Title: Cs as a low-frequency RF field sensor

Speakers: Seth Rittenhouse

Collection: Cold Atom Molecule Interactions (CATMIN)

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Abstract: "133Cs as a low-frequency RF field sensor Seth T. Rittenhouse,1 Seth Meiselman,2 Vanessa Ortiz,1 and Geoffrey A. Cranch2
1Department of Physics, the United States Naval Academy, Annapolis, MD 21402, USA
2Optical Sciences Division, U. S. Naval Research Laboratory, Washington, DC 20375, USA

Do to the extreme sensitivity of Rydberg systems to external fields, there has been a great deal of interest in using them as high precision quantum mechanical sensors. However, for intermediate principle quantum numbers (n ~ 20 - 40), using the AC Stark effect to measure the intensity ofan RF field is limited to amplitudes on the order of ERF ~ 1 V/cm. In this poster we examine the feasibility of using 133Cs as a high precision, low frequency (10-100 MHz) RF field sensor.

We propose using a DC field offset to increase the field sensitivity of the AC Stark spectrum to the intensity of the RF field. The presence of the DC offset field leads to sideband states with Rabbi frequencies that are highly sensitive to RF field intensity. Using electromagnetically induced transpareny, our initial theoretical modeling indicates that this approach might be used to create a RF field sensor with sub-millivolt per centimeter accuracy."

^{133}Cs as a low-frequency RF sensor

Seth T. Rittenhouse[1], Seth Meiselman[2], Vanessa Ortiz[1], and Geoffrey A. Cranch[2]

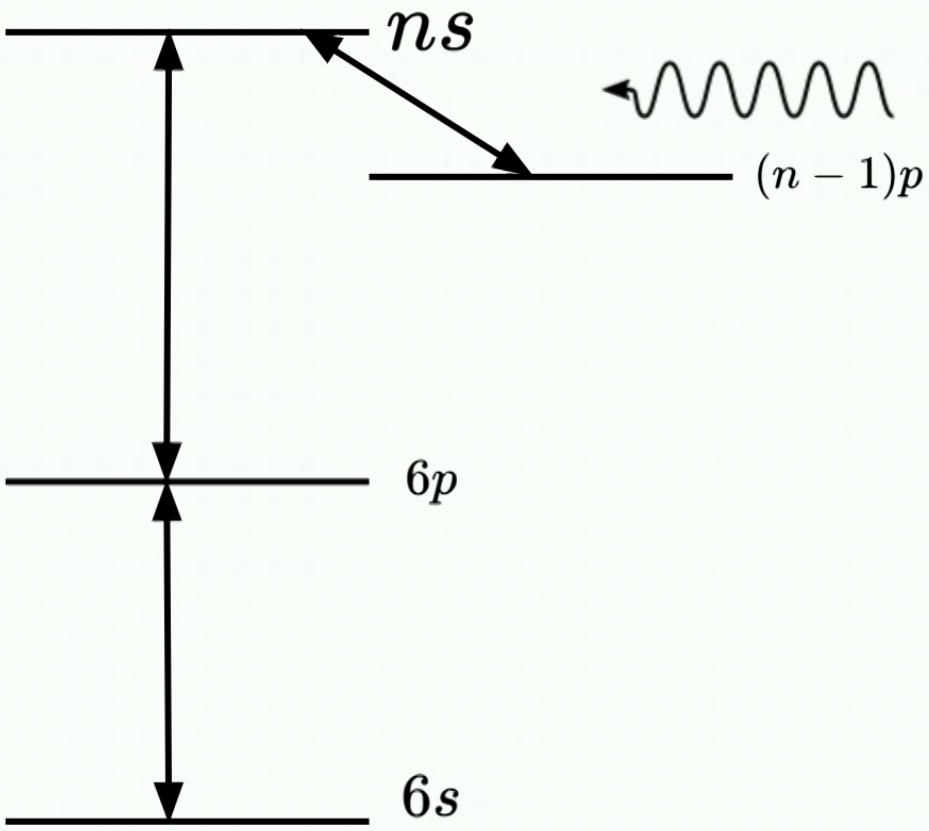
[1]*Department of Physics, The United States Naval Academy, Annapolis MD 21401, USA.*
[2]*Optical Science Division, U. S. Naval Research Lab, Washington, DC 20375, USA*



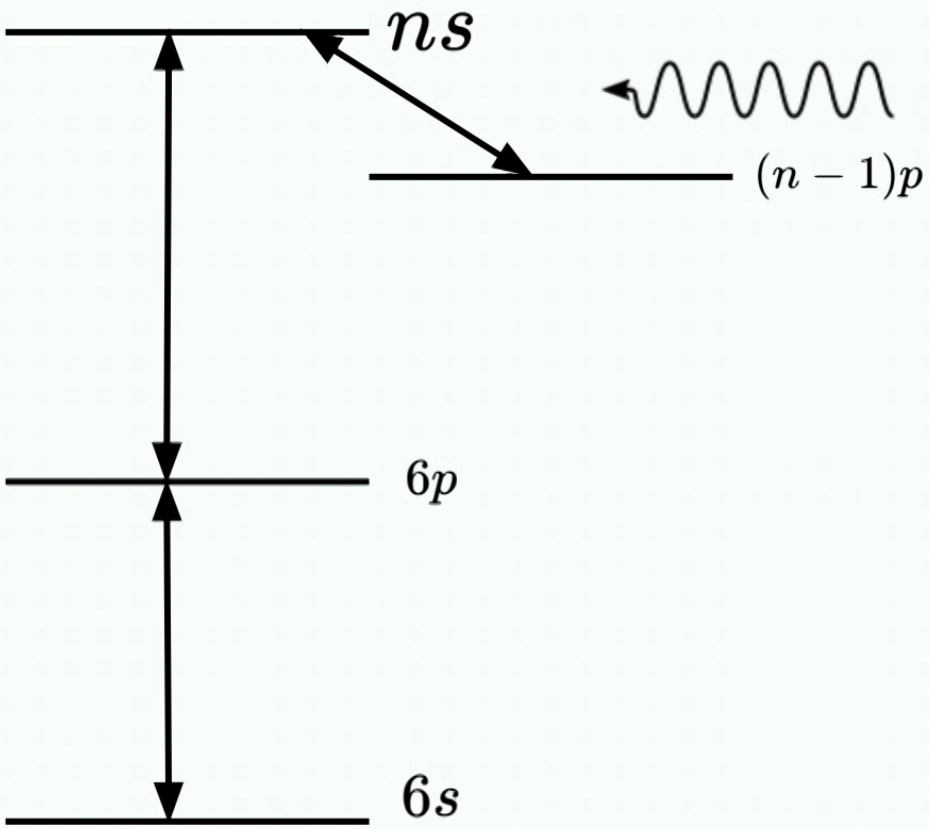


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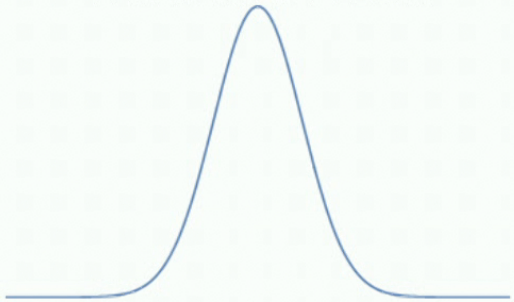
Rydberg Atoms as RF Sensors



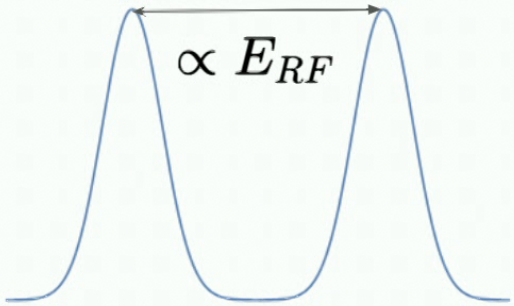
Rydberg Atoms as RF Sensors



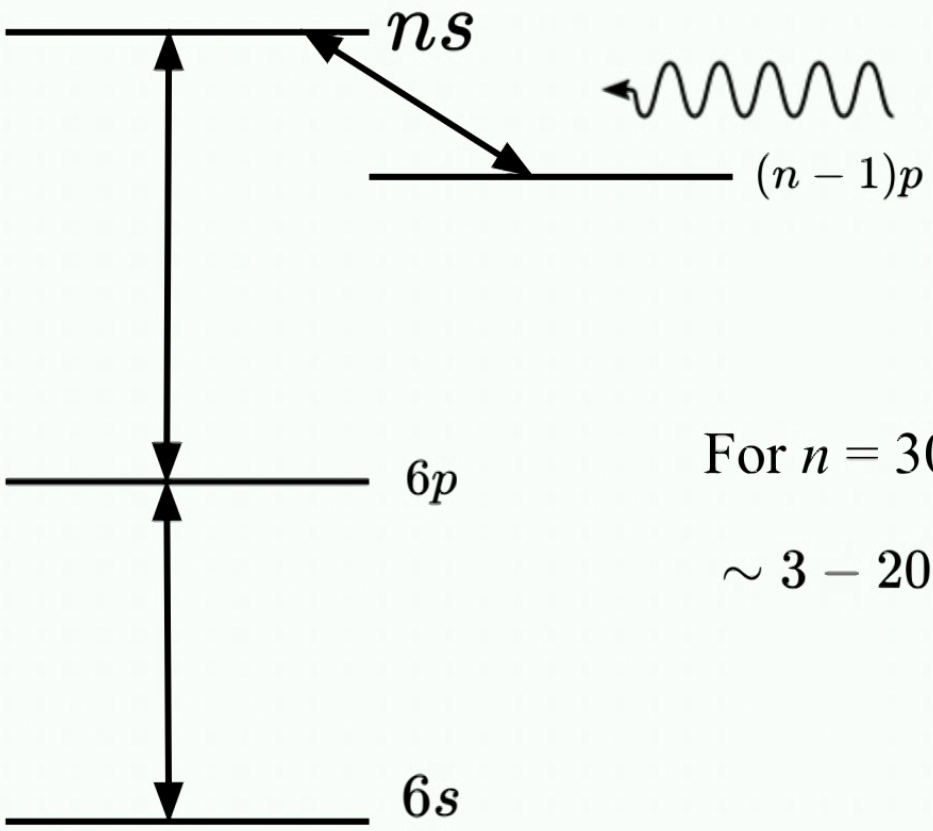
Without RF field



With RF field

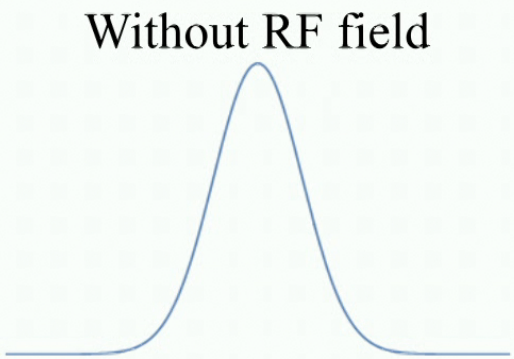


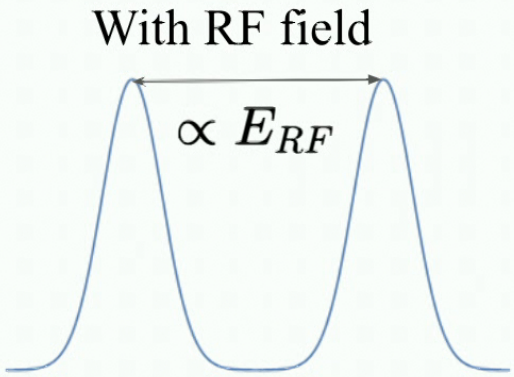
Rydberg Atoms as RF Sensors



For n = 30 - 100

$\sim 3 - 200$ GHz



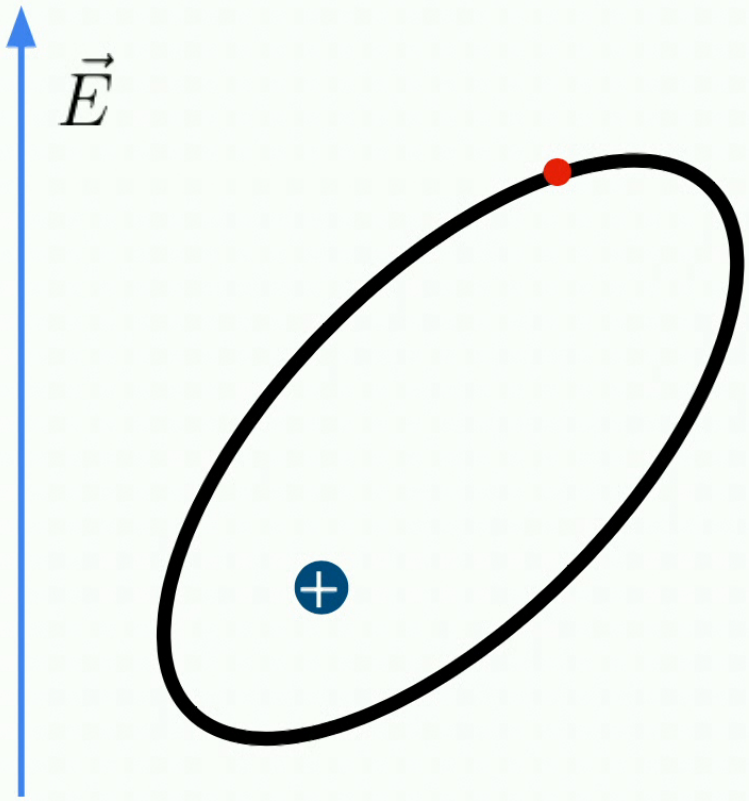


Fan *et al.*, J. Phys. B 48, 202001 (2015)

