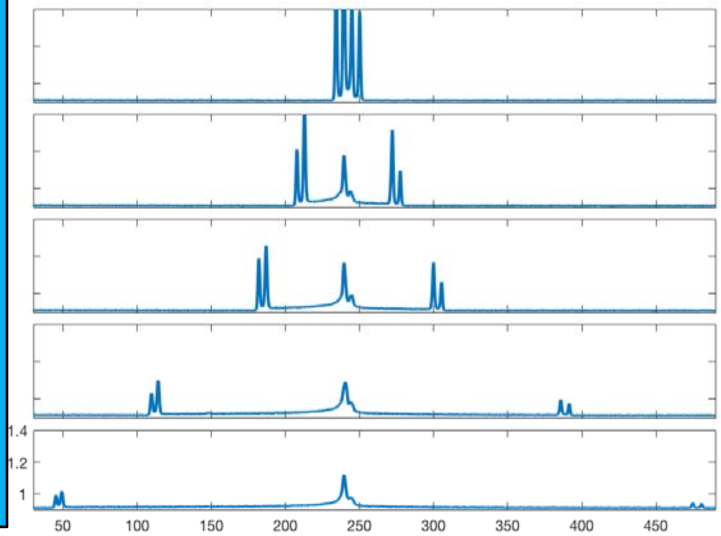
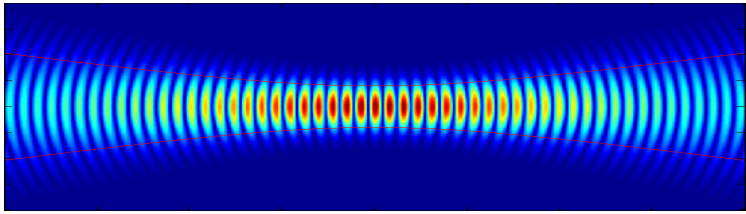
Precision measurements in fundamental physics

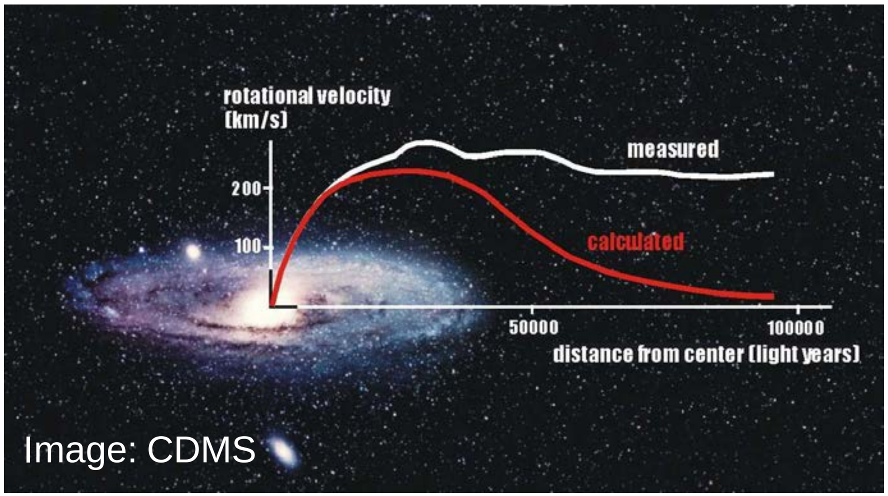


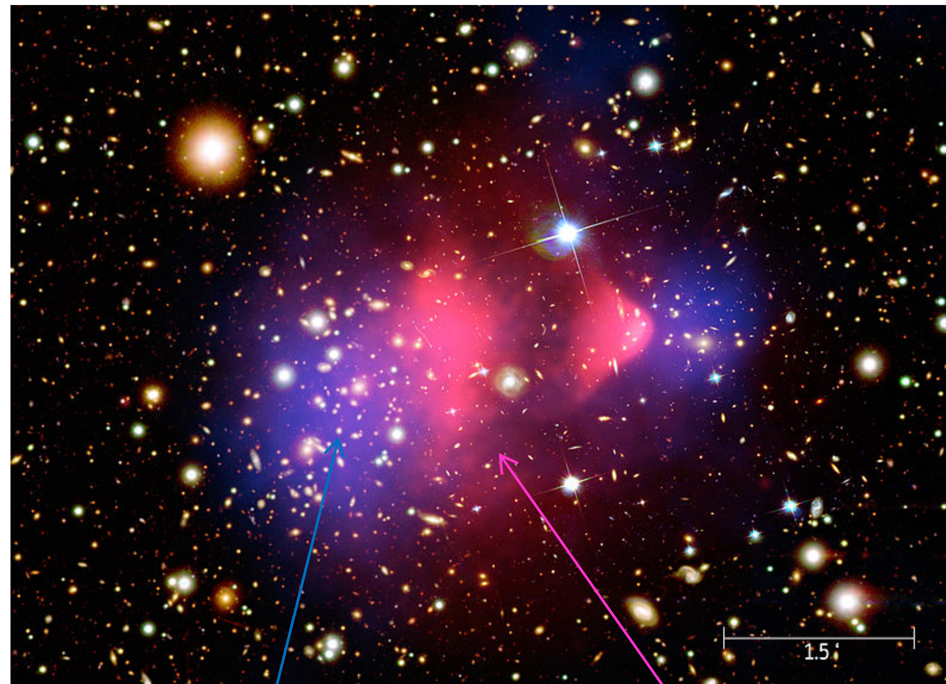
Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and H. Müller

U.C. Berkeley



Dark matter – 23% of all mass

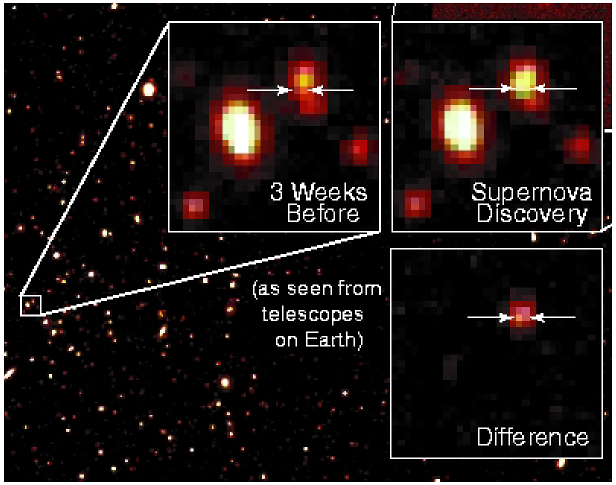




Reconstructed mass distribution

Observed luminous matter

Dark energy – 73% of all mass

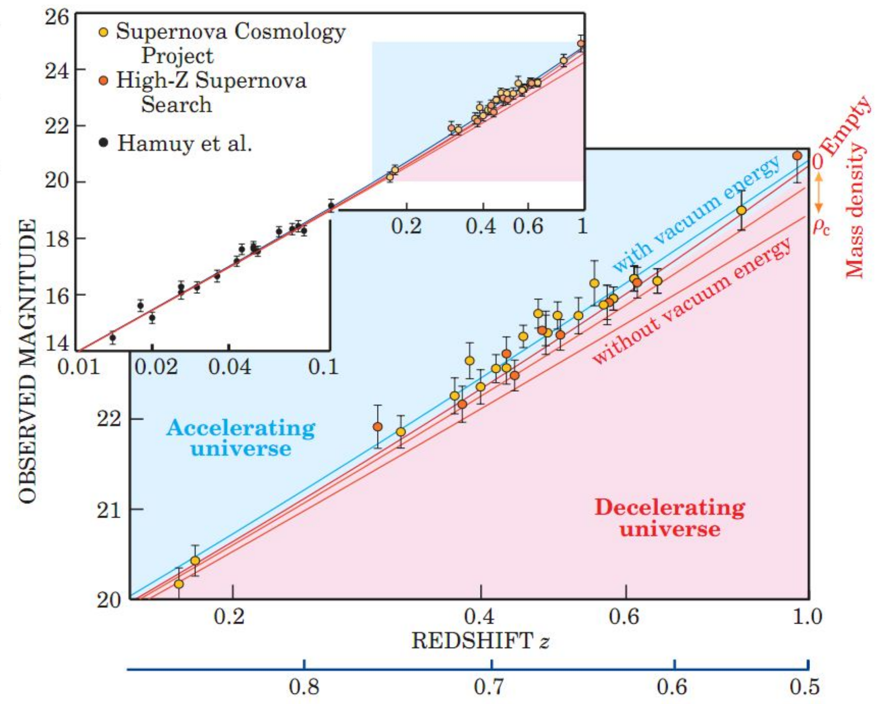


Saul Perlmutter

Brian Schmidt
Adam Riess

Early 1990's data: nothing special

Distance



Speed

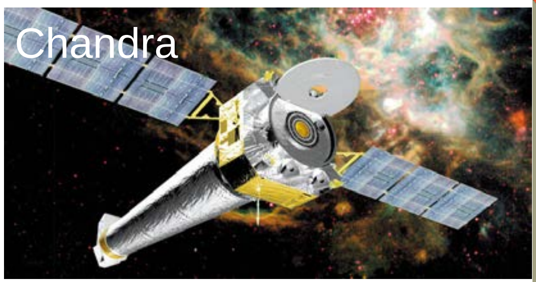
1998 data:

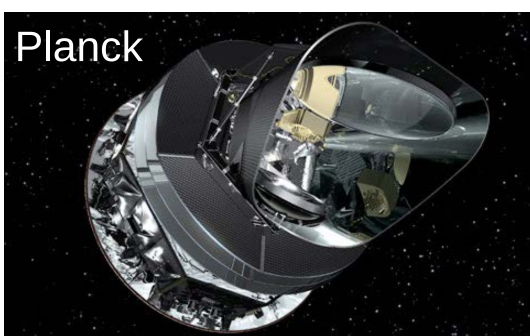
- 10 times the range
- There may be a discovery behind every order of magnitude.

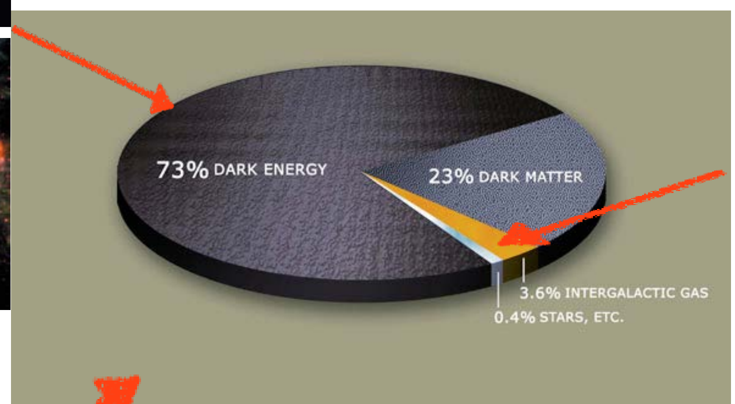
The Era of precision uncertainty

Loud and clear signals from the skies….

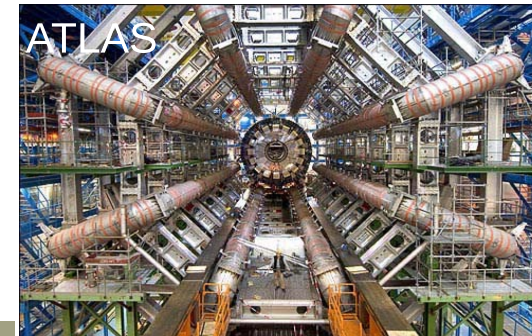
…but silence in our detectors



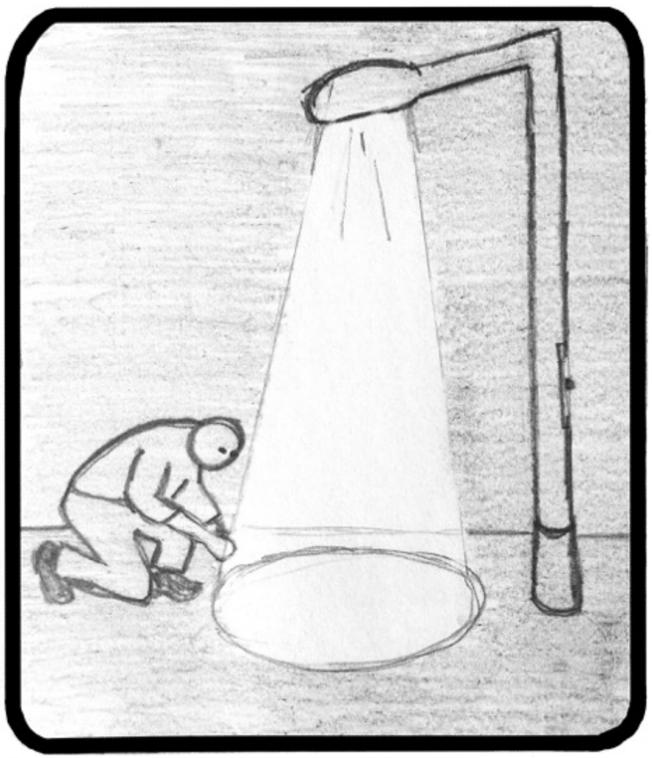
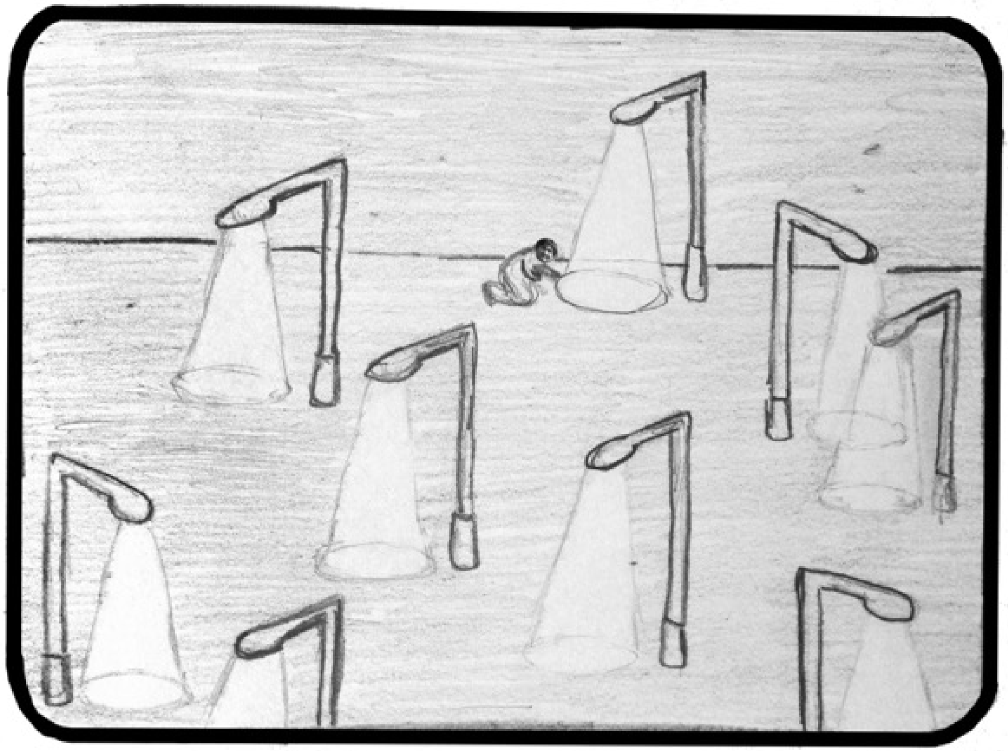




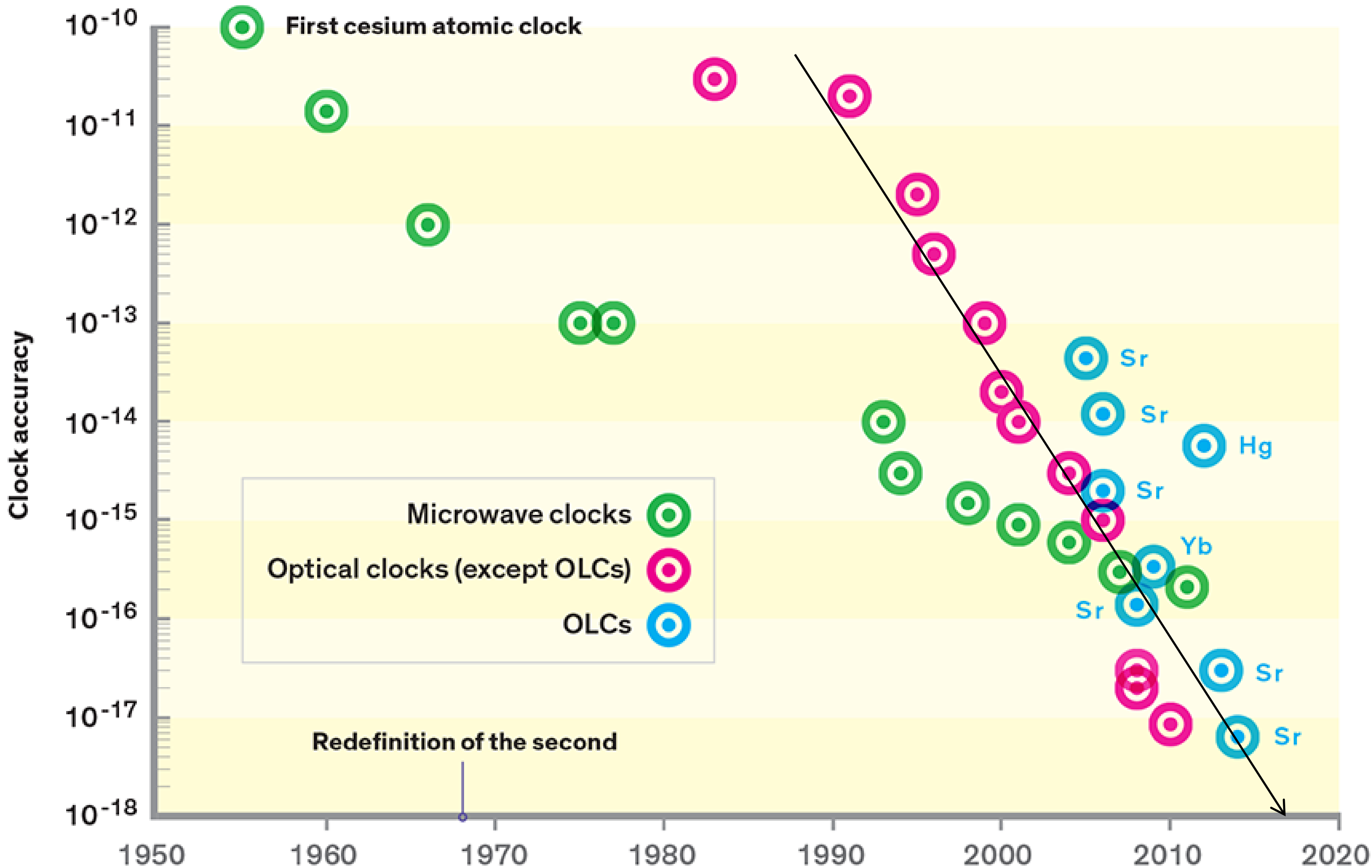
The LHC…THE particle physics experiment



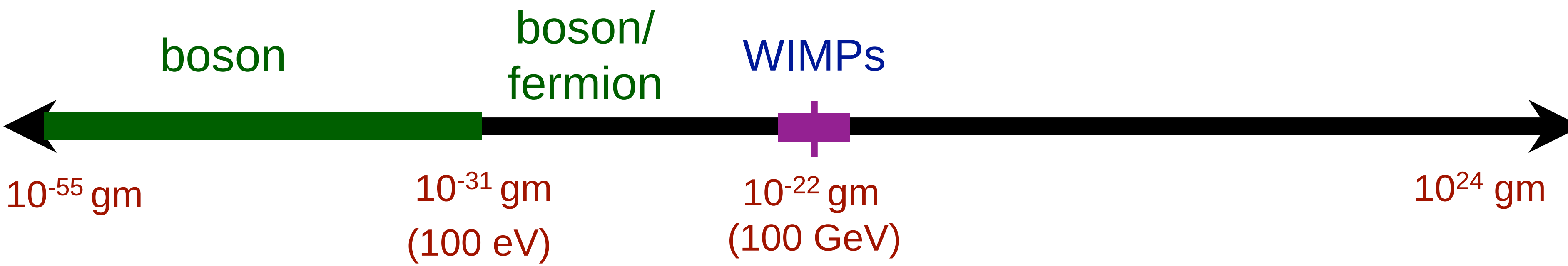
Dark matter detectors

Moore's law in atomic physics



The precision frontier



- (Ultra-) light particles are easy to generate, but hard to see.
- Collective forces from a large number of particles
- Forces are the fundamental effect of light particles
- Ultra-sensitive detectors required

Surjeet Rajendran

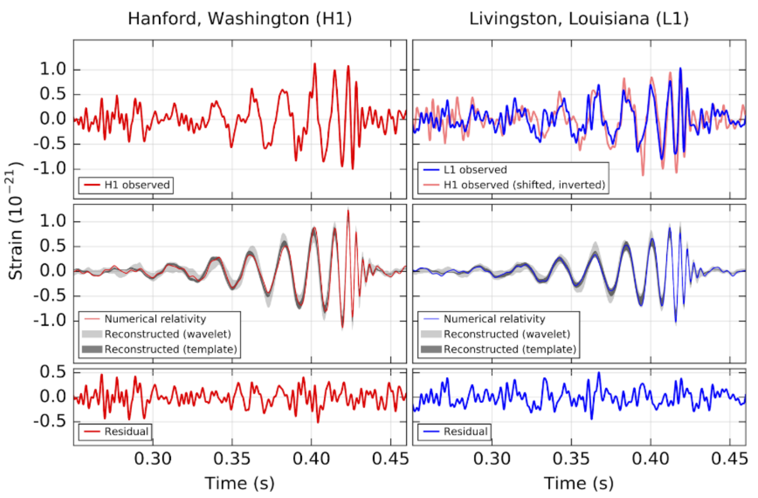
How to best sense the light dark sector

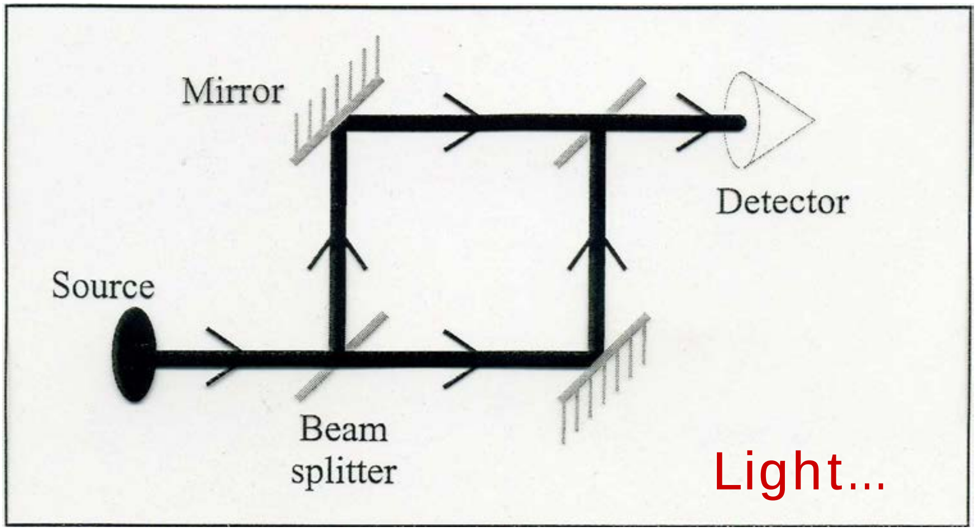
Need test particles that are

- Well understood,
- Light, neutral
- …and whose motion can be measured with extreme precision

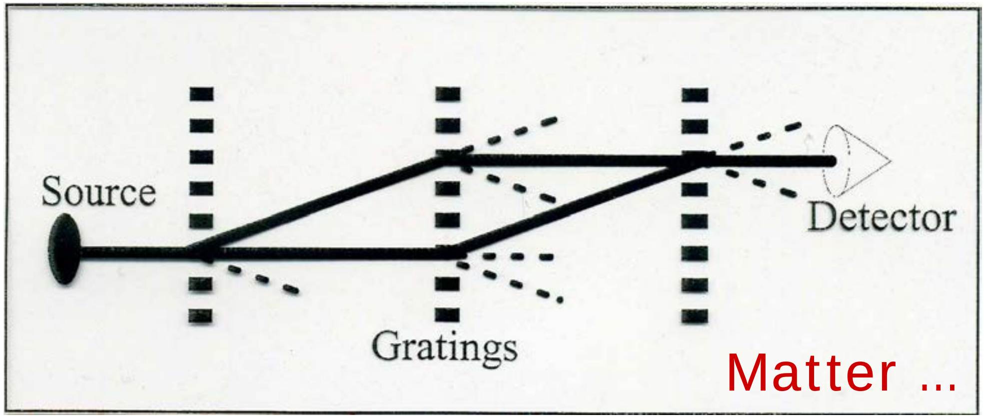
$\Rightarrow$ Interferometry with laser-cooled atoms

Interferometry…



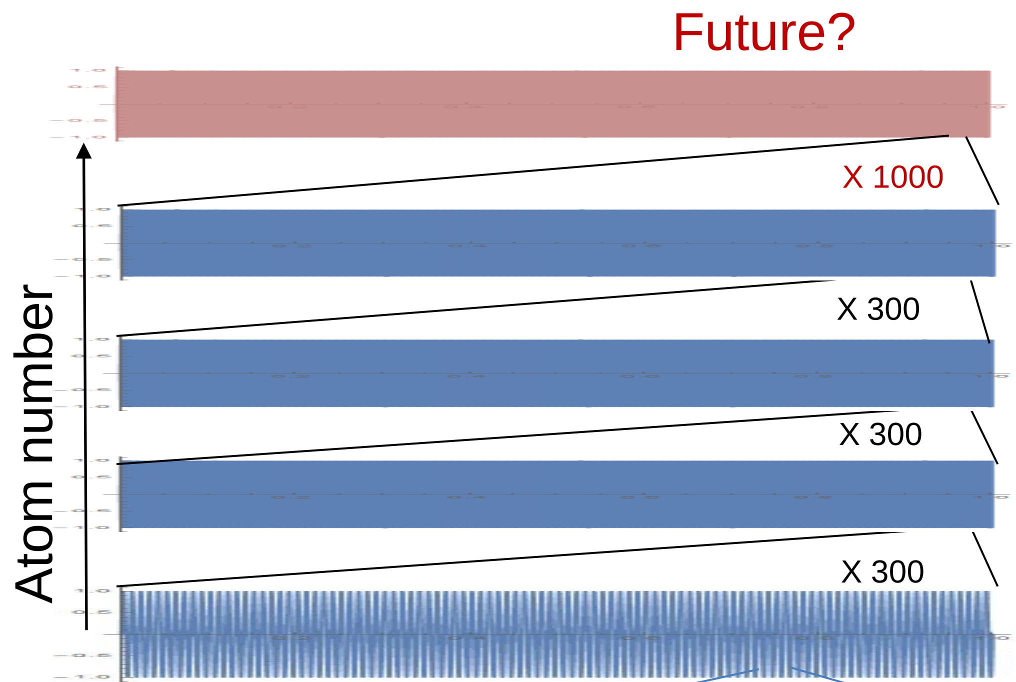


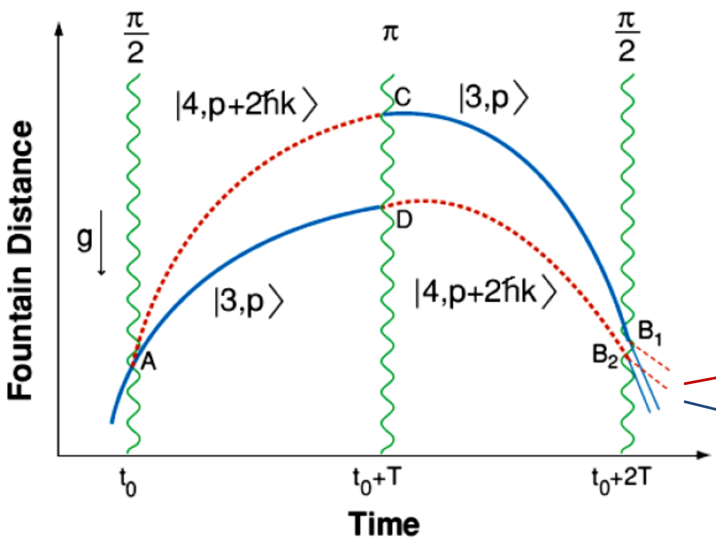
$$\lambda = \frac{h}{mv}$$

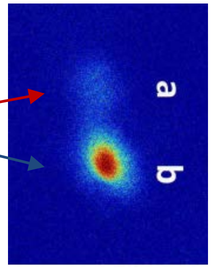


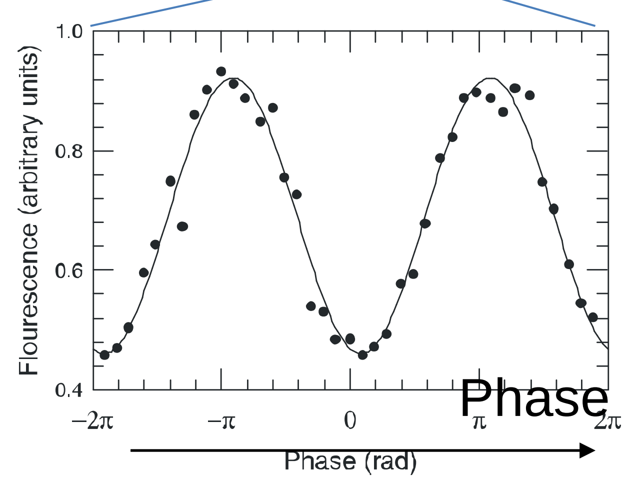
Light pulse atom interferometer

- Particles / waves
- Forces from the dark sector change deBroglie wavelength
- Laser wavelength as a ruler

