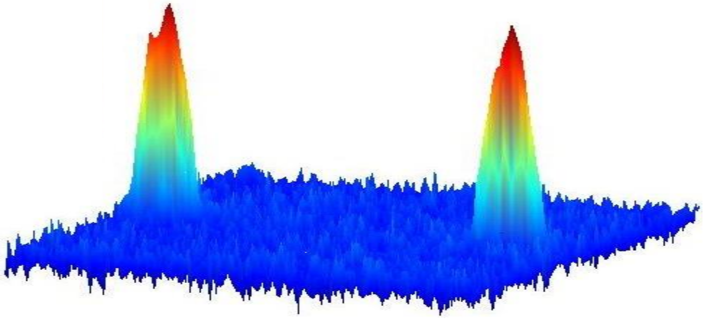
Tune-out wavelength spectroscopy:
A new technique to characterize atomic structure

Cass Sackett
UVa



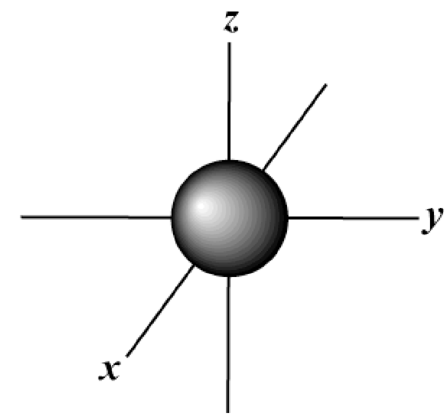
Outline

- Atomic parity violation experiments
  - why they are important but stalled
- Tune-out spectroscopy
  - what it is, how we do it
- Results
  - and comparison to theory
- Next steps
  - progress so far

Atomic parity violation

- S states in atoms have even parity

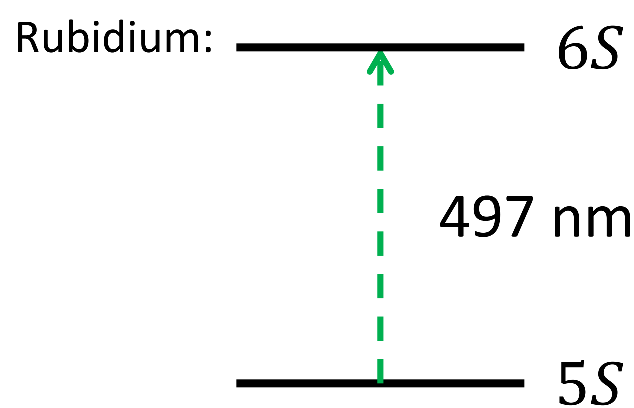
$$\psi(-\mathbf{r}) = \psi(\mathbf{r})$$



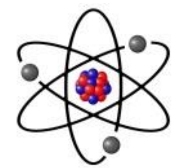
- Transition $|nS\rangle \to |n'S\rangle \sim \langle nS|\mathbf{d}|n'S\rangle = 0$

$\Rightarrow$ forbidden!

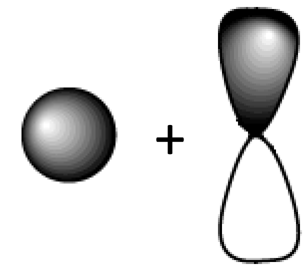
$$\mathbf{d} = e\mathbf{r}$$



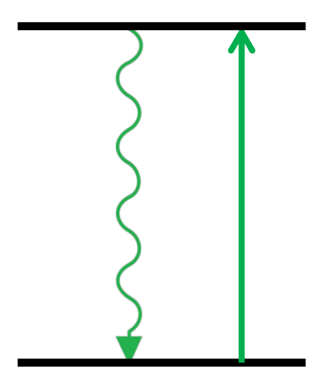
Atomic parity violation



- Electron interacts with nucleus
  - weak interaction violates parity
  - mixes P character into S states
  - allows transition!

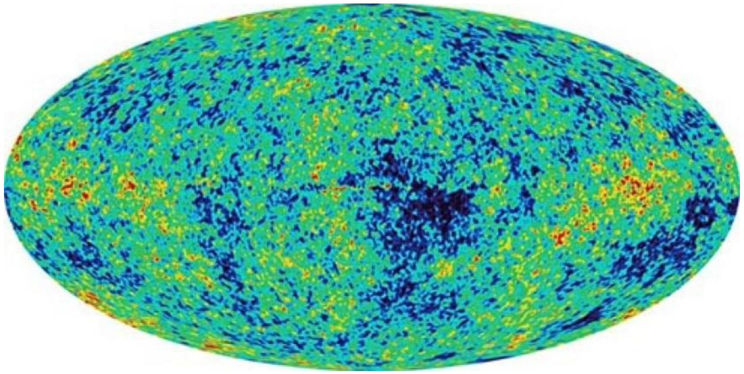


- Measure transition rate
  - get strength of weak interaction



Fundamental symmetries

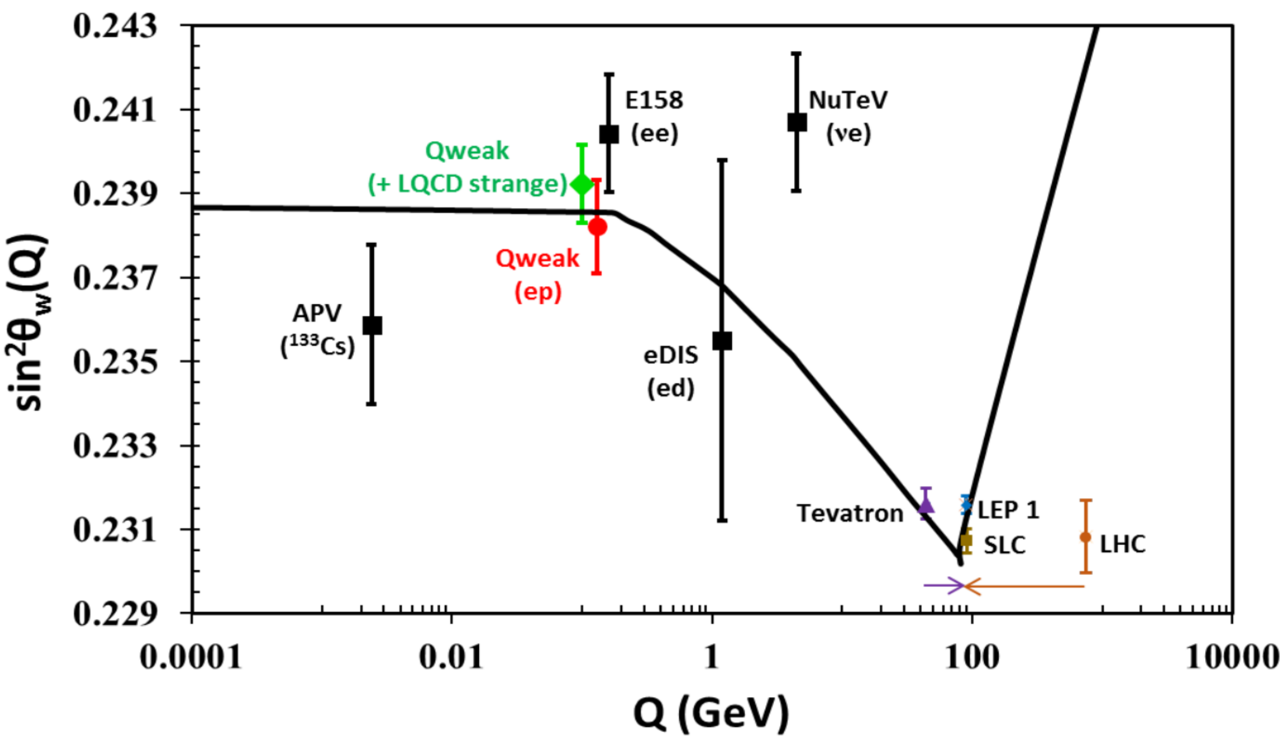
- Weak interaction violates CP symmetry
- So does the universe overall
  - too much to explain via Standard Model



- Study symmetry violations
  - look for surprises

Weak interaction

- Measure energy-dependence of weak interaction



- Steady improvements
  - Except for atomic result, from 1995

Interpreting APV

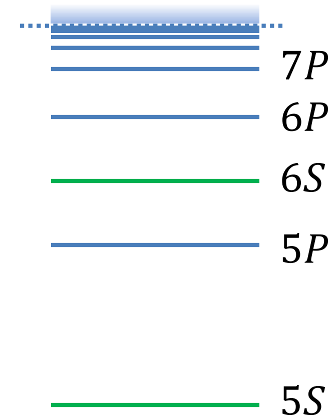
- Measure transition rate, relate to weak interaction

$$A_{PNC} = \sum_{n'=5}^{\infty} \left(\frac{\langle 6S_{1/2} | d | n'P_{1/2} \rangle \langle n'P_{1/2} | H_{PNC} | 5S_{1/2} \rangle}{E_{5S} - E_{n'P_{1/2}}} + \frac{\langle 6S_{1/2} | H_{PNC} | n'P_{1/2} \rangle \langle n'P_{1/2} | d | 5S_{1/2} \rangle}{E_{6S} - E_{n'P_{1/2}}} \right)$$

$\langle n'P_{1/2} | H_{PNC} | nS_{1/2} \rangle$: gives interaction strength

$\langle nS_{1/2} | d | n'P_{1/2} \rangle$: dipole matrix elements

Interpreting APV



- Need precise dipole matrix elements

Principle: $\langle 5S|d|5P\rangle$

– measure accurately

Intermediate: $\langle 5S|d|nP\rangle$ and $\langle 6S|d|nP\rangle$ for $n \leq 12$

– calculate accurately

Tail: $\langle 5S|d|nP\rangle$ and $\langle 6S|d|nP\rangle$ for $n > 12$

– estimate

Also some additional corrections, calculated

Error contributions

- Contributions to PNC error:

Terms	Rel. contribution	Uncertainty
Principle	0.88	0.0015
Intermediate	0.08	0.0015
Tail	0.02	0.004
Other	0.01	0.001
Total	**1.00**	**0.005**

- 1995 experiment uncertainty: 0.0035

  Limited by theory, mostly tail contribution

How to improve?

