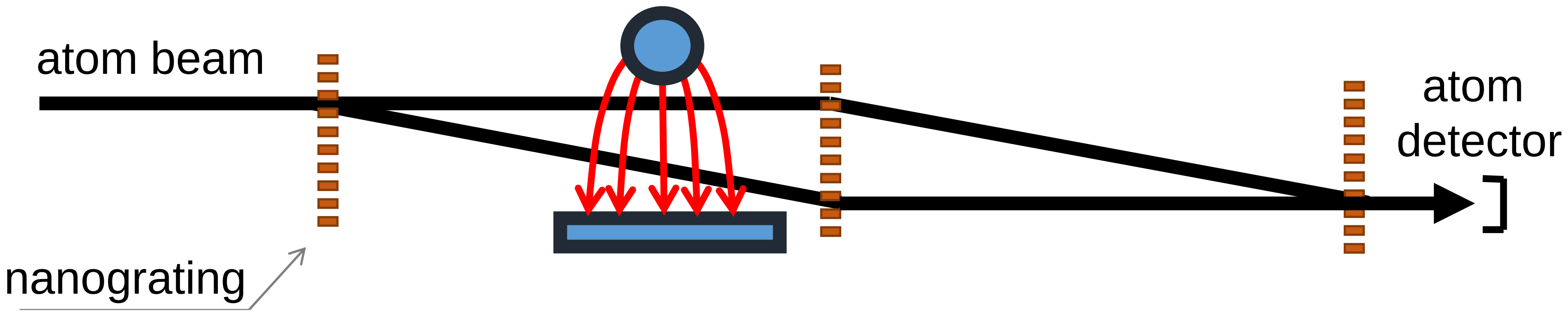
Atom Interferometry Measurements of Atomic Polarizabilities and Tune-out Wavelengths

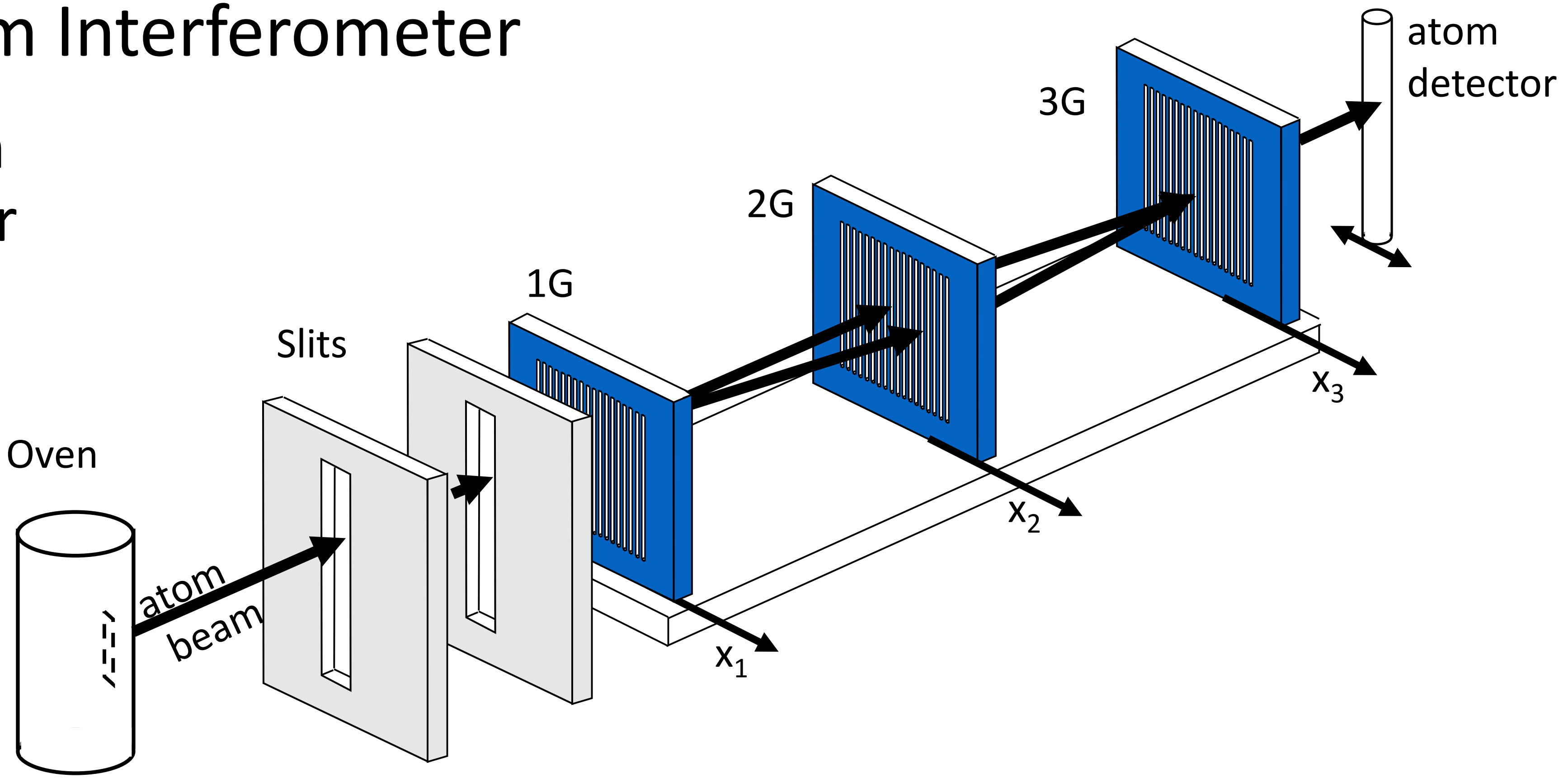
Alex Cronin, University of Arizona



UVA Physics Colloquium March 18, 2016

Our Atom Beam Interferometer

- Space Domain
- Mach-Zehnder
- Nanogratings



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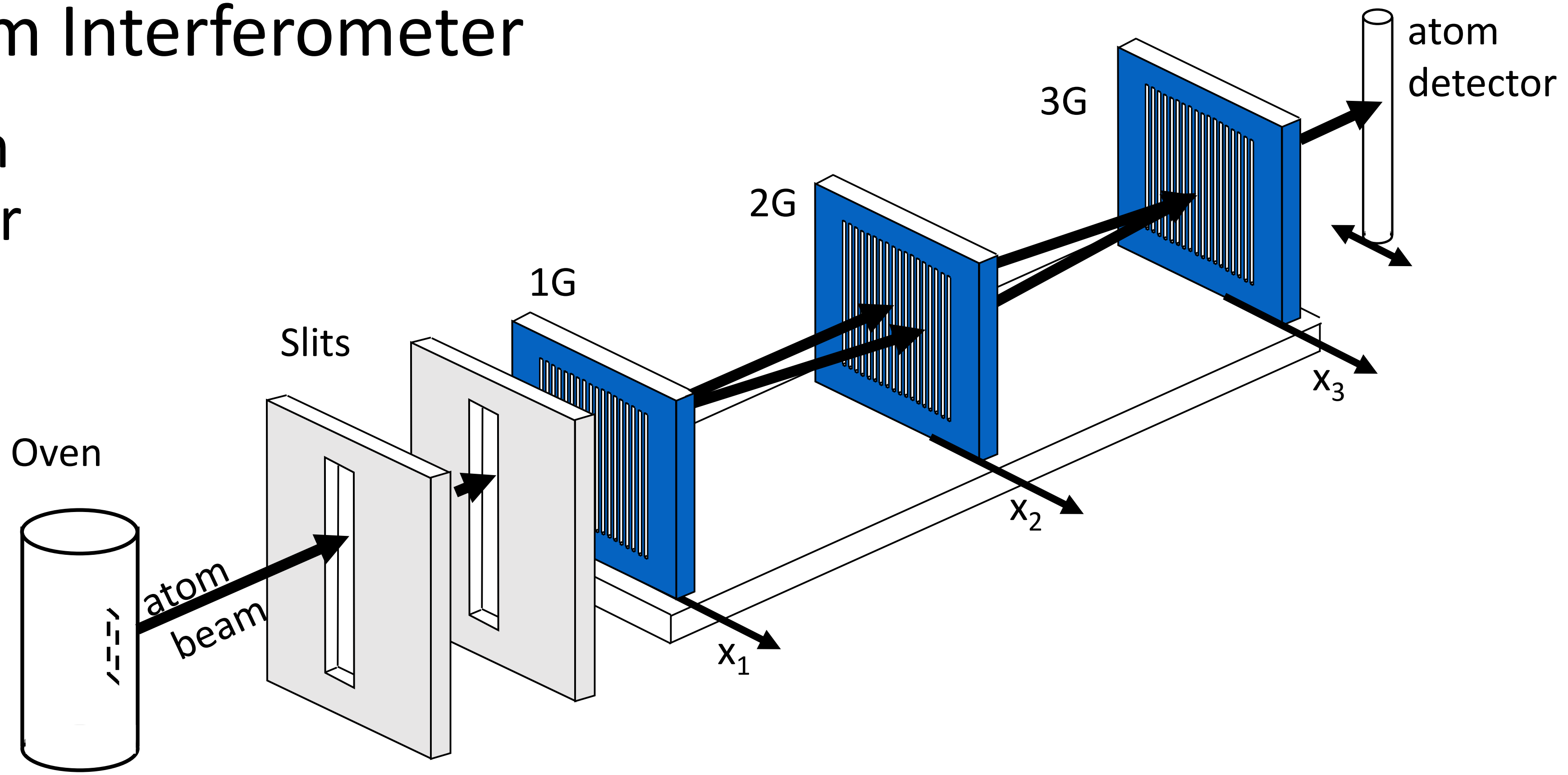

Applications for Atom Interferometry:

- Inertial sensing:
- Atomic properties:
- Quantum phenomena:

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- Space Domain
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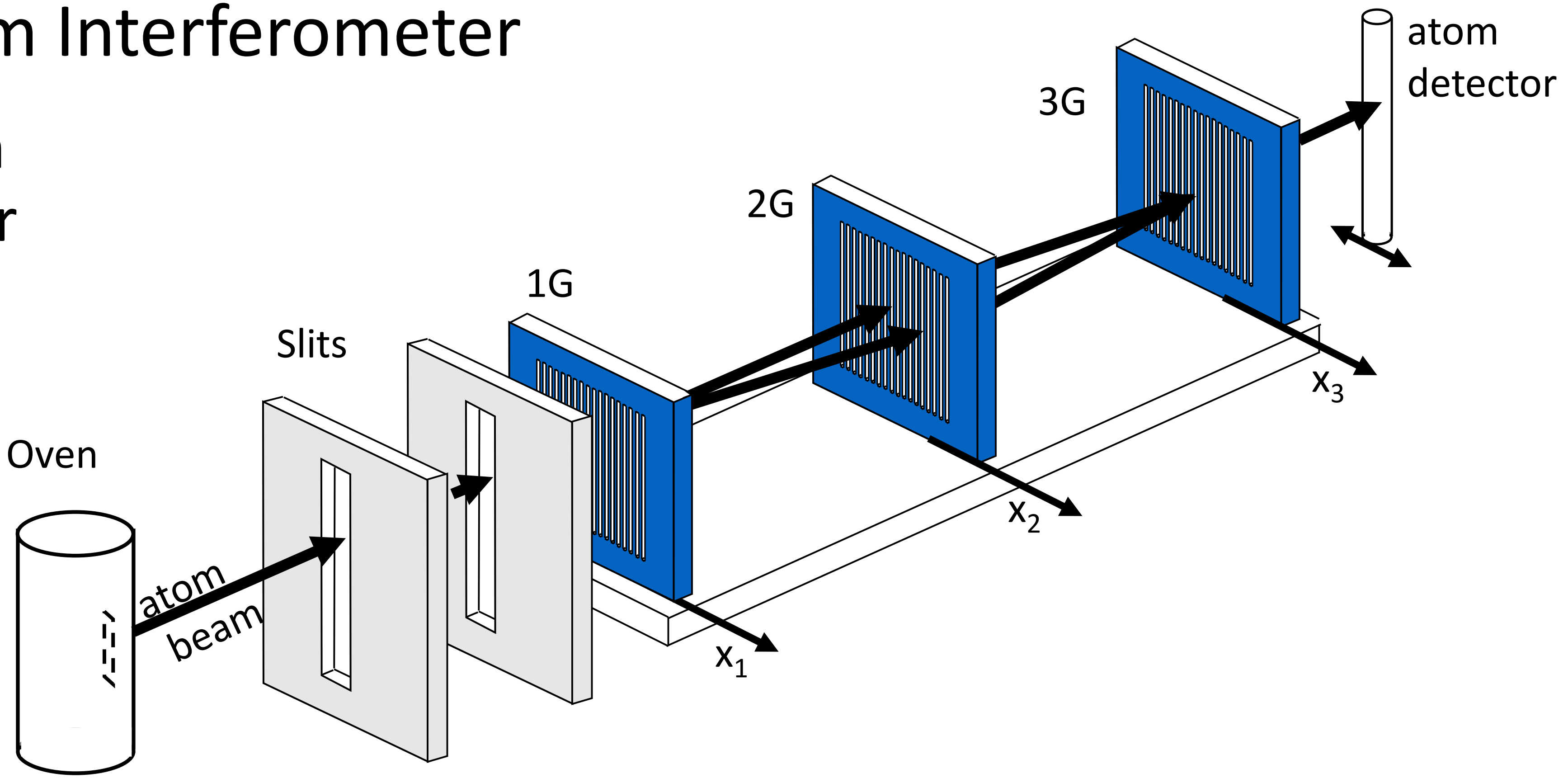

Applications for Atom Interferometry:

- Inertial sensing: g, Ω, ∇g, $\Delta\Omega$, G, WEP tests, Grav. waves?, DE?, DDM?
- Atomic properties: $\alpha(0)$, τ, $\langle k|D|i\rangle$, f_{ik}, C_6, $\alpha(\omega)$, λ_{zero}, C_3, C_6, hyperpol. γ?
- Quantum phenomena: (de)coherence, topological phases, h/m, α_{fs}

Our Atom Beam Interferometer

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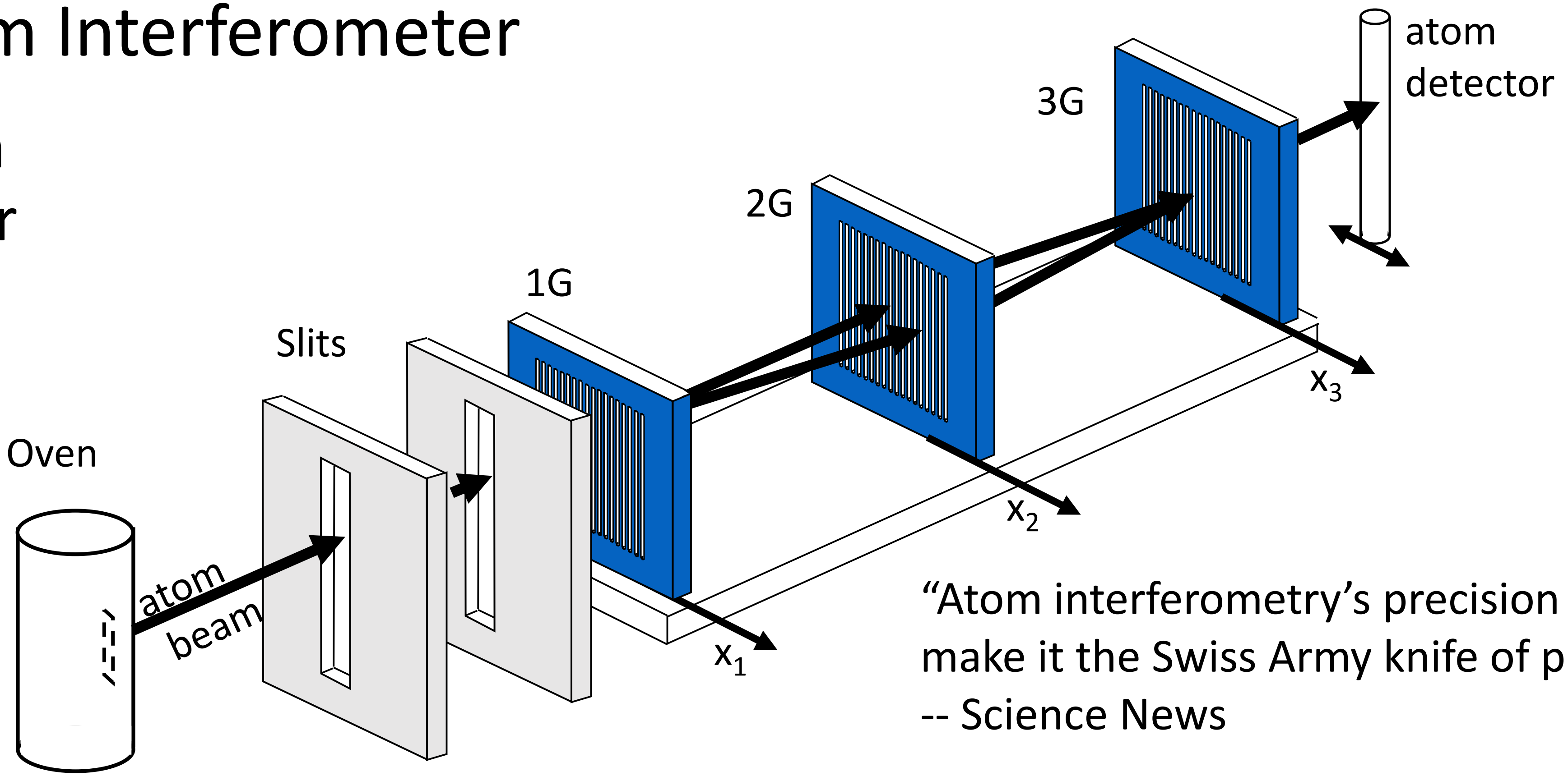

Applications for Atom Interferometry:

“Atom interferometry’s precision could make it the Swiss Army knife of physics”
-- Science News

- Inertial sensing: g, Ω, ∇g, $\Delta\Omega$, G, WEP tests, Grav. waves?, DE?, DDM?
- Atomic properties: $\alpha(0)$, τ, $\langle k|D|i\rangle$, f_{ik}, C_6, $\alpha(\omega)$, λ_{zero}, C_3, C_6, hyperpol. γ?
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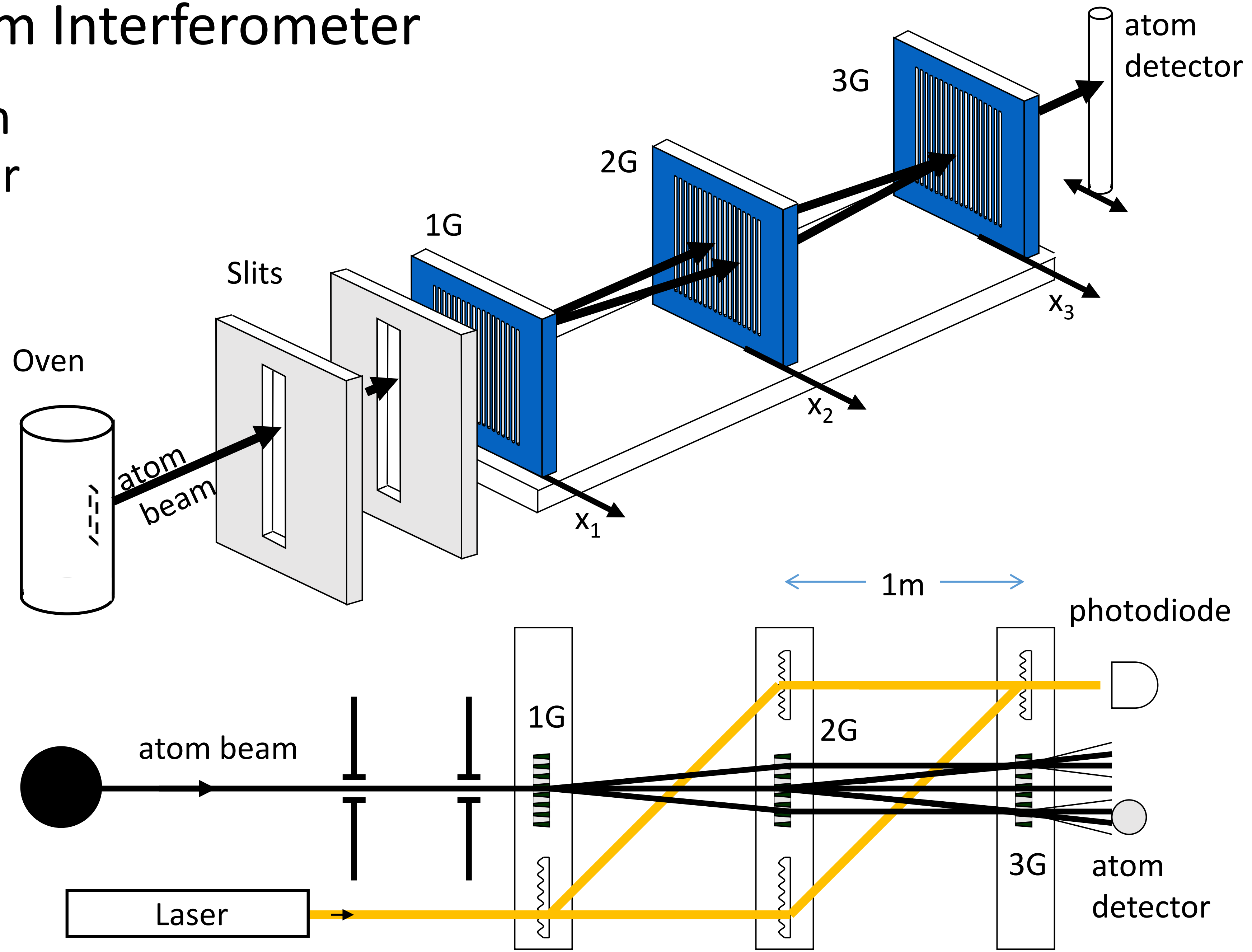
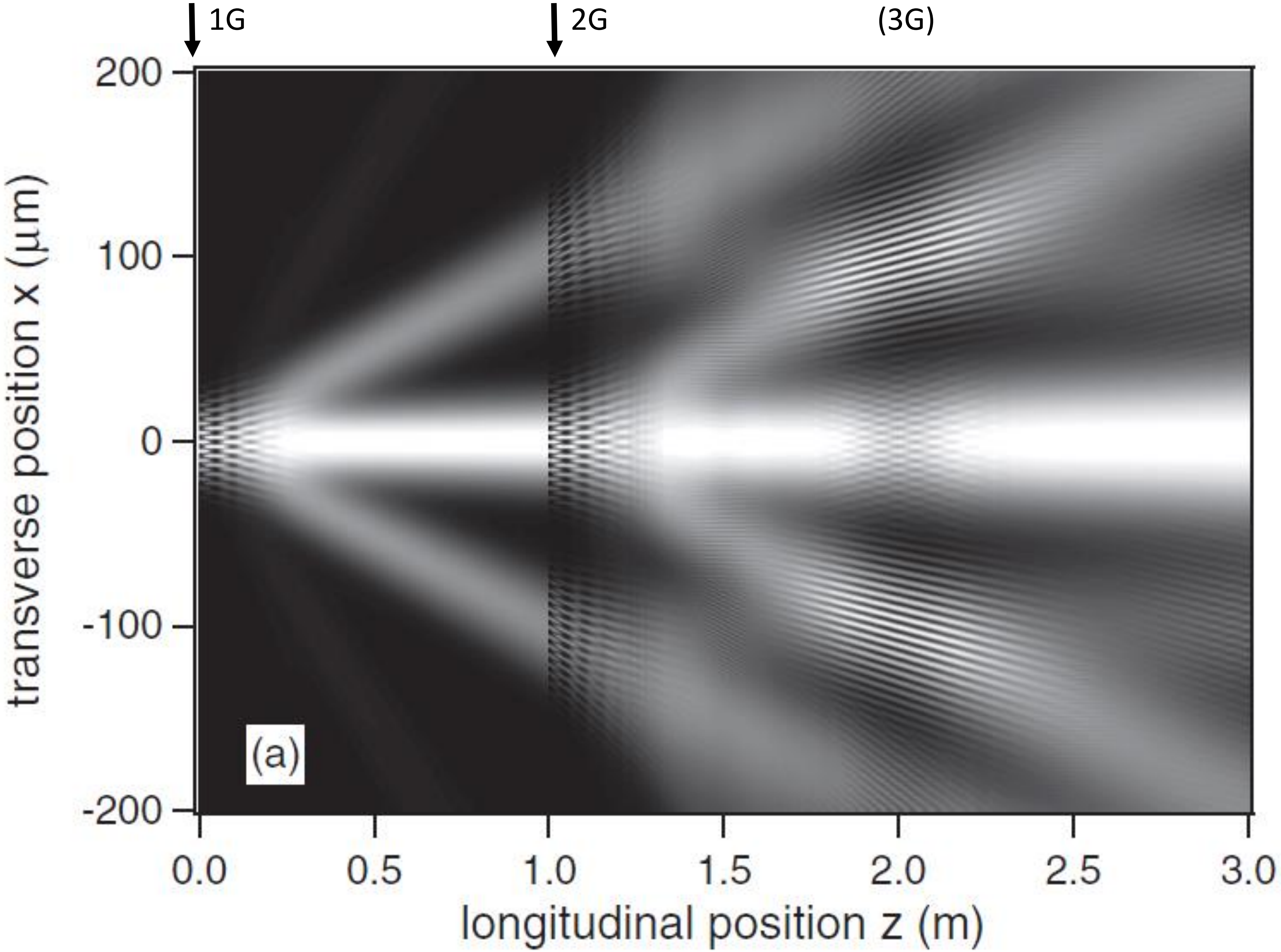




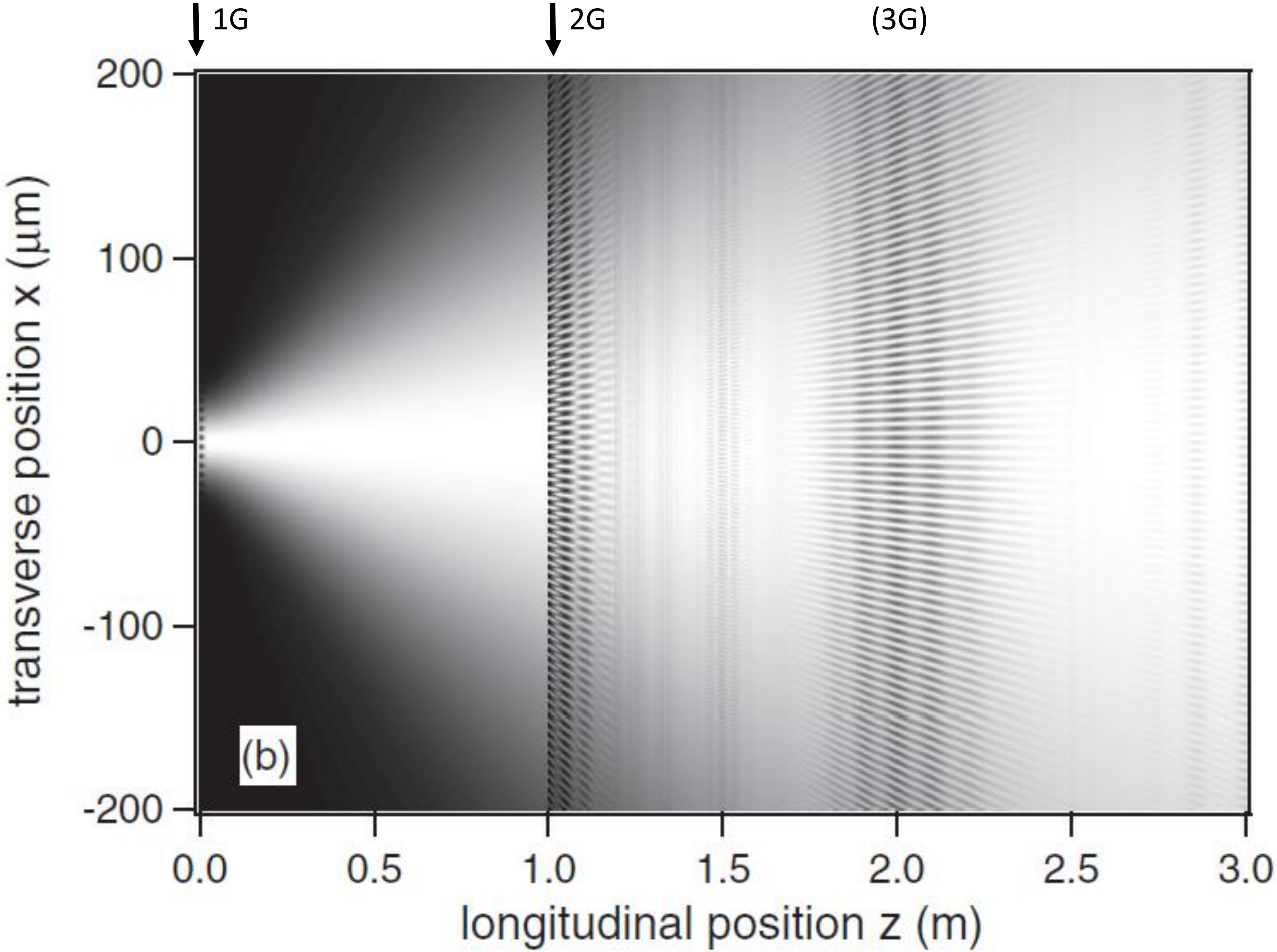
Gaussian Schell Model (GSM) Atom Beam Simulations

Parameters:

- atom λdB
- grating period
- Transverse coherence
- Longitudinal coherence
- Beam width
- dB wavefront curvature

PRA **78**, 013601 (2008)

PRA **89**, 033612 (2014)



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PRA **78**, 013601 (2008)

