MPIPKS Dresden

Mesoscopic Phenomena 2004

Local blockade of Rydberg excitation in an ultracold gas

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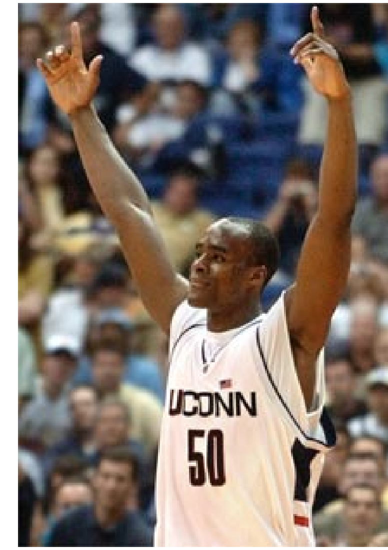
Monday, October 11 2004

Outline



- Motivations and Introduction
- Rydberg atoms, phase gate, excitation blockade
- Our findings (theory/experiment)
- Next steps/Conclusions

- Go Huskies !!!

Motivations/Introduction

- Quantum information
  - Strong interactions between components (qubits)
    - ← To entangle states and process information before decoherence sets in
  - Weak coupling to environment
    - ← To minimize decoherence
- Why ultracold Rydberg atoms ?
  - Strong interactions when 2 atoms are excited to Rydberg states
  - Extremely weak interactions between ground state atoms
  - Hyperfine ground states of alkali atoms ideal for qubits
  - Quantum gates could be realized on short timescale
  - Conditional excitation (blockade) predicted
    - ← Controllable interactions
    - ← Ensemble of atoms behave as a single atom

What is a Rydberg ?

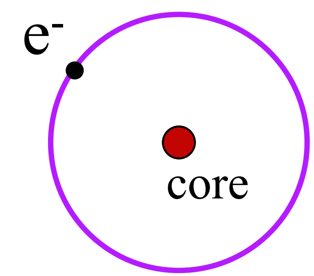
- Here are 3 types of Rydberg ! (Careful with the web!)
- A 1st type
  - P. A. (Per Axel) Rydberg (1860-1931), the first curator of The New York Botanical Garden Herbarium

- A 2nd type
  - Viktor Rydberg (1828-1895) . One of the great swedish romanticists. He wrote many poems.

- The “real” one !
  - Johannes Robert Rydberg (1854-1919): swedish physicist.

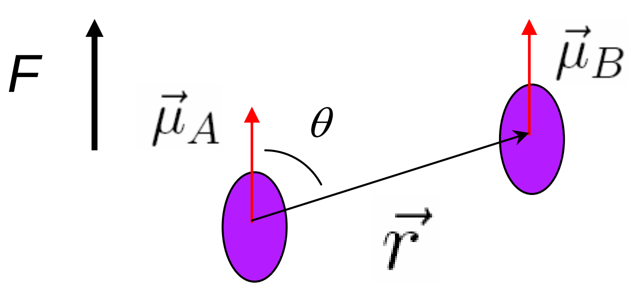
Rydberg Atoms

- Alkali atoms are good candidates to encode qubits:
  - Measurement high quantum efficiency: e.g., cycling transition.
  - Easy cooling and trapping
  - Low decoherence times.



- Rydberg atoms resemble hydrogen atom:
  - Radius and dipole moment scale as n^2
  - Energy $\propto 1/(n-\delta_{n,l})^2$, quantum defect $\delta_{n,l}$
- Long lifetimes $\propto n^3$. $50p$, τ=238 μs (τ =.02 μs for $5p$)
- Large polarizability $\propto n^7$: Stark mixing other l by electric fields F

$$|\widetilde{49p}\rangle = \alpha|49p\rangle + \beta|49s\rangle + \ldots \text{ with } \beta = 0.11\,F \Rightarrow \tilde{\mu}_{pp} = 2\alpha\beta\mu_{sp}$$



$$V_{d-d} = \frac{\vec{\mu}_A \cdot \vec{\mu}_B}{r^3} - 3\frac{(\vec{r}\cdot\vec{\mu}_A)(\vec{r}\cdot\vec{\mu}_B)}{r^5}$$

Phase Gates

- Truth table: $|m\rangle \otimes |n\rangle \Rightarrow e^{imn\phi} |m\rangle \otimes |n\rangle$
- Logical states: $|0\rangle$ or $|1\rangle$
  - alkali atoms: 2 hyperfine states
- "Simple" phase control gate
  - use atoms in an optical lattice
  - state preparation (single-qubit gates):
    - optical pumping + Raman pulses

$$|A\rangle = \frac{1}{\sqrt{2}} \{ |0\rangle + |1\rangle \}$$

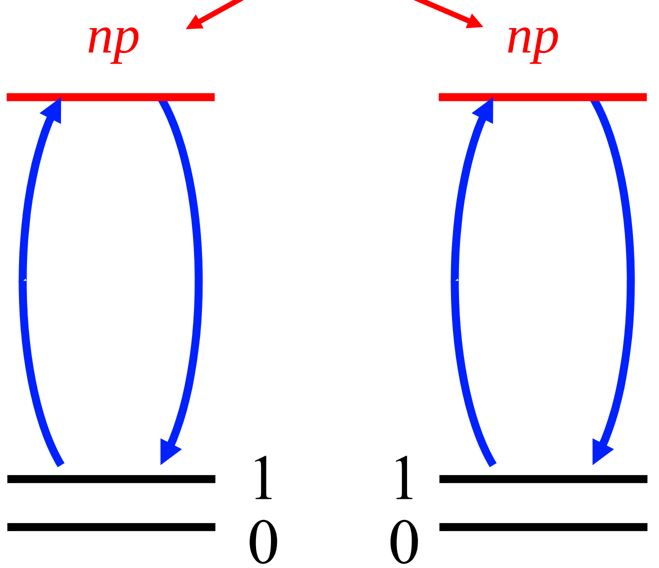
$$|B\rangle = \frac{1}{\sqrt{2}} \{ |0\rangle + |1\rangle \}$$

- Two-qubit state

$$|Q\rangle \neq |A\rangle \otimes |B\rangle$$

$$|Q\rangle = |00\rangle + |01\rangle + |10\rangle - |11\rangle$$

Induce *np*-*np* interactions with an external field

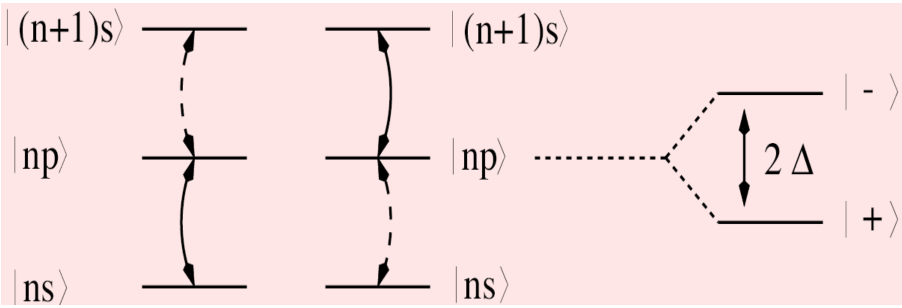


$\phi(t) = 2\pi\mu_A\mu_B\, t/ h R^3$

$\phi=\pi$ for $\tau=5.3\mu$sec

($n=50$, $R=25$ μm, $\Phi=3$ V/cm)

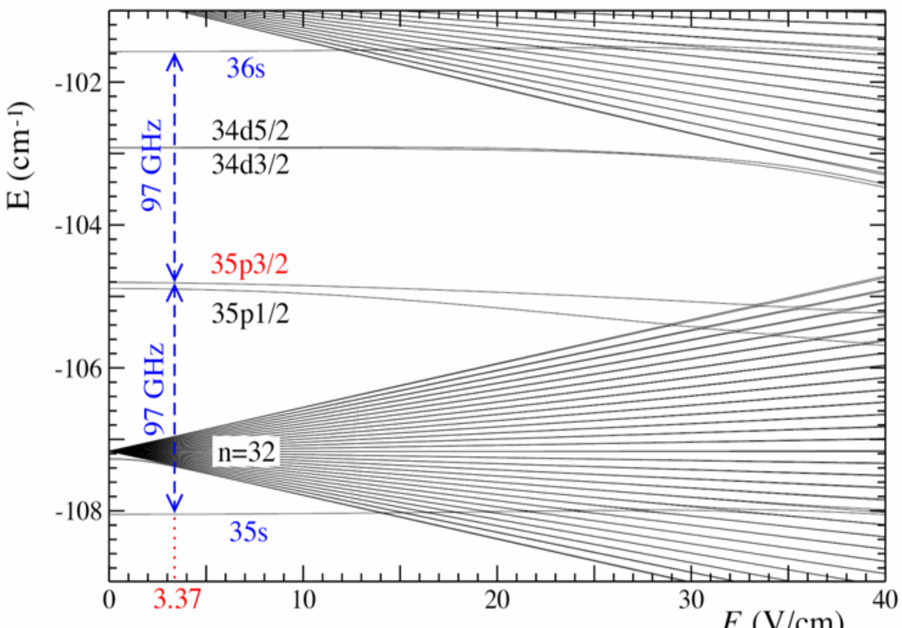
Resonant Dipole-Dipole

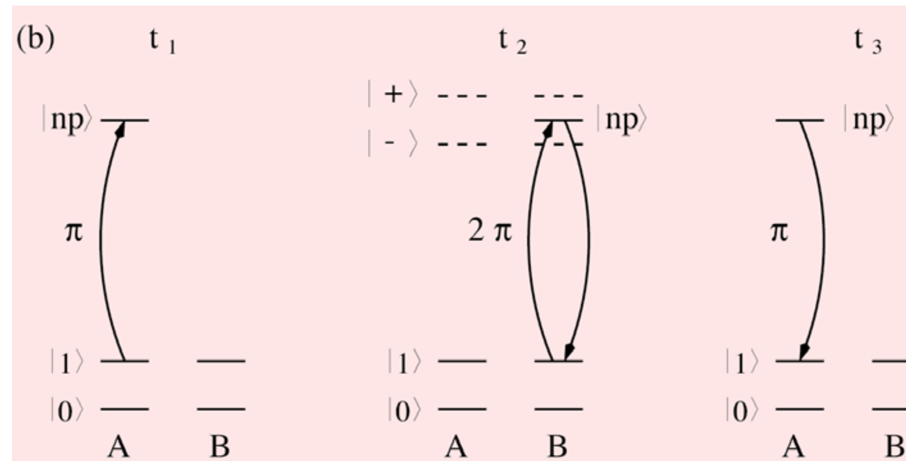


$$|\pm\rangle = \frac{1}{\sqrt{2}}\left(|pp\rangle \pm \frac{1}{\sqrt{2}}(|ss'\rangle + |s's\rangle)\right)$$

$$2\Delta \sim \frac{\mu_{ps'}\mu_{ps}}{r^3}$$

- Tune to exact resonance with *F*





$$|00\rangle \rightarrow |00\rangle \qquad |01\rangle \rightarrow -|01\rangle$$
$$|10\rangle \rightarrow -|10\rangle \qquad |11\rangle \rightarrow -|11\rangle$$

- Gate Fidelity not sensible to atomic separation as long as: $\gamma_L \ll \Delta$ and $\Omega \ll \Delta$.