- Measure dipole matrix elements
  - especially high-n tail
- Hard to do directly
  - infinitude of states
  - difficult to calibrate measurements

Measuring matrix elements

- Shine laser on atom
  - detuned from any transition

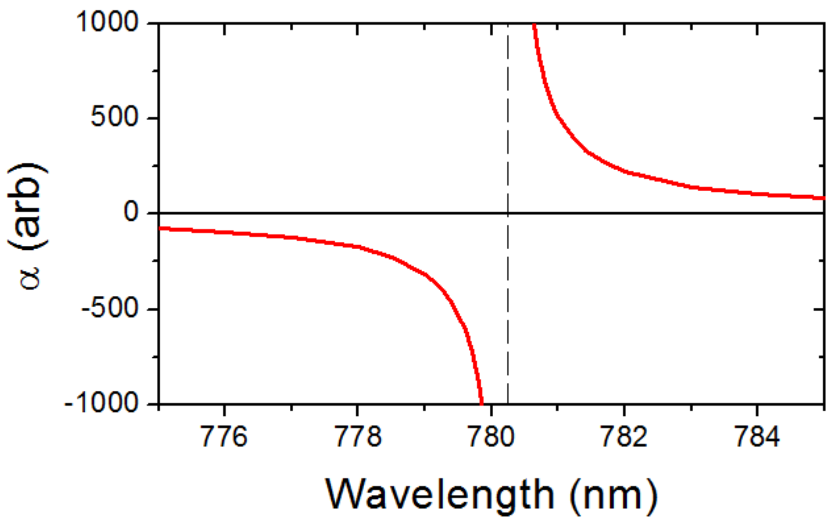
- Get energy shift

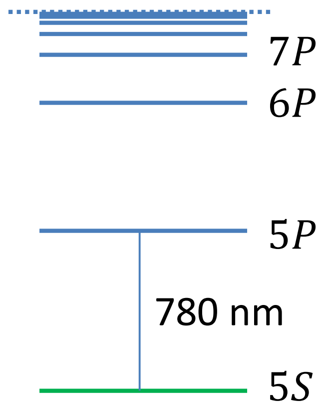
$$U = -\frac{1}{2}\alpha\langle\mathcal{E}^2\rangle \propto -\alpha I$$

α = electric polarizability
$\mathcal{E}$ = electric field
I = laser intensity

- α depends on laser frequency ω
  - Large for laser close to resonance

Measuring matrix elements





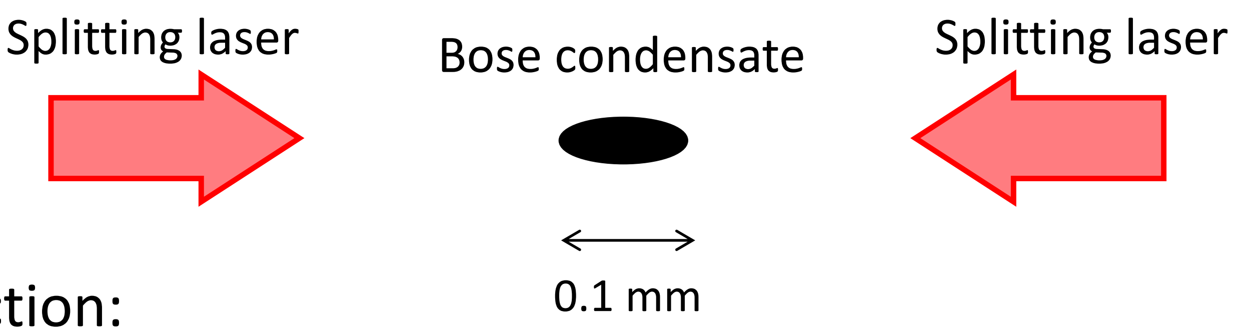
- Polarizability of $5S$ ground state

$$\alpha(\omega) \propto \sum_{\substack{n\geq 5 \\ J=1/2,3/2}} \left|\langle nP_J|\mathbf{d}|5S_{1/2}\rangle\right|^2 \frac{E_{nJ}-E_{5S}}{\left(E_{nJ}-E_{5S}\right)^2-\omega^2} + \alpha_{\mathrm{core}}$$

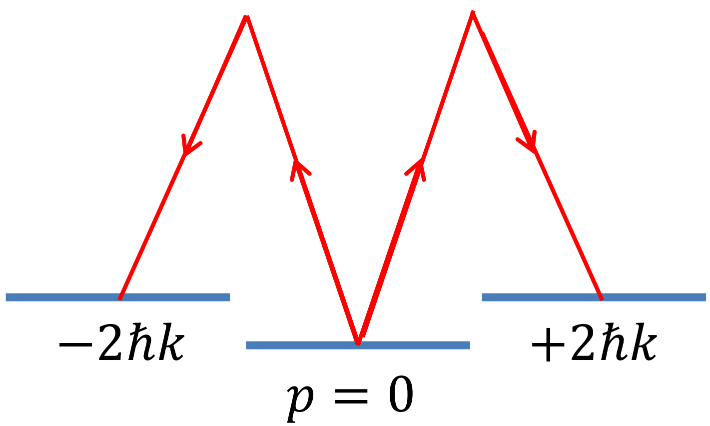
- Similar to PNC expression

Measuring matrix elements

- Measure α directly?
- One way: atom interferometer



Split wave function:



$$\frac{2\hbar k}{m} = 1.2 \text{ cm/s}$$

Atom interferometer

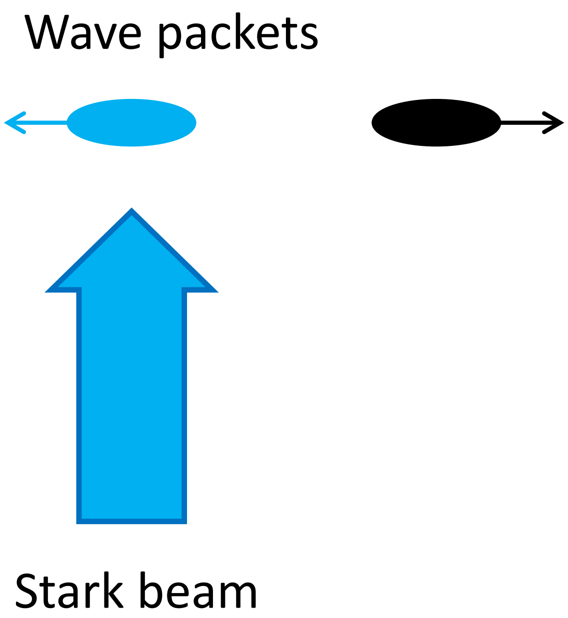
- Could measure α directly
- One way: atom interferometer

Wave packets

Let packets propagate

Atom interferometer

- Could measure α directly
- One way: atom interferometer



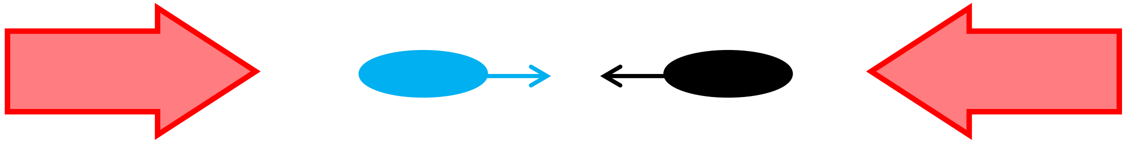
Shine laser on one packet

Phase shift

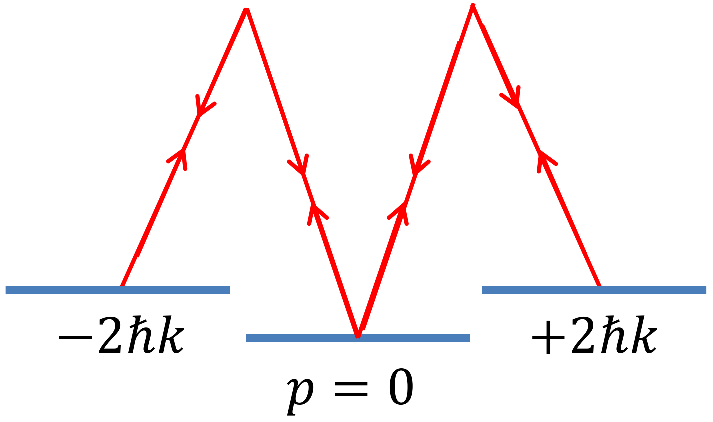
$$\phi_{\mathrm{stark}} = -\frac{Ut}{\hbar}$$

Atom interferometer

- Could measure α directly
- One way: atom interferometer



Reverse momentum of packets



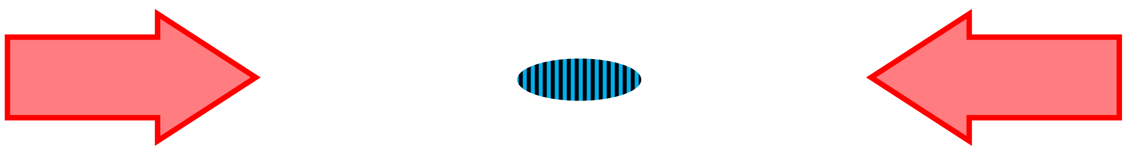
Atom interferometer

- Could measure α directly
- One way: atom interferometer

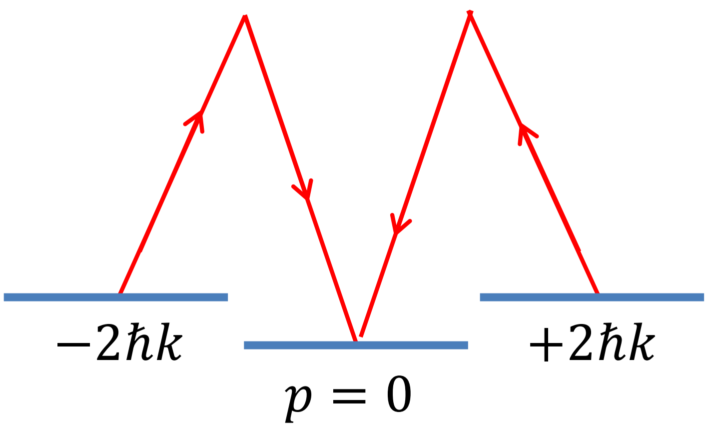
Packets return to starting point

Atom interferometer

- Could measure α directly
- One way: atom interferometer



Recombine with laser:



Interference:
Fraction of atoms returned to $p = 0$ is

$$\cos^2 \phi_{\text{stark}}$$

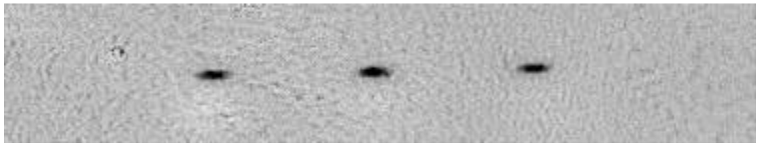
Atom interferometer

- Could measure α directly
- One way: atom interferometer

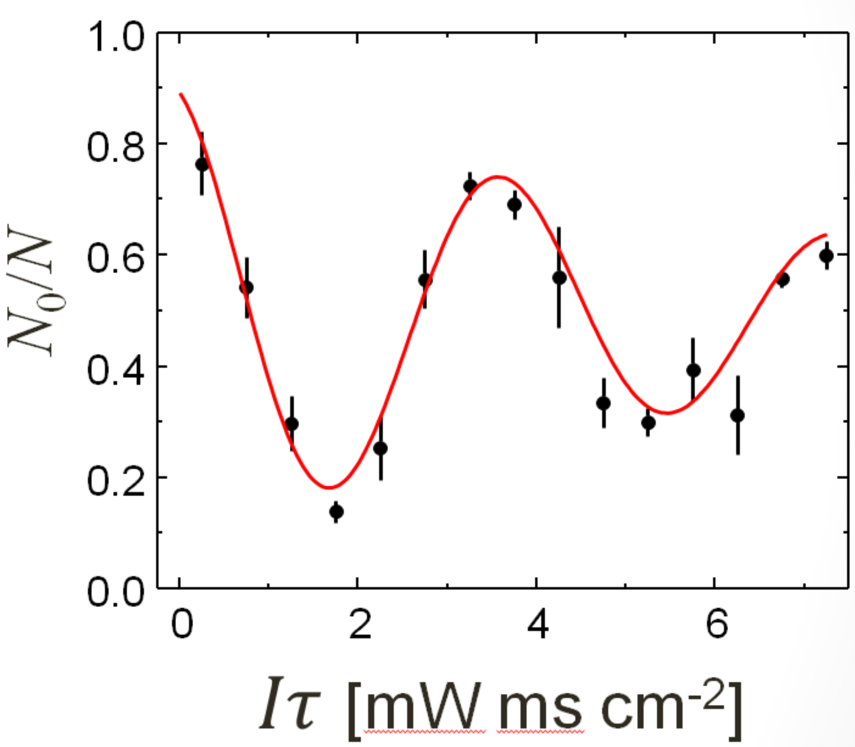
Let wave packets separate

Interference:
Fraction of atoms returned to $p = 0$ is

$$\cos^2 \phi_{\text{stark}}$$



Atom interferometer



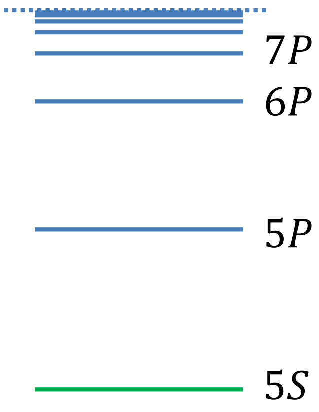
- Fit $\alpha = 5.65(16) \times 10^6$ atomic units at 780.23 nm
- 3% error, from intensity calibration
- Know $|\langle 5P|\mathbf{d}|5S\rangle|^2$ to 0.1% from lifetime

Need $\sim 10^{-5}$ precision to extract all contributions to α

Measuring matrix elements

- Polarizability of $5S$ ground state

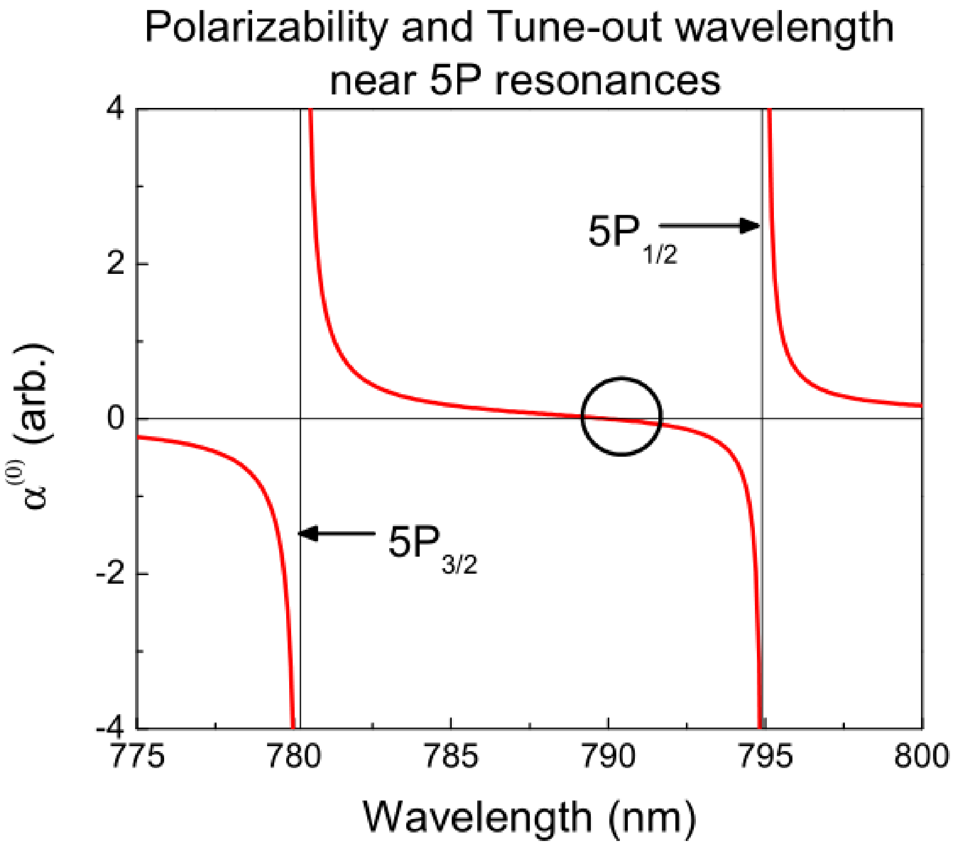
$$\alpha(\omega) \propto \alpha_{\mathrm{core}} + \sum_{\substack{n\geq 5 \\ J=1/2,3/2}} \left|\langle nP_J|\mathbf{d}|5S\rangle\right|^2 \frac{E_{nJ} - E_{5S}}{\left(E_{nJ} - E_{5S}\right)^2 - \omega^2}$$



- Find another method?

Tune-out measurement

In between resonances, α passes through 0

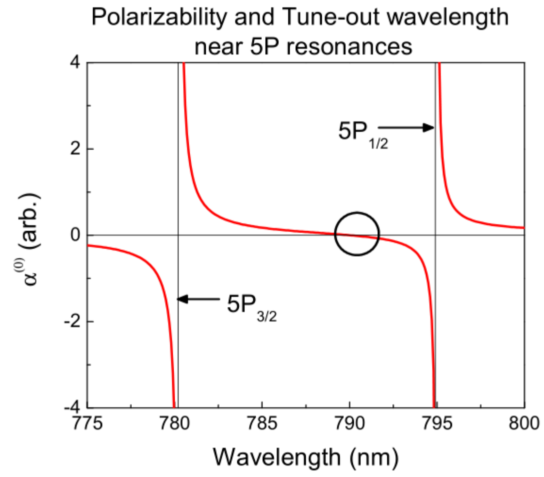


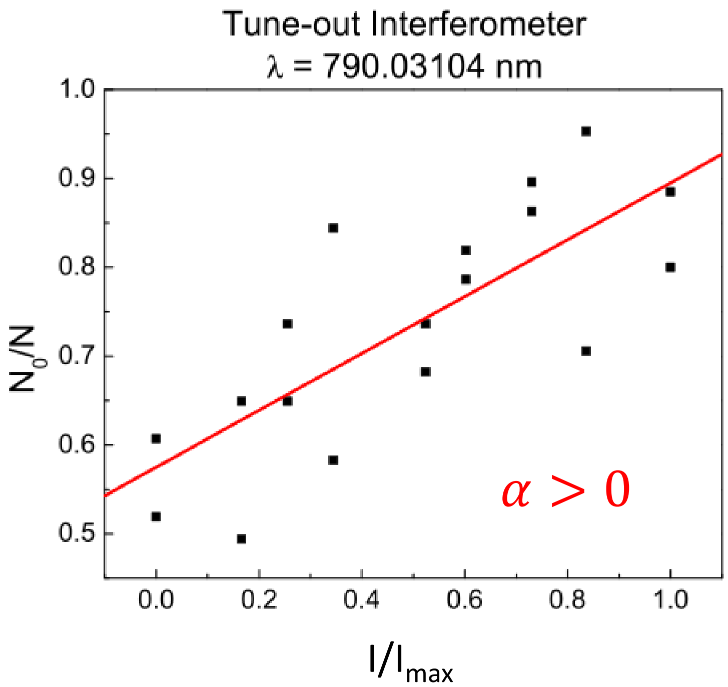
Location of zero doesn't depend on laser intensity

