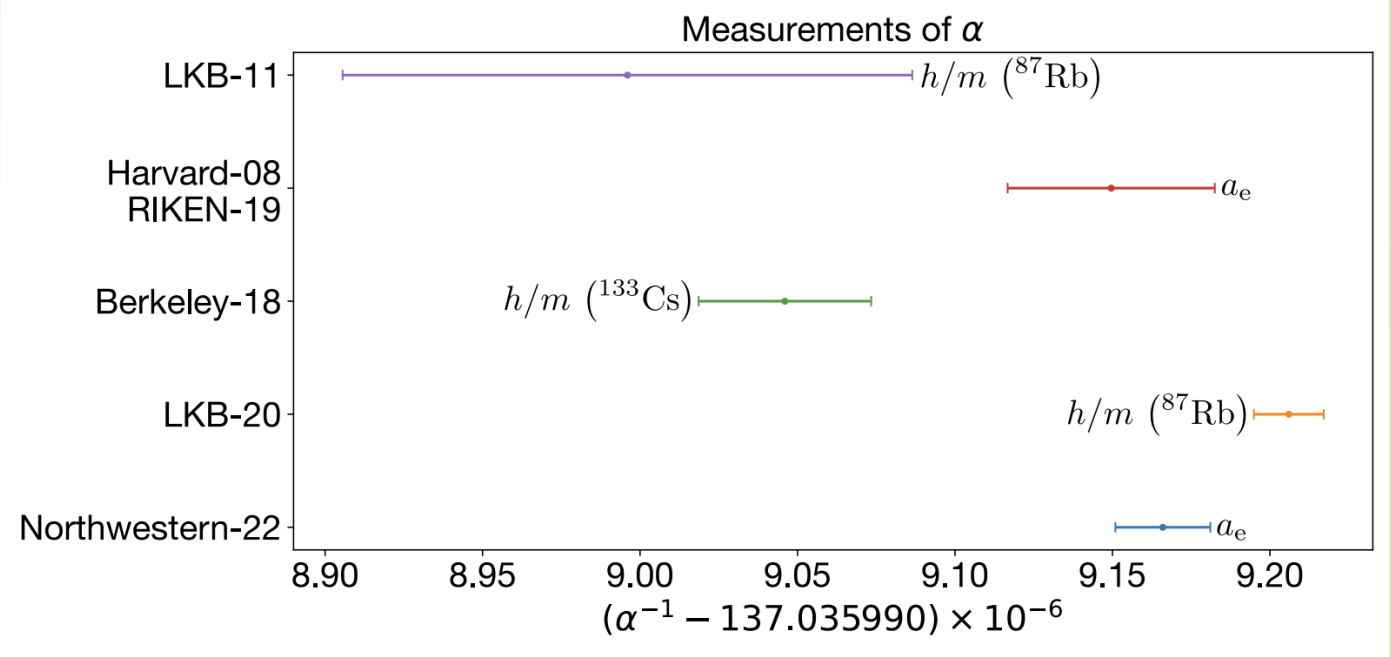
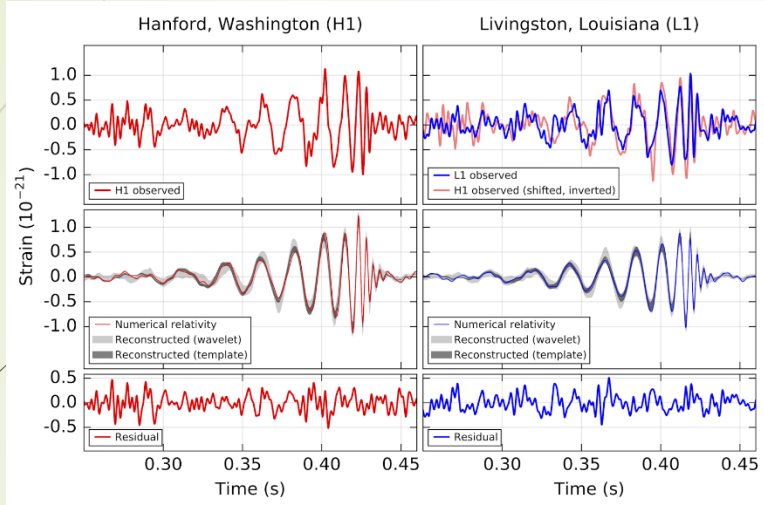


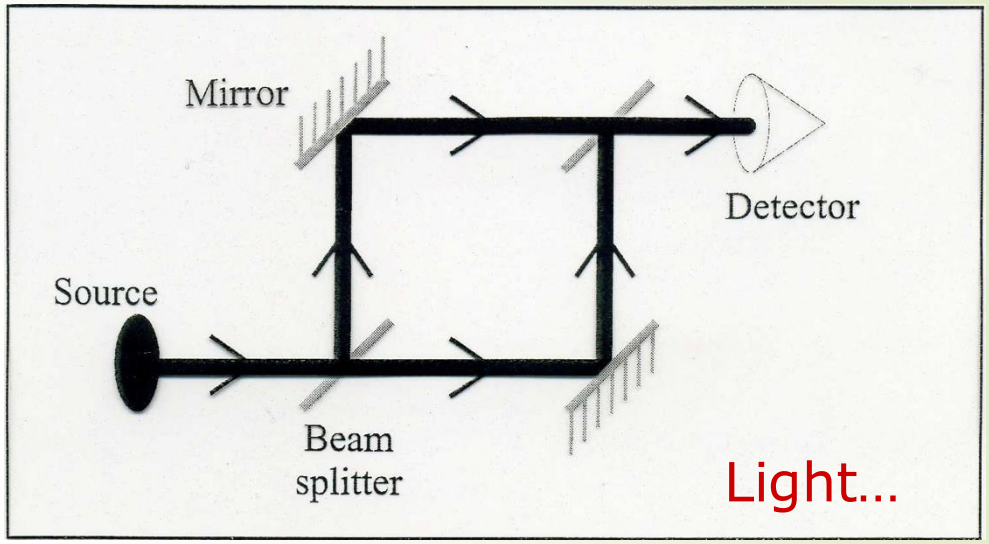
Testing the Standard Model by measuring the Fine Structure Constant

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

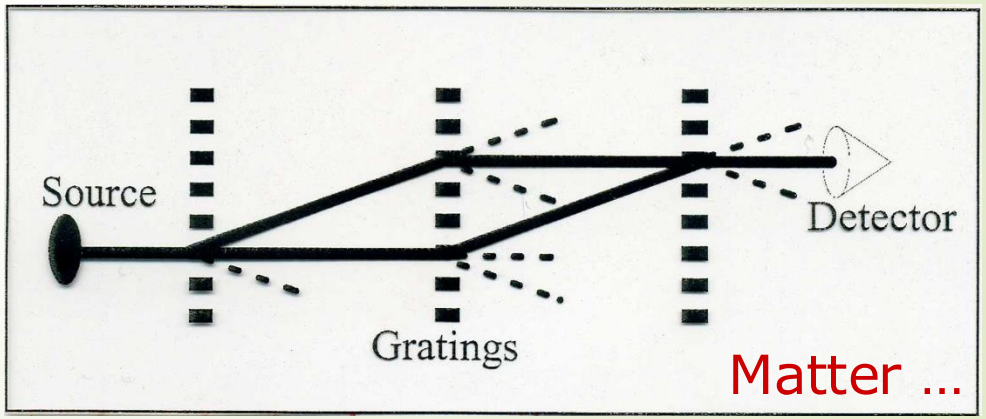
Holger Müller
UC Berkeley

Interferometry….

