

Testing the Standard Model by measuring the Fine Structure Constant

“One of the greatest damn mysteries of physics: a magic number that comes to us with no understanding” - Richard Feynman

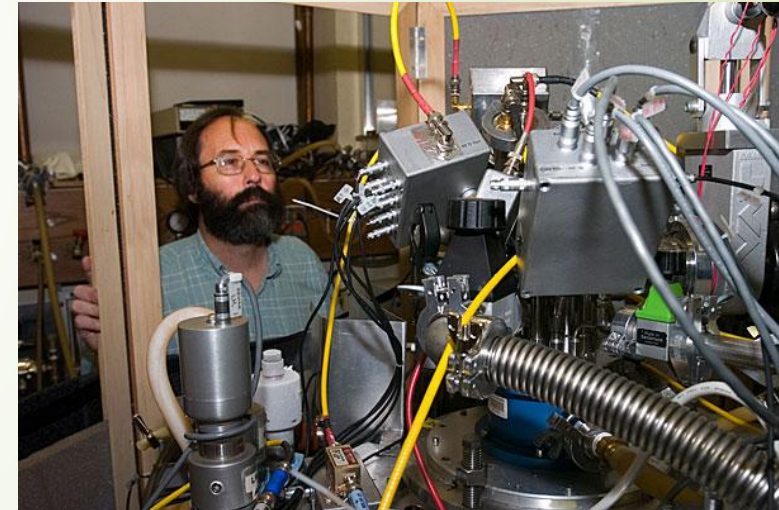
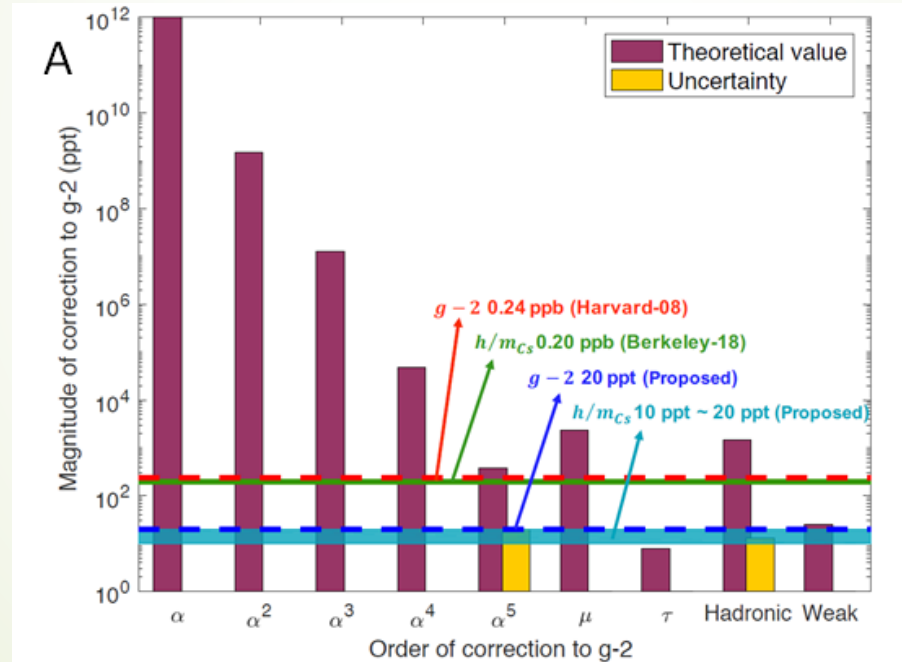
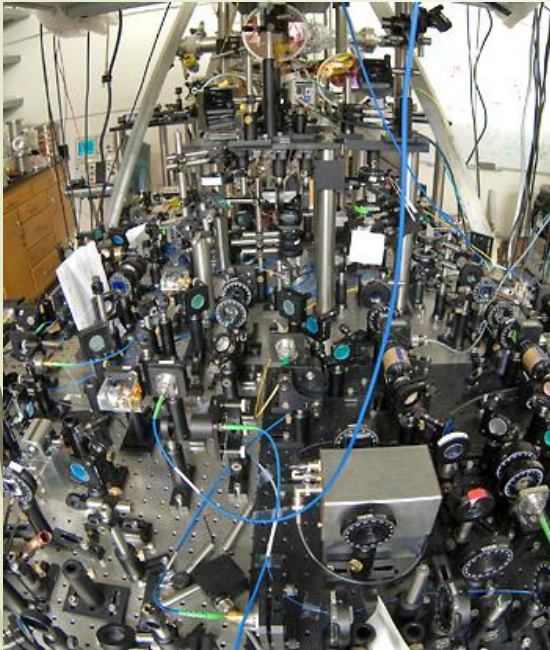
Holger Müller
UC Berkeley

Alpha vs $g-2$: most precise test of the standard model

Fine structure constant
Anomaly

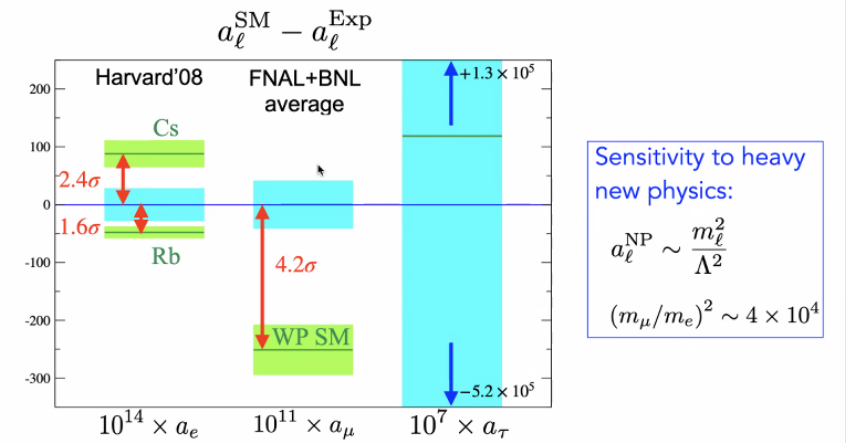
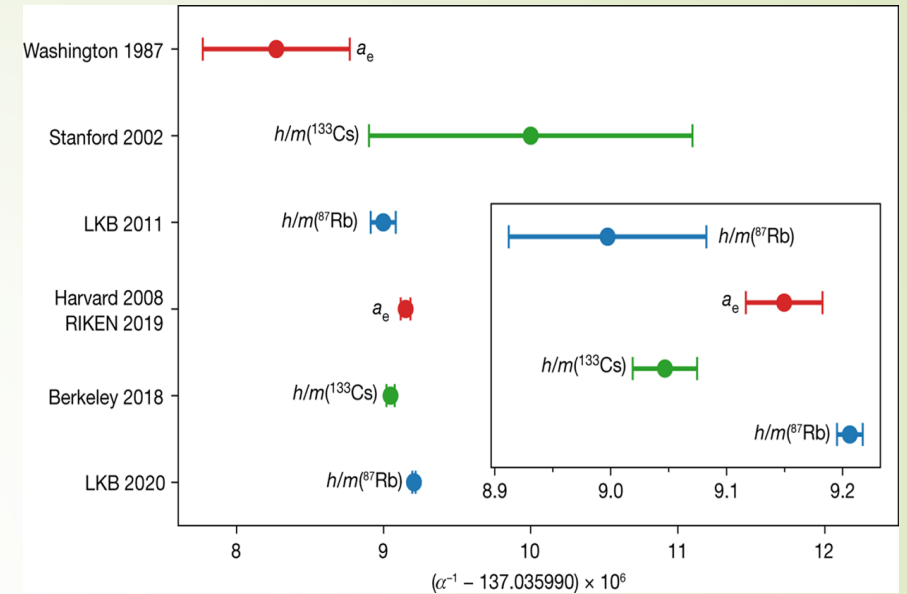
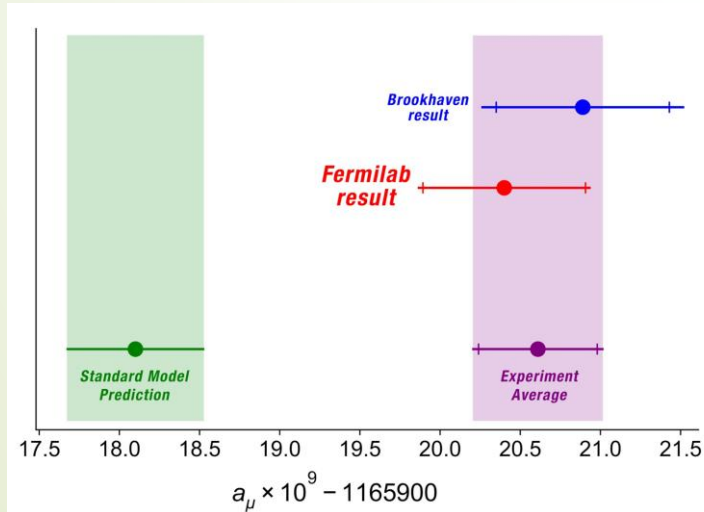
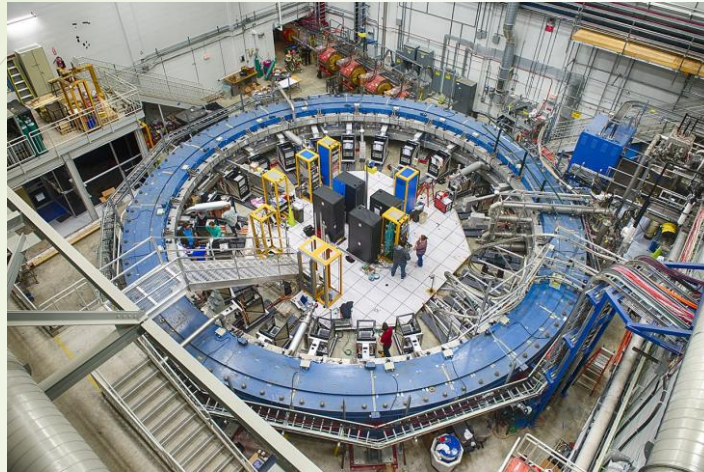
Standard Model

Gyromagnetic



Sensitive to hypothetical particles beyond the standard model

New urgency...



Cs: α from Berkeley group [Parker et al, Science 360, 6385 (2018)]

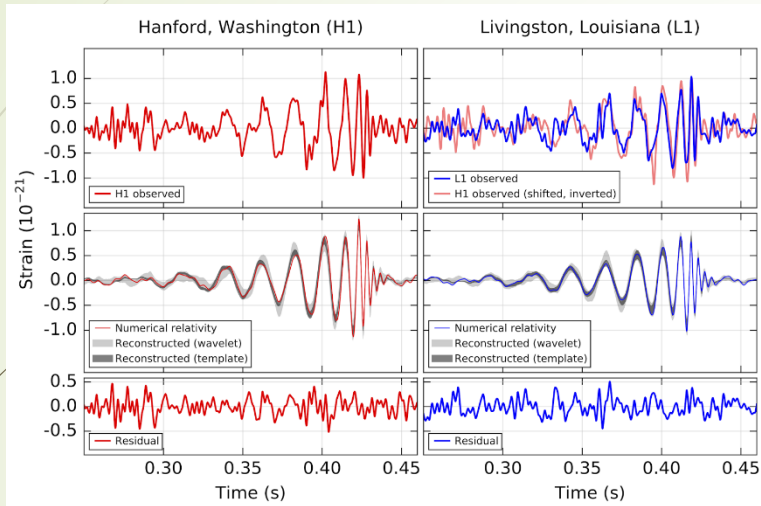
Rb: α from Paris group [Morel et al, Nature 588, 61-65(2020)]

Sensitivity to heavy new physics:

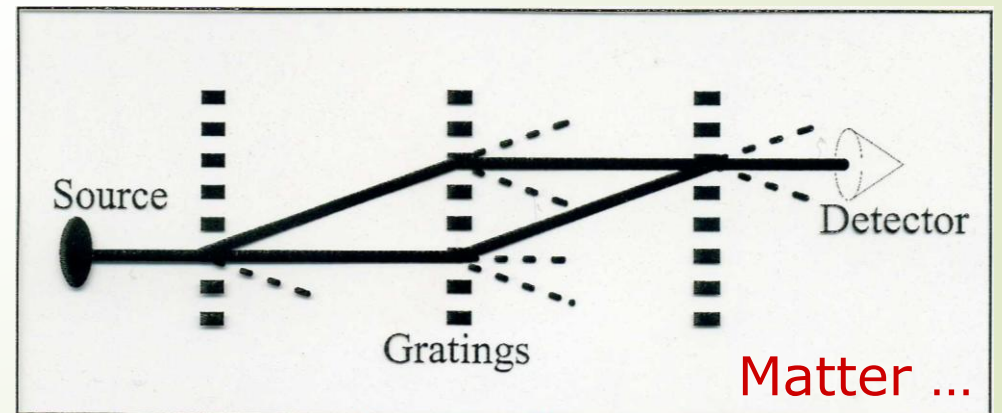
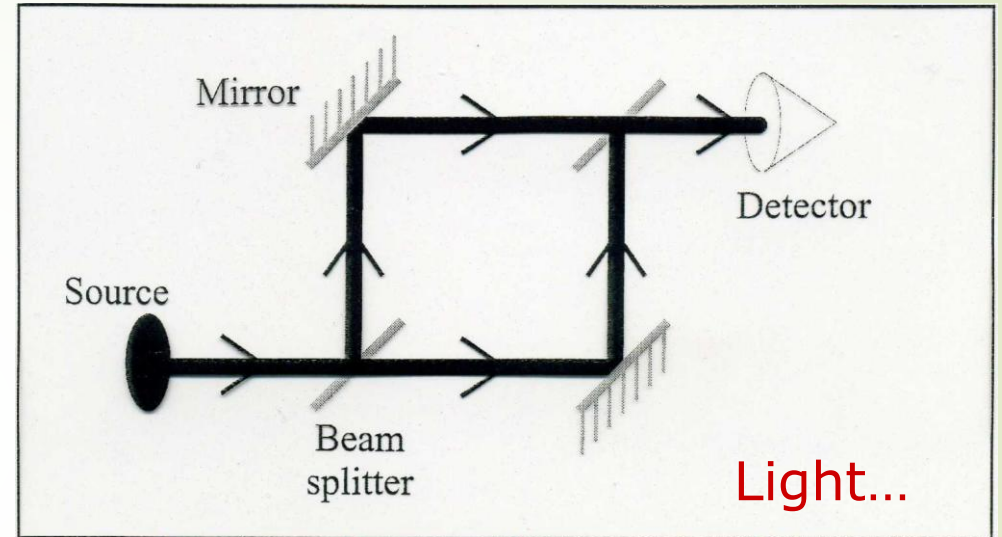
$$a_\ell^{\text{NP}} \sim \frac{m_\ell^2}{\Lambda^2}$$

$$(m_\mu/m_e)^2 \sim 4 \times 10^4$$

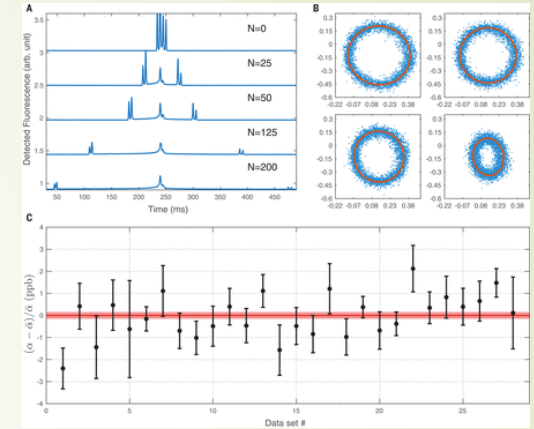
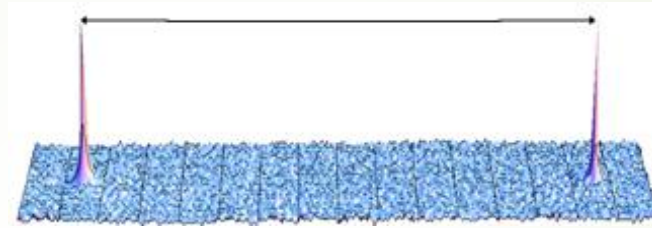
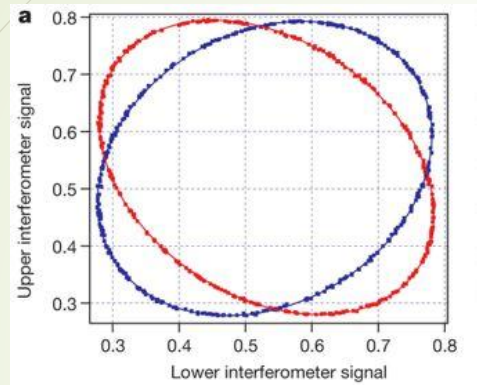
Interferometry....