D. Jaksch, J. I. Cirac, P. Zoller, S.L. Rolston, R. Côté, and M.D. Lukin, PRL **85**, 2208 (2000).

Rydberg-Rydberg interactions

- Higher dispersion terms
  - *np*+*ns* or *np*+*nd* :

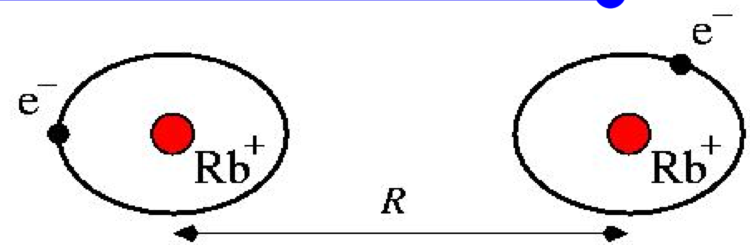
$$V(R) = \frac{C_3}{R^3} \quad \text{with} \quad C_3 = A(np|r|n\ell)^2$$

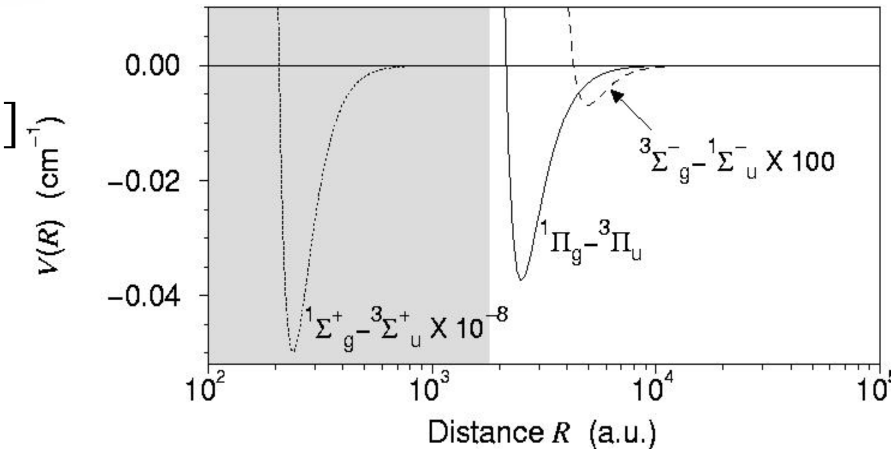
  - *np*+*np* :
    [Marinescu, PRA **56**, 4764 (1997).]

$$V(R) = -\frac{C_5}{R^5} - \frac{C_6}{R^6} - \frac{C_8}{R^8}$$

$C_3 \propto n^4$, $C_5 \propto n^8$

$C_6 \propto n^{11}$, $C_8 \propto n^{15}$



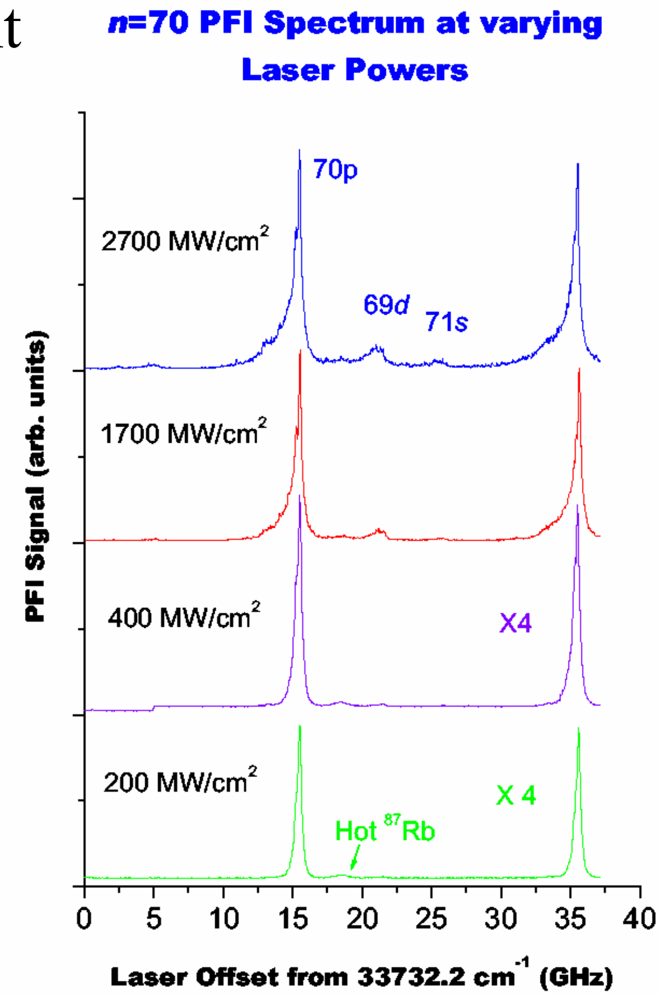


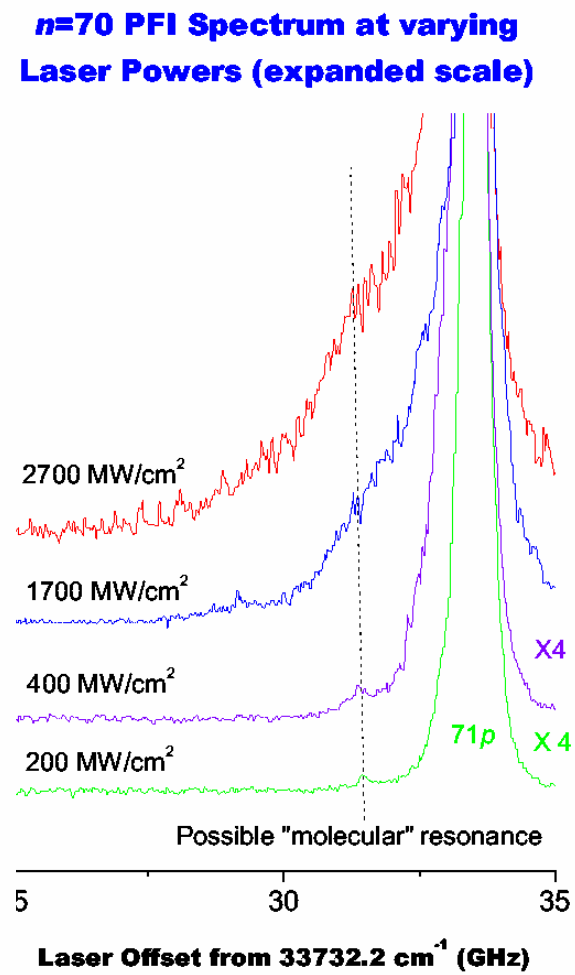
- Combination of coefficients can lead to long-range wells
  - “stable” if electron wavefunctions do not overlap (non-shaded region)
  - very extended molecules (few μm or more) : **macrodimers**