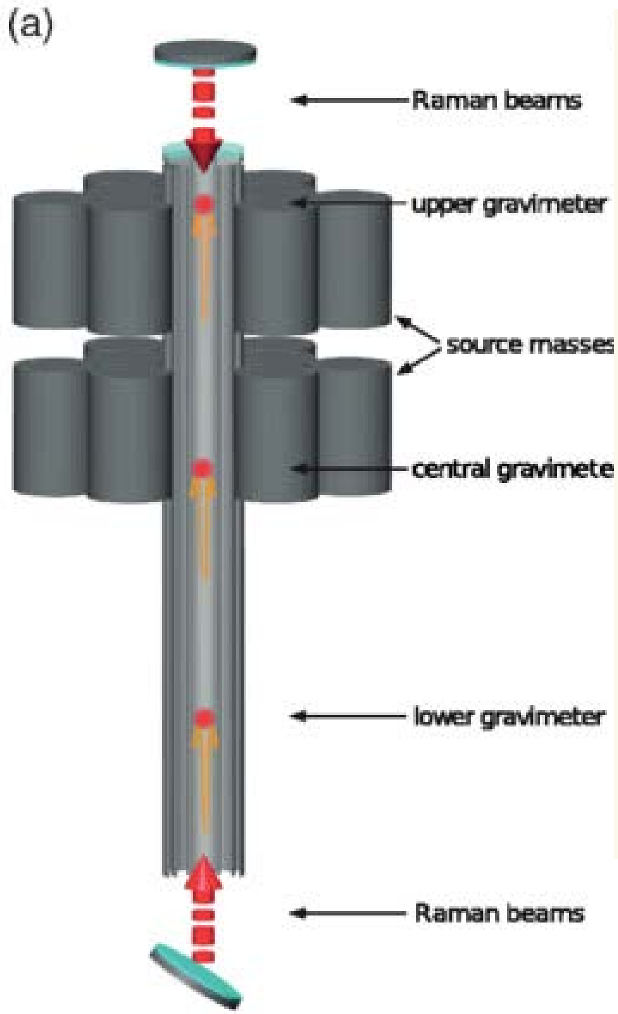


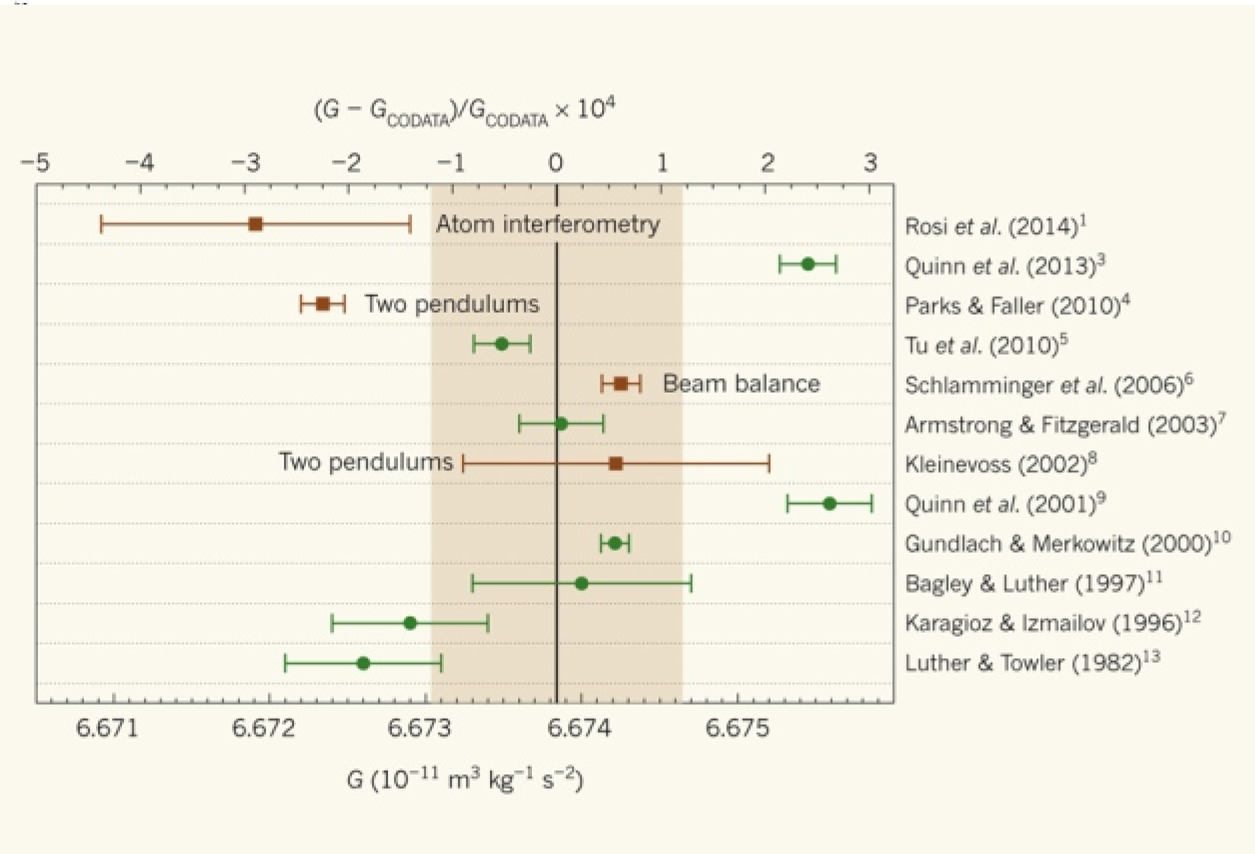




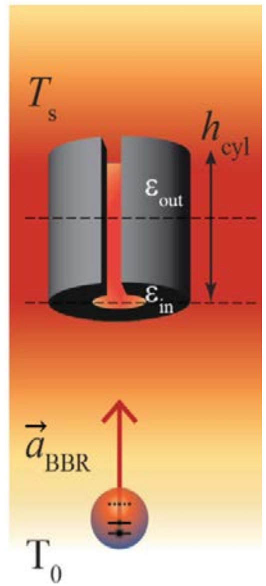


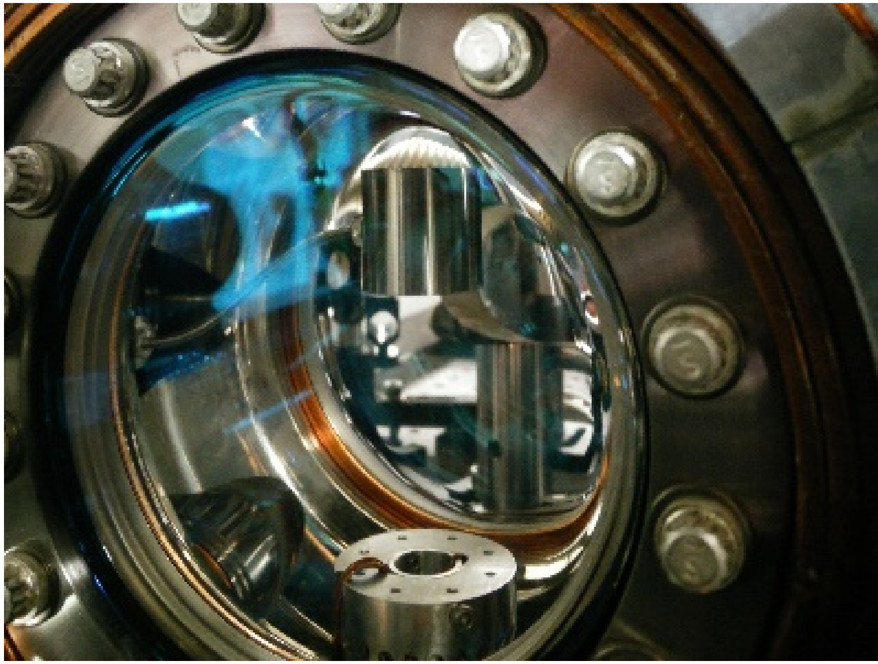
Precision measurement: G





Rosi et al., Nature 2014



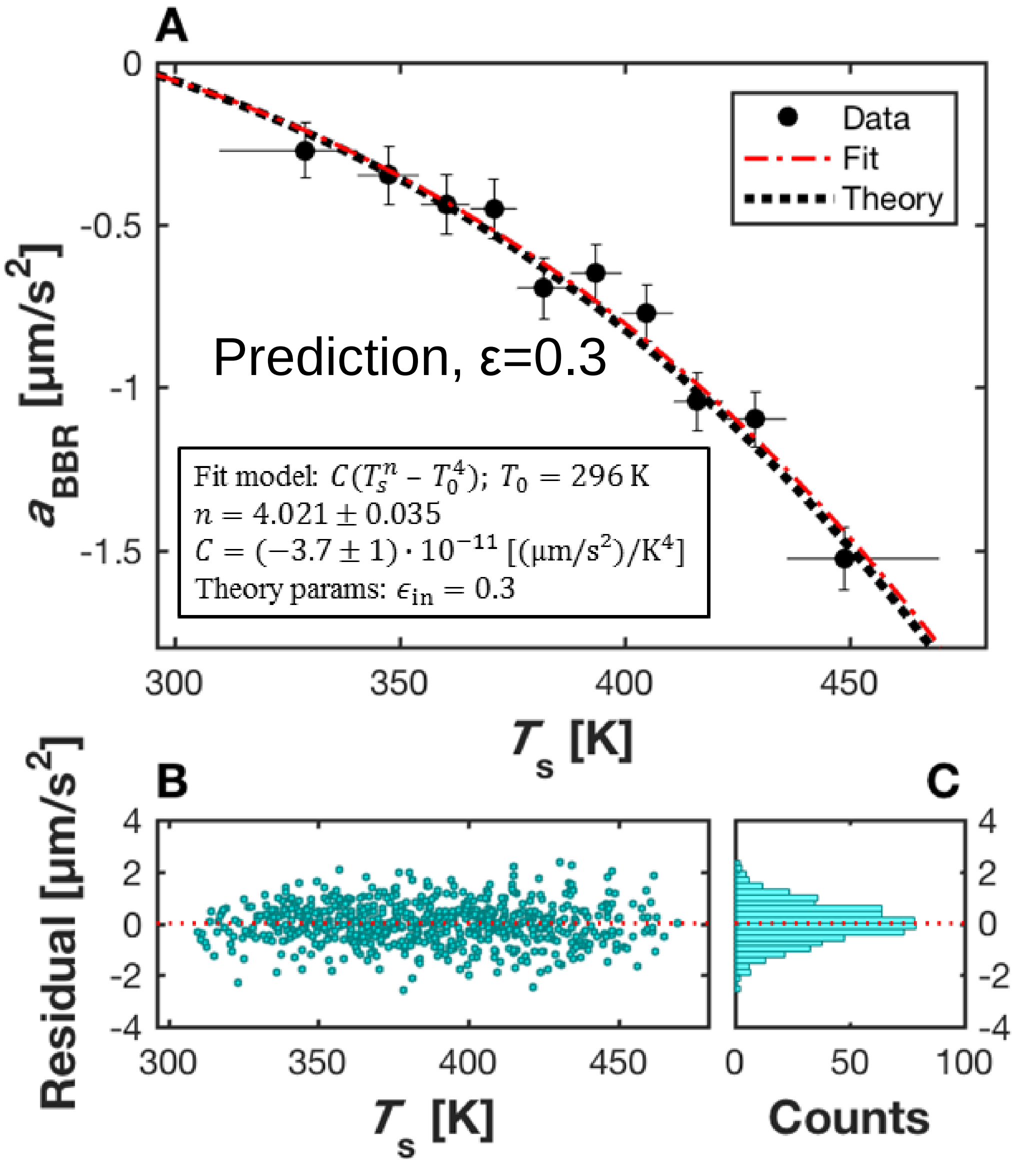


Attractive force from blackbody radiation

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

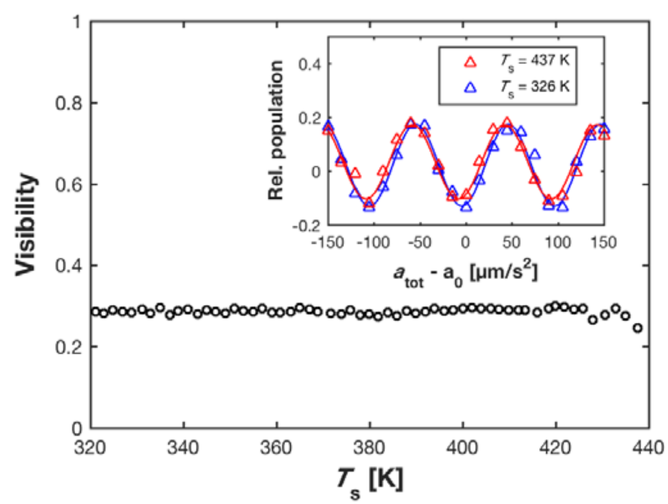
Only one room temp. blackbody photon absorbed every 10^5 years…

Measurement

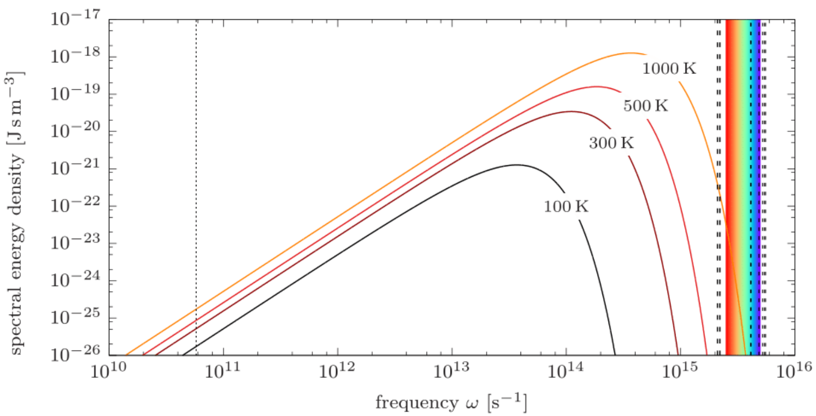


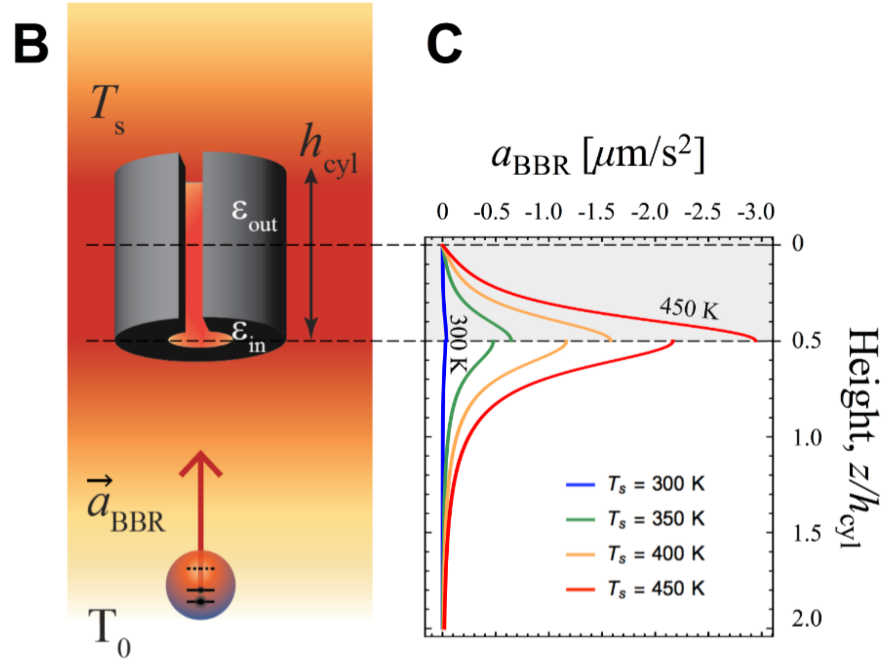
Systematic Effects Ruled Out:

- Pressure from outgassing (opposite sign, exp(T)-dependence, loss of coherence)
- Constant AC Stark effects (e.g., would cancel between interferometer arms)



Theory

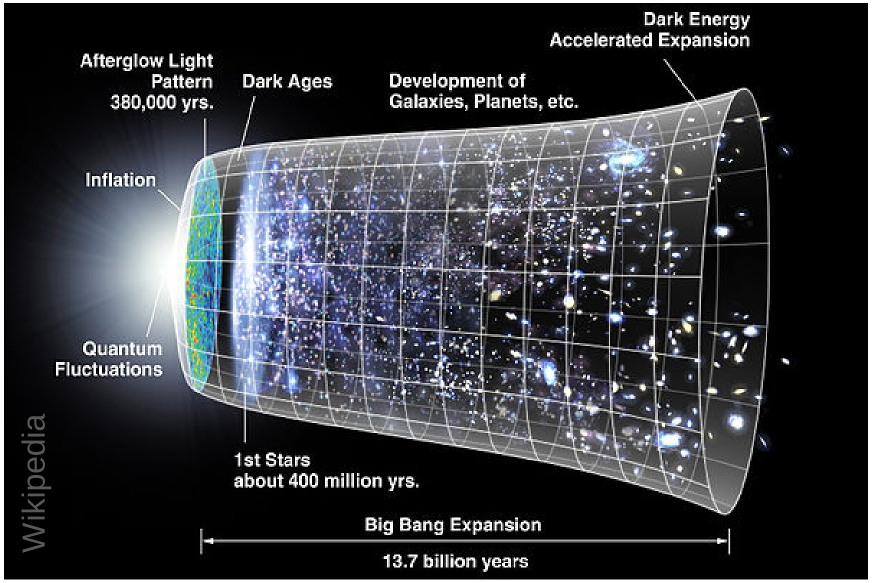




$$\Delta E_0 = -2\,\frac{\alpha_{Cs}\,\sigma T_s^4}{c\varepsilon_0},$$

$$a = -\alpha_{Cs}\,\frac{\sigma\left(T_s^4 - T_0^4\right)}{c\,\varepsilon_0\,m_{Cs}}\,\frac{R^2}{r^3}\ .$$

- Absorptivity α and emissivity ϵ = α = 0.35±0.05 (measured)
- Source and ambient radiation
- Reflections

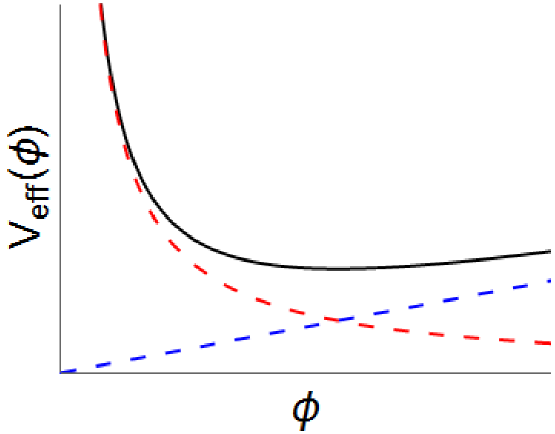


Dark energy scalar fields

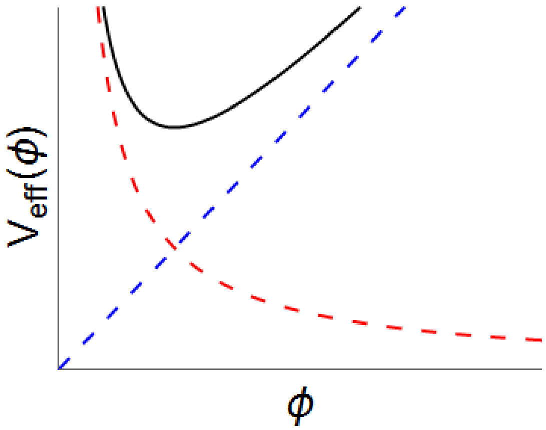
M. Jaffe, P. Haslinger, V. Xu, J. Khoury, B. Elder, M. Upadhye and H. Muller

Screened DE-matter-coupling

Low density (vacuum)
Light, long-ranged field

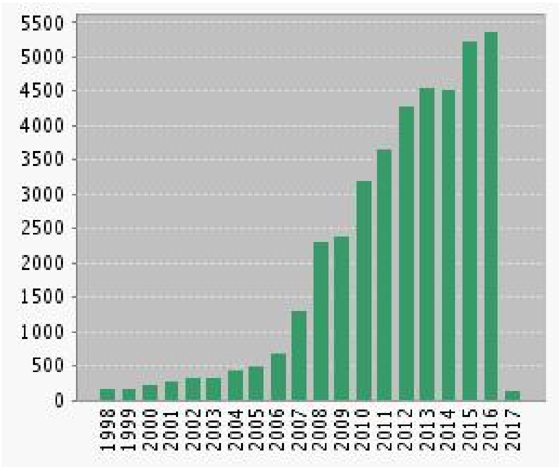


High density (in matter)
Heavy, short-ranged



- Quintessence can be light in space, yet evade detection
- Chameleons, *f*(*R*), symmetrons,…
- **Good fit for dark energy, challenging to rule out**

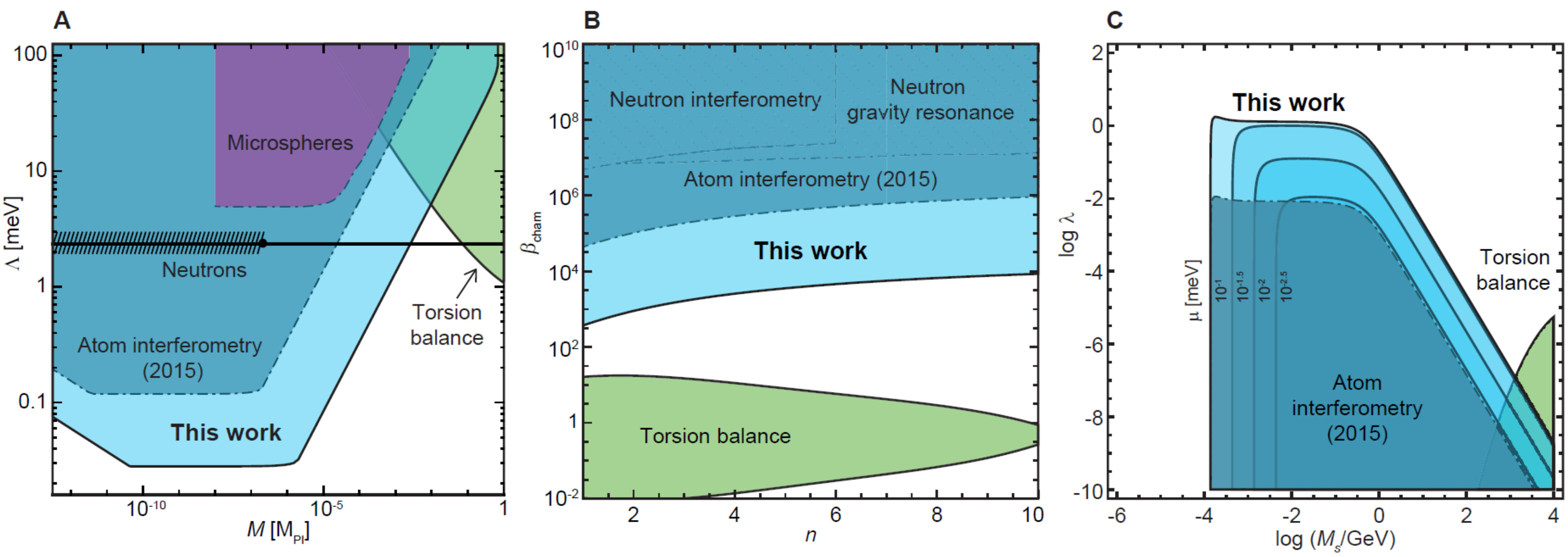
Citations/year



Limits on dark-energy scalars

Chameleons

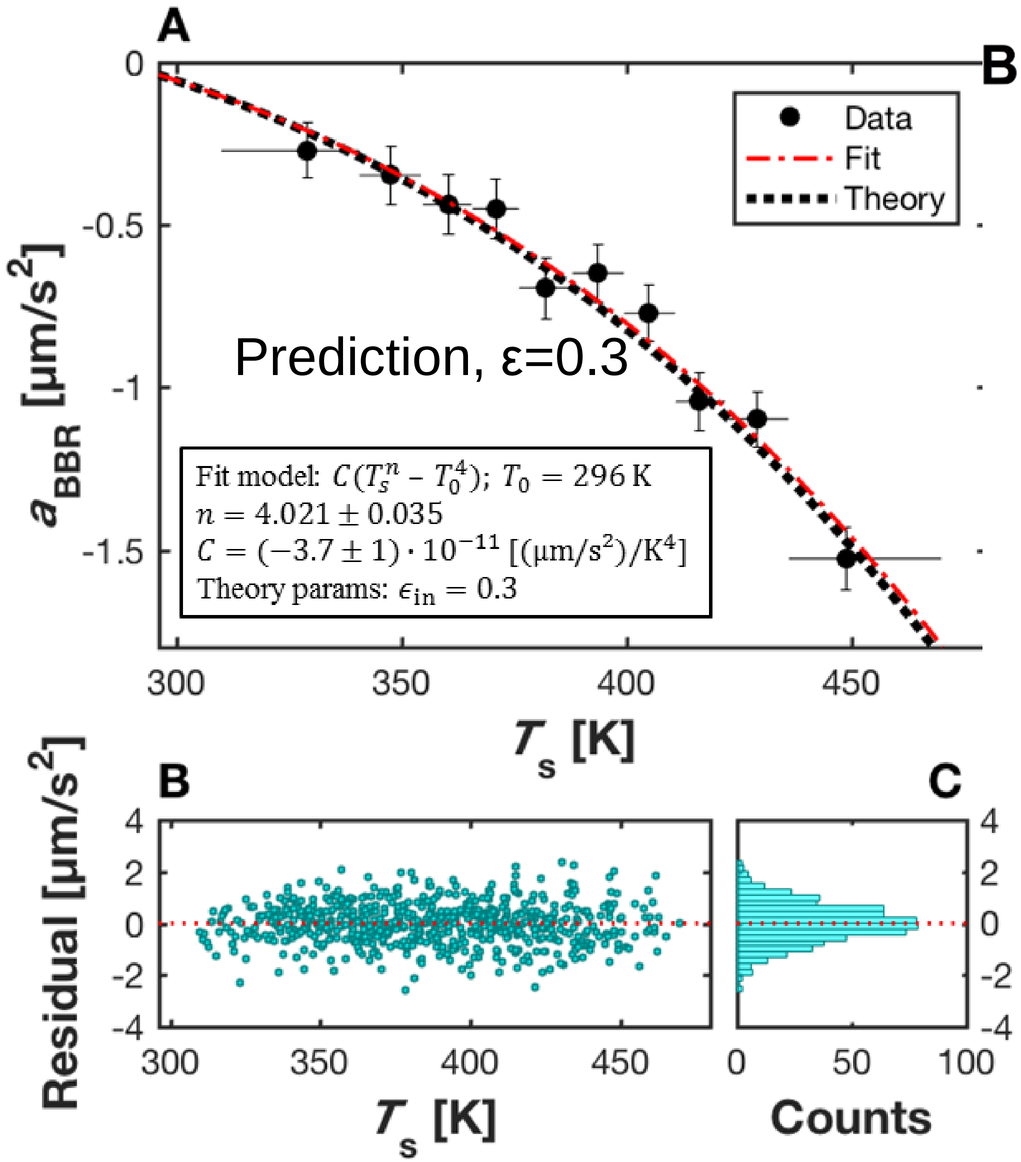
Symmetrons

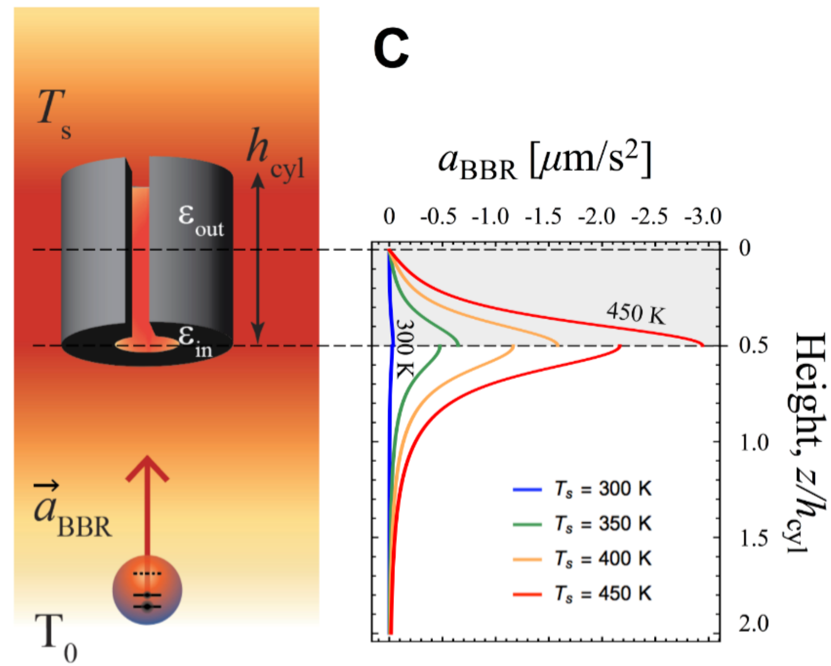


Interaction strength

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

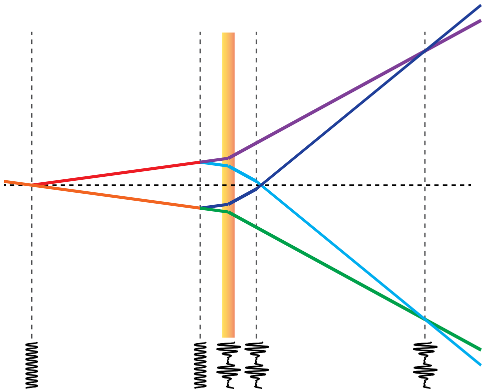
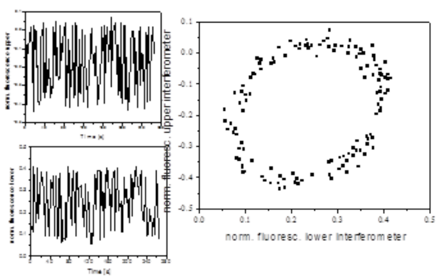
Force from blackbody radiation

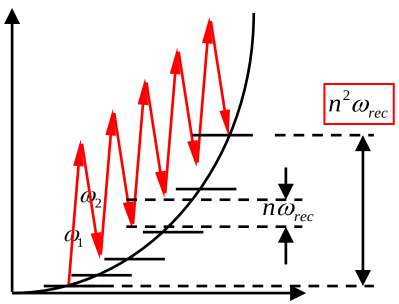


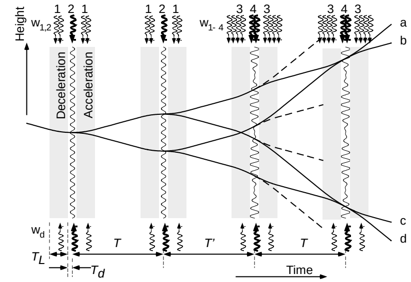


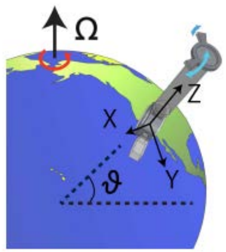
arXiv:1704.03577

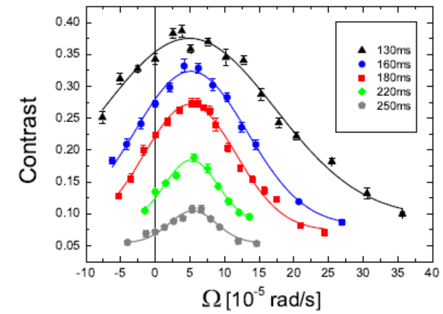
Technology





Noise rejection
- 2,500 fold gain in sensitivity
- Now used by the Biraben group, LKB Paris
- Chiow et al., PRL 2009

Multiphoton Bragg diffraction
- Up to 24 photon kicks
- Now used, e.g., at Stanford, Western Australia, Paris, …
- H.M. et al, PRL 2008

Optical lattice beam splitter
- Up to 800 photon kicks: record!
- H.M. PRL 2009, Parker, PRL 2015; Estey, PRL 2014

Coriolis compensation
- Needed in world's most sensitive interferometers
- Now used, e.g., at Stanford
- Lan et al., PRL 2012

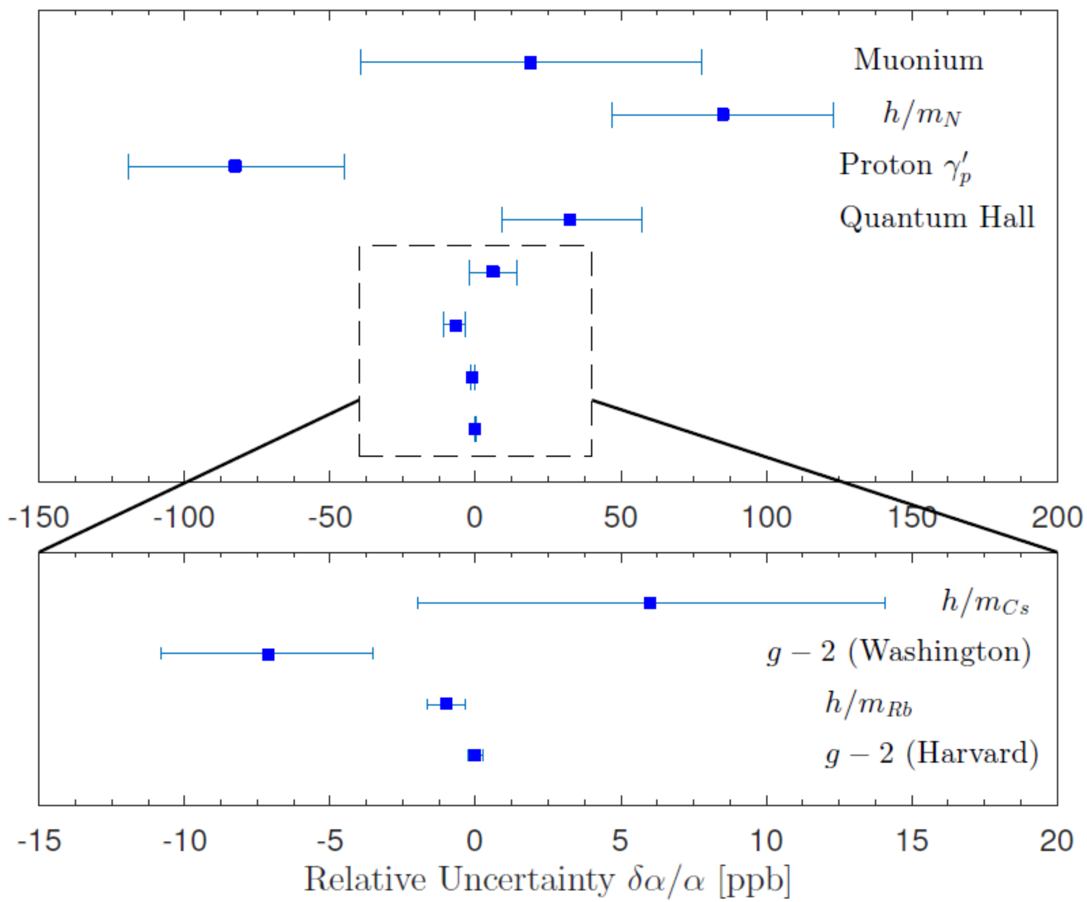
Fine structure constant

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



Fine Structure Constant

Current Status of α

Electron's magnetic moment anomaly g-2 : 0.37 ppb

D. Hanneke *et al.* PRL **100**, 120801 (2008)

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots + a_{\mu,\tau} + a_{\text{hadronic}} + a_{\text{weak}}$$

Photon Recoil Measurement (Rb) : 4.6 ppb M. Cadoret *et al*. PRL **101**, 230801 (2008)

Photon Recoil Measurement (Cs) : 7.4 ppb A. Wicht *et al.*, Phys. Scr. T **102**, 82 (2002).