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



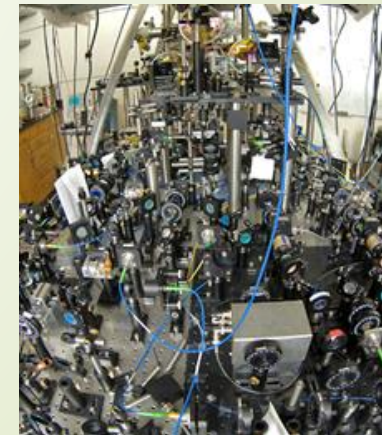
Precision atom interferometry



Measurement of G

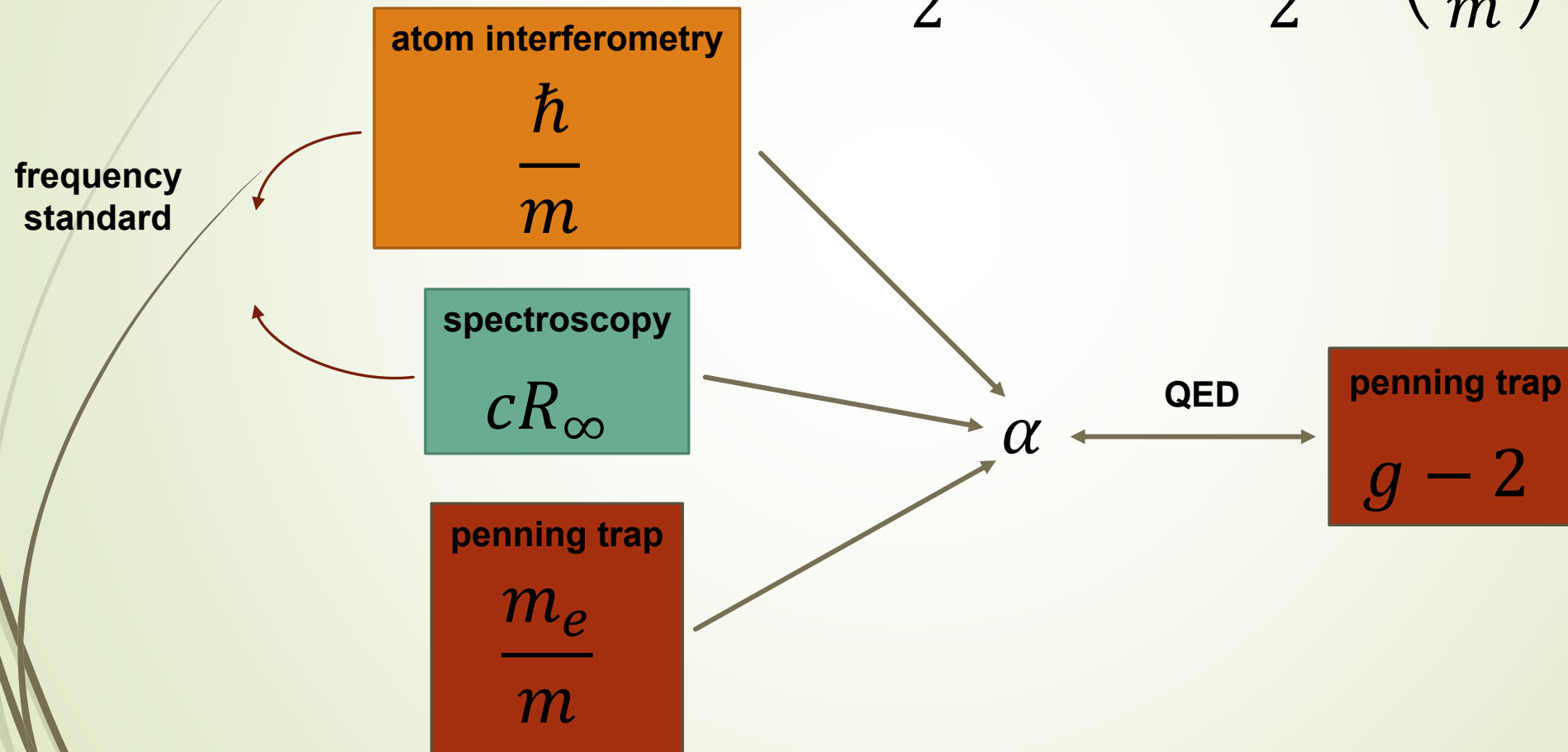
Tests of GR and QM

Fine-structure constant

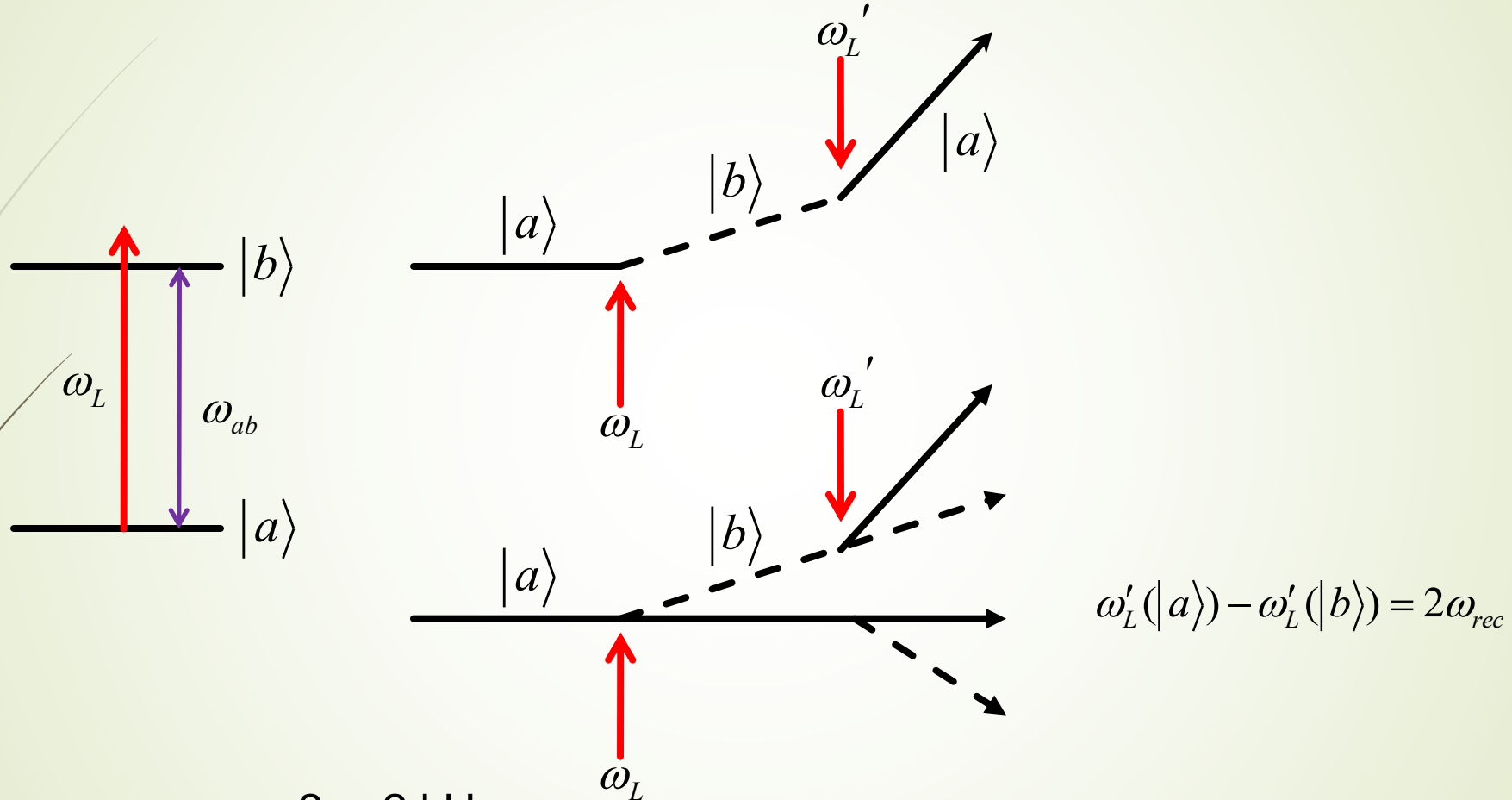


α from \hbar/m

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



Photon Recoil Measurement

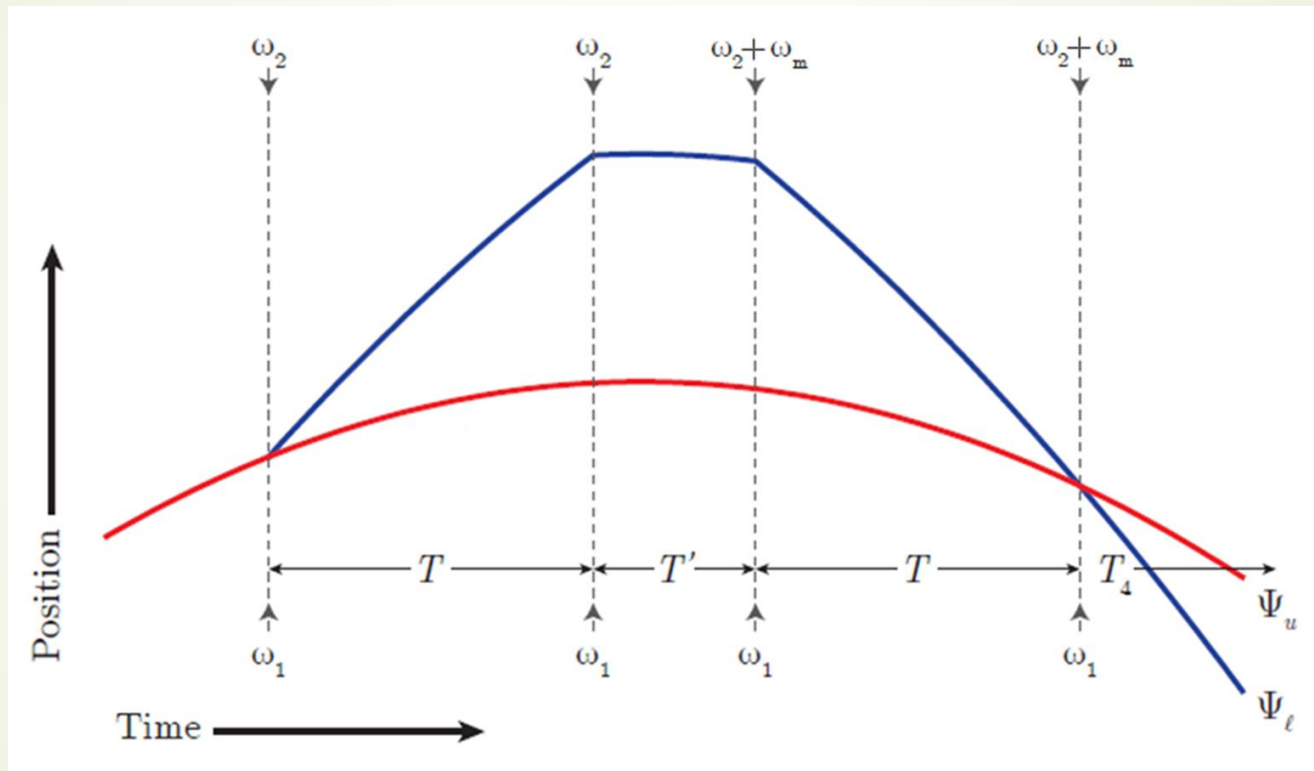


- $\omega r \sim 2\pi \times 2$ kHz,
- Accuracy 10^{-10}
- Need to pinpoint resonance to $0.2 \mu\text{Hz}$ or 6×10^{-22}
- 10,000 times better accuracy than precision of best clocks

Atom-interferometer measurement of α

the first 5 digits...

