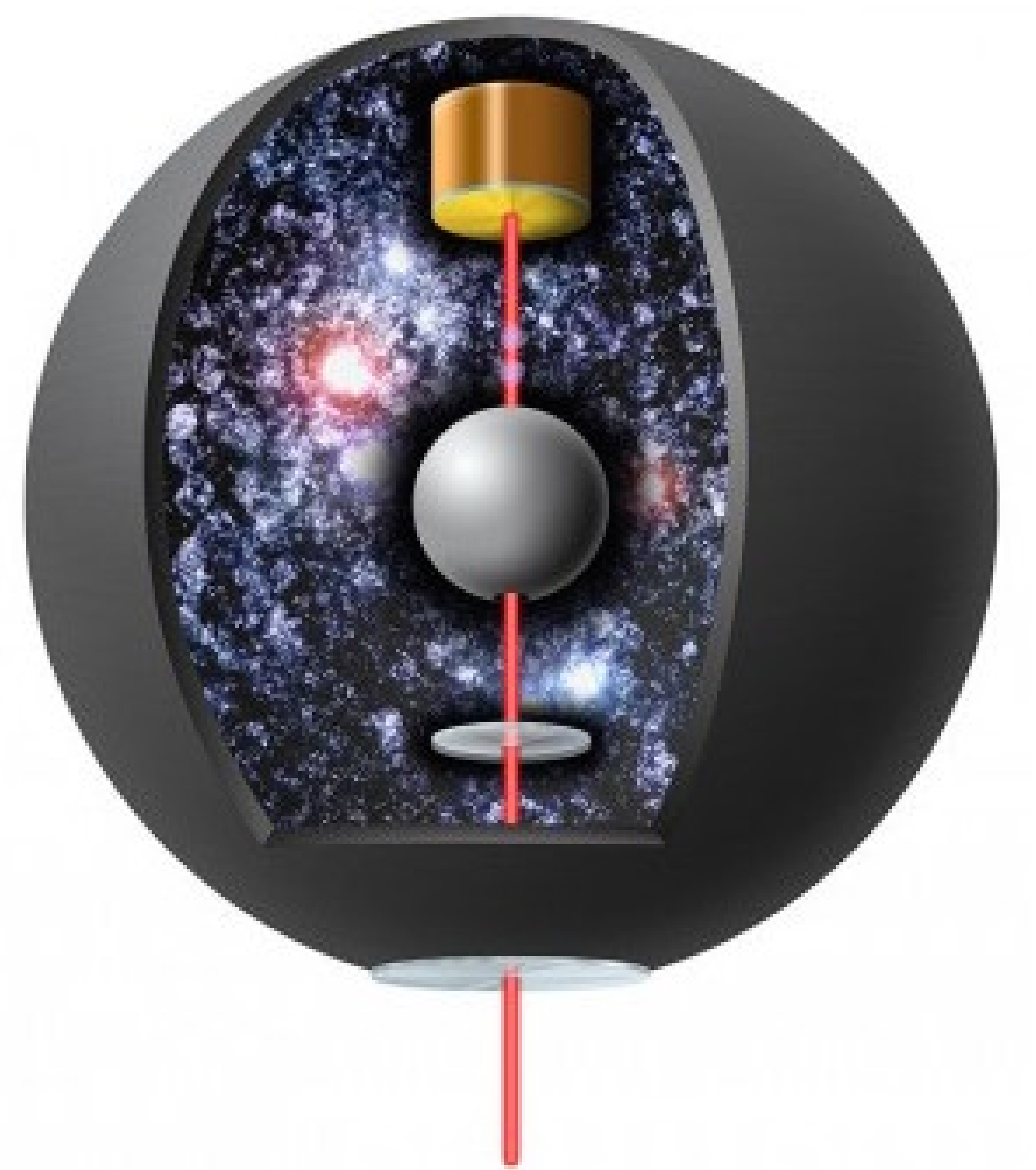
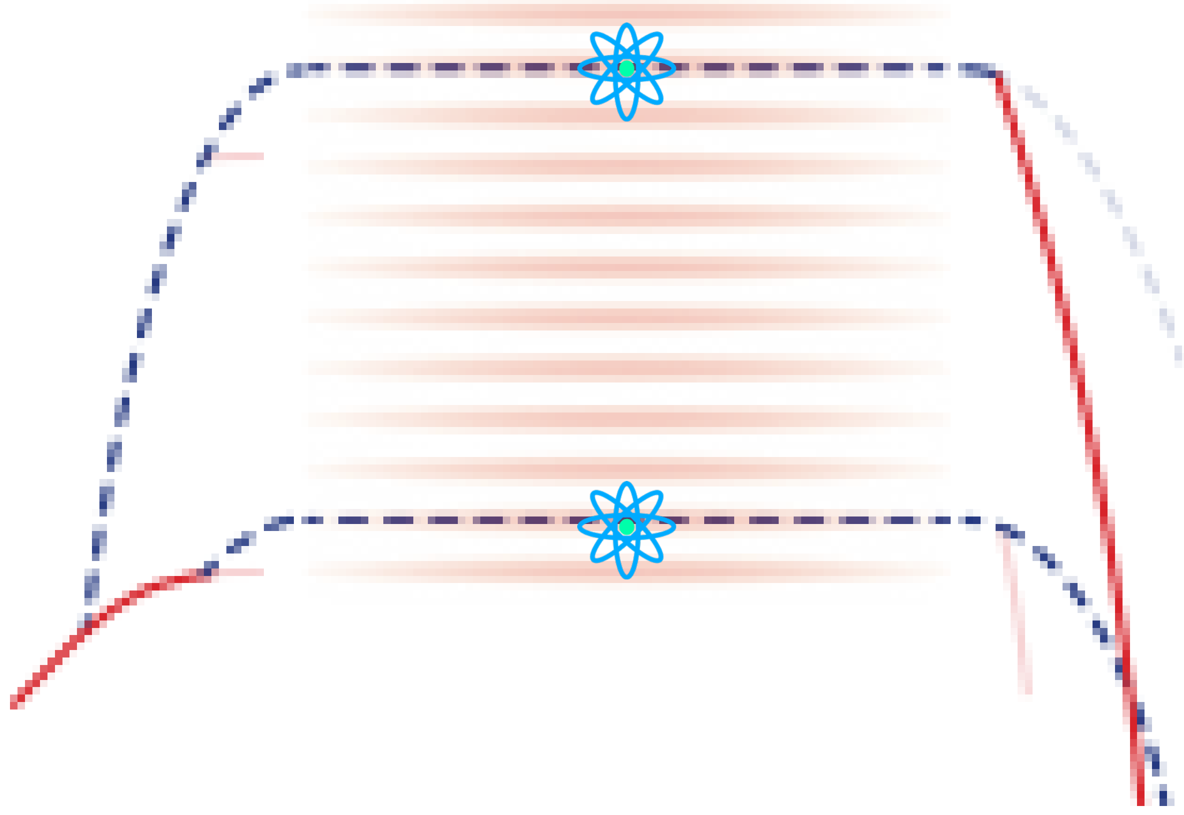
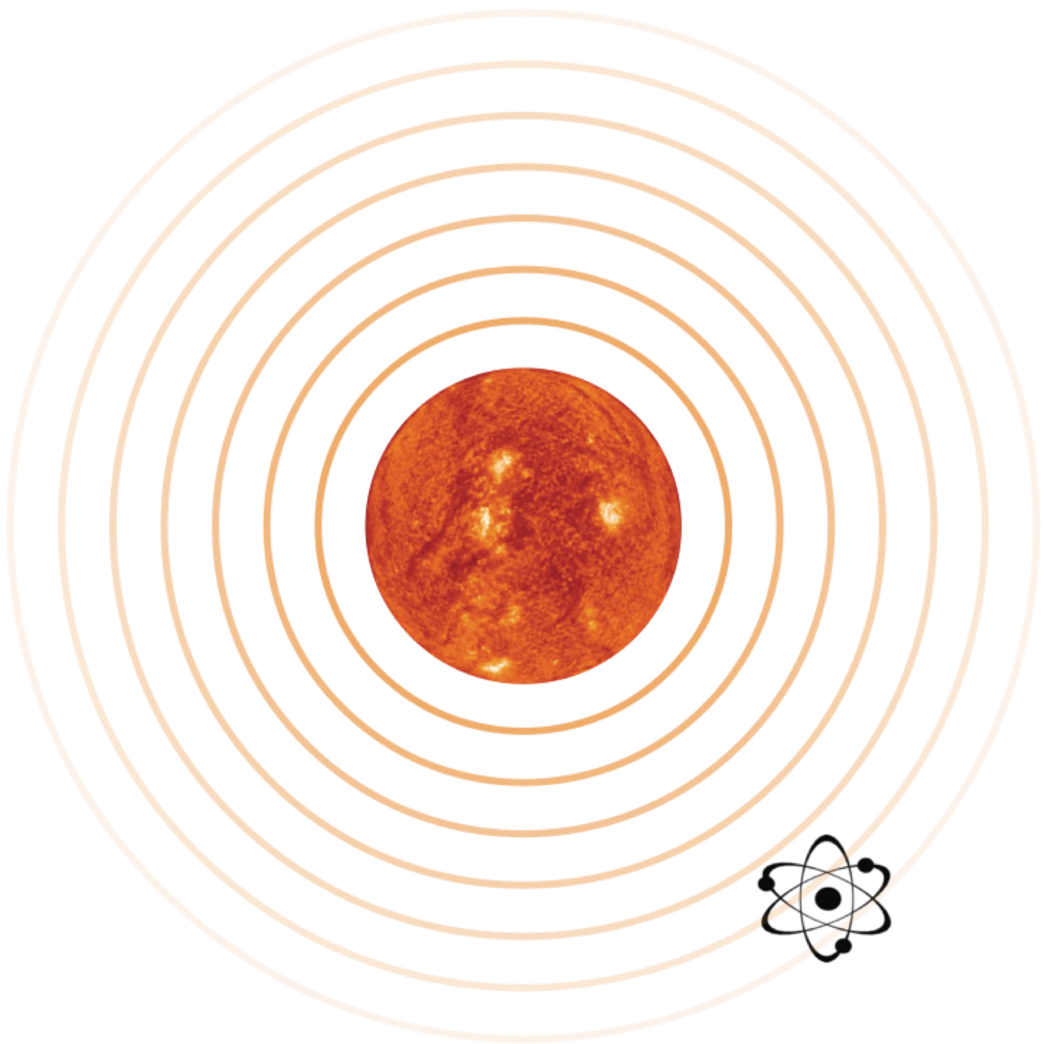
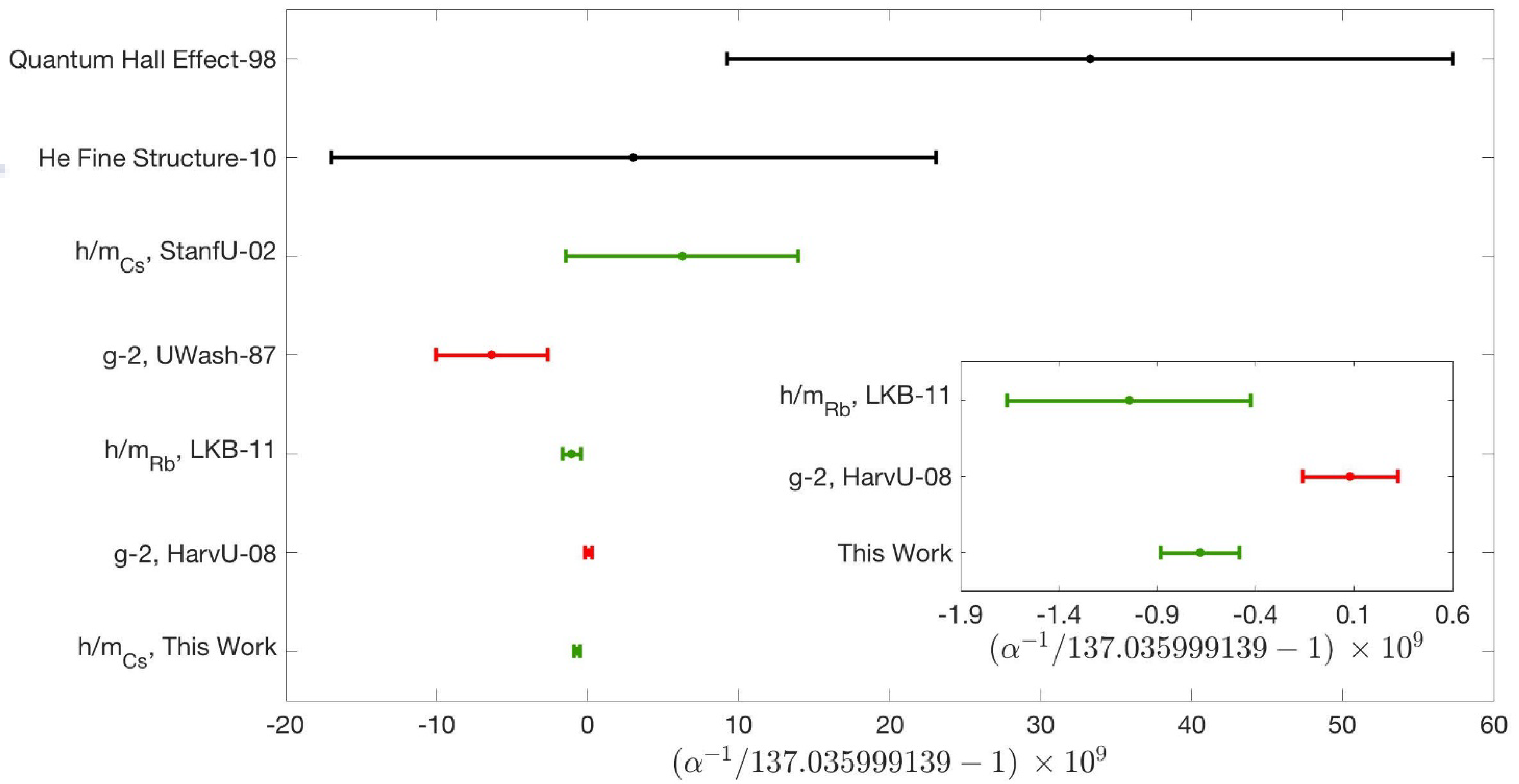








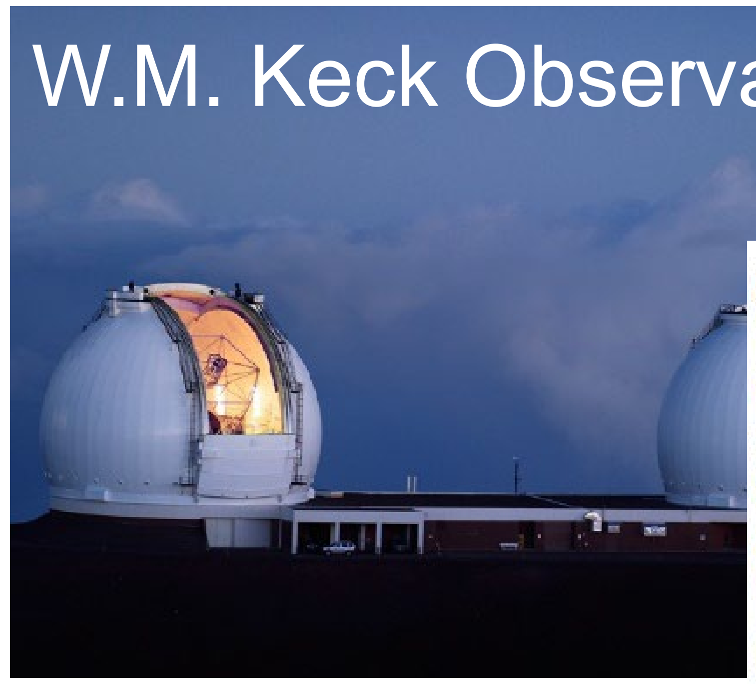
Atom interferometry in fundamental physics

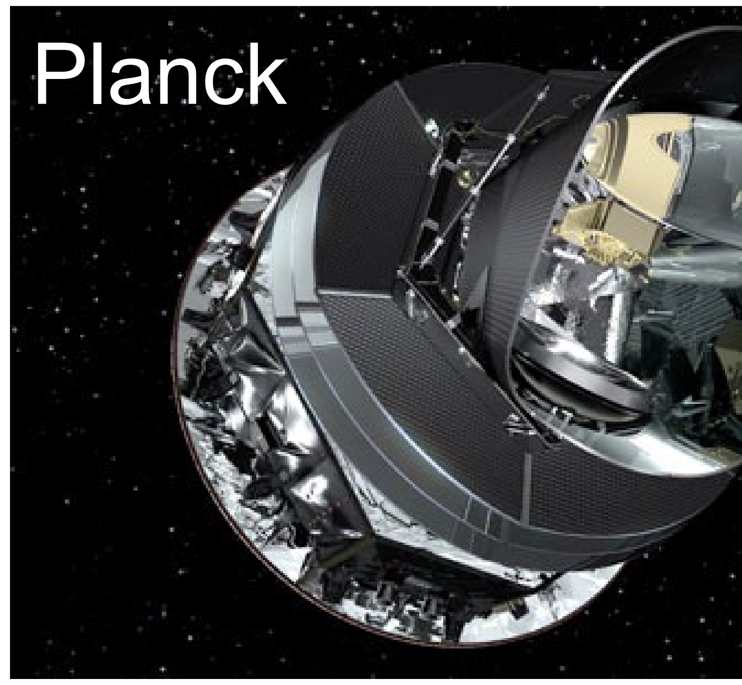
Holger Müller
LBNL
UC Berkeley

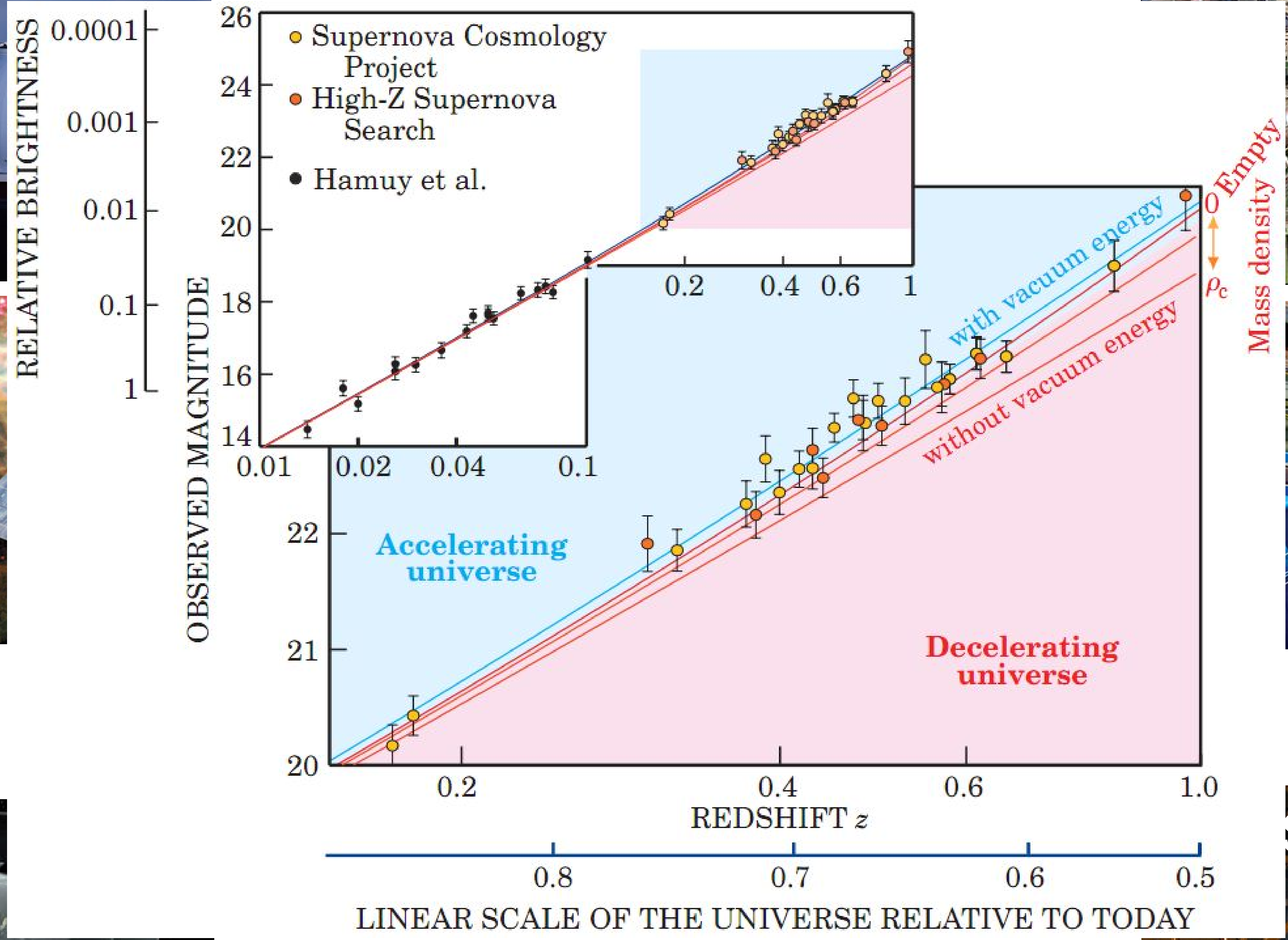
The Era of precision uncertainty

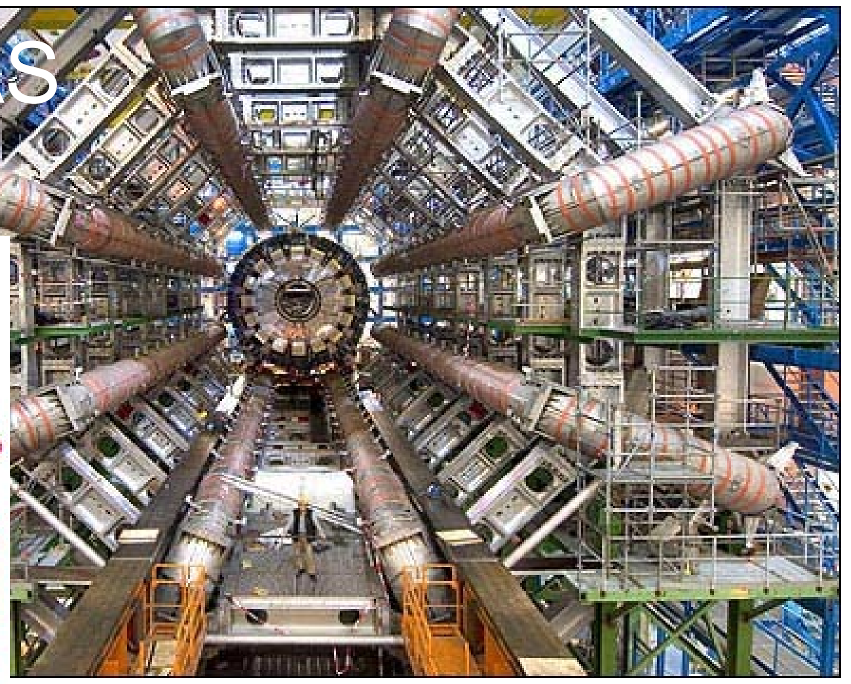
Loud and clear signals from the skies….