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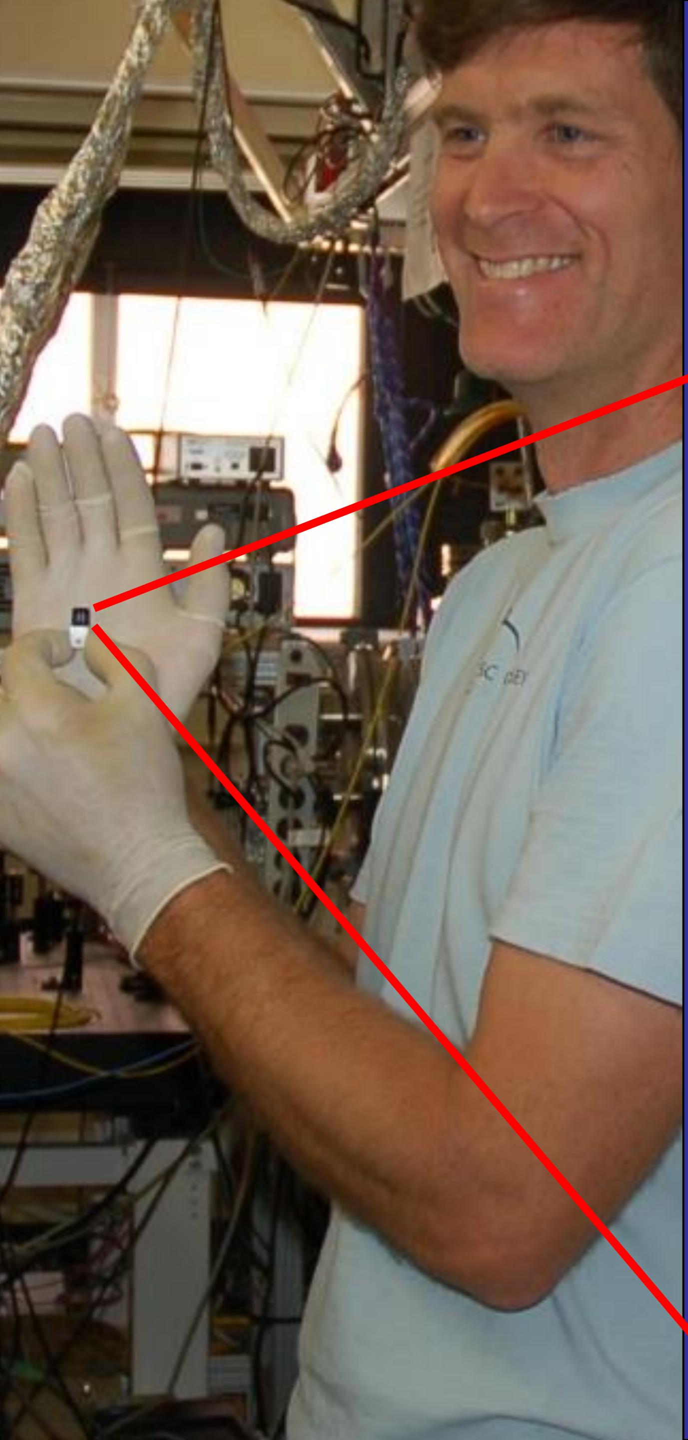
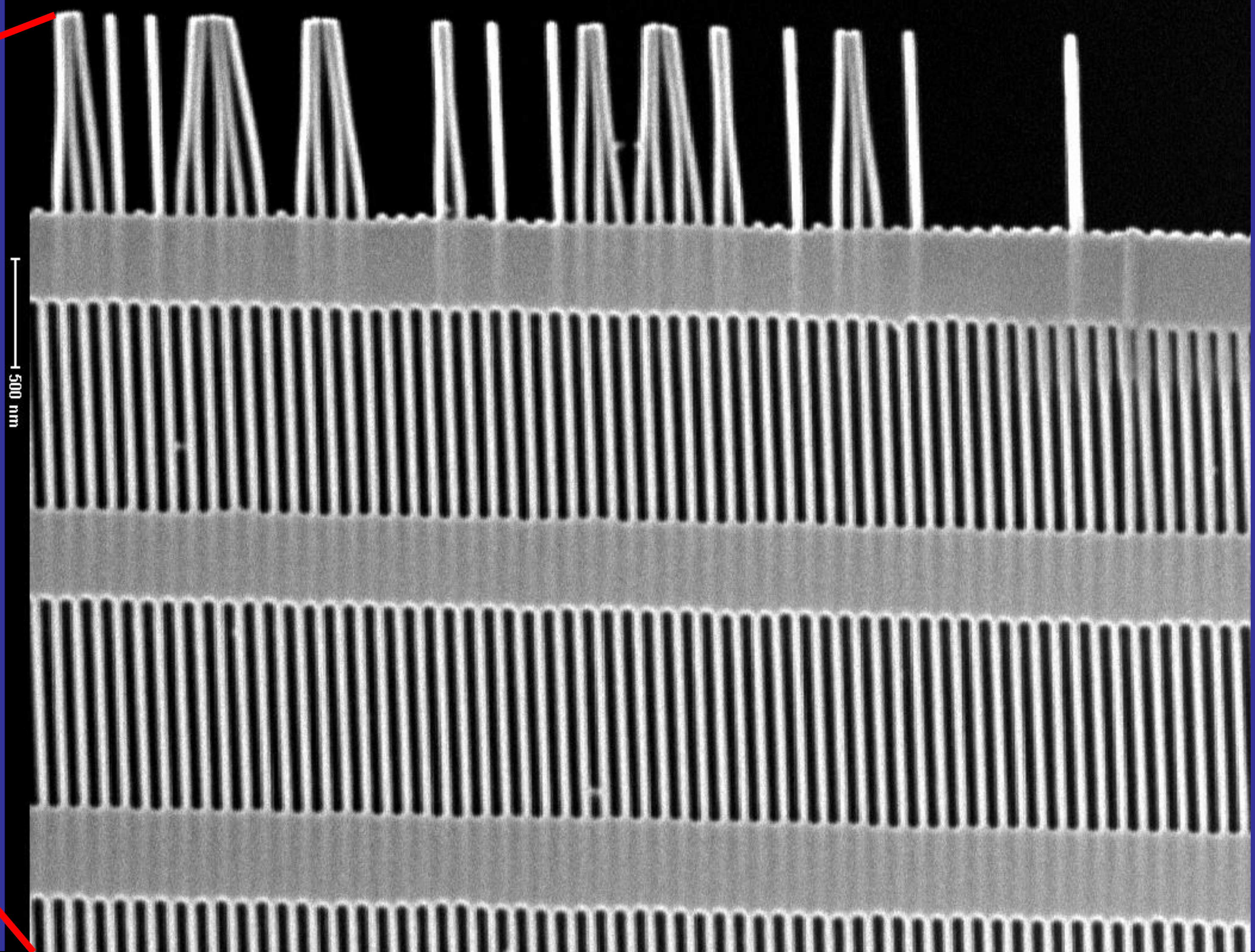
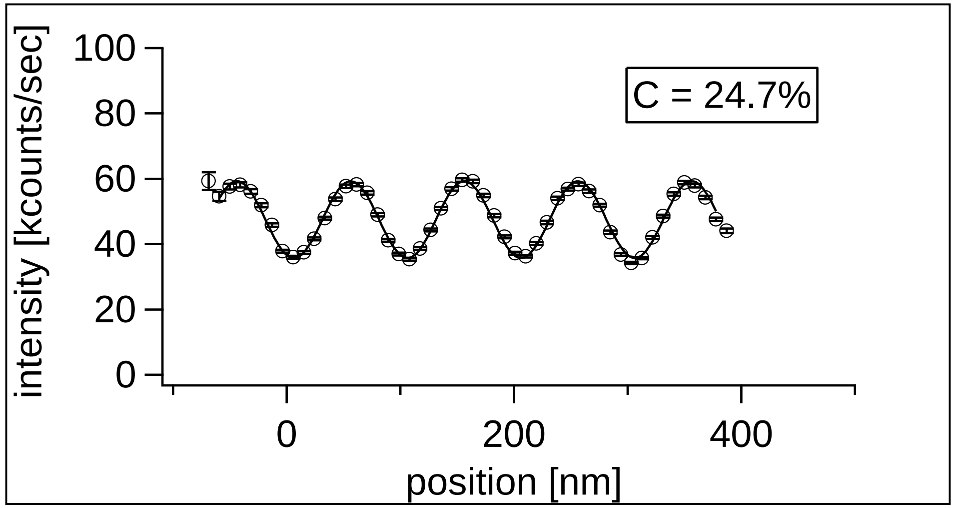
Nanograting w/ gap for C_3 expt

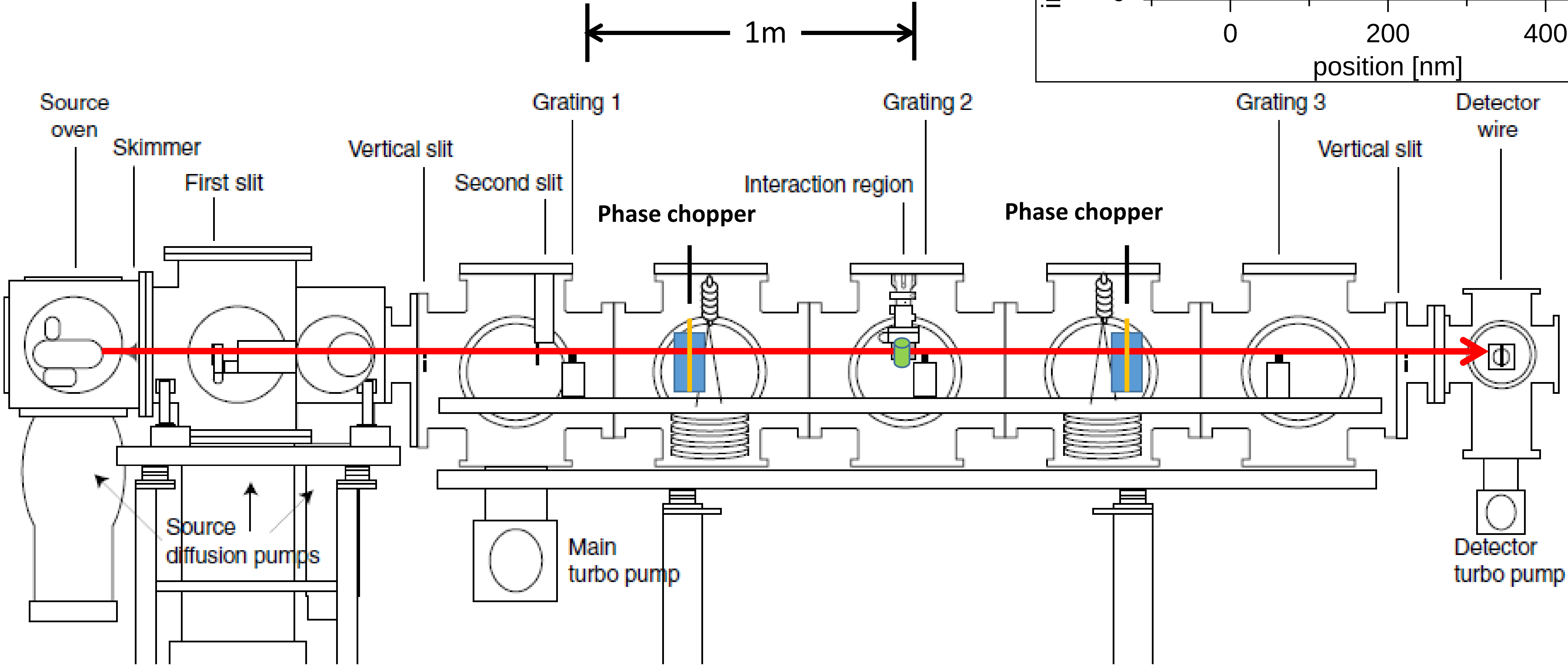


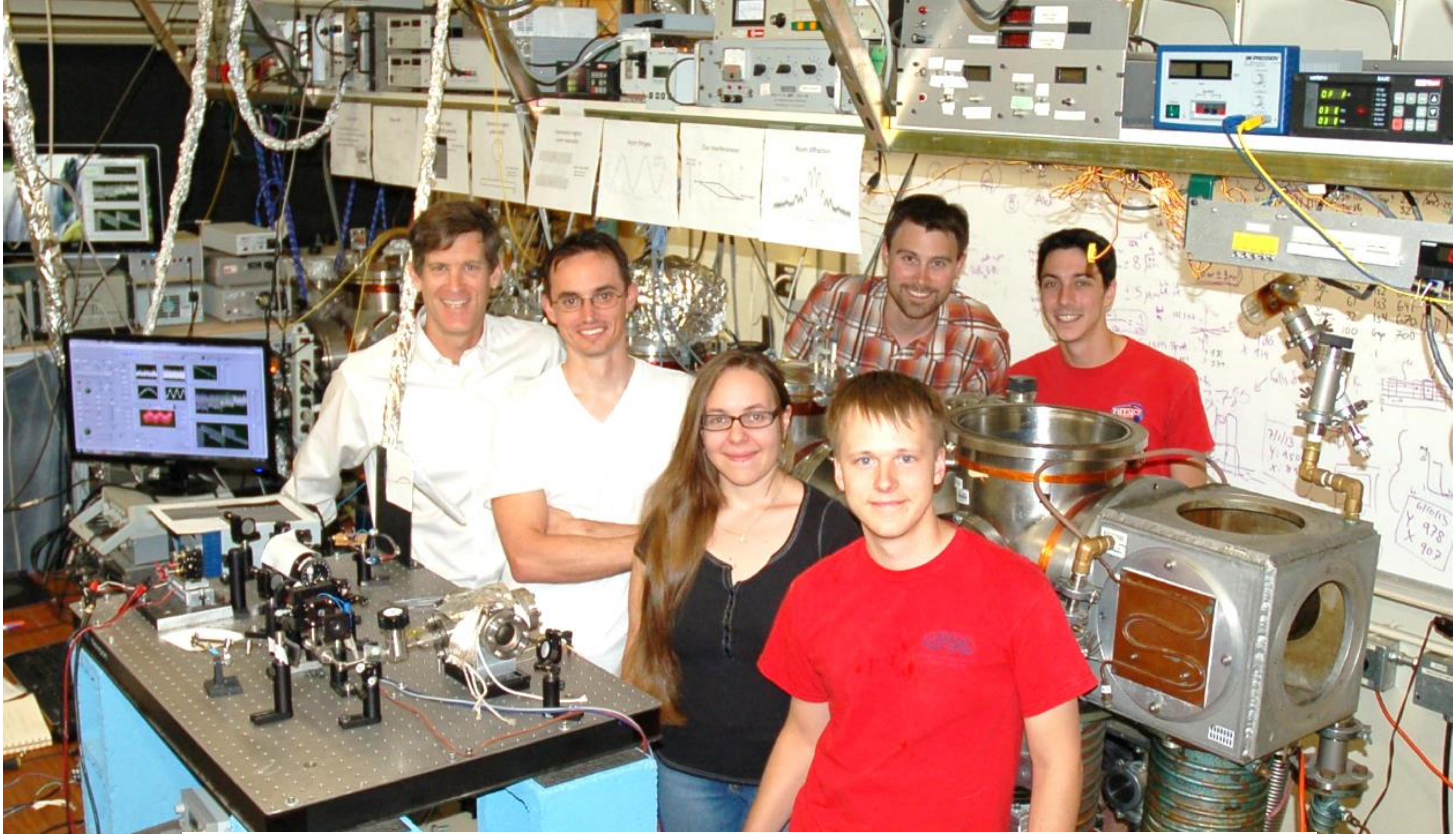


1 um

Atom Beam Interferometer Machine

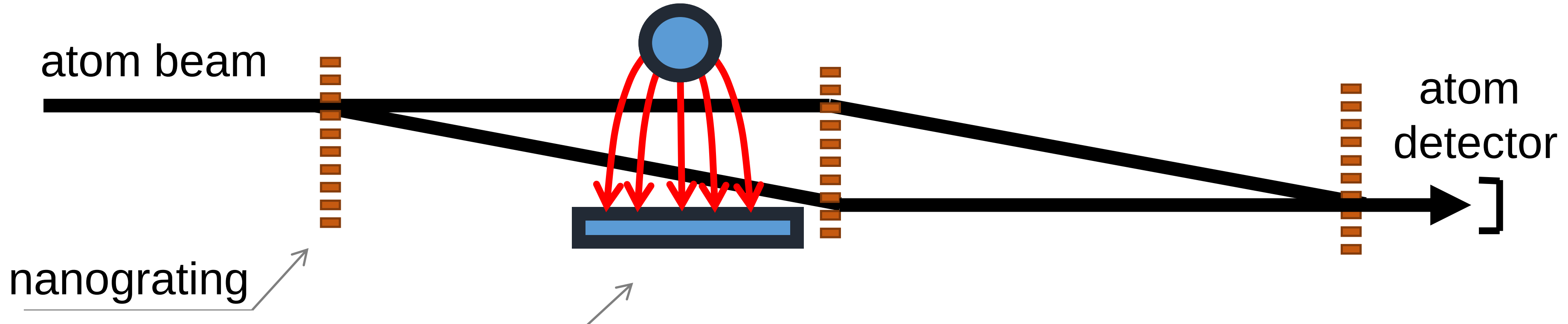






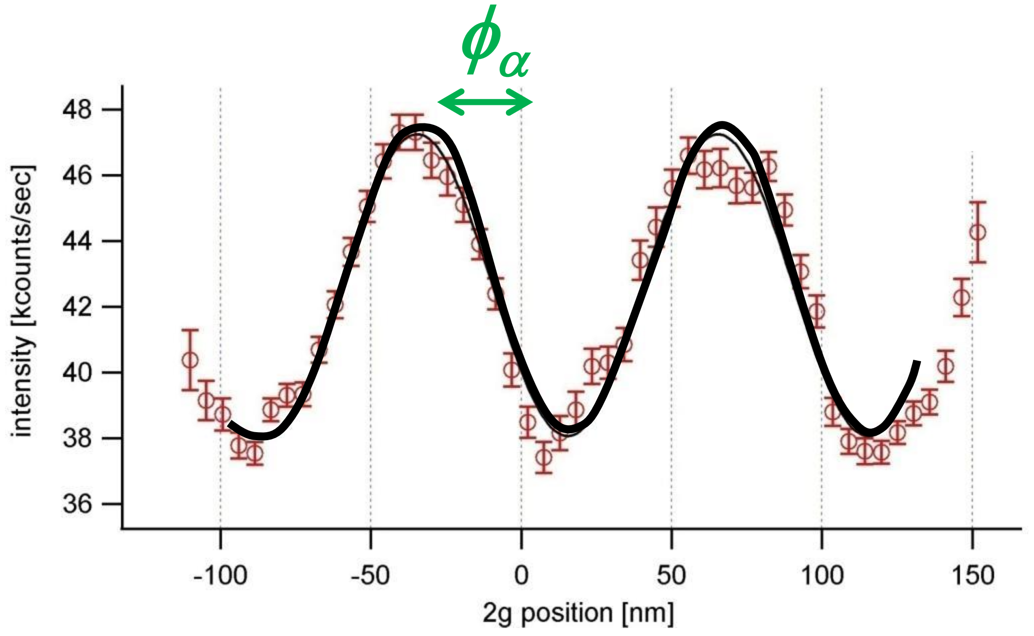
University of Arizona Atom Interferometry Laboratory
Front Row (from left): Alex Cronin, Ivan Hromada, Raisa Trubko, Maxwell Gregoire
Back Row (from left): Will Holmgren, James Greenberg

Atomic Polarizability (α) Experiment

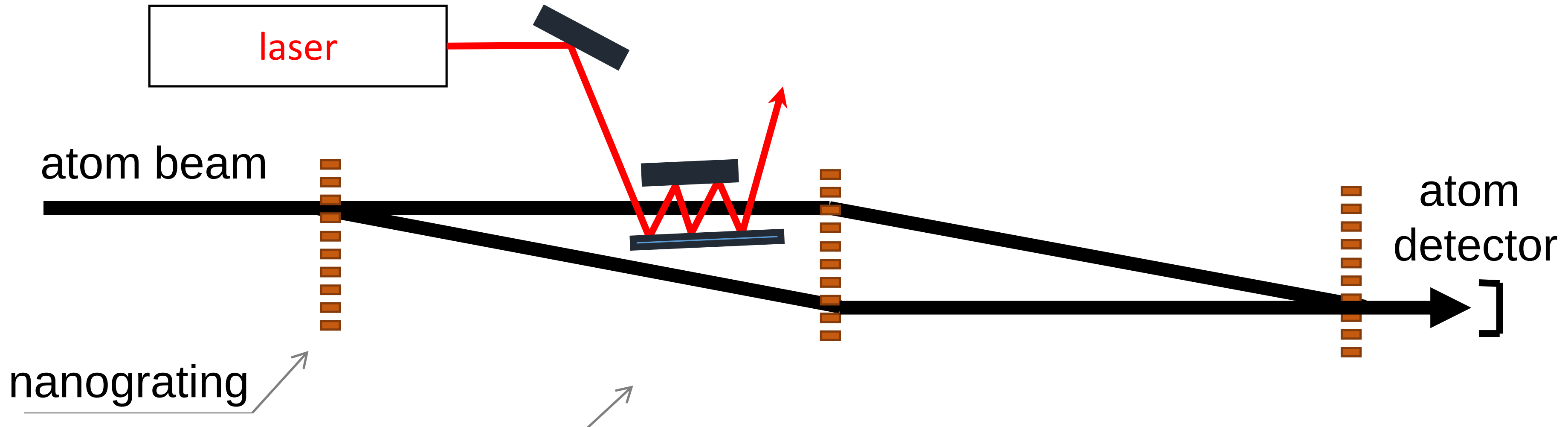


E-field gradient
for α measurement

$$U = -\frac{1}{2}\alpha E^2$$

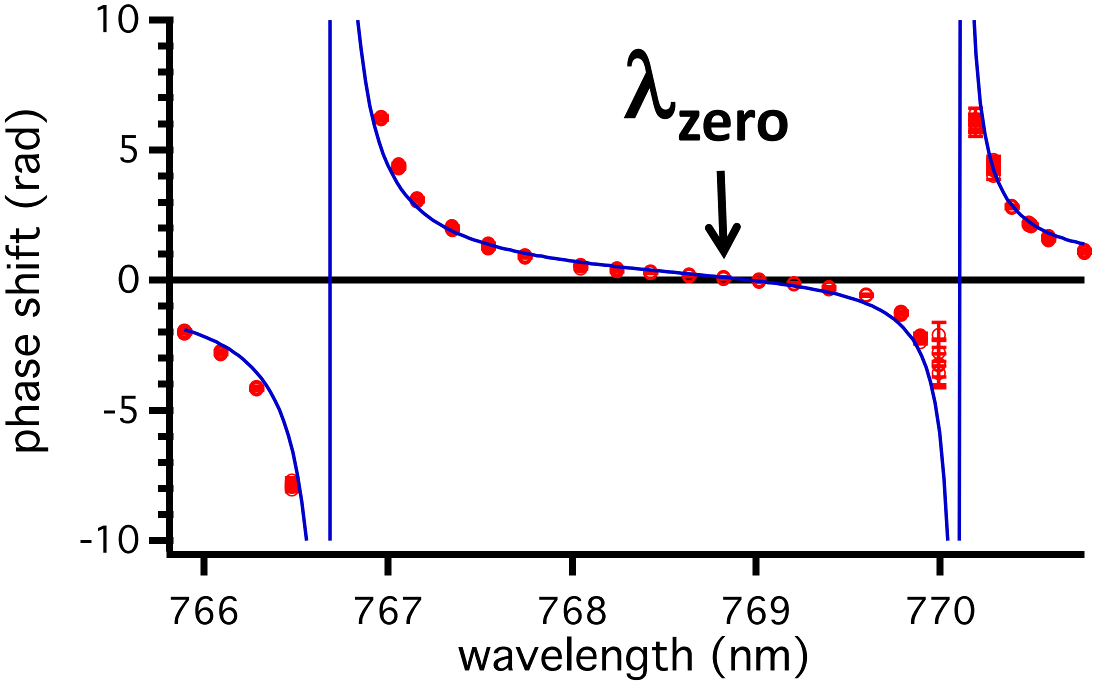


Tune Out Wavelength (λ_{zero}) Experiment

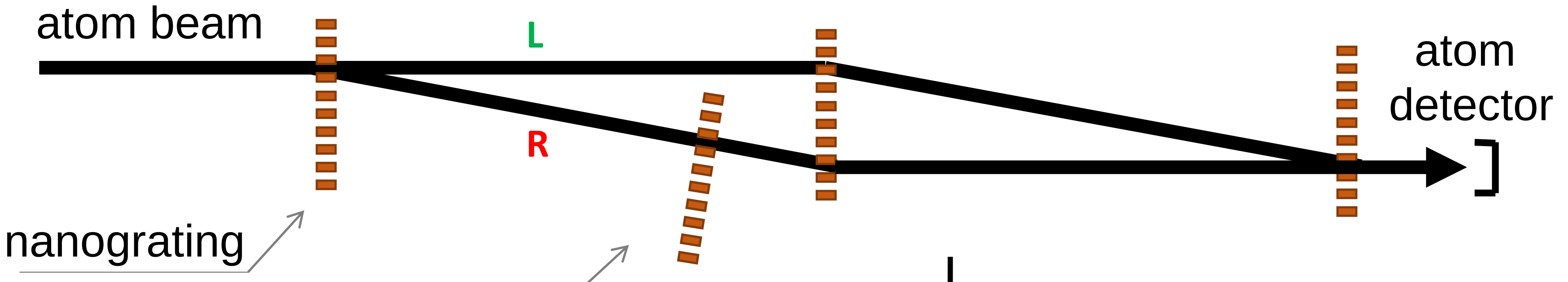


Interaction Laser
for λ_{zero} measurement

$$U = -\frac{\alpha(\omega) I}{2\epsilon_0 c}$$

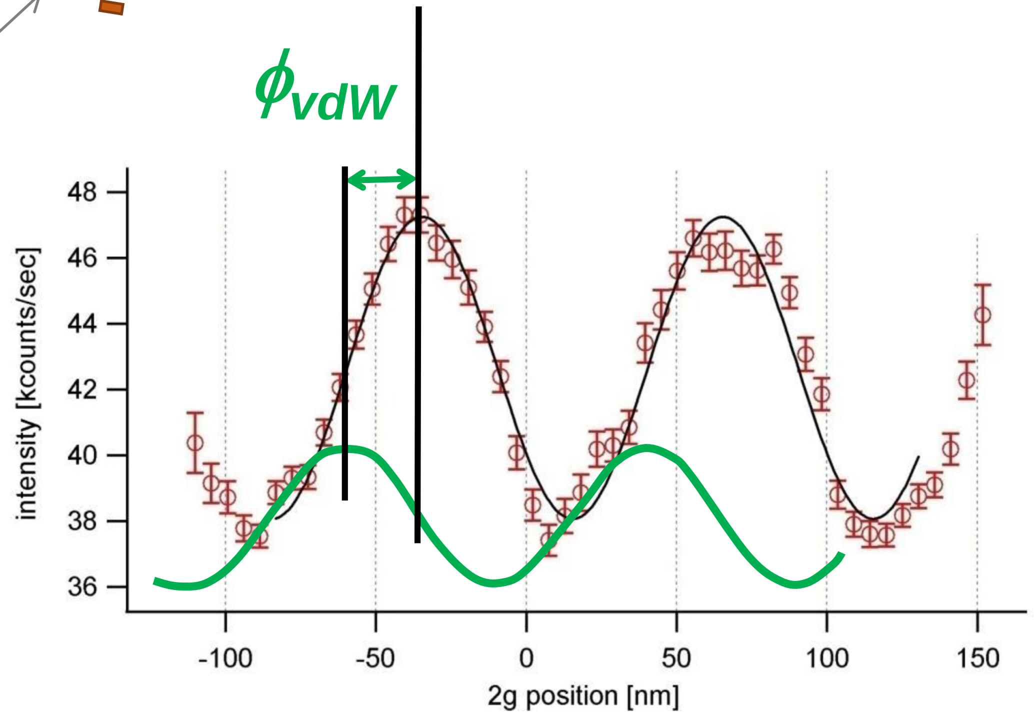


Van der Waals (C_3) Experiment



Interaction Grating
for vdW C_3 studies

$$U = -\frac{C_3}{r^3}$$



Physics Motivations:

- Meas. of $\alpha(0)$ let us report lifetimes τ, dipole matrix elements $\langle k|r|i\rangle$, and f_{ik}
- Combinations of C6 and $\alpha(0)$ measurements let us report α_{core}
- Meas. of λ_{zero} let us report ratios of dipole matrix elements $\langle P_{3/2}|r|S_{1/2}\rangle / \langle P_{1/2}|r|S_{1/2}\rangle$
- Meas. of $\alpha(0)$, C_3, and λ_{zero} probe different functions of oscillator strengths f_{ik}

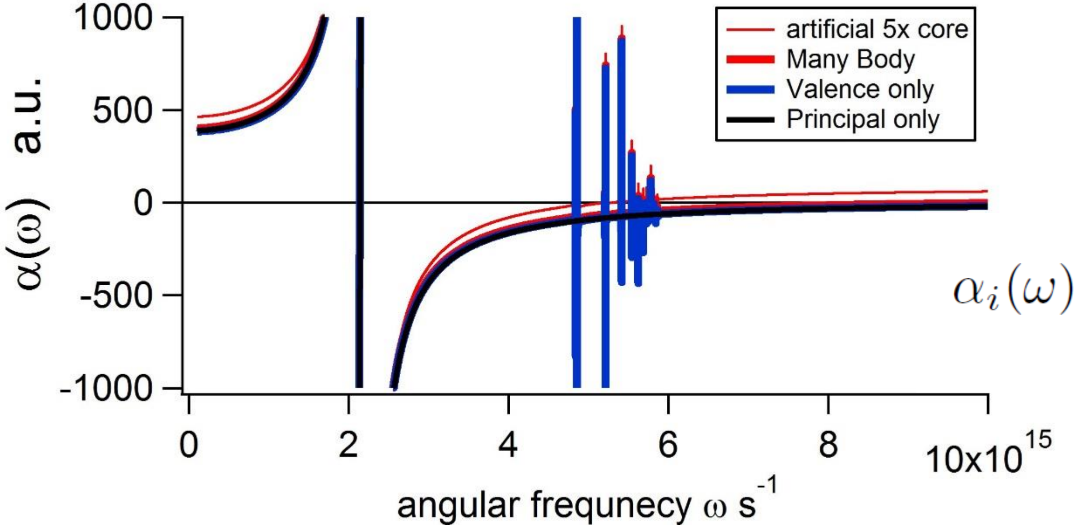
Measurements of $\alpha(0)$, C_3, and λ_{zero} probe different functions of atomic oscillator strengths f.

$$\alpha_i(\omega) = \frac{e^2}{m} \sum \frac{f_{ik}}{\omega_{ik}^2 - \omega^2} \longrightarrow \alpha_i(0) = \frac{e^2}{m} \sum \frac{f_{ik}}{\omega_{ik}^2}$$

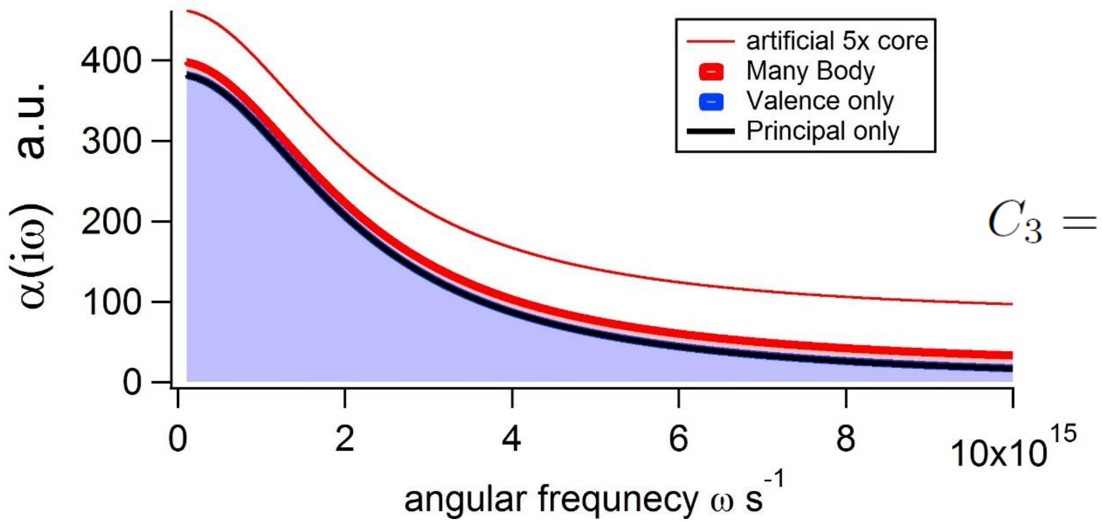
$$C_3 = \frac{\hbar}{4\pi} \int \alpha(i\omega) g(i\omega) \longrightarrow C_3 = \frac{\hbar e^2}{8m} \sum \frac{f_{ik}}{\omega_{ik}}$$

$$\alpha(\omega_{\mathrm{zero}}) = 0 \longrightarrow \frac{\omega_{\mathrm{zero}}^2 - \omega_1^2}{\omega_2^2 - \omega_{\mathrm{zero}}^2} \approx \frac{f_1}{f_2}$$

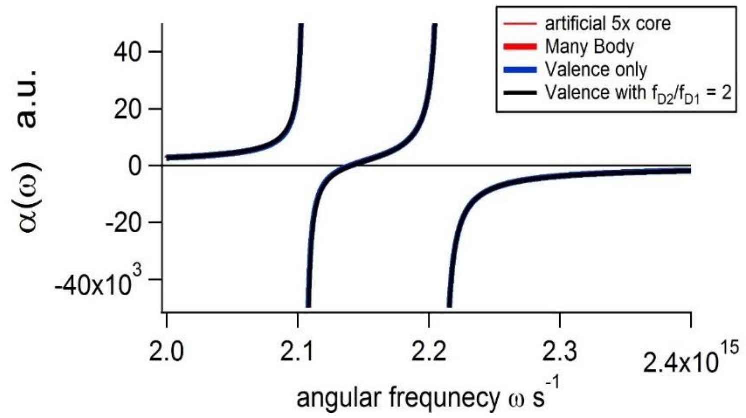
Measurements of $\alpha(0)$, C_3, and λ_{zero} probe different functions of atomic oscillator strengths f.

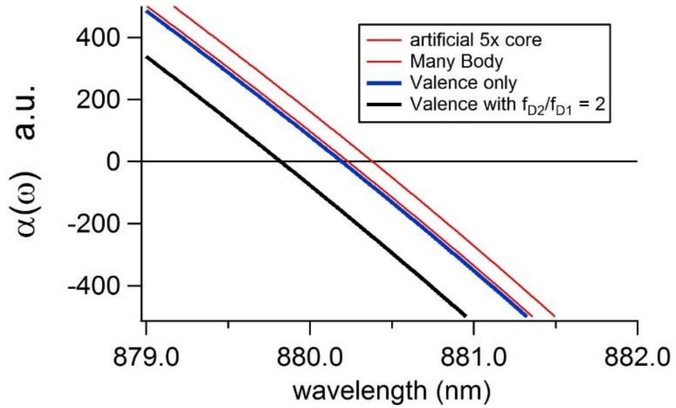


$$\alpha_i(\omega) = \frac{e^2}{m} \sum \frac{f_{ik}}{\omega_{ik}^2 - \omega^2}$$



$$C_3 = \frac{\hbar}{4\pi} \int \alpha(i\omega) g(i\omega)$$

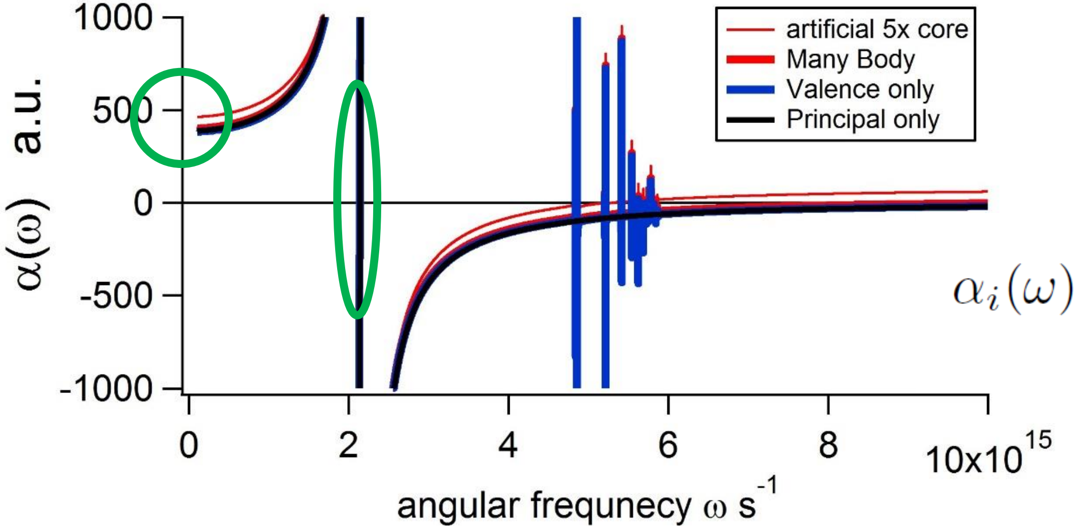




λ_{zero} in more detail.