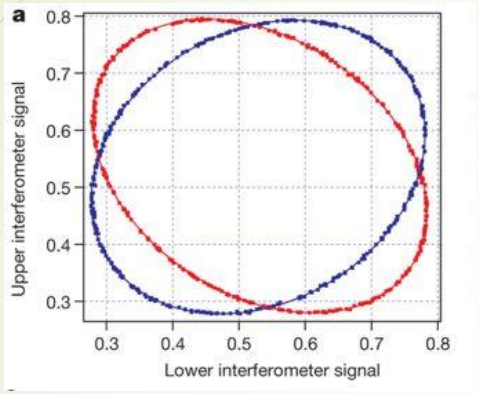


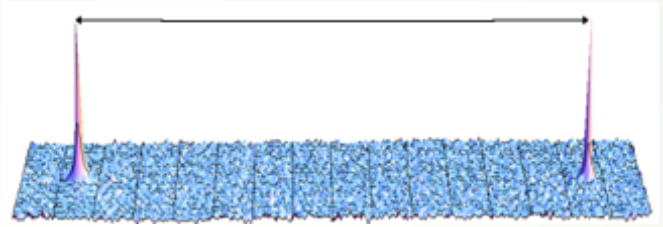


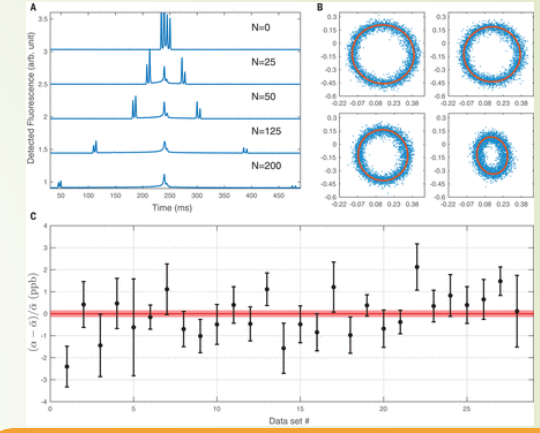
$$\lambda = \frac{h}{mv}$$



Precision atom interferometry







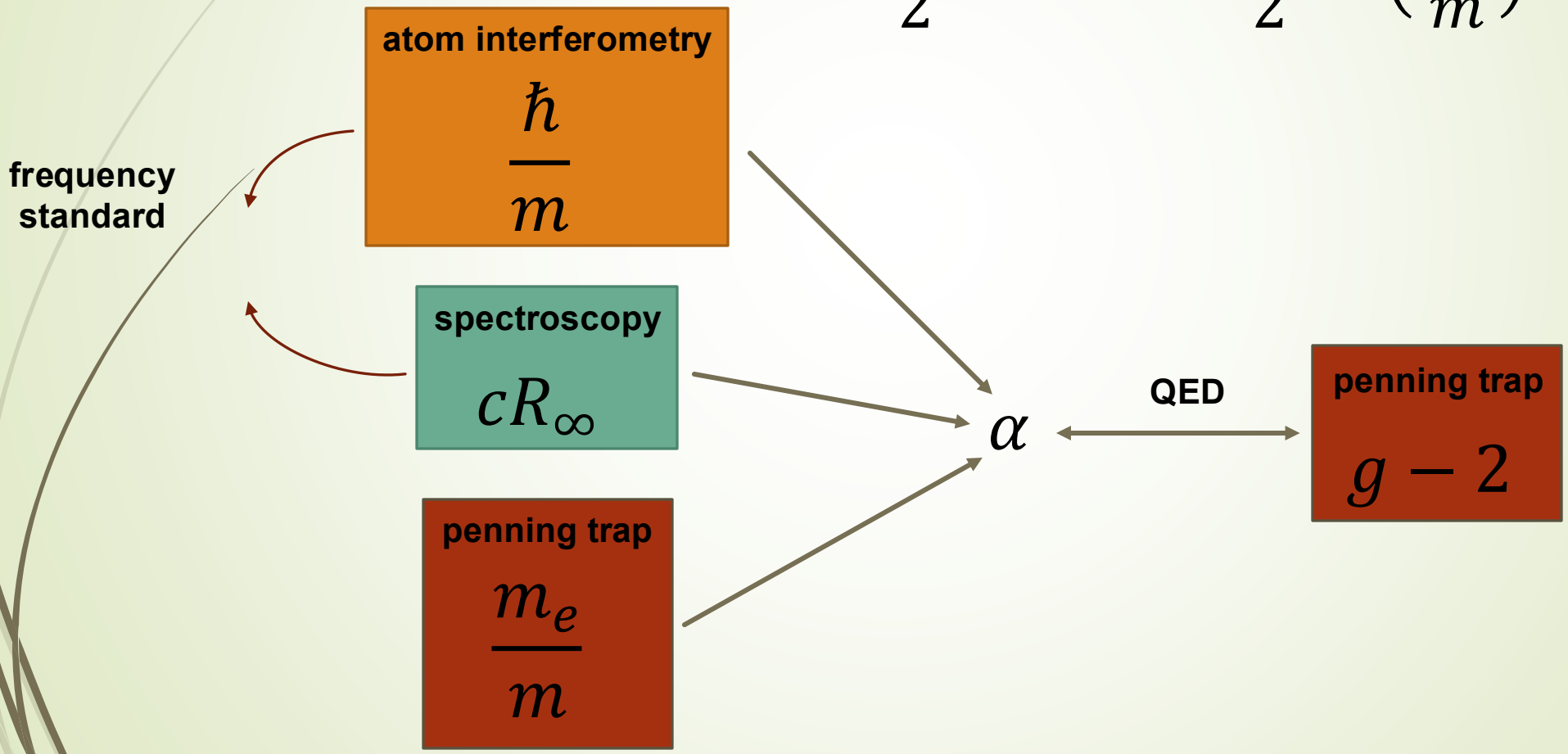
Measurement of G

Tests of GR and QM

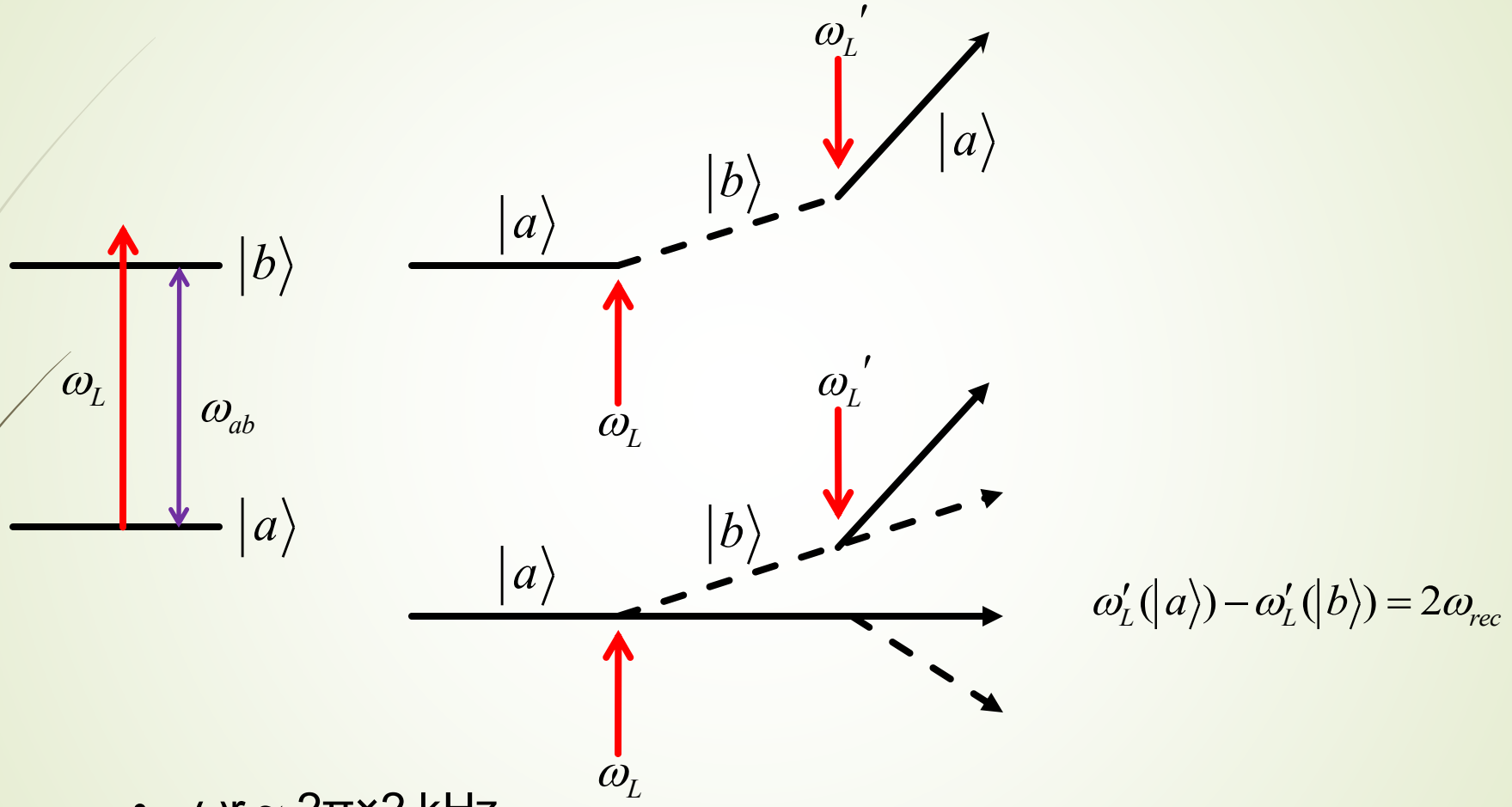
Fine-structure constant

α from ħ/m

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



Photon Recoil Measurement

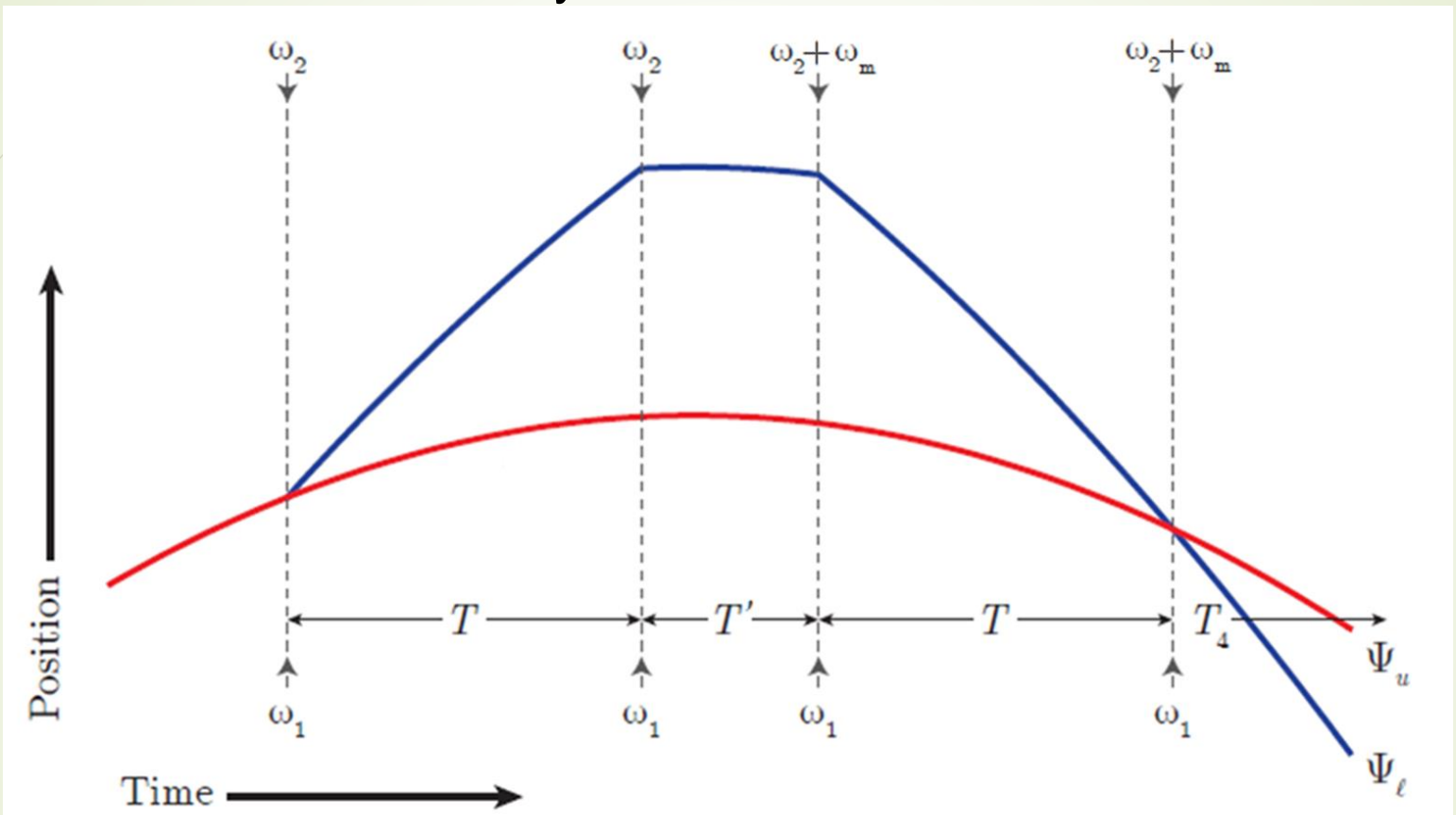


$$\omega_L'(|a\rangle) - \omega_L'(|b\rangle) = 2\omega_{rec}$$

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

Atom-interferometer measurement of α

Ramsey-Bordé Interferometer



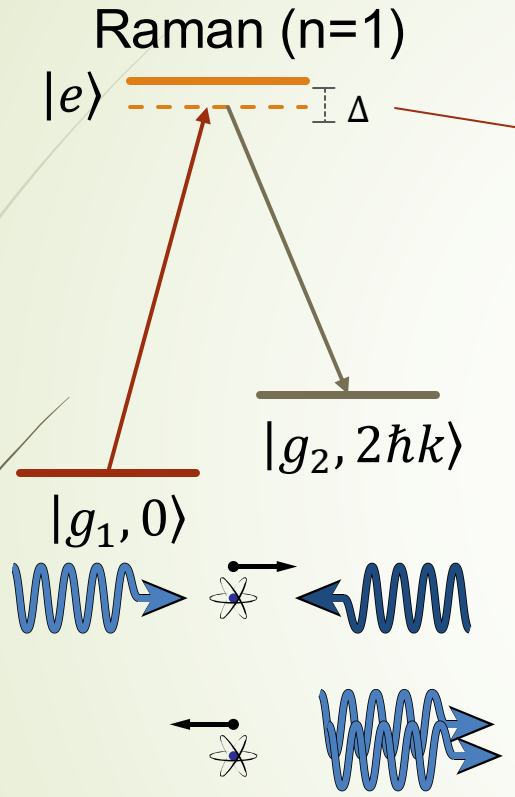
$$\Phi_{RB} = 8n^2\omega_r T - 2nkg(T + T')T - n\omega_m T$$

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

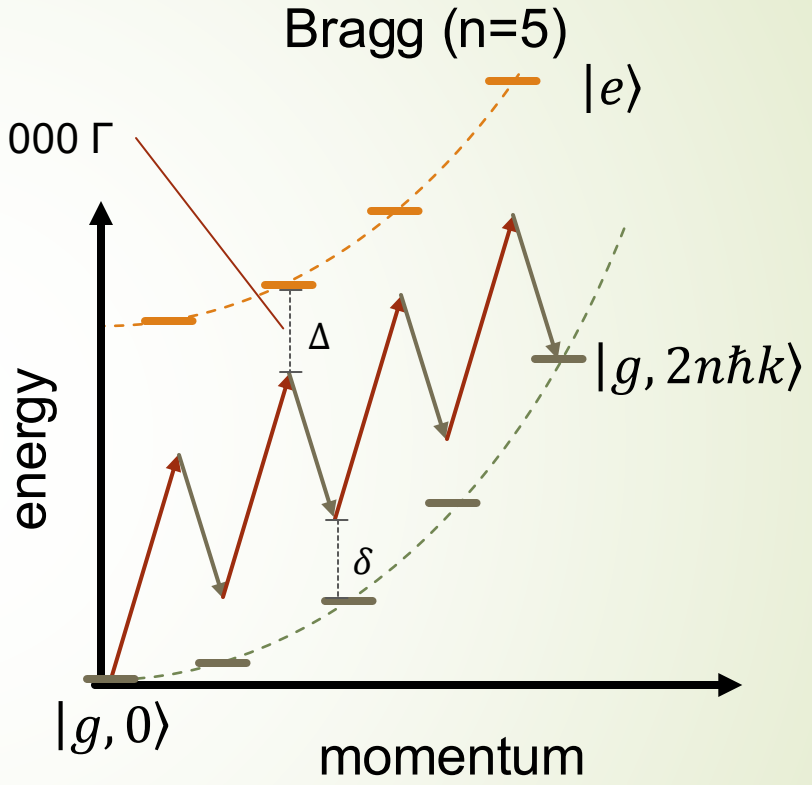
ω_r, k → h/m → α

Multi-Photon Bragg Diffraction

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



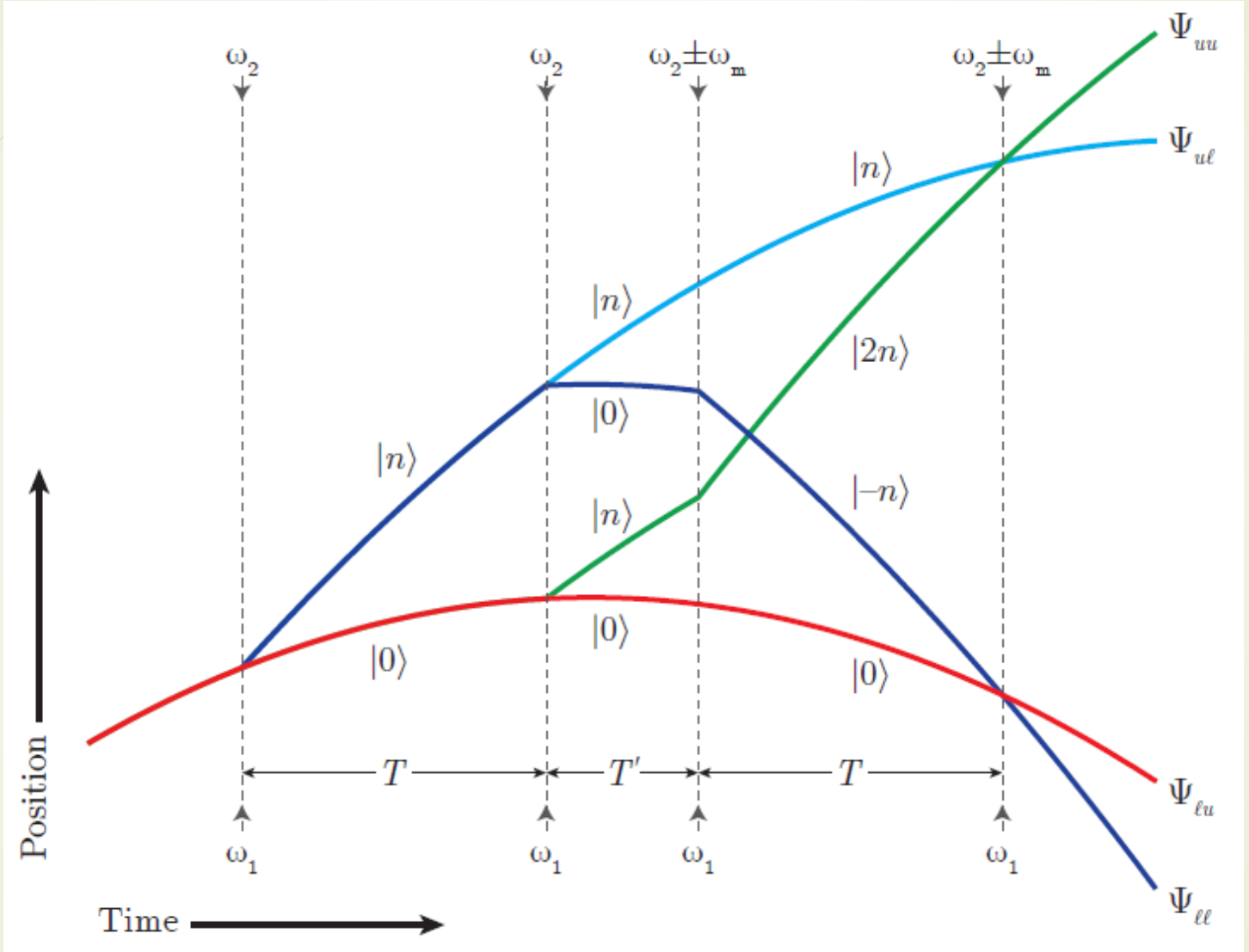
Detuning ~1000 Γ



Bragg gives you:

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

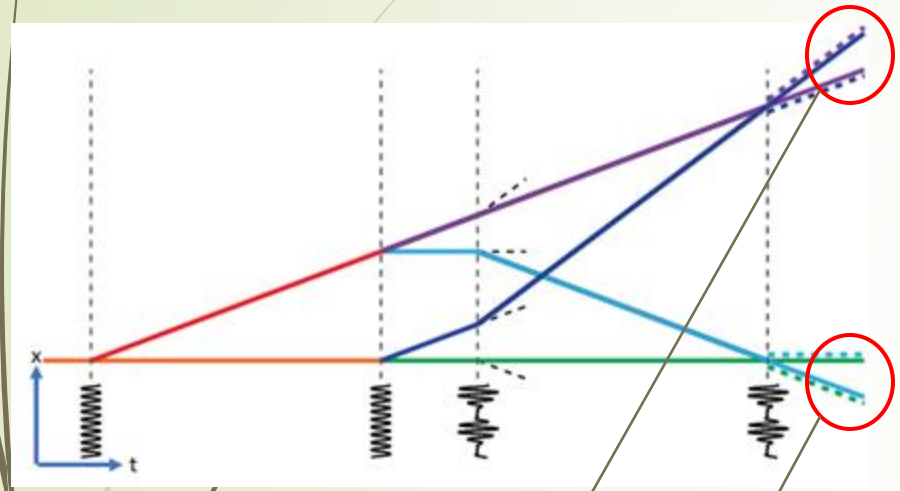
Simultaneous Conjugate Interferometers

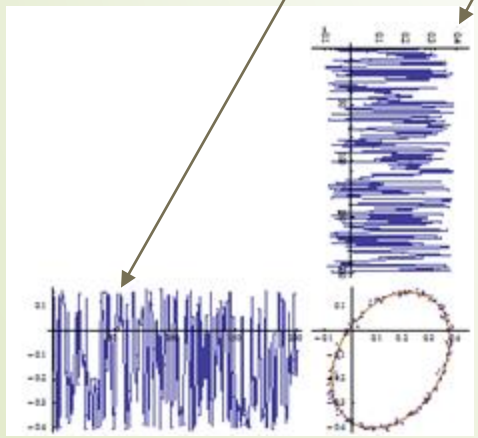


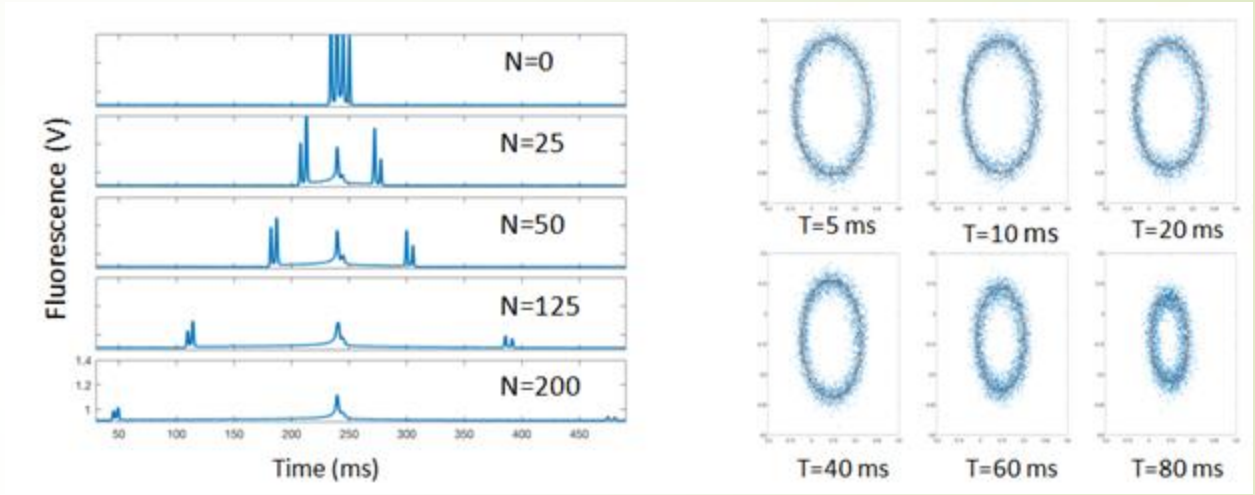
$$\Phi_{RB} = \pm 8n^2\omega_r T \pm n\omega_m T + 2nkg(T + T')T$$

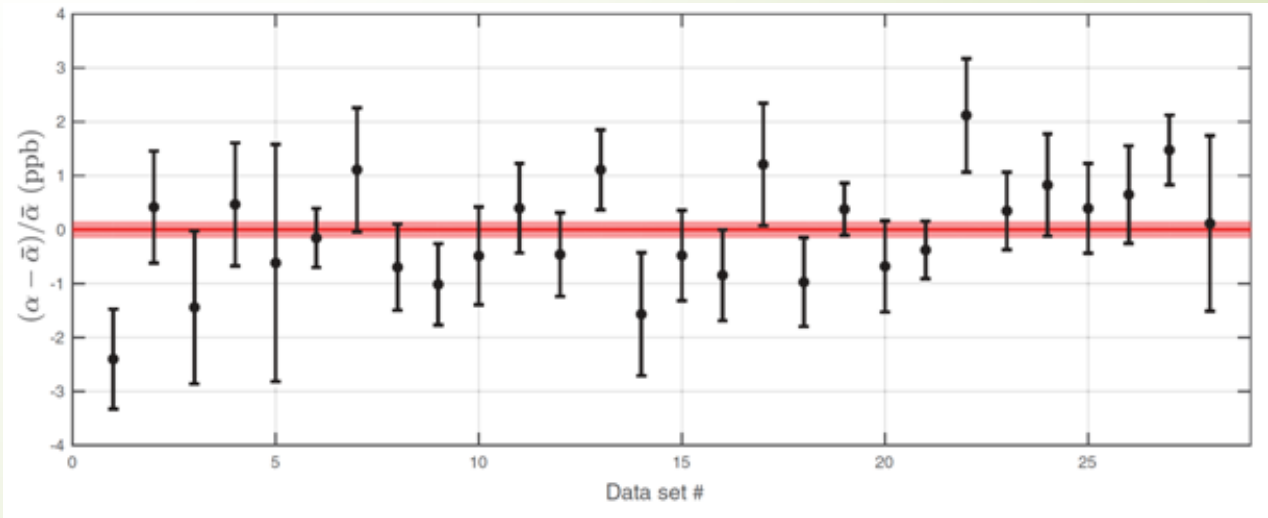
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$