C. Boisseau, I. Simbotin, & R. Côté, PRL **88**, 133004 (2002)

Spectral evidence

- As Rydberg density increases (with I), effect of C's becomes apparent

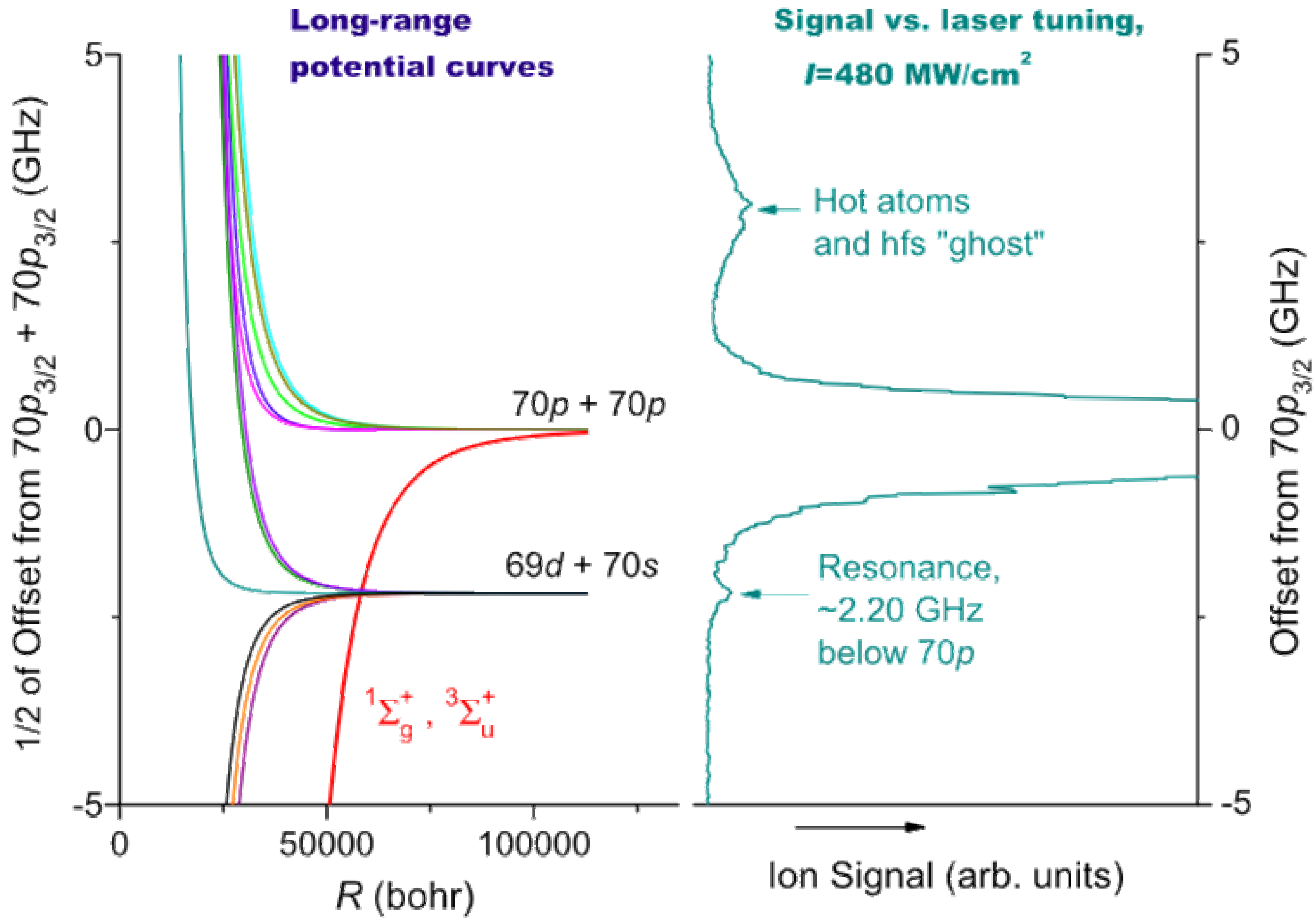




See also recent work by M. Weidemüller's group (arXiv:physics/0404075).

Molecular resonance

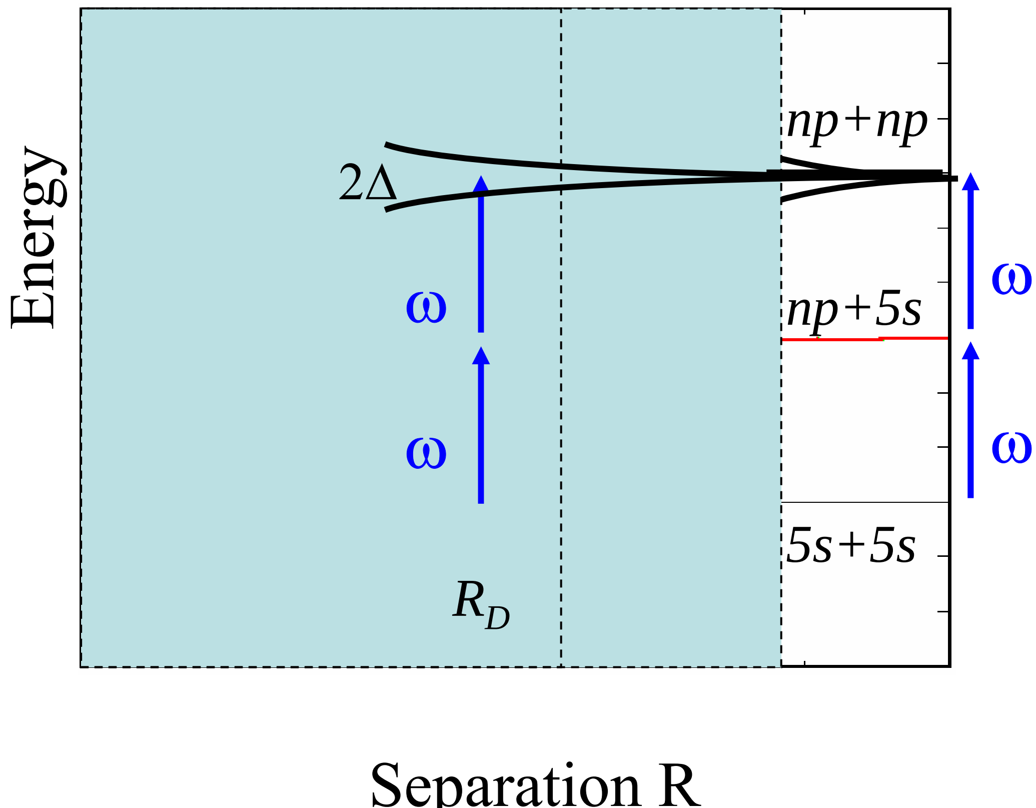
- At large Rydberg densities ⇒ additional spectral features
  - Observed $n \sim$ 50-90
  - Avoided crossing at very long range (~ 58,000 a.u.)
  - Position scales as n^{-3}
  - quadratic I dependence
- Agrees well with our curves



S.M. Farooqi, D. Tong, S. Krishnan, J. Stanojevic, Y.P. Zhang, J.R. Ensher, A.S. Estrin, C. Boisseau, R. Côté, E.E. Eyler, and P.L. Gould, PRL **91**, 183002 (2003).

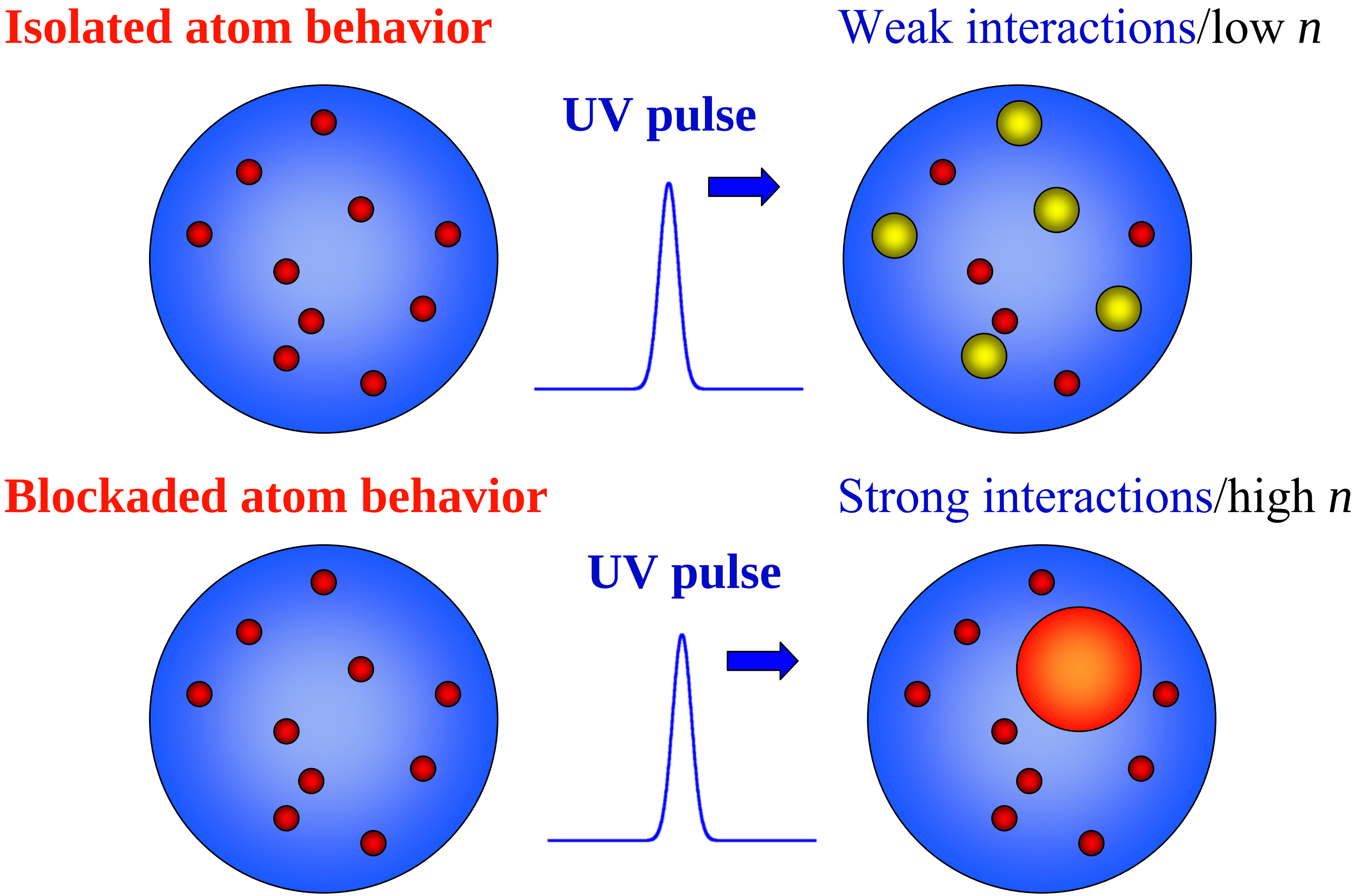
van der Waals Blockade

- van der Waals $\propto n^{11}$
  - interactions shift the two-photon resonance
- Low *n* or densities
  - Weak interactions between Rydberg atoms
  - 2-photon resonance is shifted at “small” *R*
  - below R_D , excitation of 2 Rydberg atoms (or more) is prohibited
  - Isolated atom behavior



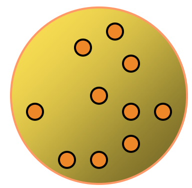
- large *n* or densities
  - strong molecular interactions
  - resonance shifted at large *R*
  - *Blockaded* behavior

A sketch


Isolated atom behavior
Weak interactions/low *n*
UV pulse
Blockaded atom behavior
Strong interactions/high *n*
UV pulse

Blockade

- Ensemble of atoms
  - few μm in size
  - 10-100 atoms



- Collective states

$|g\rangle$: All atoms in ground state.

