Title: Precision Spectroscopy of Atomic Lithium

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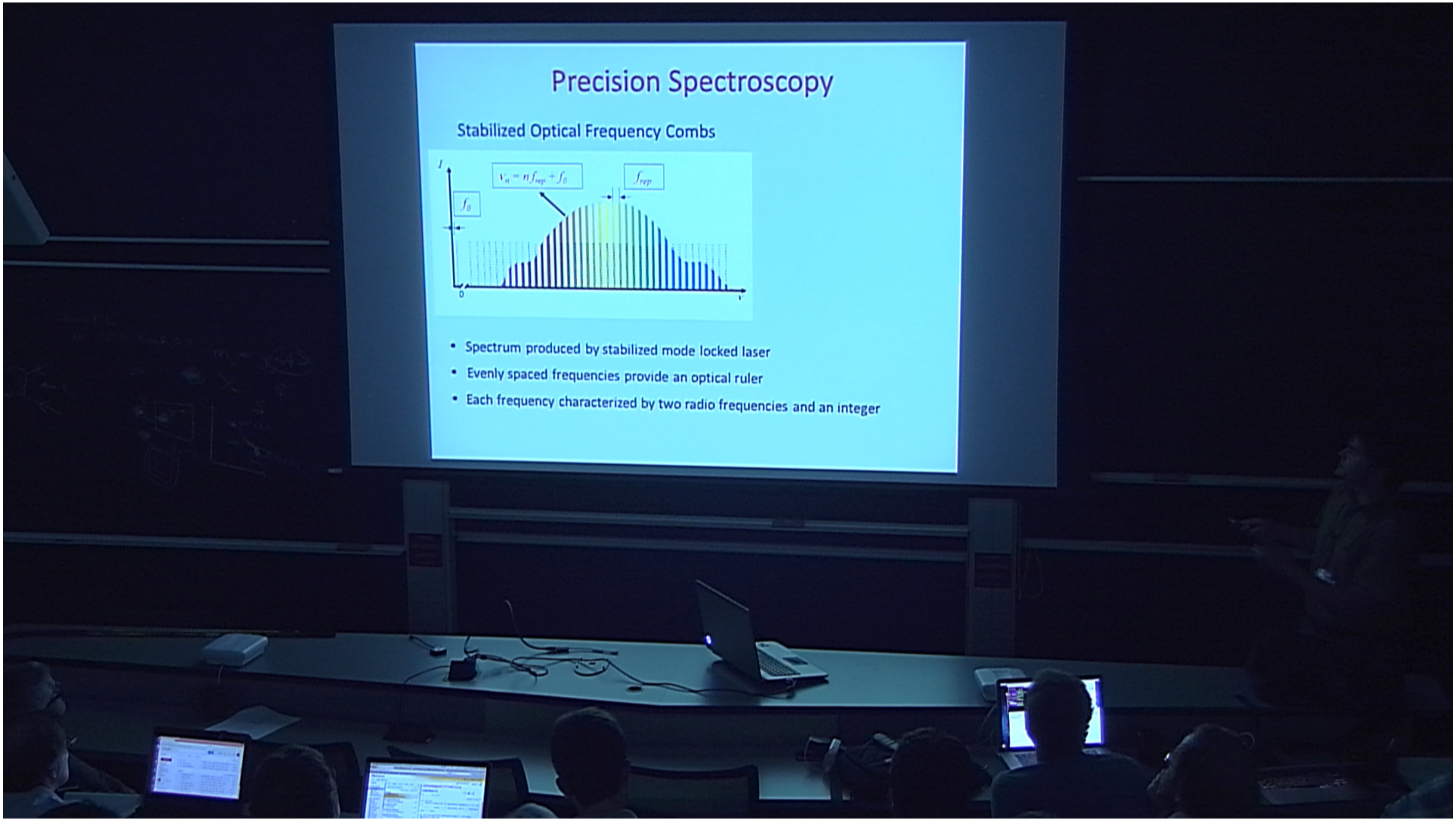
URL: http://pirsa.org/14060022

Abstract: The simplicity of the atomic structure of lithium has long made it a system of theoretical interest. With the development of stabilized optical frequency combs, it is possible to achieve experimental accuracies that provide significant tests of atomic theory calculations as well as a window into nuclear structure. I will discuss an ongoing experimental effort at Oberlin College to measure the energy levels of lithium using a stabilized optical frequency comb.



Precision Spectroscopy

Stabilized Optical Frequency Combs

- Spectrum produced by stabilized mode locked laser
- Evenly spaced frequencies provide an optical ruler
- Each frequency characterized by two radio frequencies and an integer

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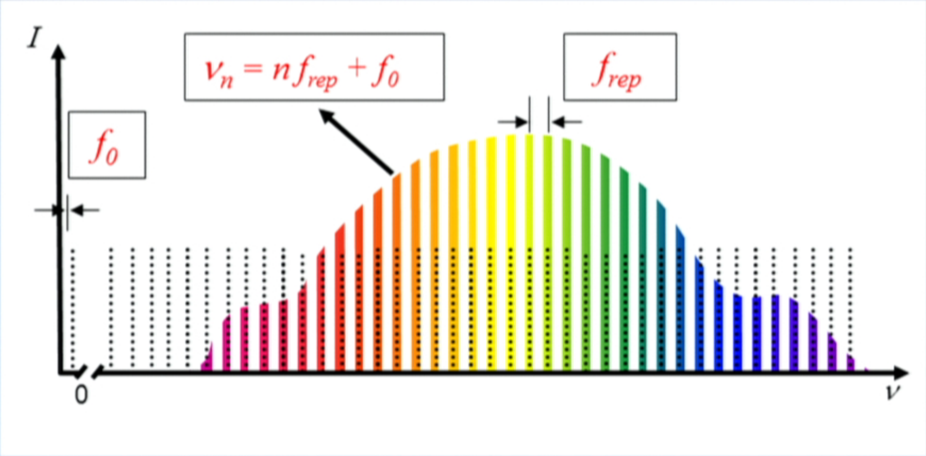
Stabilized Optical Frequency Combs



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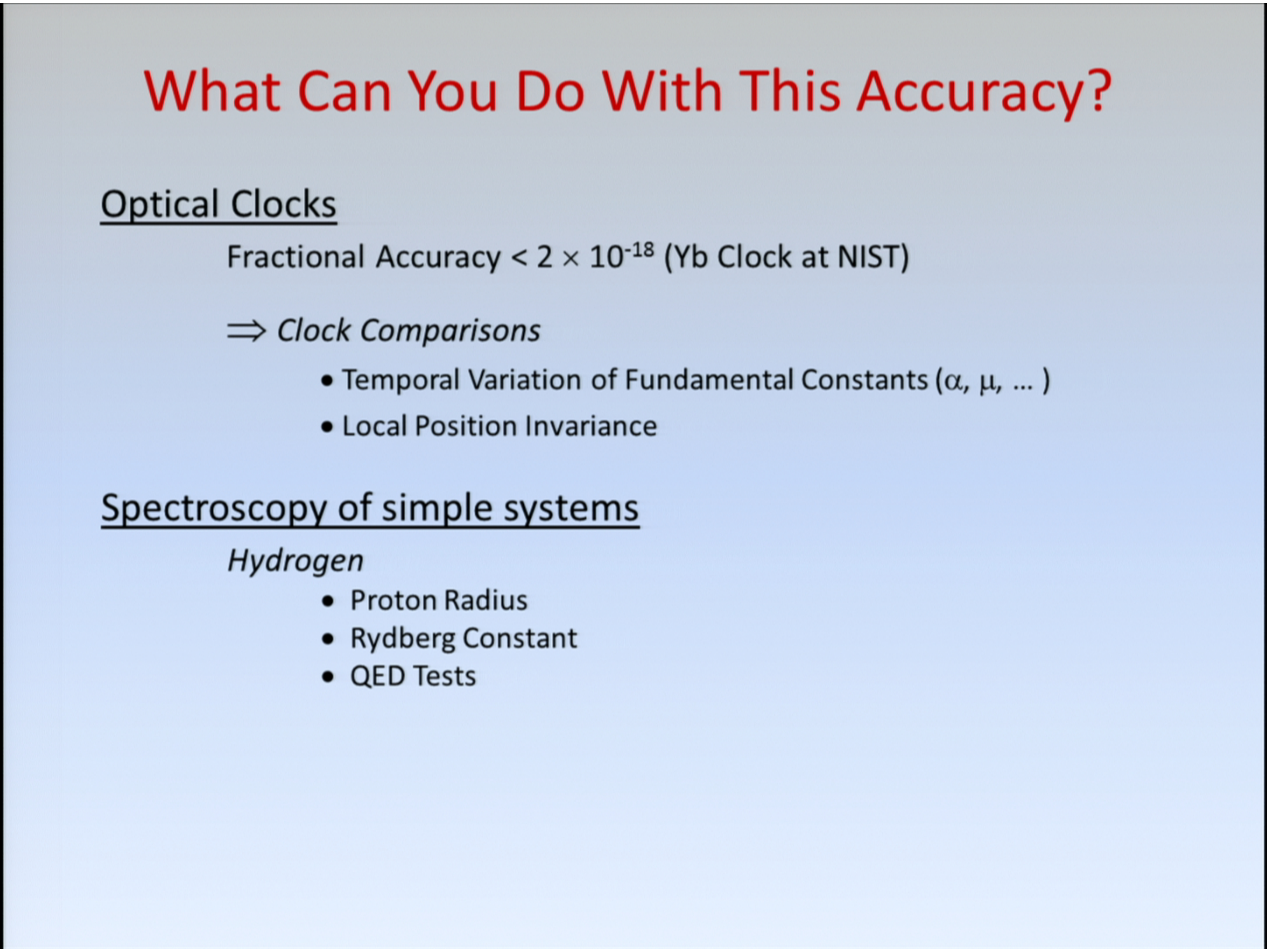