$\alpha(\omega)=0$ at $\omega=2\pi c/\lambda_{zero}$

Measurements of $\alpha(0)$, C_3, and λ_{zero} probe different functions of atomic oscillator strengths *f*.



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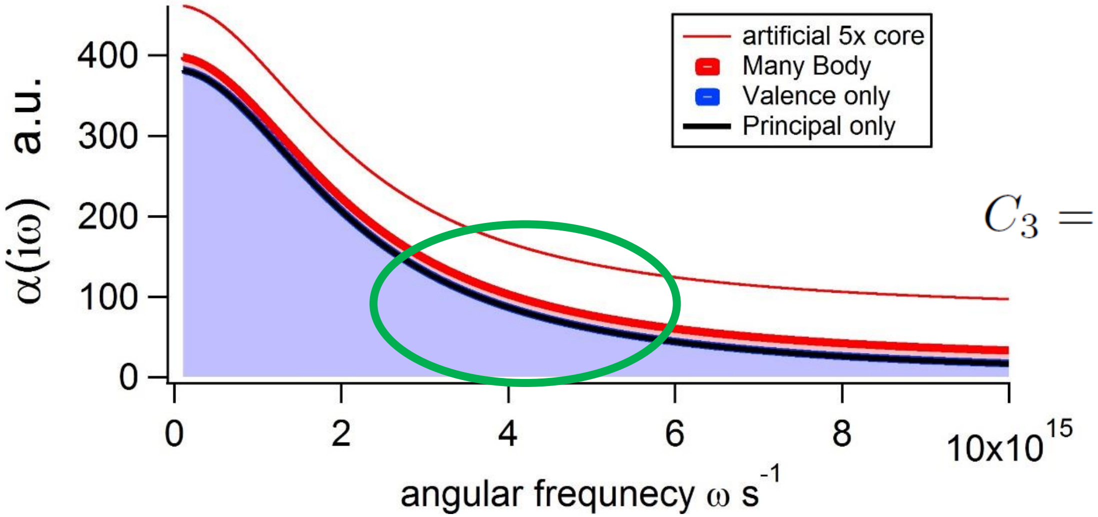
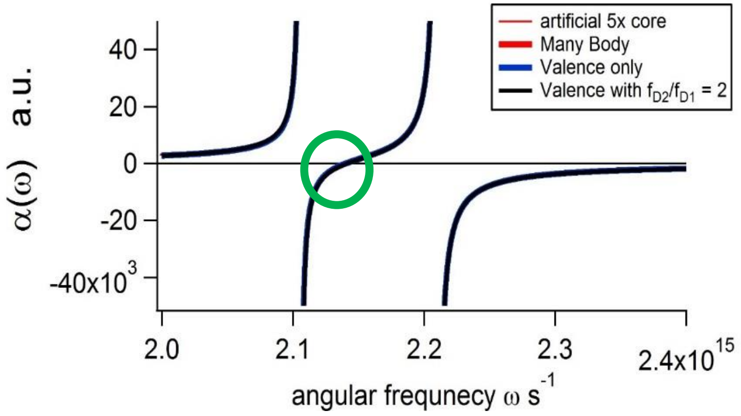
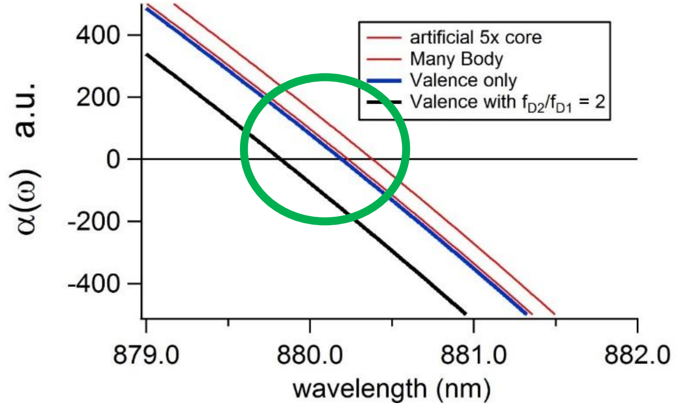


$$C_3 = \frac{\hbar}{4\pi} \int \alpha(i\omega) g(i\omega)$$





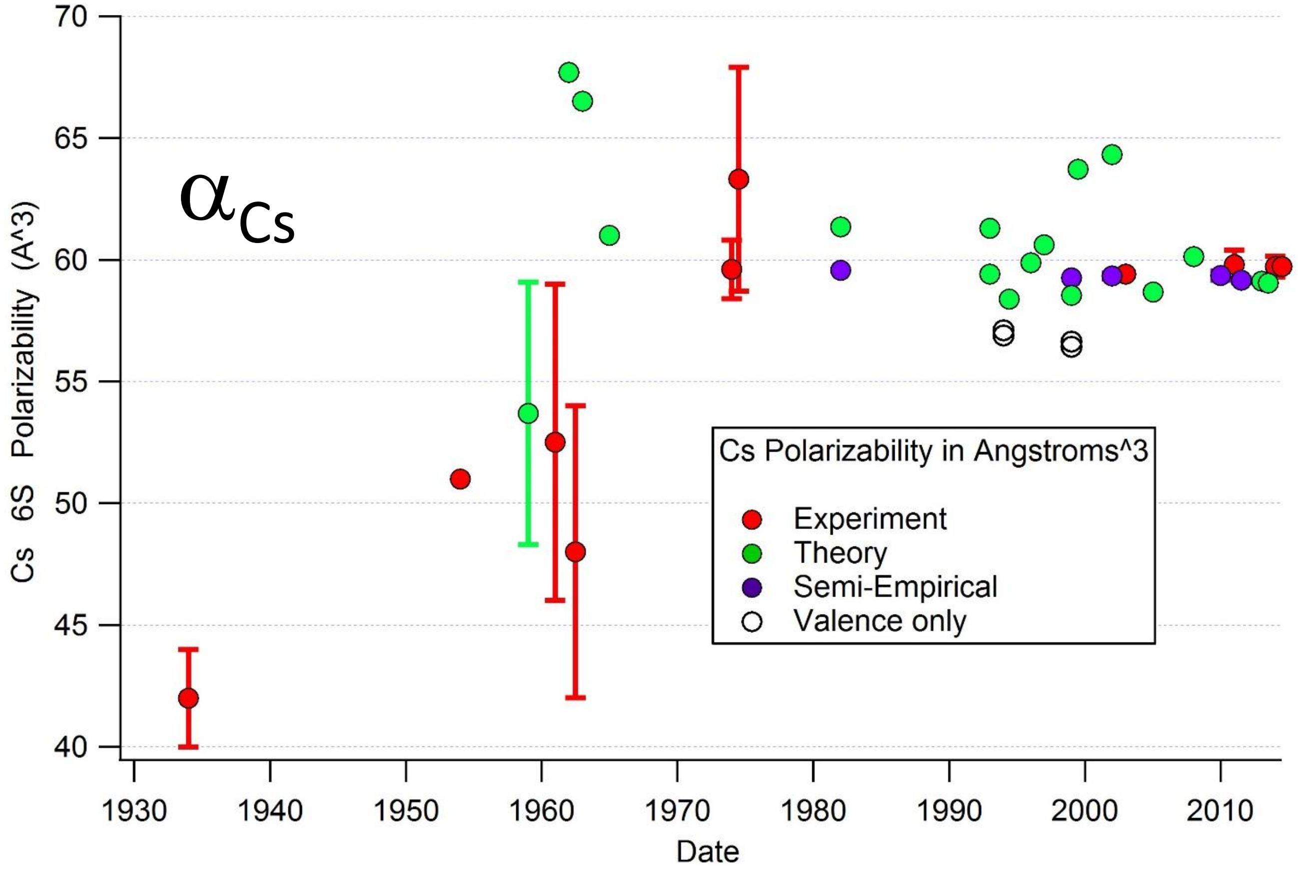
λ_{zero} in more detail.

$\alpha(\omega)=0$ at $\omega=2\pi c/\lambda_{zero}$

Historical measurements of α_{Cs}

α [A^3]	Year	Author
42	1934	Stark
51	1954	Zakarias
53.7	1959	Dalgarno
67.7	1962	Sternheimer
48	1962.5	Zorn
52.5	1961	Bederson
61.3	1993	Kello
59.6	1974	Molof
63.3	1974.5	Zorn
59.26	1999	DJSB99
58.68	2005	Lim
59.13	2013	Borschevsky
59.42	2003	Amini+Gould
63.72	1999.5	Lim
59.42	1993	Fuentealba
59.8	2011	Holmgren NJ
59.72	2014	Hromada

α [A^3]	Year	Author
59.04	2013.5	Iskrenova
58.38	1994.4	van Wijngaar
60.61	1997	Patil+Tang
66.5	1963	Reitz
61	1965	Crown
64.31	2002	Magnier
59.87	1996	Dolg
61.35	1982	Christiansen
59.57	1982	Fuentalba
58.54	1999	Lim
60.12	2008	Dulieu
59.34	2002	Derevianko
59.15	2011	Knize SBT11
59.36	2010	Porsev PBD1

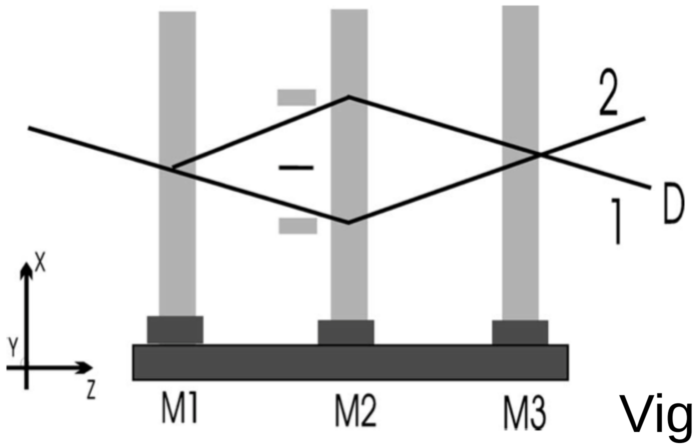


$$U = -\frac{1}{2}\alpha E^2$$

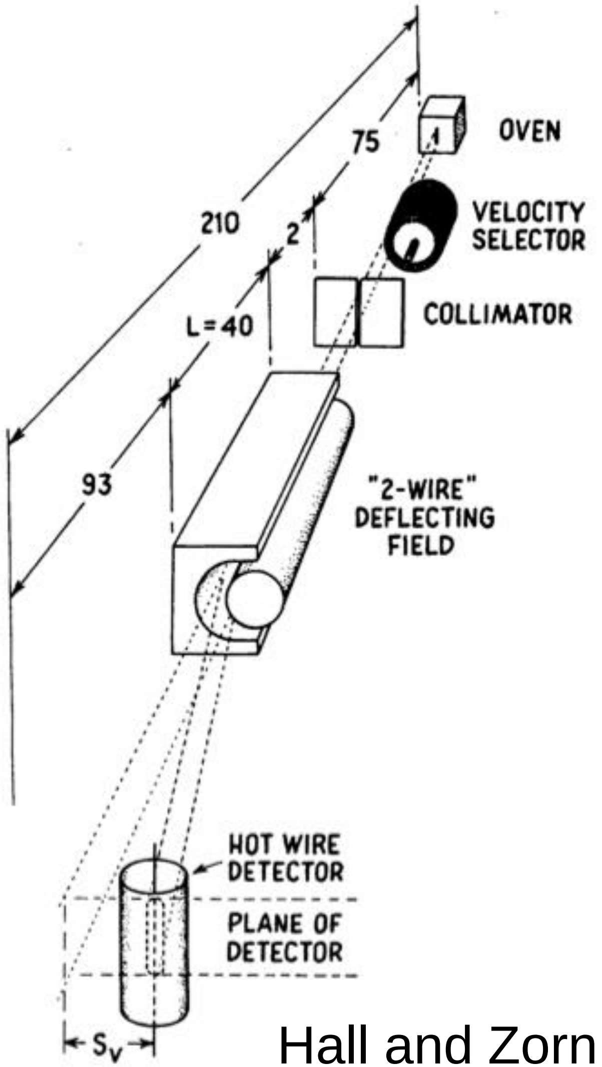
$$\alpha_i(0) = \frac{e^2}{m}\sum \frac{f_{ik}}{\omega_{ik}^2} = \frac{e^2}{3}\sum_k \frac{|\langle i|r|k\rangle|^2}{E_i - E_k}$$

Historical polarizaility measurement techniques

- Beam deflection
  - Miller and Bederson (1974)
  - Hall and Zorn (1974)
- Interferometry
  - Pritchard (1995)
  - Vigue (2006)

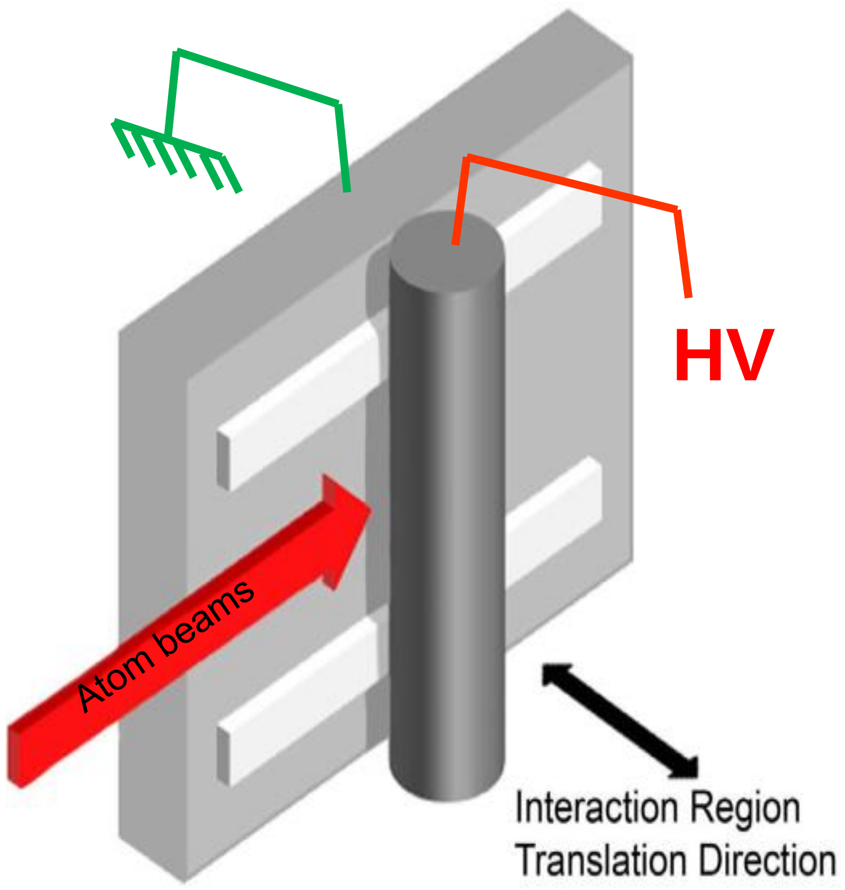


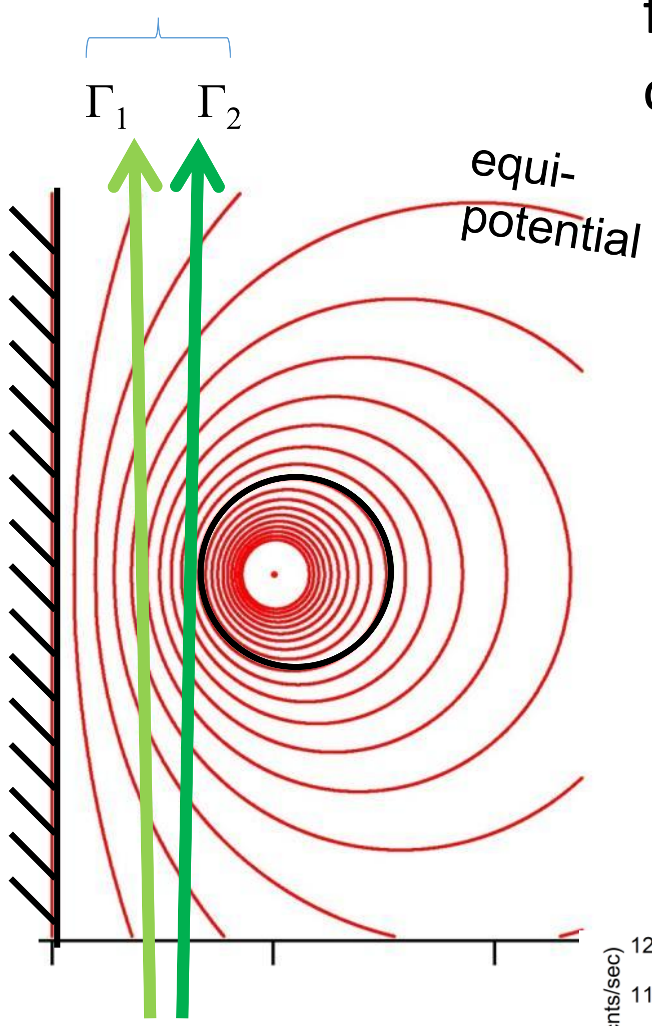
Vigue (2006)



Hall and Zorn (1974)

Our 2010 E-field apparatus

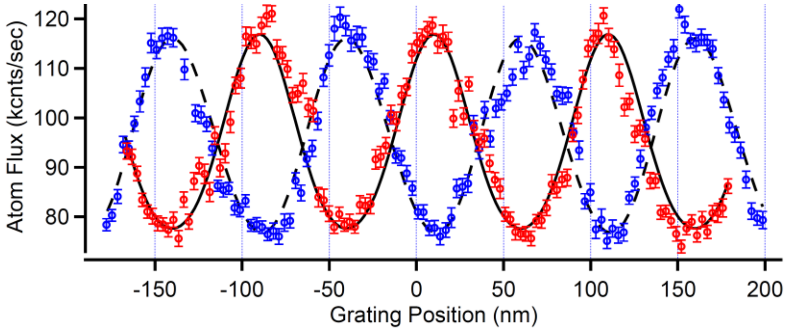




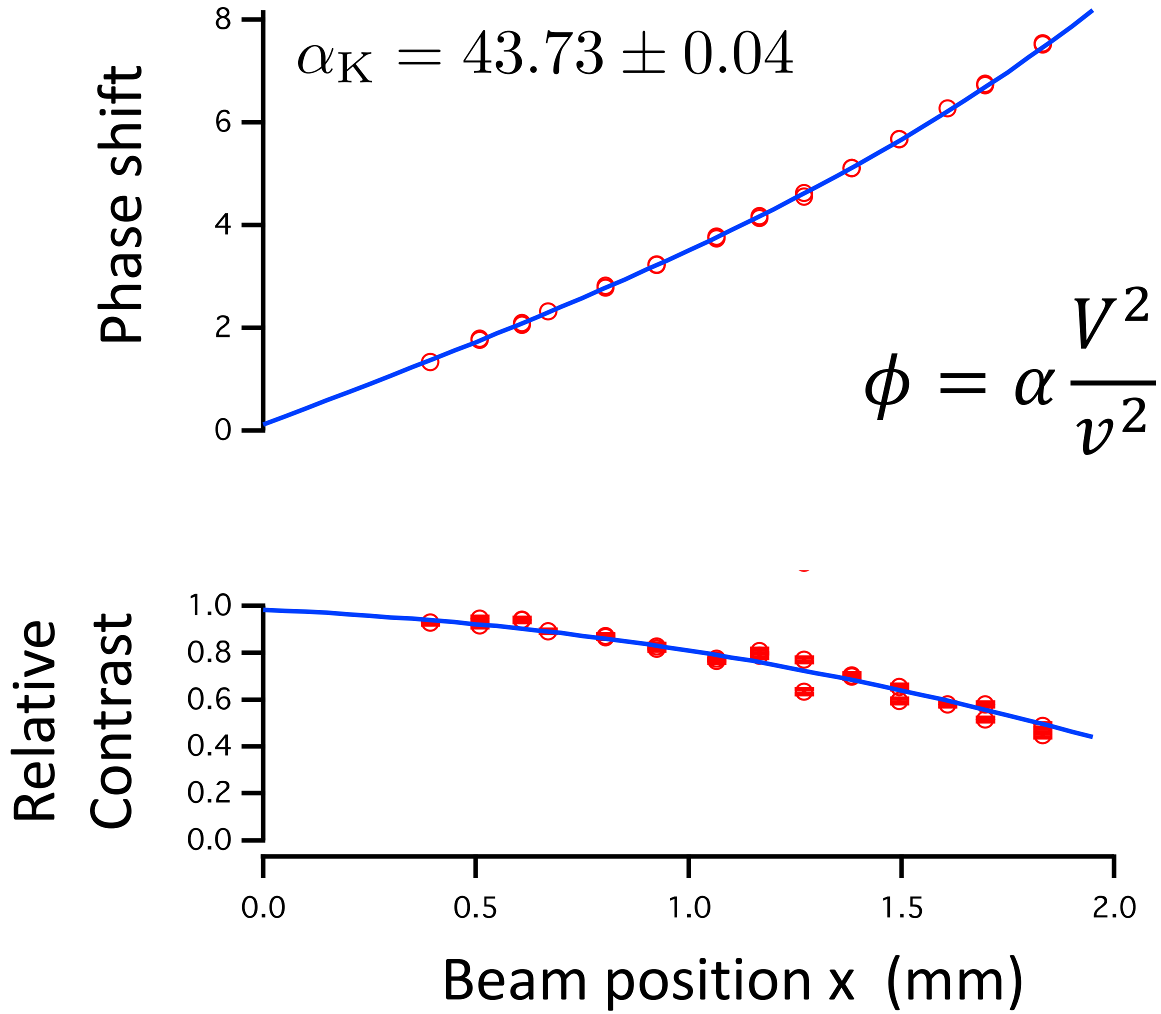
E-fields cause a phase ϕ for atom waves that depends on atomic polarizability α

$$\phi_\Gamma = \frac{\alpha}{2\hbar v} \int_\Gamma E^2 d\ell$$

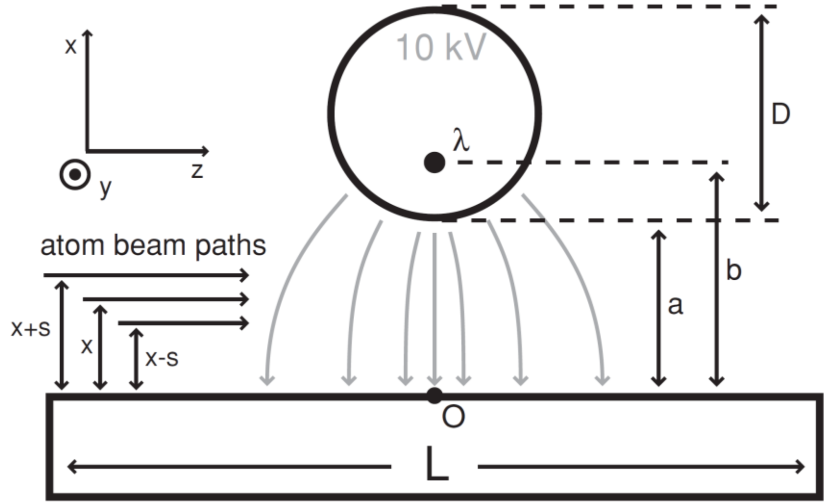
Differential phase shift $\phi_{\Gamma 2} - \phi_{\Gamma 1}$ *depends on* α *and* v^{-2}.



Phase and contrast measurements with cylinder-plane electrodes



$$\phi = \alpha \frac{V^2}{v^2} f(x)$$

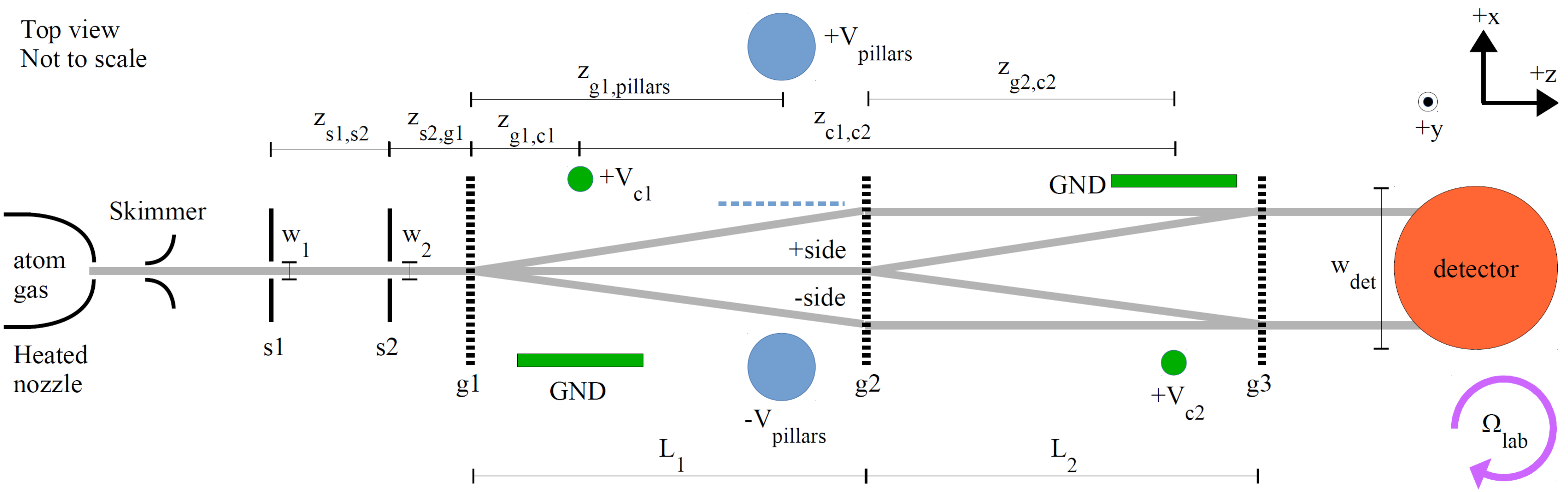


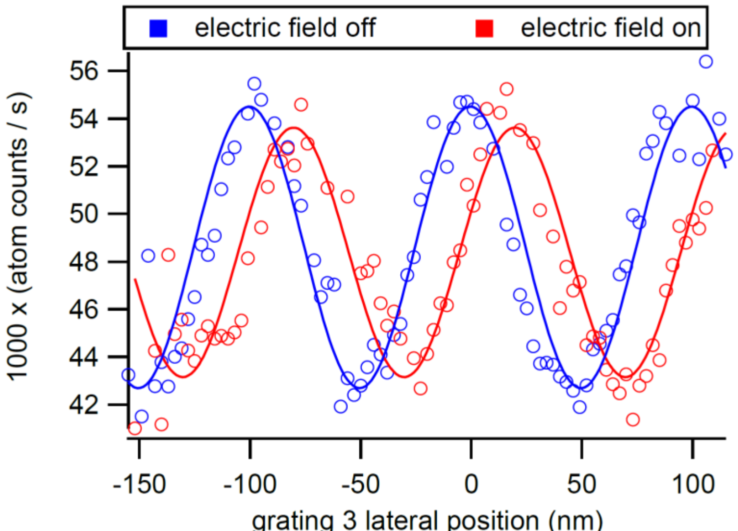
To report polarizability α

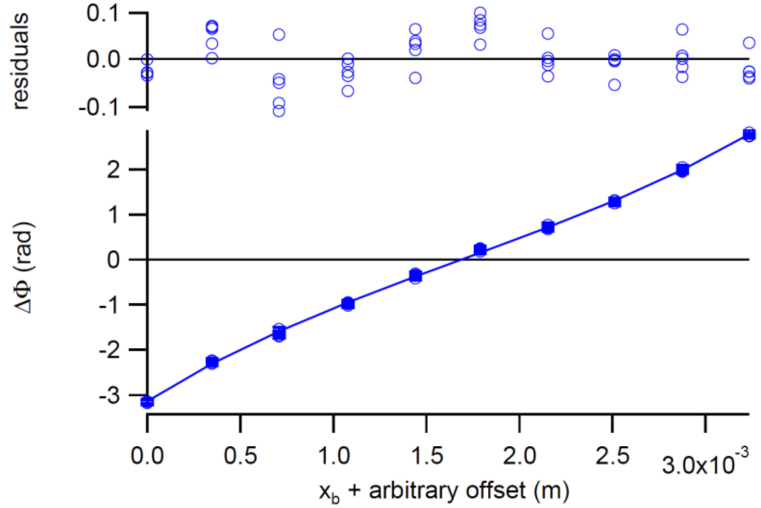
Get $f(x)$ from apparatus geometry.

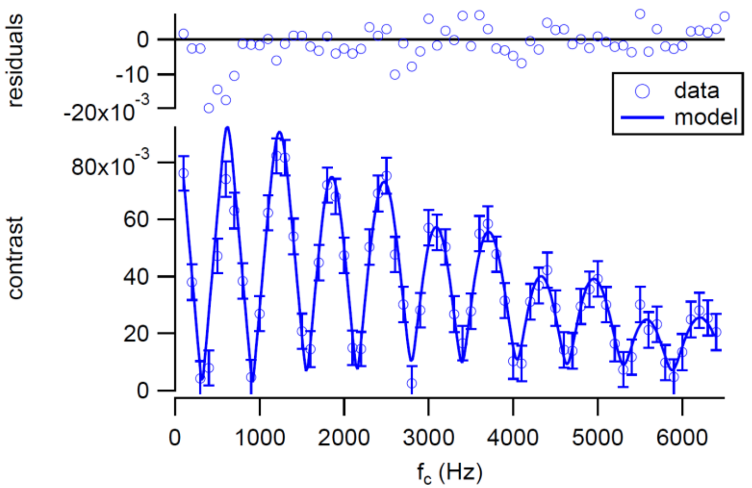
Measure ϕ and velocity distribution $P(v)$

Our 2015 α(0) measurement apparatus: 2-cylinders & 2 phase choppers









Contrast measurements with cylinder-cylinder electrodes

Contrast vs phase due to E-gradient enables measurement of Ω_e to 5%, or $\boldsymbol{g}\sin\theta$ to 2%.

BS Thesis 2014 by James Greenberg

- Broad P(v) sharpens C peak
- Can measure both Ω_e and ***g*** by using multiple v.
- Contrast loss can also affect Polarizability measurements
- E-gradient can improve dynamic range of aIFM gyroscopes (Dispersion Compensation)

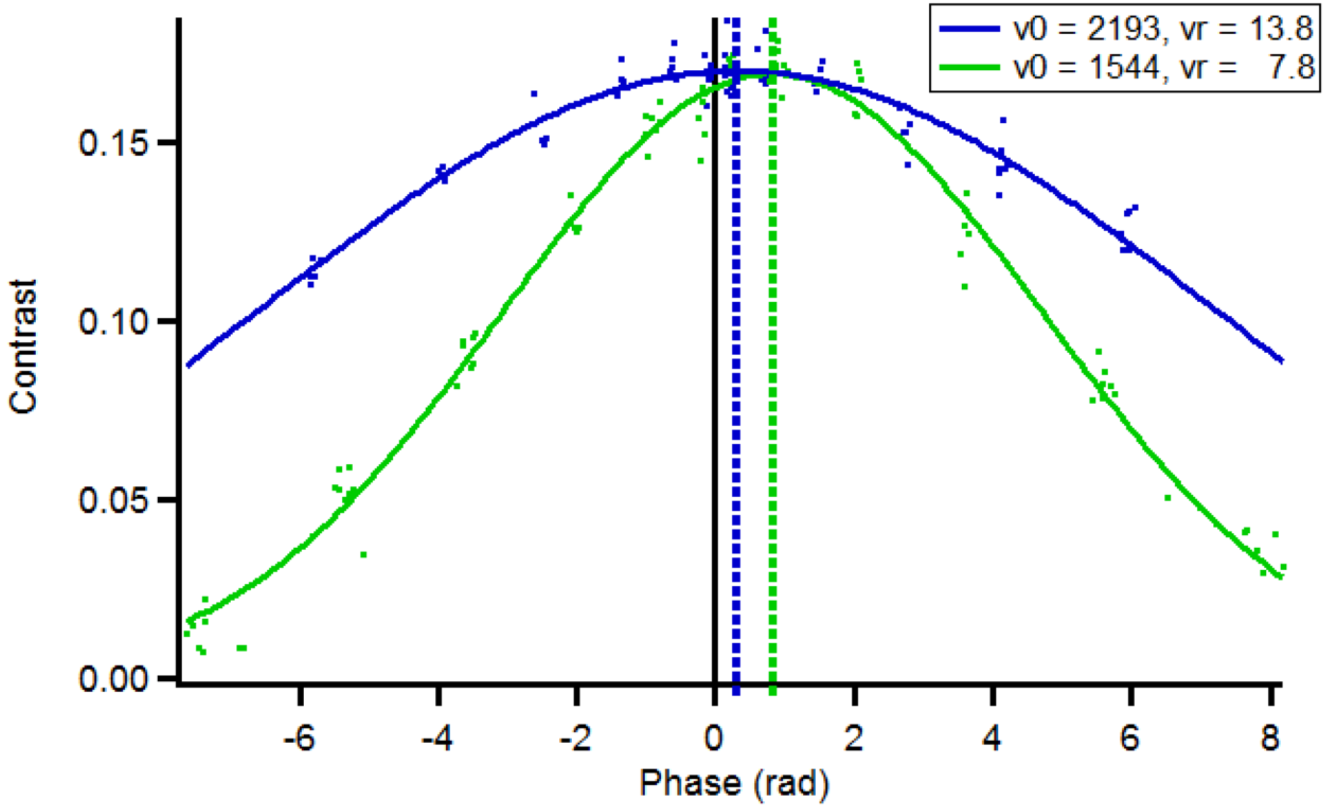


Figure 3.1: Two sets of raw contrast vs. phase data with different beam conditions and Gaussian fits. Φ_{Cmax} is denoted by the dotted vertical lines. The larger v_0 leads to a smaller Φ_{Cmax}. Larger v_r leads to slower loss of contrast.