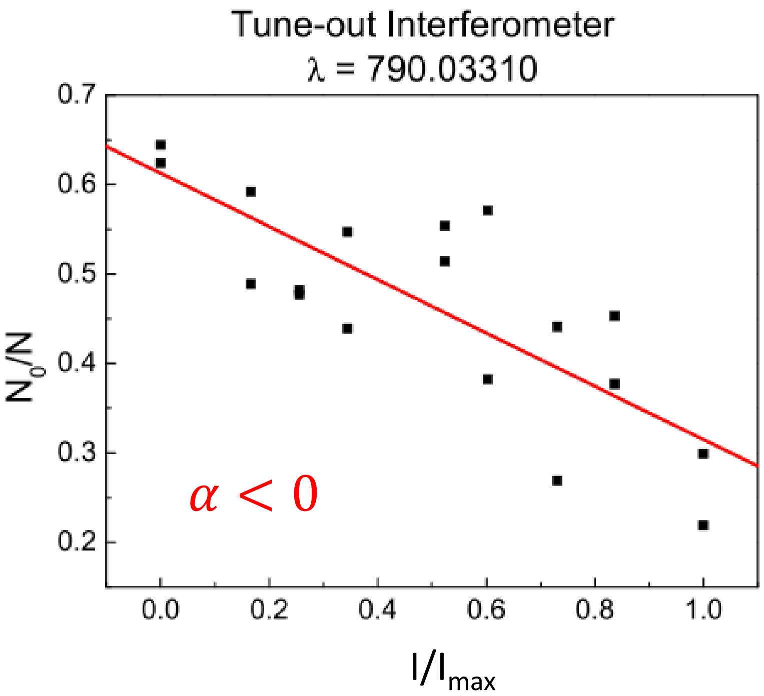
Call λ_0 = tune-out wavelength

Tune-out measurement

- Use same atom interferometer technique
- Measure slope

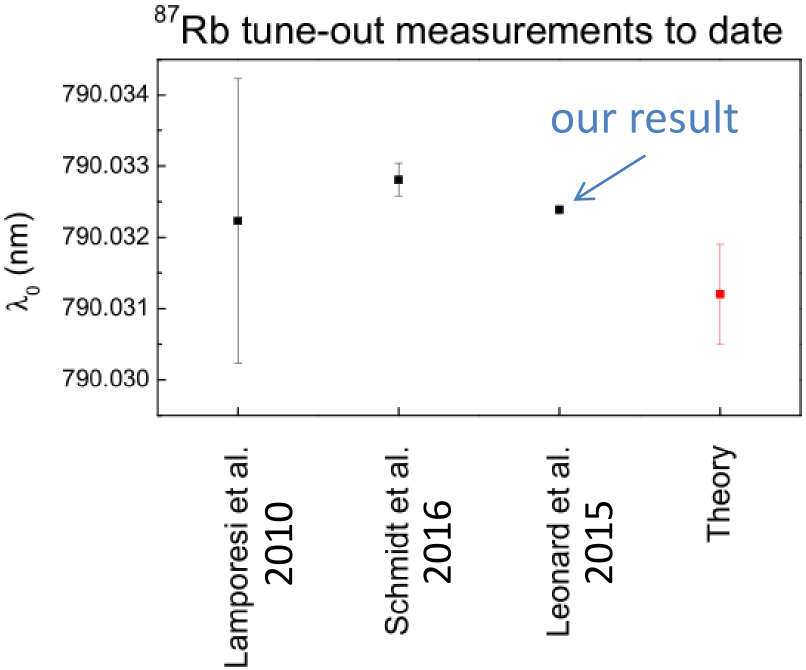


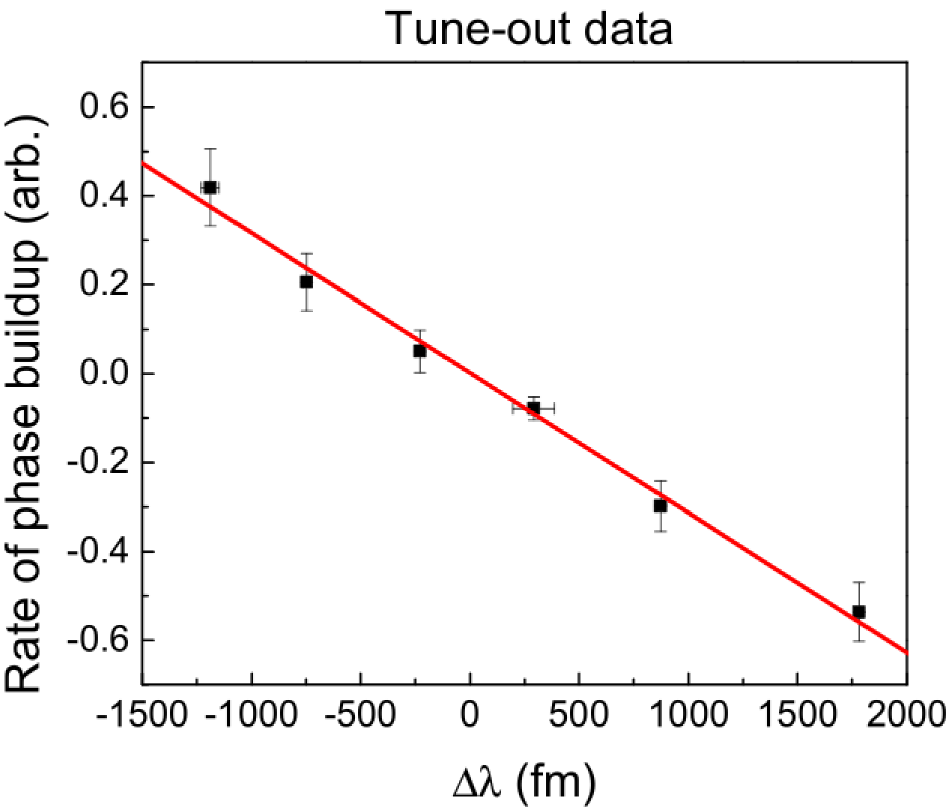




Tune-out measurement

Find $\lambda_0 =$
$790.032326\ (32)$ nm





60 × better than previous exp.
8 × better than subsequent

Compare to theory

- Measurement doesn't directly give matrix elements
- Use theory to extract information

$$\alpha = \alpha_{\text{core}} + \sum_{\substack{n \geq 5 \\ J = 1/2, 3/2}} \frac{d_{nJ}^2 \omega_{nJ}}{{\omega_{nJ}}^2 - \omega^2}$$

$$\omega_{nJ} = E_{nP_J} - E_{5S_{1/2}}$$

$$d_{nJ} = \langle nP_J | \mathbf{d} | 5S_{1/2} \rangle$$

- Contributions:

$$\alpha = \alpha_{\text{prin}} + \alpha_{\text{int}} + \alpha_{\text{tail}} + \alpha_{\text{core}}$$