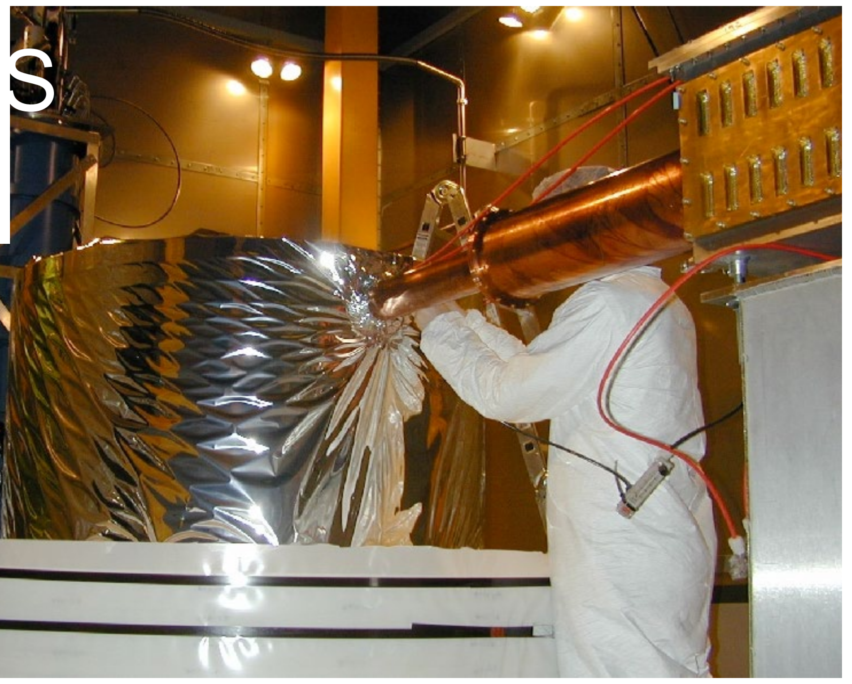
…but silence in our detectors



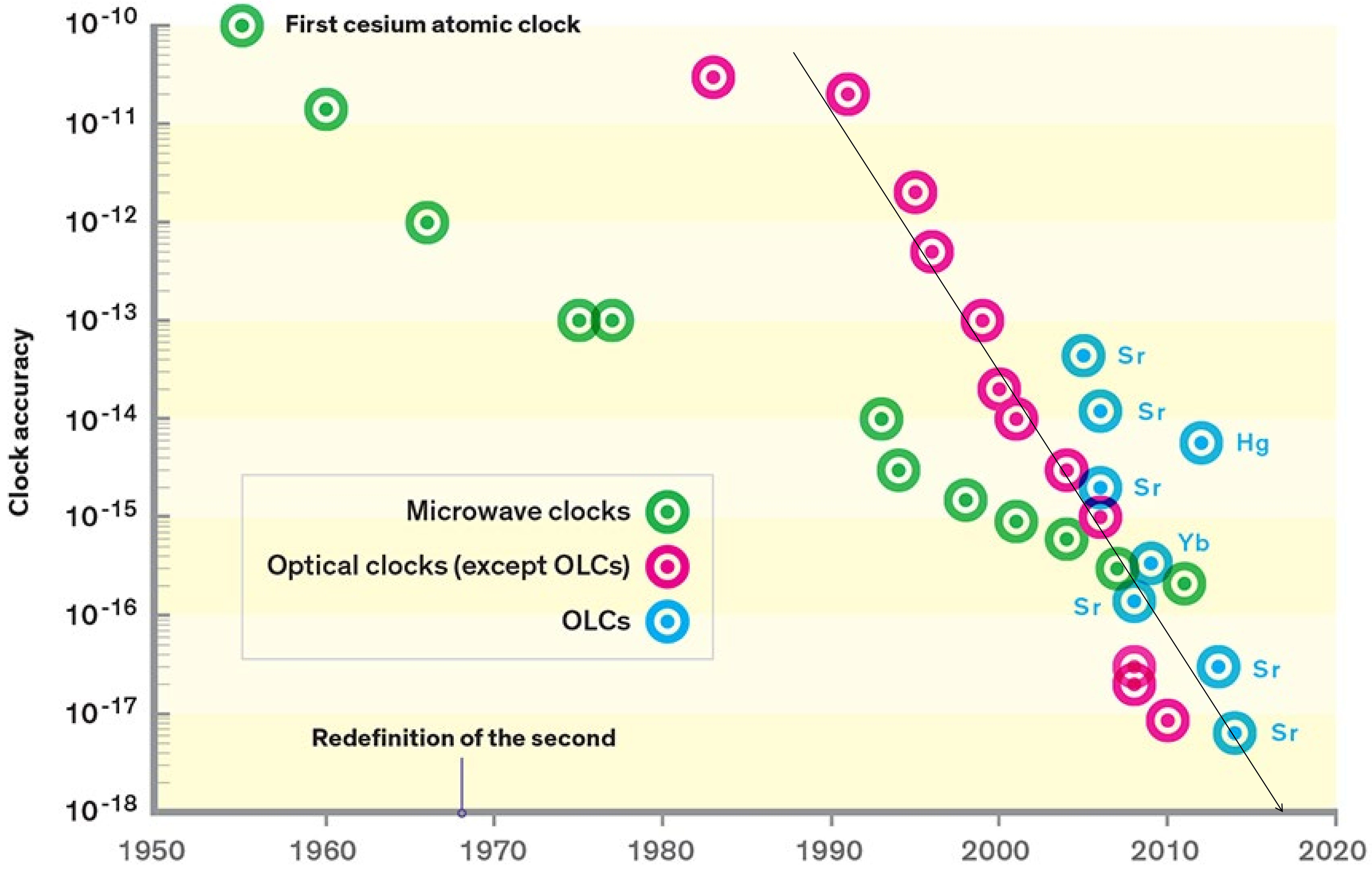




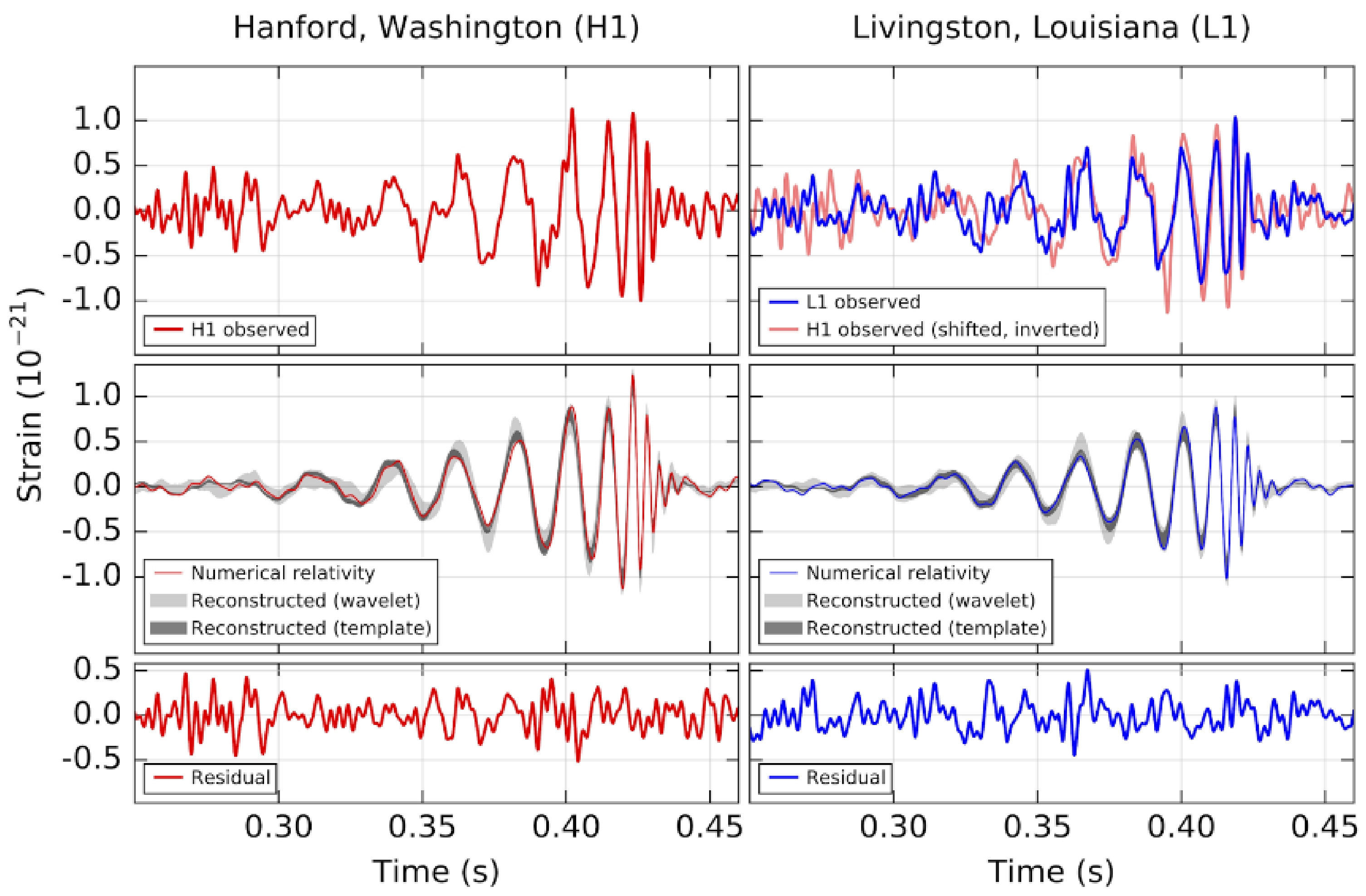


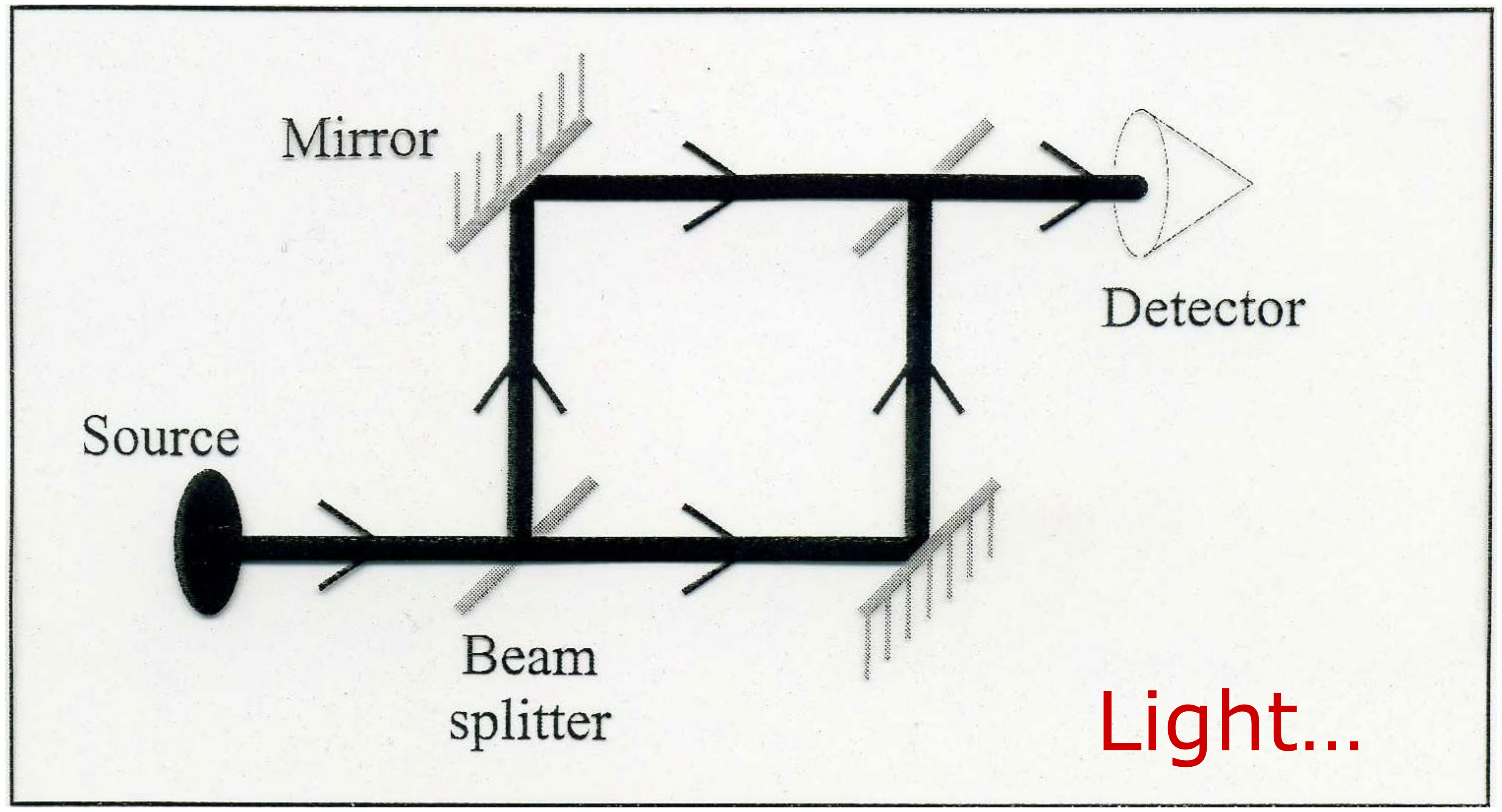


Moore’s law in atomic physics



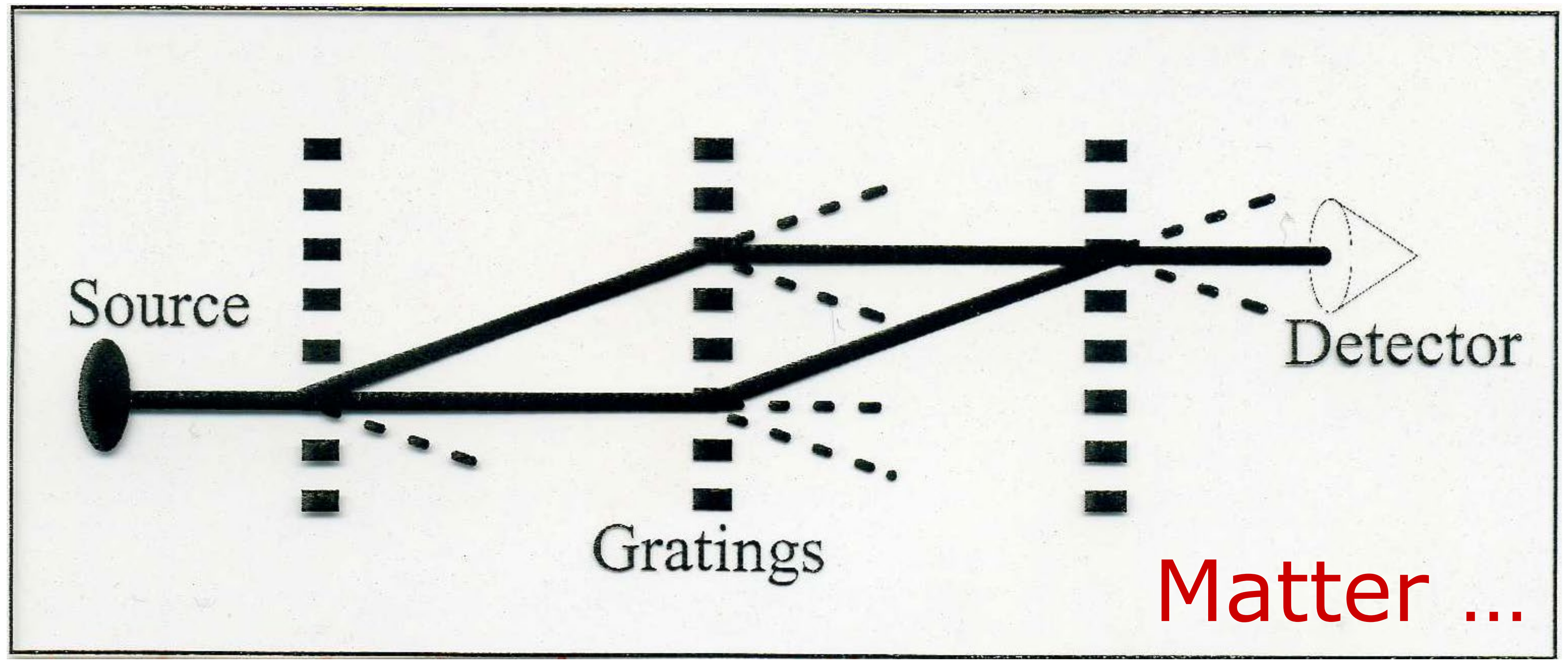
Interferometry…





Light…

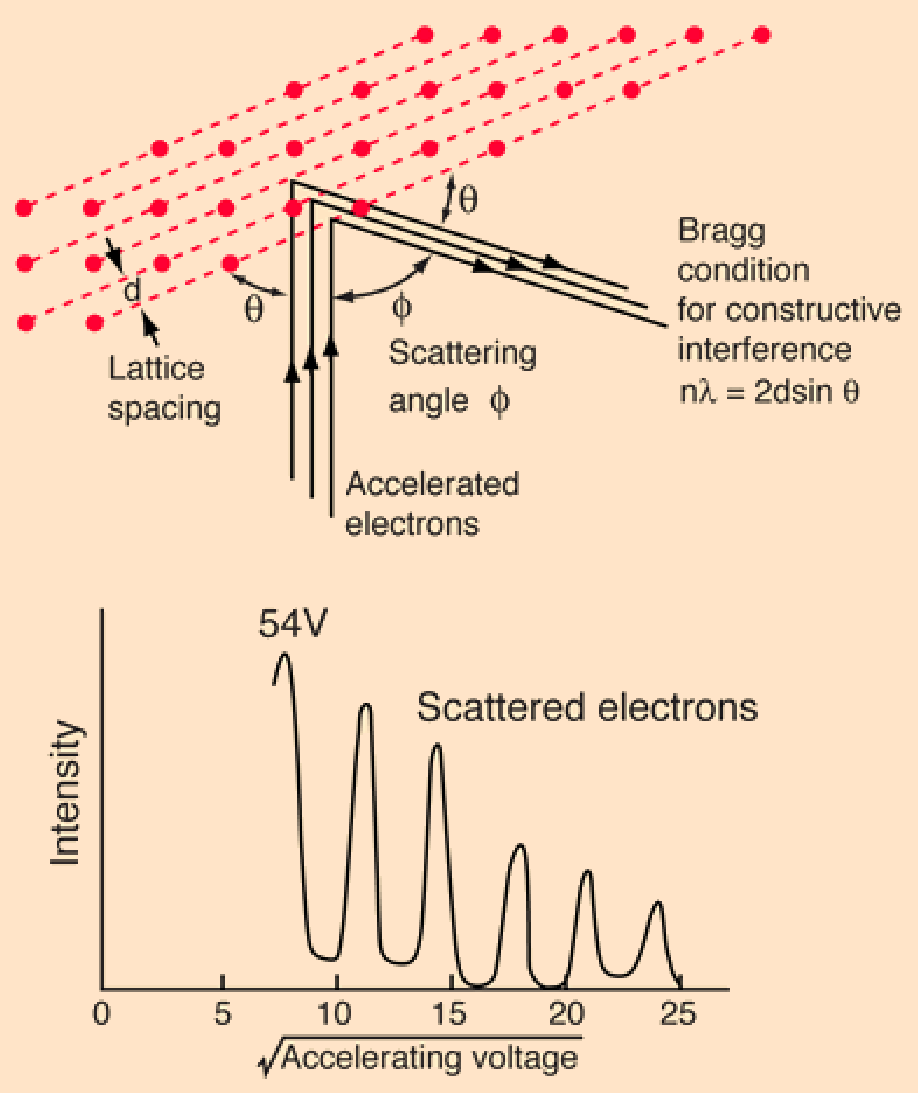
$$\lambda = \frac{h}{mv}$$



Matter …

Timeline

De Broglie, 1924: Matter waves



Davisson, C. J., "Are Electrons Waves?," Franklin Institute Journal 205, 597 (1928)

Davisson and Germer, 1928: electron interference

VOLUME 66, NUMBER 21 PHYSICAL REVIEW LETTERS 27 MAY 1991

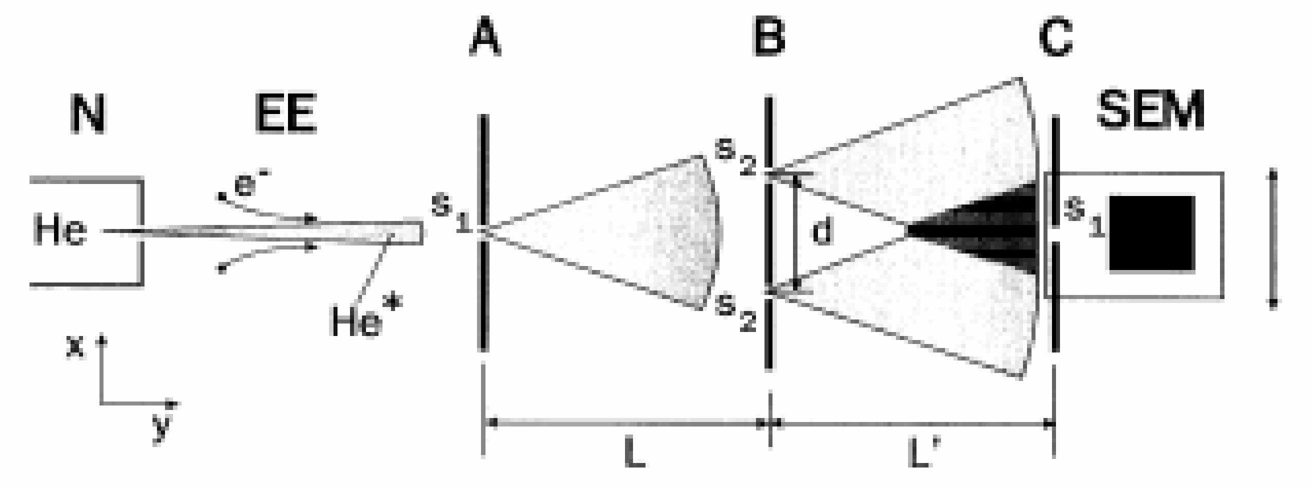
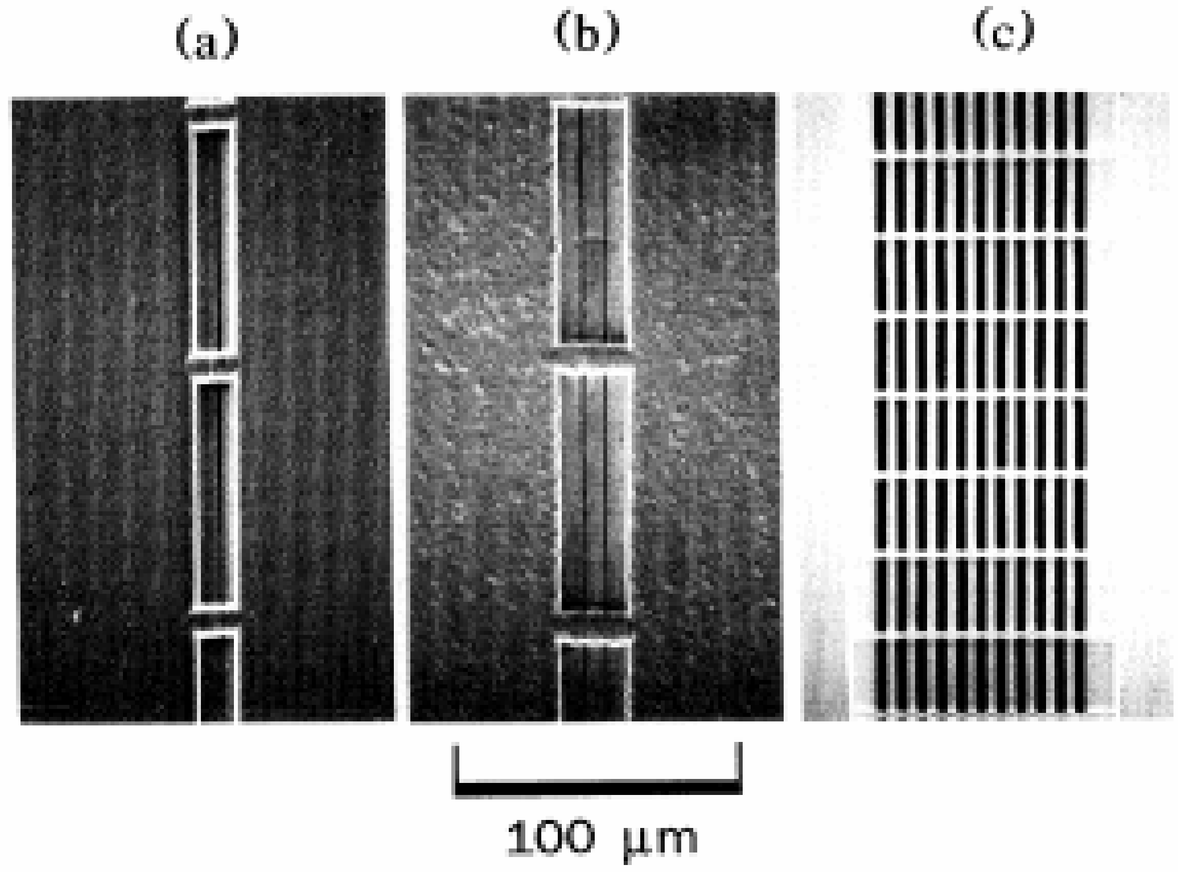


FIG. 2. Schematic representation of the experimental setup: nozzle system and gas reservoir N; electron impact excitation EE; entrance slit A, double slit B, and detector screen C; secondary electron multiplier SEM (mounted together with C on a translation stage). Dimensions: $d=8$ μm, $L=L'=64$ cm; slit widths: $s_1=2$ μm, $s_2=1$ μm.



Carnal and Mlynek, 1991: Atom interferometer with material gratings

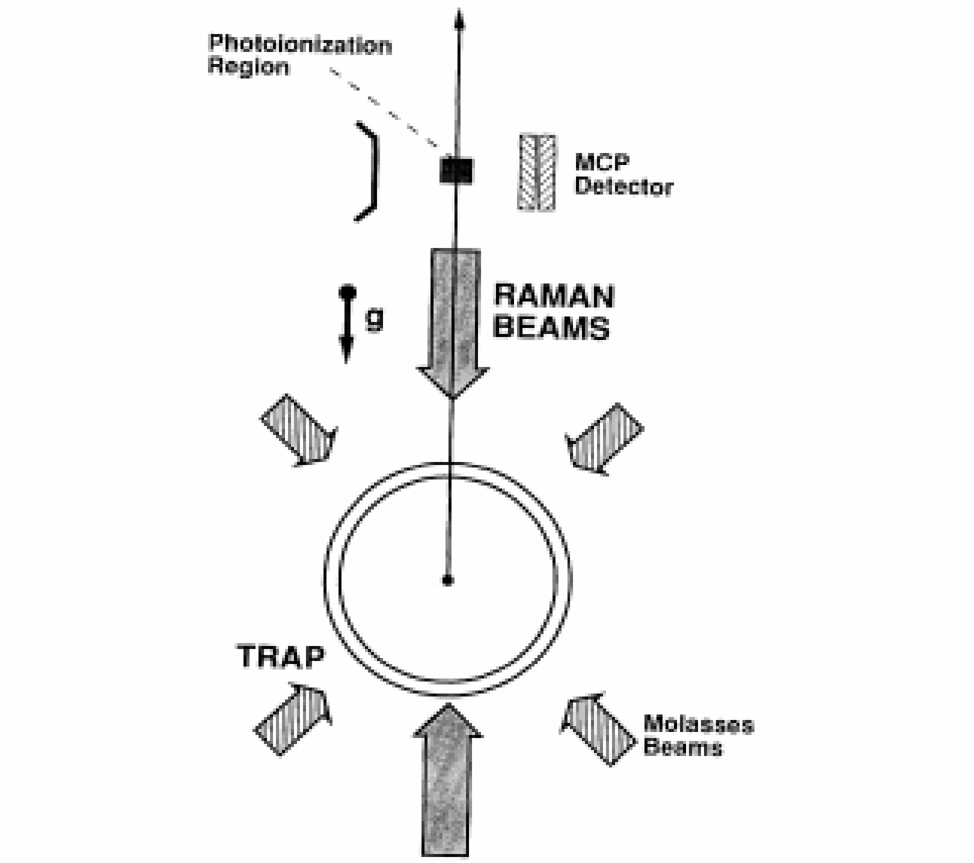


FIG. 2. A schematic of the apparatus used to demonstrate the interferometer illustrated in Fig. 1(b). Atoms were loaded into an optomagnetic trap, cooled, launched, and then optically pumped into the $F=1$ hyperfine state. Approximately 50 msec following their launch, the set of Raman beams is pulsed on three times to drive $\pi/2$-π-$\pi/2$ pulse sequence. After 135 msec, atoms in the $F=2$ state were detected by resonant photoionization. The repetition rate of the experiment was 1 Hz. Not shown are the other set of molasses beams and the atomic beam used to load the trap.

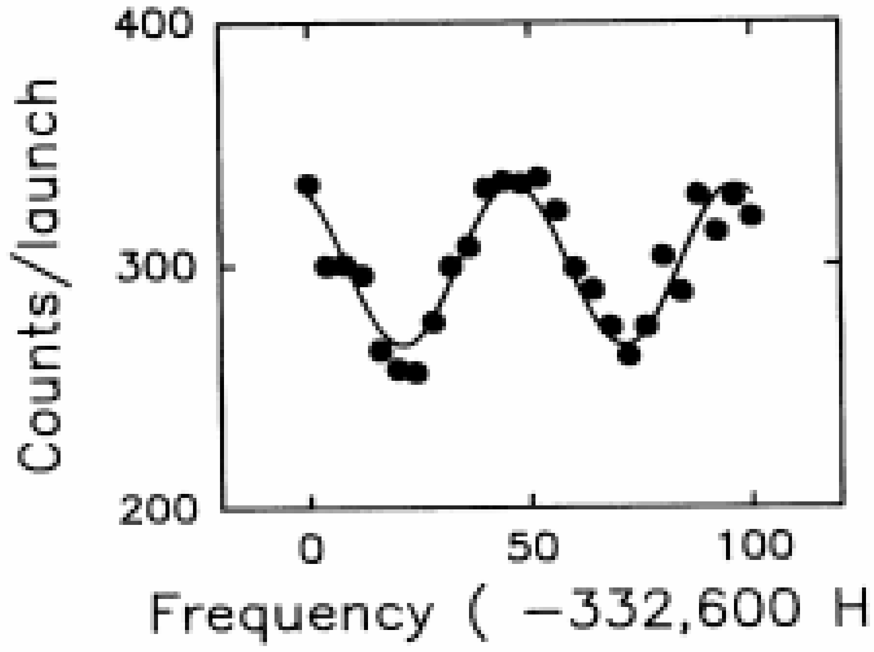


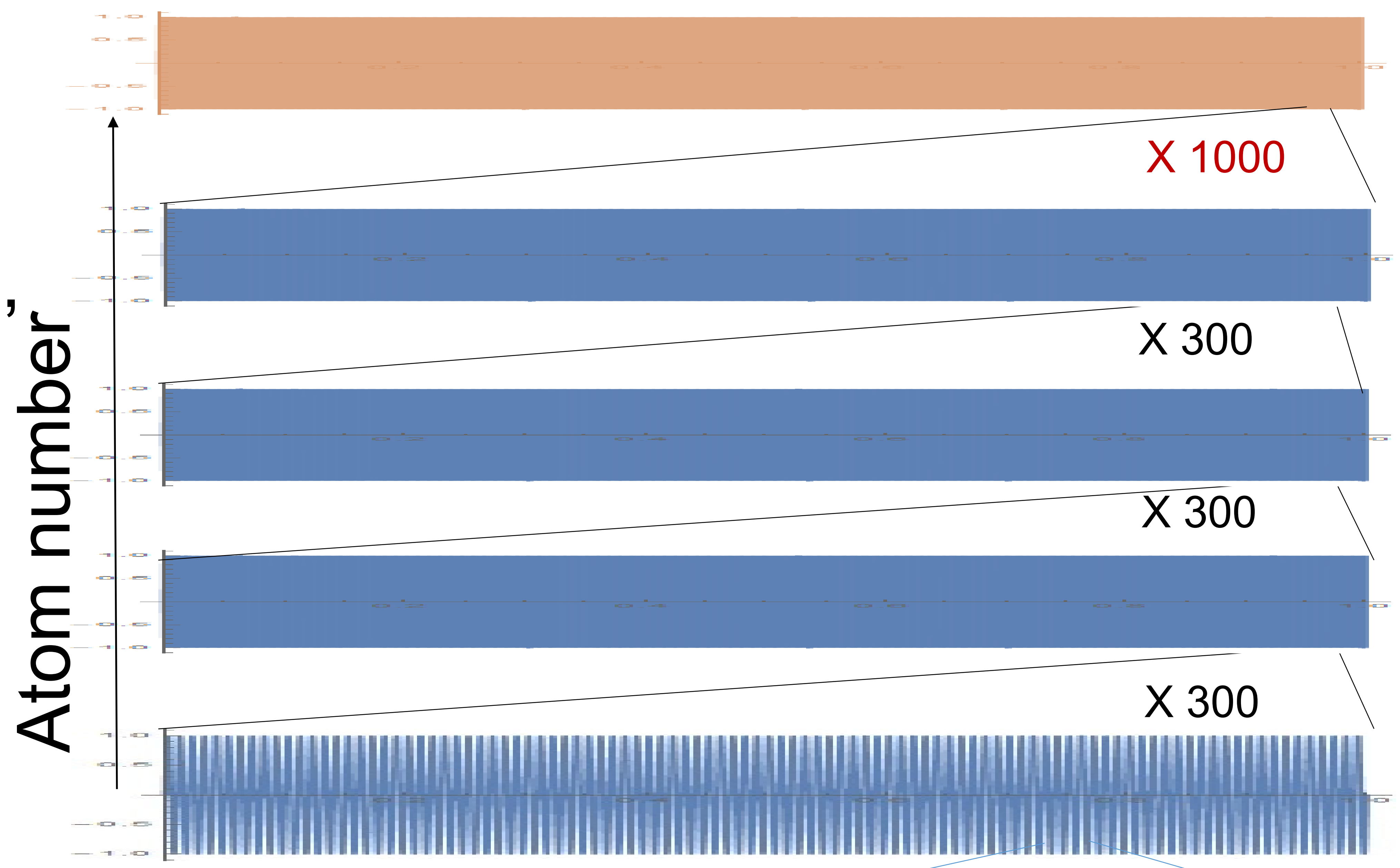
FIG. 3. Interferometer fringes from a frequency scan of the Raman laser beams when the time between pulses is 10 msec. The solid line is a nonlinear least-squares fit to the data. The linewidth of the resonance is determined by the time between the $\pi/2$ and π pulses, and is not a free parameter.

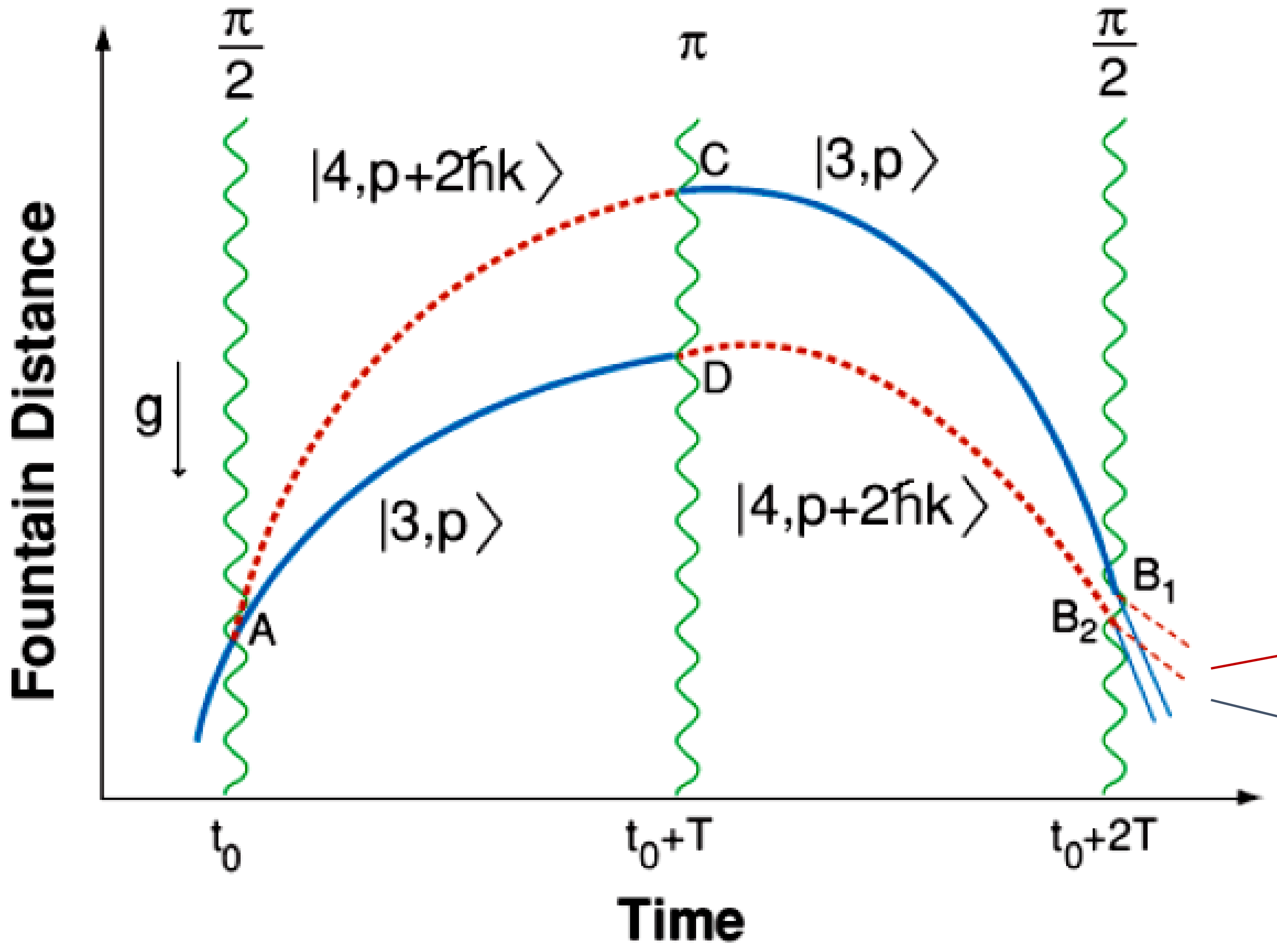
Kasevich and Chu as well as Riehle et al, 1991: Light-pulse atom interferometry

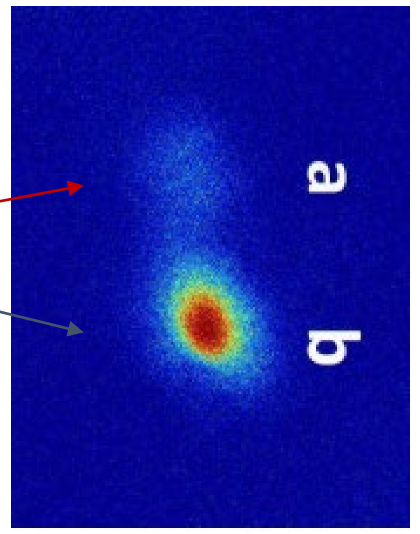
Light pulse atom interferometer

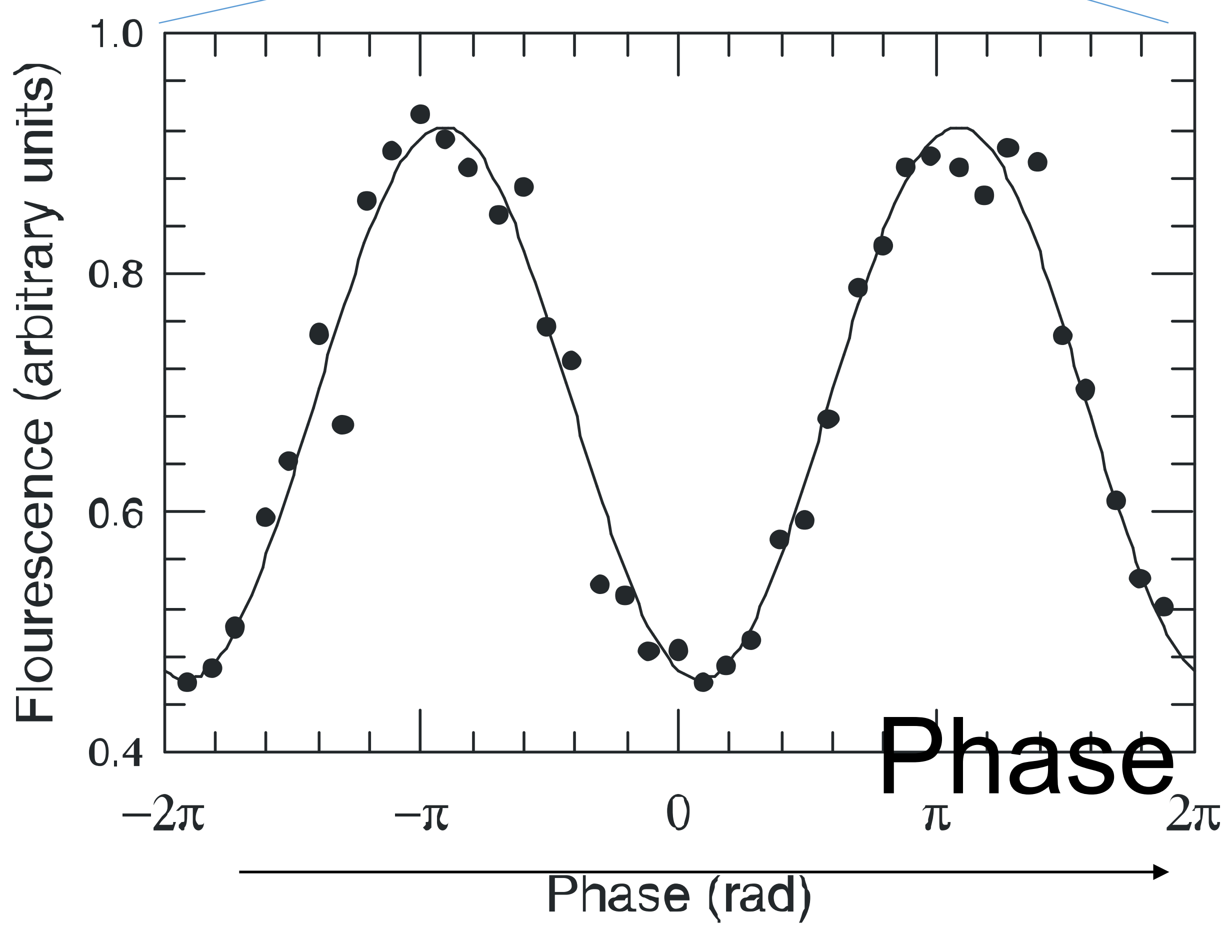
- Particles / waves
- Phase determined by Lagrangian, $L=E_{kin}-E_{pot}$,
- Laser wavelength as a ruler

Future?

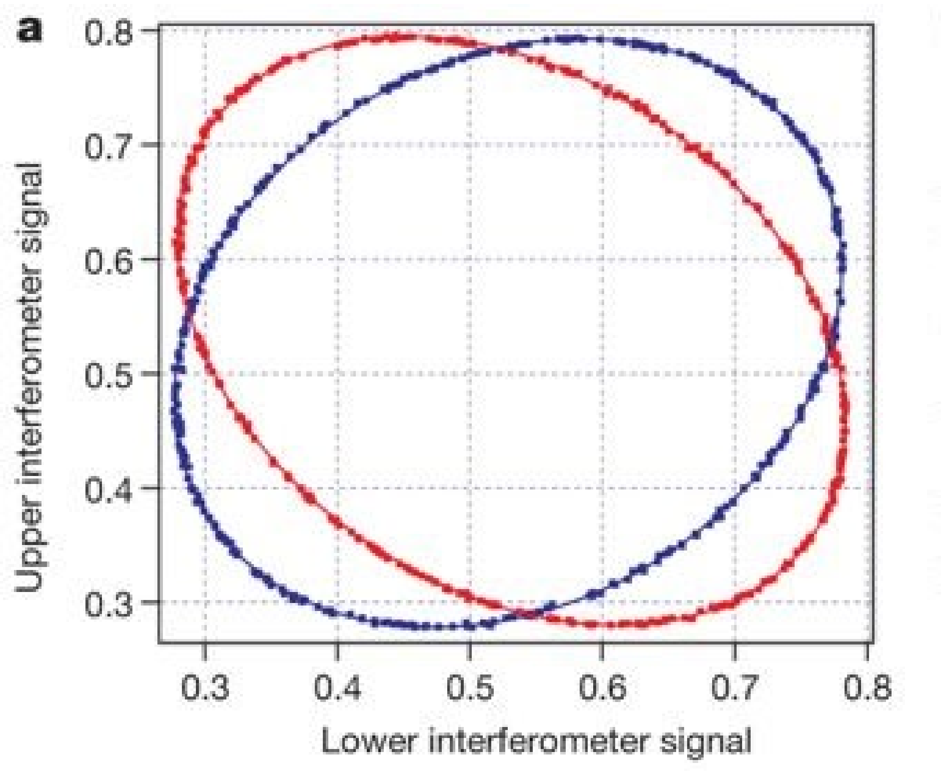




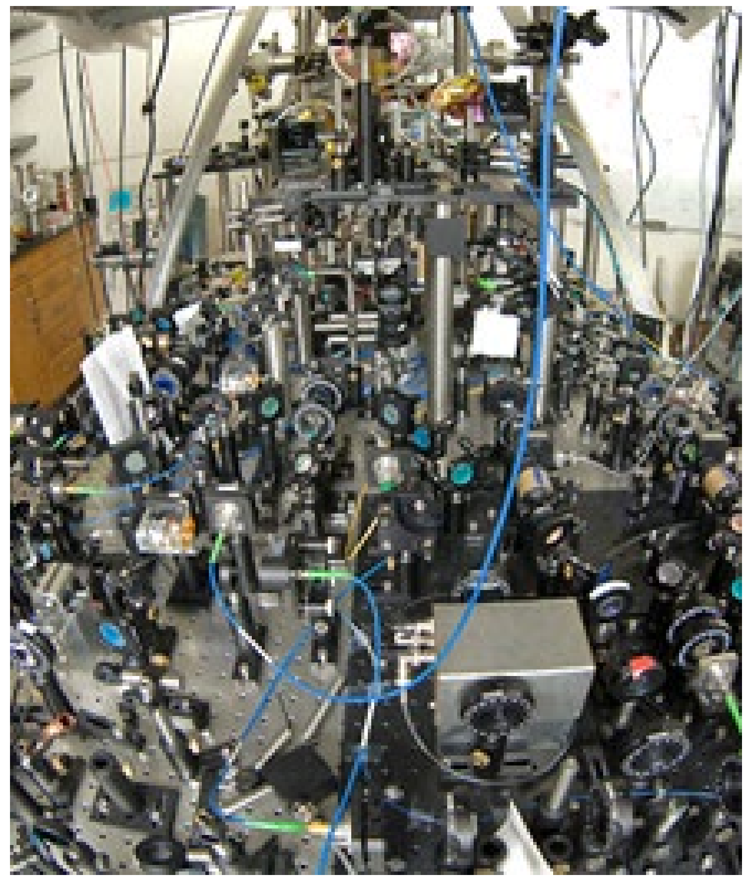


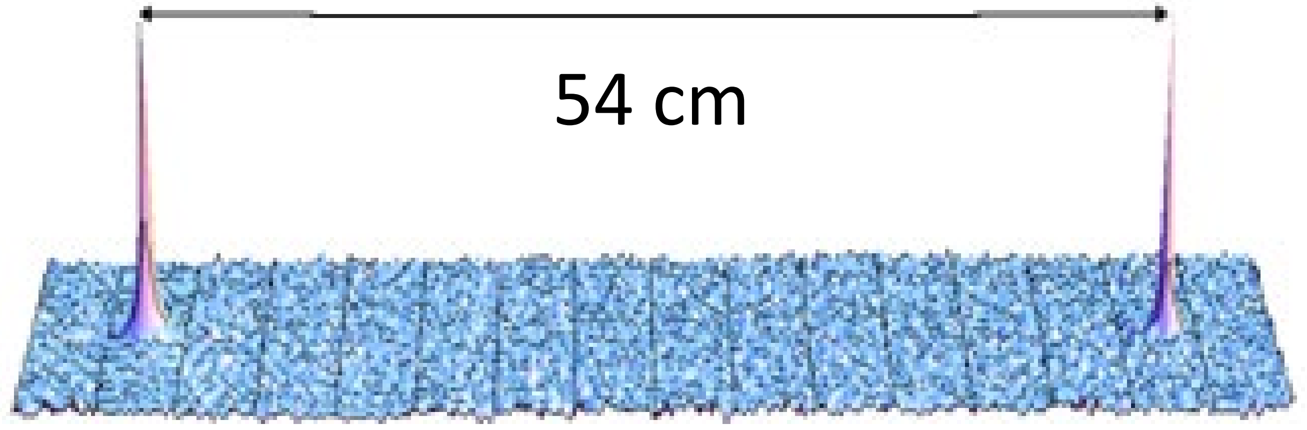


Precision interferometry



Rosi et al. **Nature** 510, 518-521 (2014)