Extracting signal

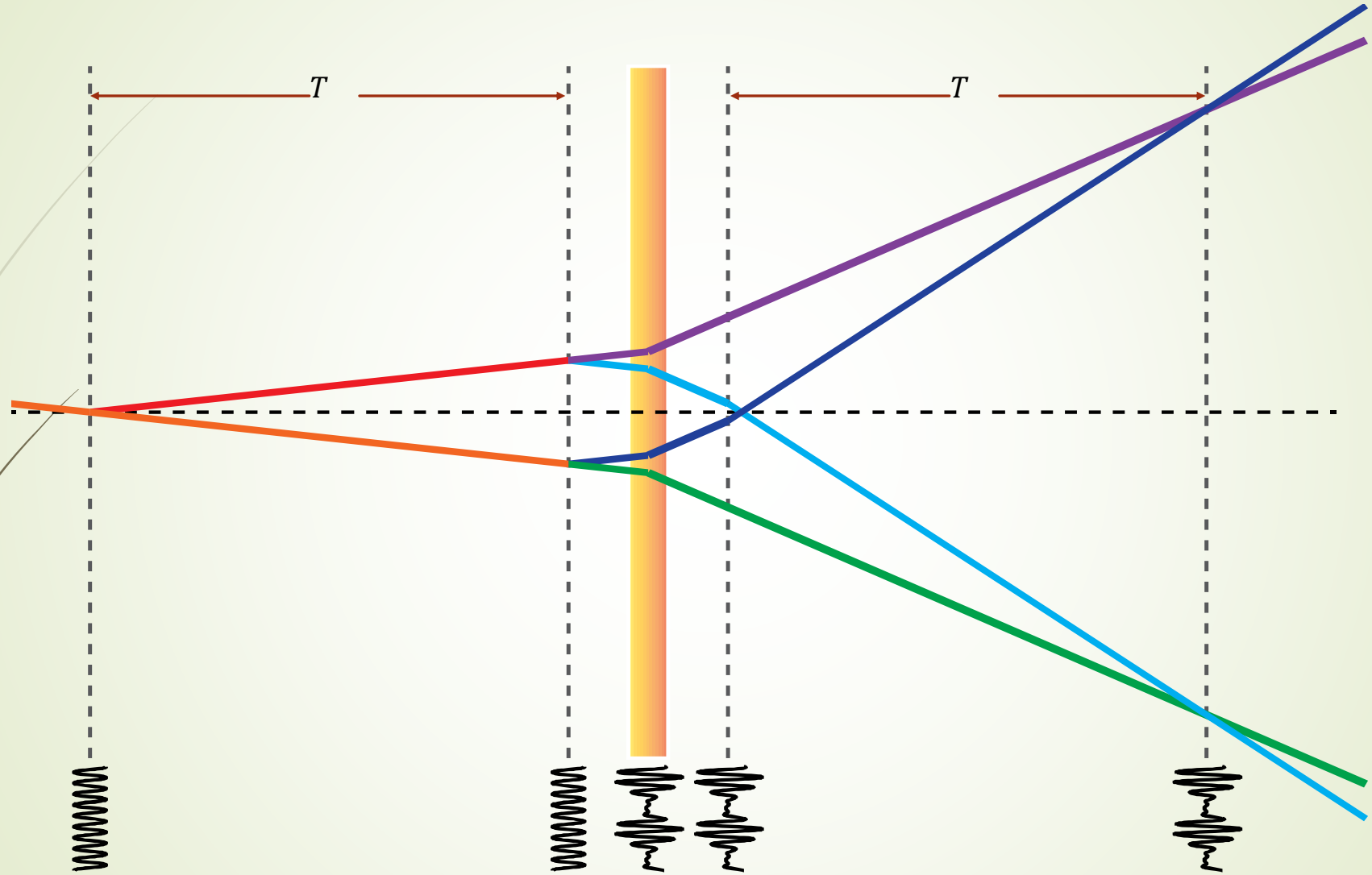






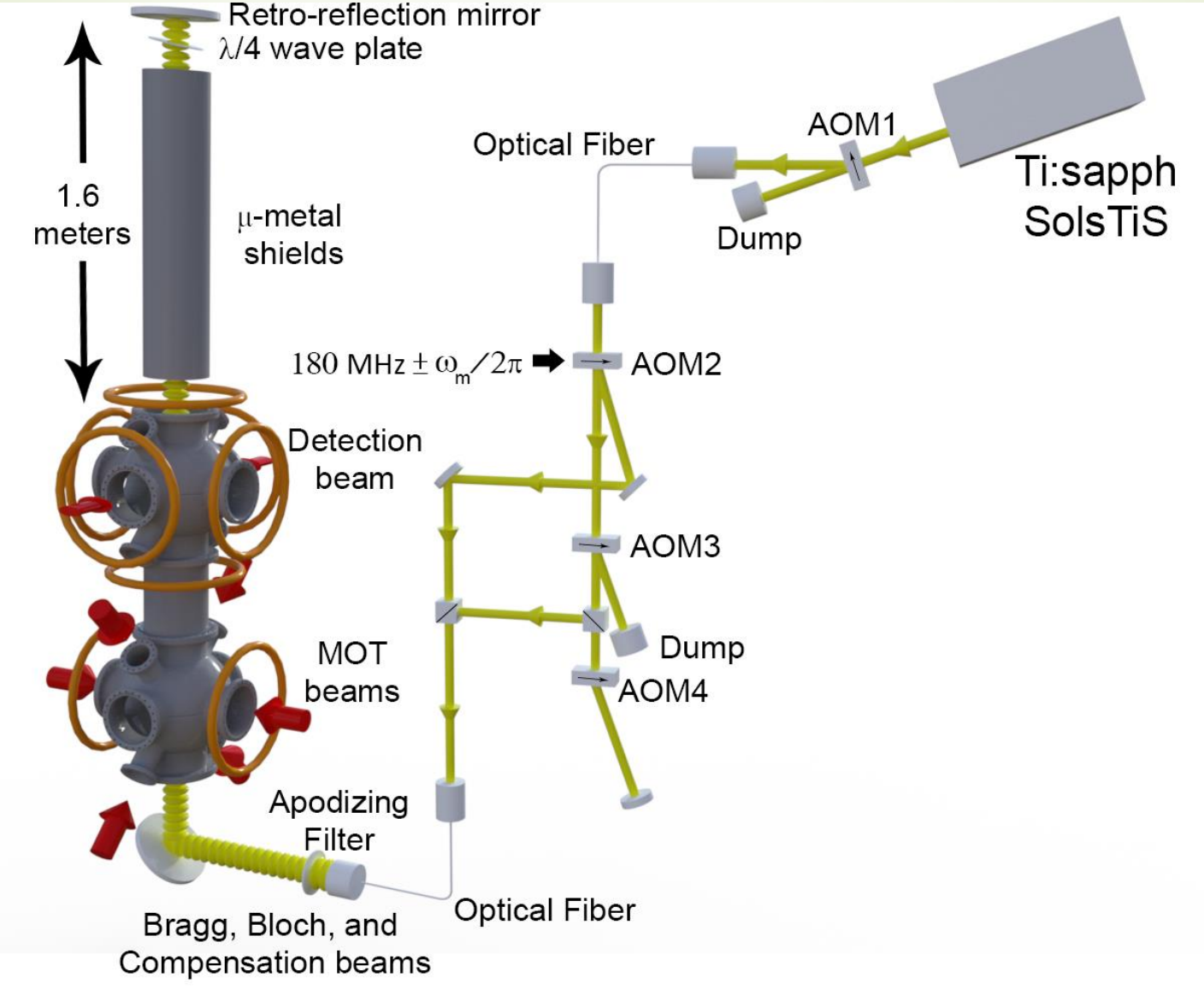


Bloch Oscillations

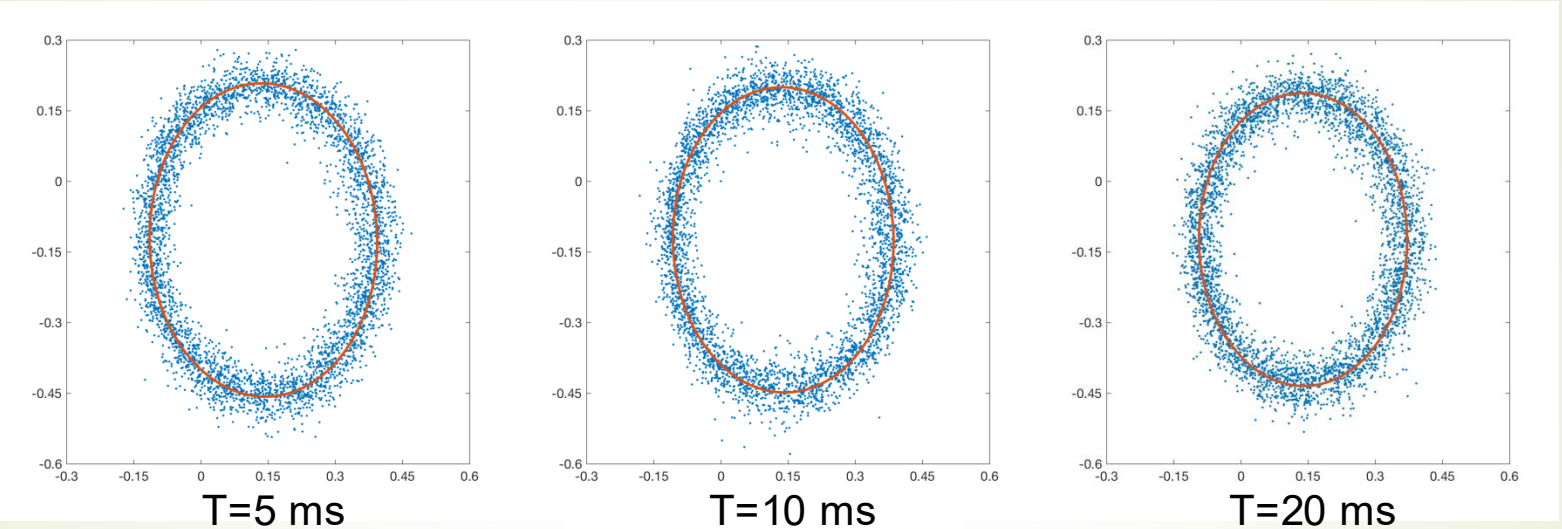


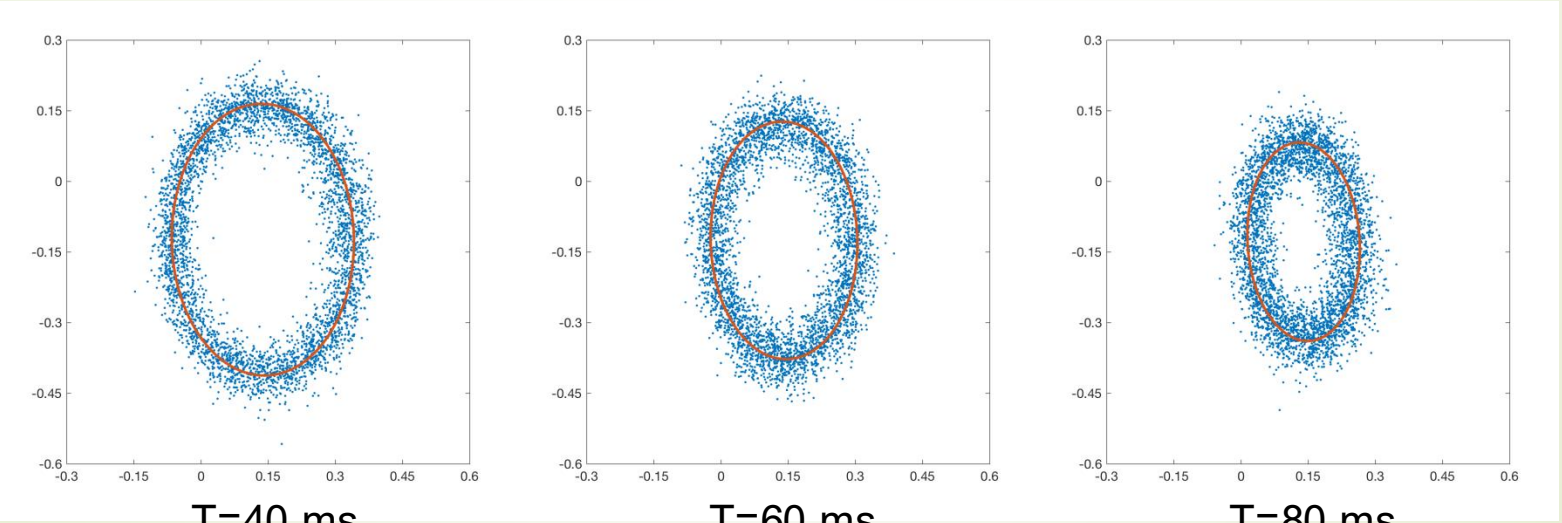
$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T$$

2018 measurement: Setup



n=5, N=125 Ellipses



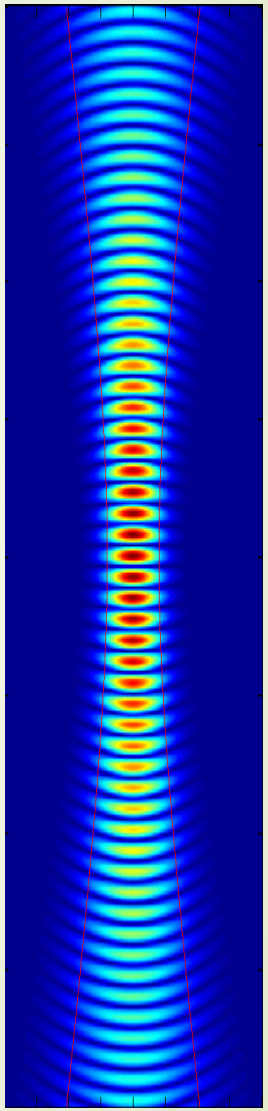


0.16 ppb systematic errors

Effect	Sect.	Value	δa/a (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	ρ=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'

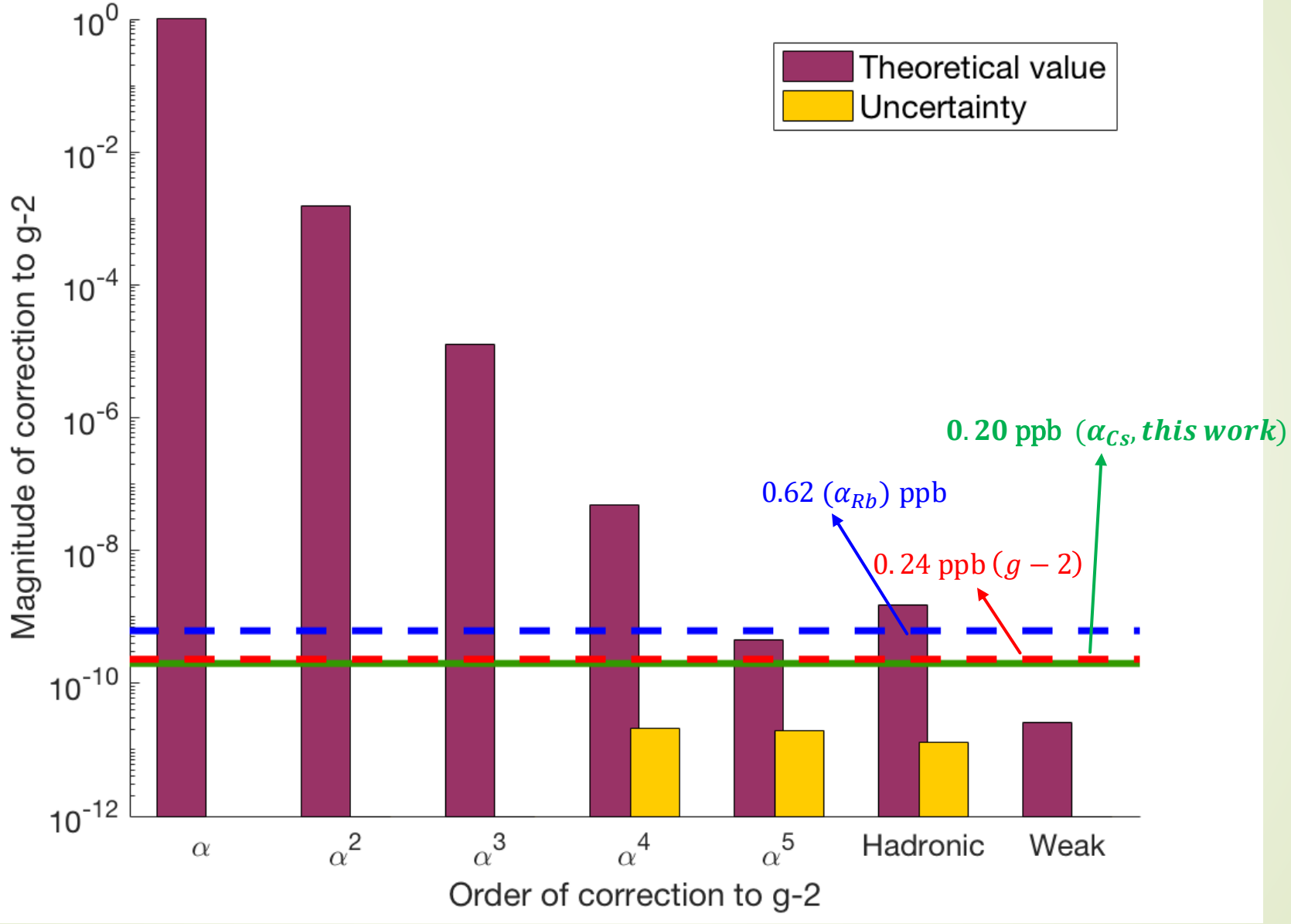


Systematic Checks

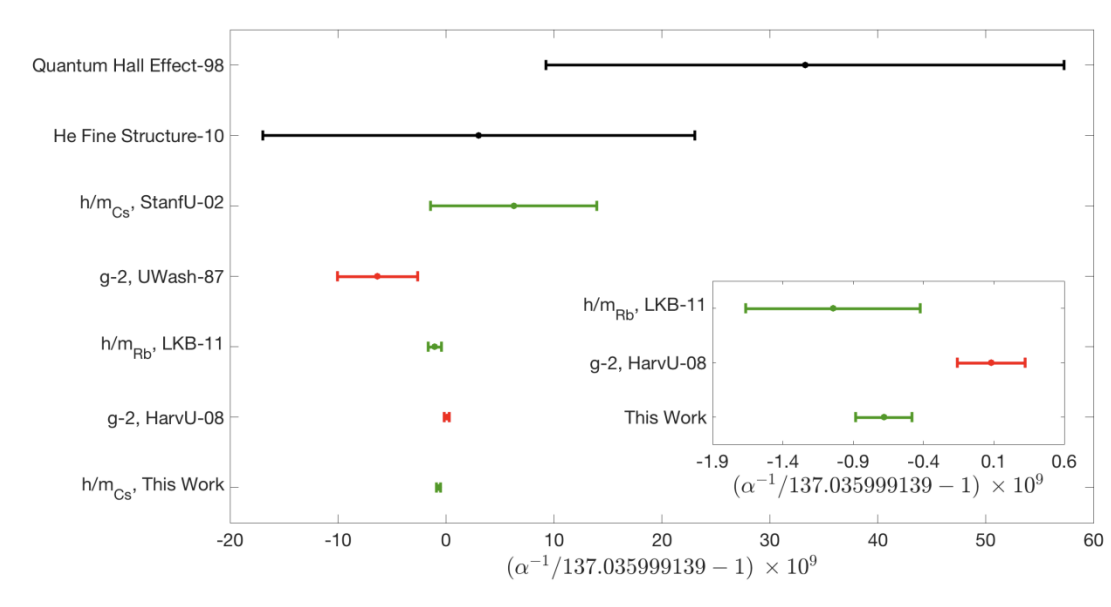
Variations of alpha w.r.t.:

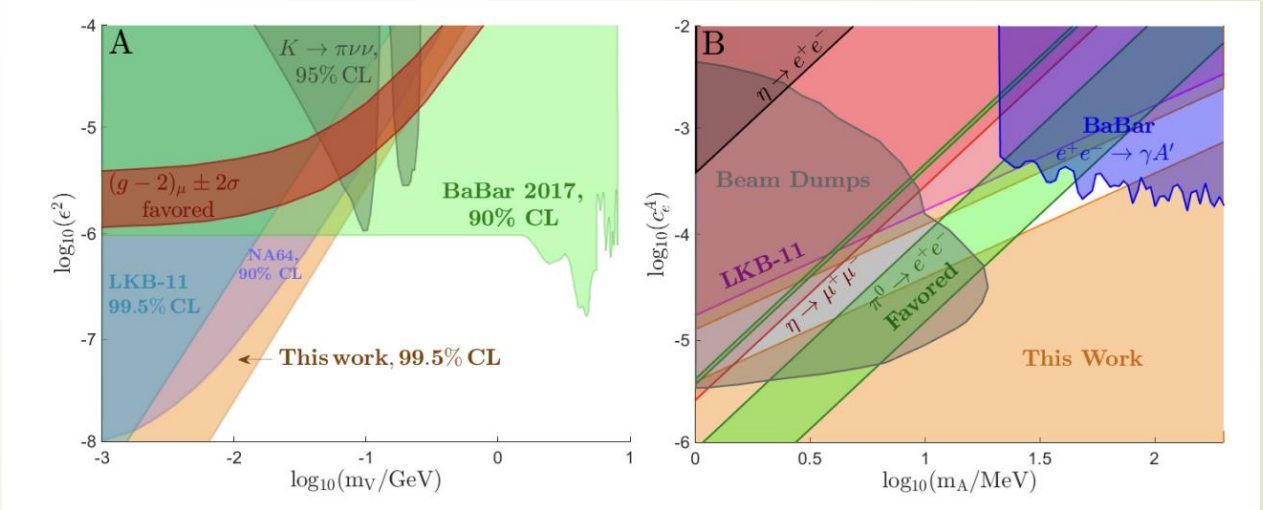
- Bloch order
- Bloch power
- Contrast
- Detection region
- Pulse intensity: overall and pulse/pulse ratio
- Speckle phase
- ω_m mixing (RF)
- ω_m mixing (optics)
- Delay of interferometer sequence
- Bias B-field
- Single-photon detuning
- Data Analysis parameters (cuts, fitting, etc.)
- Fountain alignment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

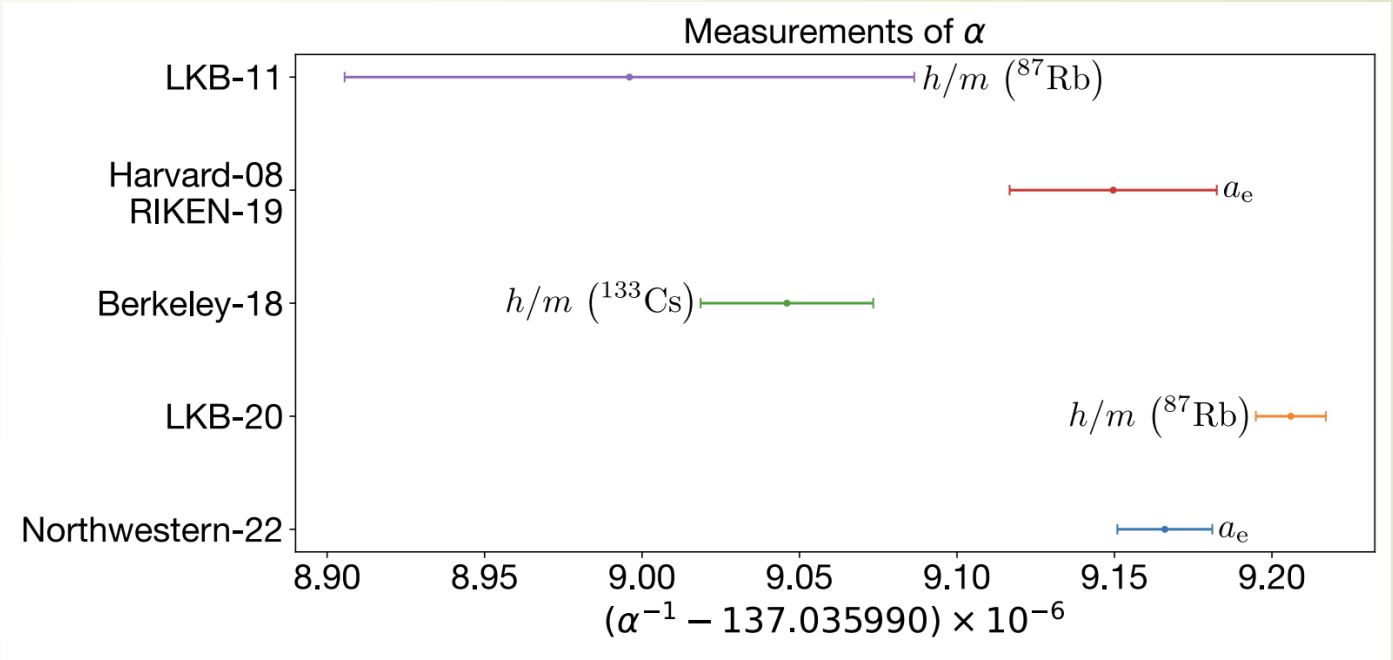
Results


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

Results

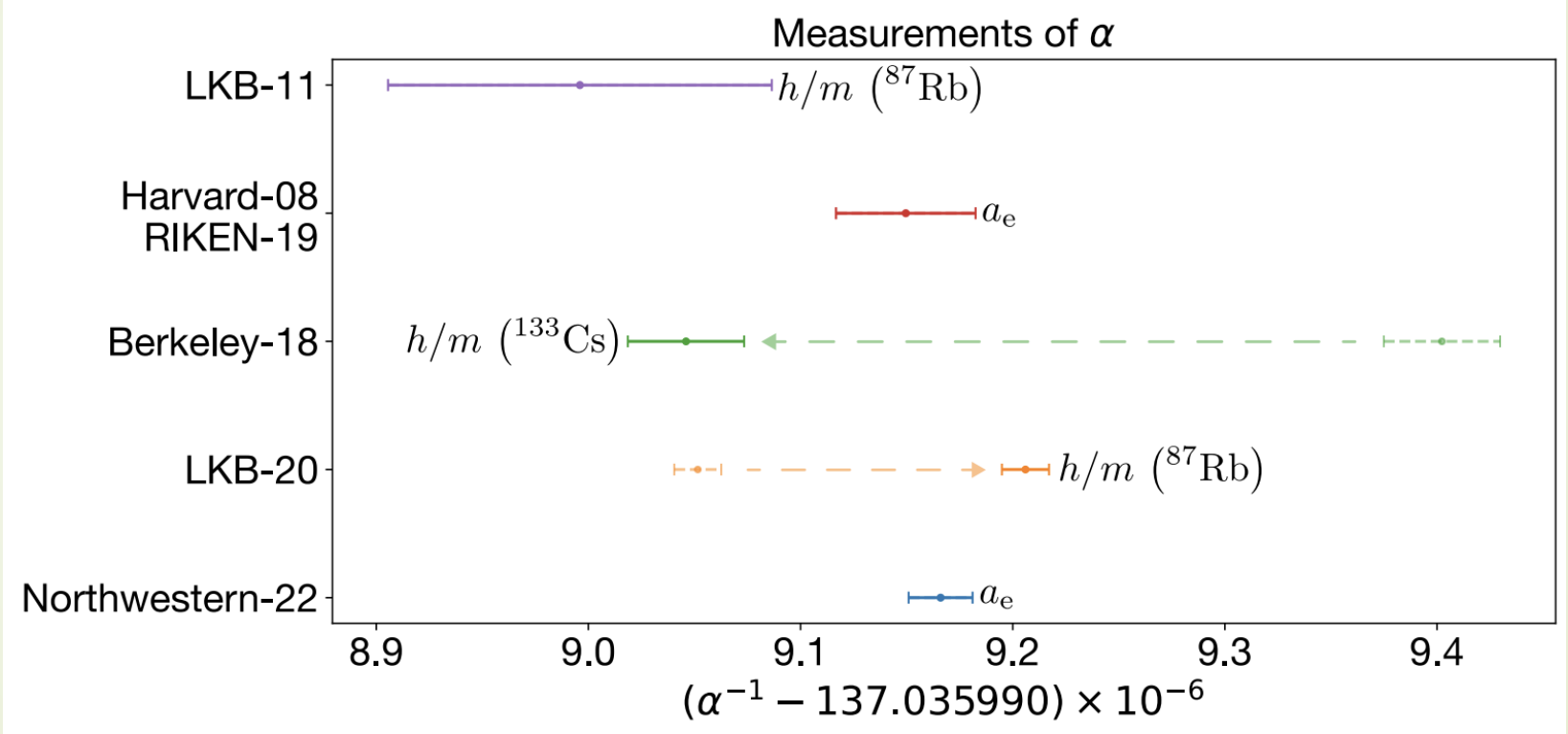

Quantum Hall Effect-98
He Fine Structure-10
h/m$_{Cs}$, StanfU-02
g-2, UWash-87
h/m$_{Rb}$, LKB-11
g-2, HarvU-08
h/m$_{Cs}$, This Work
-20 -10 0 10 20 30 40 50 60
$(\alpha^{-1}/137.035999139 - 1) \times 10^9$
h/m$_{Rb}$, LKB-11
g-2, HarvU-08
This Work
-1.9 -1.4 -0.9 -0.4 0.1 0.6
$(\alpha^{-1}/137.035999139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


A
$K \to \pi\nu\nu$, 95% CL
$(g-2)_\mu \pm 2\sigma$ favored
BaBar 2017, 90% CL
NA64, 90% CL
LKB-11 99.5% CL
This work, 99.5% CL
$\log_{10}(\epsilon^2)$
$\log_{10}(m_V/\mathrm{GeV})$
B
$\eta \to e^+e^-$
BaBar
$e^+e^- \to \gamma A'$
Beam Dumps
LKB-11
$\eta \to \mu^+\mu^-$
$\pi^0 \to e^+e^-$
Favored
This Work
$\log_{10}(c_e^A)$
$\log_{10}(m_A/\mathrm{MeV})$

