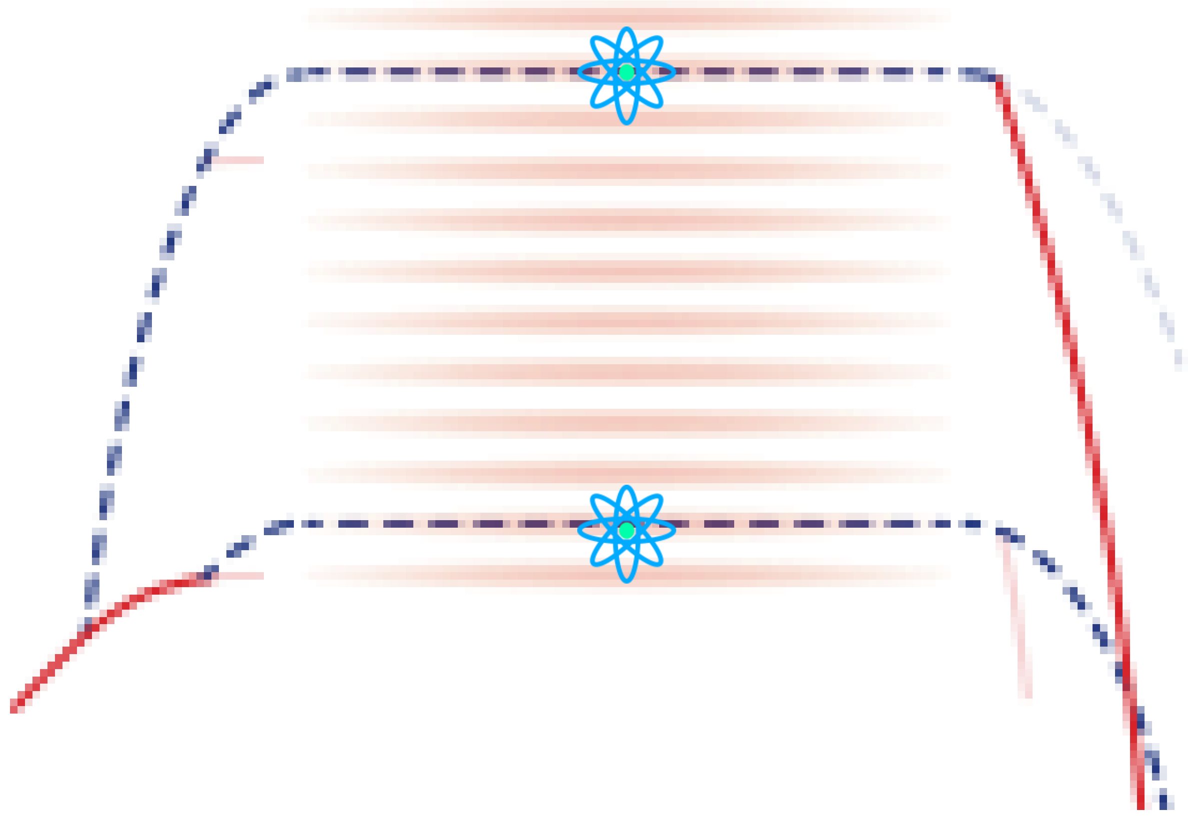
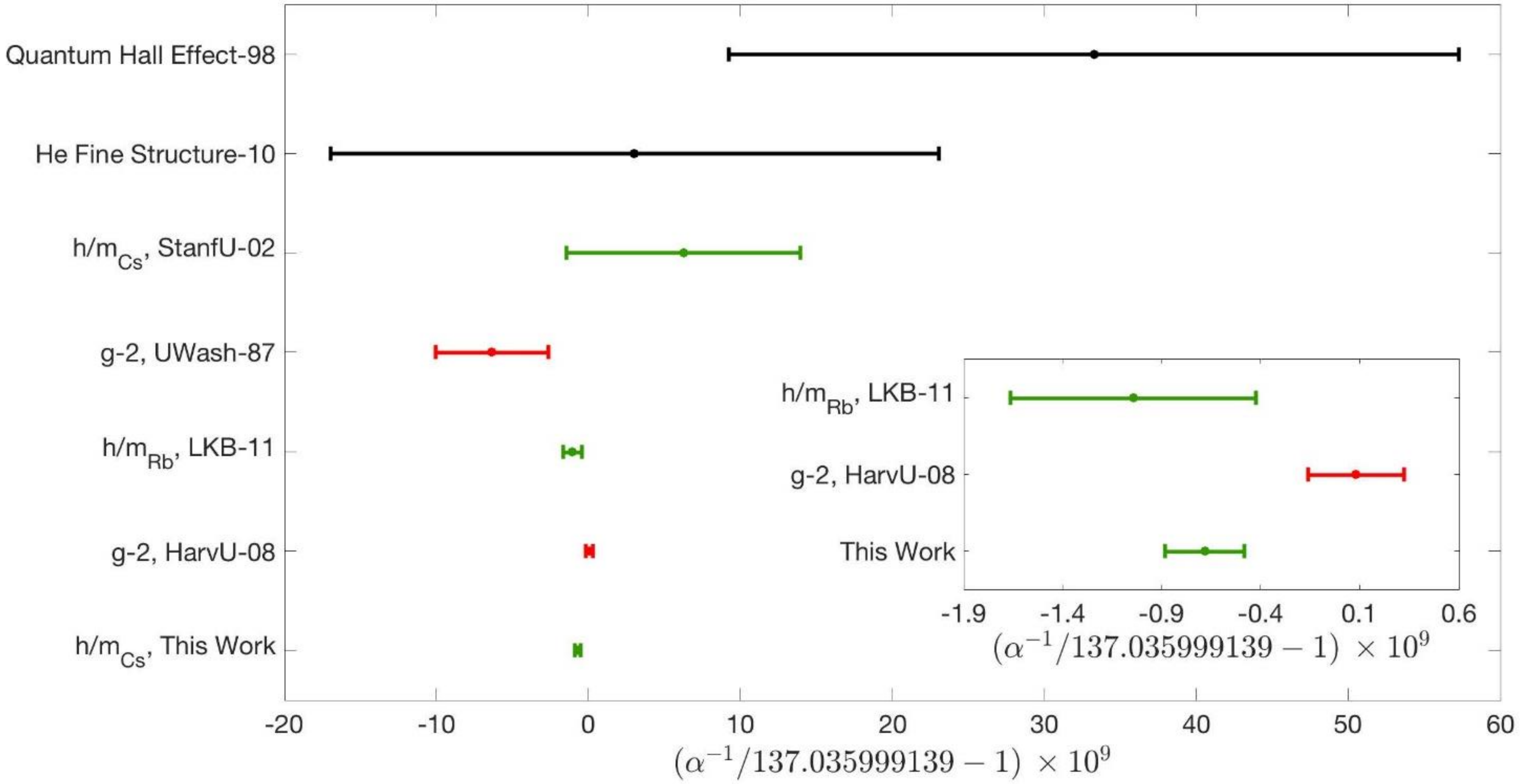
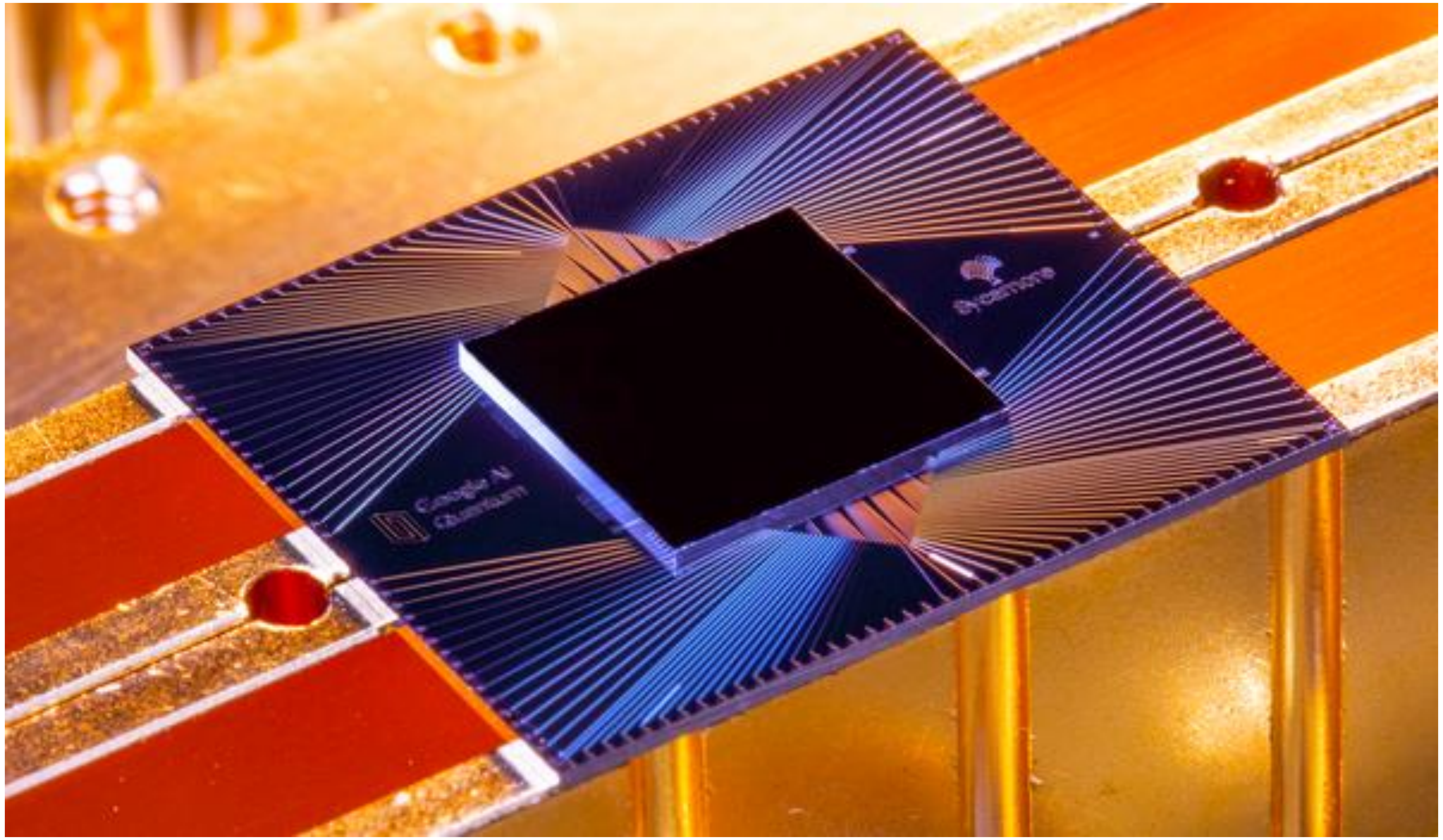




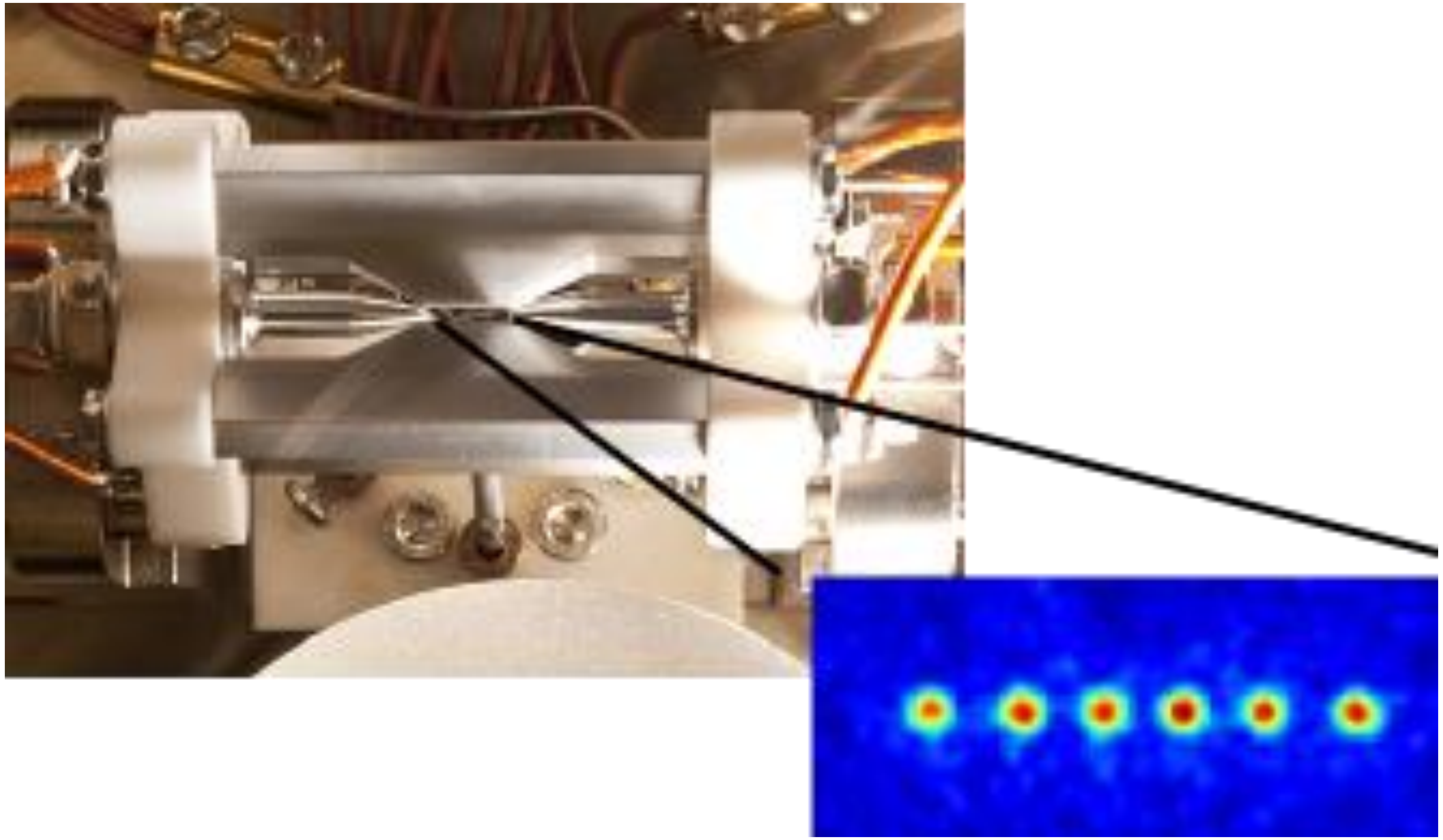
Quantum sensing in ultra-clean optical lattices

Holger Müller
group
UC Berkeley



Quantum computing: has it been achieved?

- Extended Church-String thesis: all reasonable digital models of computation are polynomially equivalent
- Feynman ‘81: Can’t simulate QM on a computer with exponential overhead
- Q-computers are digital (Bernstein ‘93), programmable (Simons ‘94), NOT polynomially equivalent (Shor)
- Supremacy: A practical application, not necessarily useful, violating the extended Church-Turing thesis.
  - Milestone towards useful Q computers
  - Testing QM in the limit of high complexity
  - Need to prove that the task is prohibitively hard for class. Computers
  - Prove the Q-computer actually carried out the task

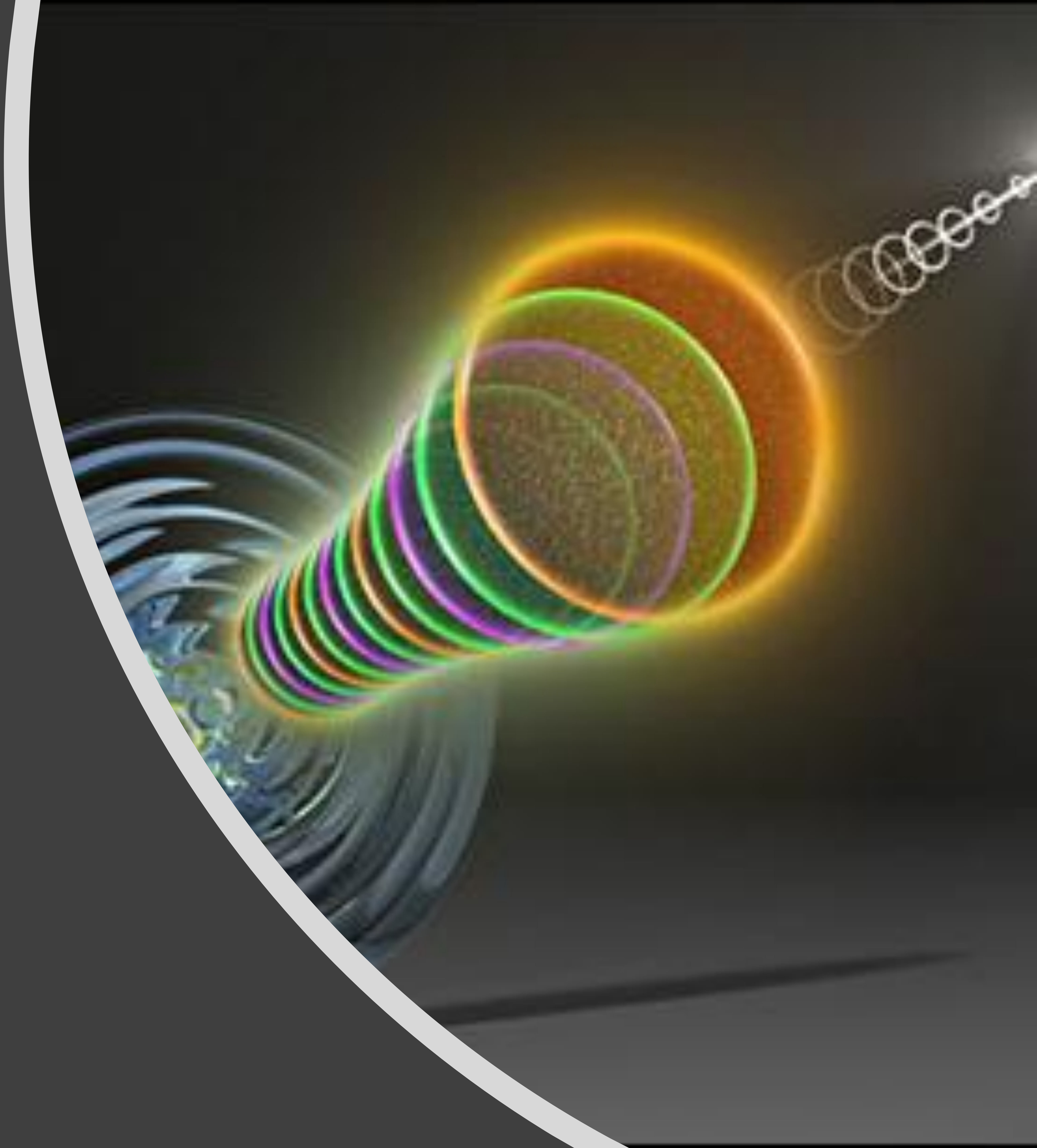


Quantum computers don’t solve useful problems yet

- Near-term quantum computers are NISQ - noisy, immediate-scale quantum),
- 10s-100s of qbits
- Q speedup from interference!
  - Random circuits hard to simulate.
  - Supercomputers assumes that quantum circuit is perfect
- Simulation: new materials, chemistry, Cm physics
- High-energy lattice QCD simulations
- Quantum walks, qubitization
- Electronic structure calcs. Variational quantum solver. But QMA-hard (quantum analog to NP hard
- Simulations of high-energy physics