Ramsey-Bordé Interferometer



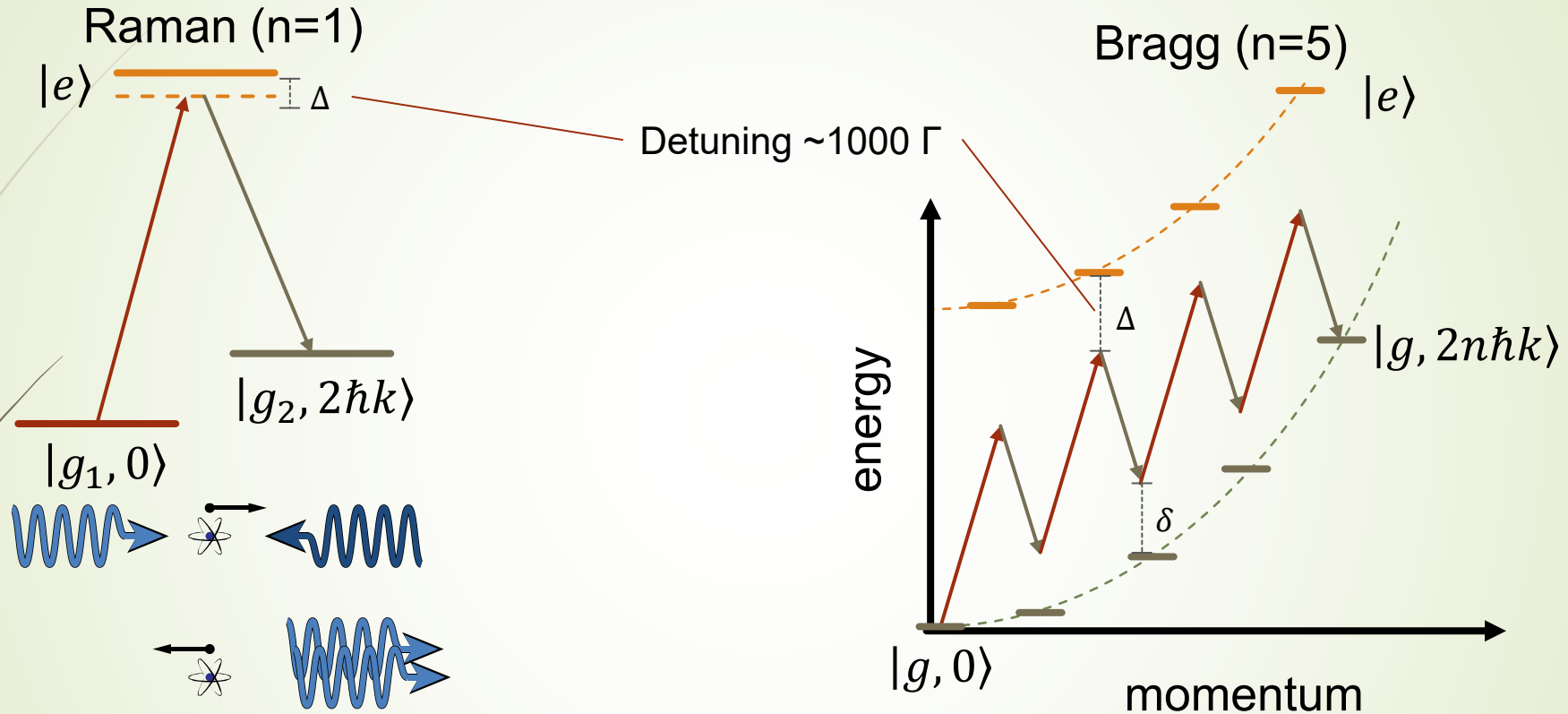
$$\Phi_{RB} = 8n^2 \omega_r T - 2nkg(T + T')T - n\omega_m T$$

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

$$\begin{array}{l} \omega_r \longrightarrow \\ k \longrightarrow \end{array} \hbar/m \longrightarrow \alpha$$

Multi-Photon Bragg Diffraction

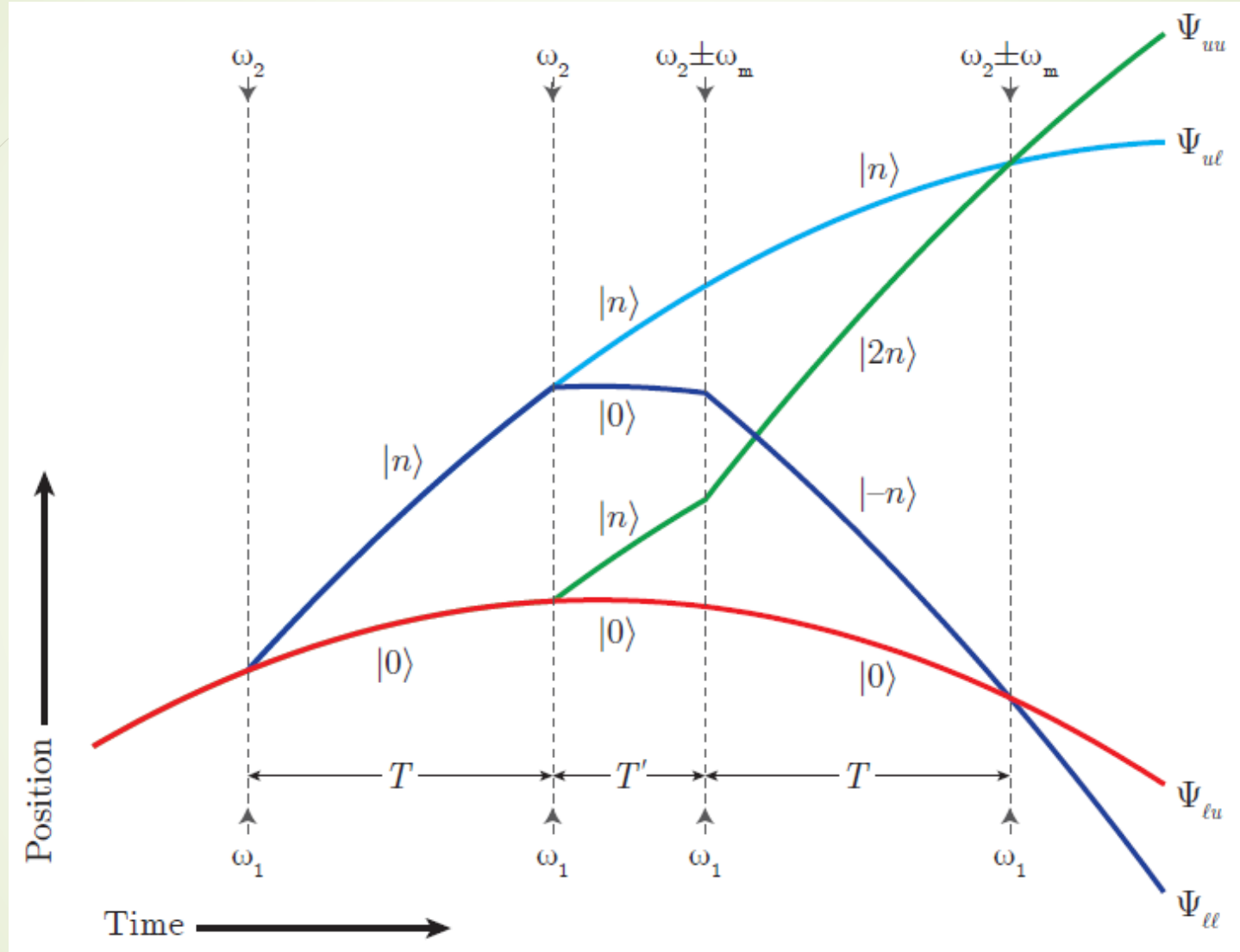
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$



Bragg gives you:

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

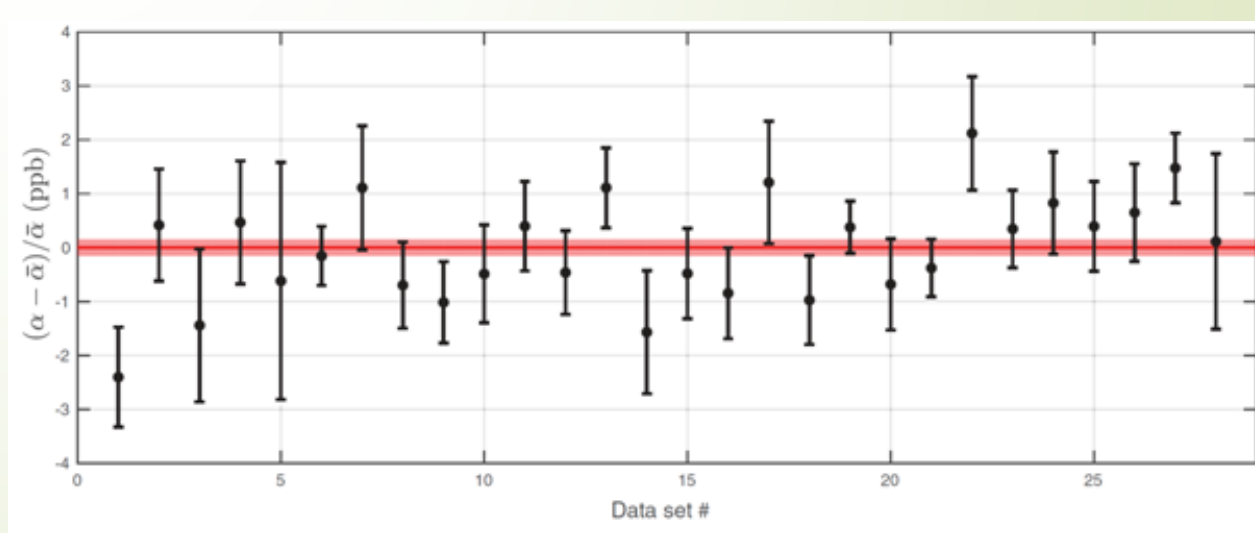
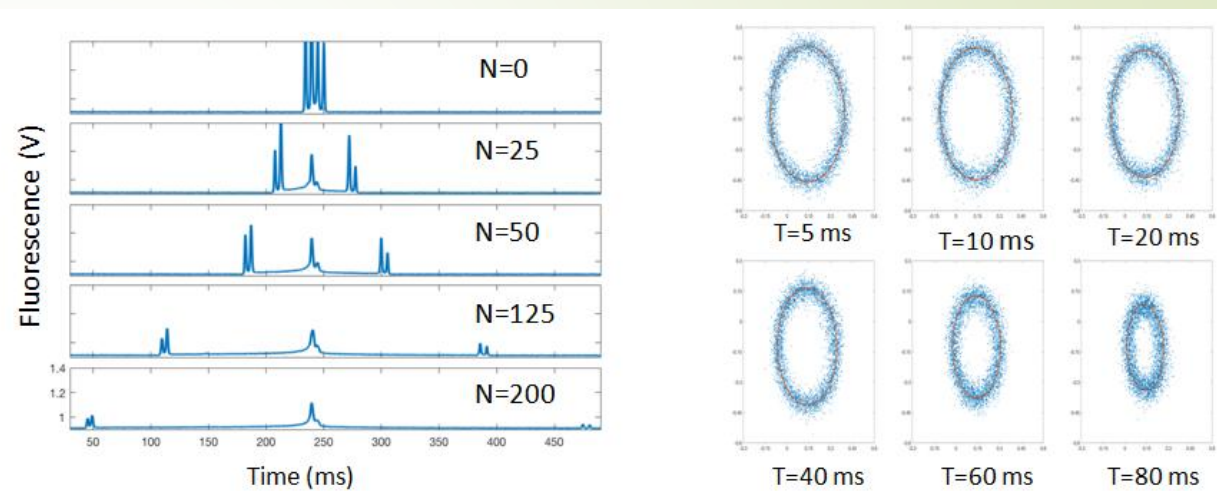
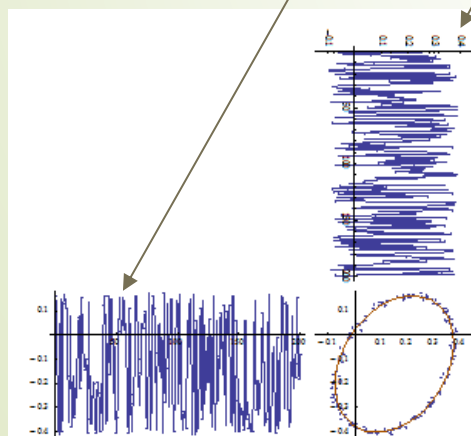
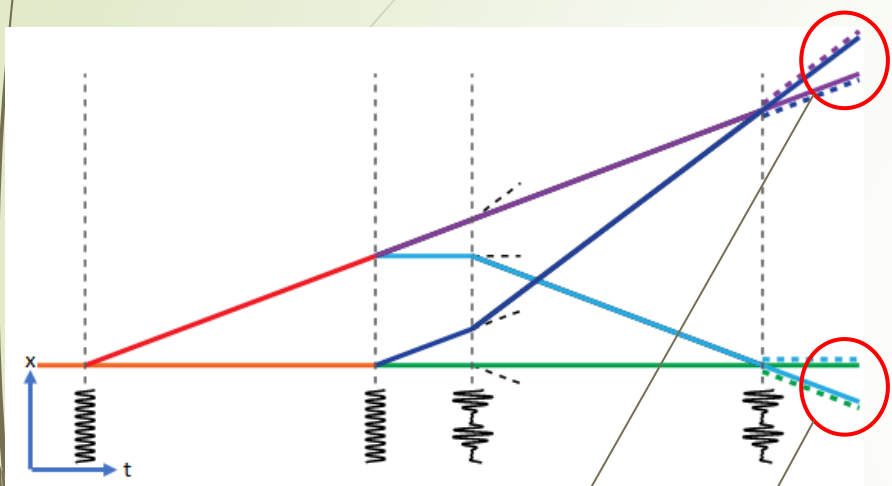
Simultaneous Conjugate Interferometers



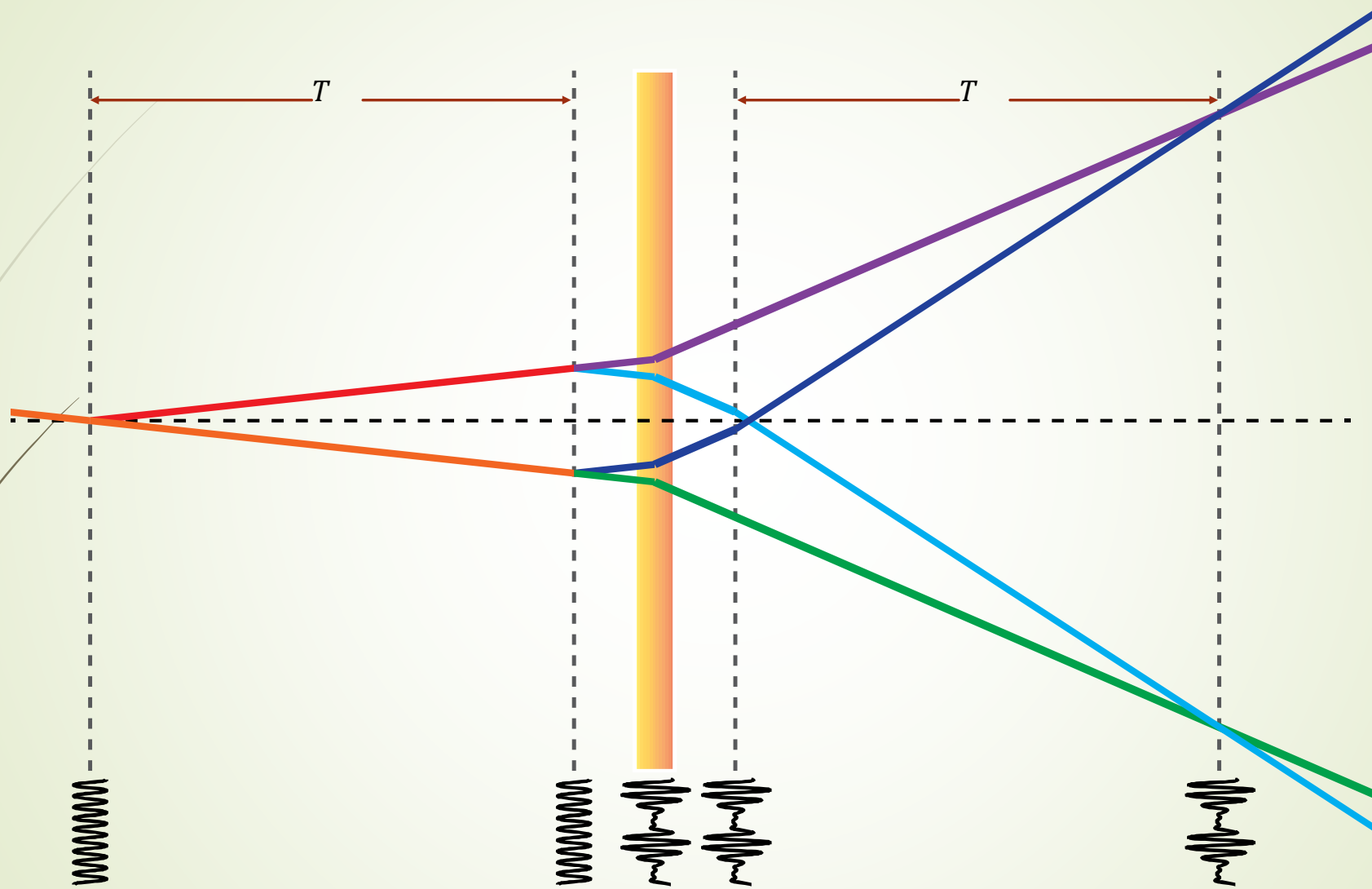
$$\Phi_{RB} = \pm 8n^2 \omega_r T \pm n \omega_m T + 2nkg(T + T')T$$