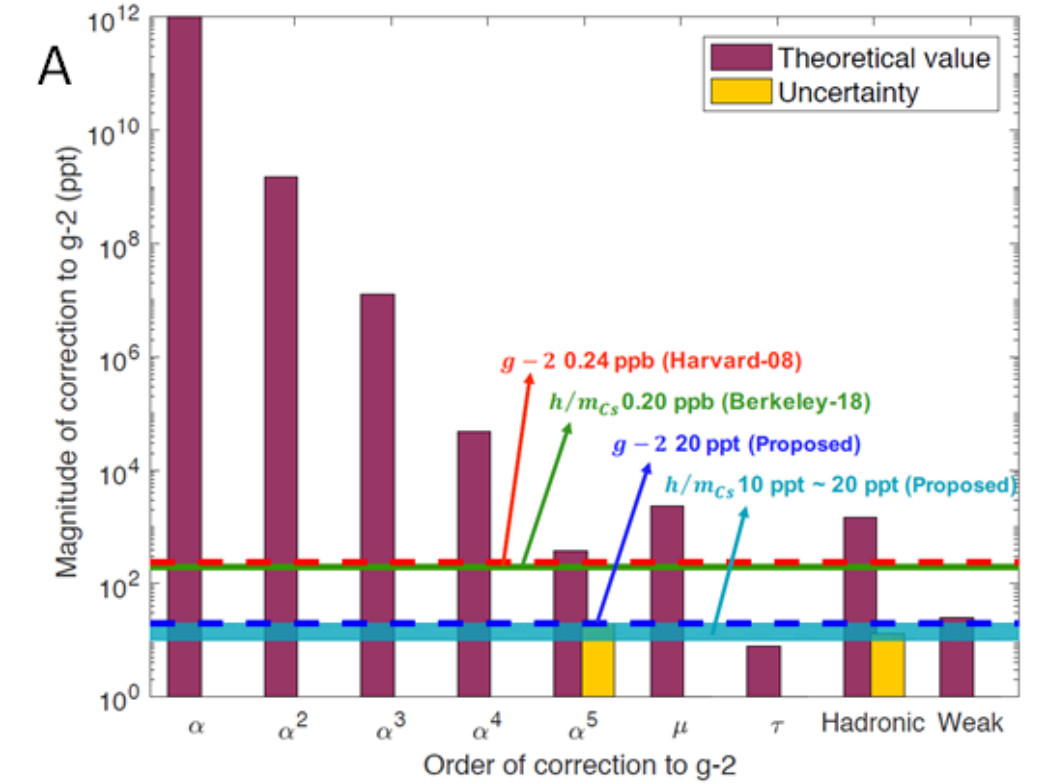


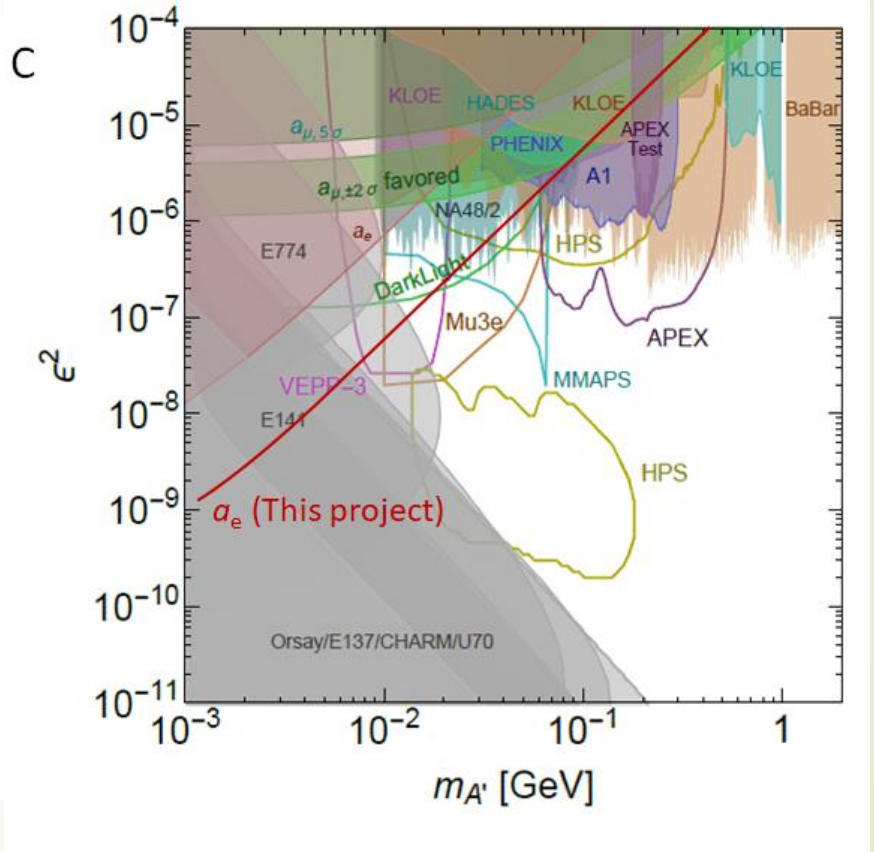
New measurement

Beam-related systematics are large



New physics reach





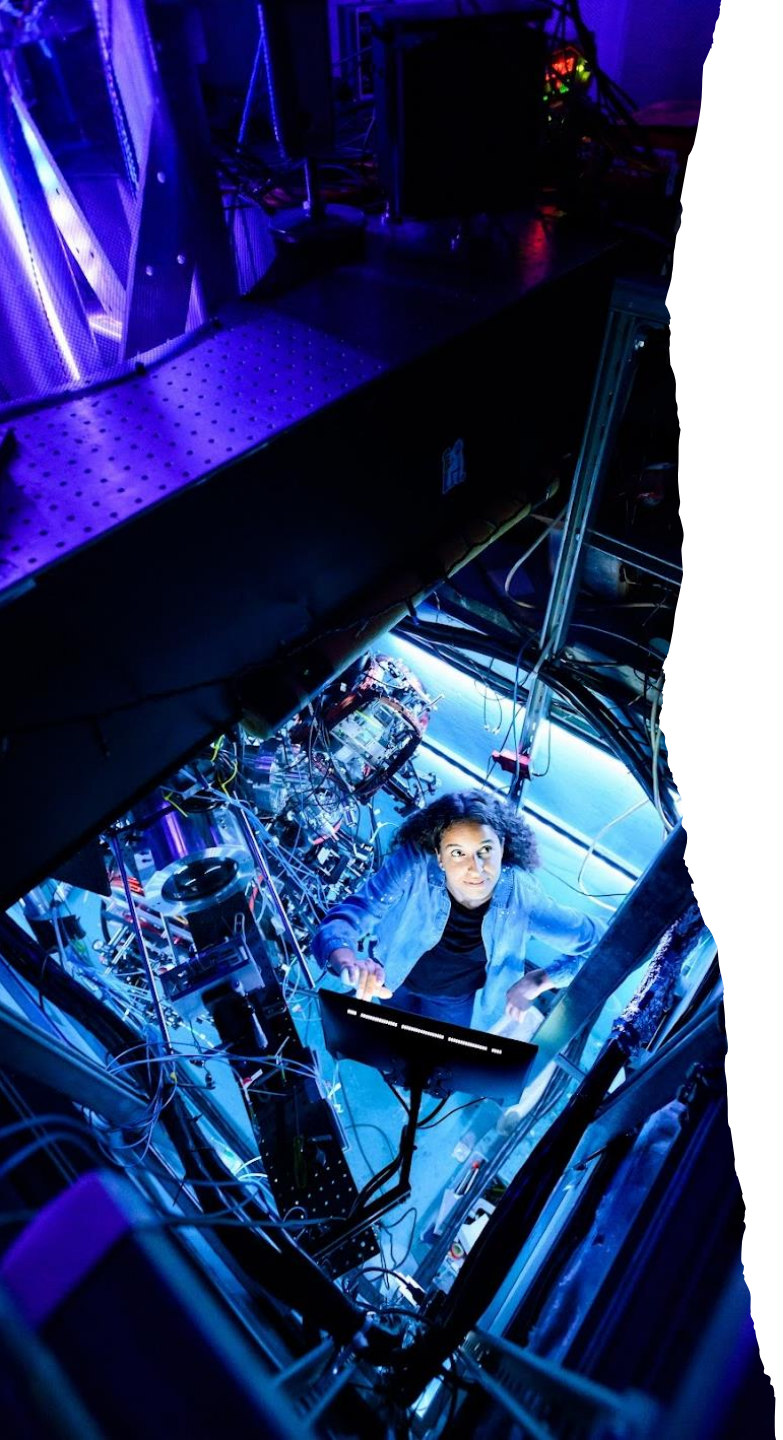
Approach…

Effect	Value	δa/a (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

Larger, cleaner laser beam

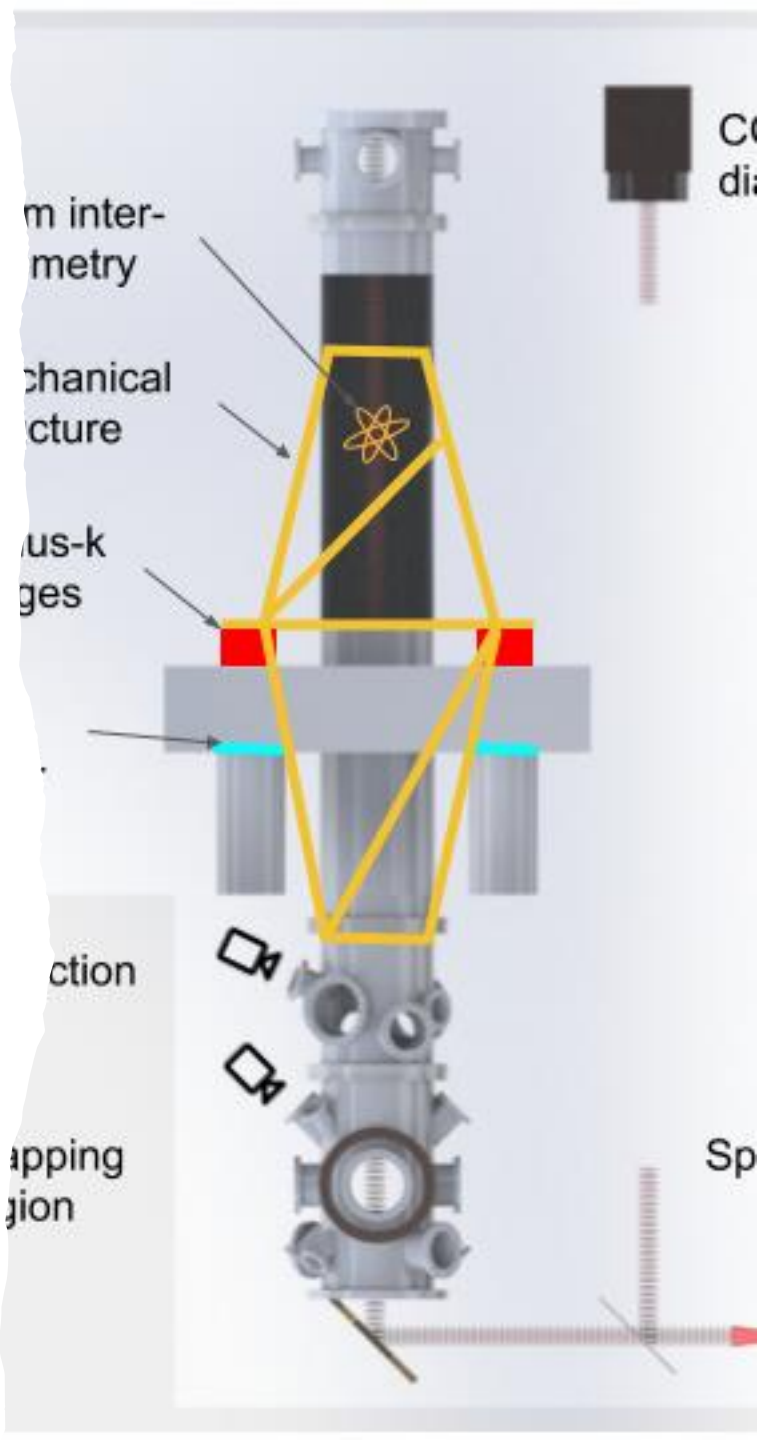
Better measurement/ characterization

Directly test model of laser-beam distortions



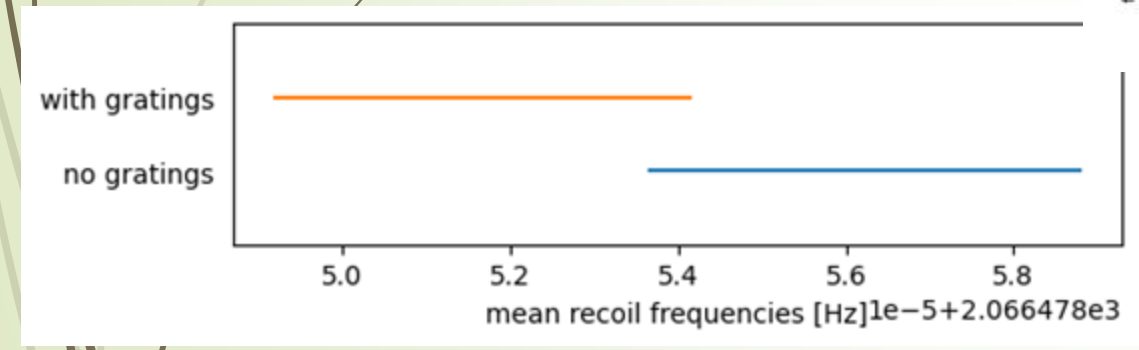
Extreme control over laser beam uniformity

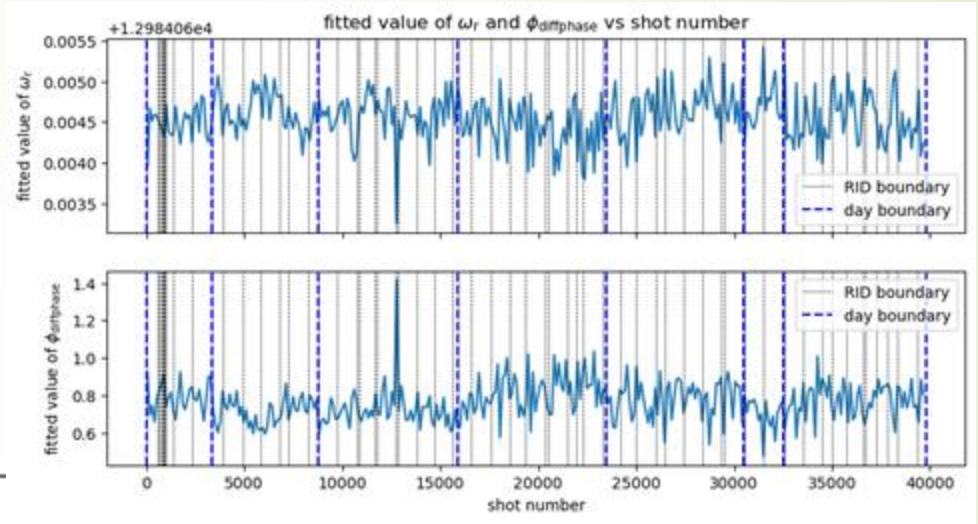
- **30 cm clear aperture of the beam tube**
- **Beam characterization**



Measuring the effect of beam distortions…

- Known beam distortions by an amplitude-grating
- 56.2(2.5) μHz without vs 51.6(2.5) μHz with grating

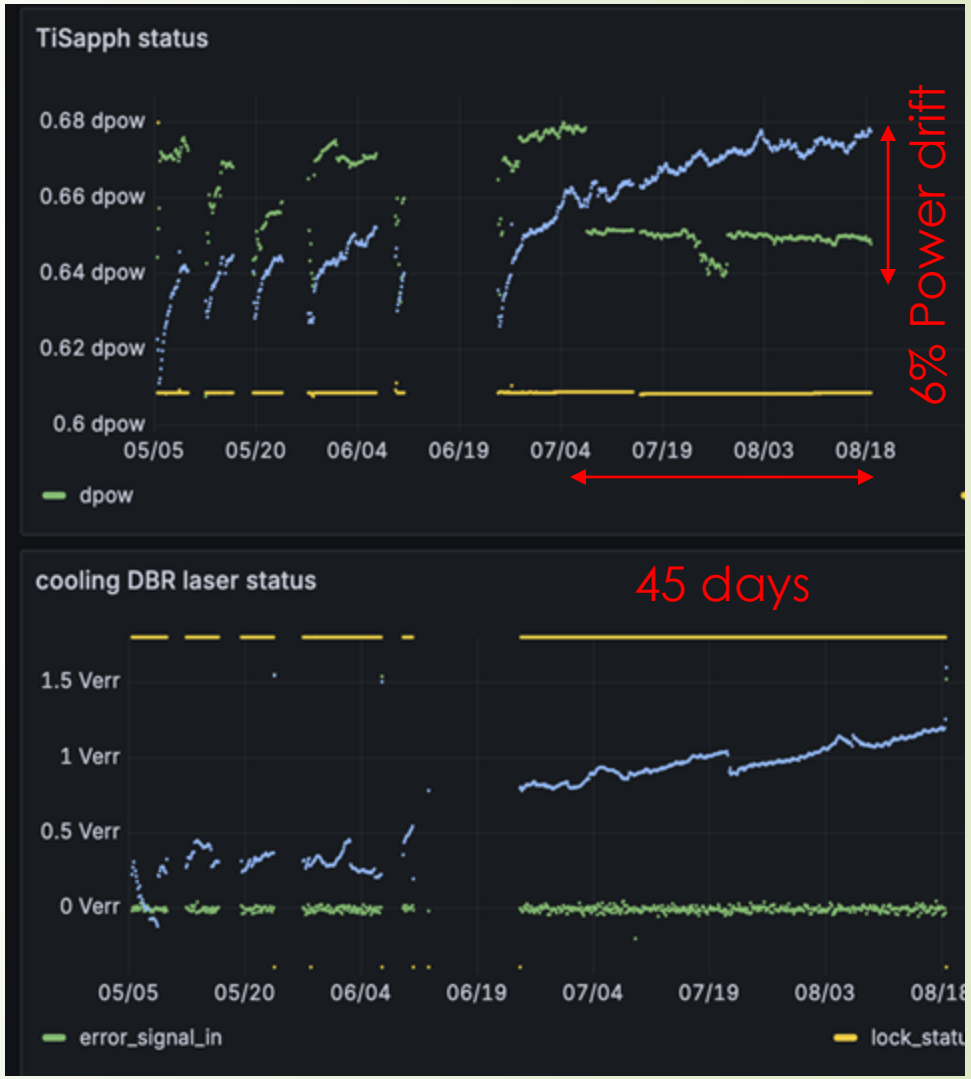




…but (for now) unable to resolve the shifts

High uptime for data collection

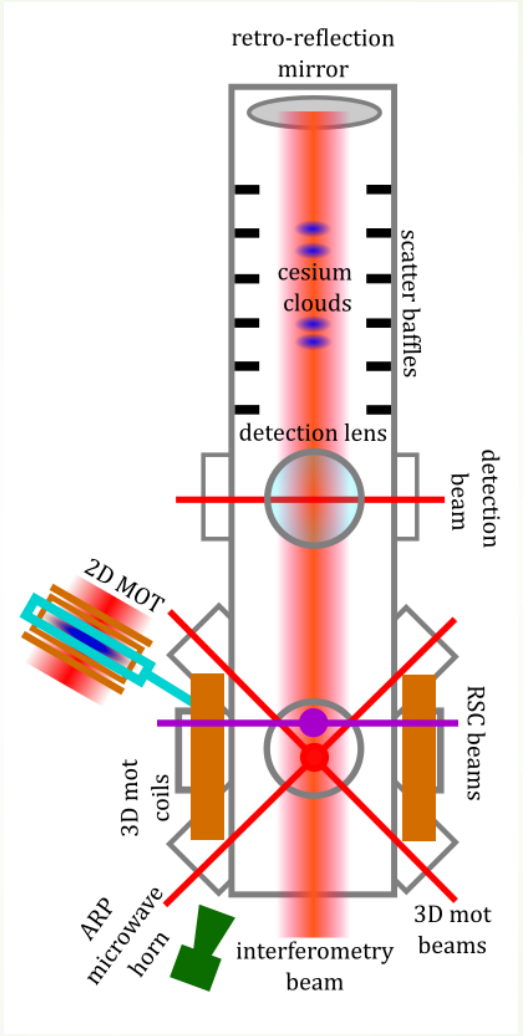
- Near-continuous data taking May-August
- Control software (Artiq) rarely crashes
- Automatic re-locking for lasers
- ~150,000 shots collected in 5 days
- Minimal tuning / maintenance

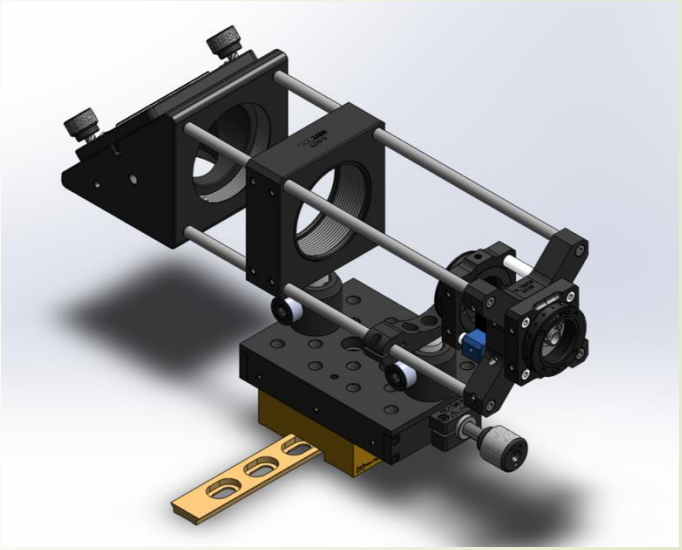


New MOT telescopes, improved alignment

Unexpected Benefit: Vastly Improved State Preparation!

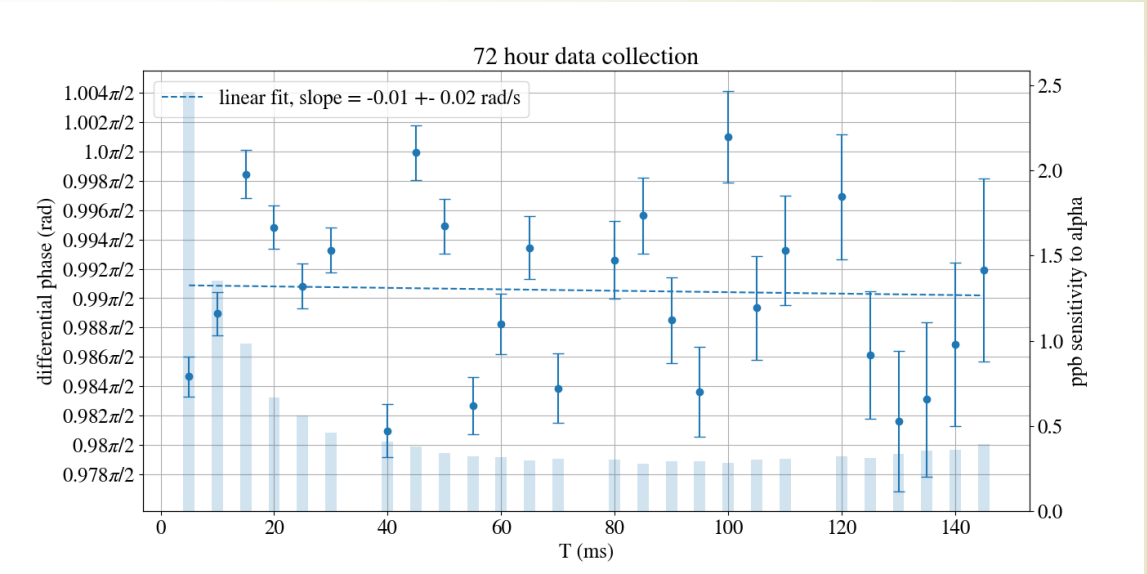
- 3~4x Molasses launch signal
- 4x RSC signal
- 3x Increased Velocity Selection





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

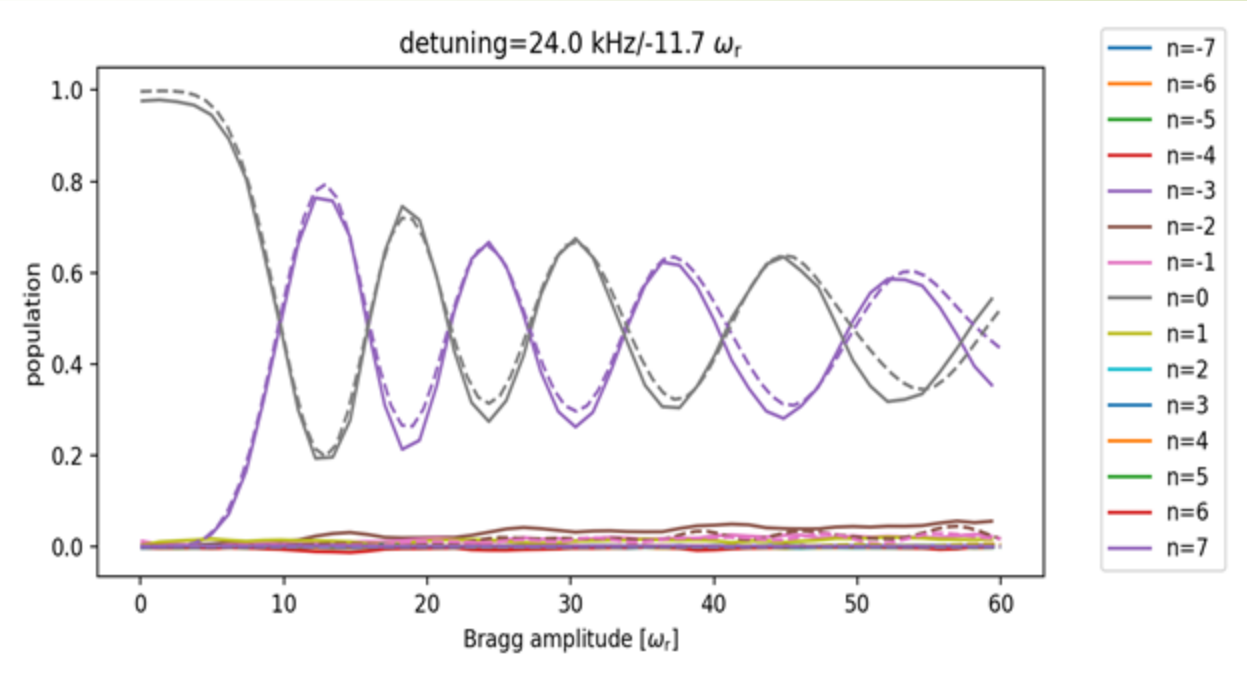


Simulation test

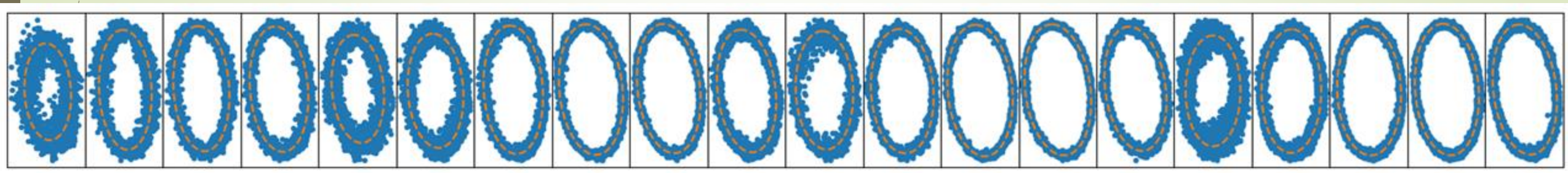
Can we predict interferometer contrast, maybe even phase?