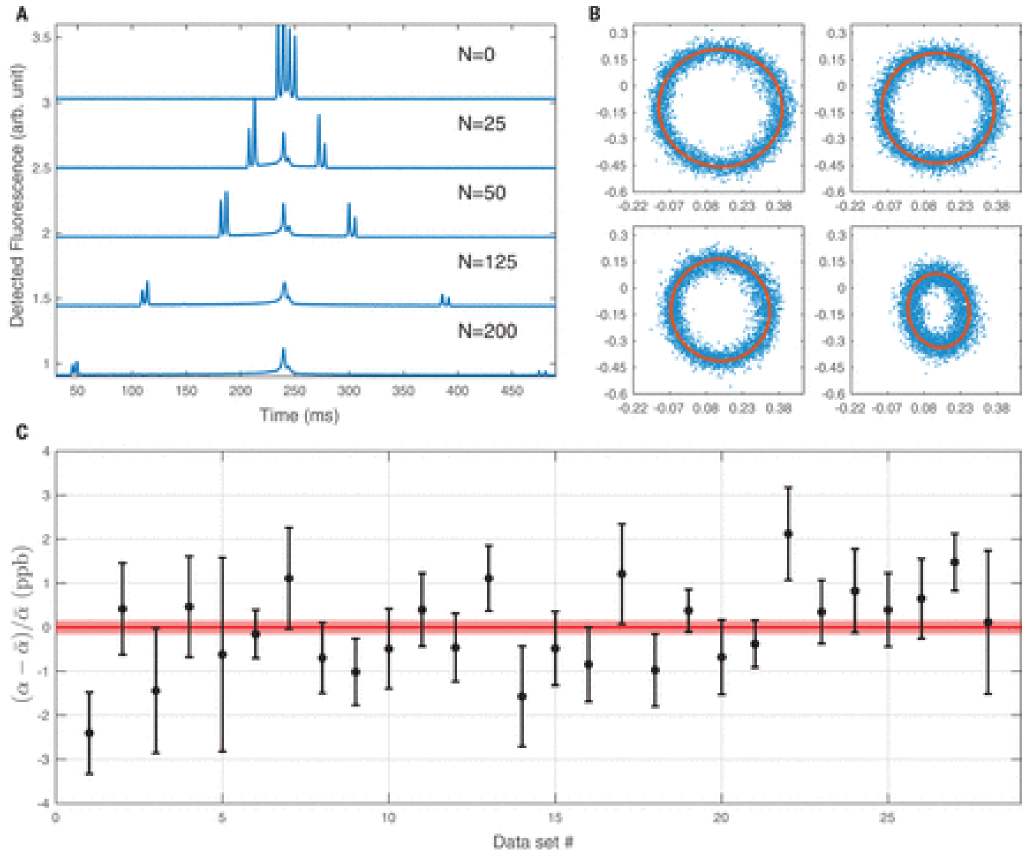


Kovachy et al. **Nature** 528, 530-533 (2015)

Measurement of Newton's gravitational constant ***G***

Measuring the fine structure constant α at Berkeley

Tests of GR and QM
Stanford 10m atomic fountain



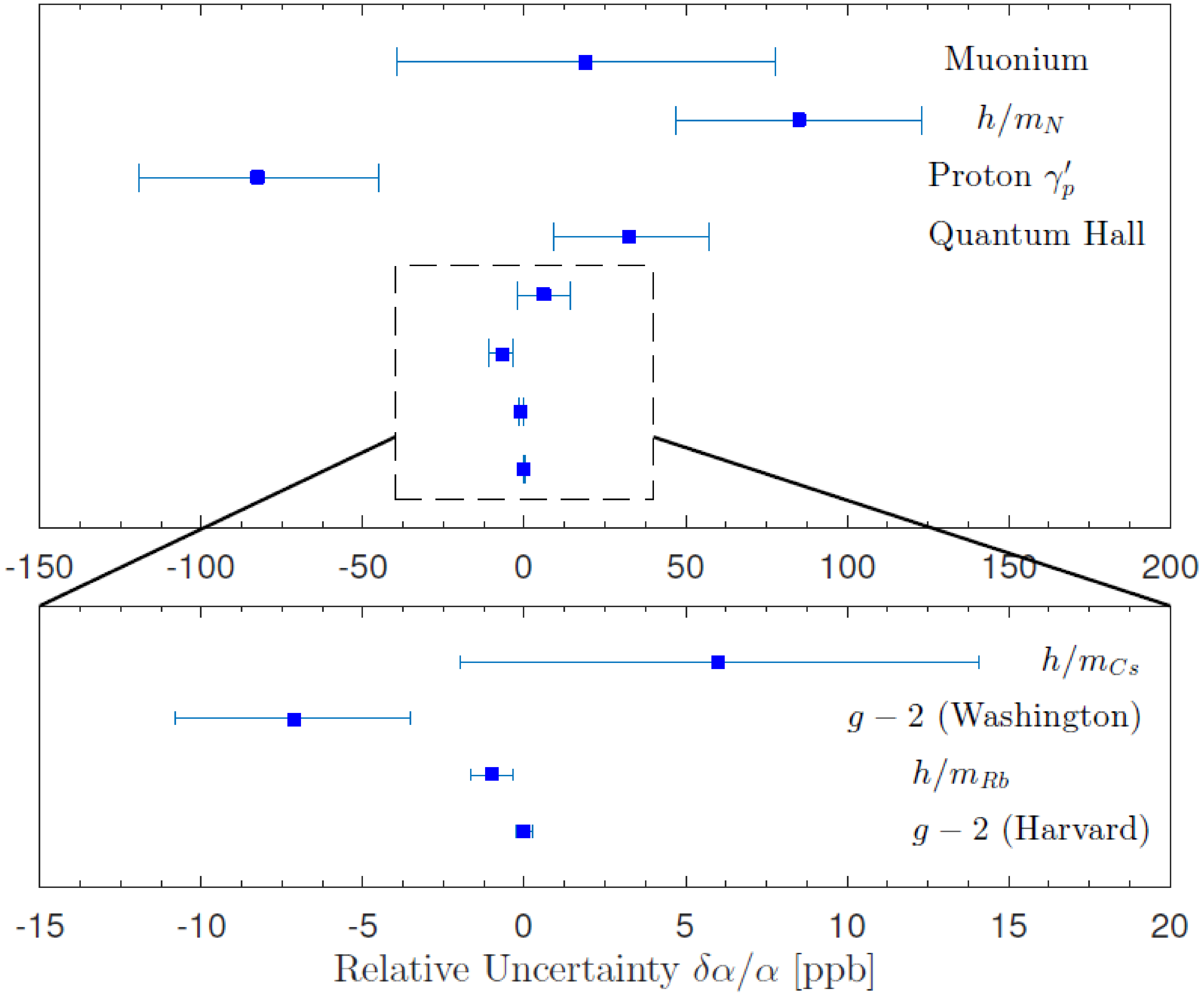
Parker et al. **Science** 360, 191-195 (2018)

The Fine Structure Constant

Measures the strength of the electromagnetic interaction

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

2014 CODATA



The Fine Structure Constant

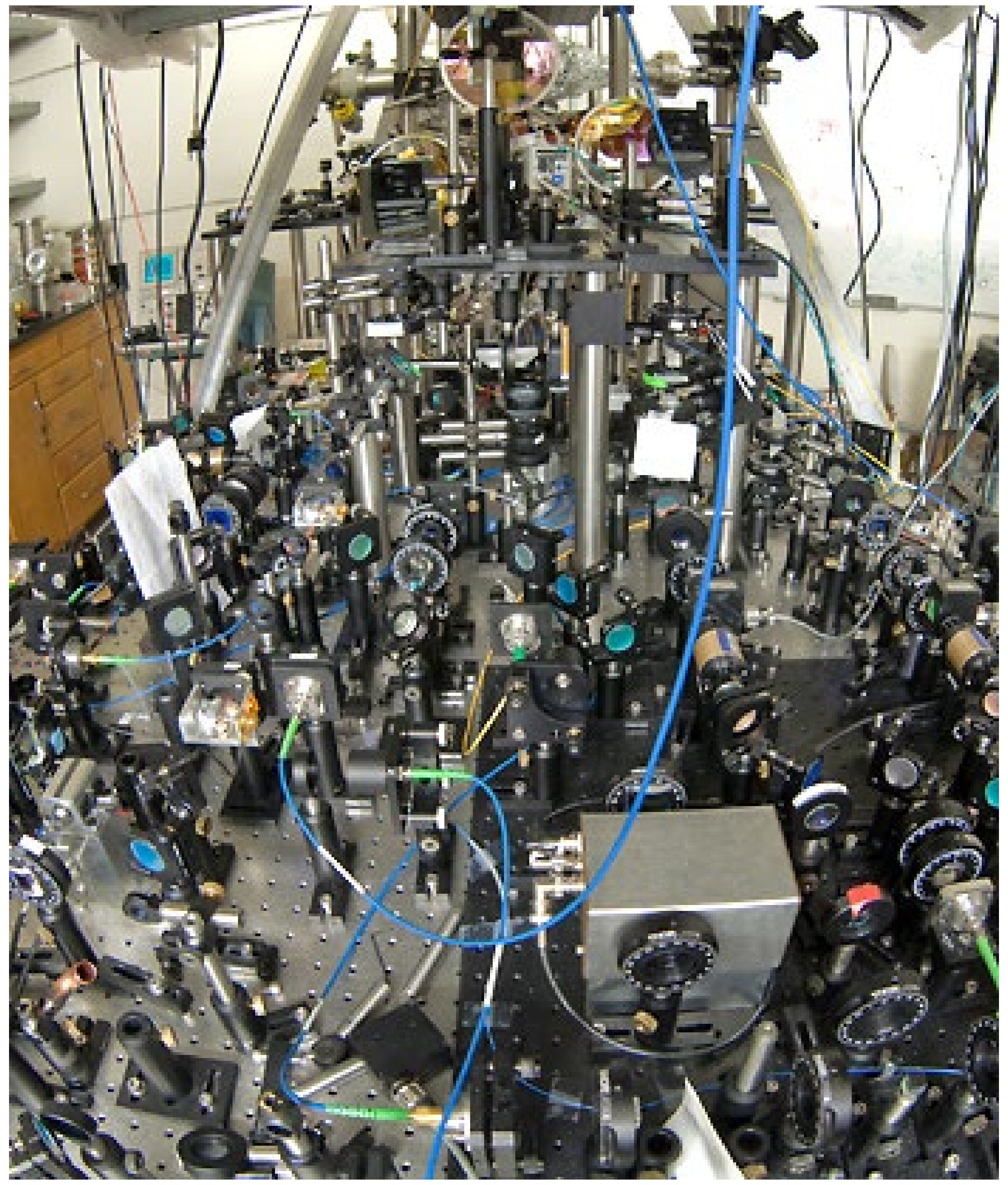
137 is…(https://primes.utm.edu/curios/page.php/137.html)

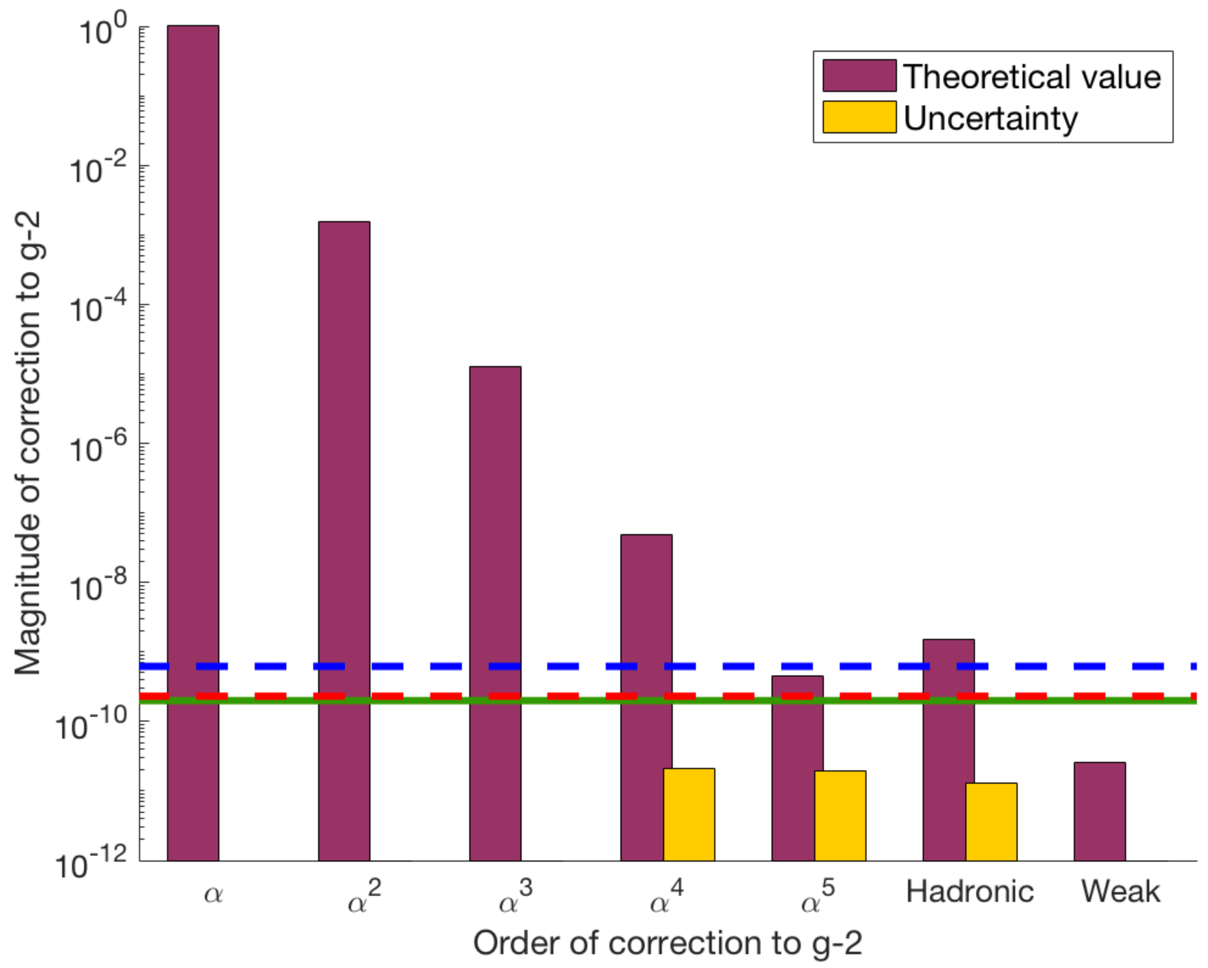
- The numerical value of “Kaballah” (קַבָּלָה)
- Genesis 25:17: “And these are the years of the life of Ishmael, an **hundred and thirty and seven** years. …” It is also the age of Moses father and Levi
- The day before his inauguration, President Obama made a 137-mile train trip from Philadelphia to 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

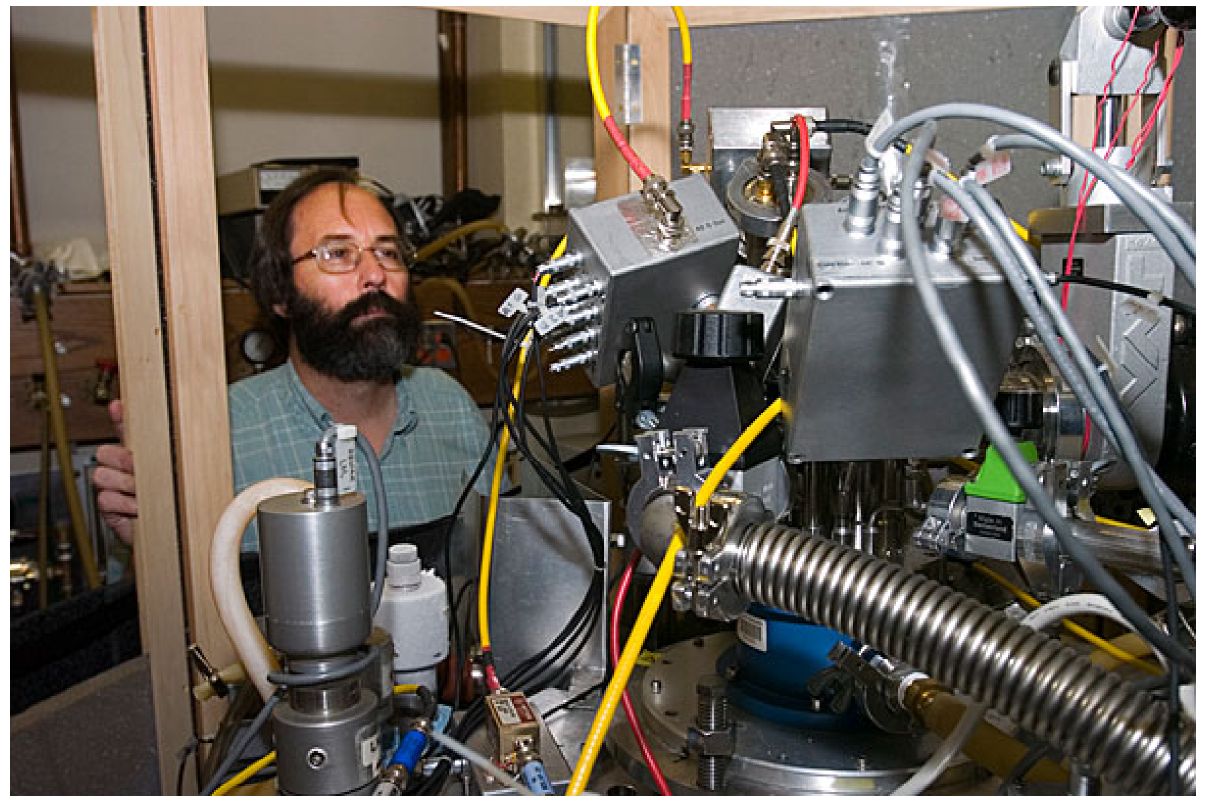
The most precise theory/experiment comparison in science

Fine structure constant

Electron magnetic moment







Unknown particles may shift magnetic moment

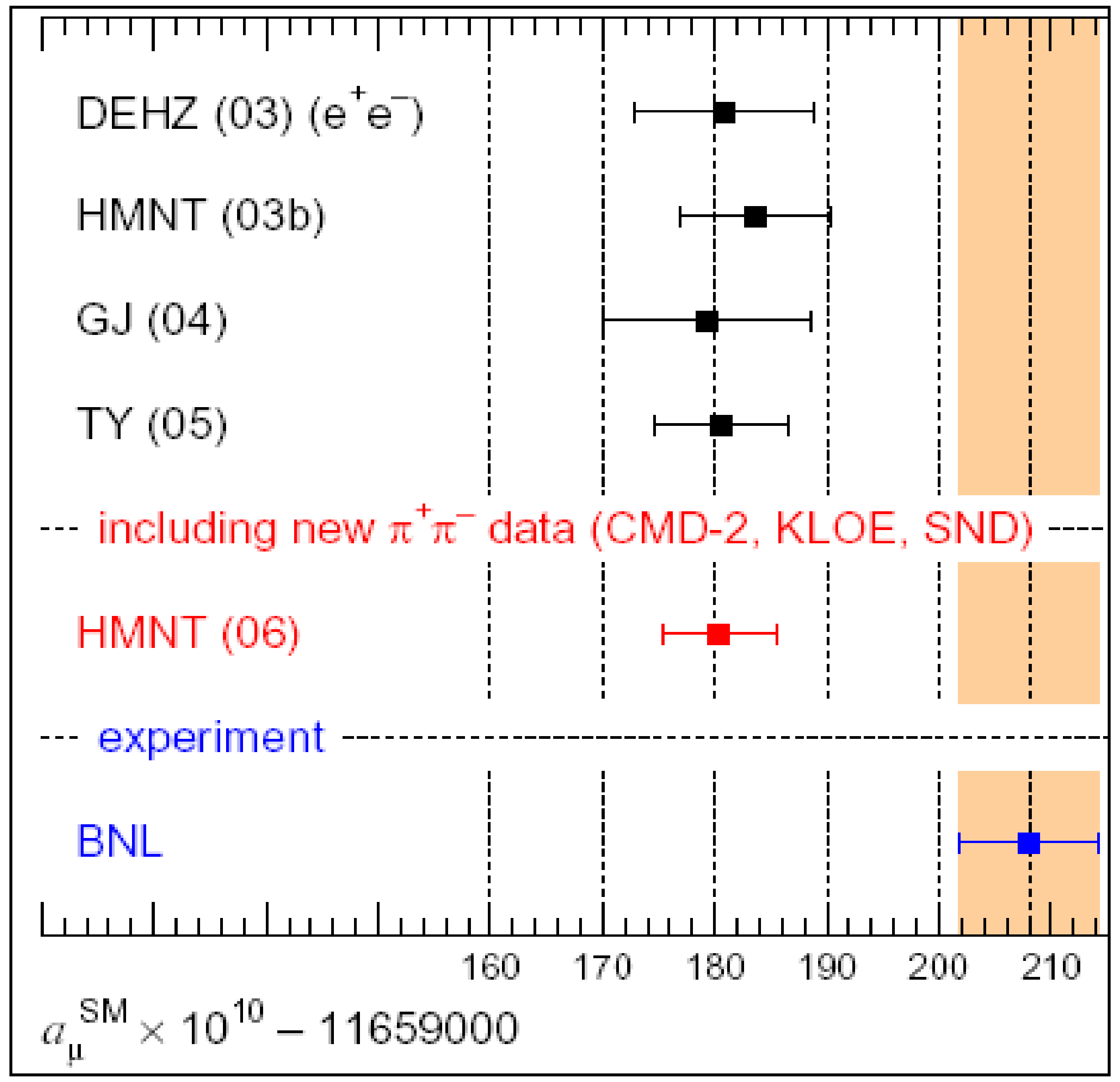
Muon g-2 mystery

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

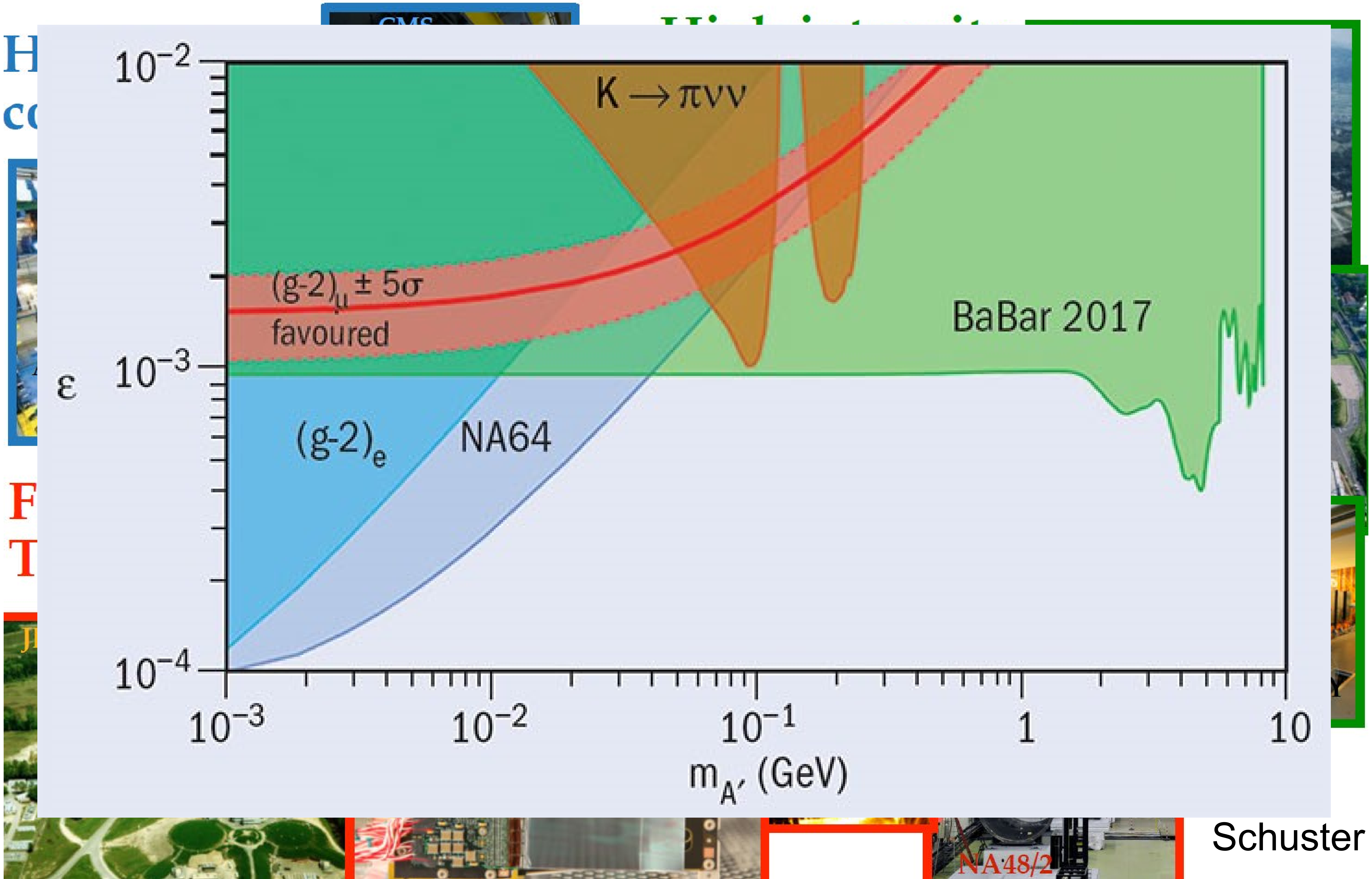
- Muon g-2
- Proton radius puzzle?
- ^{8}Be decay
- Astrophysical hints?
  - 511 keV line
  - keV gamma-ray excess
  - Galactic center excess



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

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

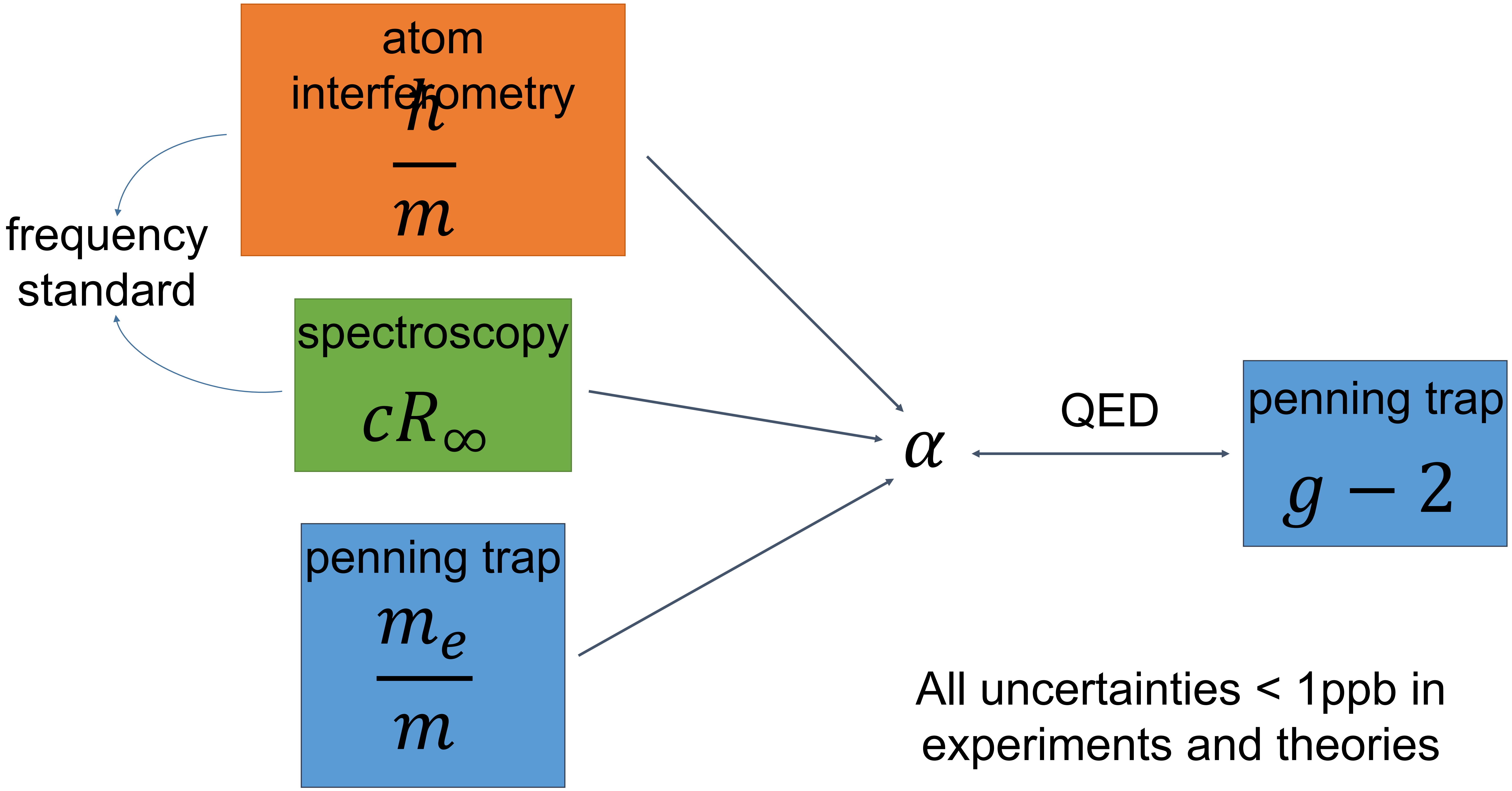
Ongoing dark photon searches



Schuster

α from ħ/m

$$hcR_\infty = \frac{1}{2}\alpha^2 m_e c^2 = \frac{1}{2}\alpha^2 \left(\frac{m_e}{m}\right) mc^2$$



atom interferometry

$\frac{\hbar}{m}$

frequency standard

spectroscopy

cR_∞

penning trap

$\frac{m_e}{m}$

α

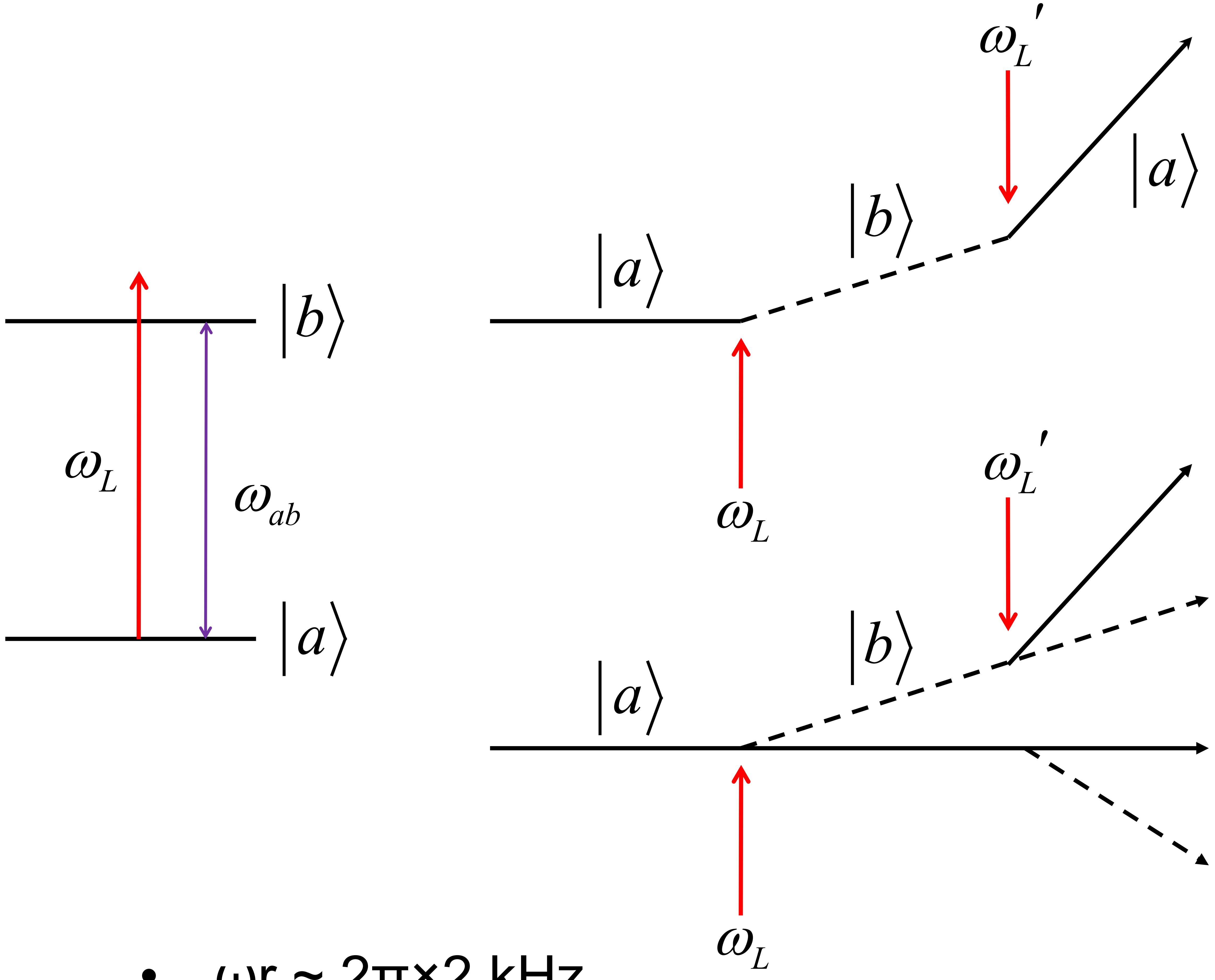
QED

penning trap

$g-2$

All uncertainties < 1ppb in experiments and theories

Photon 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

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

1891

Reality

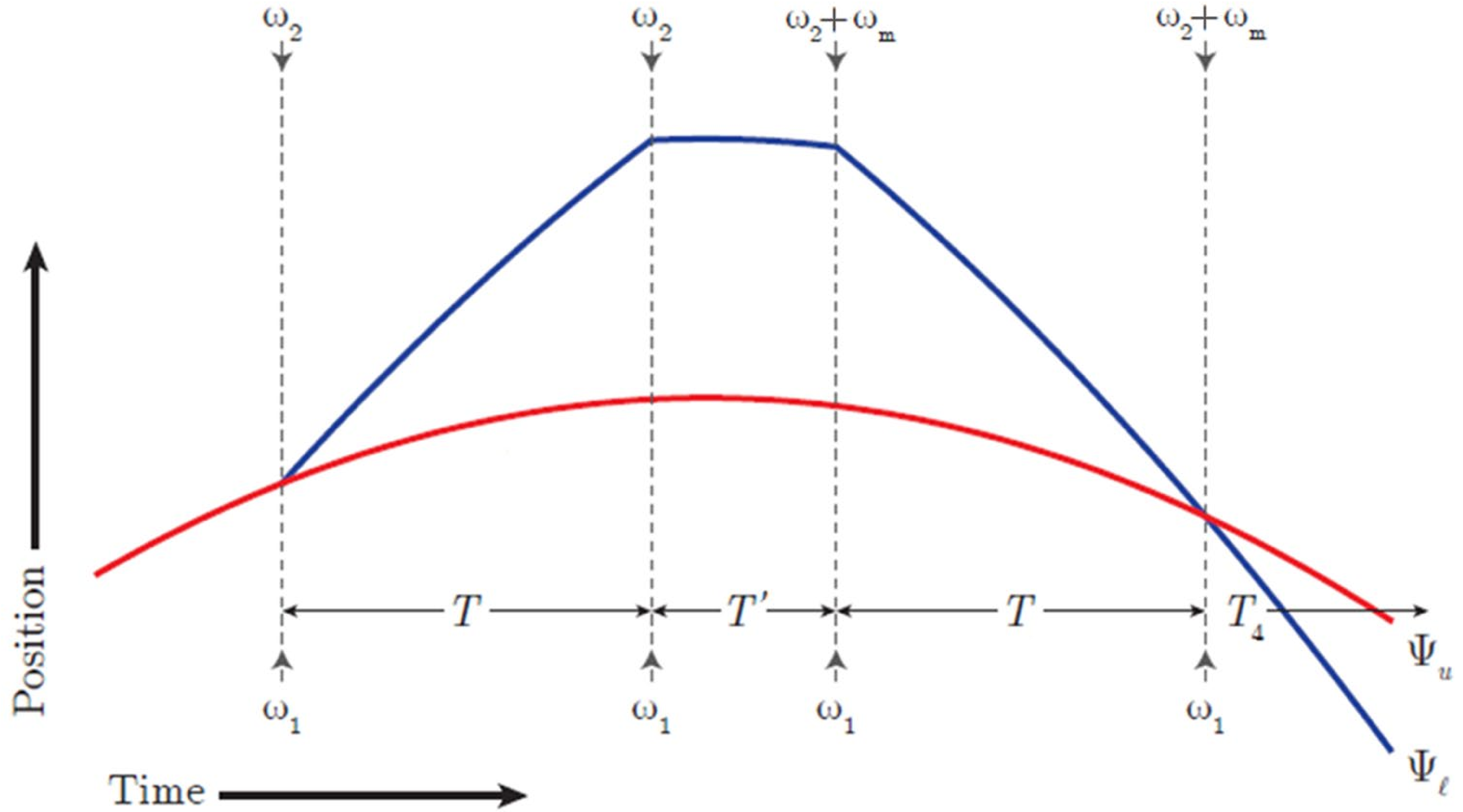
1891

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB
Lawrence Berkeley National Laboratory

