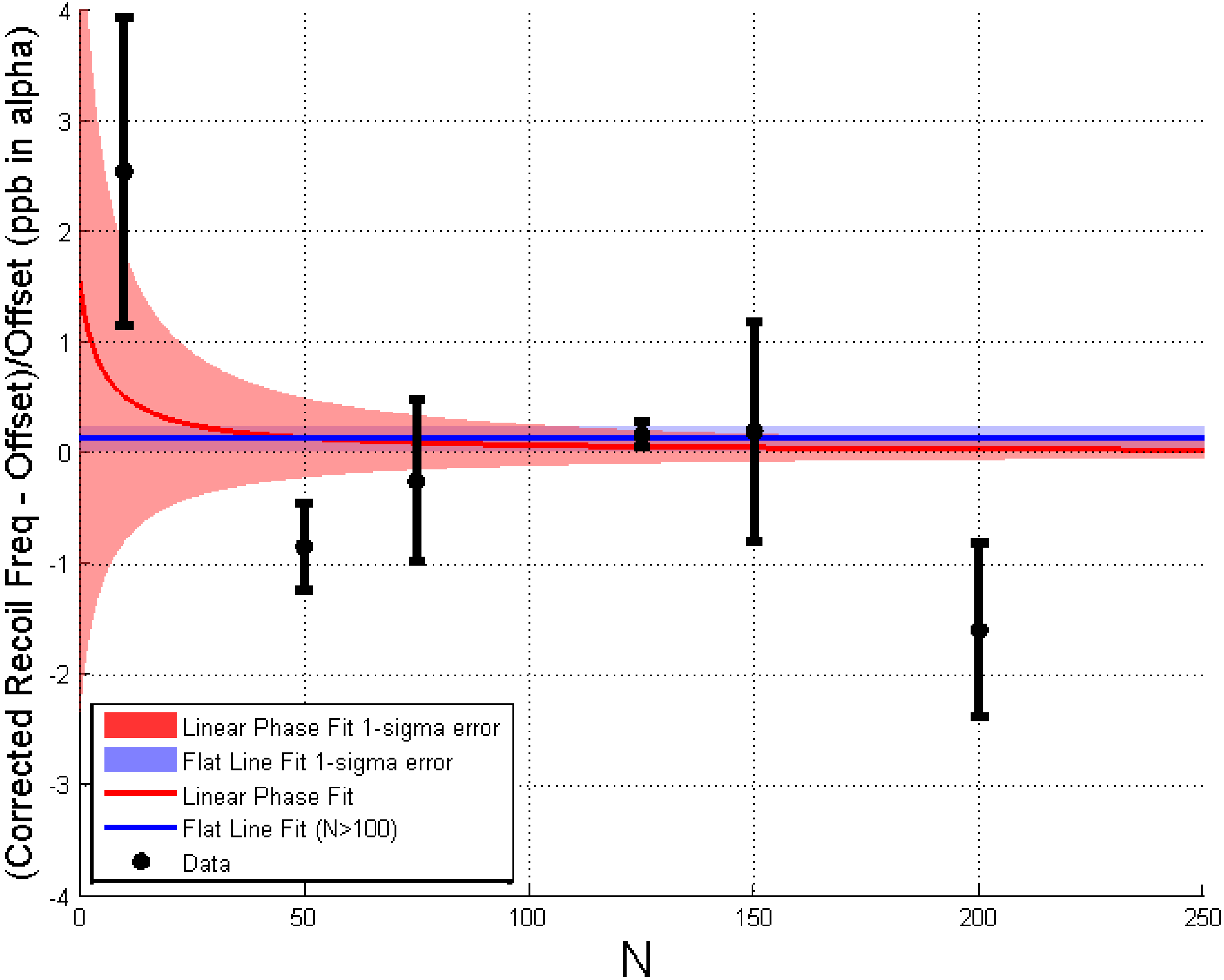
- Anomalous residuals → ~1 ppb
- Dust, scratches, scattering on wall
- 2 Problems:
  - Inhomogenous Rabi frequency
  - Phase shift due to transverse kicks
- Fiber doesn't make Gaussian beams
- Spatial Filtering via Apodizer + Fountain Alignment Monitor





$200 Apodizing Filter

α vs N



(Corrected Recoil Freq - Offset)/Offset (ppb in alpha)
4
3
2
1
0
-1
-2
-3
-4
0
50
100
150
200
250
N
Linear Phase Fit 1-sigma error
Flat Line Fit 1-sigma error
Linear Phase Fit
Flat Line Fit (N>100)
Data

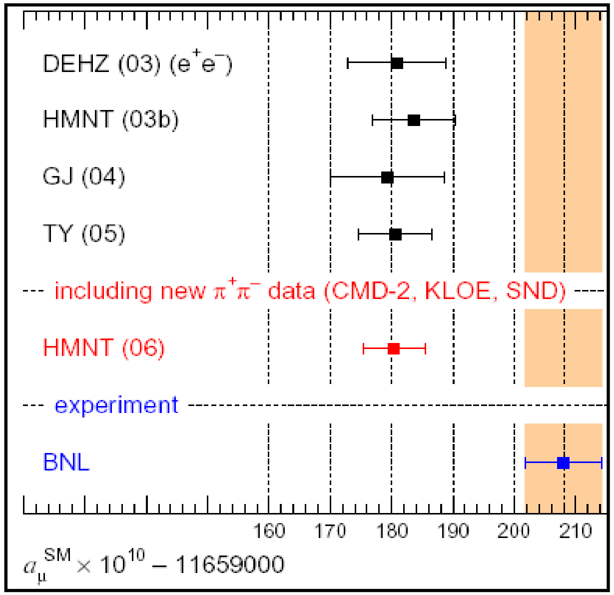
Dark photons

Whatever the dark sector is made of, only three interactions are allowed by standard model symmetries