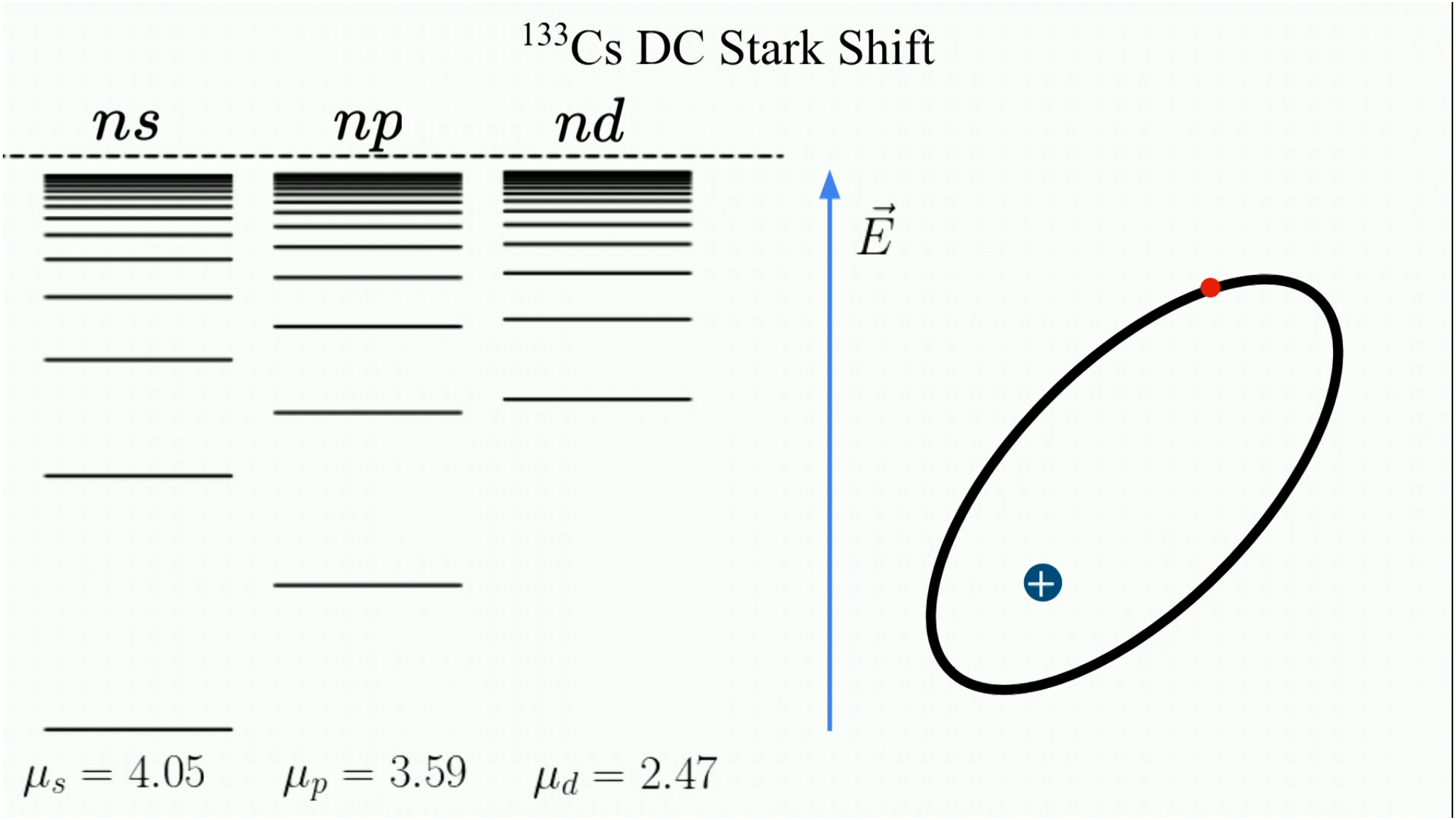
Outline

- DC and AC Stark Effect
- Floquet and sidebands
- EIT and Thermal averaging
- Summary and the future

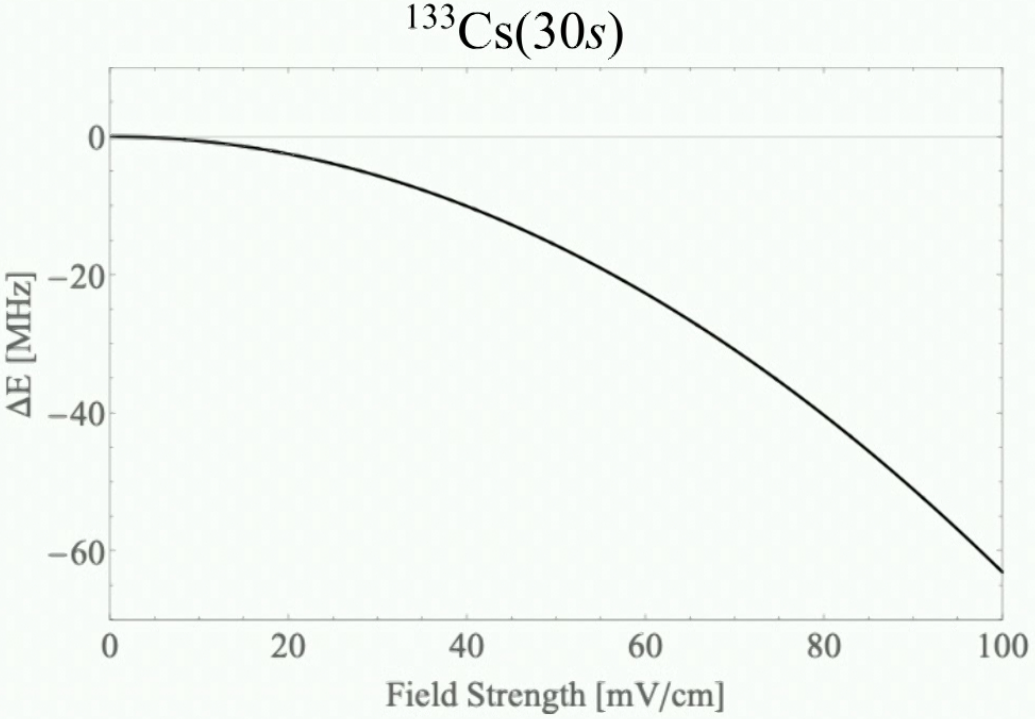
^{133}Cs DC Stark Shift



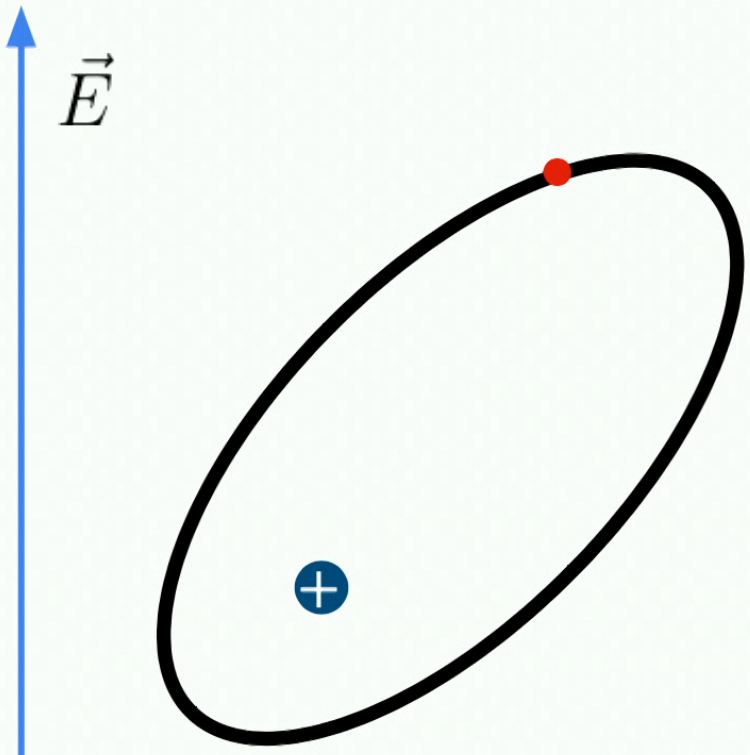
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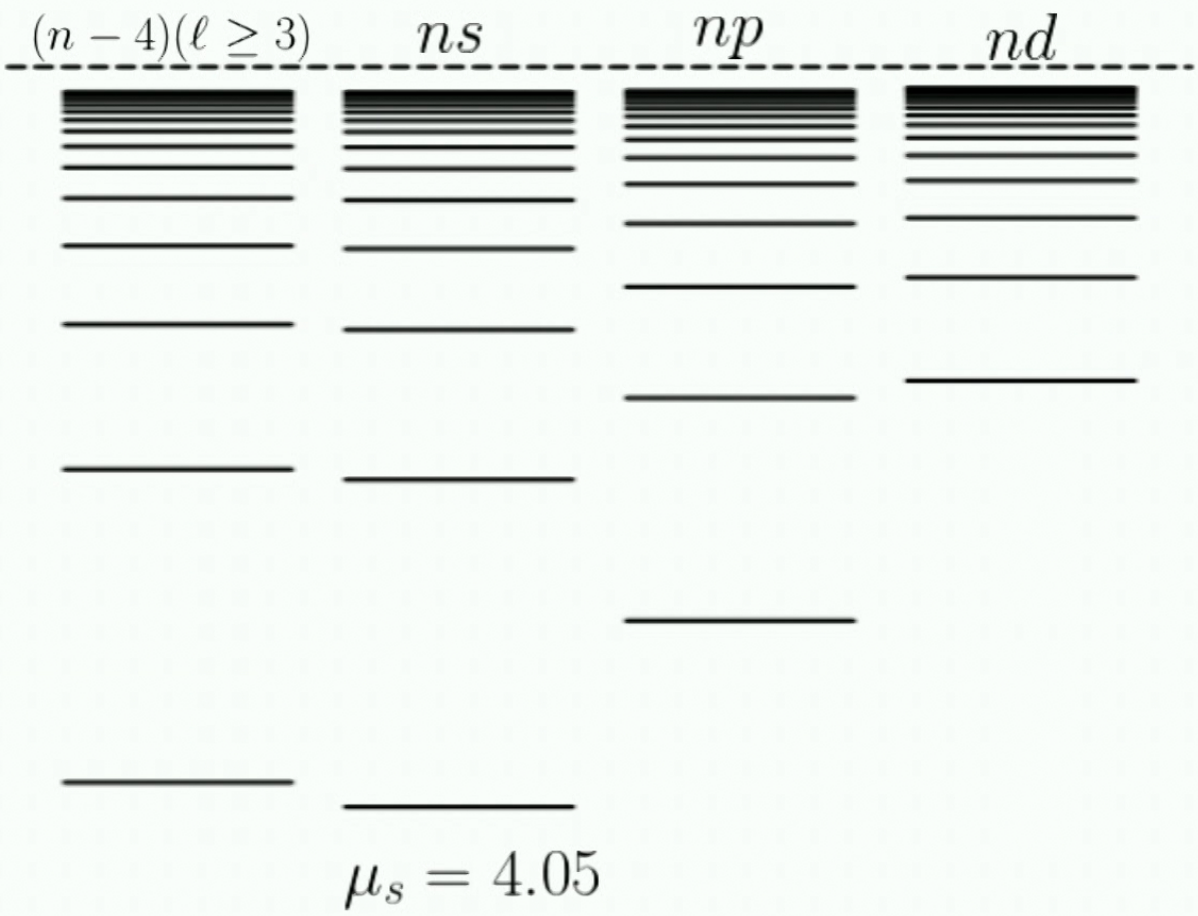
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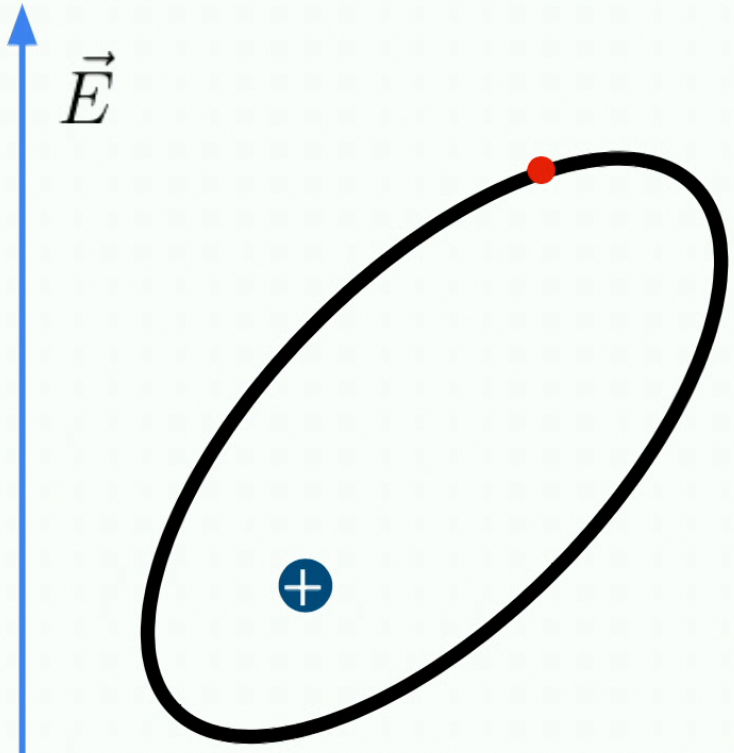


