Coupled atom-cavity system: a quantum sensor

by

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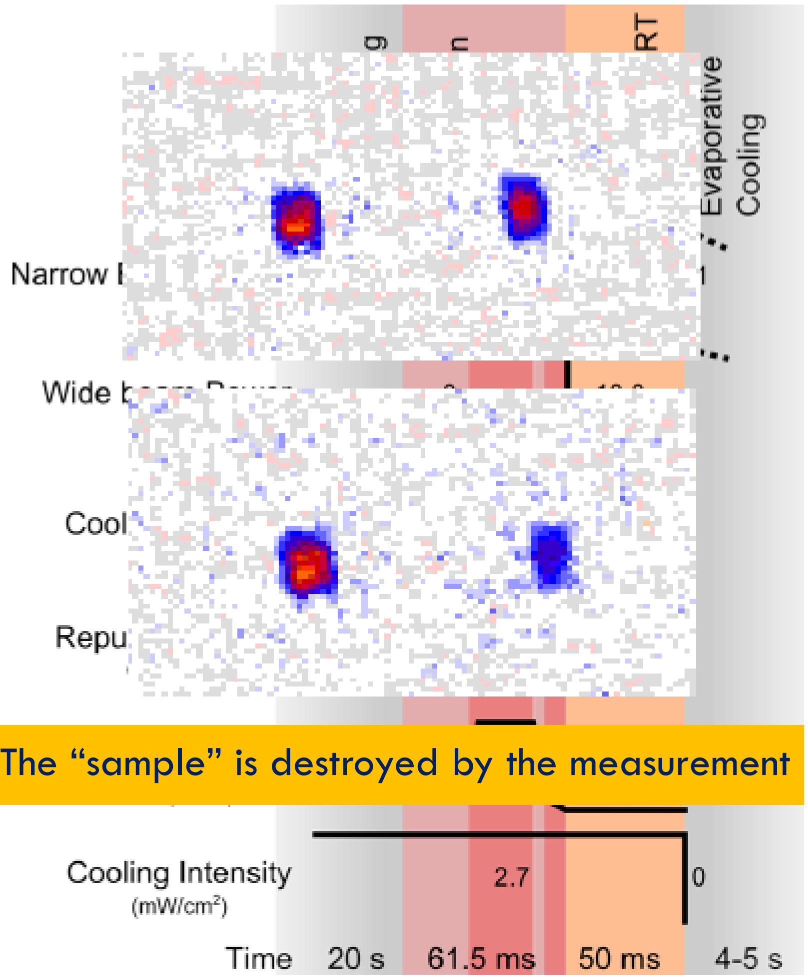
How is a typical measurement done?

Species that interact directly with light:

Atoms detected by fluorescence/absorption:

Bose Einstein condensate, atoms in a trap etc.

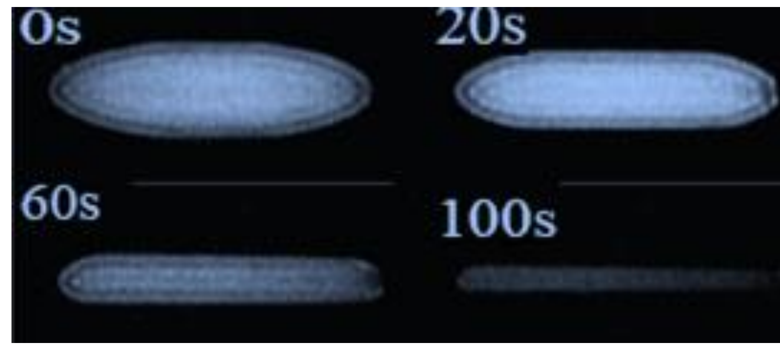


The “sample” is destroyed by the measurement

Ions detected by fluorescence:

Example: Ca^+, Ba^+, Yb^+ etc

Images of the fluorescing ion is recorded



Ca^+ ions reacts with Rb

PRL 107, 243202 (2011)