20 hours of velocity and α_K measurements

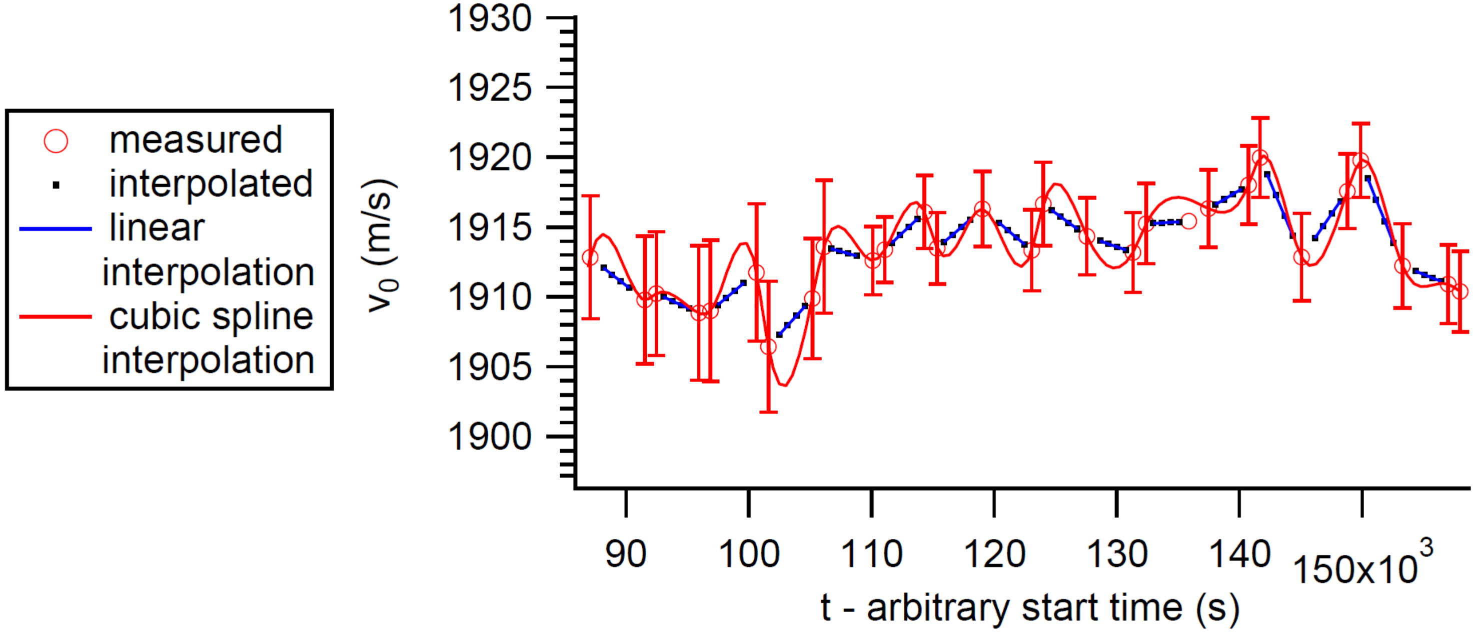


TABLE III. Absolute measurements of Cs, Rb, and K static, ground-state polarizabilities.

Atom	avg v_0 (m/s)	avg v_r	α(stat.)(sys.) (Å^3)
Cs	1585	19.8	59.45(3)(11)
Rb	1890	22.9	47.44(3)(9)
K	2113	13.2	42.97(2)(8)

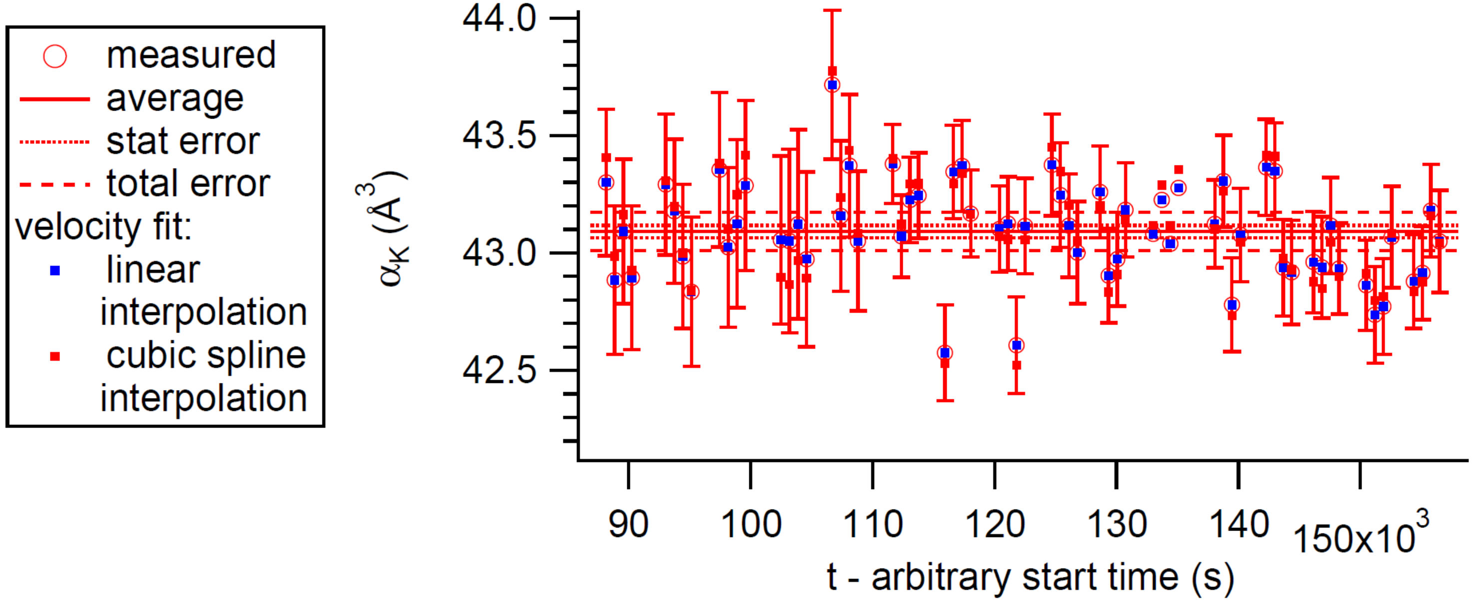


TABLE IV. Ratio measurements of Cs, Rb, and K static, ground-state polarizabilities. The systematic errors in each ratio, which arise from the fact that the systematic errors in different measurements are not perfectly correlated, are negligible compared to the statistical errors.

Ratio	Value(stat.)	Sys. Err.
α_{Cs}/α_K	1.3835(9)	$4 \cdot 10^{-5}$
α_{Cs}/α_{Rb}	1.2532(10)	$5 \cdot 10^{-6}$
α_{Rb}/α_K	1.1040(9)	$3 \cdot 10^{-5}$

3 methods to measure atom beam velocity

- Atom diffraction
- Phase Choppers
- Pulsed beam TOF

Pulsed atom beam velocity measurement with TOF

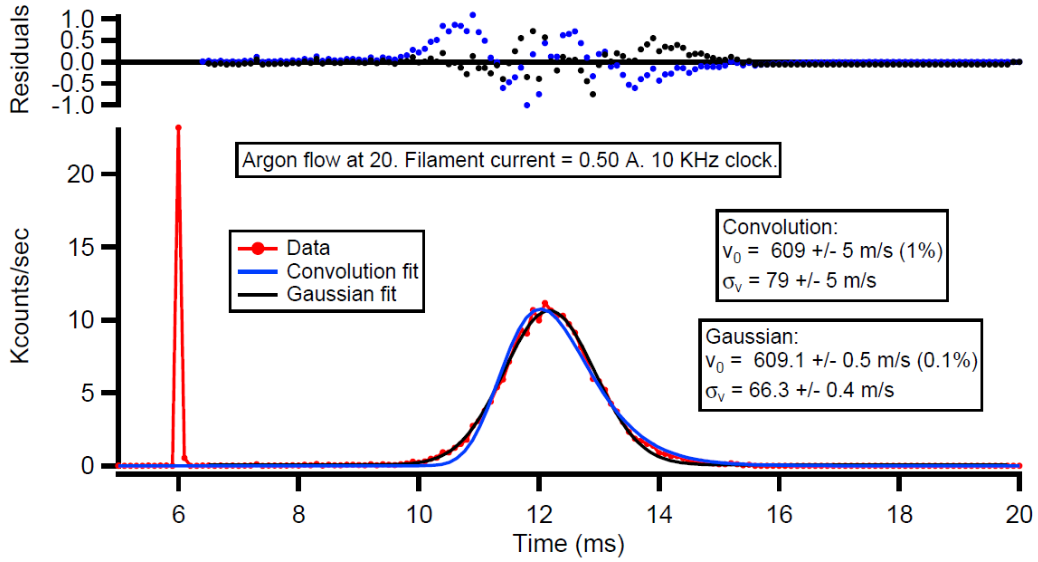


Figure 2.8: TOF measurement for a metastable argon beam. Two fits are made to the data: A Gaussian fit in black and a convolution of Equation 2.25 with a 0.35 ms impulse and metastable lifetime decay function in blue. The corresponding velocity distribution results are shown in the boxes.

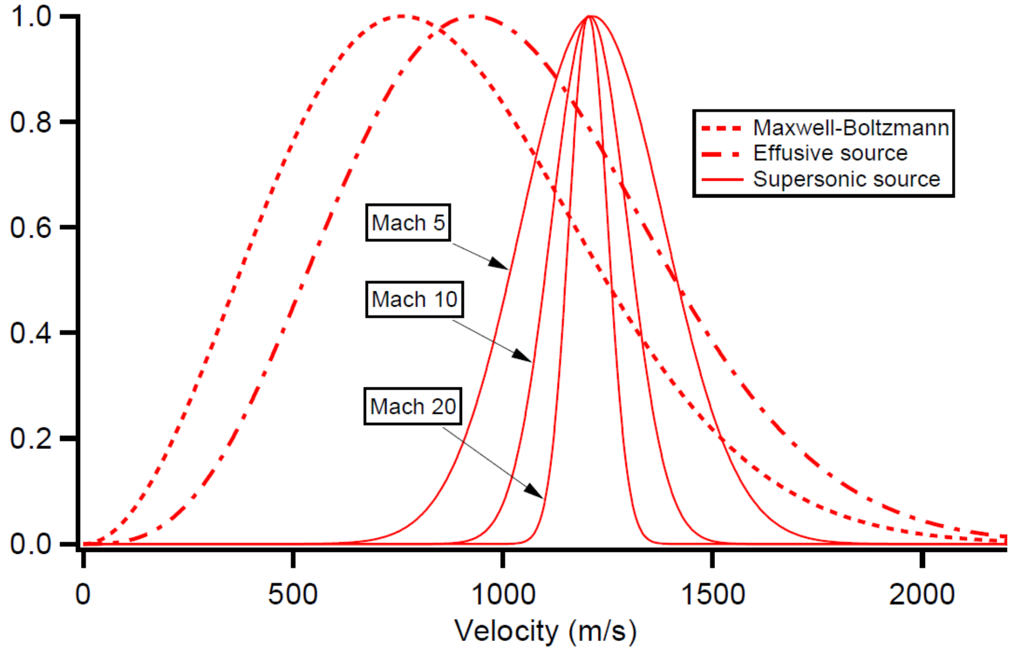
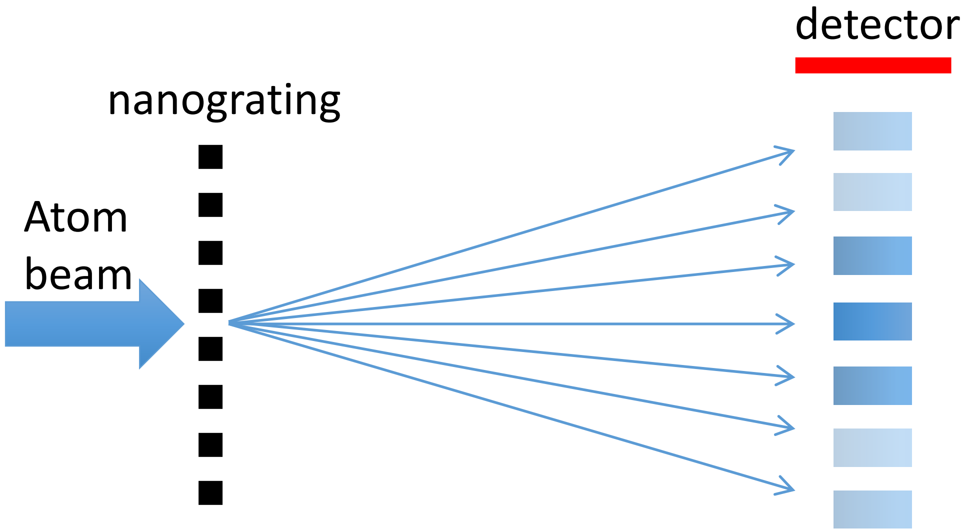


Figure 2.1: A comparison of the Maxwell-Boltzmann, effusive, and supersonic distribution functions for a sodium source with reservoir temperature of 800 K. Mach numbers of 5, 10, and 20 are used for the supersonic distributions.

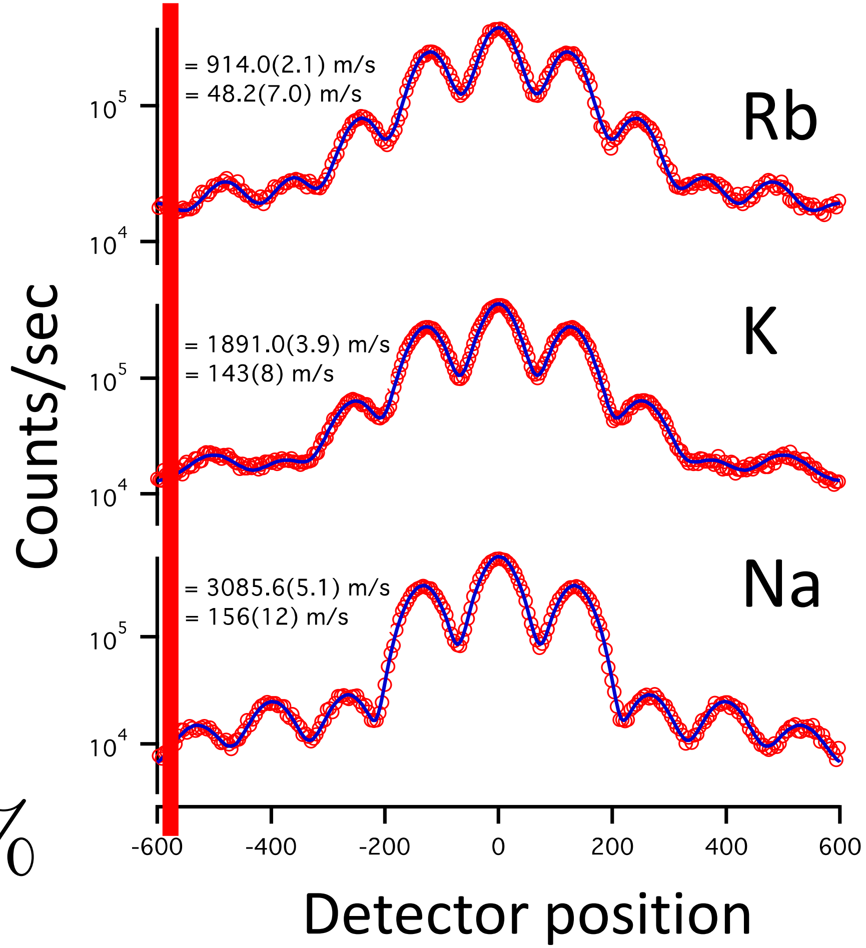
TOF data → Velocity distributions P(v) $\frac{\delta v}{v} \leq 0.8\%$

Atom beam velocity measurement with diffraction

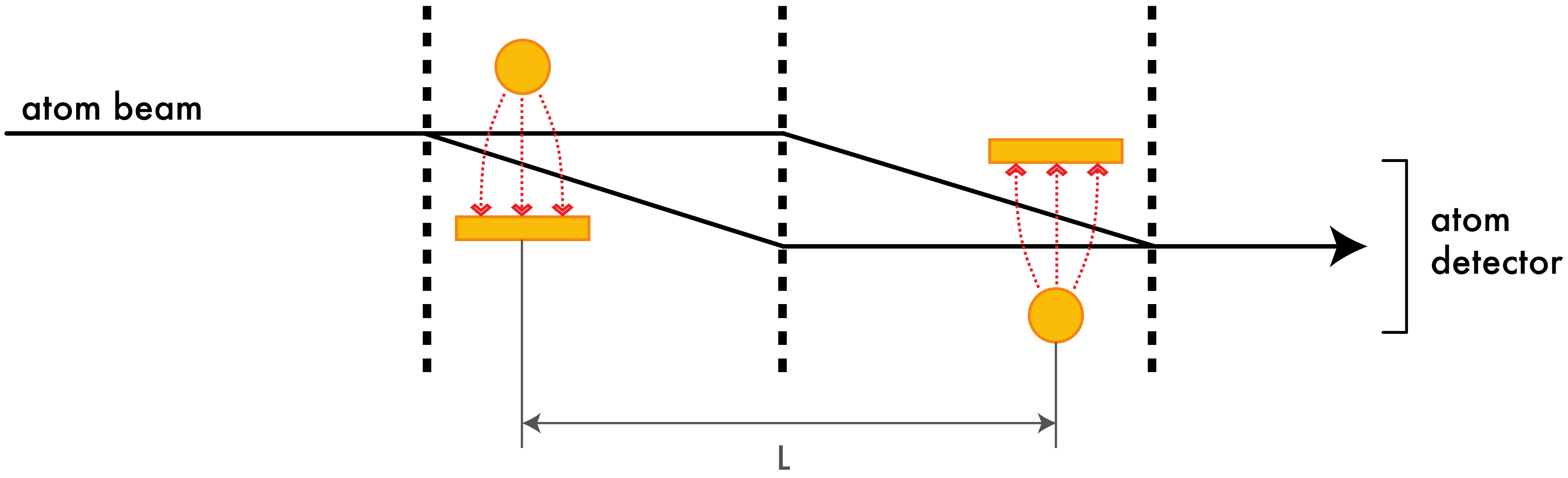
Measure de Broglie wavelength
using atom beam diffraction



$$\lambda_{\mathrm{dB}} = \frac{\hbar}{mv} \qquad \frac{\delta v}{v} \leq 0.25\%$$



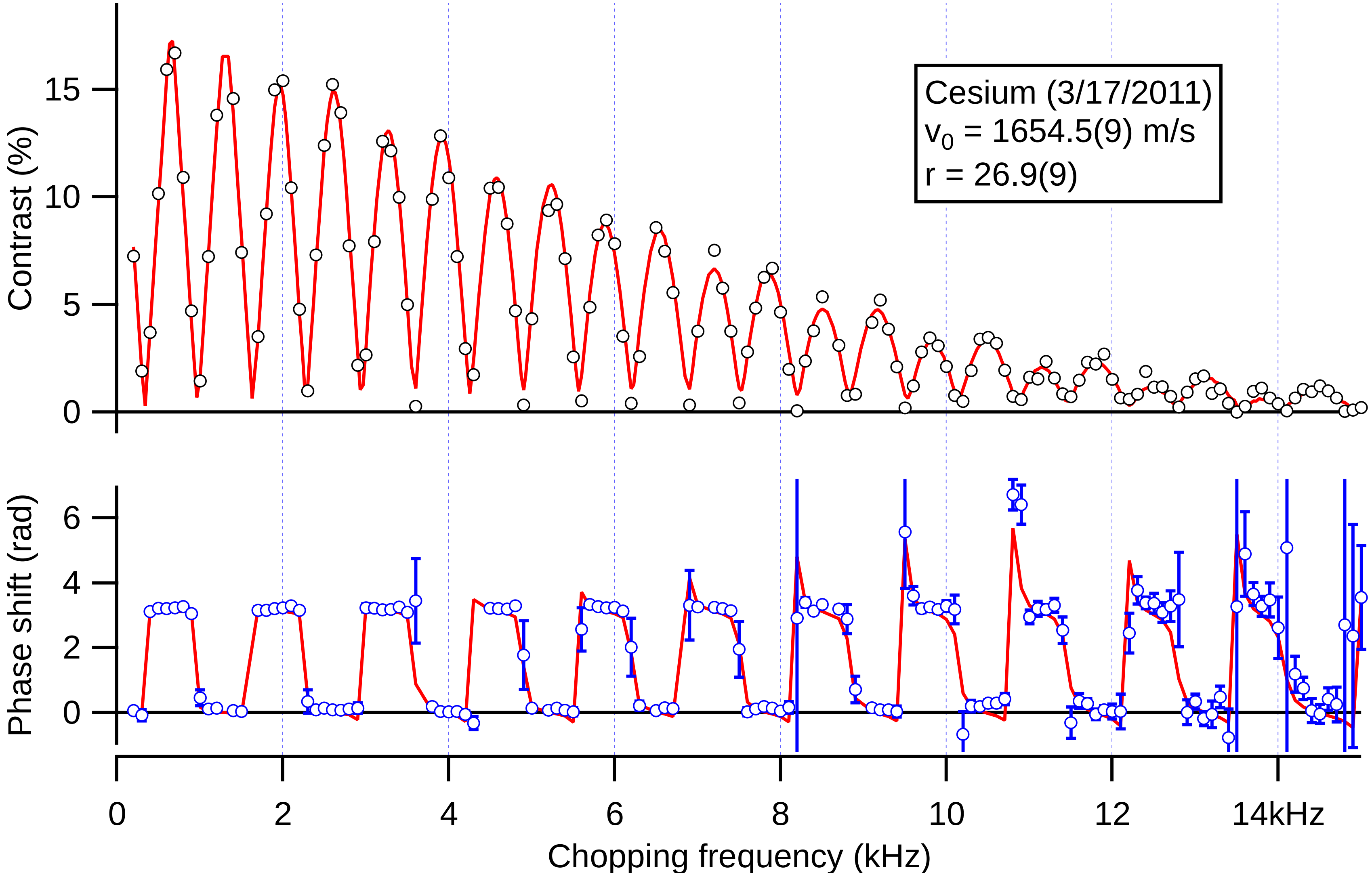
Phase choppers for velocity measurement



- Pulsed electric fields periodically apply π phase shifts
- Interferometer contrast oscillates as we change the chopping frequency f
- Max contrast when $f = n\ v/L = n\ f_0$

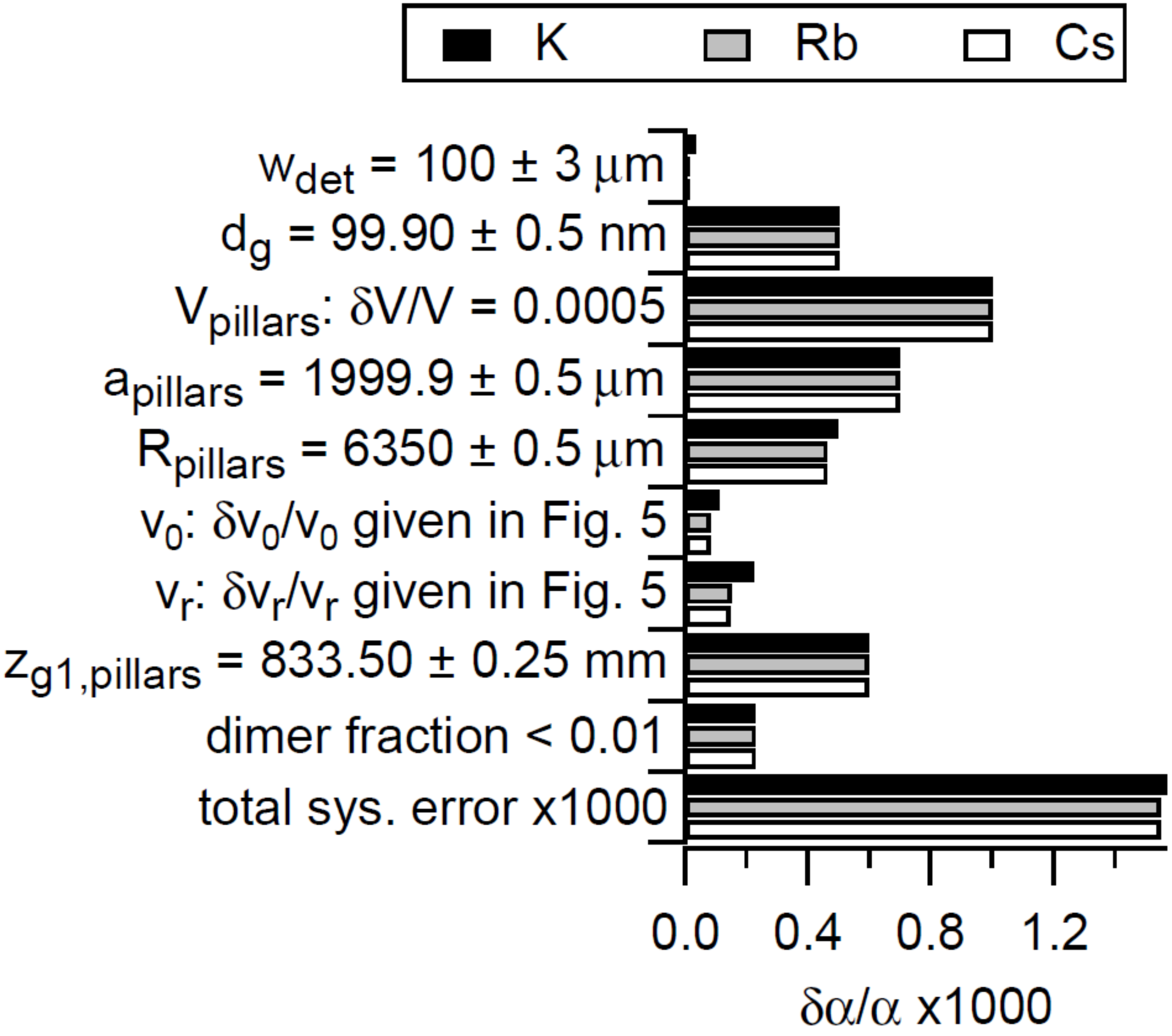
Published in: Holmgren et al. NJP 2011

Velocity measurement with phase choppers

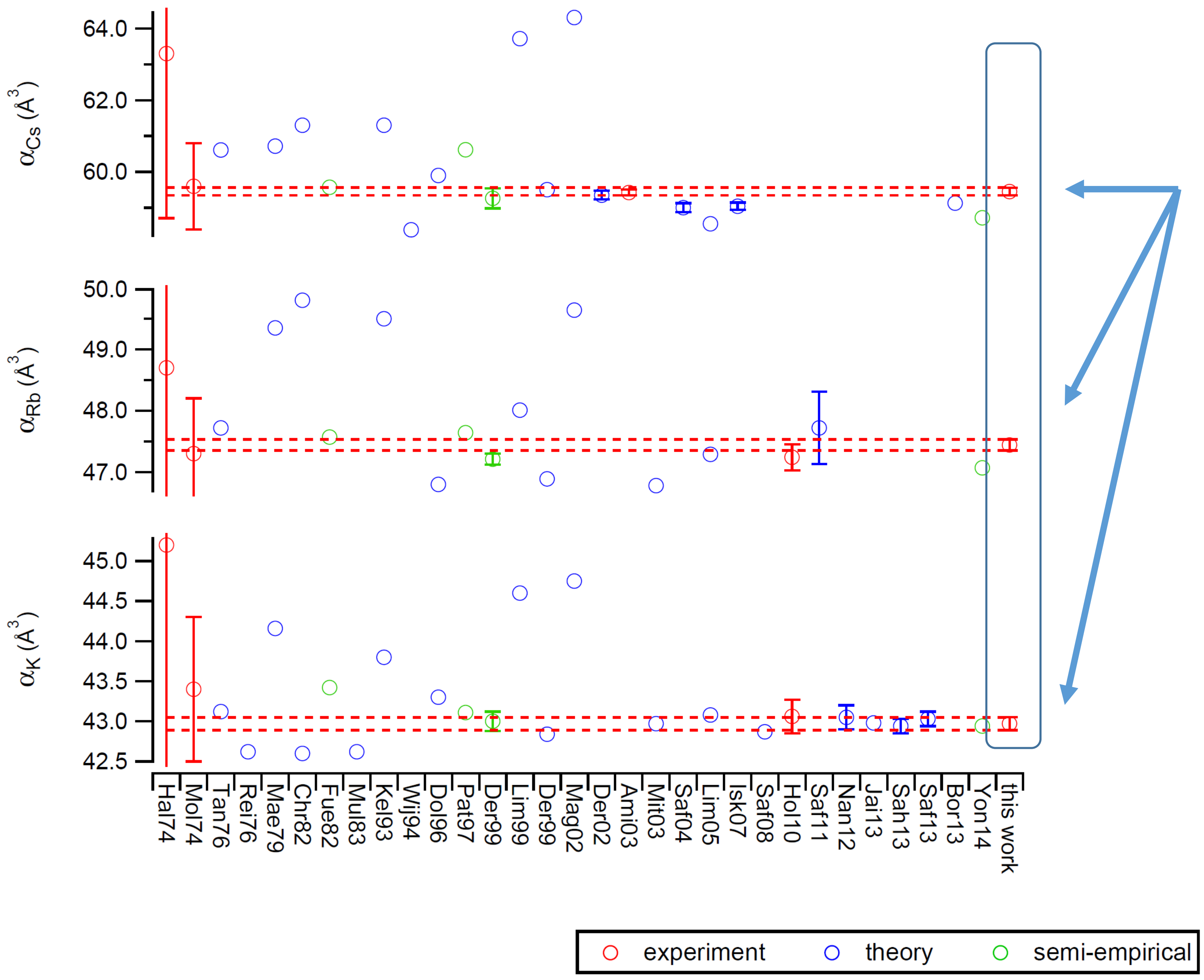


$$\frac{\delta v}{v} \leq 0.06\%$$

Error budget for
Our 2015 polarizability
Measurements.

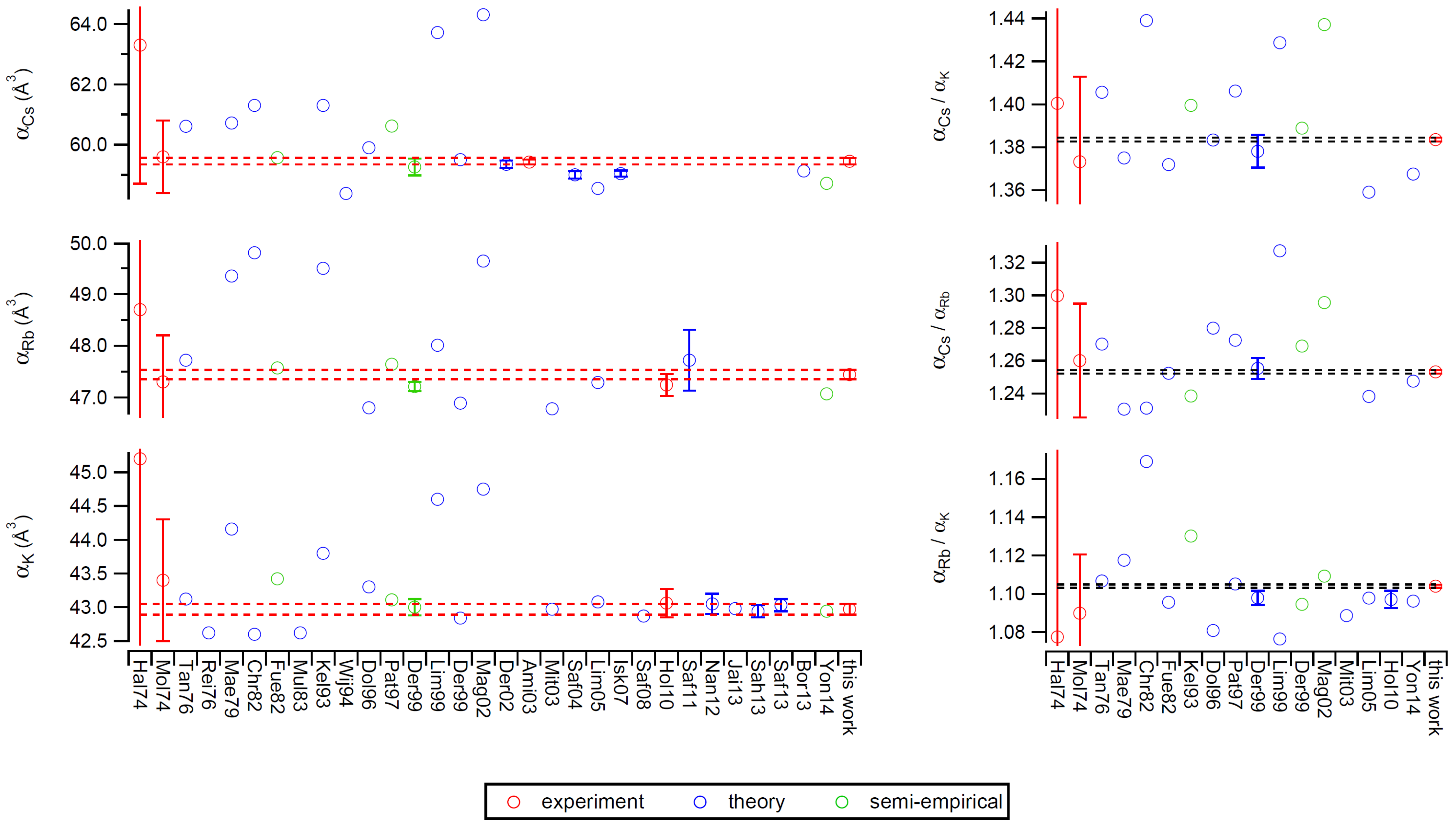


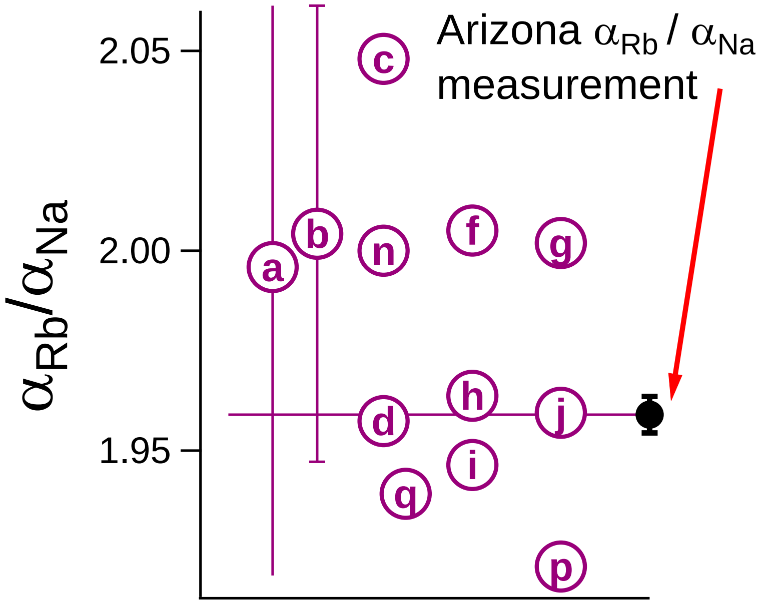
2015 Results: α measurements for Cs, Rb, and K with 0.2% unc.