Alpha in Atom Recoil Frequency

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

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

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

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

Determined by the atom recoil frequency

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

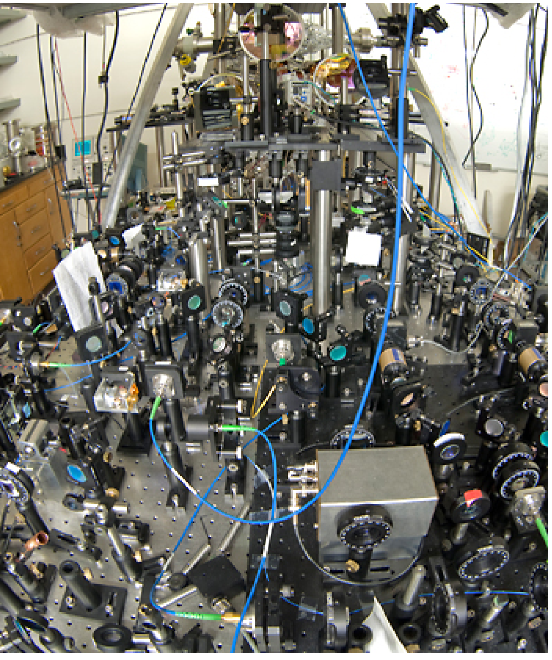
Cs D2 Transition
0.015ppb

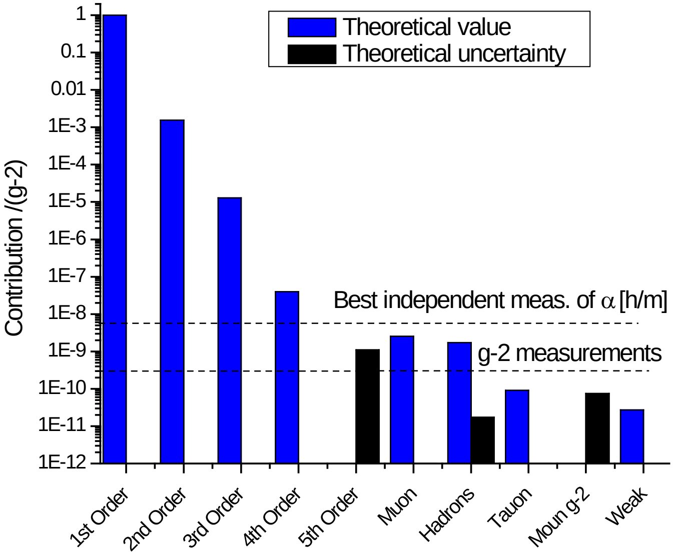
Lowest : 0.23ppb

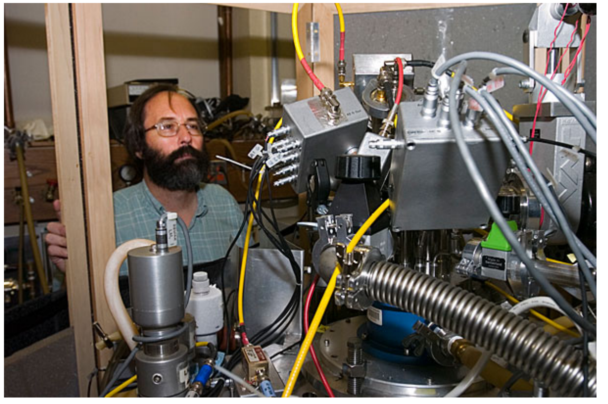
The most precise theory/experiment comparison in science

Fine structure constant

Electron gyromagnetic moment



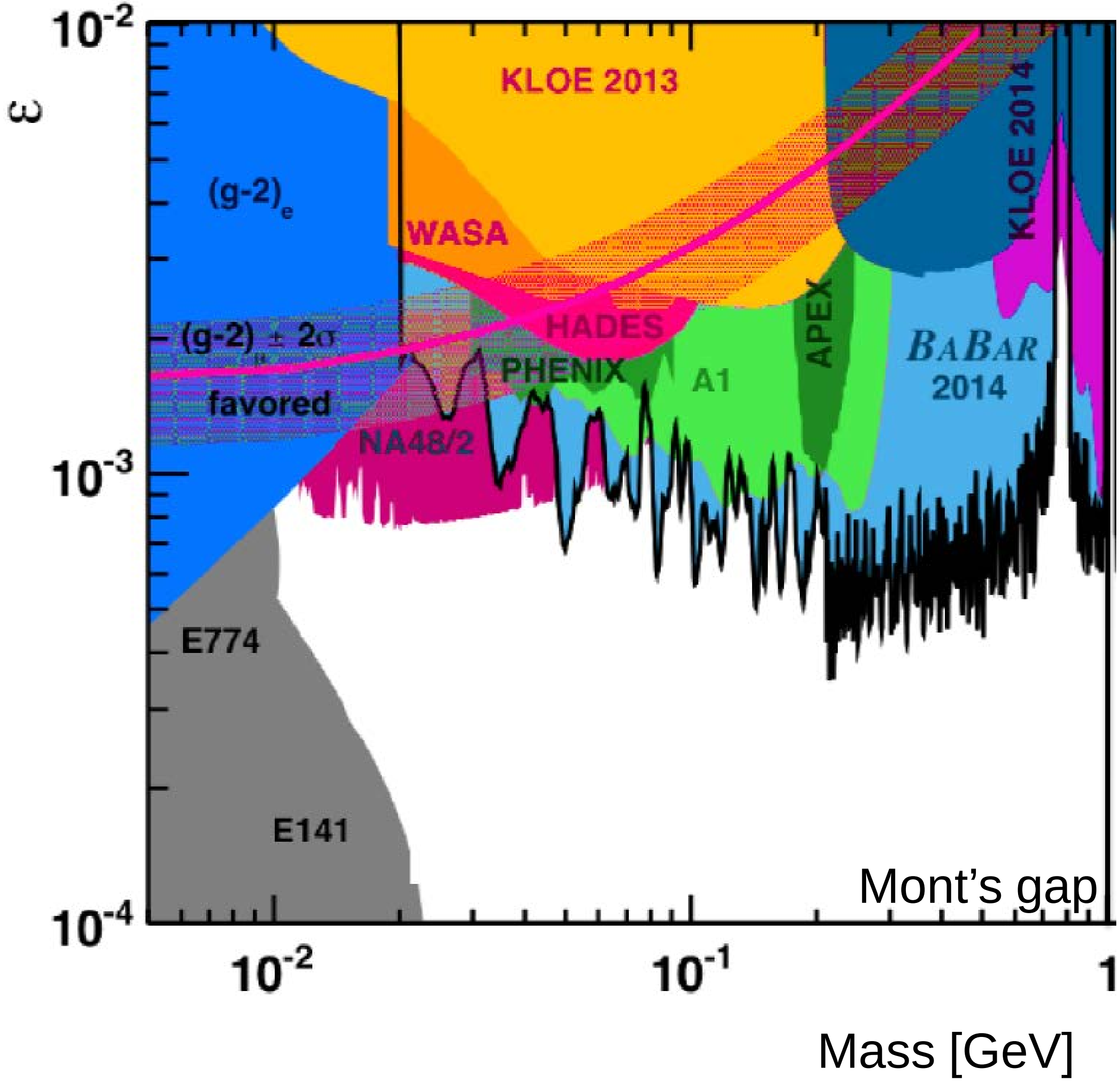




Dark photons shift magnetic moment versus fine structure constant

Measures how strong a magnet an electron is

Dark photons limits



Impact

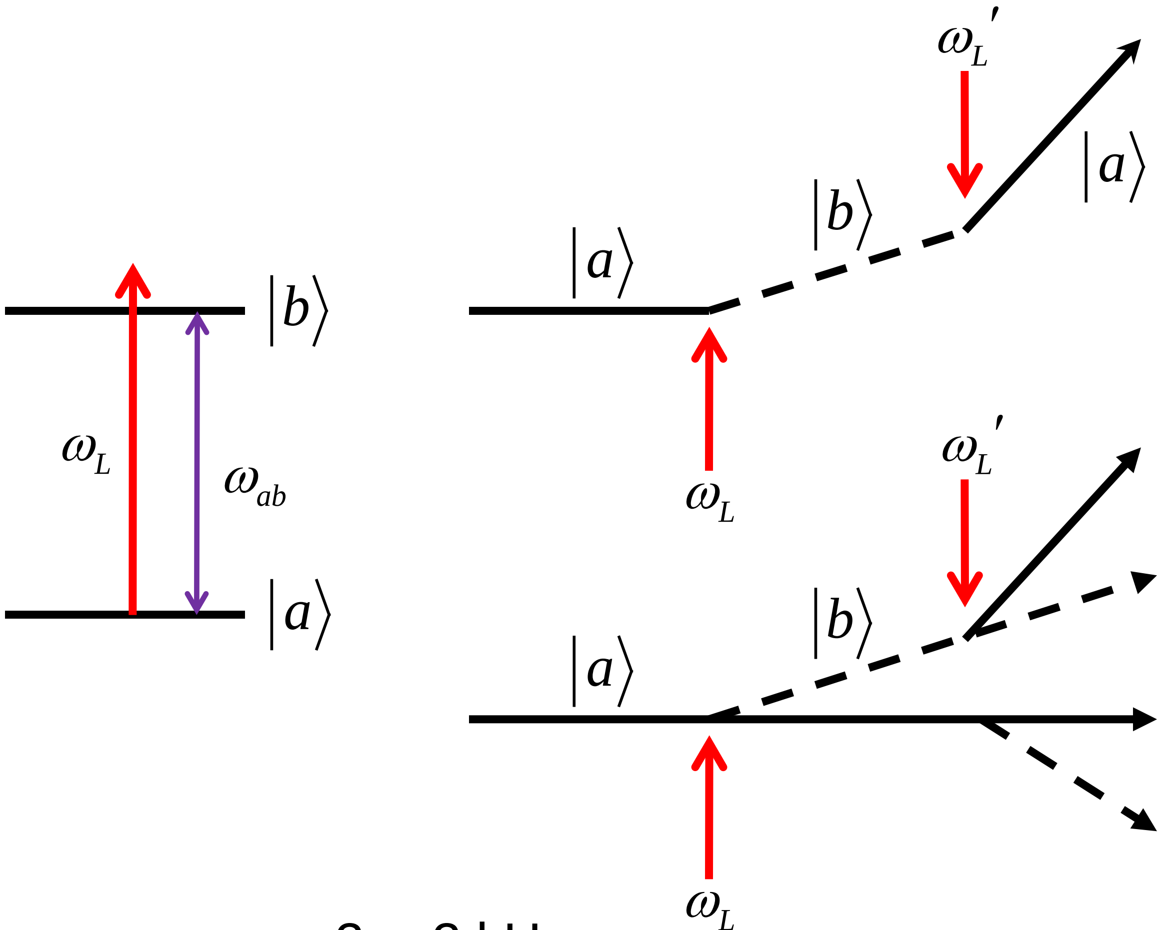
- Most precise measurement of the fine structure constant
- Confirms the most precise prediction in all of science

- Search dark photons beyond the reach of colliders
    - Detection: first new particle after Higgs, potentially opening up portal to even more dark sector particles
    - Exclusion would free up enormous resources in collider labs

- First atom interferometer to control systematic errors at 10^{-12} level

Principle

Photon Recoil Measurement

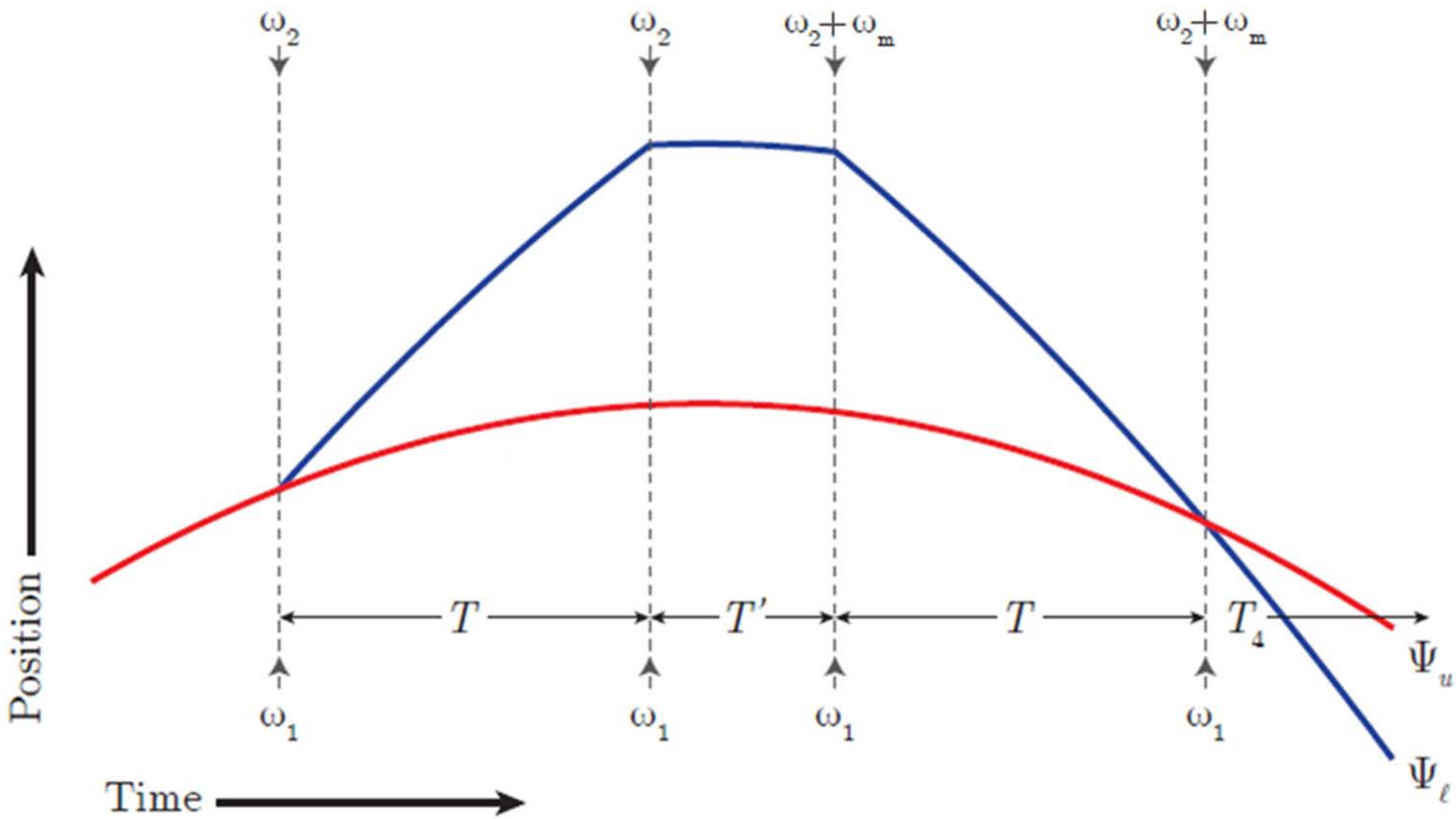


$$\omega_L'(|a\rangle) - \omega_L'(|b\rangle) = 2\omega_{rec}$$

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

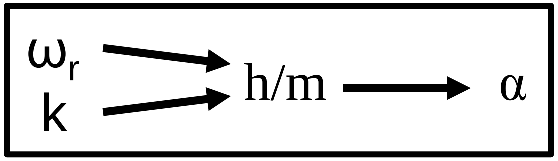
Atom-interferometer measurement of α

Ramsey-Bordé Interferometer

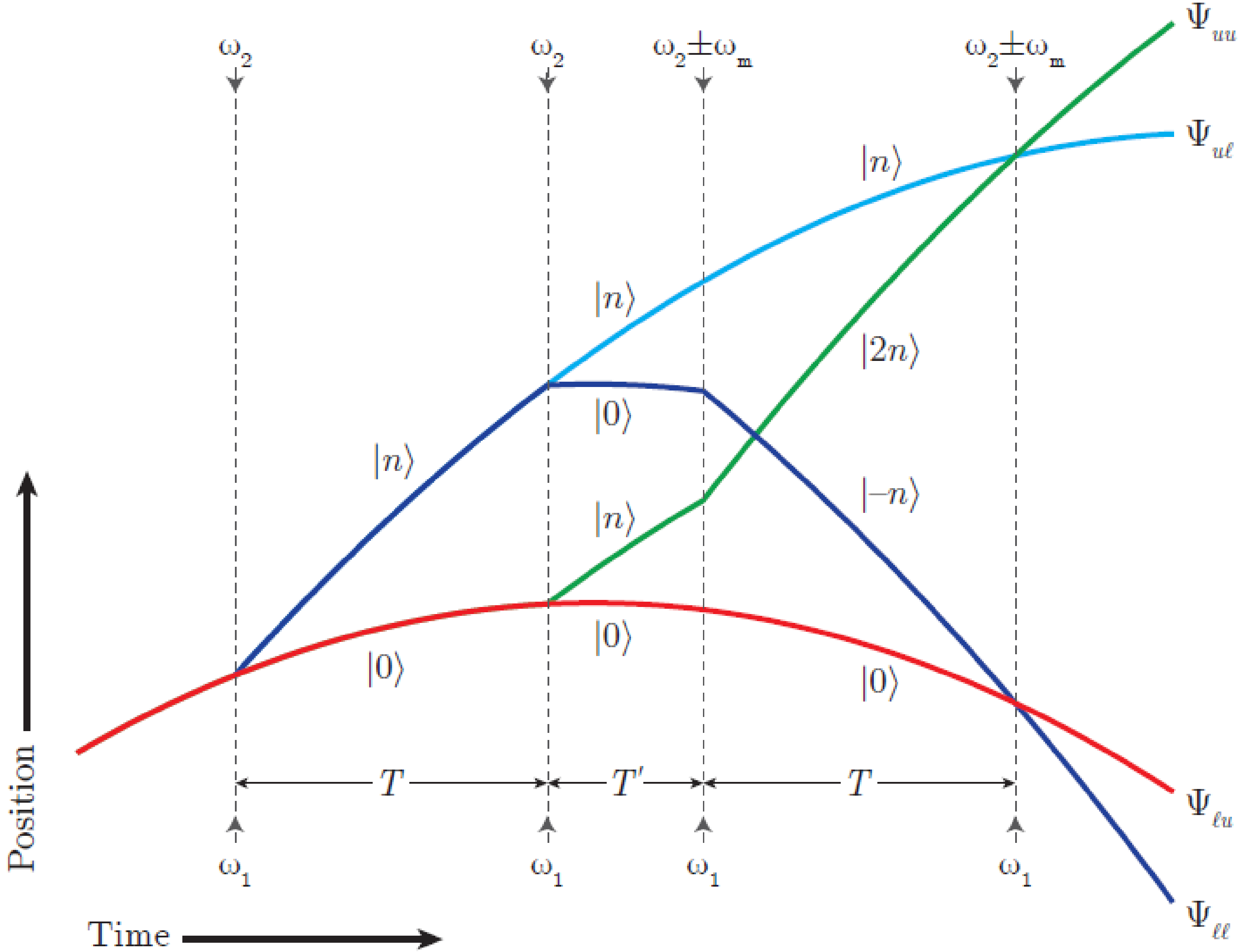


$$\Phi_{RB} = 8n^2\omega_r T - 2nkg(T+T')T - n\omega_m T$$

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



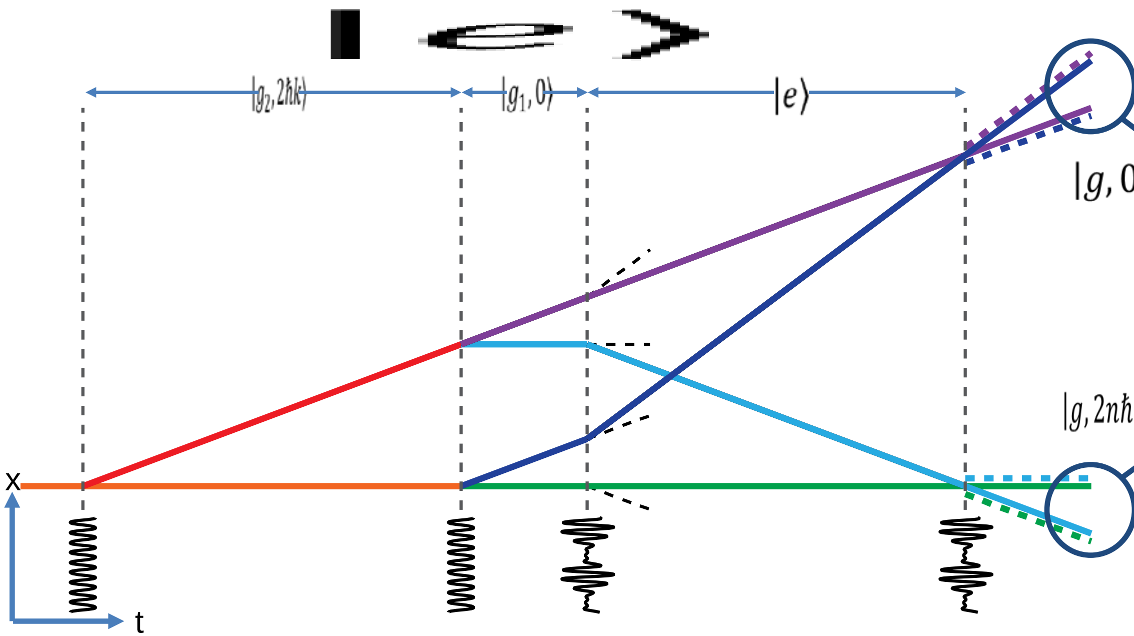
Simultaneous Conjugate Interferometers

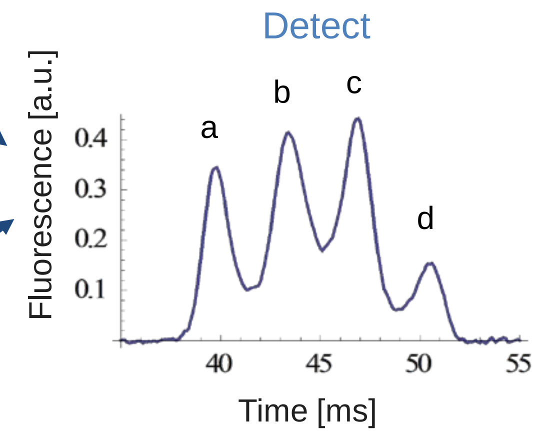


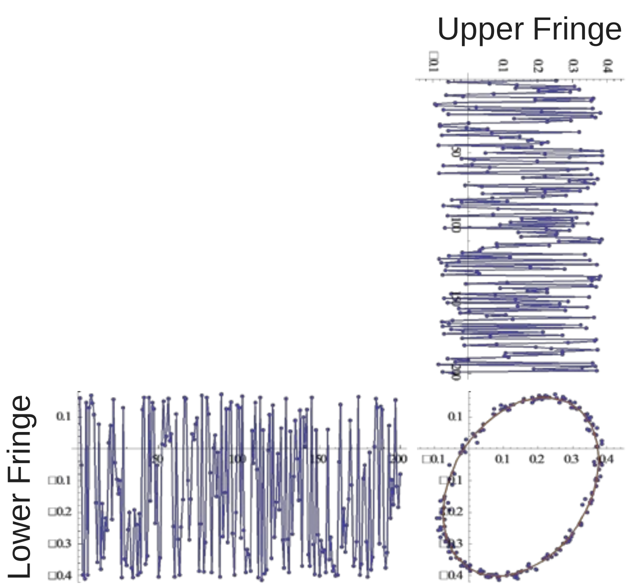
$$\Phi_{RB} = \pm 8n^2\omega_r T \pm n\omega_m T + 2nkg(T + T')T$$

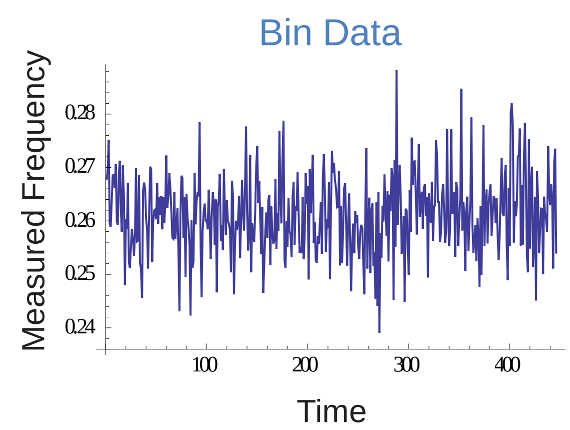
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$

Phase Extraction



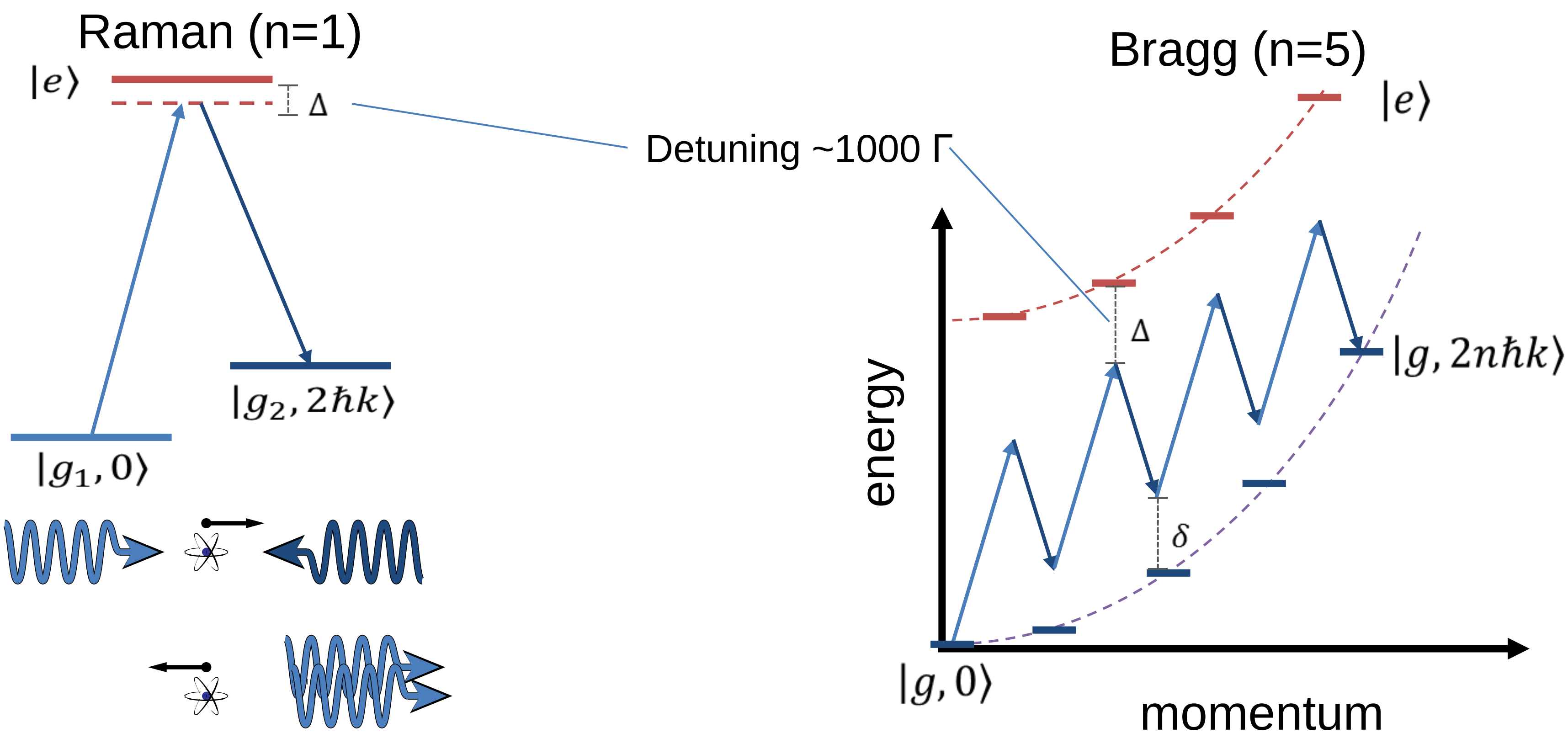






Multi-Photon Bragg Diffraction

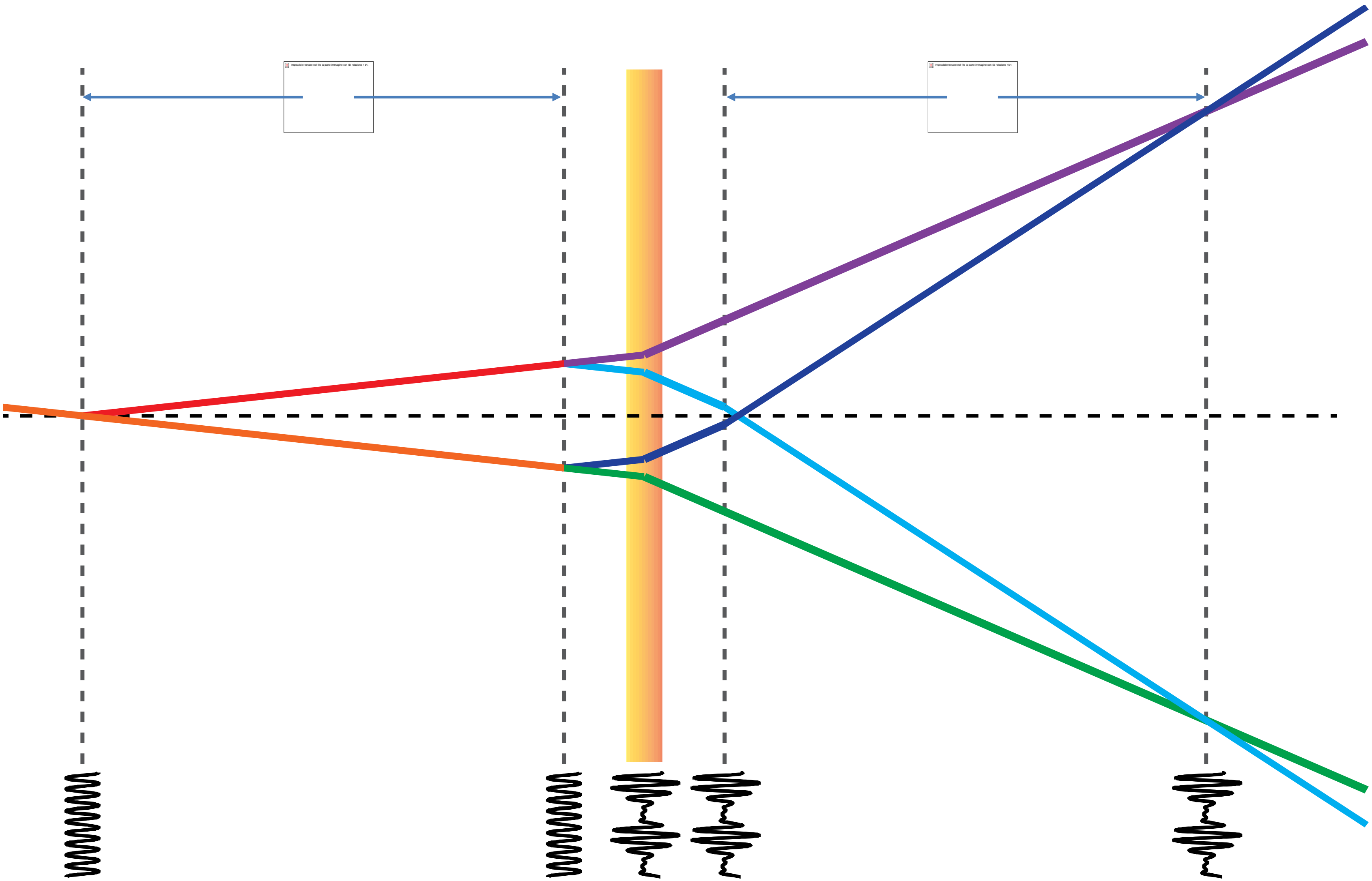
$$\Phi_{RB,Diff} = 16n^2\omega_r T - 2n\omega_m T$$



Bragg gives you:

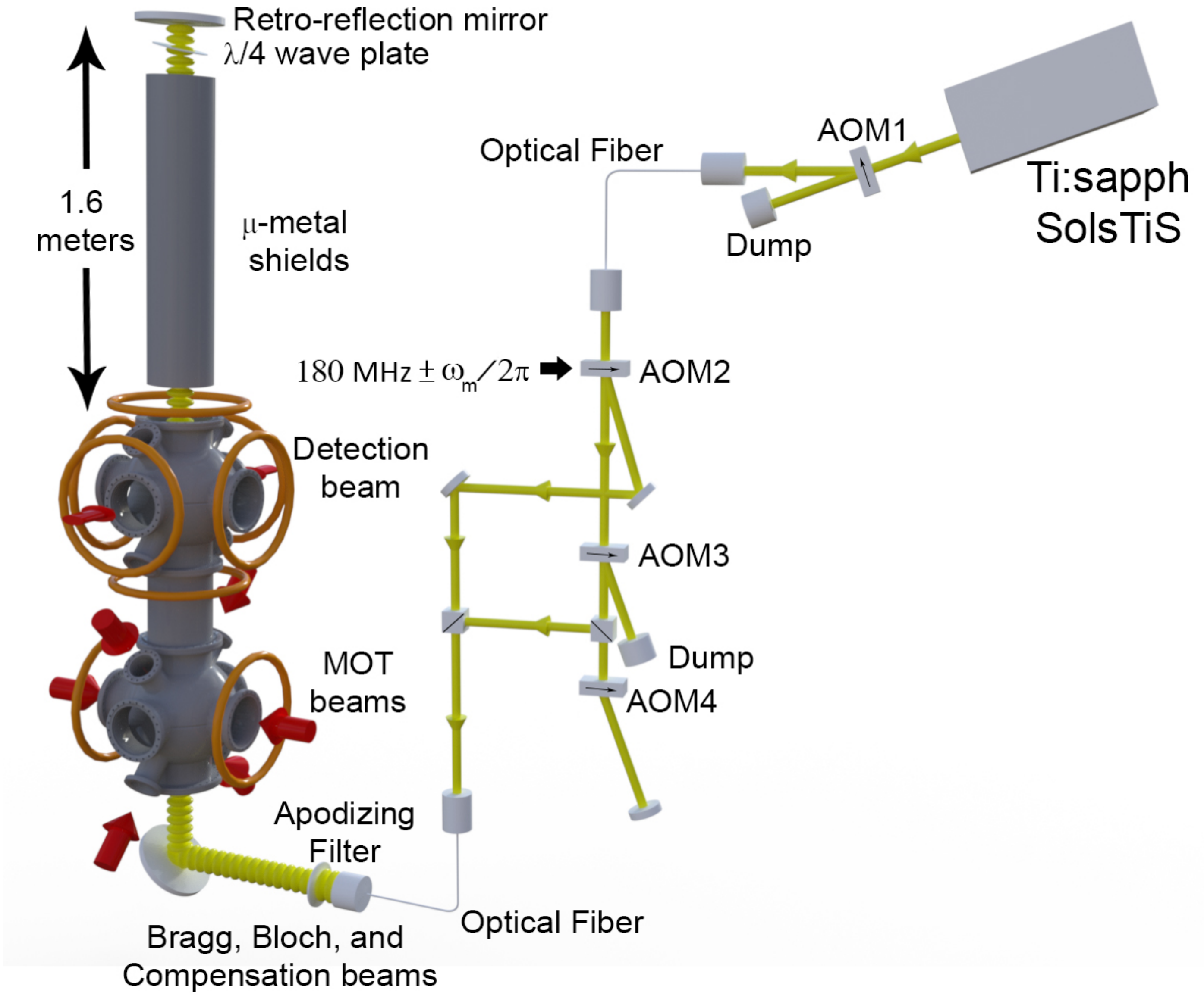
- More photons transferred per pulse (higher sensitivity)
- Atoms stay in same internal state (Zeeman, AC Stark systematics suppressed)