$$\Delta E = \frac{1}{2}\alpha E^2 \qquad \alpha = 5.07 \times 10^9 \text{ a.u.}$$

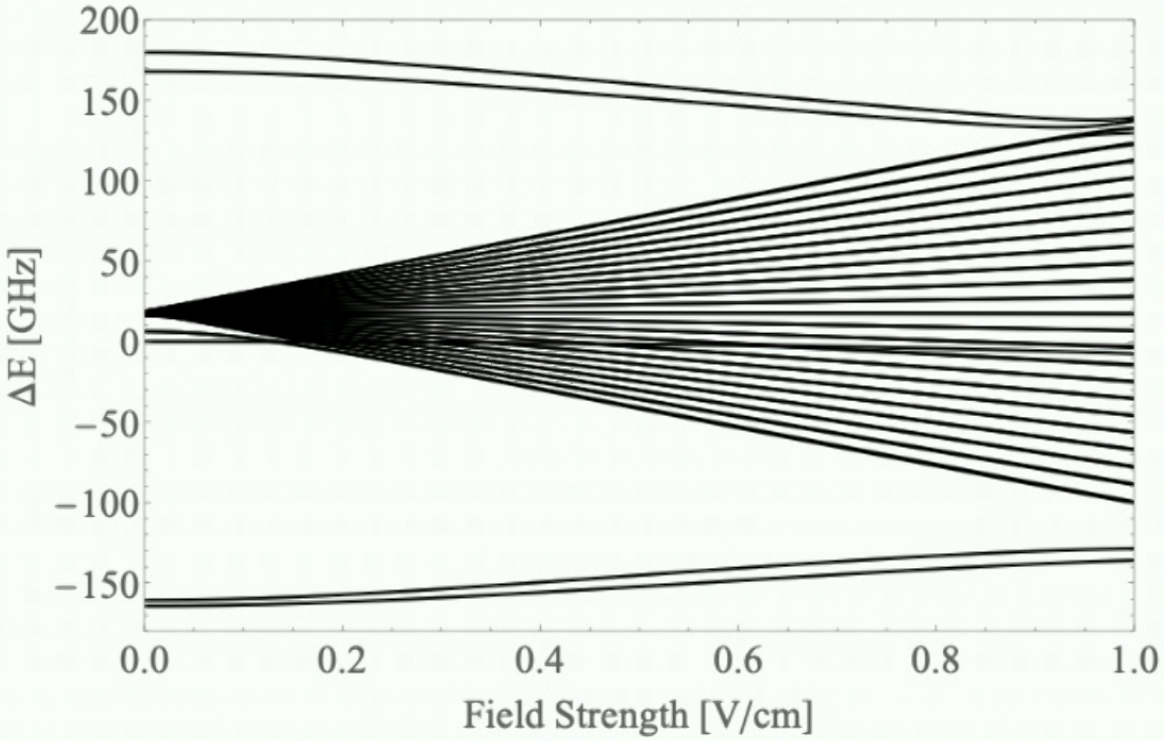


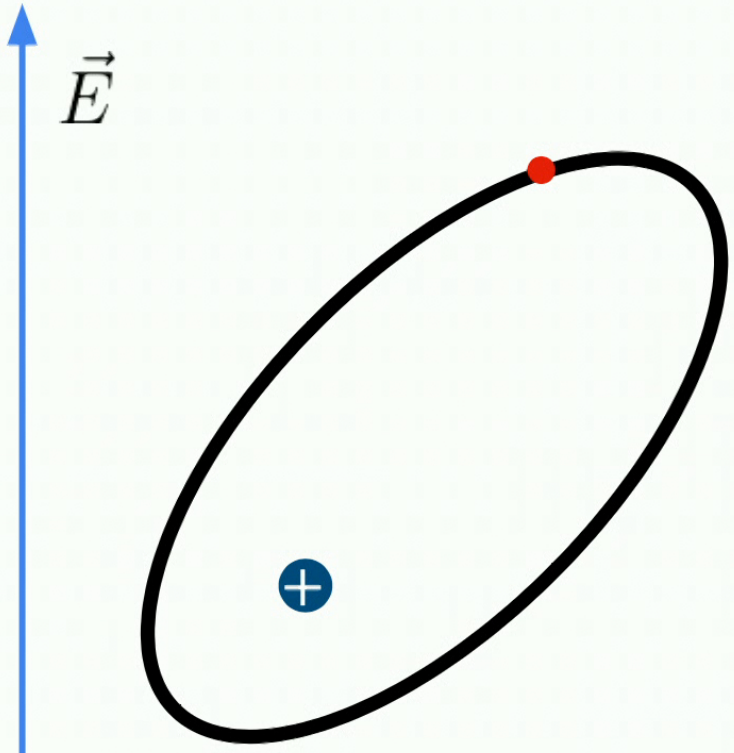
Complication: Degenerate States



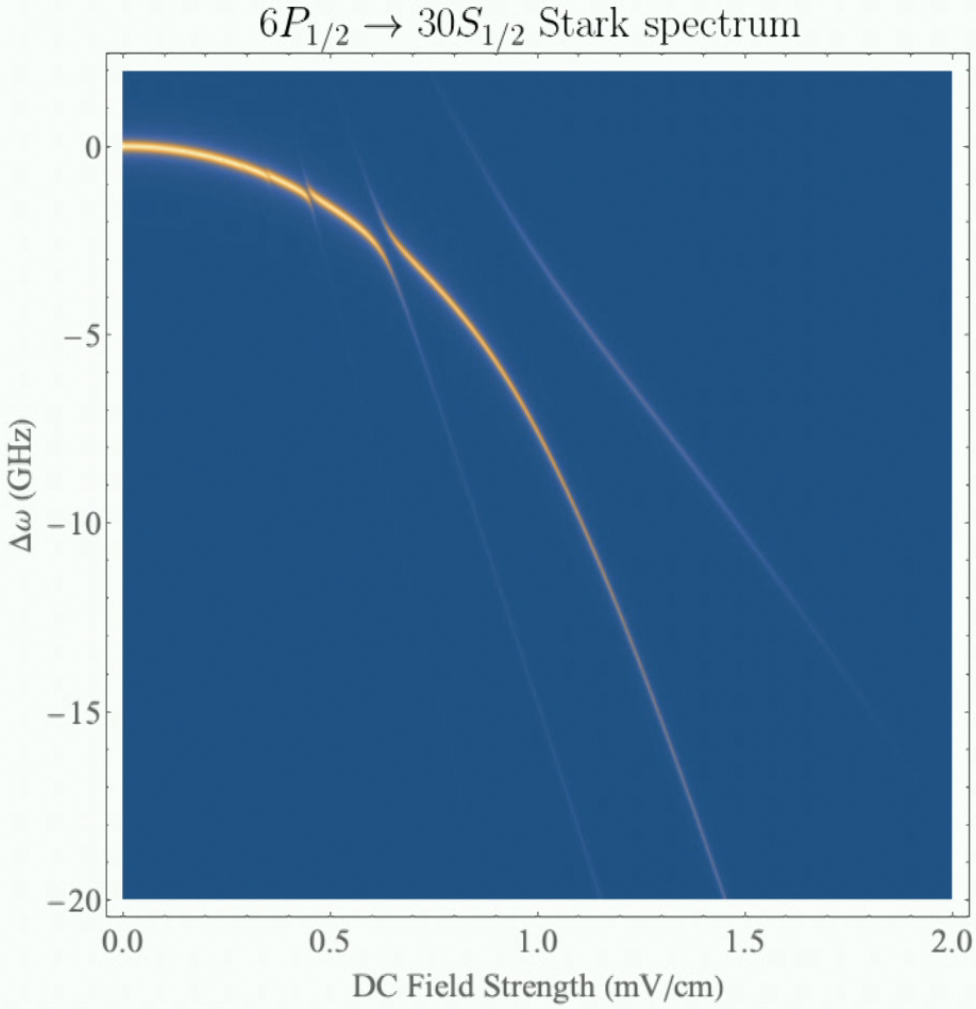


Complication: Degenerate States





Stark Spectrum



Low Frequency AC Stark effect

For low frequency AC fields, energy shift is roughly given by time average of the DC field

$$\vec{E} = \vec{E}_0 \sin(2\pi f t) \qquad f \sim 10 \text{ MHz}$$

$$\Delta E_{AC} \sim \langle \Delta E_{DC} \rangle_t$$

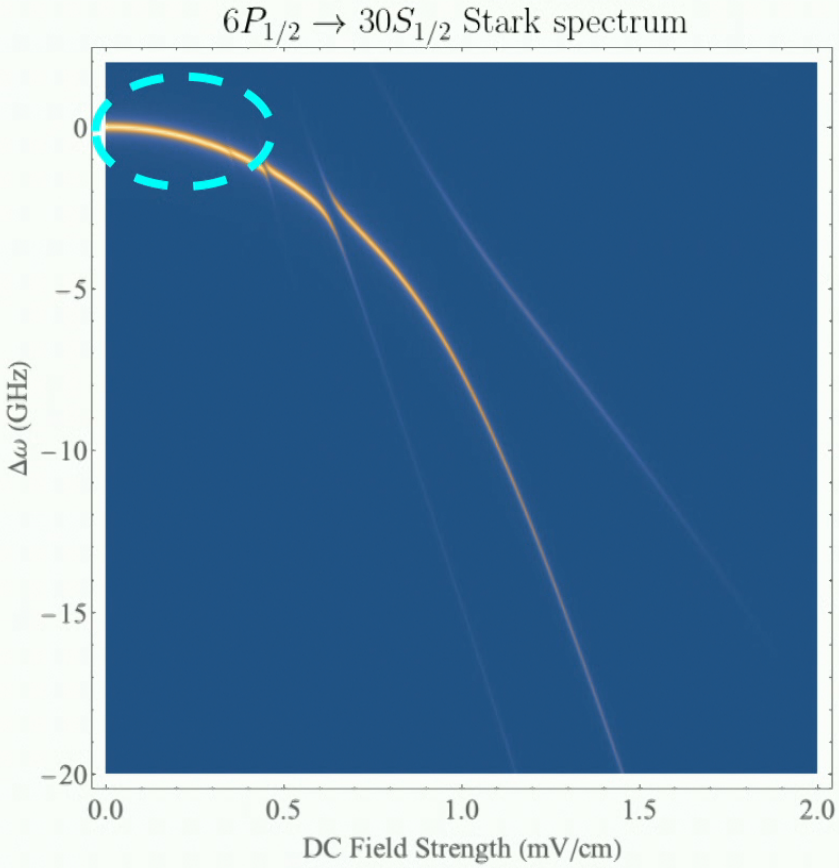
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Weak fields: DC shift is quadratic