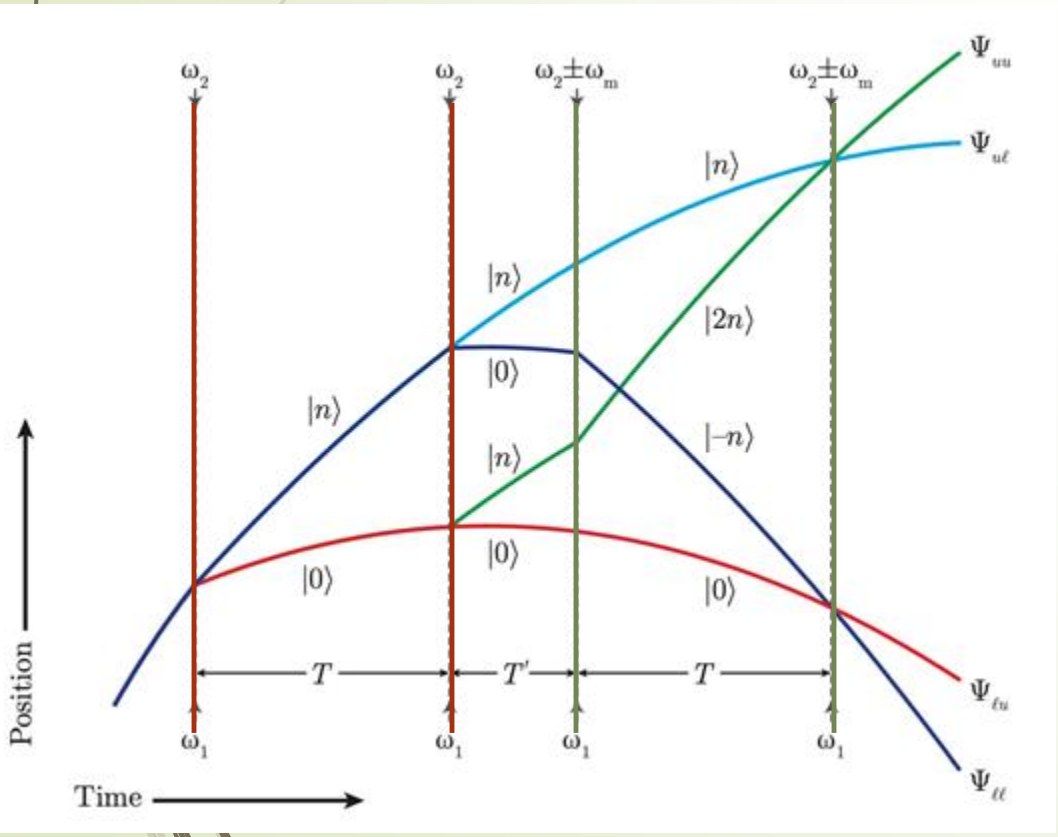
Matching simulation and experiment

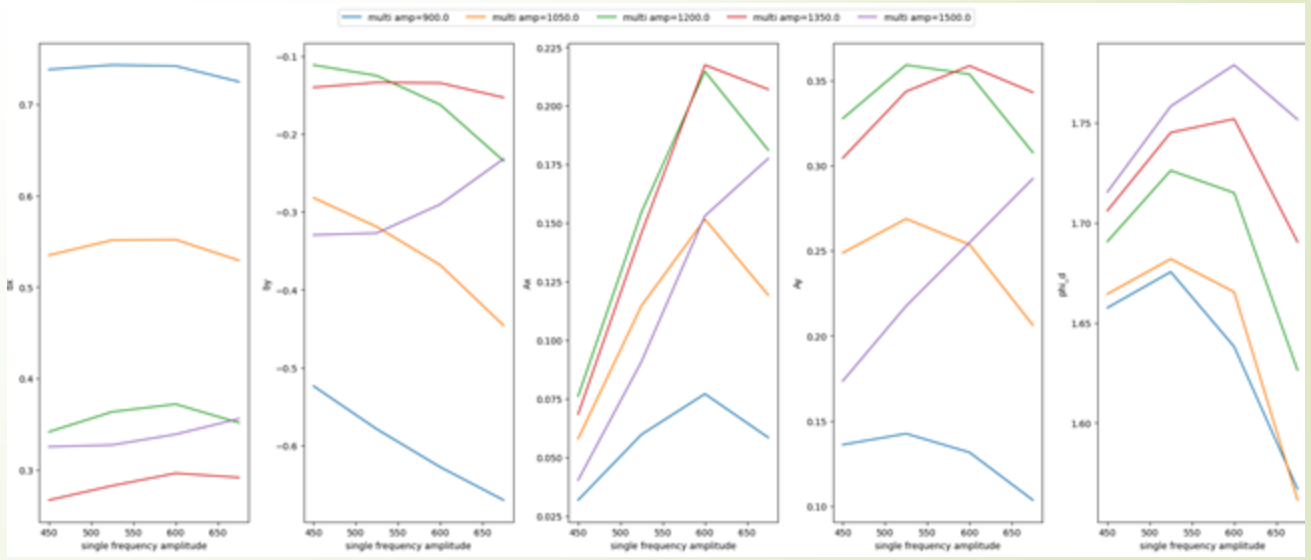
- Step-by step approach to simulate the experiment, from individual elements to full experiment
- Robust simulation to be confident about systematics
- Currently working on single Bragg pulse

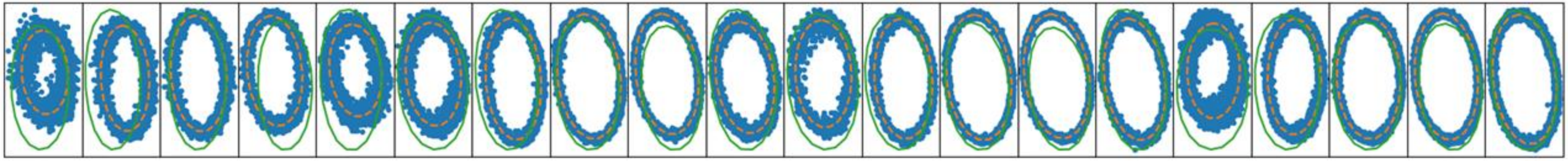


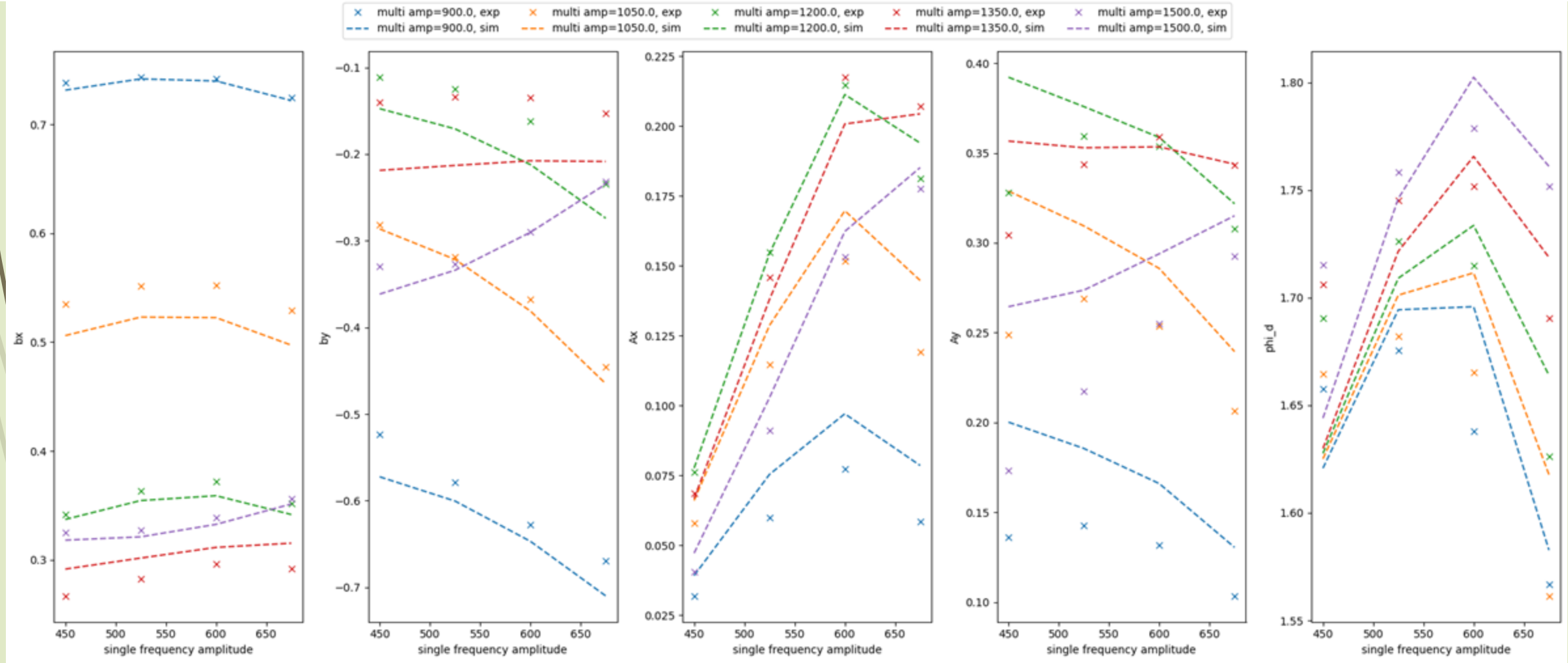
Simulation test: experiment dataset







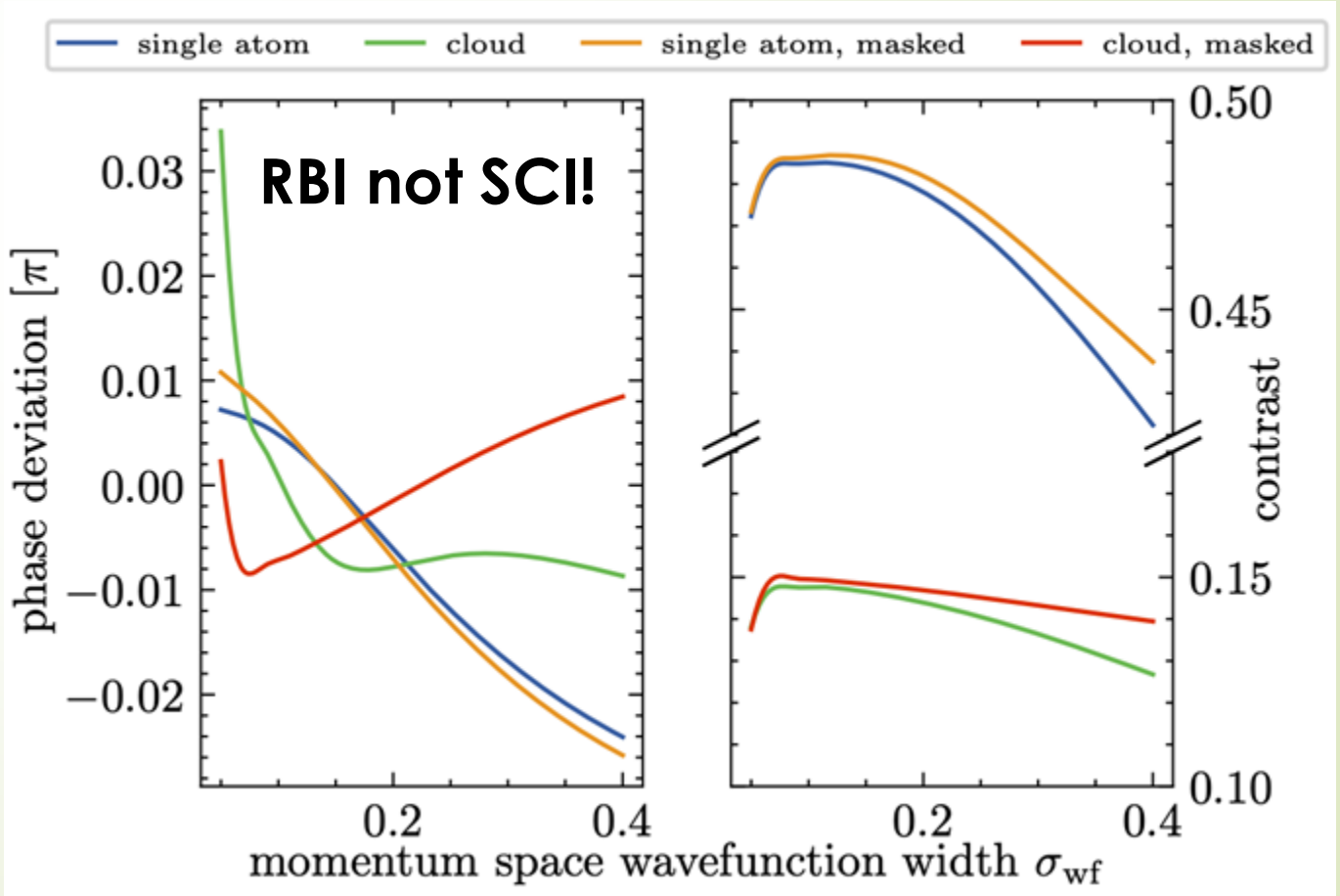



multi amp=900.0, exp
multi amp=900.0, sim
multi amp=1050.0, exp
multi amp=1050.0, sim
multi amp=1200.0, exp
multi amp=1200.0, sim
multi amp=1350.0, exp
multi amp=1350.0, sim
multi amp=1500.0, exp
multi amp=1500.0, sim
bx
by
Ax
Ay
phi_d
single frequency amplitude

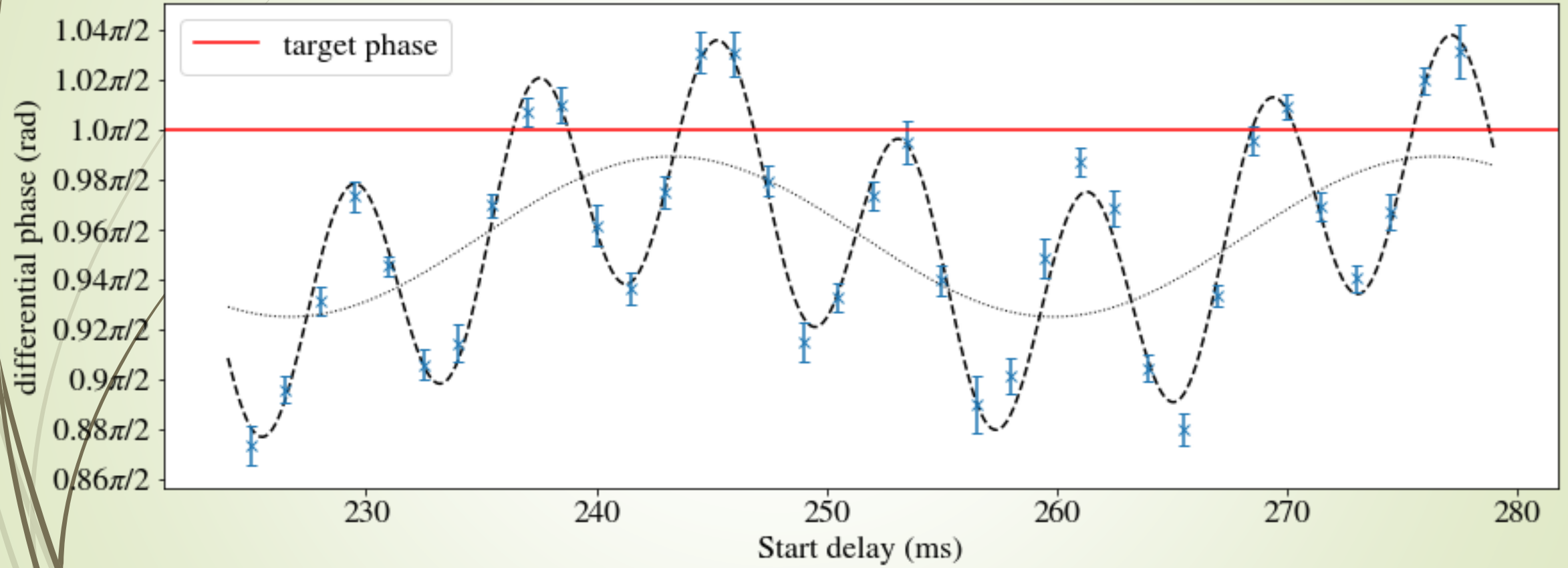
Simulation next steps: what is missing?