$|q^n\rangle$: Collective state of n-atoms in q.

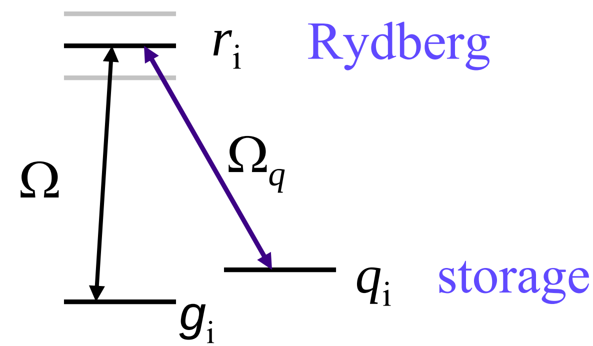
$|r^1\rangle$: Only one excitation allowed in r.

- Prepare initial state

$$|g\rangle \overset{\Omega\sqrt{N}}{\rightarrow} |r^1\rangle \overset{\Omega_q}{\rightarrow} |q^1\rangle$$

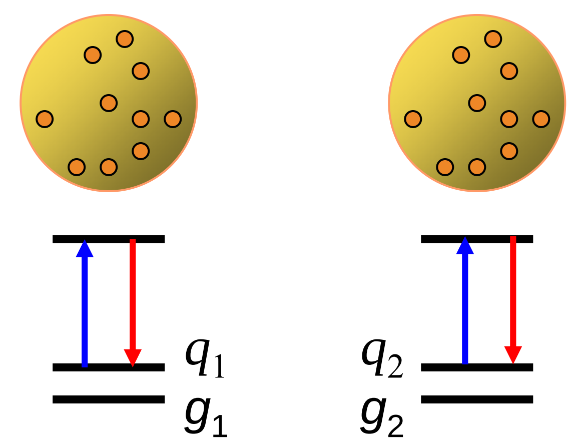
  - Based on conditional excitation
  - Ensemble behaves as a "super-atom"

- Single-atom levels:



- Phase gate

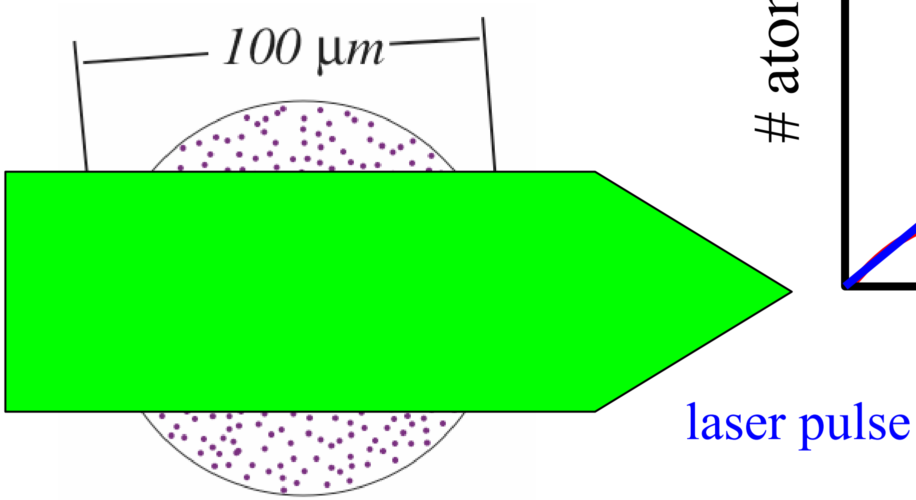
$$|g_1g_2\rangle \rightarrow |g_1g_2\rangle \qquad |g_1q_2\rangle \rightarrow |g_1q_2\rangle$$
$$|q_1g_2\rangle \rightarrow |q_1g_2\rangle \qquad |q_1q_2\rangle \rightarrow -|q_1q_2\rangle$$

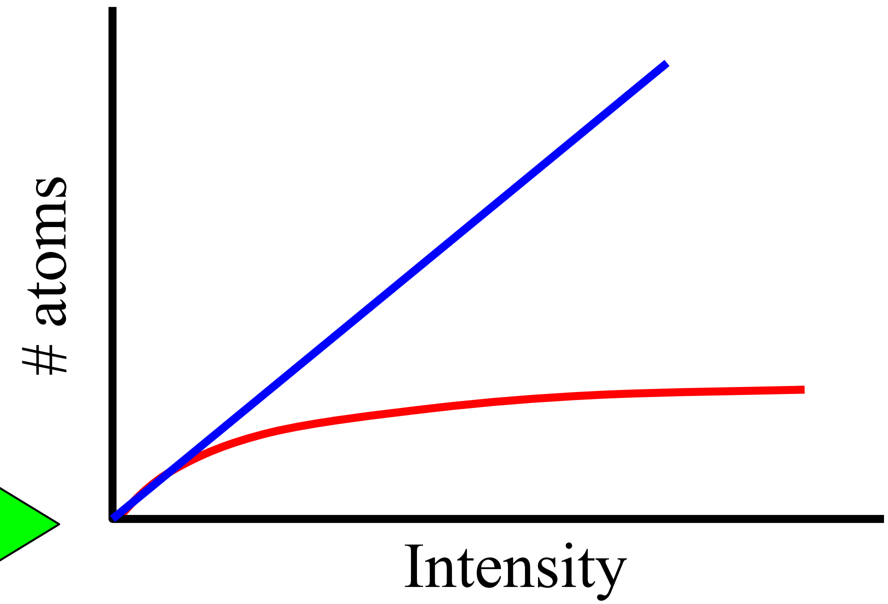


M.D. Lukin, M. Fleischhauer, R. Côté, L.M. Duan, D. Jaksch, J.I. Cirac, and P. Zoller, PRL **87**, 037901 (2001)

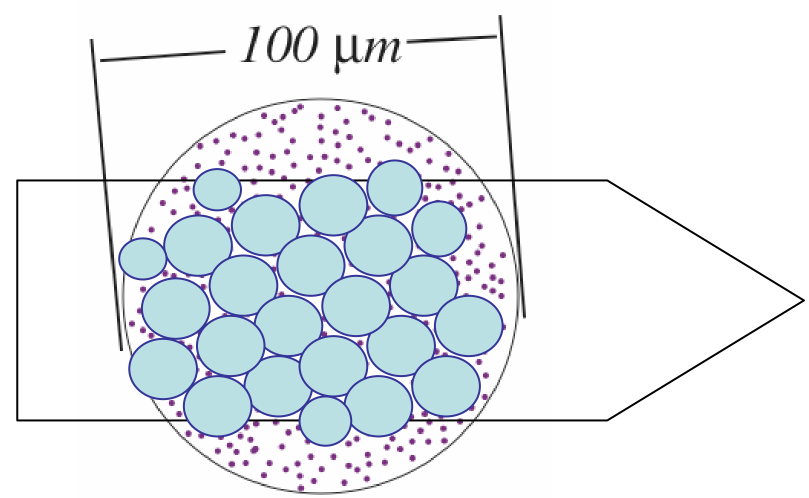
About a larger sample ?