- Vector portal "massive photon"
- Higgs portal
- Neutrino portal

Hints

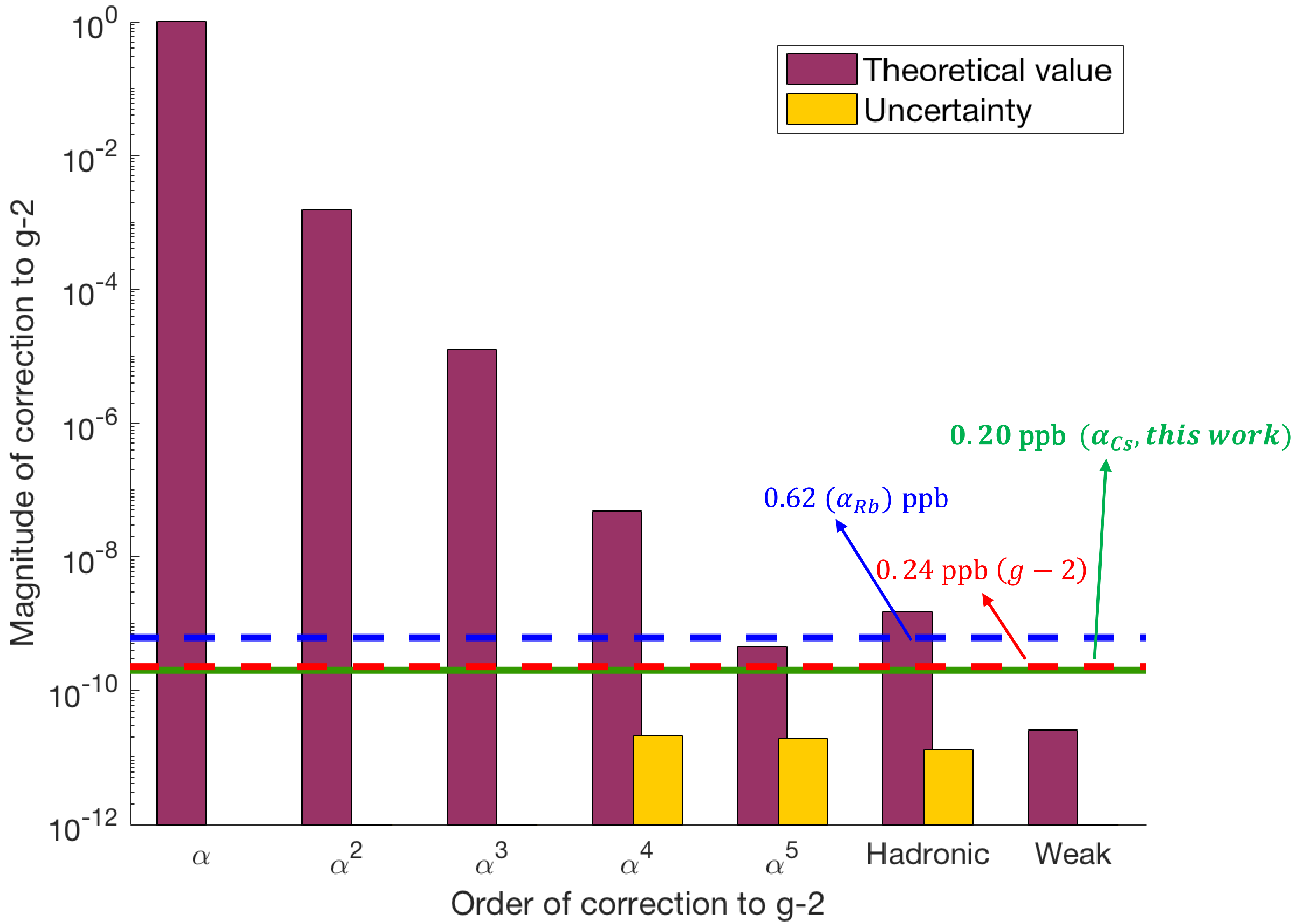
- Muon g-2
- Proton radius puzzle?
- ^{8}Be decay
- Astrophysical hints?
  - 511 keV line
  - keV gamma-ray excess
  - Galactic center excess



"Arguably, the strongest experimental evidence for physics beyond the standard model" (David Hertzog)

K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner

Results



Magnitude of correction to g-2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Theoretical value
Uncertainty
0.20 ppb (α_{Cs}, *this work*)
0.62 (α_{Rb}) ppb
0.24 ppb ($g-2$)
α
α^2
α^3
α^4
α^5
Hadronic
Weak
Order of correction to g-2

4 hbar k Bragg pulse