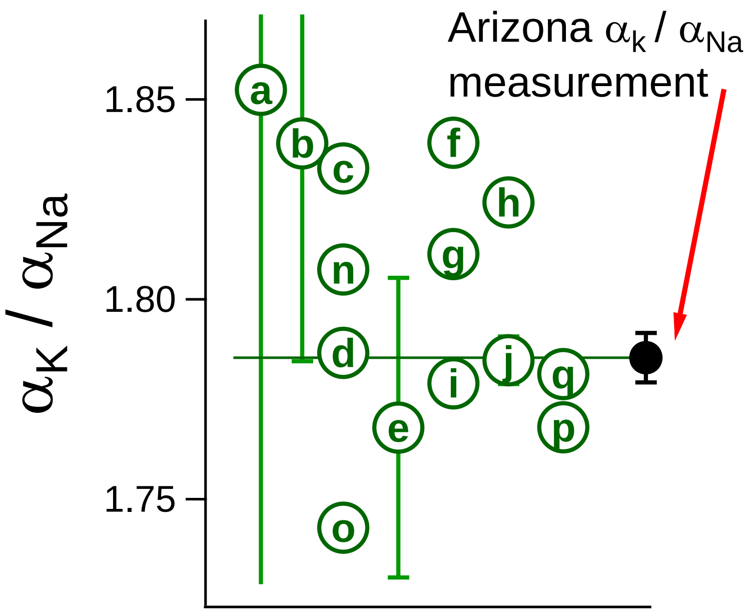


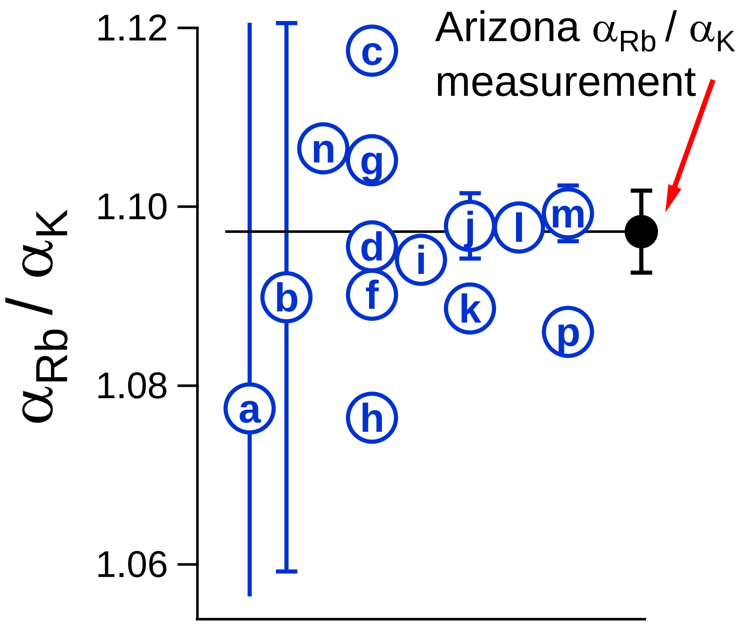
Our measurements PRA 2015

2015 Results: α measurements for Cs, Rb, and K with 0.2% unc.









● = Holmgren et al. PRA **81**, 053607 (2010)

Our measured ratios of polarizabilities serve as a benchmark test for theoretical calculations [c]-[o]:

[a] W.D. Hall and J.C. Zorn, PRA **10**, 1141 (1974)
[b] R.W. Molof, H.L. Schwartz, T.M. Miller, and B. Bederson, PRA**10**, 1131 (1974)
[c] F. Maeder and W. Kutzelnigg, Chem. Phys. **42**, 95 (1979).
* [d] P. Fuentealba, J. Phys. B **15**, L555 (1982).
[e] W. Muller, J. Flesch, and W. Meyer, J. Chem. Phys. **80**, 3297 (1984).
[f] M. Marinescu, H.R. Sadeghpour, and A. Dalgarno, Phys. Rev. A **49**, 5103 (1994).
[g] S.H. Patil and K.T. Tang, J. Chem. Phys. **106**, 2298 (1997).
[h] I.S. Lim, et al., Phys. Rev. A **60**, 2822 (1999).
[i] M.S. Safronova, W.R. Johnson, and A. Derevianko, Phys. Rev. A **60**, 4476 (1999).
* [j] A. Derevianko, W.R. Johnson, M.S. Safronova, and J.F. Babb, Phys. Rev. Lett. **82**, 3589 (1999).
[k] J. Mitroy and M.W.J. Bromley, Phys. Rev. A **68**, 052714 (2003).
* [l] I.S. Lim, P. Schwerdtfeger, B. Metz, and H. Stoll, J. Chem. Phys. **122**, 104103 (2005).
[m] B. Arora, M.S. Safronova, and C.W. Clark, Phys. Rev. A **76**, 052516 (2007).
[n] E.-A. Reinsch and W. Meyer, Phys. Rev. A **14**, 915 (1976).
[o] K.T. Tang, J.M. Norbeck, and P.R. Certain, J. Chem. Phys. **64**, 3063 (1976).
[p] theory from DJSB99 without core electrons

Polarizability α in terms of oscillator strengths (f_{ik}), lifetimes (τ), dipole matrix elements <k|r|i>, and line strengths S

$$\alpha_i(\omega) = \frac{e^2}{m}\sum_{k\neq i}\frac{f_{ik}}{\omega_{ik}^2-\omega^2} \longrightarrow \alpha(0) = \frac{e^2}{m}\left[\frac{f_{1/2}}{\omega_{D1}^2}+\frac{f_{3/2}}{\omega_{D2}^2}\right]+\alpha_r$$

$$\alpha_i(\omega) = 2\pi\epsilon_0 c^3\sum_{k\neq i}\frac{A_{ik}\omega_{ik}^{-2}}{\omega_{ik}^2-\omega^2}\frac{g_k}{g_i} \longrightarrow \alpha(0) = 2\pi\epsilon_0 c^3\left[\frac{\tau_{1/2}^{-1}}{\omega_{D1}^4}+2\frac{\tau_{3/2}^{-1}}{\omega_{D2}^4}\right]+\alpha_r$$

$$\alpha_i(\omega) = \frac{2}{3\hbar}\sum_{k\neq i}\frac{|\langle k|e\vec{r}|i\rangle|^2\omega_{ik}}{\omega_{ik}^2-\omega^2} \longrightarrow \alpha(0) = \frac{1}{3}\left(\frac{|D_{D1}|^2}{\hbar\omega_{D1}}+\frac{|D_{D2}|^2}{\hbar\omega_{D2}}\right)+\alpha_r$$

$$\alpha_i(\omega) = \frac{1}{3\hbar}\sum_{k\neq i}\frac{S_{ik}\omega_{ik}}{\omega_{ik}^2-\omega^2} \longrightarrow \alpha(0) = \frac{1}{3\hbar}\left[\frac{S_{D1}}{\omega_{D1}}+\frac{S_{D2}}{\omega_{D2}}\right]+\alpha_r$$

$$\alpha_r = \alpha_{v'} + \alpha_{core} + \alpha_{cv}$$

Results based on our 2015 Polarizability measurements

Quantity	Cs	Rb	K
$\lvert D_{1/2} \rvert$	4.510(4)	4.255(4)	4.116(4)
$\lvert D_{3/2} \rvert$	6.347(6)	5.989(6)	5.793(6)
$\tau_{1/2}$ (ns)	34.75(6)	27.39(5)	26.61(5)
$\tau_{3/2}$ (ns)	30.34(6)	26.15(5)	26.51(5)
$f_{1/2}$	0.3453(6)	0.3459(7)	0.3342(6)
$f_{3/2}$	0.7179(14)	0.6981(14)	0.6649(13)
$S_{1/2}$	20.34(4)	18.11(5)	16.94(3)
$S_{3/2}$	40.29(8)	35.87(7)	33.56(6)
C_6	6877(23)	4734(31)	3891(21)
$\alpha_{Np_{1/2}}$ ($\mathrm{\AA}^3$)	196.87(11)	120.38(9)	89.96(8)

$$f_{1/2} = \frac{(\alpha - \alpha_r)}{\left(\frac{e^2}{m\omega_{D1}^2}\right)} \left(\frac{1}{1 + R\frac{\omega_{D1}}{\omega_{D2}}} \right)$$

$$f_{3/2} = \frac{(\alpha - \alpha_r)}{\left(\frac{e^2}{m\omega_{D2}^2}\right)} \left(\frac{1}{R^{-1}\frac{\omega_{D2}}{\omega_{D1}} + 1} \right)$$

$$\tau_{1/2} = \frac{2\pi\epsilon_0 c^3}{[\alpha(0) - \alpha_r]} \left[\frac{1}{\omega_{D1}^4} + \frac{R}{\omega_{D2}\omega_{D1}^3} \right]$$

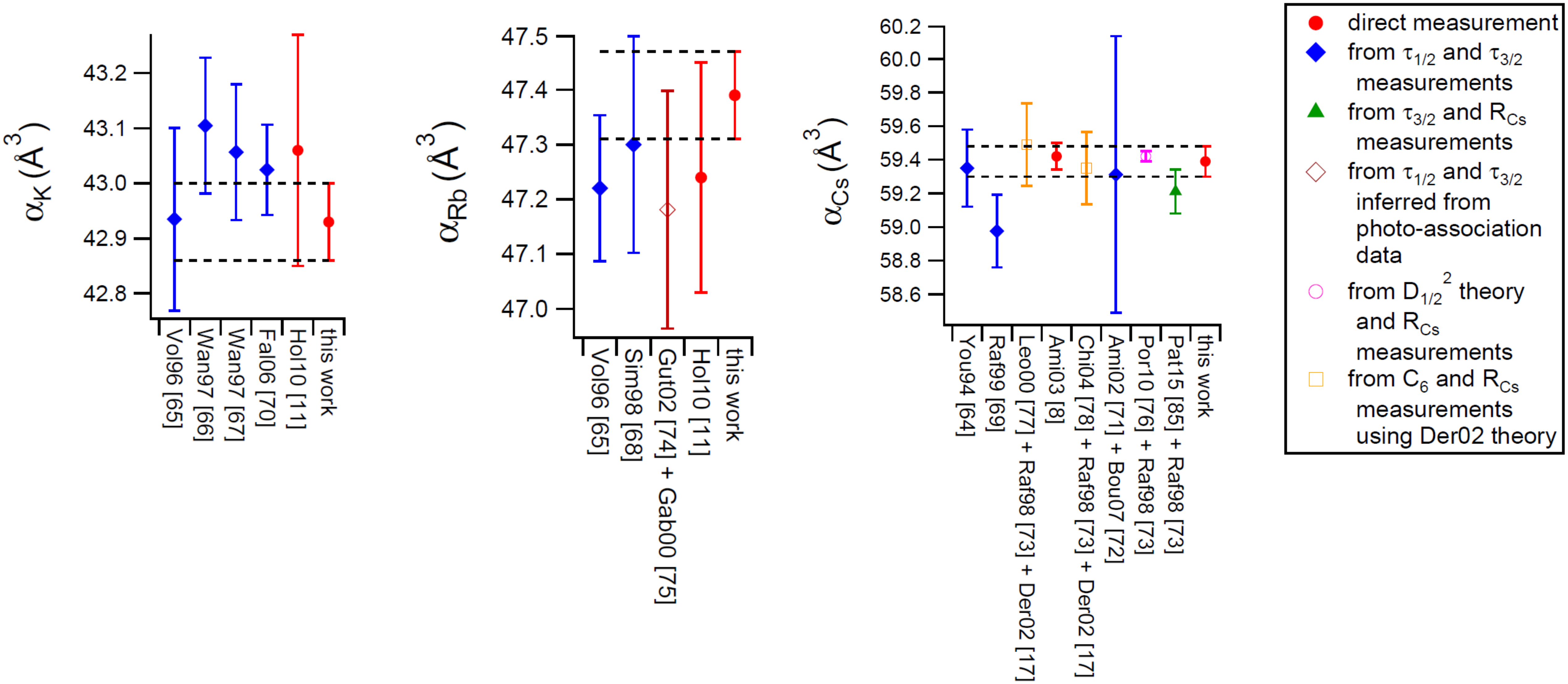
$$\tau_{3/2} = \frac{2\pi\epsilon_0 c^3}{[\alpha(0) - \alpha_r]} \left[\frac{2}{R\omega_{D1}\omega_{D2}^3} + \frac{2}{\omega_{D2}^4} \right]$$

$$|D_{D1}|^2 = \frac{3\,[\alpha - \alpha_r]}{\frac{1}{\hbar\omega_{D1}} + \frac{R}{\hbar\omega_{D2}}}$$

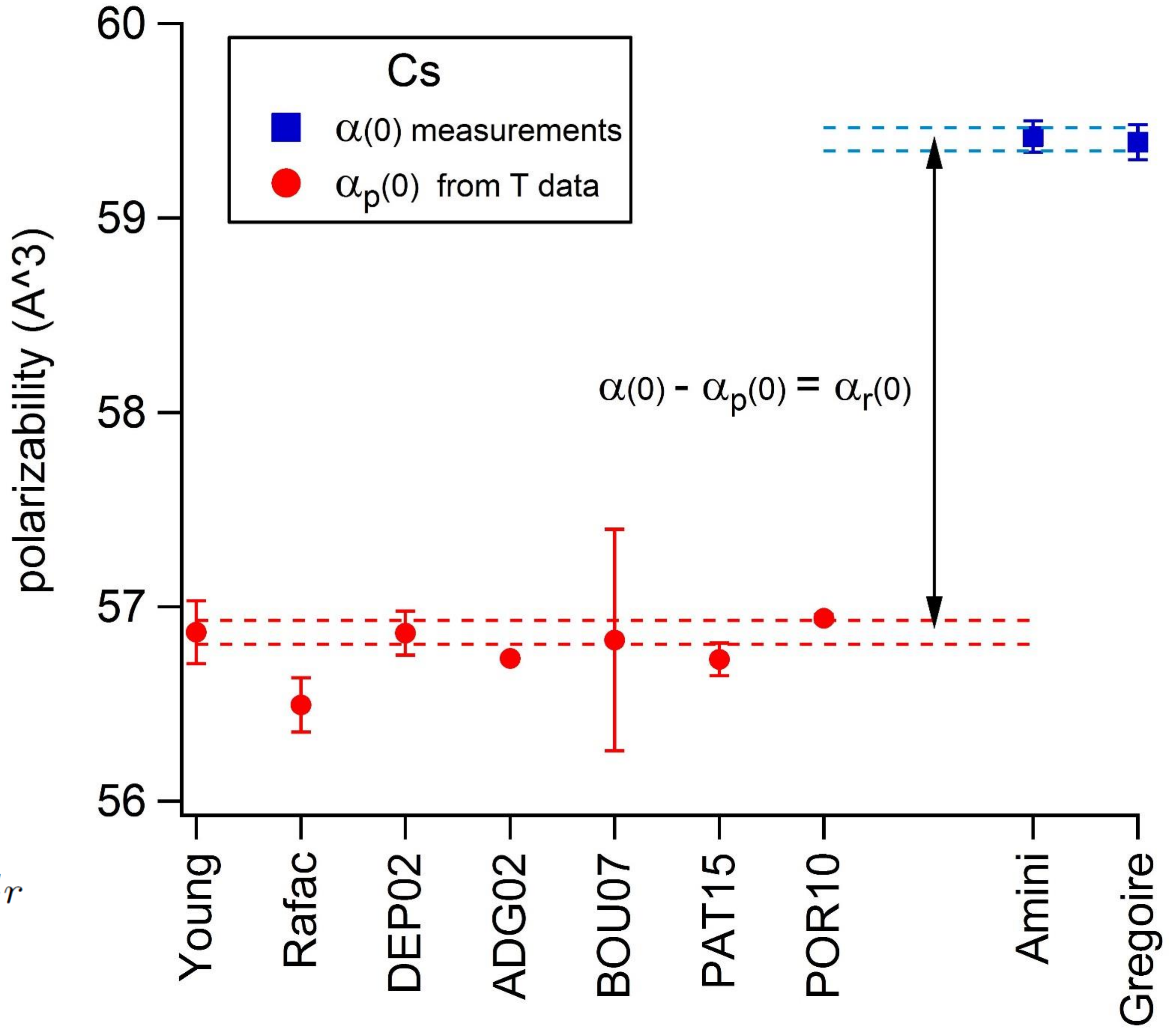
$$|D_{D2}|^2 = \frac{3\,[\alpha - \alpha_r]}{\frac{1}{R\hbar\omega_{D1}} + \frac{1}{\hbar\omega_{D2}}}$$

$$R \equiv \frac{S_{D2}}{S_{D1}} = \frac{|D_{D2}|^2}{|D_{D1}|^2} = \frac{f_{D2}}{f_{D1}}\frac{\omega_{D1}}{\omega_{D2}} = 2\frac{\tau_{1/2}}{\tau_{3/2}}\left(\frac{\omega_{D1}}{\omega_{D2}}\right)^3$$

Comparison to α(0) values inferred from other measurements

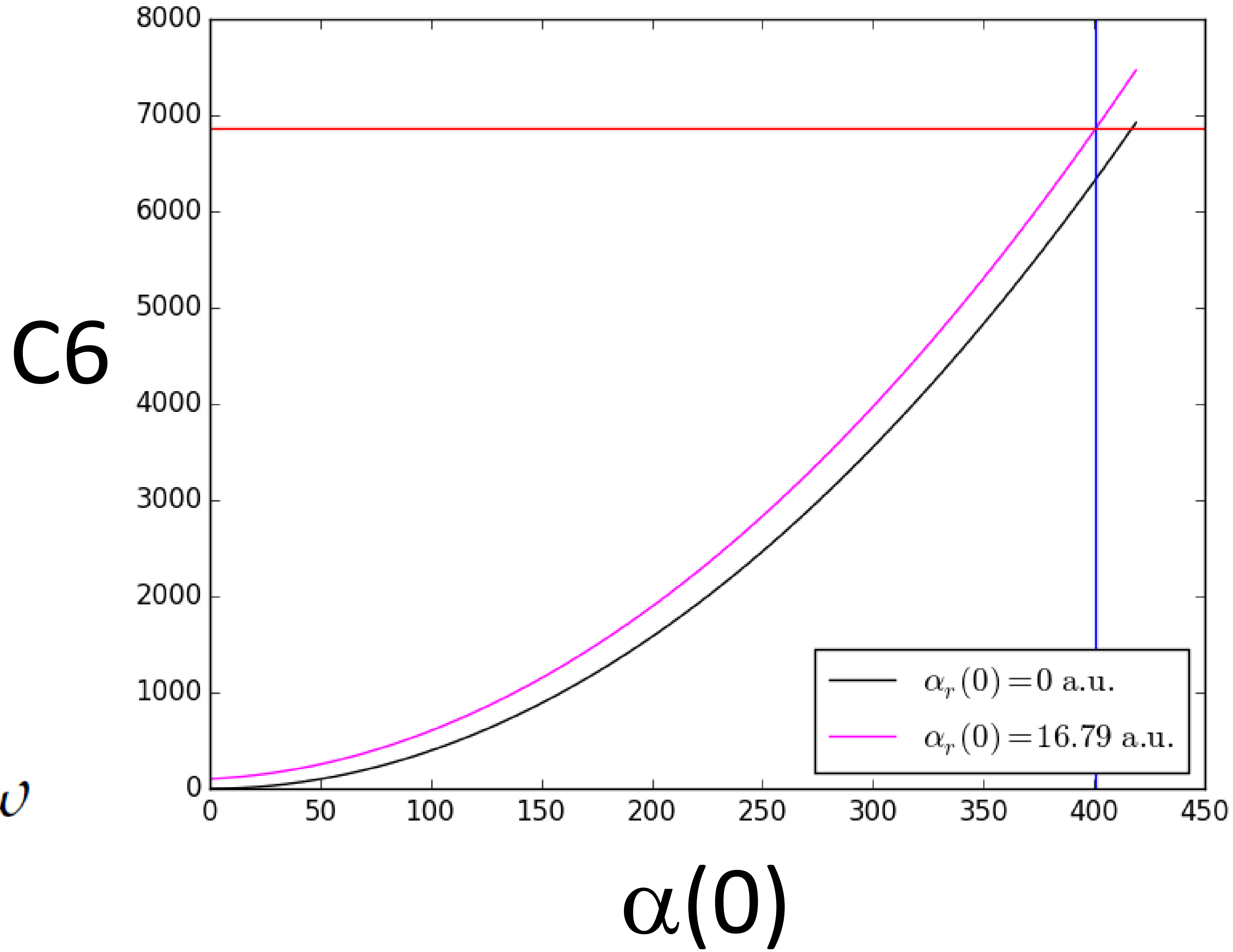


Combine our $\alpha(0)$ meas.
w/ other lifetime meas.
to report $\alpha_r(0)$.



$$\alpha(0) = 2\pi\epsilon_0 c^3 \left[\frac{\tau_{1/2}^{-1}}{\omega_{D1}^4} + 2\frac{\tau_{3/2}^{-1}}{\omega_{D2}^4}\right] + \alpha_r$$

Combine C6 meas.
w/ our α(0) meas.
to report $\alpha_r(0)$.

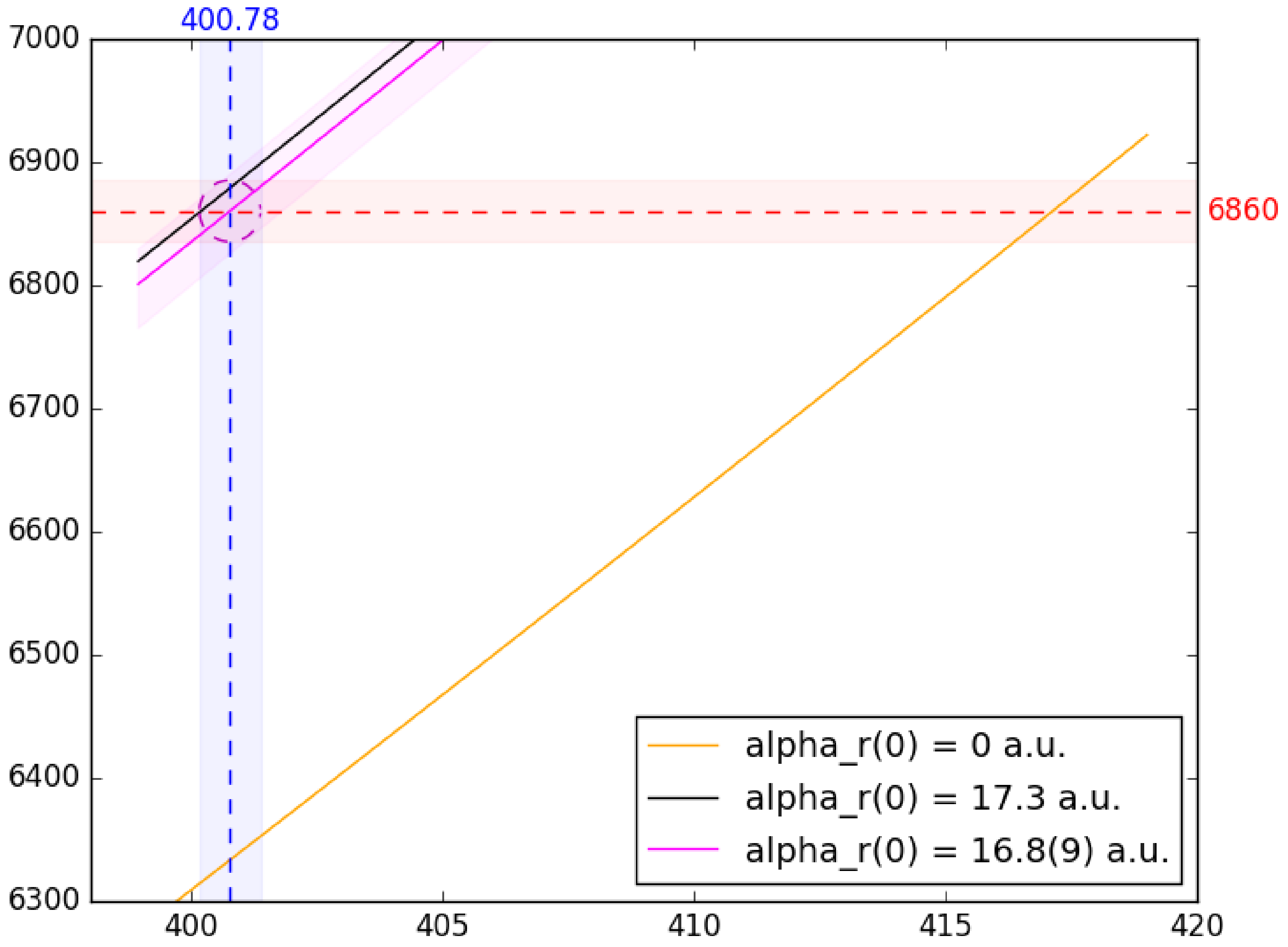


$$C_6 = \frac{3\hbar}{\pi}\int_0^\infty [\alpha(i\omega)]^2\, d\omega$$

$$C_6 = \frac{3\hbar}{\pi}\int_0^\infty [\alpha_p(i\omega) + \alpha_r(i\omega)]^2\, d\omega$$

Combine C6 meas.
w/ our $\alpha(0)$ meas.
to report $\alpha_r(0)$.

C6

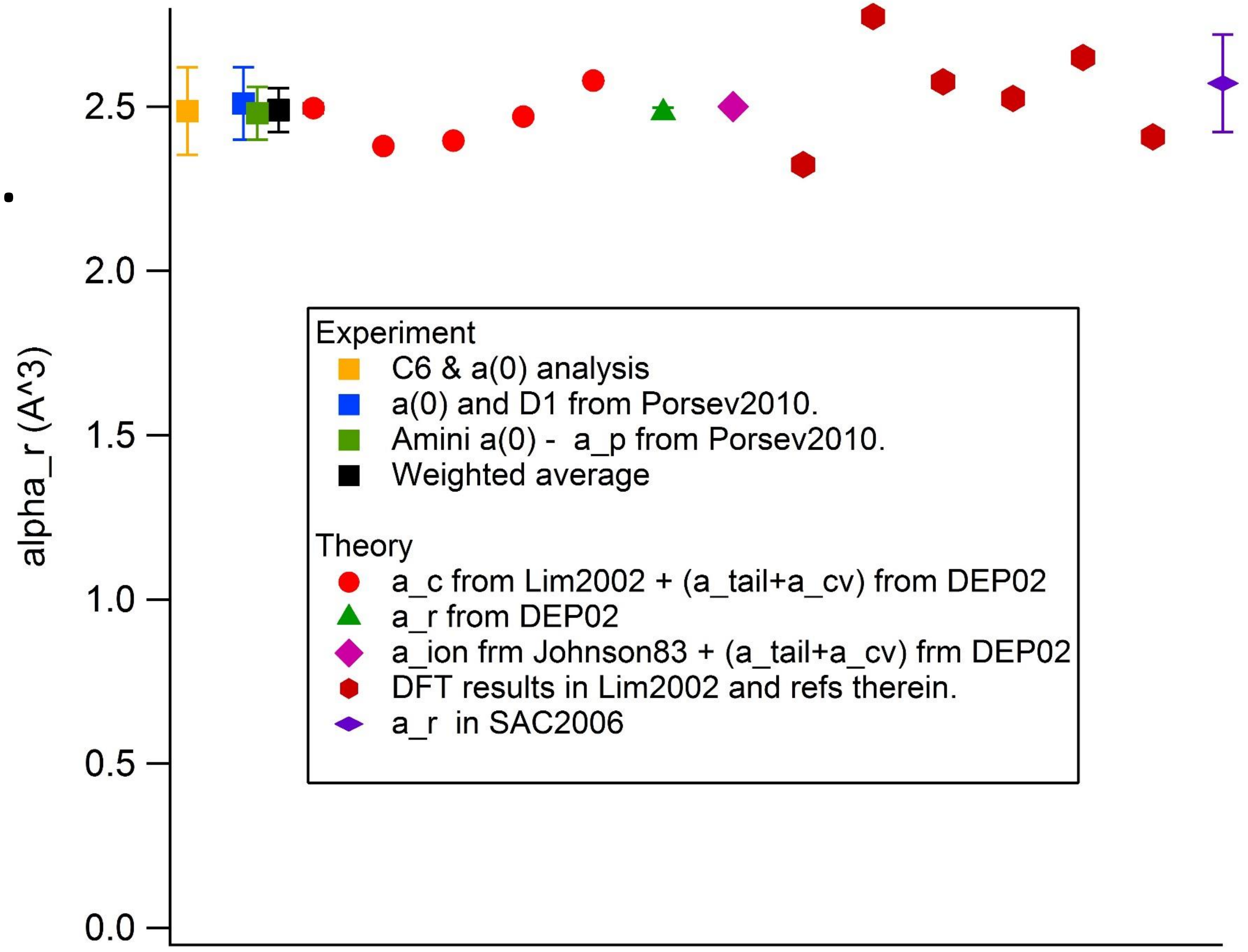


$\alpha(0)$

$$C_6 = \frac{3\hbar}{\pi}\int_0^\infty [\alpha(i\omega)]^2 \, d\omega$$

$$C_6 = \frac{3\hbar}{\pi}\int_0^\infty [\alpha_p(i\omega) + \alpha_r(i\omega)]^2 \, d\omega$$

We thus meas.
α_r with <10% unc.



Static Dipole Polarizability

SUMMARY:

- Measured $\alpha(0)$ for Na, K, Rb, Cs with 0.2% unc. Ratios with 0.1%.
- Listed in CRC handbook, sum-check MBPT calculations of <k|r|i>

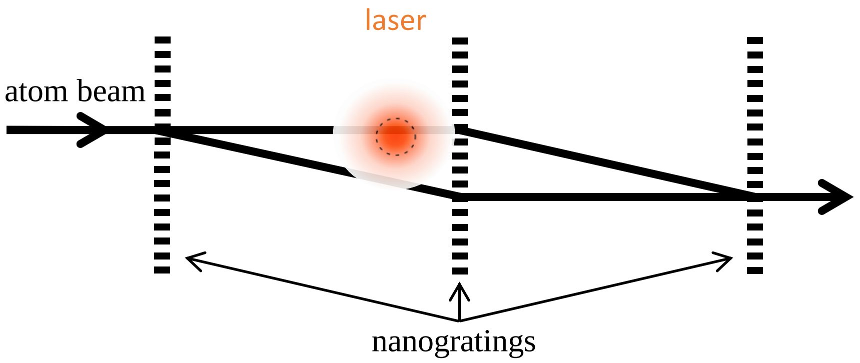
NEXT STEPS:

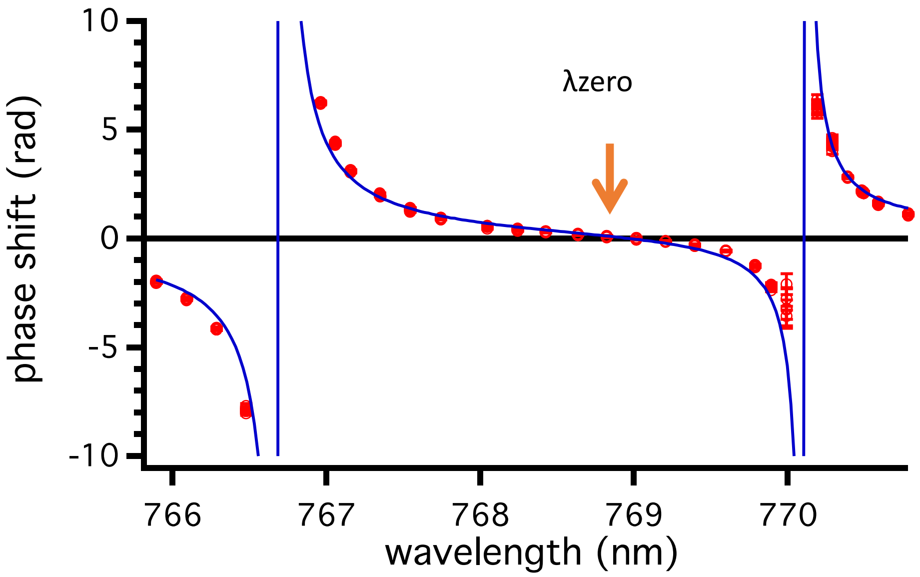
- Use this method for Sr and Yb to improve atomic clocks
- Use Li and He* to anchor ratios
- Measure $\alpha(0)$ for molecules to test DFT
- Use ∇E for dispersion compensation in gyroscopes / accelerometers

SURPRISES:

- Few ab initio theories are this accurate
- Several other experiments can be used to deduce $\alpha(0)$
- Velocity measurements were challenging because ∇E is a λ_{dB} Lens
- We can report α_{core} by combining measurements.