Atom-interferometer measurement of α

Ramsey-Bordé Interferometer



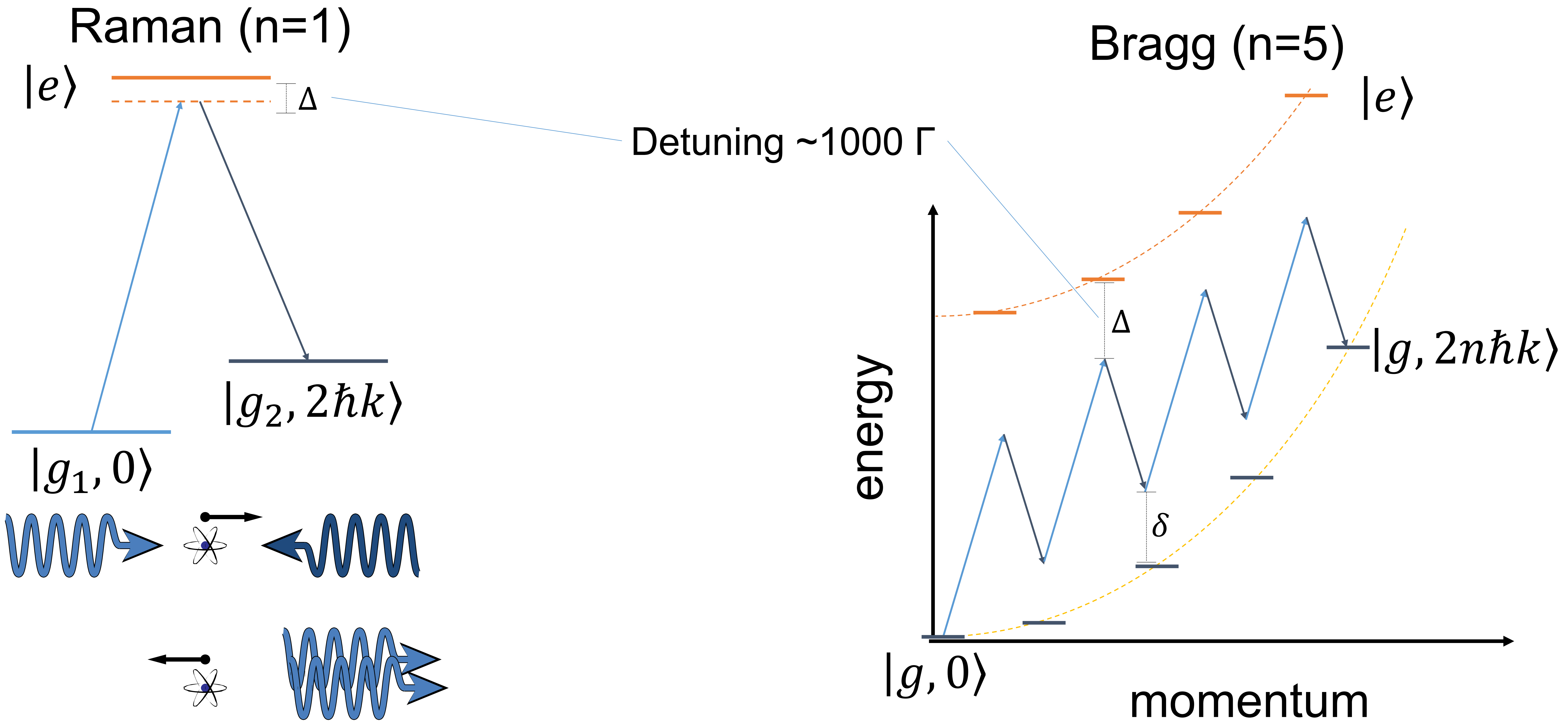
$$\Phi_{RB} = 8n^2\omega_r T - 2nkg(T+T')T - n\omega_m T$$

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

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

Multi-Photon Bragg Diffraction

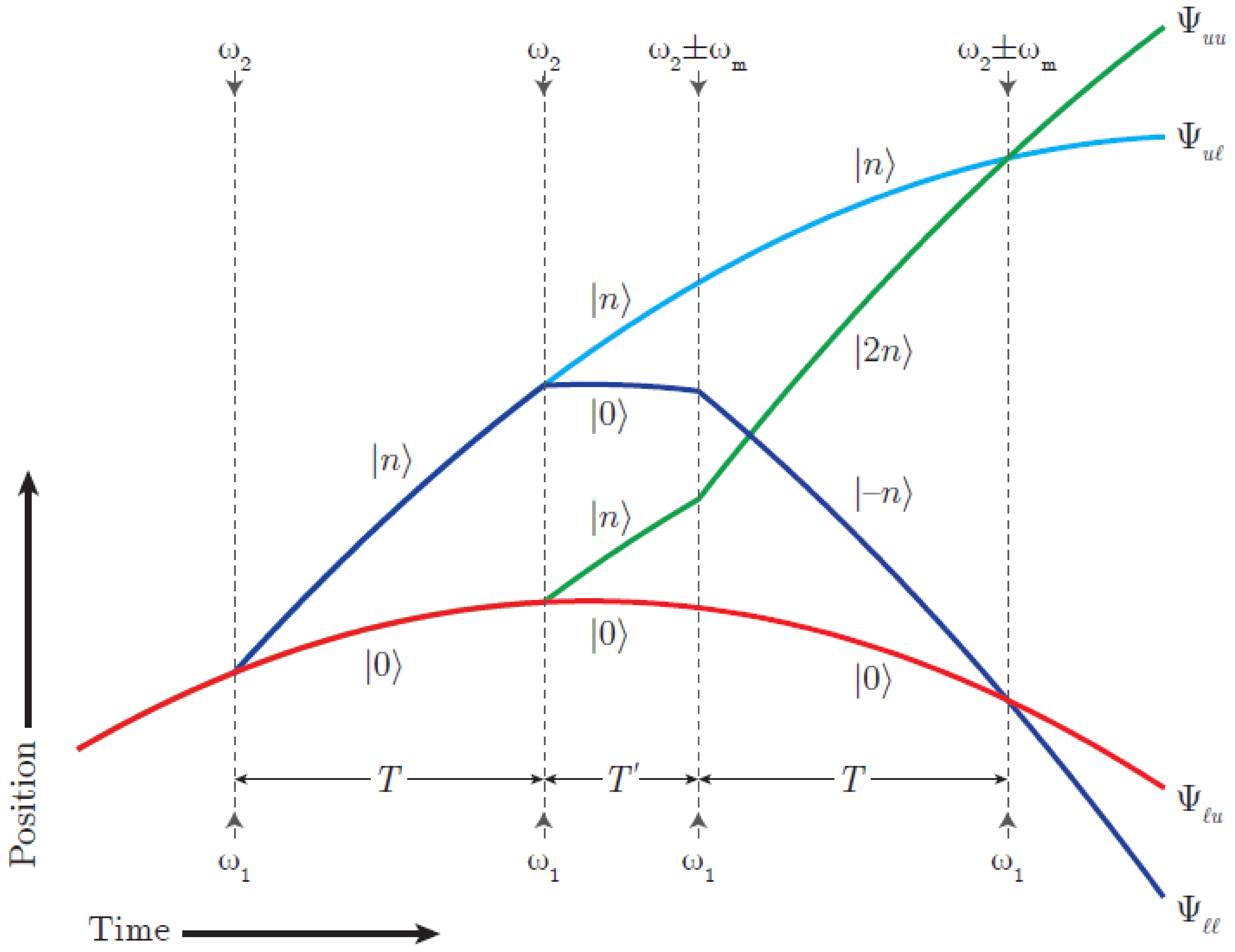
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$



<u>Bragg gives you:</u>

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

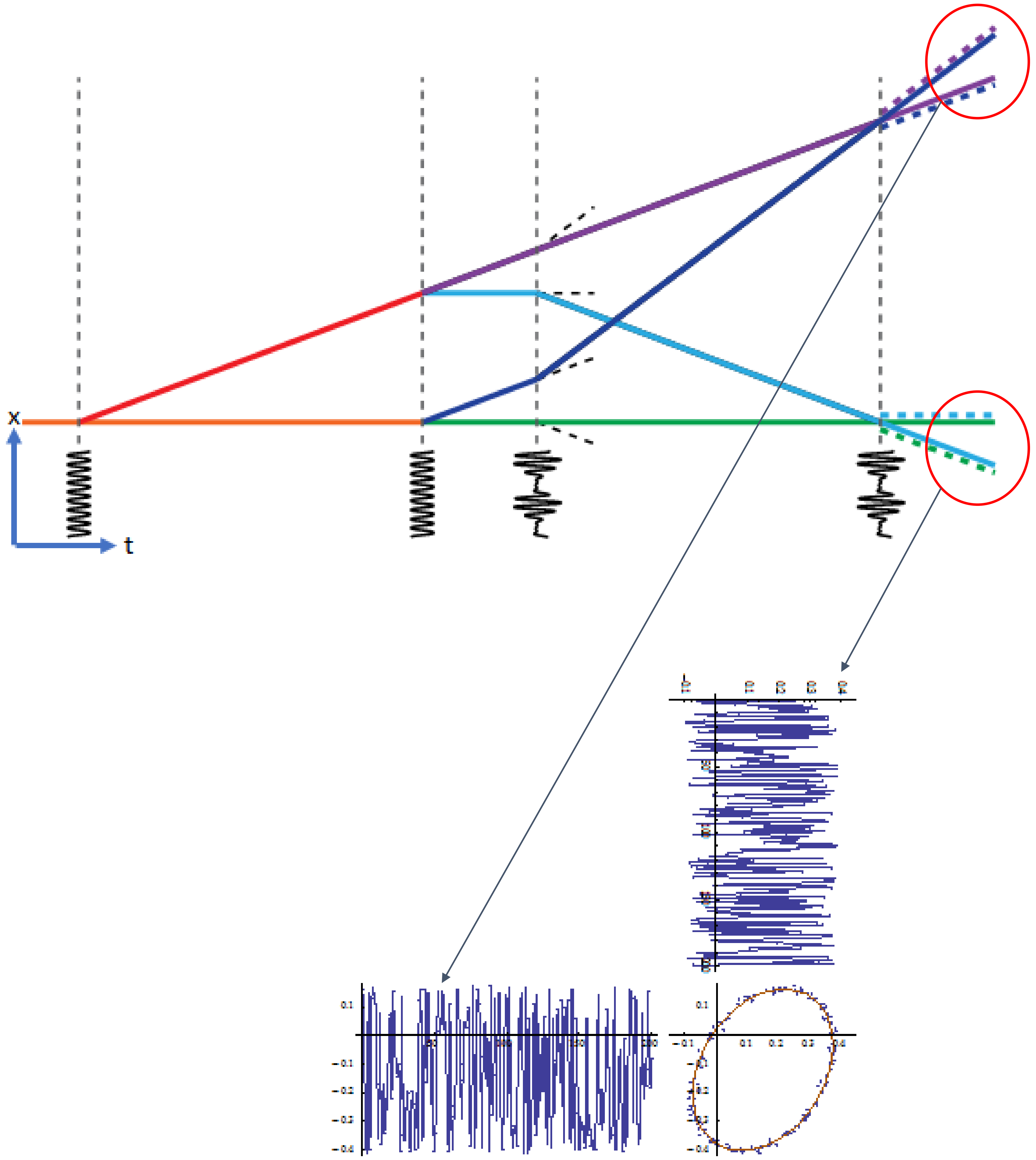
Simultaneous Conjugate Interferometers

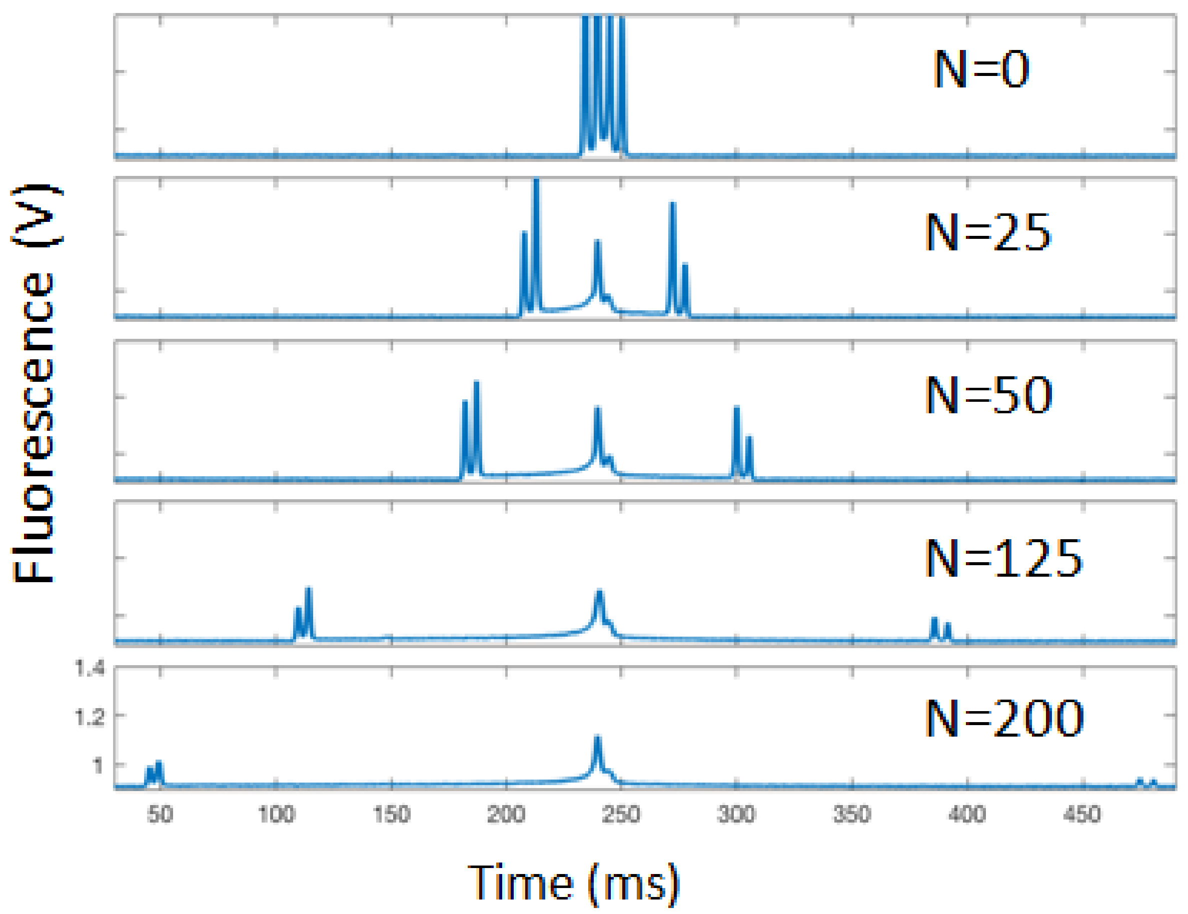


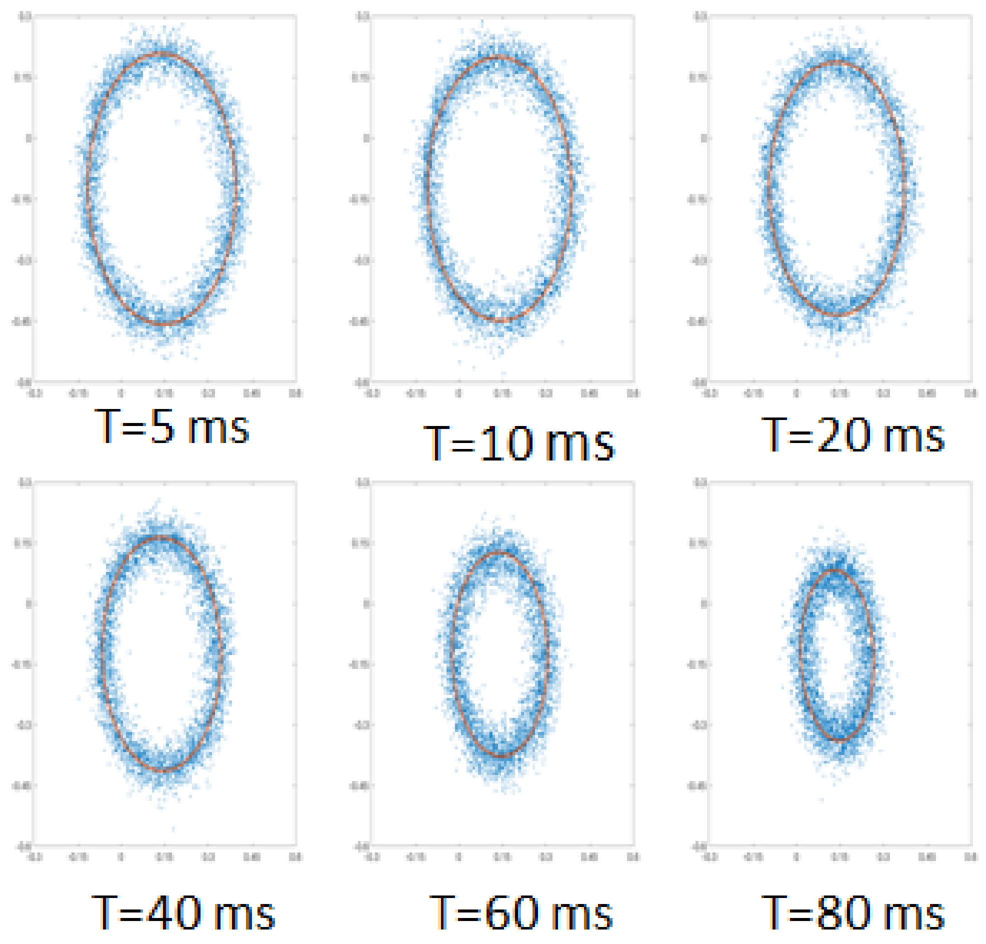
$$\Phi_{RB} = \pm 8n^2\omega_r T \pm n\omega_m T + 2nkg(T+T')T$$

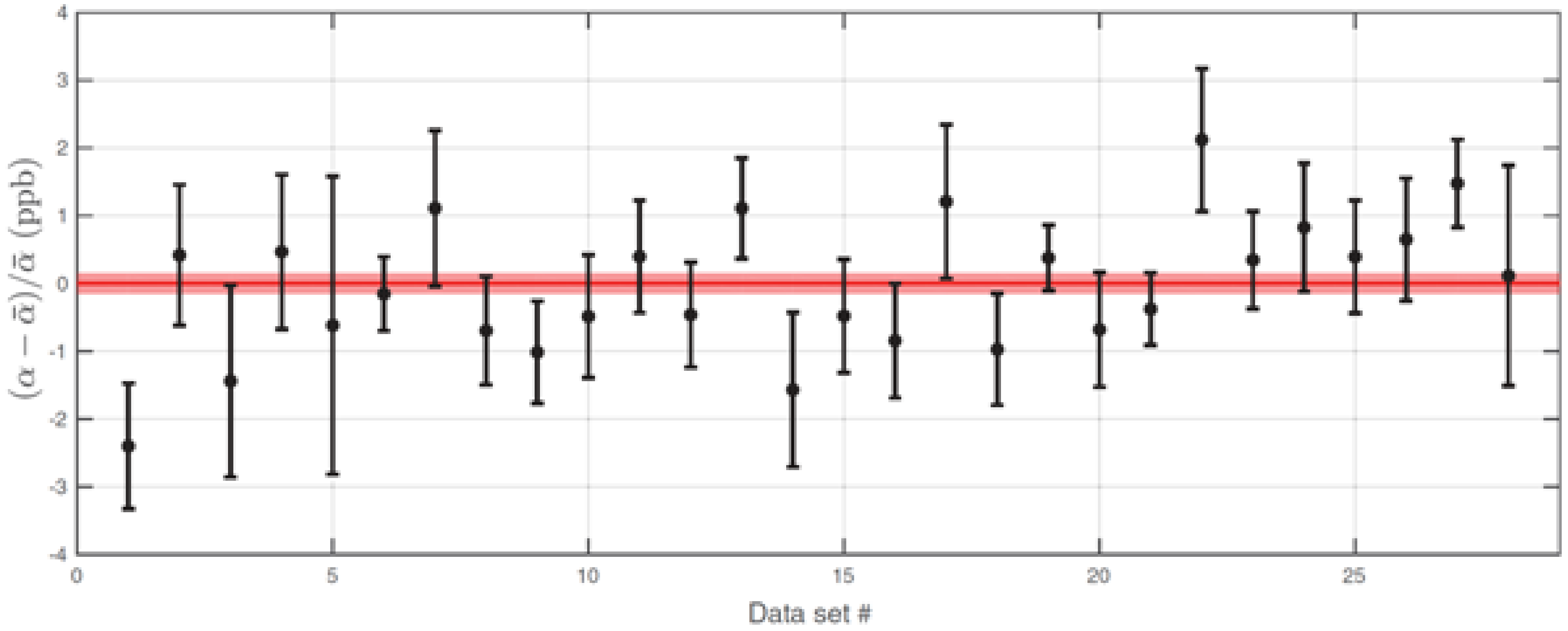
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$

Extracting signal









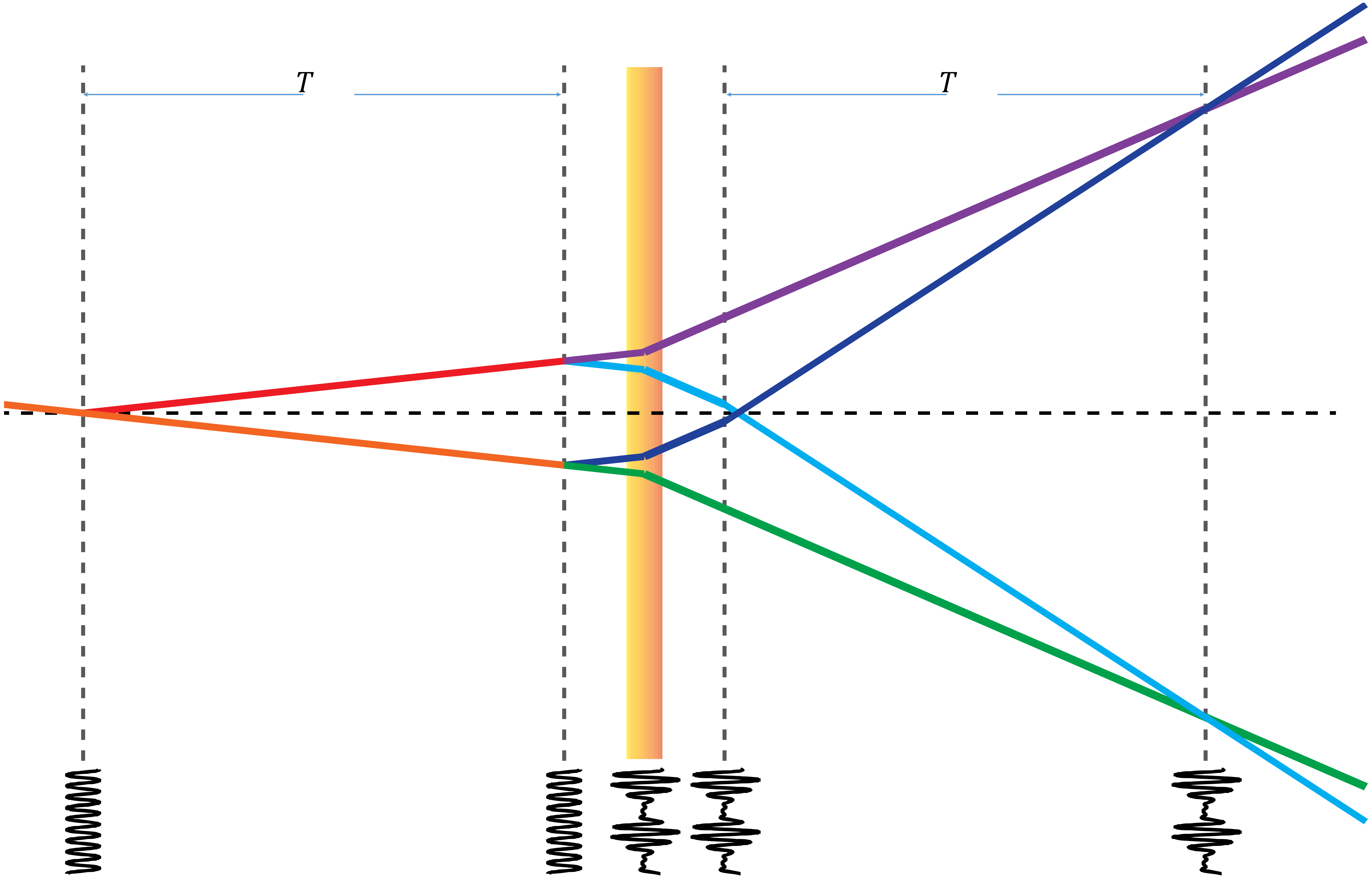
Now it’s my turn to leave Stanford

1891

1868

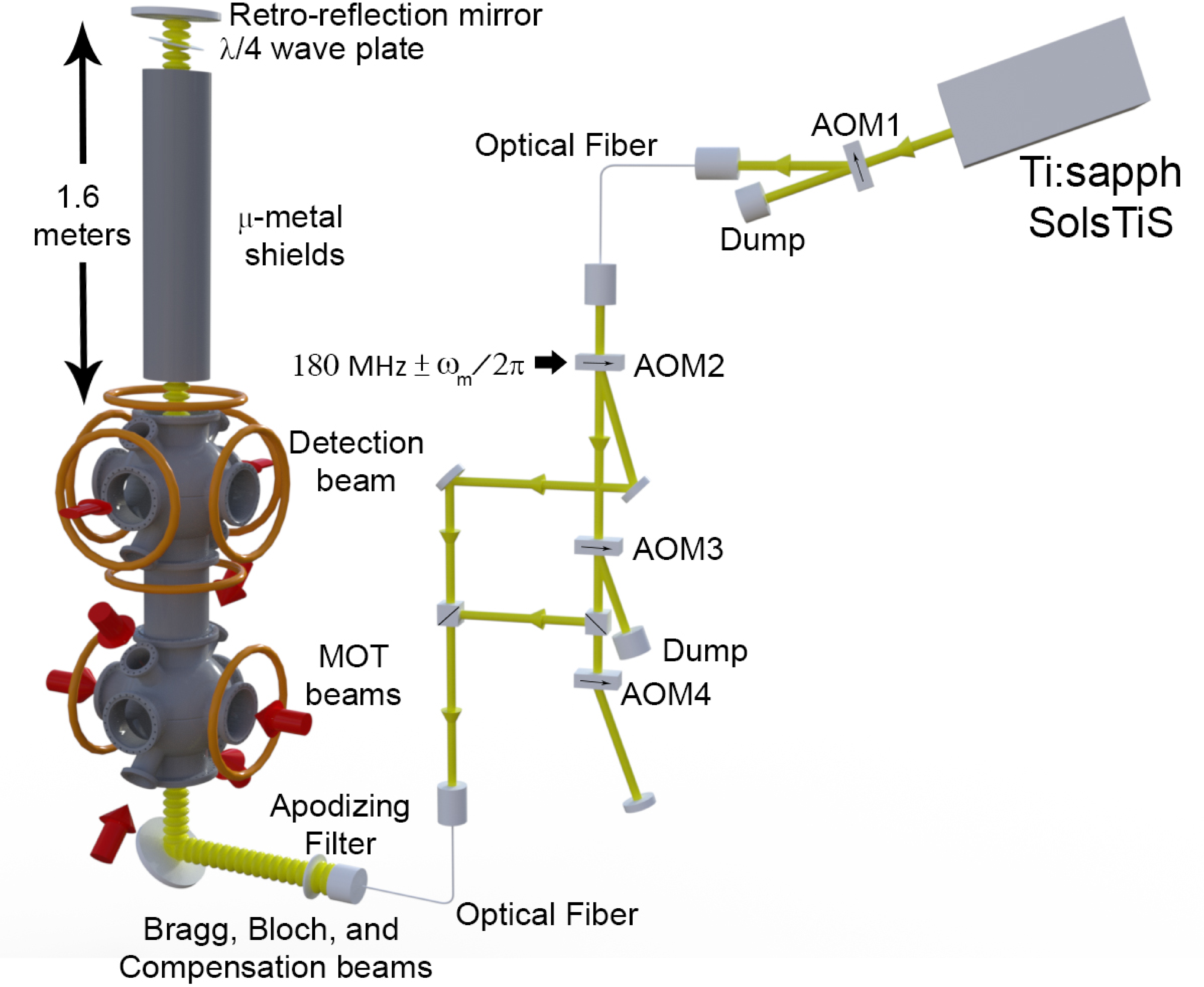
Berkeley
UNIVERSITY OF CALIFORNIA

Bloch Oscillations

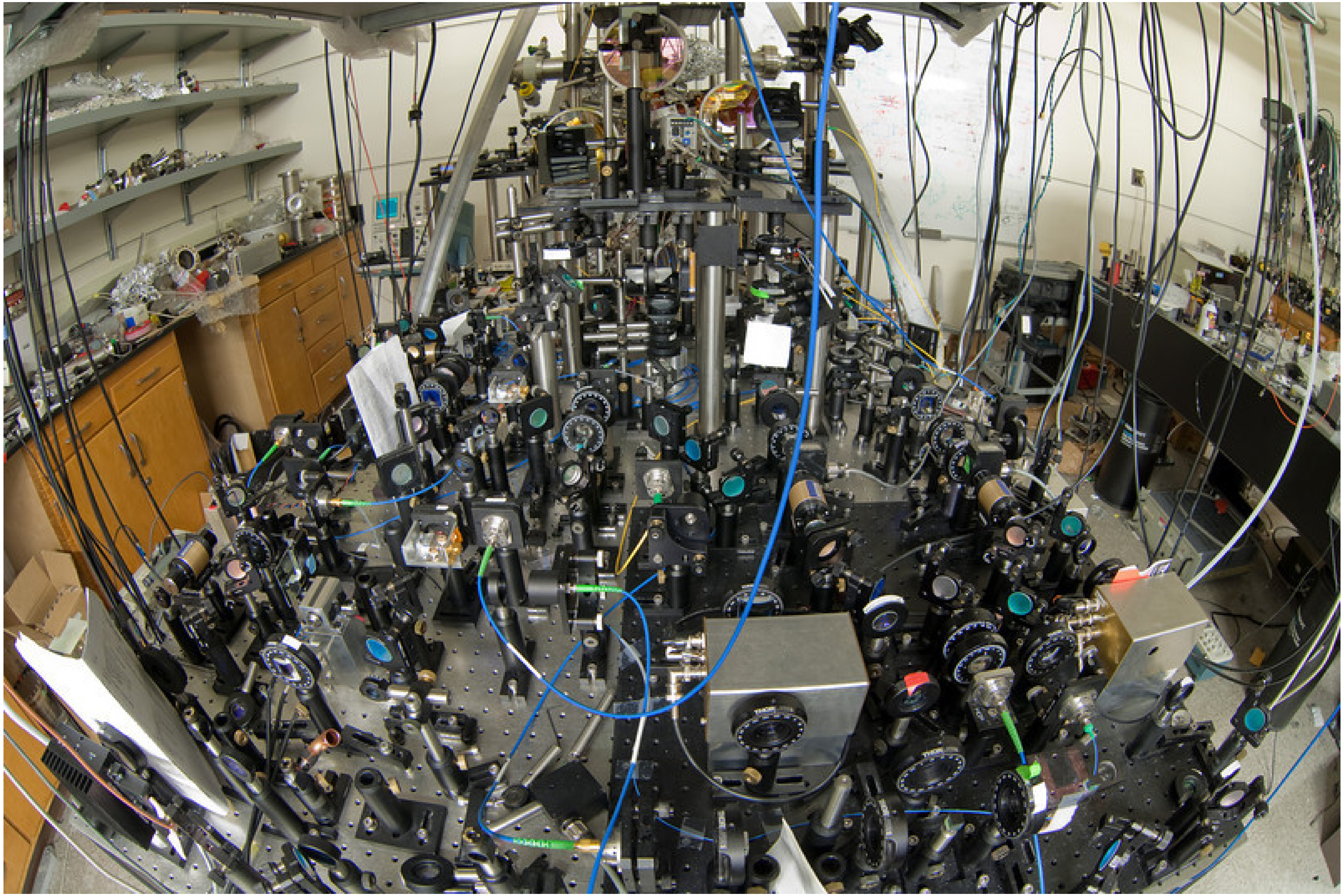


$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T$$

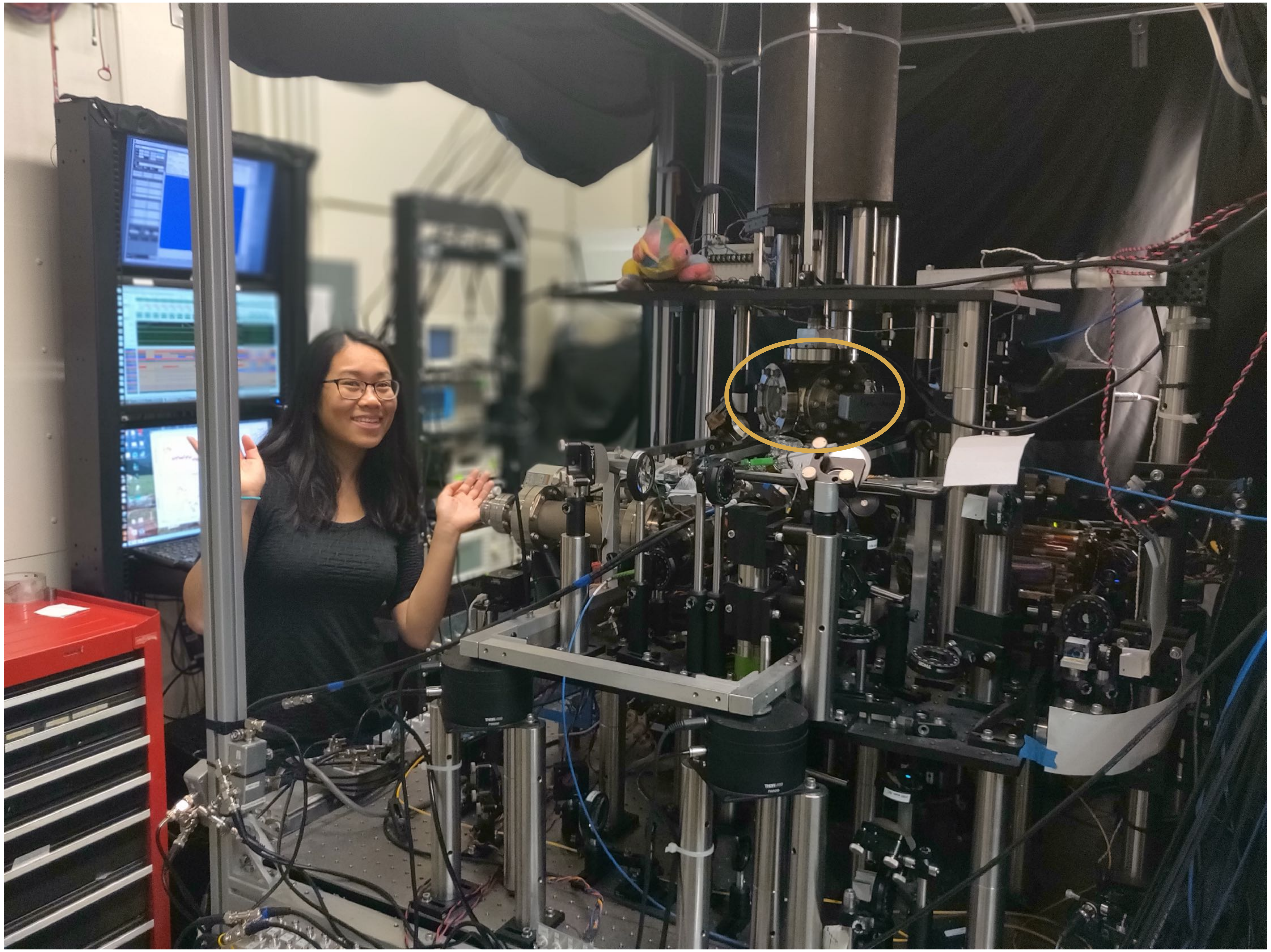
Setup



Retro-reflection mirror
$\lambda/4$ wave plate
1.6 meters
μ-metal shields
Optical Fiber
AOM1
Ti:sapph SolsTiS
Dump
$180\ \mathrm{MHz} \pm \omega_m/2\pi$
AOM2
Detection beam
AOM3
Dump
AOM4
MOT beams
Apodizing Filter
Optical Fiber
Bragg, Bloch, and Compensation beams