Quantum frontiers

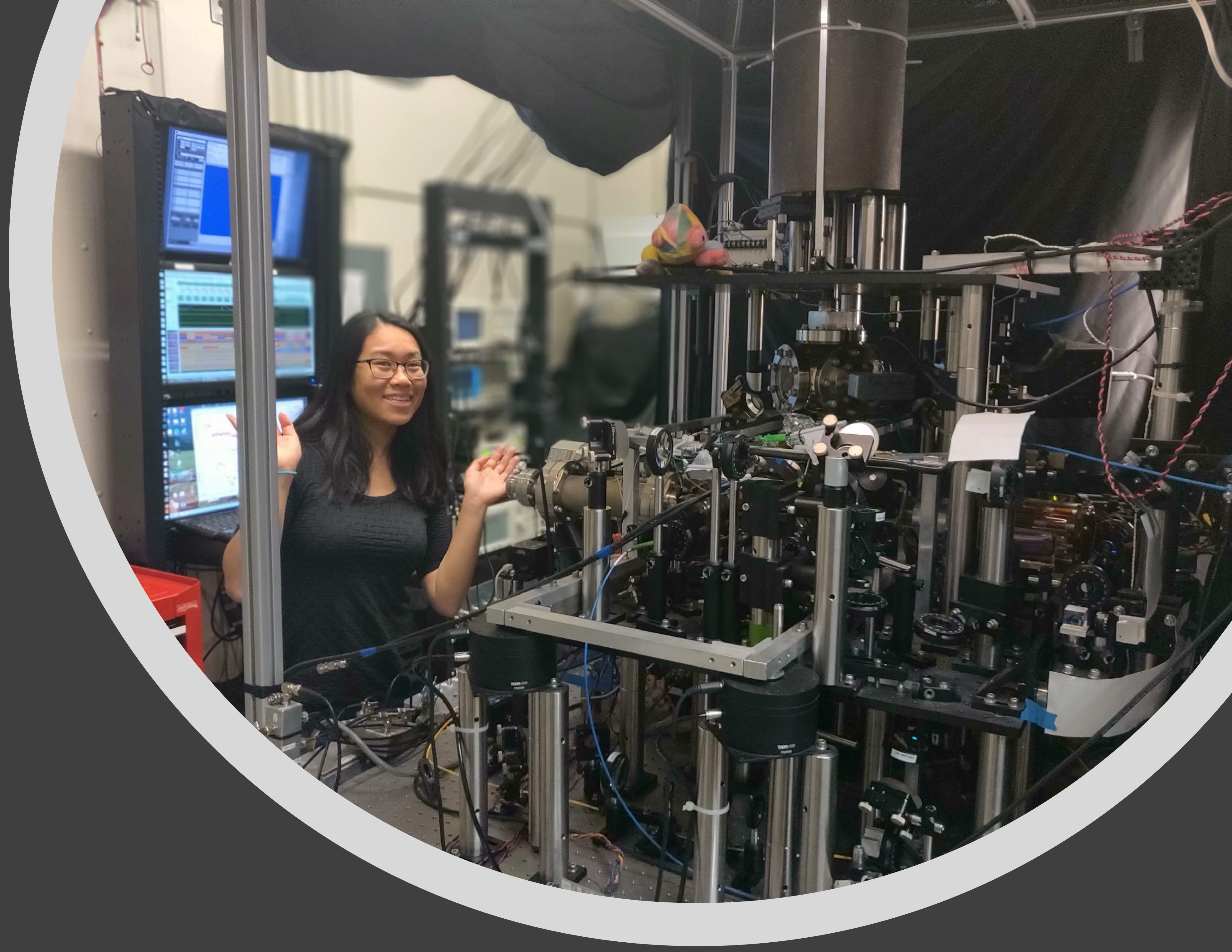
- Sensing, communication, computing
- Frontiers: Short distance, long distance, complexity (more is different)
- Decoherence. No interaction with the environment except when you need it
- Error correction: encode information nonlocally in a highly entangled state, so the environment cannot interact locally with the information
- Error rate today 10^{-3}, about 10^{-2} per measurement (better for trapped ions)
- Quantum chaos in quantum random walks?
- Analog many qubits that resemble a system; Digital: gate-based universal quantum computer
- Atom interferometer for prec. Measurement, navigation

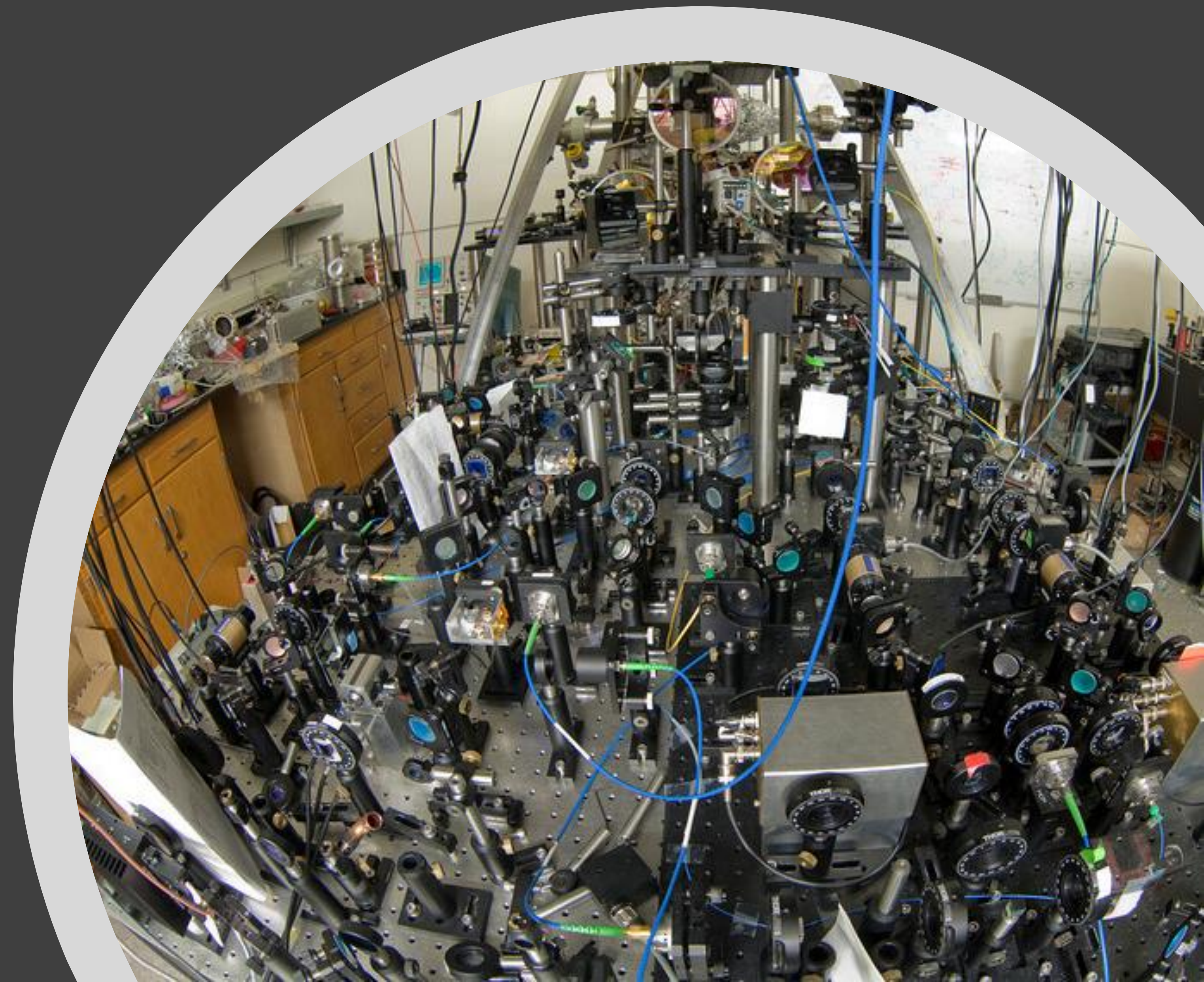


Quantum sensing, simulation, and -computing

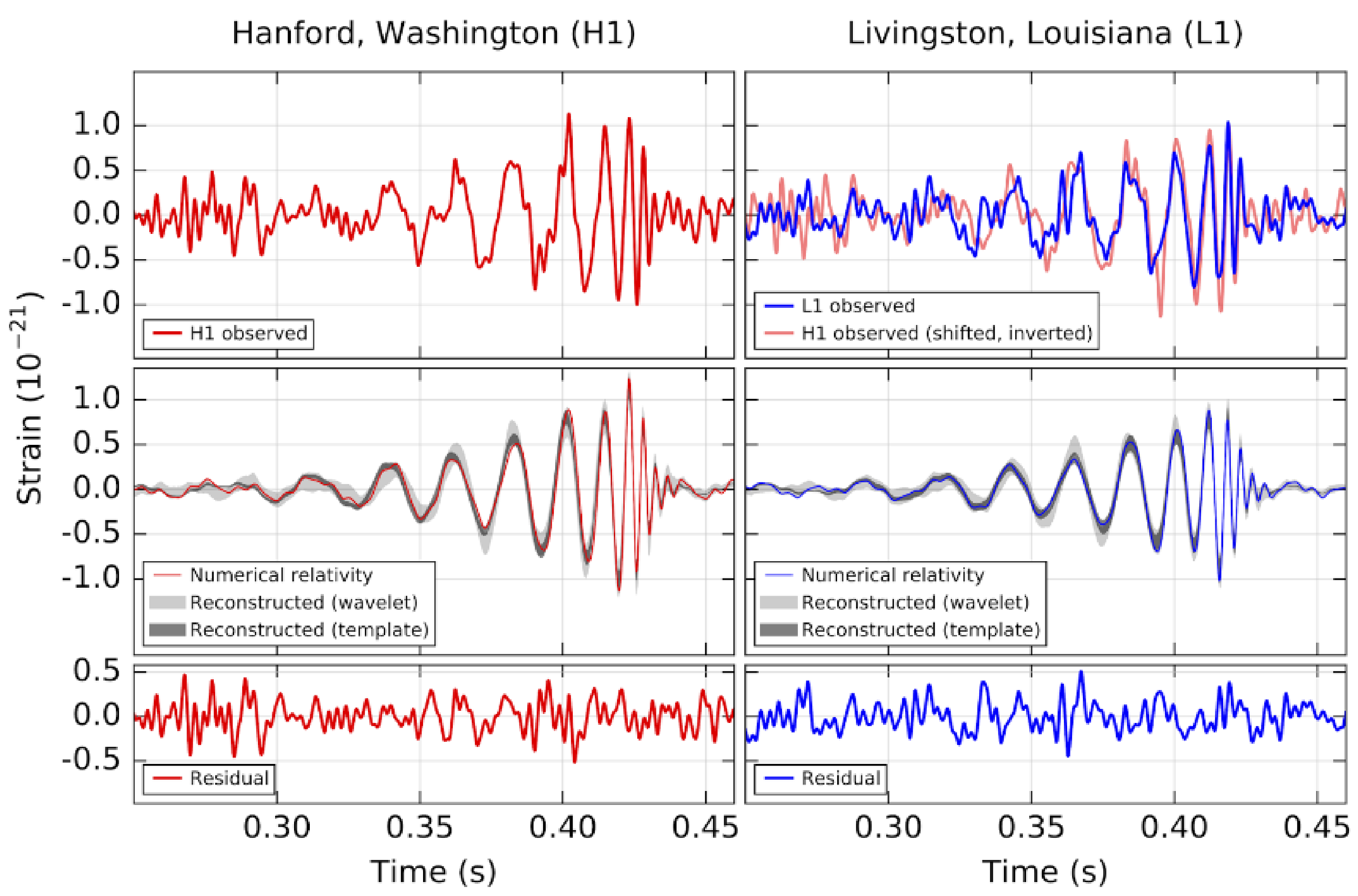
- Quantum simulations with cold atoms in opitcal lattices are currently the most powerful
- QuantISED project “Search for beyond the standard model physics by measuring the fine structure constant”
- Ultra-precise optical lattices keep the Qubit alive
- Ultracold neutral atoms trapped within optical lattice potentials make the largest current quantum simulations [2–4].
- Translational invariance

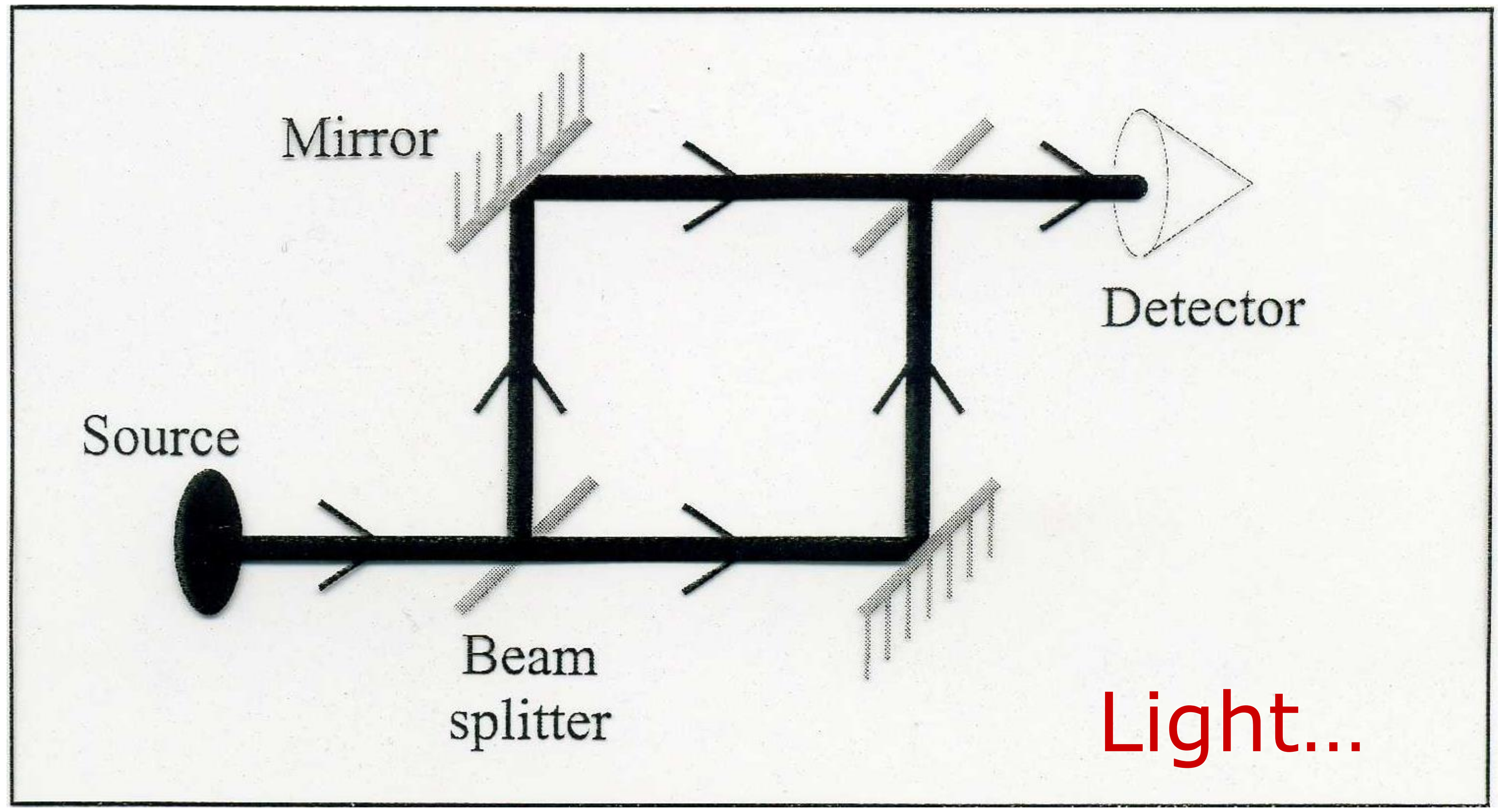
I. Bloch et al., Nature Physics (2012); E. Zohar et al., Rep. Prog. Phys. 79, (2016); S. P. Jordan, K. S. M. Lee, and J. Preskill, Science (2012)