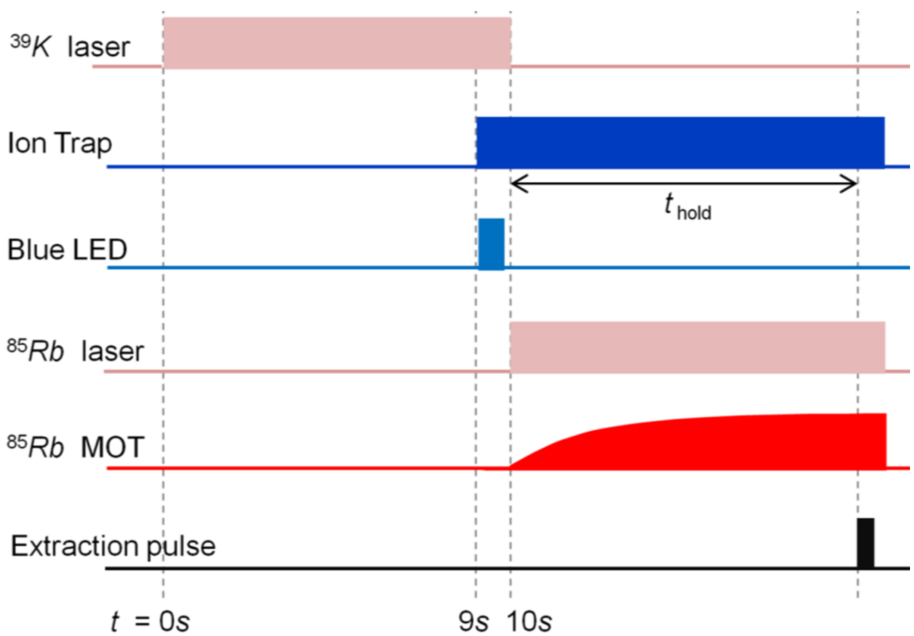
Problem: Quantum state is scrambled
Light alters ion-atom interaction

How is a typical measurement done?

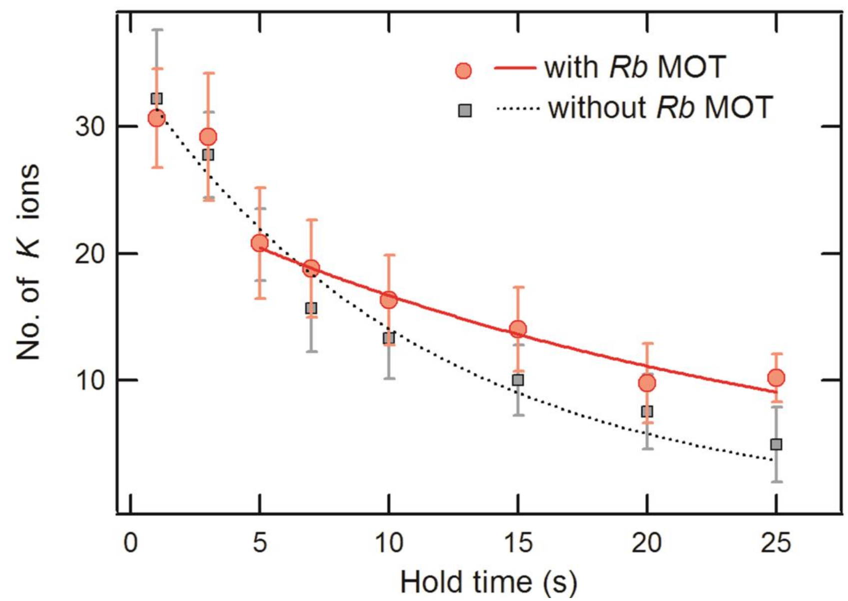
Species that don't interact directly with light:

Ions that do not fluoresce: Rb^+, K^+, Na^+, Li^+ etc.