α_{prin}: $5P$ states

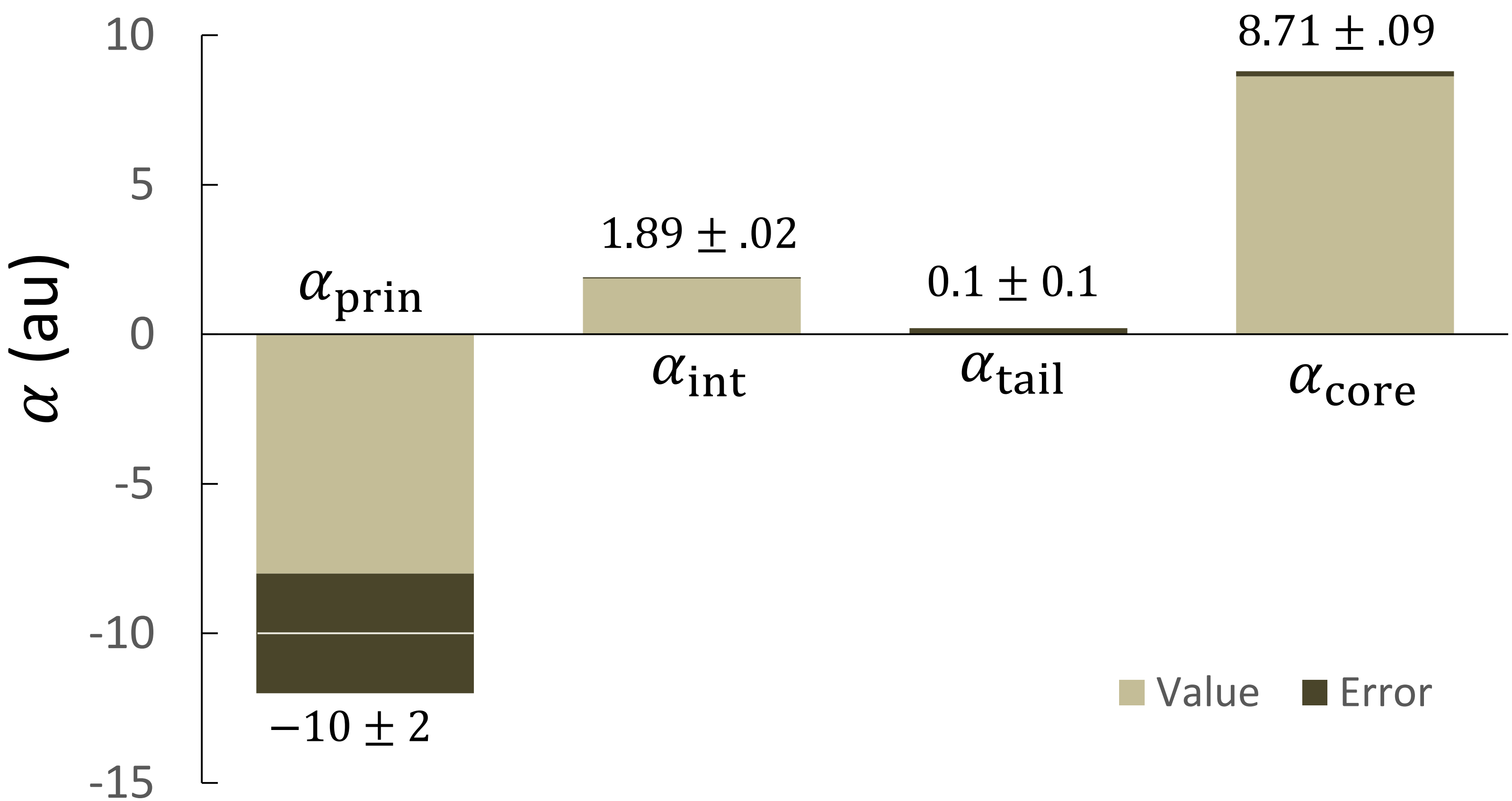
α_{int}: $n = 6$ to 12

α_{tail}: $n > 12$

α_{core}: core electrons

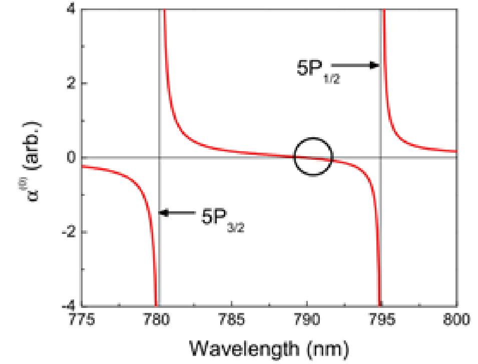
Compare to theory

- Calculate contributions for $\lambda = \lambda_0$ (M. Safronova):



Experiment says sum = 0 ± 0.1 au

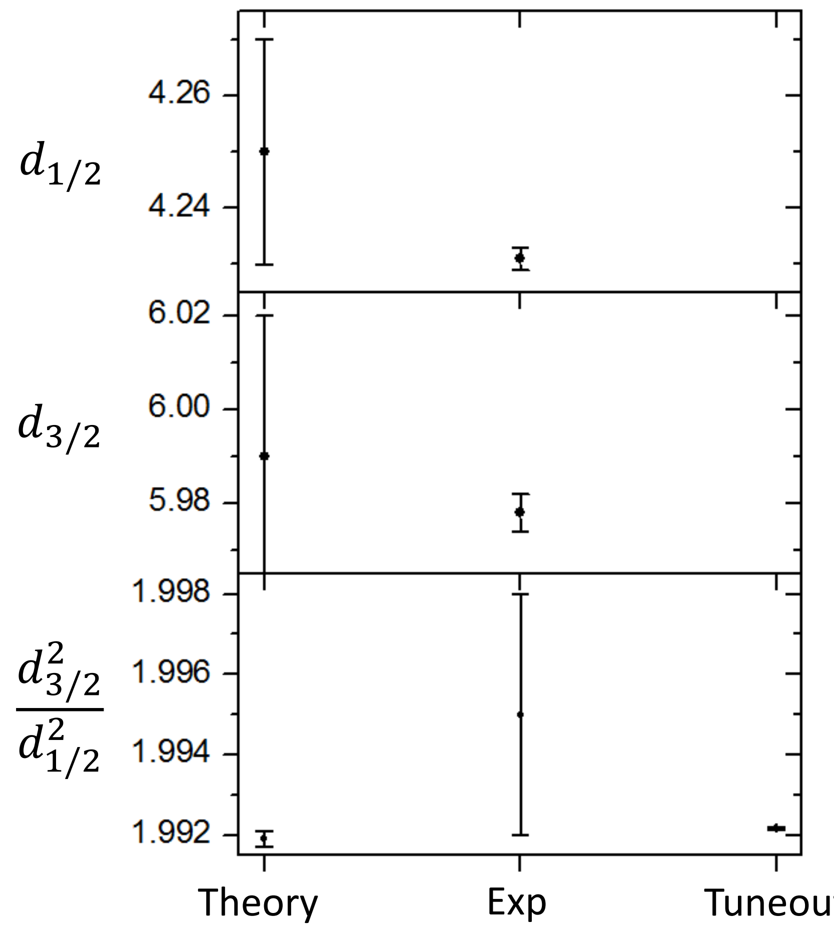
Compare to theory



- Measurement specifies $\alpha_{\text{prin}} = 5P$ contributions
  Mainly ratio $d_{3/2}^2/d_{1/2}^2$

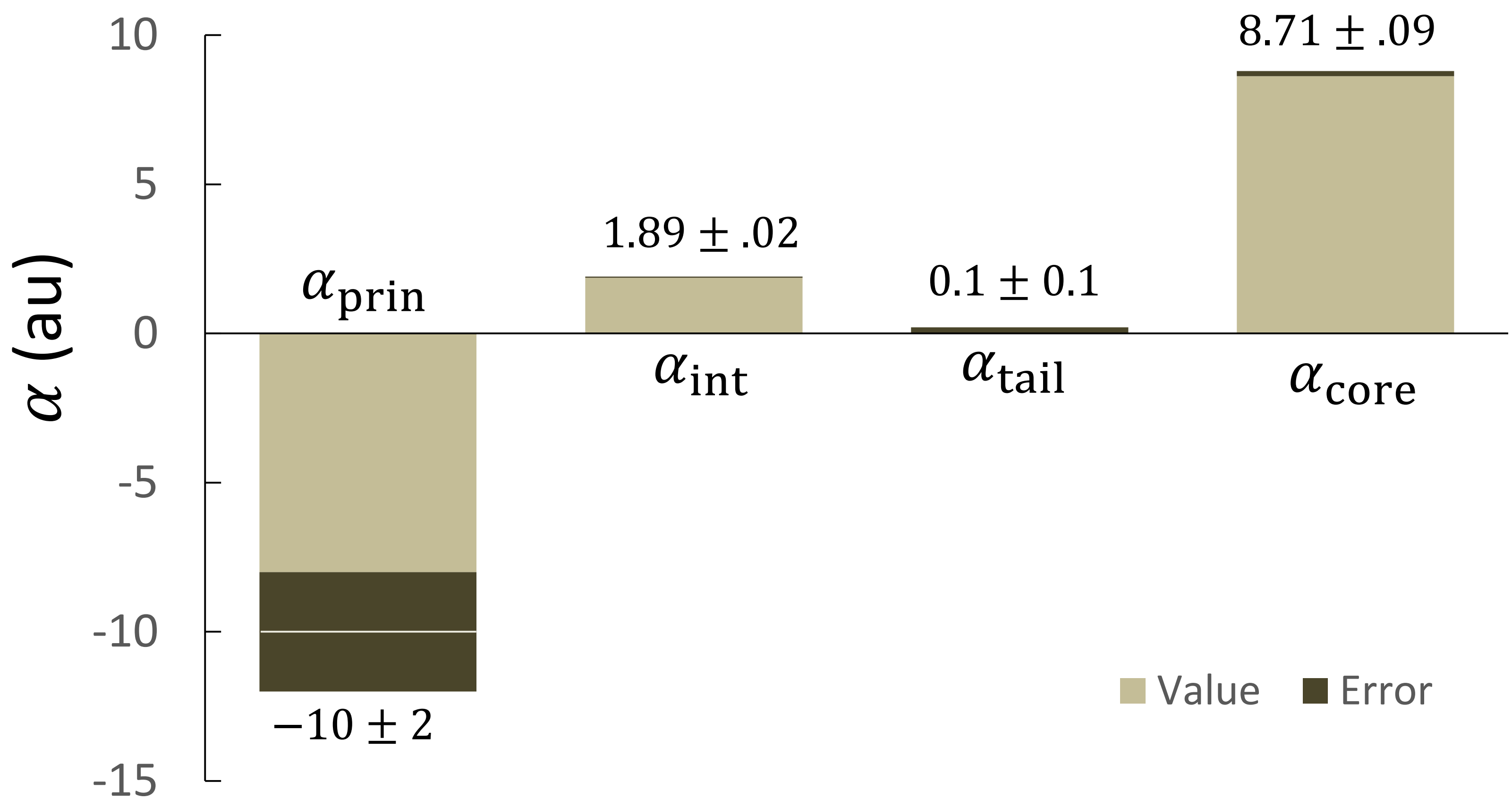
- Theory for ratio much more accurate than individual d's