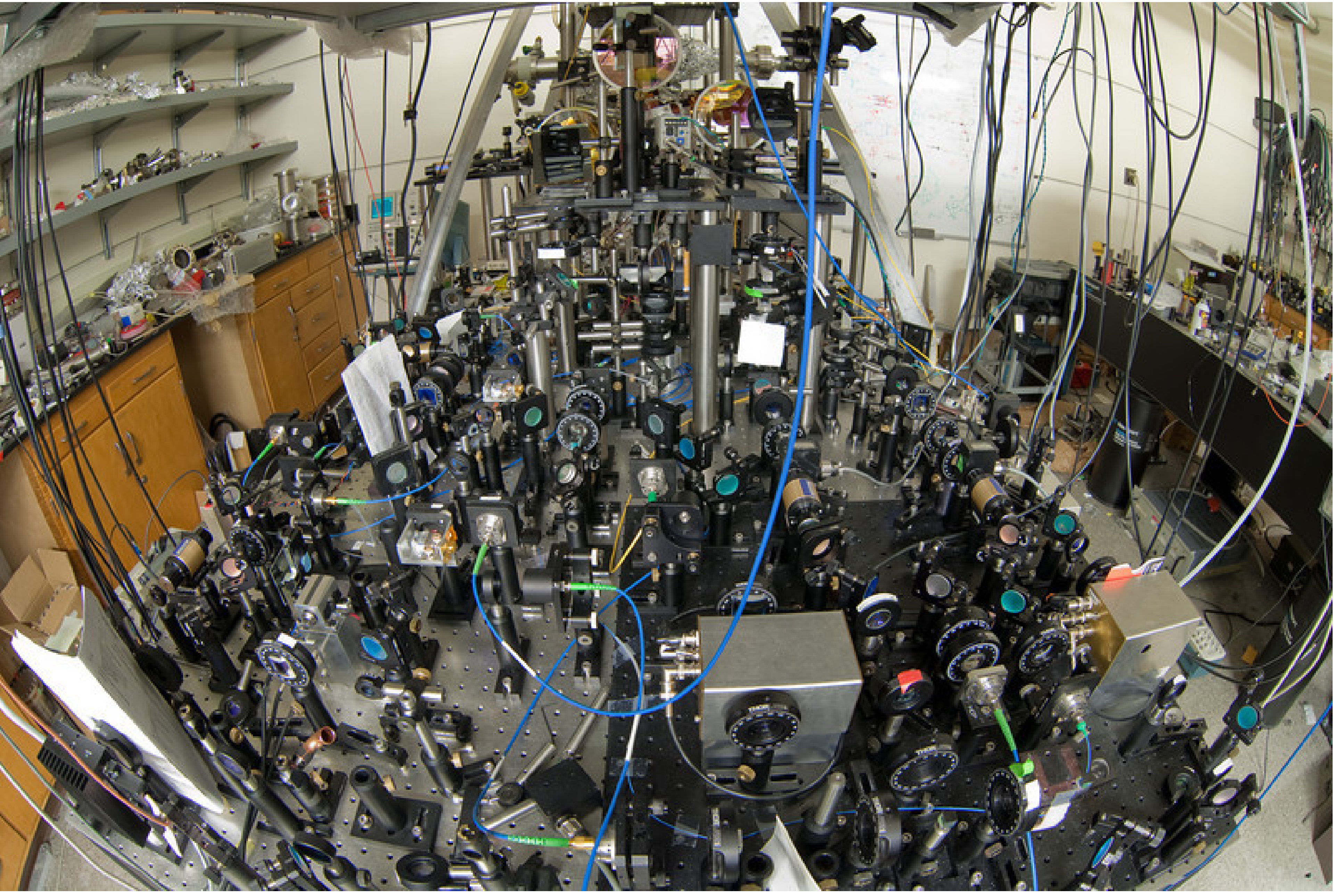
Bloch Oscillations



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

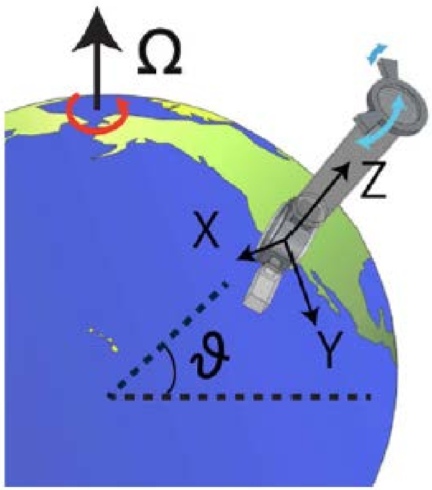
Setup


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

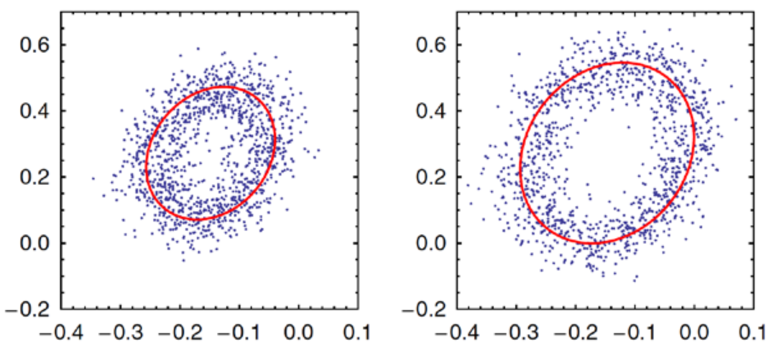


Tricks for Increased Sensitivity

Coriolis Compensation



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

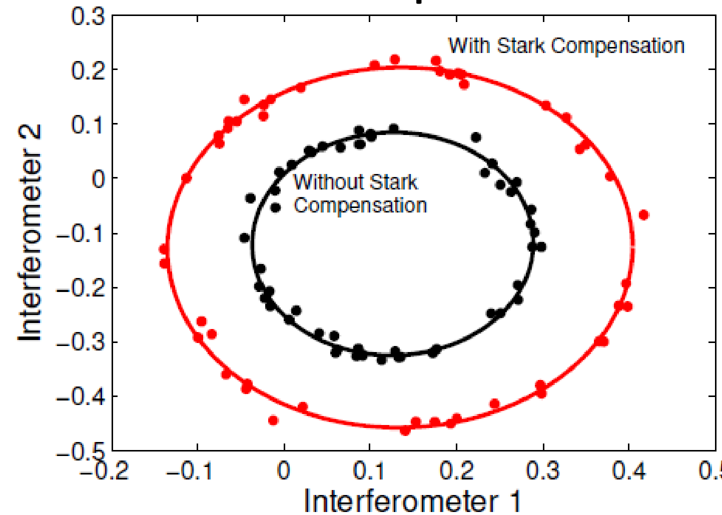


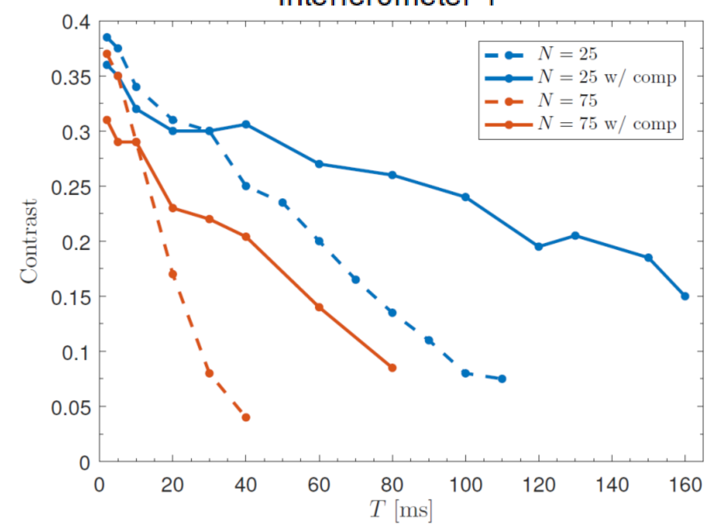
Without compensation

With compensation

x3.5 contrast gain

Stark Compensation

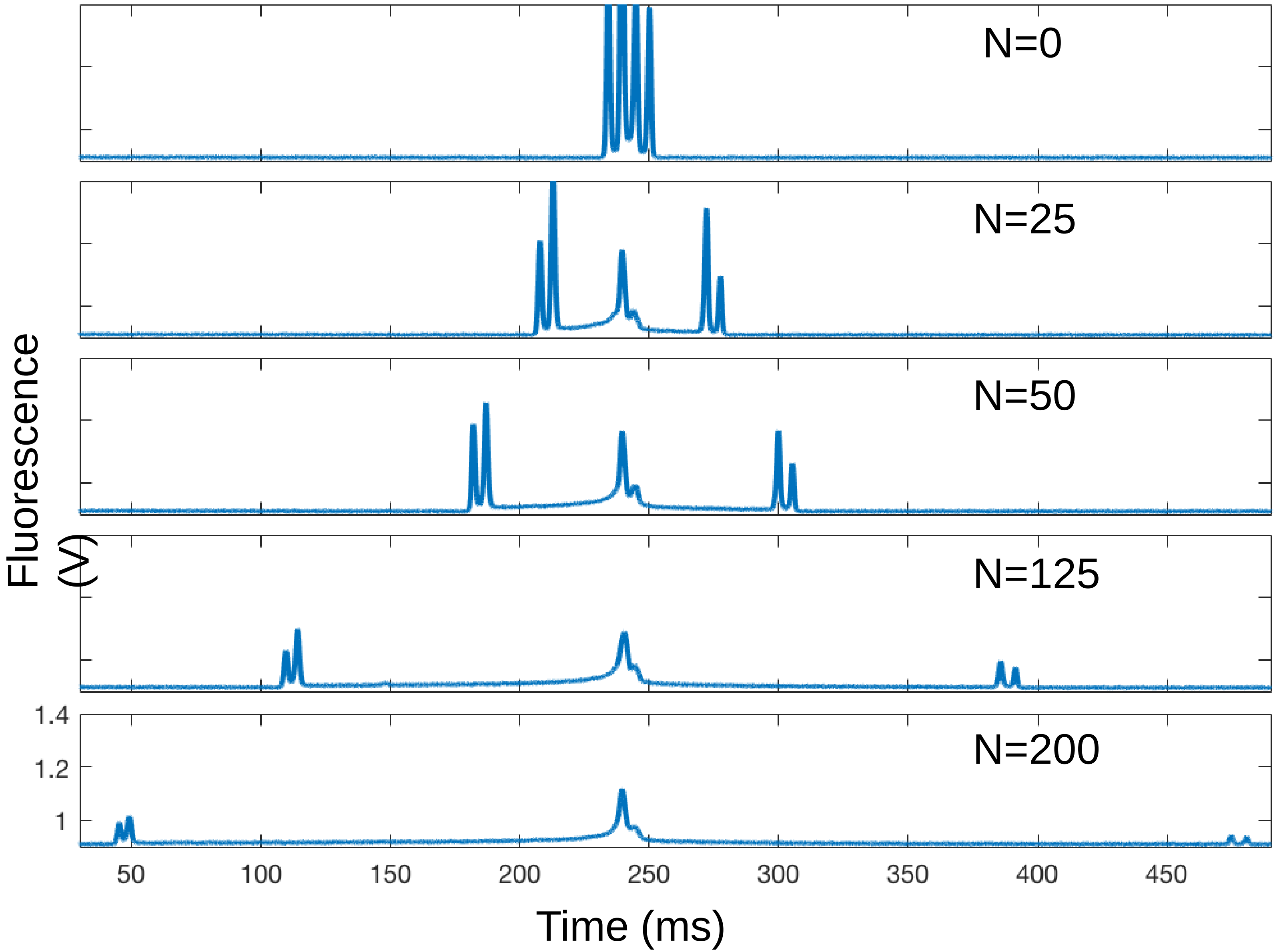




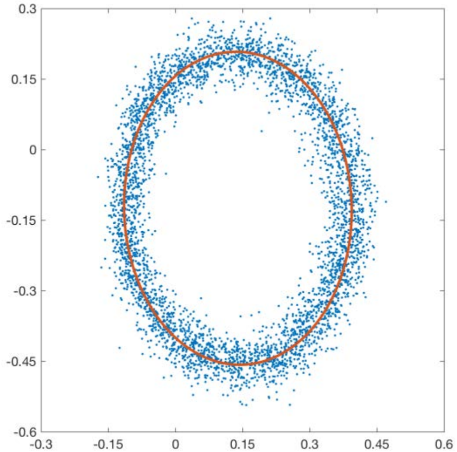
Up to N=200

>12Mrad phase diff. measurable!

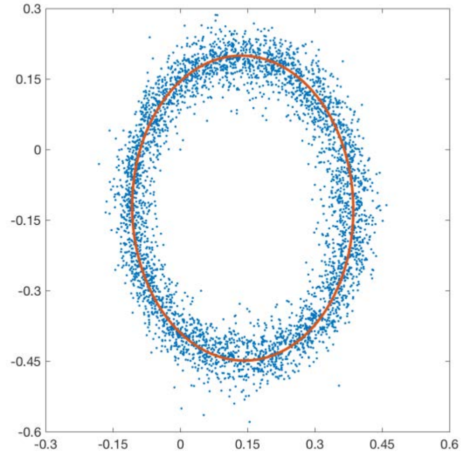
Fluorescence Traces



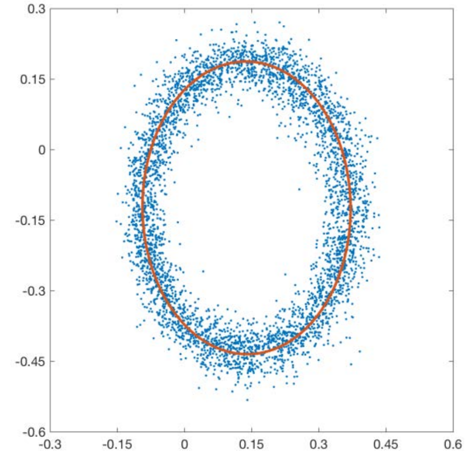
n=5, N=125 Ellipses



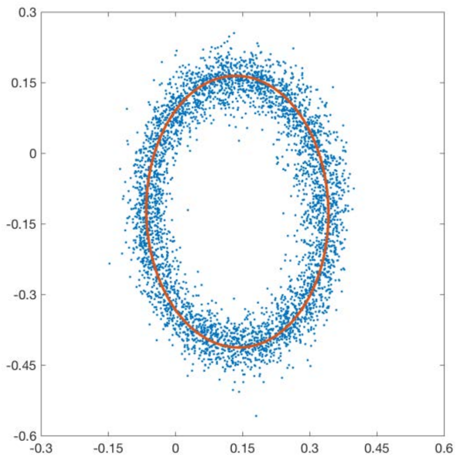
T=5 ms



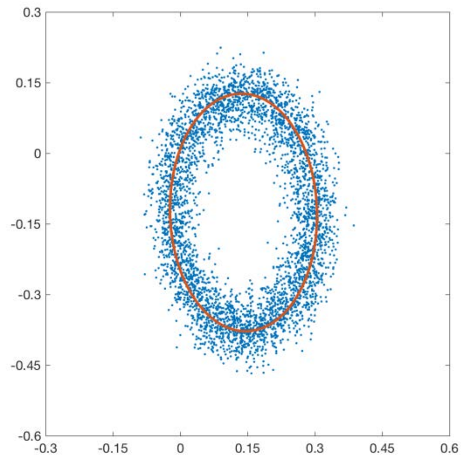
T=10 ms



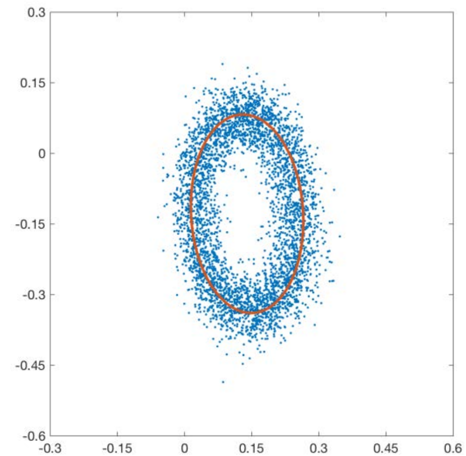
T=20 ms



T=40 ms



T=60 ms

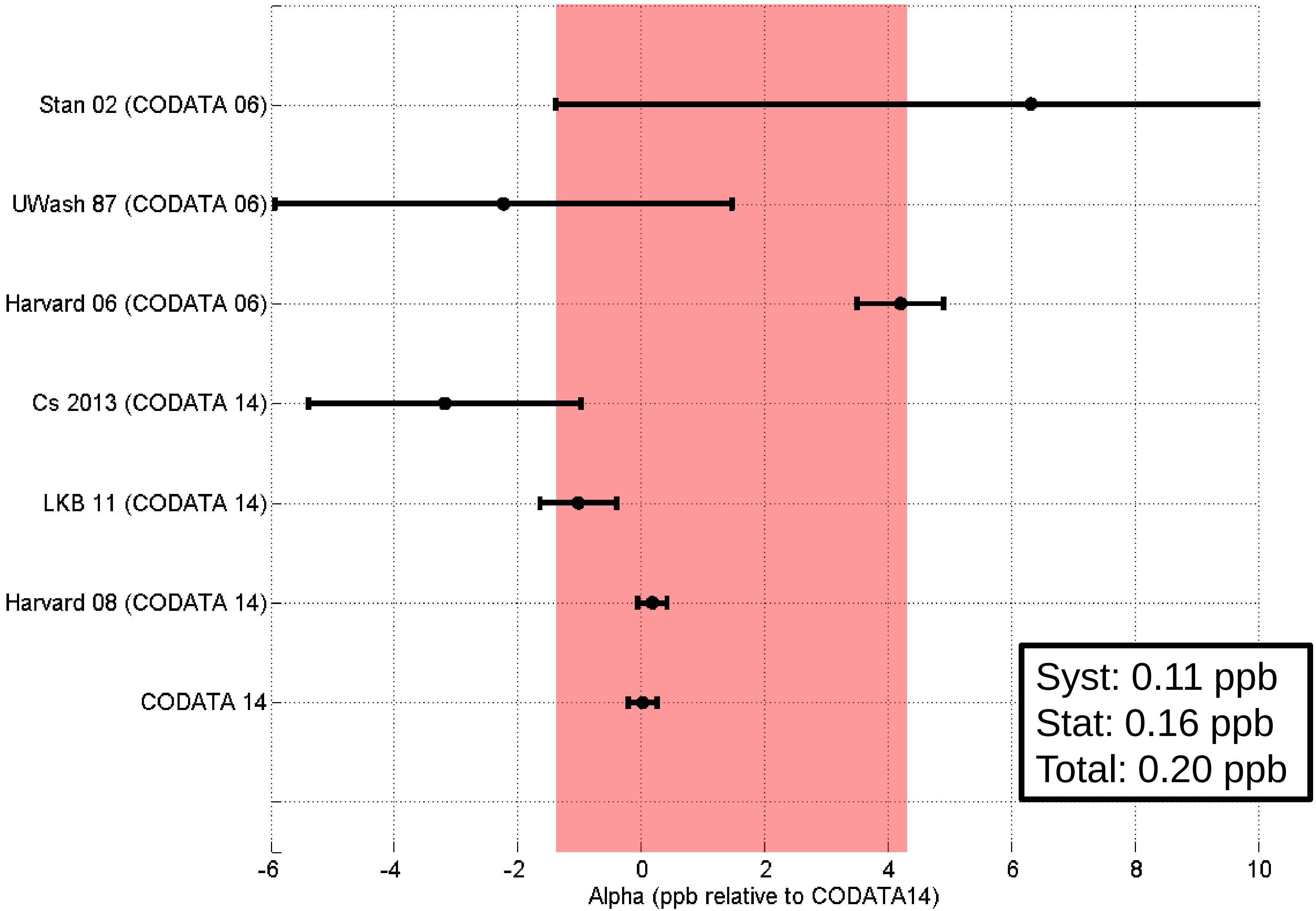


T=80 ms

Suppression of Bias

- Blinding
  - Random number [-1 MHz, +1 MHz] chosen by Rana Adhikari (Caltech)
  - Added to Laser Wavenumber (+/- 3 ppb)
  - Given to us as encrypted file
- Two Independent Data Analysis Programs
  - Same raw datasets
  - Agree

Blind Analysis



Systematics

0.16 ppb systematic errors

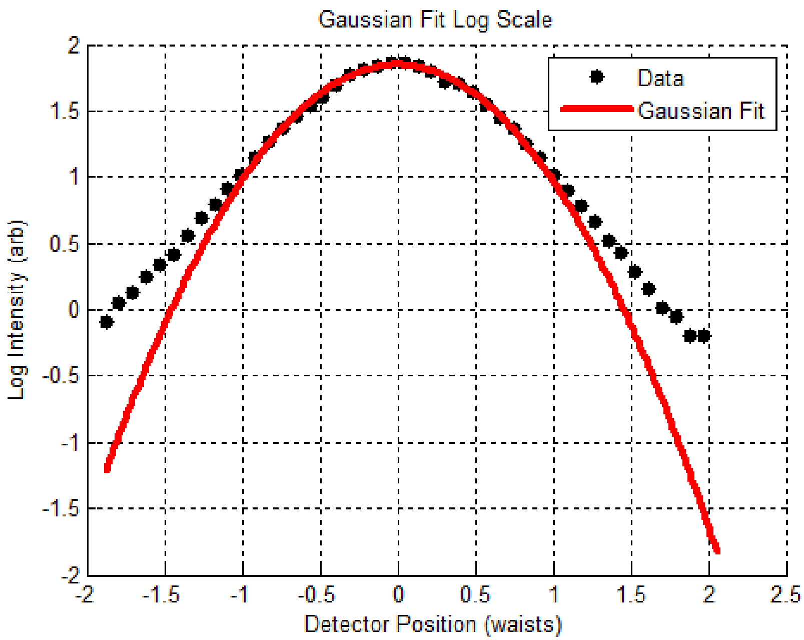
Effect	Sect.	Value	$\delta\alpha/\alpha$ (ppb)
Laser Frequency	1	N/A	-0.24 ± 0.03
Acceleration Gradient	4A	$\square=(2.13 \pm 0.01)\times10^{-6}/s^2$	-1.69 ± 0.02
Gouy phase	3	w_0=3.21±0.008 mm, z_0=0.5±1.0 m	-3.60± 0.03
Wavefront Curvature	12	$\langle r^2\rangle^{1/2}$=0.58 mm	0.15 ± 0.03
Beam Alignment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

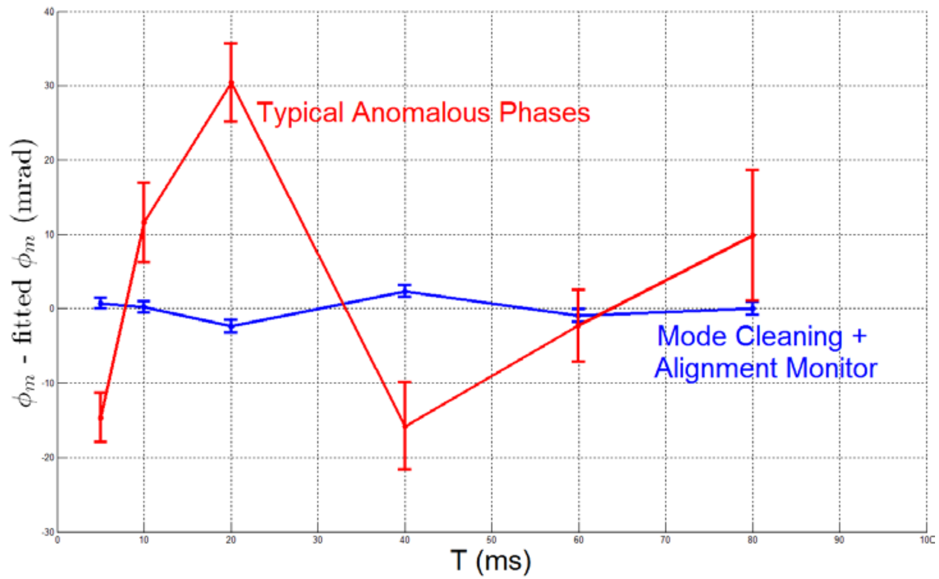
Big

‘New’

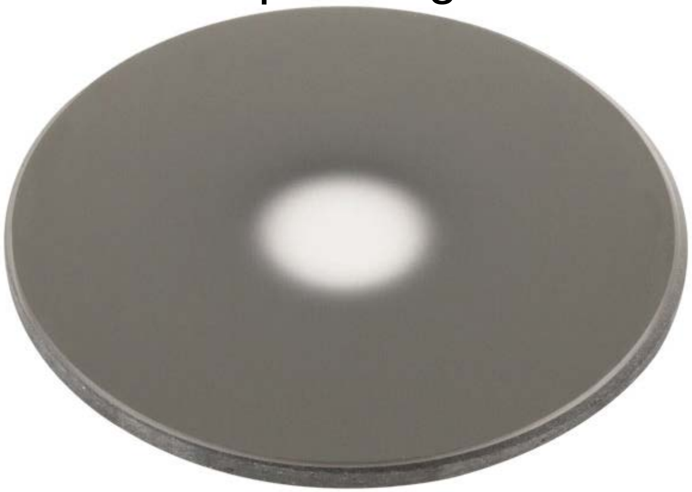
Speckle Phase

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





$200 Apodizing Filter



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

Systematic Checks

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

Dark photons

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

- Vector portal "massive photon"
- Higgs portal
- Neutrino portal

Hints

- Muon g-2
- Proton radius puzzle
- Astrophysical hints?
  - 511 keV line
  - keV gamma-ray excess
  - Galactic center excess

Dark photons

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Hints

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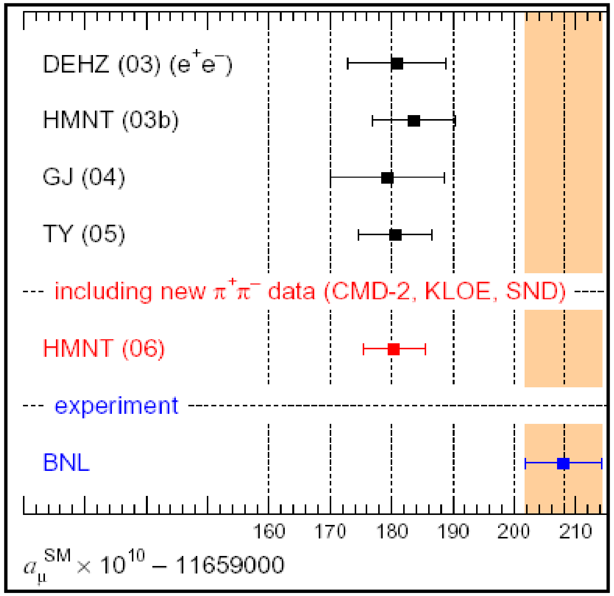
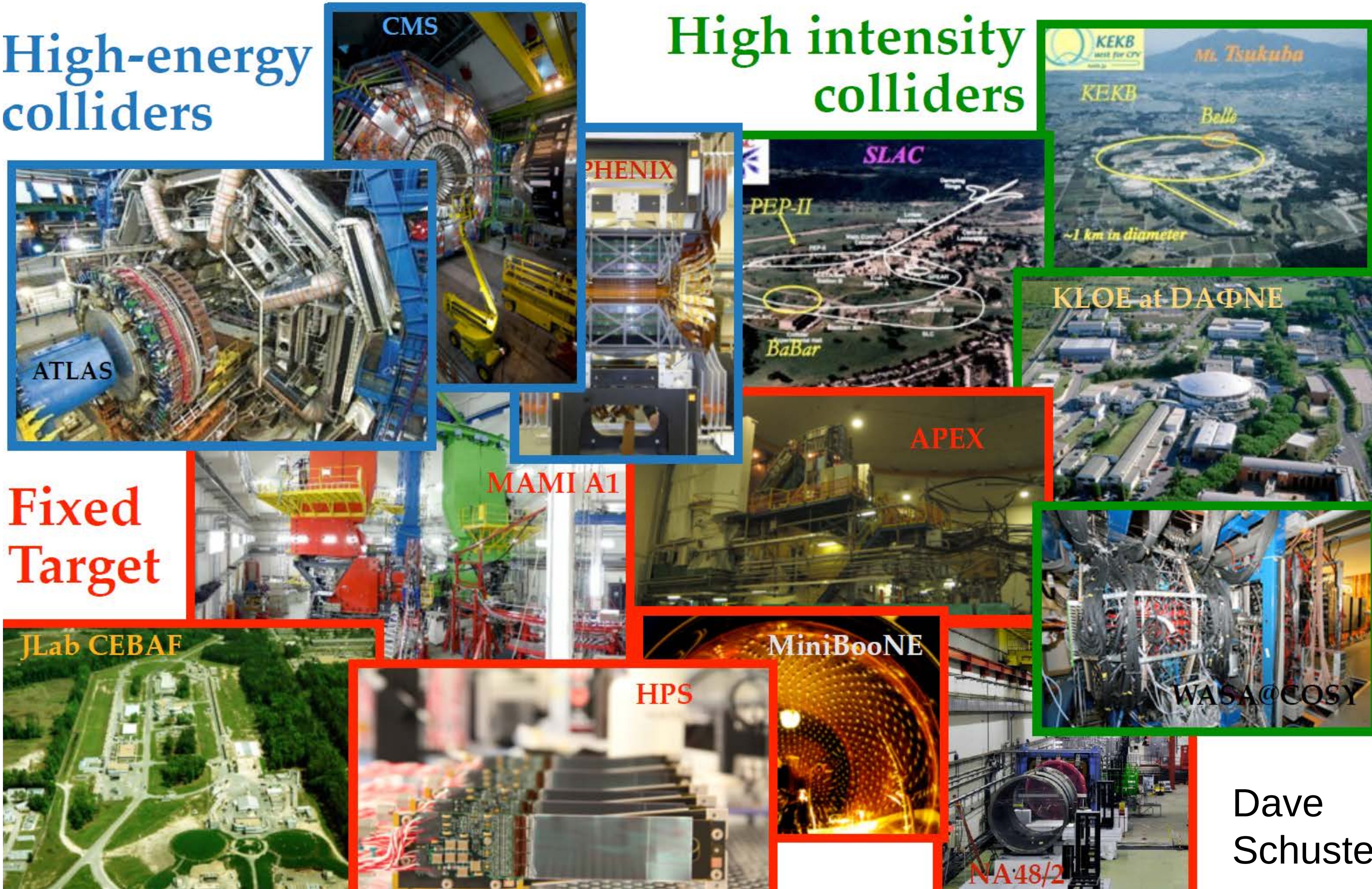
- ^{8}Be decay
- Astrophysical hints?
  - 511 keV line
  - keV gamma-ray excess
  - Galactic center excess



