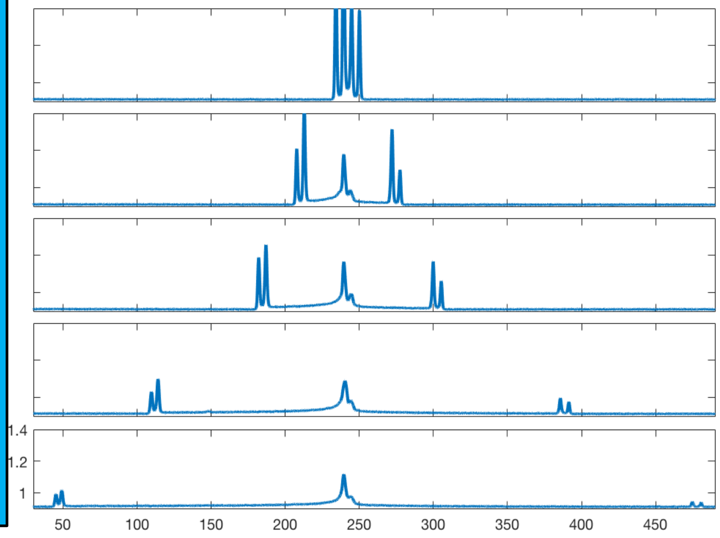
A measurement of the fine structure constant as test of the standard model



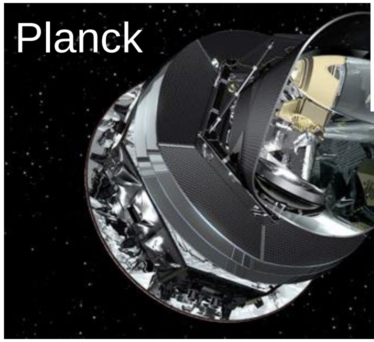
Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and H. Müller

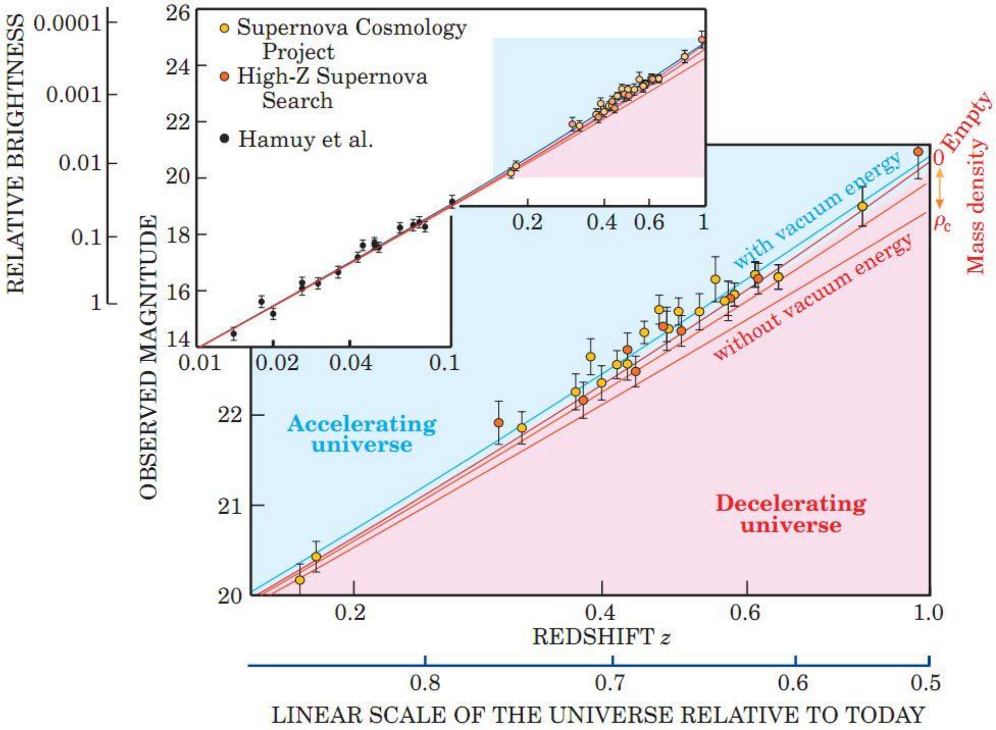
U.C. Berkeley

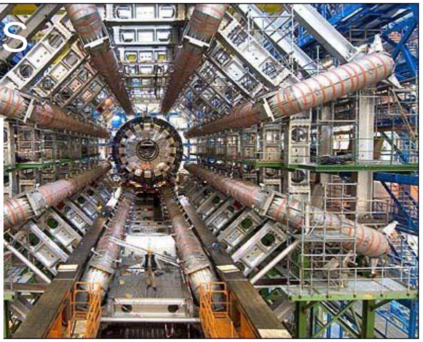
The Era of precision uncertainty

Loud and clear signals from the skies….

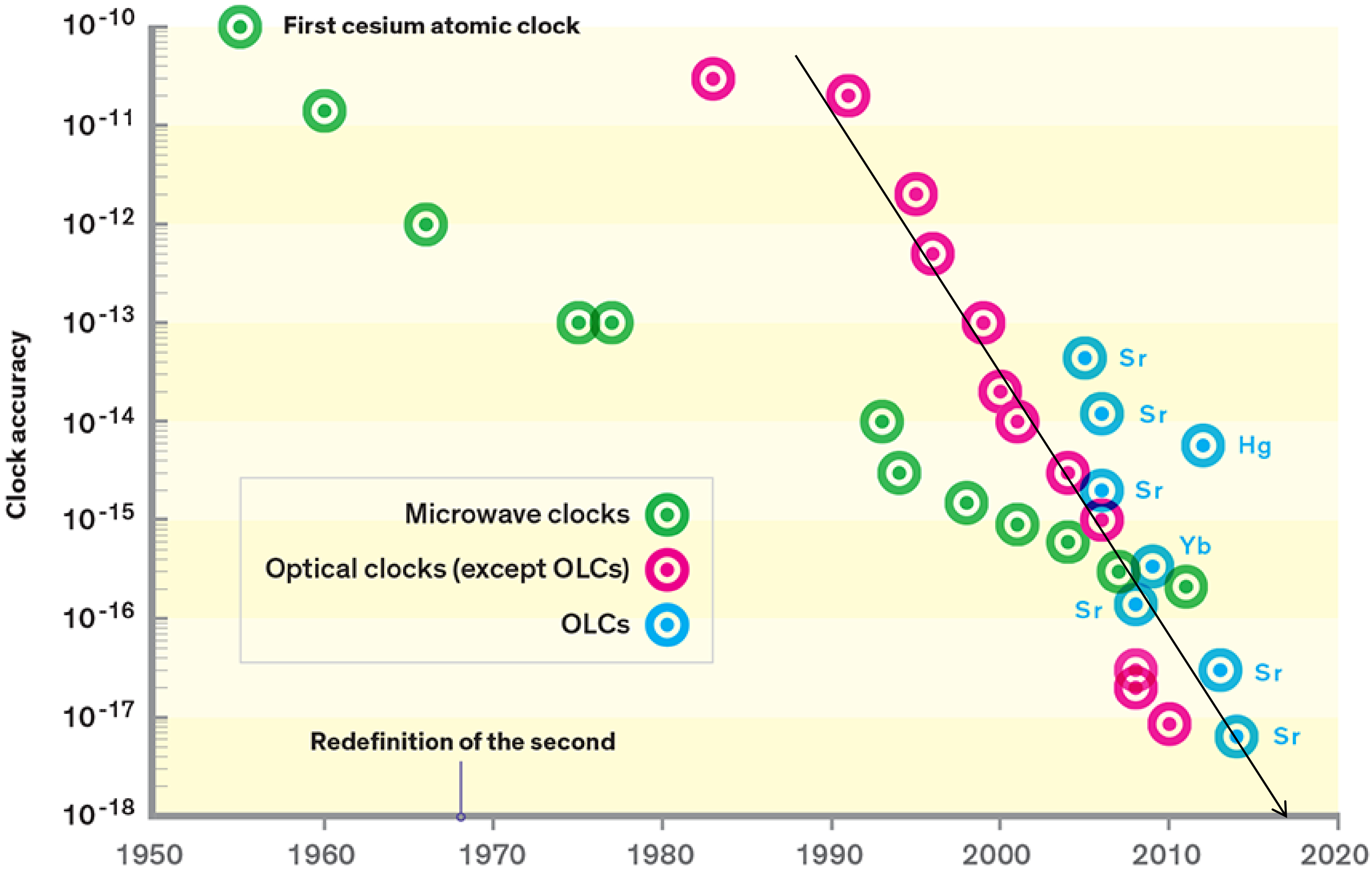
…but silence in our detectors







Moore's law in atomic physics



Finishing my postdoc

2004-2018

2003: “We can write 3 PRLs in the first year”

The plan

- PRL 1: Multiphoton Bragg diffraction
- PRL 2: Simultaneous interferometers
- PRL 3: Fine structure constant

Reality

- Measurement of the fine-structure constant as a test of the Standard Model. Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and Holger Müller, *Science* **360,** 191-195 (2018).
- Controlling the Multiport Nature of Bragg Diffraction in Atom Interferometry. Richard H. Parker, Chenghui Yu, Brian Estey, Weicheng Zhong, Eric Huang, and Holger Müller, *Phys. Rev. A* **94,** 053618 (2016).
- High resolution atom interferometers with suppressed diffraction phases. Brian Estey, Chenghui Yu, Holger Müller, Pei-Chen Kuan, and Shau-Yu Lan, *Phys. Rev. Lett.* **115,** 083002 (2015)
- A clock directly linking time to a particle’s mass. Shau-Yu Lan, Pei-Chen Kuan, Brian Estey, Damon English, Justin Brown, Michael Hohensee, and Holger Müller, *Science* **339,** 554 (2013)
- Influence of the Coriolis force in atom interferometry. Shau-Yu Lan, Pei-Chen Kuan, Brian Estey, Philipp Haslinger, and Holger Müller, *Phys. Rev. Lett*. **108,** 090402 (2012).
- A precision measurement of the gravitational redshift by the interference of matter waves. Holger Müller, Achim Peters, and Steve Chu, Nature 463, 926 (2010).
- Atom interferometers with scalable enclosed area, Holger Mueller, Sheng-wey Chiow, Sven Herrmann, and Steven Chu, *Phys. Rev. Lett.* **102,** 240403 (2009).
- 6 W, 1 kHz linewidth, tunable continuous-wave near-infrared laser, Sheng-wey Chiow, Sven Herrmann, Holger Müller, and Steven Chu, *Optics Express* **17,** 5246 (2009).
- Noise-Immune Conjugate Large-Area Atom Interferometers, Sheng-wey Chiow, Sven Herrmann, Steven Chu, and Holger Müller, *Phys. Rev. Lett.* **103,** 050402 (2009).
- Atom Interferometry with up to 24-Photon-Momentum-Transfer Beam Splitters, Holger Müller, Sheng-wey Chiow, Quan Long, Sven Herrmann, and Steven Chu, *Phys. Rev. Lett.* **100,** 180405 (2008)
- Diffraction between the Raman-Nath and the Bragg regime: Effective Rabi frequency, losses, and phase shifts. Holger Müller, Sheng-wey Chiow, and Steven Chu, *Phys. Rev. A* **77,** 023609 (2008).
- Multiphoton- and simultaneous conjugate Ramsey-Borde atom interferometers. Holger Müller, Sheng-wey Chiow, S. Herrmann, and S. Chu, AIP Conf. Proc. 977, 291 (2008).
- Coherent Control of Ultracold Matter: Fractional Quantum Hall Physics and Large-Area Atom Interferometry. Edina Sarajlic, Nathan Gemelke, Sheng-wey Chiow, Sven Herrman, Holger Müller, and Steven Chu, Proc. 21st ICAP (2008).
- Extended cavity diode lasers with tracked resonances, Holger Müller, Sheng-wey Chiow, Quan Long, Christoph Vo, and Steven Chu, *Appl. Opt.* **46,** 7997-8001 (2007).
- Nanosecond electro-optical switching with a repetition rate above 20MHz, Holger Müller, Sheng-wey Chiow, Sven Herrmann, Steven Chu, *Rev. Sci. Instrum.* **78,** 124702 (2007).
- A new photon recoil experiment: towards a determination of the fine structure constant. Holger Müller, Sheng-wey Chiow, Quan Long, Christoph Vo, and Steven Chu, *Appl. Phys. B* **84,** 633-642 (2006).

“Will you ever leave Stanford?”

The plan

- No

Reality

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB
Lawrence Berkeley National Laboratory

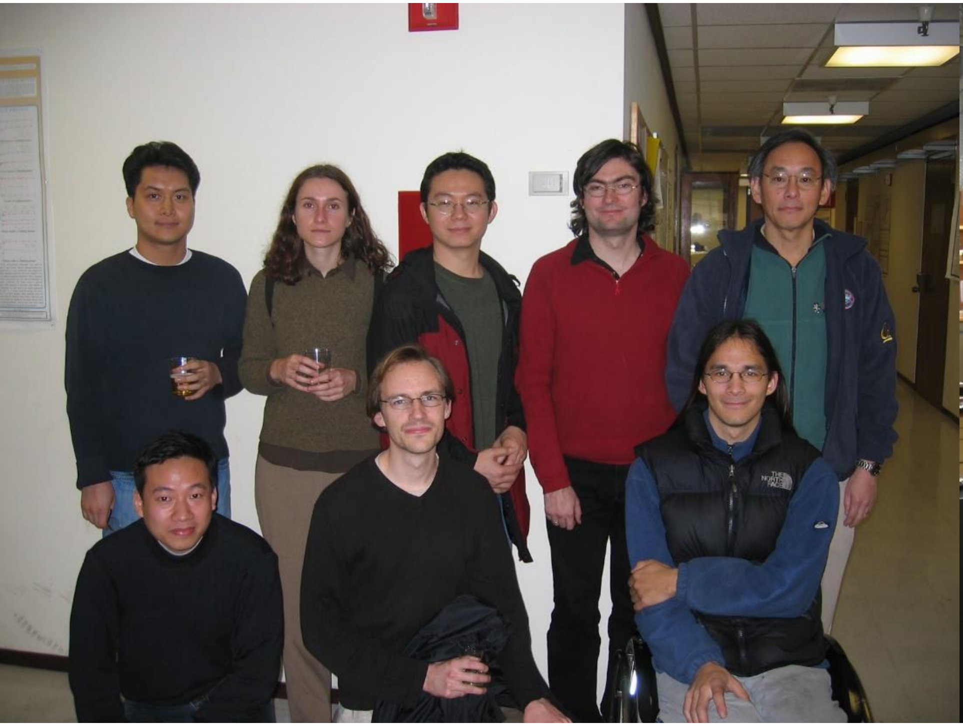
1891

NEWS IN BRIEF

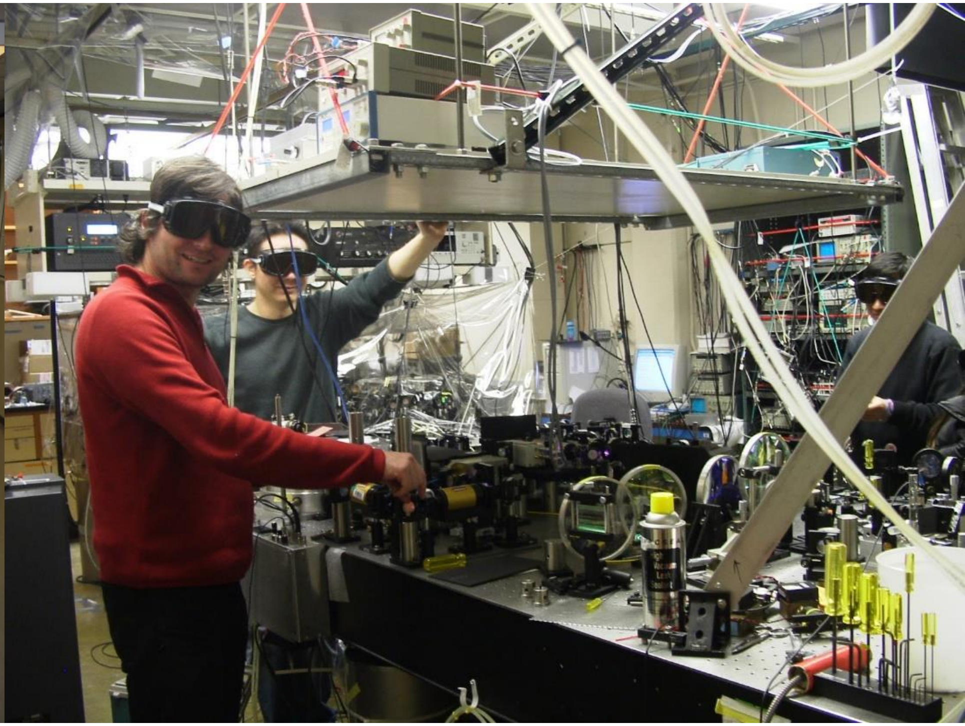
Hungover Energy Secretary Wakes Up Next To Solar Panel

2/07/13 11:52am · SEE MORE: SCIENCE & TECHNOLOGY

WASHINGTON—Sources have reported that following a long night of carousing at a series of D.C. watering holes, Energy Secretary Steven Chu