- Confirmed by tune-out measurement



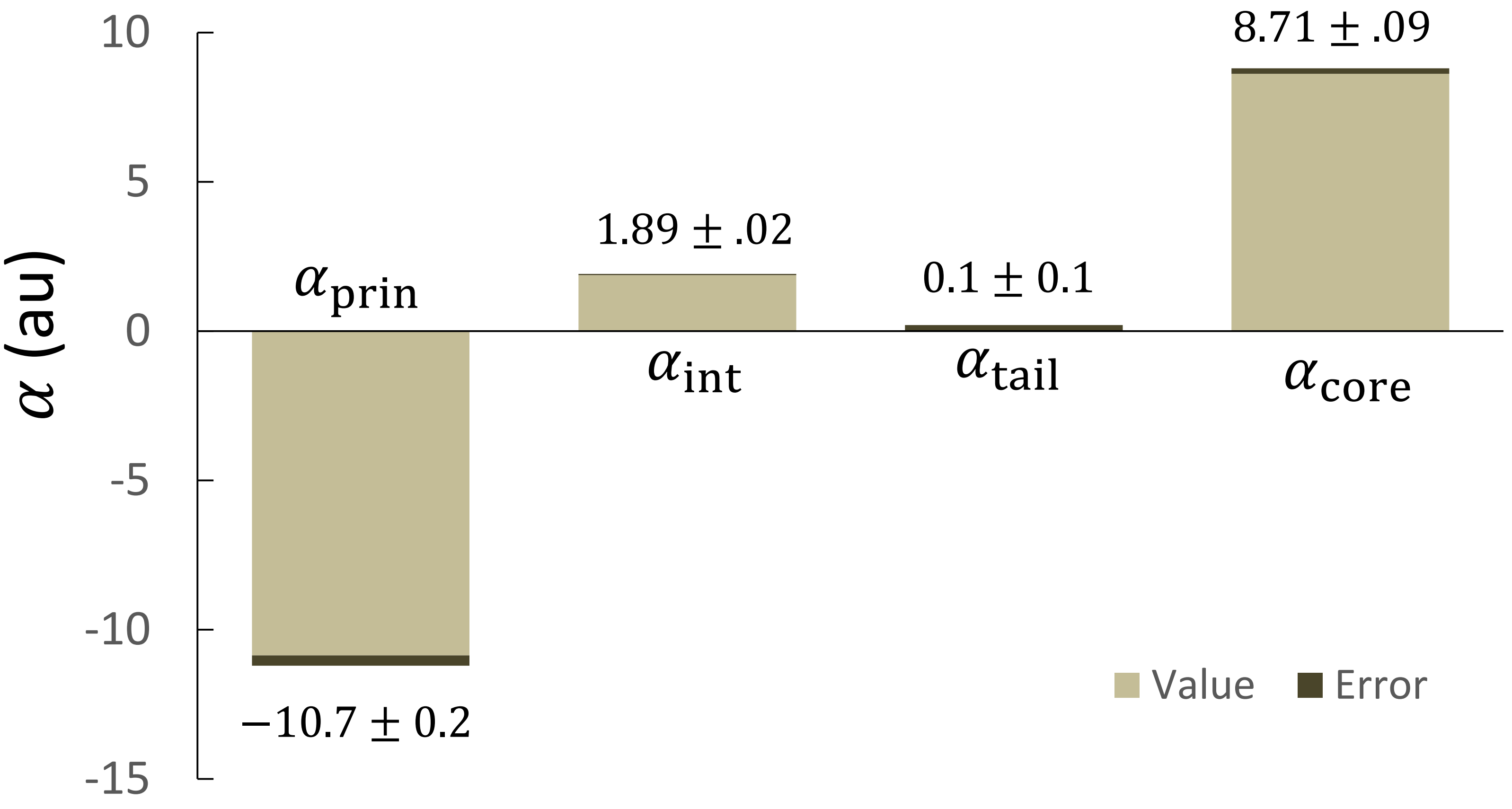
Compare to theory

- Original theory:



Compare to theory

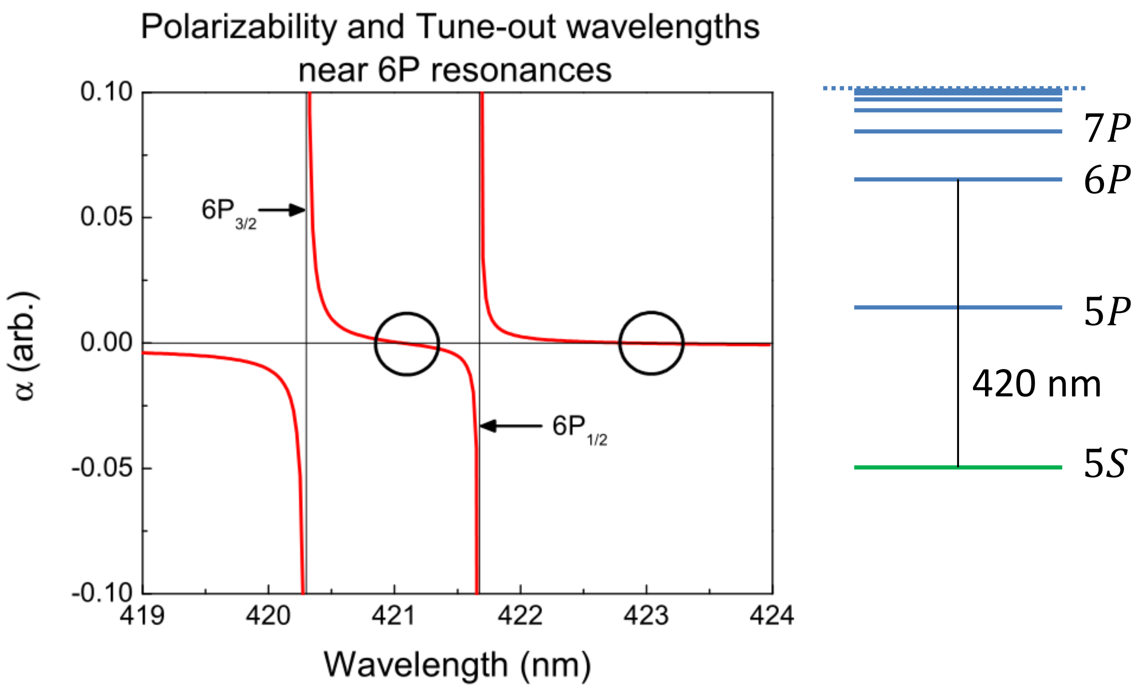
- With tune-out constraint:



Can we get more information? Especially for tail?

More measurements

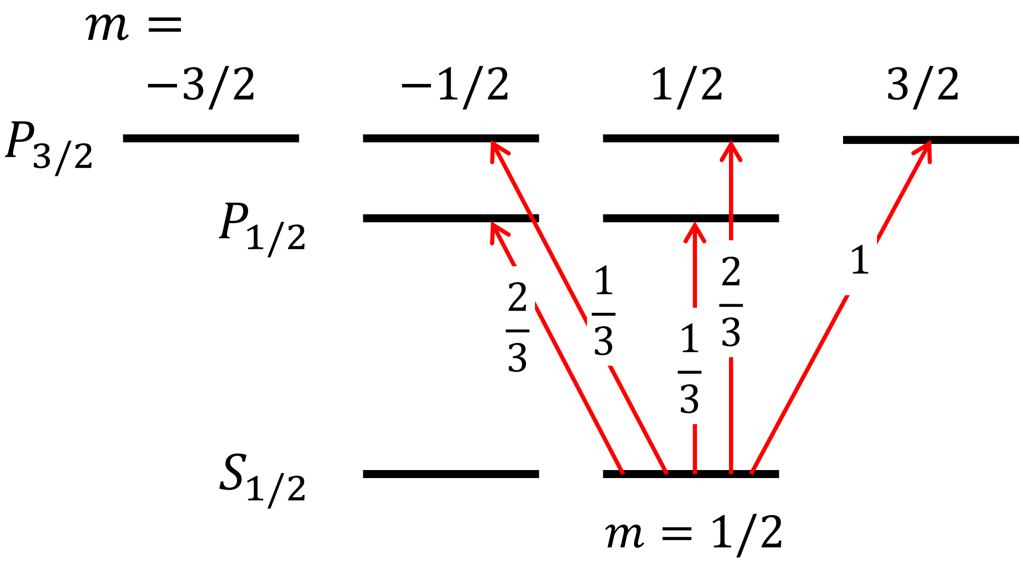
- More tune-out wavelengths near other P states

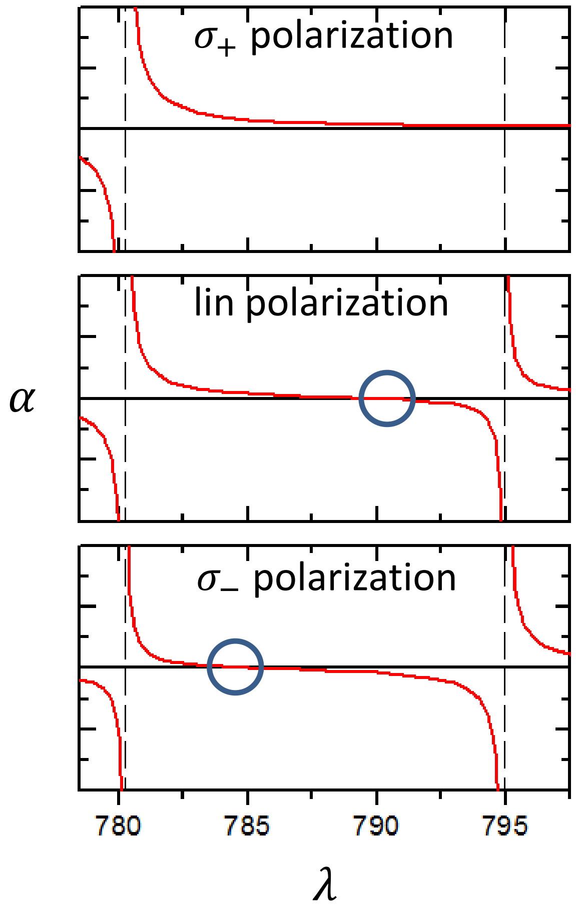


- Two more data points
  - Also two new parameters $d_{6,1/2}$ and $d_{6,3/2}$
  - Not a solution

More measurements

- Another degree of freedom: light polarization
- Atoms prepared in $m = 1/2$
- Coupling depends on polarization





Polarization effects

- Two components to polarizability:

$$\alpha = \alpha^{(0)} + v\alpha^{(1)}$$

scalar ($\alpha^{(0)}$) vector ($\alpha^{(1)}$)

v = degree of circular polarization

$$\alpha^{(0)} = \alpha^{(0)}_{\text{core}} + \sum_{n\geq 5}\left[\frac{d^2_{n3/2}\omega_{n3/2}}{{\omega_{n3/2}}^2 - \omega^2} + \frac{d^2_{n_{1/2}}\omega_{n1/2}}{{\omega_{n1/2}}^2 - \omega^2}\right]$$

$$\alpha^{(1)} = \alpha^{(1)}_{\text{core}} + \sum_{n\geq 5}\left[\frac{d^2_{n3/2}\omega}{{\omega_{n3/2}}^2 - \omega^2} - \frac{2d^2_{n_{1/2}}\omega}{{\omega_{n1/2}}^2 - \omega^2}\right]$$

Polarization effects

- Measuring $\alpha^{(0)}$ and $\alpha^{(1)}$ gives two data points per λ_0
  - different dependence on matrix elements