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

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

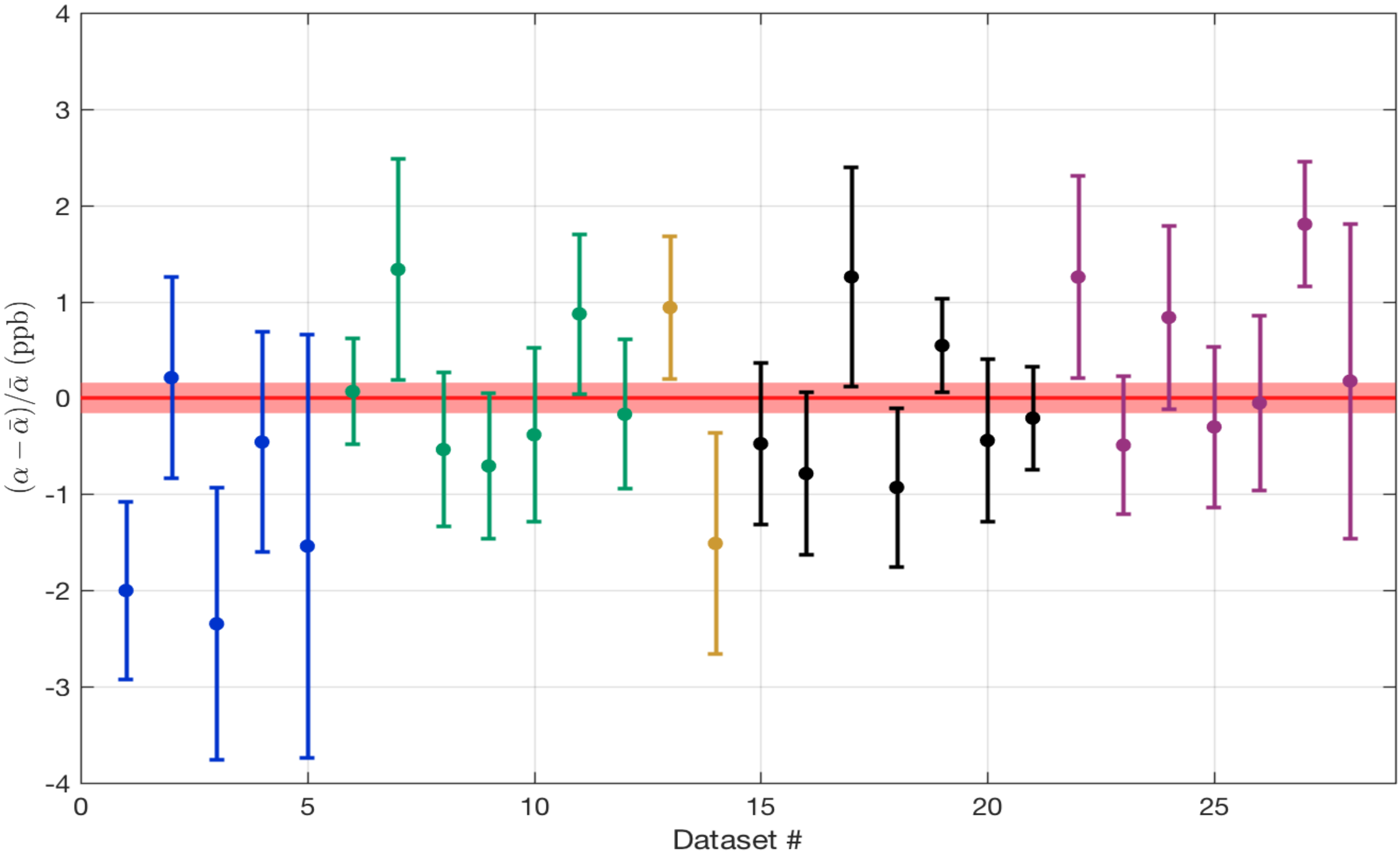
Ongoing dark photon searches



Dave Schuster

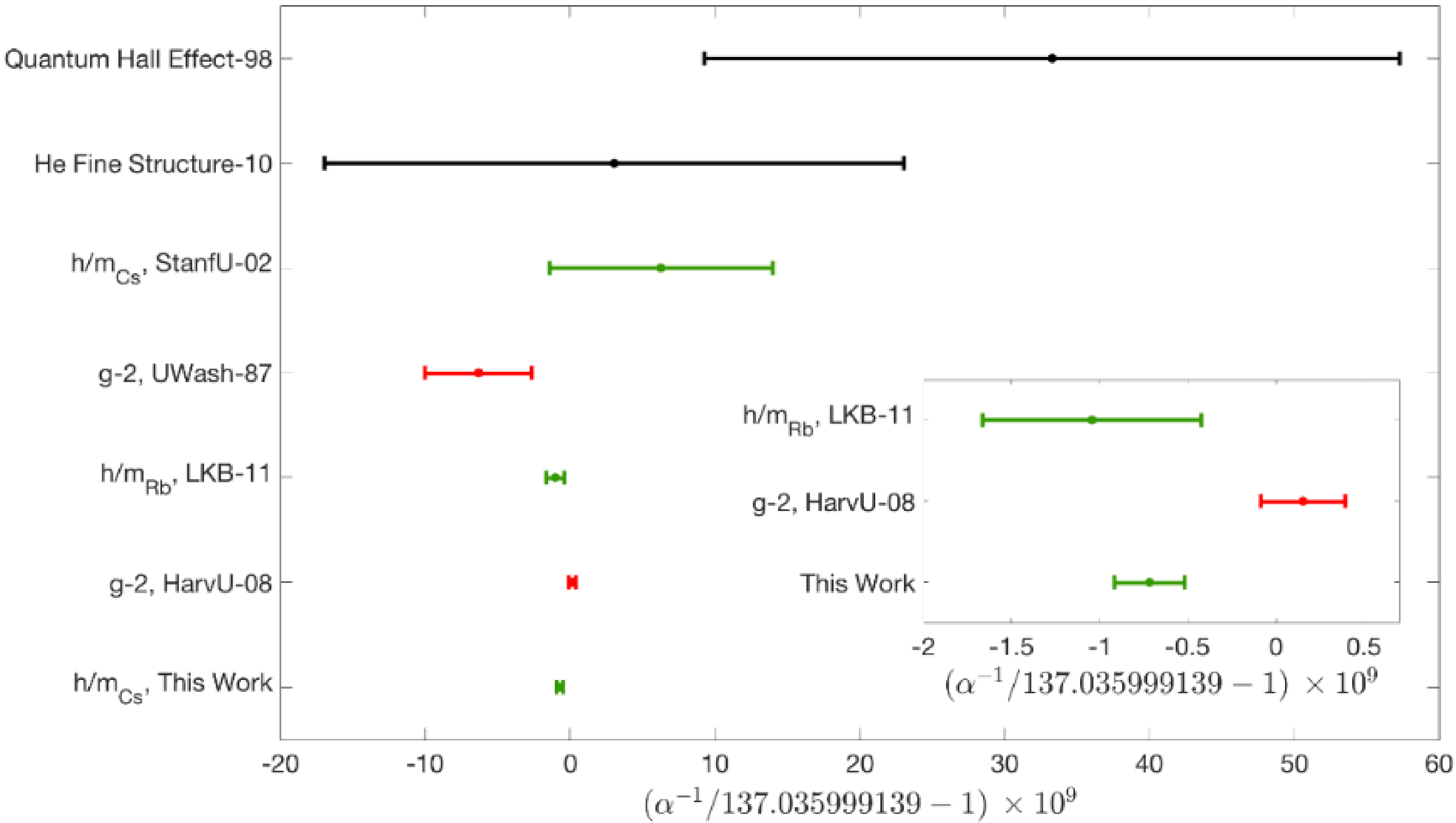
Results

Results



$(\alpha - \bar{\alpha})/\bar{\alpha}$ (ppb)
Dataset #
4
3
2
1
0
-1
-2
-3
-4
0
5
10
15
20
25

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
-2
-1.5
-1
-0.5
0
0.5
$(\alpha^{-1}/137.035999139 - 1) \times 10^9$

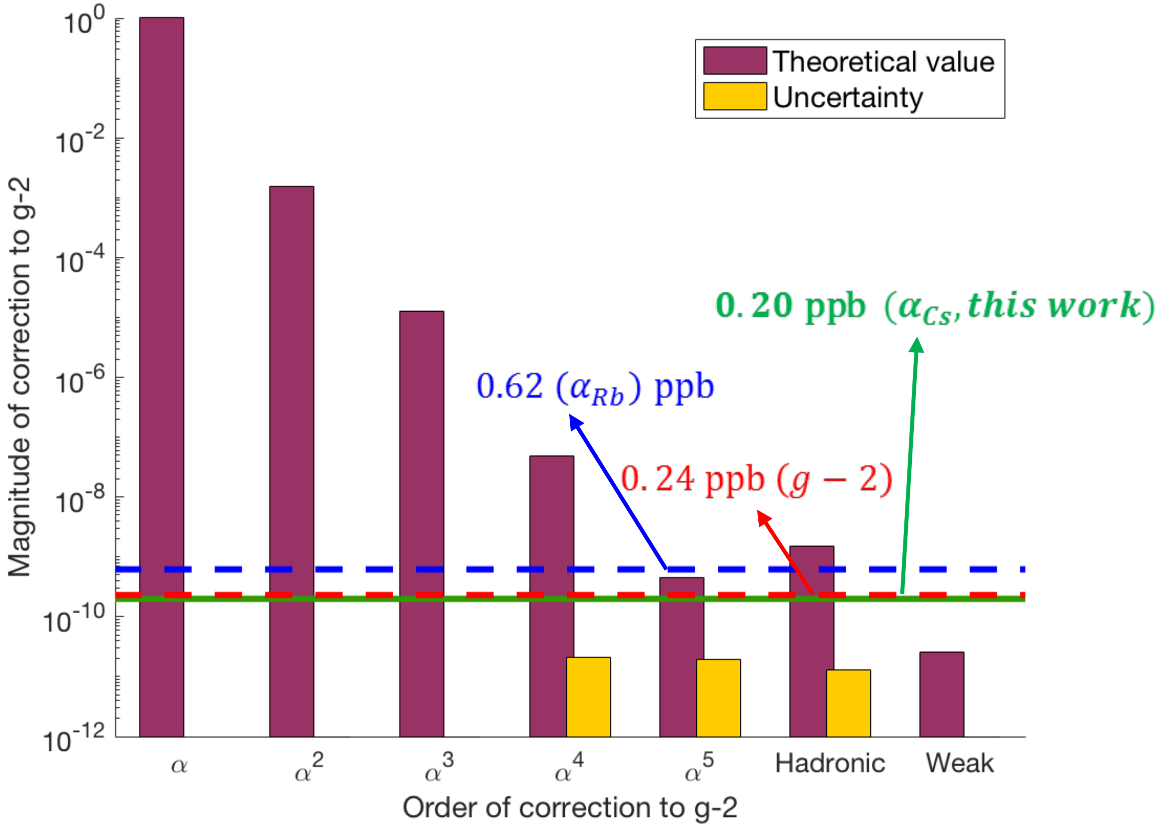
Results

$\alpha^{-1} = 137.035999070(27)$ (0.20 ppb)

$a(\alpha) = g/2 - 1 = 0.00115965218149(23)$

$\delta a = a_{meas} - a(\alpha) = -0.76(0.36) \times 10^{-12}$

1-sigma confidence level $|\delta a| < 1.1 \times 10^{-12}$



Results

α^{-1} = 137.035999070(27) (0.20 ppb)

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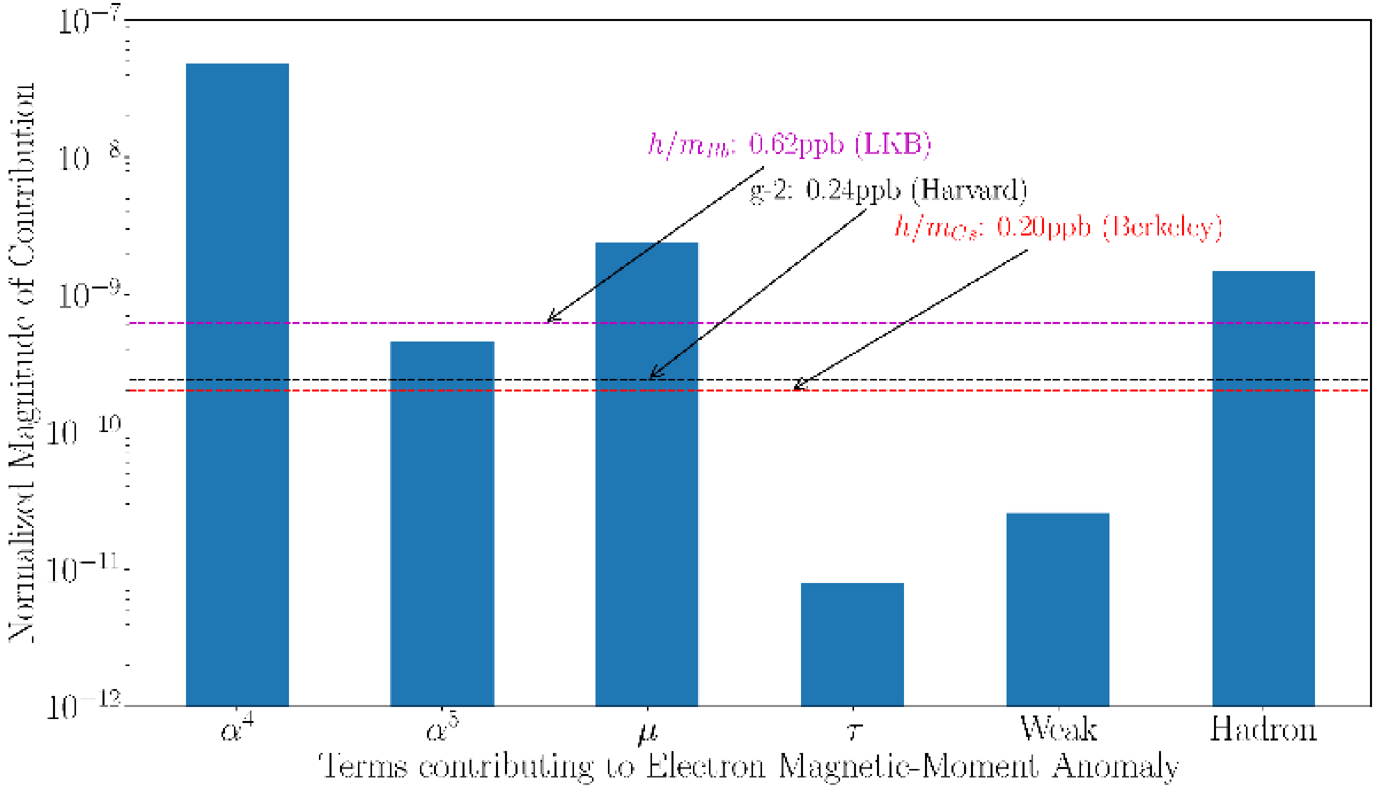
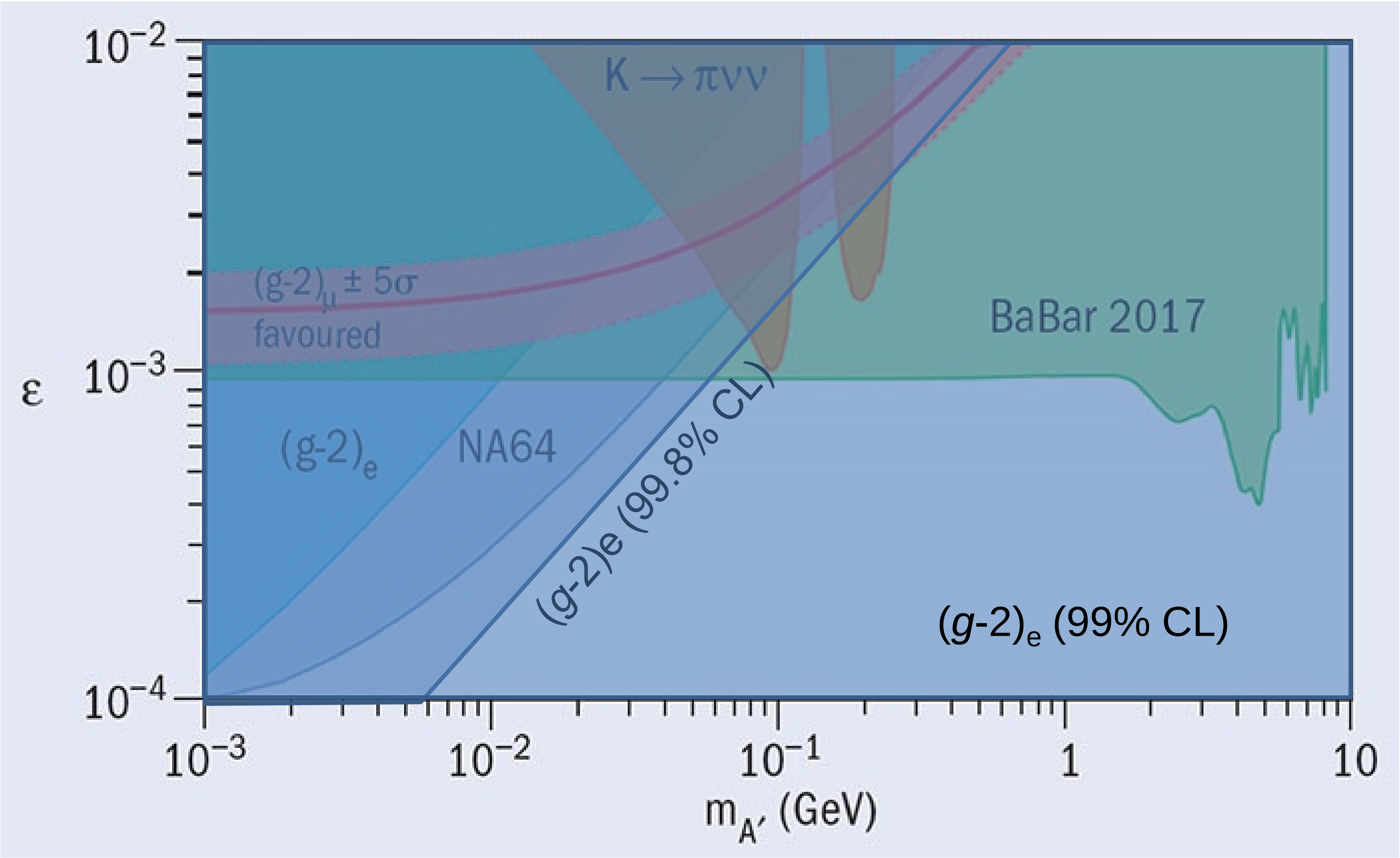
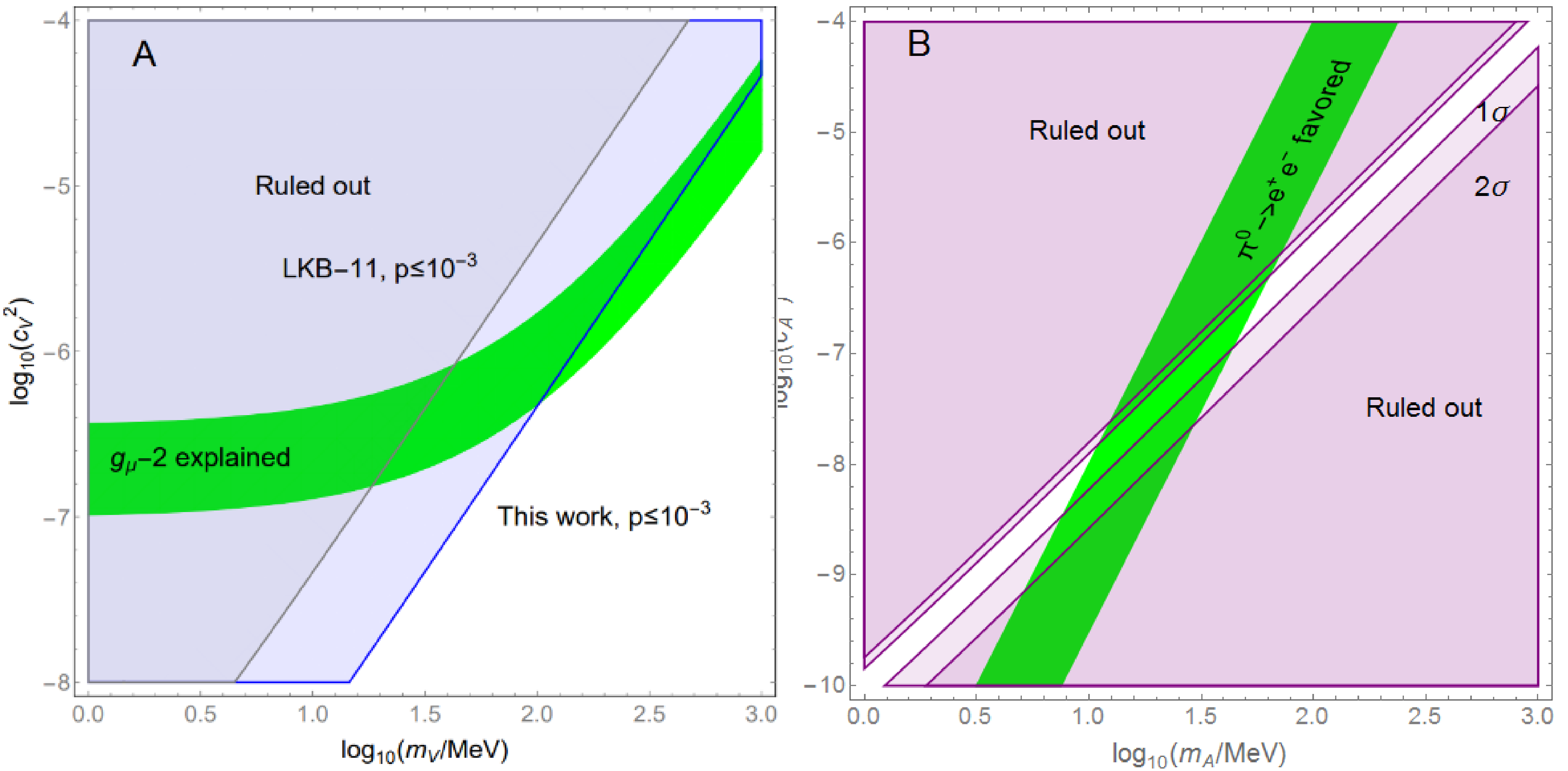


Dark photon limits

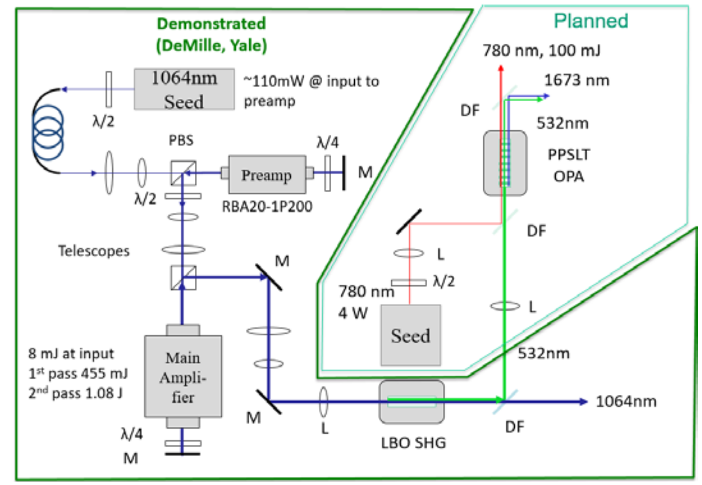


Dark photons & axial vectors



Future Upgrades

- Big Vacuum System
  - x20 waist → x400 supp.
- Pulsed Laser
  - x1000 eff. power
- EM/Acoustic Shielded Room
- 2 MOT Chambers
  - Better Fountain Alignment
- Science Chamber
  - Dark Matter studies



Thank you!

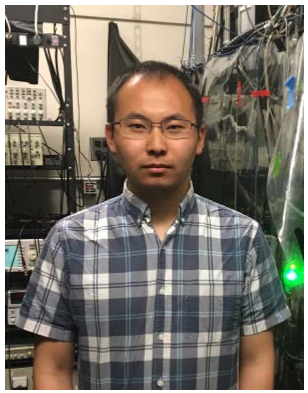
Postdoc:
R. Parker

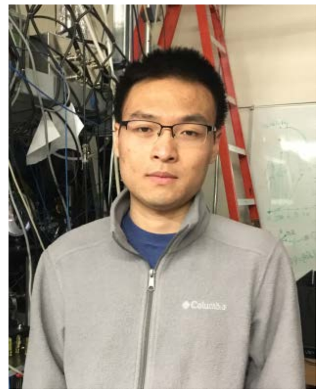
Grad:
Chenghui Yu

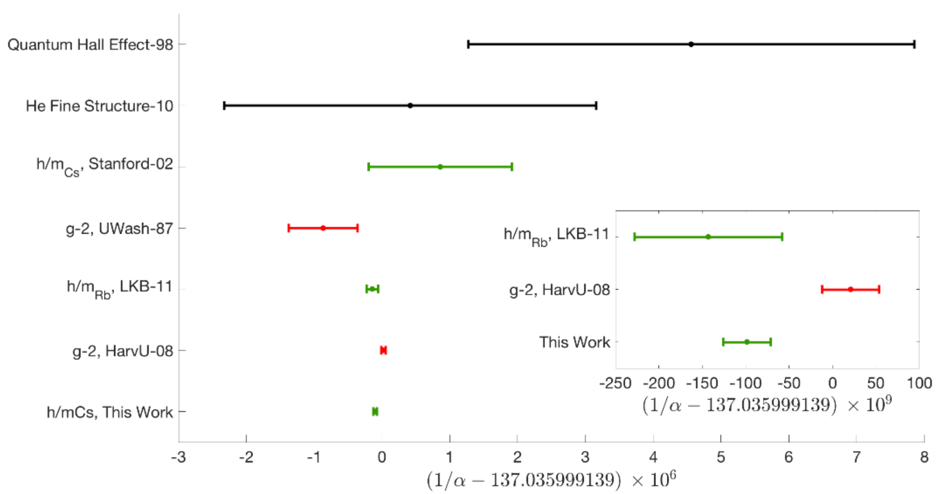
Grad:
Weicheng Zhong

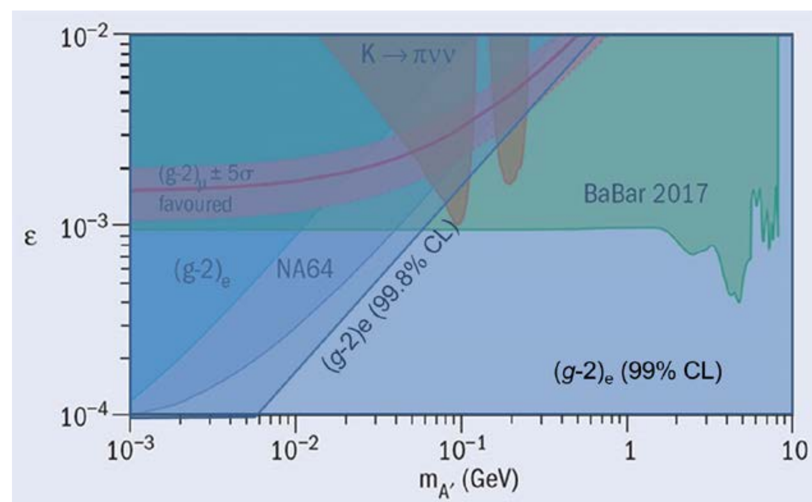
Former Grad:
Brian Estey

PI: Holger
Müller



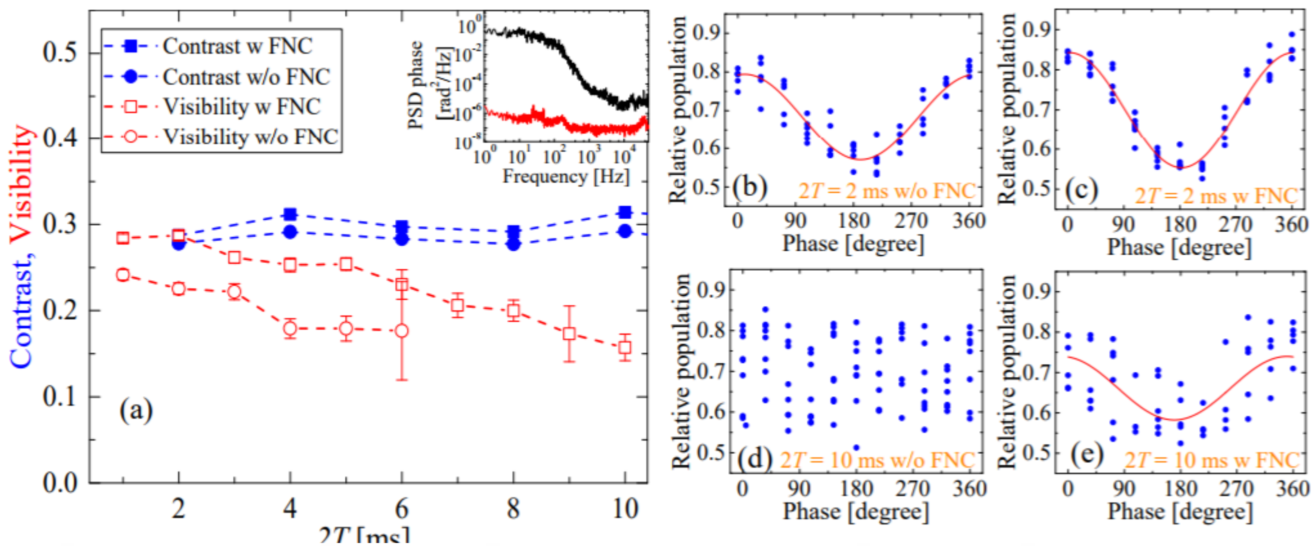


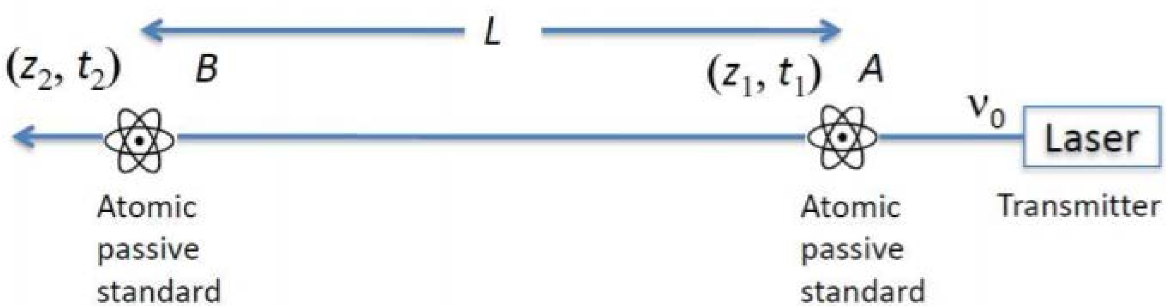




Atom interferometry with the Sr optical clock transition

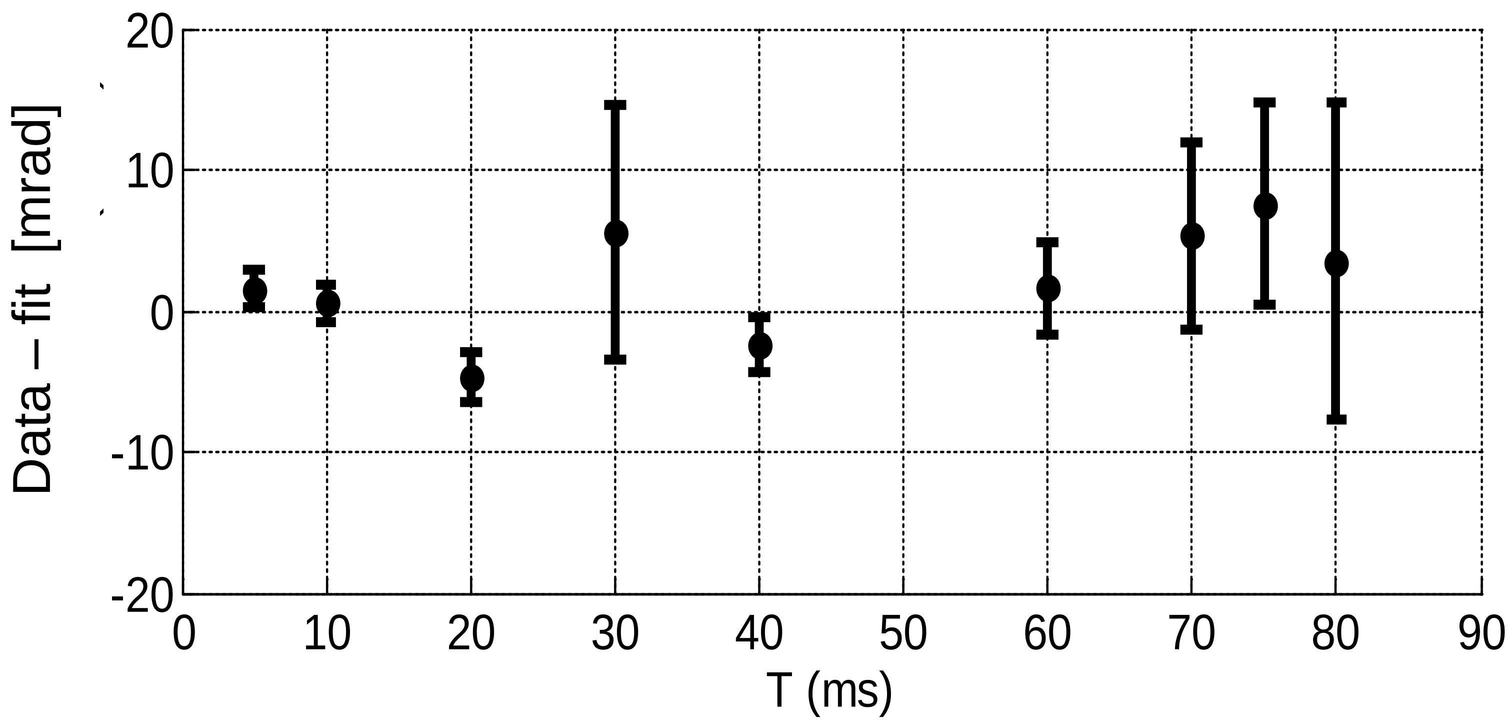
Liang Hu,* Nicola Poli,† Leonardo Salvi, and Guglielmo M. Tino‡
Dipartimento di Fisica e Astronomia and LENS - Università di Firenze, INFN - Sezione di Firenze, Via Sansone 1, 50019 Sesto Fiorentino, Italy
(Dated: August 18, 2017)