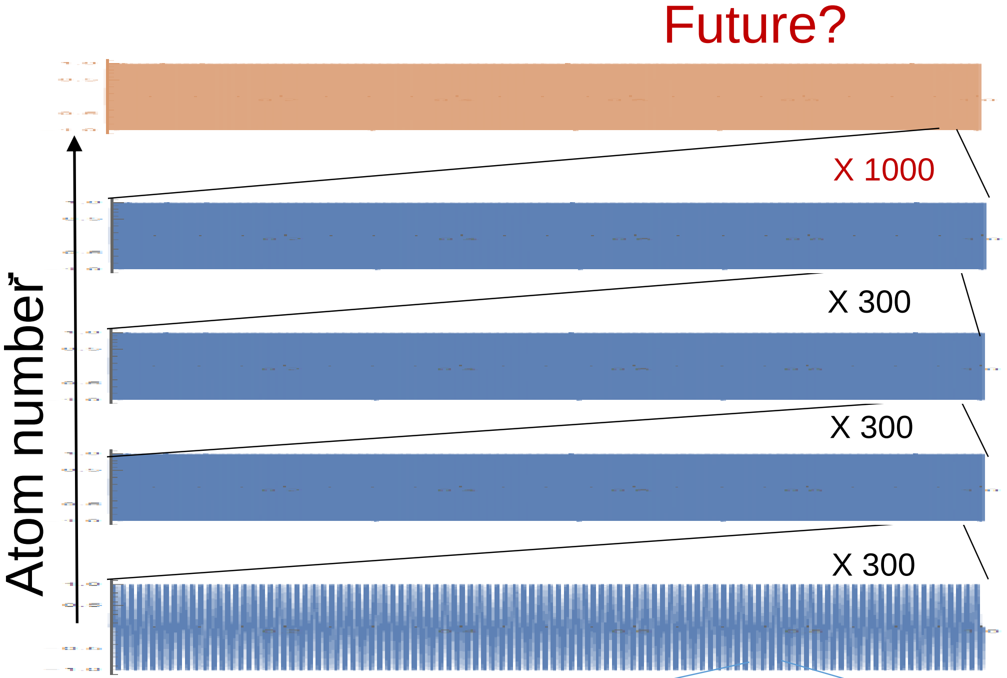
Feb 2005

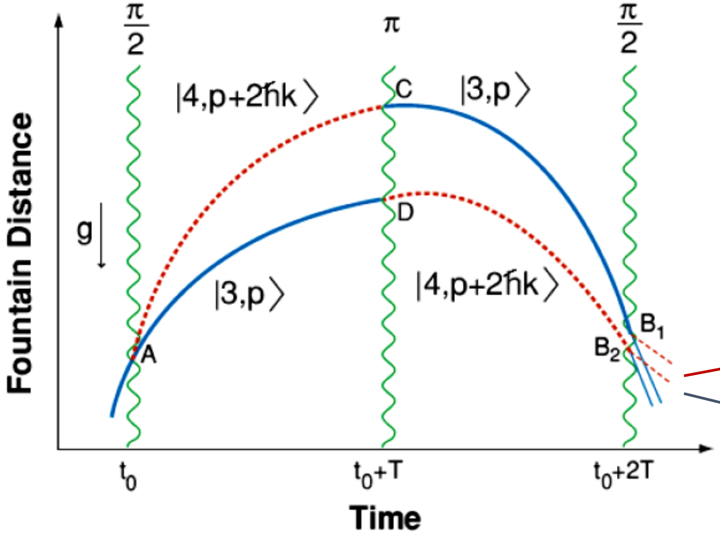


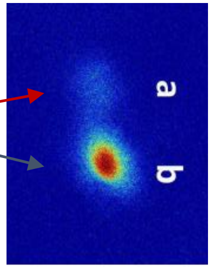
Apr 2005

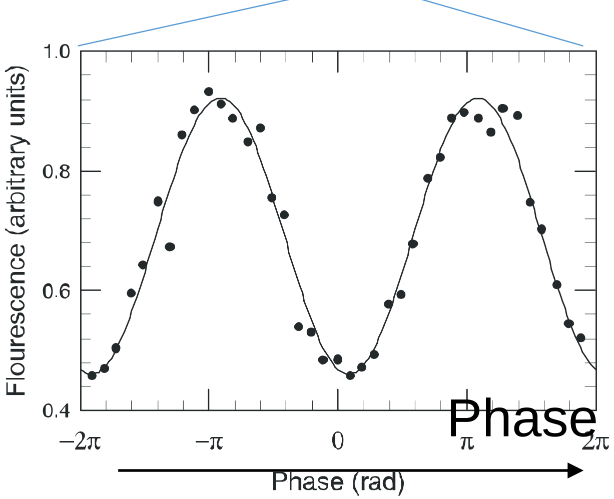
Light pulse atom interferometer

- Particles / waves
- Phase determined by Lagrangian, $L=E_{kin}-E_{pot}$,
- Laser wavelength as a ruler





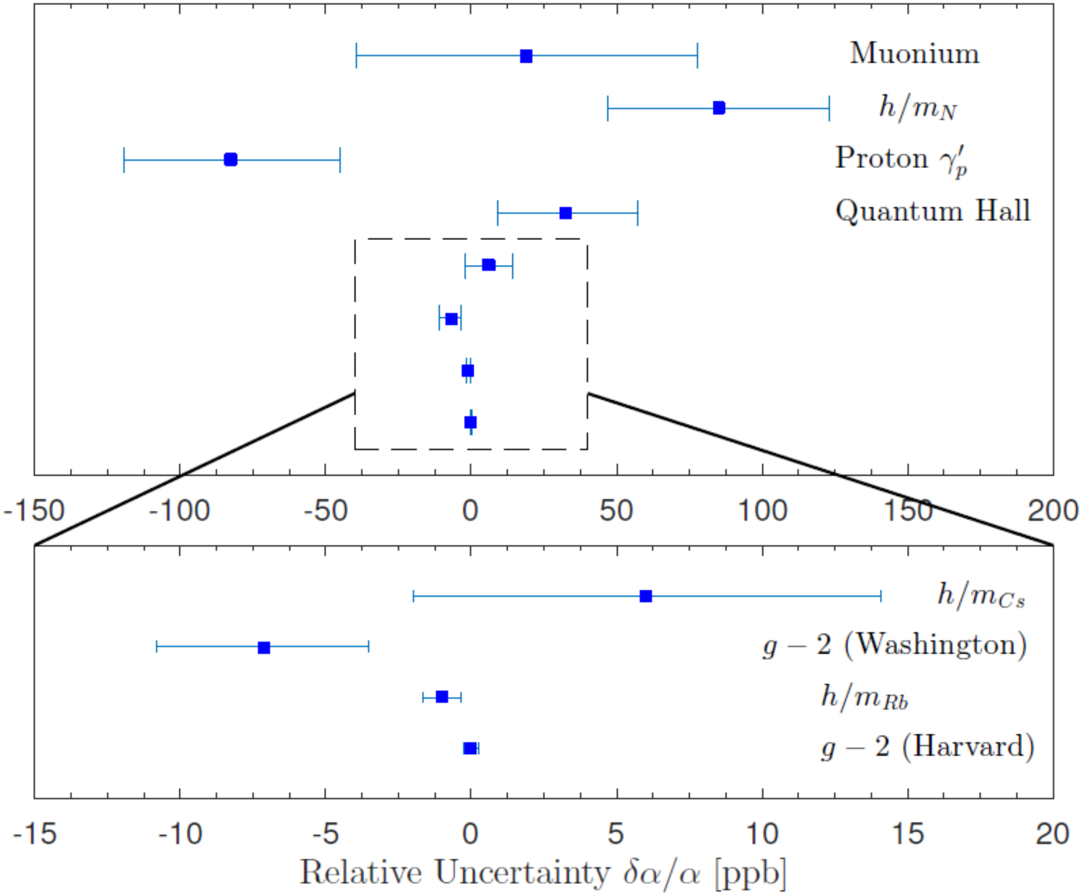




The fine structure constant

2014 CODATA

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



The Fine Structure Constant

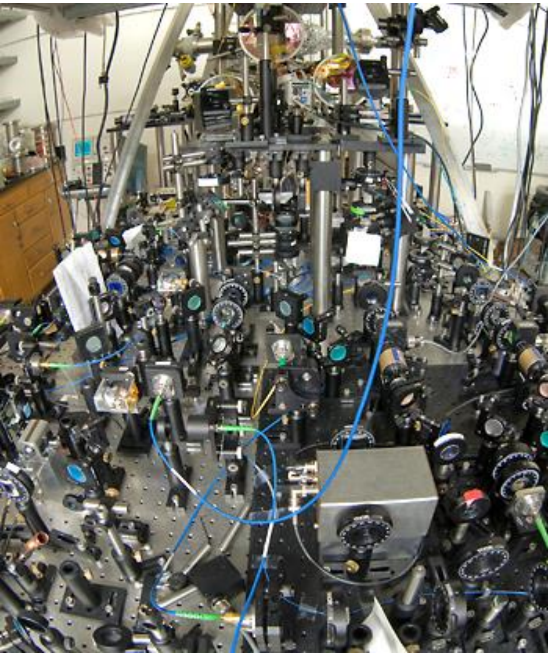
137 is…(https://primes.utm.edu/curios/page.php/137.html)

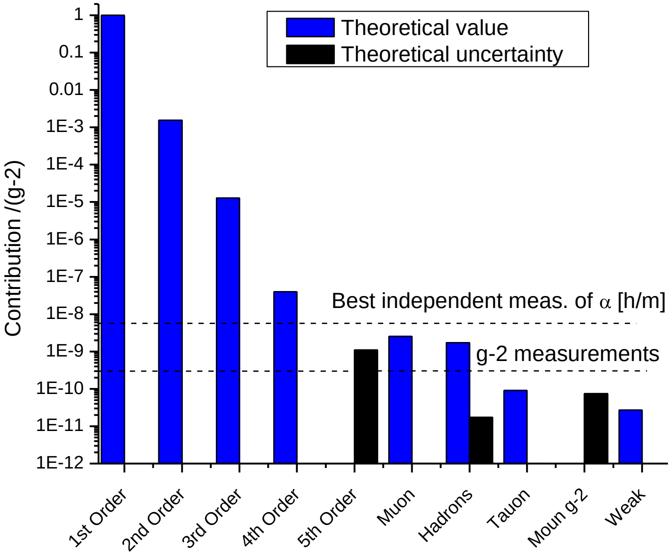
- The numerical value of “Kaballah” (קַבָּלָה)
- Genesis 25:17: “And these are the years of the life of Ishmael, an **hundred and thirty and seven** years. …” It is also the age of Moses father and Levi
- The day before his inauguration, President Obama made a 137-mile train trip from Philadelphia to Washington, DC.
- There are 137 Hawaiian islands, islets, and shoals
- W. Pauli died in room 137 of Rotkreuz Hospital, Zurich.
- WMAP’s age of the universe is 13.7 billion years
- 33rd prime number
- The largest prime factor of 123456787654321
- Karpov and Kasparov played 137 draws in chess
- Chlorophyll ($C_{55}H_{72}MgN_4O_5$) consists of 137 atoms

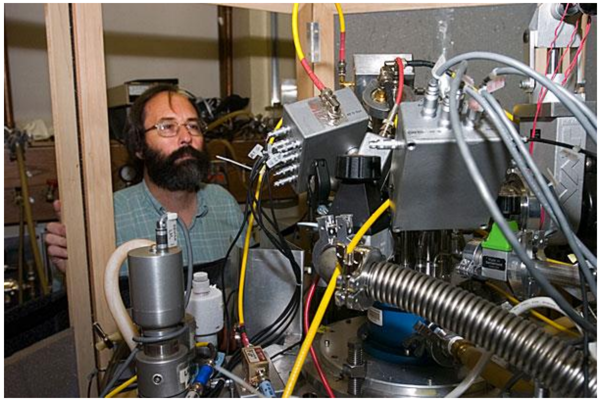
The most precise theory/experiment comparison in science

Fine structure constant

Electron gyromagnetic moment







Dark photons shift magnetic moment versus fine structure constant

Measures how strong a magnet an electron is

Alpha in the atom recoil frequency

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

Rydberg Constant
0.007 ppb P. J. Mohr *et al.*, Rev. Mod. Phys. **80**, 633 (2008).

Cs mass in u
0.18ppb M. P. Bradley *et al.*, Phys. Rev. Lett. **83**, 4510 (1999).

Electron mass in atomic mass units u
0.43 ppb P. J. Mohr *et al.*, Rev. Mod. Phys. **80**, 633 (2008).

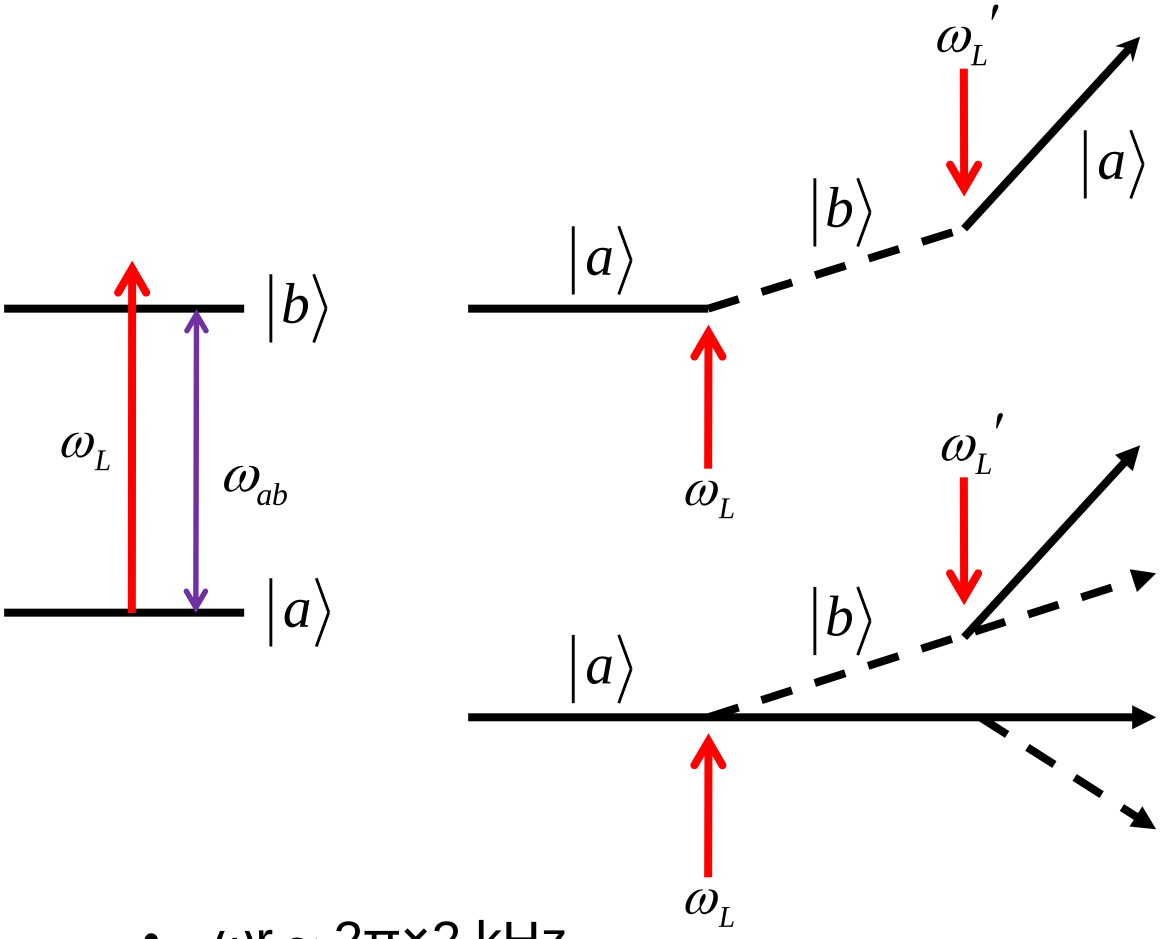
Determined by the atom recoil frequency

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

Cs D2 Transition
0.015ppb

Lowest : 0.23ppb

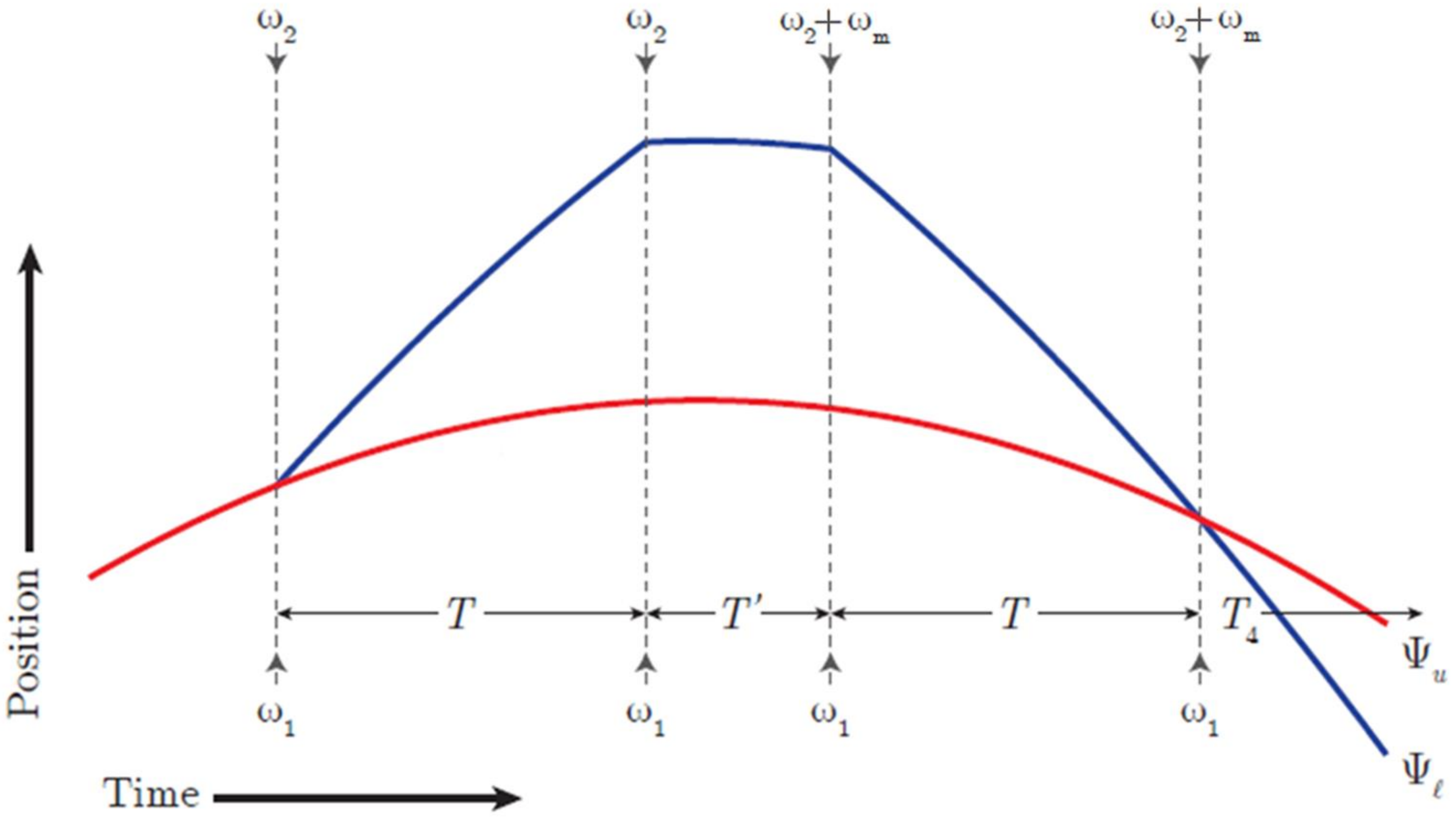
Recoil measurement



$$\omega_L'(|a\rangle) - \omega_L'(|b\rangle) = 2\omega_{rec}$$

- ωr ~ 2π×2 kHz,
- Accuracy 10^{-10}
- Need to pinpoint resonance to 0.2 μHz or 6x10^{-22}
- 10,000 times better accuracy than precision of best clocks