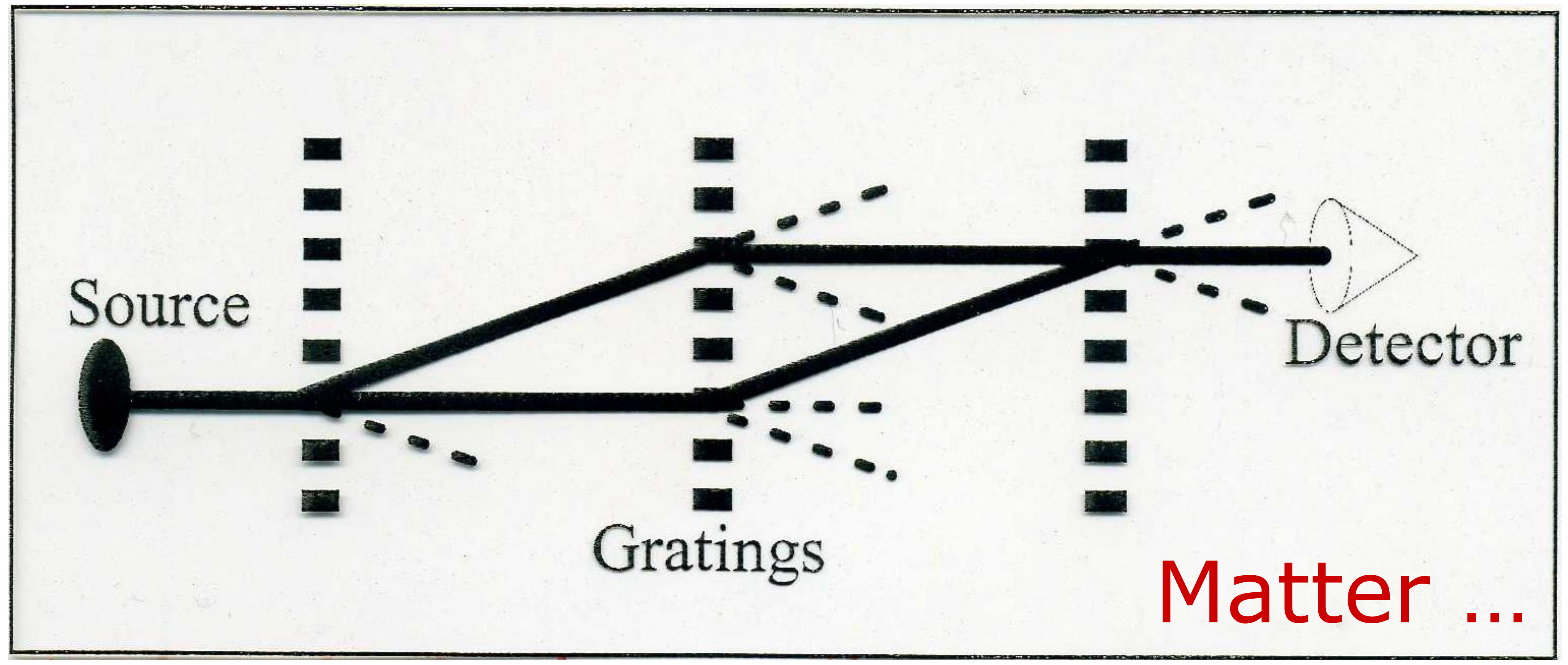


Interferometry…

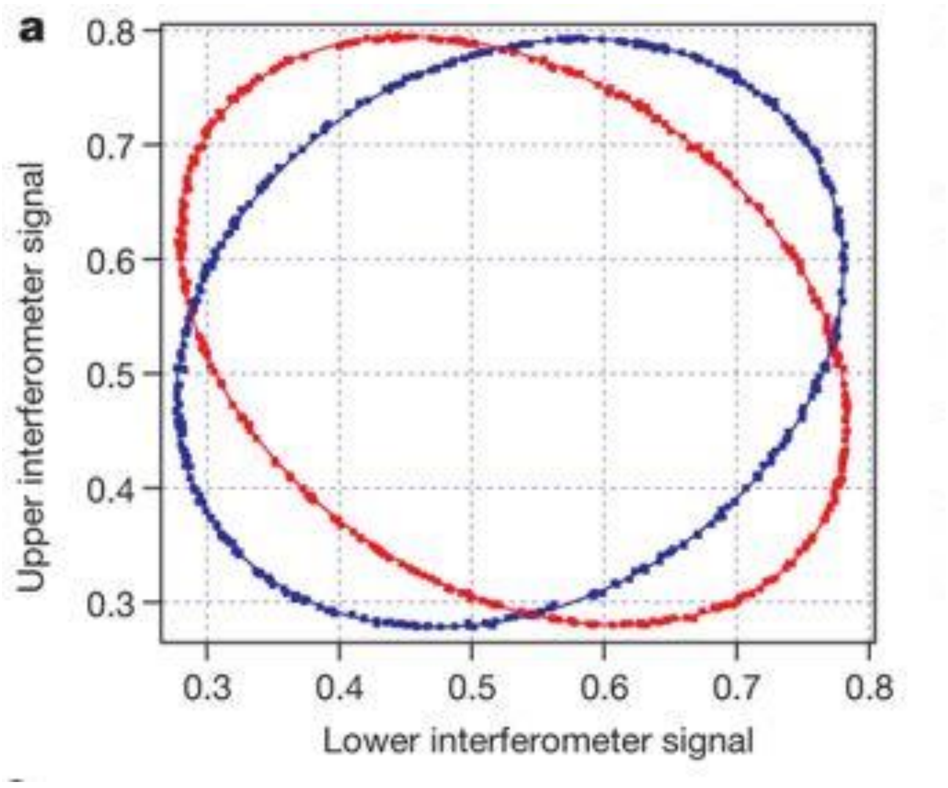




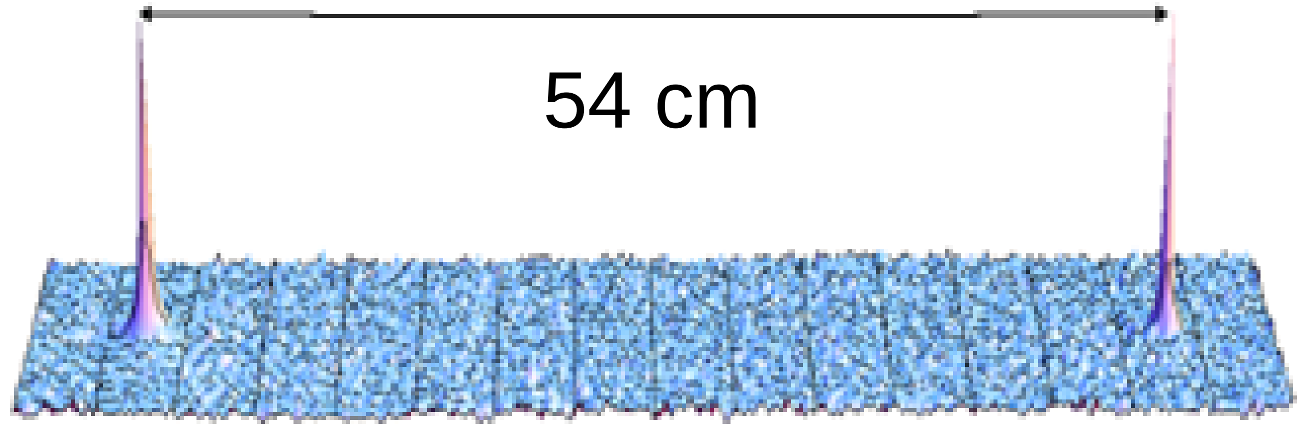
$$\lambda = \frac{h}{mv}$$



Precision atom interferometry



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

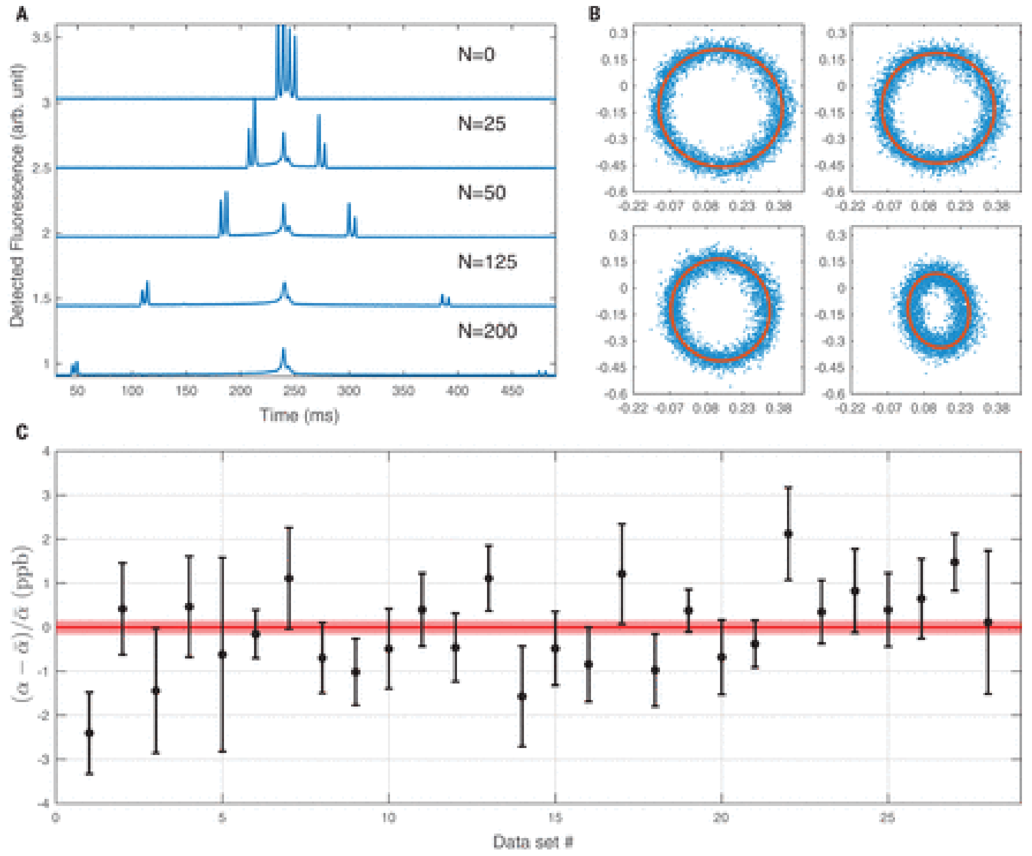


Kovachy et al. **Nature** 528, 530-533 (2015)

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

Measuring the fine structure constant α at Berkeley

Tests of GR and QM
Stanford 10m atomic fountain

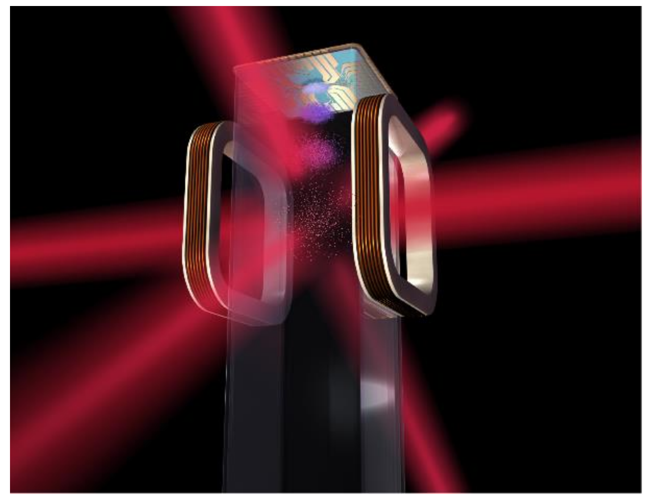


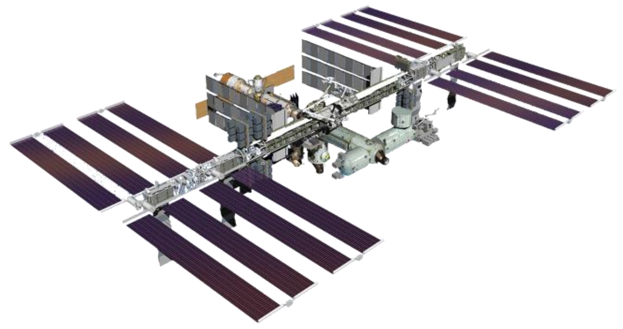
Parker et al. **Science** 360, 191-195 (2018)

Long interrogation times

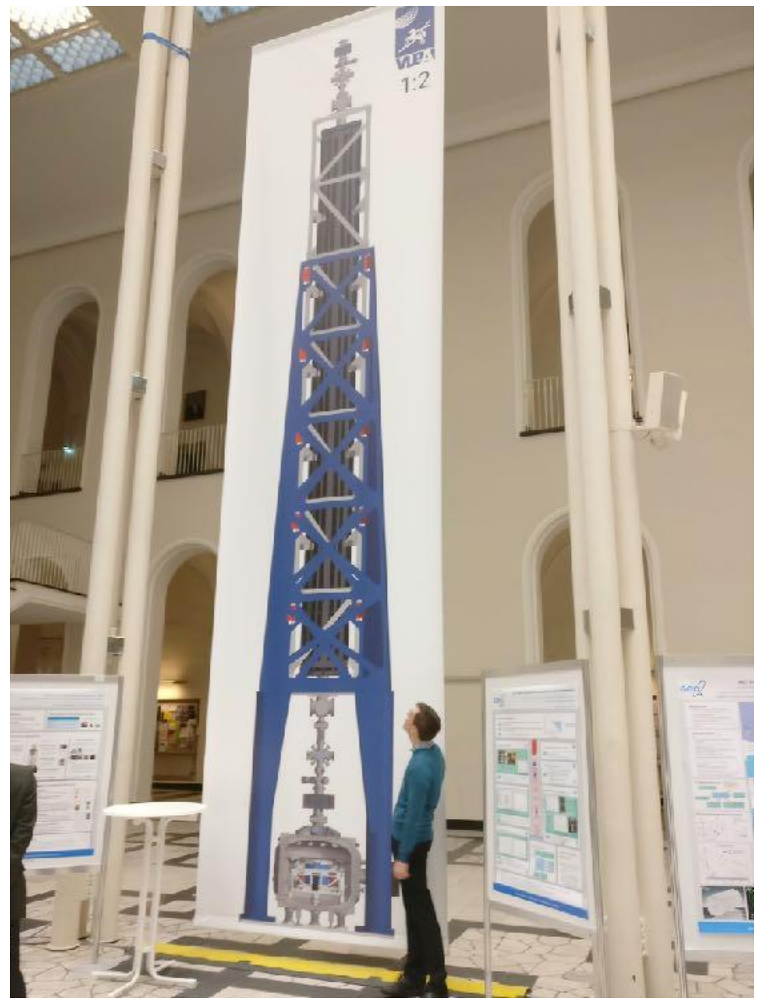
- Large phase accumulation → high precision
- But gravity…
  - Big experiments
  - Space

Kasevich group @ Stanford (pc: Sugarbaker PhD thesis)





Cold Atom Lab Science Poster

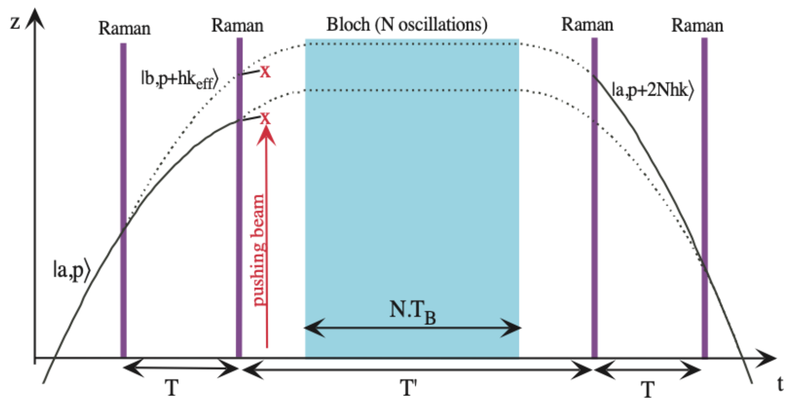


VLBAI IQO @ Hannover

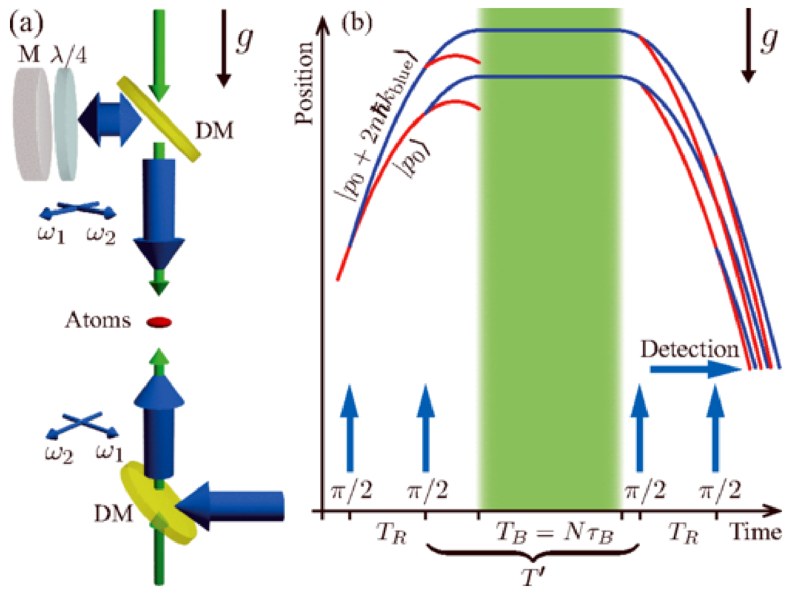
+ MIGA, MAIUS, BECCAL, …

What if we held the atoms?

- Has been demonstrated



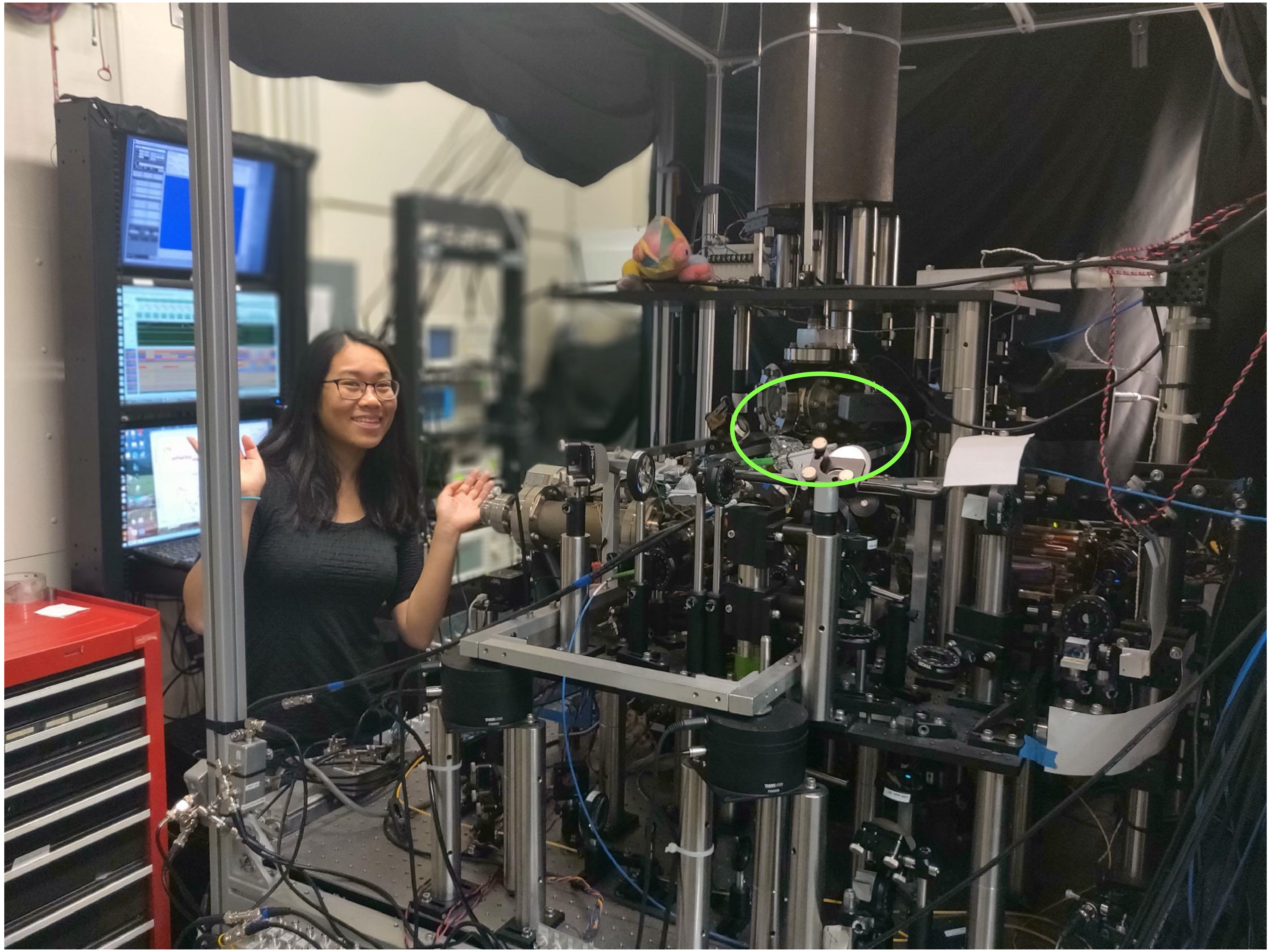
Charriere et al., **PRA** 85, 013639 (2012)

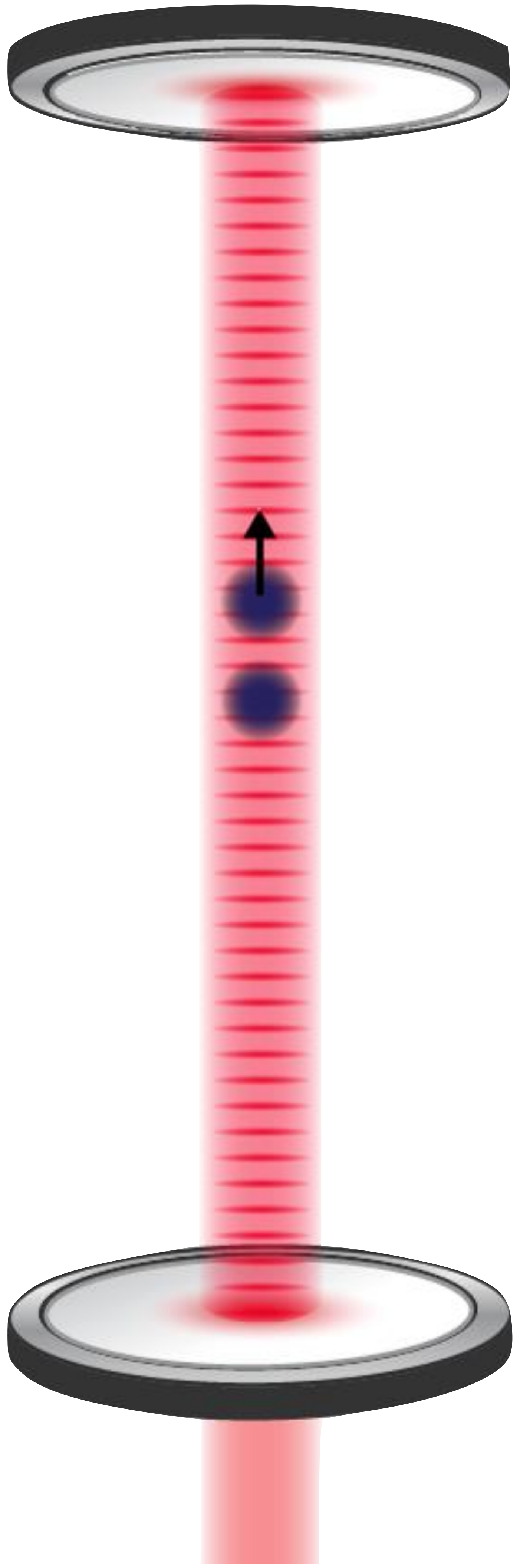


Zhang et al., **PRA** 94, 043608 (2016)