What Can You Do With This Accuracy?

Optical Clocks

Fractional Accuracy < 2 × 10^{-18} (Yb Clock at NIST)

⇒ *Clock Comparisons*

- Temporal Variation of Fundamental Constants (α, μ, …)
- Local Position Invariance

Spectroscopy of simple systems

Hydrogen

- Proton Radius
- Rydberg Constant
- QED Tests

Lithium

Lithium

Accurate Atomic Structure Calculations

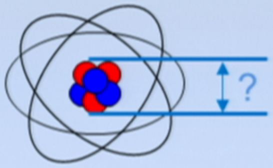
Nonrelativistic Solutions to Schödinger Equation + Relativistic Corrections

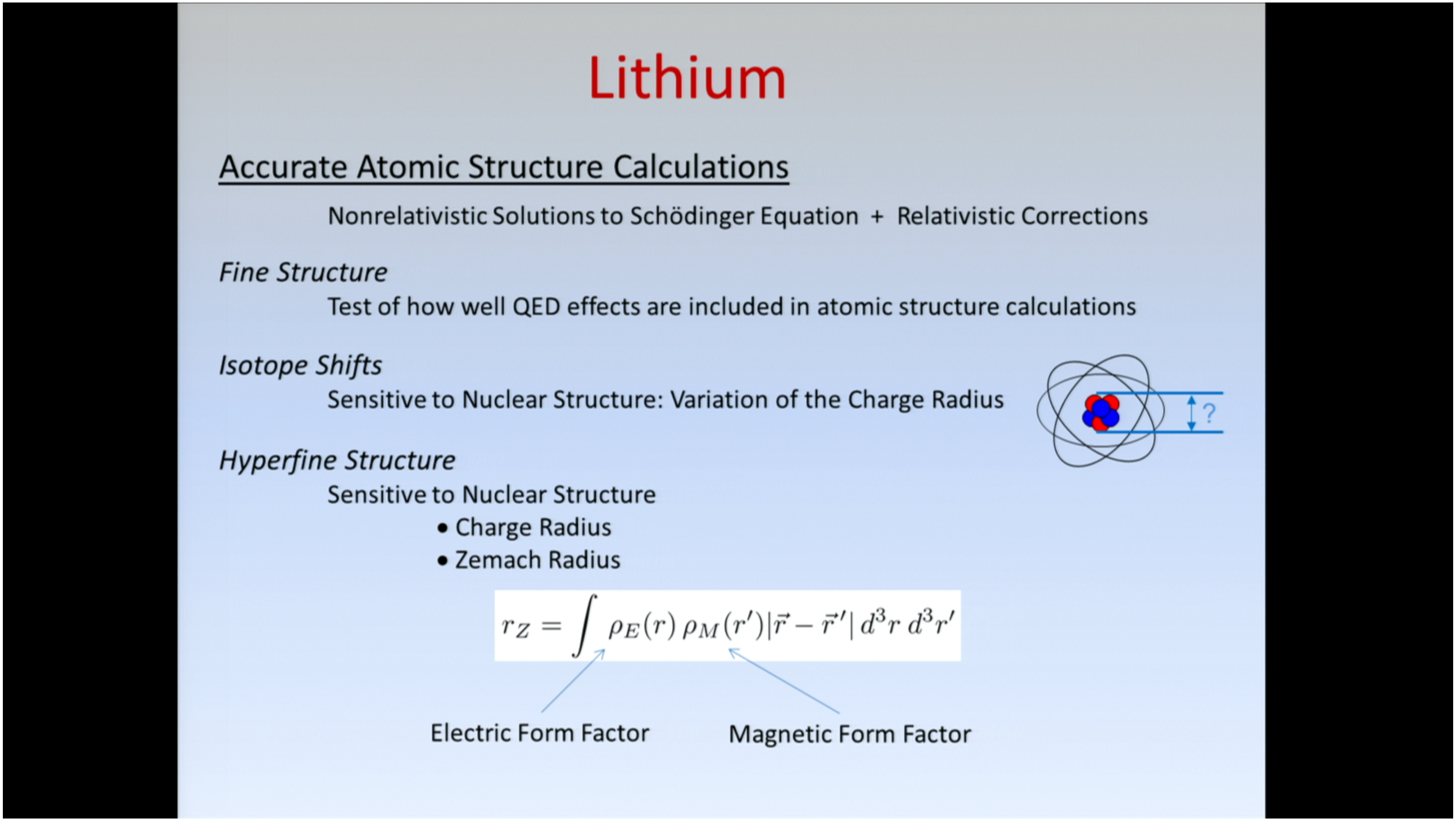
Fine Structure

Test of how well QED effects are included in atomic structure calculations

Isotope Shifts

Sensitive to Nuclear Structure: Variation of the Charge Radius





Lithium

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Sensitive to Nuclear Structure: Variation of the Charge Radius