Ramsey-Borde interferometer

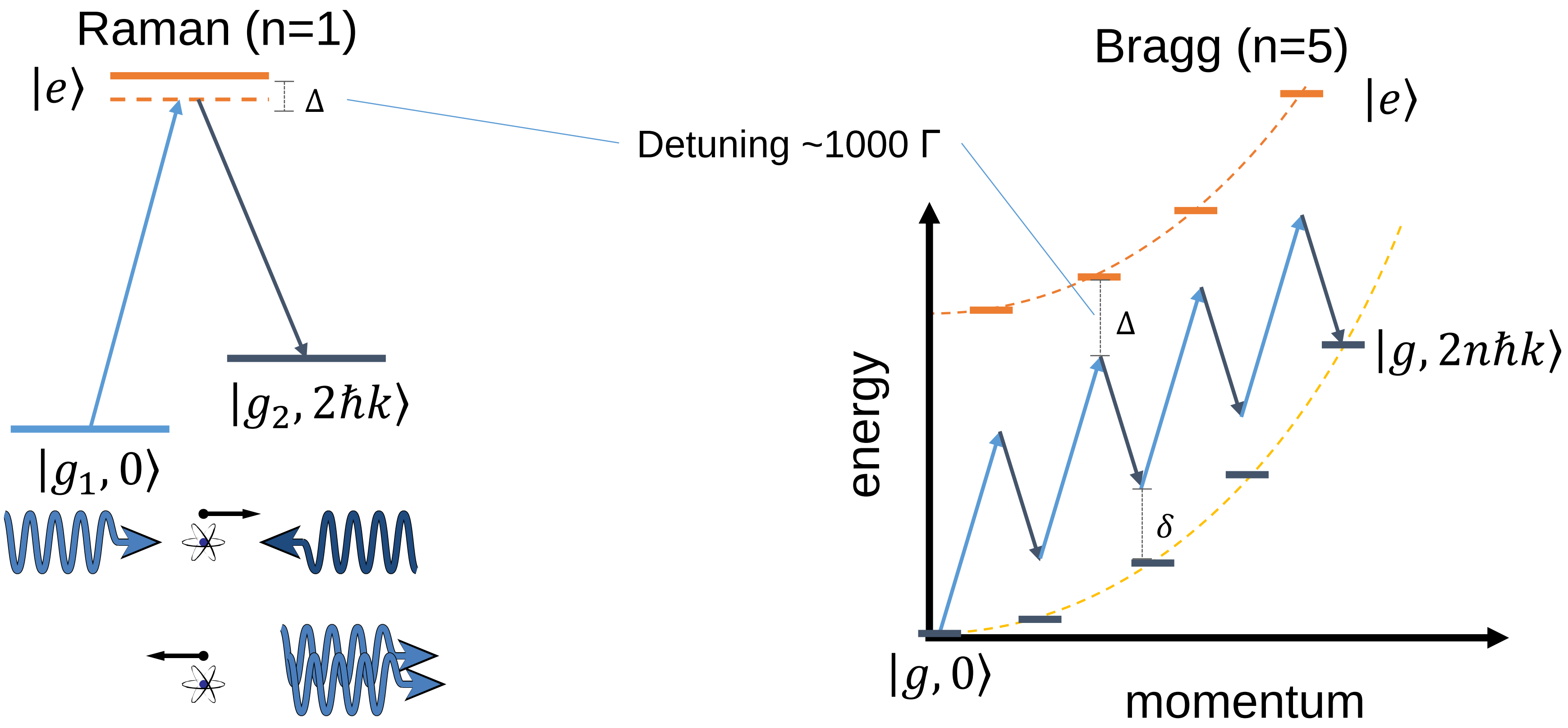


$$\Phi_{RB} = 8n^2\omega_r T - 2nkg(T+T')T - n\omega_m T$$

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

$$\begin{tikzcd} \boxed{\omega_r} \arrow[dr] & & \\ & h/m \arrow[r] & \alpha \\ k \arrow[ur] & & \end{tikzcd}$$

Multiphoton Bragg diffraction

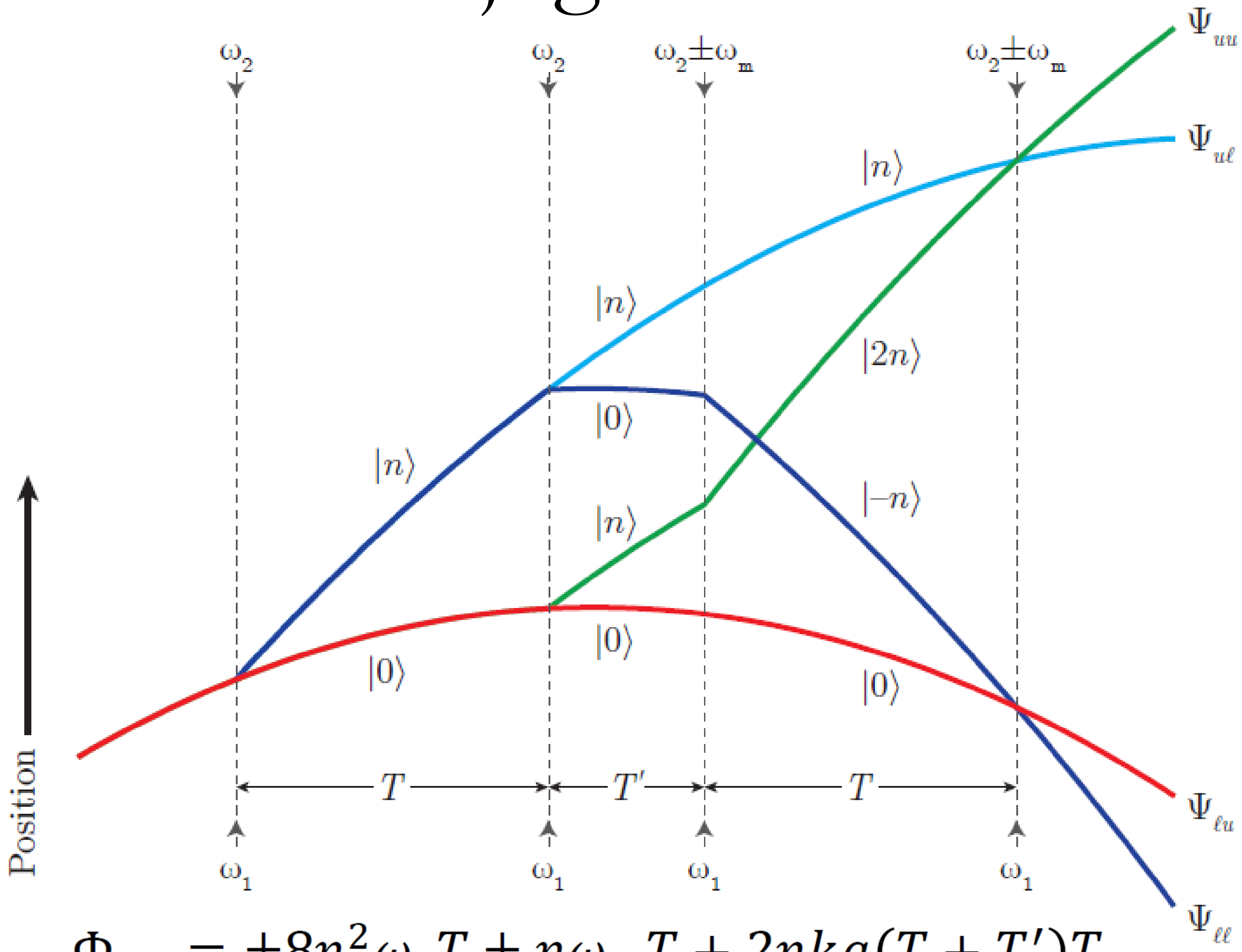


Bragg gives you:

- More photons transferred per pulse (higher sensitivity)
- Atoms stay in same internal state (Zeeman, AC Stark systematics suppressed)

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

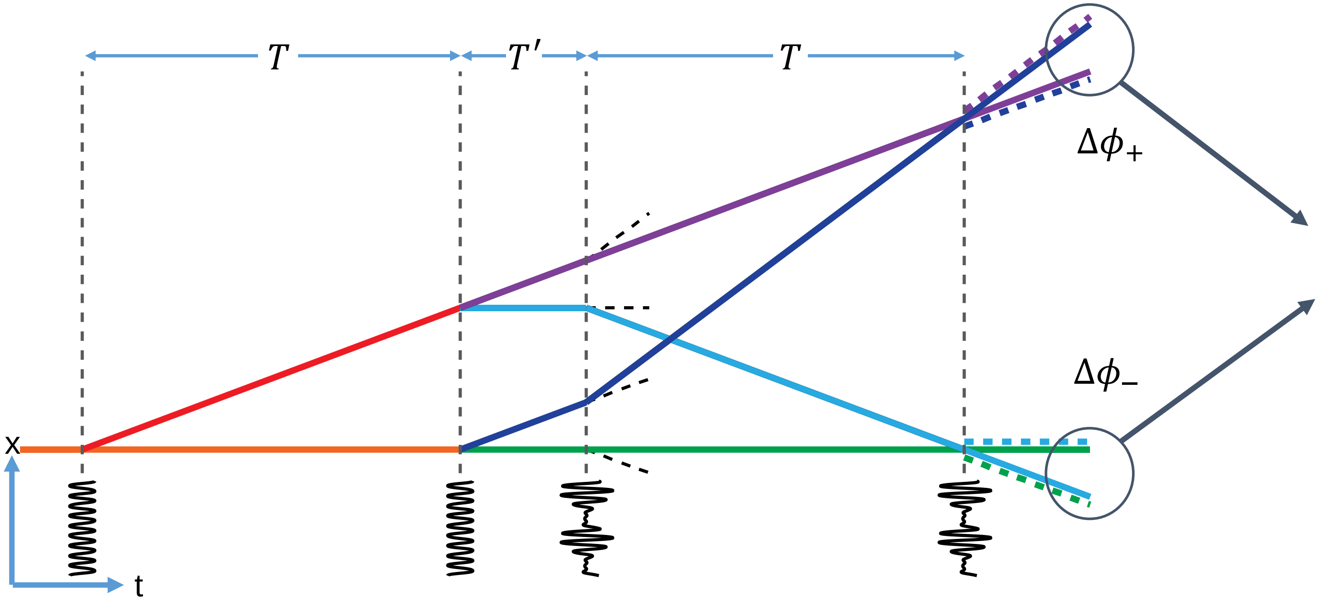
Simultaneous conjugate interferometers



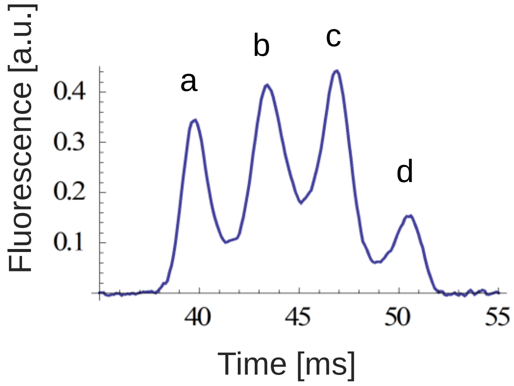
$$\Phi_{RB} = \pm 8n^2\omega_r T \pm n\omega_m T + 2nkg(T+T')T$$