The ions are detected on a charge sensitive detector



Cooling of low mass ions by heavier atoms

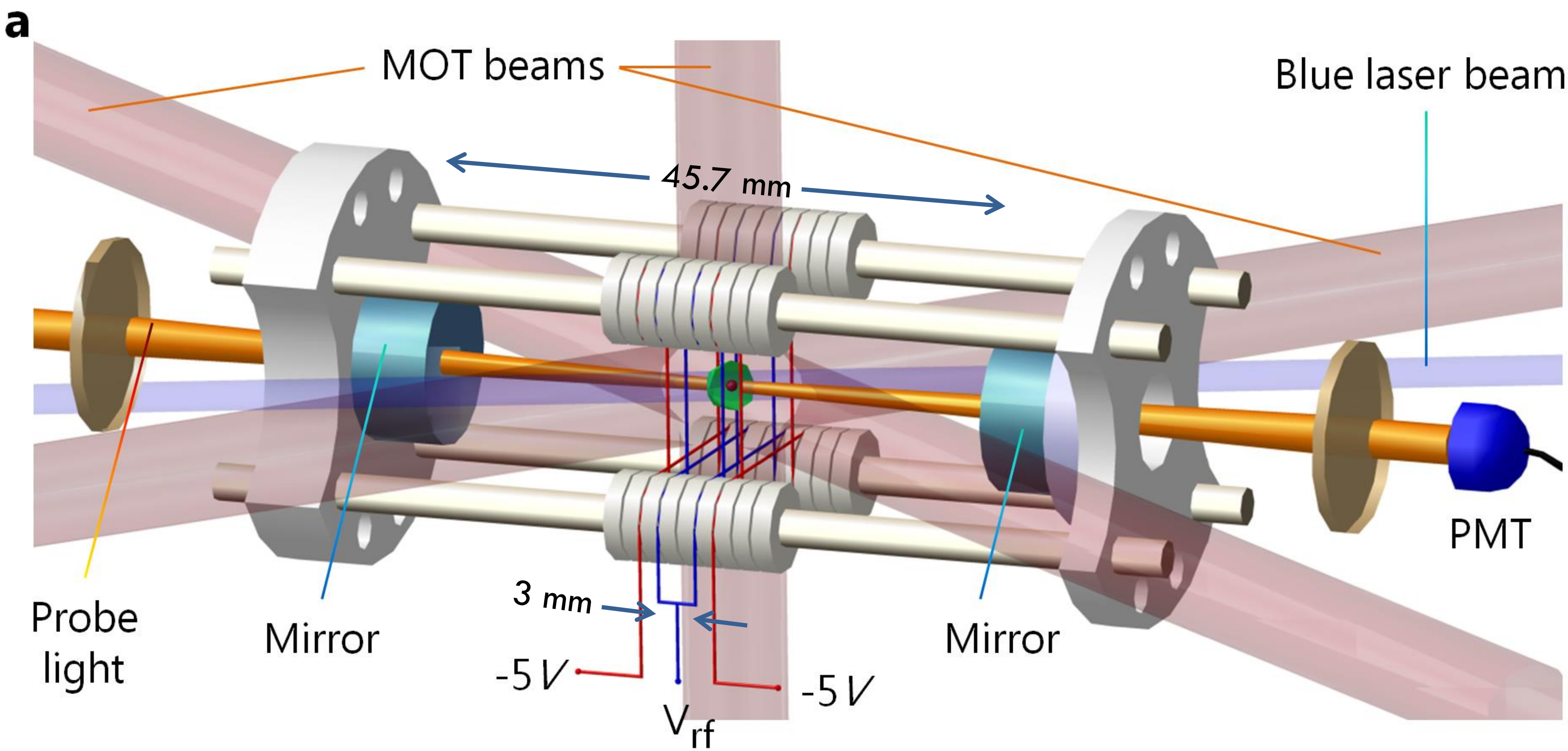


Problem: Ions are lost from the trap, Destructive detection

S. Dutta *et al.*
arXiv: 1512.04197

Challenge: measure ion-atom interaction non-destructively