- low *n* or densities
  - isolated atom behavior

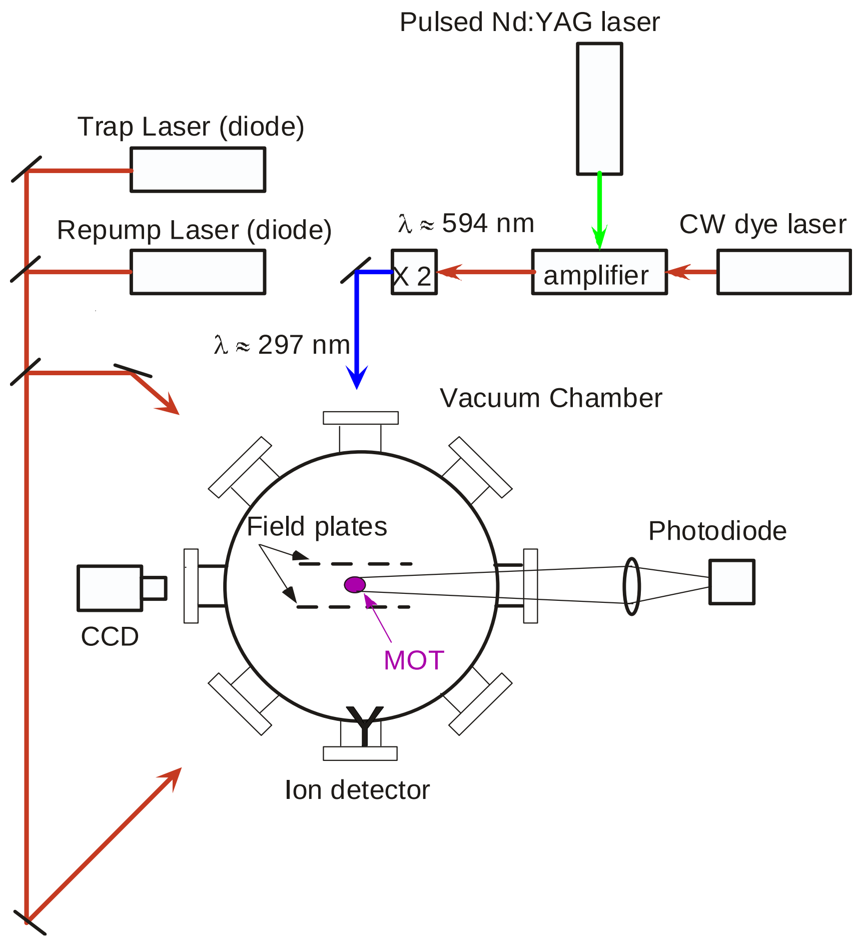




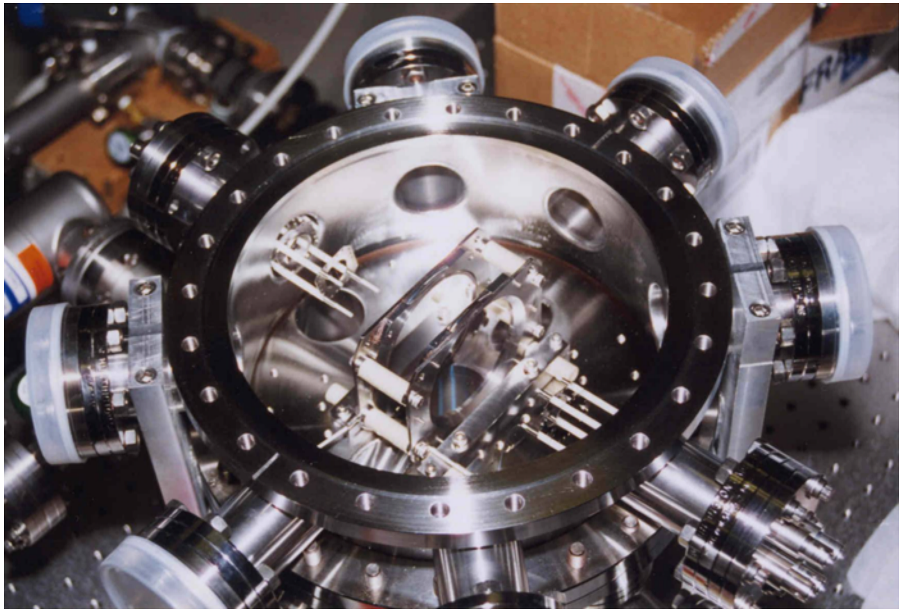
- large *n* or densities
  - locally blockaded domains



Experimental Scheme

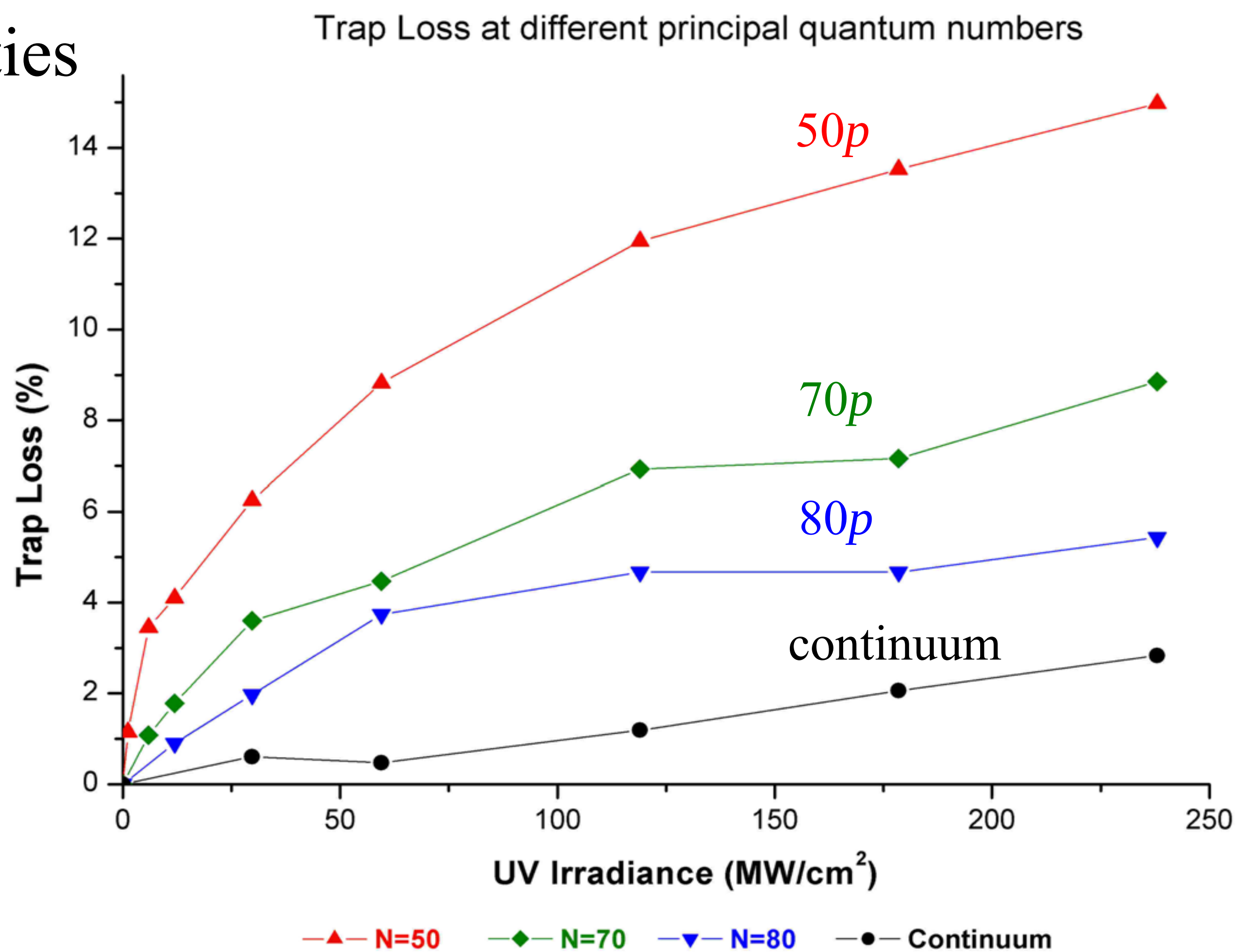


- Direct one-photon excitation with 10 nsec transform-limited laser pulse.
- Detection via trap fluorescence dip or delayed pulsed field ionization.



Early Measurements

- Suppression
  - stronger as *n* grows
- Large intensities
  - Ionization ?



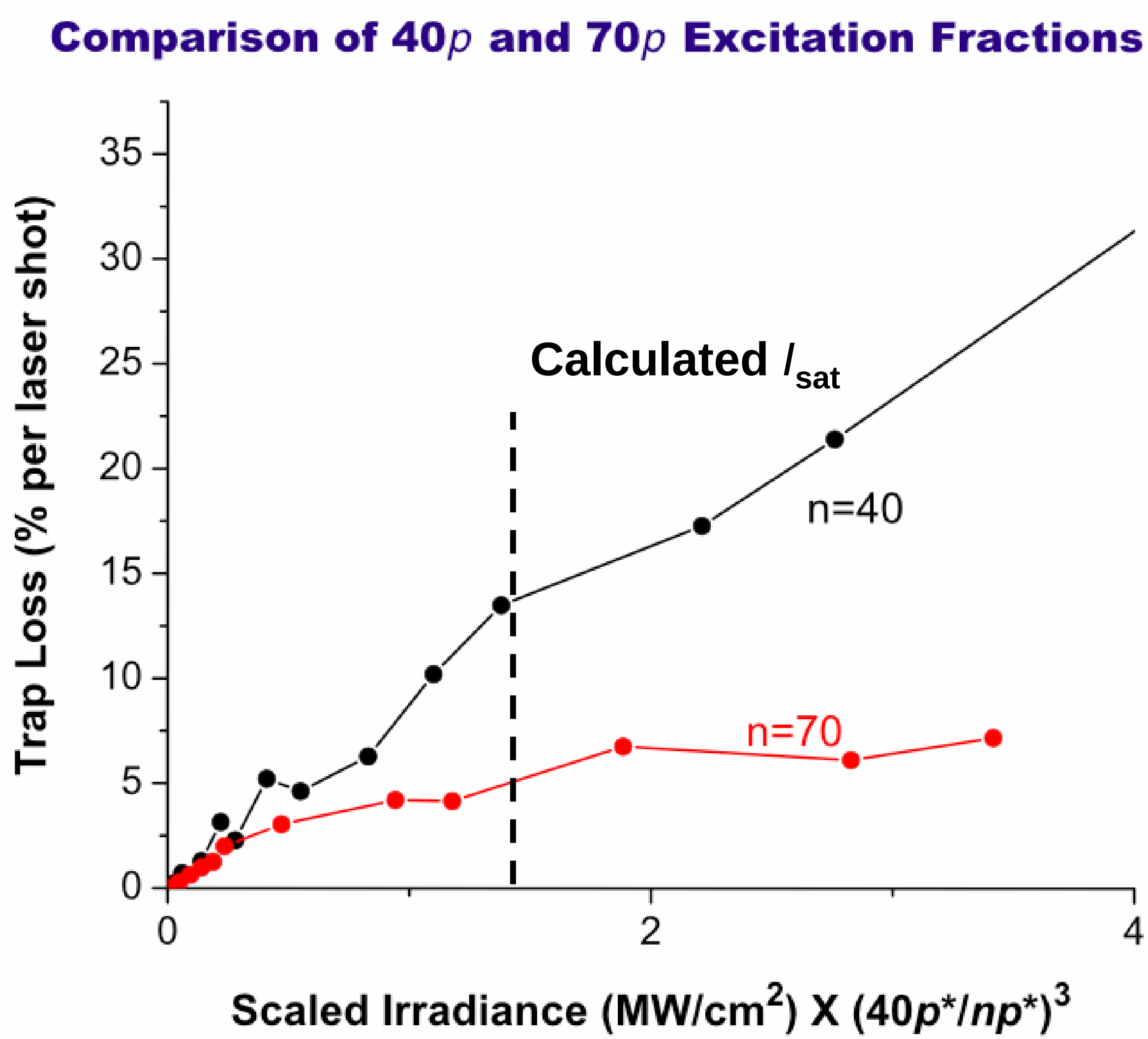
40*p*-70*p* Comparison

- At lower *I* (no ionization), using scaled irradiance (n^{-3})

– 40*p* linear signal: individual atoms

– 70*p* rapid saturation: excitation blockade (domain formation)

– shape depends on laser intensity profile



New measurements

Solid line for *n*=30:

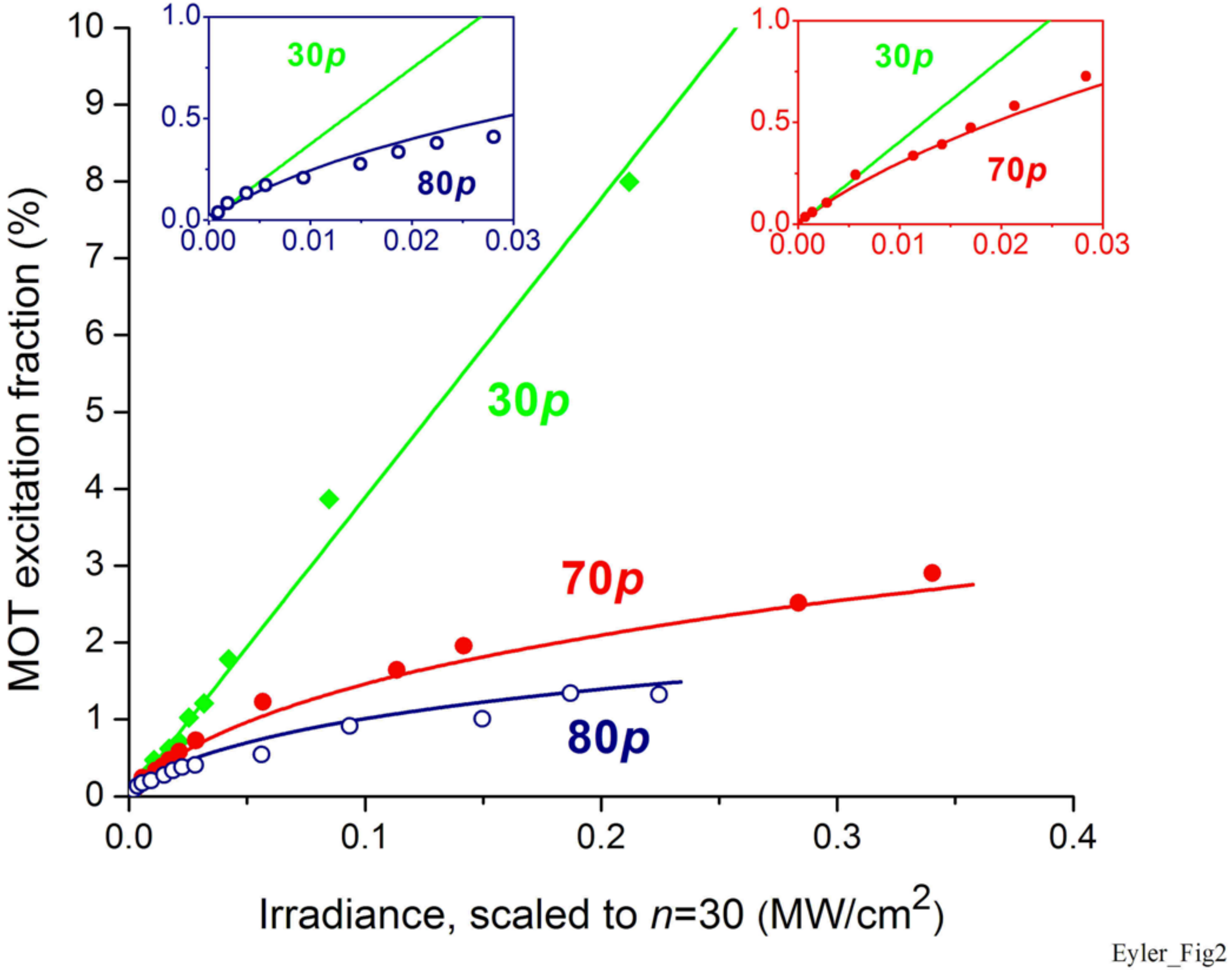
Linear fit, agrees with predicted slope for isolated-atom excitation within 2%.

Solid lines for *n*=70 and for *n*=80:

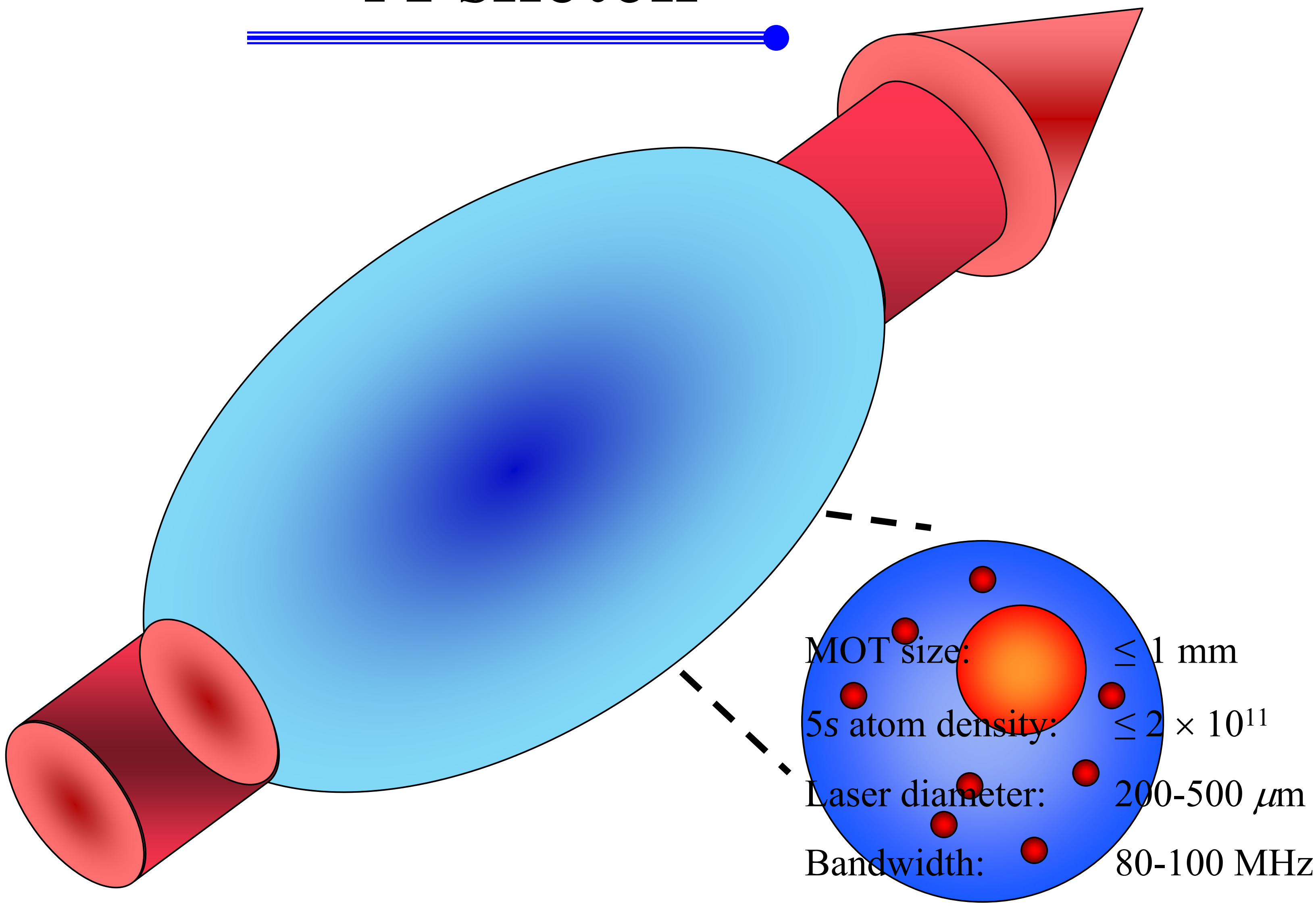
Mean field calculation with $\alpha = 2.4$.

Saturation irradiance:

$\cong$0.5 MW/cm^2.



A sketch



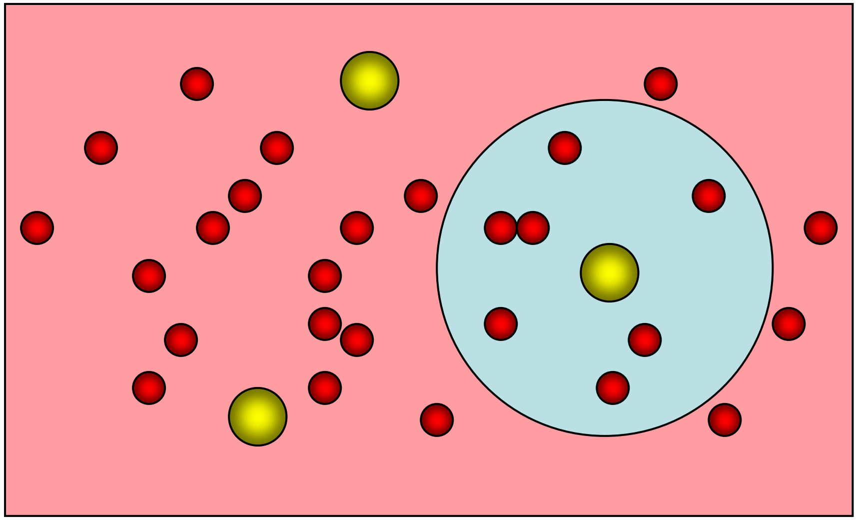
See D. Tong *et al.*, PRL **93**, 063001 (2004).