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

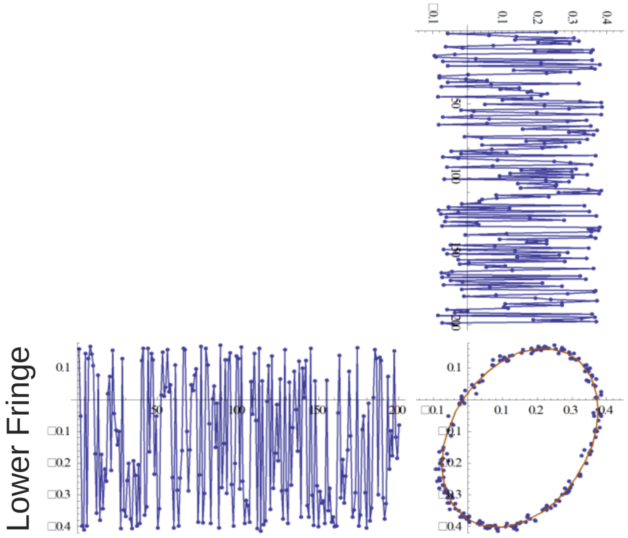
Phase extraction



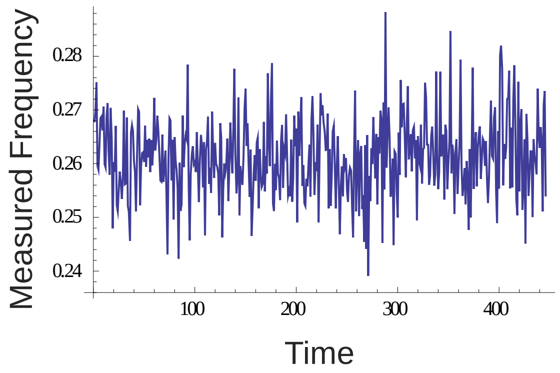
Detect

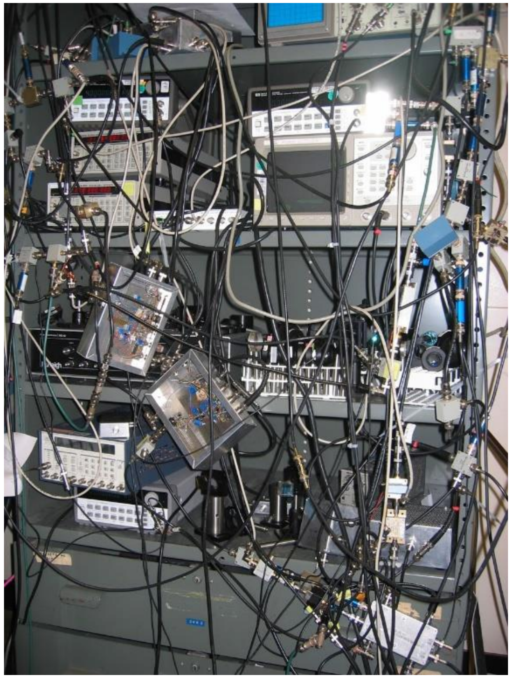


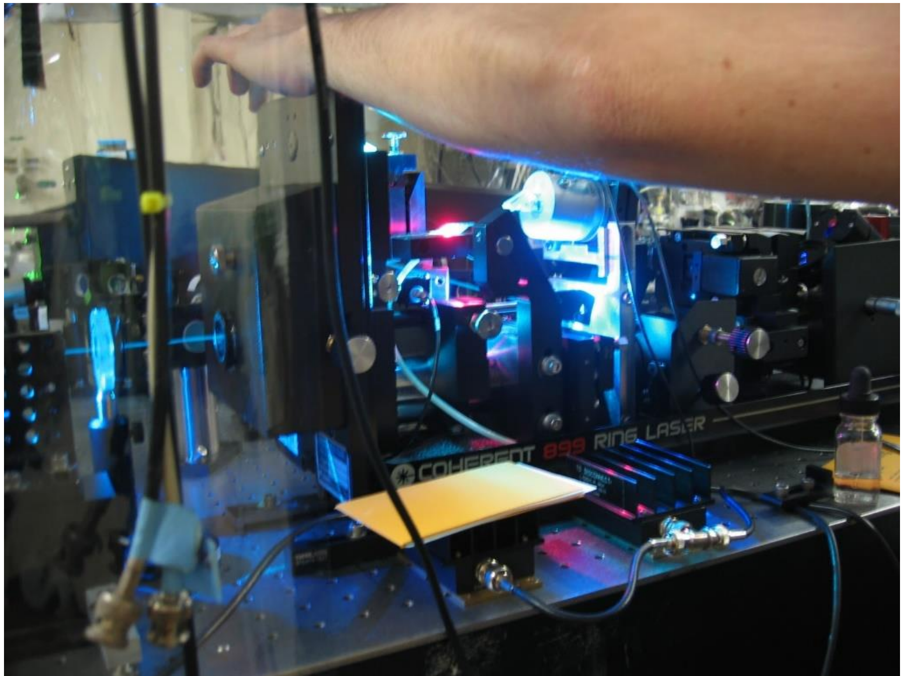
Upper Fringe



Bin Data

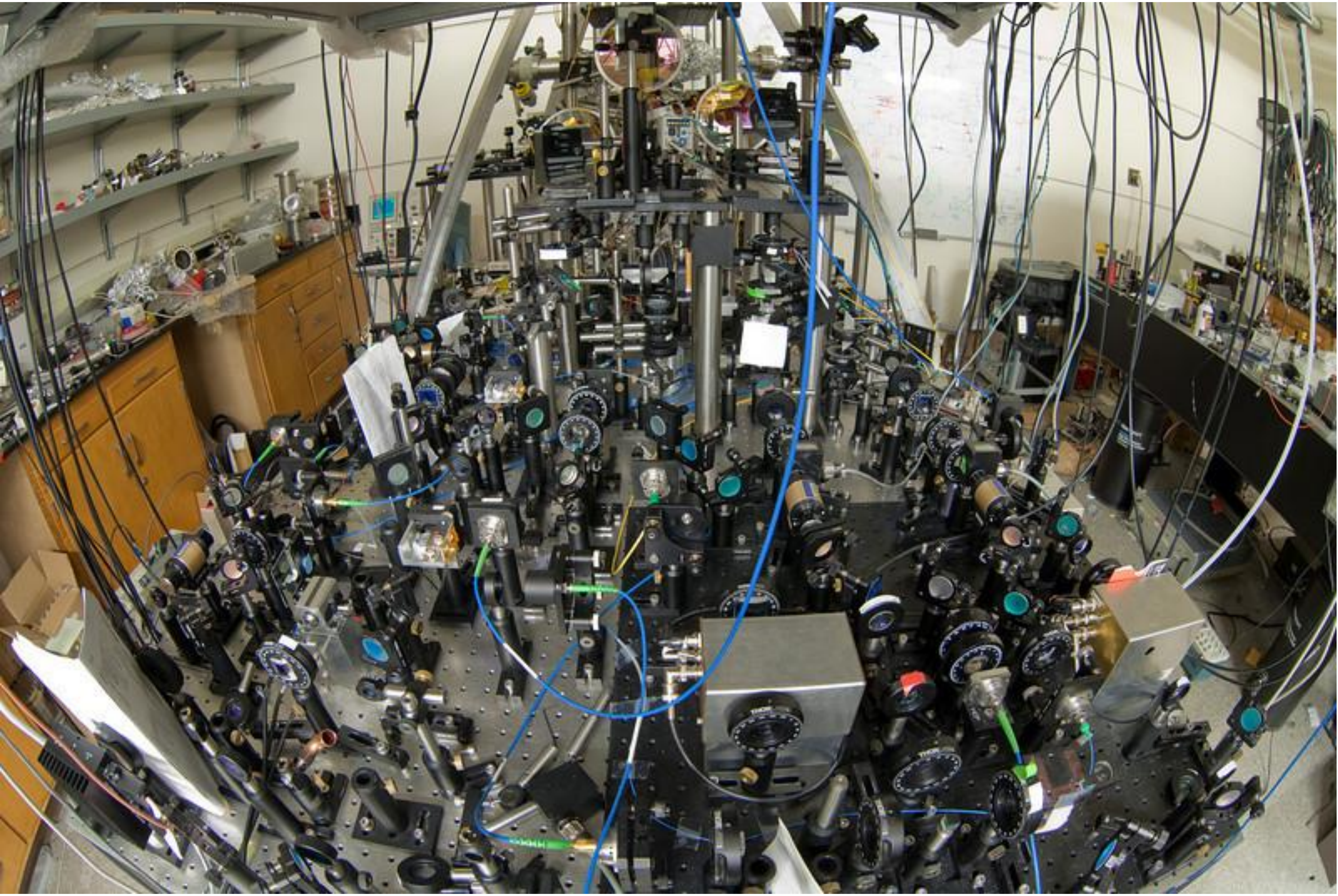




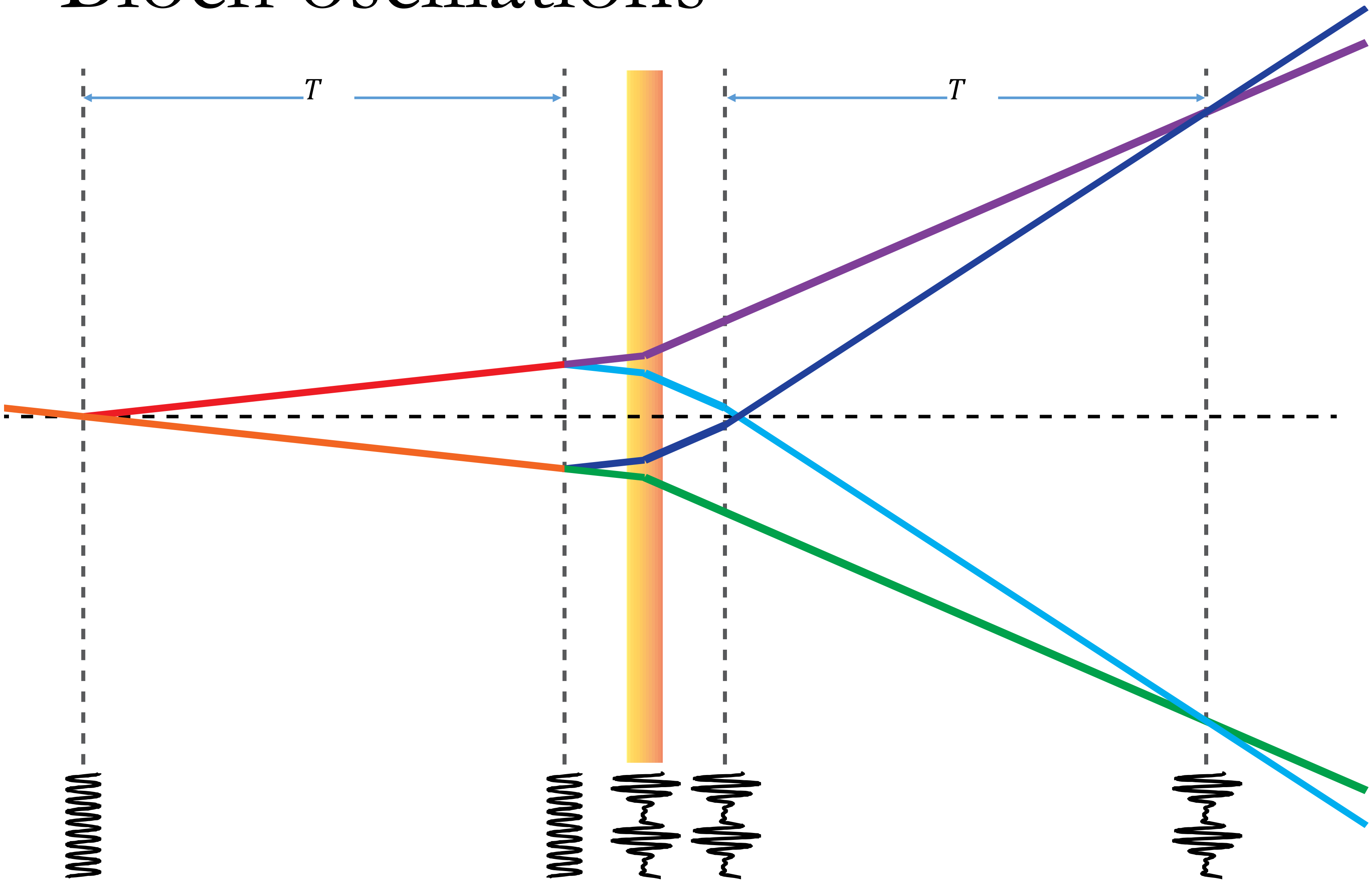


COHERENT 899 RING LASER

Now it’s my turn to leave Stanford



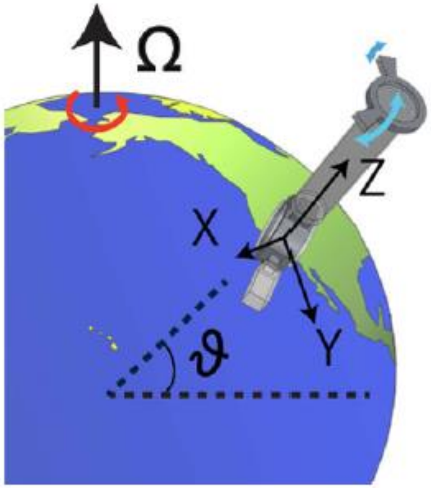
Bloch oscillations



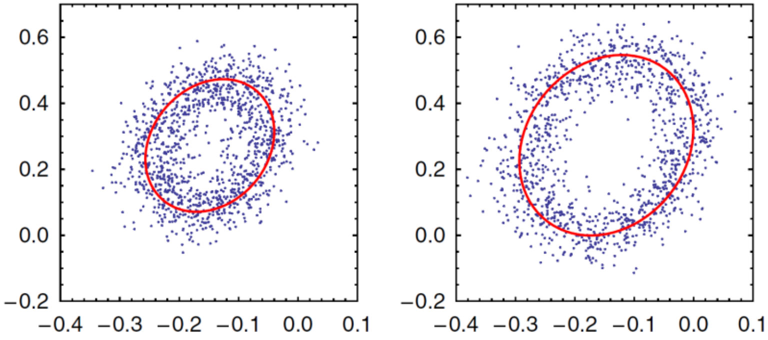
$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T$$

Tricks for Increased Sensitivity

Coriolis Compensation



$10\hbar k,\ T = 180ms$

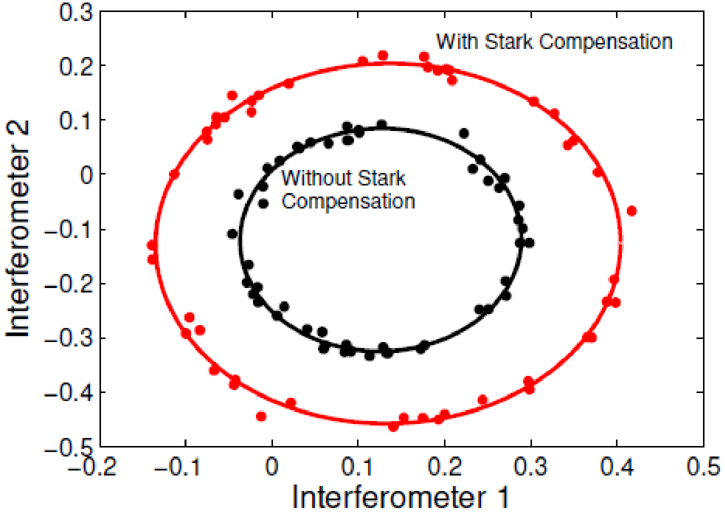


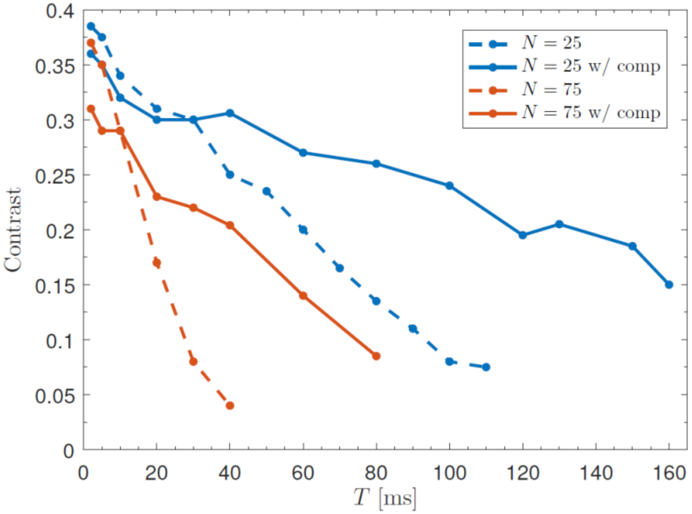
Without compensation

With compensation

x3.5 contrast gain

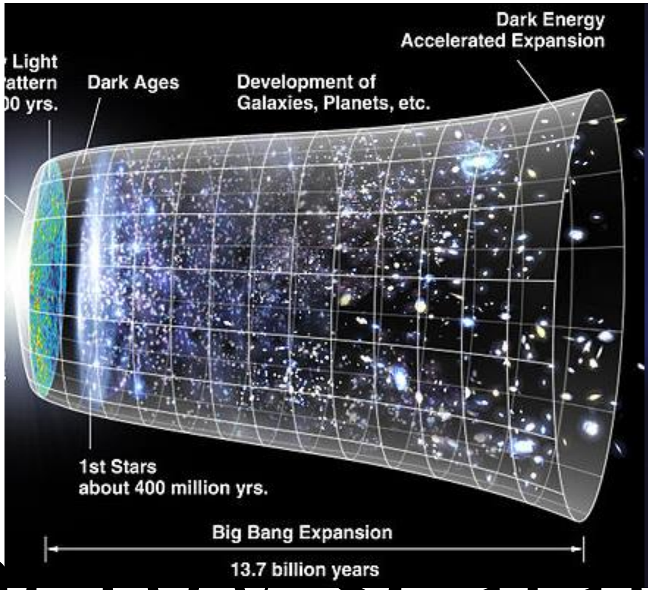
Stark Compensation

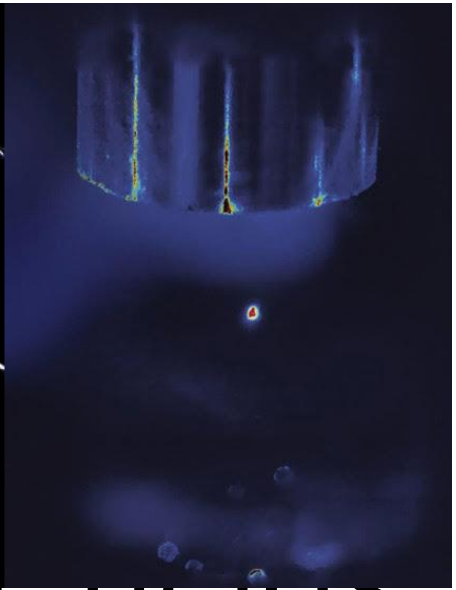




Up to N=200

>12Mrad phase diff. measurable!





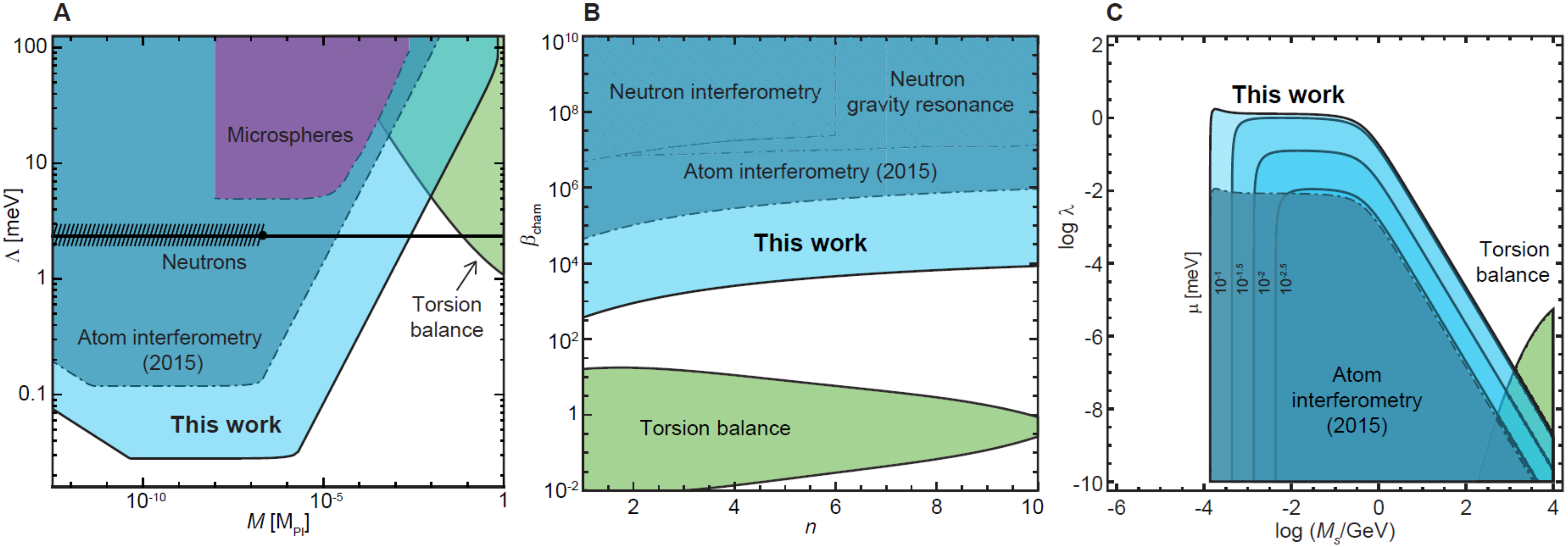
Dark energy scalar fields

M. Jaffe, P. Haslinger, V. Xu, J. Khoury, B. Elder, M. Upadhye and H. Muller

Limits on dark-energy scalars

Chameleons

Symmetrons

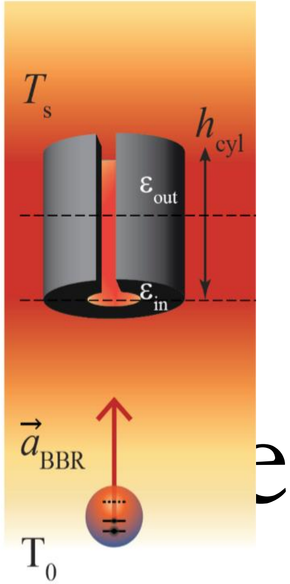


→

Interaction strength

M. Jaffe, P. Haslinger, V. Xu, P. Hamilton, A. Upadhye, B. Elder, J. Khoury, and HM, Nature Physics, doi: 10.1038/nphys4189