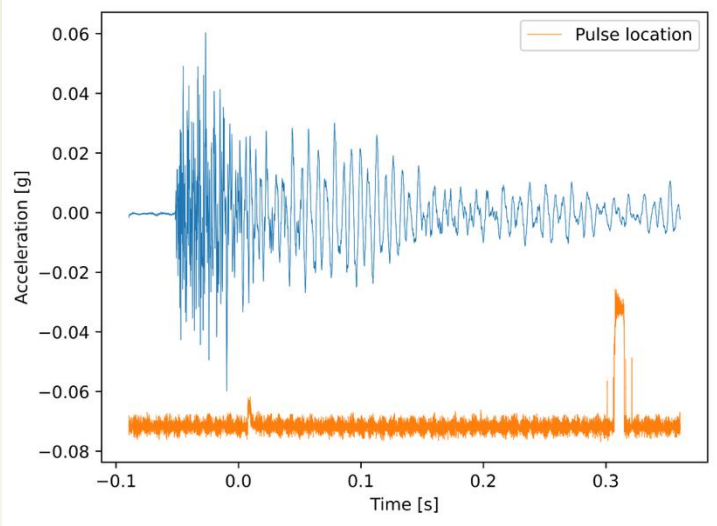
- Parasitic ports/momentum states
- Effects due to the finite width of the position space wavefunction?

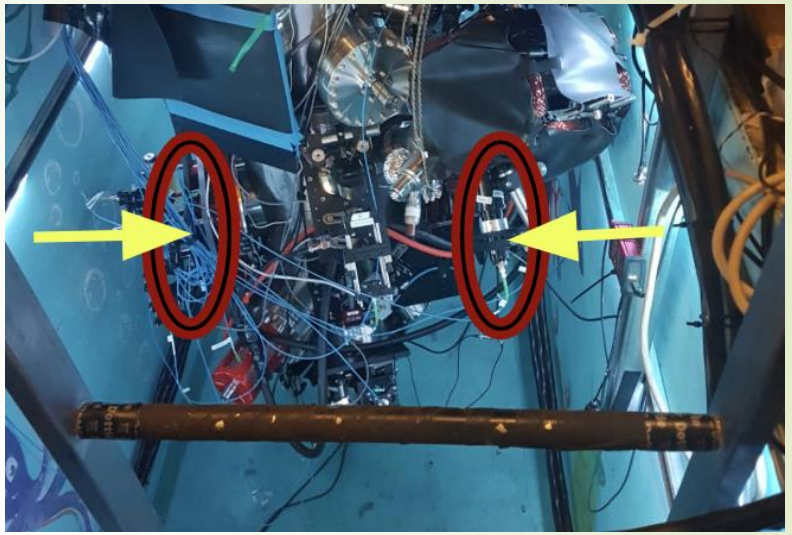
1000 atom cloud computed using full wavefunction simulation



A new systematic…



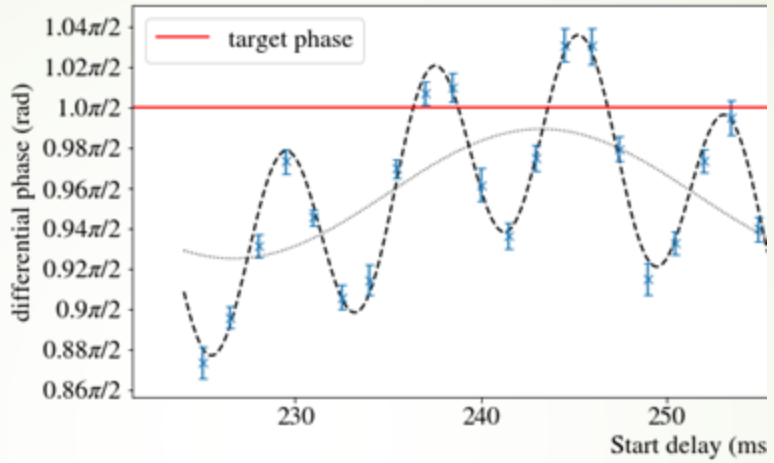


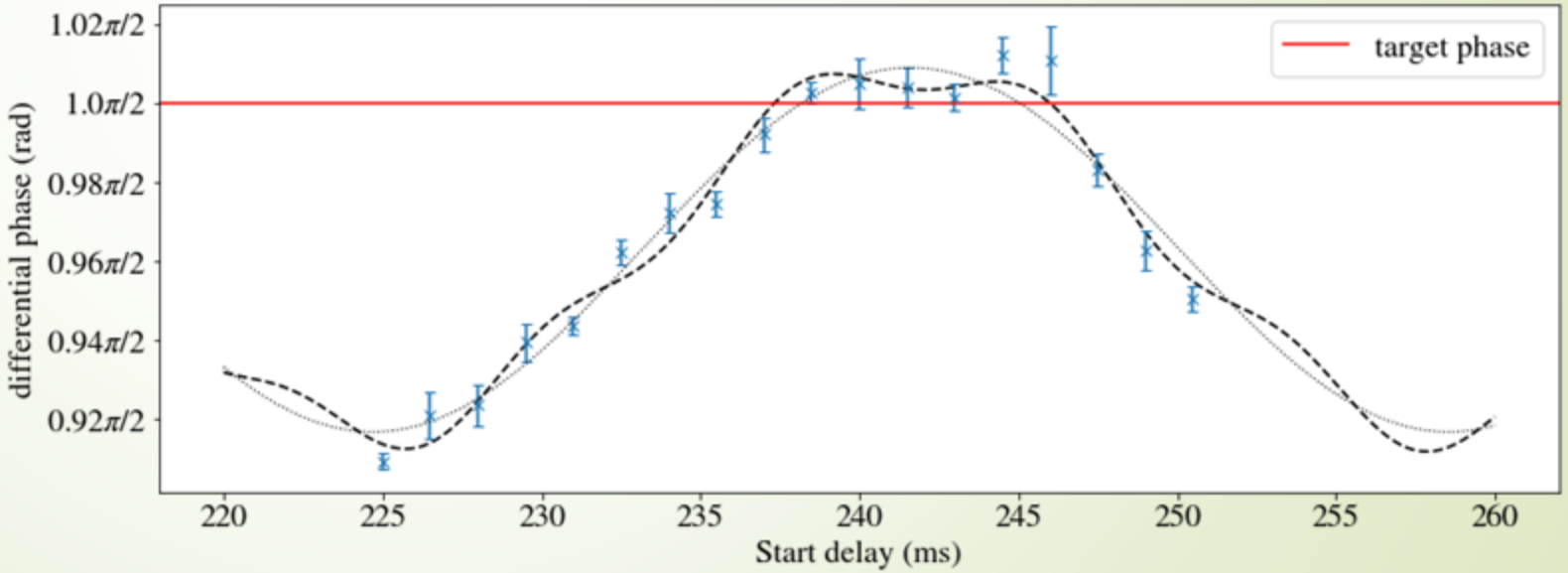


The coils are shaking the chamber

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

Perturbed by adding sandbags to the top mirror

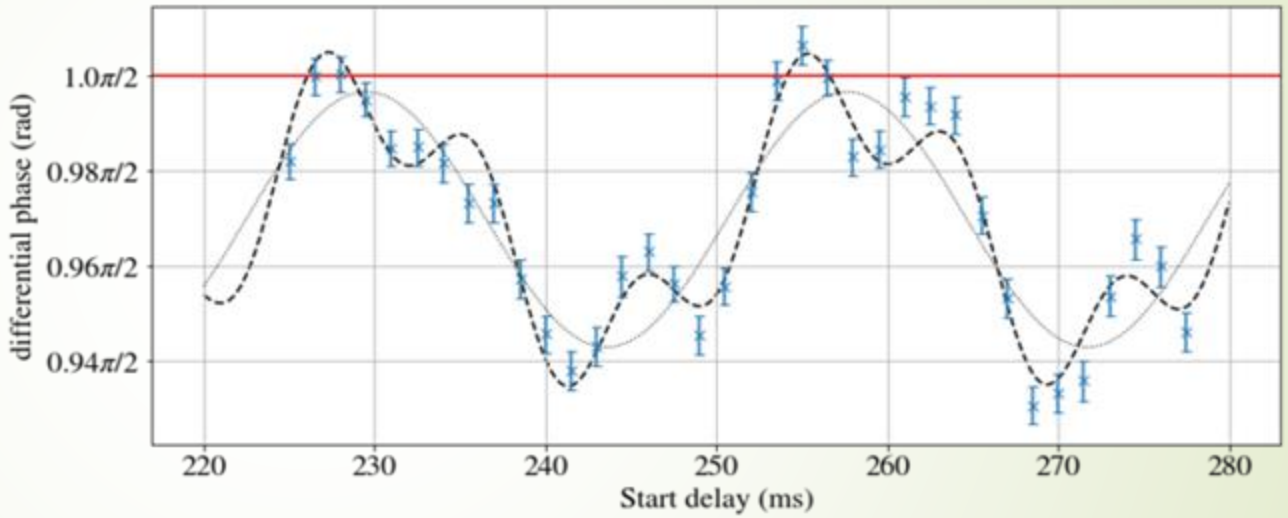




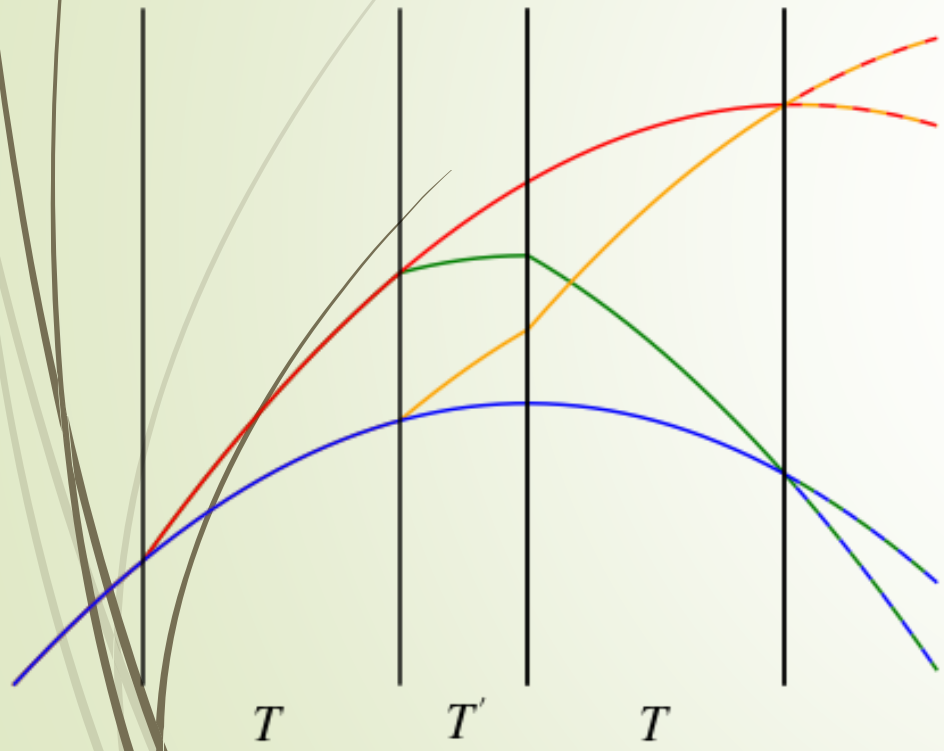
Damping still leaves ~200 mrad of phase oscillations

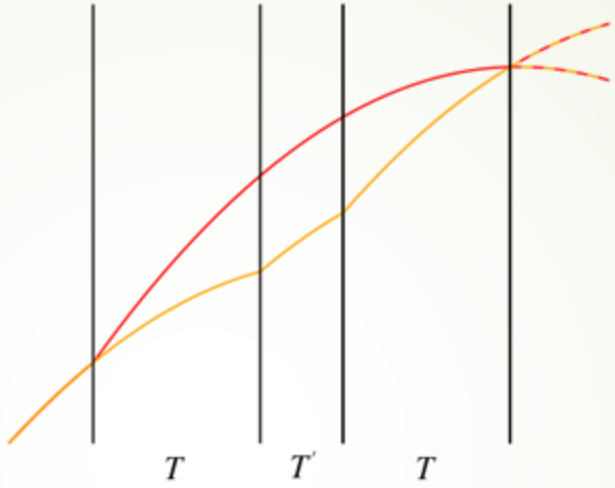
Despite accelerometer on top reading no vibrations

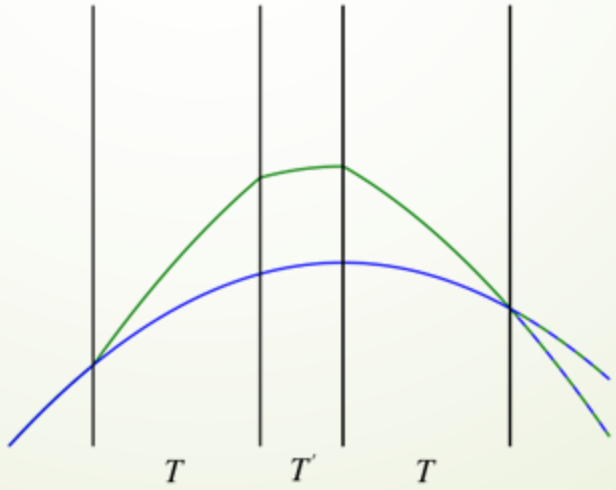
- Heavy sandbags on mirror mount
- Xorbathane on chamber body
- Weights on bottom breadboard



We *should* be insensitive to vibrations

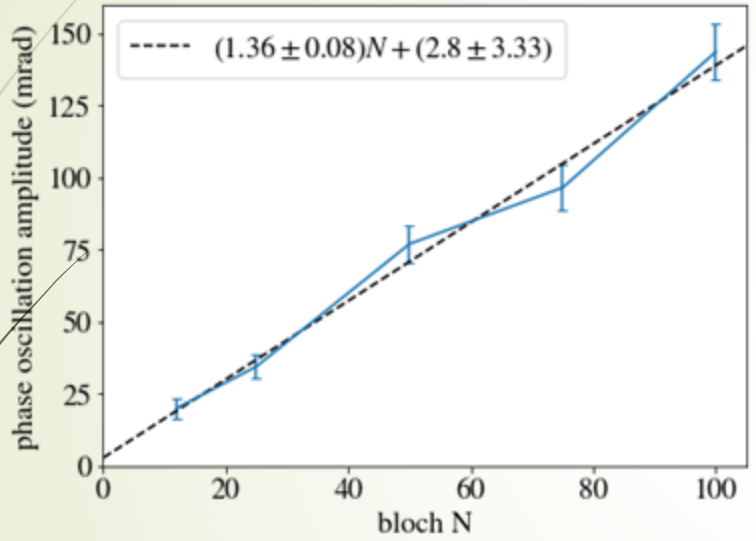


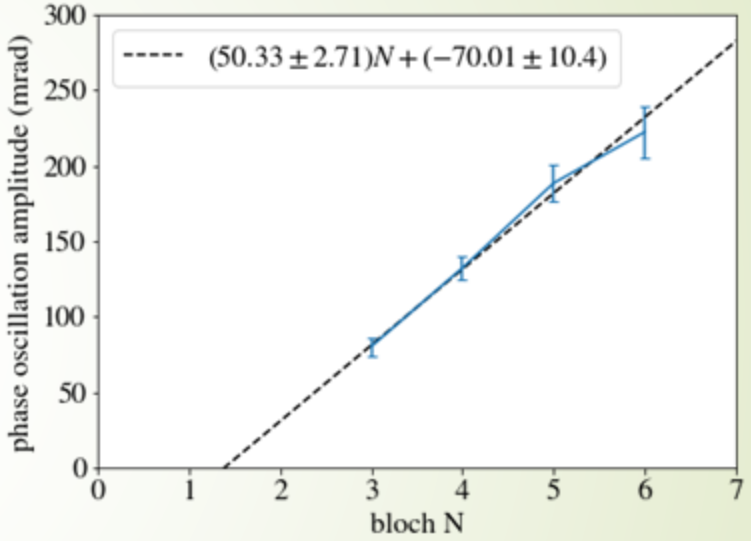


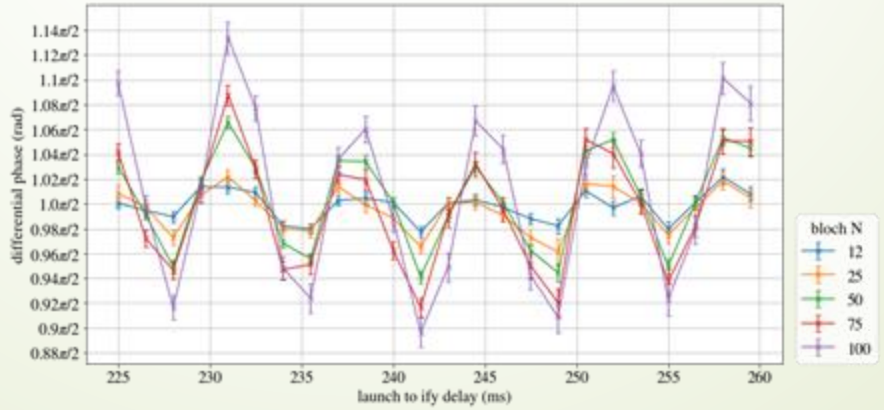


Every time the lower path of the upper interferometer is deflected up, the upper path of the lower interferometer is deflected down

Effect ∝ number of Bloch oscillations and increases with Bragg order

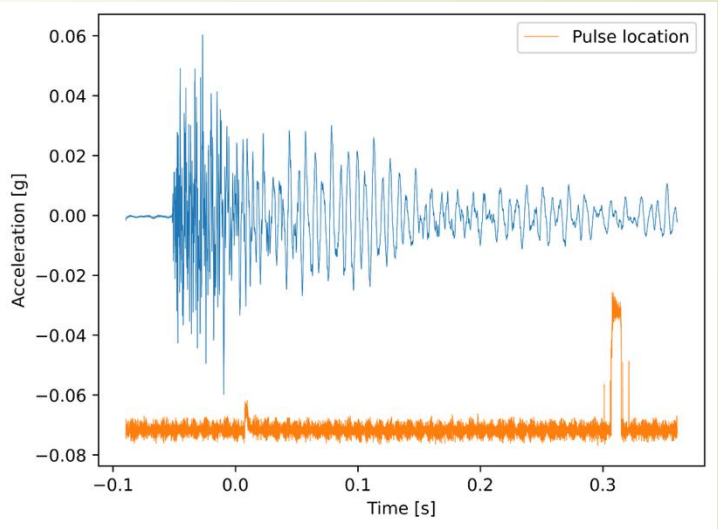






Vibrations may generate parasitic interferometers…

- The recoil velocity v_r is 3.5 mm/s
- Typical mirror velocity $\omega\, a$ ~ 1 mm/s mistunes the two-photon resonance sufficiently to generate (weak) unwanted diffraction orders
- **Hard to model, still under investigation**



