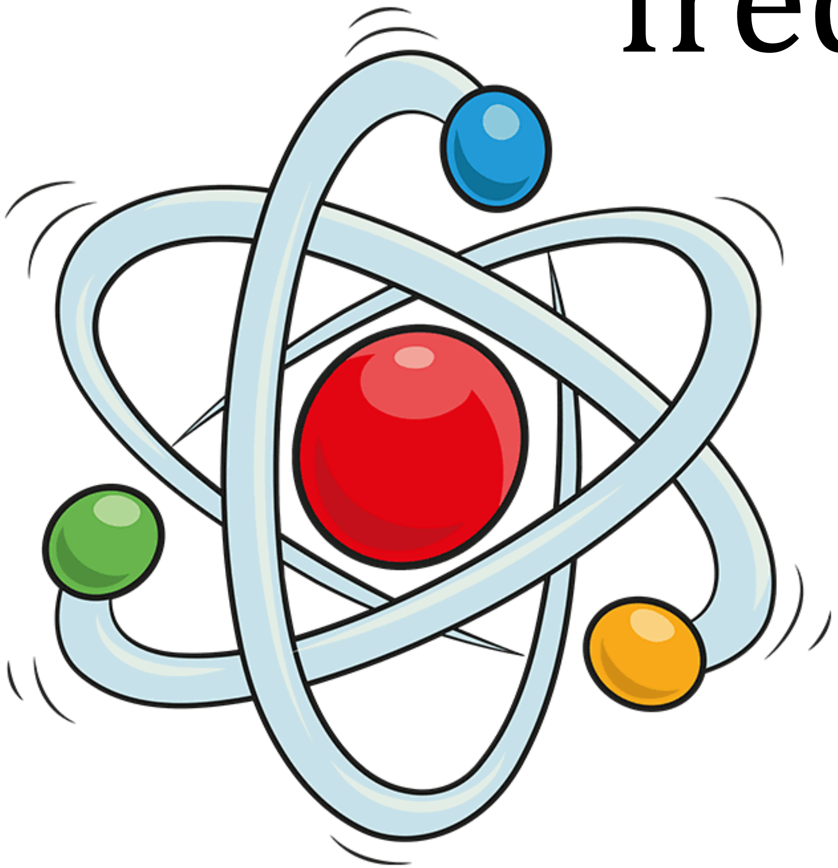
Rydberg atom-based radio frequency sensor



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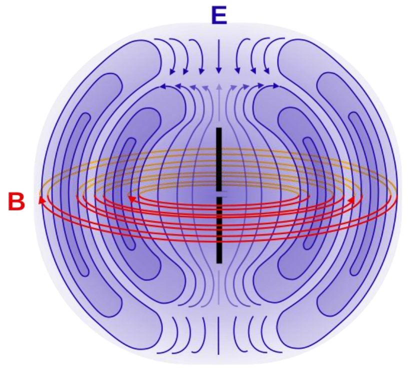
Seminar 1

Limitations of the classical receivers

1. Low sensitivity: thermal motion of electrons perturbs the electric current in an antenna
   (sensitivity = minimum amplitude of the input signal required to produce an output signal with a specified signal-to-noise ratio)
2. Limited bandwidth: optimal response bandwidth constrained by the size of antenna

$$l = \lambda/2$$

3. Electric field distortion: perturbation of detected field due to the coupling with antenna
4. Anisotropy of the radiation and detection: doughnut shaped axially symmetric fields