Precision Measurements of Tune-Out Wavelengths with an Atom Interferometer

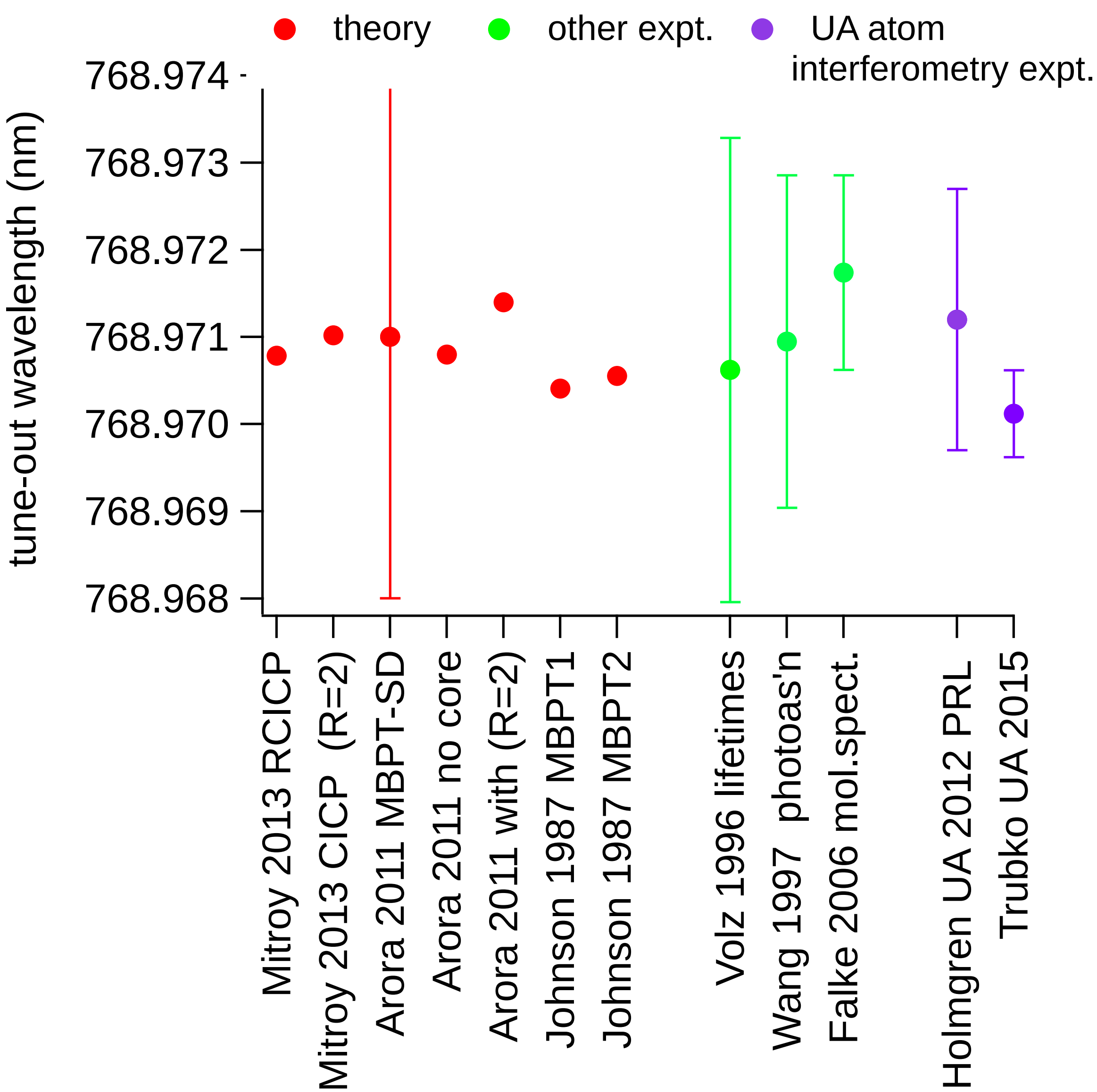




Raisa Trubko, Maxwell D. Gregoire, and Alexander D. Cronin

College of Optical Sciences and Department of Physics
University of Arizona
DAMOP 2015

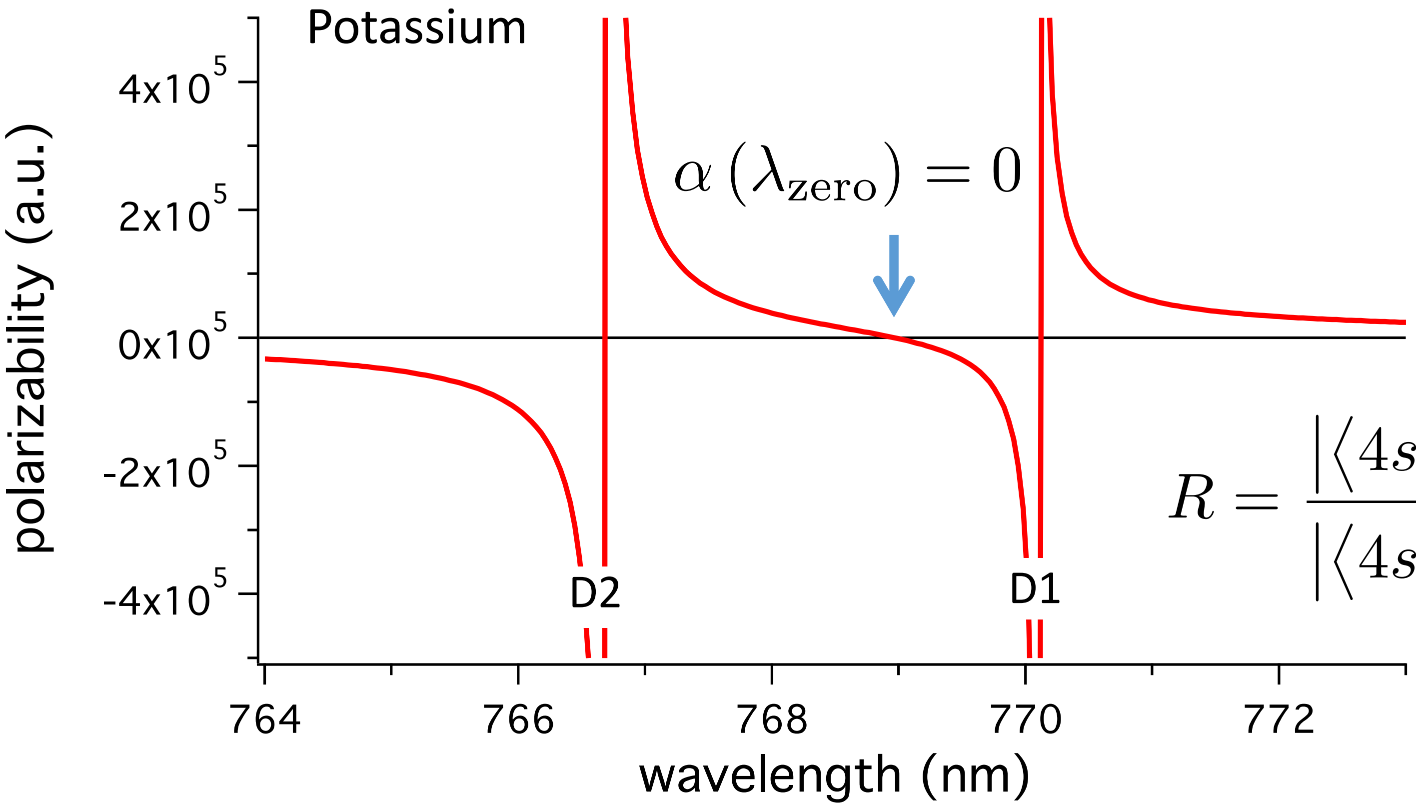
2015 Tune-Out Wavelength Measurement for K atoms



λ_{zero} = 768.9701(5) nm

Source of error	λ_{zero} error (pm)
laser wavelength	0.1
broadband light	0.3
laser polarization & lab rotation rate	0.2
Doppler shift	0.1
Total systematic error	0.4
Total statistical error	0.3
Total error	0.5

Origin of tune-out wavelengths and motivation for measurements



$$R = \frac{\left|\langle 4s||d||2p_{3/2}\rangle\right|^2}{\left|\langle 4s||d||2p_{1/2}\rangle\right|^2}$$

$$\alpha(\omega) = \frac{1}{3\hbar}\left(\frac{\left|\left\langle 4s\,||d||\,4p_{\frac{1}{2}}\right\rangle\right|^2 \omega_{D1}}{\omega_{D1}^2 - \omega^2} + \frac{\left|\left\langle 4s\,||d||\,4p_{\frac{3}{2}}\right\rangle\right|^2 \omega_{D2}}{\omega_{D2}^2 - \omega^2}\right) + \alpha_{other}$$

Origin of tune-out wavelengths and motivation for measurements

$$\alpha(\omega) = \frac{1}{3\hbar}\sum_k \frac{\left|\langle k\,||d||\,g\rangle\right|^2 \omega_k}{\omega_k^2 - \omega^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

$$\alpha\left(\omega\right) = \sum_k \frac{S_k\,\omega_k}{\omega_k^2 - \omega^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

$$\alpha(\omega) = 6\pi\epsilon_o c^3 \sum_k \frac{\Gamma_k}{\left(\omega_k^2 - \omega^2\right)\omega_k^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

$$\alpha\left(\omega\right) = \frac{e^2}{m}\sum_k \frac{f_k}{\omega_k^2 - \omega^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

Origin of tune-out wavelengths and motivation for measurements

$$\alpha(\omega) = \frac{1}{3\hbar}\sum_k \frac{\left|\langle k\,||d||\,g\rangle\right|^2 \omega_k}{\omega_k^2 - \omega^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

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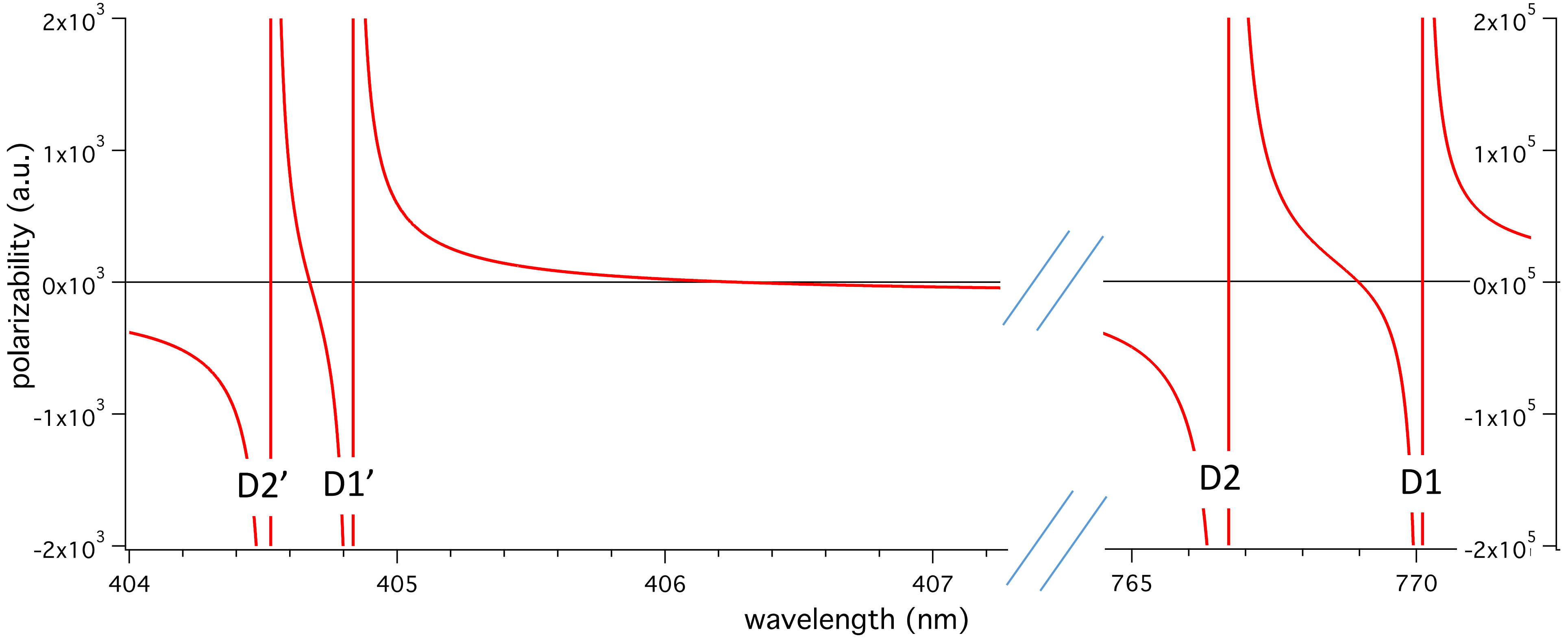


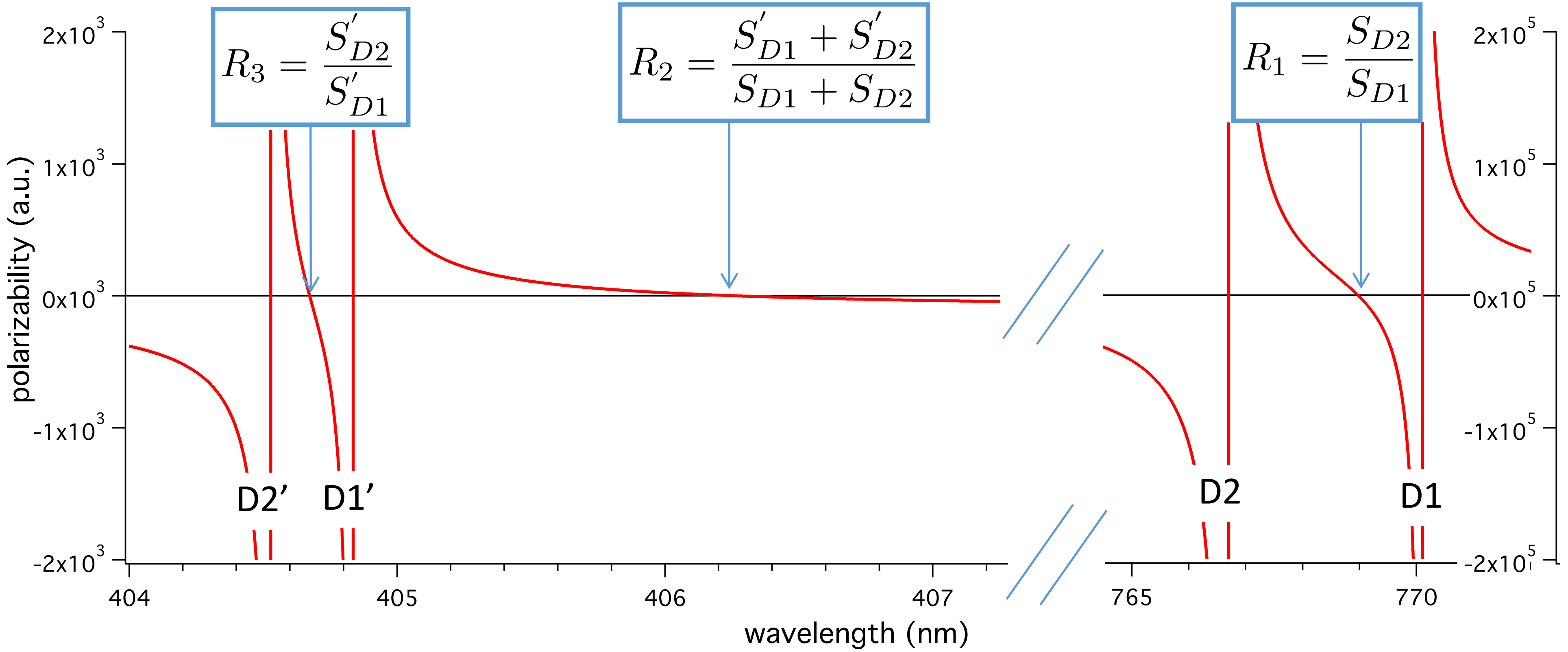
Origin of tune-out wavelengths and motivation for measurements

$$\alpha(\omega) = \frac{1}{3\hbar}\sum_k \frac{|\langle k\,||d||\,g\rangle|^2\,\omega_k}{\omega_k^2-\omega^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

$$\alpha(\omega) = \sum_k \frac{S_k\,\omega_k}{\omega_k^2-\omega^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

$$\alpha(\omega) = 6\pi\epsilon_o c^3 \sum_k \frac{\Gamma_k}{(\omega_k^2-\omega^2)\,\omega_k^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

$$\alpha(\omega) = \frac{e^2}{m}\sum_k \frac{f_k}{\omega_k^2-\omega^2} + \alpha_{\text{core}} + \alpha_{\text{other}}$$

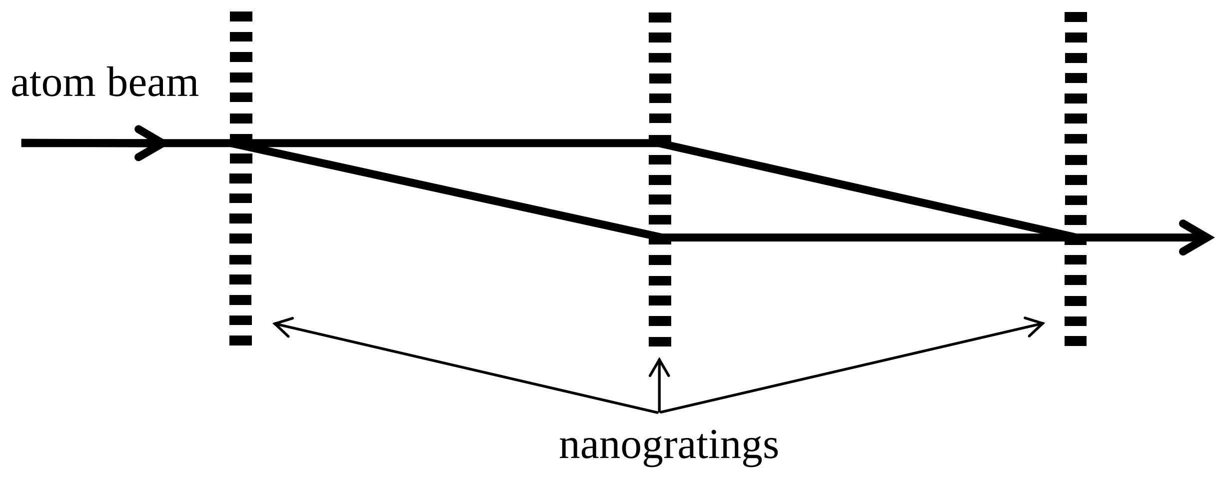


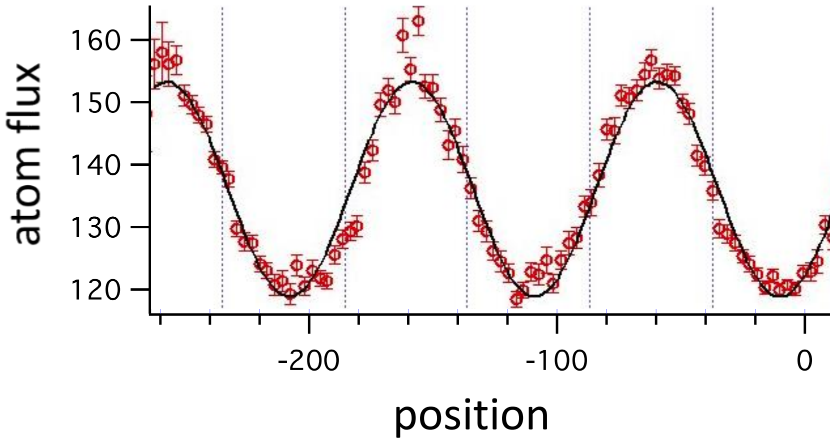
Science Impact and Experimental Sensitivities Comparison

λ_{zero} theory (nm)	relative exper. uncertainty (pm)	slope $d\alpha/d\lambda$ (a.u.)	σ_{theory} / $\sigma_{experiment}$	$\Delta\lambda_{zero}$ due to α_{core} (pm)	what we learn
^{7}Li 670.971626(1)	0.0004	9,500,000	2.5	<0.01	Hyper-polarizability
^{39}K 768.791 (3)	0.10	42,000	30	0.15(1)	R1
^{39}K 405.980 (40)	51	83	0.8	66(4)	R1, (core)
^{39}K 404.720 (40)	0.68	5,700	57	0.96(5)	R2 & R3
^{87}Rb 790.034 (7)	1.7	2,500	4	2.3(1)	R1, (core)
^{87}Rb 423.050 (80)	56	75	1.4	132(7)	R2, (R3 & core)
^{87}Rb 421.080 (50)	8.4	500	6	18(1)	Core & R3, (R2)
^{133}Cs 880.250 (40)	11	400	3.8	38(2)	R1, (core)
^{133}Cs 460.220 (20)	38	110	0.5	124(6)	R2, (R3, core)
^{133}Cs 457.310 (30)	38	110	0.8	138(7)	Core, (R2 & R3)
^{133}Sr 689.230 (30)	2.6	1,600	11.5	4.0(2)	Intercom. f_{ik}

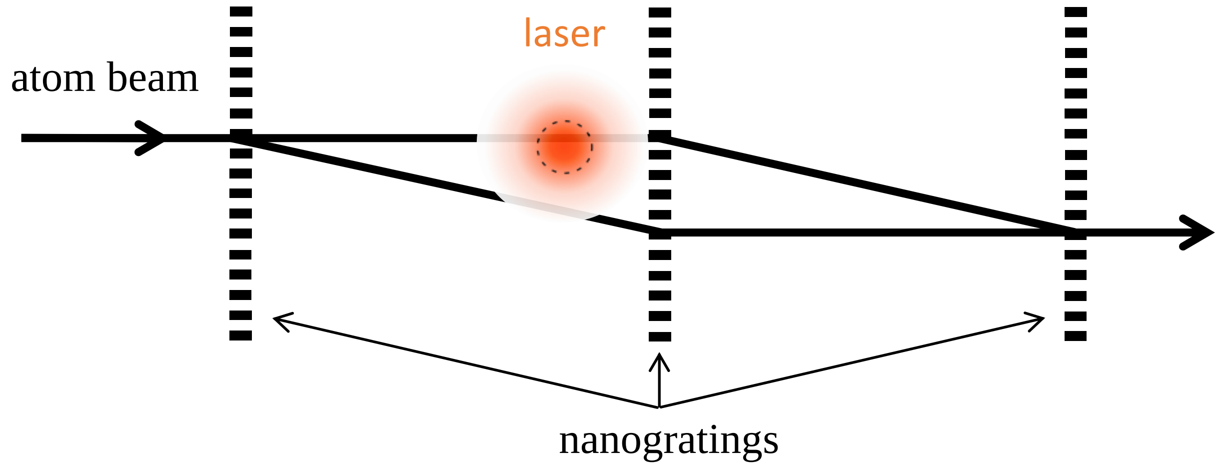
*Adapted from Cronin 2012 NSF proposal

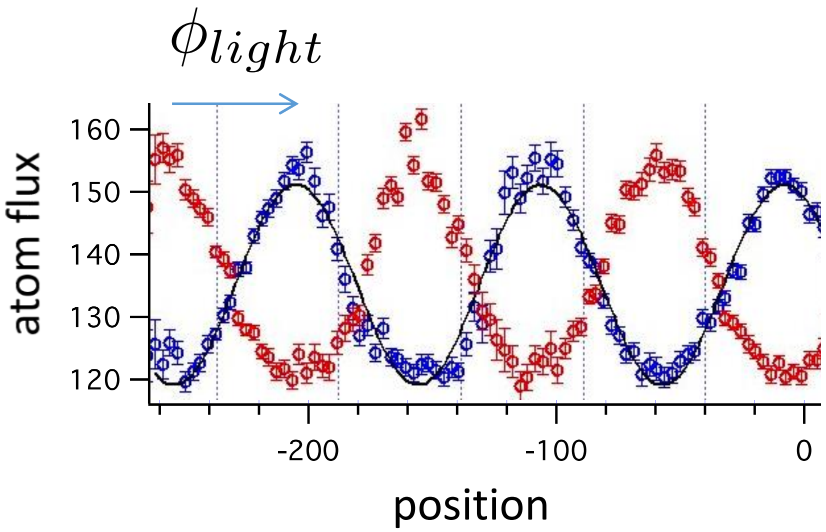
Precision Measurements with Atom Interferometry



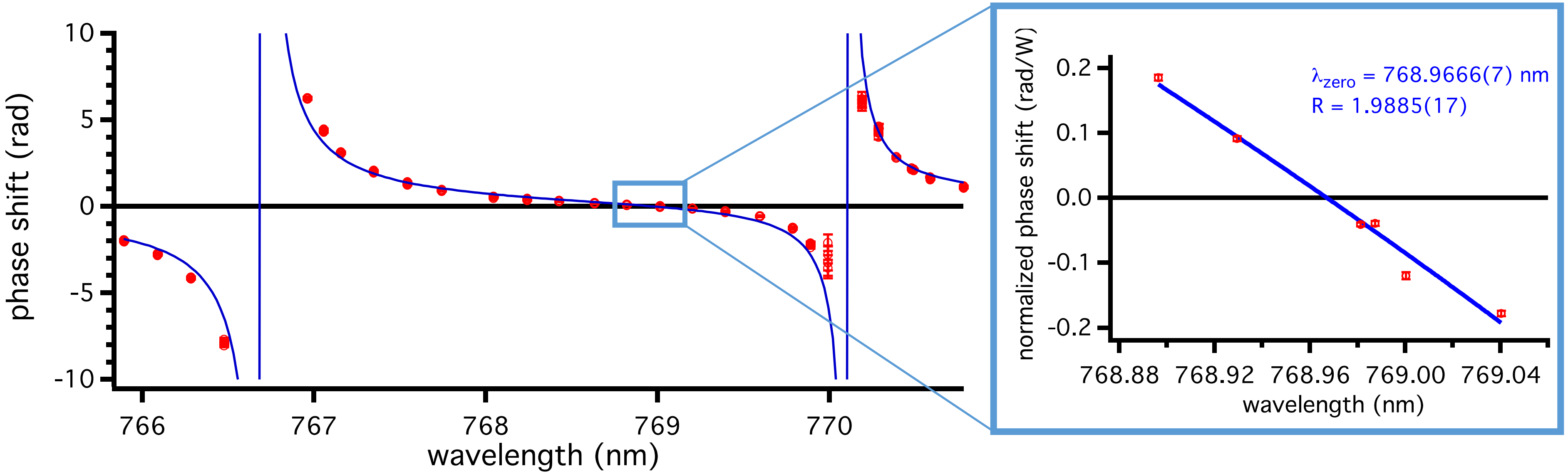


Precision Measurements with Atom Interferometry





Tune-out wavelength measurements with atom interferometry



$$\phi(\omega) = \frac{\alpha(\omega)}{\epsilon_0 c\hbar v}\int_{-\infty}^{\infty} I(\omega, z)dz$$

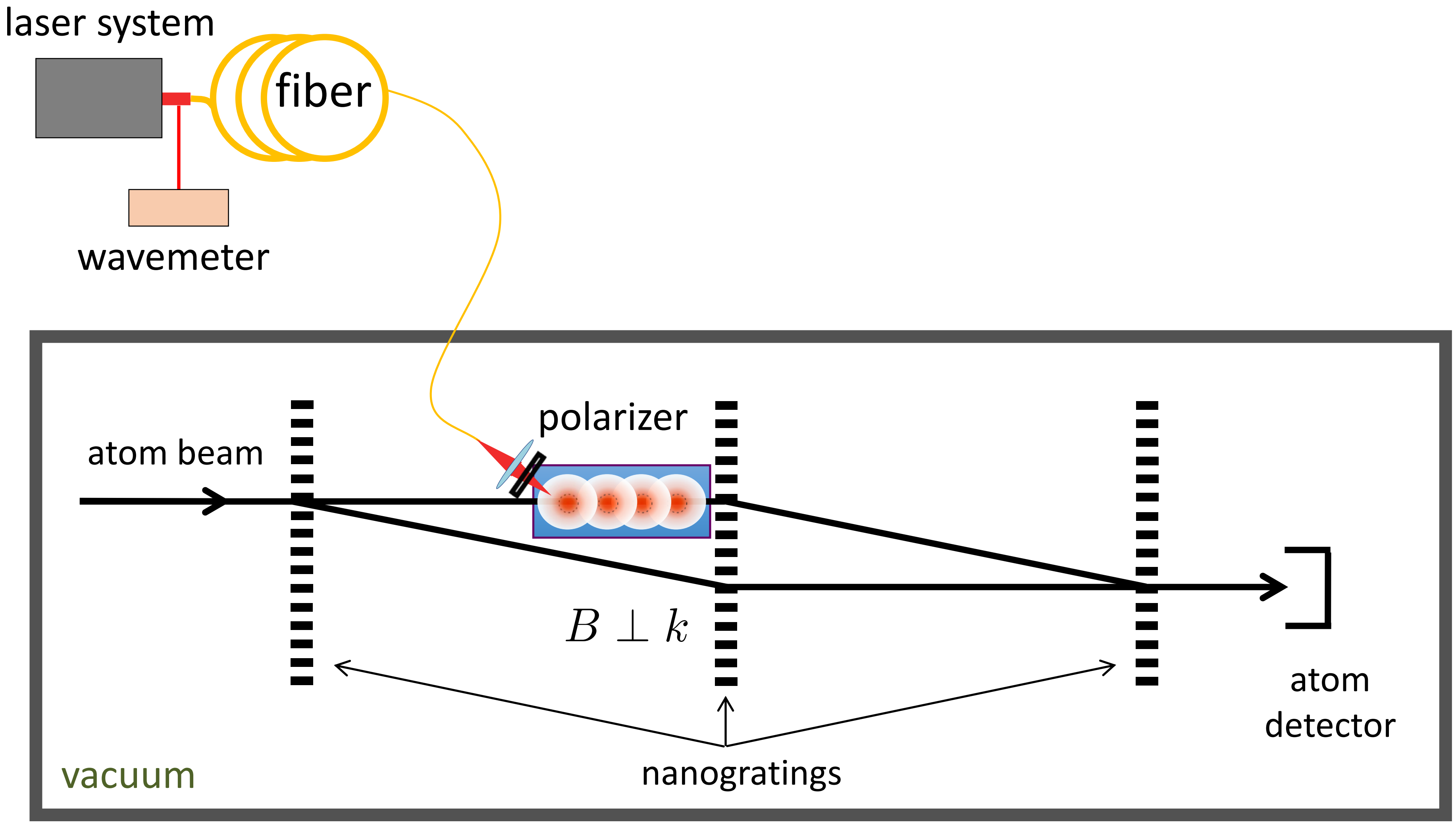
v = atom beam velocity

$I(\omega, z)$ = laser beam irradiance

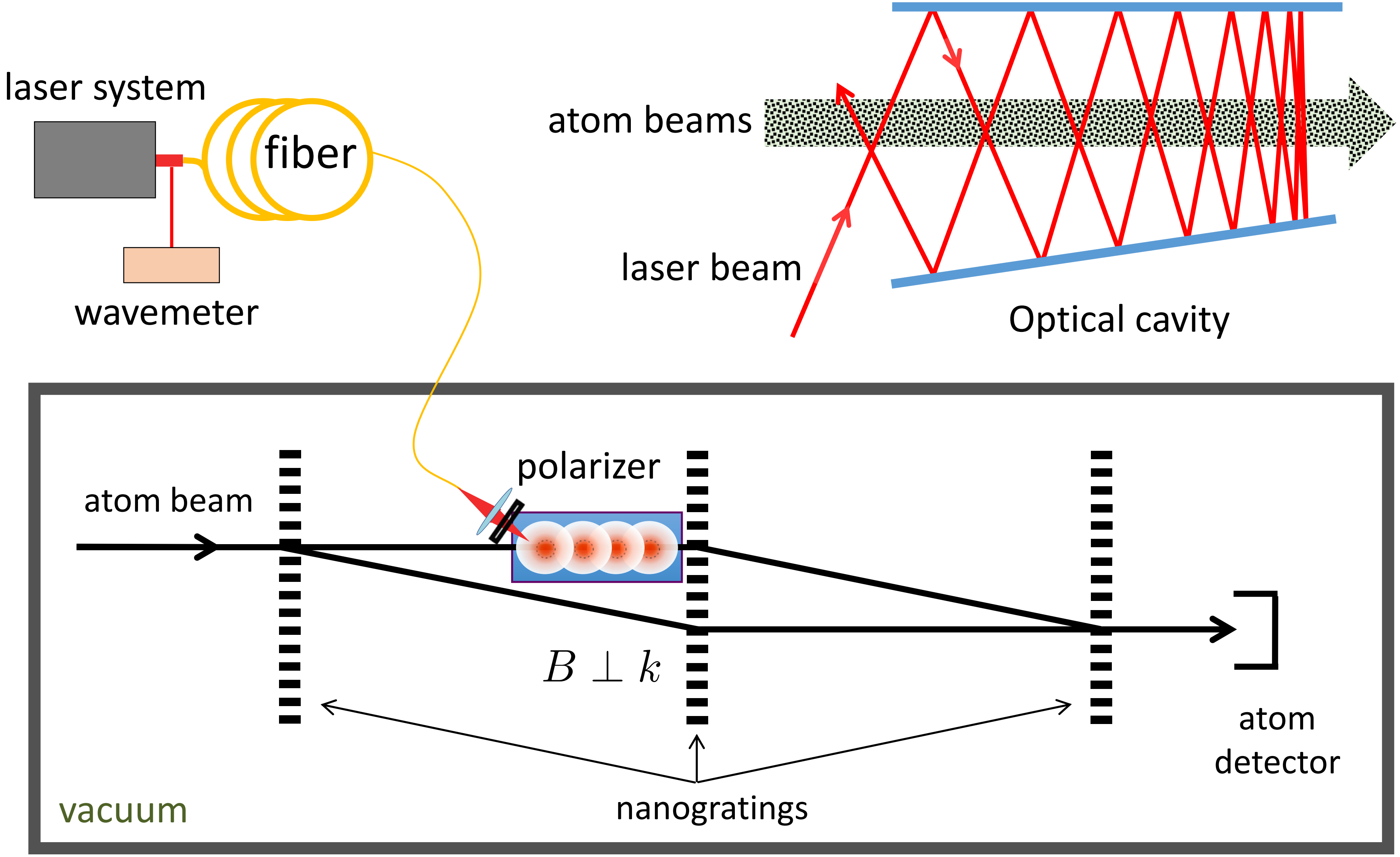
z = coordinate along atom beam propagation

[1] William F. Holmgren, Raisa Trubko, Ivan Hromada, and Alexander D. Cronin, "Measurement of a wavelength of light for which the energy shift for an atom vanishes," Phys. Rev. Lett. 109, 243004 (2012).