- Limited by wavefront distortions
- Requires extreme trap uniformity

Experimental setup



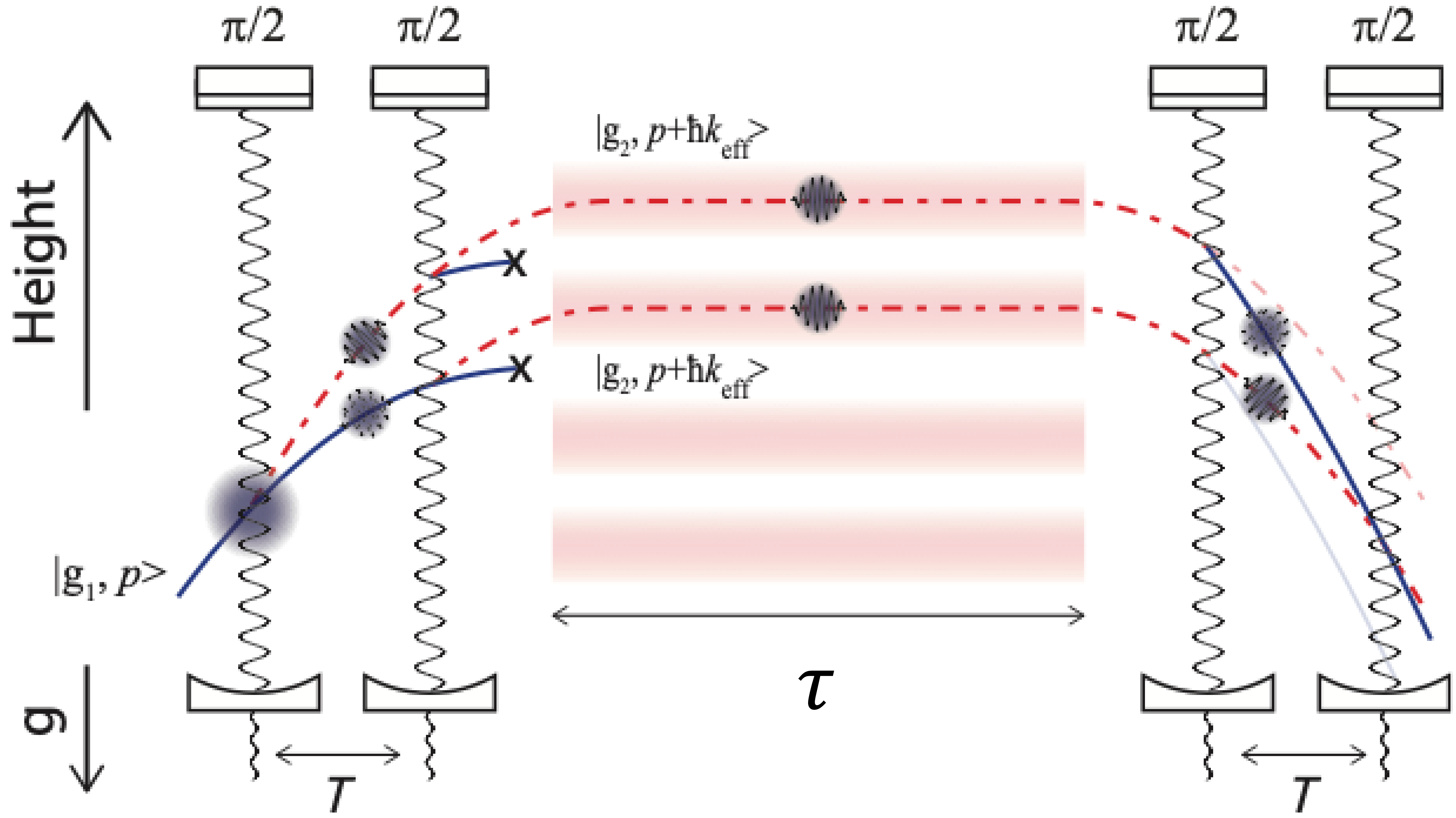


Higher Laser Intensity

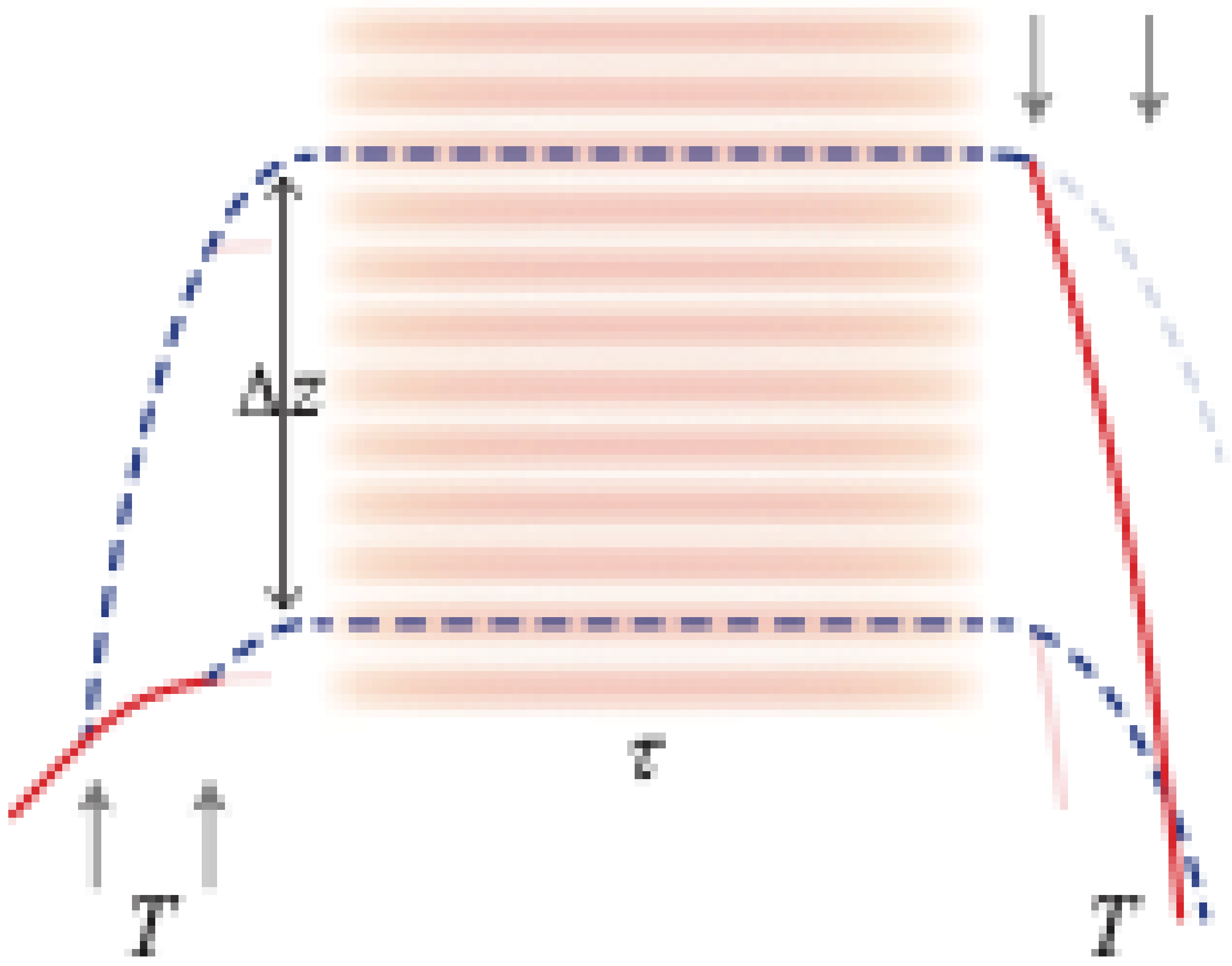
Smooth Wavefronts

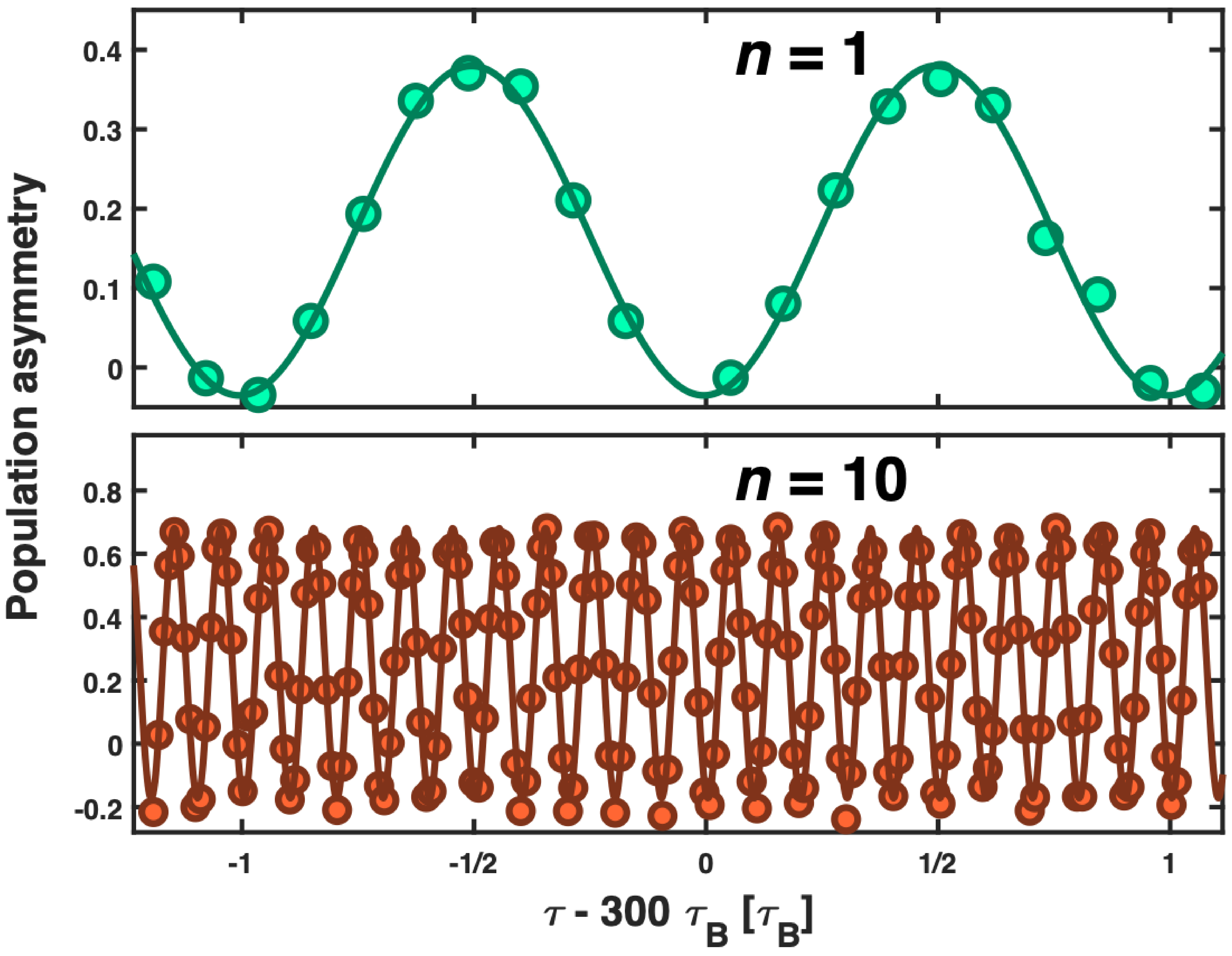
Well-defined beam parameters

Lattice interferometer geometry



Free evolution phase



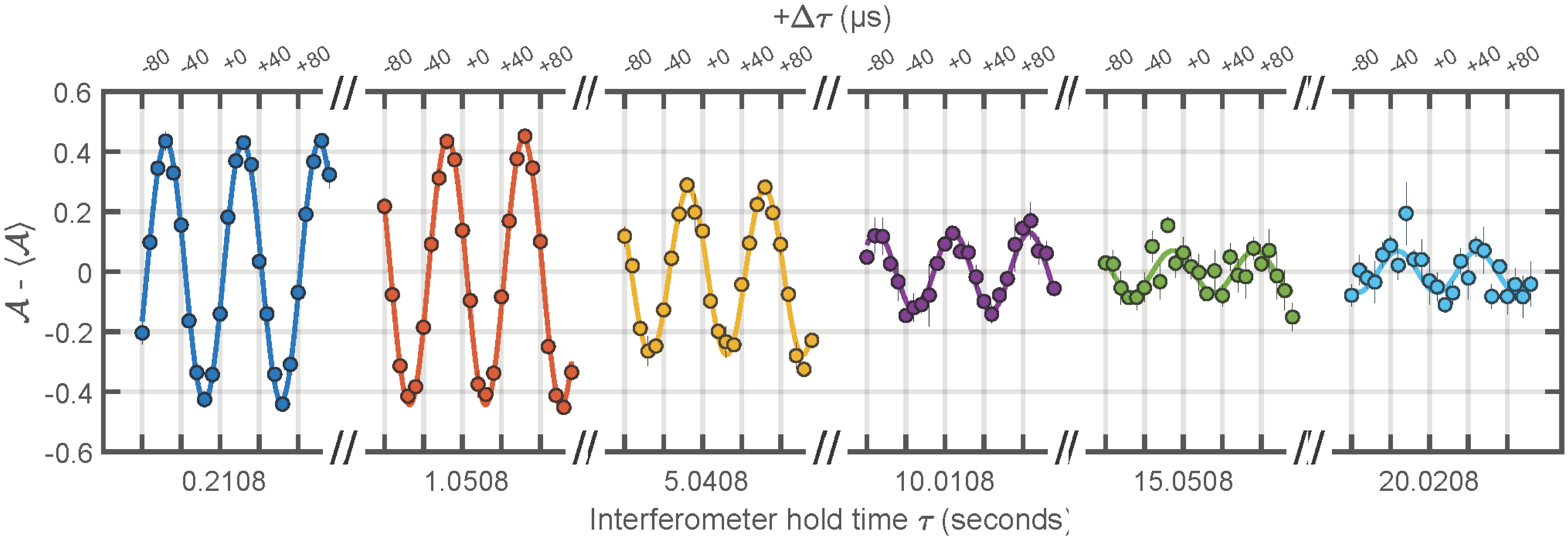


Sweep out free evolution phase

$$\Delta\phi_{FE} = \frac{mg\Delta z}{\hbar}\tau$$

with τ