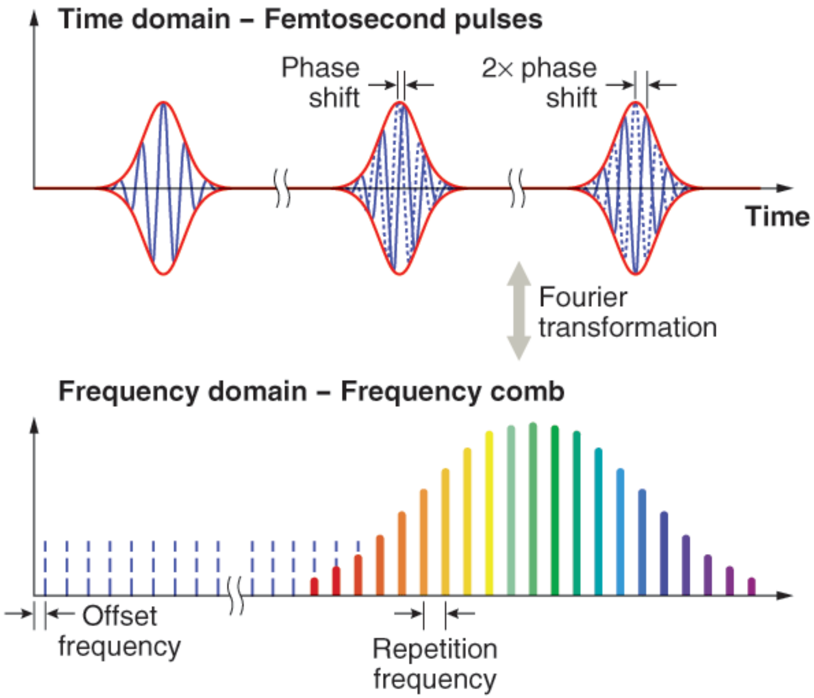


Yu, Tinto 2010

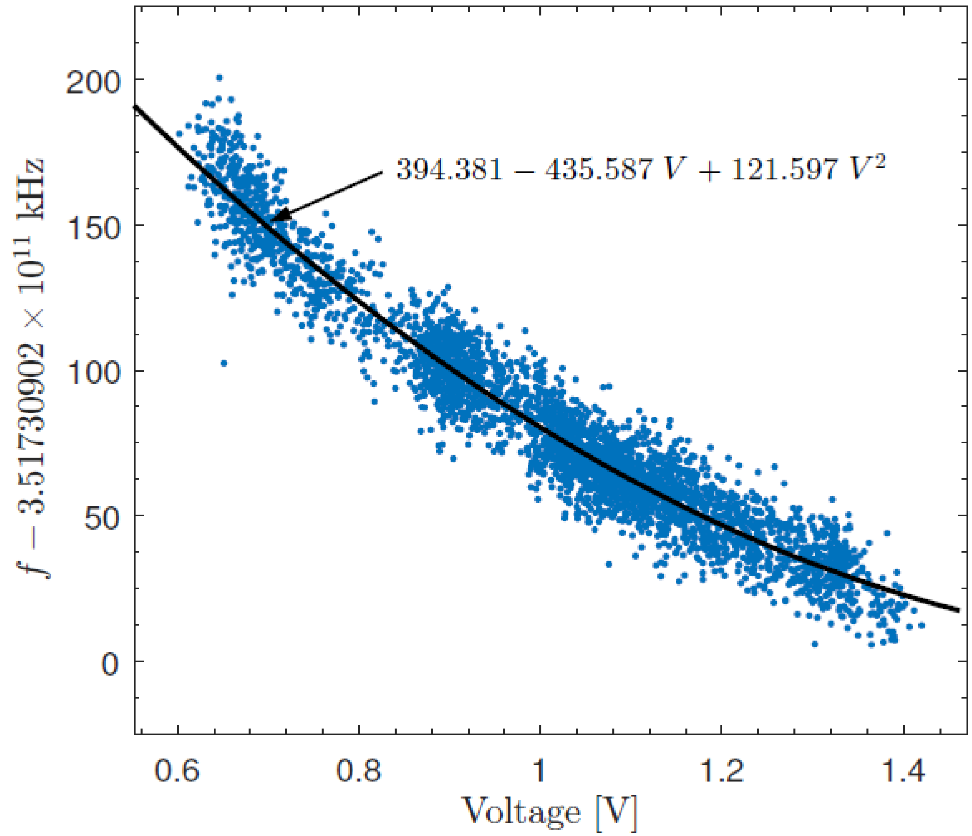
Residuals (if any) are now unresolved



Laser Frequency



$$f_n = nf_r + f_{offset}$$

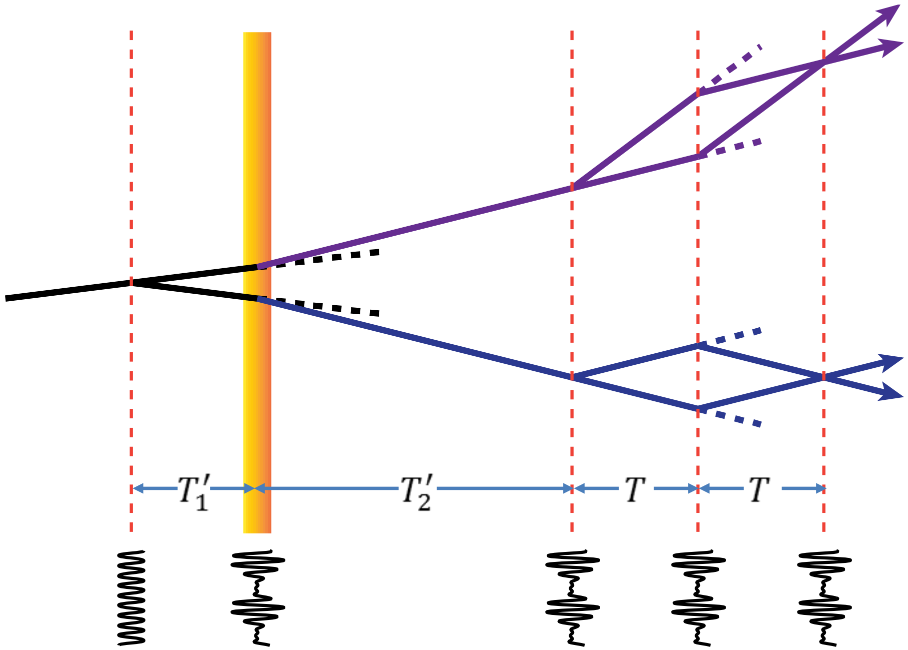


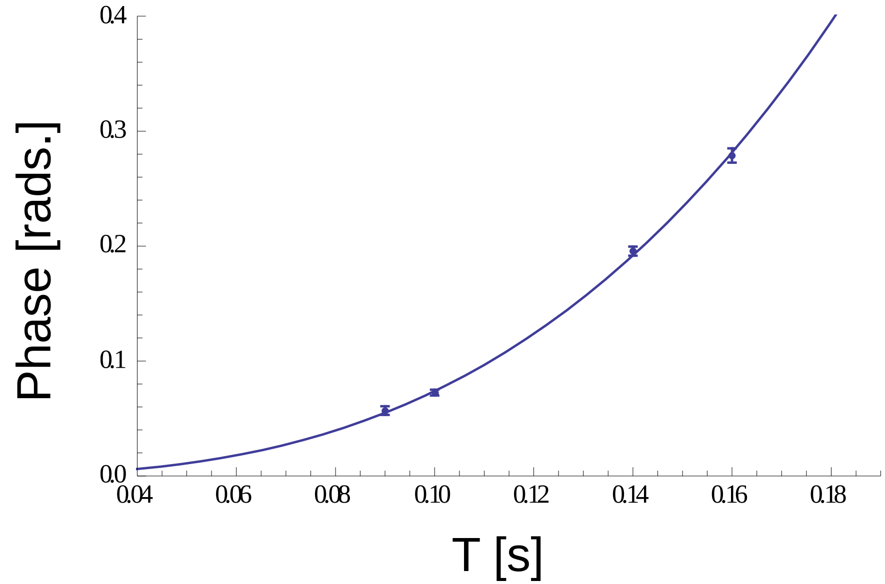
Laser frequency as a function of power send into the spectroscopy

Frequency residual = 10 kHz → 0.03 ppb

Gravity Gradient

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





$$\Delta E_O = -2\,\frac{\alpha_{Cs}\,\sigma T_S^4}{c\,\varepsilon_0},$$

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

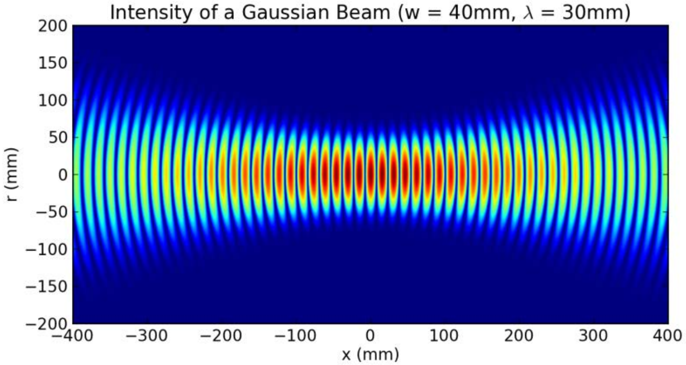
Shift in alpha = -1.41 +/- 0.02 ppb

Gouy Phase Systematic

$$E(r,z) = E_0 \frac{w_0}{w(z)} e^{-\frac{r^2}{w(z)^2}} e^{-ik(z-z_0)-\frac{ikr^2}{2R(z-z_0)}+i\zeta(z-z_0)}$$

$$z_R = \frac{\pi {w_0}^2}{\lambda} \sim 50\text{ m} \qquad w(z) = w_0\sqrt{1+\frac{z^2}{z_R^2}}$$

$$\zeta(z) = \tan^{-1}\left(\frac{z}{z_R}\right) \qquad R(z) = z\left(1+\frac{{z_R}^2}{z^2}\right)$$

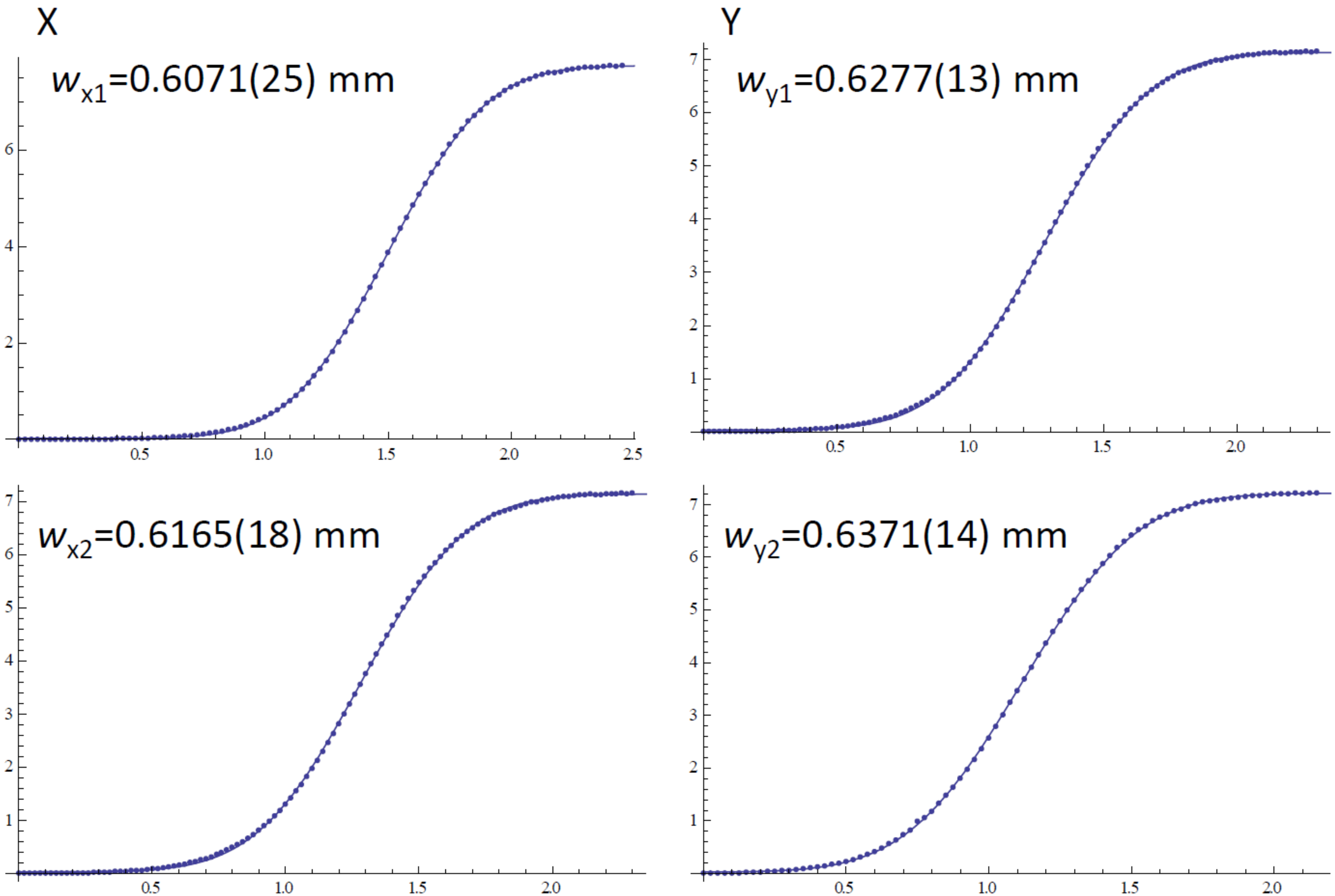


$$k_{eff} = k - \frac{1}{z_R} + \frac{z_0^2}{z_R^3} + \frac{kr^2}{2z_R^2} + \mathcal{O}(\frac{z_0^2}{z_R^2})$$

Knife edge measured

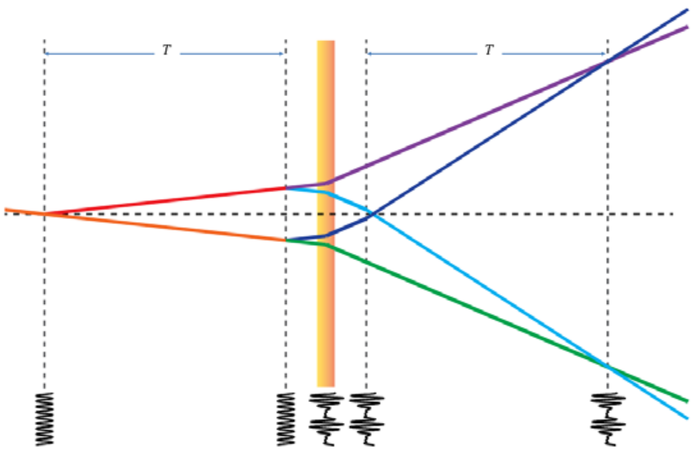
Estimated based on atom position using Monte Carlo simulation

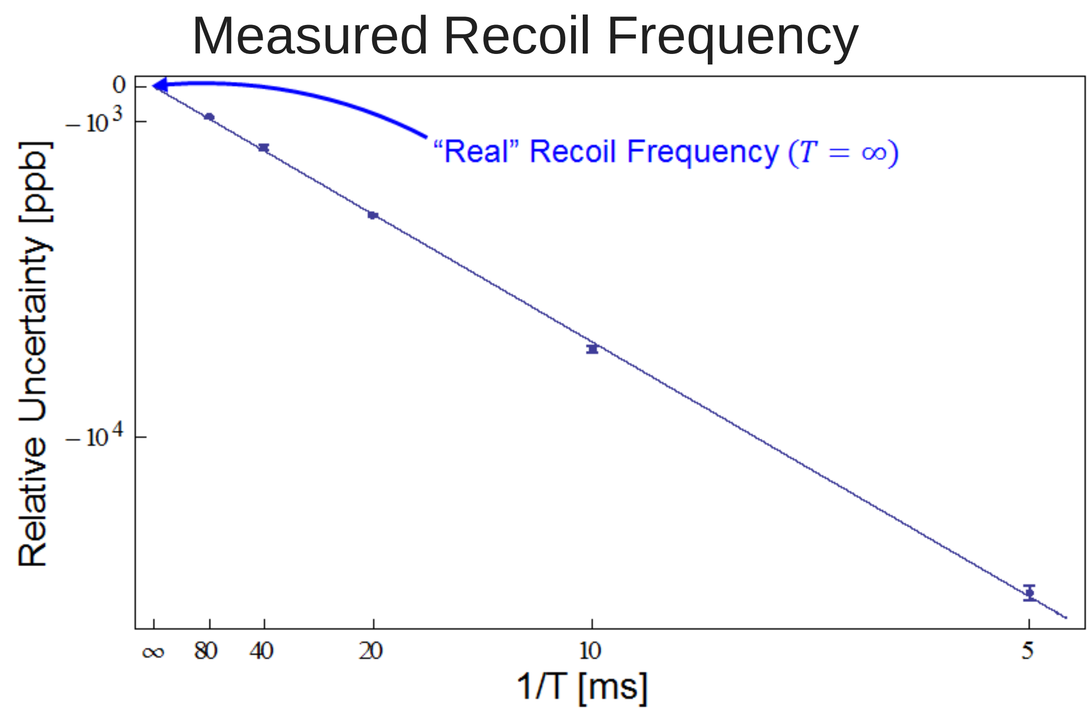
Gouy Phase


X
Y
w_{x1}=0.6071(25) mm
w_{y1}=0.6277(13) mm
w_{x2}=0.6165(18) mm
w_{y2}=0.6371(14) mm

Diffraction Phase

$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T + \Phi_0$$





Measured Frequency

Recoil Frequency

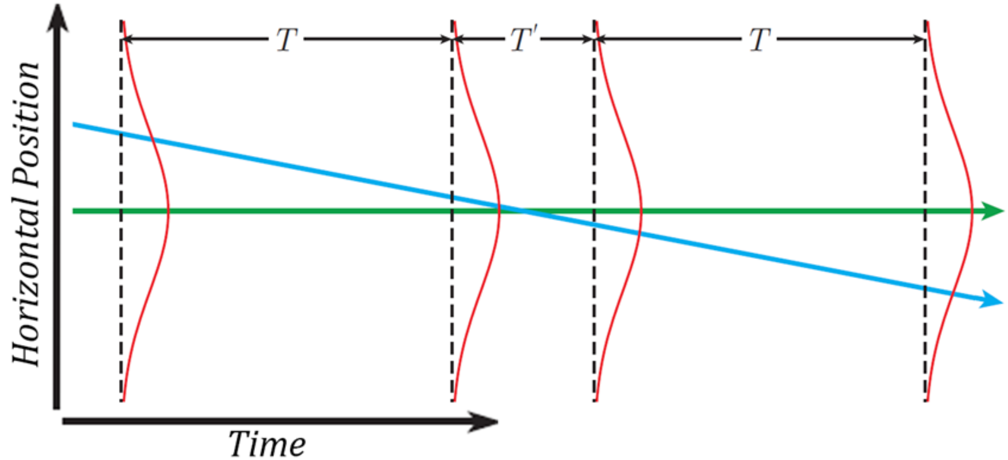
Diffraction Phase

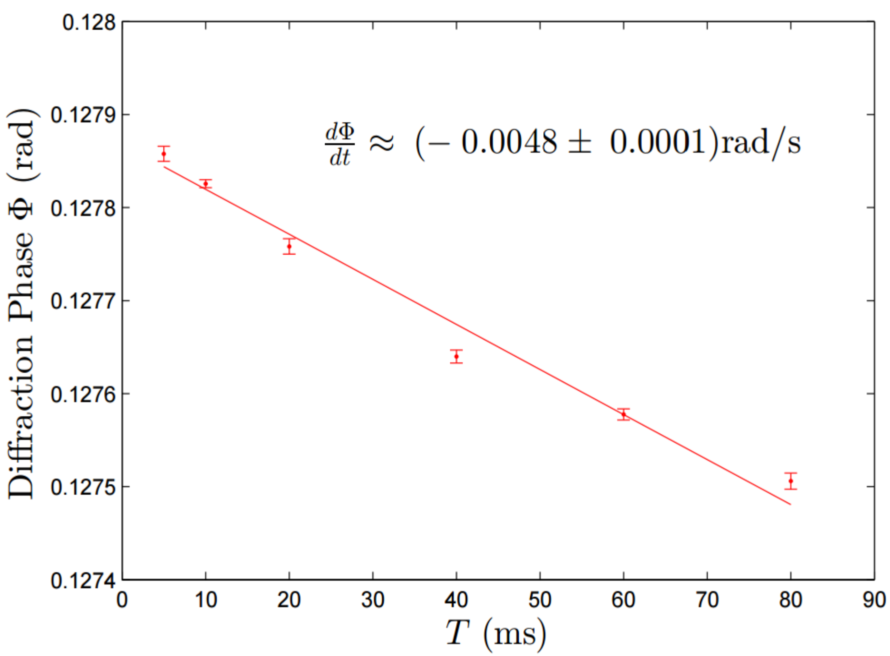
$$\omega_m = 8(n+N)\omega_r + \frac{\Phi_0}{2nT}$$

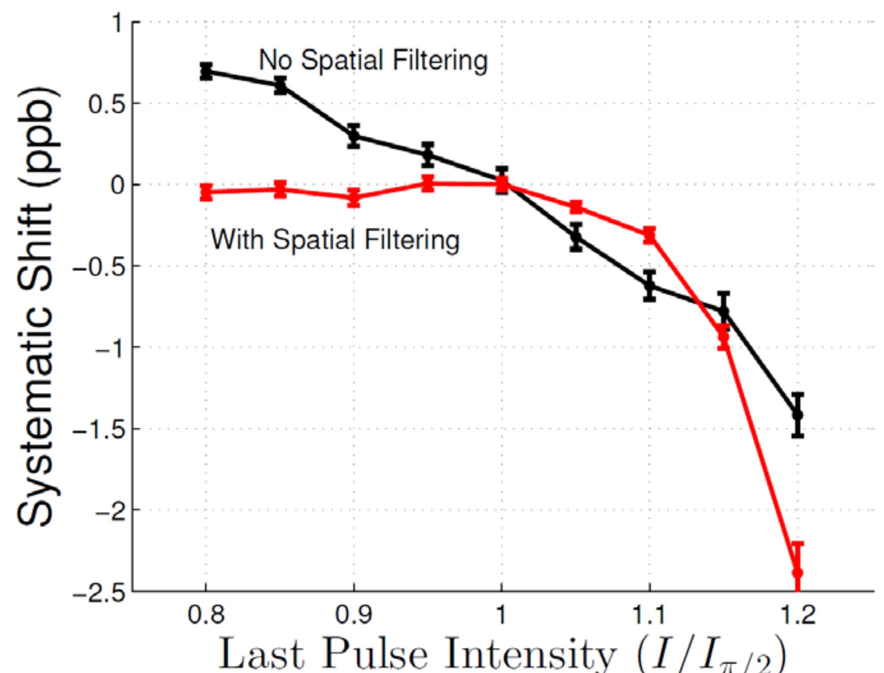
Clipping Phase

$$\Delta\Phi_{RB+Bloch} = 16n(n+N)\omega_r T - 2n\omega_m T + \Phi_0 + \eta T + \ldots$$

- Atom Motion → T-dependent diffraction phase
- Sensitive to pulse intensities, detection volume, …
- 2-point Spatial Filtering
  - Reduce VS waist
  - Reduce detection volume







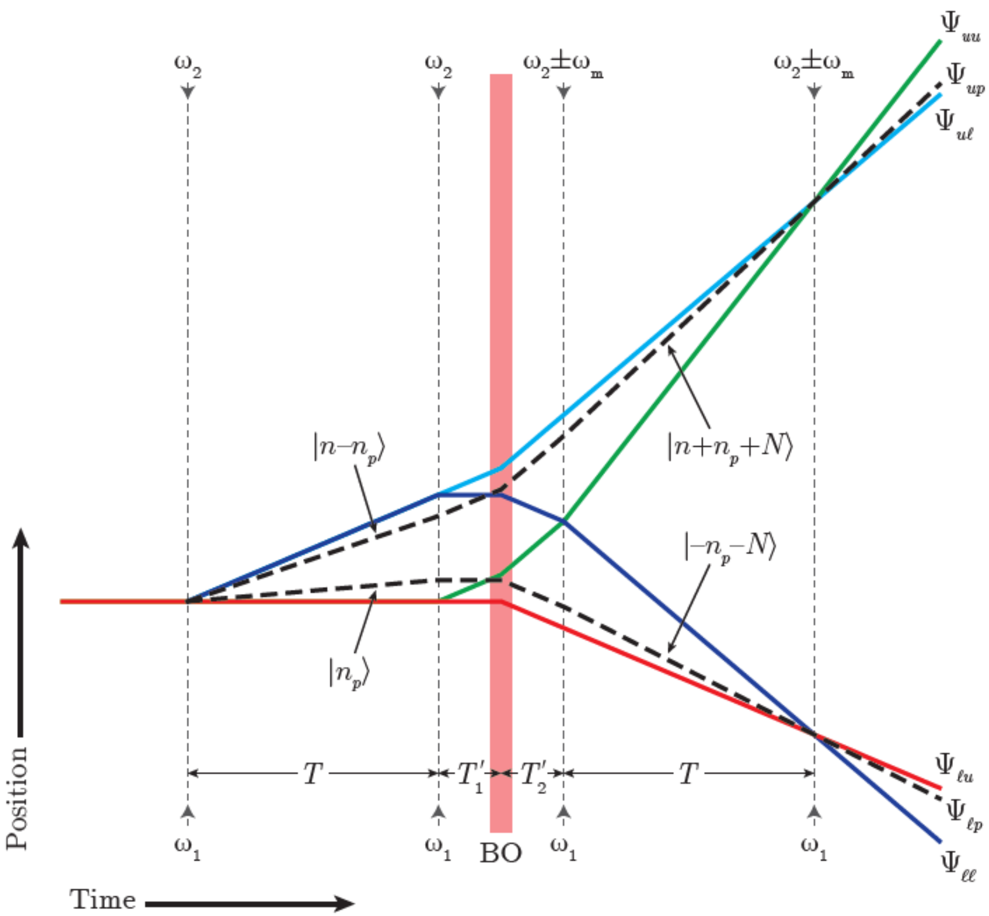
Estey, PRL 2015; Parker, PRA 2016

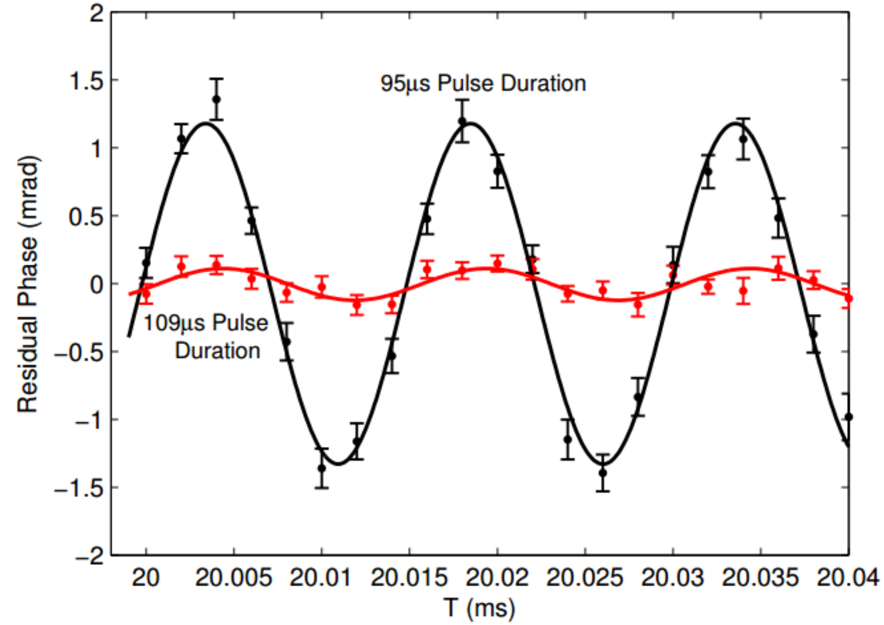
Atom motion

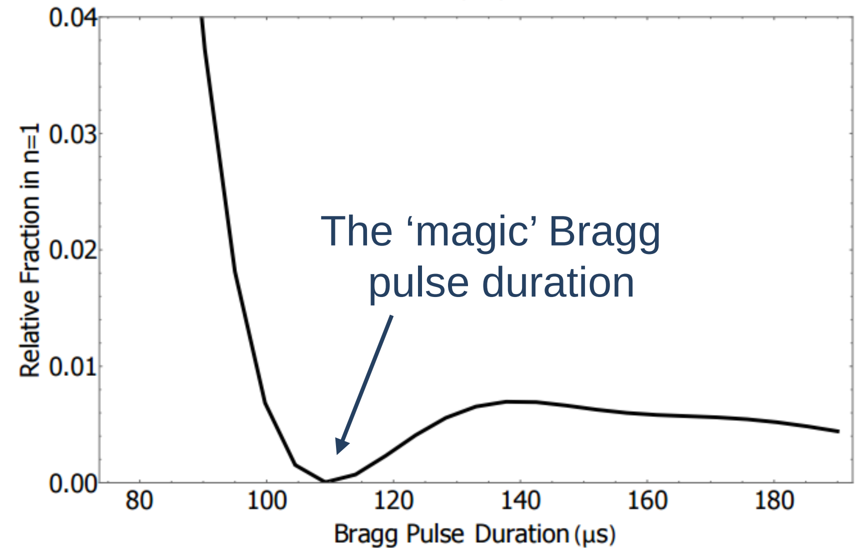
Effect	Value	□□/□(ppb)
Cloud radius (mm)	2.2 ± 1	± 0.026
Vertical velocity width (vr)	1.5 ± 0.25	± 0.031
Ensemble horizontal velocity (vr)	0 ± 0.5	± 0.032
Initial horizontal position (mm)	0 ± 1	± 0.034
Intensity ($I_{□/2}$)	1.02 ± 0.02	± 0.028
Last pulse intensity ratio	1.0 ± 0.02	± 0.034

Parasitic Interferometers

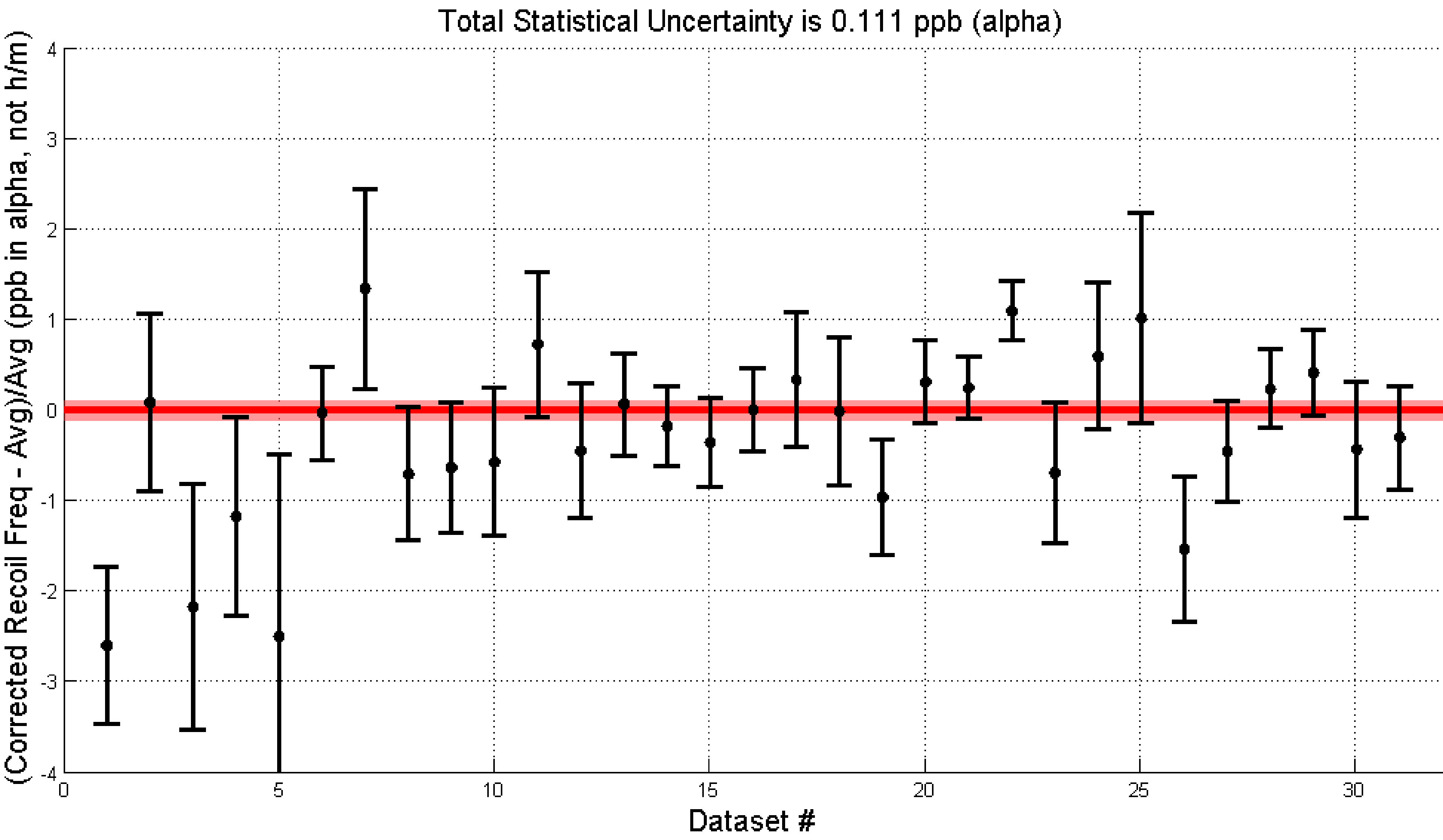
$$\phi_p = \pm 8 n_p (n_p + N)\omega_r T \pm n_p \omega_m T + \phi_c(n_p)$$







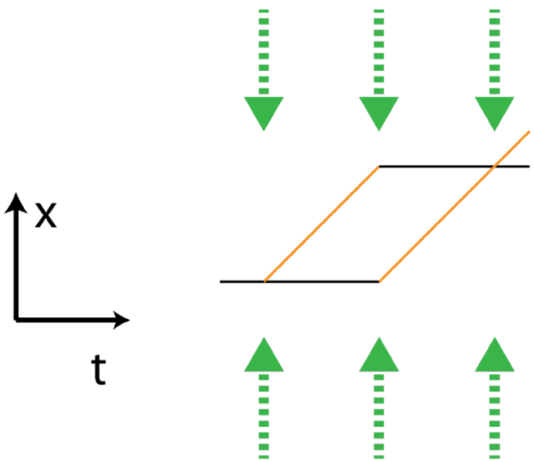
Recent Data



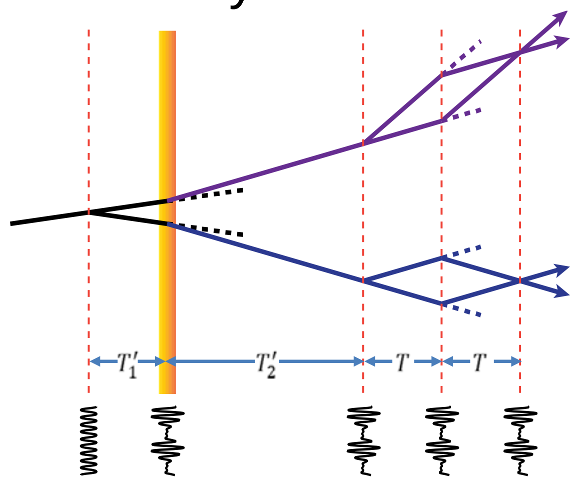
Total Statistical Uncertainty is 0.111 ppb (alpha)
(Corrected Recoil Freq - Avg)/Avg (ppb in alpha, not h/m)
4
3
2
1
0
-1
-2
-3
-4
0
5
10
15
20
25
30
Dataset #