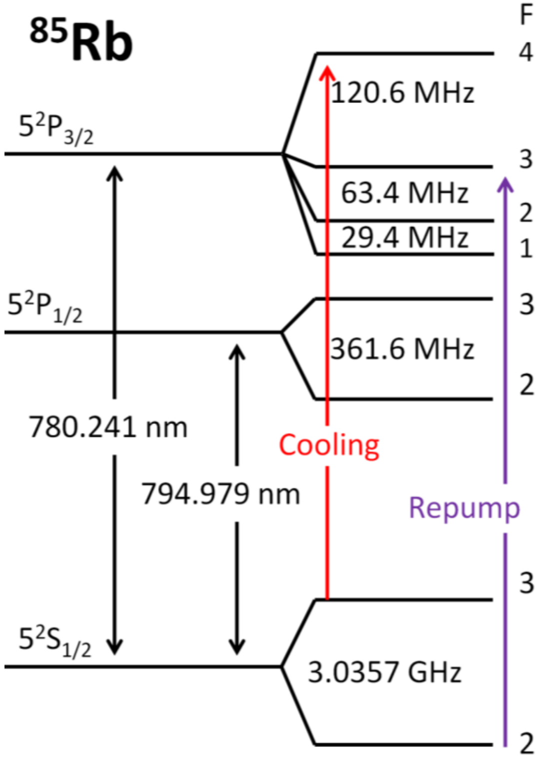
Trapping ions and atoms within a cavity

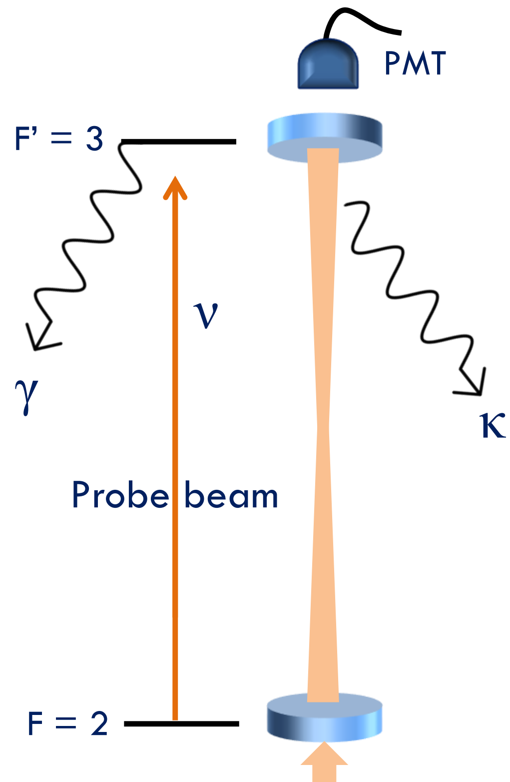


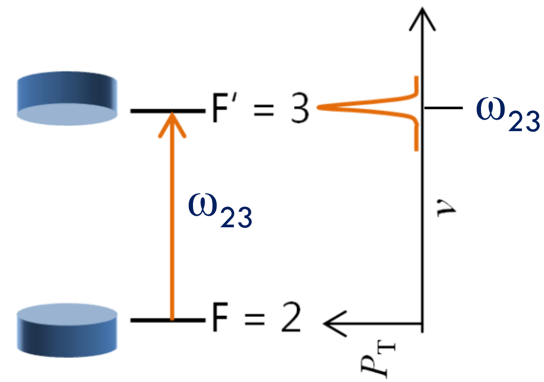
Cavity finesse ~ 650 (low), Free Spectral Range ~ 3.3 GHz, Line width ~ 5 MHz

^{85}Rb atoms prepared in a dark MOT: all atoms in F=2 ground state, very little fluorescence