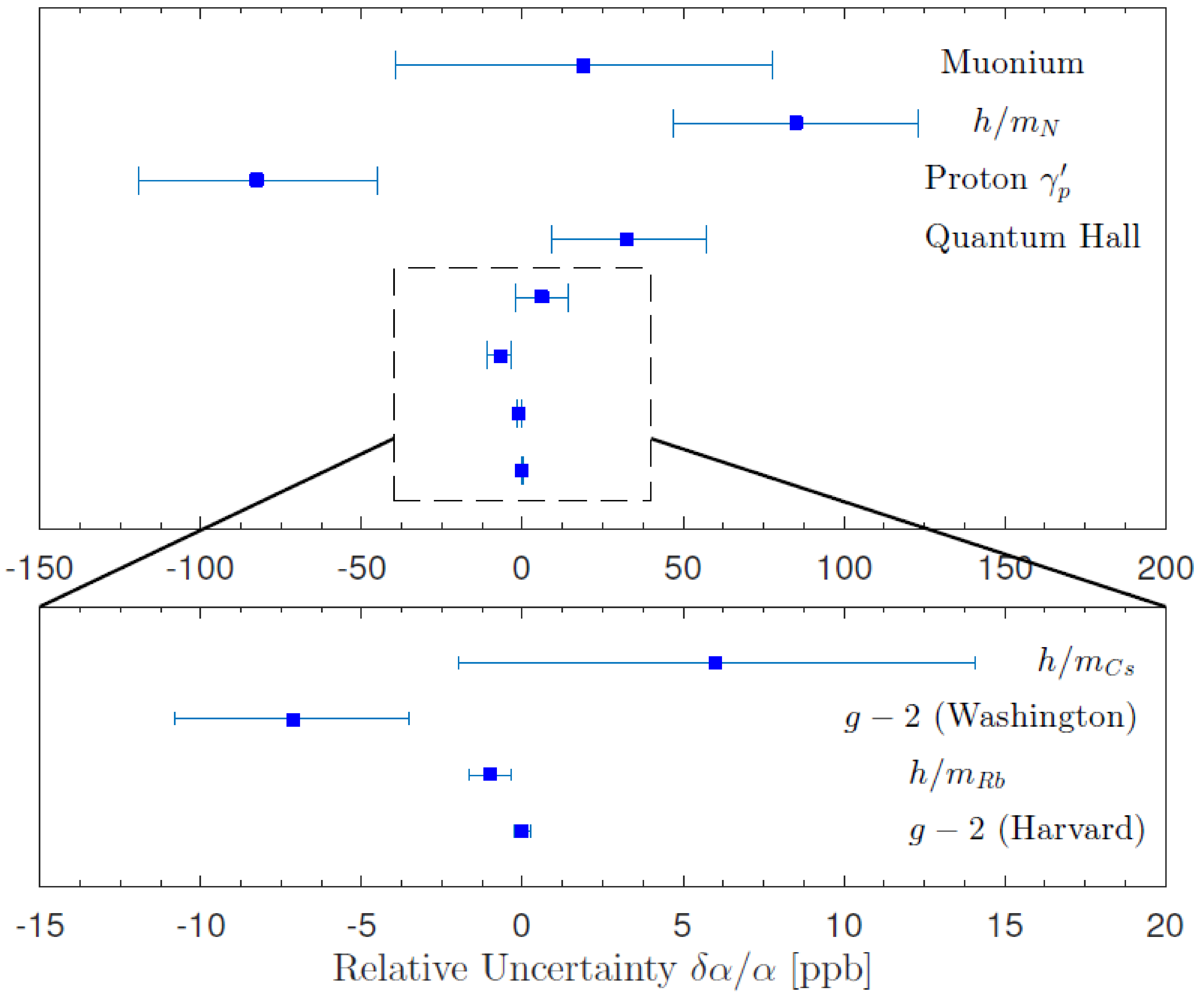
Long holds


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

The Fine Structure Constant

Measures the strength of the electromagnetic interaction

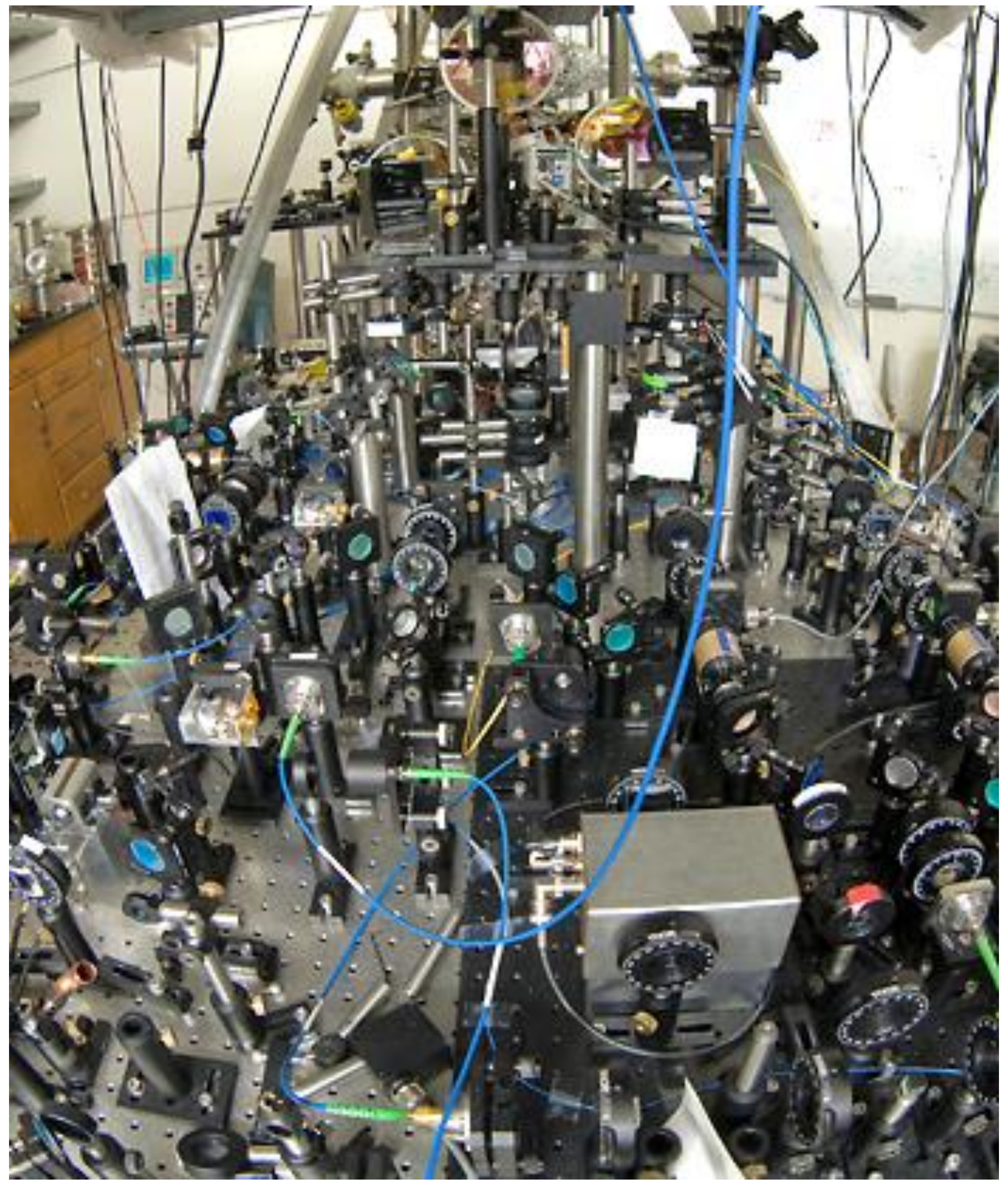
$$\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137.035999139(31)} \quad (0.23\text{ppb})$$ 2014 CODATA

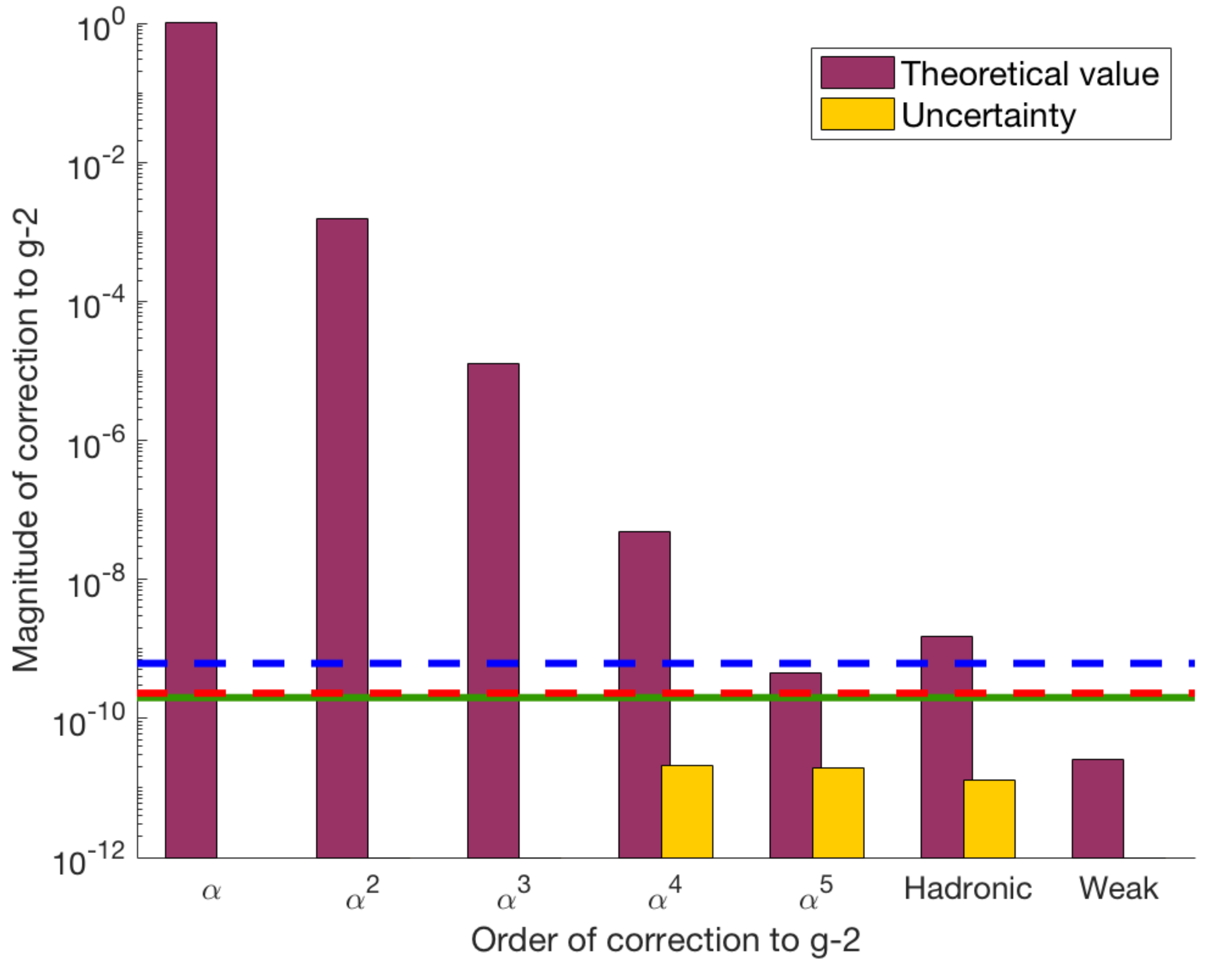


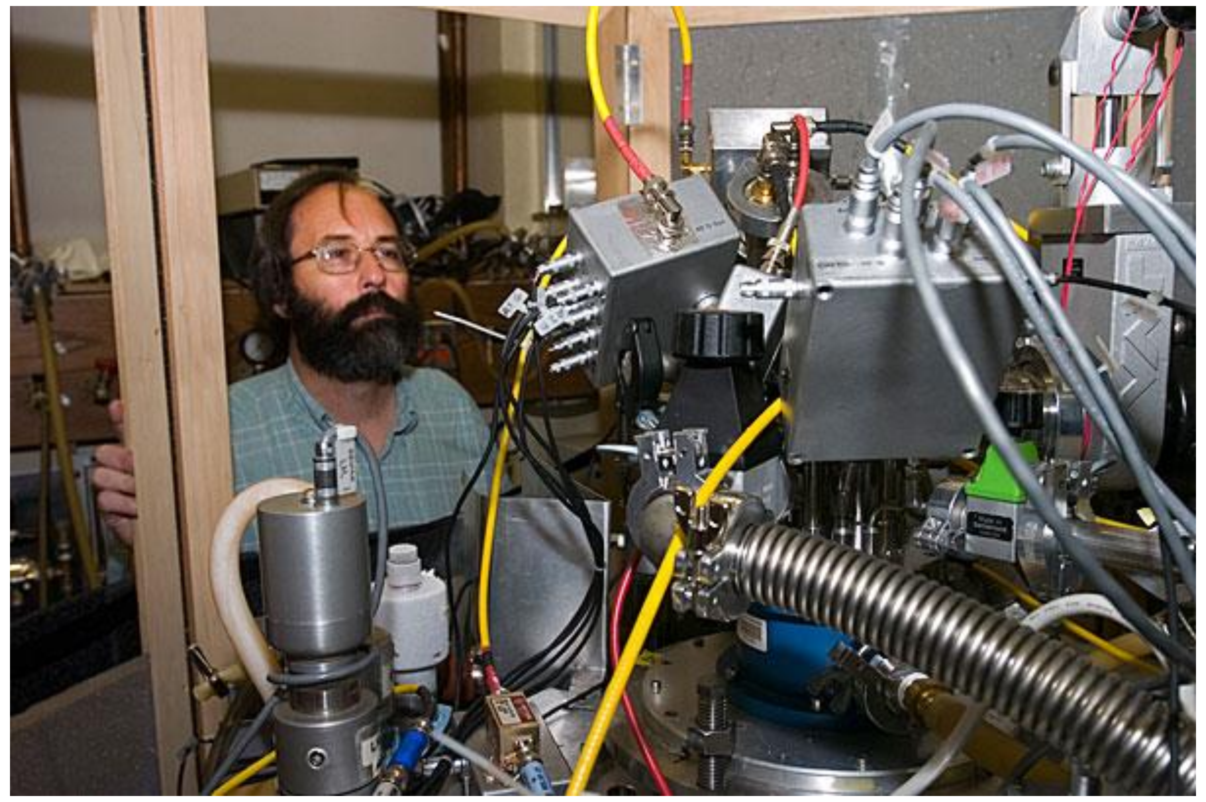
The most precise theory/experiment comparison in science