Hyperfine Structure

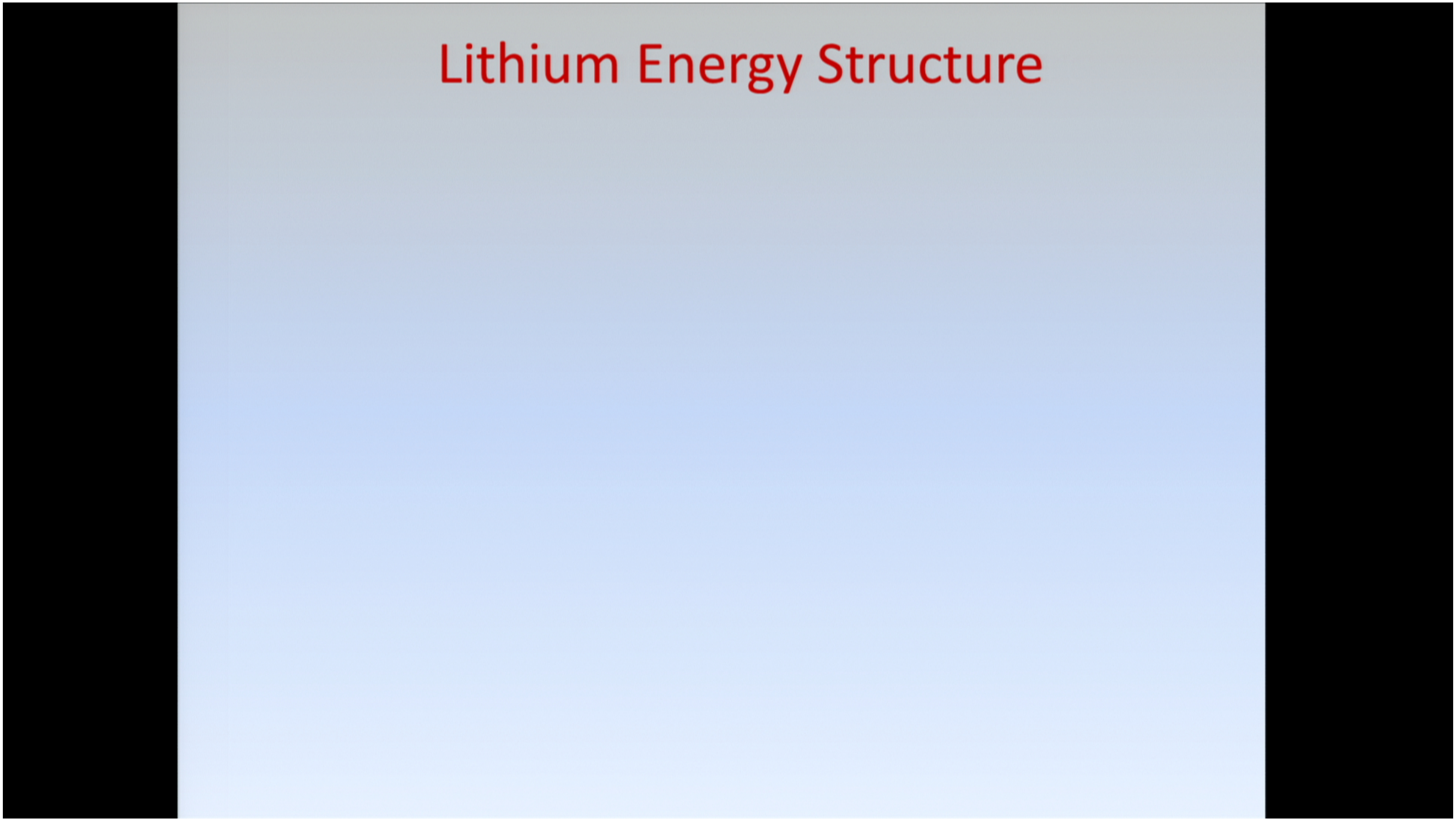
Sensitive to Nuclear Structure

- Charge Radius
- Zemach Radius

$$r_Z = \int \rho_E(r)\,\rho_M(r')|\vec{r}-\vec{r}\,'|\,d^3r\,d^3r'$$

Electric Form Factor

Magnetic Form Factor



Lithium Energy Structure

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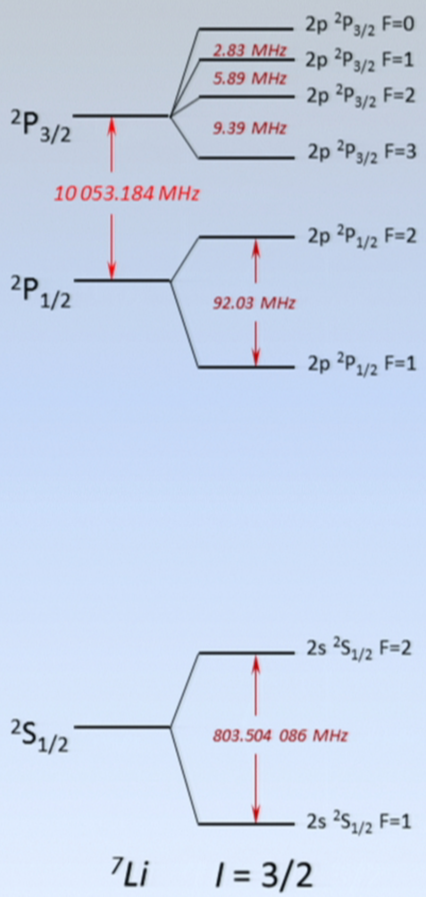

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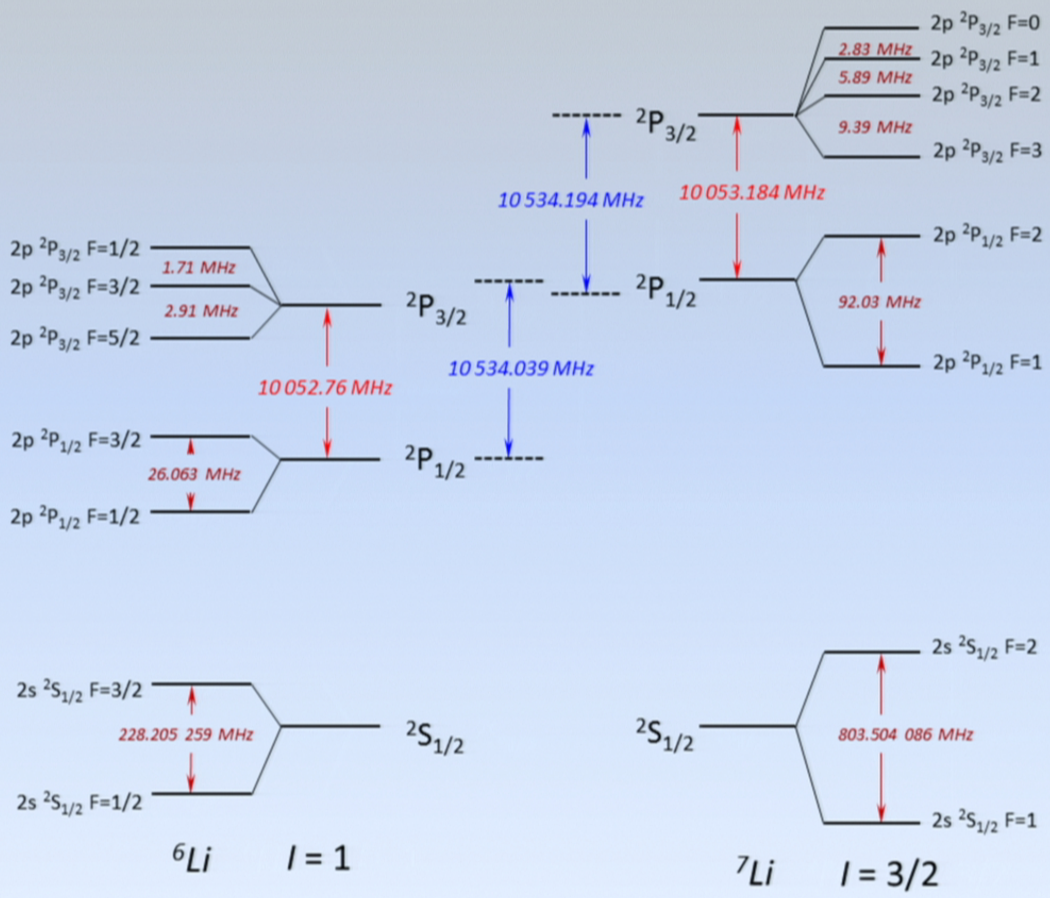
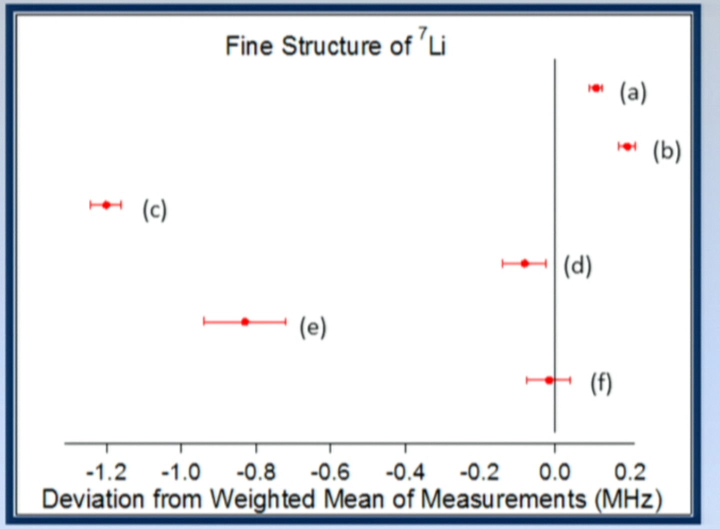
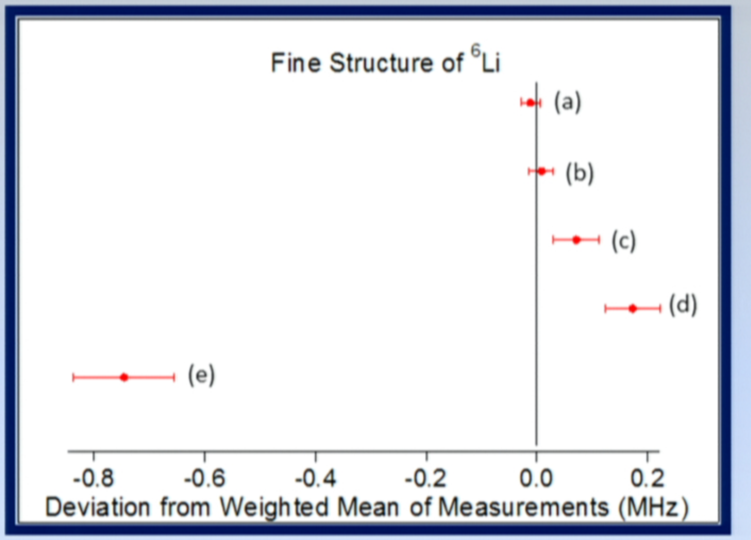