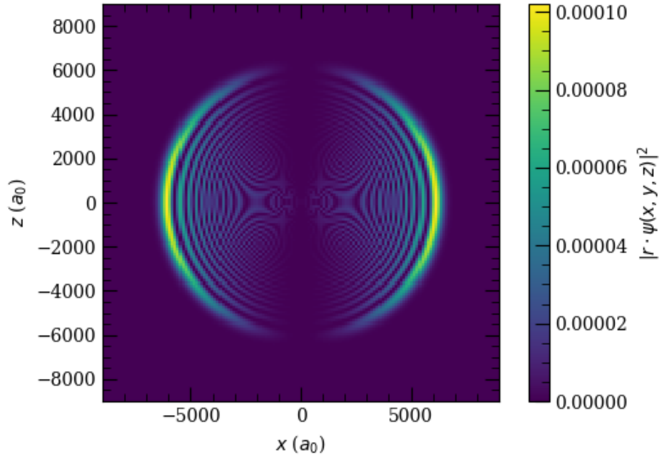


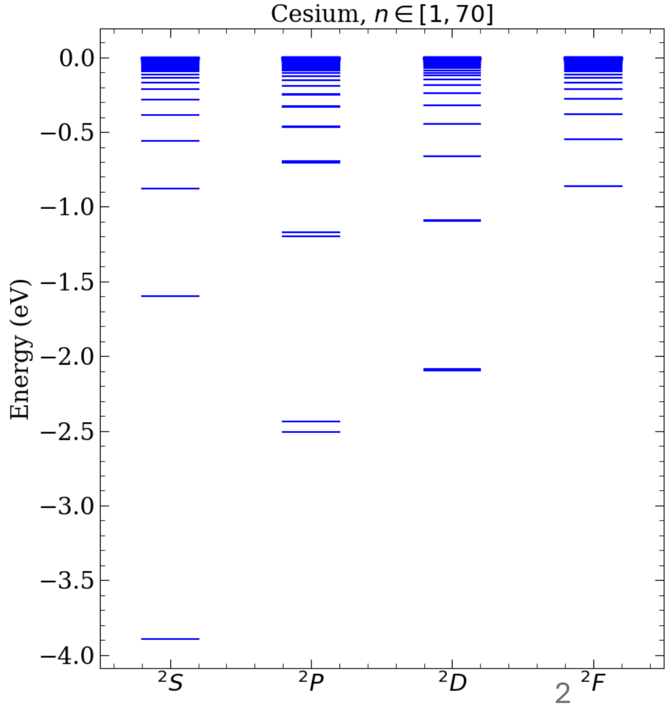
Atom-based sensors

Rydberg atoms: atoms in states with a high principal quantum number n

Properties of Rydberg atoms

1. Coupling to radio frequency fields: spacing between levels of Rydberg atoms $\propto n^{-3}$
2. High polarizability: high dipole moment $\mathbf{p} = -e\mathbf{d}$ $\longrightarrow$ high sensitivity to electric fields
3. Long lifetimes: reaching hundreads of microseconds $\frac{1}{\tau_0} = \sum_{n'} A_{nn'} \longrightarrow \tau_0 \propto n^3$
4. Hydrogen-like atoms: $E_{nl} = -\frac{R_y}{(n-\delta_{nl})^2} \longrightarrow n_\star = n - \delta_{ln}$

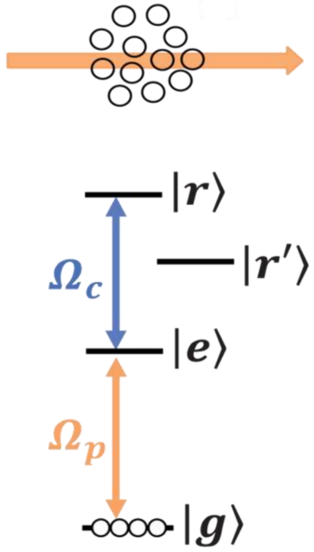




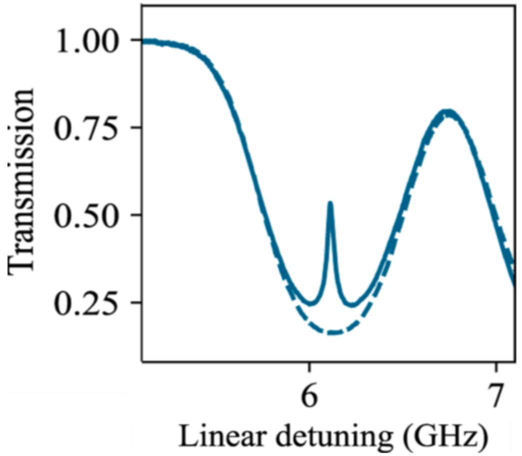
Preparation and detection of Rydberg atoms