Fine structure constant

Electron magnetic moment



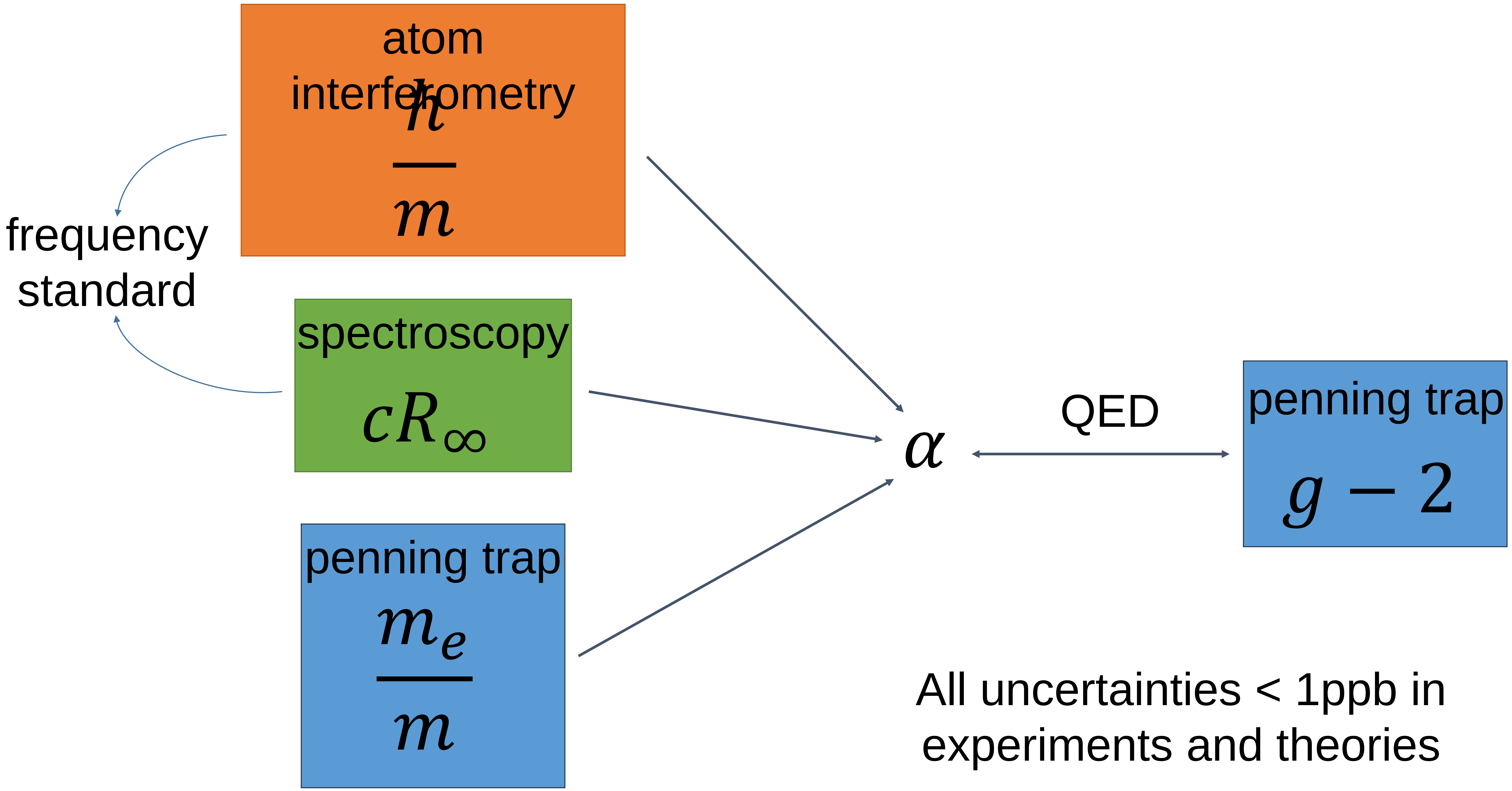




Unknown particles may shift magnetic moment

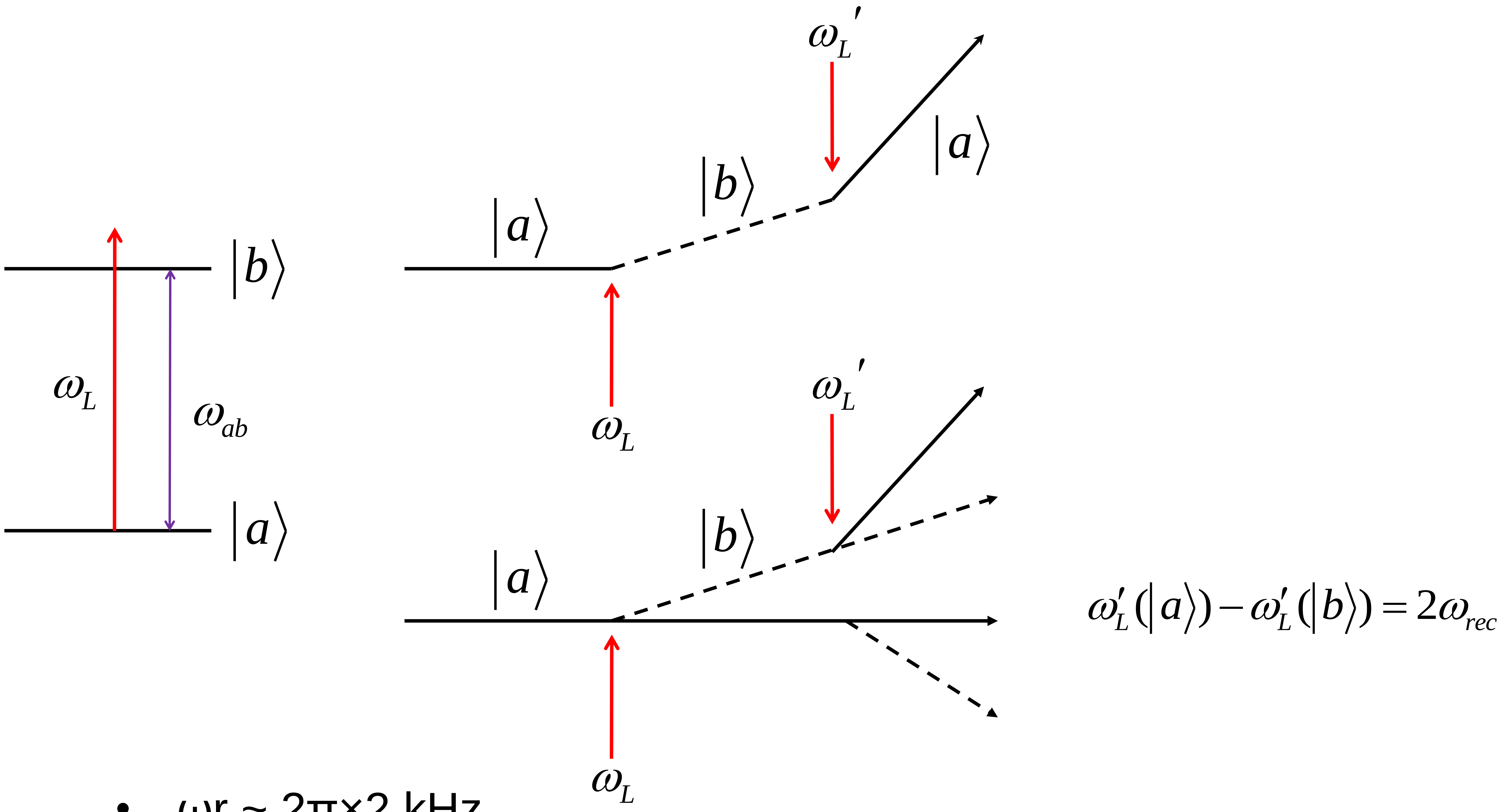
α from ħ/m

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



All uncertainties < 1ppb in experiments and theories

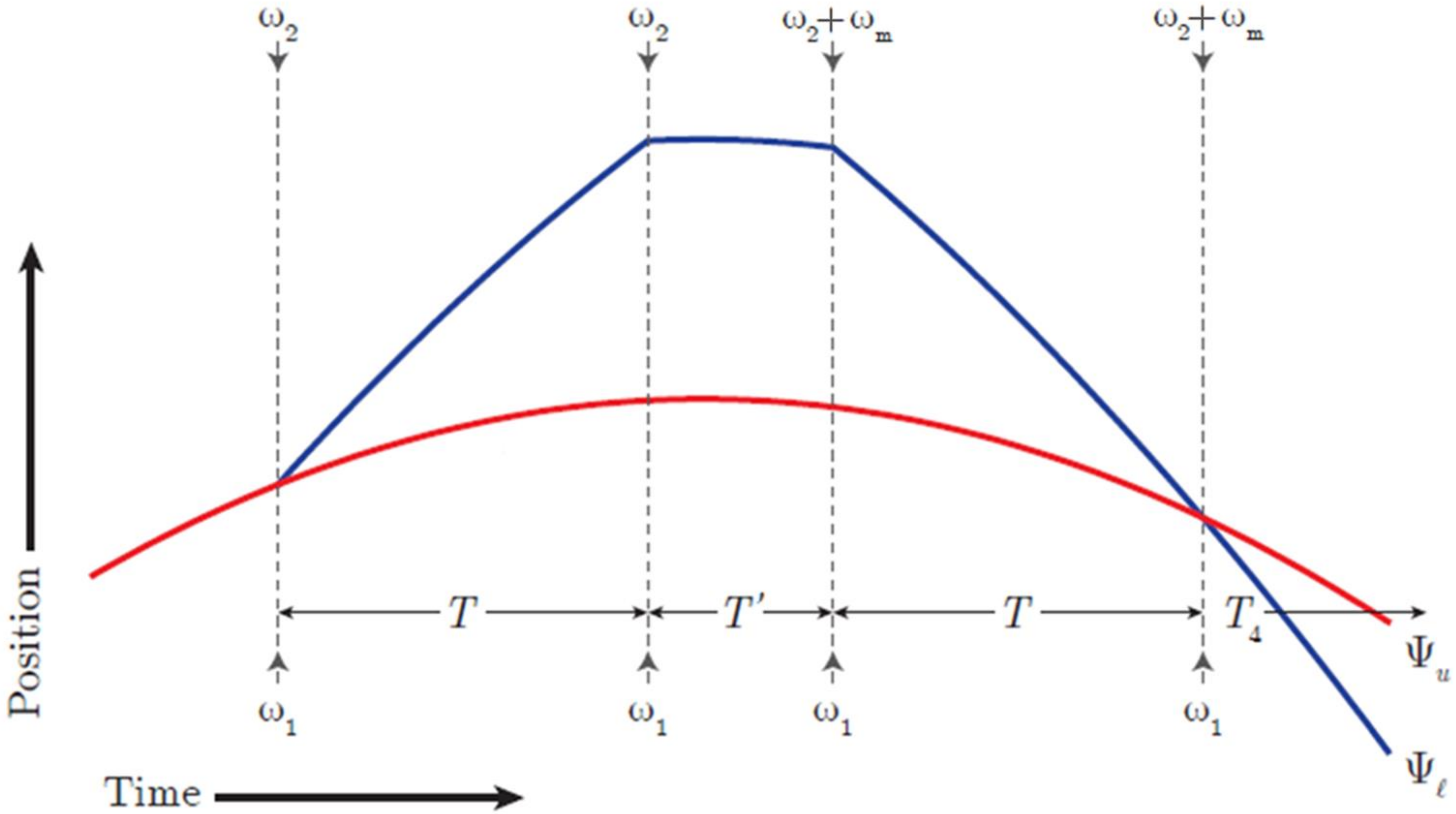
Photon Recoil Measurement



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

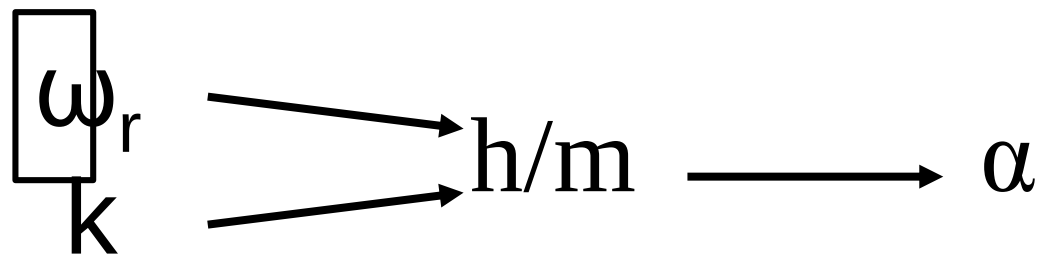
Atom-interferometer measurement of α

Ramsey-Bordé Interferometer



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

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

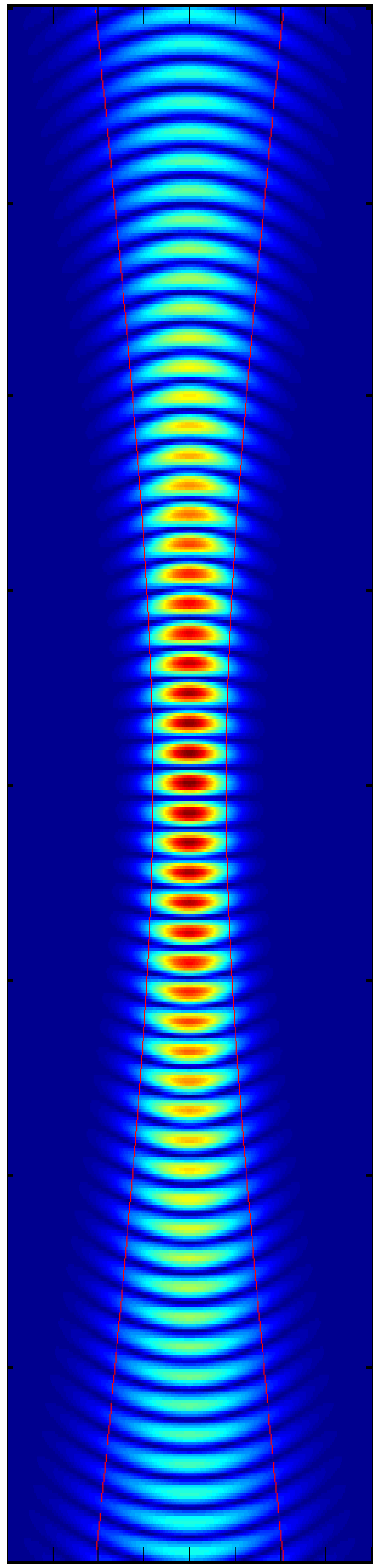


0.16 ppb systematic errors

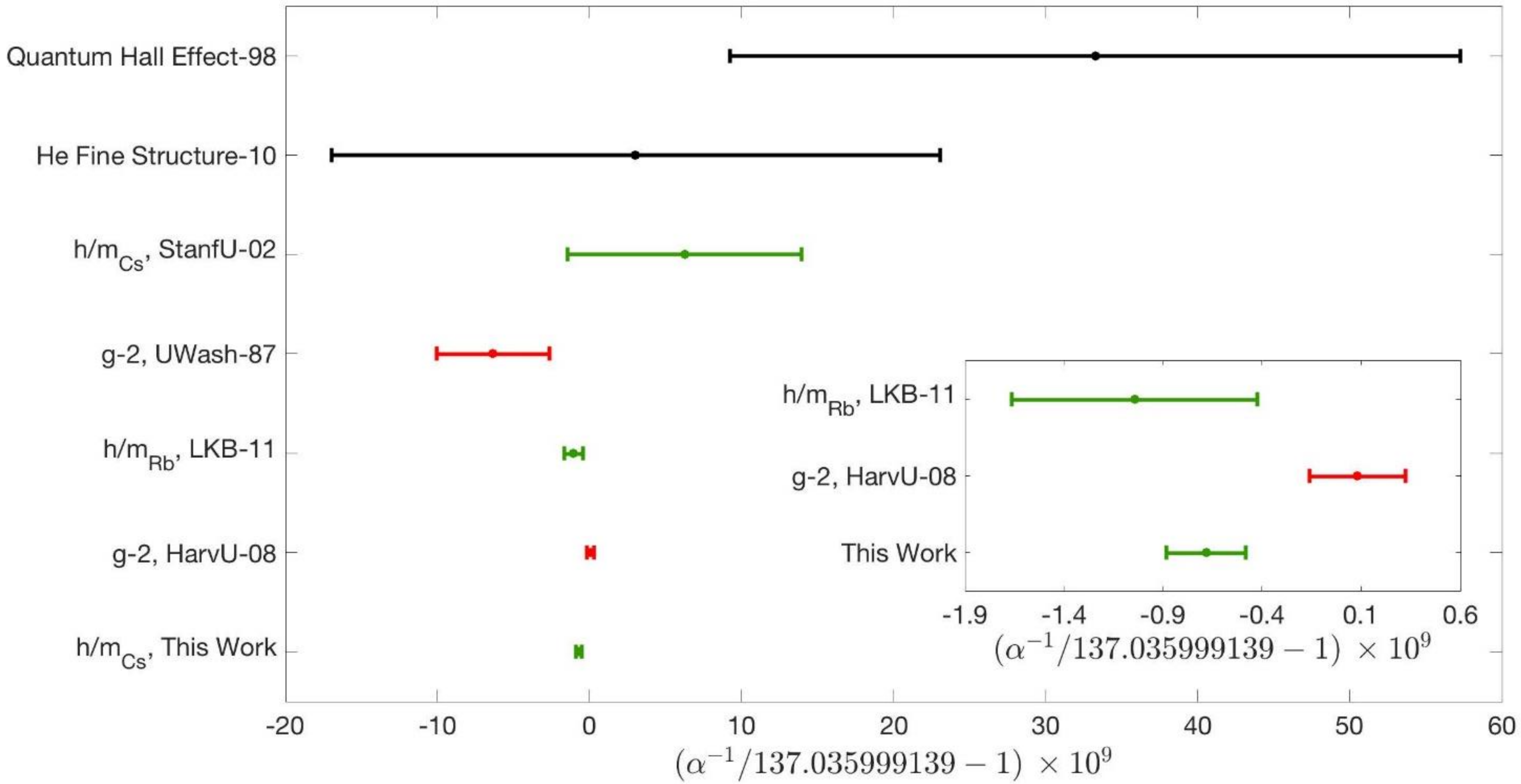
Effect	Sect.	Value	δα/α (ppb)
Laser Frequency	1	N/A	-0.24 ± 0.03
Acceleration Gradient	4A	□=(2.13 ± 0.01)×10^{-6}/s^2	-1.69 ± 0.02
Gouy phase	3	w_0=3.21±0.008 mm, z_0=0.5±1.0 m	-3.60± 0.03
Wavefront Curvature	12	$\langle r^2\rangle^{1/2}$=0.58 mm	0.15 ± 0.03
Beam Alignment	5	N/A	0.05 ± 0.03
BO Light 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=30×10^{-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'

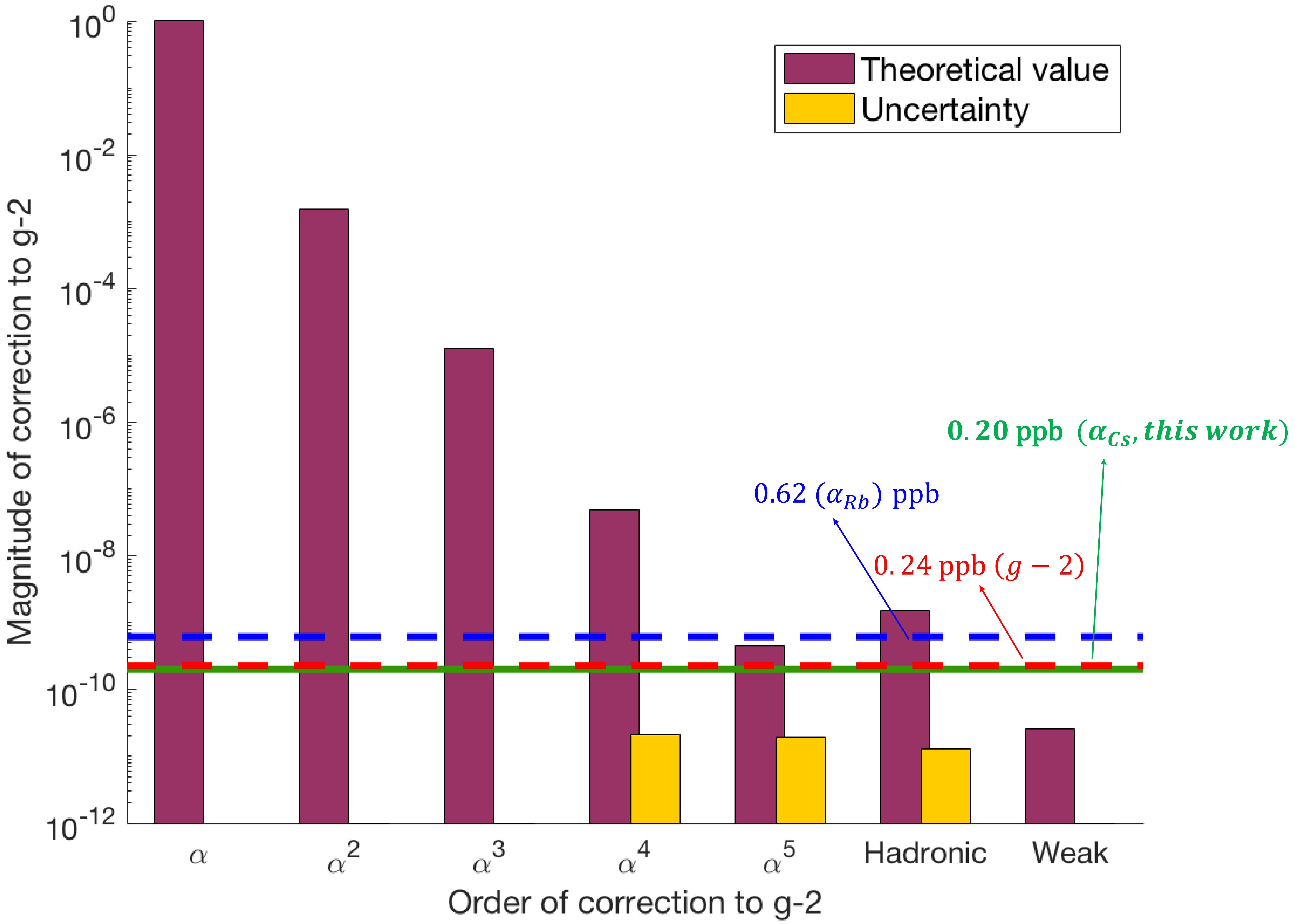


Results



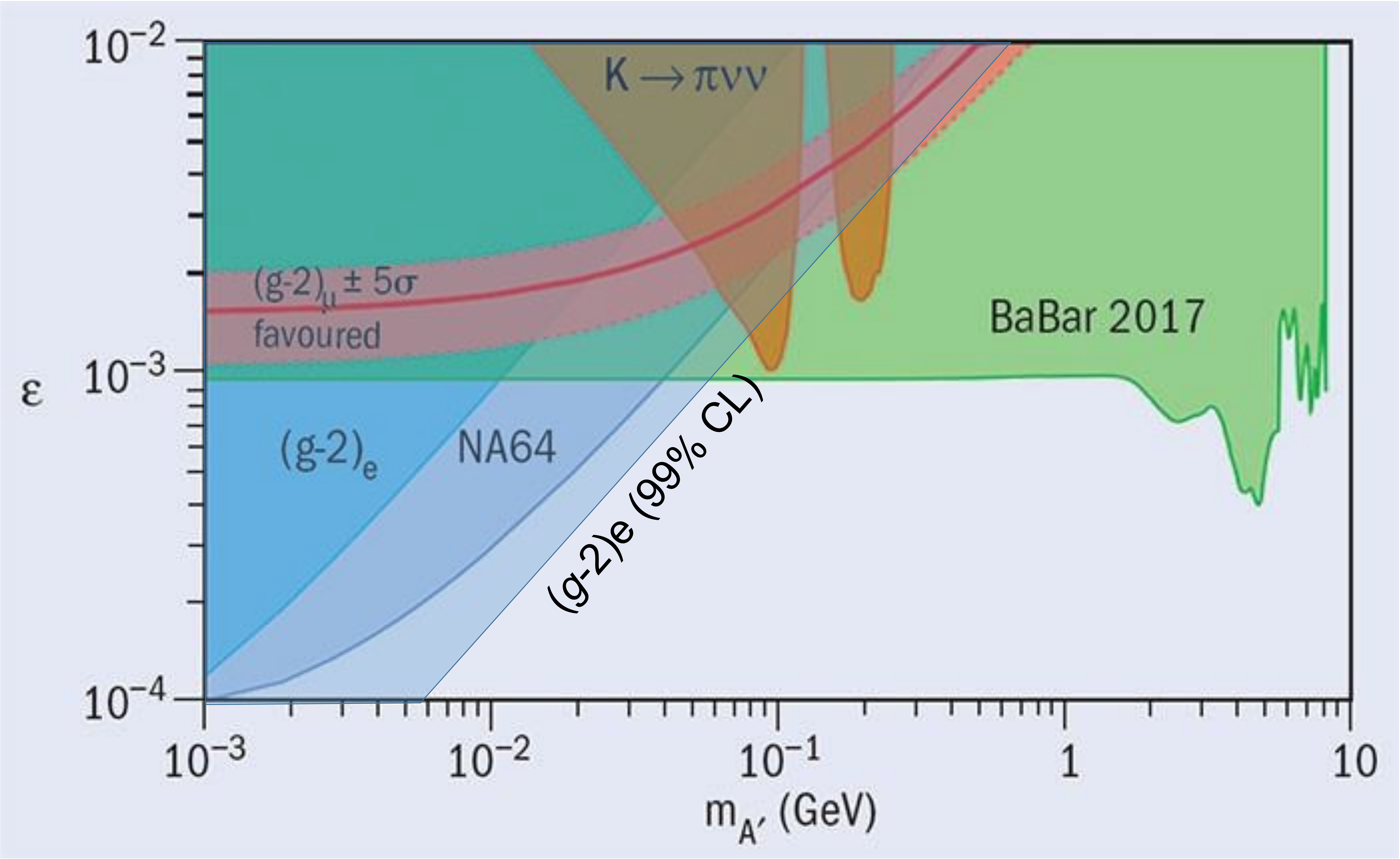
Quantum Hall Effect-98
He Fine Structure-10
h/m$_{Cs}$, StanfU-02
g-2, UWash-87
h/m$_{Rb}$, LKB-11
g-2, HarvU-08
h/m$_{Cs}$, This Work
-20
-10
0
10
20
30
40
50
60
$(\alpha^{-1}/137.035999139 - 1) \times 10^9$
h/m$_{Rb}$, LKB-11
g-2, HarvU-08
This Work
-1.9
-1.4
-0.9
-0.4
0.1
0.6
$(\alpha^{-1}/137.035999139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