Mitigation: New MOT coils, not mounted to the chamber

Sometimes you trap the atoms

Sometimes the atoms trap you

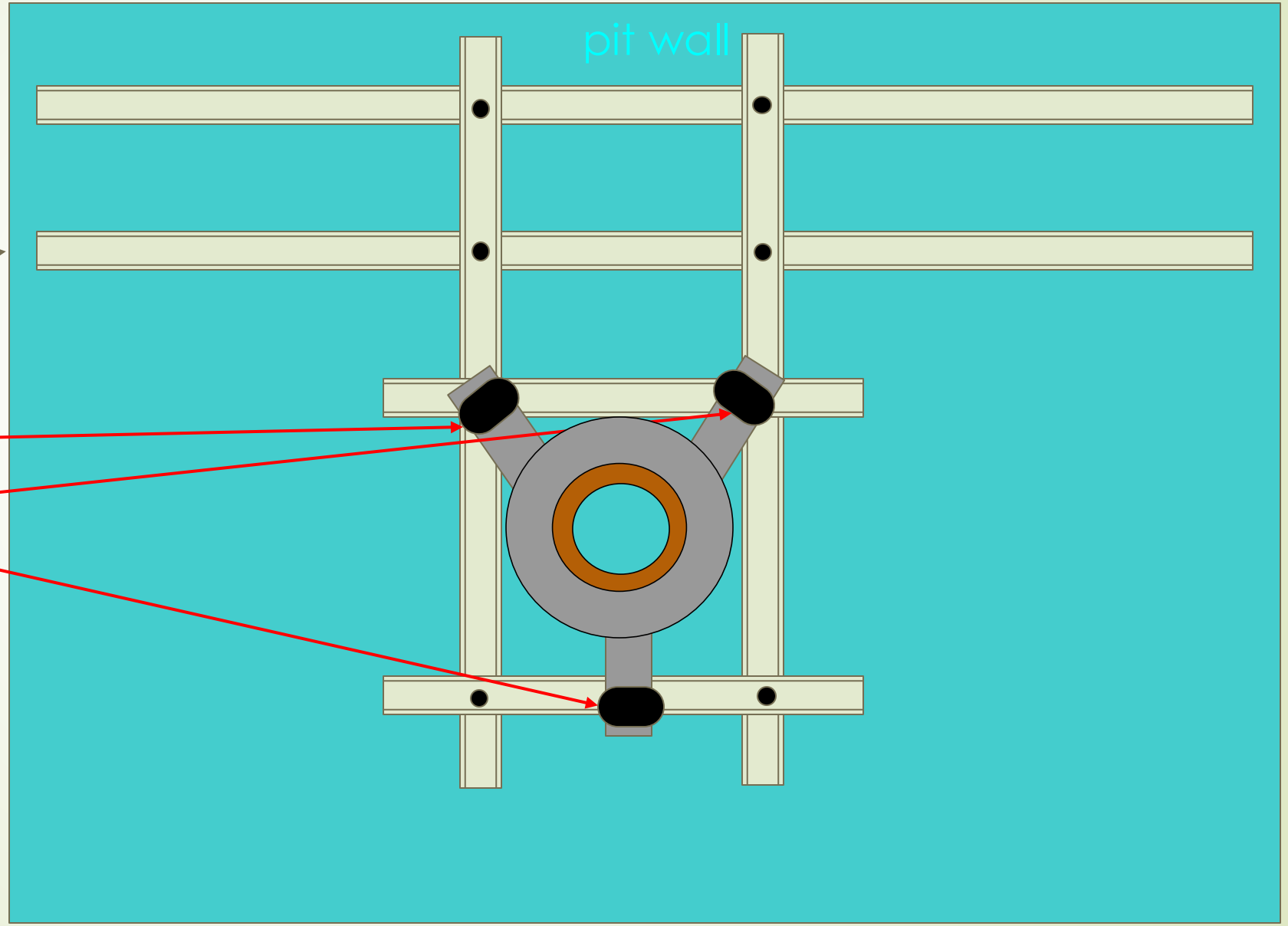
Mounting the Coils to the Wall

- No drilling required!

SIDE VIEW

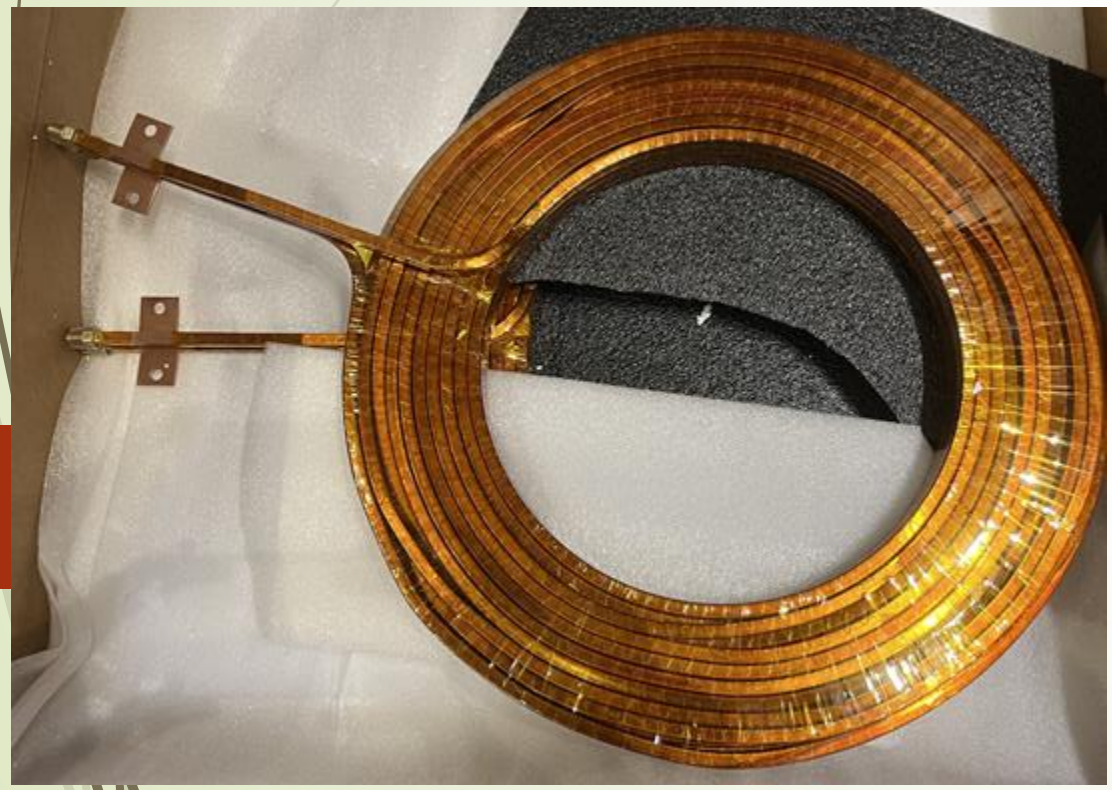
Existing unistrut

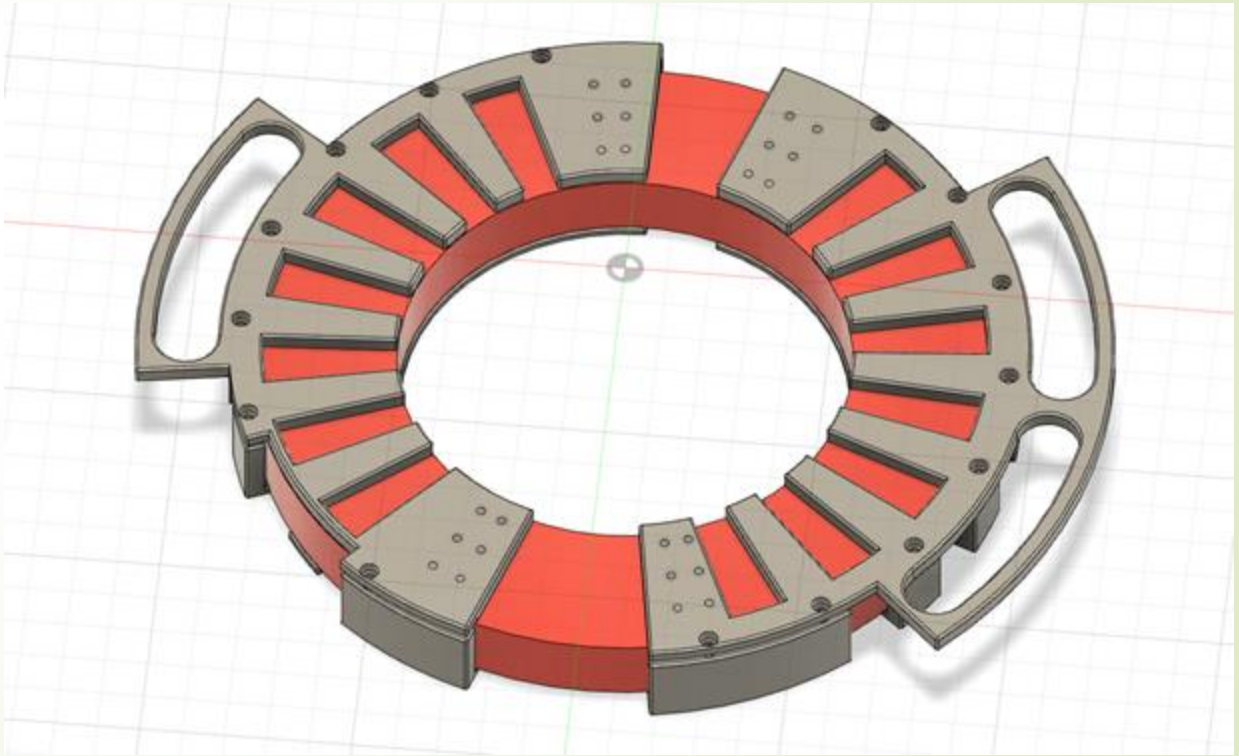
Thorlabs pillars posts + holders

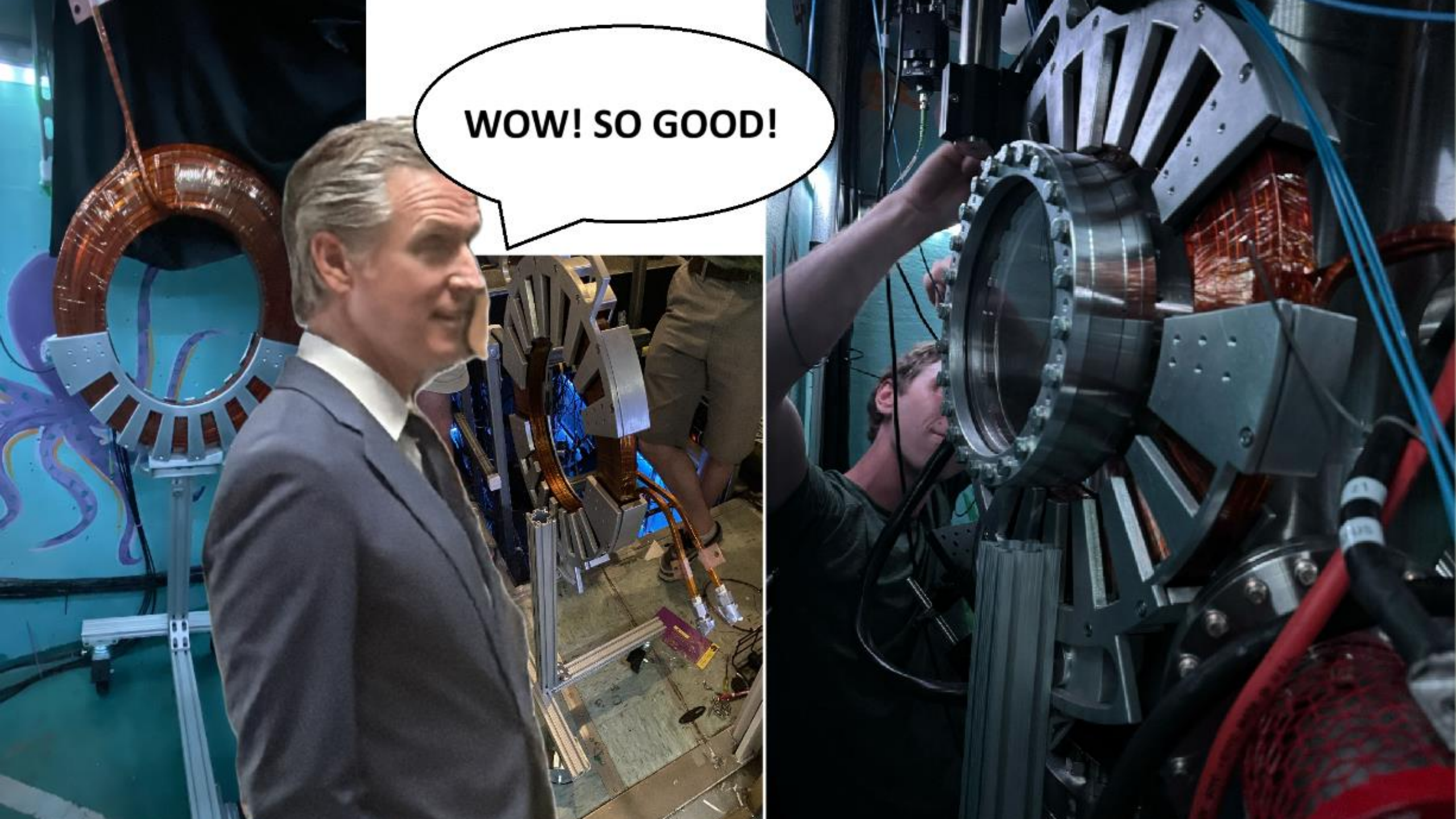


New MOT Coils + Coil Mounts

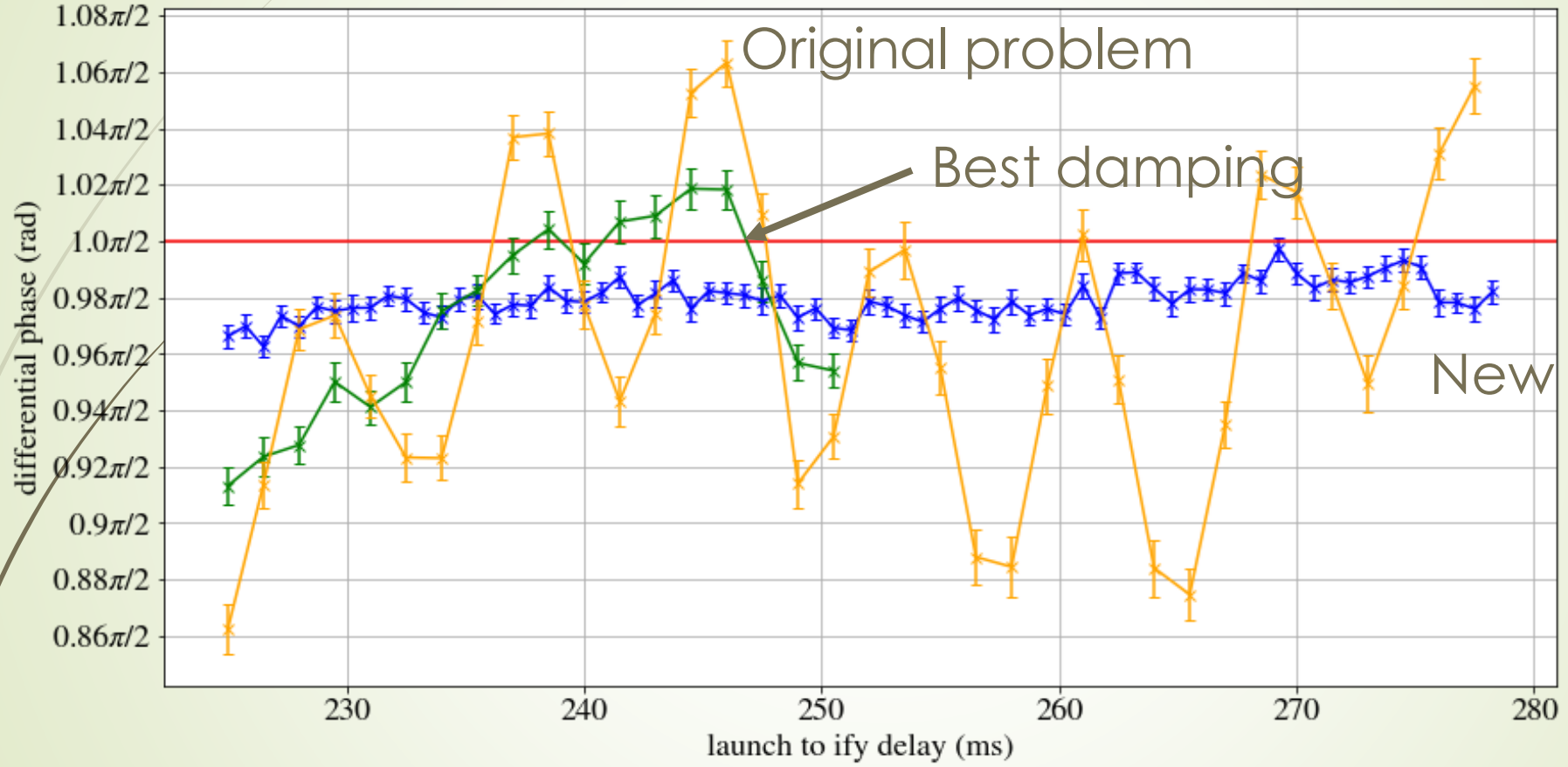
- Designed by Madeline
- Cutouts on bobbin to reduce weight and prevent eddy currents






WOW! SO GOOD!

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