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

Extracting signal

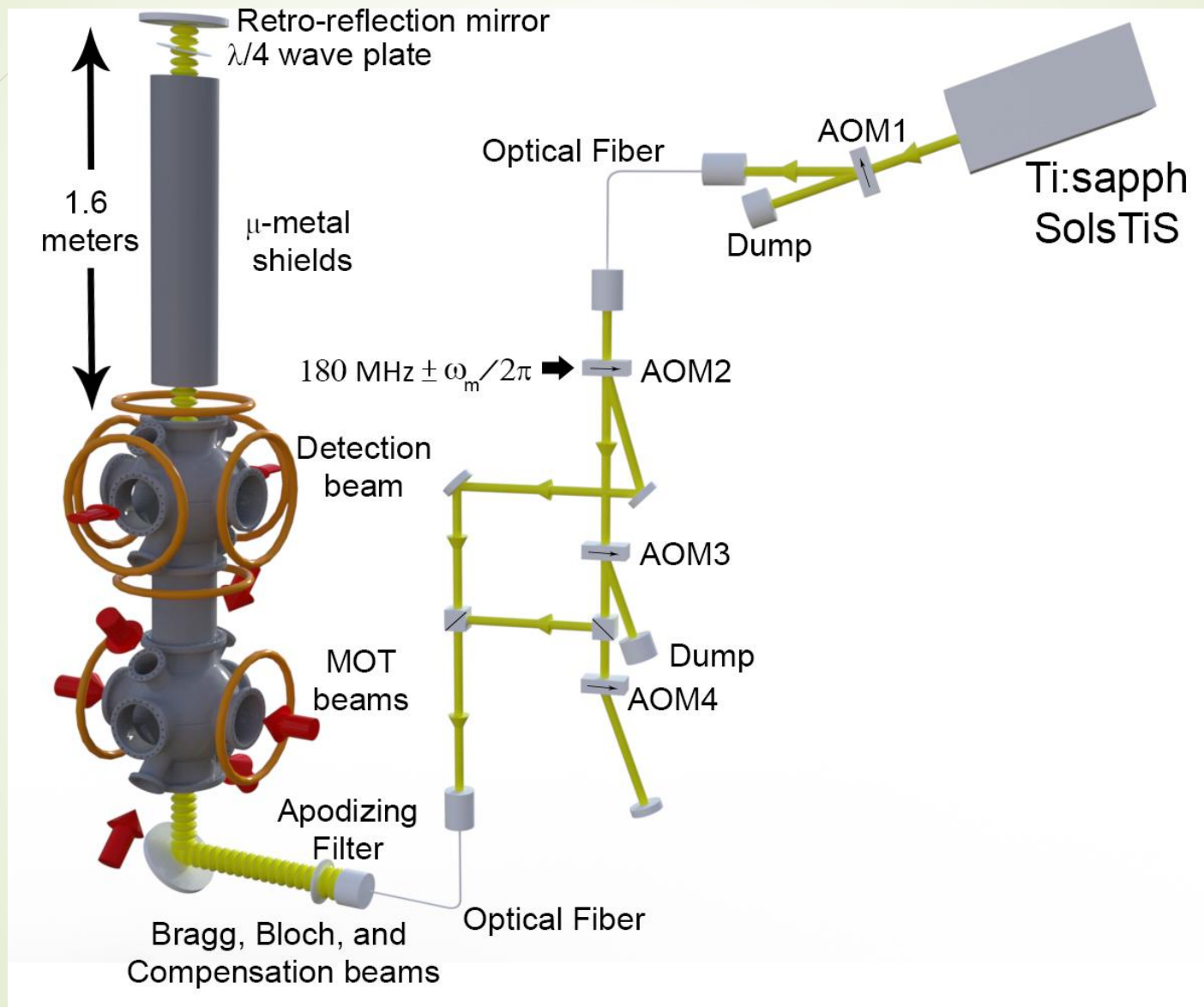


Bloch Oscillations

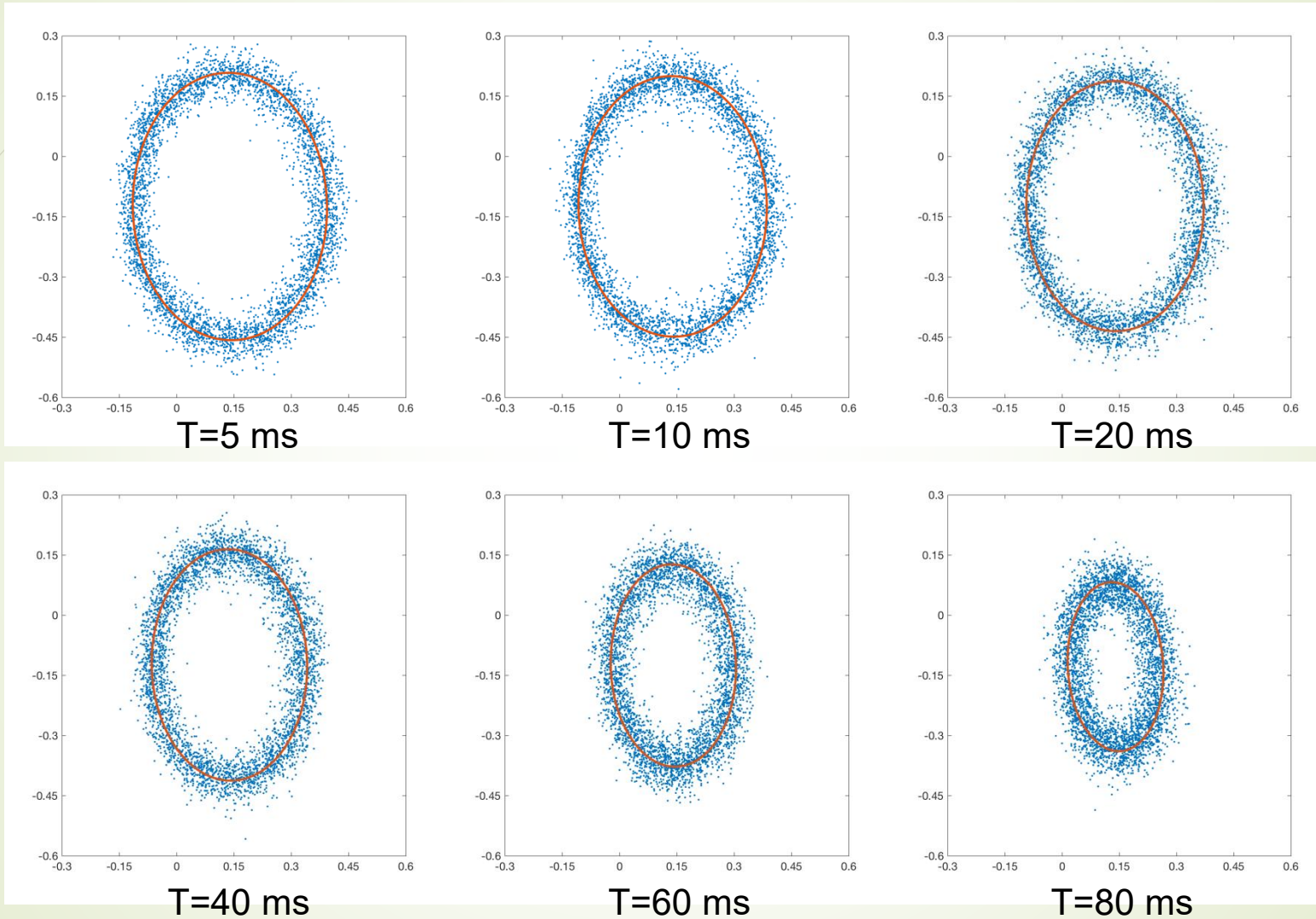


$$\Delta\Phi_{RB+Bloch} = 16n(n + N)\omega_r T - 2n\omega_m T$$

2018 measurement: Setup

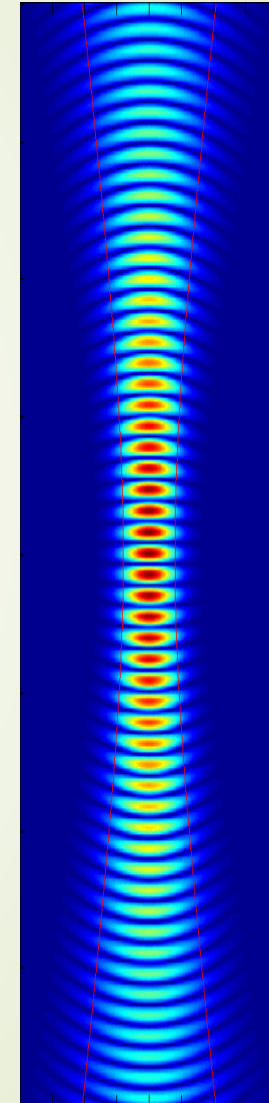
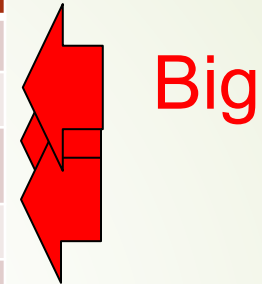


$n=5$, $N=125$ Ellipses



0.16 ppb systematic errors

| Effect | Sect | Value | $\delta a/a$ (ppb) |
|---------------------------|------|---|--------------------|
| Laser Frequency | 1 | N/A | -0.24 ± 0.03 |
| Acceleration Gradient | 4A | $\mathbb{A}=(2.13 \pm 0.01) \times 10^{-6}/s^2$ | -1.69 ± 0.02 |
| Gouy phase | 3 | $w_0=3.21 \pm 0.008$ mm, $z_0=0.5 \pm 1.0$ 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 | $n_{\text{cloud}}-1=30 \times 10^{-12}$ | 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) | | $5.48579909067 \times 10^{-4} u$ | ± 0.02 |
| Cesium Mass (4,17) | | 132.9054519615 u | ± 0.03 |

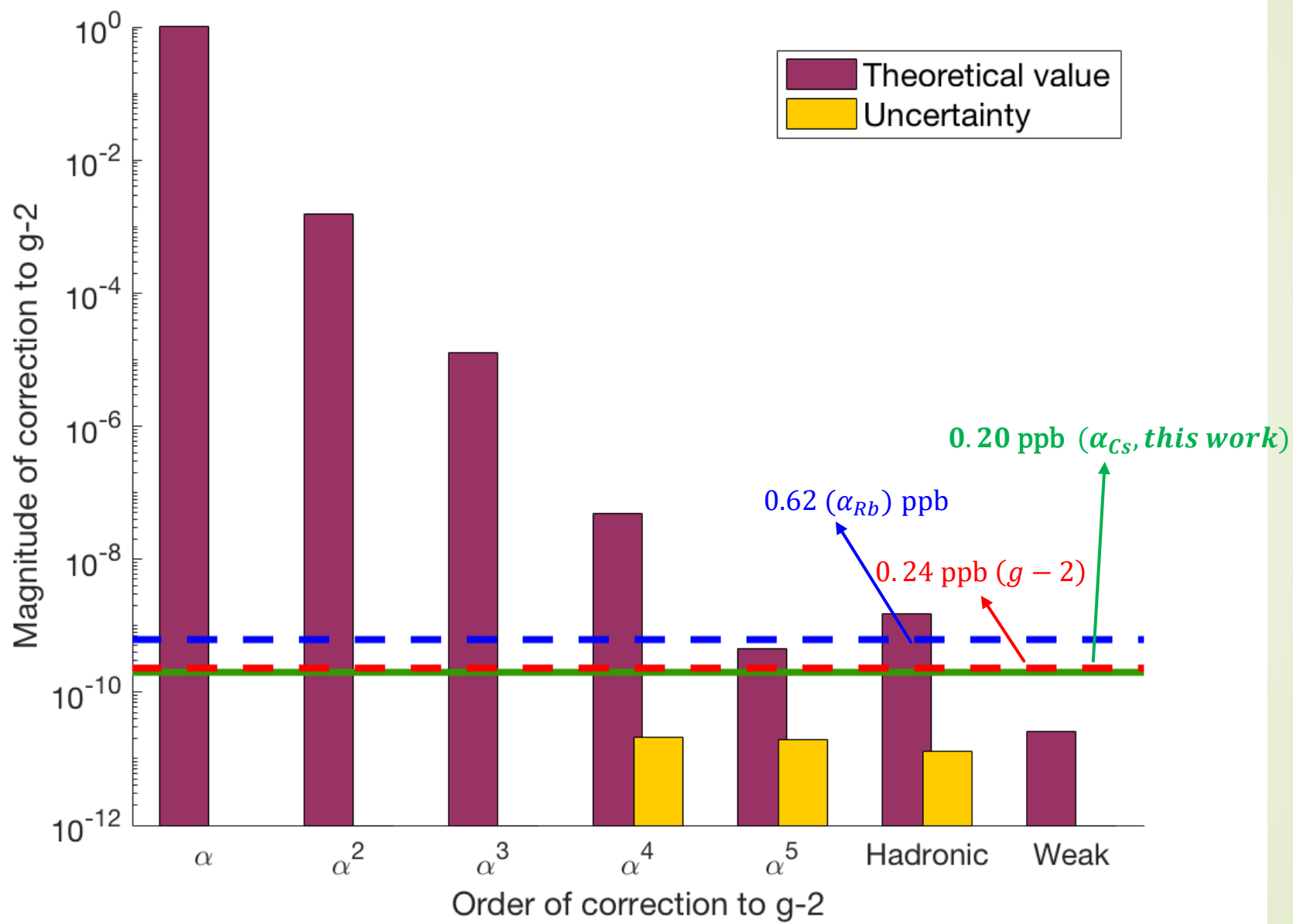


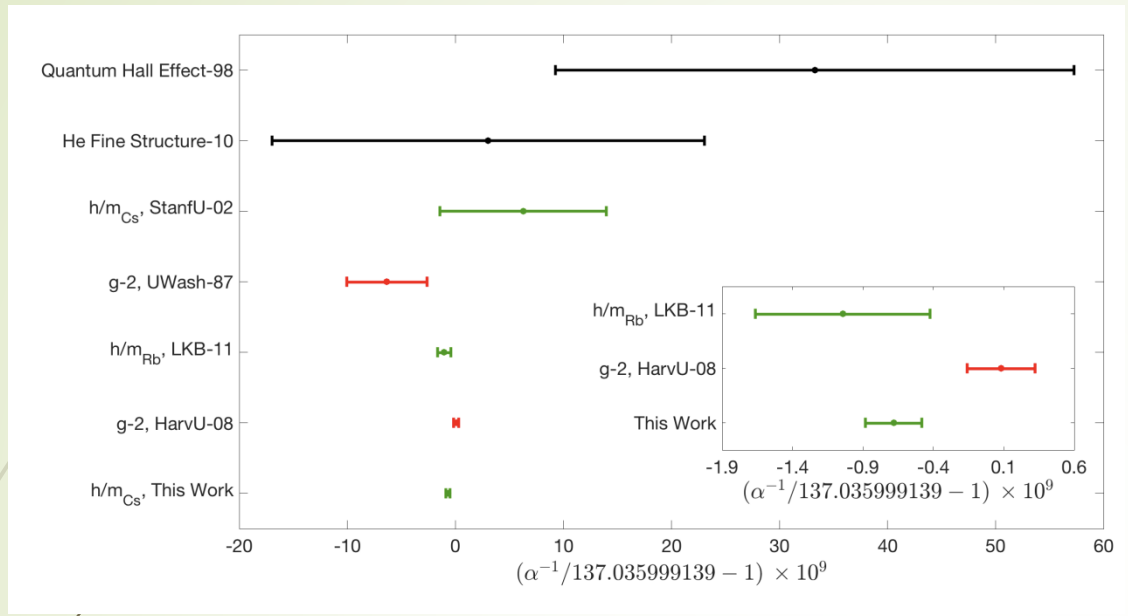
Systematic Checks

Variations of alpha w.r.t.:

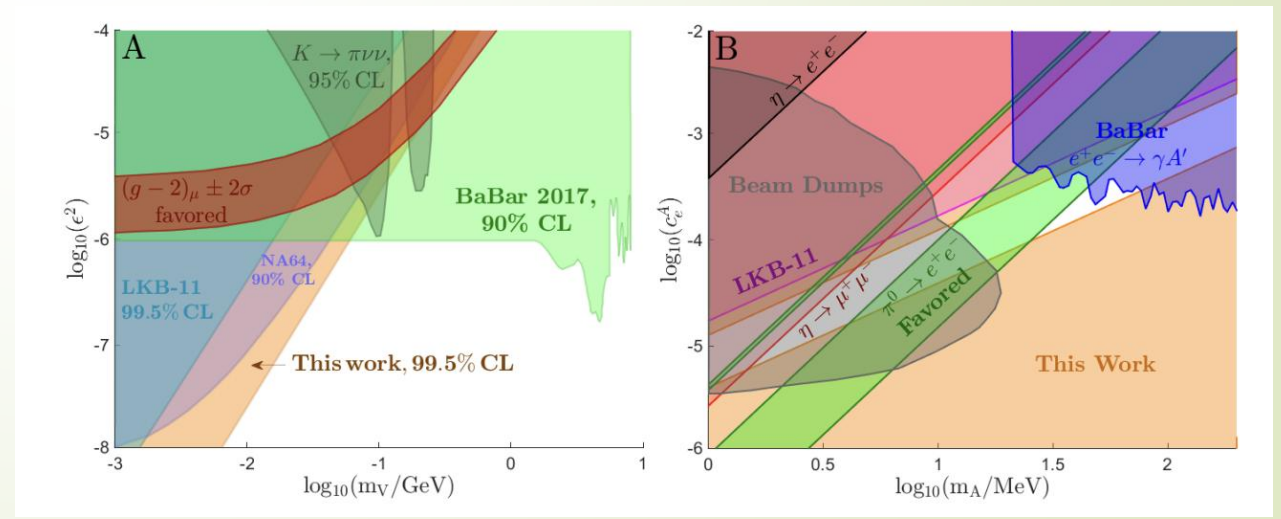
- ▶ Bloch order
- ▶ Bloch power
- ▶ Contrast
- ▶ Detection region
- ▶ Pulse intensity: overall and pulse/pulse ratio
- ▶ Speckle phase
- ▶ ω_m mixing (RF)
- ▶ ω_m mixing (optics)
- ▶ Delay of interferometer sequence
- ▶ Bias B-field
- ▶ Single-photon detuning
- ▶ Data Analysis parameters (cuts, fitting,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

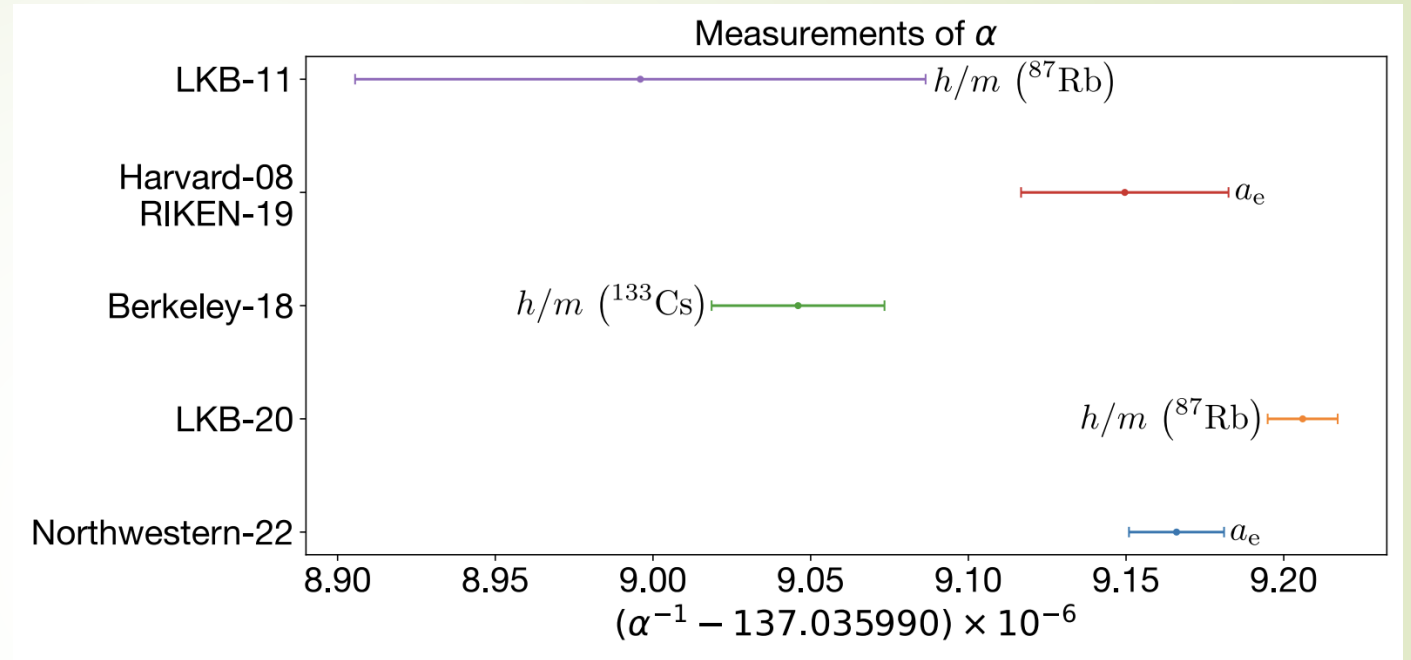
Results





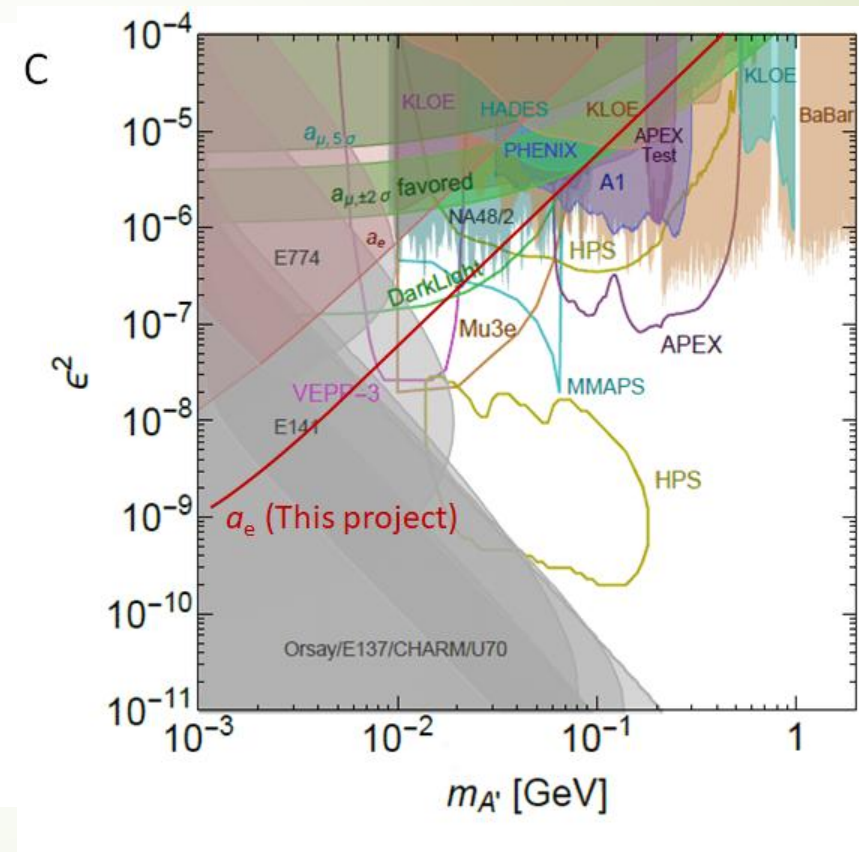
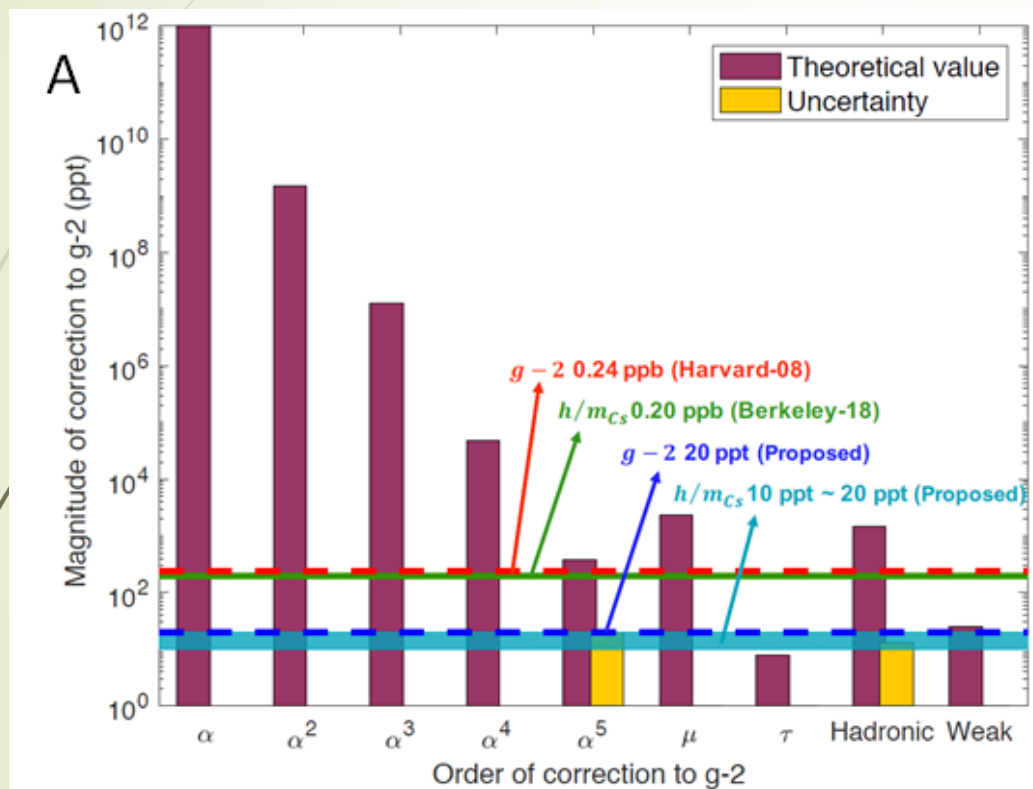
Results





New measurement

New physics reach



Approach...

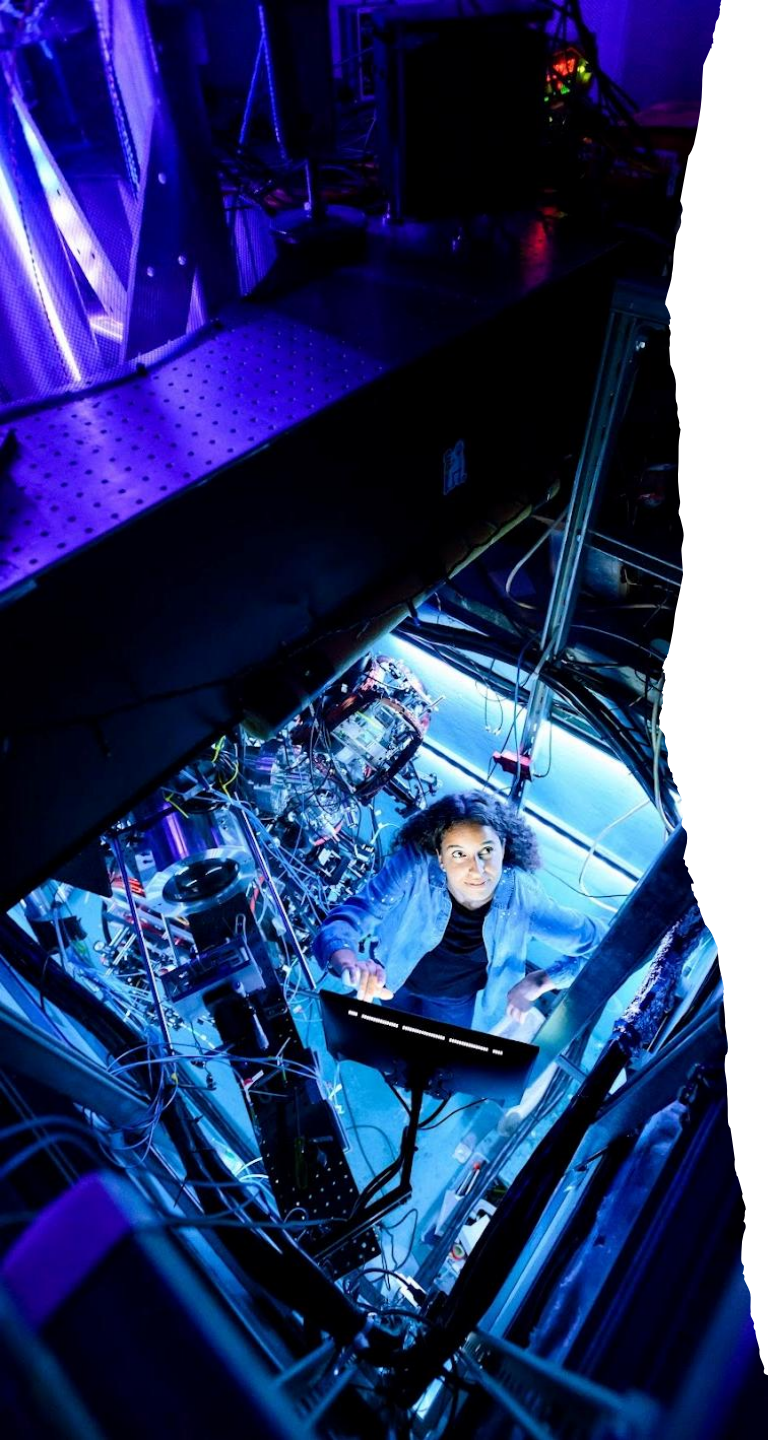
| Effect | Value | $\delta a/a$ (ppb) |
|---------------------------|--|--------------------|
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| Acceleration Gradient | $\gamma = (2.13 \pm 0.01) \times 10^{-6} / s^2$ | -1.69 ± 0.02 |
| Gouy phase | $w_0 = 3.21 \pm 0.008$ mm, $z_0 = 0.5 \pm 1.0$ m | -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 | $n_{\text{cloud}} - 1 = 30 \times 10^{-12}$ | 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) | $5.48579909067 \times 10^{-4}$ u | ± 0.02 |
| Cesium Mass (4,17) | 132.9054519615 u | ± 0.03 |