- In experimental setups: cesium and rubidium
- Preparation: two-photon excitation with a weak probe Ω_p and a stong coupling Ω_c laser between the ground state $|g\rangle$, an intermediate excited state $|e\rangle$, and a Rydberg state $|r\rangle$
- Detection: electromagnetically induced transparecy (EIT)

  emerges on two-photon resonance → the atom evolves in the dark state $|0\rangle = \dfrac{\Omega_c|g\rangle - \Omega_p|r\rangle}{\sqrt{\Omega_p^2 + \Omega_c^2}}$
  → transparency for the probe



- Spectroscopy: measuring transmission of the probe beam through an atomic vapor cell as a function of frequency of either the control beam or the radio frequency
- EIT creates a transmission peak



Radio frequency (RF) field detection

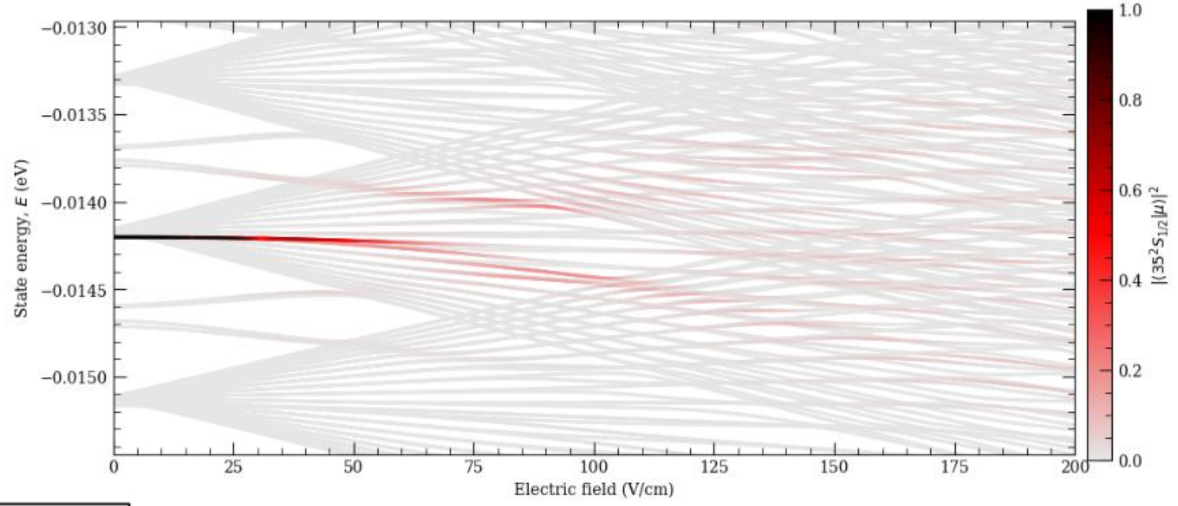
Stark effect: splits and modifies energy levels in presence of an external electric field