Low Frequency AC Stark effect

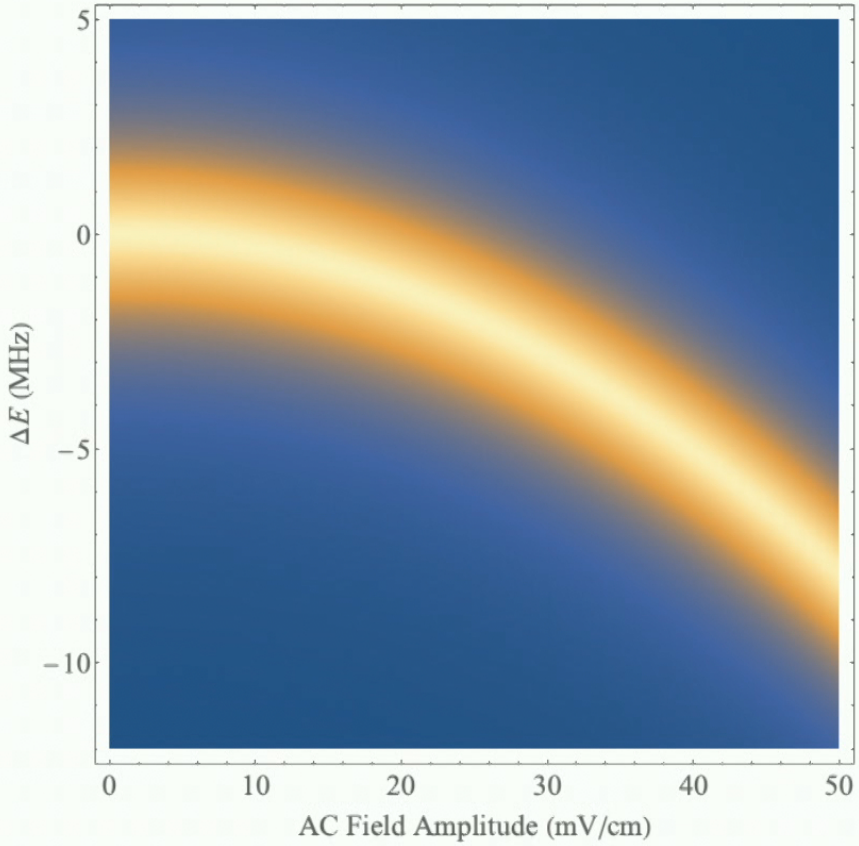
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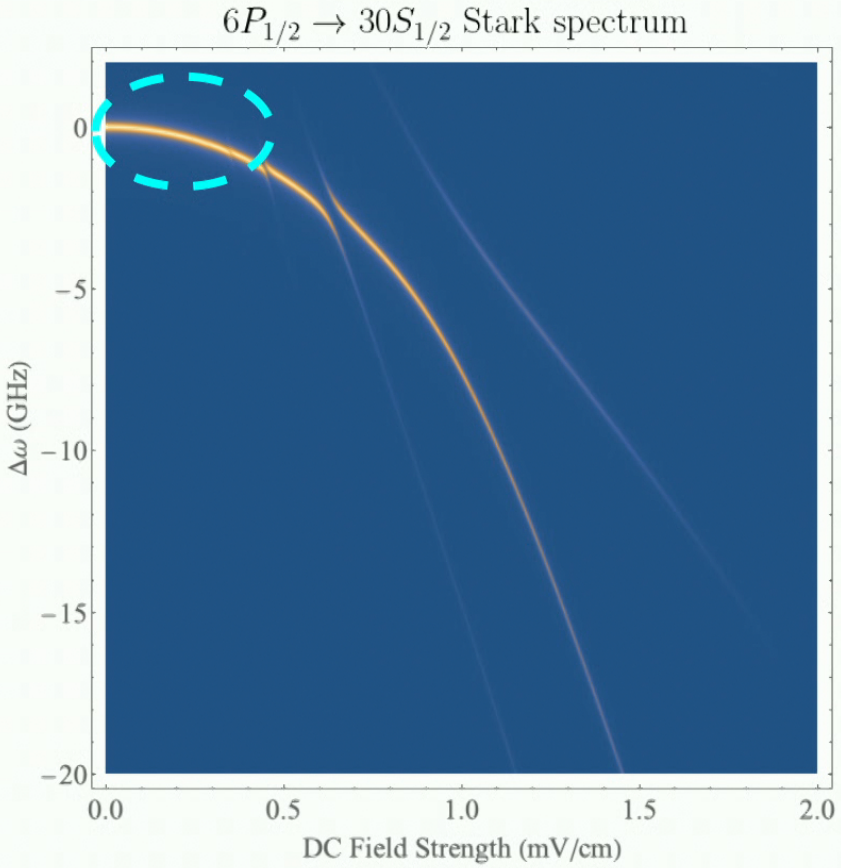
$$\Delta E_{AC} \sim \frac{1}{4}\alpha \left|\vec{E}_0\right|^2$$



See Meyer *et al.*, J. Phys. B 53, 034001(2020) for an good overview of feasibility.

Low Frequency AC Stark effect

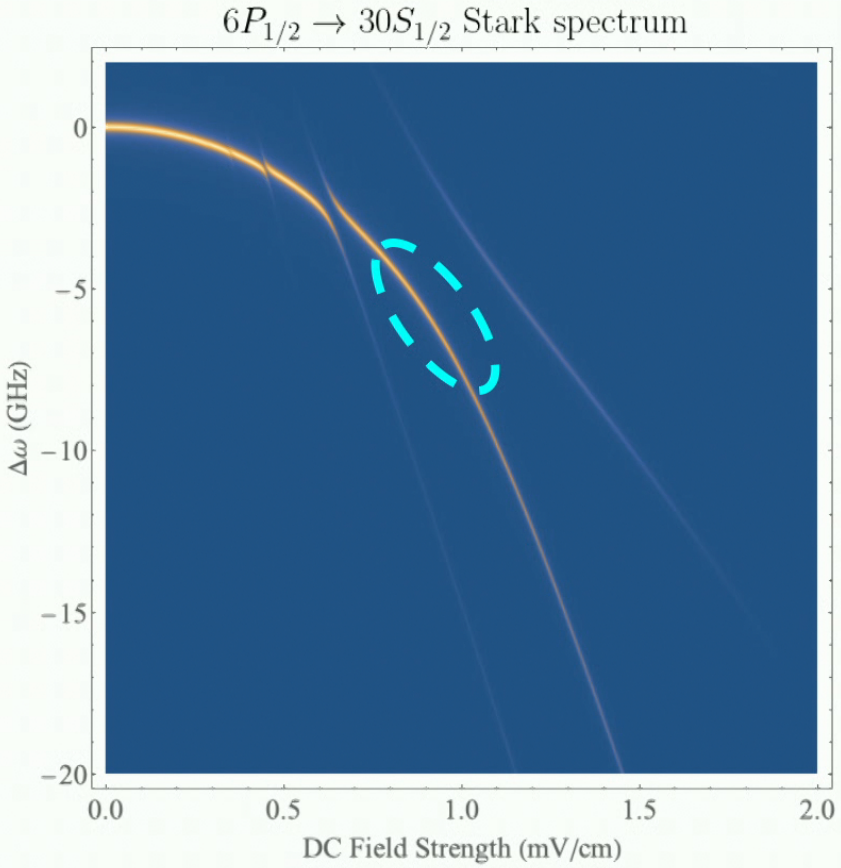
Problem: Quadratic shift means low sensitivity



Low Frequency AC Stark effect

Problem: Quadratic shift means low sensitivity

Solution: Use a DC offset to increase AC field sensitivity

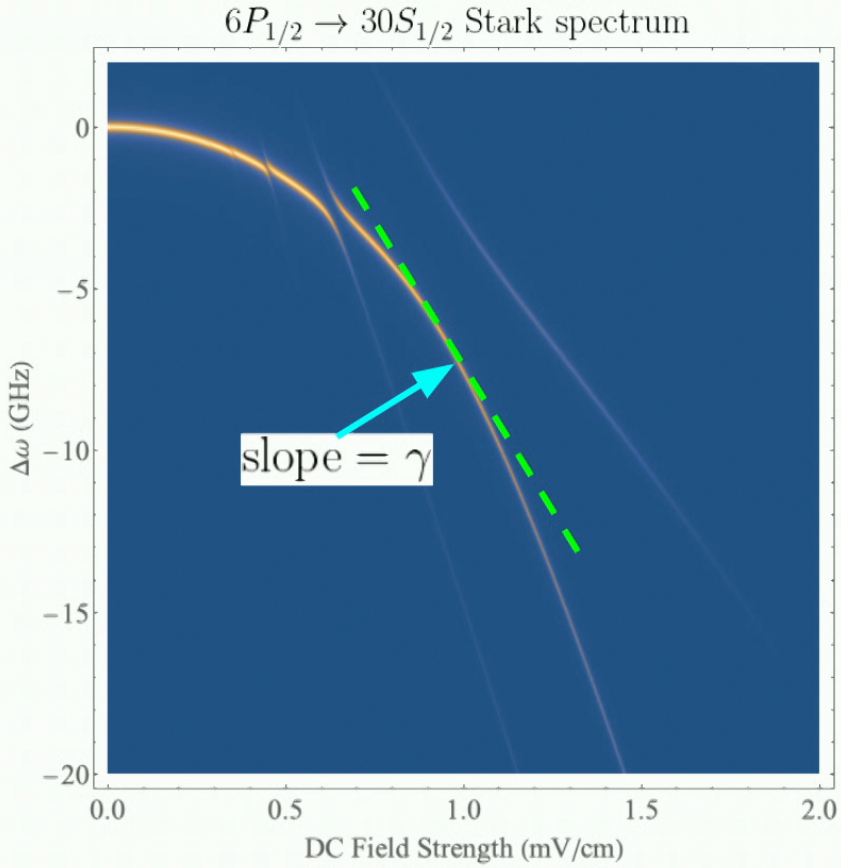


Low Frequency AC Stark effect

Problem: Quadratic shift means low sensitivity

Solution: Use a DC offset to increase AC field sensitivity

$$\Delta E \approx \Delta E_{DC} + \gamma E_{AC}(t)$$



Jau and Carter, Phys. Rev App. 13, 054034 (2022).
Chai and Jone, DAMOP 2020, Session M02.2 (2020).

Low Frequency AC Stark effect

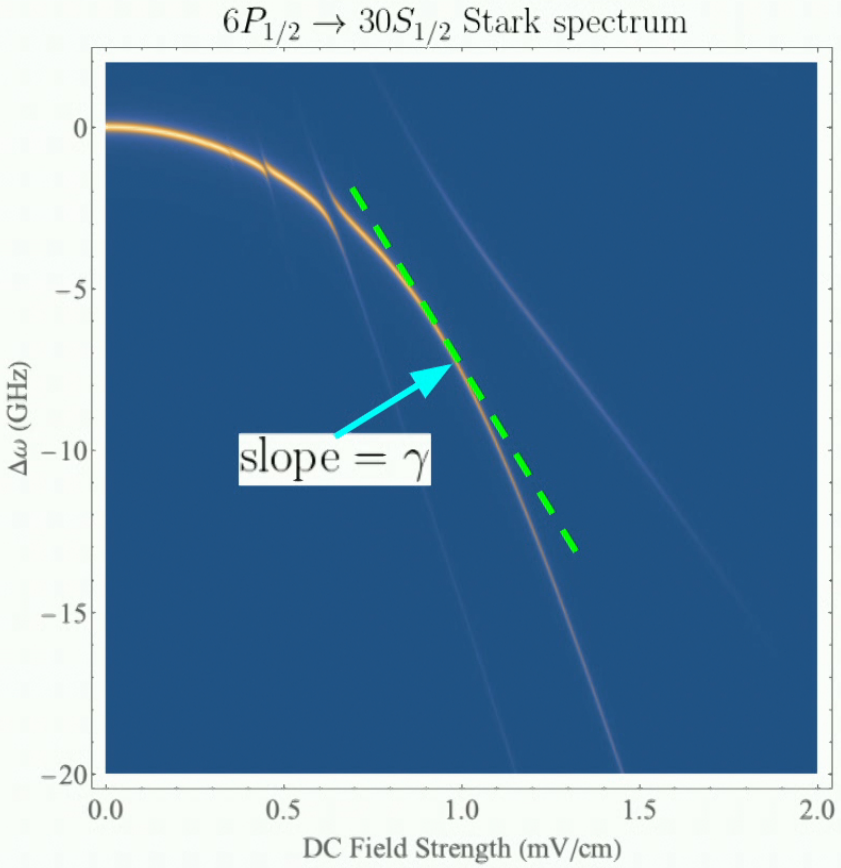
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Linear term cancels out in the time average…