Larger, cleaner
laser beam

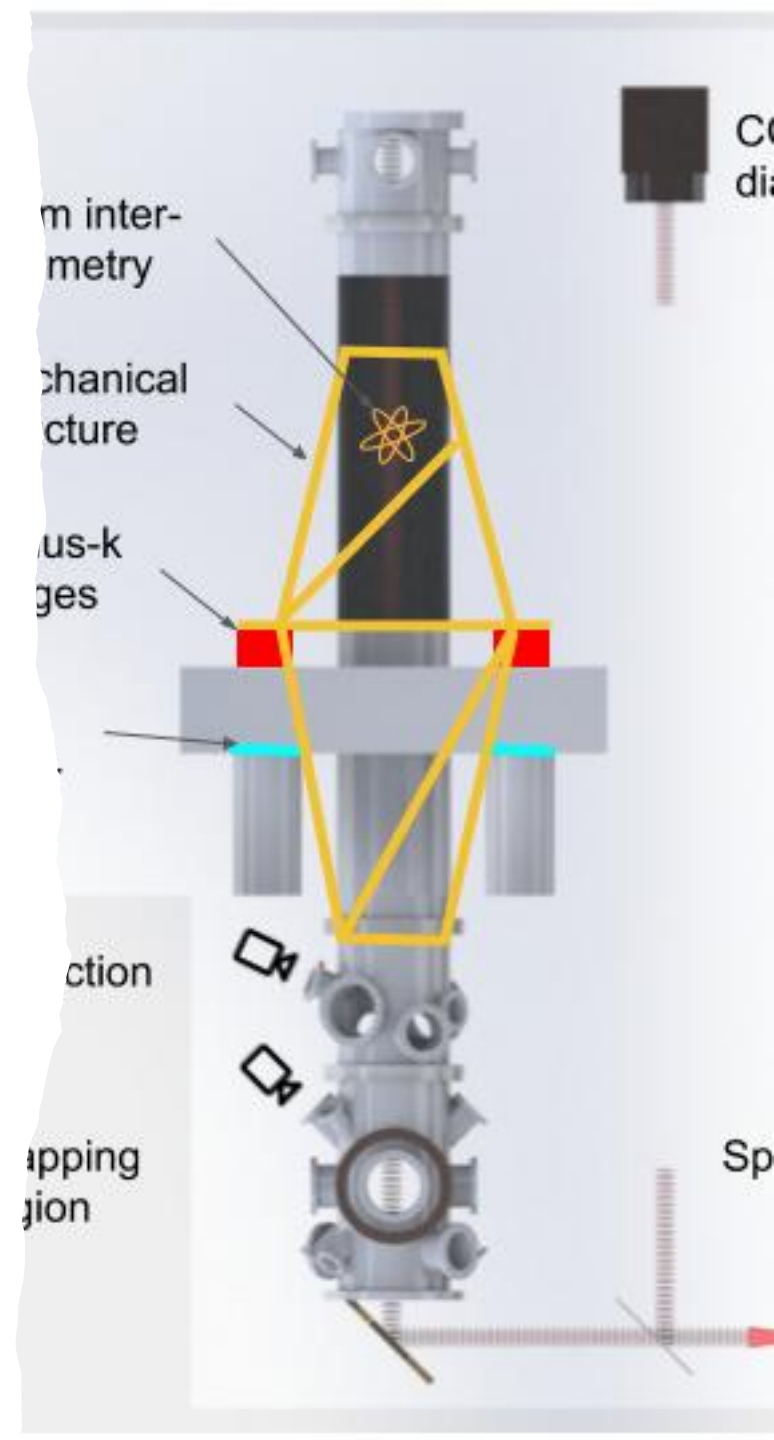
Better
measurement/
characterization

Directly test
model of laser-
beam
distortions



Extreme control over laser beam uniformity

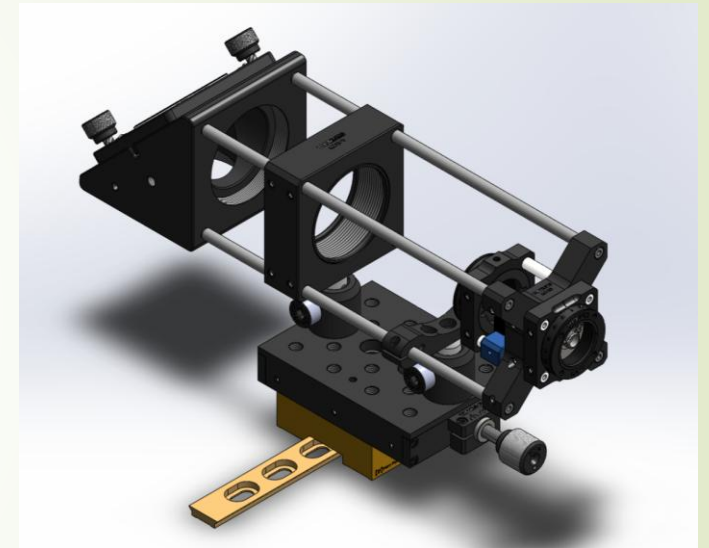
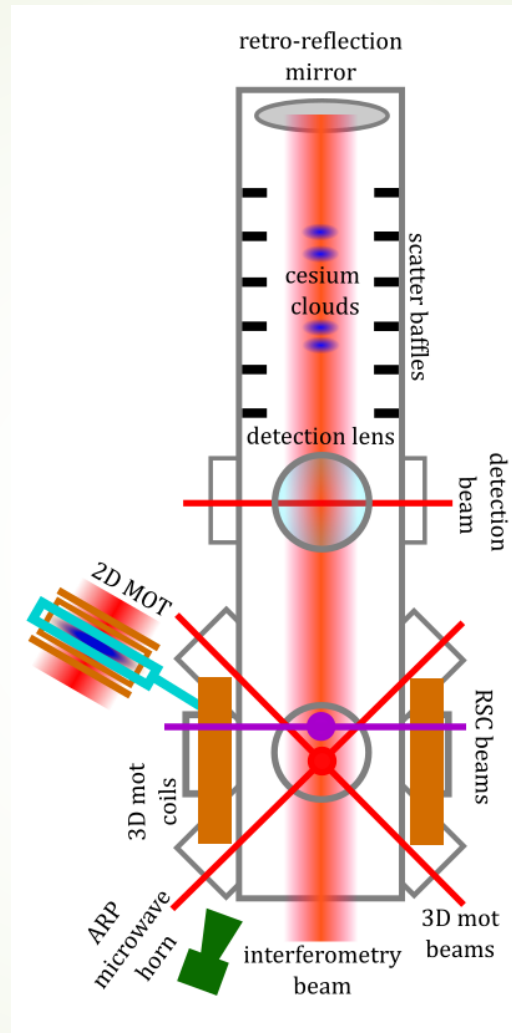
- 30 cm clear aperture of the beam tube
- Beam characterization



New MOT telescopes, improved alignment

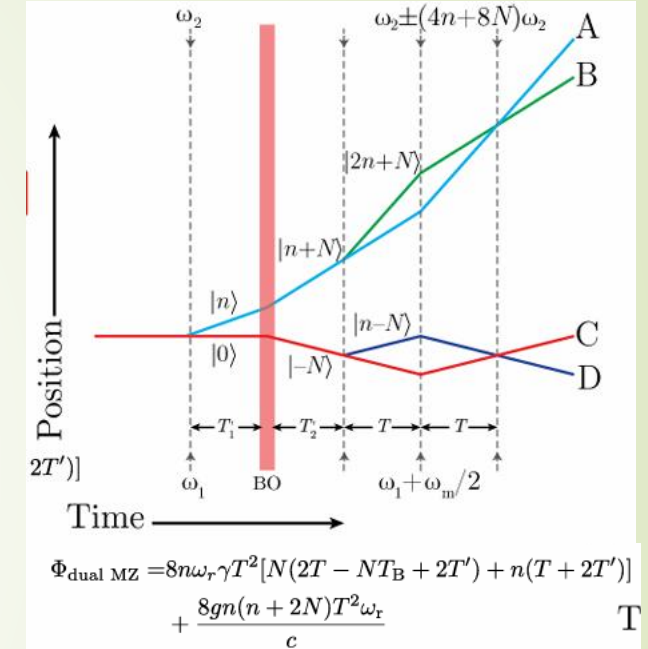
Unexpected Benefit: Vastly Improved State Preparation!

- ↓ 3~4x Molasses launch signal
- ↓ 4x RSC signal
- ↓ 3x Increased Velocity Selection



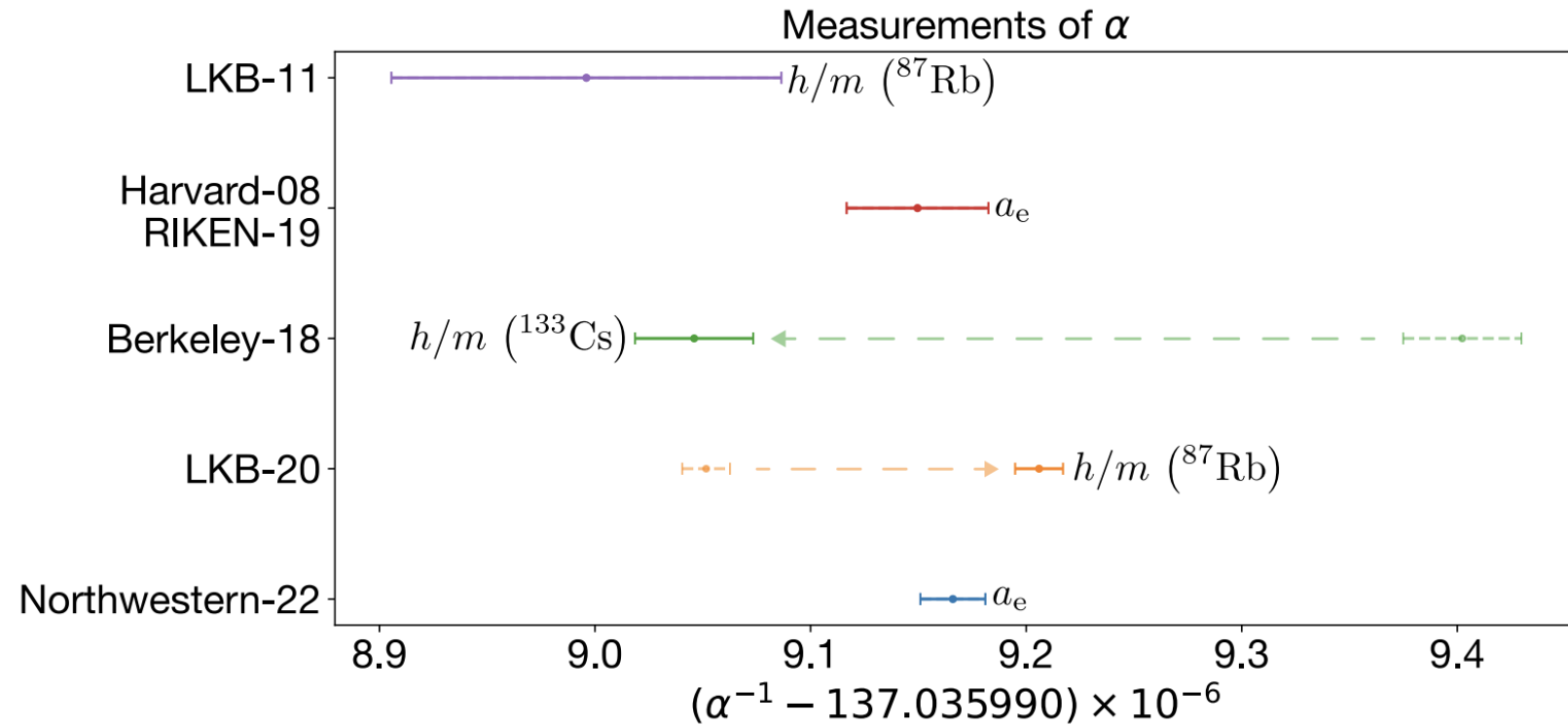
“Straightforward systematics”

- Laser frequency (± 0.03 ppb) => Frequency comb
- Acceleration gradient (± 0.02 ppb) => Measure
- Beam alignment (± 0.03 ppb) => Fiber backcoupling
- Density shift, Index of refraction => Vacuum
- Sagnac effect
- Modulation frequency wavenumber