Matter Wave Interferometry

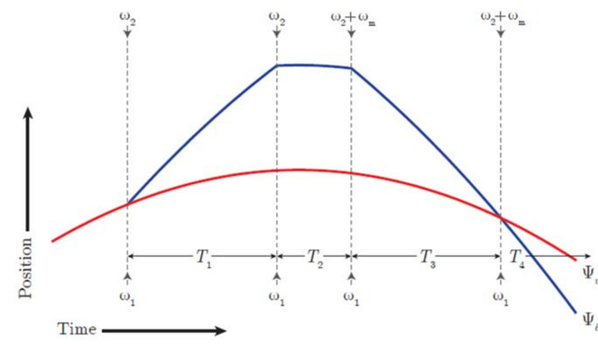
Local Gravity



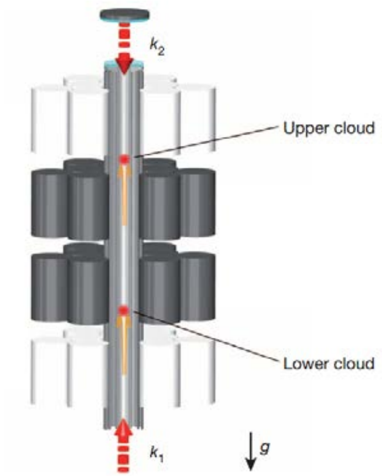
Gravity Gradients



Recoil Frequency

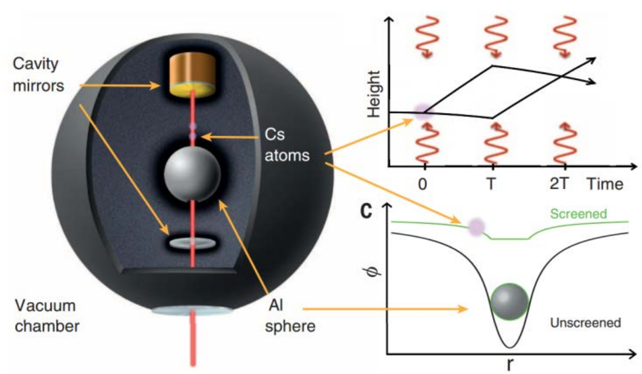


Newton's G



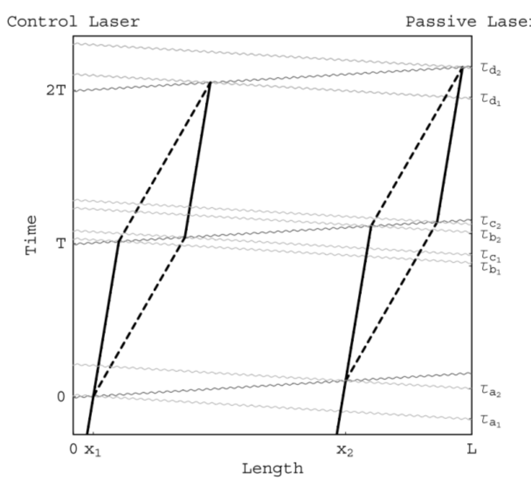
Nature, 510, 518 (2014)

Dark Energy



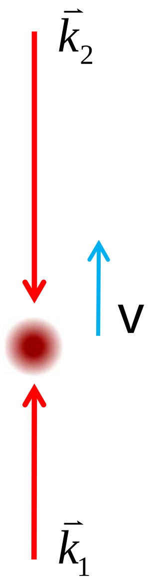
Science, 349, 849 (2015)

Gravitational Waves



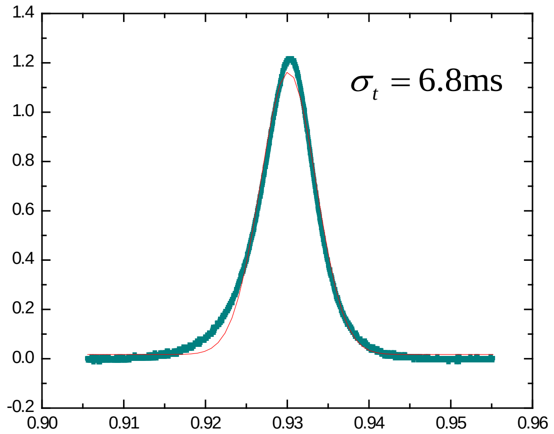
Phys. Lett. B, 678, 1 (2009)

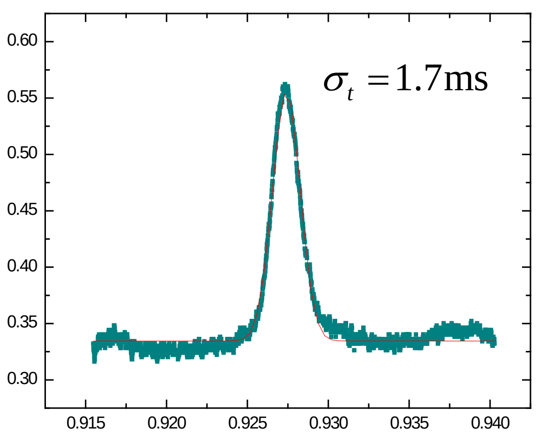
Velocity Selection



- $2\mu k$ of atoms has velocity spread ~2cm/sec After 1s of time of flight, atoms will drift out of interferometer beams

- $100\mu s$ selection pulse selects about 1/10 of atoms corresponding to hundreds of nK





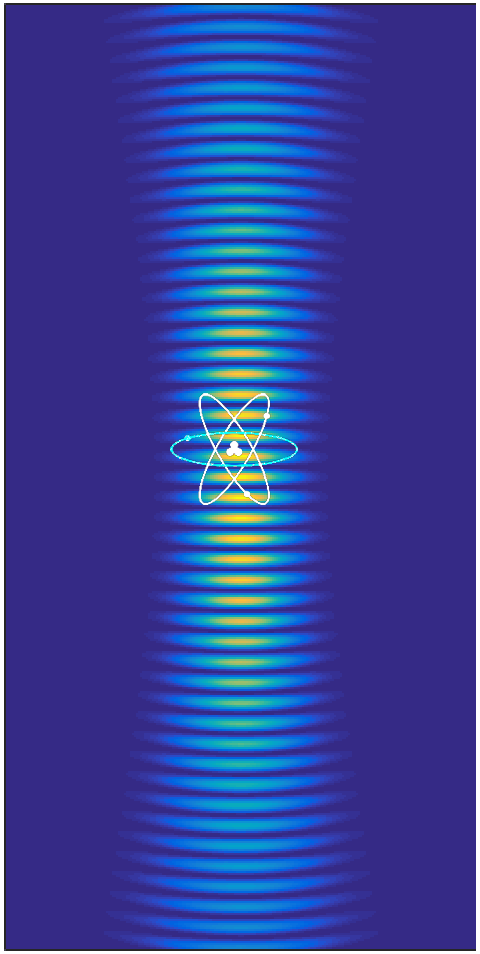
BO intensity gradient

Six frequencies

$$\left(I_{\pm}^{\downarrow}\right)' = I_{0,\pm} \frac{z_4 - z_0}{\left(1 + \frac{\left(z_0 - z_4\right)^2}{z_R^2}\right)^{3/2} z_R^2},$$

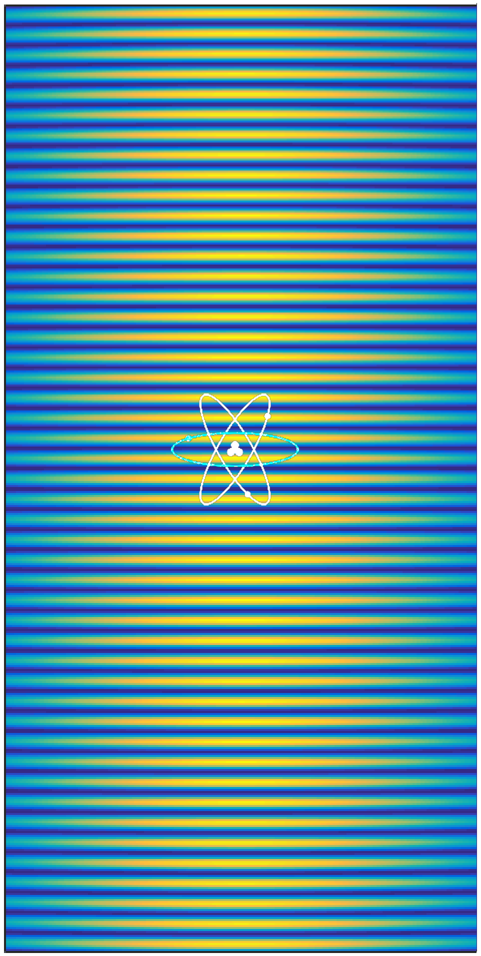
$$\Delta I \approx \left[\left(I_{+}^{\downarrow}\right)' - \left(I_{-}^{\downarrow}\right)'\right] d + \tilde{I}'' \delta d + \frac{1}{2}\left[\left(I_{+}^{\downarrow}\right)'' - \left(I_{-}^{\downarrow}\right)''\right] d^2.$$

Laser beam quality



- 0.3 cm beam radius
- Wavelength errors ~$(\lambda/\text{radius})^2$
- Beam splitter losses ~$(\lambda/\text{radius})^4$

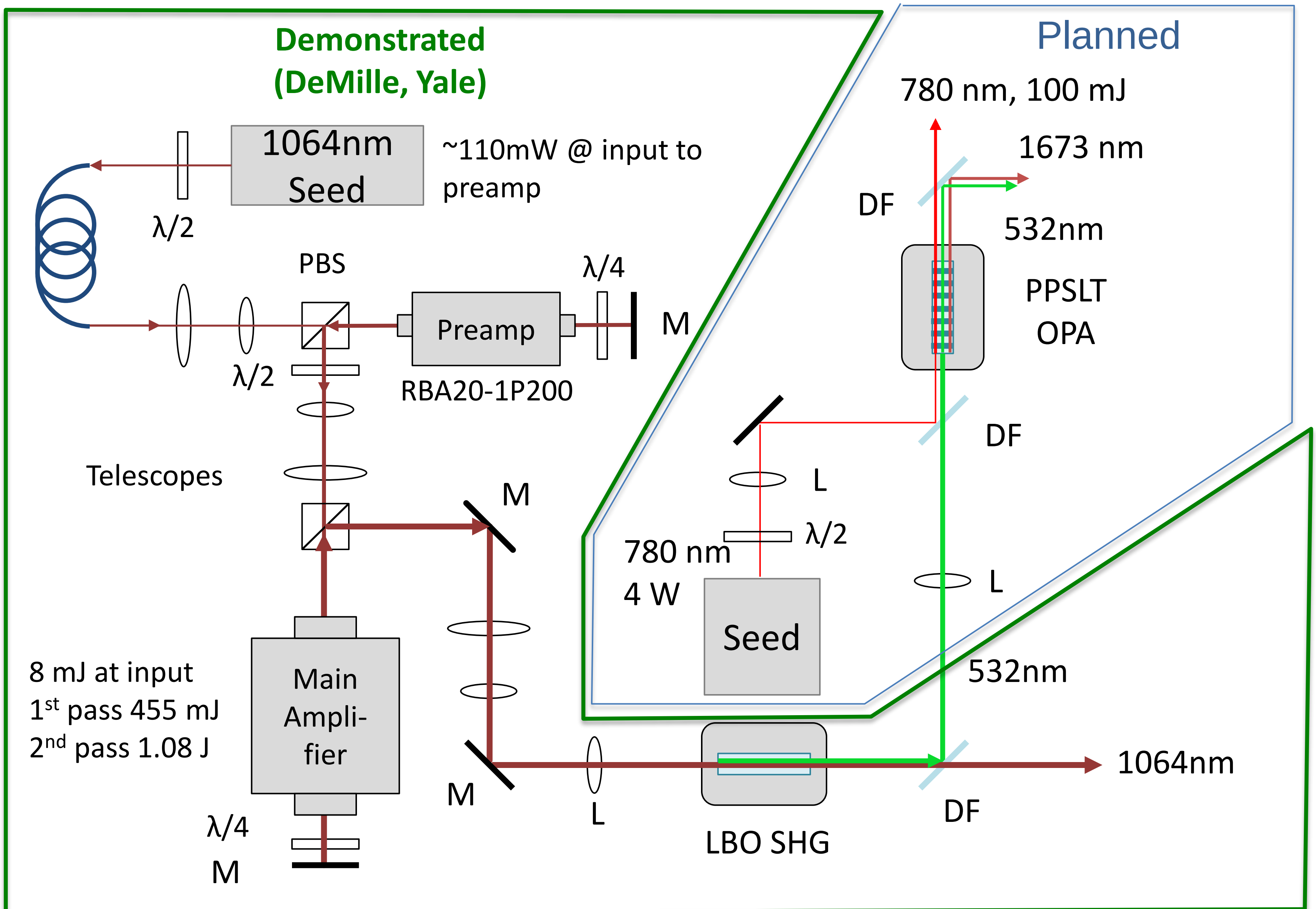
A more nearly perfect laser beam



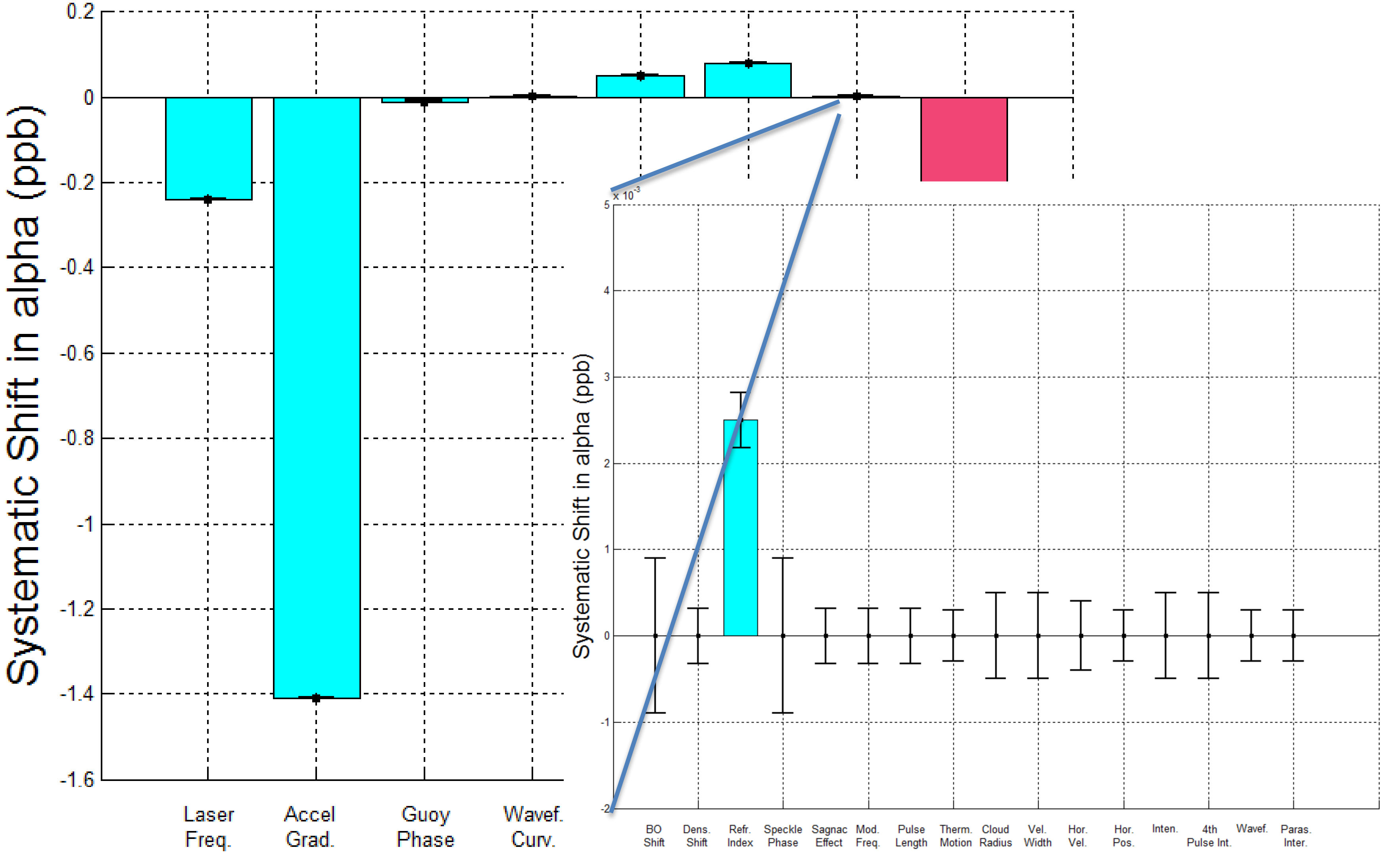
- This project ~ 6 cm radius
- Wavelength errors ~$(\lambda/\text{radius})^2$
- 400-fold higher accuracy
- Beam splitter losses ~$(\lambda/\text{radius})^4$
- higher momentum transfer, and thus sensitivity

Thick beam will unleash the potential of atom interferometry

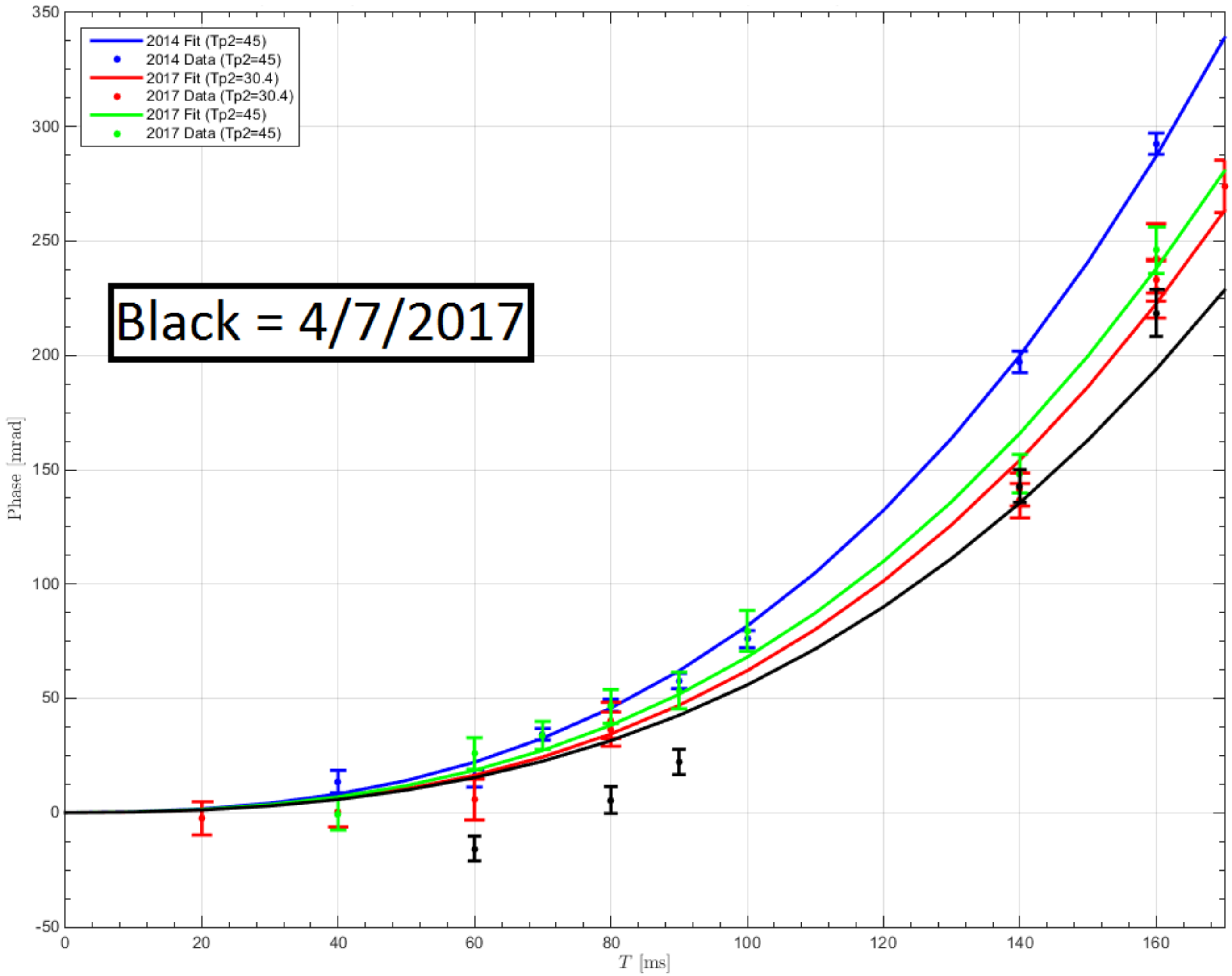
The death star



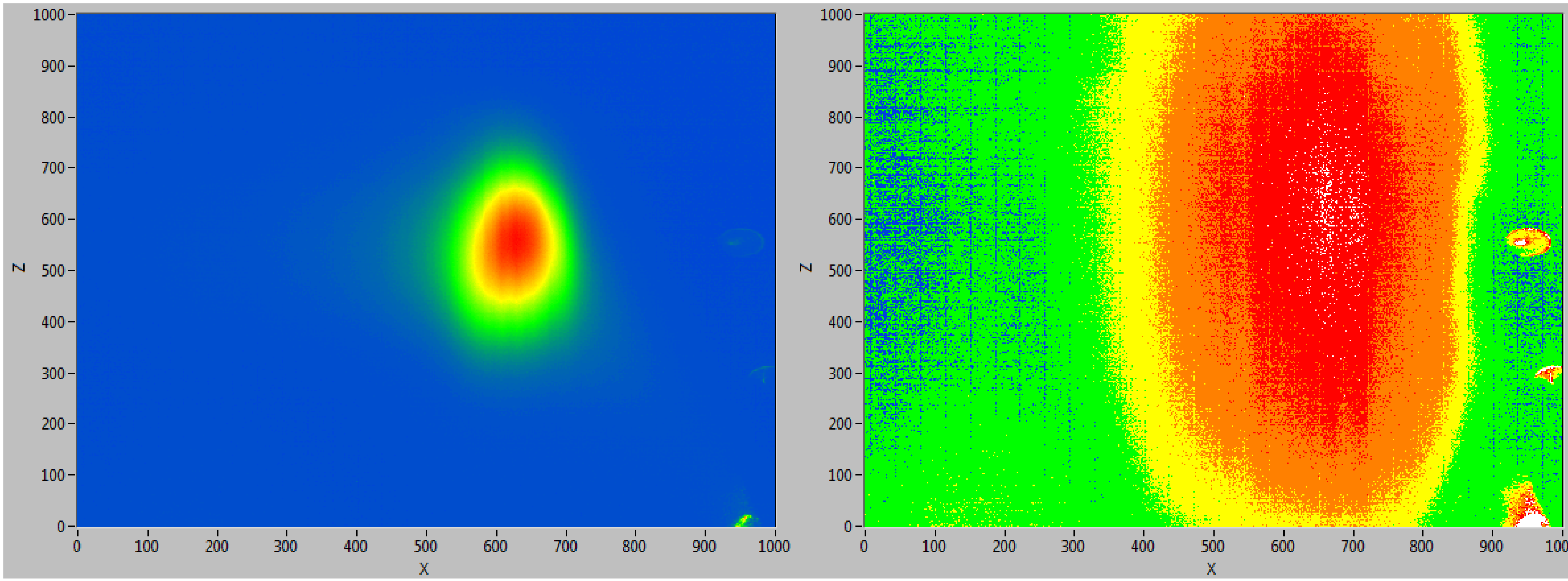
0.002 ppb with thick beam



Gradiometer phase



Atom images



1000
900
800
700
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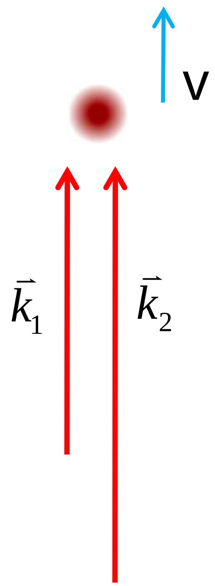
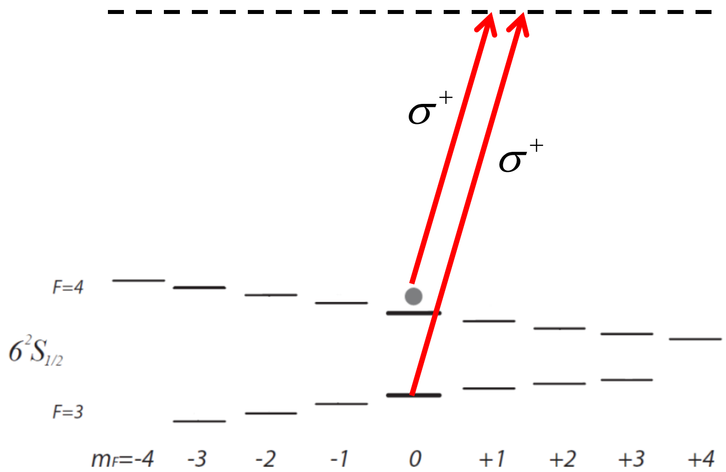
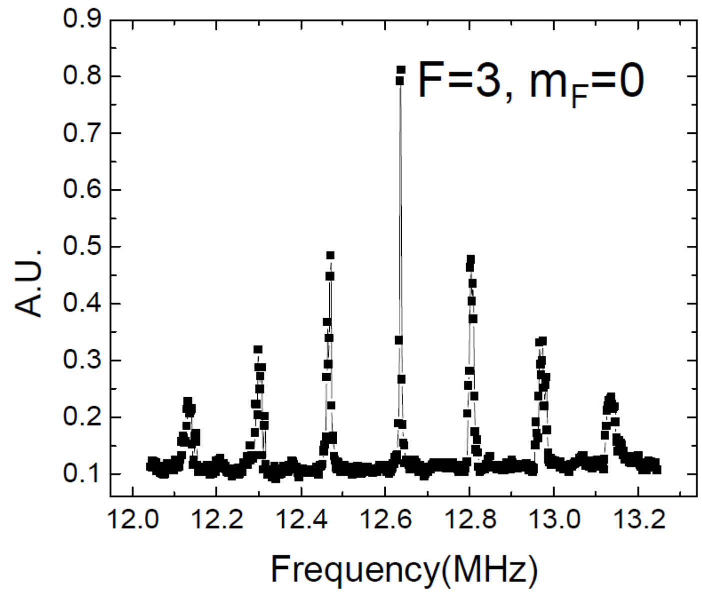
900
1000
X

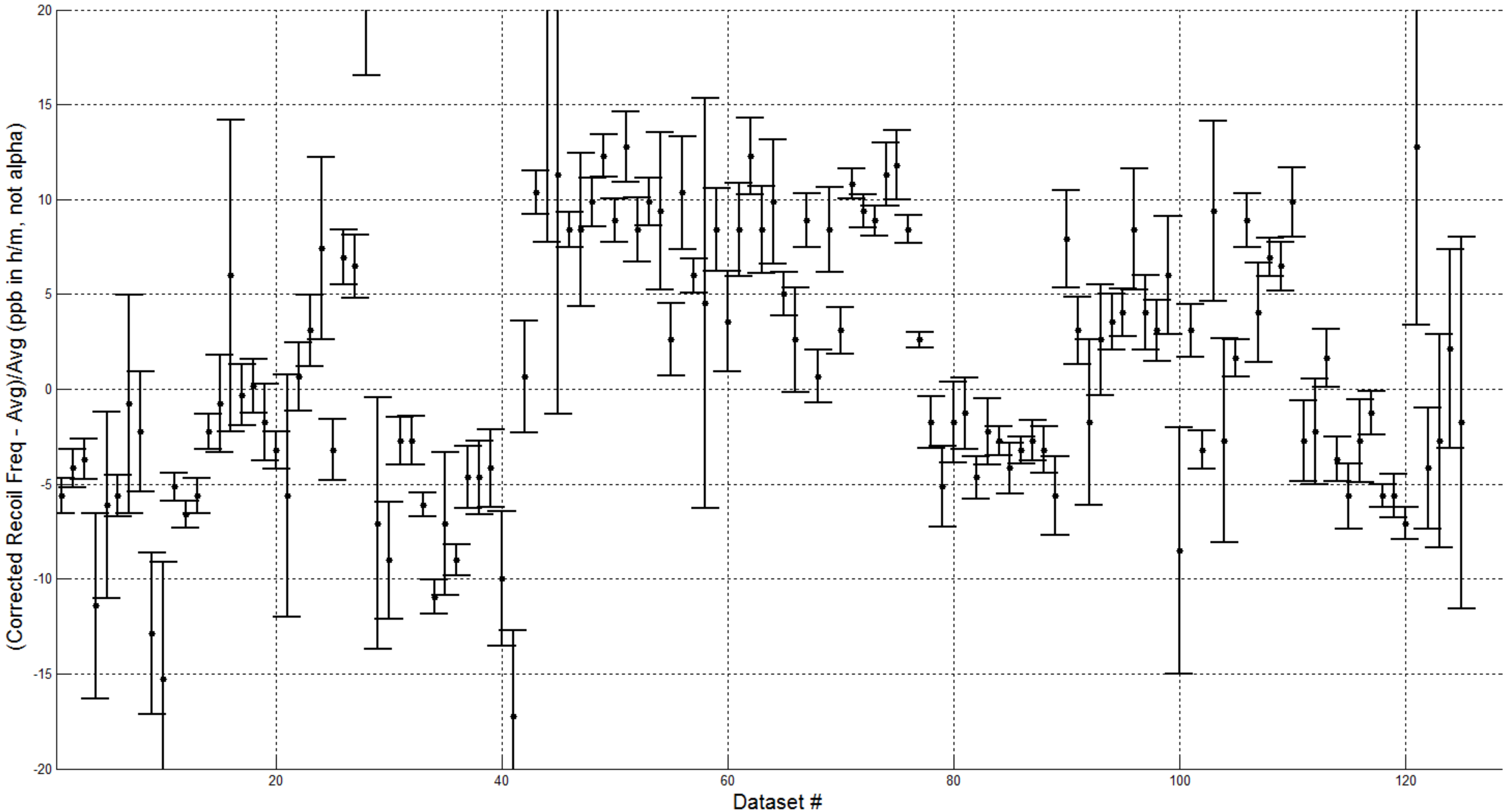
State Selection





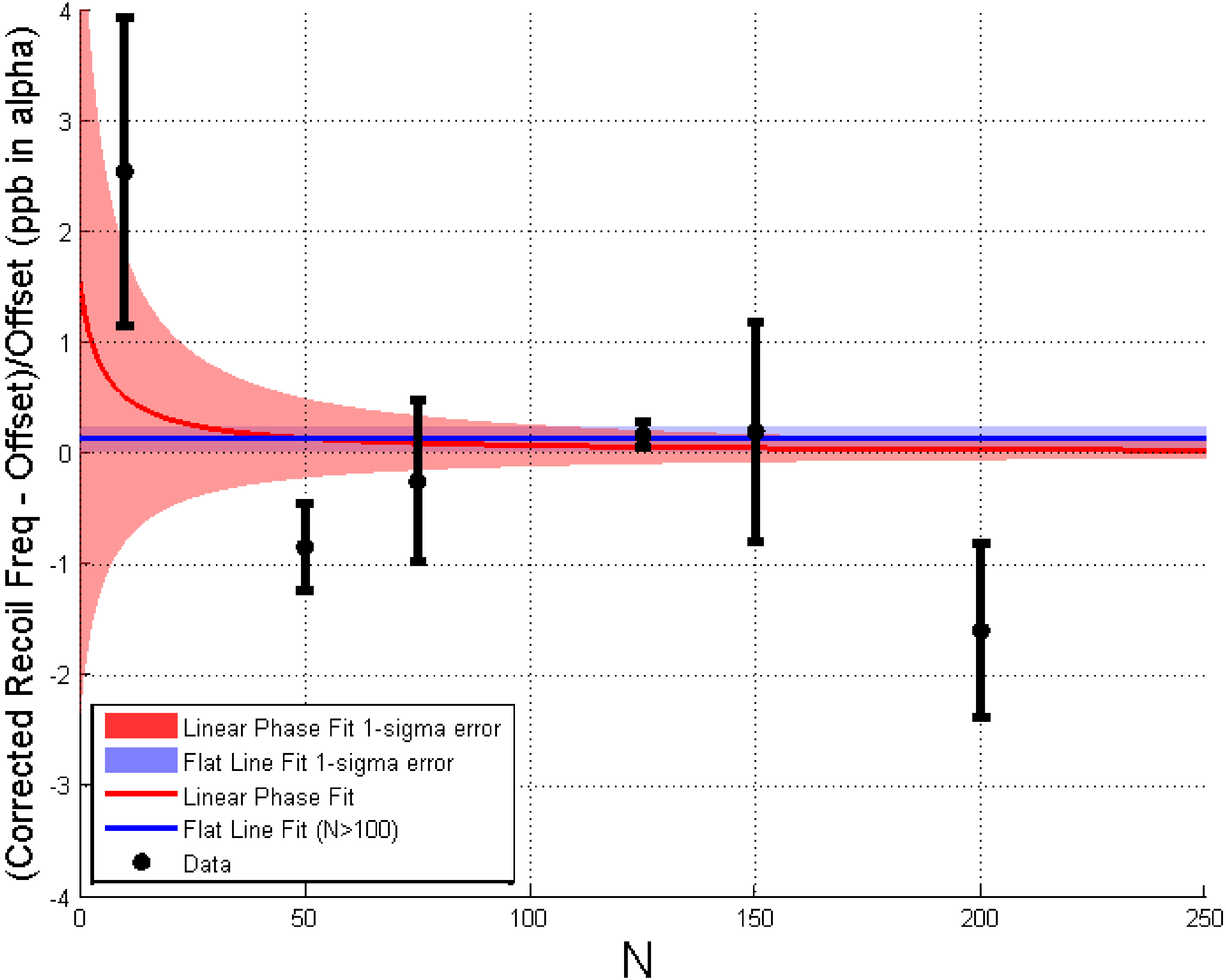


Ye Olde Data

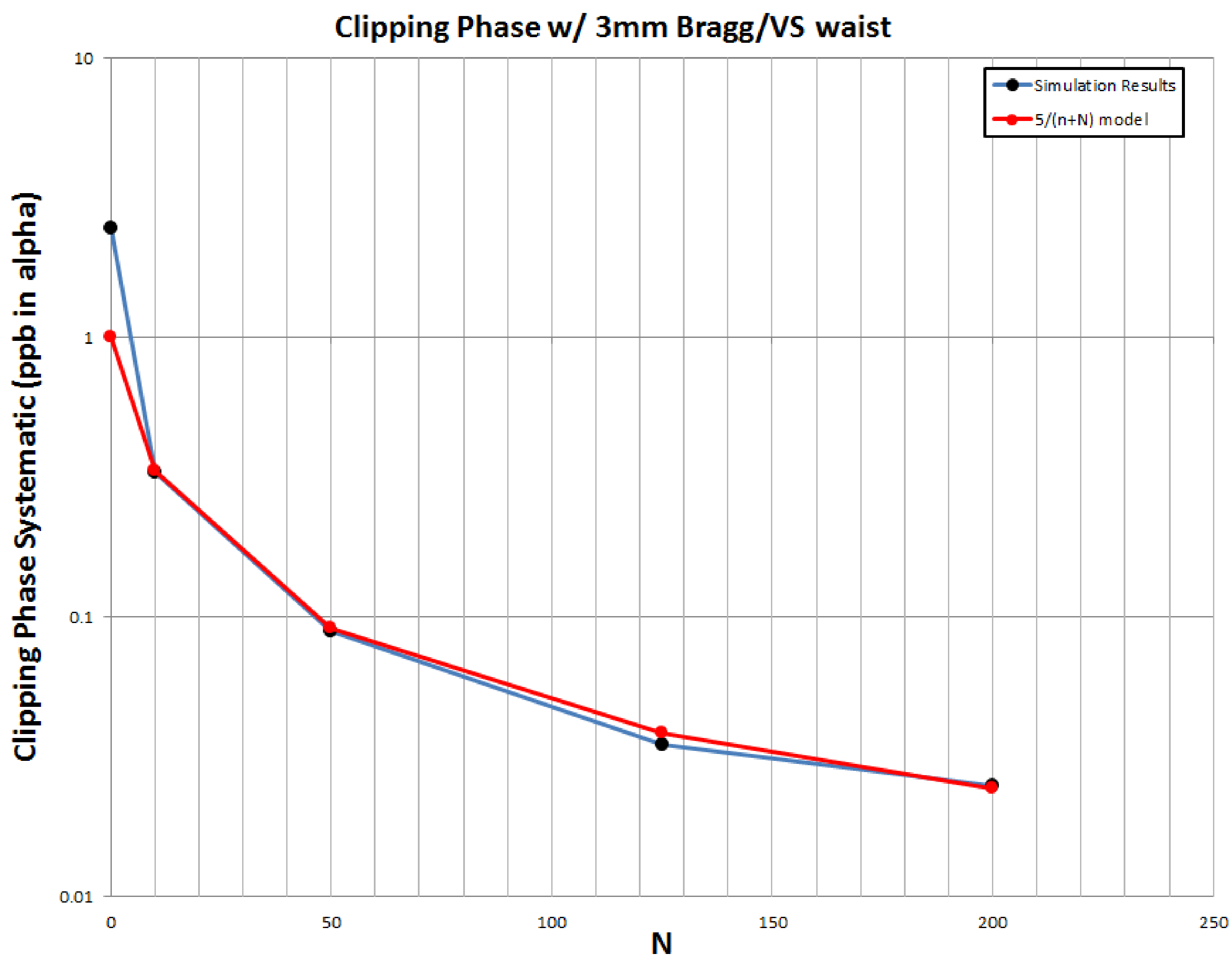


(Corrected Recoil Freq - Avg)/Avg (ppb in h/m, not alpha)
20
15
10
5
0
-5
-10
-15
-20
20
40
60
80
100
120
Dataset #