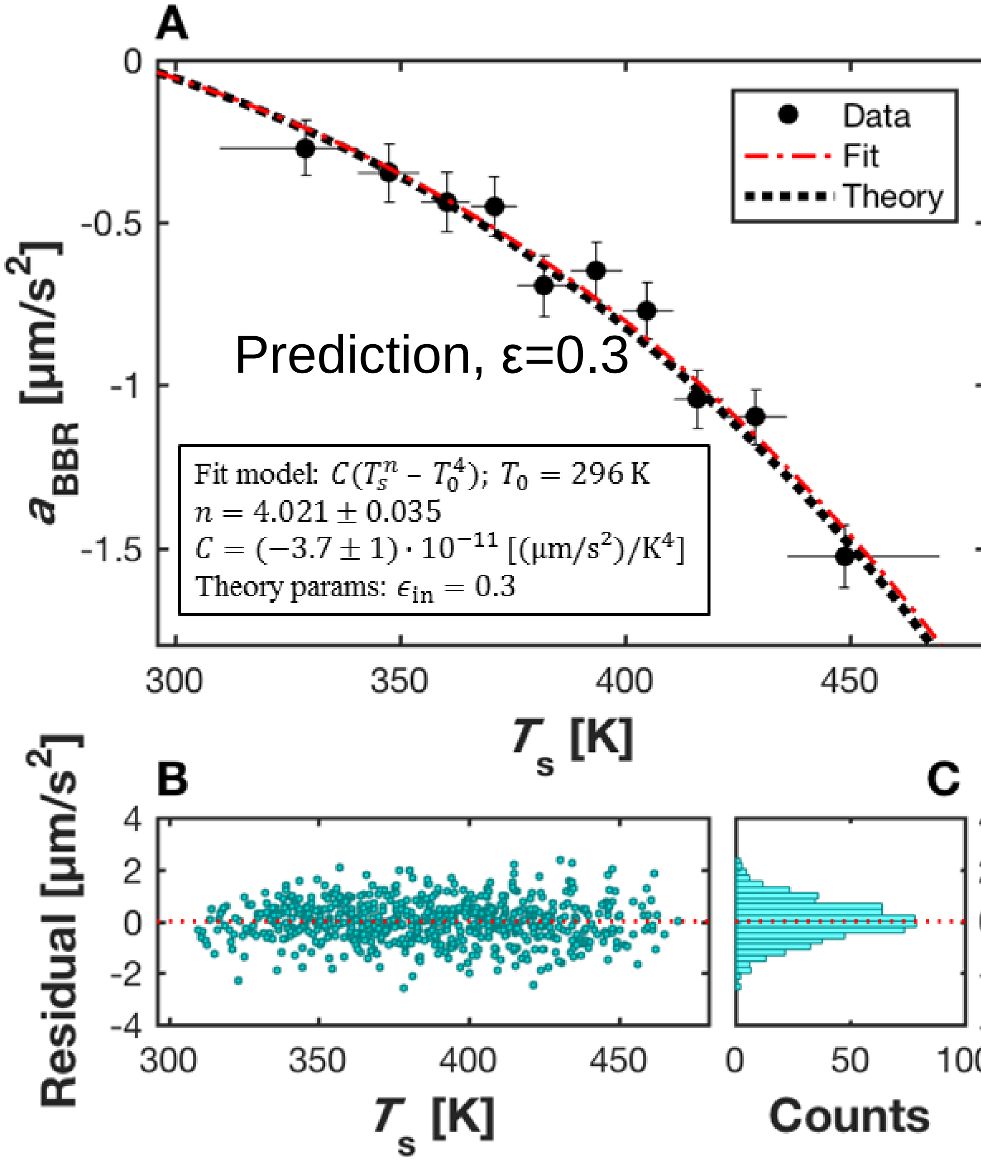
Attractive e blackbody radiation



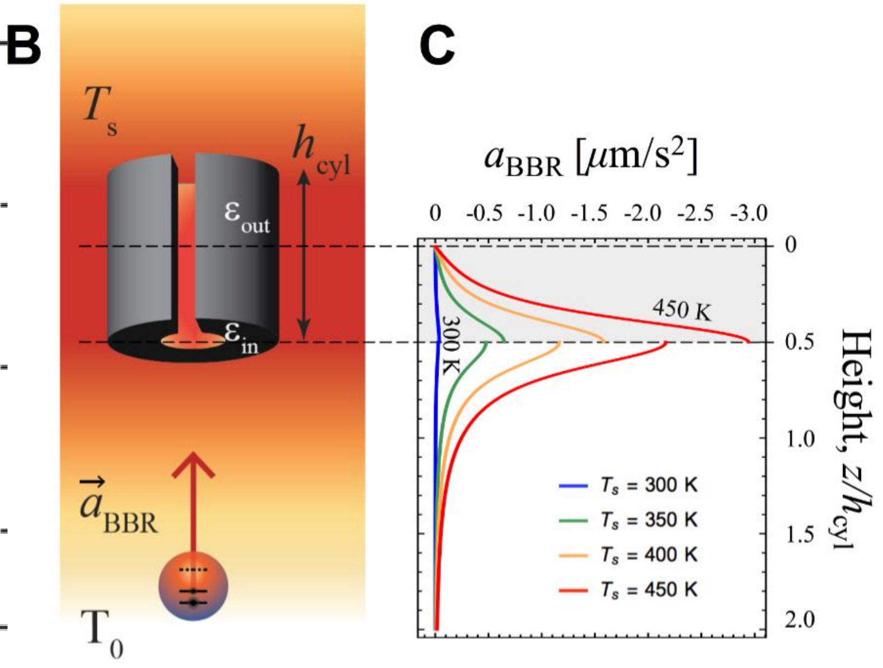
P. Haslinger, M. Jaffe, V. Xu, M. Sonnleithner, H. Ritsch, M. Ritsch & HM

Only one room temp. blackbody photon absorbed every 10^5 years…

Force from blackbody radiation

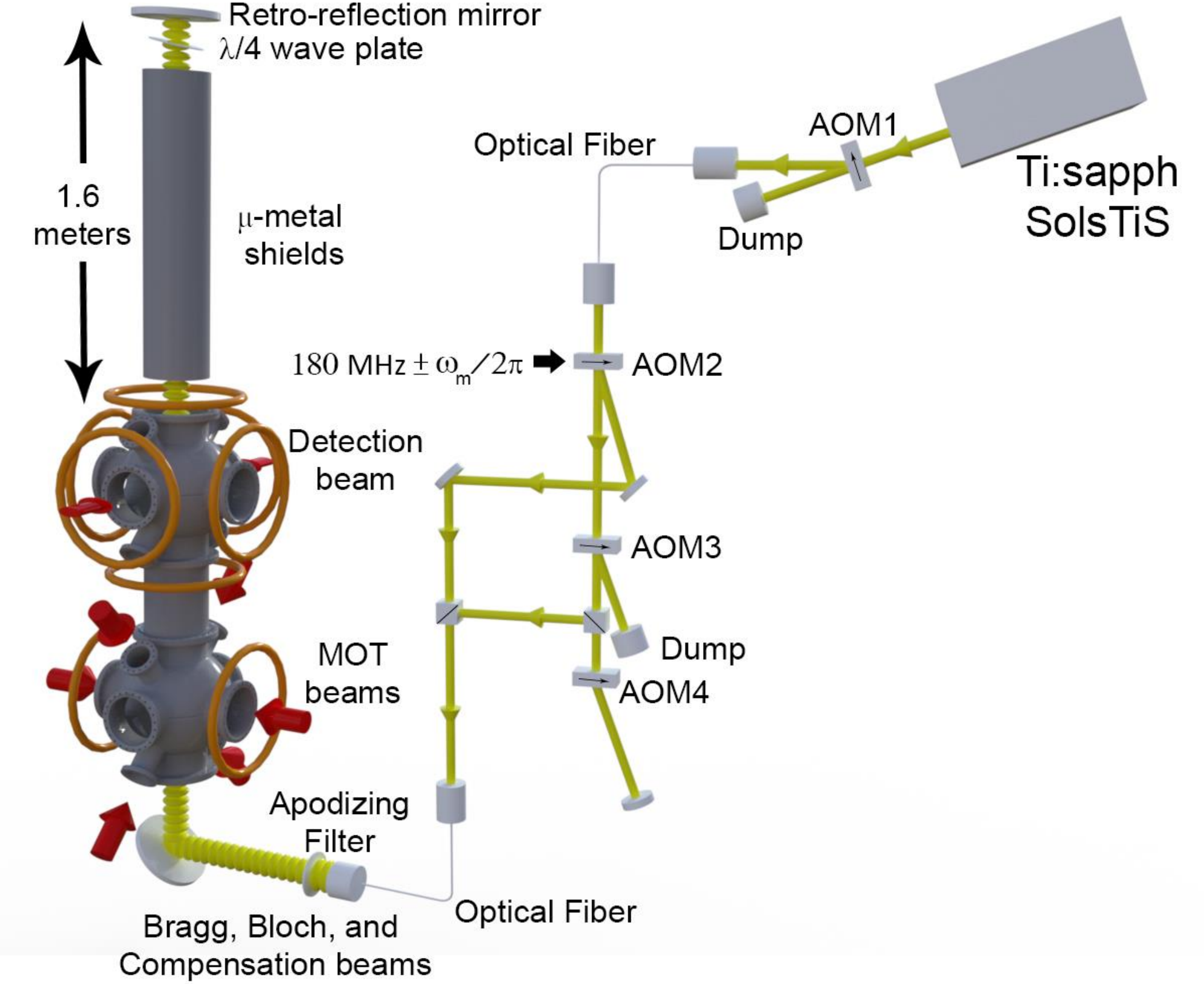


Prediction, ε=0.3

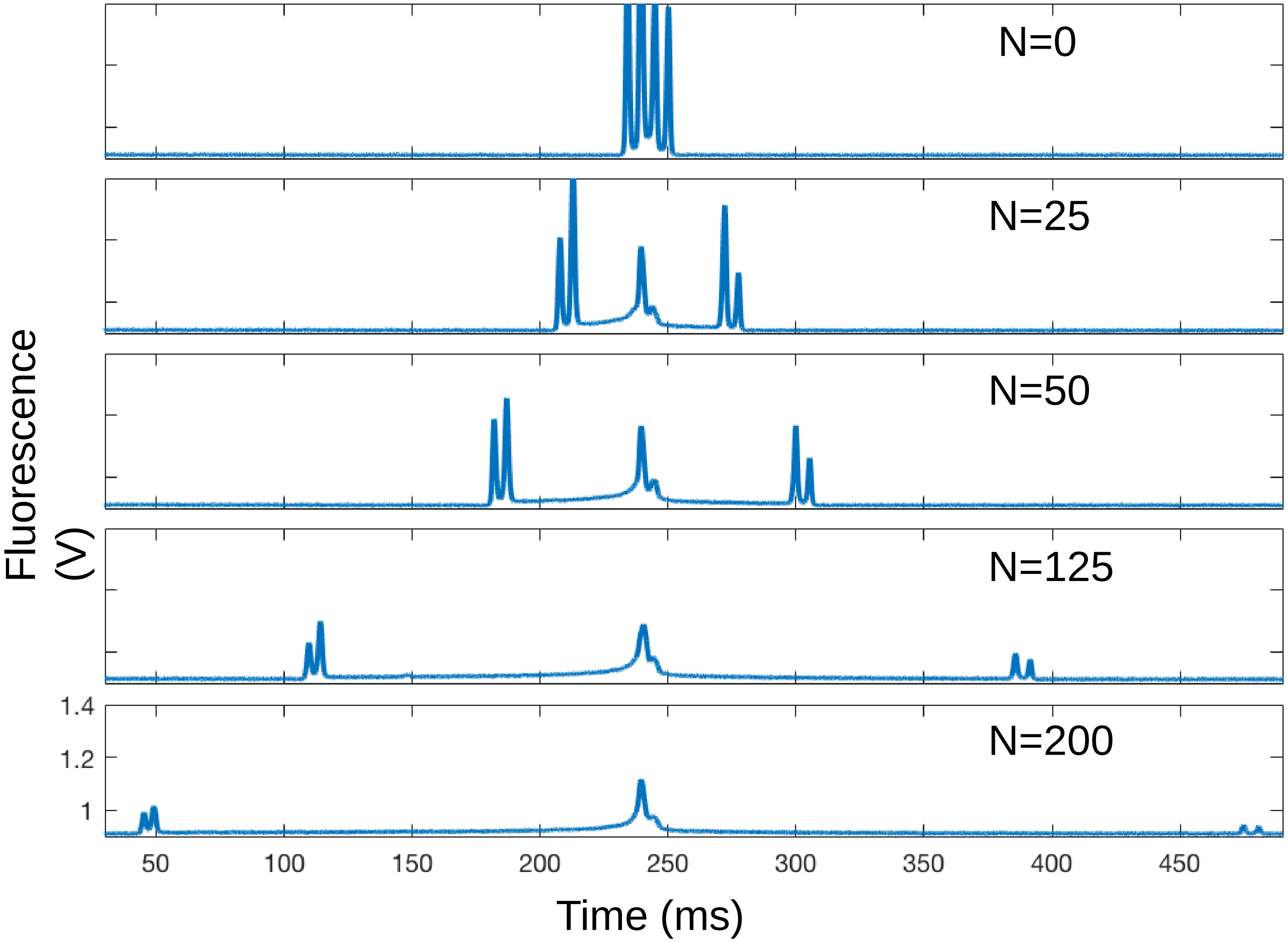


arXiv:1704.03577

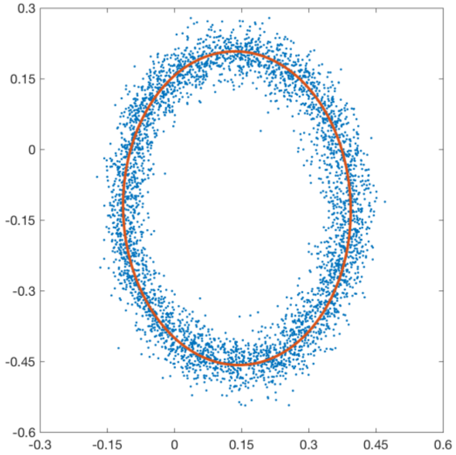
Setup


Retro-reflection mirror
λ/4 wave plate
1.6 meters
μ-metal shields
Optical Fiber
AOM1
Ti:sapph SolsTiS
Dump
180 MHz ± ω_m/2π
AOM2
Detection beam
AOM3
Dump
MOT beams
AOM4
Apodizing Filter
Optical Fiber
Bragg, Bloch, and Compensation beams