Previous Measurements

Fine Structure





References

(a) R.C. Brown, *et al*. Phys. Rev. A **87**, 032504 (2013).
(b) C.J. Sansonetti, *et al.* Phys. Rev. Lett. **107**, 023001 (2011).
(c) D. Das and V. Natarajan, Phys. Rev. A **75**, 052508 (2007).
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(f) H. Orth, H. Ackermann, and E.W. Otten, Z. Physik A **273**, 221 (1975).

Why is the agreement so poor?

Large frequency splitting (10 GHz) difficult to measure without frequency comb

Hyperfine structure of the 2 $^2P_{3/2}$ state is unresolved ($\gamma_0 \cong 6$ MHz)

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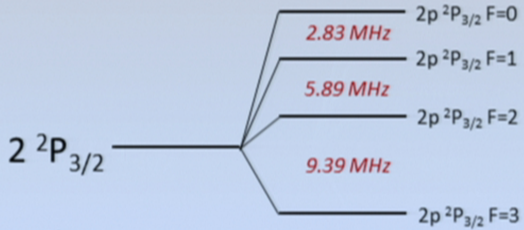

⇒ Interference in the fluorescence distribution

C.J. Sansonetti, et al. Phys. Rev. Lett. **107**, 023001 (2011).

$$\boxed{\frac{dW_{i\to f}}{d\Omega} = \frac{\pi\,\varepsilon^2\,\omega_s^3}{h^3\,c^3\,\epsilon_0}\left|\sum_j \frac{\left(\hat{\epsilon}_s^*\cdot\vec{d}_{fj}\right)\left(\hat{\epsilon}_L\cdot\vec{d}_{ji}\right)}{\omega_{ji}-\omega_L-\frac{i\,\gamma_j}{2}}\right|^2}$$

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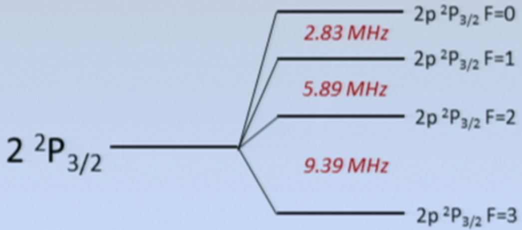

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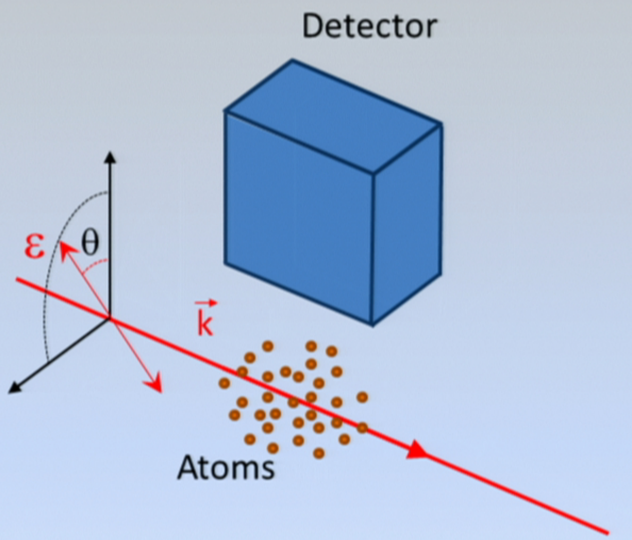
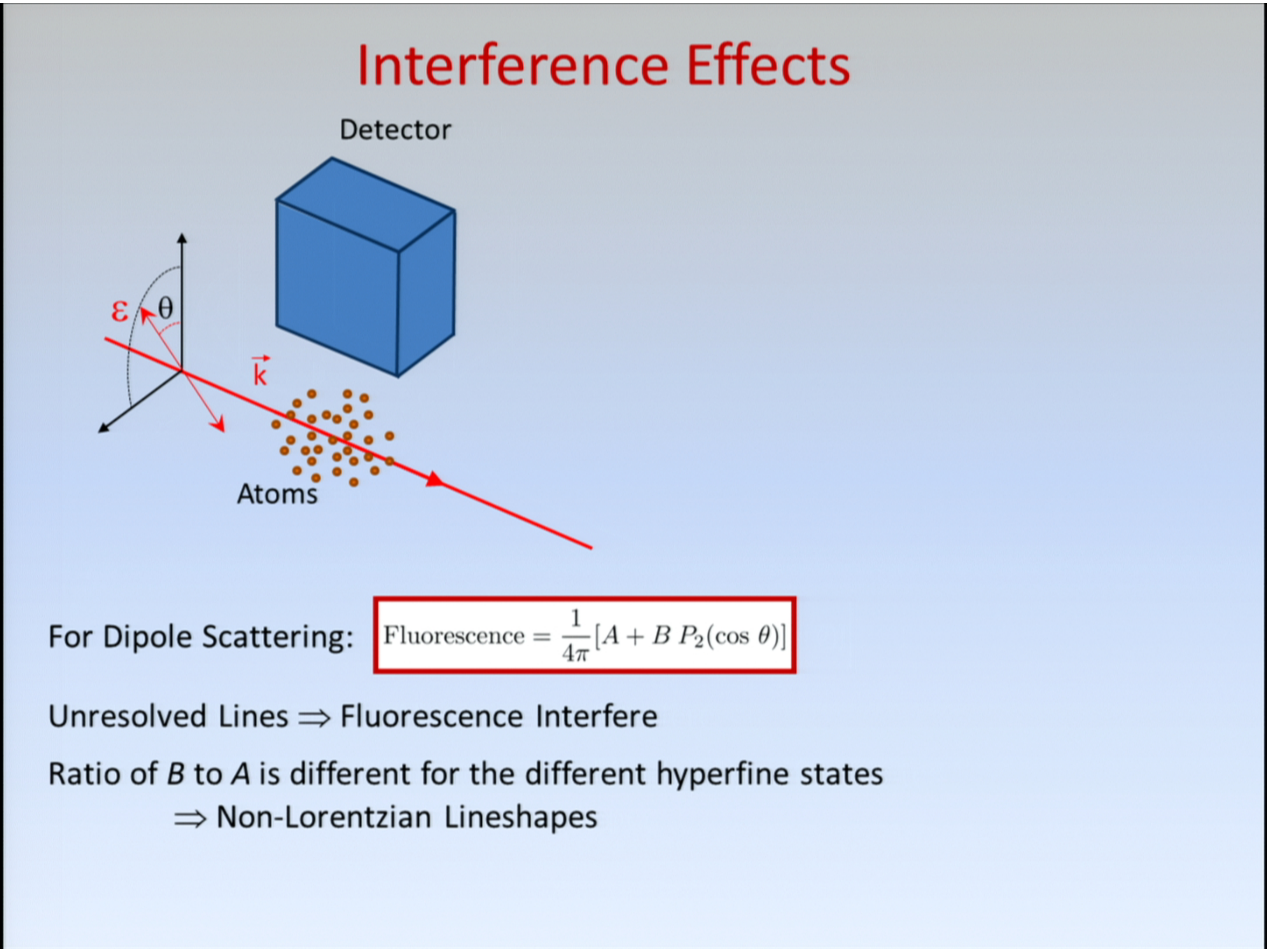
Non-Lorentzian contribution to the line shape that depends on the angle of polarization relative to detection