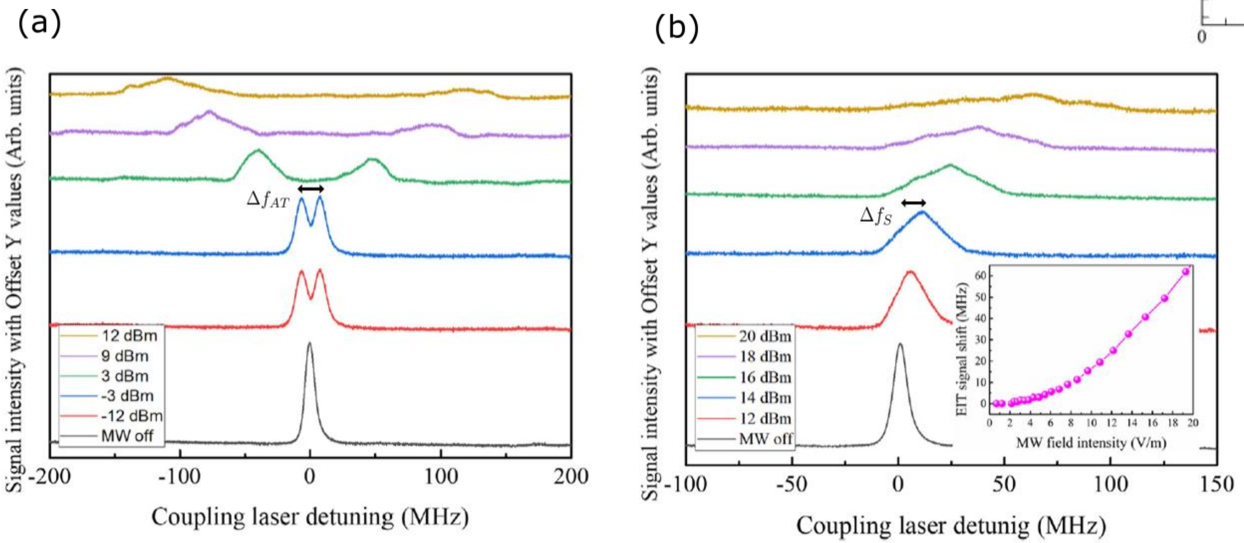
a) Autler-Townes splitting: resonant fields