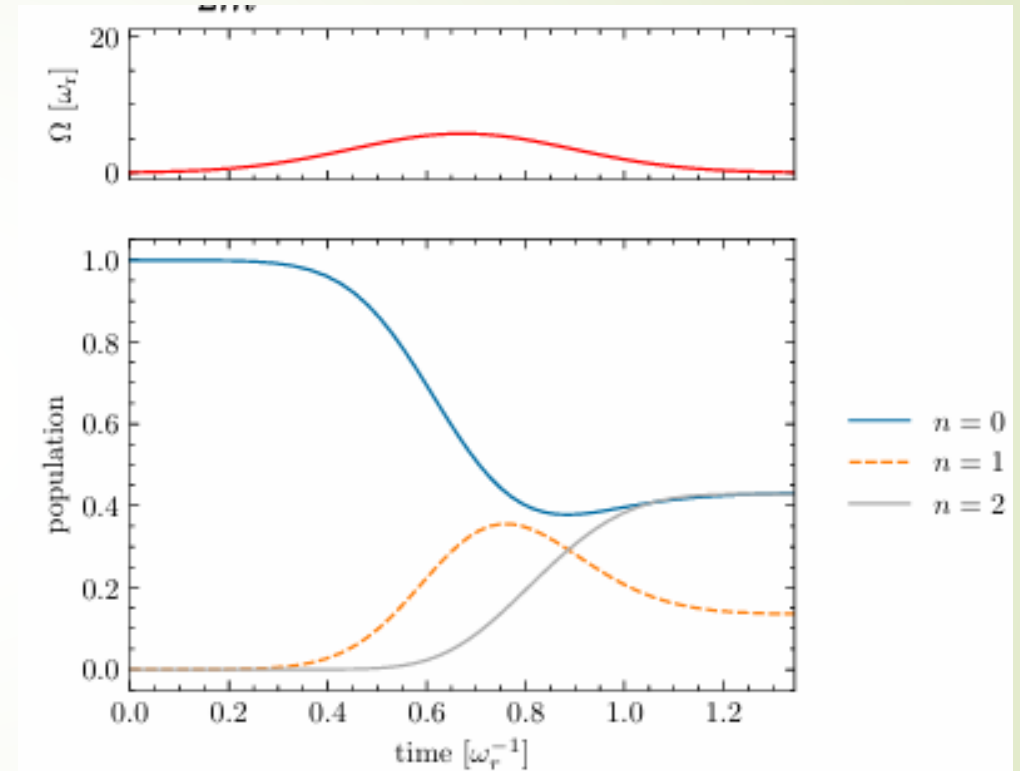
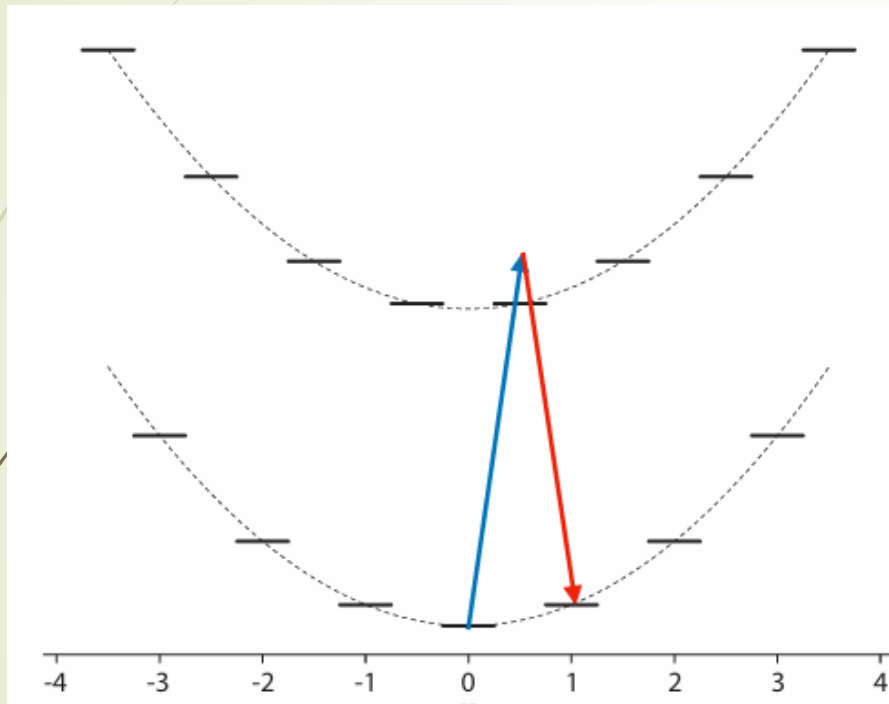


Beam-related systematics are large

- Gouy phase
- Speckle phase
- Thermal motion of atoms
- Non-Gaussian waveform
- Parasitic interferometer



Bragg beamsplitter problems



- Dynamics during pulse will change the imparted phase
- Beamsplitters populate unwanted momentum states

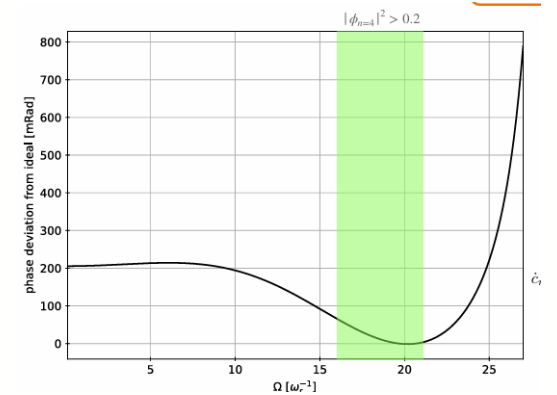
Anomalous phase

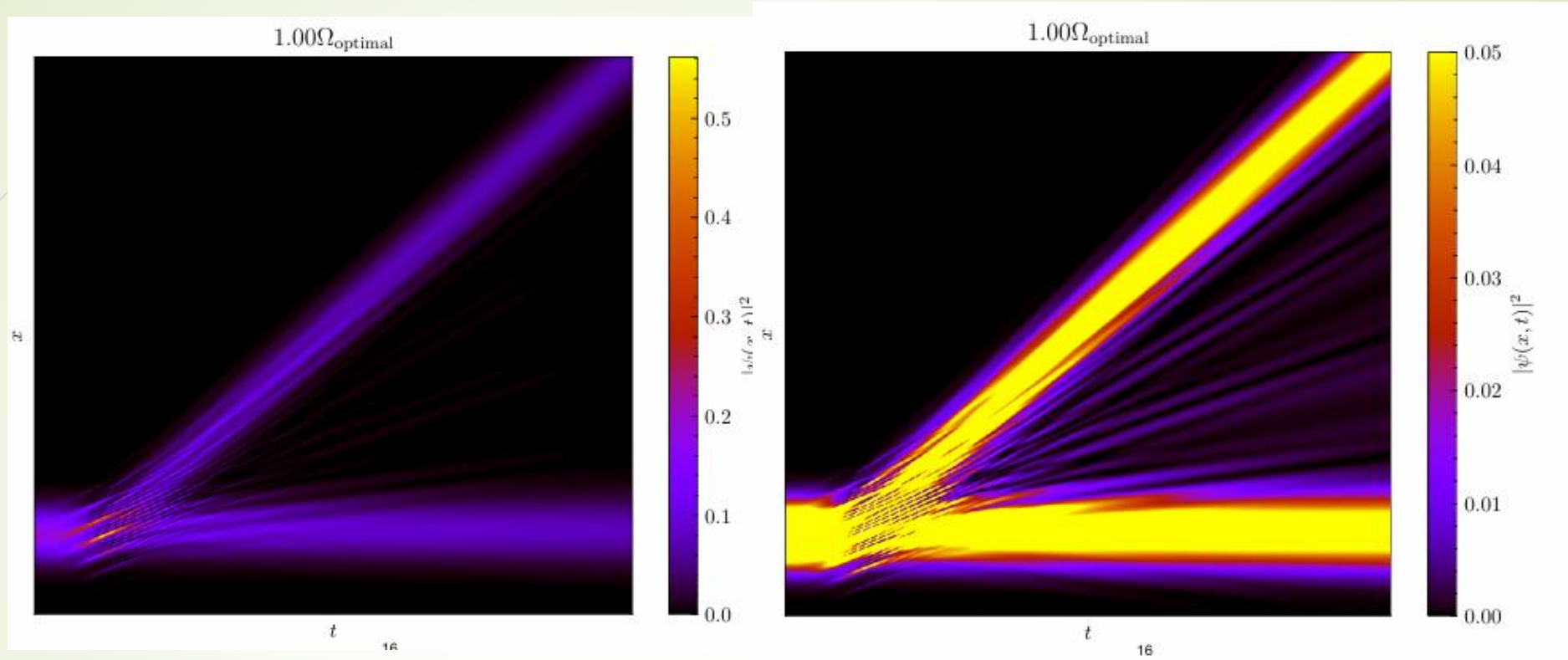
Need ~ 2 mrad uncertainty

$$i\hbar \frac{\partial}{\partial t} \Psi(x, t) = \left[\frac{\hat{p}^2}{2m} + V(x, t) \right] \Psi(x, t)$$

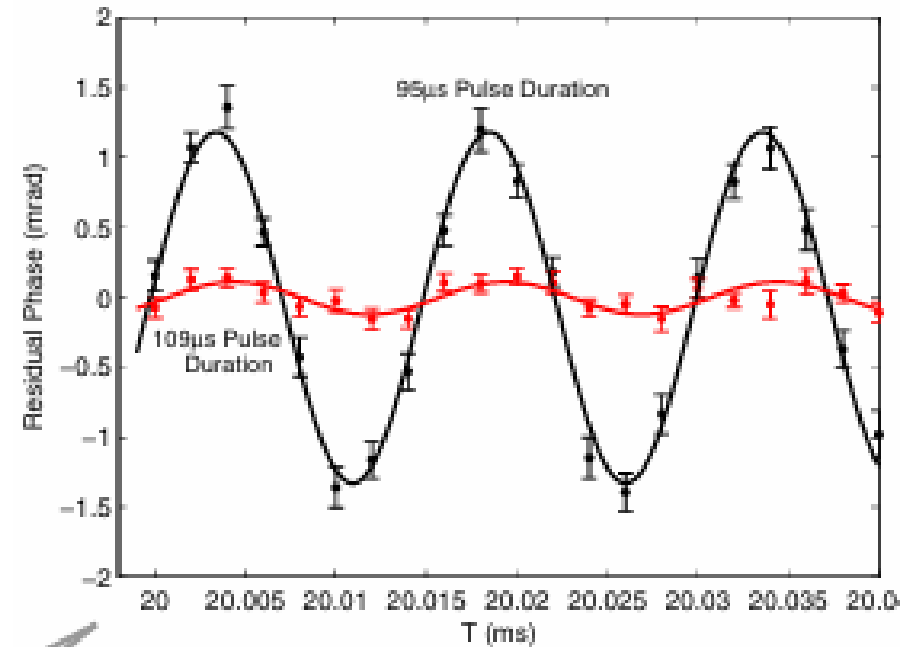
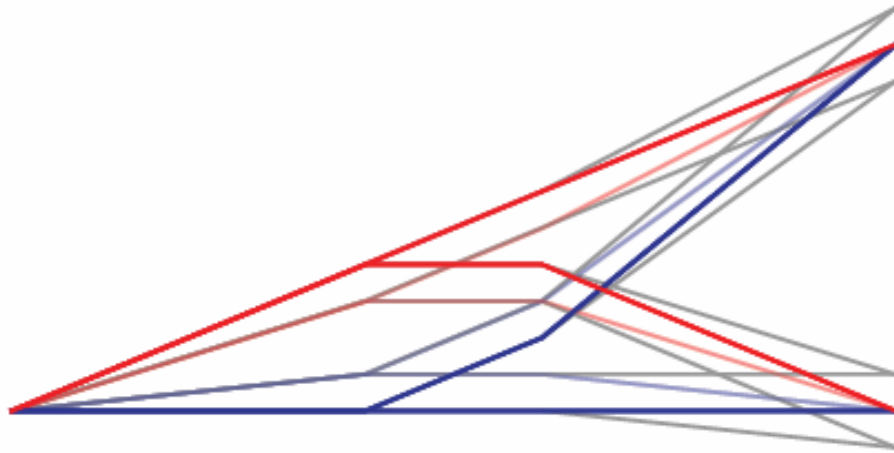
$$V(x, t) = 2\hbar\Omega_{\text{eff}}(t) \cos^2(kx - \delta t/2)$$

$$\begin{aligned} & \vdots \\ \dot{c}_0 &= i \frac{\Omega_{\text{eff}}}{2} [c_{-1} e^{i(-\delta-4)t} + c_1 e^{i(\delta-4)t}] \\ \dot{c}_1 &= i \frac{\Omega_{\text{eff}}}{2} [c_0 e^{i(-\delta+4)t} + c_2 e^{i(\delta-12)t}] \\ & \vdots \\ \dot{c}_j &= i \frac{\Omega_{\text{eff}}}{2} [c_{j-1} e^{i(-\delta+8j-4)t} + c_{j+1} e^{i(\delta-8j-4)t}] \\ & \vdots \\ \dot{c}_{n-1} &= i \frac{\Omega_{\text{eff}}}{2} [c_{n-2} e^{i(-\delta+8n-12)t} + c_n e^{i(\delta-8n+4)t}] \\ \dot{c}_n &= i \frac{\Omega_{\text{eff}}}{2} [c_{n-1} e^{i(-\delta+8n-4)t} + c_{n+1} e^{i(\delta-8n-4)t}] \\ & \vdots \end{aligned}$$





Parasitic ports



Parasitic ports

- ▶ Parasitic interference mostly due to 1st order
- ▶ Can be avoided by “magic” Bragg pulse duration

[Parker et al, PRA 053618]

Gouy Phase

- k varies across Gaussian wavefront

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

- Small scale intensity fluctuations lead to a shift in k

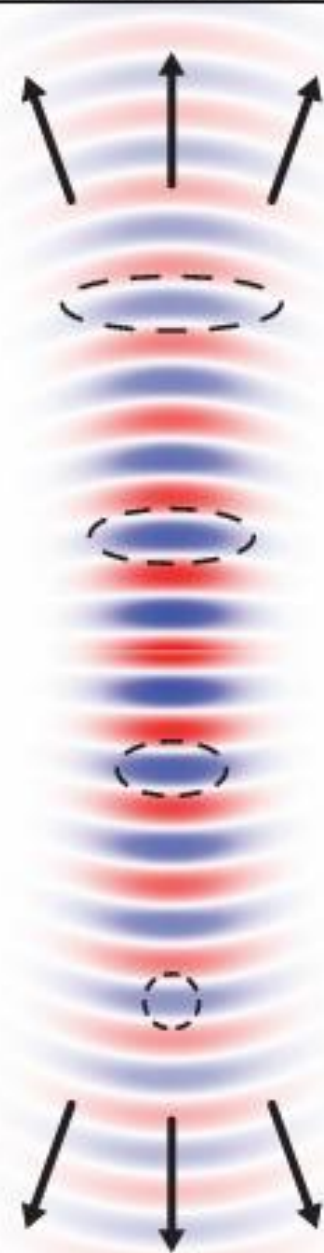
$$\frac{\delta k}{k} = -\frac{1}{2k^2} \frac{\nabla_{\perp}^2 E}{E}$$