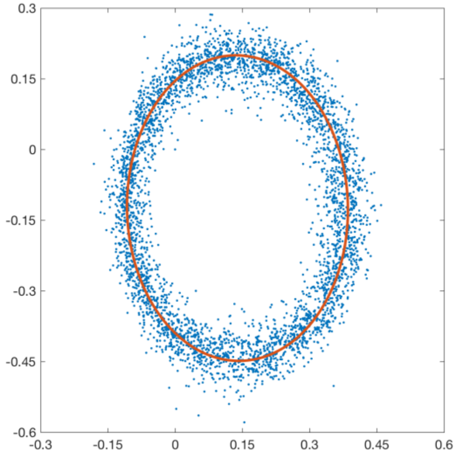
Fluorescence Traces



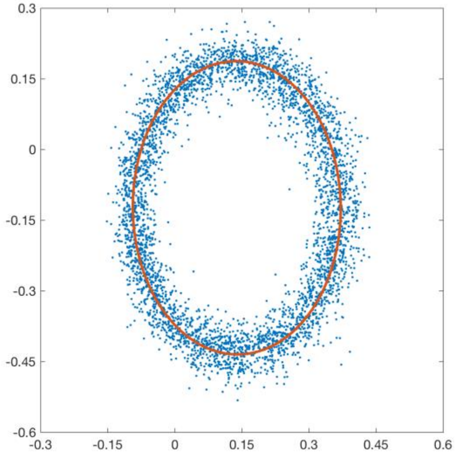
n=5, N=125 Ellipses



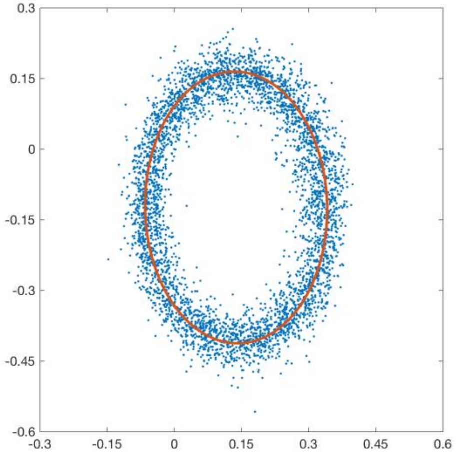
T=5 ms



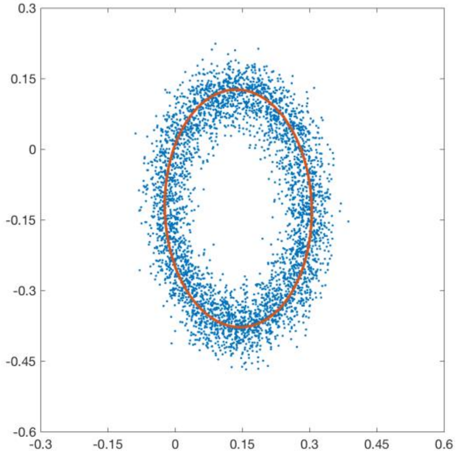
T=10 ms



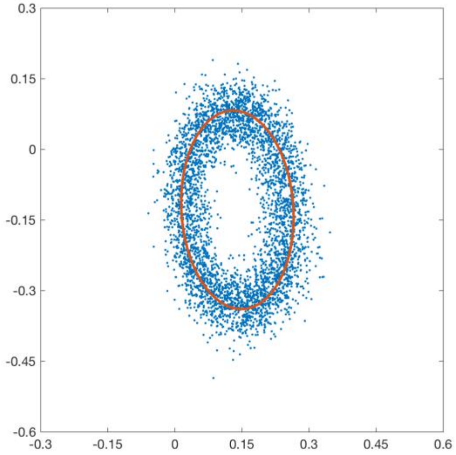
T=20 ms



T=40 ms

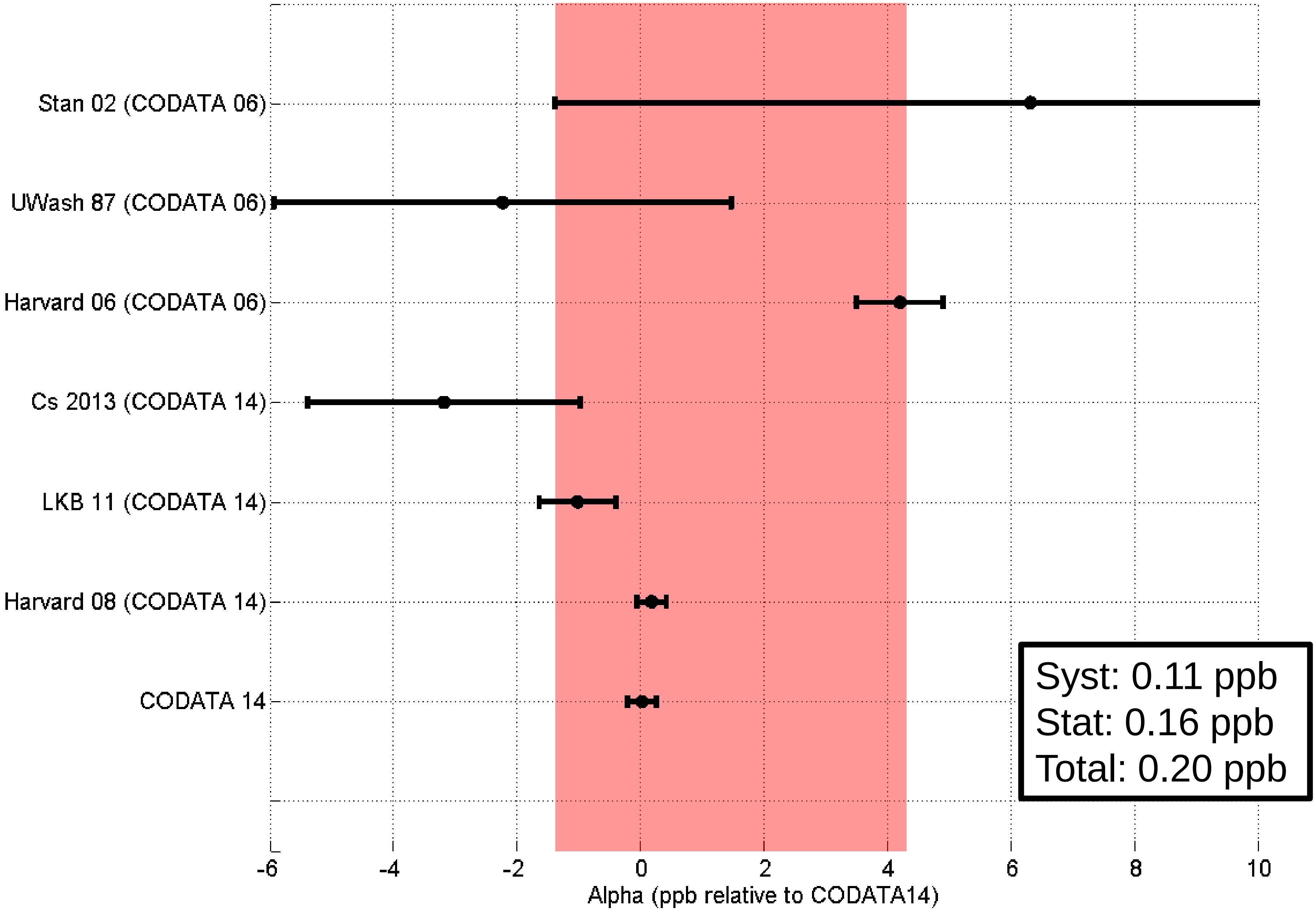


T=60 ms



T=80 ms

Blind Analysis



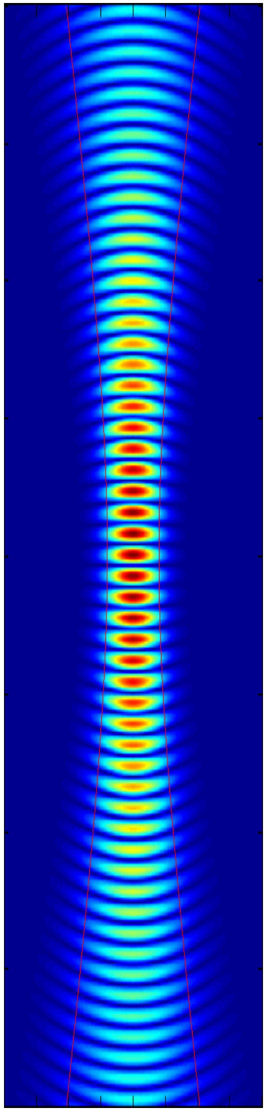
Syst: 0.11 ppb
Stat: 0.16 ppb
Total: 0.20 ppb

0.16 ppb systematic errors

Effect	Sect.	Value	$\delta\alpha/\alpha$ (ppb)
Laser Frequency	1	N/A	-0.24 ± 0.03
Acceleration Gradient	4A	□=(2.13 ± 0.01)×10^{-6}/s^2	-1.69 ± 0.02
Gouy phase	3	w_0=3.21±0.008 mm, z_0=0.5±1.0 m	-3.60± 0.03
Wavefront Curvature	12	$\langle r^2\rangle^{1/2}$=0.58 mm	0.15 ± 0.03
Beam Alignment	5	N/A	0.05 ± 0.03
BO Light Shift	6	N/A	0 ± 0.004
Density Shift	7	$\rho=10^6$ atoms/cm^3	0 ± 0.003
Index of Refraction	8	$n_{cloud}-1=30\times10^{-12}$	0 ± 0.03
Speckle Phase Shift	4B	N/A	0 ± 0.04
Sagnac Effect	9	N/A	0 ± 0.001
Mod. Frequency Wavenumber	10	N/A	0 ± 0.001
Thermal Motion of Atoms	11	N/A	0 ± 0.08
Non-Gaussian Waveform	13	N/A	0 ± 0.03
Parasitic Interferometers	14	N/A	0 ± 0.03
Total Systematic Error			-5.33 ± 0.12
Total Statistical Error			± 0.16
Electron Mass (18)		5.48579909067×10^{-4} u	± 0.02
Cesium Mass (4,17)		132.9054519615 u	± 0.03

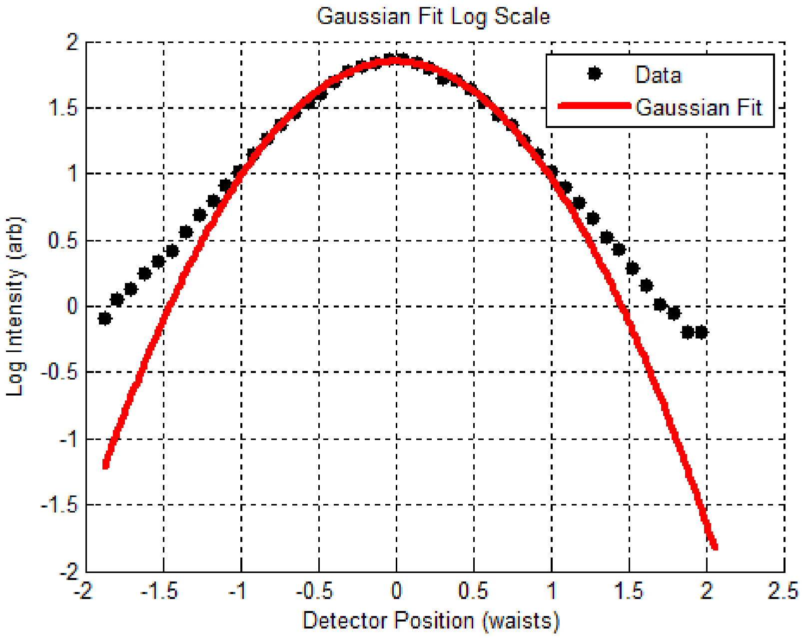
Big

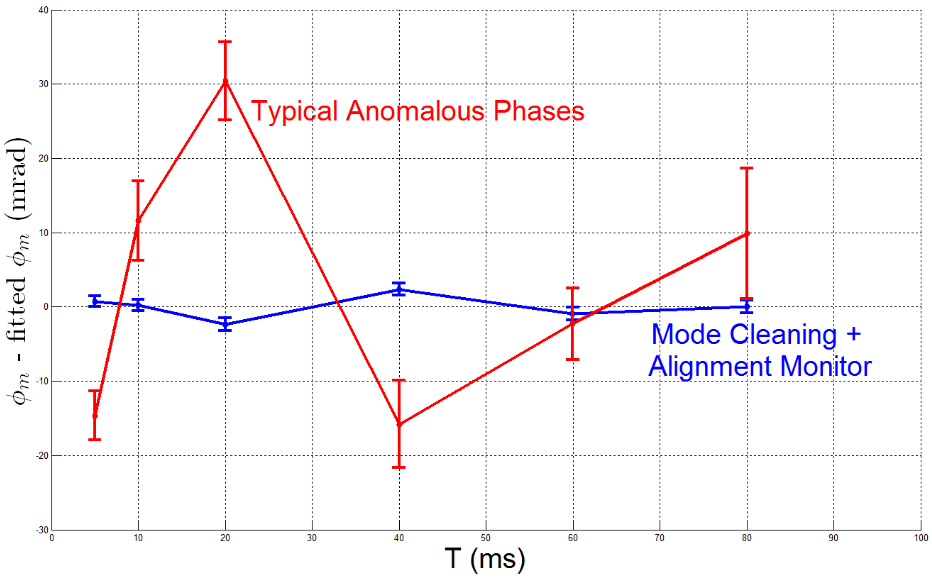
‘New’



Speckle Phase

- 30 mrad anomaly → 8 ppb at *N*=0
- >10x suppression by mode filtering
- 25x suppression by *N*=125



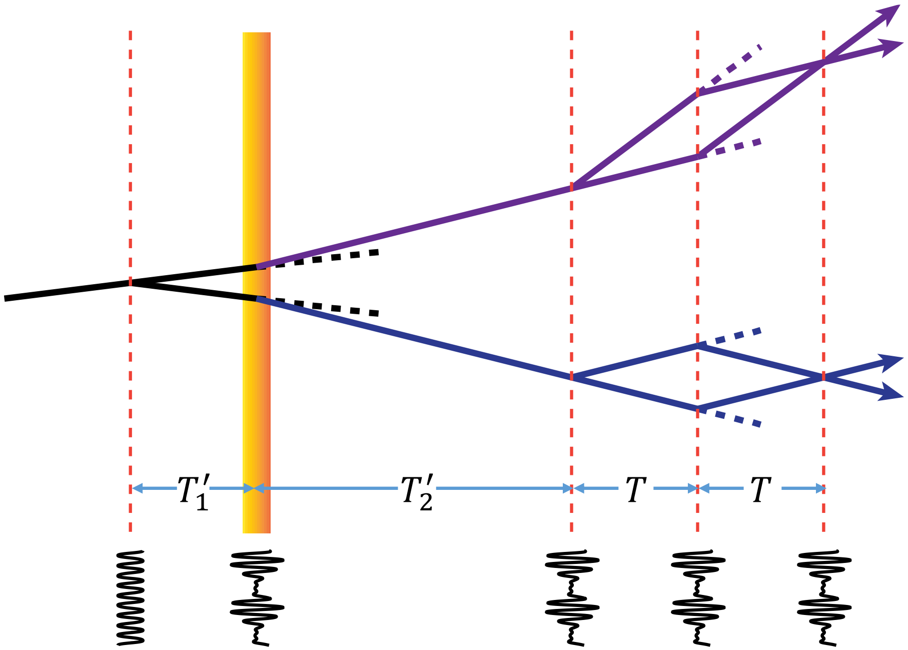


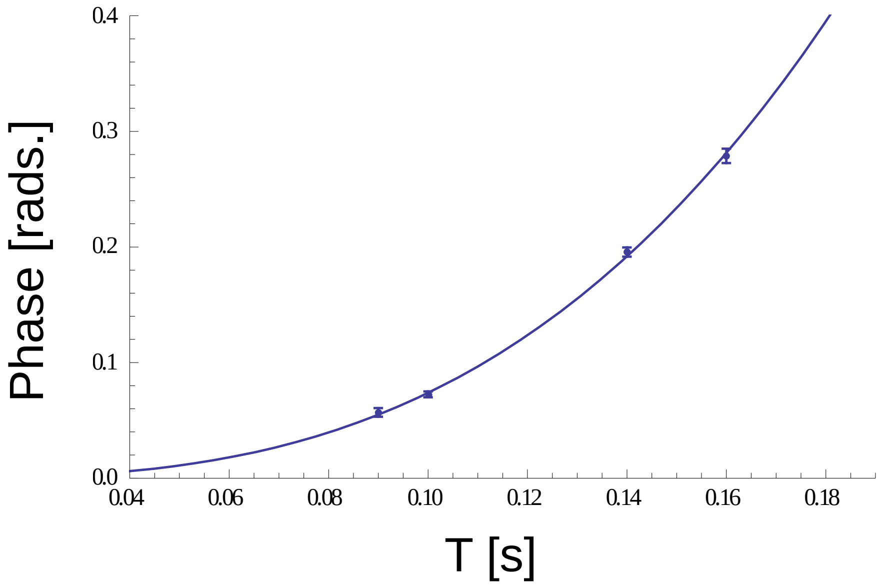
$200 Apodizing Filter

- Fiber doesn't make Gaussian beams
- Spatial Filtering via Apodizer + Fountain Alignment Monitor

Gravity Gradient

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





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

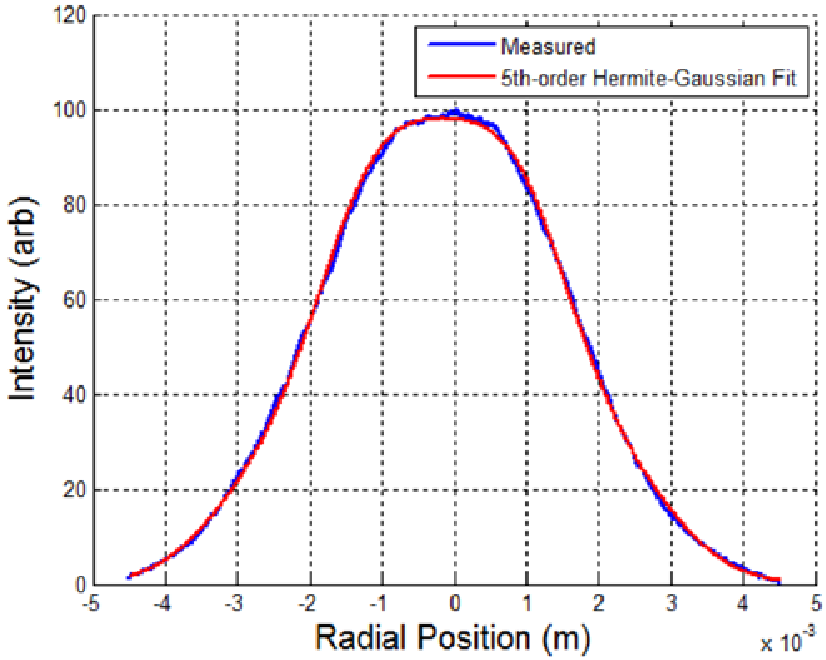
$$\gamma = 1.295(32) \times 10^{-6}\,\frac{m}{s^2}\frac{1}{m}$$

Shift in alpha = -1.41 +/- 0.02 ppb

Revised Gouy Phase

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

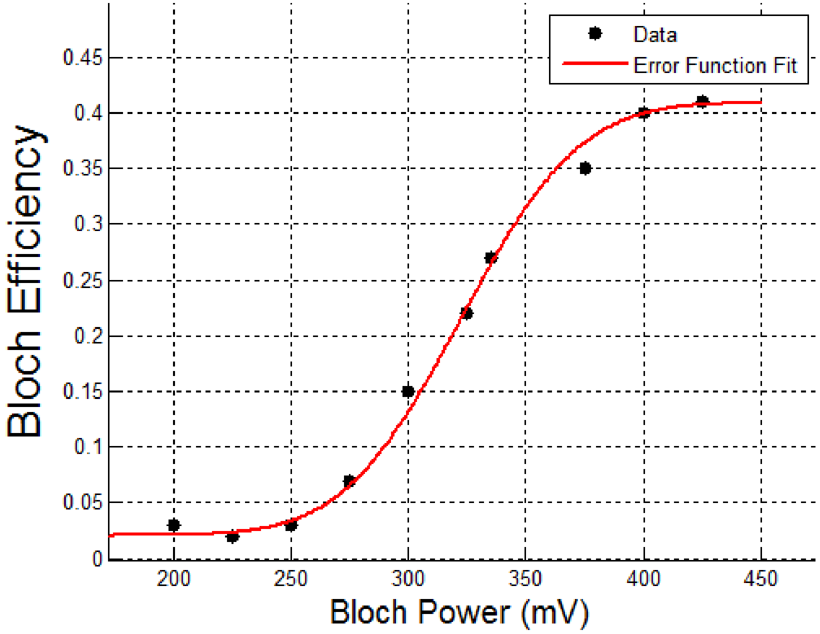
- Previously used knife-edge measurements to verify beam was Gaussian (within error)
- Suspected not Gaussian, based on 3D propagation
- With Scanning-slit/CCD, determined not Gaussian
- Use Monte Carlo to determine on-axis and wavefront-curvature corrections



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 for LKB
- Use 3D Monte Carlo, CCD images, and Bloch Efficiency data to estimate effect
- <0.1 ppb for us



Systematic Checks

Variations of alpha w.r.t.:

- Bloch order
- Bloch power
- Contrast
- Detection region
- Pulse intensity: overall and pulse/pulse ratio
- Speckle phase
- ω_m mixing (RF)
- ω_m mixing (optics)
- Delay of interferometer sequence
- Bias B-field
- Single-photon detuning
- Data Analysis parameters (cuts, fitting, etc.)
- Fountain alignment (launch direction, no spatial filtering)

Dark photons

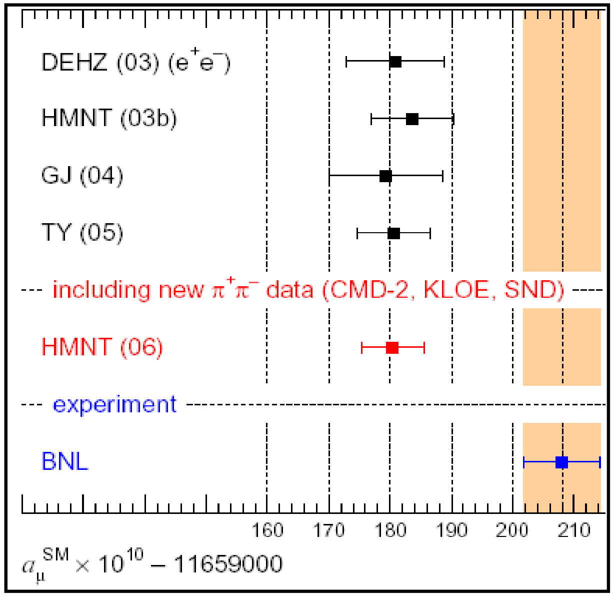
Whatever the dark sector is made of, only three interactions are allowed by standard model symmetries

- Vector portal
- Higgs portal
- Neutrino portal

“massive photon”