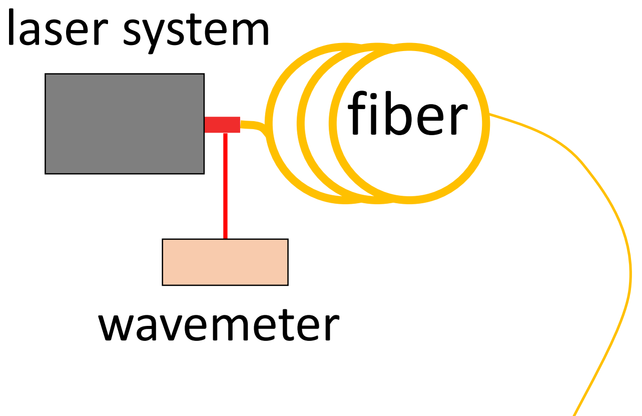
2015 Experimental Set-up

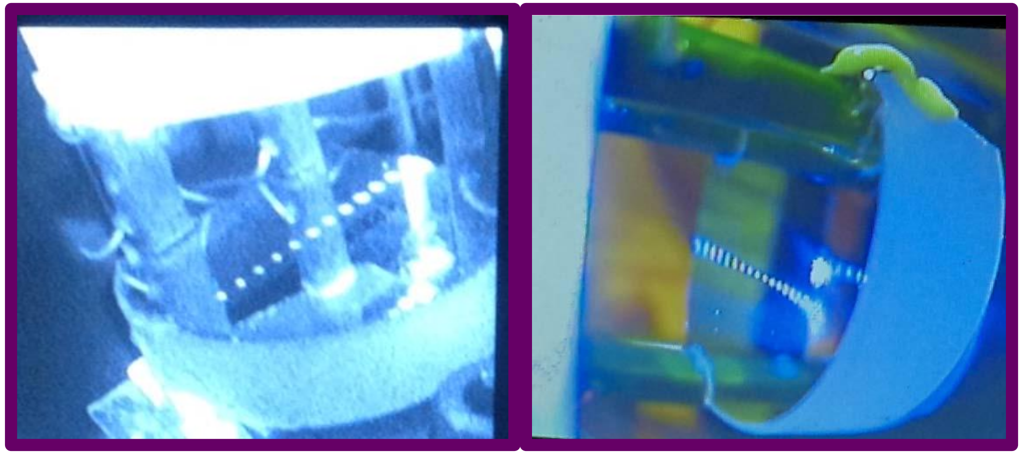


2015 Experimental Set-up

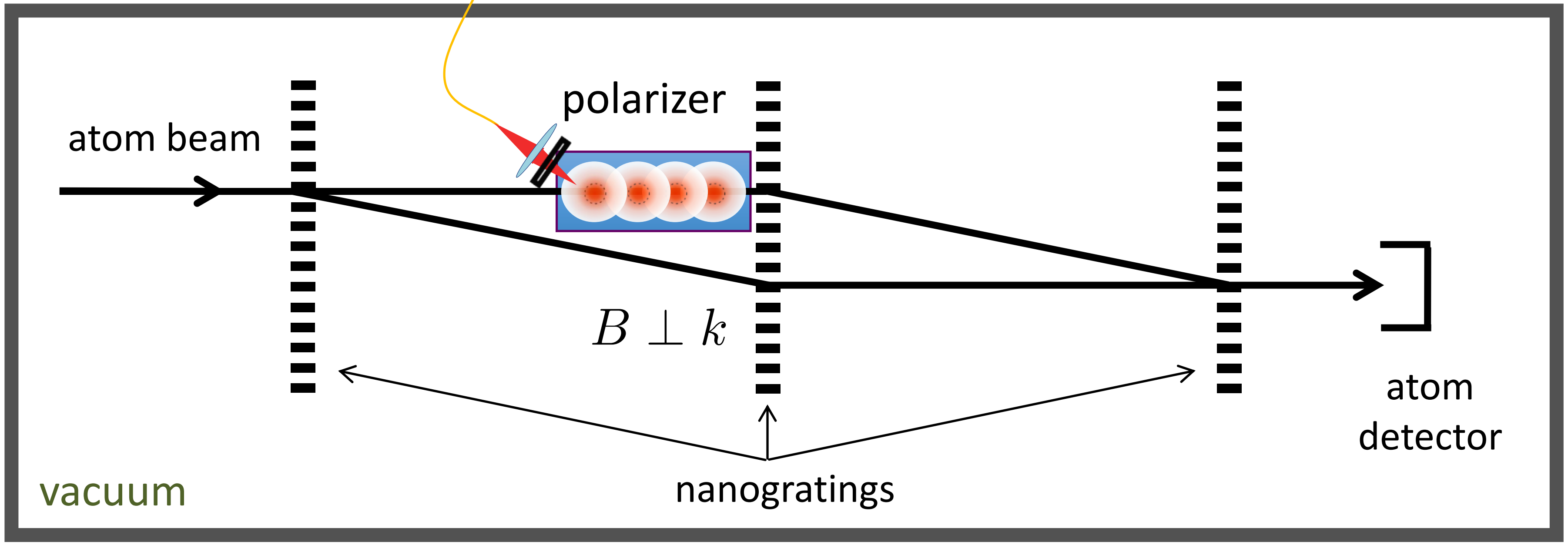


2015 Experimental Set-up

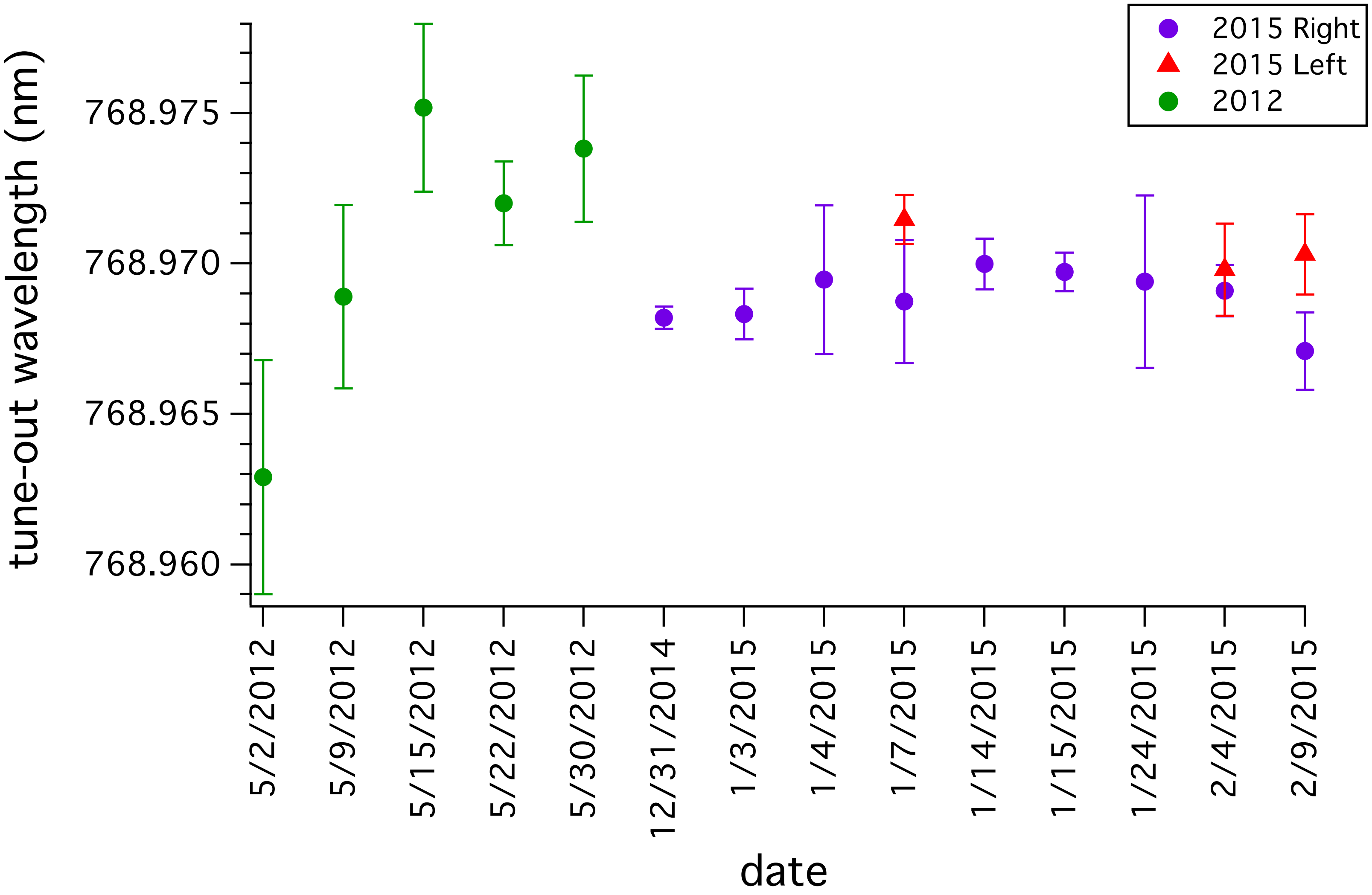




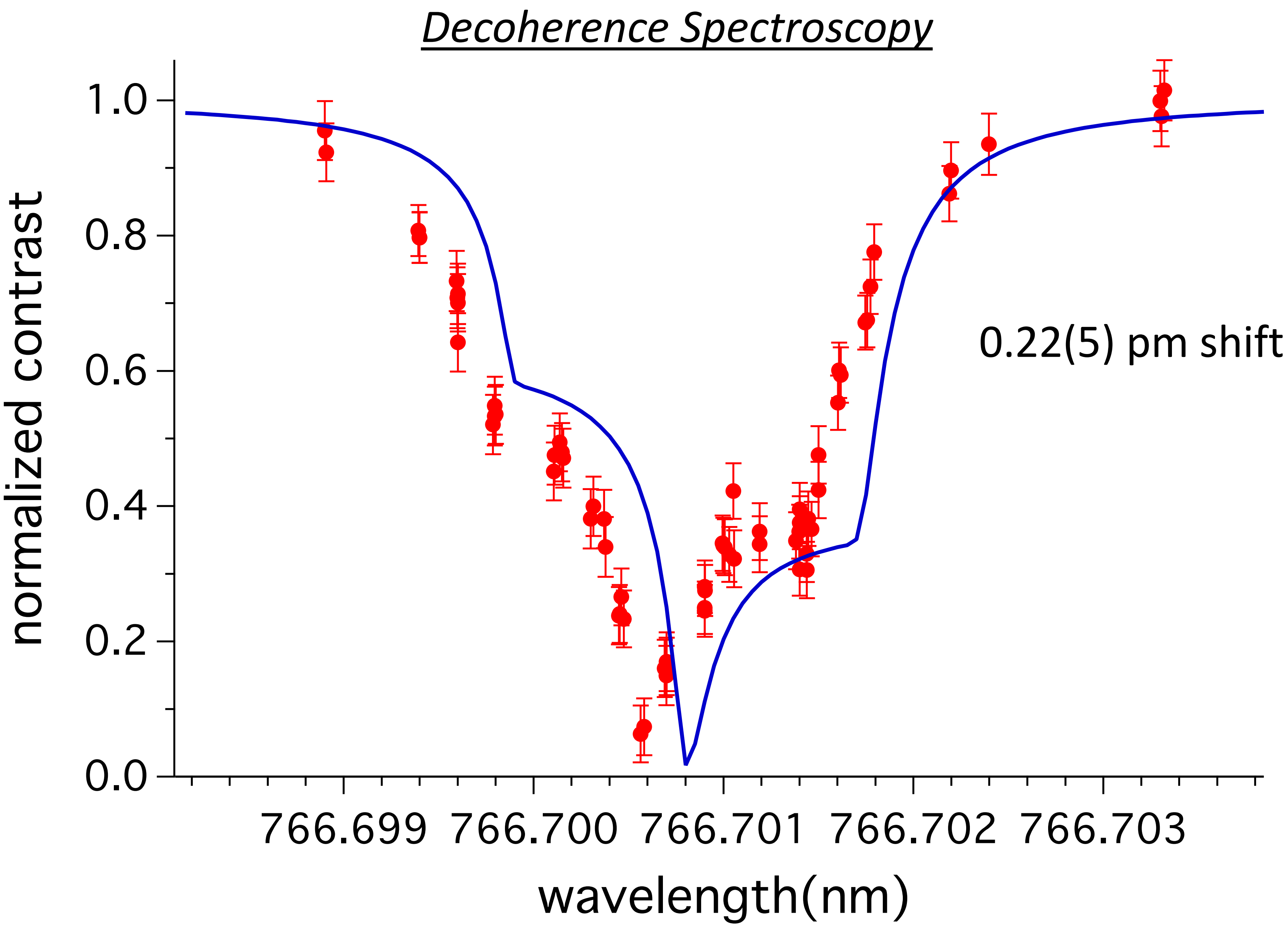
Optical cavity



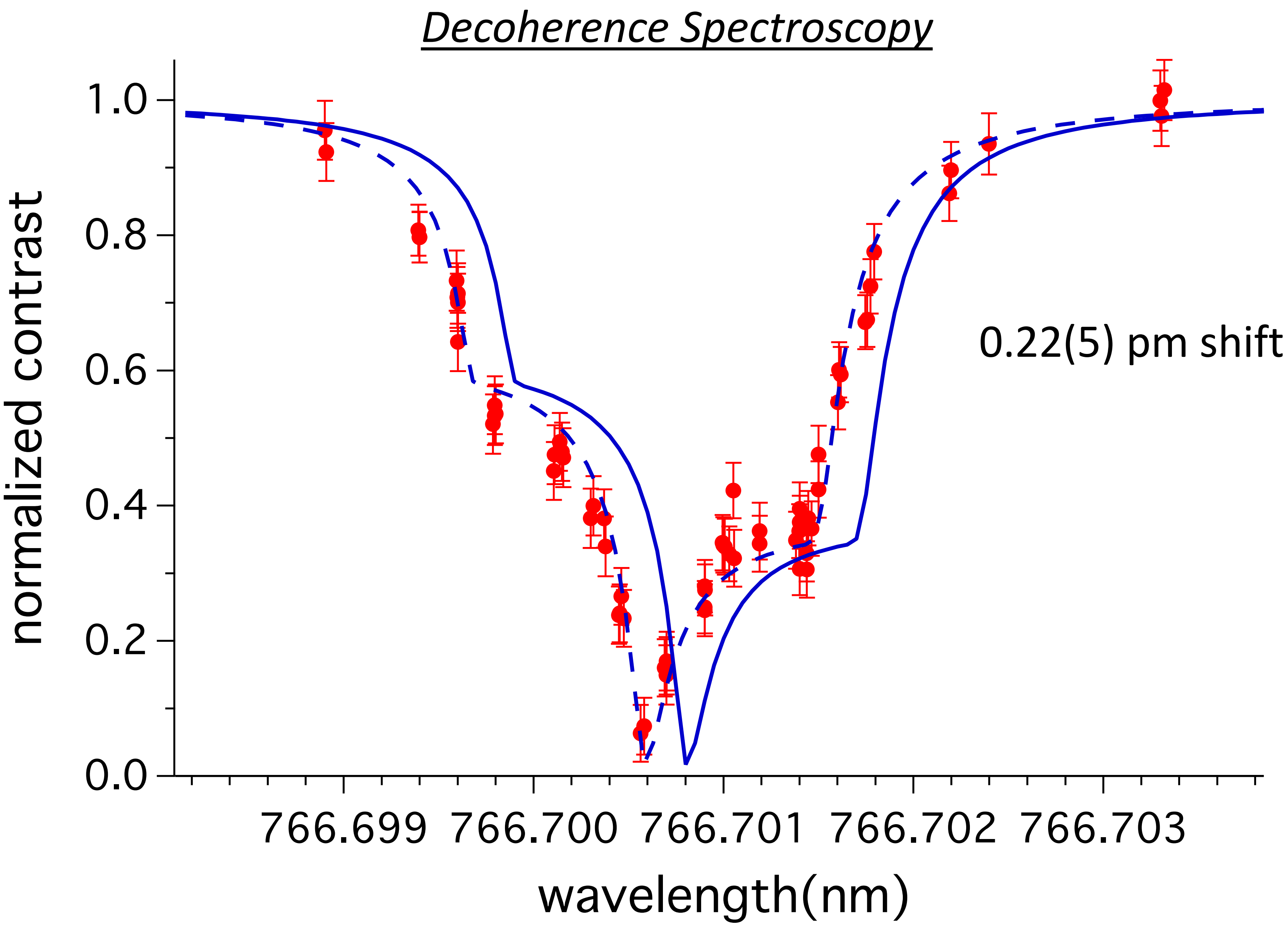
2012 and 2015 Tune-Out Wavelength Data



Doppler Shift & Wavemeter Calibration

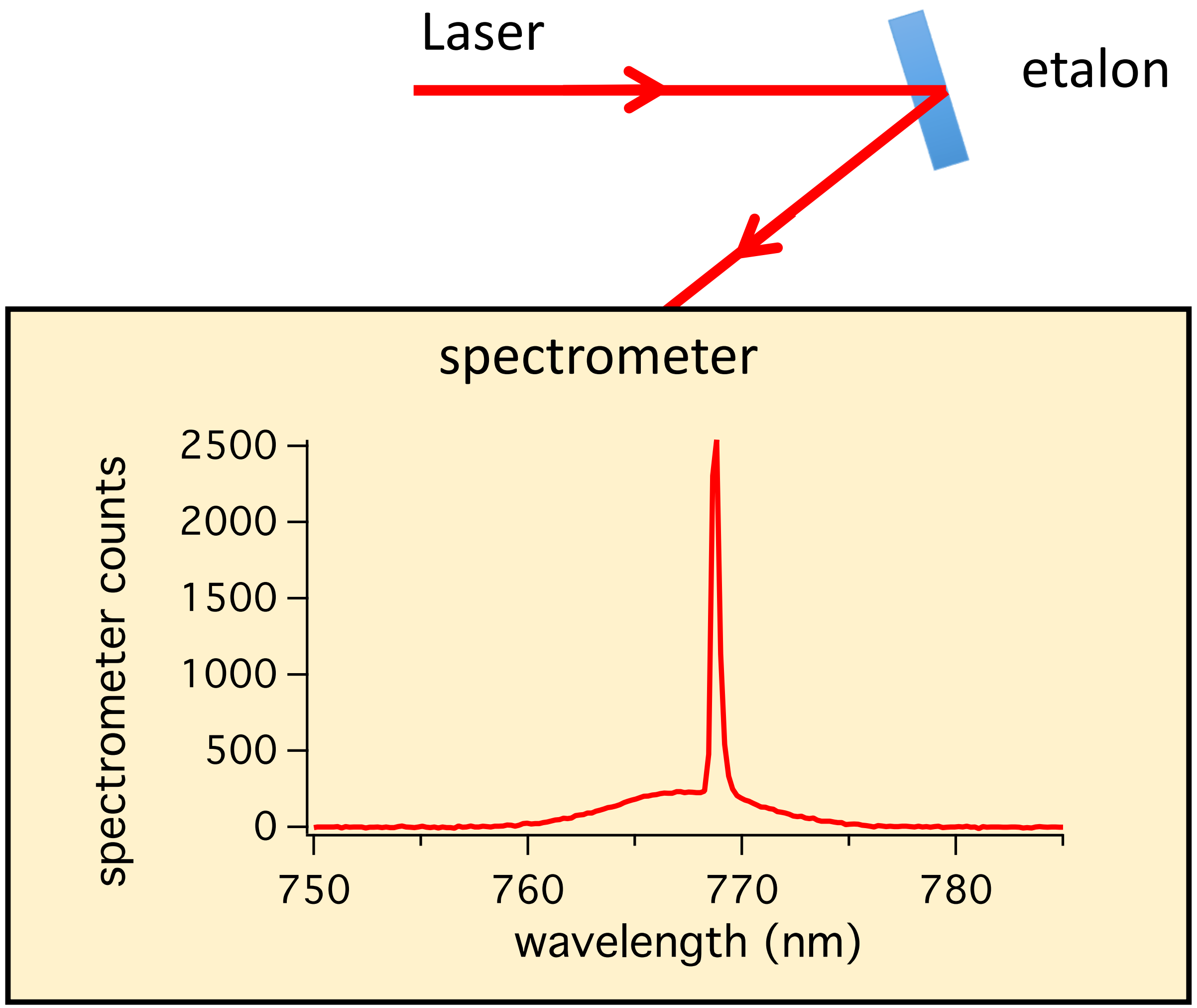


Doppler Shift & Wavemeter Calibration



Measurement of broadband light from TA

$$\text{Power} = P_{\text{mono}}\delta\left(\omega_L\right) + P_{\text{BB}}e^{\frac{-(\lambda-\lambda_o)^2}{2\sigma^2}}$$



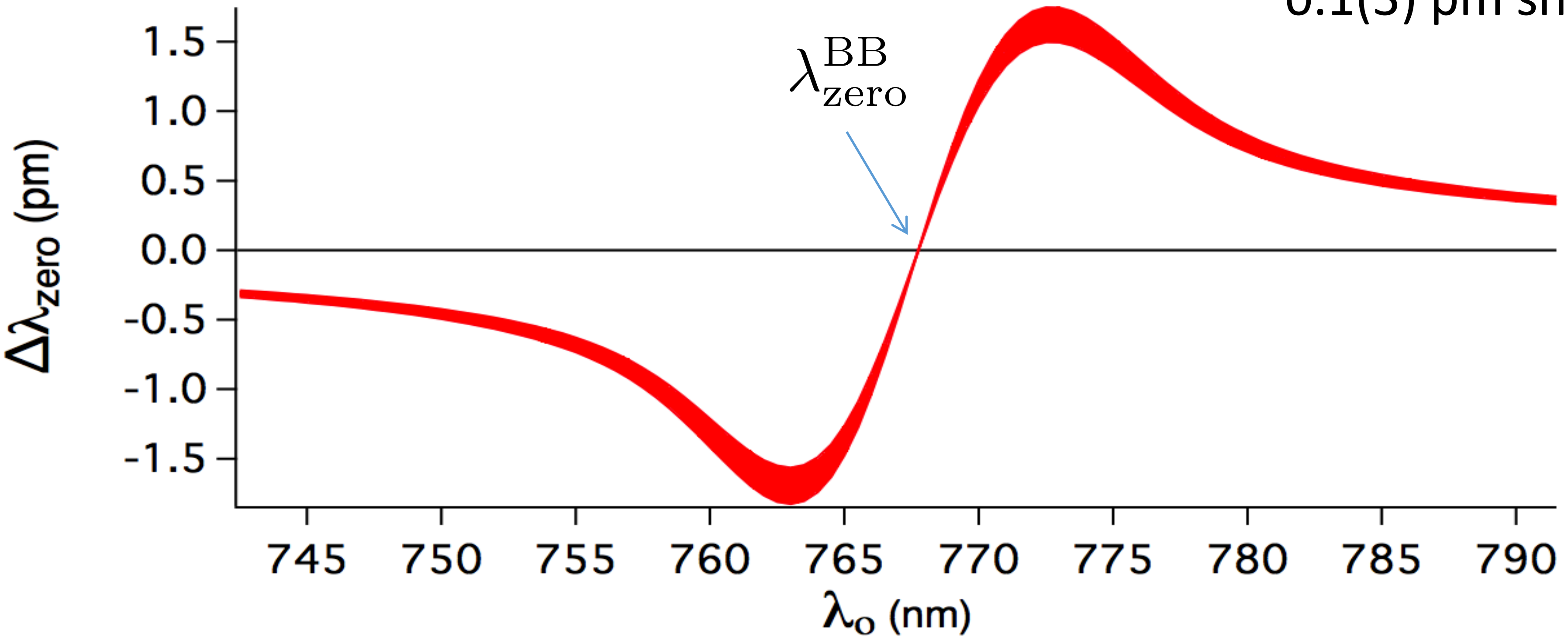
Error in λ_{zero} due to broadband light from TA

$$\text{Power} = P_{\text{mono}}\delta\left(\omega_L\right) + P_{\text{BB}}e^{\frac{-(\lambda-\lambda_o)^2}{2\sigma^2}}$$

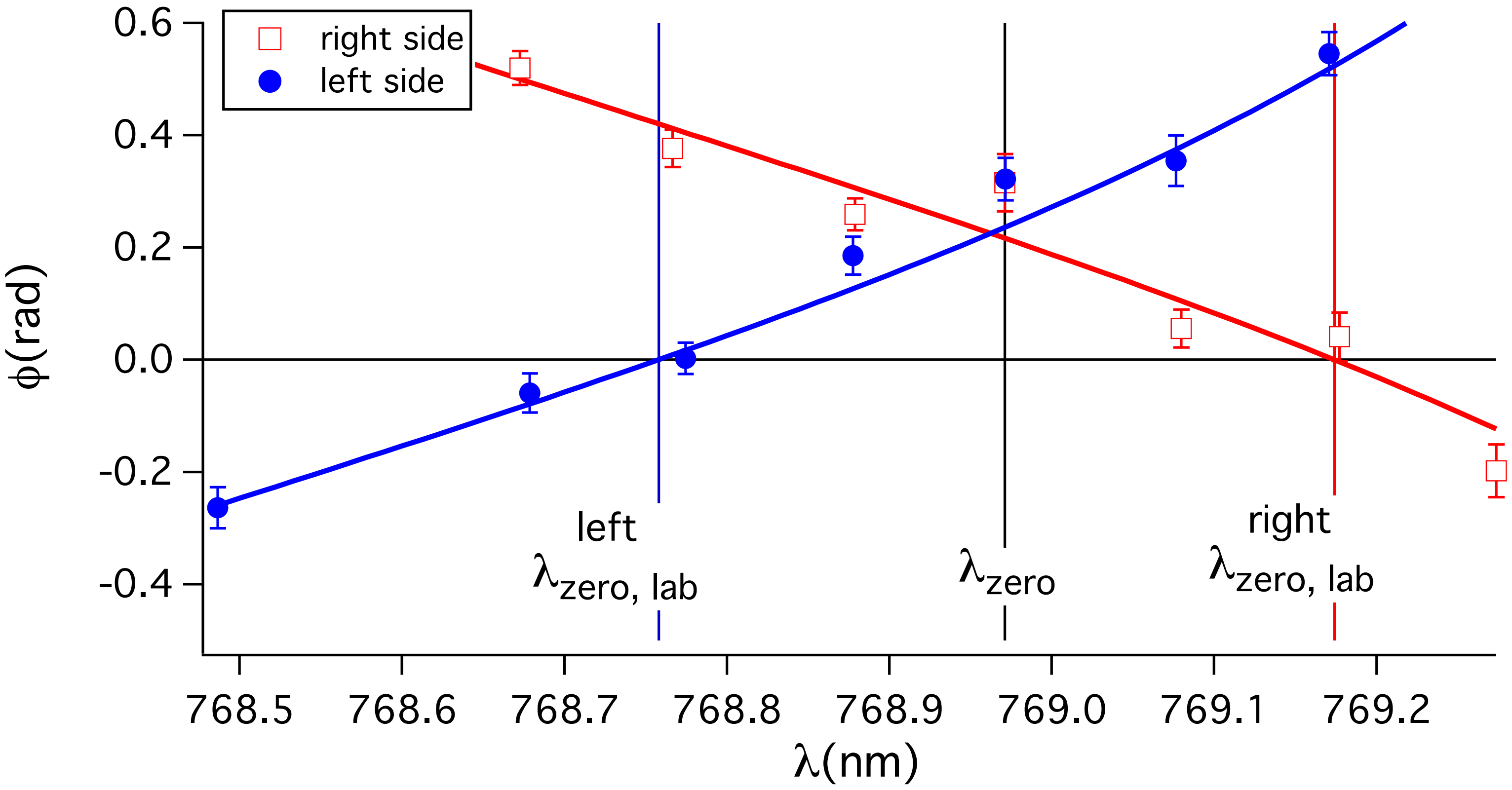
$$\phi = \int \left[P_{\text{mono}}\left(\omega\right) + P_{\text{BB}}\left(\omega\right)\right]\alpha\left(\omega\right)d\omega$$

$$\Delta\lambda_{\text{zero}} = \frac{\Delta\lambda}{\Delta\phi}\int P_{\text{BB}}\left(\omega\right)\alpha\left(\omega\right)d\omega$$

0.1(3) pm shift

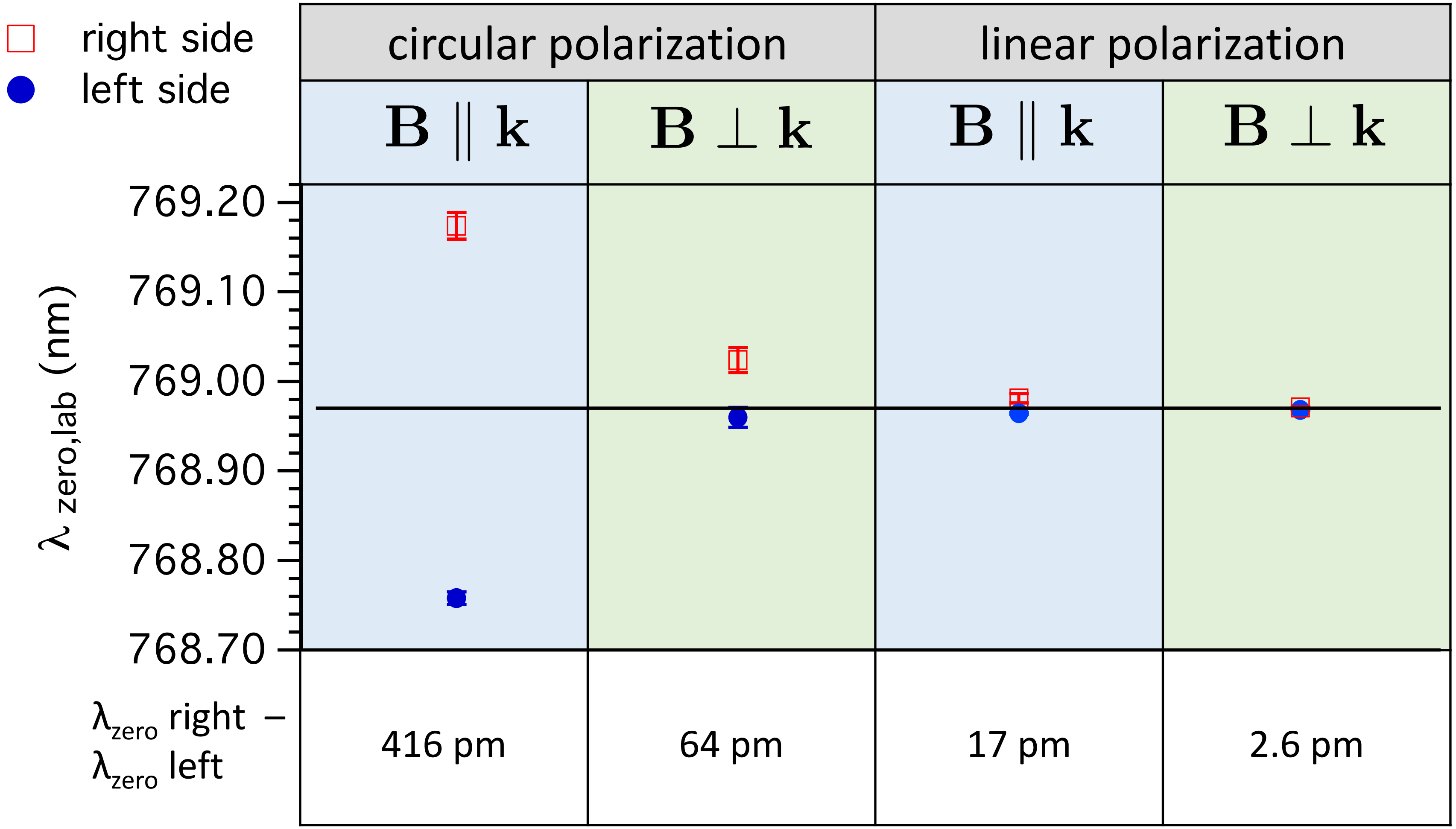


Error in λ_{zero} due to elliptical polarization and Earth's rotation



[2] Raisa Trubko *et. al.*, "Atom interferometer gyroscope with spin-dependent phase shifts induced by light near a tune-out wavelength," Phys. Rev. Lett. 114, 140404 (2015).