$$\Delta f_{AT} = \frac{\mathcal{P}_{rr'}|E|}{\hbar}$$

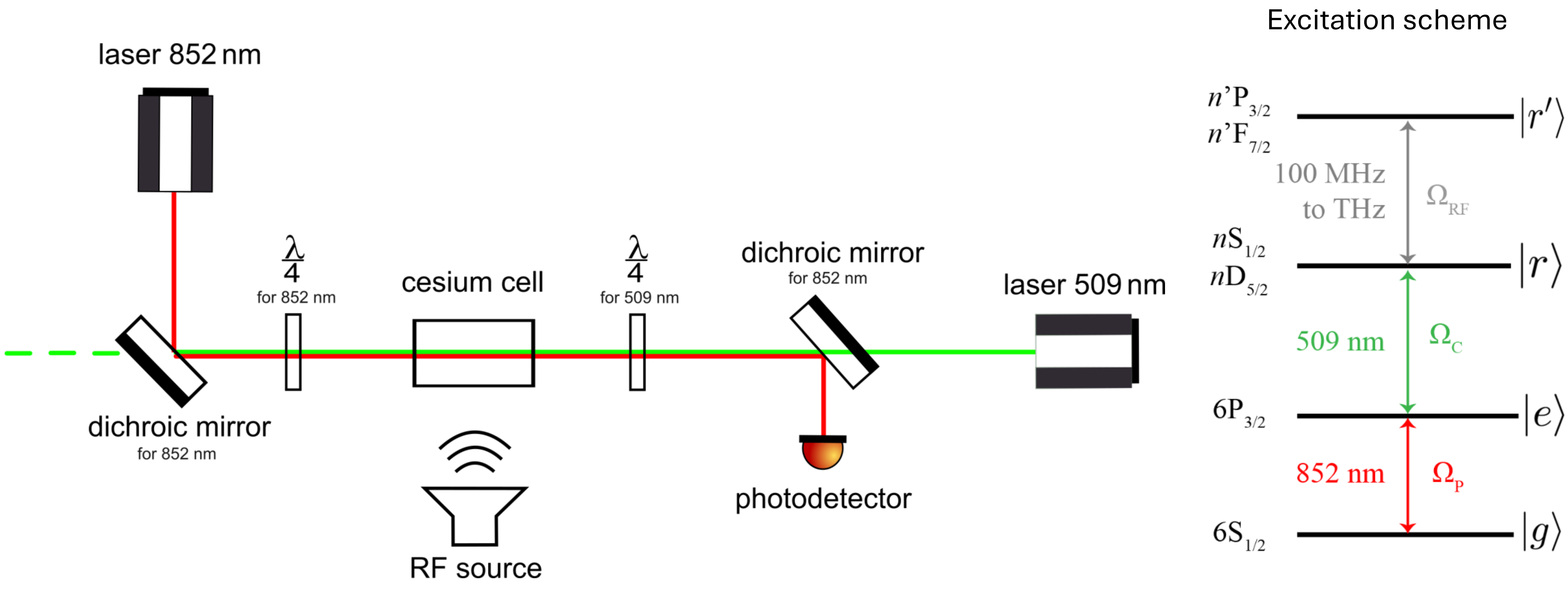
b) Stark shift: non-resonant fields

$$\Delta f_S = \frac{\alpha}{2}|E|^2$$





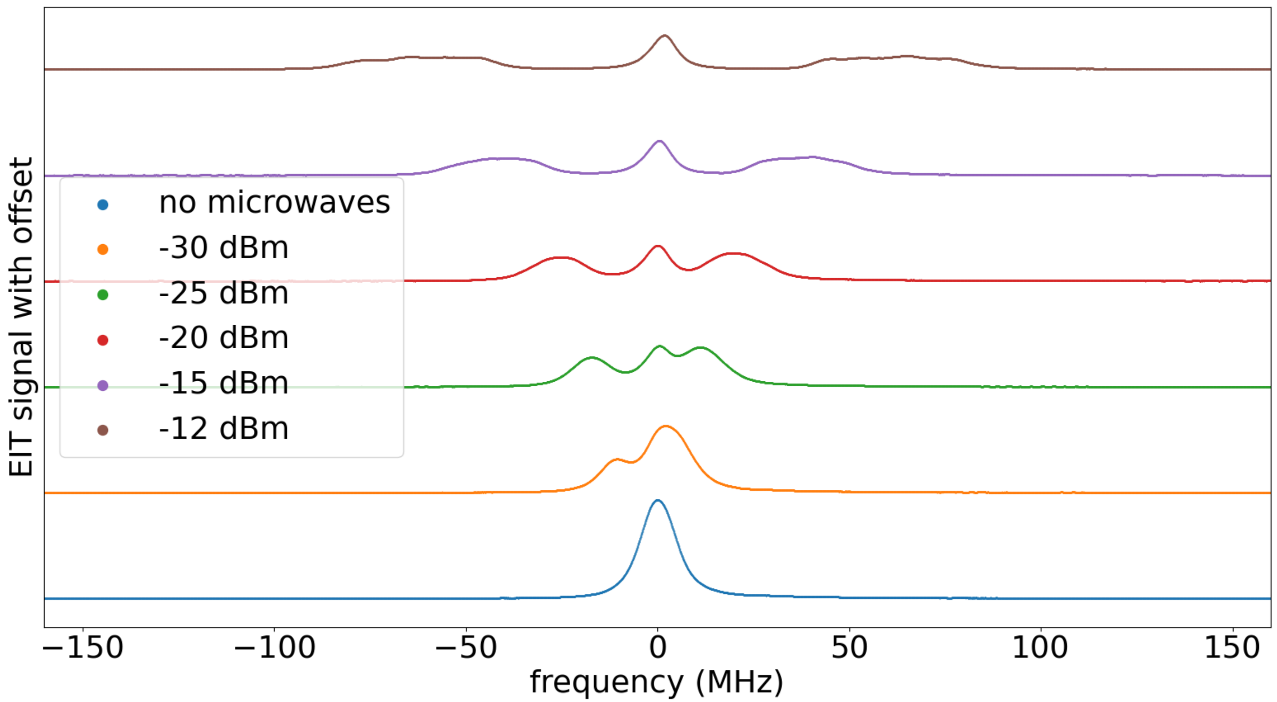