Interference Effects





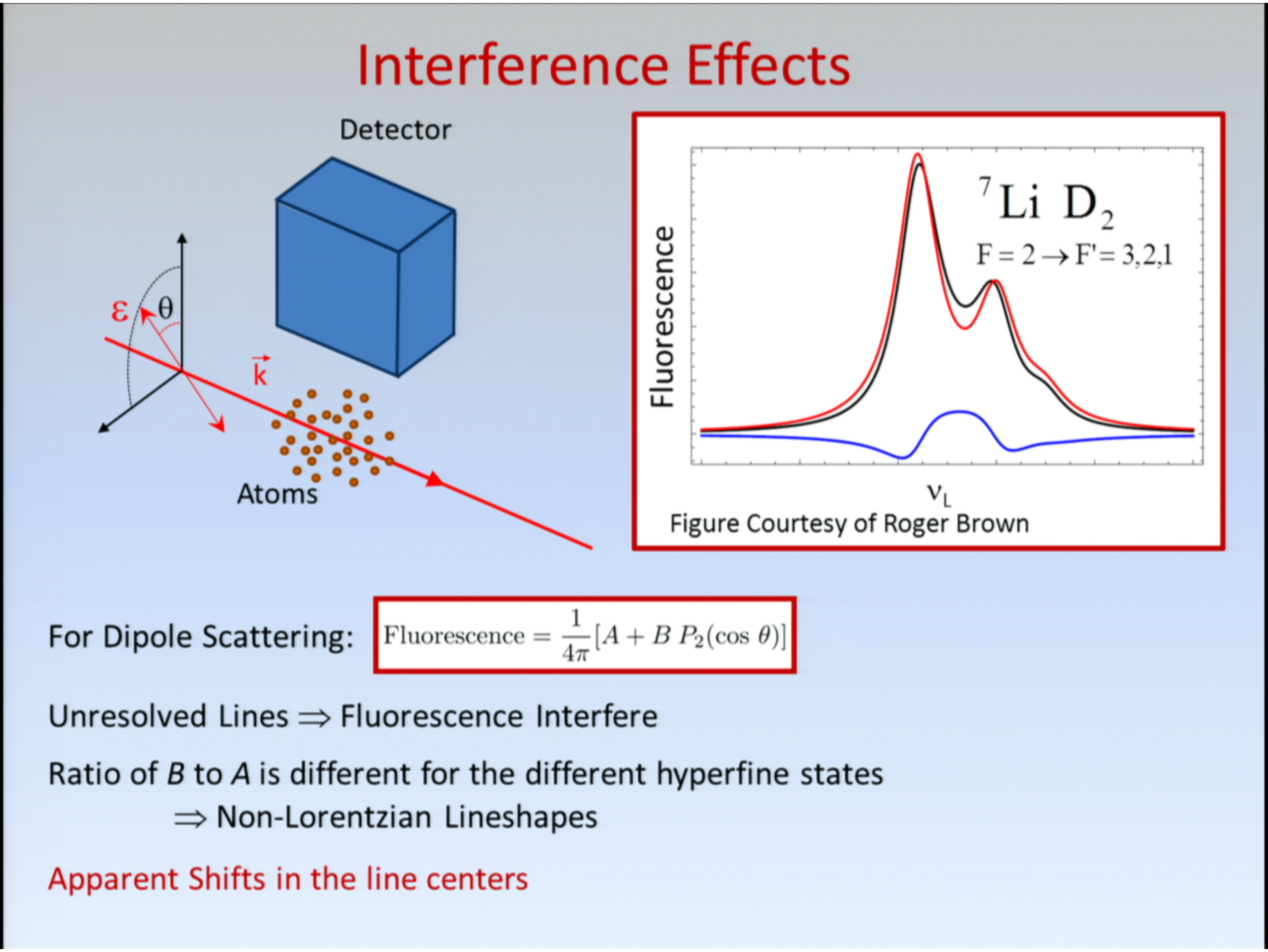
Interference Effects

For Dipole Scattering: $\boxed{\text{Fluorescence} = \frac{1}{4\pi}[A + B\, P_2(\cos\,\theta)]}$

Unresolved Lines $\Rightarrow$ Fluorescence Interfere

Ratio of *B* to *A* is different for the different hyperfine states

$\Rightarrow$ Non-Lorentzian Lineshapes



Interference Effects

Figure Courtesy of Roger Brown

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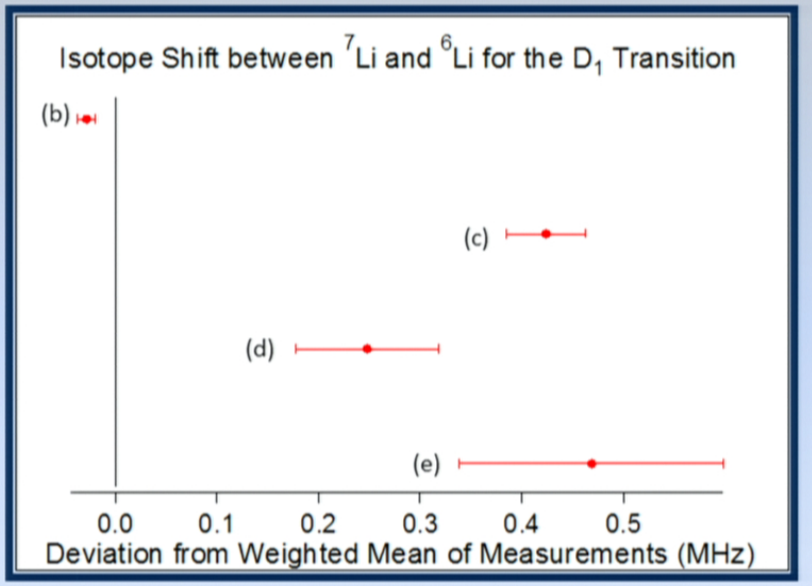
Unresolved Lines ⇒ Fluorescence Interfere

Ratio of *B* to *A* is different for the different hyperfine states
⇒ Non-Lorentzian Lineshapes

Apparent Shifts in the line centers

Does this Explain Away the Discrepancies?