The model

- Bloch-like equations for a single atom with level shifted by interactions

$$i\frac{d}{dt}c_g = \frac{\Omega}{2}c_e$$
$$i\frac{d}{dt}c_e = \varepsilon c_e + \frac{\Omega}{2}c_g$$

- Mean-field model
  - Initially, no excited atoms
  - Select a sphere of radius R_d in the sample
  - It contains one Rydberg atom (by definition)



$$\rho_e(t)V_d(t) = 1$$

$$\rho\int_{V_d} d^3r\,\left|c_e(\vec{r},t)\right|^2 = 1$$

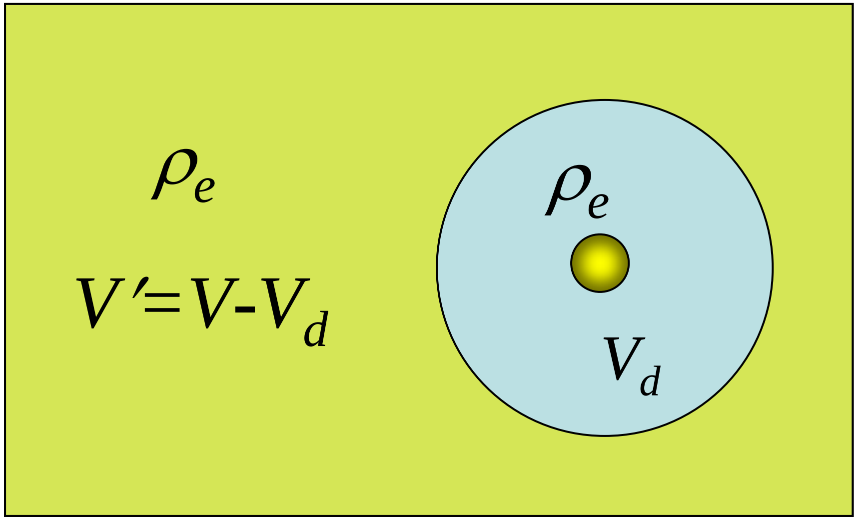
The level shift

$$\varepsilon_i = \sum_{k\neq i} \left\langle p_i p_k \middle| \hat{V} \middle| p_i p_k \right\rangle = \sum_{k\neq i} \sum_{\lambda} \left\langle p_i p_k \middle| \hat{V} \middle| \lambda \right\rangle \left\langle \lambda \middle\| p_i p_k \right\rangle$$

$$\varepsilon_i = \sum_{k\neq i} \sum_{\lambda} \frac{C_6^{(\lambda)}}{\left|\vec{r}_i - \vec{r}_k\right|^6} \left| \left\langle p_i p_k \middle| \lambda \right\rangle \right|^2$$

One pair of λ dominates (with same C_6)

- Mean-field
  - Replace sum by integral
  - ρ_e constant (same as in V_d)
  - One pair of λ dominates (with same C_6)



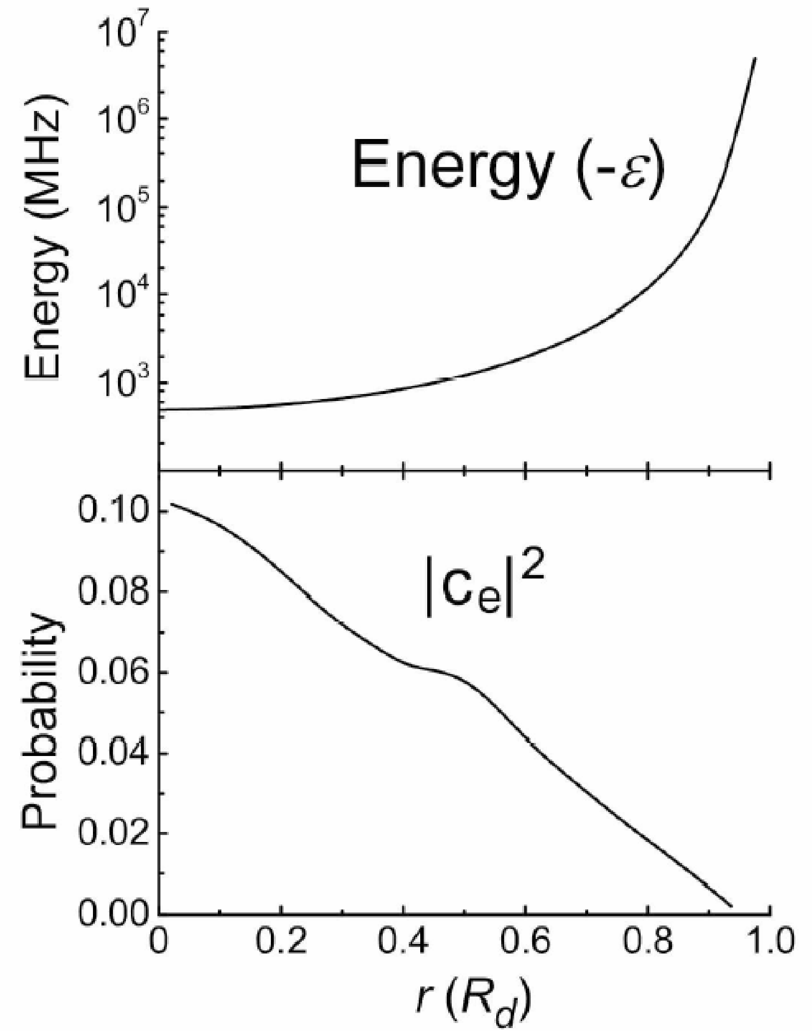
$$\varepsilon(\vec{r},t) = \rho_e(t) \int_{V'} d^3 r' \frac{-C_6}{\left|\vec{r} - \vec{r}'\right|^6} \sum_{\lambda=1}^{2} \left| \left\langle p_i p_k \middle| \lambda \right\rangle \right|^2$$

Mean-field model

- With $\boldsymbol{r} = \boldsymbol{y}\, R_d$ and $\rho_e V_d = 1$,

$$\varepsilon(\vec{y},t) = -g(\vec{y})\frac{\tilde{C}_6}{R_d^6}$$

with effective C_6 (averaging over angles)



- If Rydberg not in center of V_d
  - ε smallest in the center (y=0)
    ⇒ easier to excite
  - ε grows at the periphery (y=1)
    ⇒ harder to excite

- But $$R_d^{-3} = \rho \int_{|\vec{y}|\le 1} d^3y\, \left|c_e(\vec{y},t)\right|^2$$

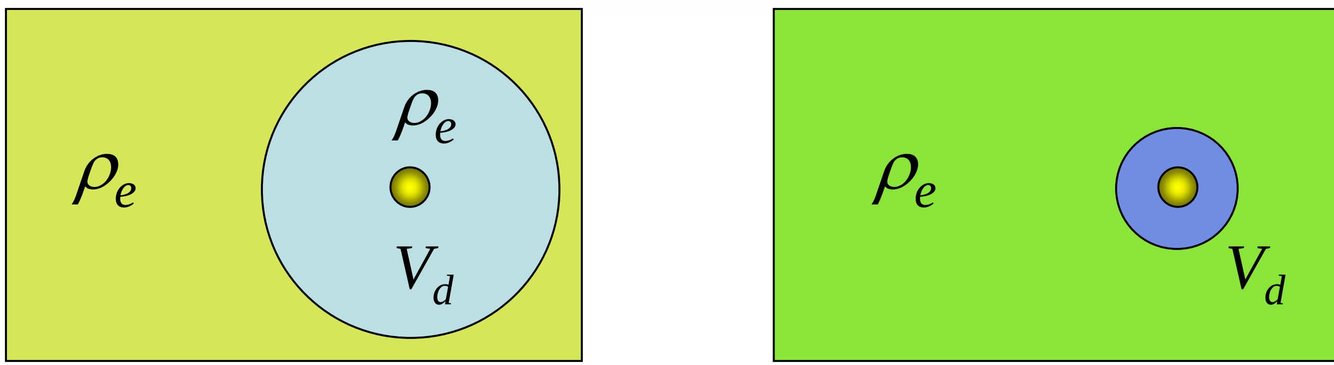
Non-linear Bloch-like Eqs.

- Including the laser chirp

$$i\frac{d}{dt}c_g = \frac{\Omega}{2}e^{i\beta t^2}c_e,$$

$$i\frac{d}{dt}c_e = -\rho^2\tilde{C}_6 g\left|\int_{|\mathbf{y}|\le 1} d^3\mathbf{y}|c_e|^2\right|^2 c_e + \frac{\Omega}{2}e^{-i\beta t^2}c_g$$

- Time evolution



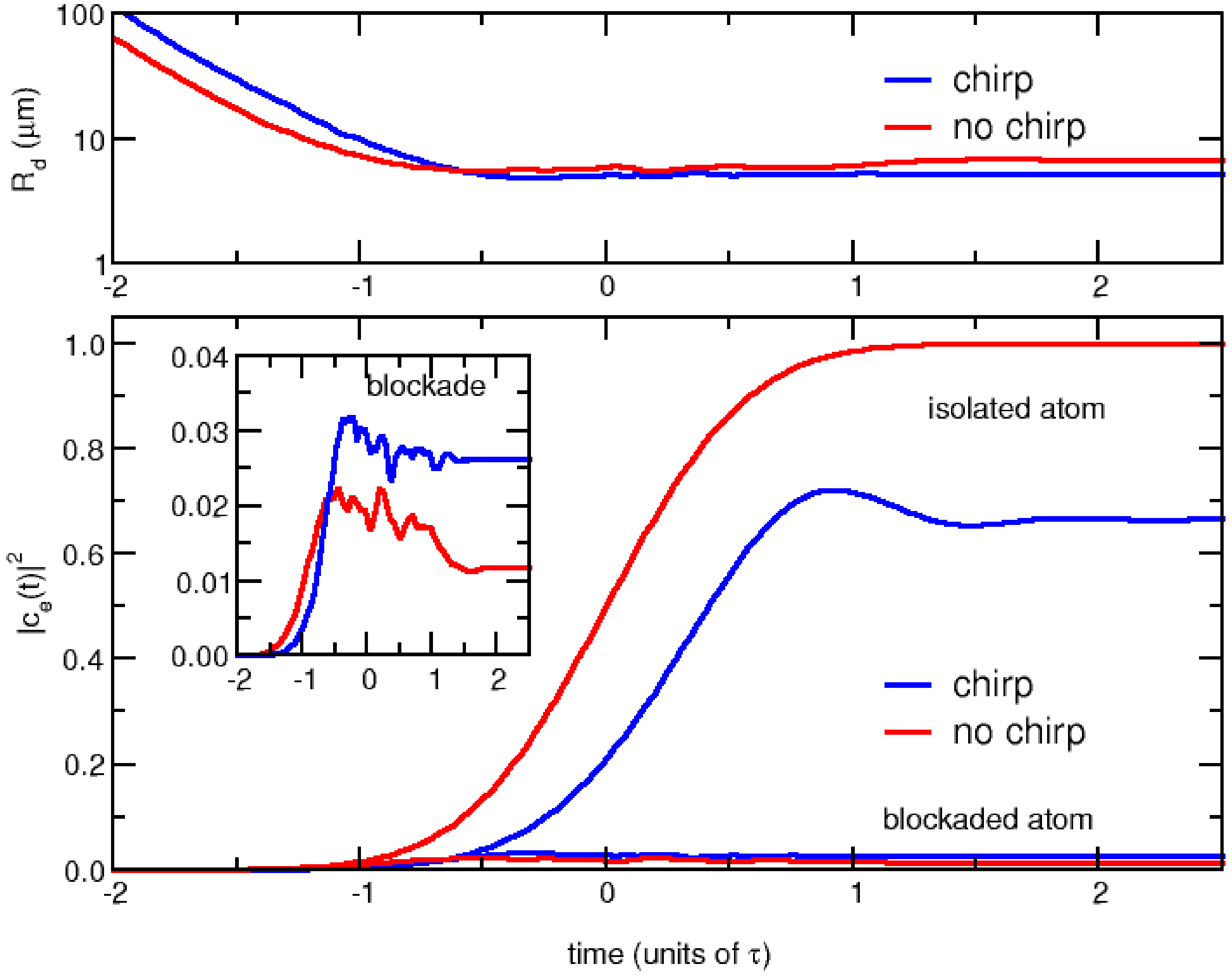
- Parameter α :