Setup in Laboratory for cold atoms



Experimental results

- Resonant RF field of different amplitudes

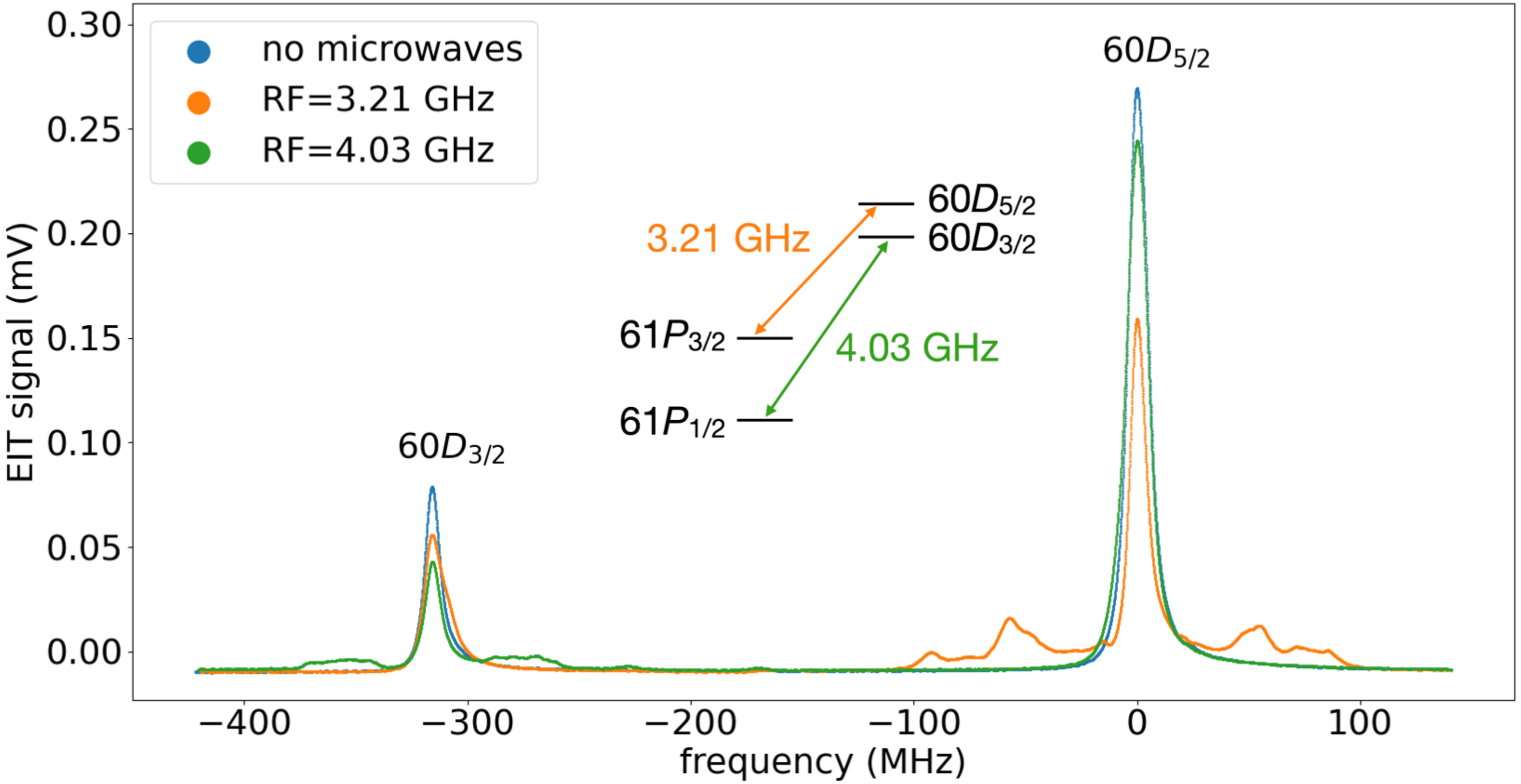
Transmission of the probe beam as a function of the coupling beam frequency