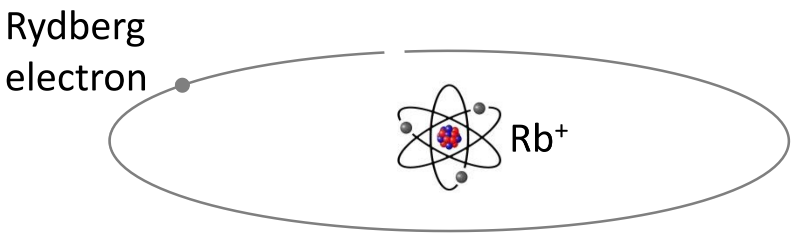
- Measure near $5P$ and $6P$ states:
  - three tune-out wavelengths
  - six polarizabilities
  - seven unknowns (all normalized to $d_{5,1/2}$):

$$d_{5,3/2} \quad d_{6,3/2} \quad d_{6,1/2} \quad \alpha^{(0)}_{\text{core}} \quad \alpha^{(1)}_{\text{core}} \quad \alpha^{(0)}_{\text{tail}} \quad \alpha^{(1)}_{\text{tail}}$$

- Measure $\alpha^{(0)}_{\text{core}}$ using Rydberg atoms

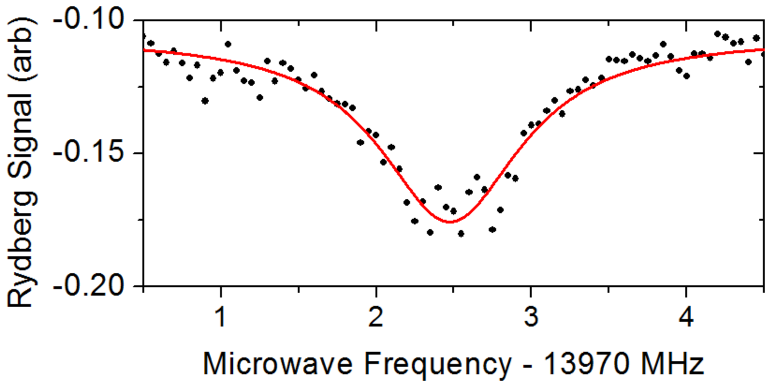
Rydberg measurement

- Electron in high-n, high-L state does not penetrate core
- Energy shifted by polarizability of core $\alpha_{core}^{(0)}$



- Collaborating with TFG to measure for Rb

Microwave spectroscopy on 18f to 18g transition:



Polarization effects

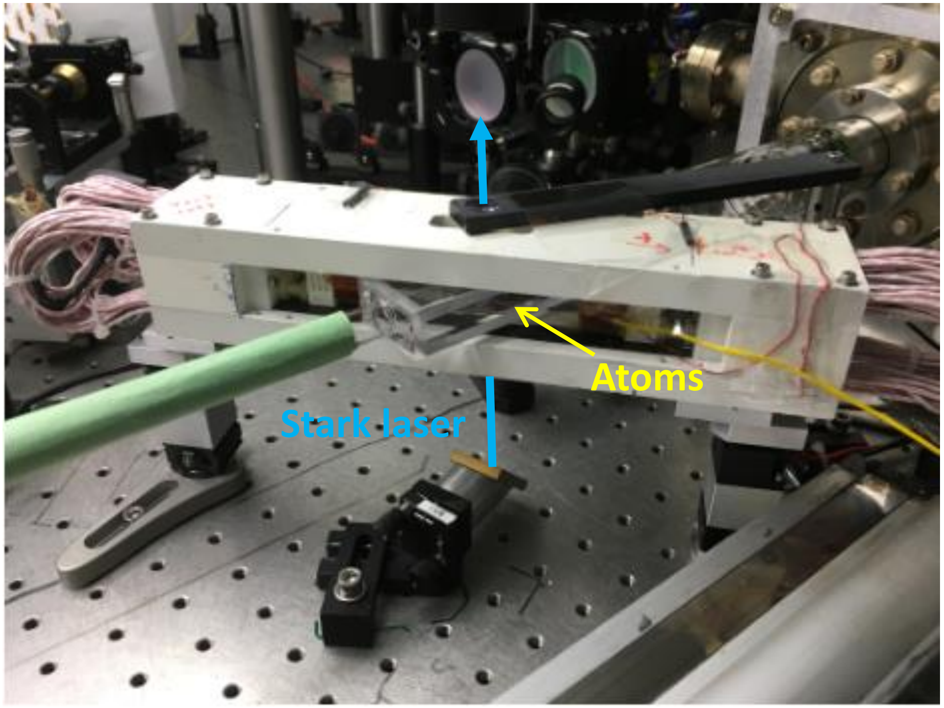
- Measuring $\alpha^{(0)}$ and $\alpha^{(1)}$ gives two data points
  - different dependence on matrix elements

- Measure near $5P$ and $6P$ states:
  - three tune-out wavelengths
  - six polarizability constraints
  - ~~seven~~ six unknowns (all normalized to $d_{5,1/2}$):

$$d_{5,3/2} \quad d_{6,3/2} \quad d_{6,1/2} \quad \cancel{\alpha^{(0)}_{\text{core}}} \quad \alpha^{(1)}_{\text{core}} \quad \alpha^{(0)}_{\text{tail}} \quad \alpha^{(1)}_{\text{tail}}$$

Polarization measurements

- Need precise control of light polarization $\sim 10^{-5}$
- Distorted by vacuum window $\sim 10^{-3}$



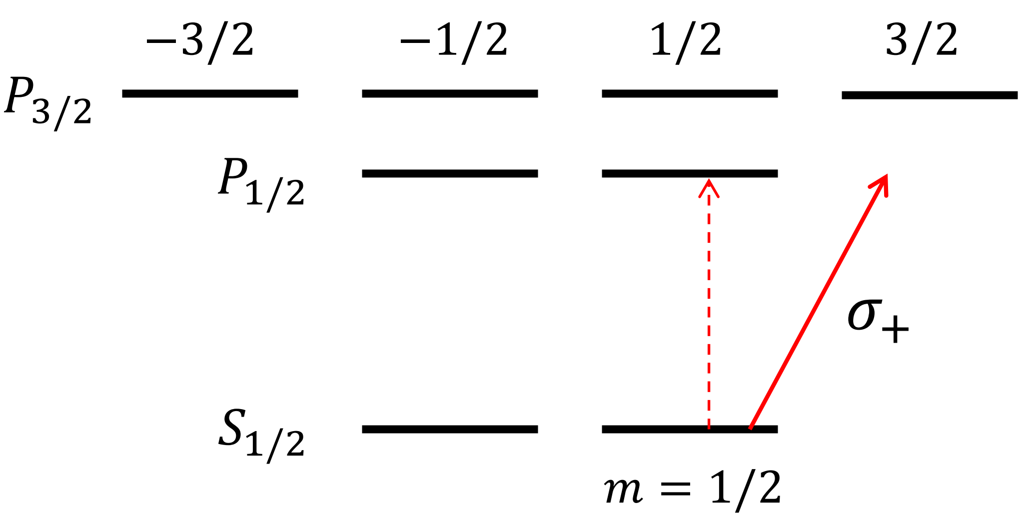
Polarization measurements

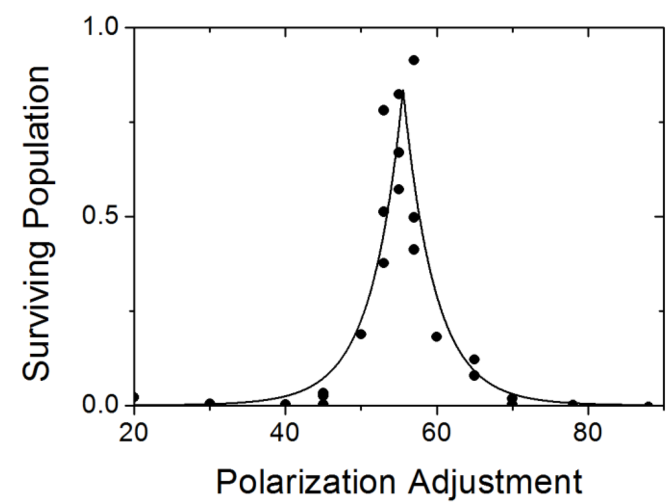
- Minimize errors using circularly polarized light:

  v parameter = ± 1 = max or min

  deviations 2nd order in distortion effect $\sim 10^{-6}$

- Establish circular polarization using atoms





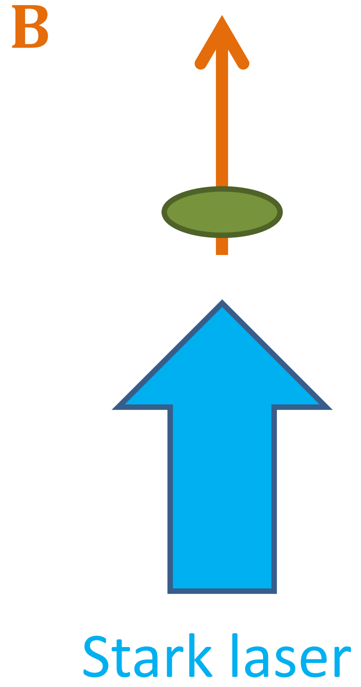
Polarization control

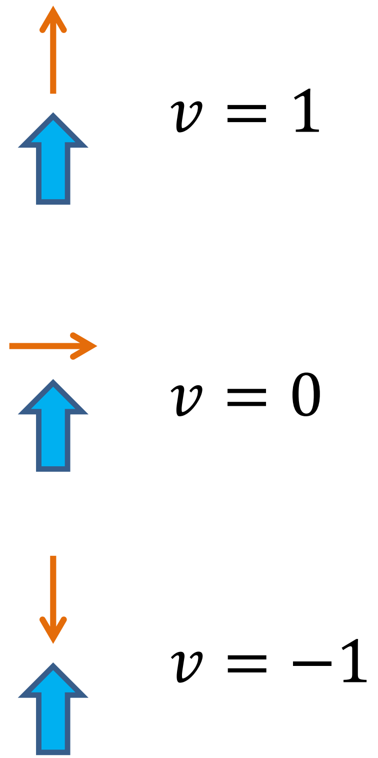
- Apply circular polarized light to atoms