- Shift in k shifts $\omega_r = \hbar k^2 / 2m$
- Also couples to thermal motion of atoms

phase front has curvature

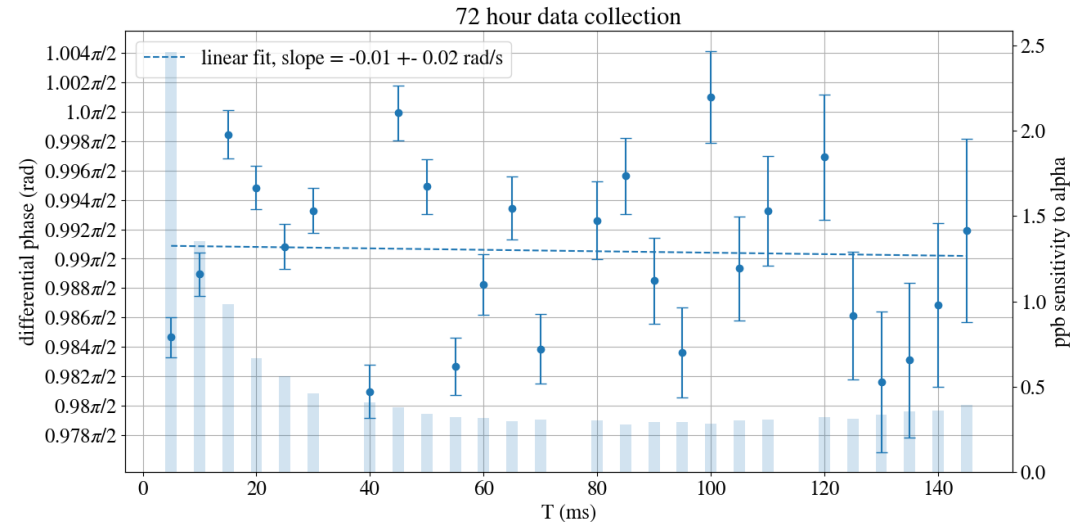


$$k \neq \omega/c$$



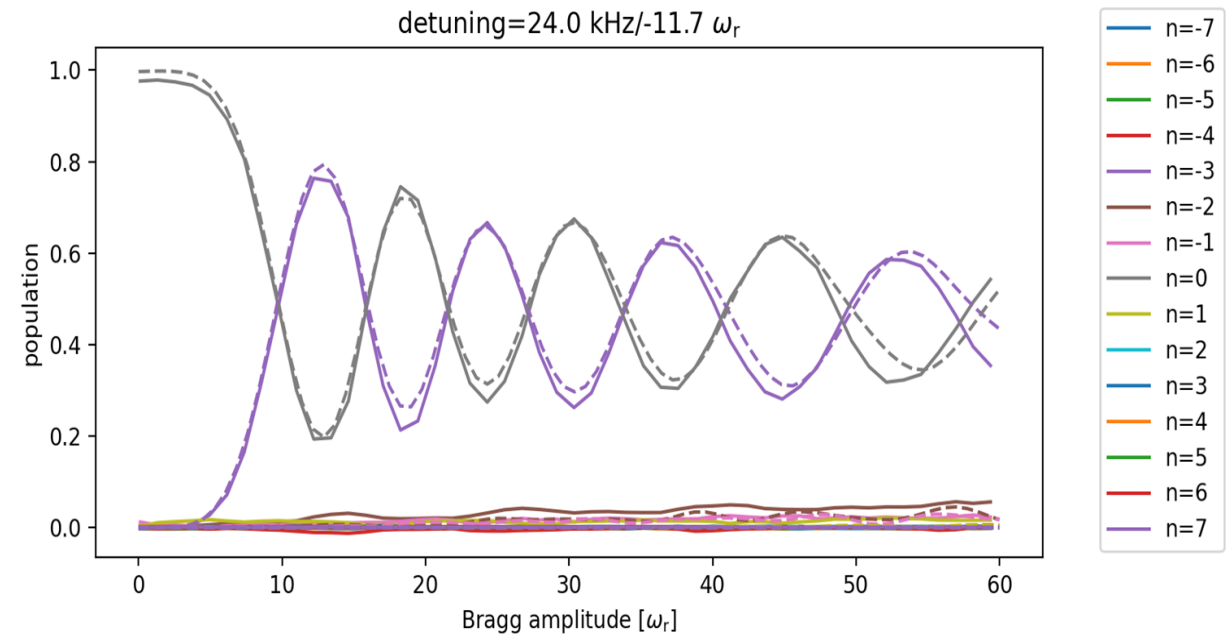
Improved statistics

- Residual systematics visible in data ...working on it now.
- $n=4$, $N=100$, T up to 145ms
- 12.5 Mrad
- Fit error 0.02 rad/s, $\delta\alpha/\alpha = 200$ ppt in 1 day (old: 160 ppt in 30 days)
- Further improvement likely

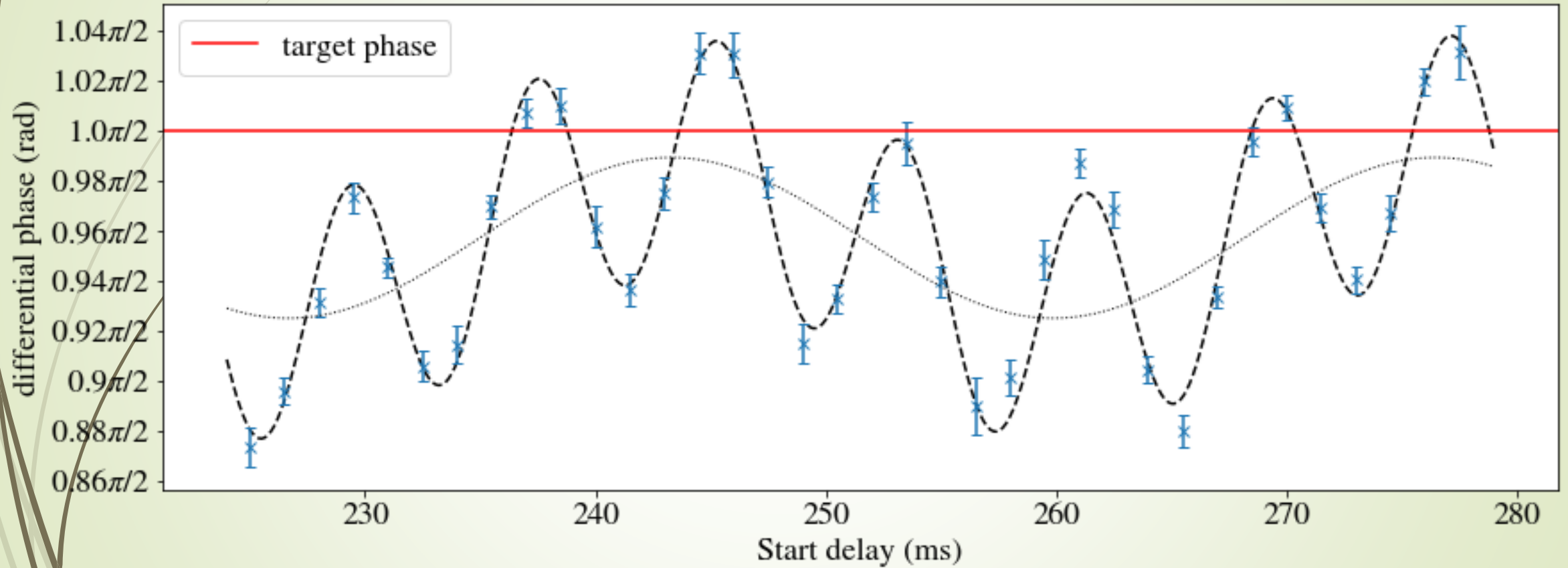


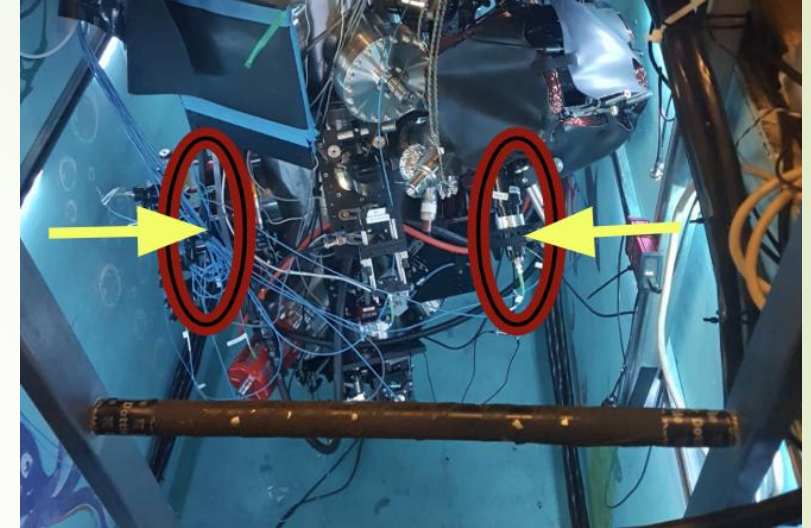
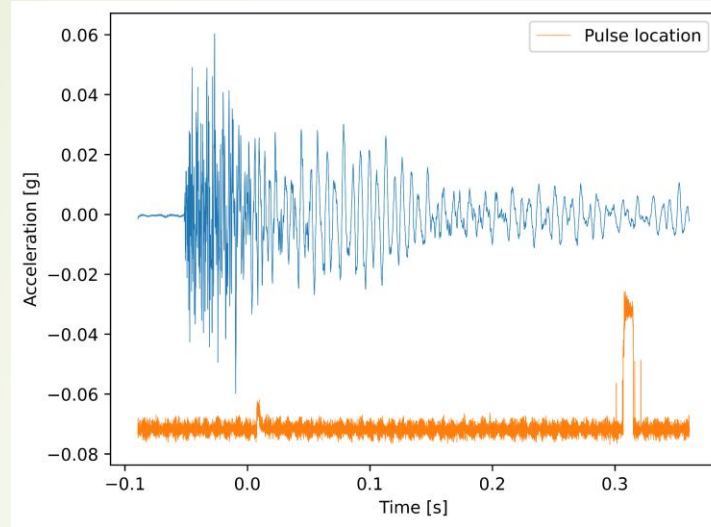
Matching simulation and experiment

- ↴ Step-by step approach to simulate the experiment, from individual elements to full experiment
- ↴ Robust simulation to be confident about systematics
- ↴ Currently working on single Bragg pulse



A new systematic...



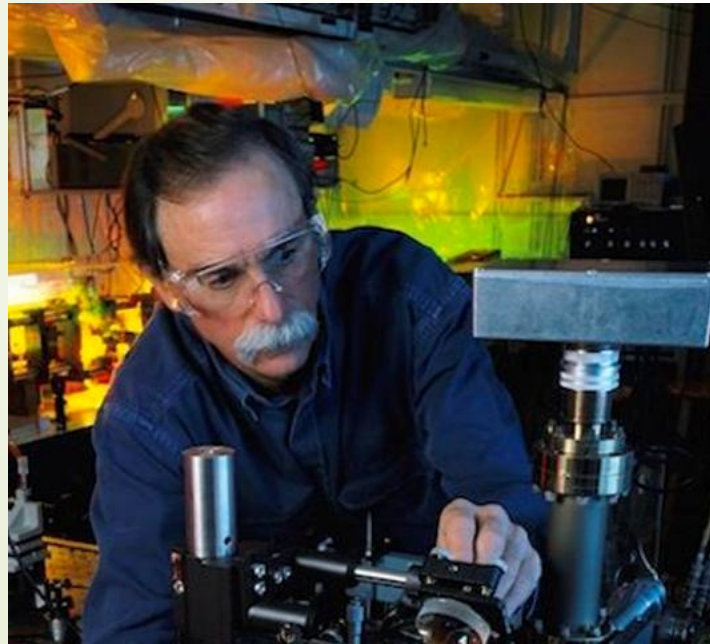


The coils are shaking the chamber

This is something we have always known (it is audible and visible)

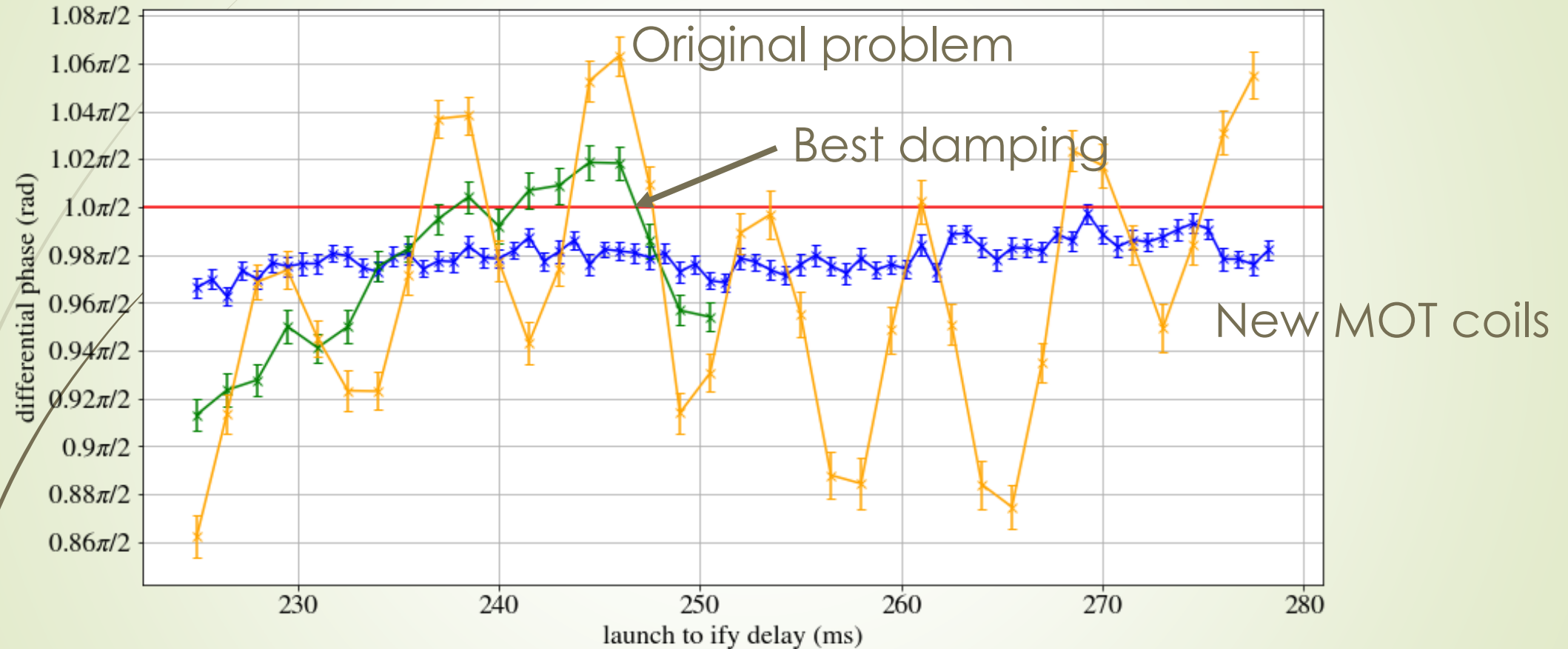
Mitigation: New MOT coils, not mounted to the chamber

Sometimes you trap the atoms



Sometimes the atoms trap you

Effect has been suppressed



...but we are still investigating the detailed cause as a test case for our simulations



Next steps

- ▶ Study systematics
 - ▶ Study pulse shapes with suppressed diffraction phase
 - ▶ Overdriven Bragg diffraction
 - ▶ Study systematics by deliberately distorting beam
- ▶ Study and implement laser-power saving schemes to increase beam diameter
- ▶ Take data with blinding scheme

Jack Roth
Madeline Bernstein
Yuno Iwasaki
Nadia Sun
Andrew Christensen
Holger Mueller