Hints

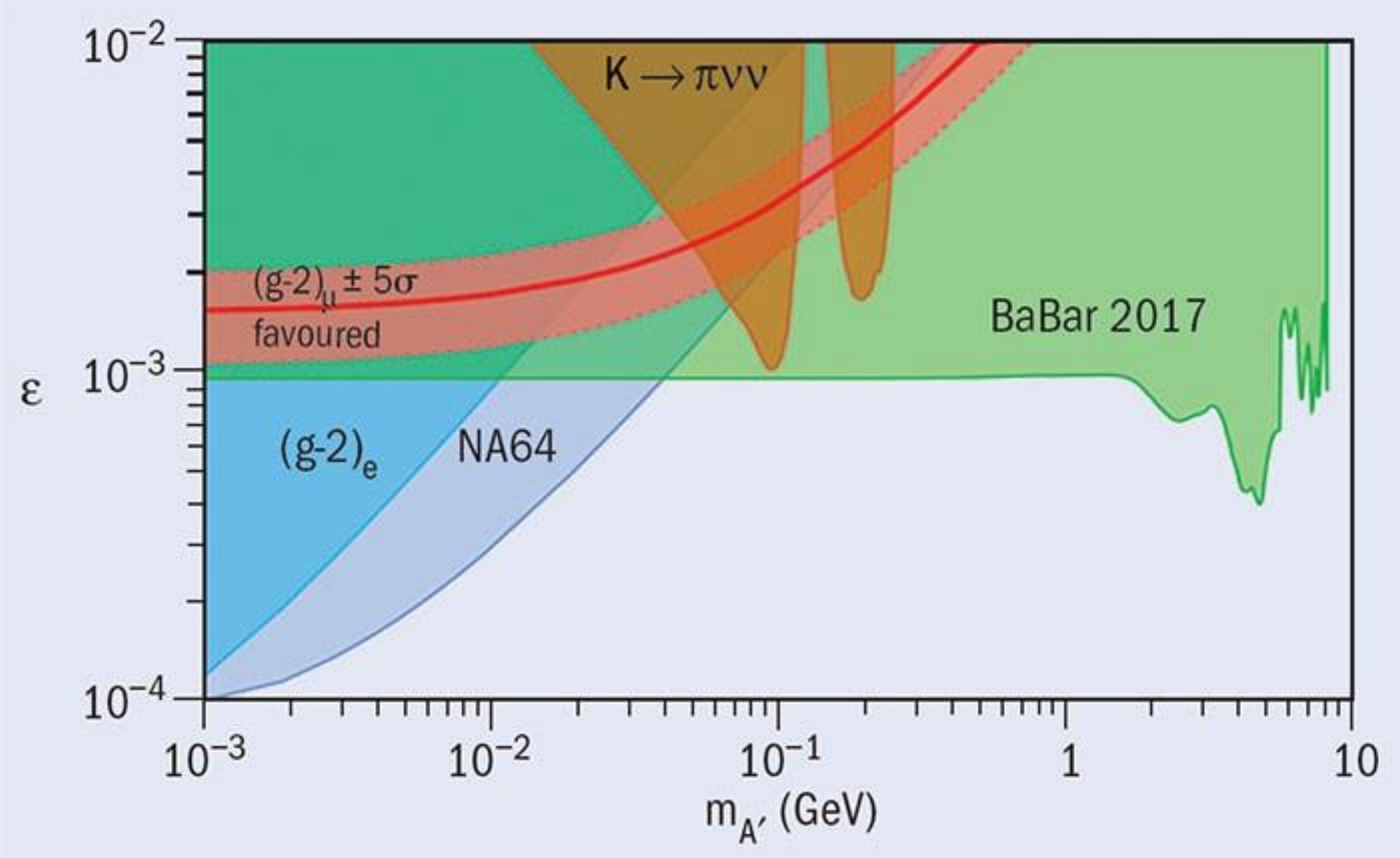
- Muon g-2
- Proton radius puzzle?
- ^{8}Be decay
- Astrophysical hints?
    - 511 keV line
    - keV gamma-ray excess
    - Galactic center excess



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

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

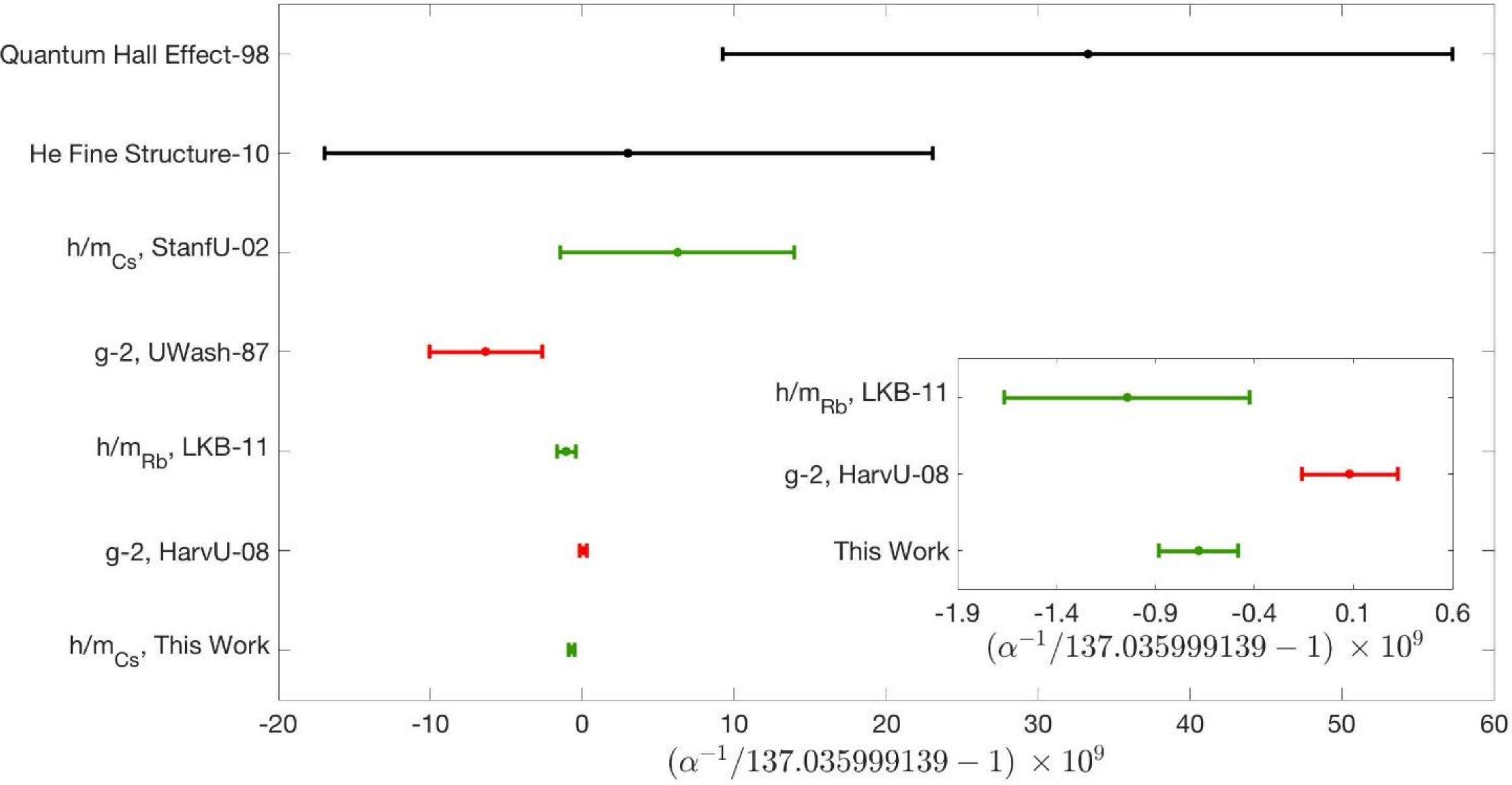
Ongoing dark photon searches



Schuster

Results

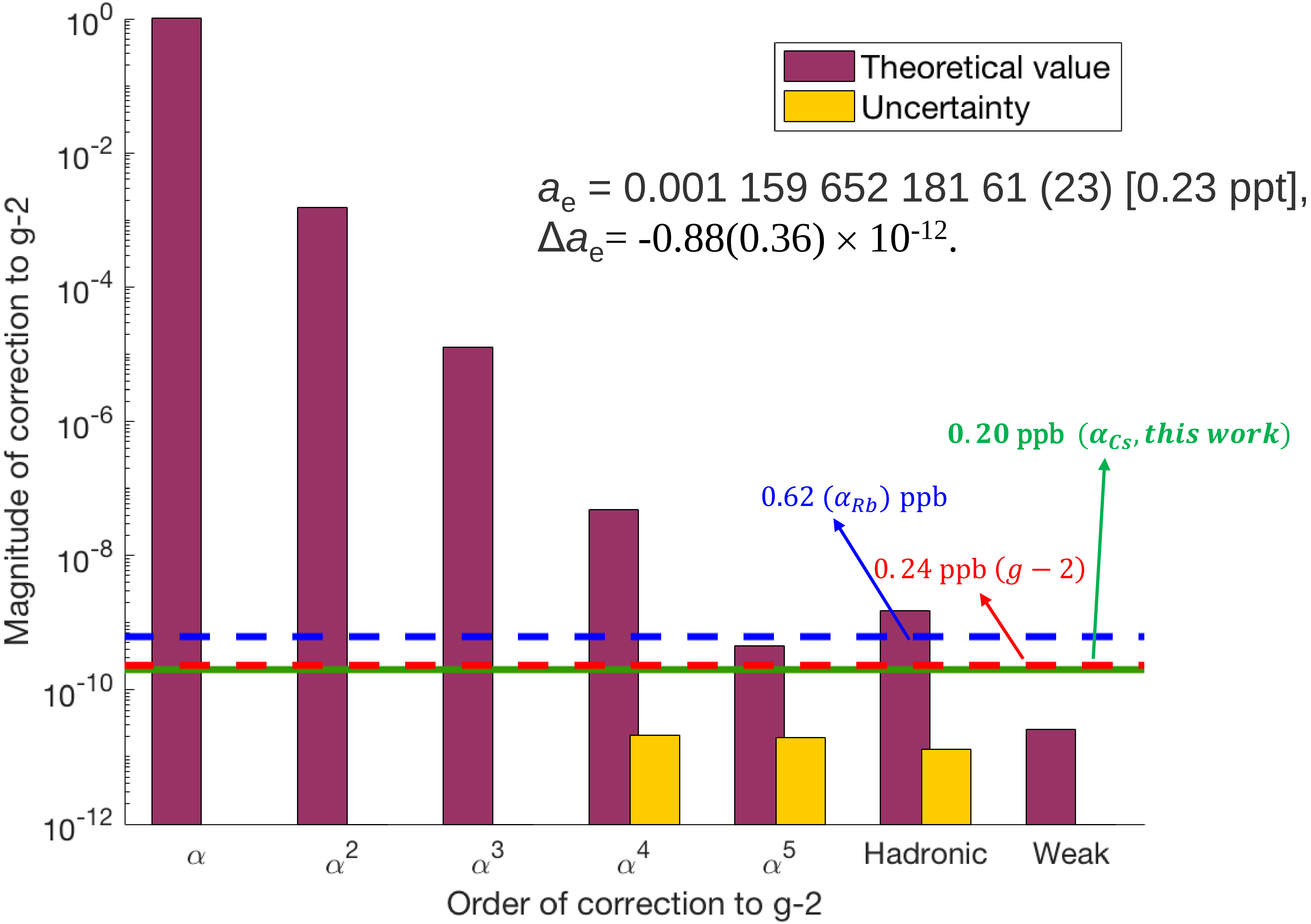
Results



α = 1/137.035 999 046 (27) [0.20 ppb]

1.3 million sigma from 1/137

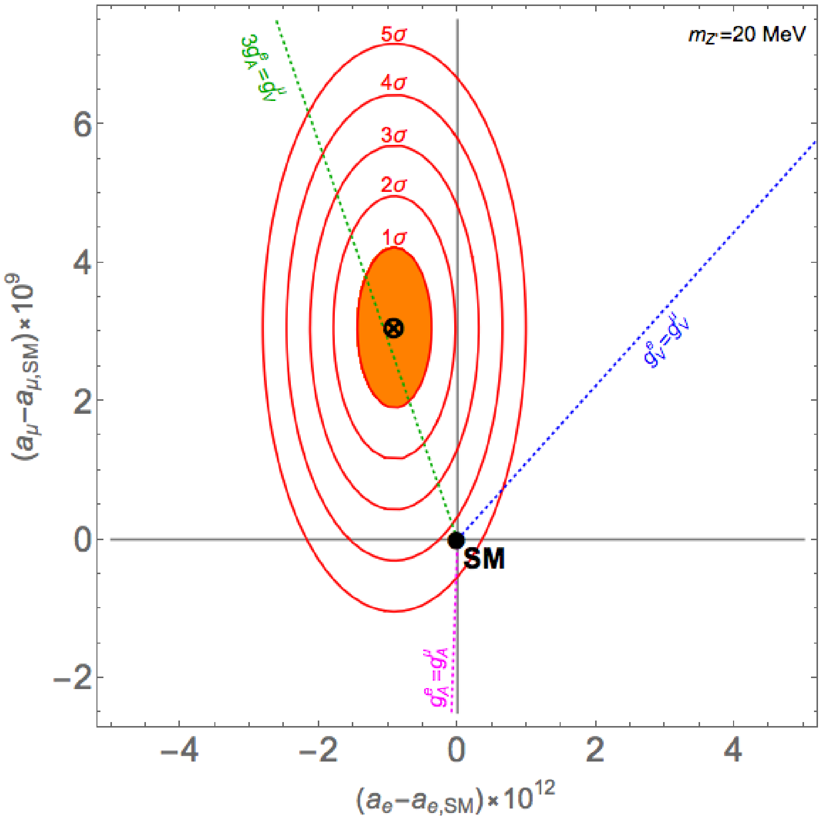
Results

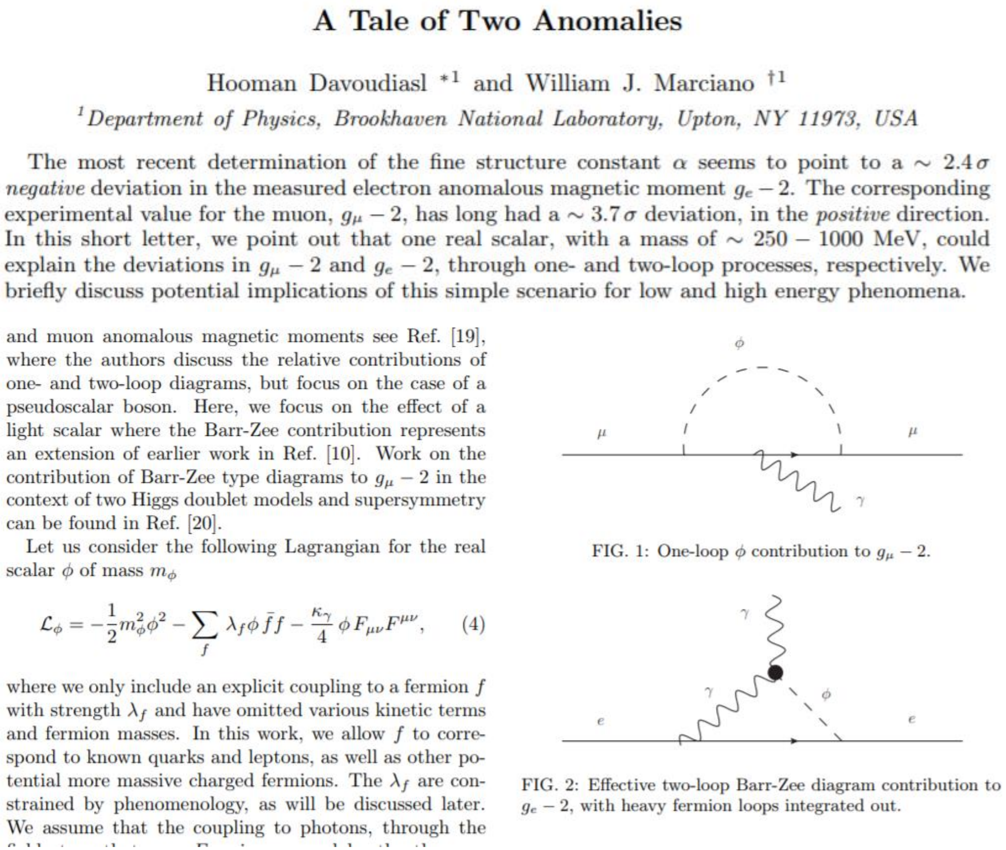


a_e = 0.001 159 652 181 61 (23) [0.23 ppt],

$\Delta a_e = -0.88(0.36) \times 10^{-12}$.

Two *g*-2 anomalies





A Tale of Two Anomalies

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

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

The most recent determination of the fine structure constant α seems to point to a $\sim 2.4\sigma$ *negative* deviation in the measured electron anomalous magnetic moment $g_e - 2$. The corresponding experimental value for the muon, $g_\mu - 2$, has long had a $\sim 3.7\sigma$ deviation, in the *positive* direction. In this short letter, we point out that one real scalar, with a mass of $\sim 250-1000$ MeV, could explain the deviations in $g_\mu - 2$ and $g_e - 2$, through one- and two-loop processes, respectively. We briefly discuss potential implications of this simple scenario for low and high energy phenomena.

and muon anomalous magnetic moments see Ref. [19], where the authors discuss the relative contributions of one- and two-loop diagrams, but focus on the case of a pseudoscalar boson. Here, we focus on the effect of a light scalar where the Barr-Zee contribution represents an extension of earlier work in Ref. [10]. Work on the contribution of Barr-Zee type diagrams to $g_\mu - 2$ in the context of two Higgs doublet models and supersymmetry can be found in Ref. [20].