Collective strong coupling of atoms to the cavity



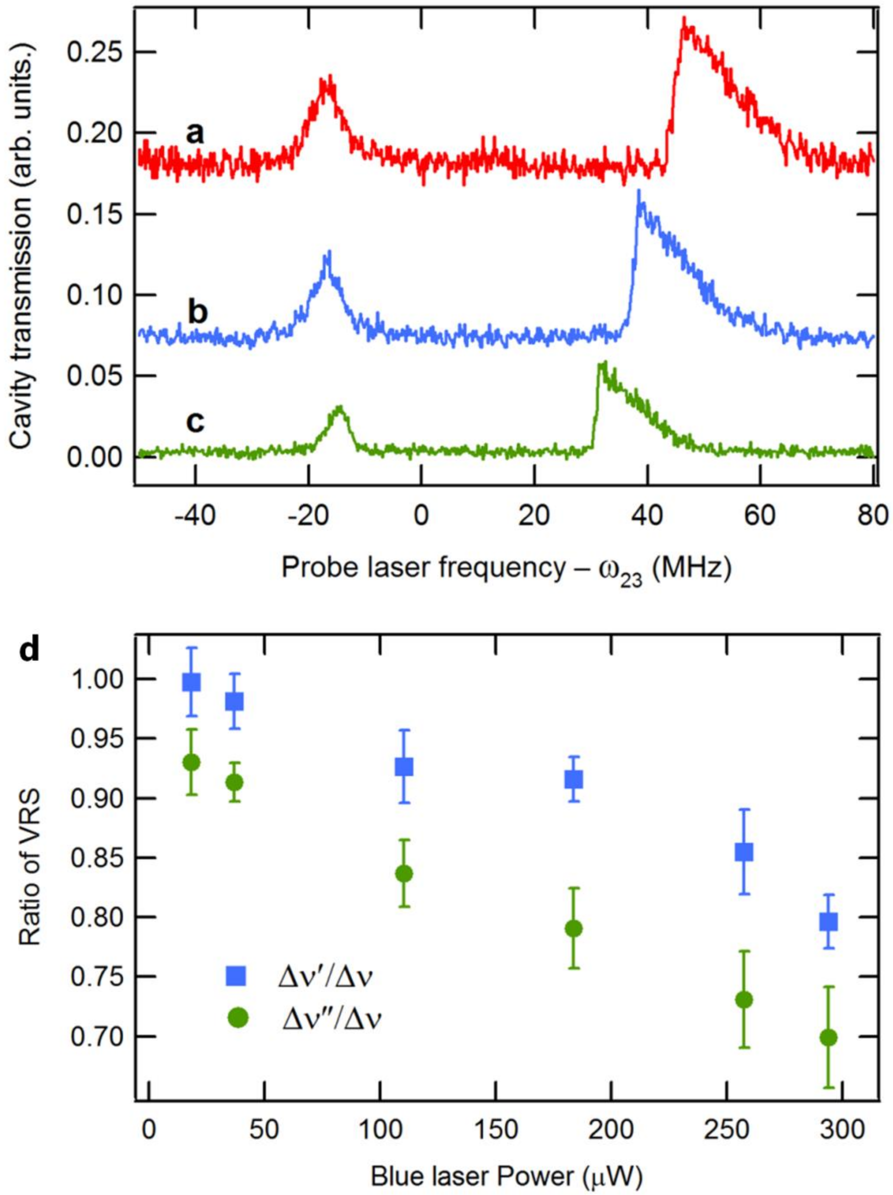




$\gamma \approx 6$ MHz

$\kappa \approx 5$ MHz

The experimental result



with atoms only $\Delta\nu = 60.4 \pm 1.4\,\text{MHz}$

with atoms and photo-ionization (PI) $\Delta\nu'$

with atoms, PI and trapped ions $\Delta\nu''$

■ with atoms and photo-ionization (PI)

● with atoms, PI and trapped ions

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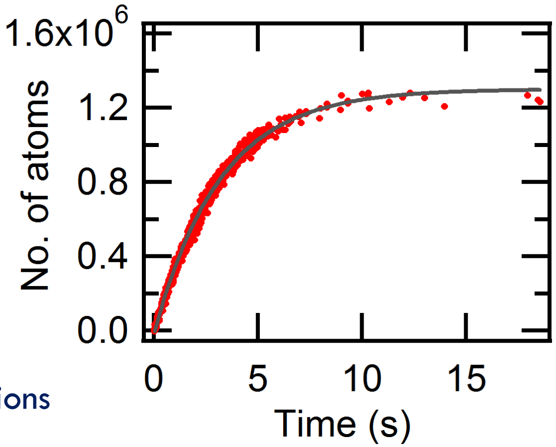
Phys. Rev. A 94, 053841 (2016)

Quantifying the measurement

The number of atoms (N_a) in the MOT is given by:

$$\frac{dN_a}{dt} = L_a - \gamma_b N_a - \gamma_p N_a - k_{aa}\int n_a^2\, d^3r - k_{ia}\int n_a n_i\, d^3r$$

- L_a: Loading rate
- $\gamma_b N_a$: Loss rate due to background gas
- $\gamma_p N_a$: Loss rate due to photo-ionization
- $k_{aa}\int n_a^2\, d^3r$: Loss due to collisions among MOT atoms — Neglect for low n_a
- $k_{ia}\int n_a n_i\, d^3r$: Loss due to collisions with ions



Quantifying the measurement

$$\frac{dN_a}{dt} = L_a - \gamma_b N_a - \gamma_p N_a - \cancel{k_{aa} \int n_a^2 \, d^3r} - k_{ia} \int n_a n_i \, d^3r$$

With PI, with trapped ions:

Assume: Ion trap volume (V_i) >> MOT volume (V_a) ; n_i uniform over V_a

$$k_{ia} \int n_a n_i \, d^3r \approx k_{ia} \, n_i \int n_a \, d^3r = k_{ia} \, n_i \, N_a = \gamma_{ia} \, N_a$$