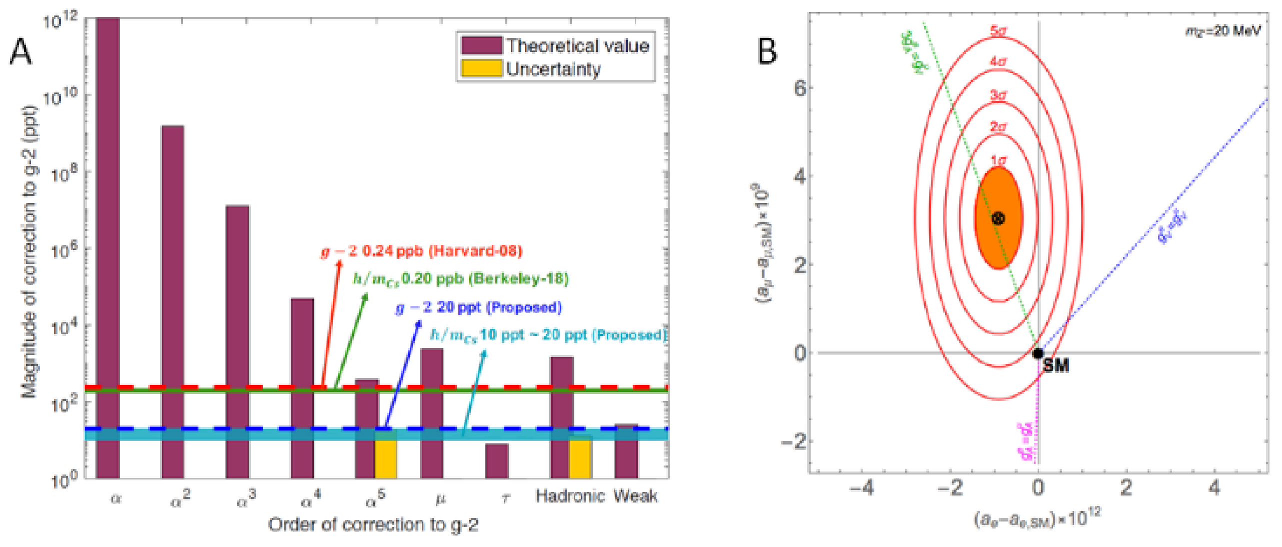
Results

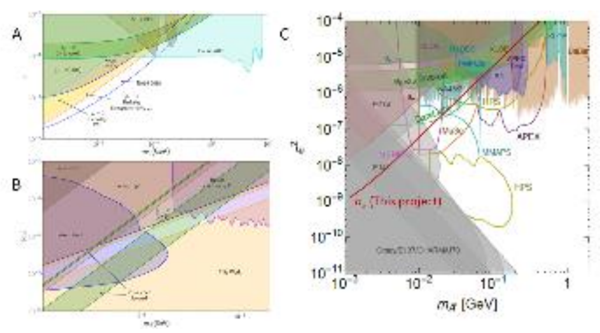


Theoretical value
Uncertainty
Magnitude of correction to g-2
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0.20 ppb $(\alpha_{Cs}$, this work$)$
0.62 (α_{Rb}) ppb
0.24 ppb $(g-2)$
α
α^{2}
α^{3}
α^{4}
α^{5}
Hadronic
Weak
Order of correction to g-2

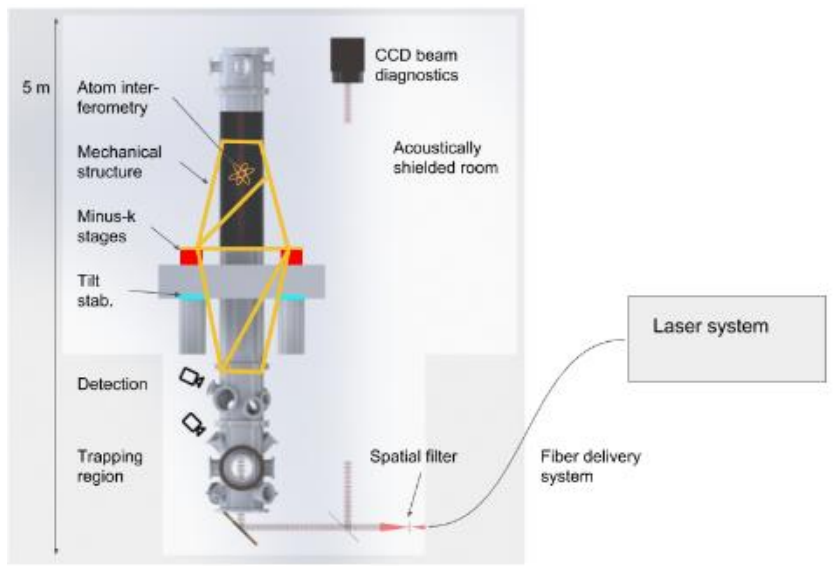
Dark photon limits



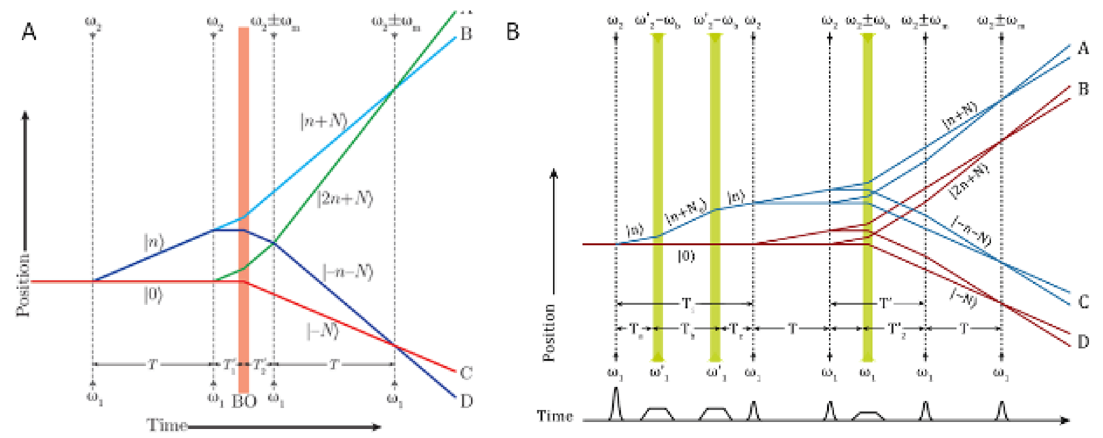




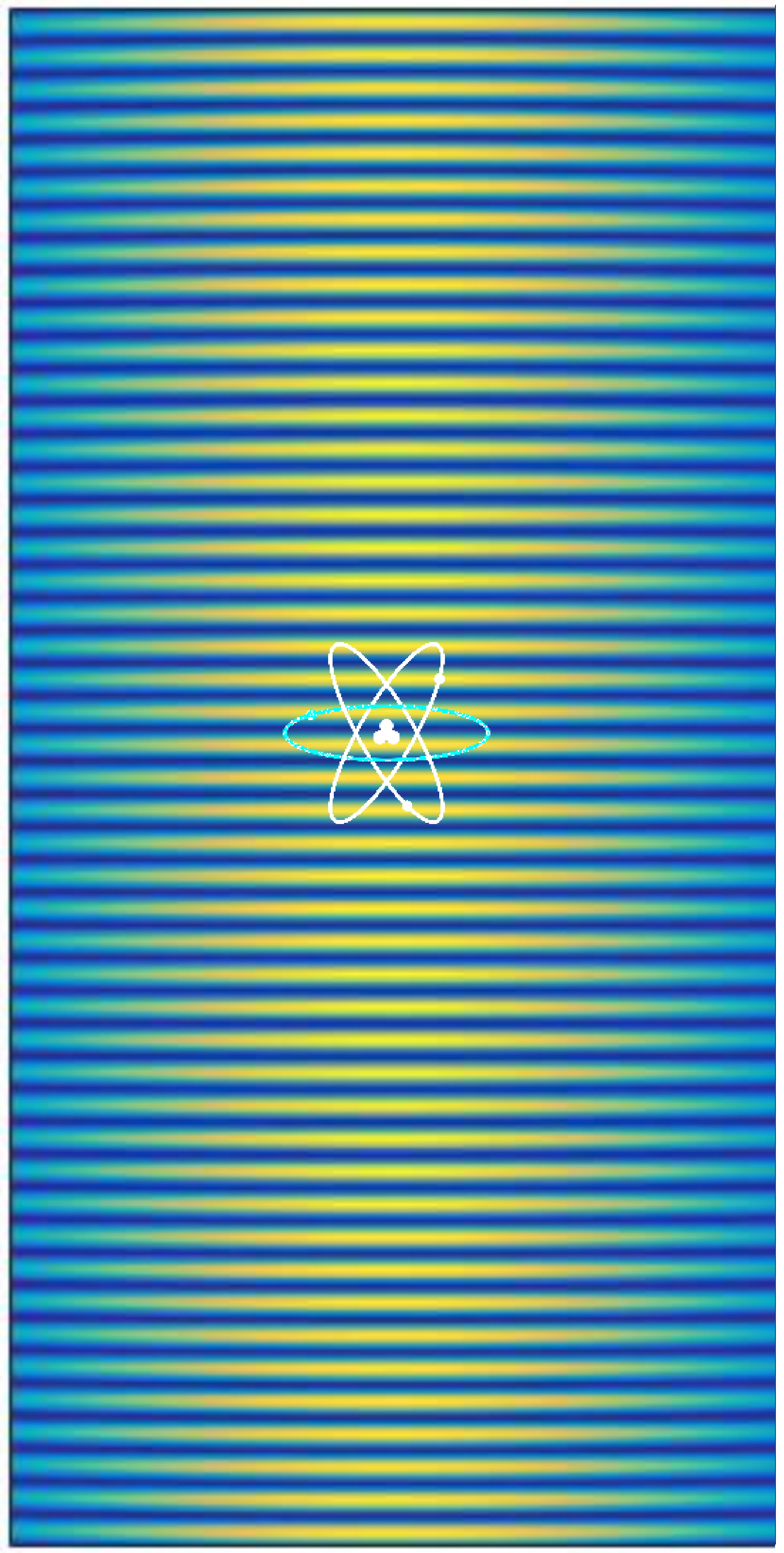
Future Upgrades to 10ppt!



- 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)



A more nearly perfect laser beam



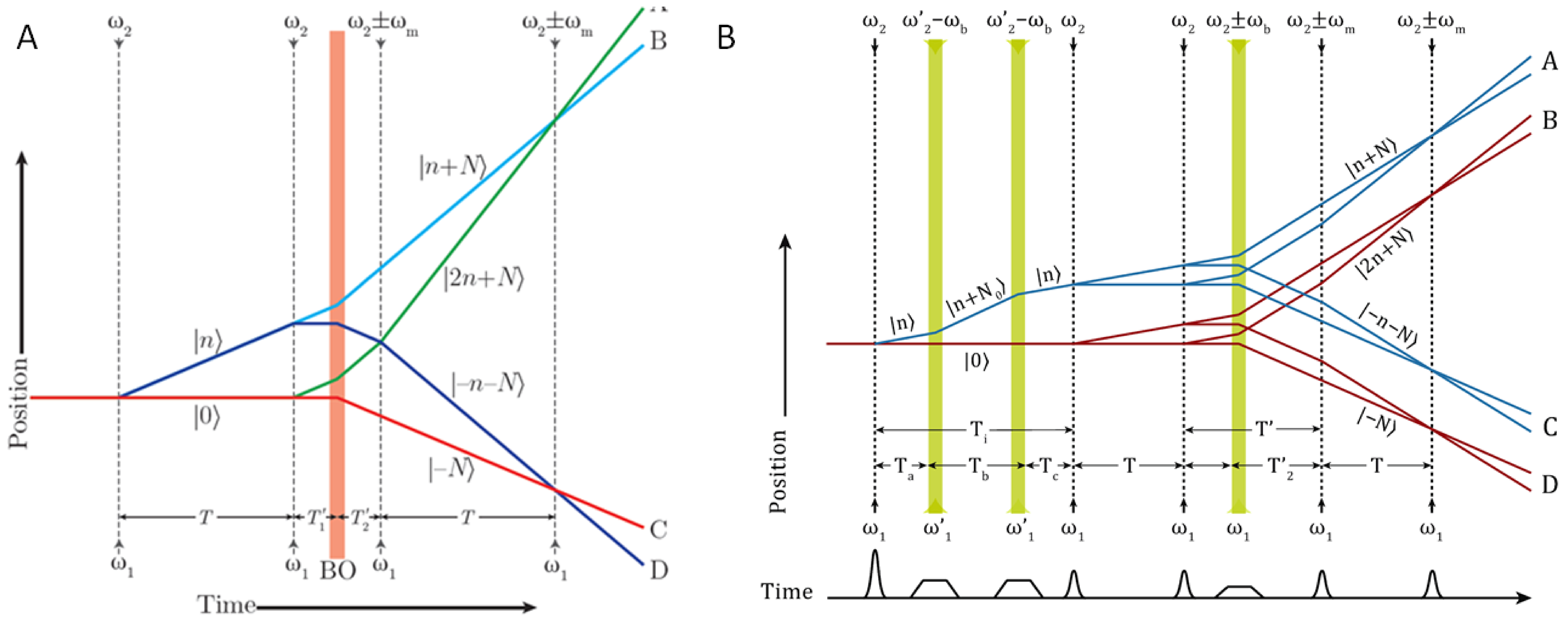
- This project ~ 6 cm radius

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

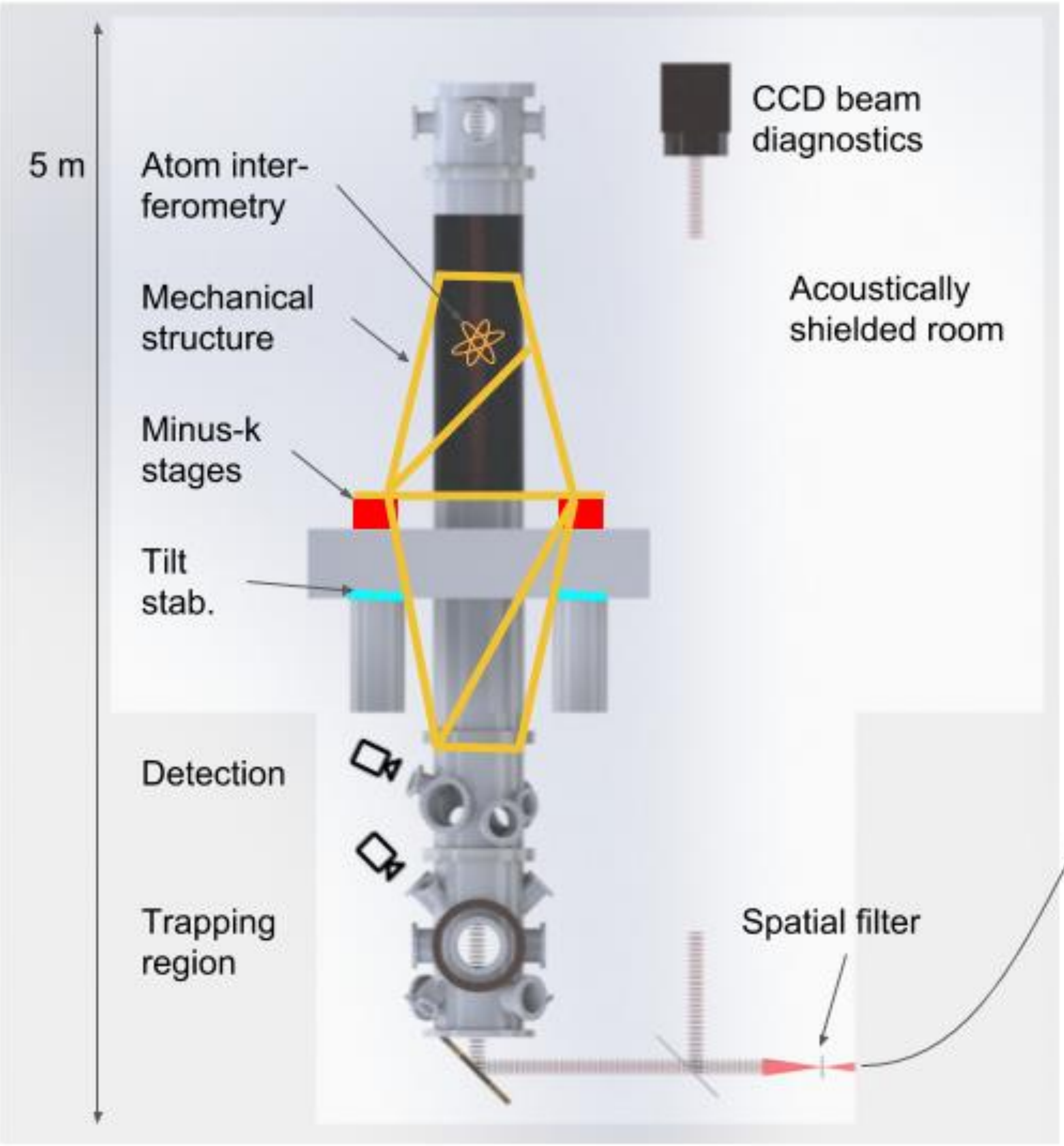
- Beam splitter losses ~$(\lambda/\text{radius})^4$
- higher momentum transfer, and thus sensitivity

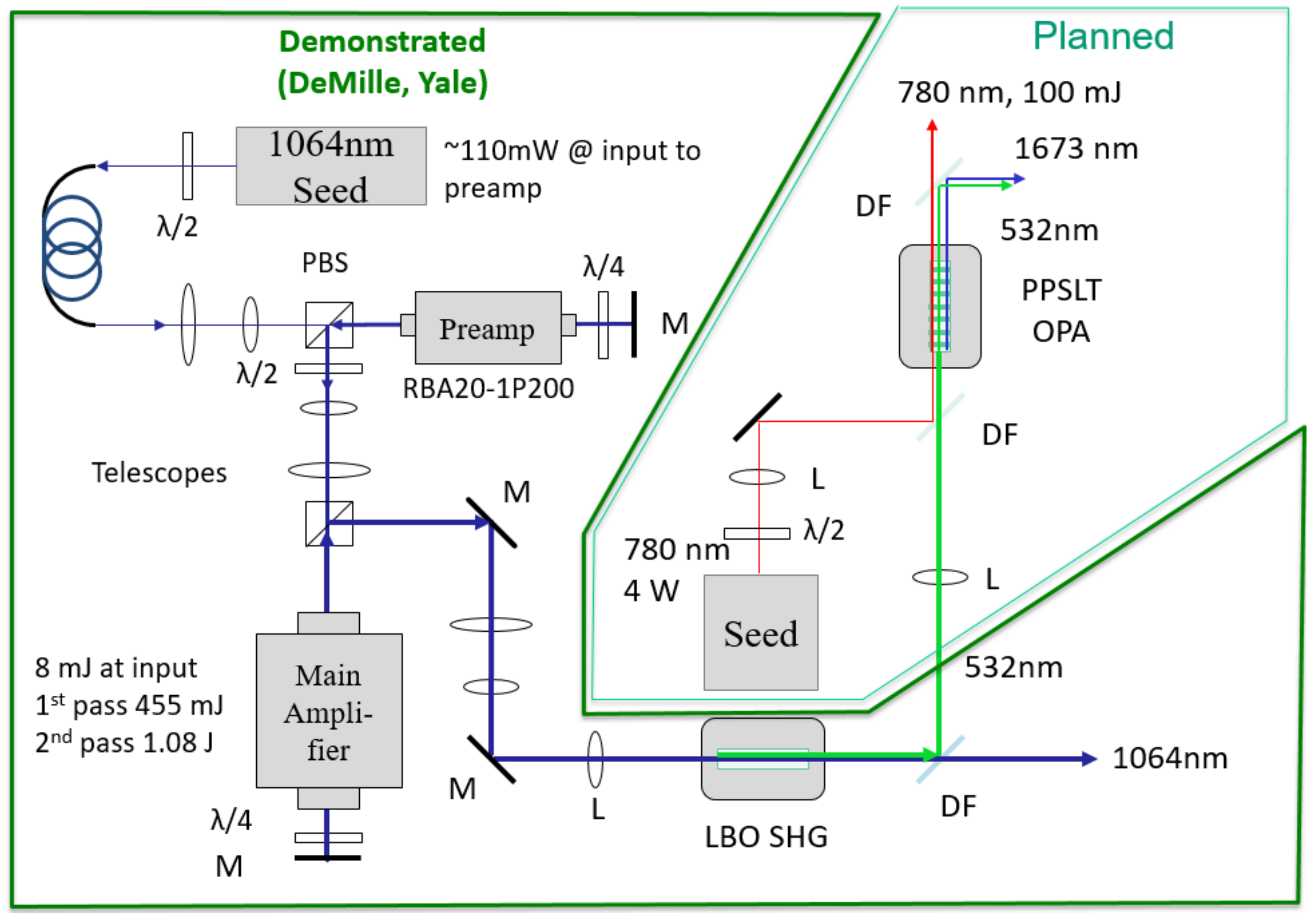
Thick beam will unleash the potential of atom interferometry