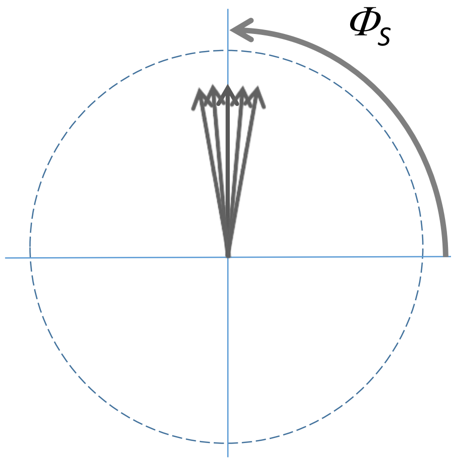
Rotation Rate Systematic Shifts in λ_{zero} measurements due to laser polarization and magnetic field orientation



How rotation affects λ_{zero} measurements

- Sagnac phase depends on atom velocity

$$\Phi_S = \frac{4\pi L^2 \Omega}{v d_g}$$



<u>Physics</u>: spin-dependent dispersion compensation

<u>Ingredients</u>

- Atom beam with a spread in velocity

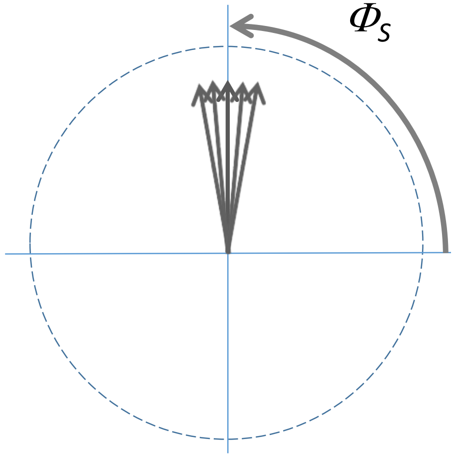
How rotation affects λ_{zero} measurements

- Sagnac phase depends on atom velocity

$$\Phi_S = \frac{4\pi L^2 \Omega}{v d_g}$$

- light-induced phase depends on atom velocity and spin

$$\Phi_L = \frac{\alpha(\omega)}{2\epsilon_o c \hbar v} \int s \cdot \left[\frac{d}{dx} I(\mathrm{r}, \omega) \right] dz$$



Physics: spin-dependent dispersion compensation

Ingredients

- Atom beam with a spread in velocity
- Atom beam with multiple spin states

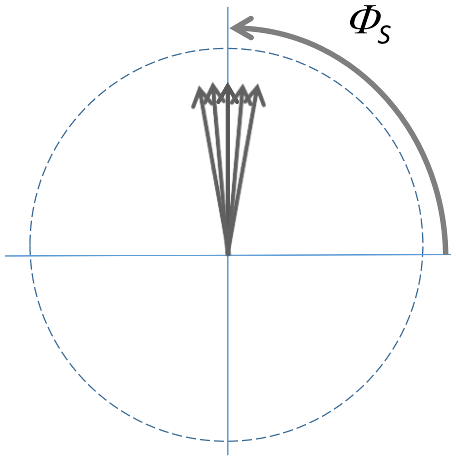
How rotation affects λ_{zero} measurements

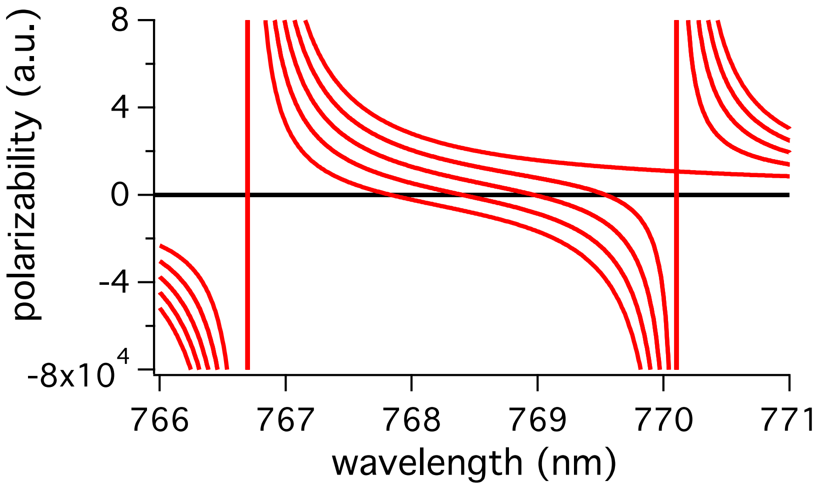
- Sagnac phase depends on atom velocity

$$\Phi_S = \frac{4\pi L^2 \Omega}{v d_g}$$

- light-induced phase depends on atom velocity and spin

$$\Phi_L = \frac{\alpha(\omega)}{2\epsilon_o c \hbar v} \int s \cdot \left[\frac{d}{dx} I(\mathrm{r}, \omega) \right] dz$$





Physics: spin-dependent dispersion compensation

Ingredients

- Atom beam with a spread in velocity
- Atom beam with multiple spin states
- Circularly polarized light
- Magnetic field parallel to optical k-vector

How rotation affects λ_{zero} measurements

- Sagnac phase depends on atom velocity

$$\Phi_S = \frac{4\pi L^2 \Omega}{v d_g}$$

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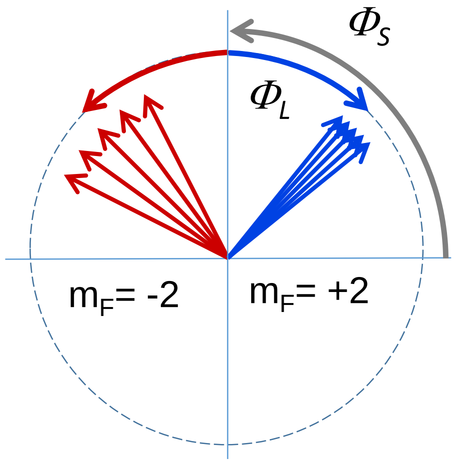
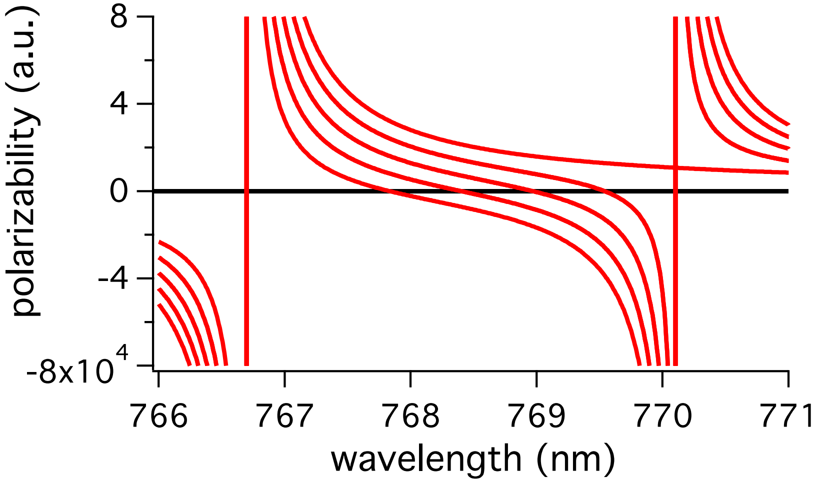


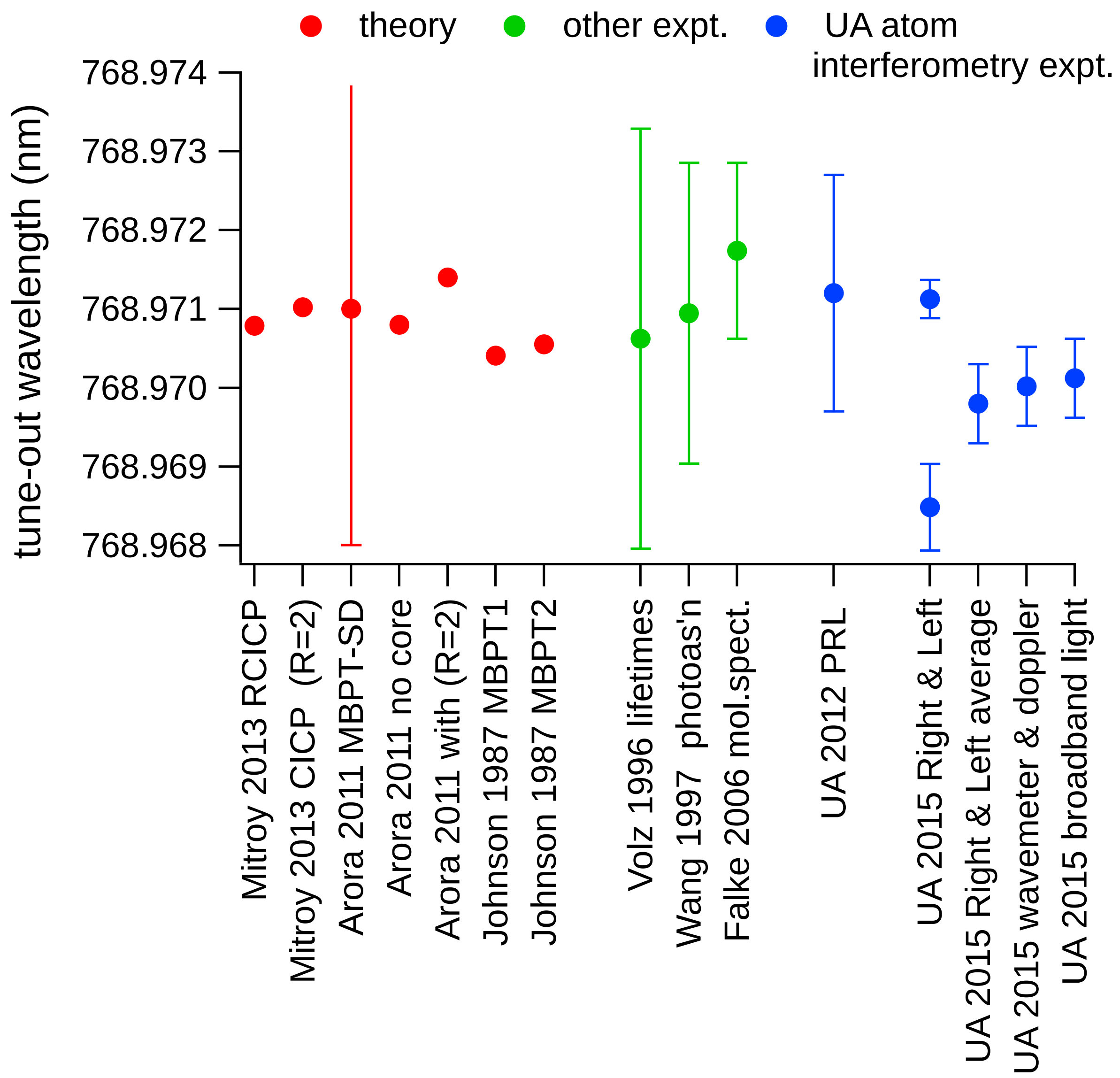


Physics: spin-dependent dispersion compensation

Ingredients

- Atom beam with a spread in velocity
- Atom beam with multiple spin states
- Circularly polarized light
- Magnetic field parallel to optical k-vector

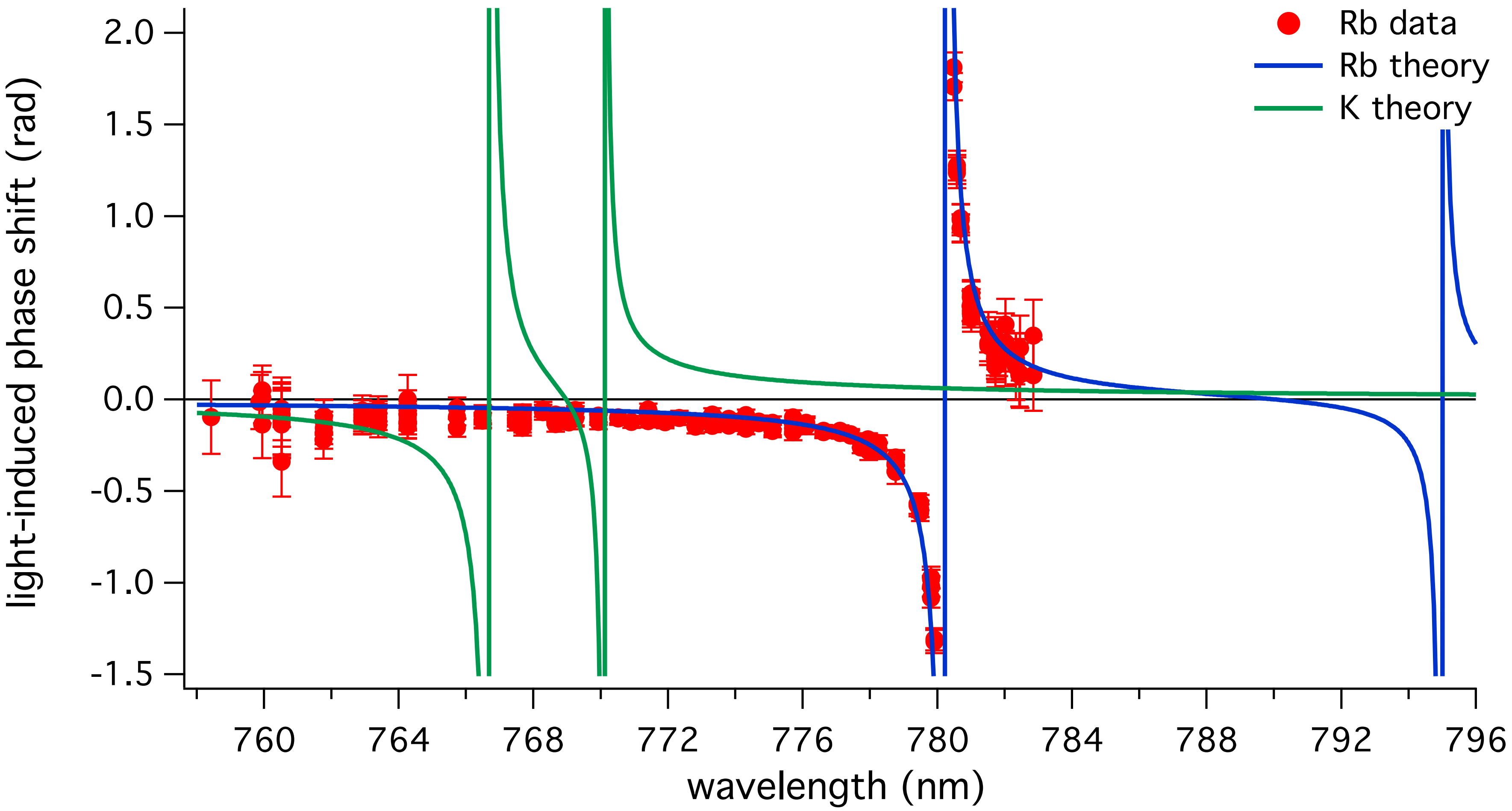
2015 Tune-Out Wavelength Measurement for K atoms



$\lambda_{zero} = 768.9701(5)$ nm

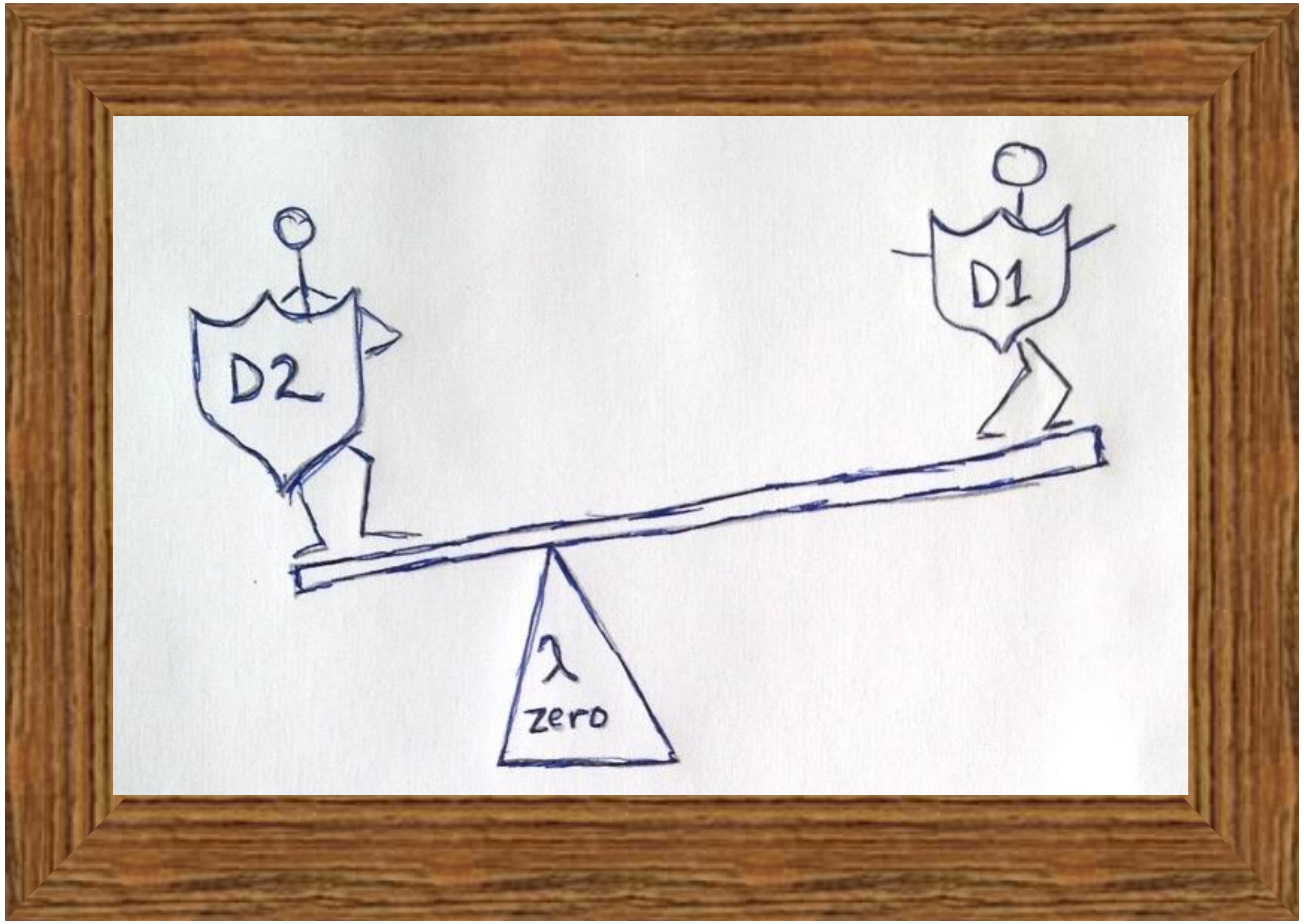
Source of error	λ_{zero} error (pm)
laser wavelength	0.1
broadband light	0.3
laser polarization & lab rotation rate	0.2
Doppler shift	0.1
Total systematic error	0.4
Total statistical error	0.3
Total error	0.5

Rb light-induced phase shift data



Tune-Out wavelengths λ_{zero}

Measurement of λ_{zero} lets us report $R=(S_{D2}/S_{D1})$

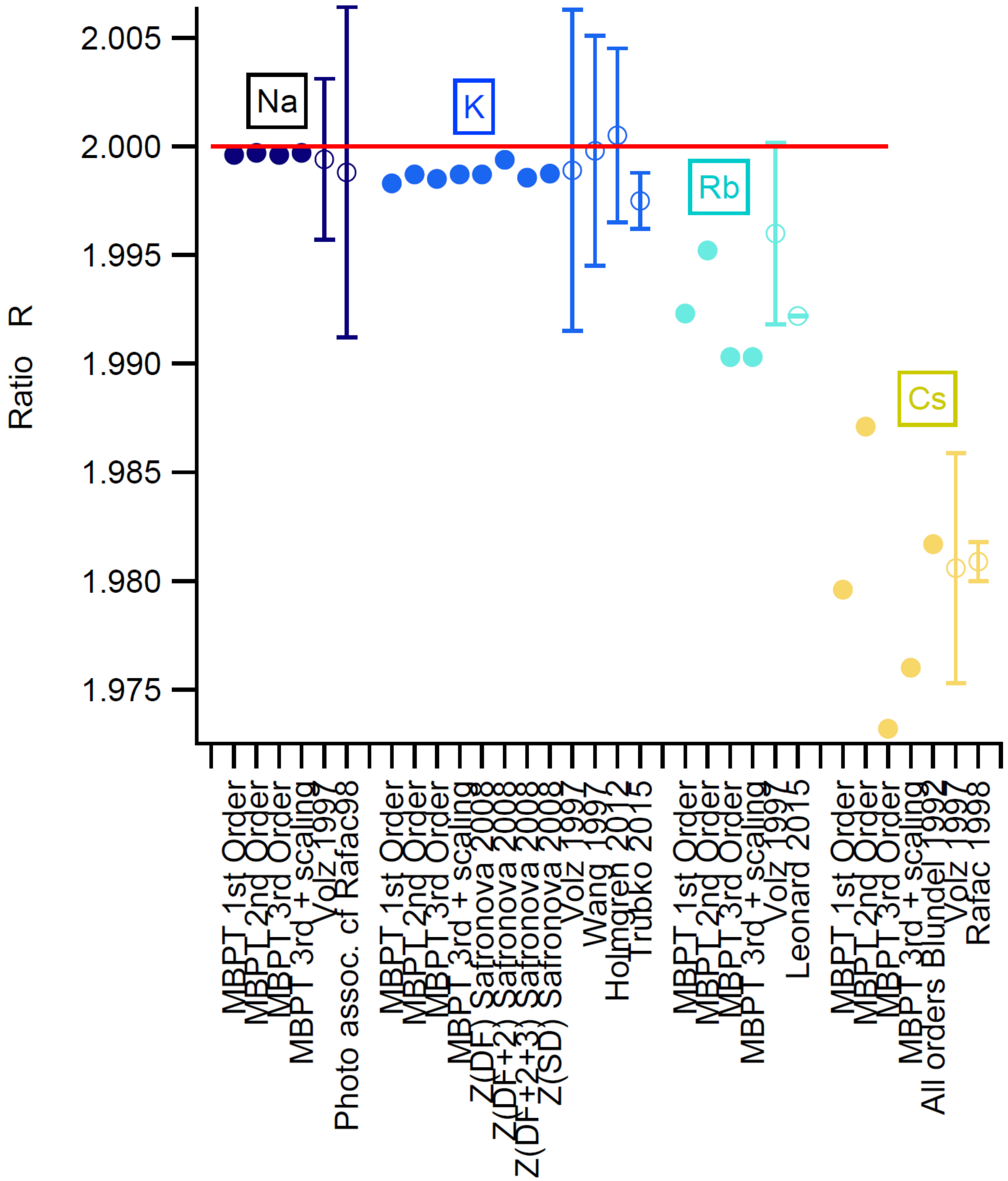


$$R_1 = \frac{\left|\langle 4s||d||2p_{3/2}\rangle\right|^2}{\left|\langle 4s||d||2p_{1/2}\rangle\right|^2}$$

$= S_{D2}/S_{D1}$

$= 1.9976(13)$

In preparation (2016)



Tune-Out Wavelength Experiments:

SUMMARY:

- Measured $\lambda_{\mathbf{zero}}$ = 768.9695(5) for K with 0.5 picometer uncertainty
- Benchmark test for ratios of $\langle 4p_J|r|4s\rangle$ calculated with MBPT
- Novel gyroscope demonstrated using $\lambda_{\mathbf{zero,lab}}$

NEXT STEPS:

- Other $\lambda_{\mathbf{zero}}$ will test other $\langle k|r|i\rangle$
- Hyperpolarizability measurement idea
- intercombination line strength measurement for Sr clocks

Talk Summary:

- Polarizability ratios (e.g. $\frac{\alpha^{\mathrm{K}}}{\alpha^{\mathrm{Na}}}$) measured with 0.1% uncertainty

- Tune-out wavelength λ_{zero} measured with 0.5 pm uncertainty

- C3 ratios (e.g. $\frac{C_3^{\mathrm{K}}}{C_3^{\mathrm{Na}}}$) measured with 2% uncertainty.

- Each type of measurement tests different functions of atomic f_{ik} .

- Nanogratings work for several atomic species

  → steps towards a "universal atom interferometer"

Atom interferometry studies of atomic structure

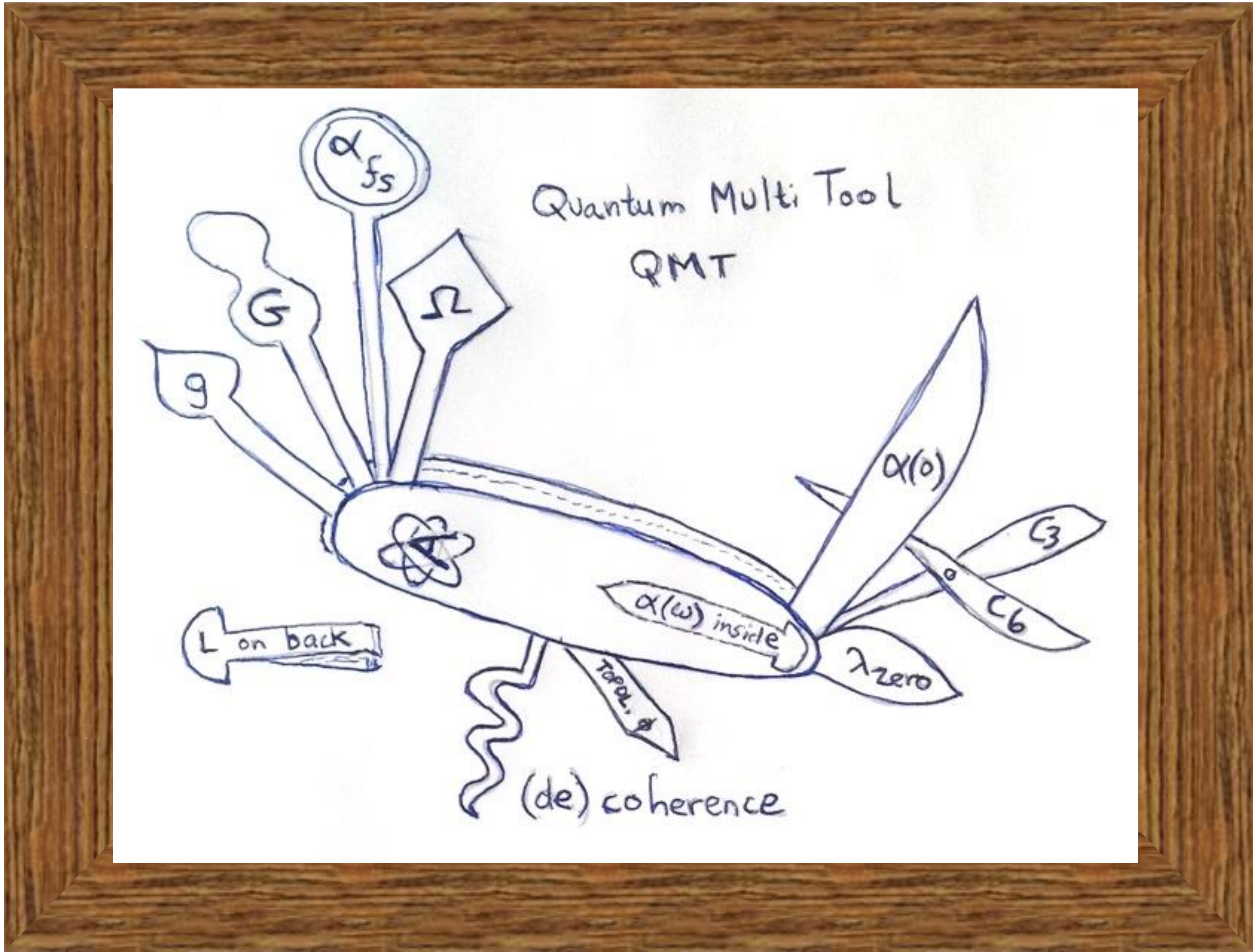
Alex Cronin, University of Arizona

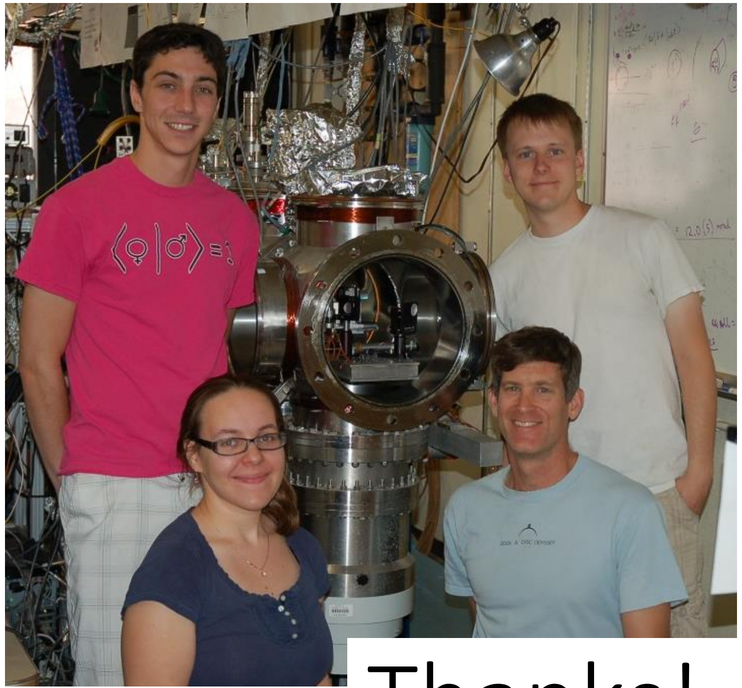
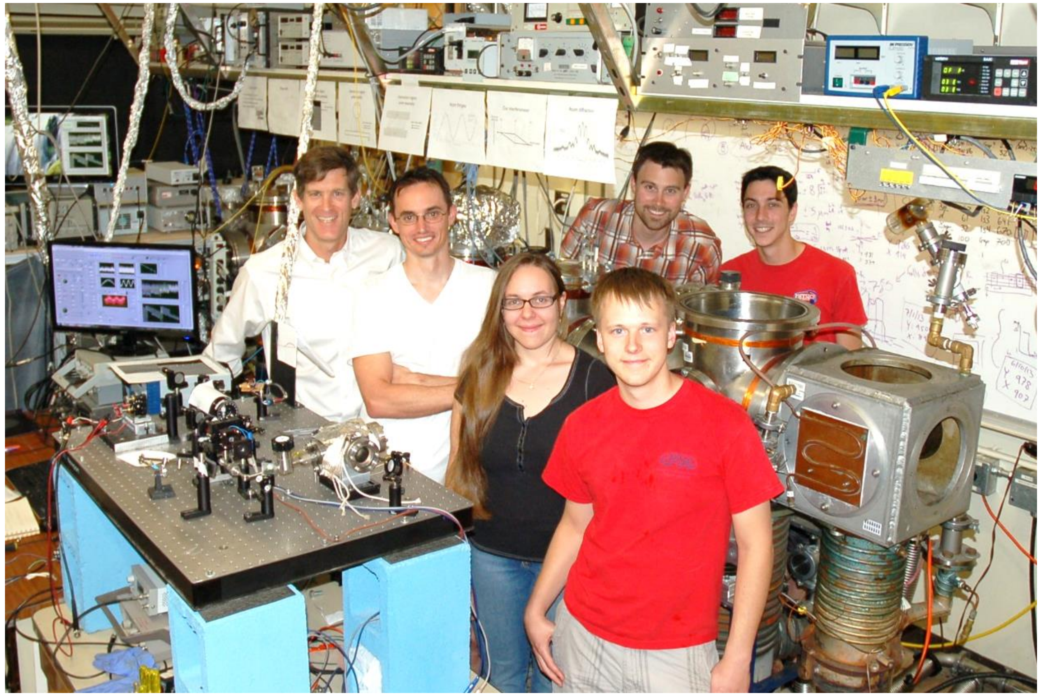
John Perreault, PhD 2005
Ben McMorran, PhD 2009
Vincent Lonij, PhD 2011
Will Holmgren, PhD 2013
Ivan Hromada, PhD 2014
Raisa Trubko, current PhD student
Maxwell Gregoire, current PhD student

Robert Wild, BS 2004
Melissa Revelle, BS 2009
Cathy Klauss, BS 2011
James Greenberg, BS 2014

We acknowledge support from NSF Grant No. 1306308
"New applications for atom interferometry with material gratings"
And a NIST PMG

Atom Interferometry: “Swiss Army Knife of Physics”



Thanks!