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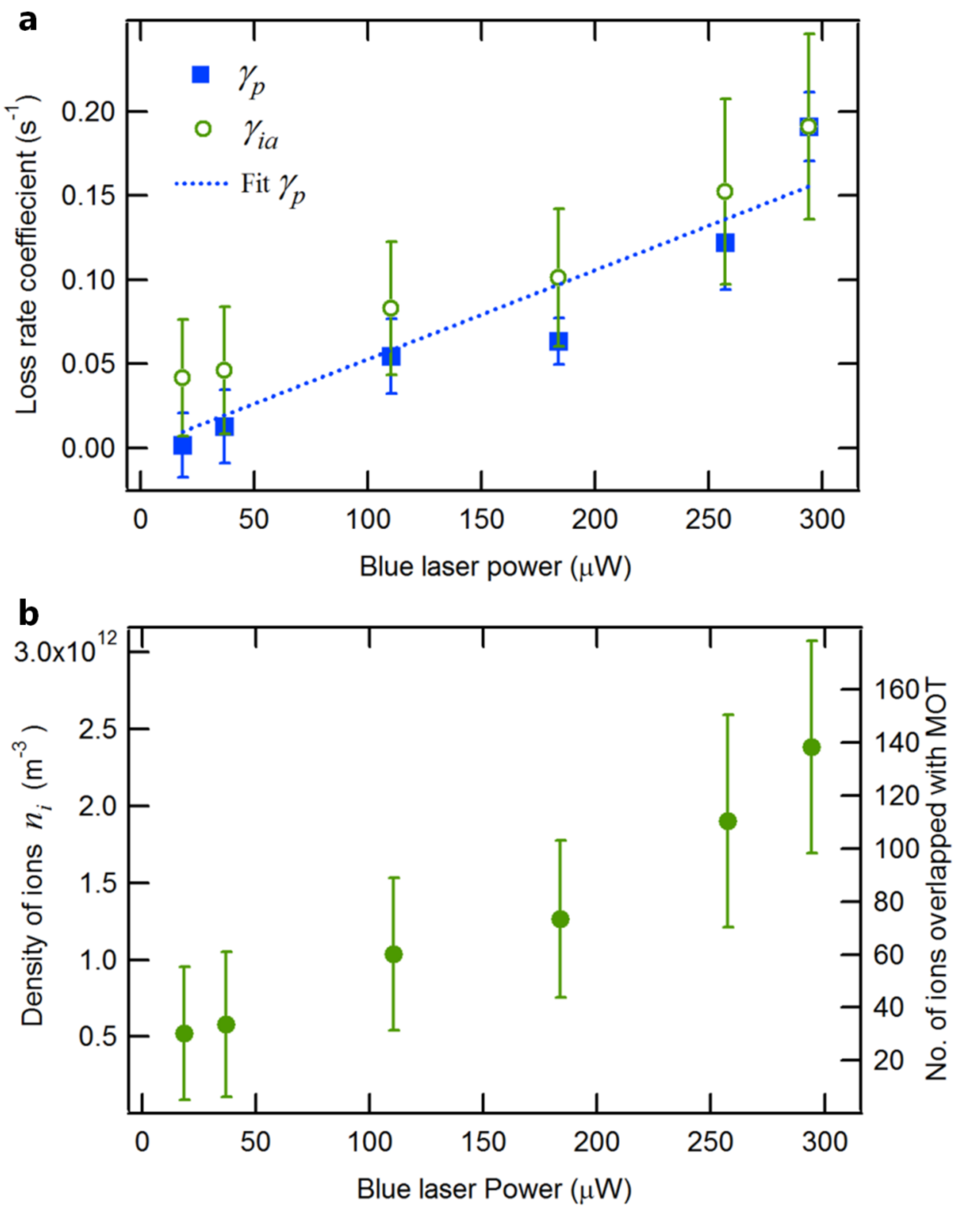
Ion-atom collision rate and ion density



$$\gamma_p = \left[(\Delta\nu / \Delta\nu')^2 - 1 \right] \gamma_b$$

$$\gamma_{ia} = \left[(\Delta\nu / \Delta\nu'')^2 - 1 - (\gamma_p / \gamma_b) \right] \gamma_b$$