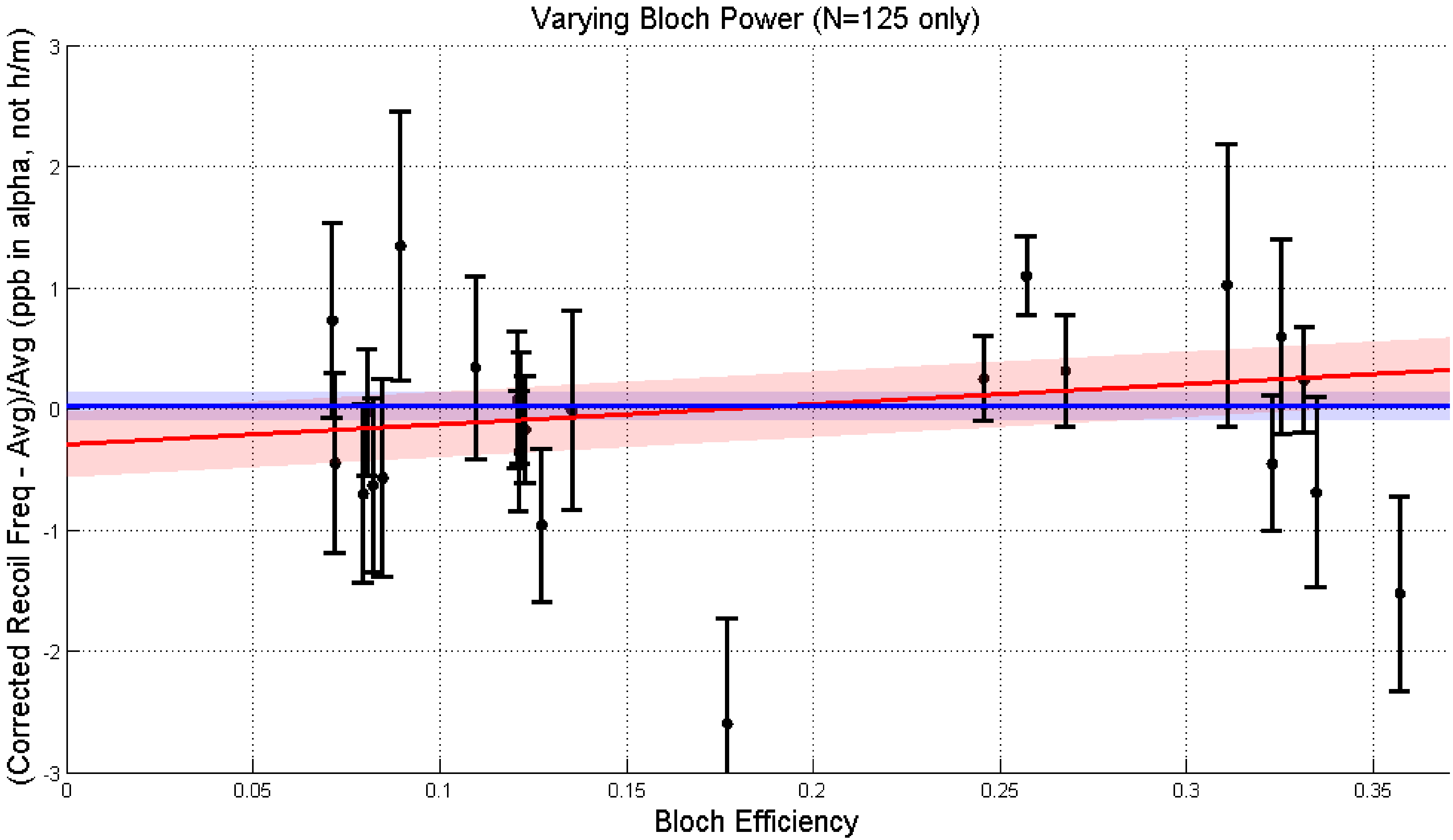
α vs Bloch order



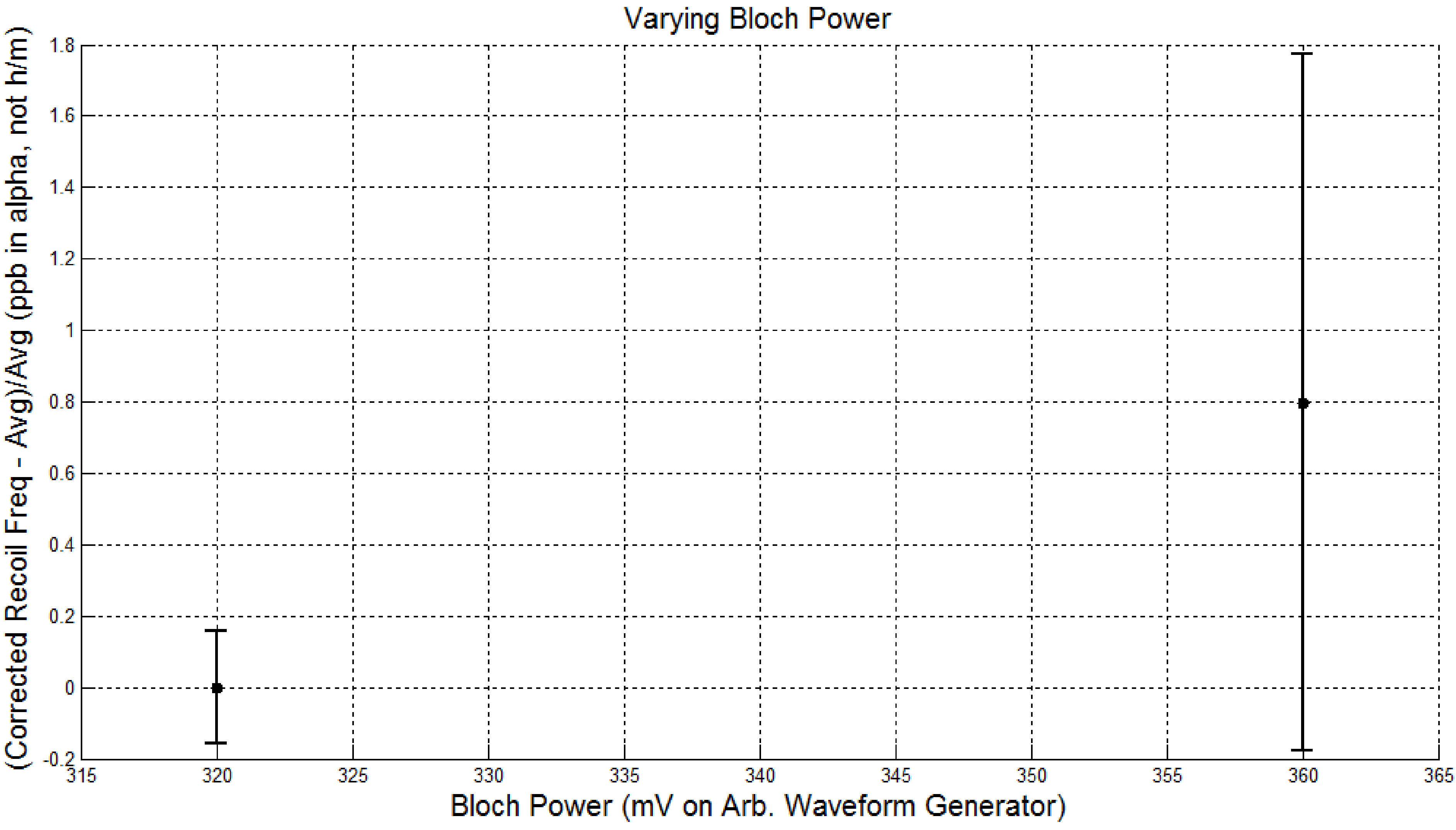
Clipping systematic vs Bloch order



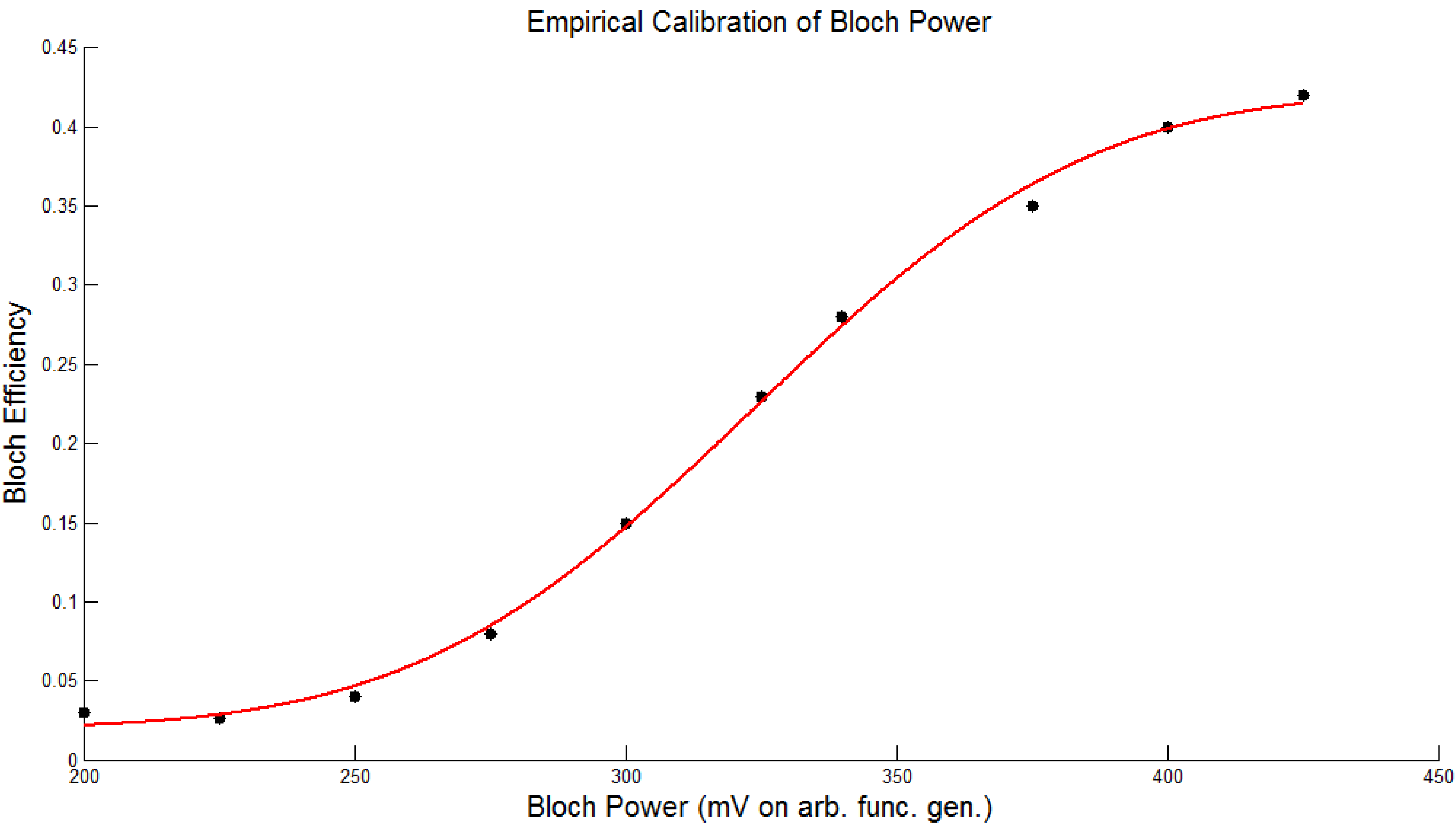
α vs Bloch power



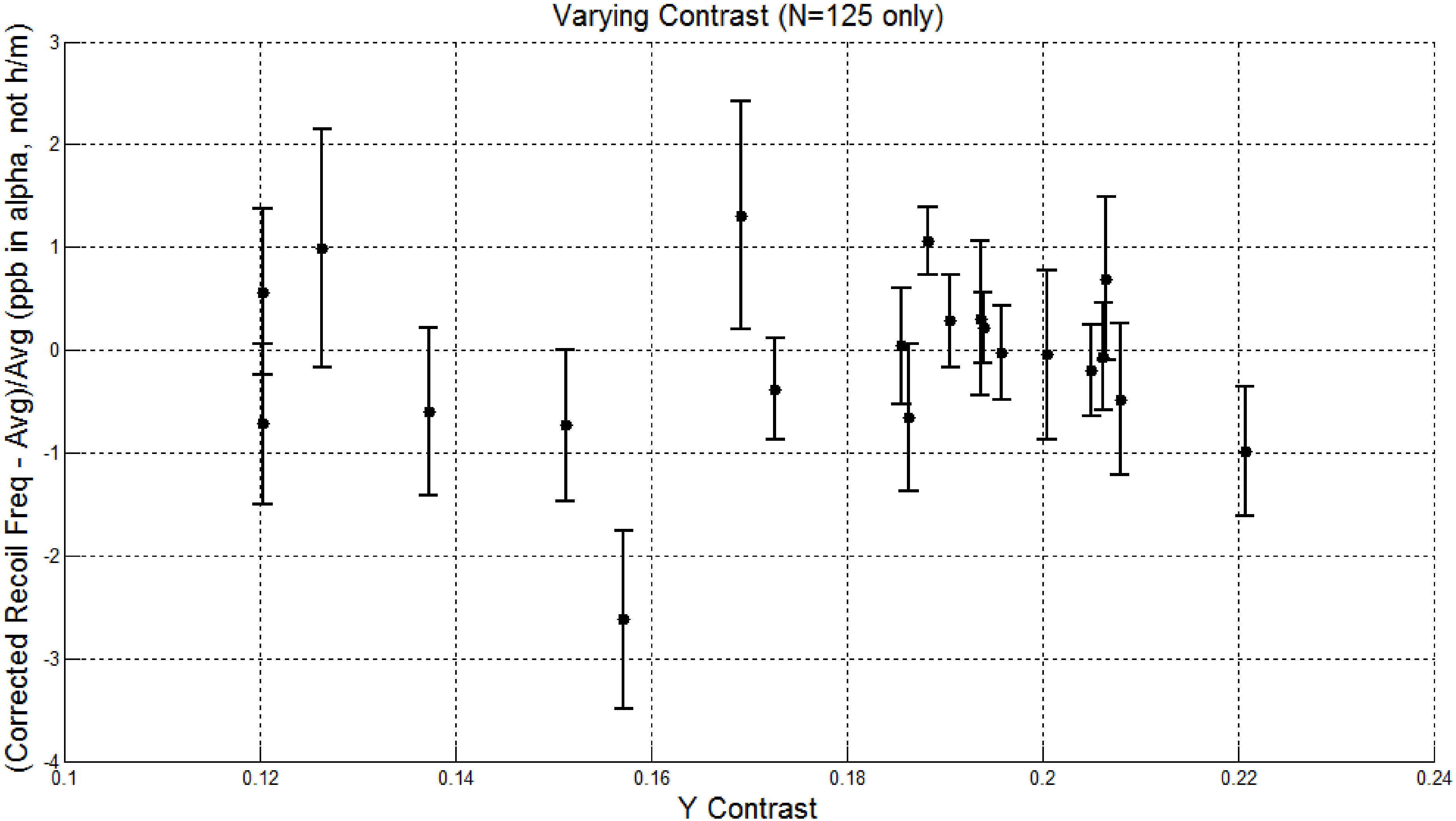
α vs Bloch Power



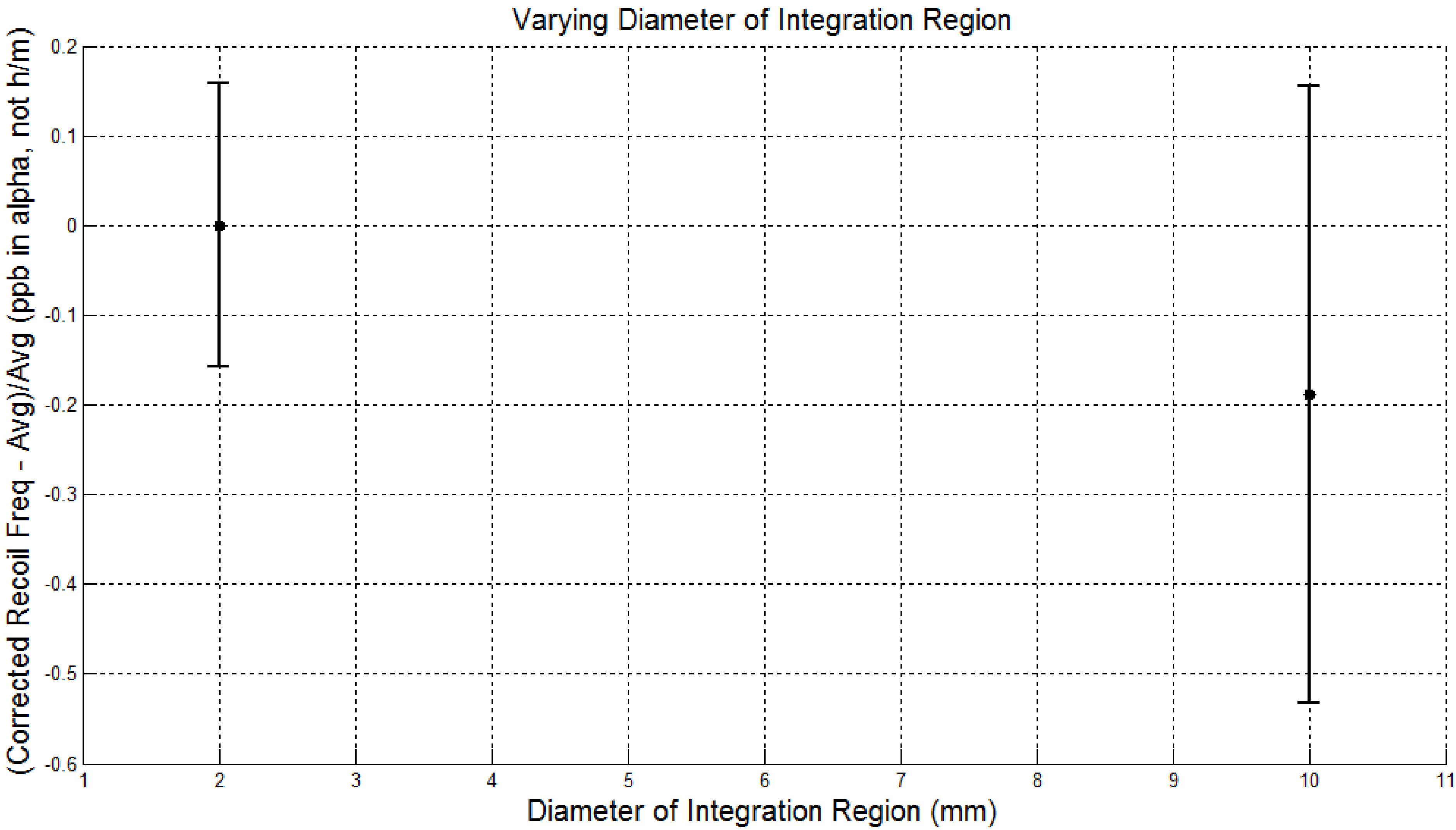
Bloch efficiency versus power



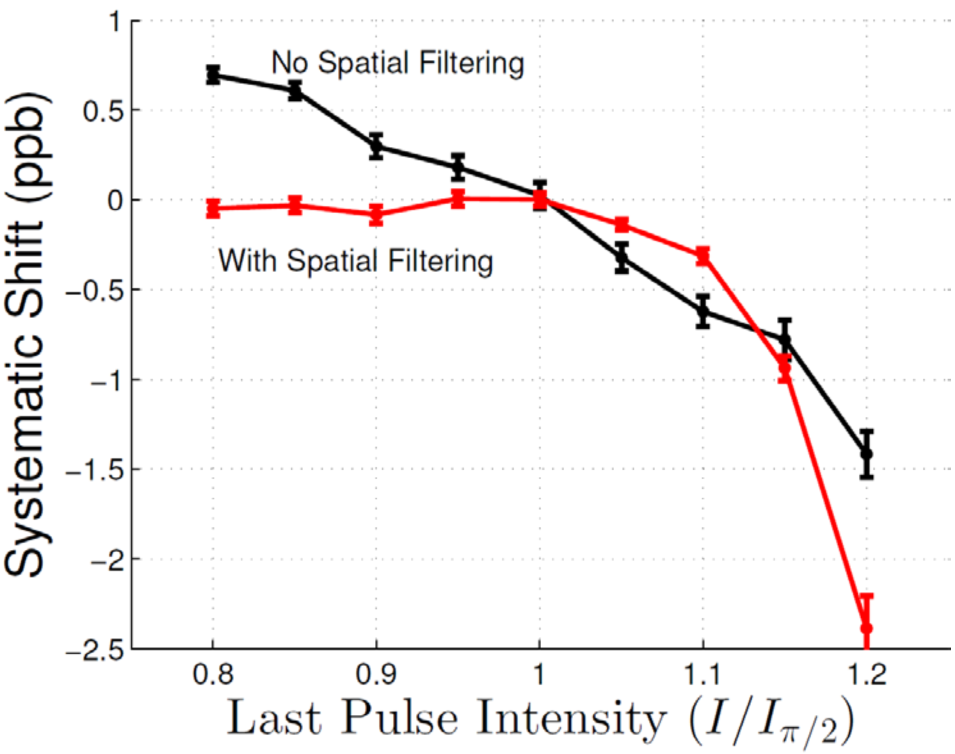
α vs ellipse contrast

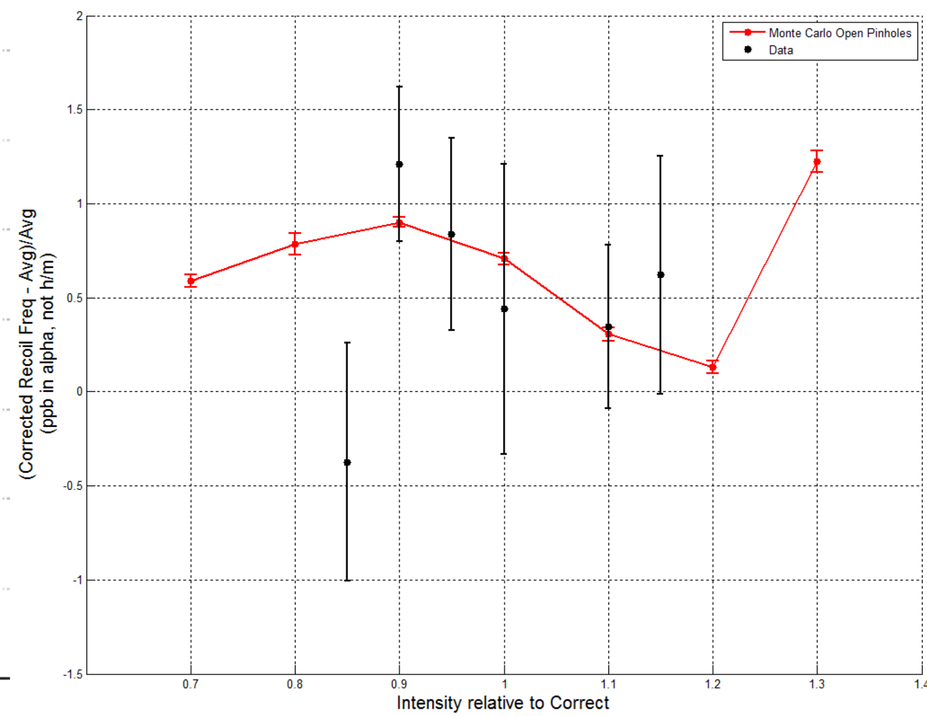


α vs detection region

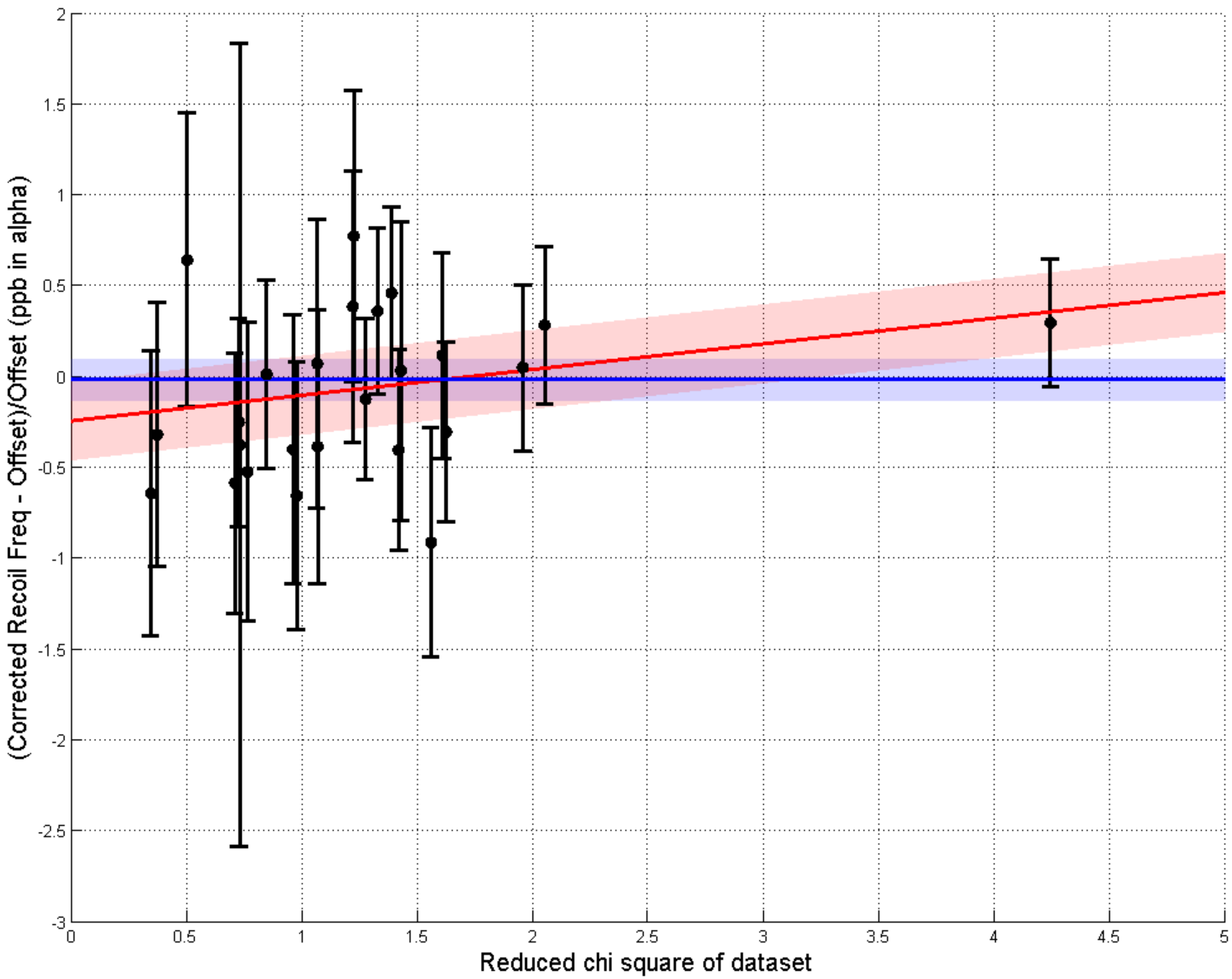


α vs Bragg intensity



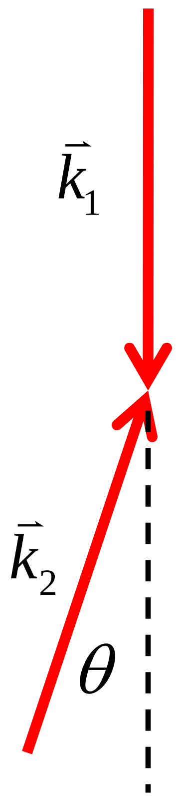


α vs speckle phase



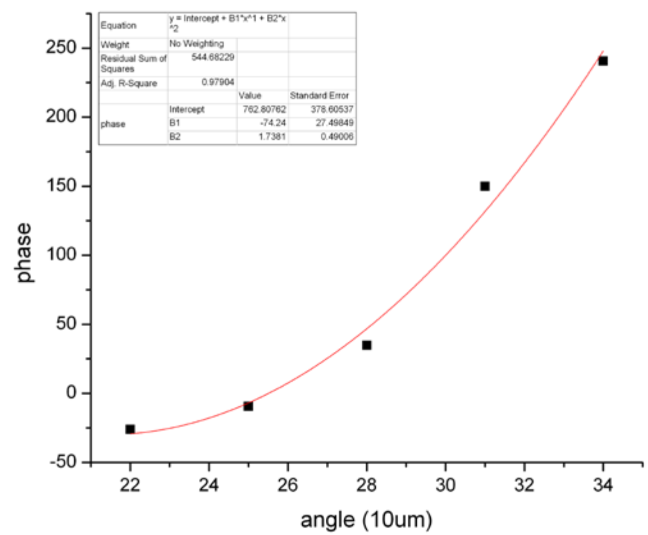
Systematic Effects

Beam Misalignment



$$\vec{k}_{eff} = \vec{k}_1 - \vec{k}_2$$

$$\left|\vec{k}_{eff}\right|^2 = (2k)^2\left(1 - \frac{\theta^2}{4}\right)$$



Experimental Sequence

Step	Parameters
Atomic Fountain	10^8 atoms/sec 4.8 m/s
↓	
Polarization Gradient Cooling	1 μK
↓	
Raman Sideband Cooling	300 nK ($\sim 1 v_r$) $F=3$, $m_F=3$
↓	
Rapid Adiabatic Passage	$F=4$, $m_F=0$
↓	
State Selection	$F=3$, $m_F=0$
↓	
Velocity Selection x2	$\sim 0.1\ v_r$ $F=3$, $m_F=0$
↓	
Interferometer Sequence	
↓	
Fluorescence Detection