→ Autler-Townes splitting of the EIT signal corresponding to the state $60D_{5/2}$, when RF field with a resonant frequency of 3.21 GHz is applied

Experimental results

- RF field resonant with different transitions

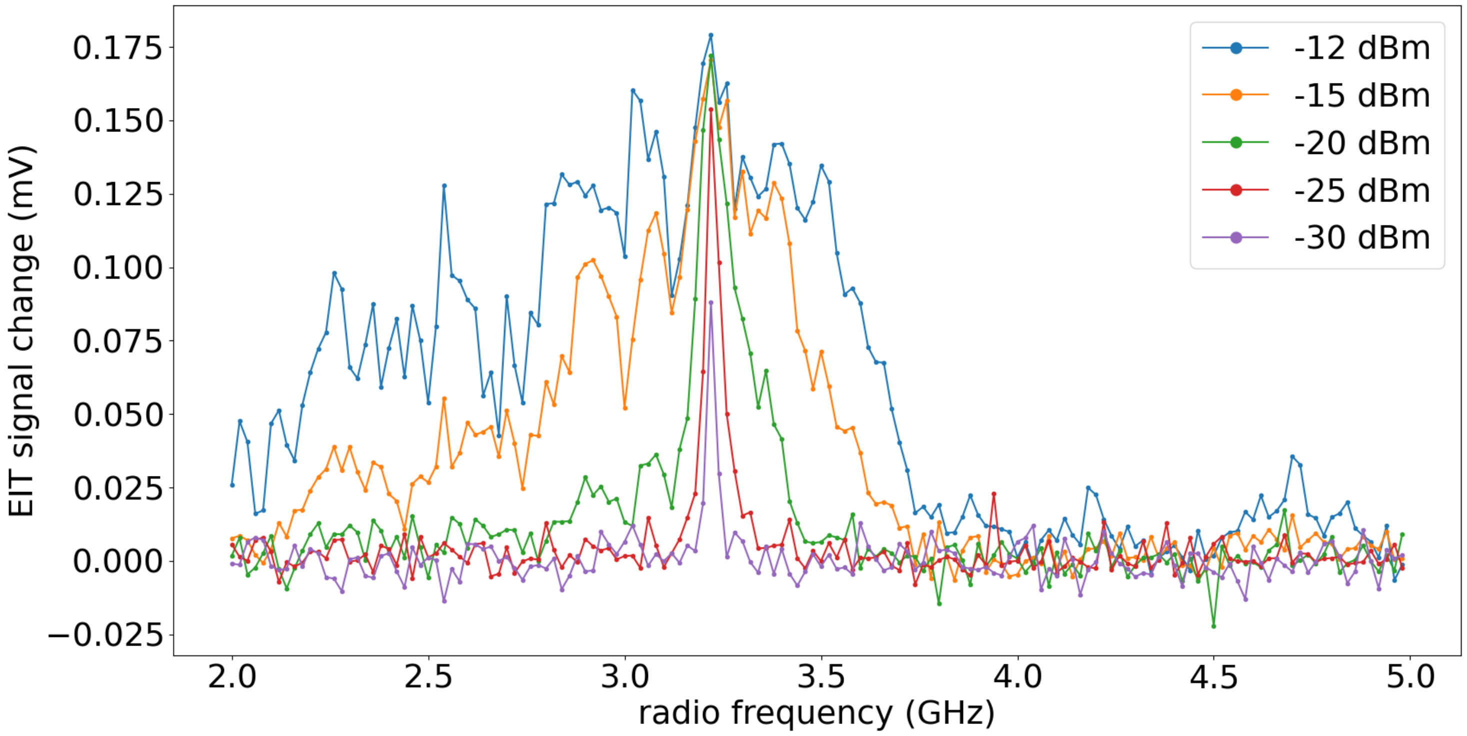


→ $60D_{5/2}$ lowers and splits when RF field with a resonant frequency of 3.21 GHz is applied

→ $60D_{3/2}$ lowers and splits when RF field with a resonant frequency of 4.03 GHz is applied