$$\Delta E_{AC} \sim \langle \Delta E \rangle_t = \Delta E_{DC}$$



Low Frequency AC Stark effect

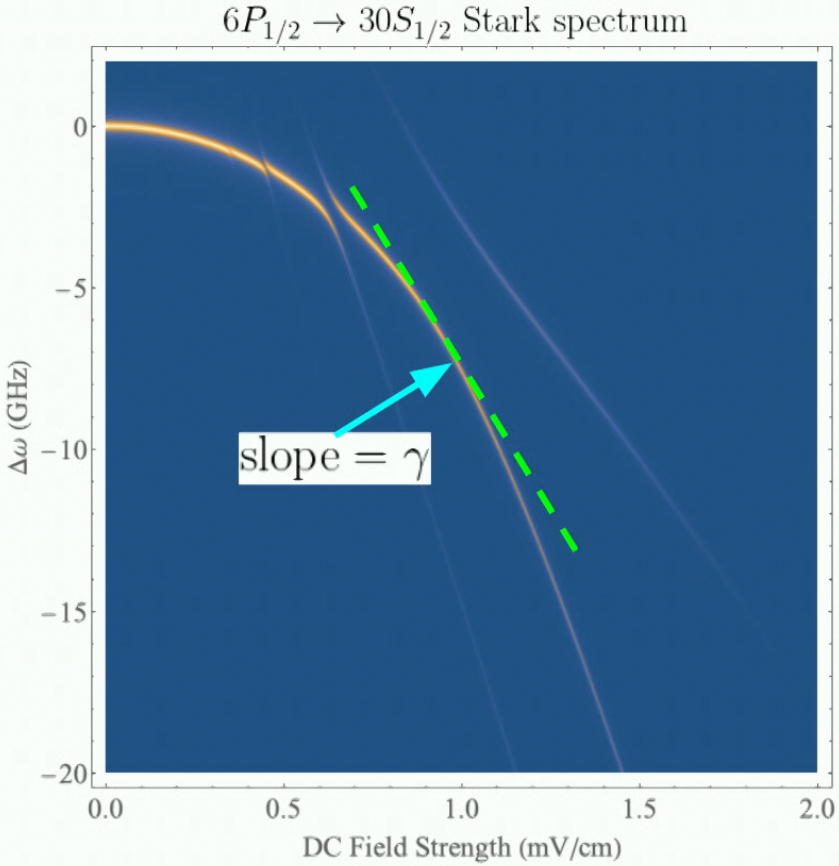
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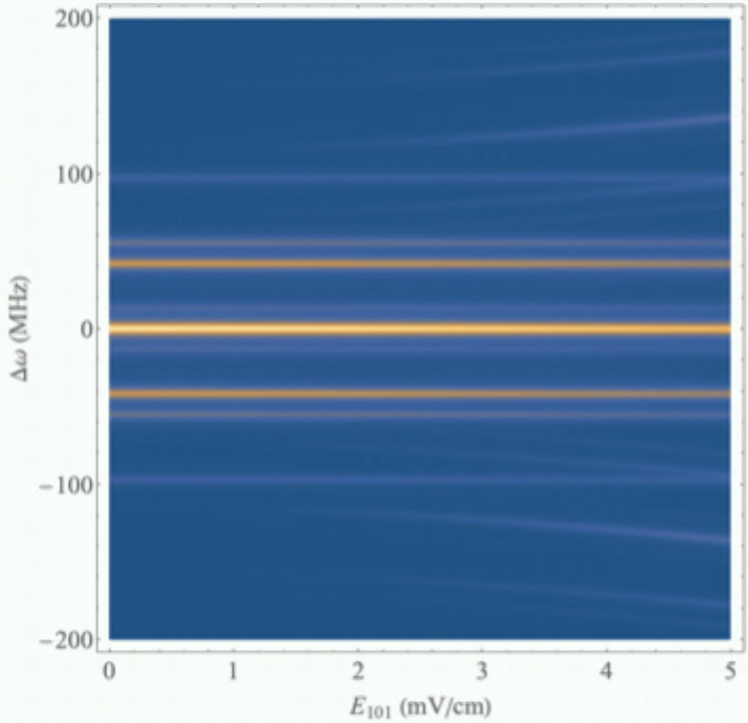
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Floquet theory and time varying, periodic potentials

$$i\hbar\frac{\partial\left|\Psi(t)\right\rangle}{\partial t}=\hat{H}(t)\left|\Psi(t)\right\rangle \quad \hat{H}(t)=\sum_{l}e^{il\omega t}\hat{H}_{l}$$

Break everything into Fourier components

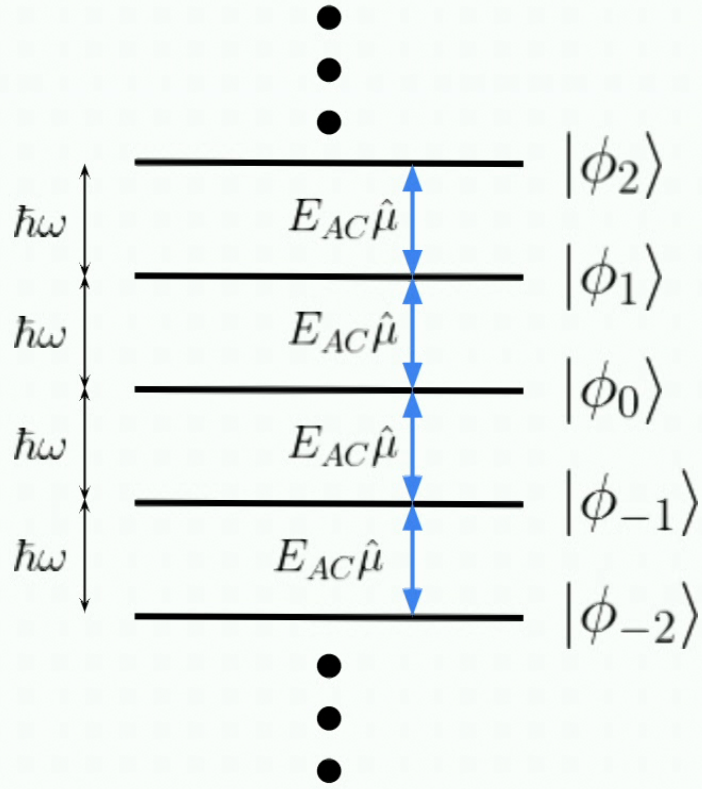
$$\left|\Psi(t)\right\rangle=e^{-iEt/\hbar}\sum_{m}e^{-im\omega t}\left|\phi_{m}\right\rangle$$

$$\sum_{m'}\hat{H}_{m'}\left|\phi_{m'-m}\right\rangle=(E+m\hbar\omega)\left|\phi_{m}\right\rangle$$

Floquet theory and time varying, periodic potentials

$$\left(\hat{H}_0 + m\hbar\omega\right)|\phi_m\rangle + E_{AC}\hat{\mu}\left(|\phi_{m+1}\rangle + |\phi_{m-1}\rangle\right) = E\,|\phi_m\rangle$$

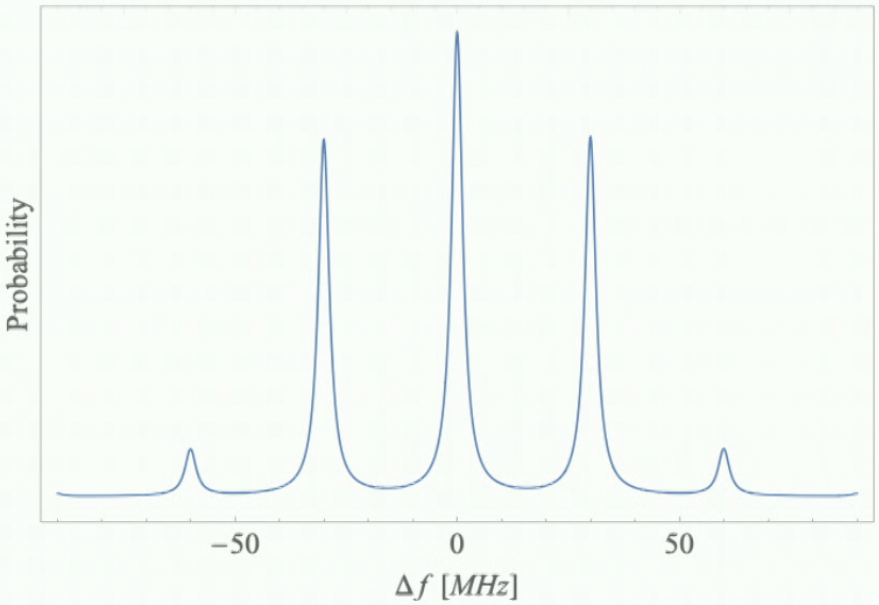
Result of coupling to neighboring fourier components?

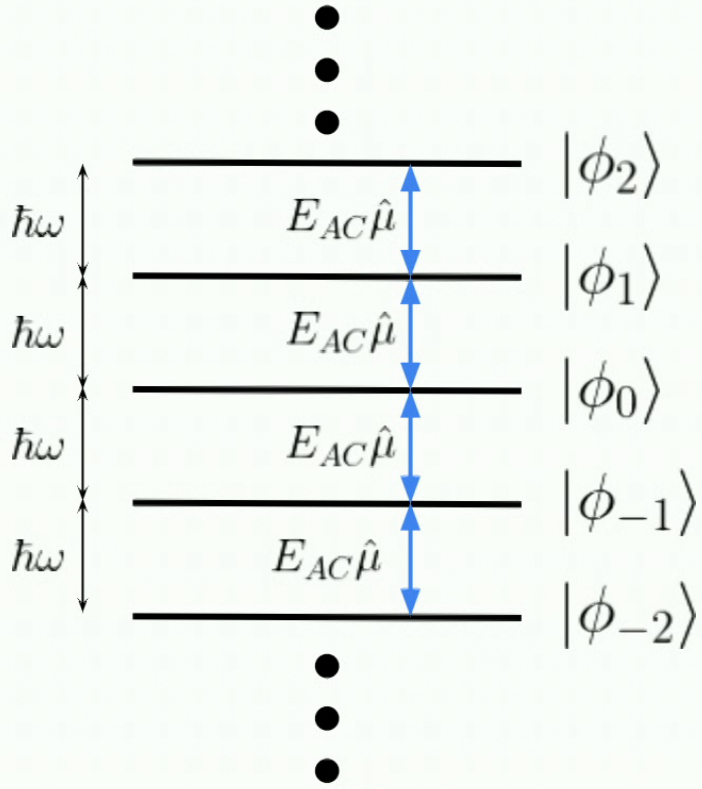


Floquet theory and time varying, periodic potentials

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Side bands!