New interferometer geometries



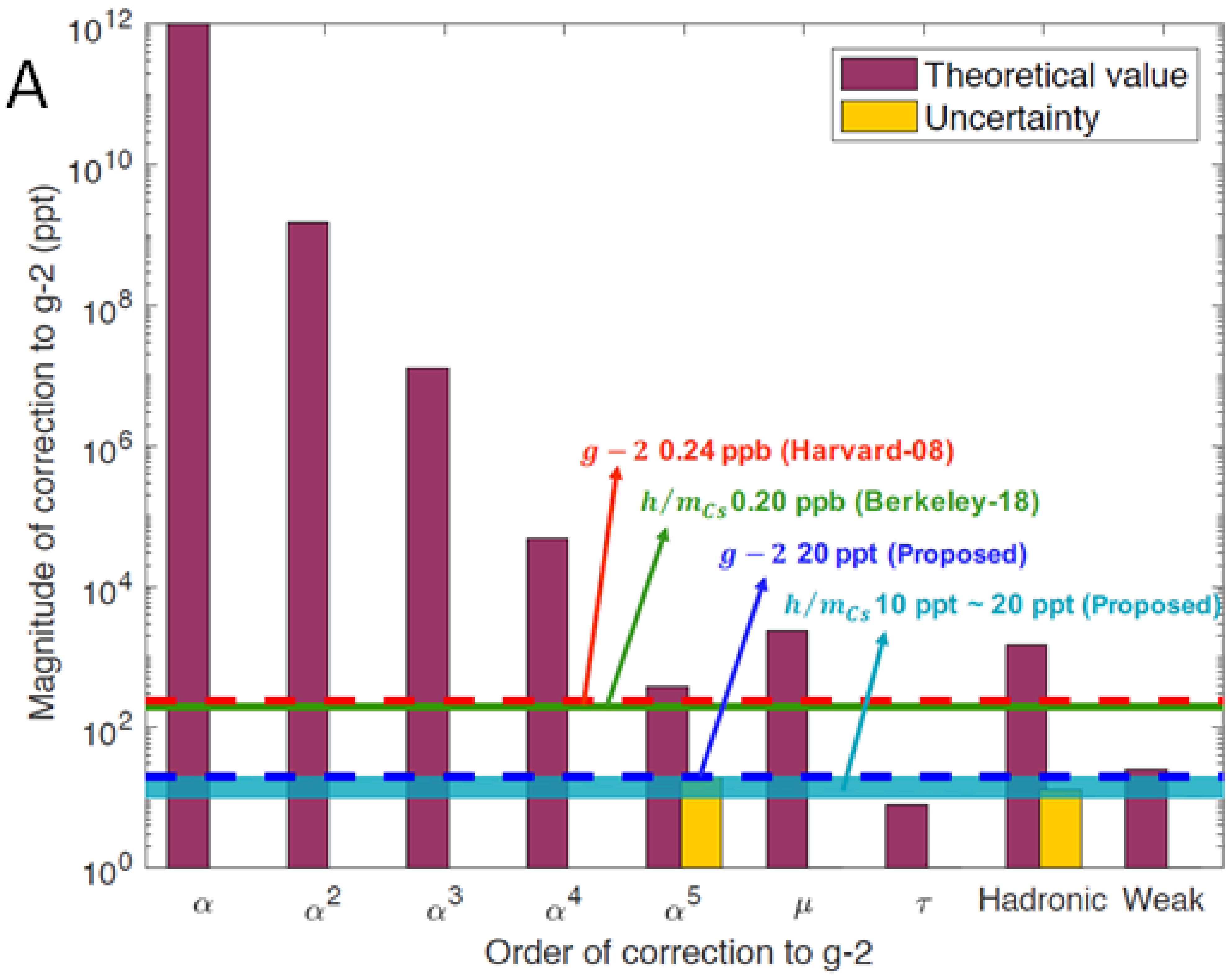
- Eliminates gravity gradient
- Moderate cost in integration rate
- Shown to work in arXiv:1901.03487

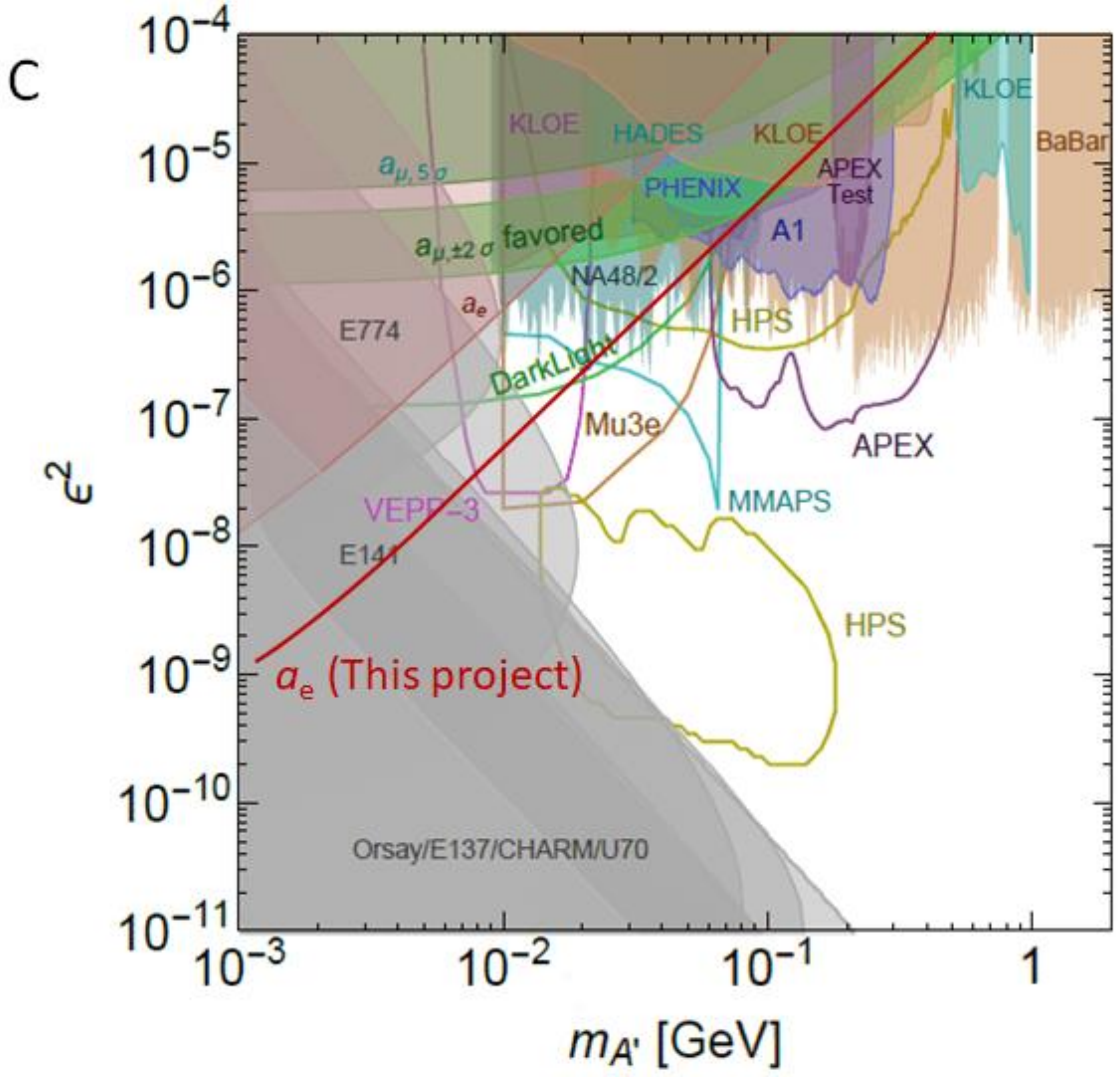




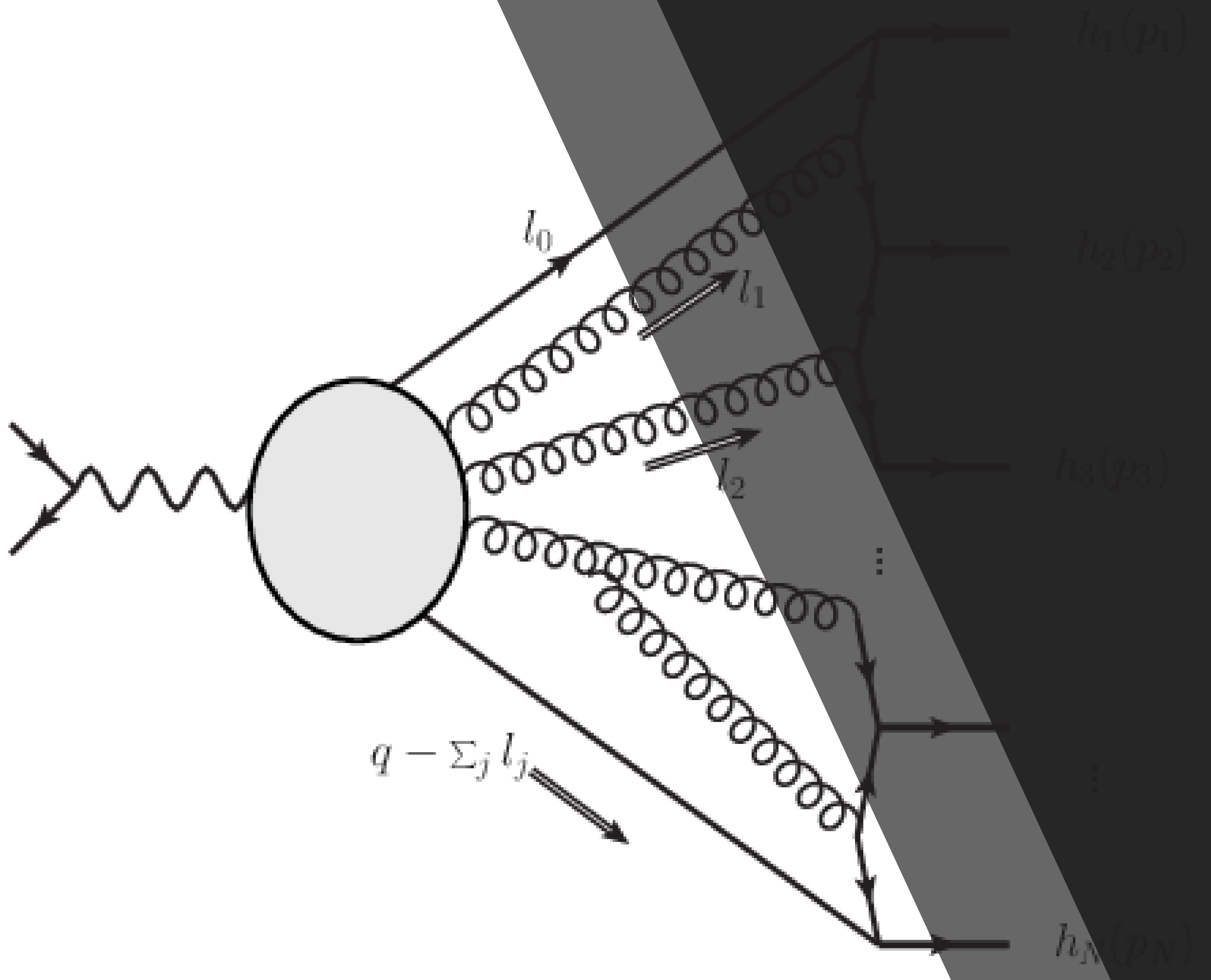
Laser system

New physics reach





Quantum computing prospects (with Christian Bauer)



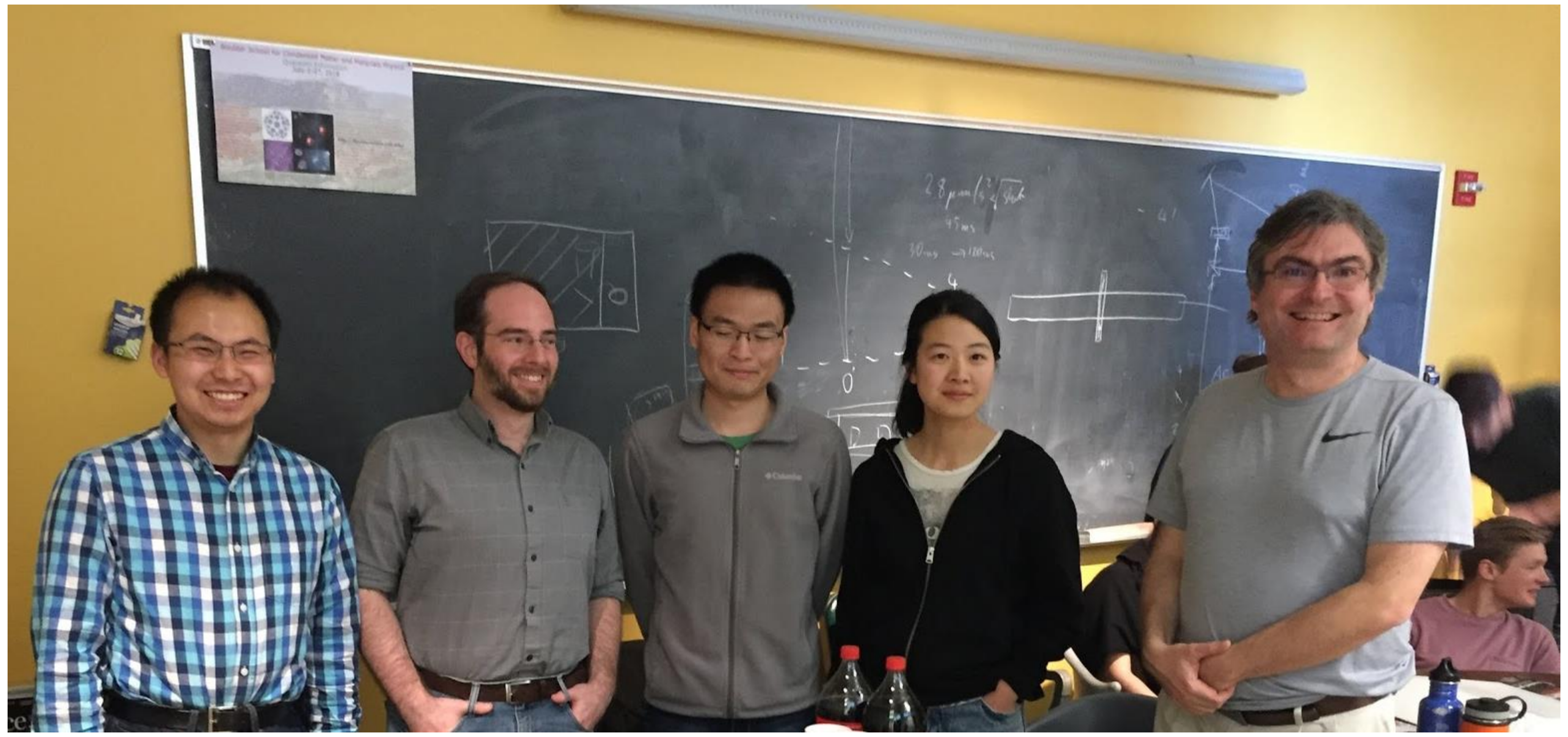
- Perturbative expansions fail when the coupling constants become too large.
- Main theoretical challenge in HEP today.
- Discretize the spatial directions
- Exponentially complex on classical computers.
- Jordan, Lee, Preskill 2012: Quantum algorithms are capable of such simulations with only polynomial growth in complexity.
- Impossible on NISQ computers => Hardware simulation son optical lattices
    - Large set of harmonic oscillators, with well defined interactions between
    - Non-local interactions
    - Add site-resolved detection and manipulation of atoms

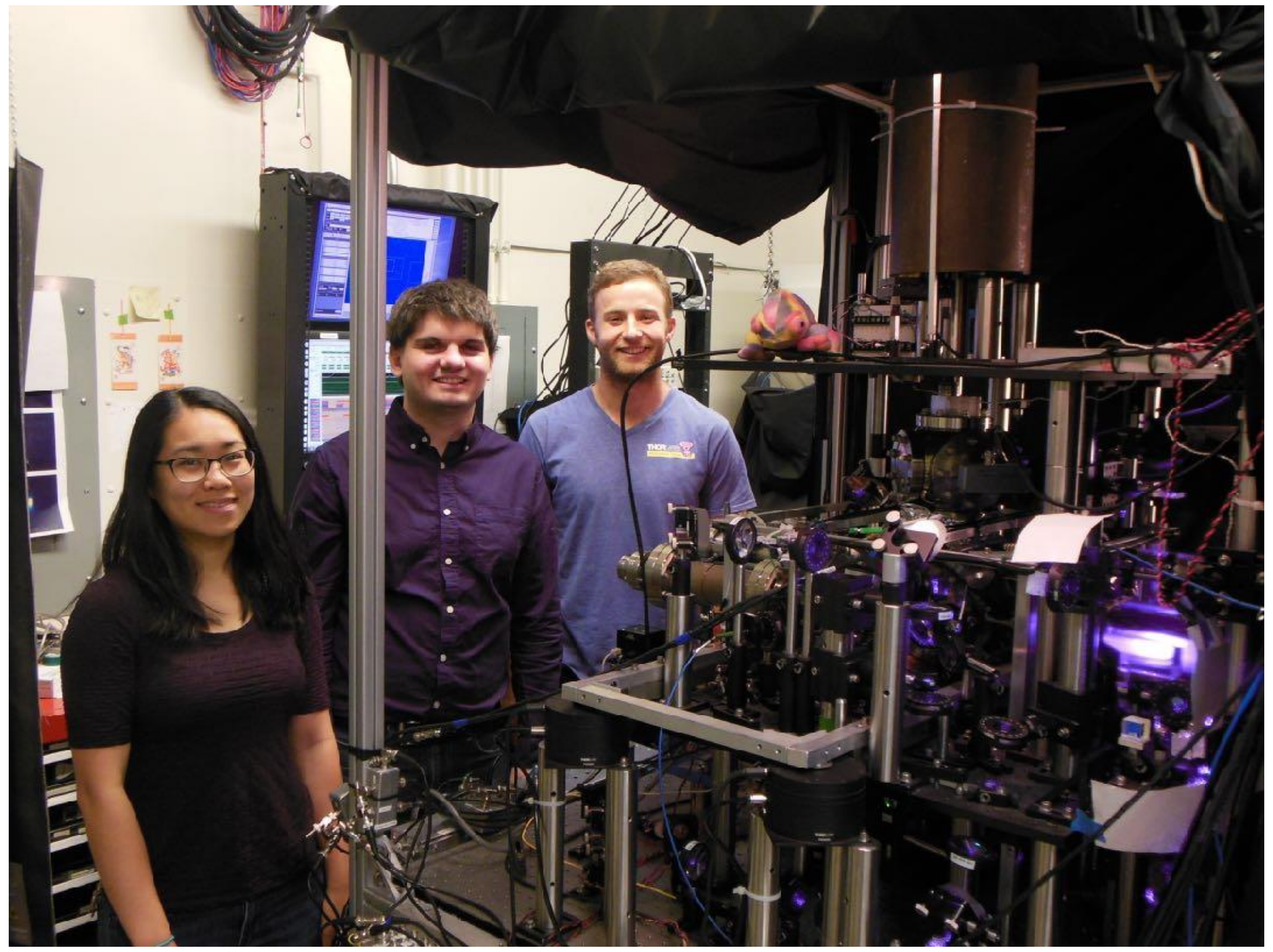
Thank you!

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

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