Experimental results

- Bandwidth dependence on the RF field amplitude



→ Narrow, resonant response around the resonant frequency of 3.21 GHz for low RF field amplitude

→ Broadband response for higher RF amplitudes

State of the art

Rydberg atom receivers:

✓ No distortion of EM field

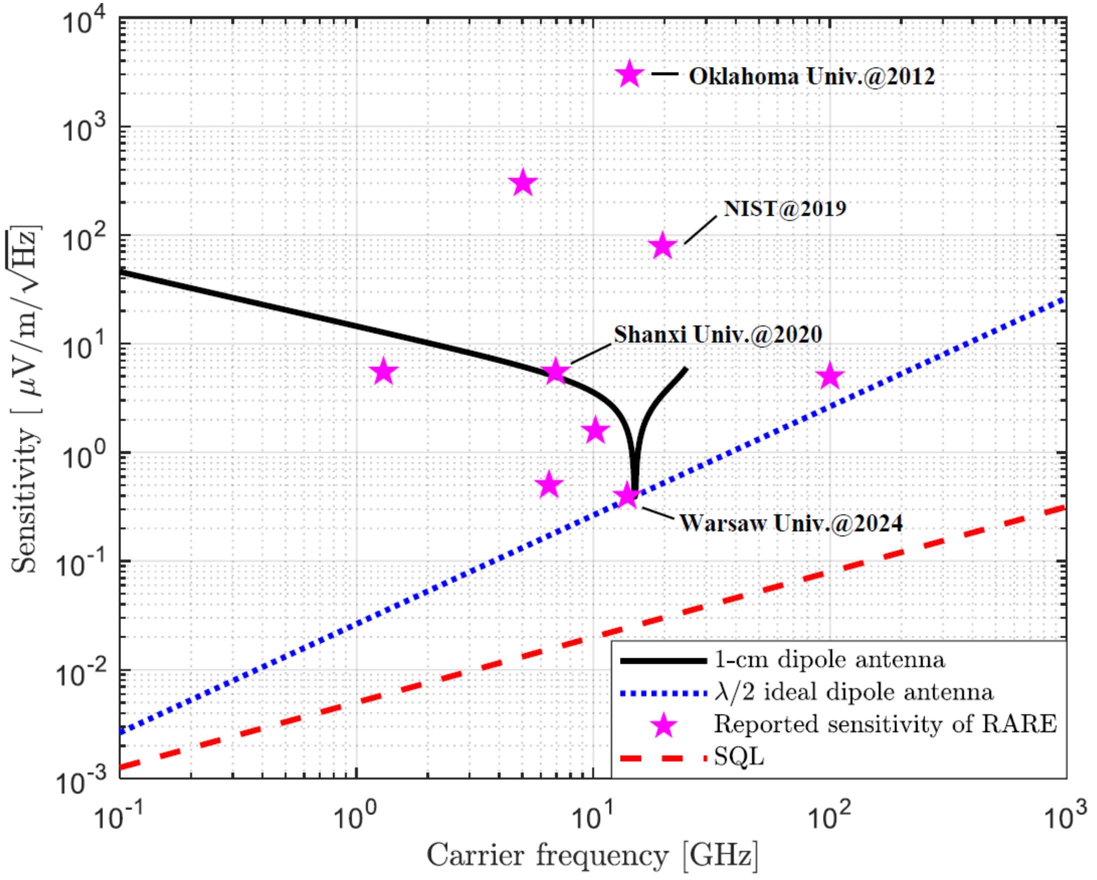
✓ Isotropic RF field sensors

✓ Broadband sensors (MHz to THz)

✓ Not limited by thermal noise, but by quantum shot noise

⟶ theoretical sensitivity limit:

$$E_{\mathrm{min}} = \frac{\hbar}{|p|}\sqrt{\frac{1}{N_a T_r}}$$



→ Rydberg receivers will surpass the fundamental sensitivity limits of ideal antennas and approach the standard quantum limit in the near future.