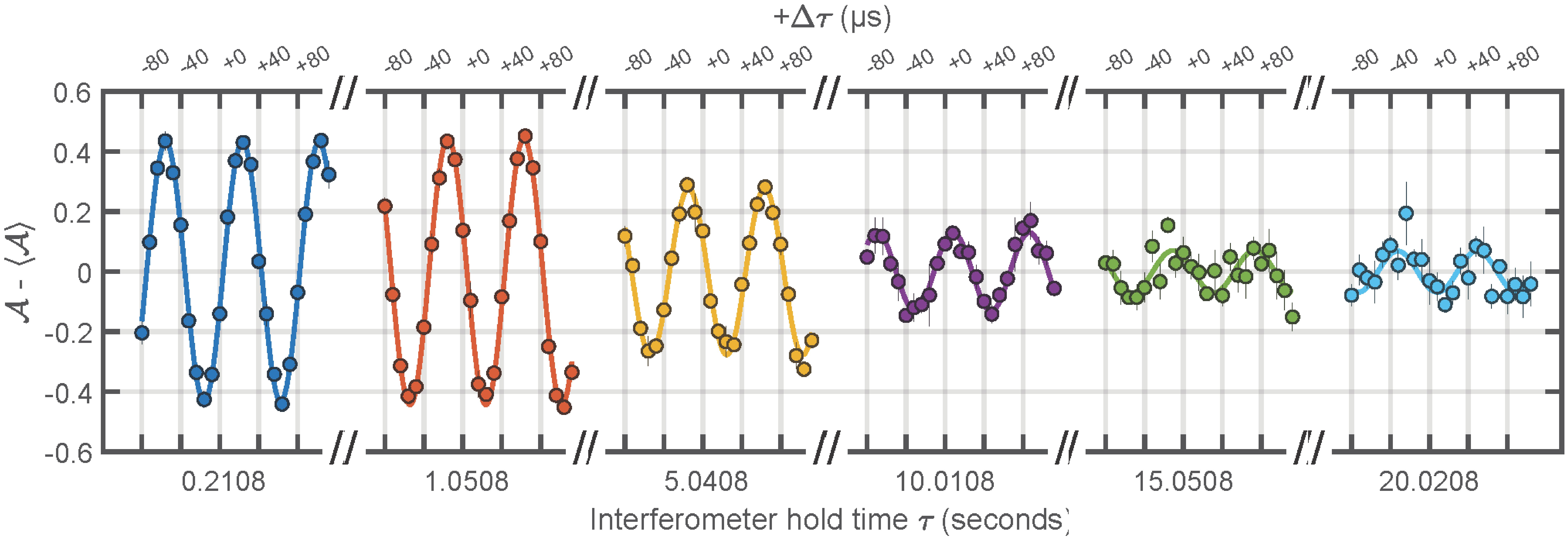
Experimental setup



- Cesium atoms
  - $\sim 10^6$ in an interferometer
- In-vacuum **cavity**

length	$\sim 40\text{cm}$
waist	$\sim 720\mu\text{m}$
finesse	~ 130
z_R	$\sim 1.90\text{m}$

Long holds


+Δτ (μs)
-80
-40
+0
+40
+80
$\mathcal{A}$ - ⟨$\mathcal{A}$⟩
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0.2108
1.0508
5.0408
10.0108
15.0508
20.0208
Interferometer hold time τ (seconds)

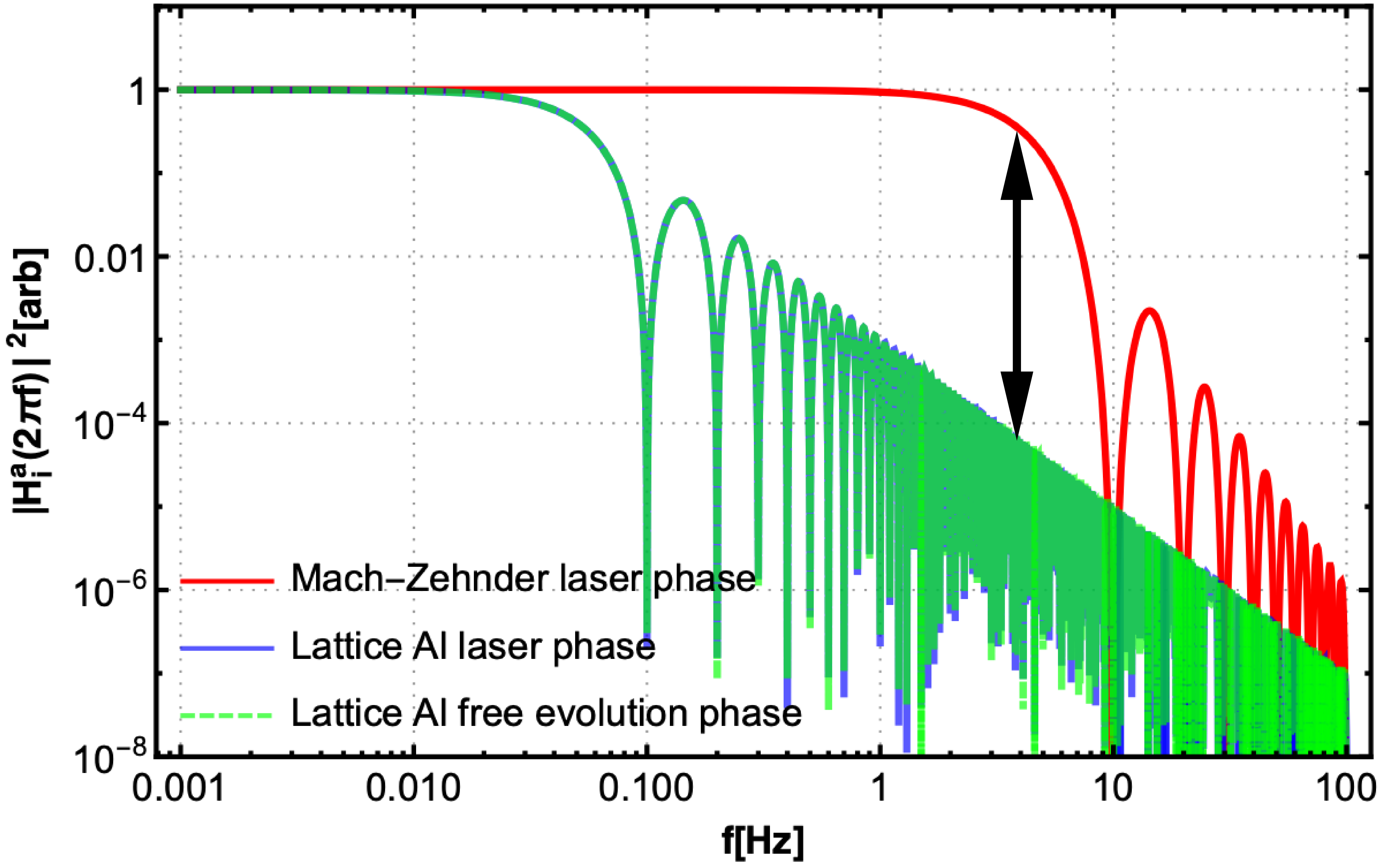
Vibration noise sensitivity

$T = 1\ ms, \tau = 10\ s$
lattice interferometer
$(z_{\text{fall}} = 5\mu\text{m})$