Let us consider the following Lagrangian for the real scalar ϕ of mass m_ϕ

$$\mathcal{L}_\phi = -\frac{1}{2}m_\phi^2\phi^2 - \sum_f \lambda_f \phi \bar{f} f - \frac{\kappa_\gamma}{4}\,\phi\, F_{\mu\nu}F^{\mu\nu}, \qquad (4)$$

where we only include an explicit coupling to a fermion f with strength λ_f and have omitted various kinetic terms and fermion masses. In this work, we allow f to correspond to known quarks and leptons, as well as other potential more massive charged fermions. The λ_f are constrained by phenomenology, as will be discussed later. We assume that the coupling to photons, through the

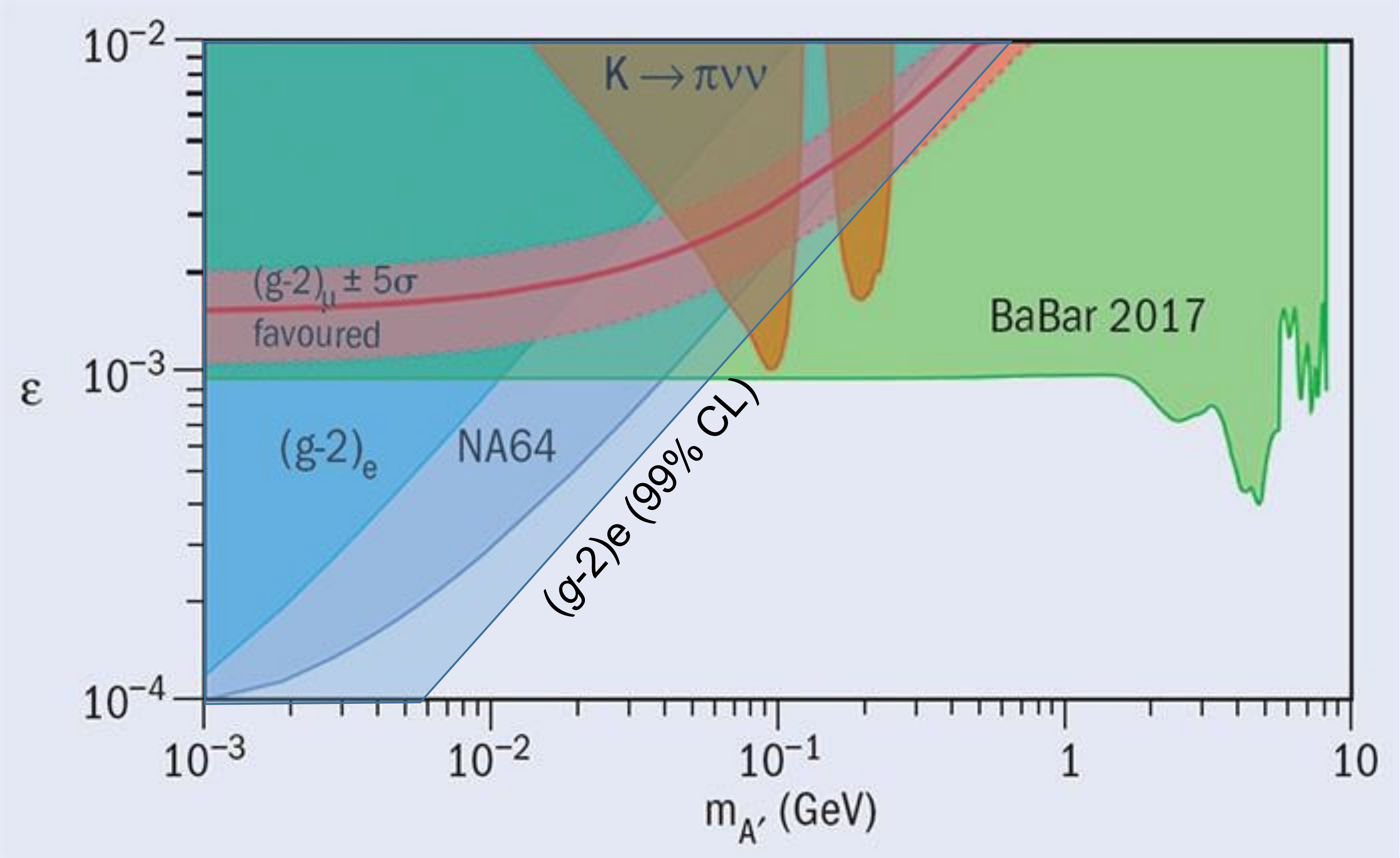
FIG. 1: One-loop ϕ contribution to $g_\mu - 2$.

FIG. 2: Effective two-loop Barr-Zee diagram contribution to $g_e - 2$, with heavy fermion loops integrated out.

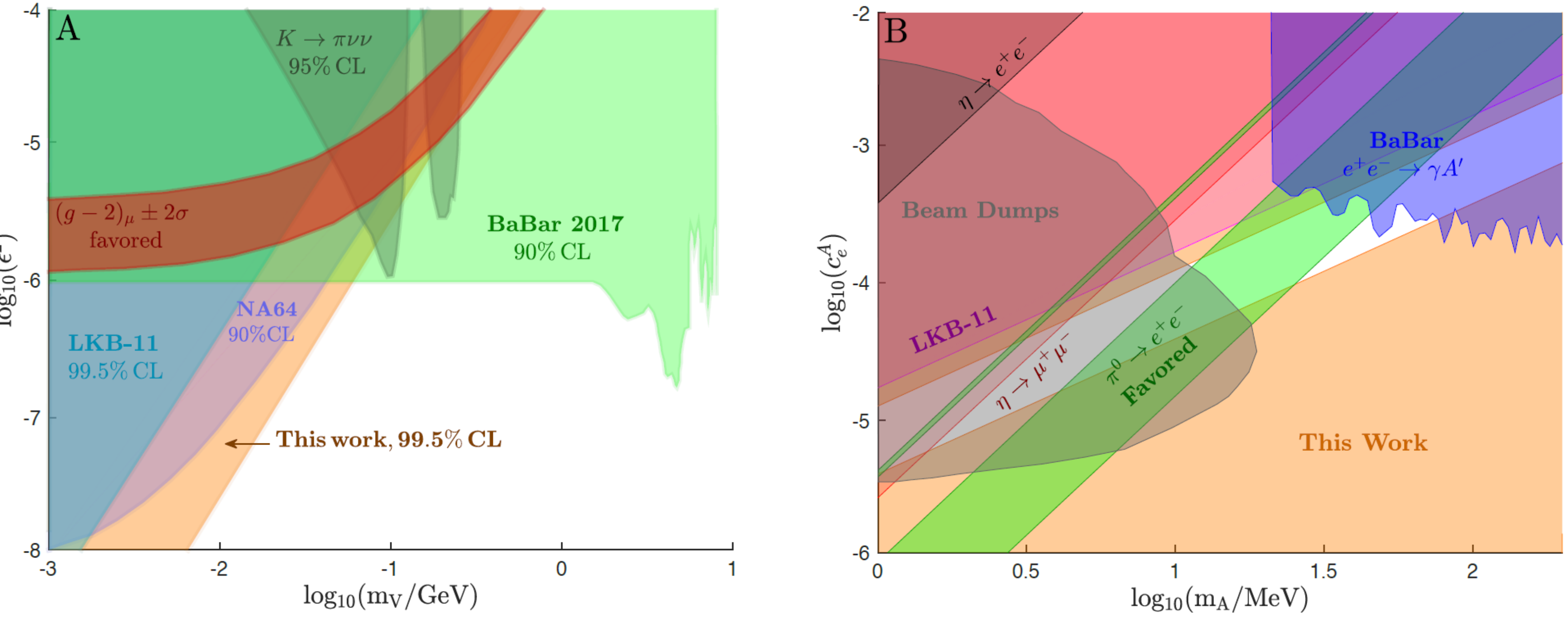
http://resonaances.blogspot.com/2018/06/alpha-and-g-minus-two.html

Davoudiasl & Marciano, arXiv:1806.10252

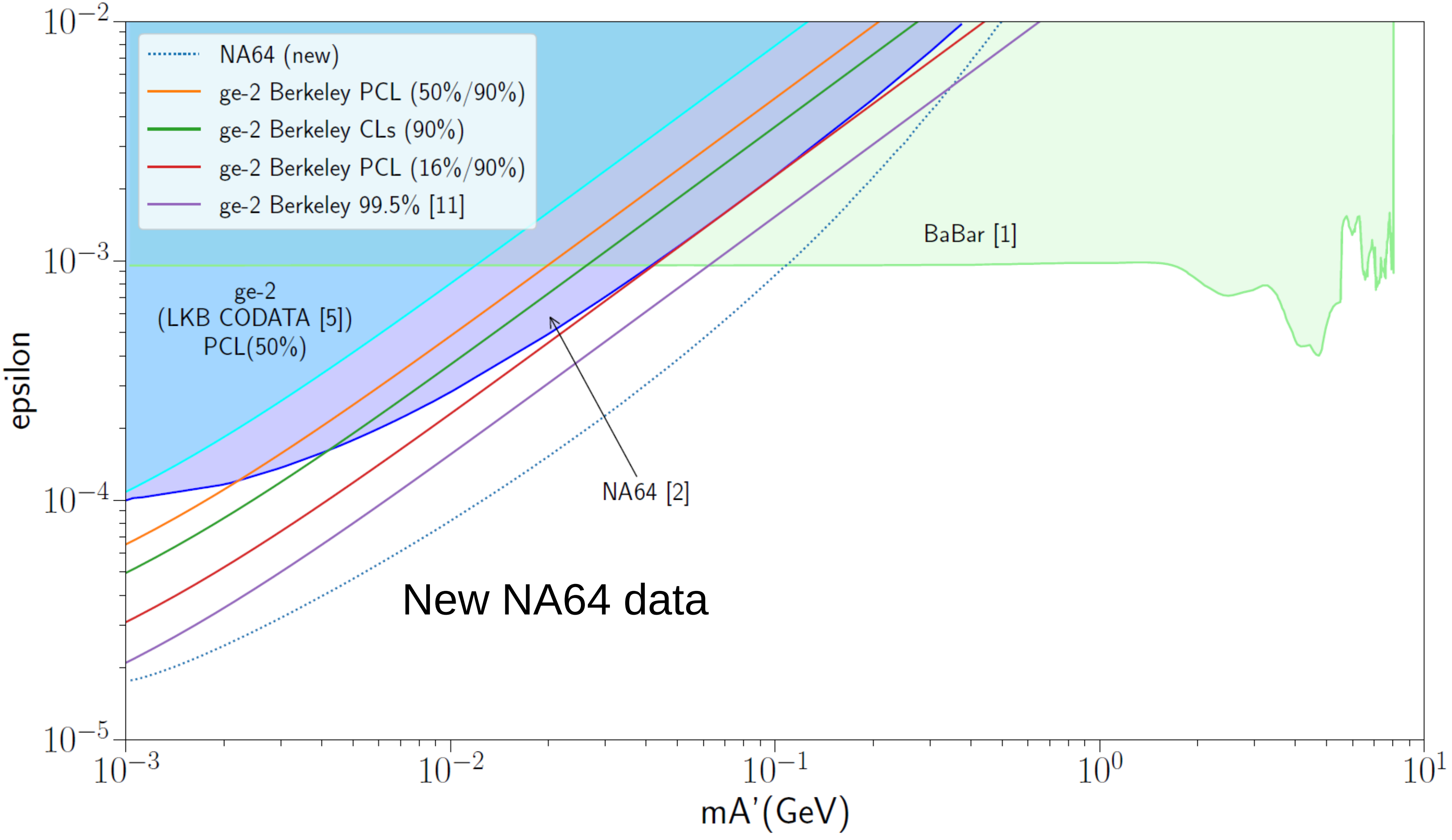
Dark photon limits



Dark photons & axial vectors



Dark photon update



New NA64 data

Other interpretations

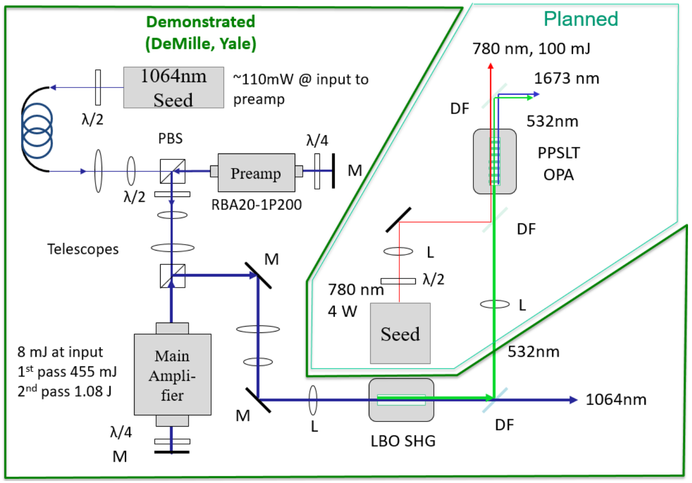
+3.7 σ positive deviation in the muon, -2.4 σ for the electron

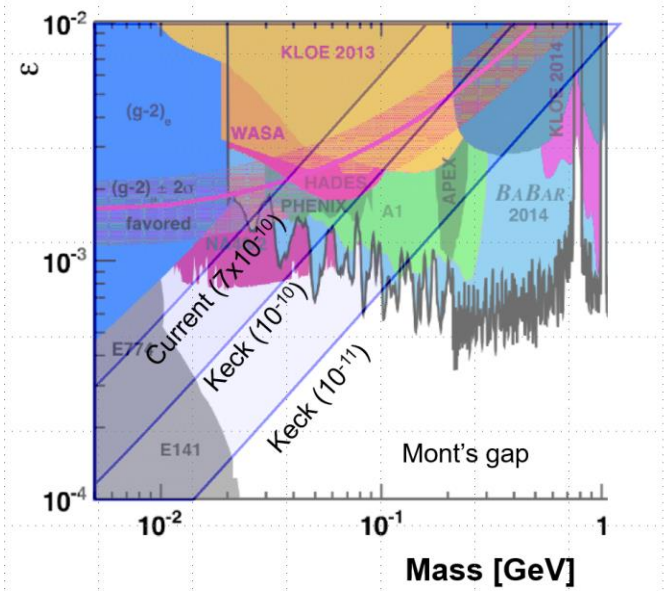
- "One real scalar, $M \sim 250 - 1000$ MeV, could explain [both] deviations through 1- and 2-loop processes, respectively." [1]
- "Requires that the muon and electron sectors effectively decouple to avoid constraints from $\mu \rightarrow e\gamma$. … Improved measurements of a_e, a_μ, as well as α are not only set to provide exciting precision tests of the SM, but, in combination with EDMs, to reveal crucial insights into the flavor structure of physics beyond the SM." [2]

[1] Davoudiasl and Marciano, arXiv:1806.10252 (2018)
[2] Crivellin, Hoferichter, and Schmidt-Wellenburg, arXiv:1807.1148 (2018)

Future Upgrades

- Broad beam
  - x20 waist → 1/400 beam-related systematics
  - x1000 eff. power
- Acoustic Shielded Room
  - Controls gravity anomalies by keeping heavy objects out
- Science Chamber
  - Dark Matter studies





Thank you!

Fine Structure Constant
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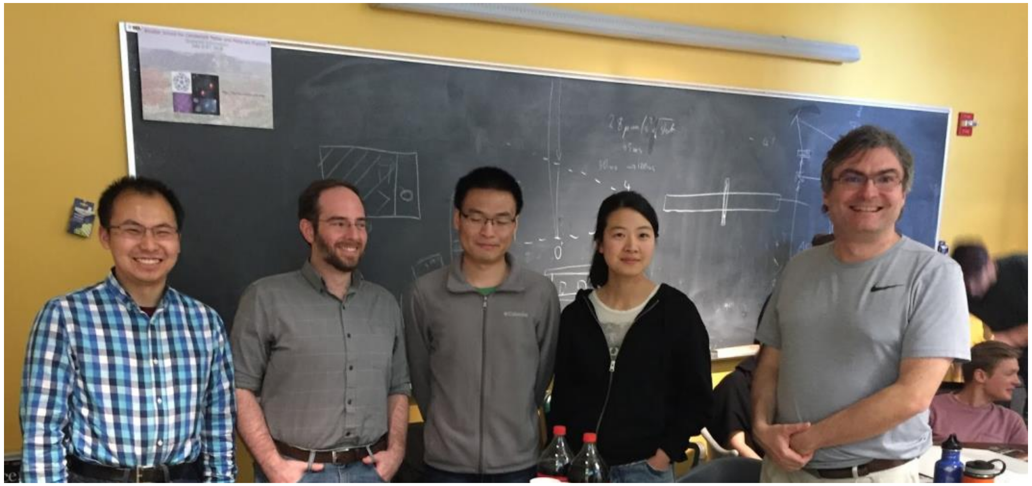
Chenghui Yu
Weicheng Zhong
Undergrad: Joyce Kwan



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Jordan Dudley,
Matt Jaffe,
Zachary Pagel
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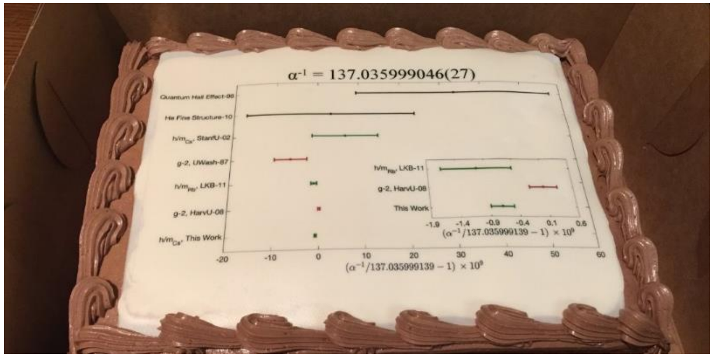

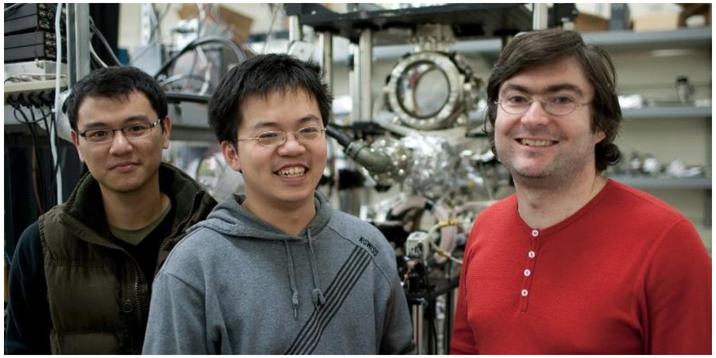

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Shau-Yu Lan (NTU)