$E_{DC} = 1\ \mathrm{V/cm} \quad E_{AC} = 2\ \mathrm{mV/cm} \quad \omega = 2\pi \times 30\ \mathrm{MHz}$

Slowly Varying weak RF fields

Assumptions:

- Field is oscillating slowly enough to follow DC state
- RF field amplitude is small enough for a linear approximation
- Wavefunctions is mostly DC Stark state with additional time behavior

$$\Delta E \approx \Delta E_{DC} + \gamma \frac{\left|\vec{E}_{AC}\right|}{2} \left(e^{+\omega t} + e^{-\omega t}\right)$$

$$\left|\Psi(t)\right\rangle = T(t) \left|\Psi_{DC}\right\rangle$$

$$T(t) = e^{-i\Delta E_{DC} t/\hbar} \sum_{l} \beta_l e^{-i\omega t}$$

Inserting into Schrödinger equation gives relation for fourier components

$$\Delta E_{DC}\beta_l + \gamma \frac{\left|\vec{E}_{AC}\right|}{2} \left(\beta_{l+1} + \beta_{l-1}\right) = \left(E_l + l\hbar\omega\right) \beta_l$$

Solution

$$\beta_l = c_1 \; J_{l+E_l/\hbar\omega}\left(\frac{\gamma E_{AC}}{\hbar\omega}\right) + c_2 \; Y_{l+E_l/\hbar\omega}\left(\frac{\gamma E_{AC}}{\hbar\omega}\right)$$

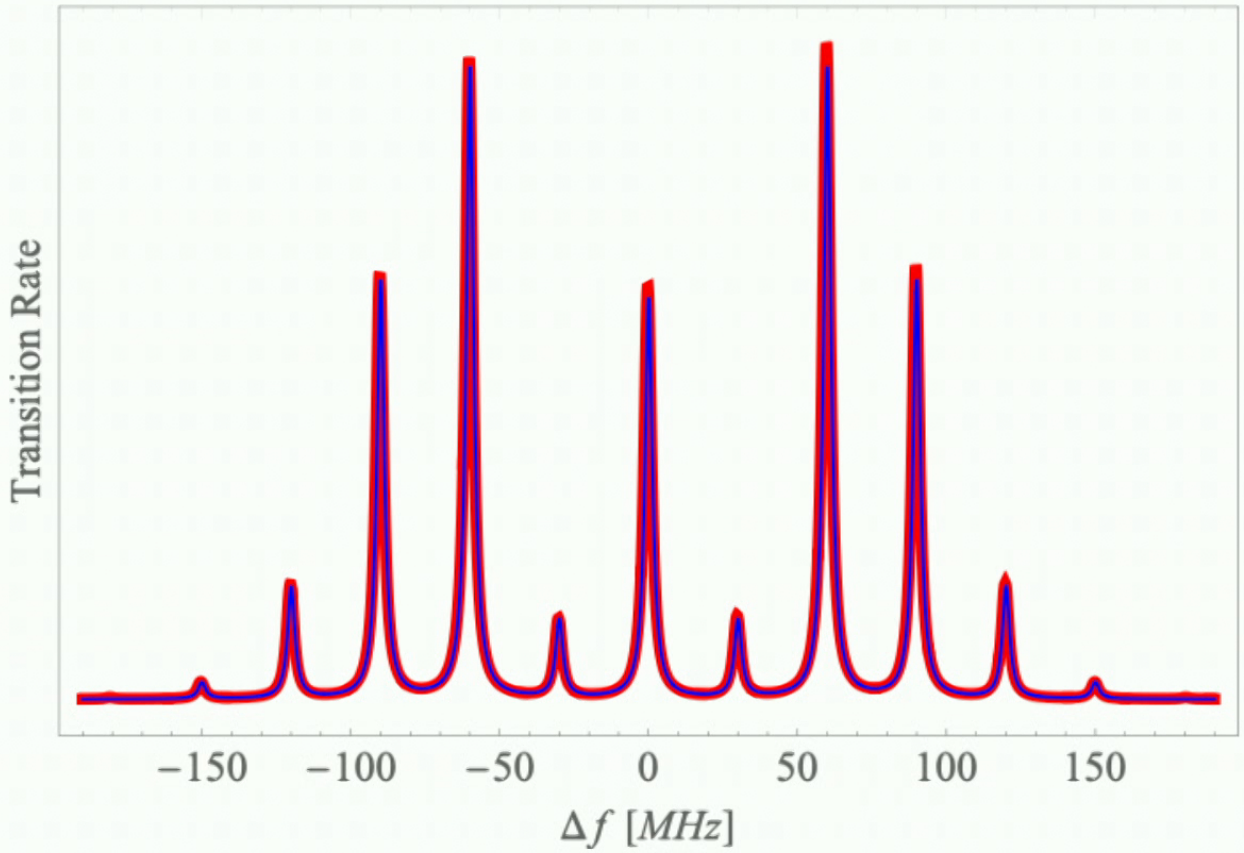
Boundary conditions: no infinite oscillation contribution: $\lim_{l\to\pm\infty} \beta_l = 0$

$$c_2^{(l)} = 0 \qquad\qquad E_l = \Delta E_{DC} + l\hbar\omega$$

Rabi frequency for transitions to sideband state:

$$\Omega_l = A_{30s}^{DC} c_1 J_l\left(\frac{\gamma E_{AC}}{\hbar\omega}\right) \Omega_{6p\to 30s}$$

$^{133}Cs(6P_{1/2} \rightarrow 30S_{1/2})$ Spectrum

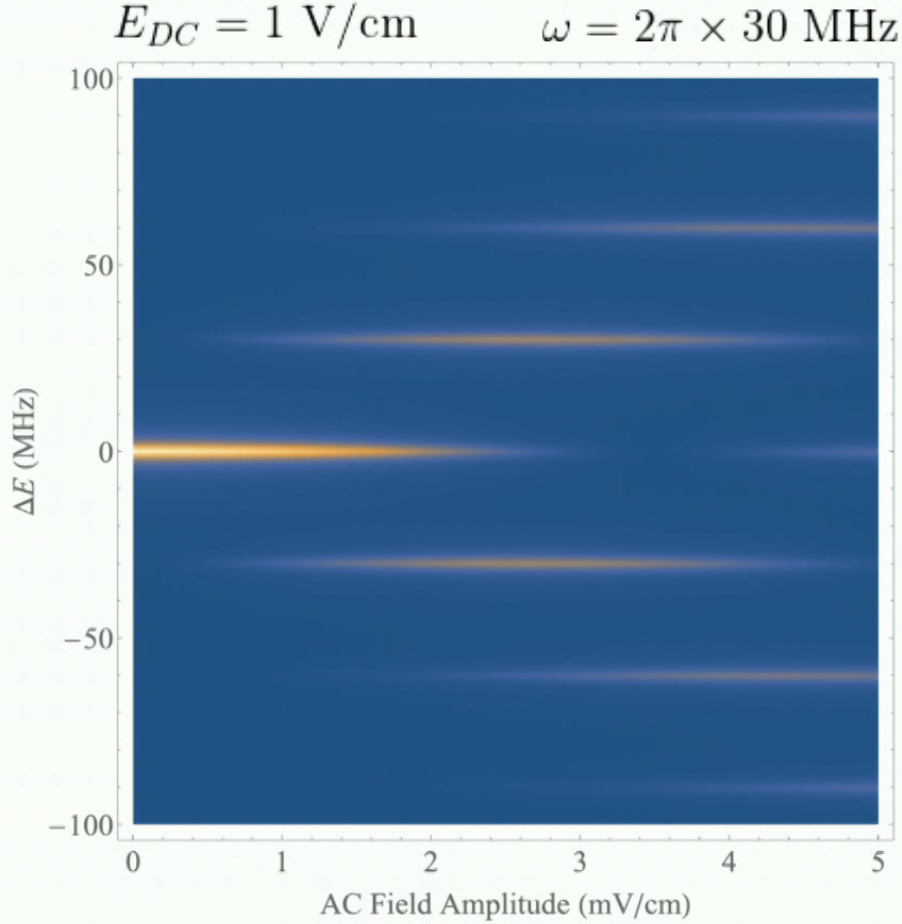


Red: Converged Floquet

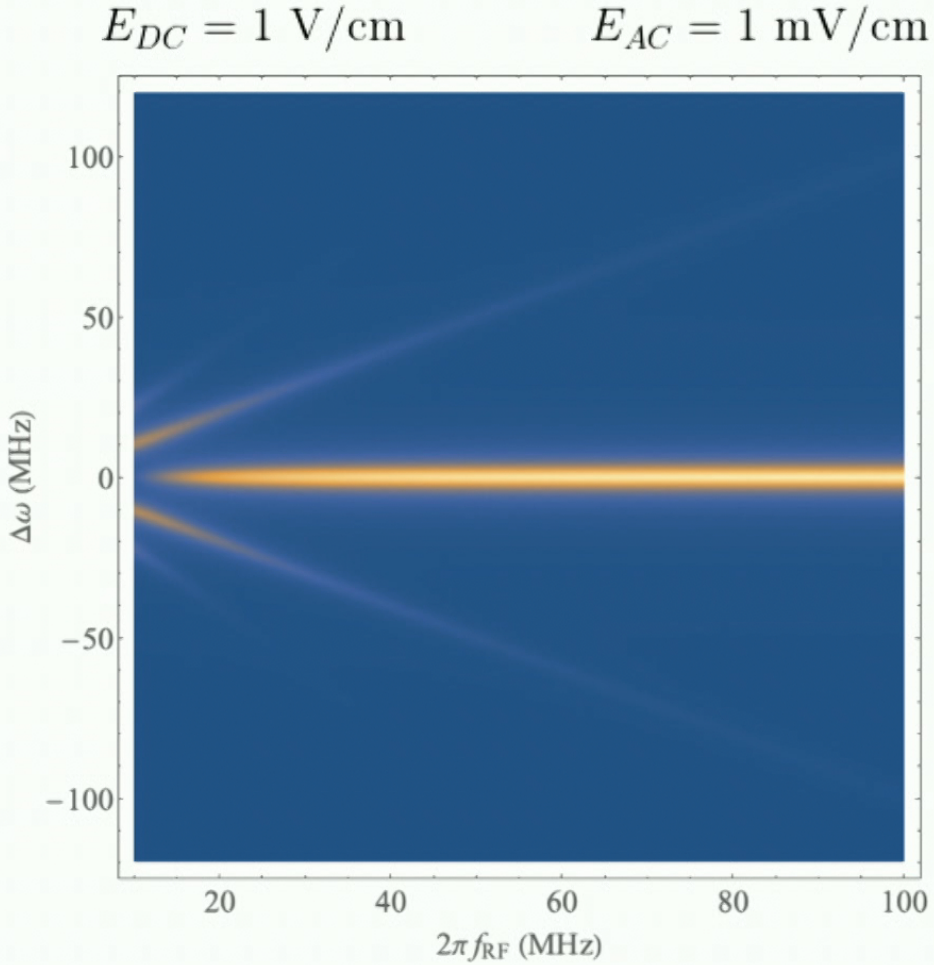
Blue: Approximation

$E_{DC} = 1$ V/cm $\quad E_{AC} = 5$ mV/cm $\quad \omega = 2\pi \times 30$ MHz

Significant variation as a function of RF Amplitude

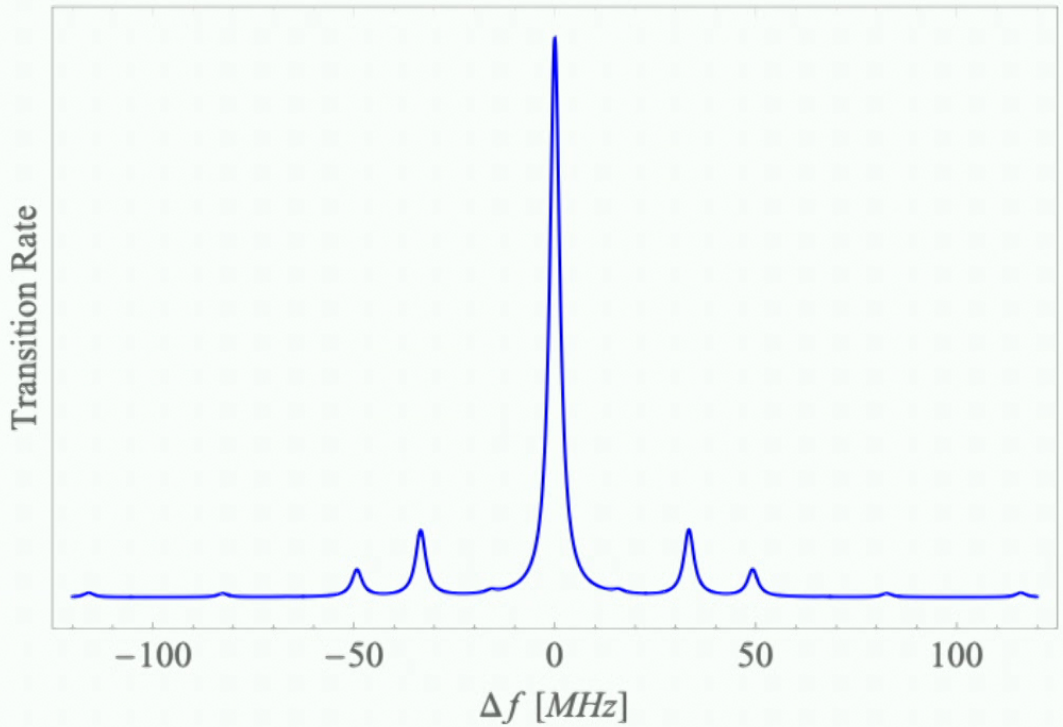


Sidebands give frequency resolution as well



Multiple incommensurate RF fields

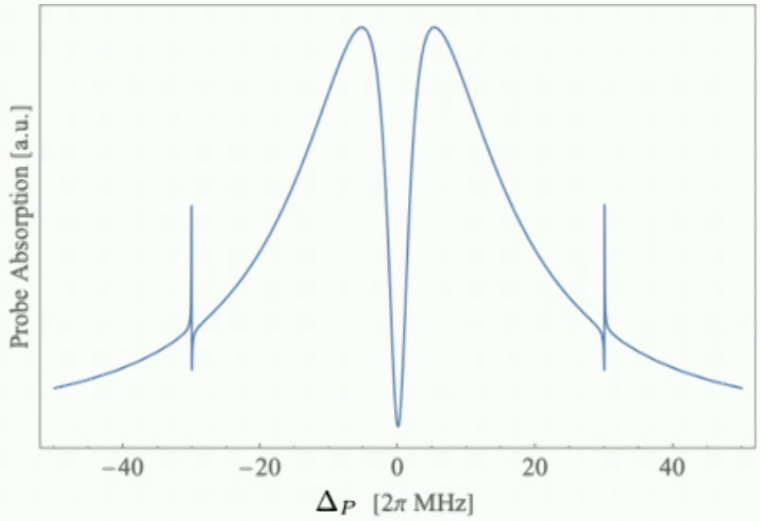
$$|\Psi(t)\rangle = e^{-iE/\hbar} \sum_{\mathbf{m}} e^{-i\mathbf{m}\cdot\mathbf{\Omega}t} |\phi_{\mathbf{m}}\rangle$$