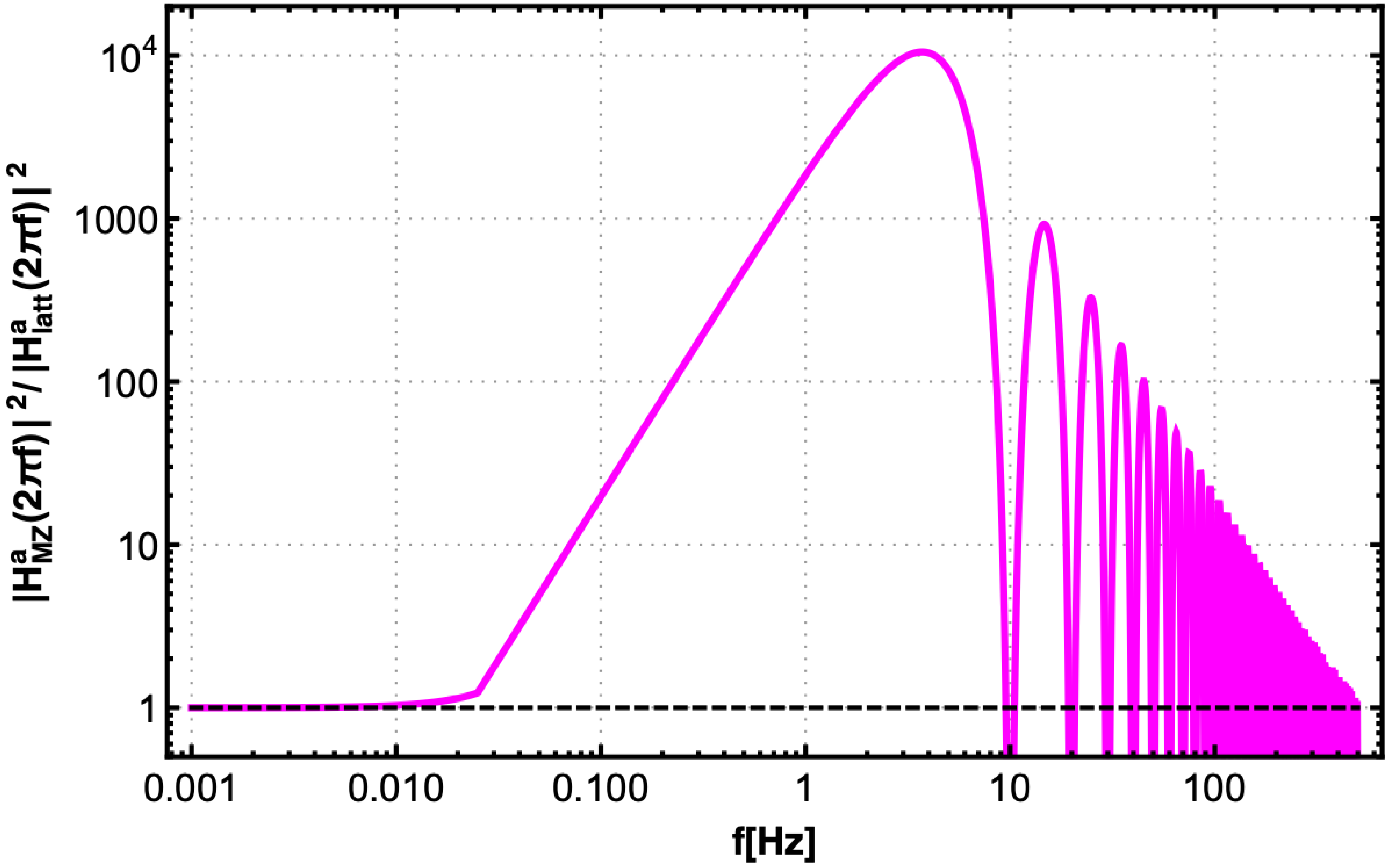
$\approx$

$T = 100\ ms$
Mach-Zehnder
$(z_{\text{fall}} = 5\text{cm})$

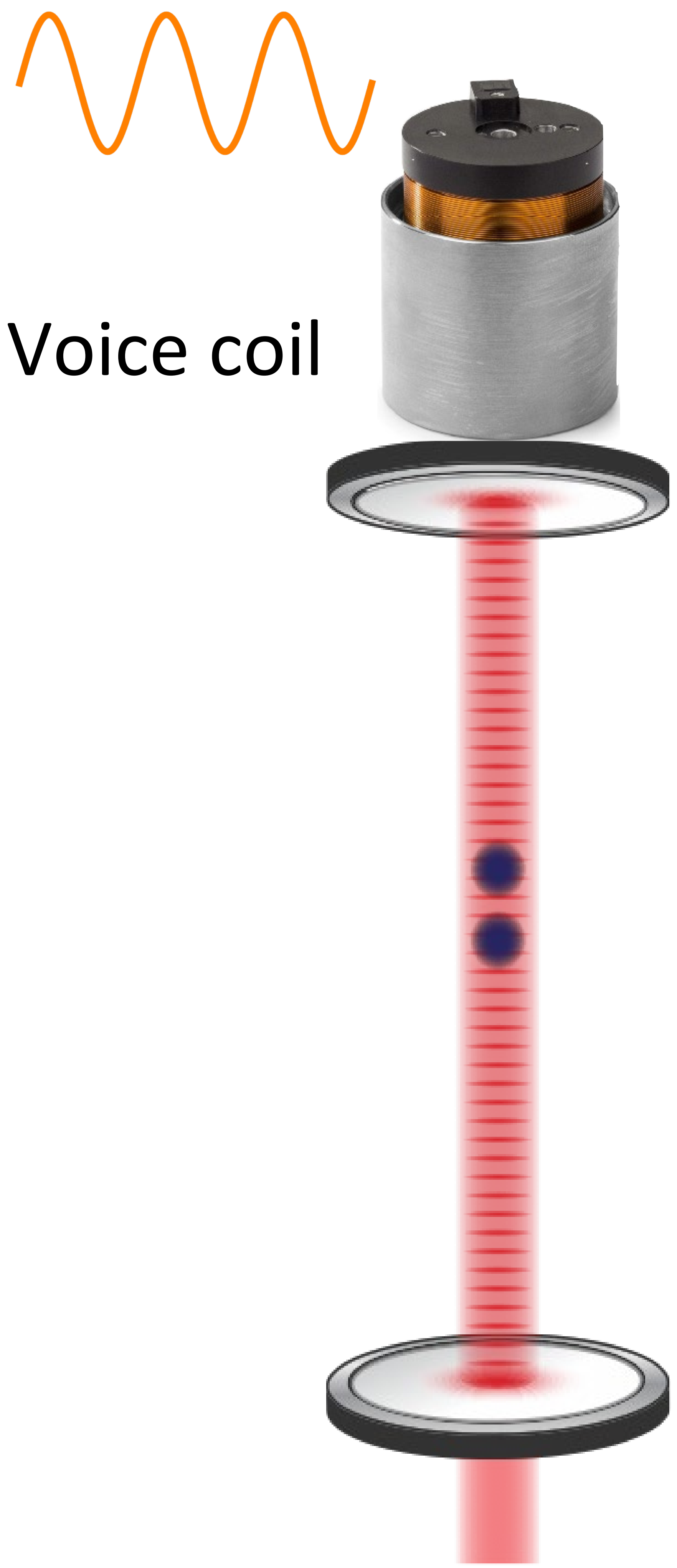
Transfer functions

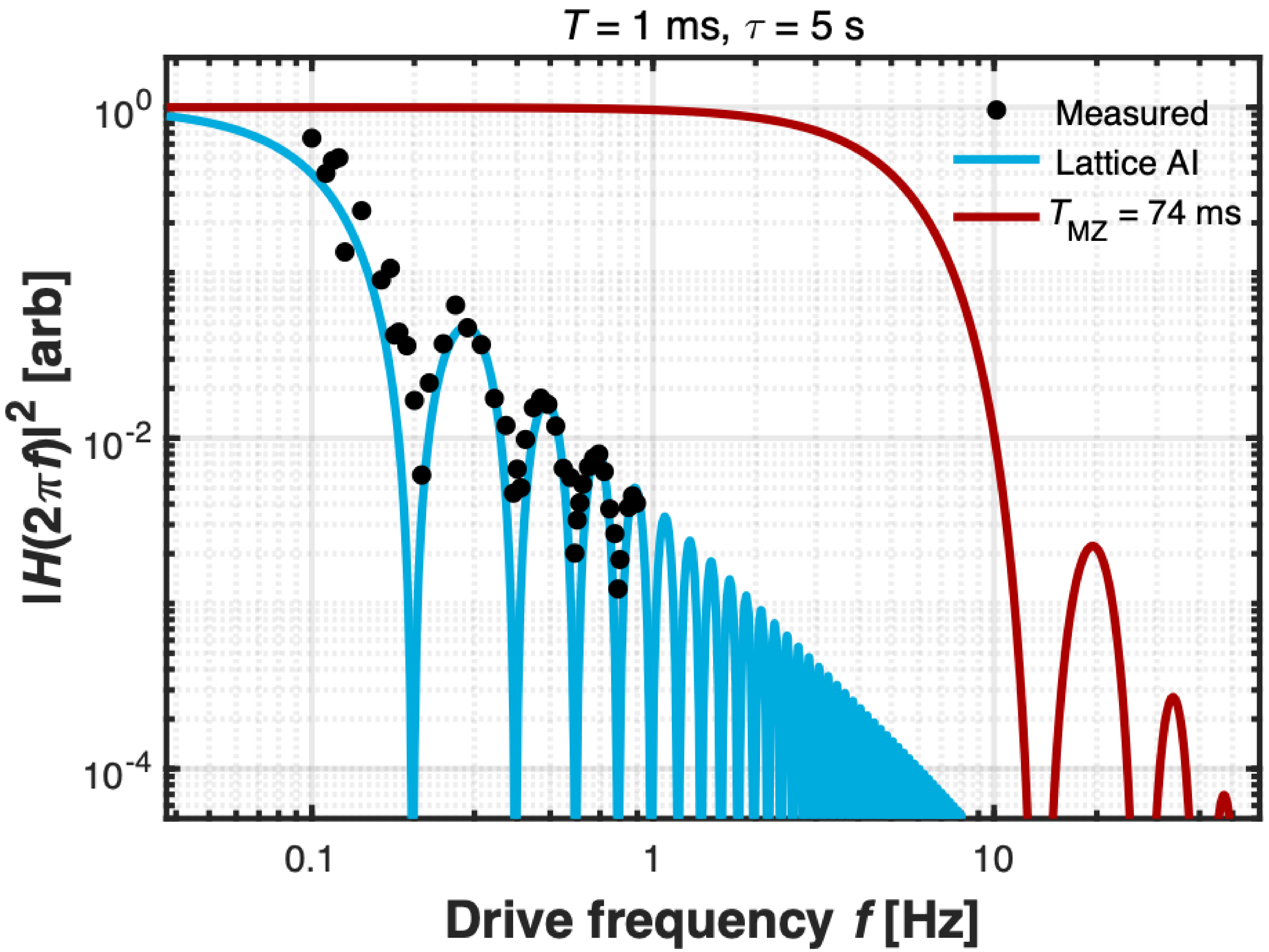


Suppression factor

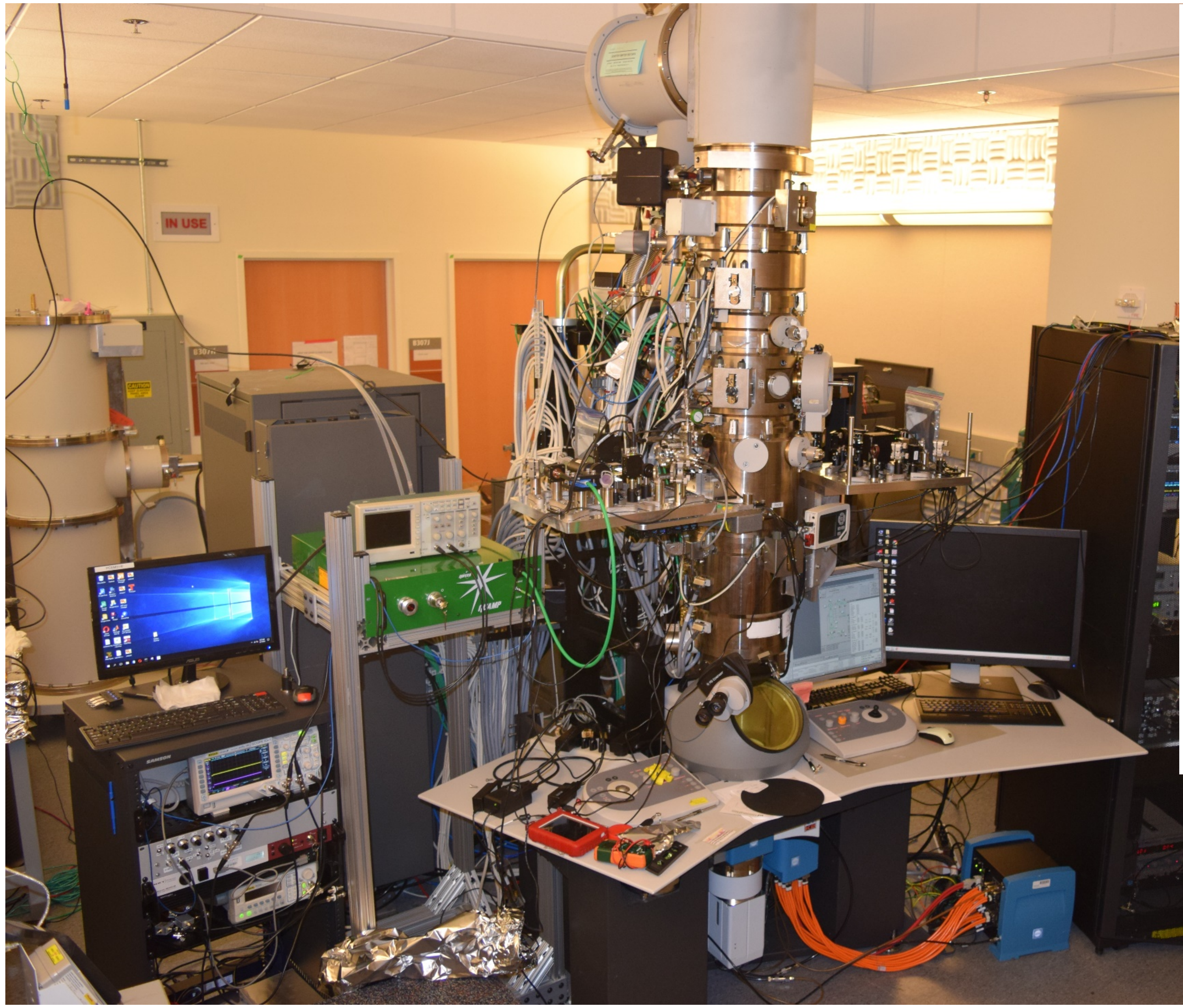


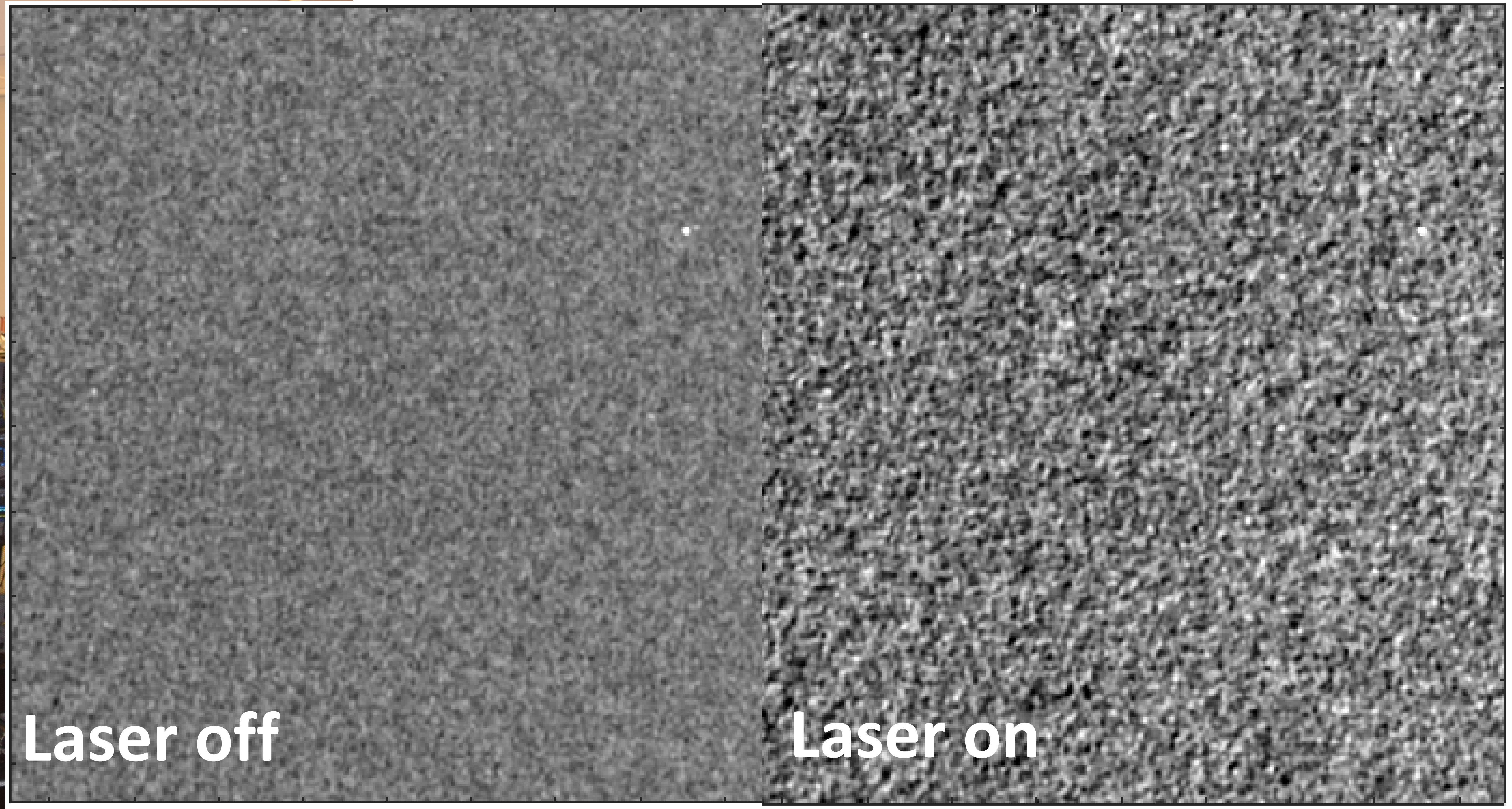
Measuring the transfer function





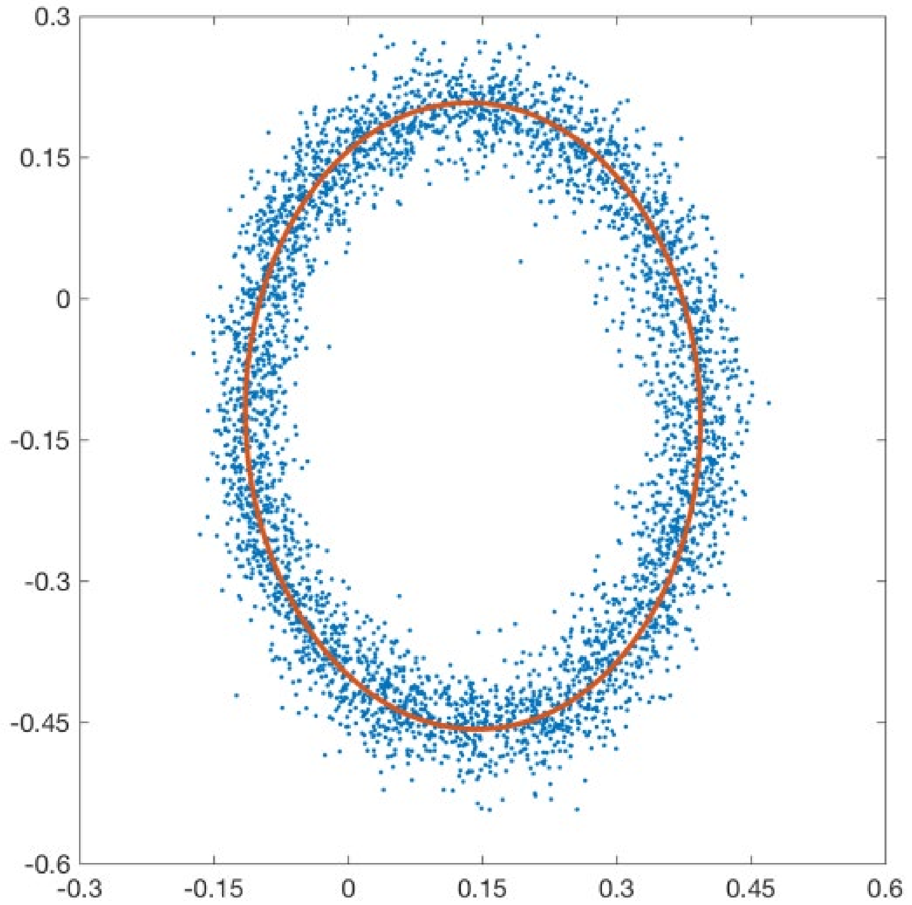
Laser-based phase contrast in TEM



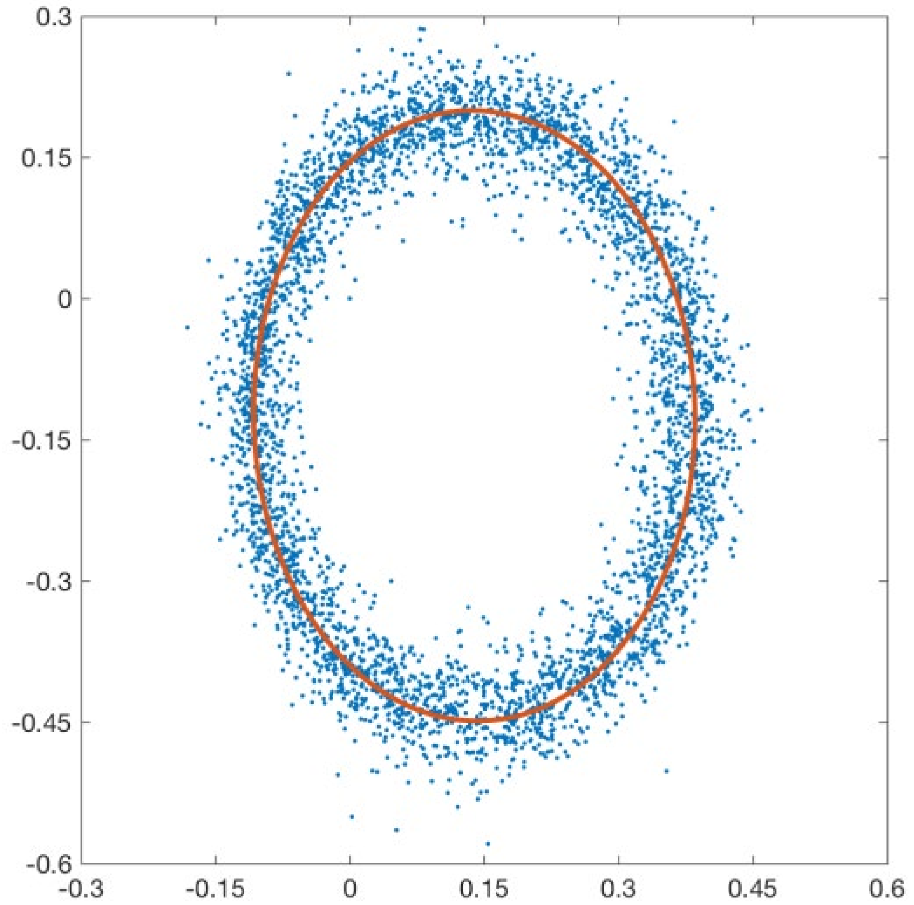


Images of a 2-nm thick carbon film

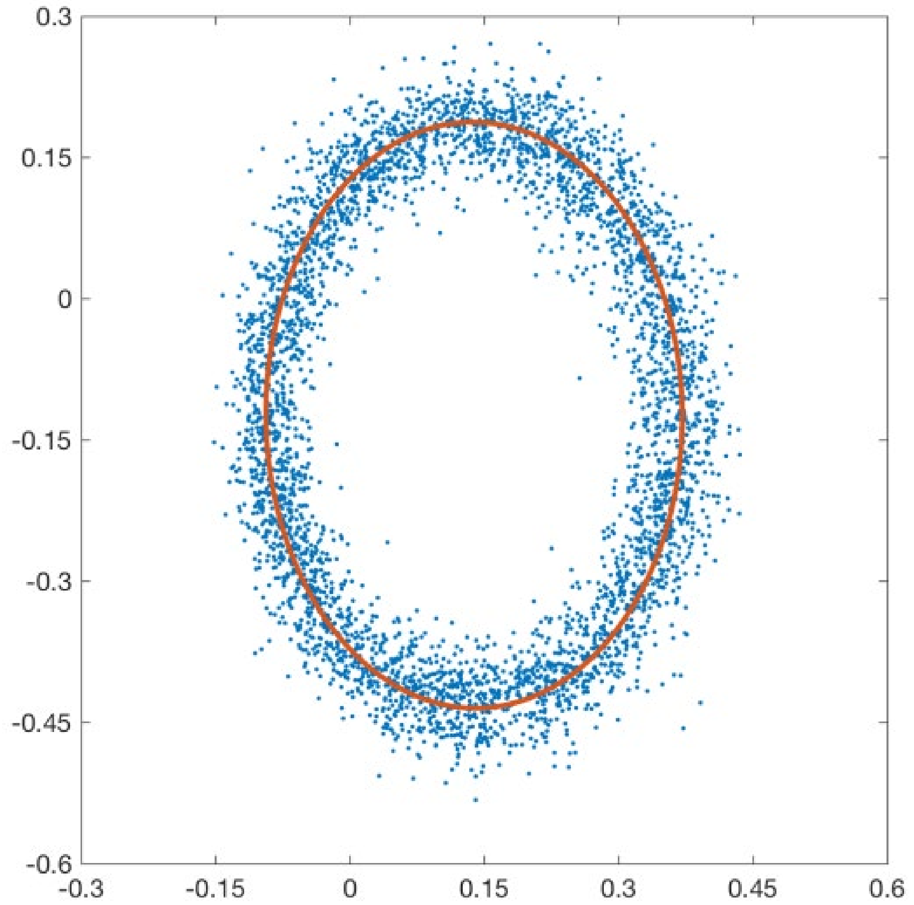
n=5, N=125 Ellipses



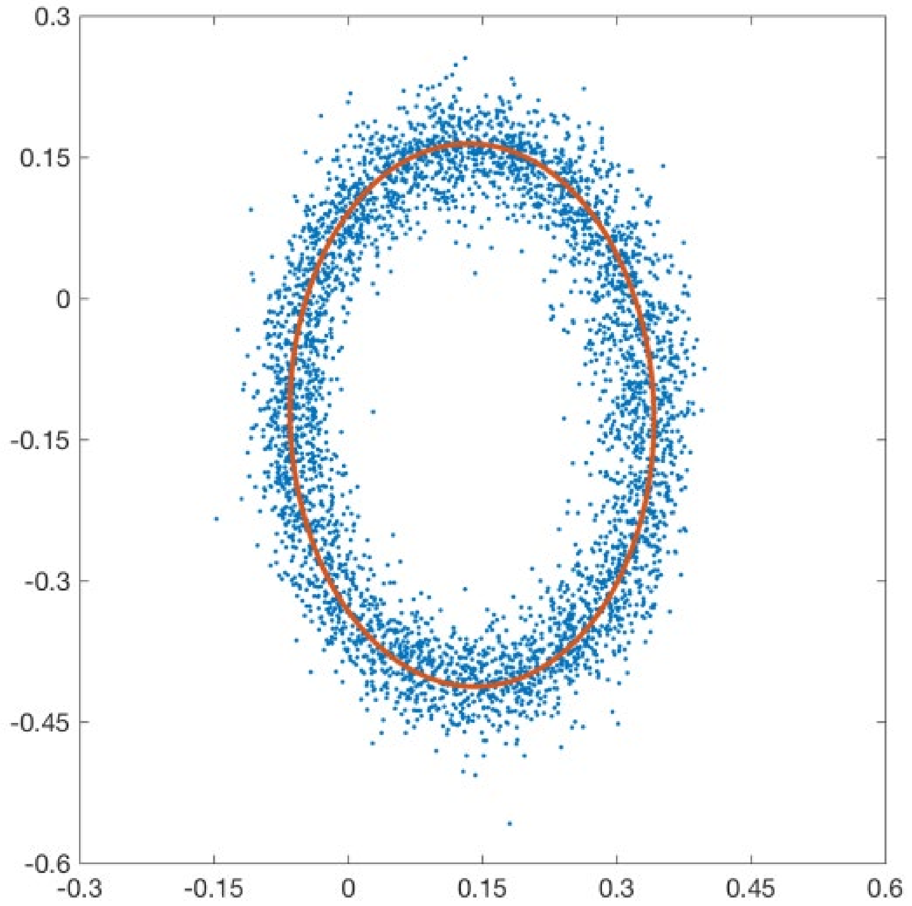
T=5 ms



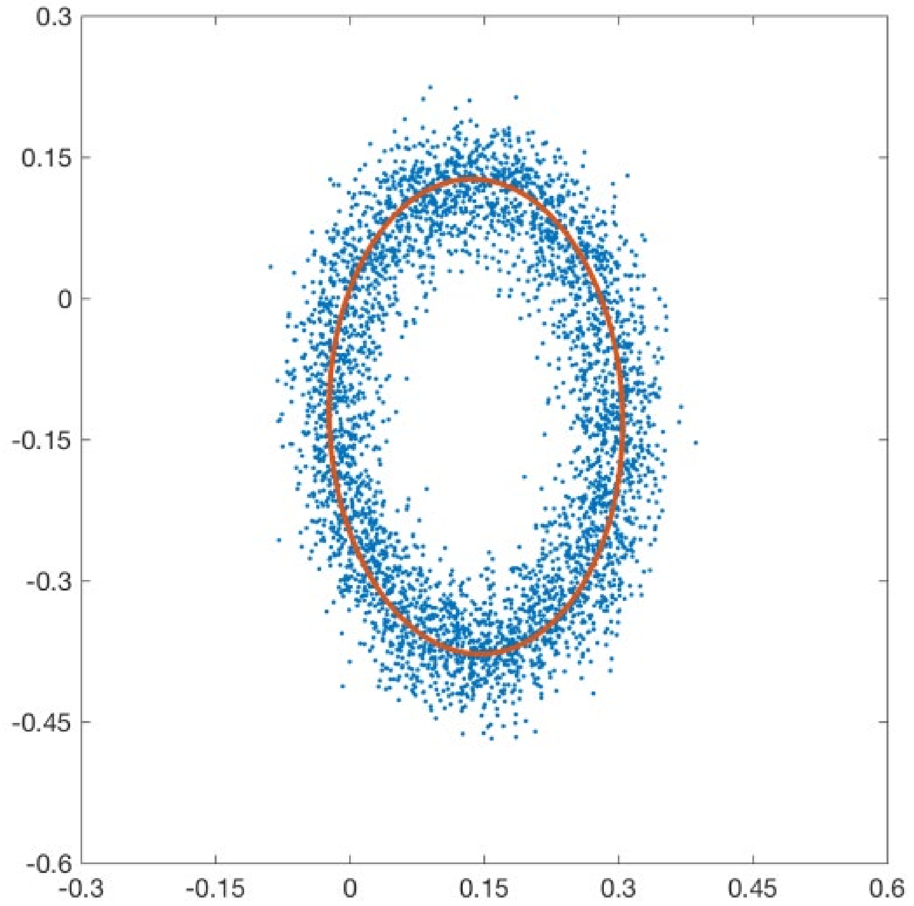
T=10 ms



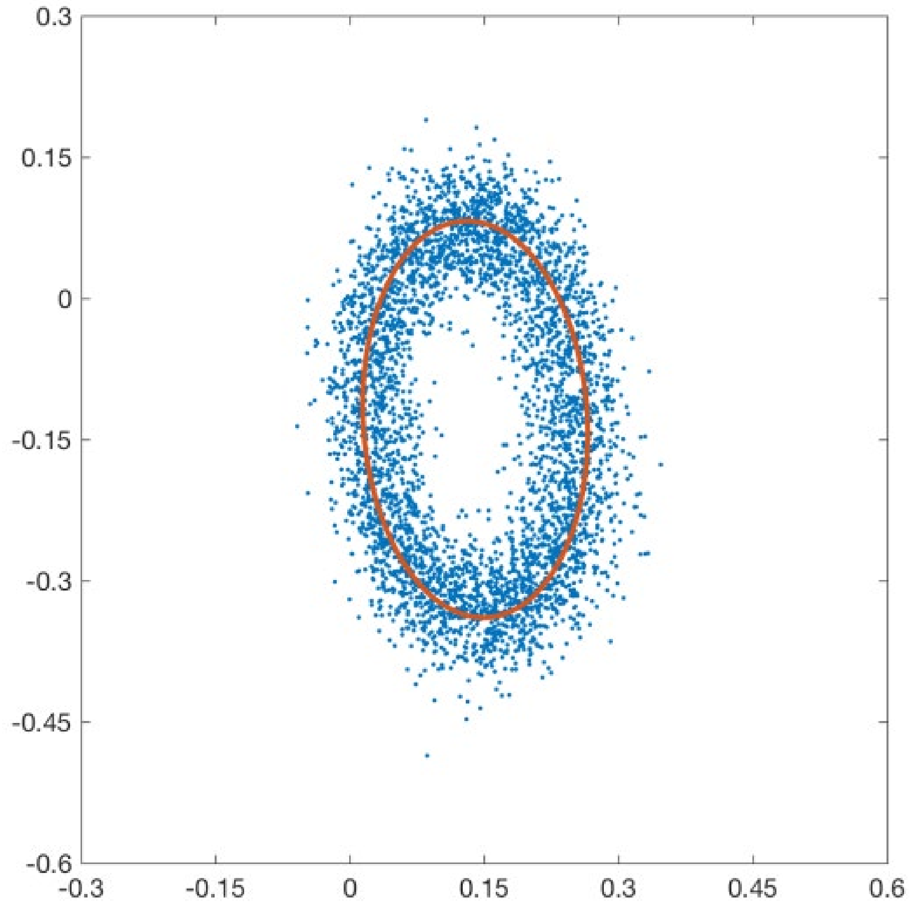
T=20 ms



T=40 ms



T=60 ms



T=80 ms

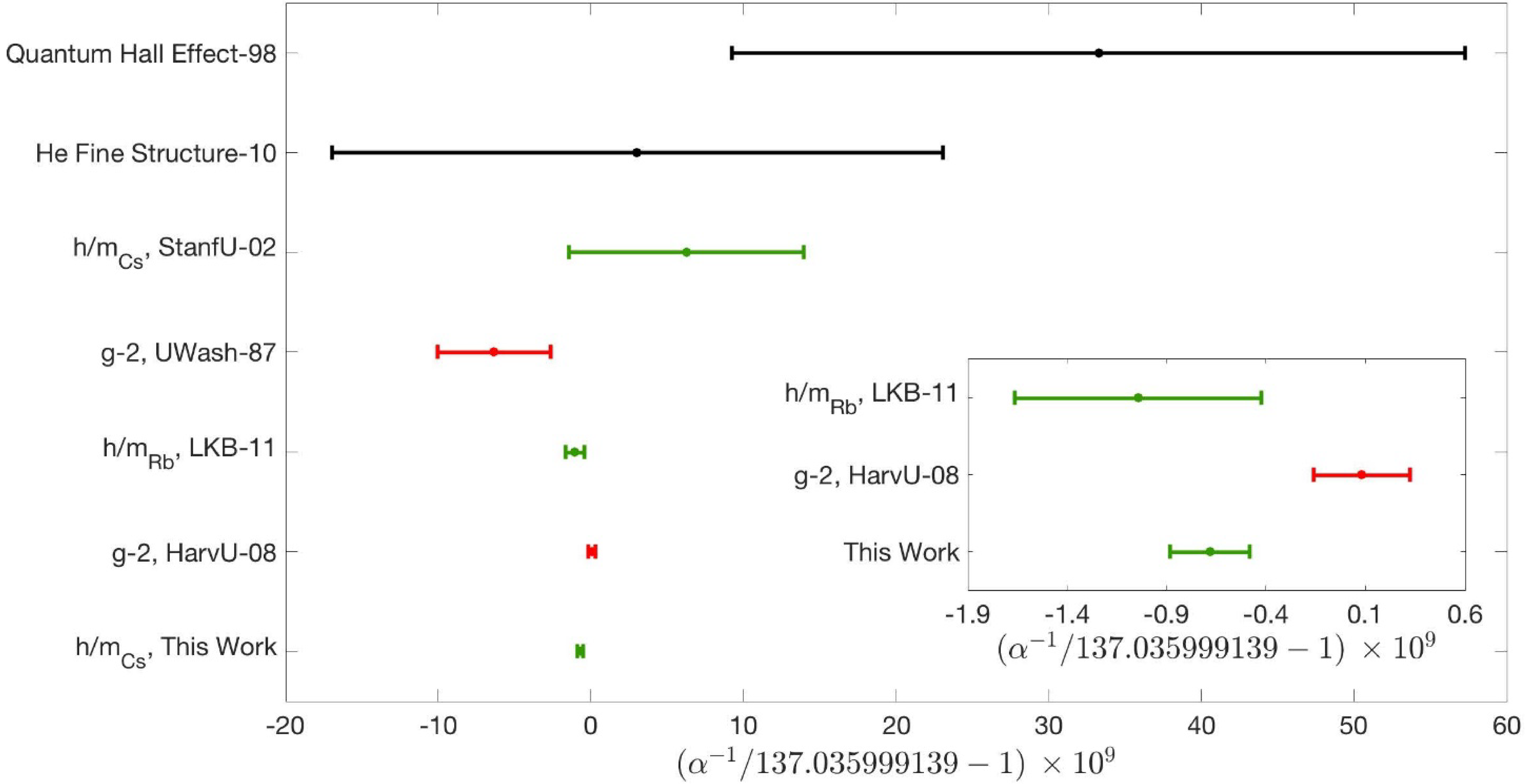
Systematic Checks

Variations of alpha w.r.t.:

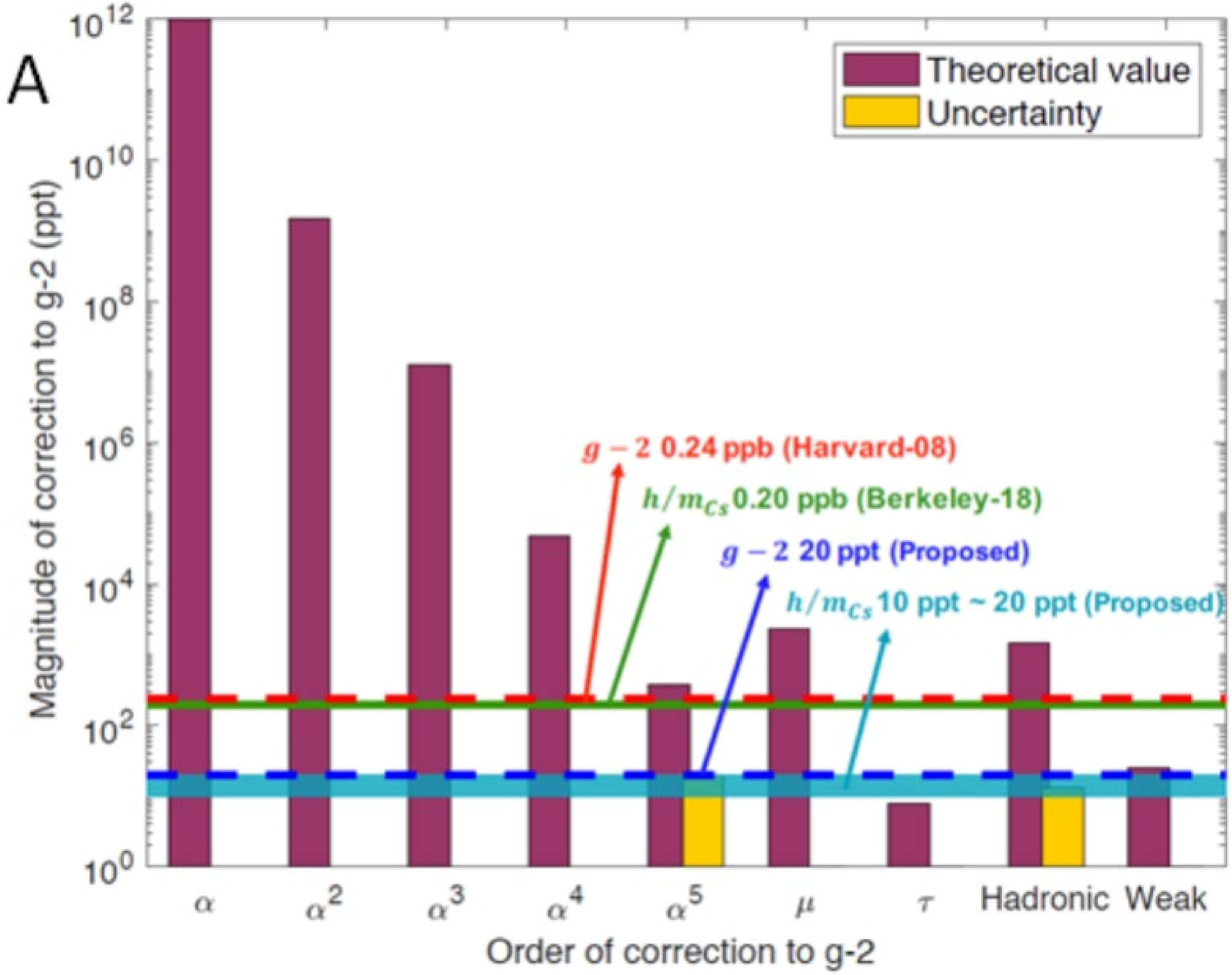
- Bloch order
- Bloch power
- Contrast
- Detection region
- Pulse intensity: overall and pulse/pulse ratio
- Speckle phase
- ω_m mixing (RF)
- ω_m mixing (optics)
- Delay of interferometer sequence
- Bias B-field
- Single-photon detuning
- Data Analysis parameters (cuts, fitting, etc.)
- Fountain alignment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

Results

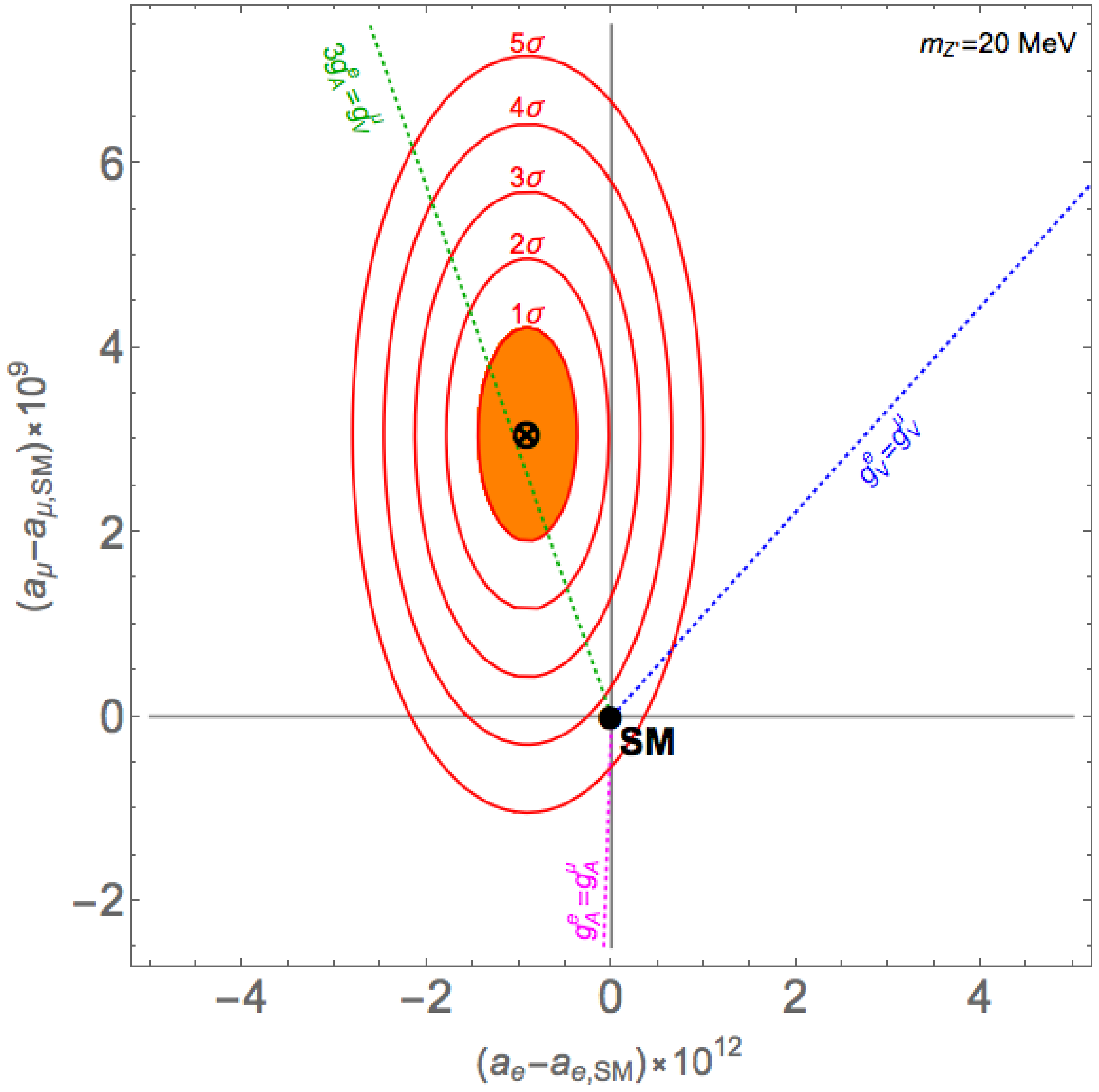
Results

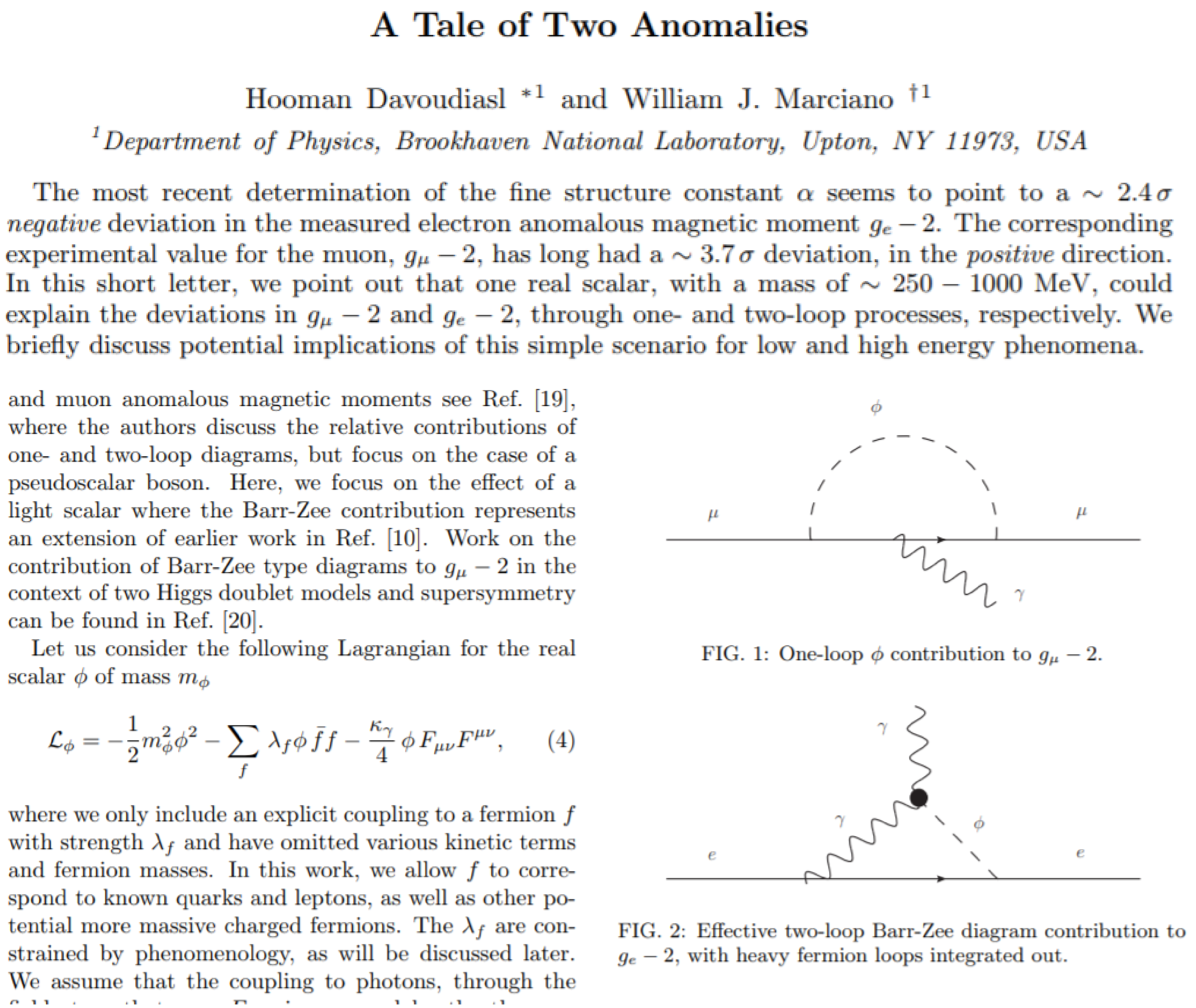

Quantum Hall Effect-98
He Fine Structure-10
h/m$_{Cs}$, StanfU-02
g-2, UWash-87
h/m$_{Rb}$, LKB-11
g-2, HarvU-08
h/m$_{Cs}$, This Work
-20
-10
0
10
20
30
40
50
60
$(\alpha^{-1}/137.035999139 - 1) \times 10^9$
h/m$_{Rb}$, LKB-11
g-2, HarvU-08
This Work
-1.9
-1.4
-0.9
-0.4
0.1
0.6
$(\alpha^{-1}/137.035999139 - 1) \times 10^9$

Testing Standard Model



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

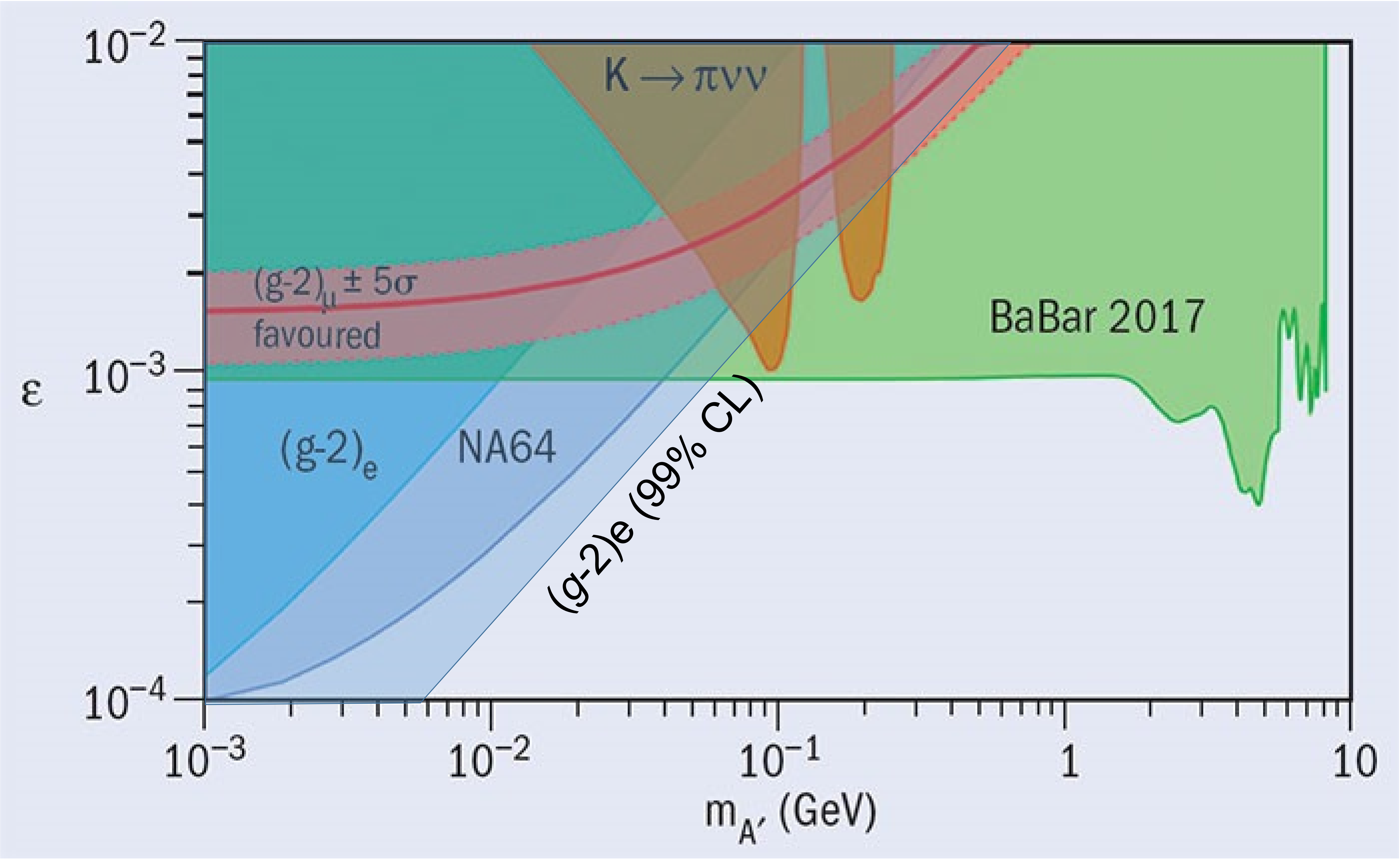
FIG. 1: One-loop ϕ contribution to $g_\mu - 2$.