Not quite, 2 $^2P_{1/2}$ state is fully resolved, but …



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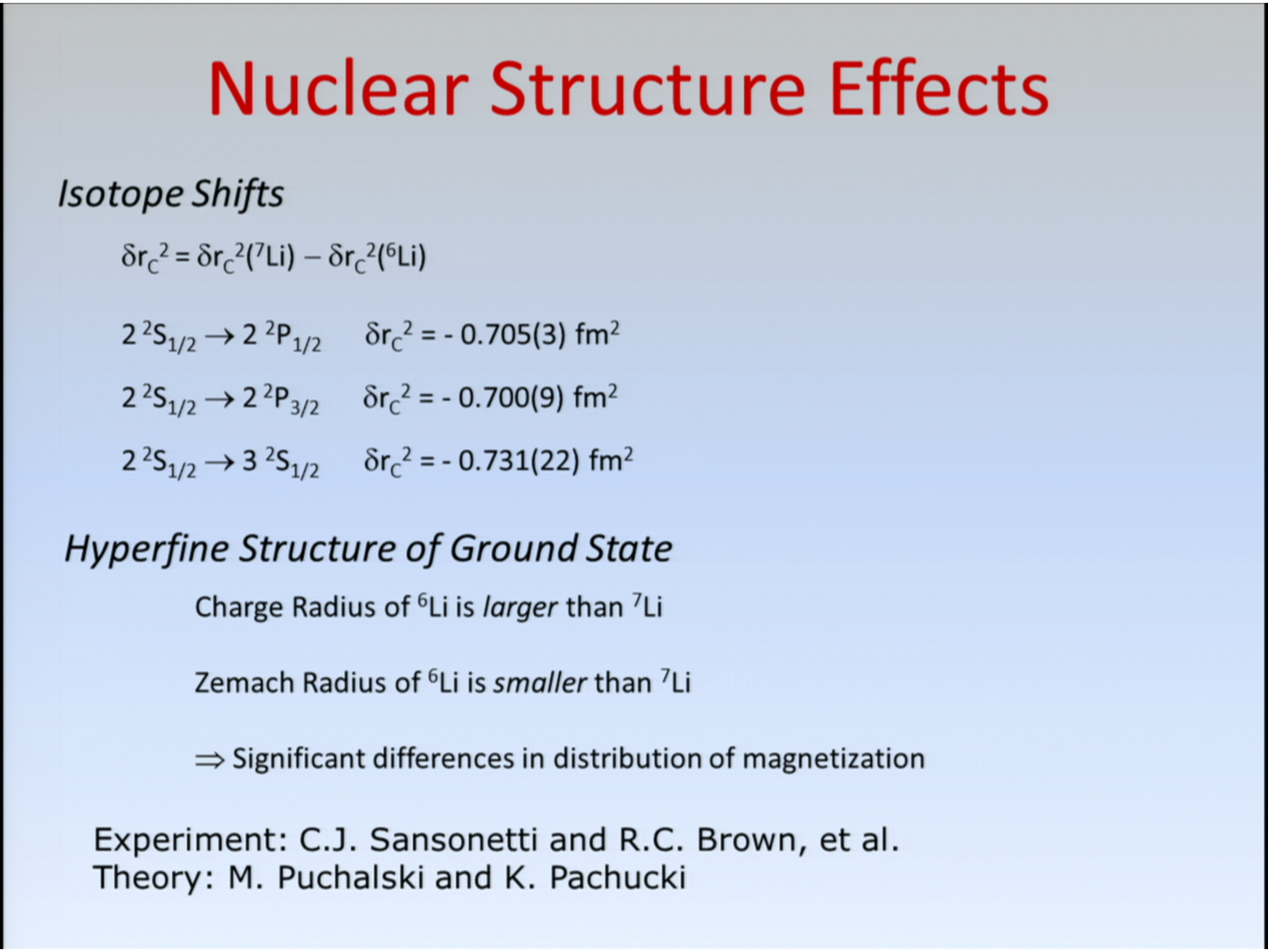


Nuclear Structure Effects

Isotope Shifts

$\delta r_C{}^2 = \delta r_C{}^2({}^7\mathrm{Li}) - \delta r_C{}^2({}^6\mathrm{Li})$

$2\,{}^2S_{1/2} \rightarrow 2\,{}^2P_{1/2}$ $\delta r_C{}^2 = -\,0.705(3)\ \mathrm{fm}^2$

$2\,{}^2S_{1/2} \rightarrow 2\,{}^2P_{3/2}$ $\delta r_C{}^2 = -\,0.700(9)\ \mathrm{fm}^2$

$2\,{}^2S_{1/2} \rightarrow 3\,{}^2S_{1/2}$ $\delta r_C{}^2 = -\,0.731(22)\ \mathrm{fm}^2$

Hyperfine Structure of Ground State

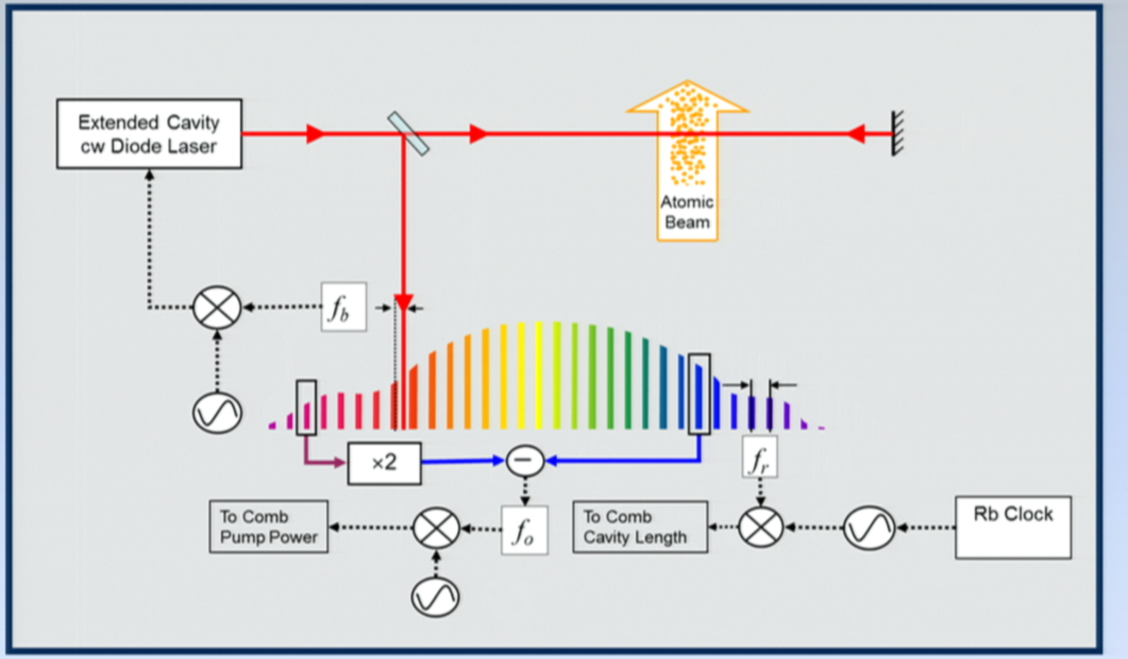
Charge Radius of ^{6}Li is *larger* than ^{7}Li