$\omega_1 = 2\pi \times 30$ MHz $\omega_2 = 2\pi \times 47$ MHz $\omega_3 = 2\pi \times 115$ MHz

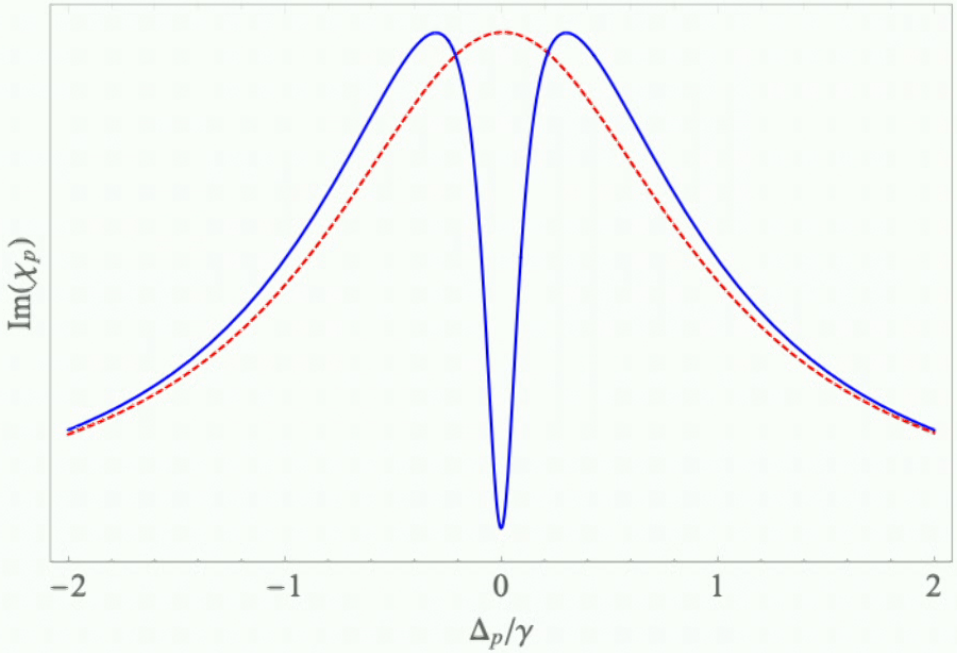
Outline

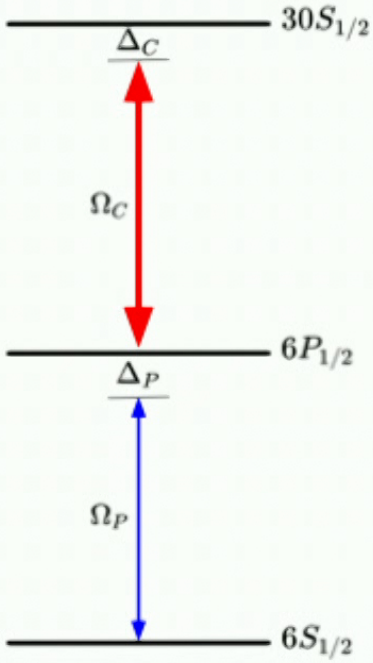
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- **EIT and Thermal averaging**
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Electromagnetically Induced Transparency

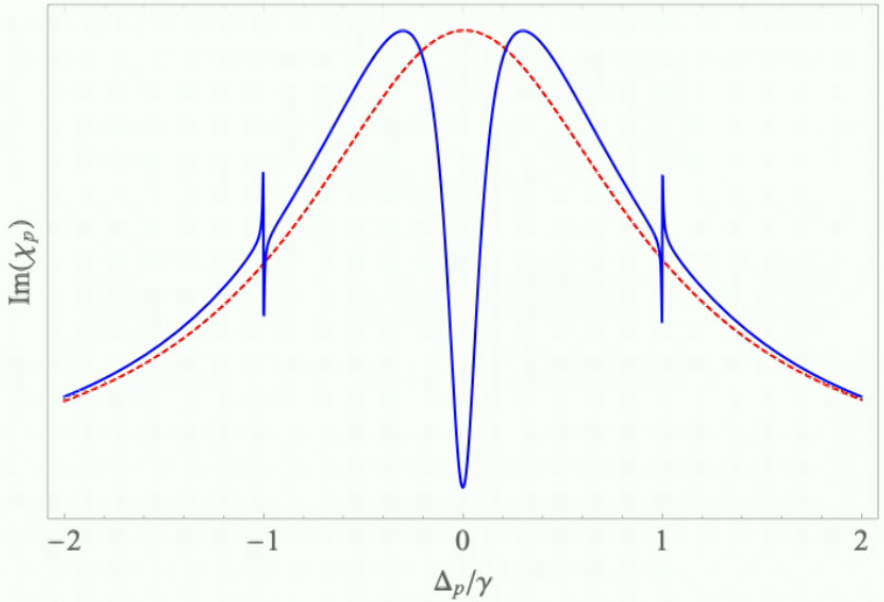
Simple version: Three level system with strong control field and a weak probe field.

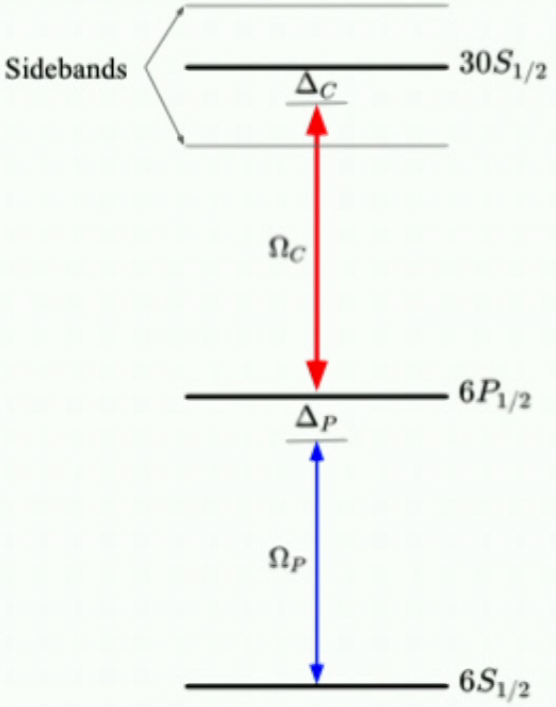




Electromagnetically Induced Transparency

Multilevel scheme, sidebands show up as asymmetric structures



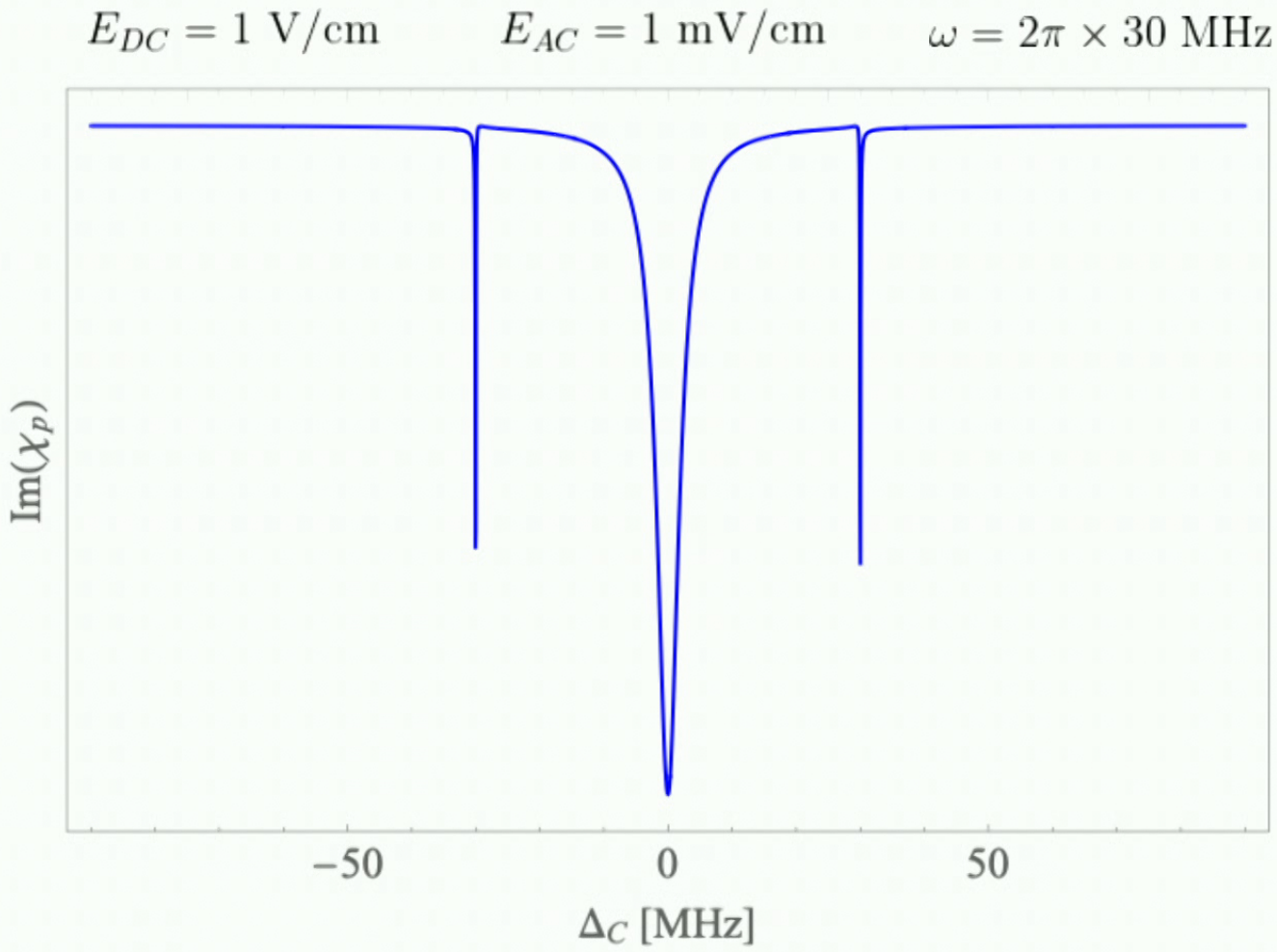


832 nm probe

510 nm control

$I_C = 1\ \mu\mathrm{W}/\mu\mathrm{m}^2$

$\Omega_{6P_{1/2}\to 30S_{1/2}} = 26\ \mathrm{MHz}$



Thermal Averaging and Doppler broadening

Room temperature gas means doppler shift must be taken into account.