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

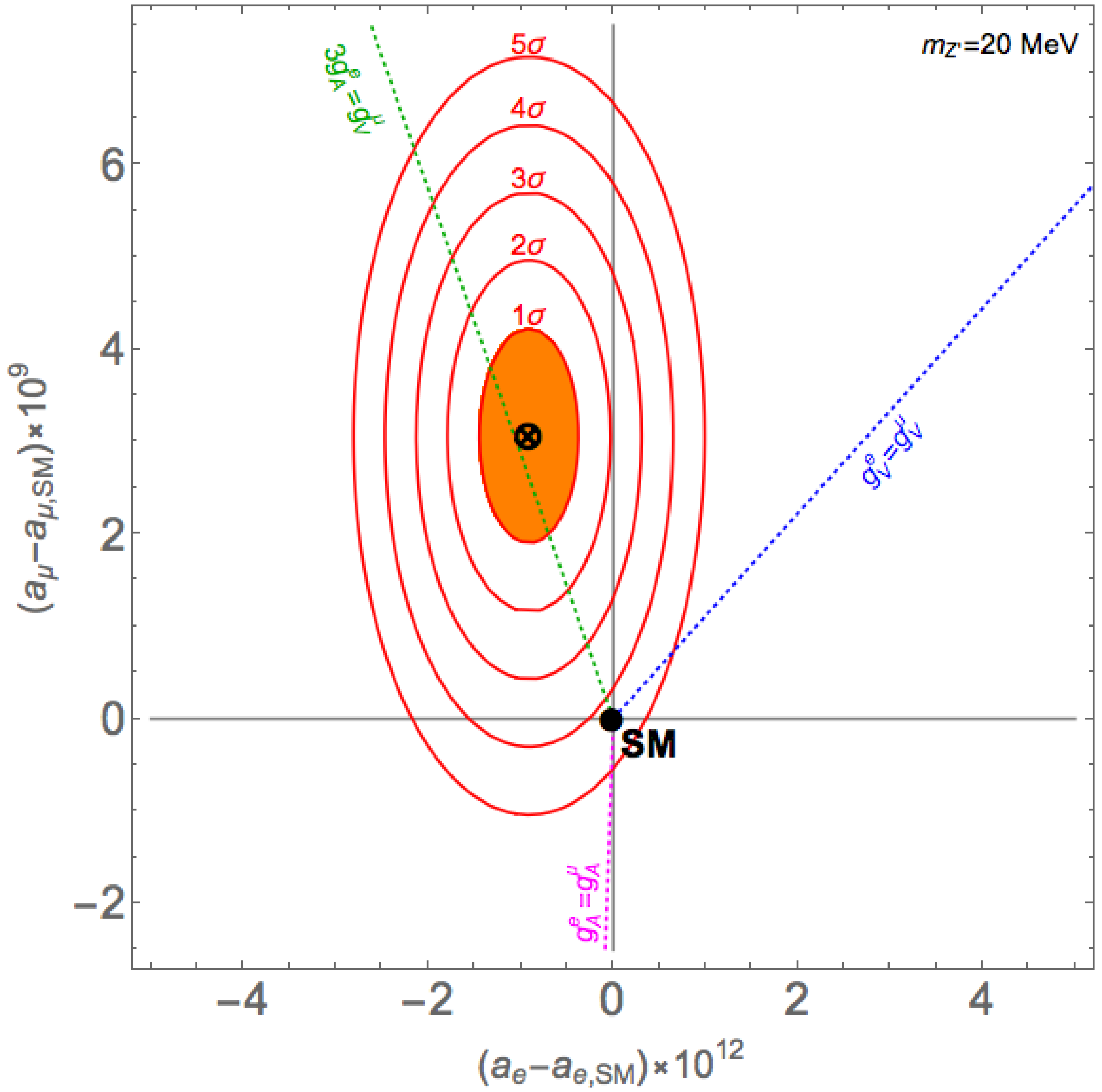
Dark photon limits

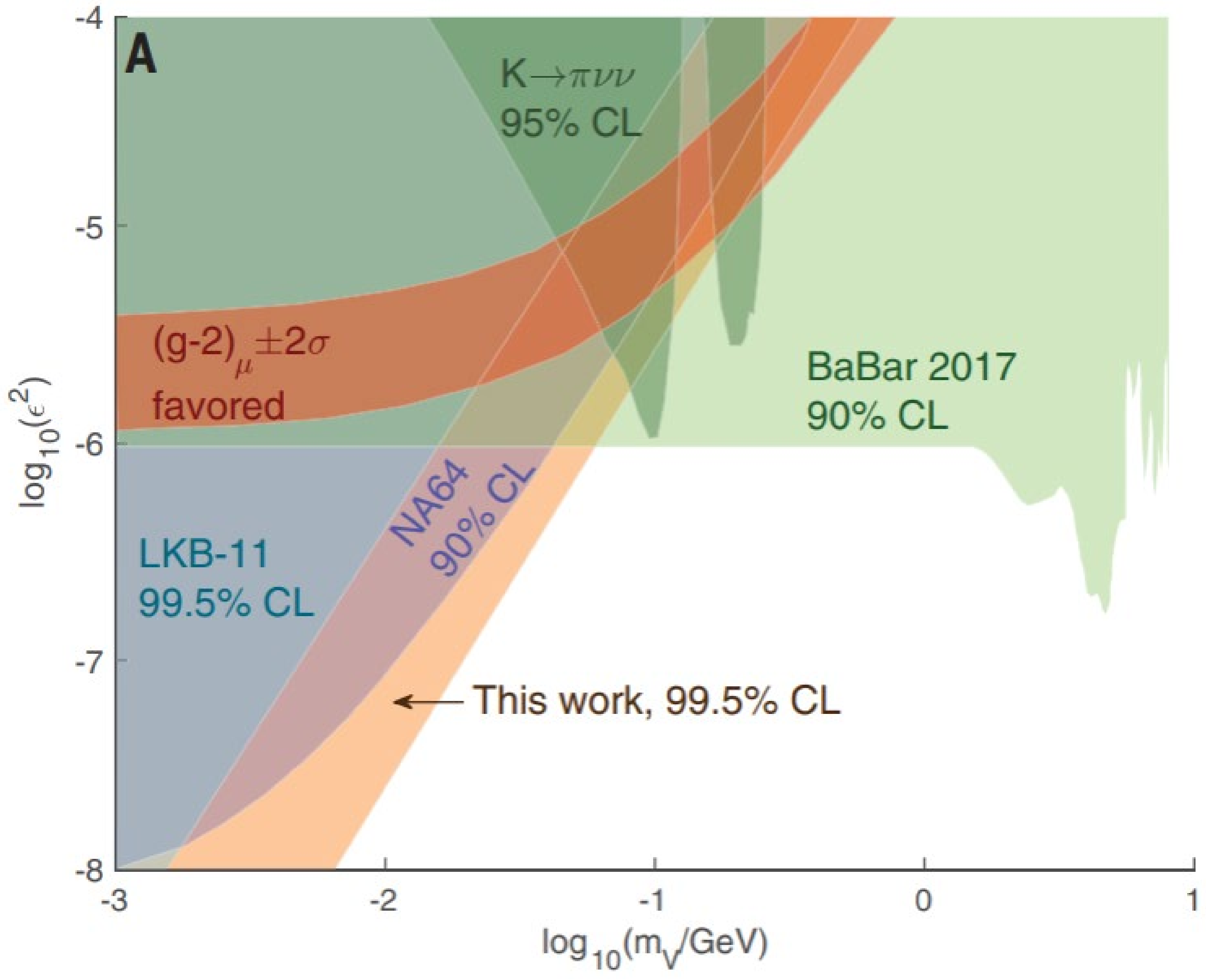


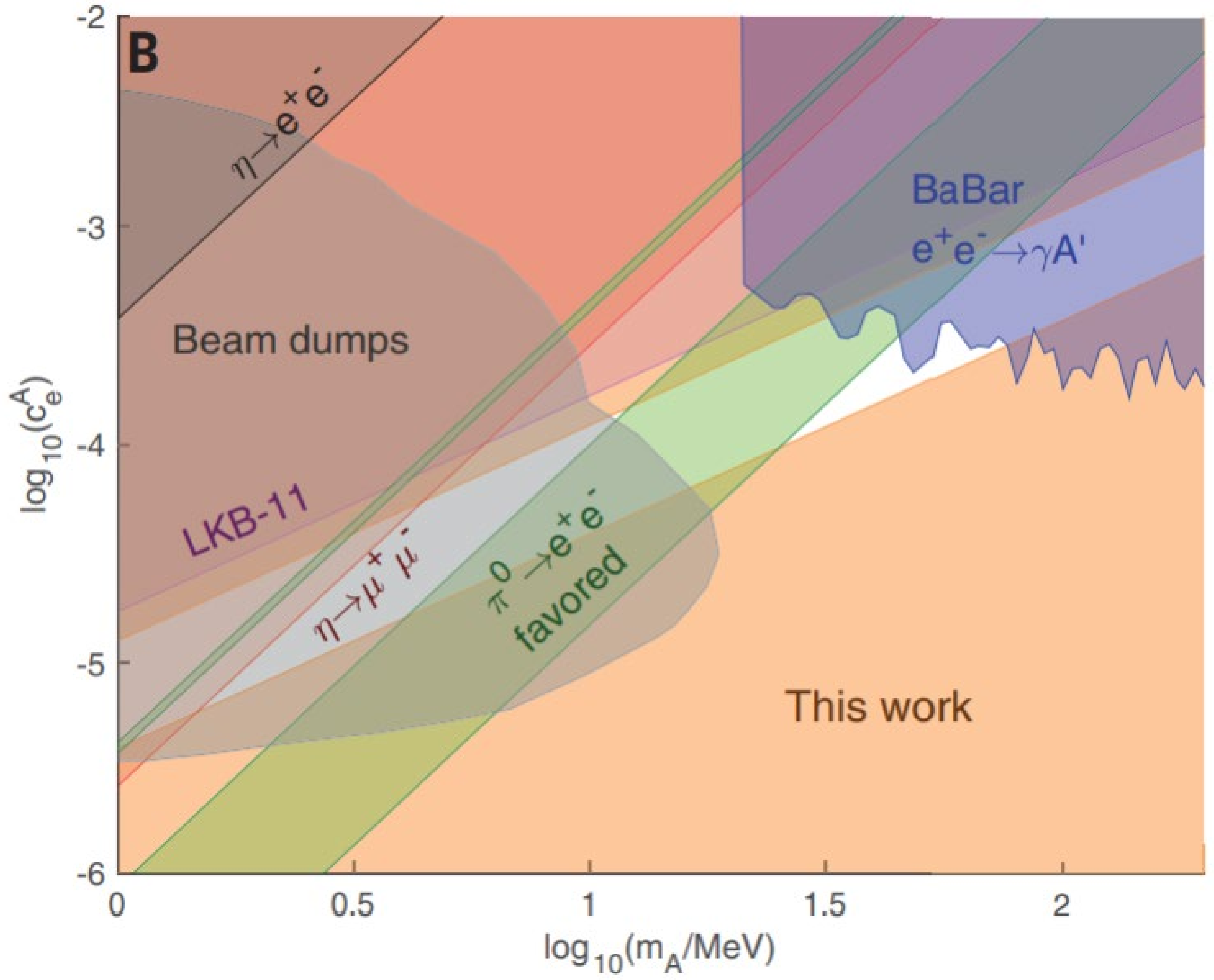
Constraining BSM Physics

Dark photons

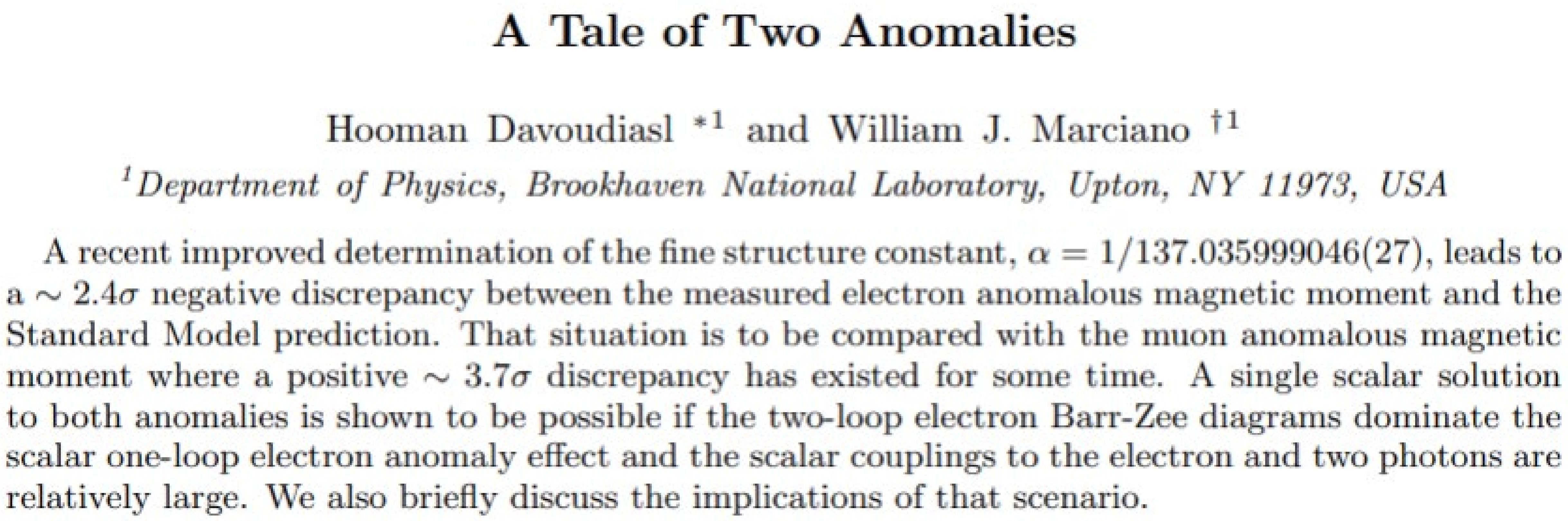
Dark axial vectors







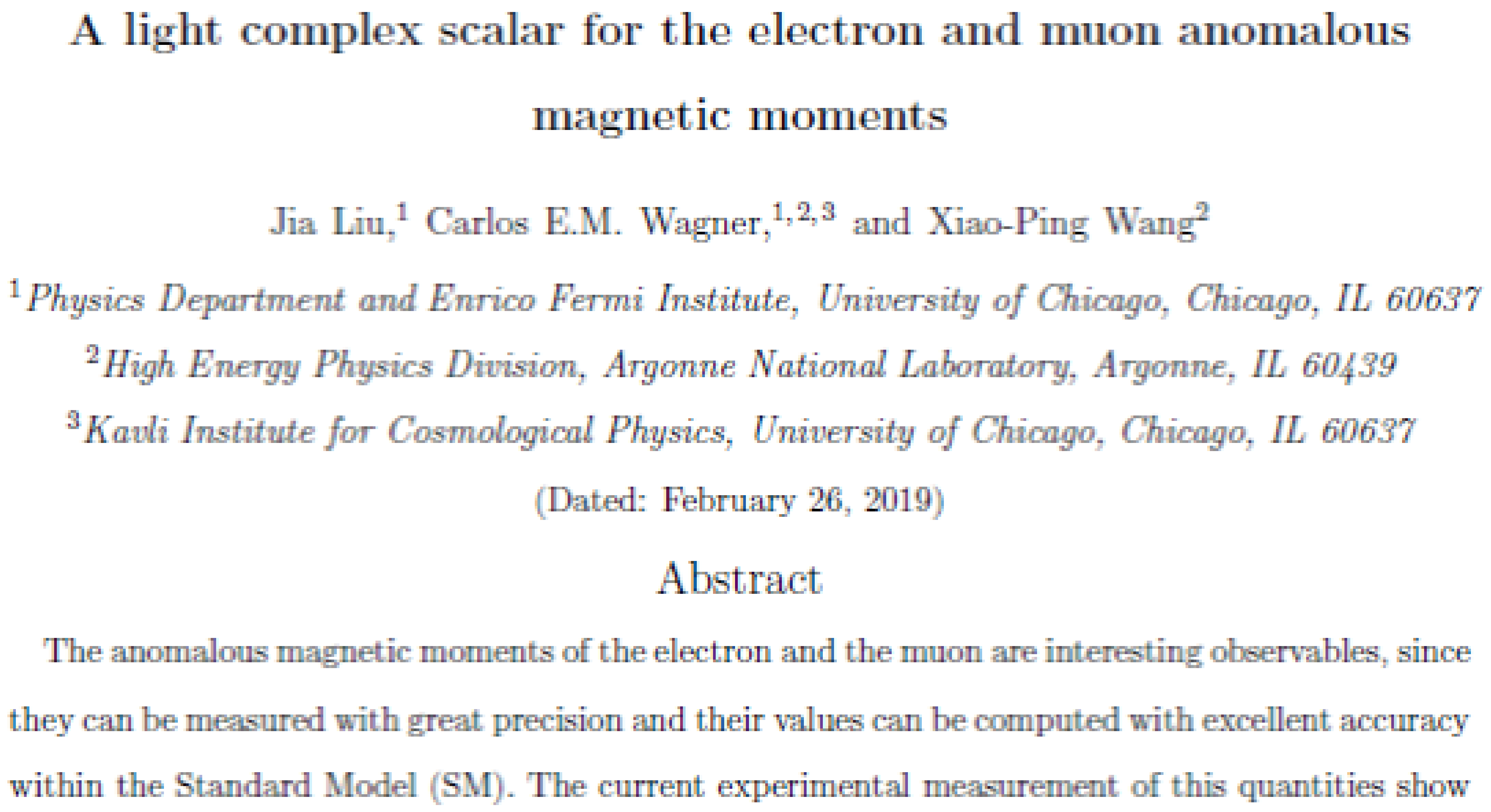
Constraining BSM Physics



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

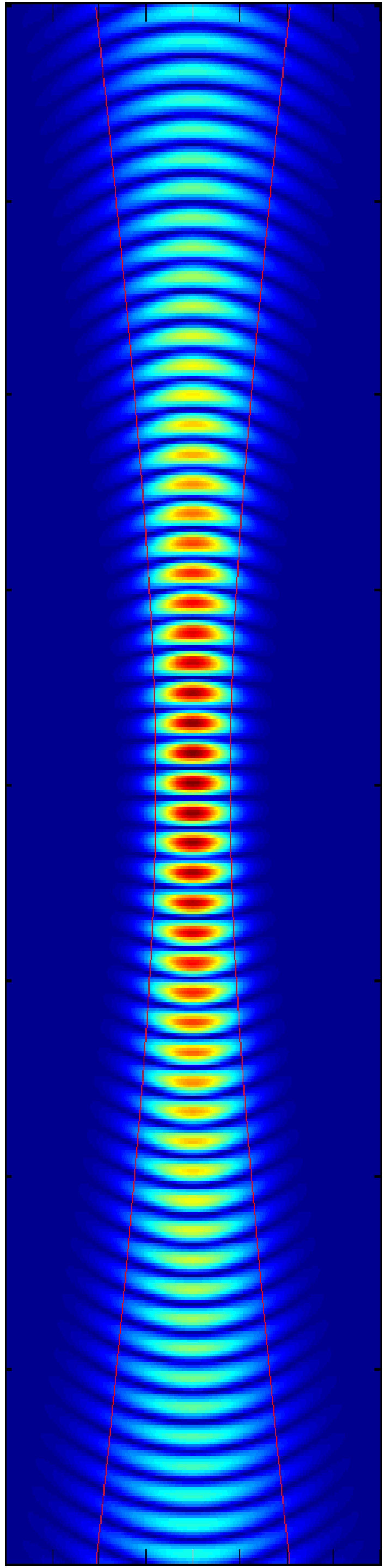
The anomalous magnetic moments of the electron and the muon are interesting observables, since they can be measured with great precision and their values can be computed with excellent accuracy within the Standard Model (SM). The current experimental measurement of this quantities show

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’



Looking forward…

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Larger, cleaner laser beam

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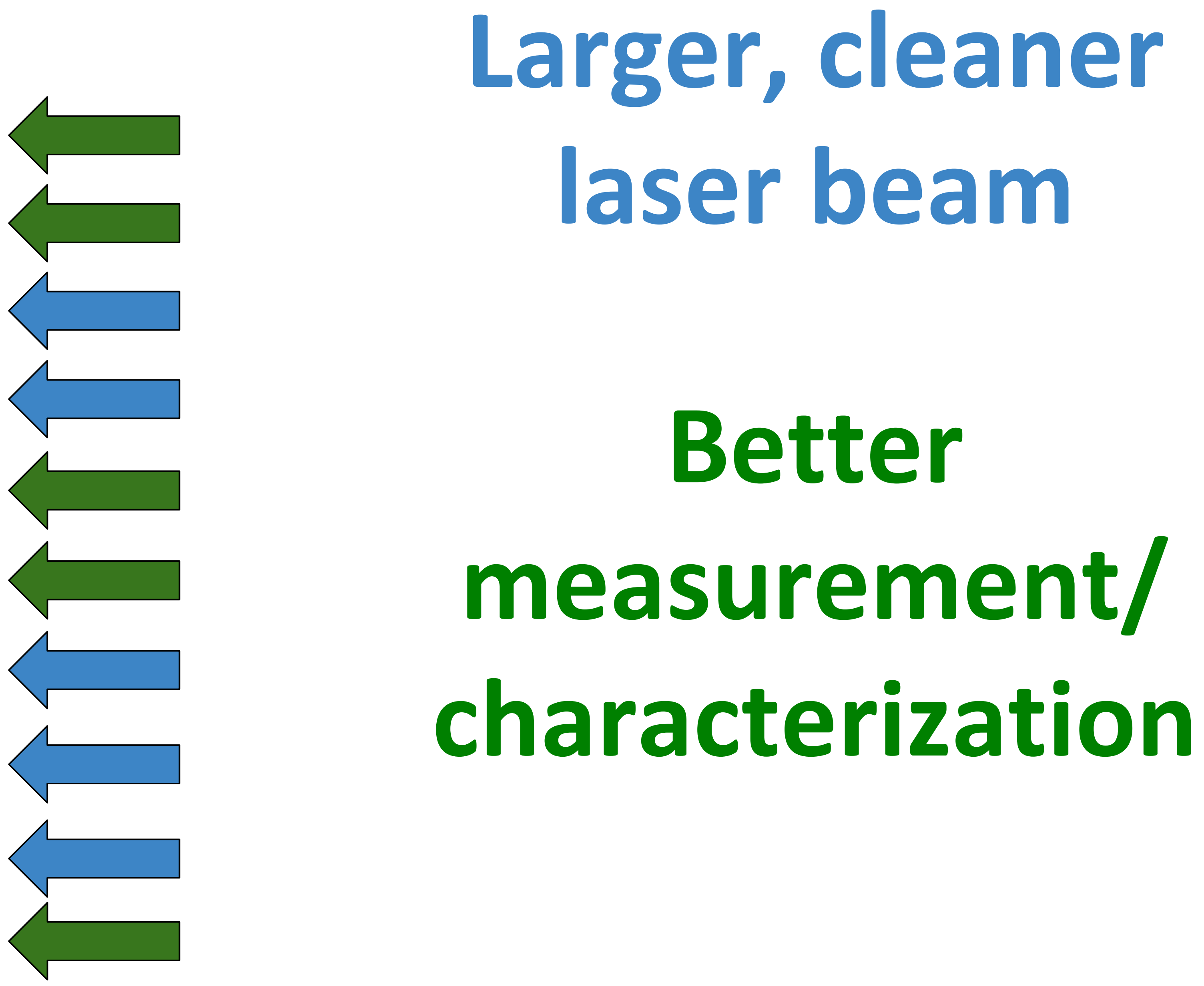

Larger, cleaner laser beam

Better measurement/ characterization

Looking forward…

Effect	Value	$\delta\alpha/\alpha$ (ppb)
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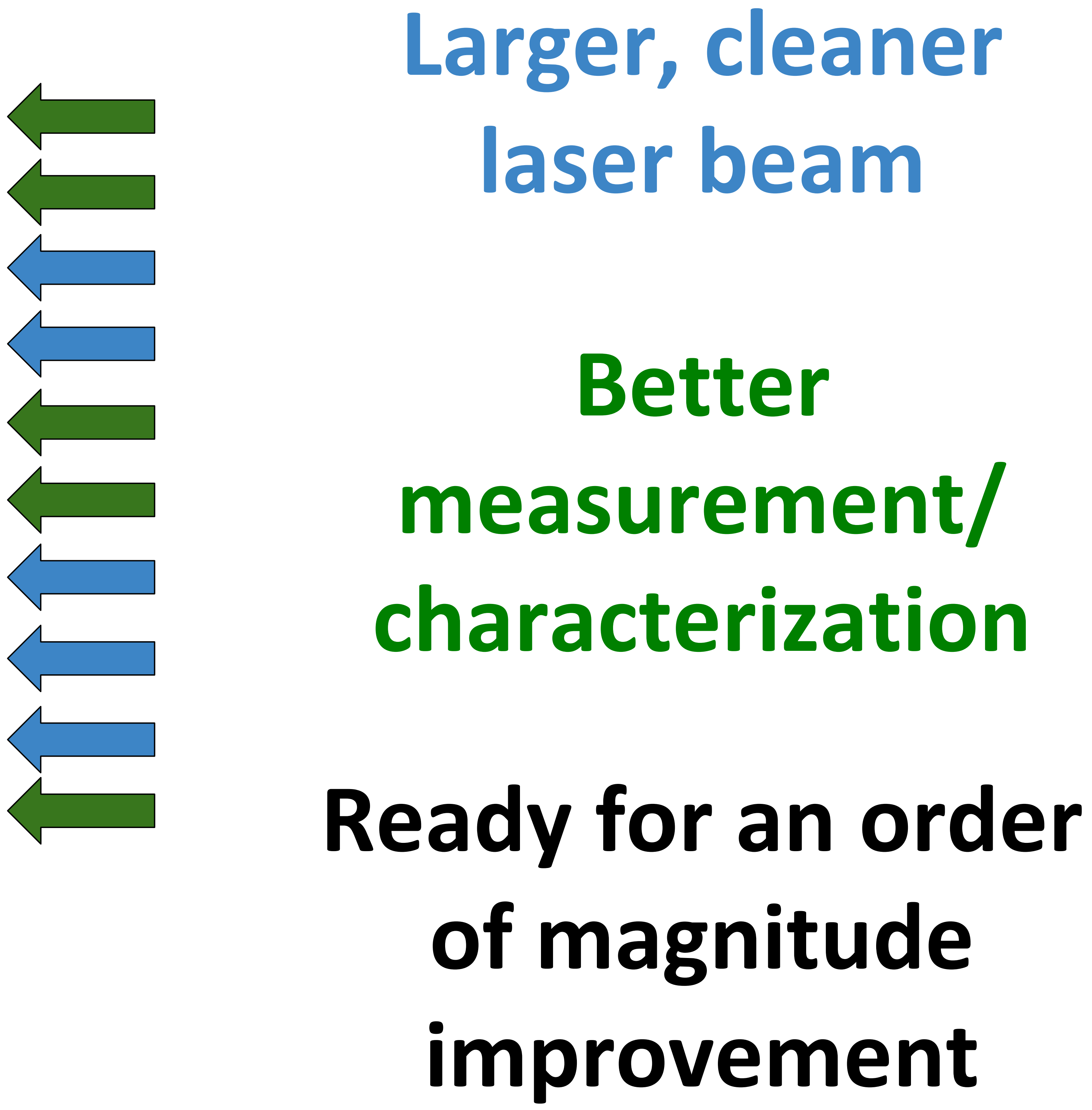
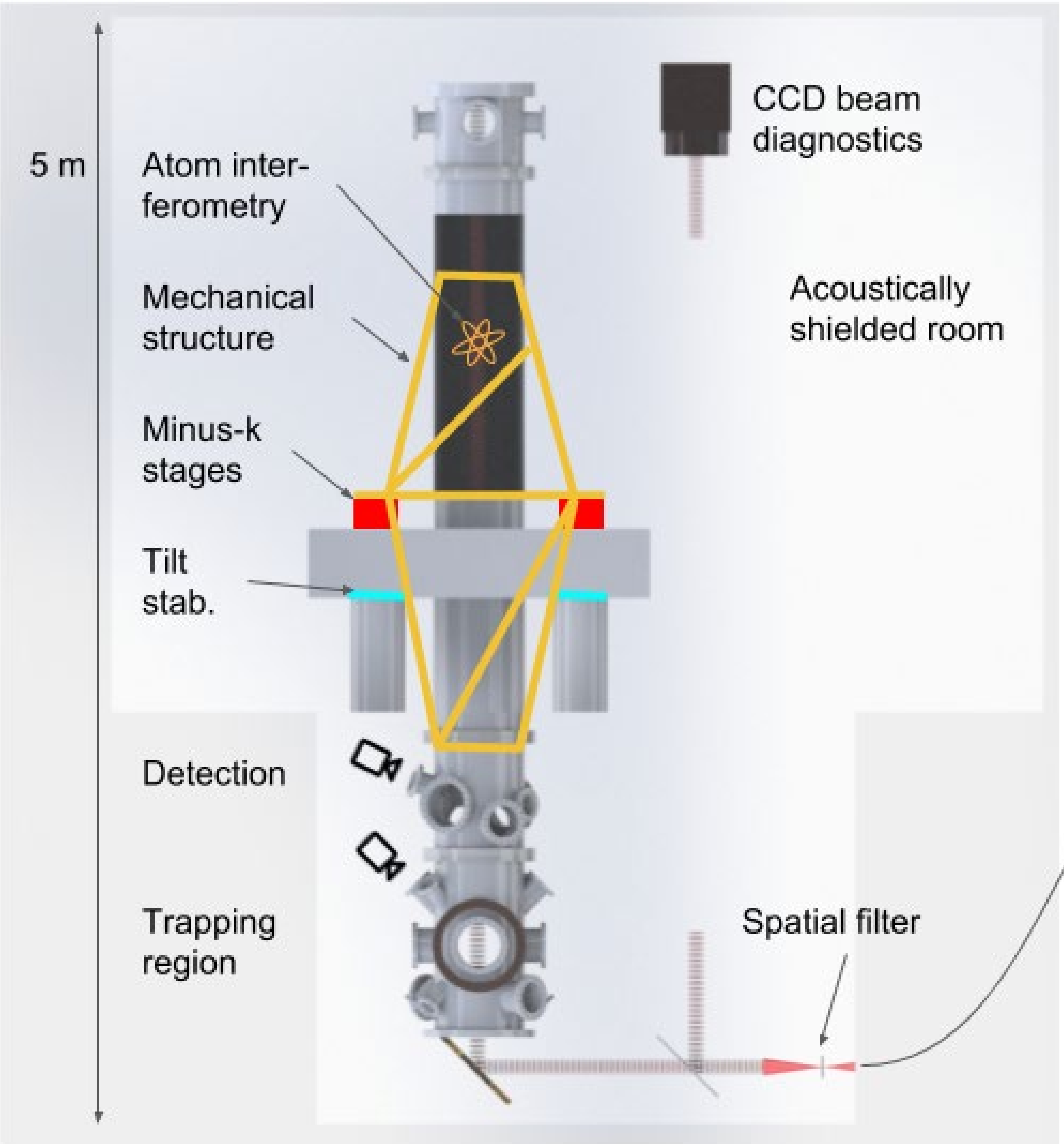


Larger, cleaner laser beam

Better measurement/ characterization

Ready for an order of magnitude improvement



5 m

Atom inter-ferometry

Mechanical structure

Minus-k stages

Tilt stab.

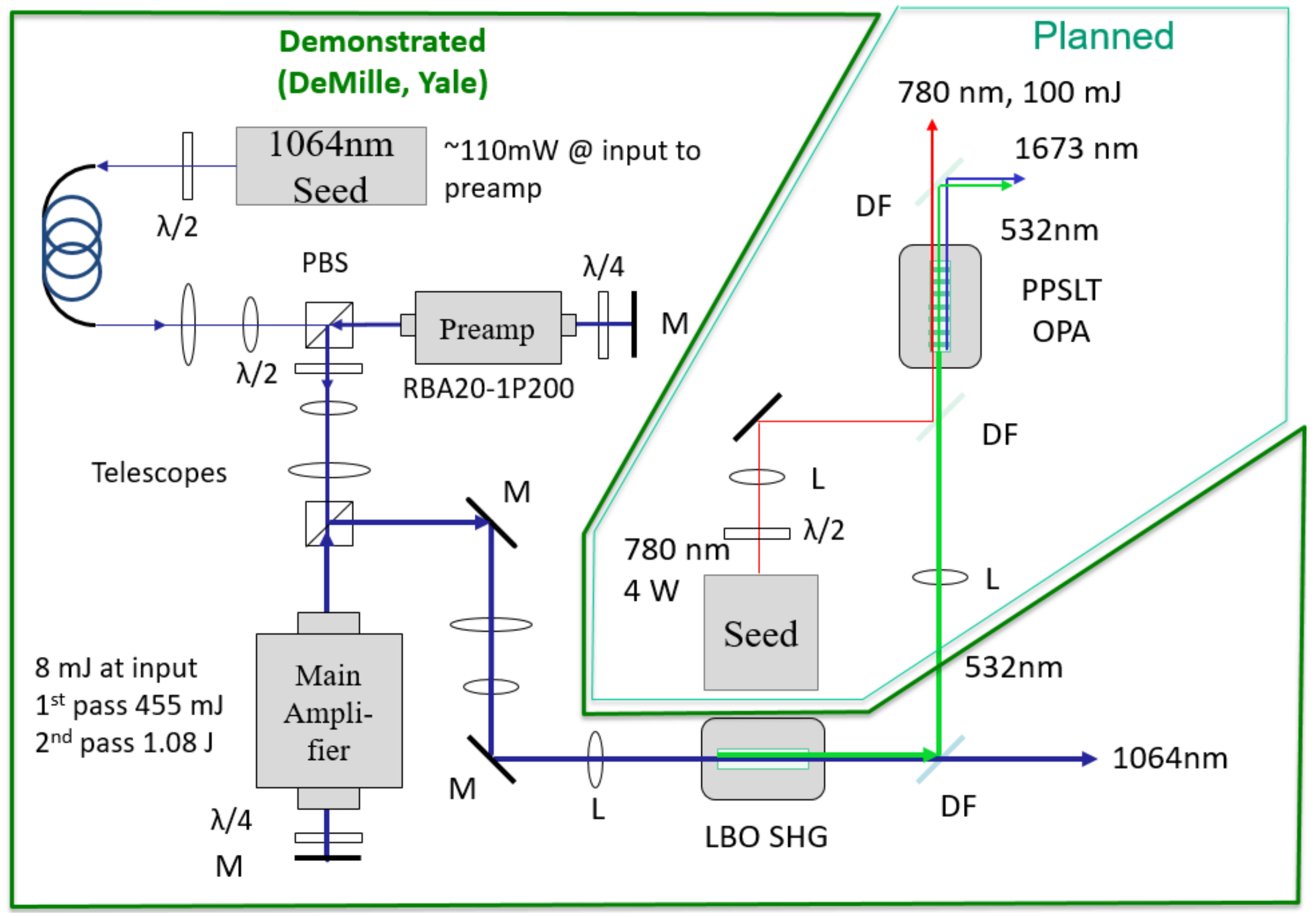
Detection

Trapping region

CCD beam diagnostics

Acoustically shielded room

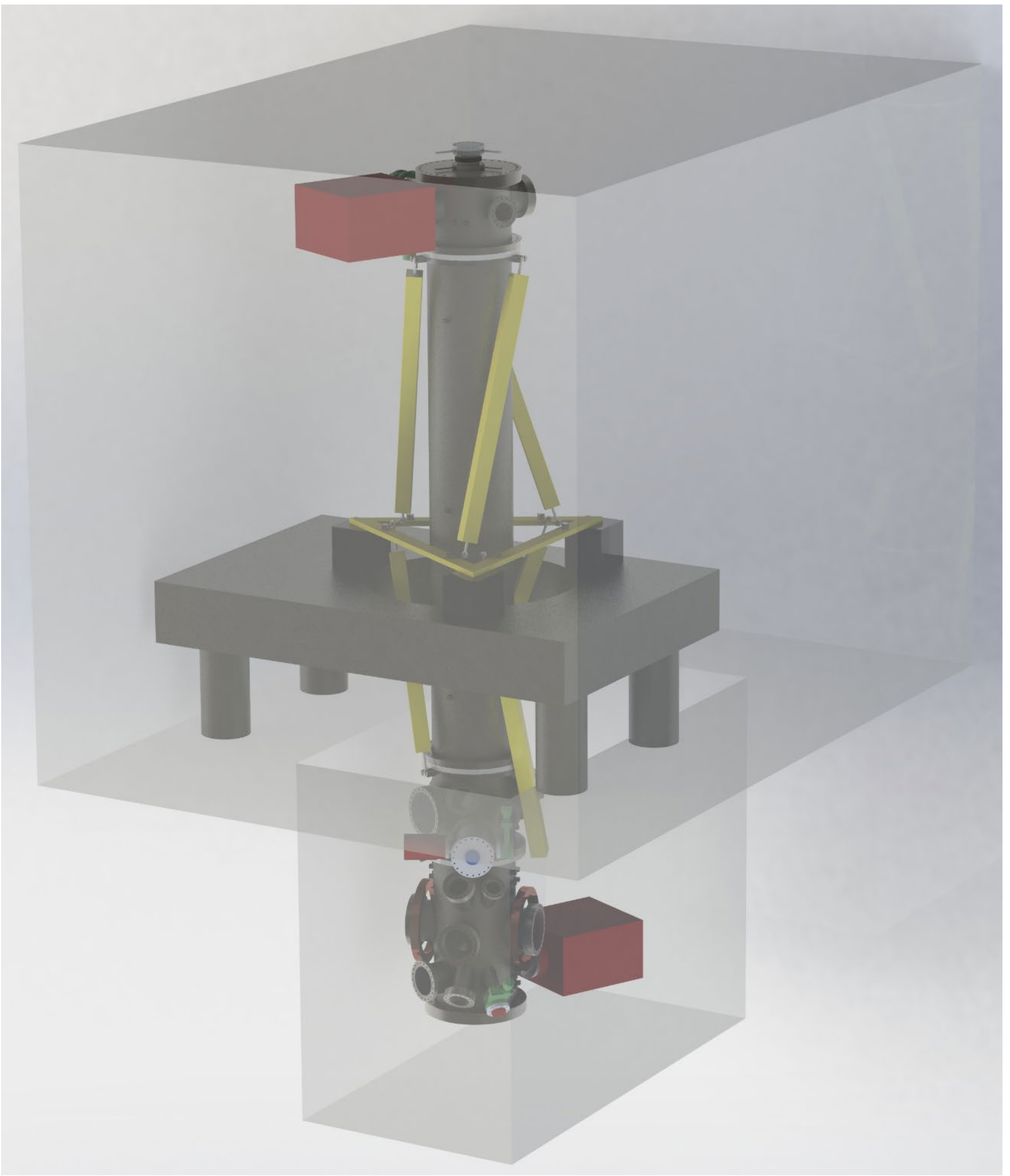
Spatial filter



Laser system

Next generation

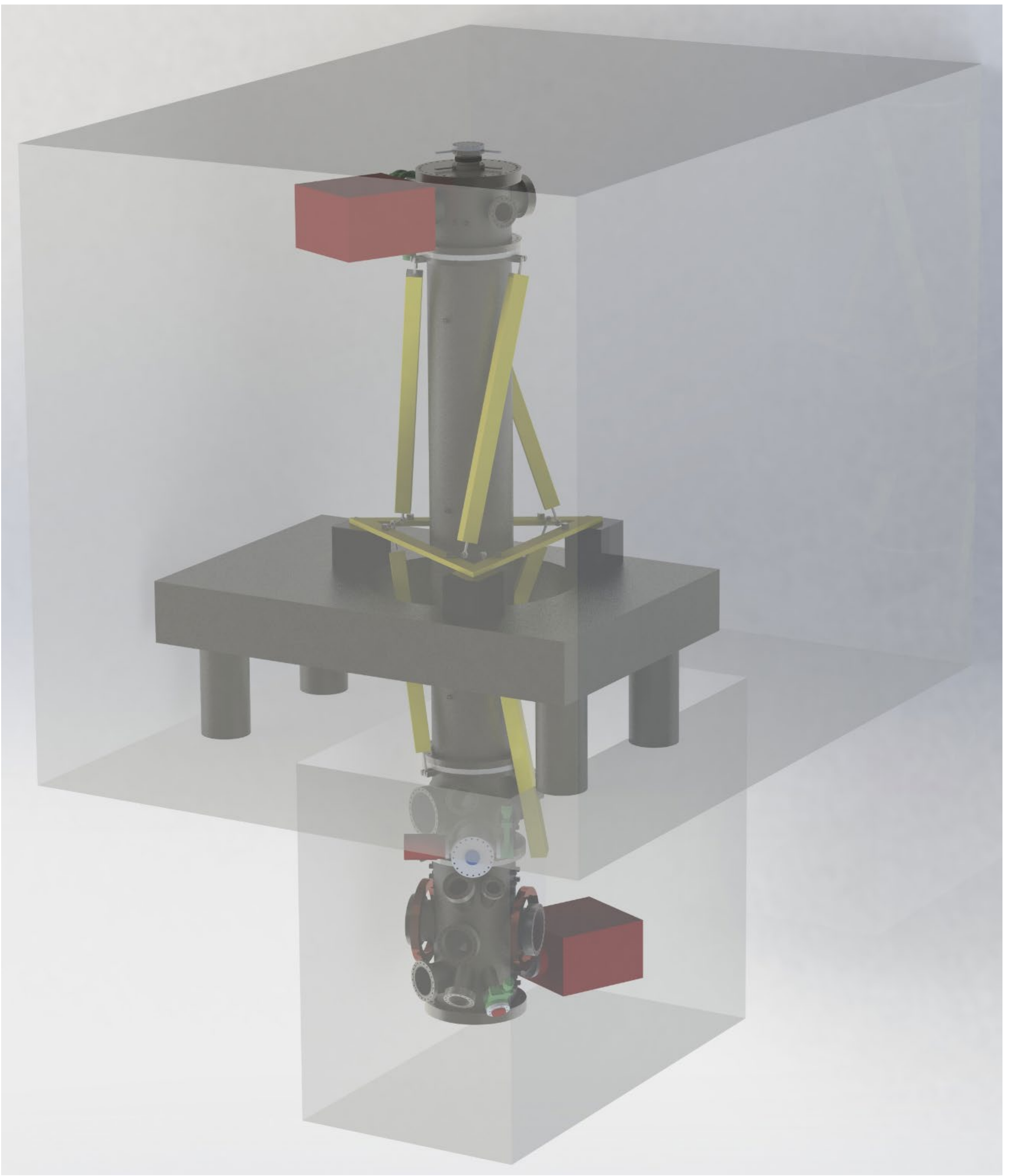
- New vacuum system
    - 25x larger cross section
    - Simplified fountain alignment
    - Vibration isolation



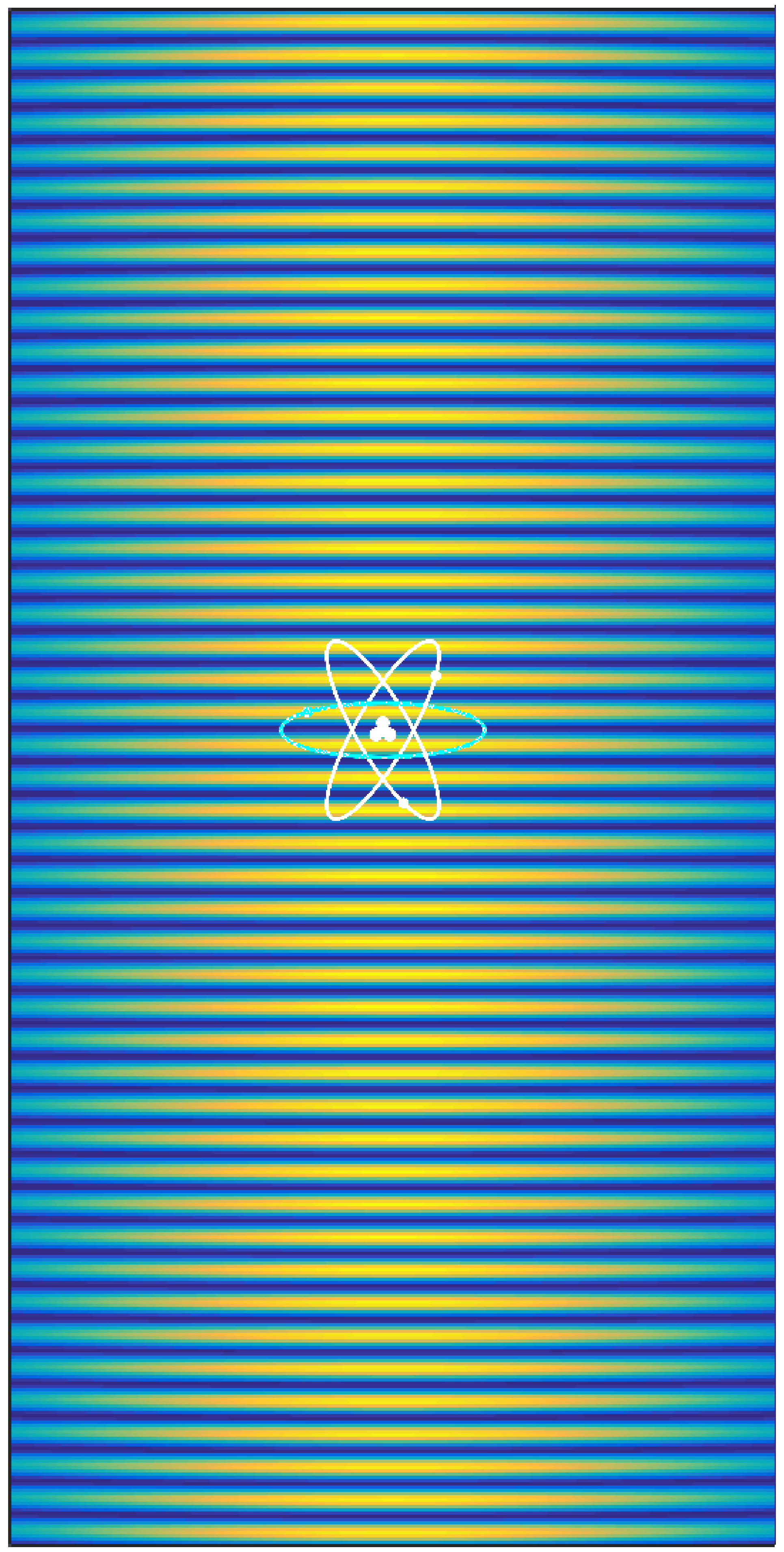
Next generation

- **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**



A more nearly perfect laser beam



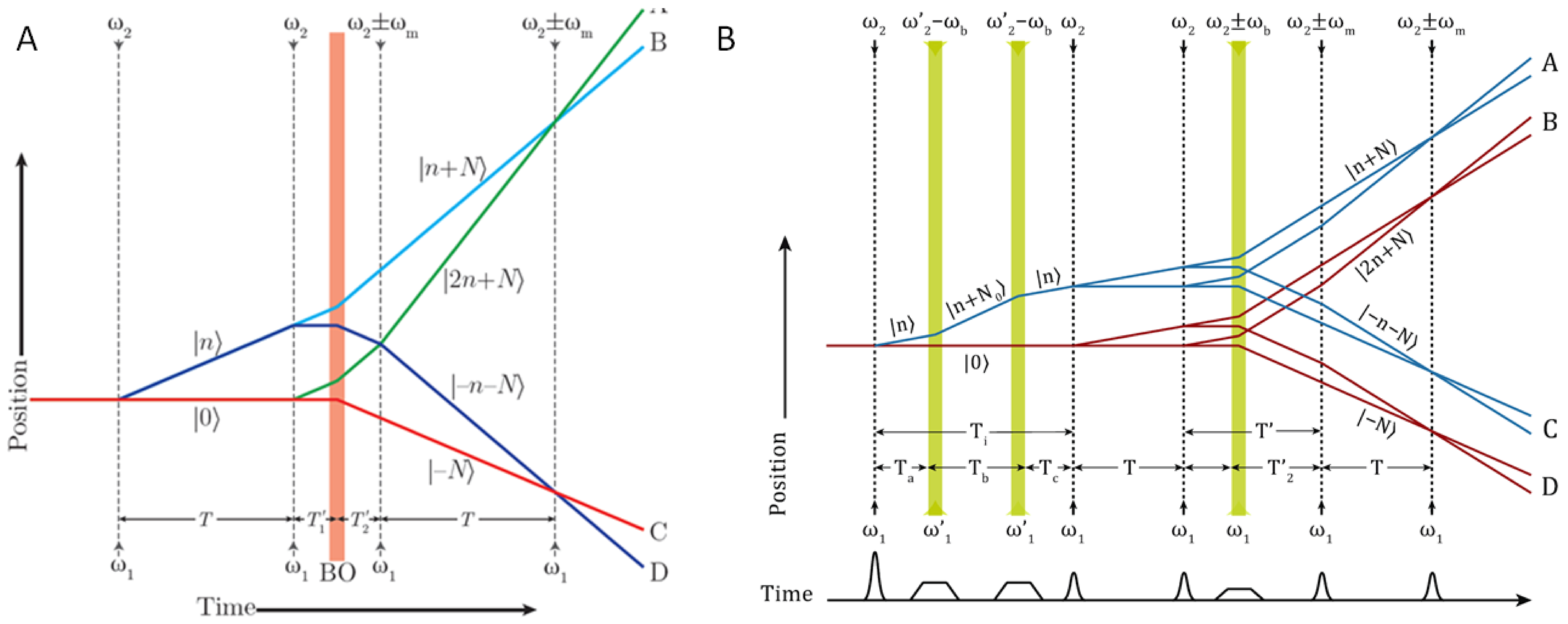
- This project ~ 6 cm radius

- Wavelength errors ~$(\lambda/\text{radius})^2$
- 400-fold higher accuracy

- Beam splitter losses ~$(\lambda/\text{radius})^4$
- higher momentum transfer, and thus sensitivity