$$\alpha = \alpha^{(0)} + v\alpha^{(1)}$$

$v \sim$ amount of circ polz

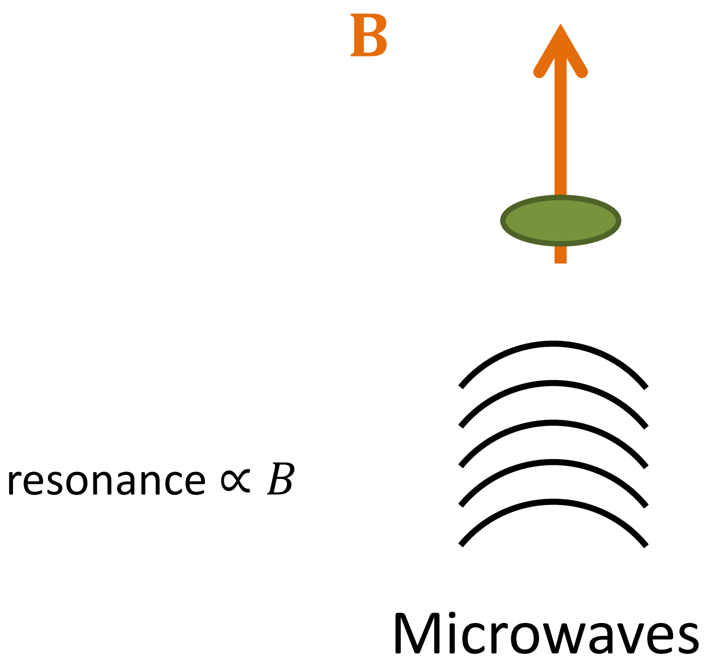
- Vary v using magnetic field





Polarization control

- Need to ensure that $\mathbf{B}$ is behaving as expected
- Use same trick with microwave spectroscopy



Polarization control

- Need to ensure that **B** is behaving as expected
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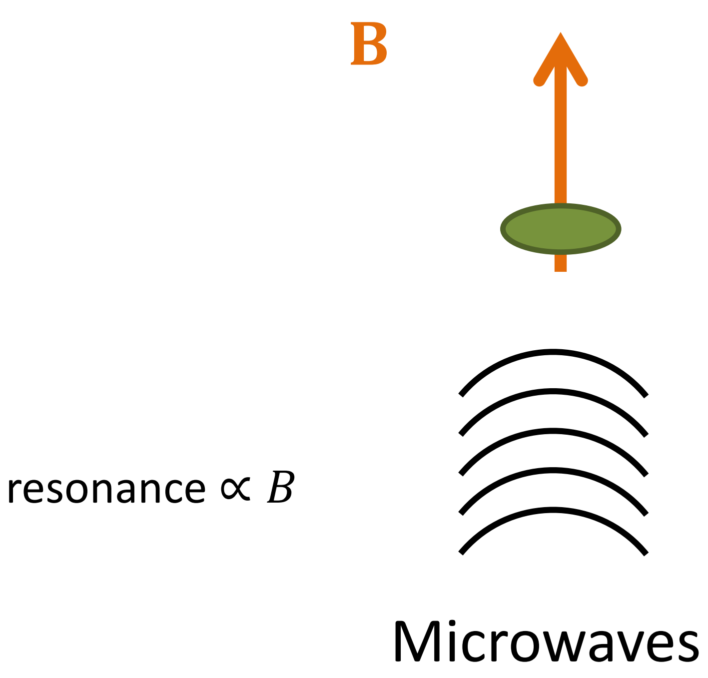
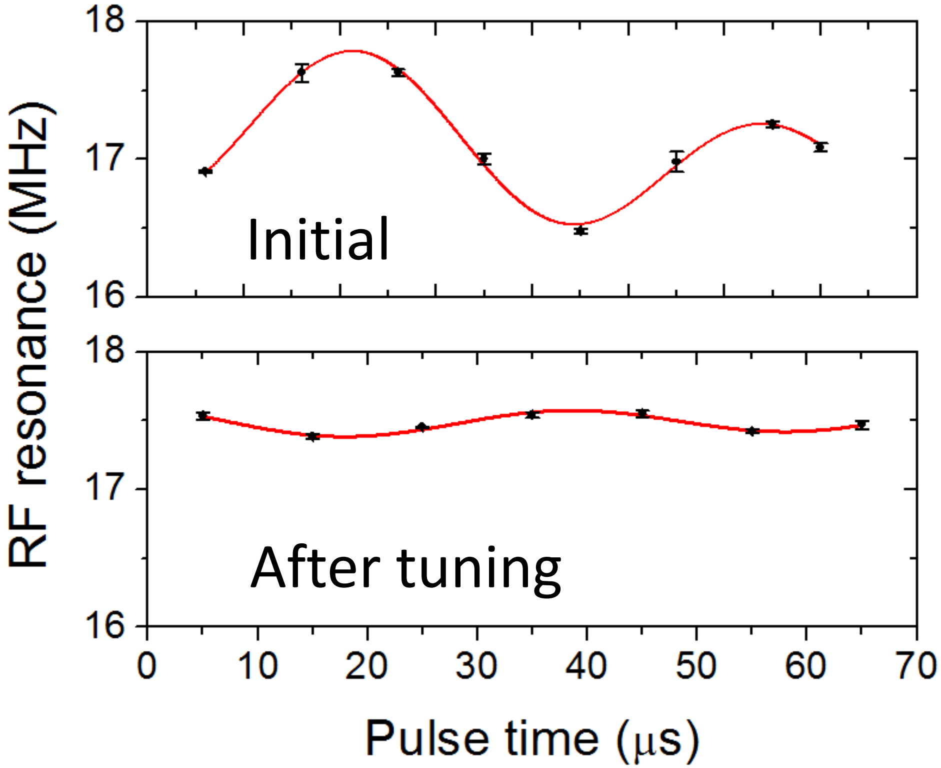




Expected results

- Completing polarization and B-field characterization
- Measure $5P$ states soon, then $6P$ states
- Monte Carlo model:

    For expected meas. accuracy, get α_{tail} to 0.01 au

    $\sim 10\times$ better than current theory

- Resolve parity violation bottleneck?

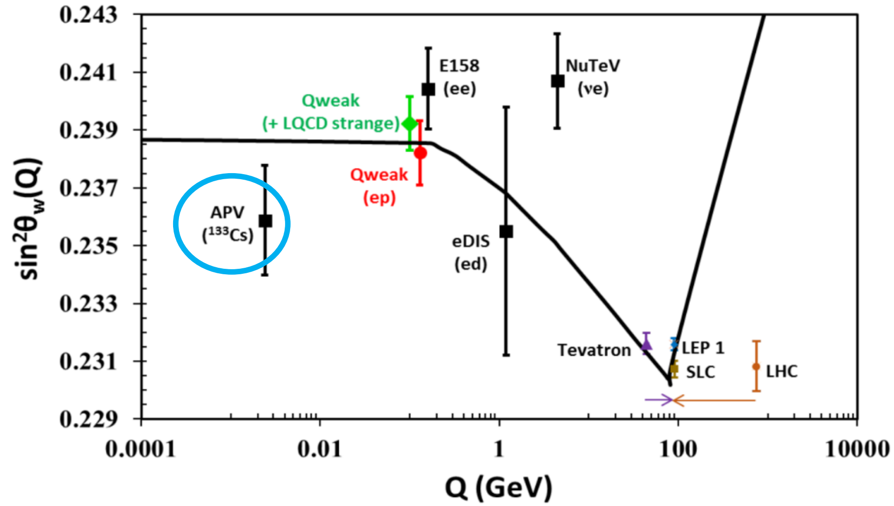
Impact

- Issues:
  - Measure with Rb, parity exp with Cs
  - Tail contribution not exactly same for α, PV exps
- Provide benchmark for theory
  - Test methods, learn what works

- Motivate PV experiment in rubidium?
  - $A_{PV} \propto Z^3$, 3× bigger in Cs
  - But new experiment more than 3× better?

Conclusions

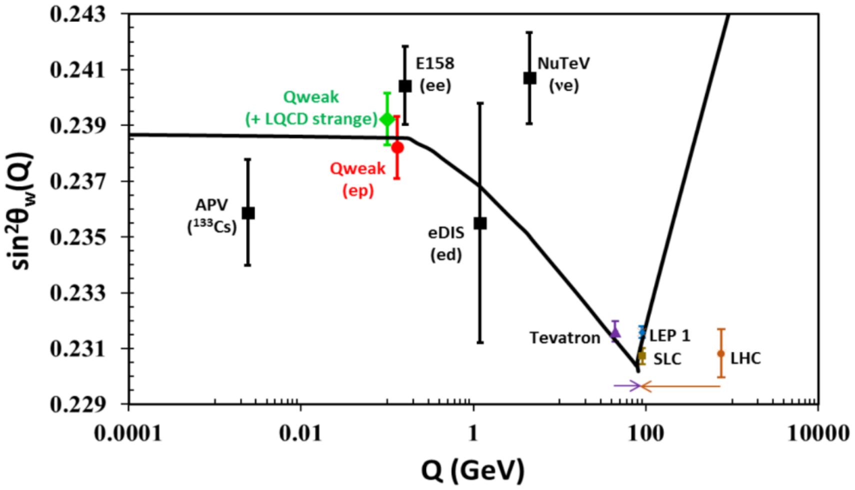
- Details of atomic structure needed for better PV exp.
- Obtain with tune-out spectroscopy



- Other applications:
  - Atomic clocks
  - EDM experiments
  - Precision atom trapping/quantum computing

Conclusions

- Illustrate how AMO experiment involve many pieces



New result will be based on advances in:

atom trapping, BEC, lasers, spectroscopy, atomic theory, ... ?

Many contributions from many people

Credits

Grad students:
- Adam Fallon
- Seth Berl
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Theory:
- Marianna Safronova

Funding:
- NSF, NASA