Zemach Radius of ^{6}Li is *smaller* than ^{7}Li

$\Rightarrow$ Significant differences in distribution of magnetization

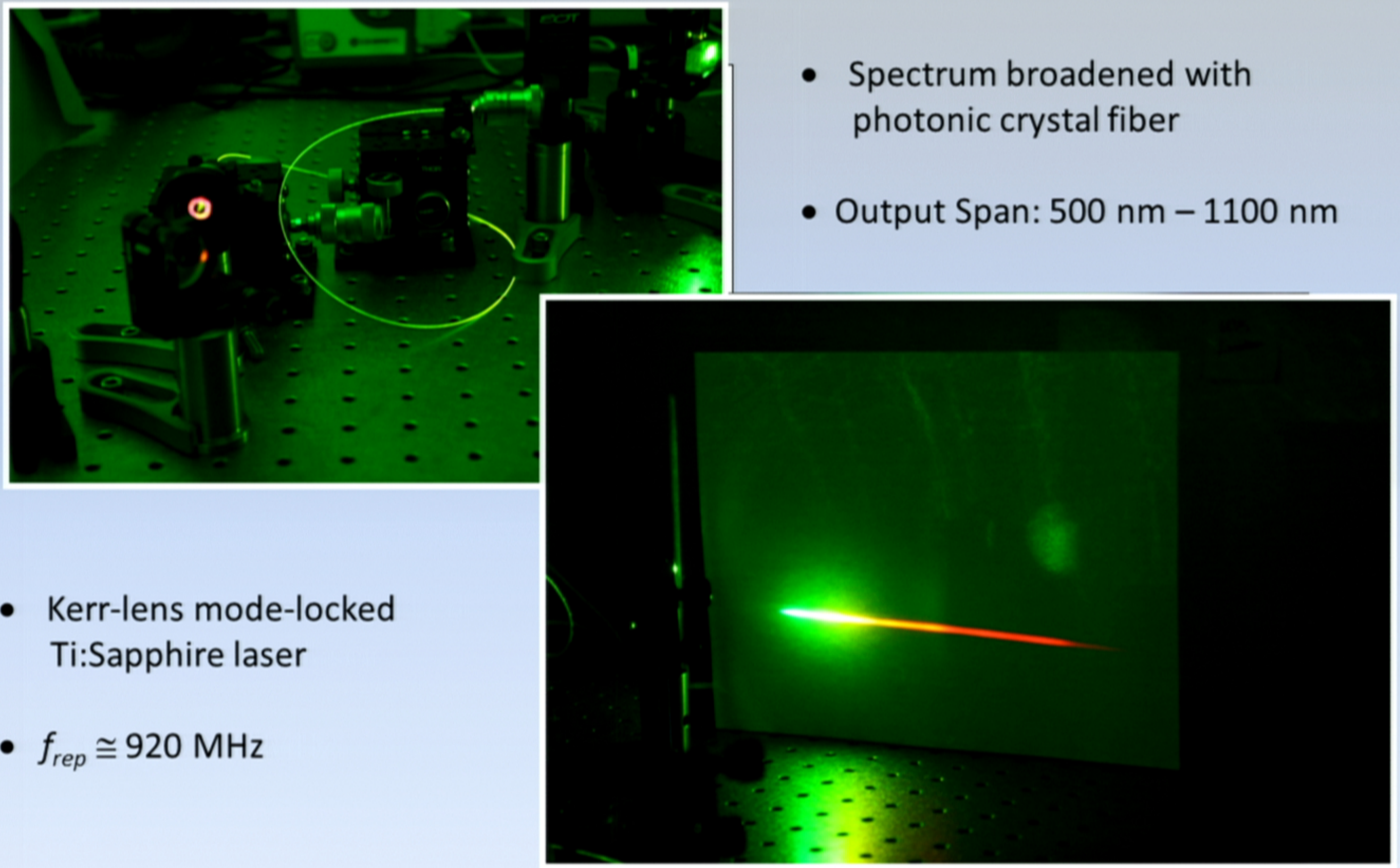
Experiment: C.J. Sansonetti and R.C. Brown, et al.
Theory: M. Puchalski and K. Pachucki

Oberlin Experiment



- Optical Frequency Comb ⇒ Absolute Frequency Control
- Stabilization of Diode Laser ⇒ Reduce systematics associated with probe laser jitter
- Next generation will laser cool and trap atoms

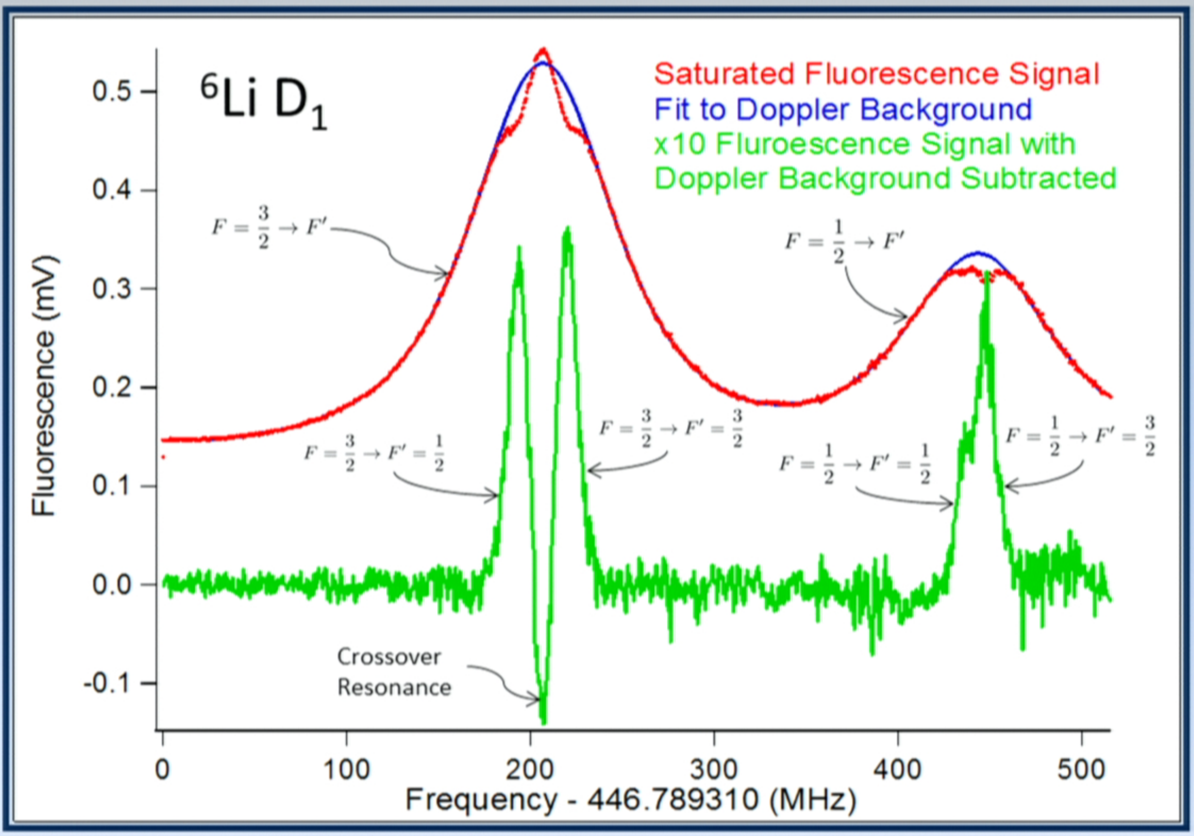
The Frequency Comb



- Spectrum broadened with photonic crystal fiber
- Output Span: 500 nm – 1100 nm

- Kerr-lens mode-locked Ti:Sapphire laser
- $f_{rep} \cong 920$ MHz

Saturated Fluorescence Spectroscopy



Good signal-to-noise ratio, but crossover resonances complicate the line shape

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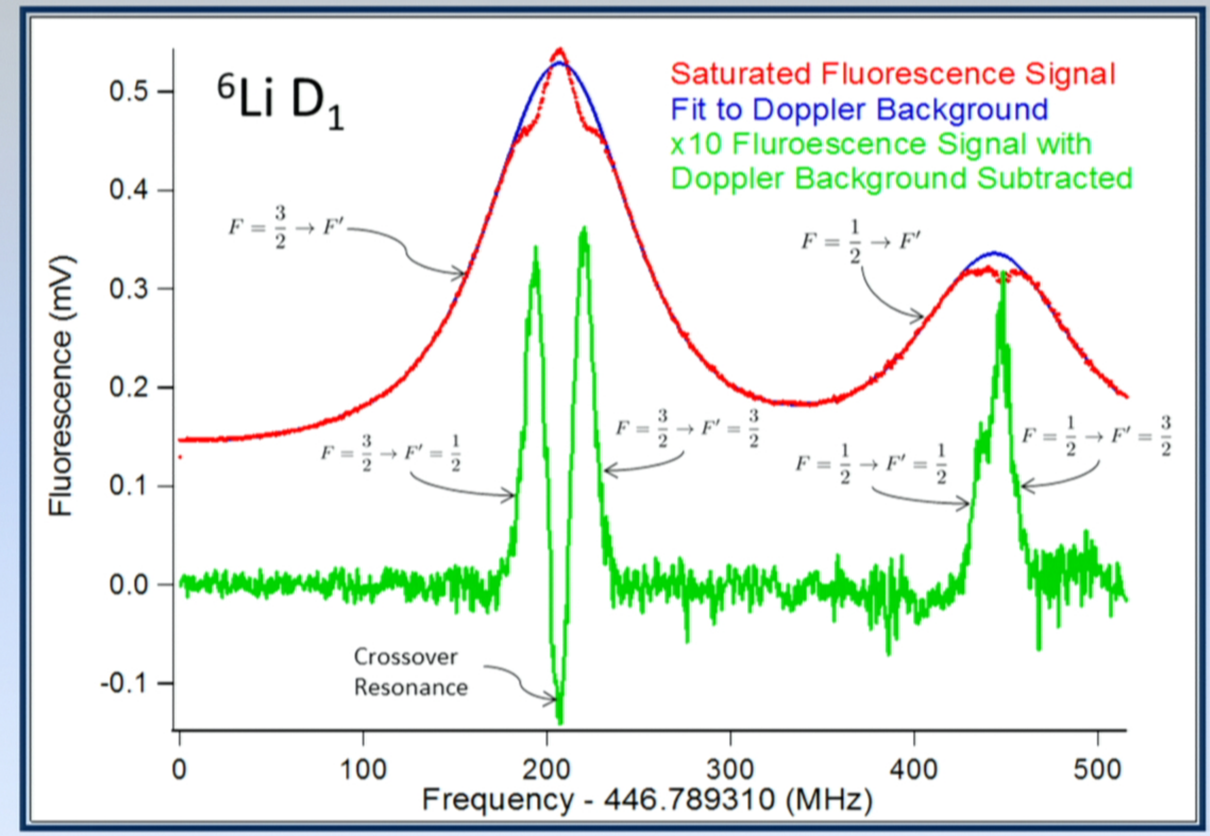