Thick beam will unleash the potential of atom interferometry

New interferometer geometries

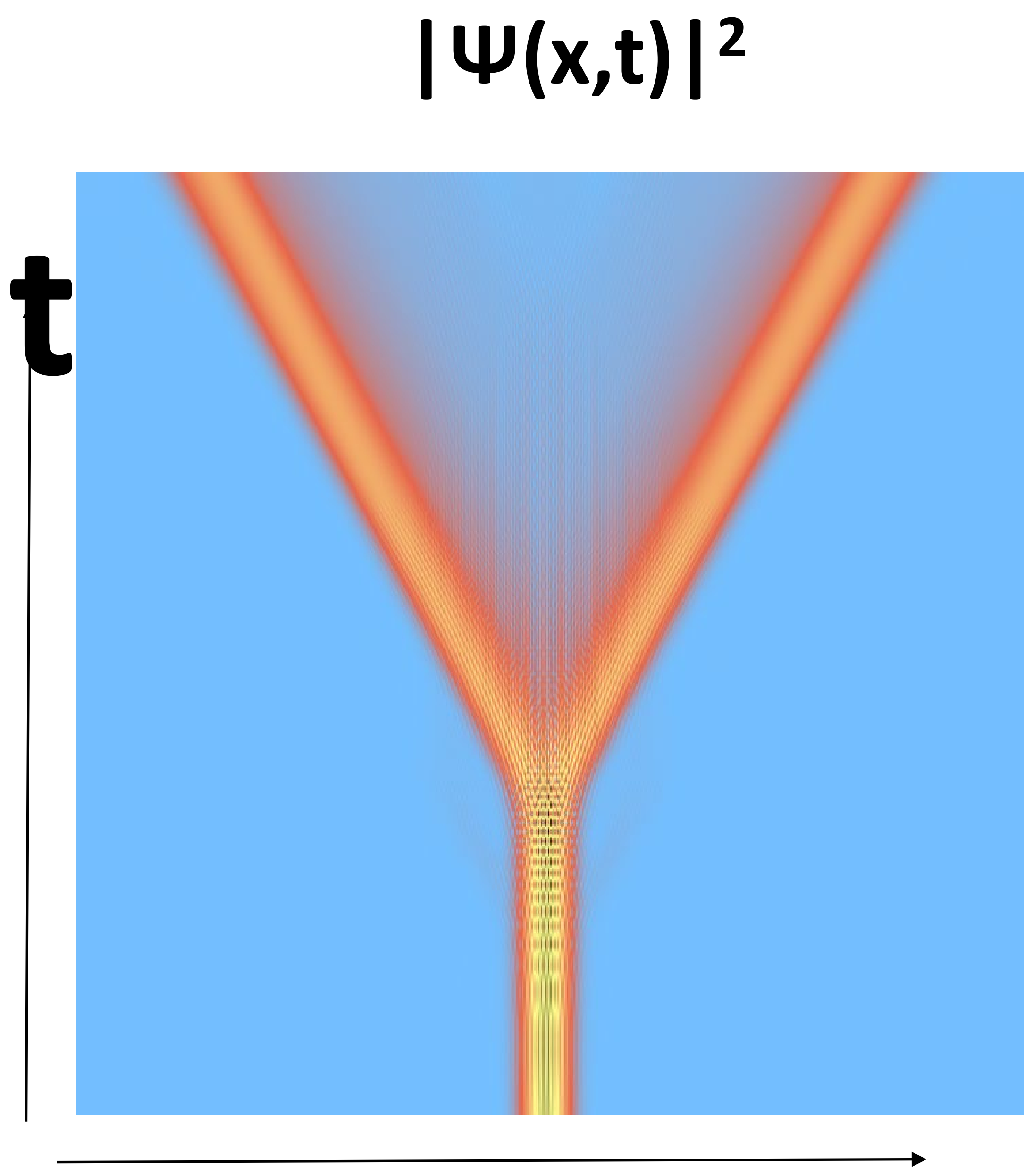


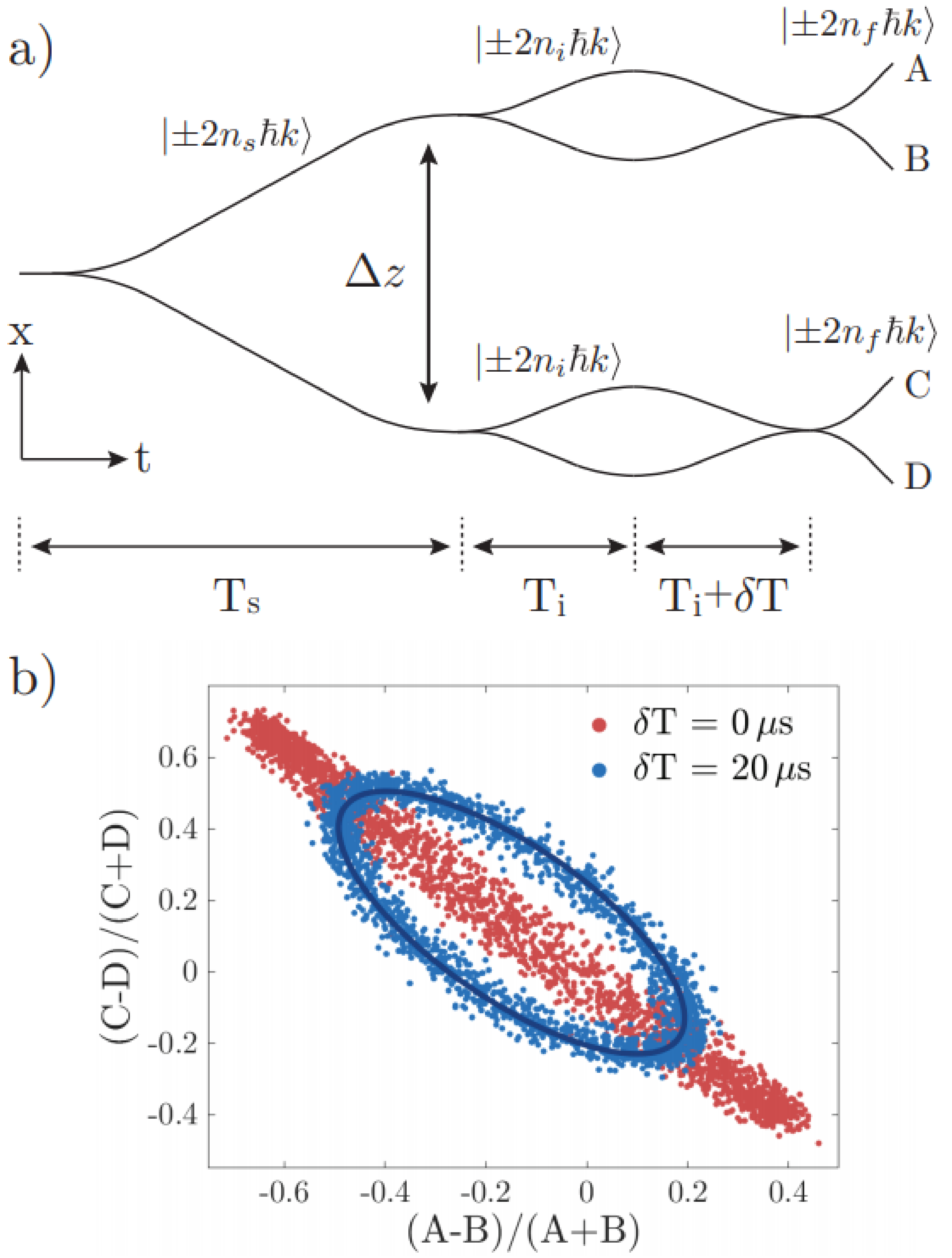
- Eliminates gravity gradient
- Moderate cost in integration rate
- Shown to work in arXiv:1901.03487

New ideas

Symmetric “Bloch beamsplitter” [4]

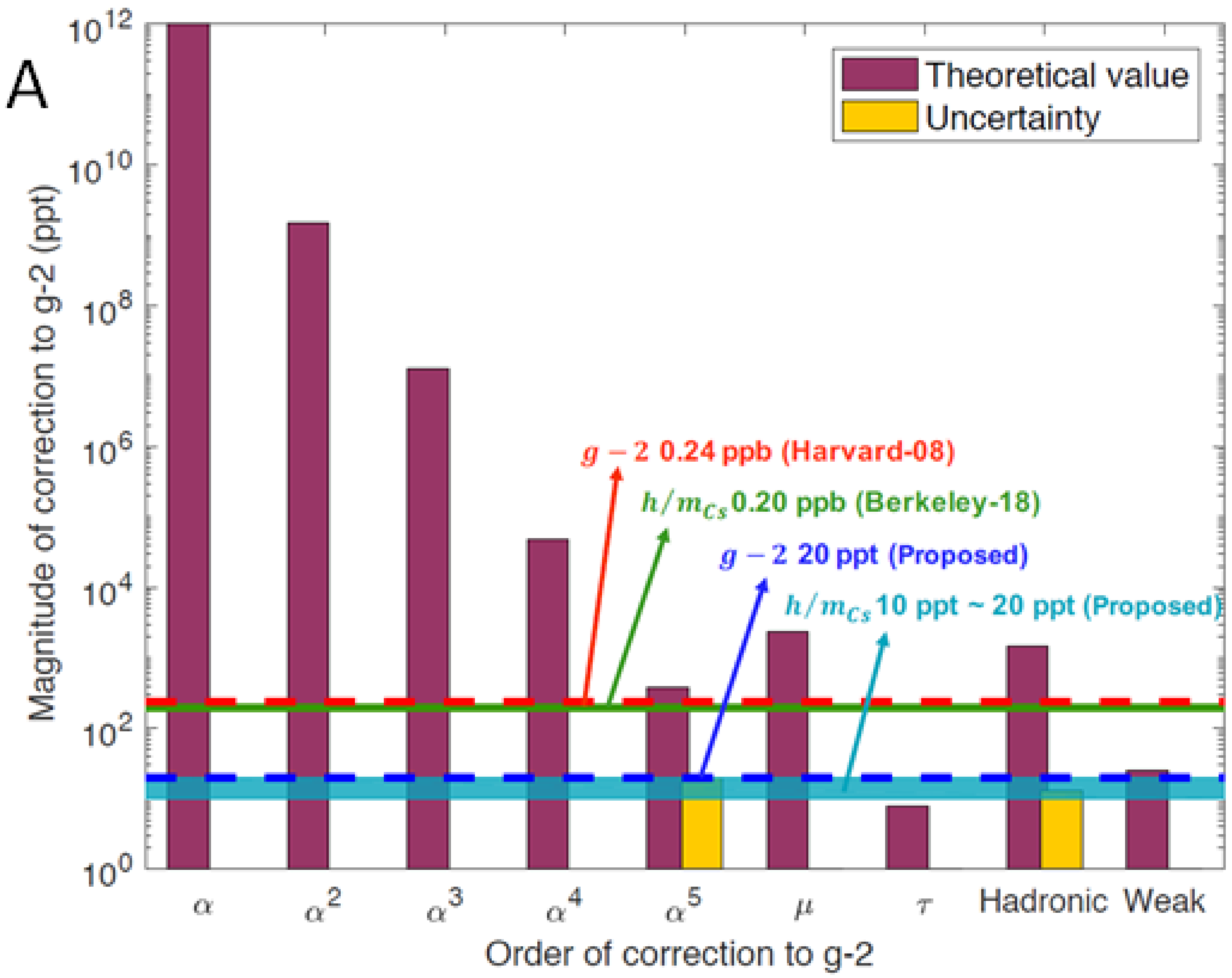
- **Eliminates diffraction phase**
- **Demonstrated 240ħk momentum transfer**

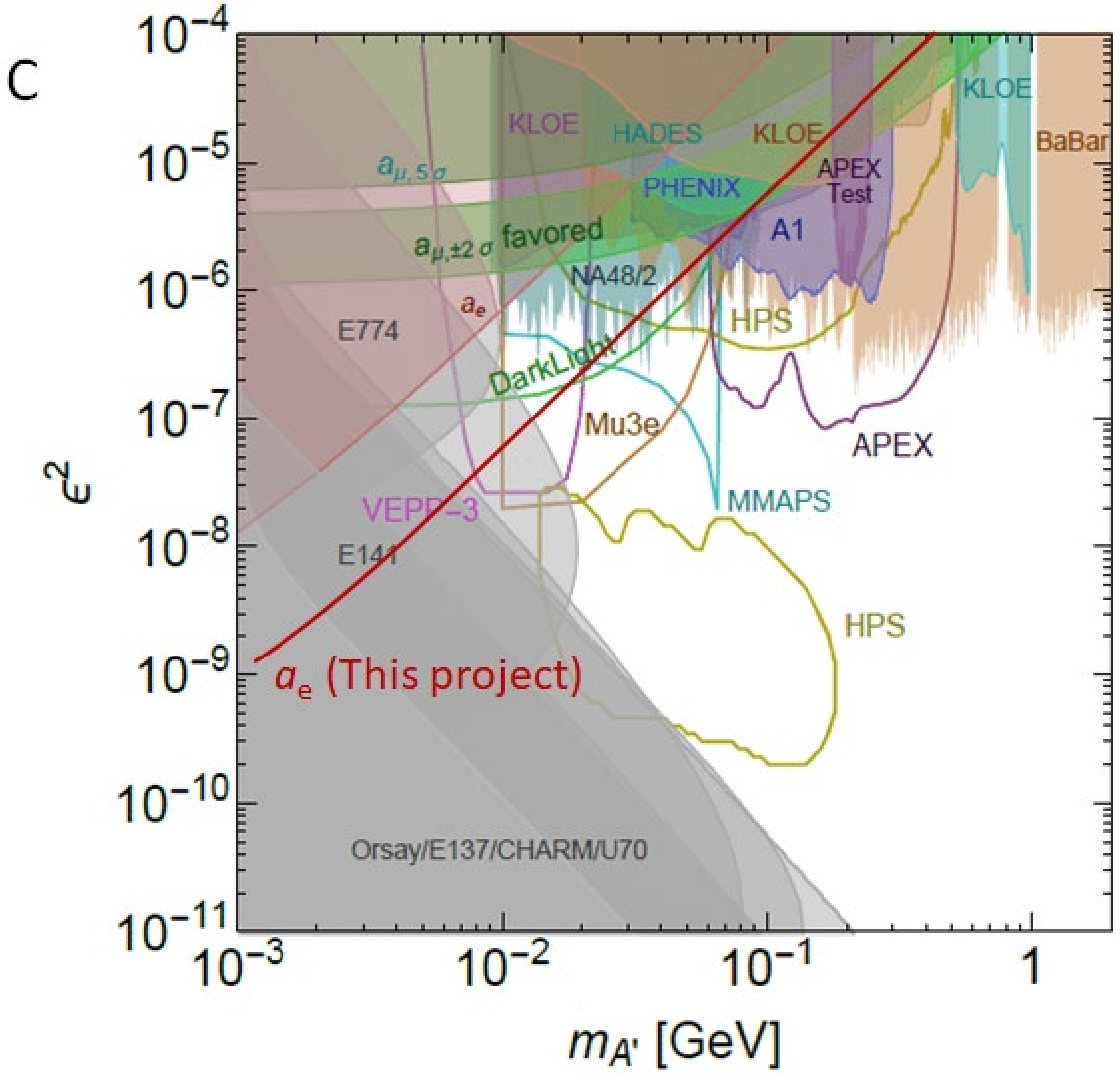




[3] Z. Pagel et al 2019, arXiv:1907.05994

New physics reach

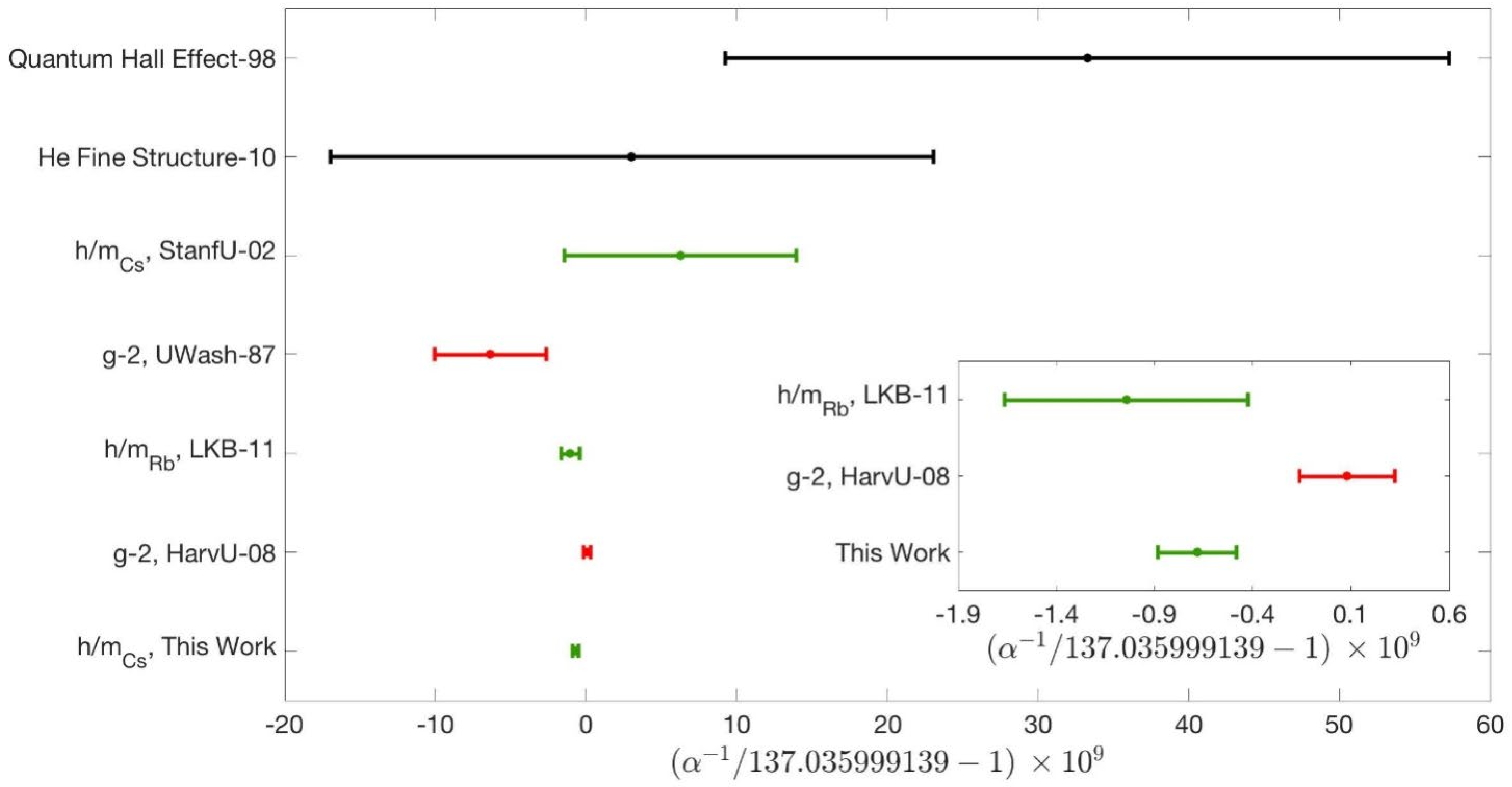


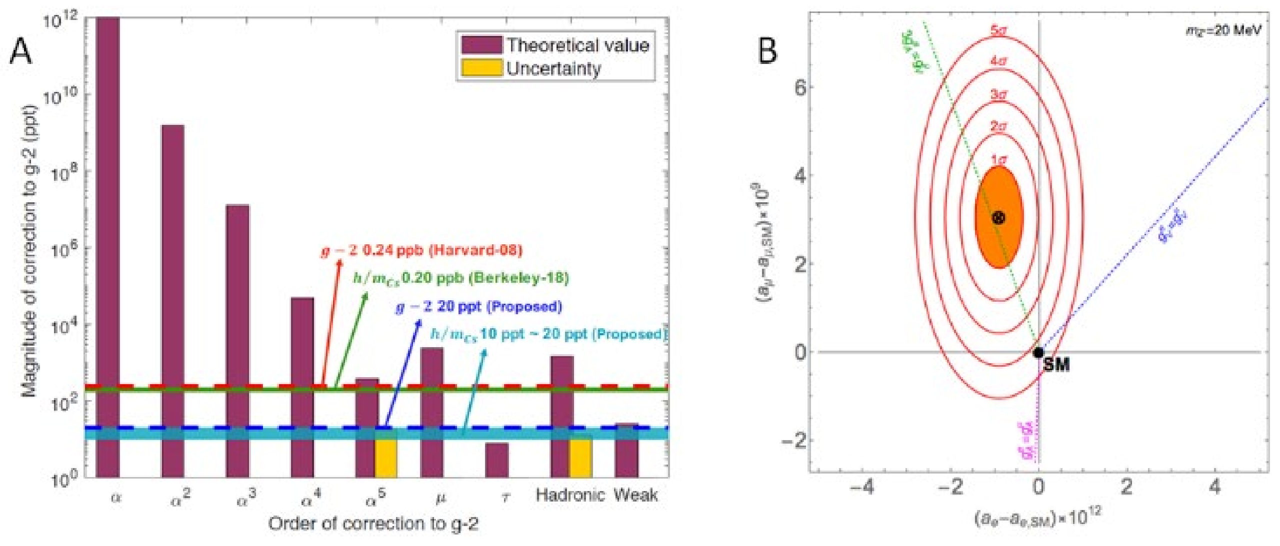


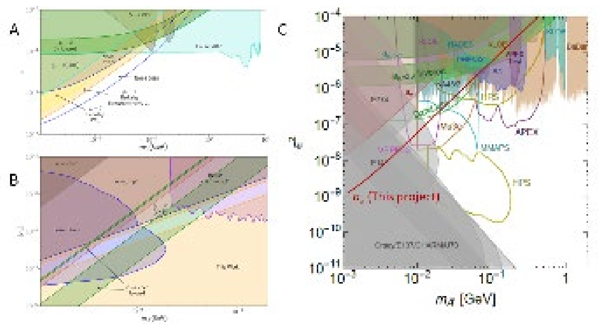
Conclusions

- 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

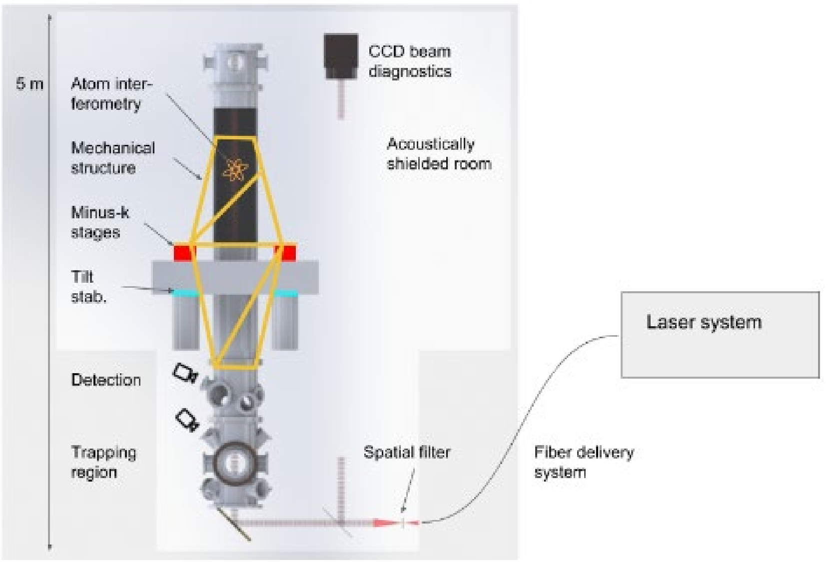
    - Collaboration with LBNL
- New ideas for cancelling gravity gradient, improving sensitivity



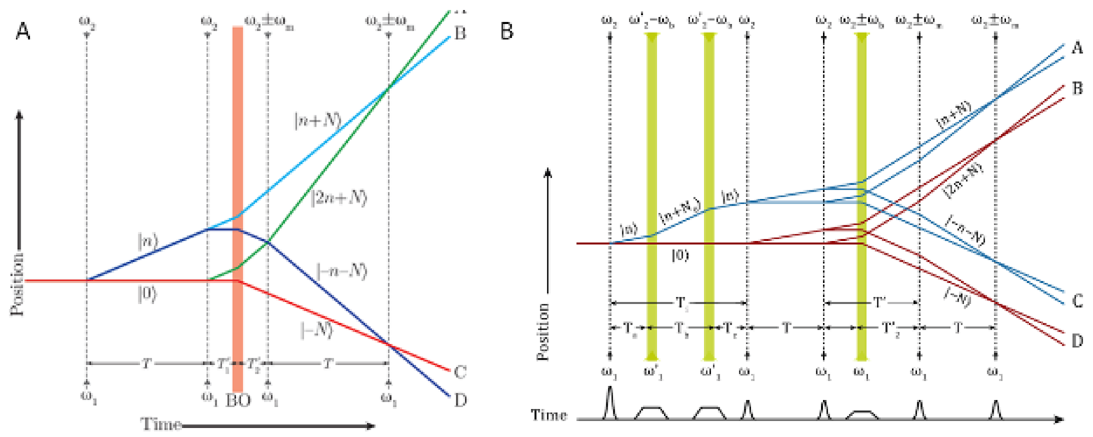




Future Upgrades to 10ppt!



- Broad beam
  - x20 waist → 1/400 beam-related systematics
- Acoustic Shielded Room
  - Controls gravity anomalies
- Improved g_e-2 (G. Gabrielse, Northwestern)
- Improved m_{Cs}/m_e (Klaus Blaum, Heidelberg)

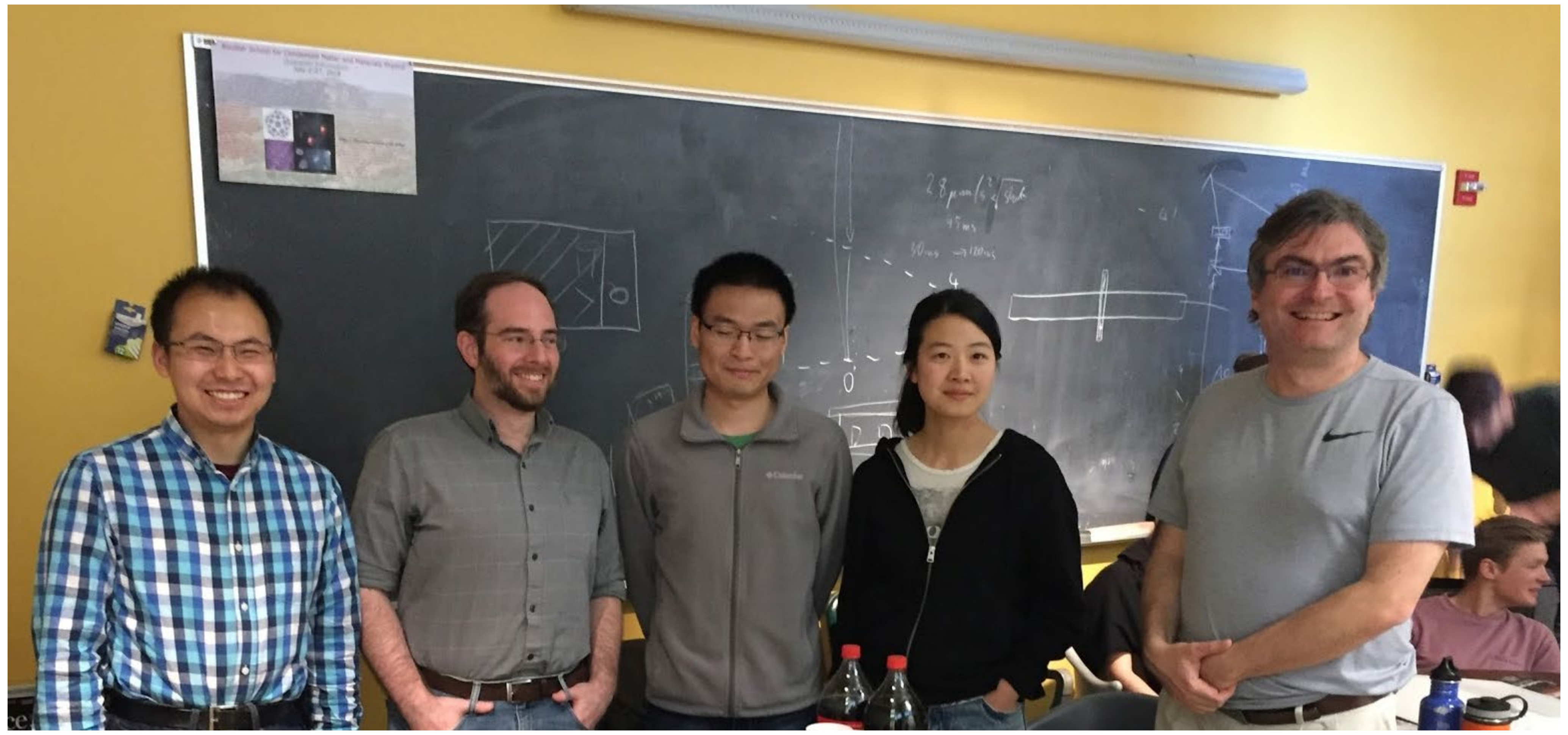


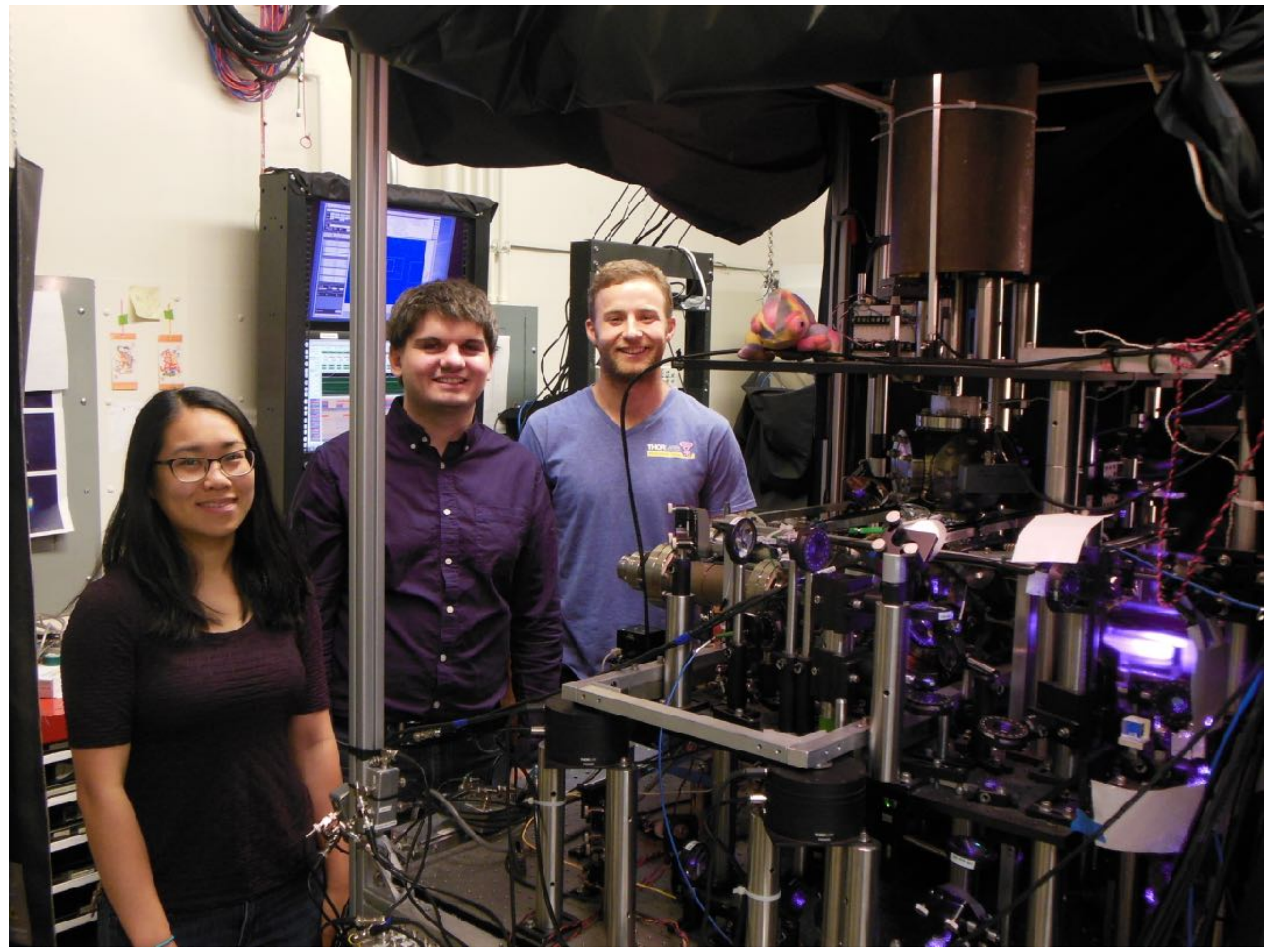
Thank you!

Fine Structure Constant
Richard Parker
Brian Estey,
Chenghui Yu
Weicheng Zhong
Zachary Pagel
Shau-Yu Lan
Pei-Chen Kuasn

Cavity Interferometer
Justin Brown
Lothar Maisenbacher
Matt Jaffe
Victoria Xu
Cris Panda
Logan Clark (on loan)
Sofus Cristensen

Atom interferometry
Xuejian Wu
Storm Weiner,
Eric Copenhaver





Phase-Contrast TEM
Sara Campbell
Osip Schwartz
Jeremy Axelrod,
Carter Turnbaugh

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Philipp Haslinger (Vienna)
Paul Hamilton (UCLA)
Mike Hohensee (LLNL)
Geena Kim (Regis)
Pei-Chen Kuan (NCKU)
Shau-Yu Lan (NTU)

Thanks!

Team alpha:

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