$$n_i = \gamma_{ia} / k_{ia}$$

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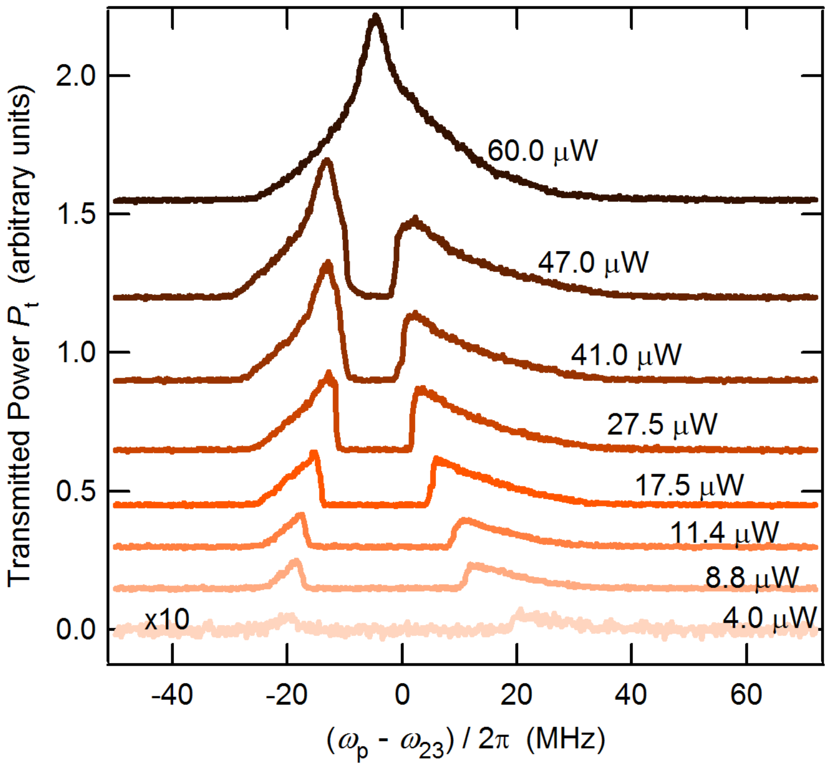
Significance of the technique

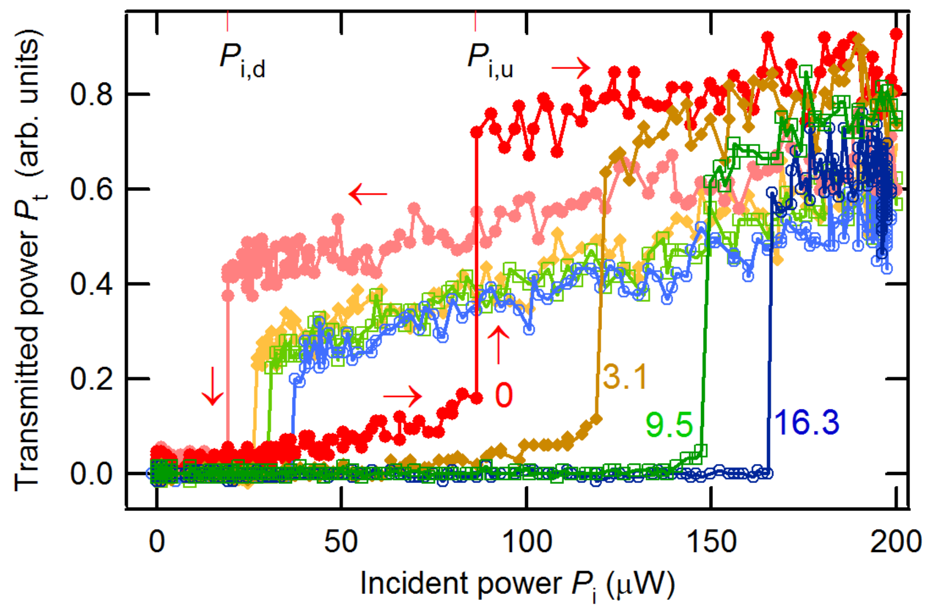
Non-destructive, in-situ measurement of ion density

- Local ion density measurement – only one other method exists for non-fluoresceing ions.