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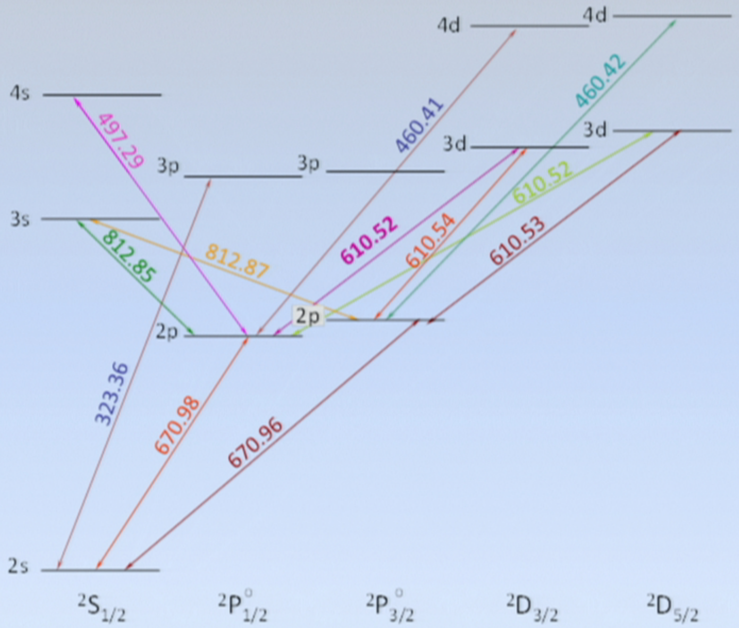
Future Plans

Extend to Higher-Lying States

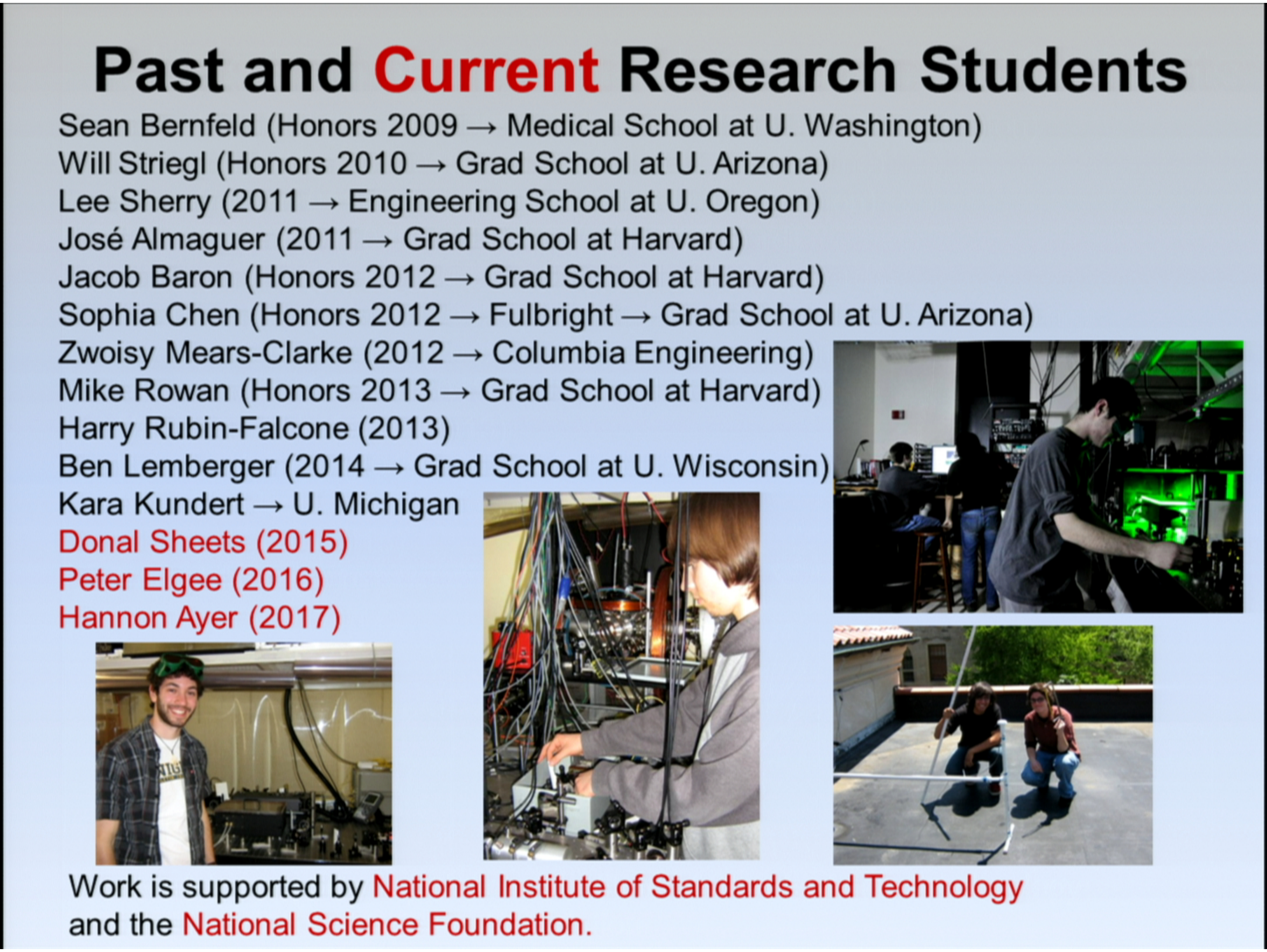
- Wavelengths for numerous states are accessible with diode lasers and/or the output of the frequency comb.
- Comprehensive study of low-lying states will provide a significant test for atomic theory.

Cool and Trap Atoms

- Will limit Doppler motion and reduce systematic effects.
- Will allow for longer interrogation times and make direct frequency-comb spectroscopy techniques possible.



Low-Lying Energy Levels



Past and Current Research Students

Sean Bernfeld (Honors 2009 → Medical School at U. Washington)
Will Striegl (Honors 2010 → Grad School at U. Arizona)
Lee Sherry (2011 → Engineering School at U. Oregon)
José Almaguer (2011 → Grad School at Harvard)
Jacob Baron (Honors 2012 → Grad School at Harvard)
Sophia Chen (Honors 2012 → Fulbright → Grad School at U. Arizona)
Zwoisy Mears-Clarke (2012 → Columbia Engineering)
Mike Rowan (Honors 2013 → Grad School at Harvard)
Harry Rubin-Falcone (2013)
Ben Lemberger (2014 → Grad School at U. Wisconsin)
Kara Kundert → U. Michigan
Donal Sheets (2015)
Peter Elgee (2016)
Hannon Ayer (2017)

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