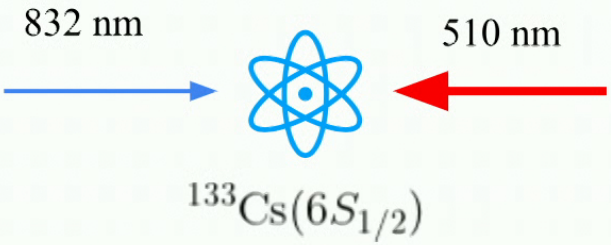
$^{133}\mathrm{Cs}(6S_{1/2})$

$$\chi_{eff}(\Delta_C, \Delta_p) = \int w(v_z)\chi_p\left(\Delta_C - \omega_c\frac{v_z}{c}, \Delta_p + \omega_p\frac{v_z}{c}\right)dv_z$$

$$w(v_z) = \frac{1}{\sqrt{2\pi}v_{th}}e^{-v_z^2/2v_{th}^2}$$

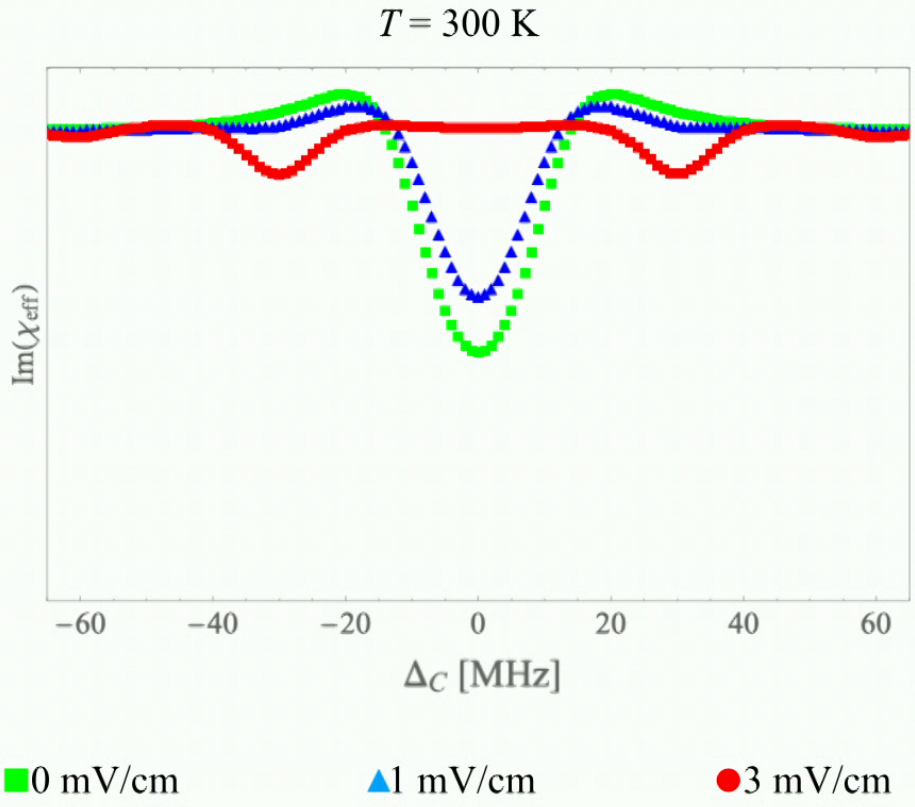
Thermal Averaging and Doppler broadening

Room temperature gas means doppler shift must be taken into account.

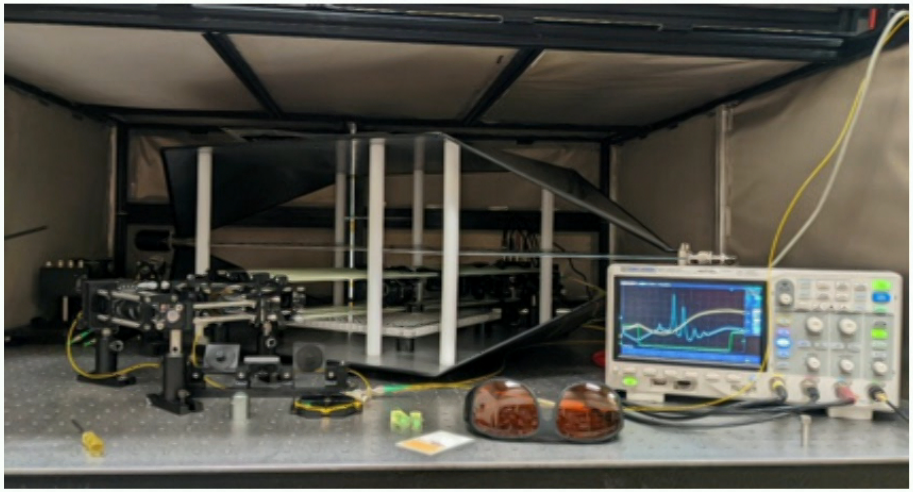


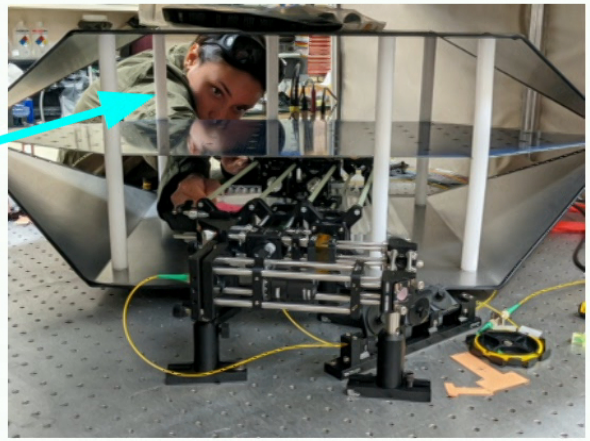
$$\chi_{eff}(\Delta_C, \Delta_p) = \int w(v_z)\chi_p\left(\Delta_C - \omega_c\frac{v_z}{c}, \Delta_p + \omega_p\frac{v_z}{c}\right) dv_z$$

$$w(v_z) = \frac{1}{\sqrt{2\pi}v_{th}}e^{-v_z^2/2v_{th}^2}$$

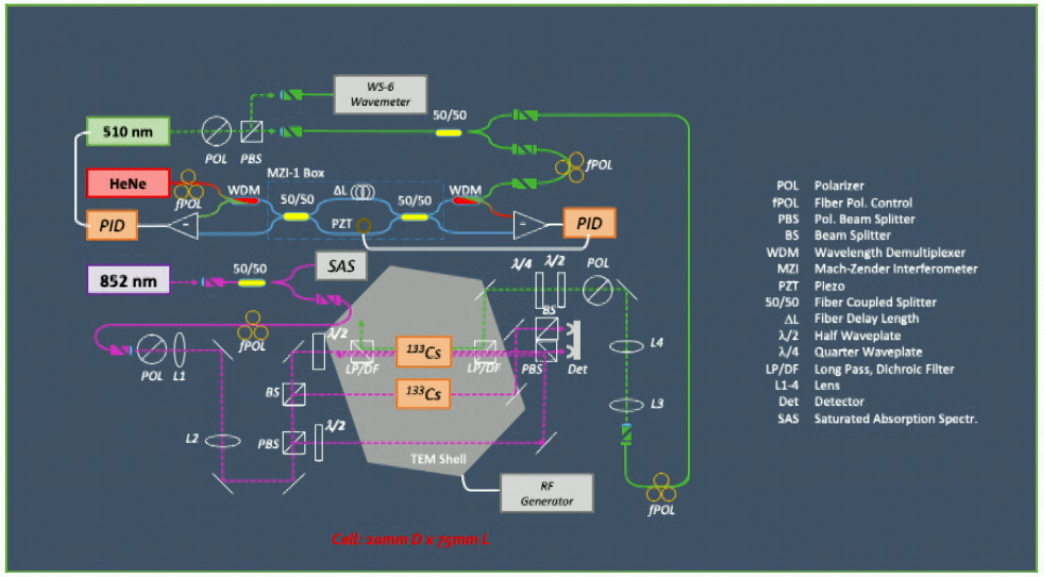


Experiment is starting up

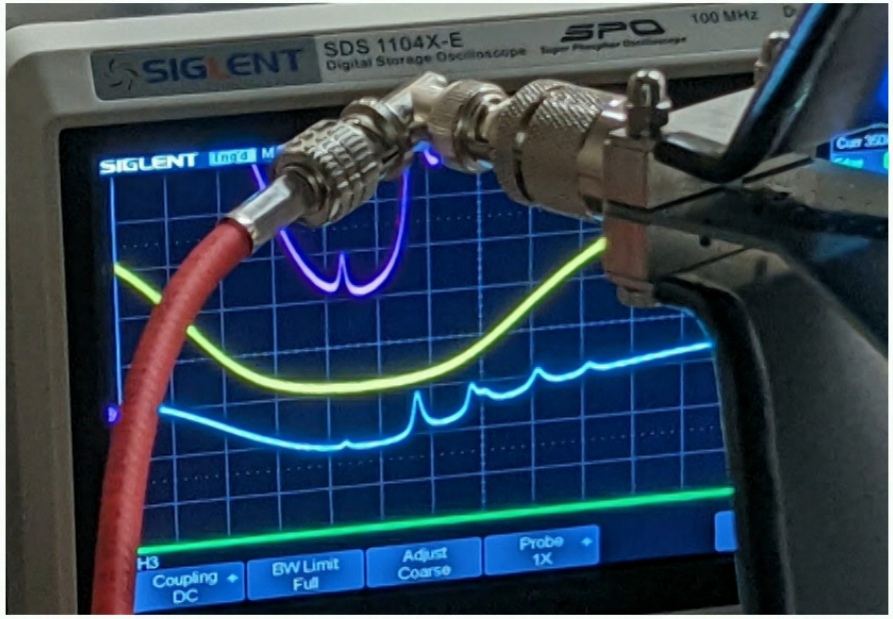




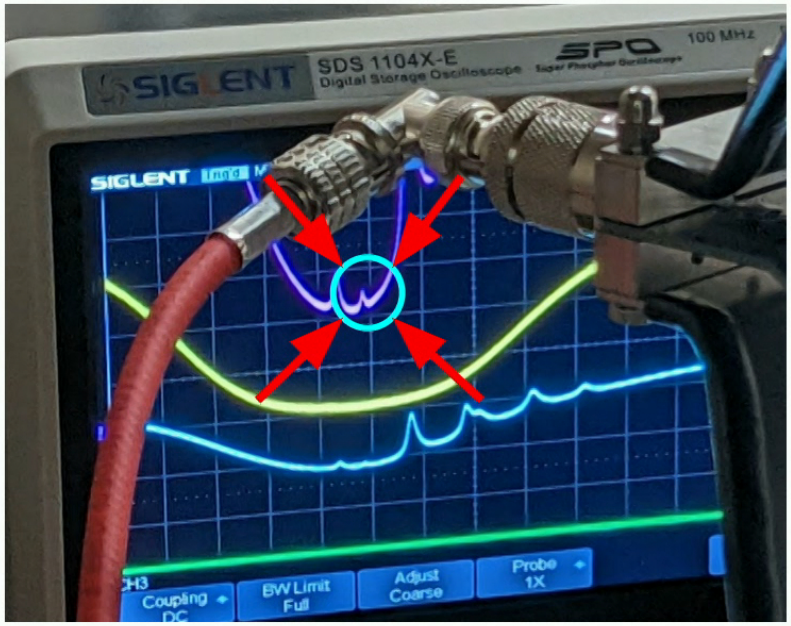
MIDN Ortiz



Initial EIT transmission for field free system



Control laser off

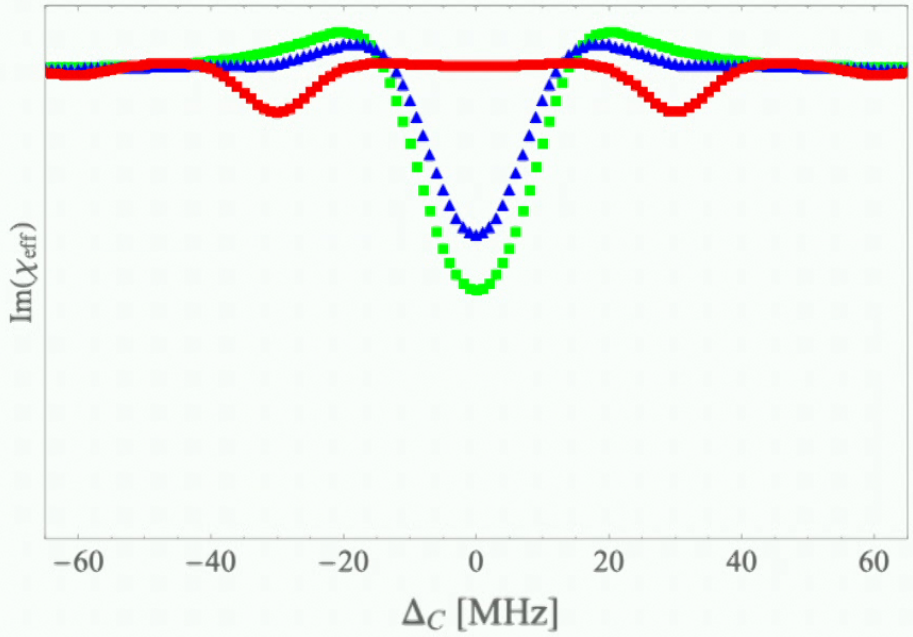


Control laser on

$\lambda = 512.53$ nm

Summary

- Low frequency AC Stark effect is unlikely to be directly useful for RF field sensing
- DC offset field produces higher AC field sensitivity
- Sideband transition rate is sensitive to AC field amplitude and frequencies
- EIT transmission window width provides effective sensitive spectroscopy for detecting sidebands even after thermal averaging



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