$$\rho_\alpha \tilde{C}_{6,\alpha}^{1/2} = \alpha\rho\tilde{C}_6^{1/2}$$

- Need averaging over density and intensity profiles in MOT

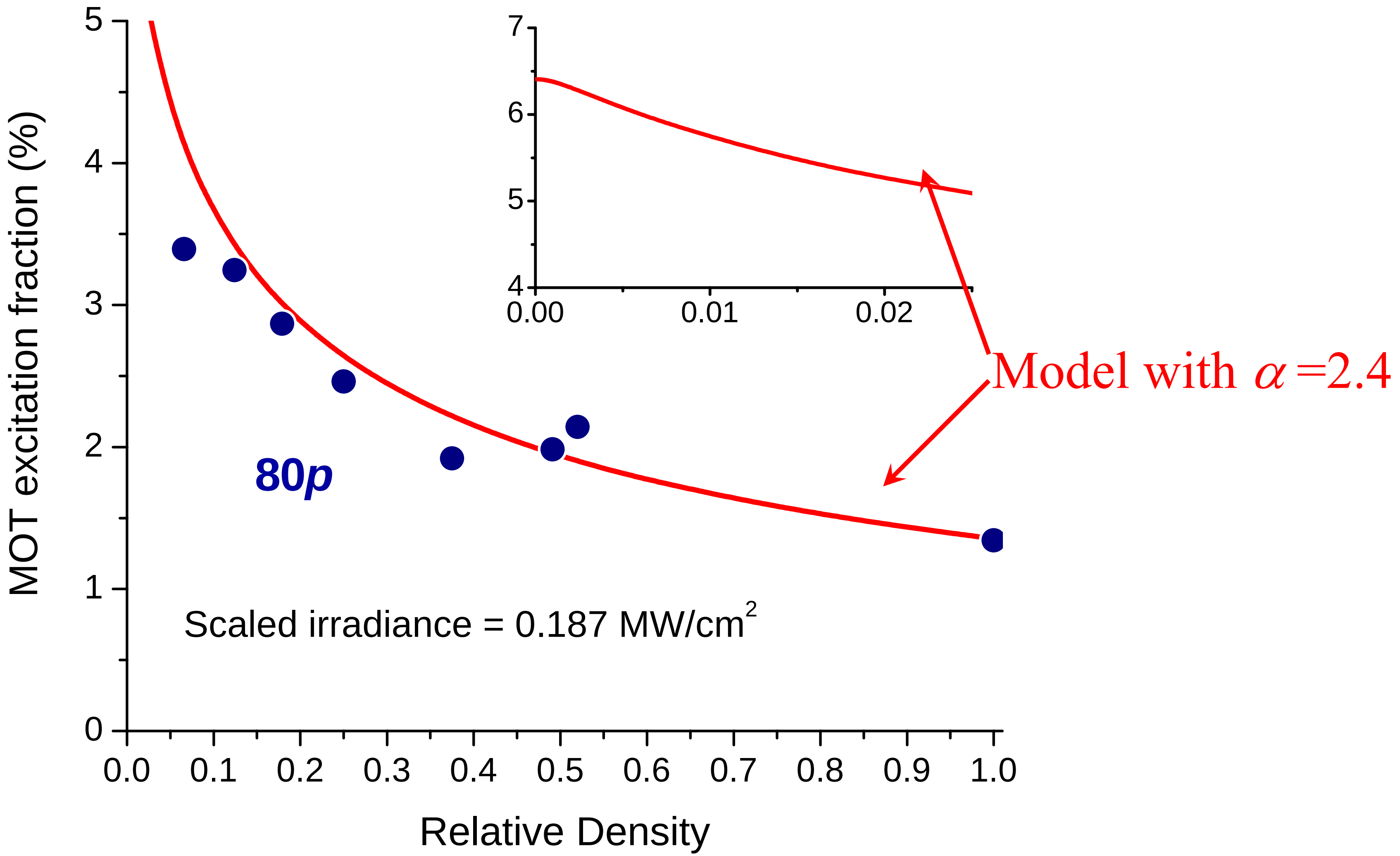
$$N_e = \int_{MOT} d^3r\, \rho_e(\rho(\vec{r}),\Omega(\vec{r}))$$

Time evolution and chirp



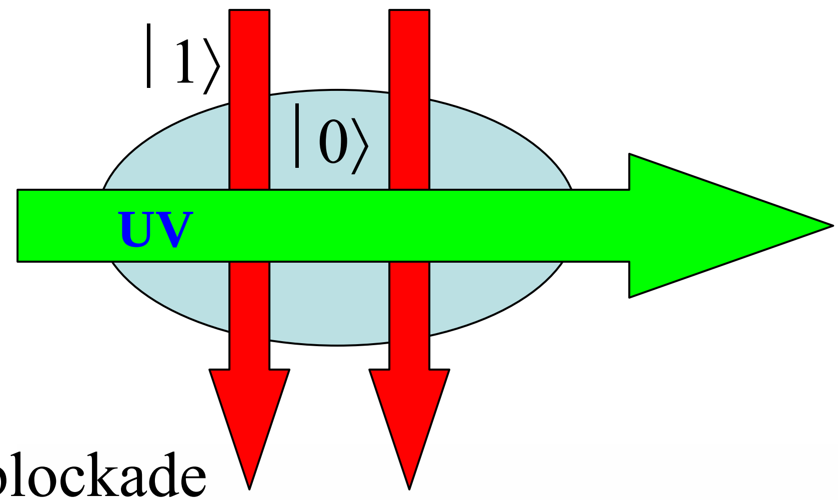
Density dependence for n=80

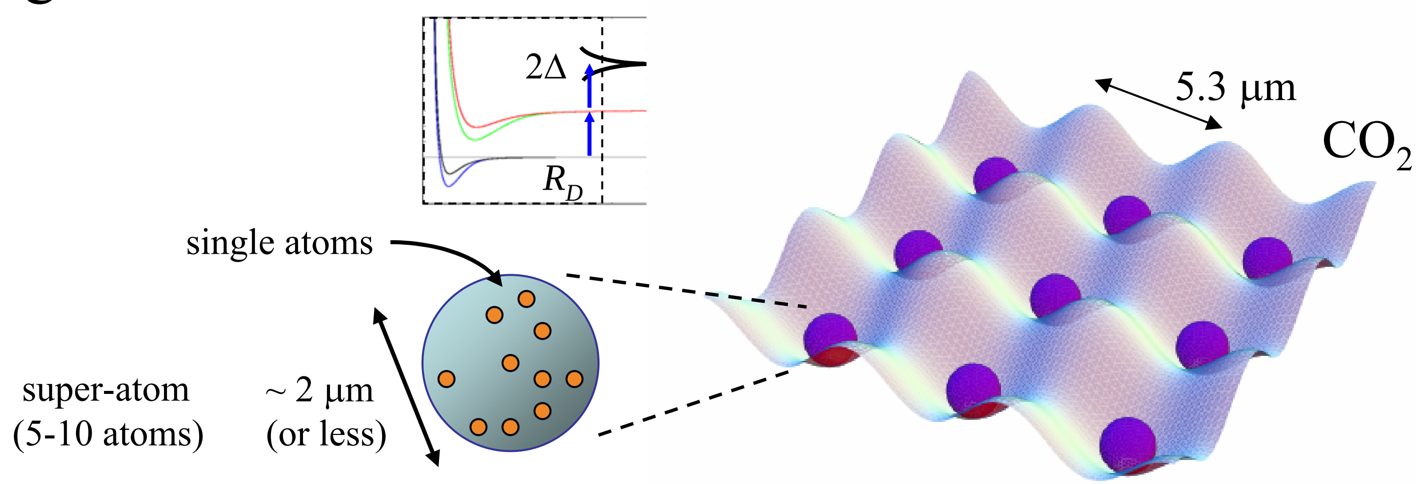
- Using MOT repump timing to vary density



Next steps …

- Better calibration and modeling of experiment
  - single-atom saturation curve
  - domain size and formation
  - Scaling with *n*
- Smaller samples
  - phase gate
- Optical lattice
  - using the “van der Waals” blockade





People

- People involved

students

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and co-workers …