Can be extended to measure quantum state specific atom-atom interaction

Vacuum-Rabi splitting depends on probe power





VRS decreases as probe power increases
Peaks become asymmetric

Cavity transmission shows optical bi-stability

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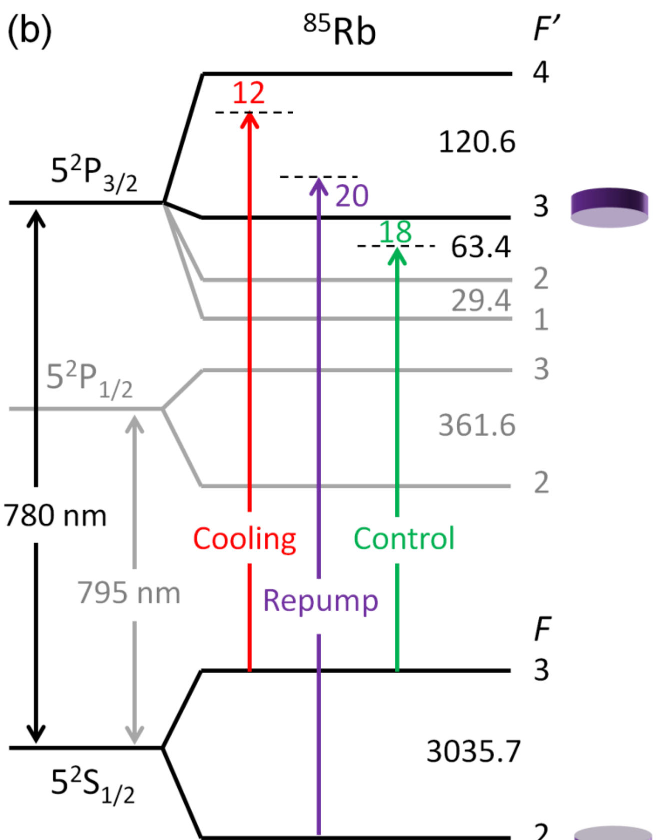
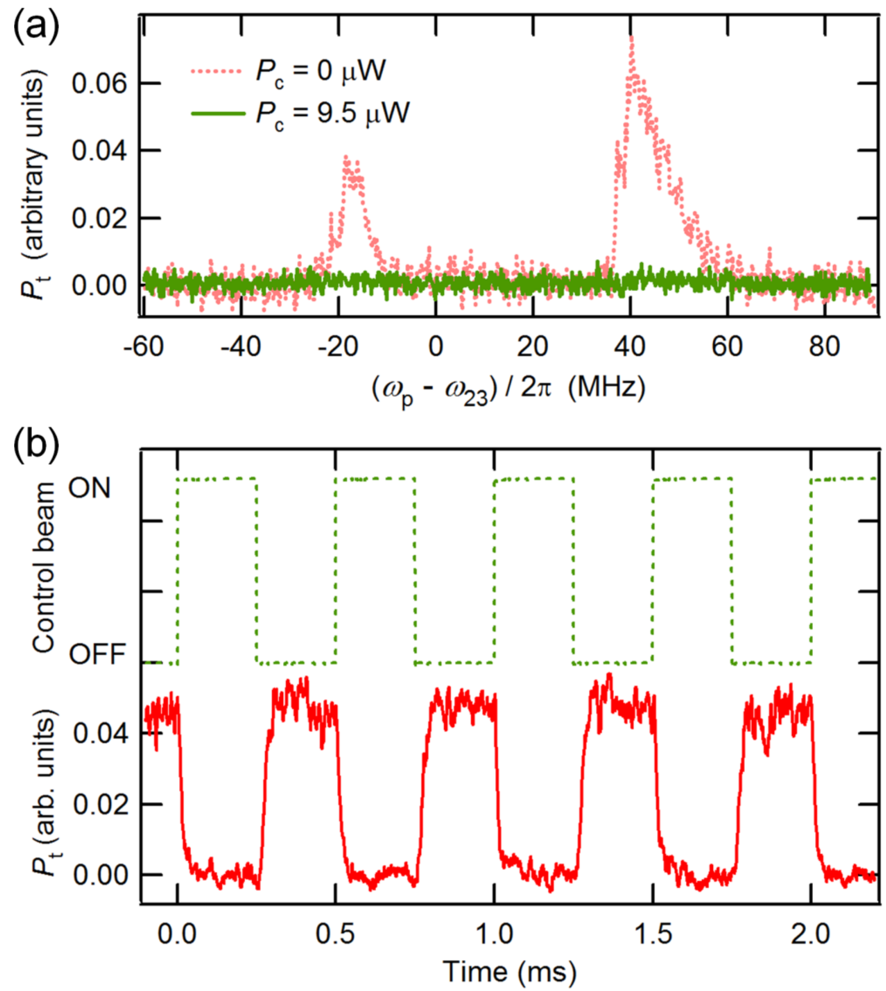
arXiv:1611.02035 (2016)

All-optical switching of cavity transmission





All-optical switching in ~10 μs, with 10 μW control beam power

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arXiv:1611.02035 (2016)