Multiphoton Microwave Ionization of Rydberg Atoms

Joshua Gurian
T.F. Gallagher

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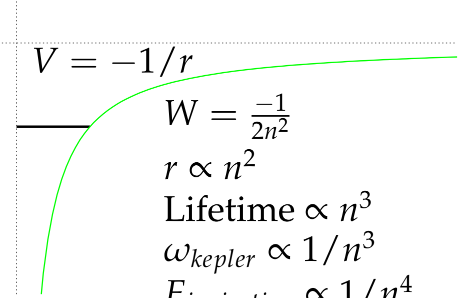
Introduction to Rydberg Atoms

Properties of Rydberg Atoms



$$V = -1/r$$

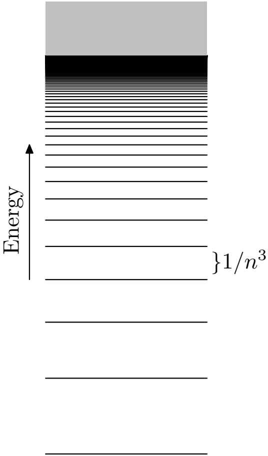
$$W = \frac{-1}{2n^2}$$

$$r \propto n^2$$

$$\text{Lifetime} \propto n^3$$

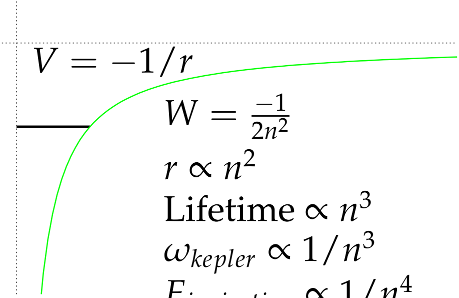
$$\omega_{kepler} \propto 1/n^3$$

$$E_{ionization} \propto 1/n^4$$



Introduction to Rydberg Atoms

Properties of Rydberg Atoms



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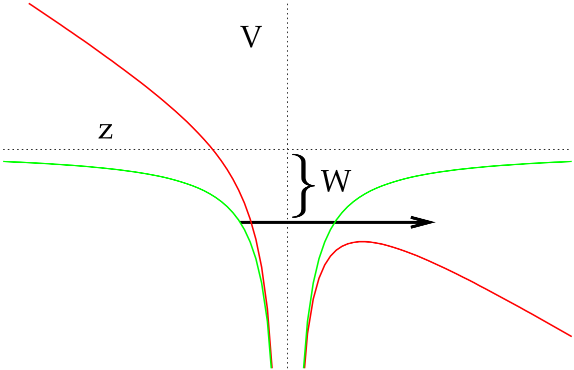
For n=100:

- $W = -1.4\,\text{meV}$
- $< r >= 0.5\,\mu\text{m}$
- $\tau = 1\,\text{ms}$
- $\omega_{kepler} = 2\pi \times 6.5\,\text{GHz}$
- $E_{ionization} = 5.7\,\text{V/cm}$

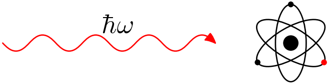
Field Ionization



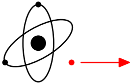
$$V(z) = \frac{-1}{|z|} - Ez$$

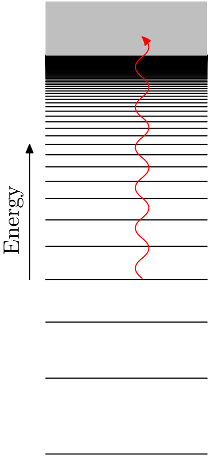
$$E = \frac{W^2}{4}$$

Photoionization

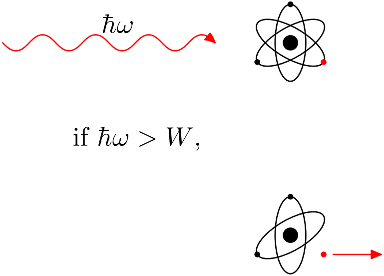


if $\hbar\omega > W$,



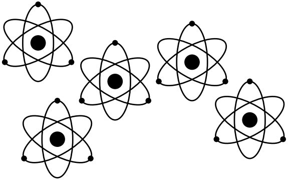


Photoionization



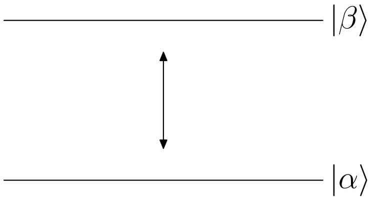
if $\hbar\omega > W$,

If we have some collection of atoms,



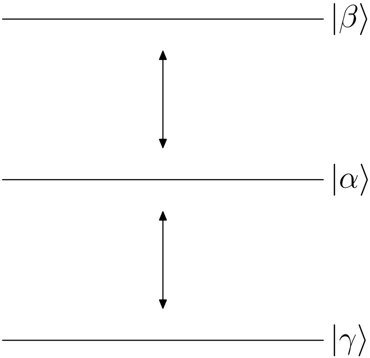
how do we calculate the ionization rate?

Fermi's Golden Rule



Fermi's Golden Rule:
$\Gamma_1 = 2\pi|\langle\alpha|\mu E|\beta\rangle|^2\rho_f$

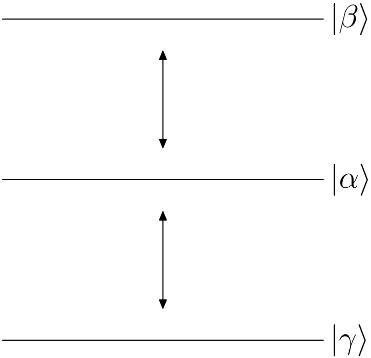
Fermi's Golden Rule



Fermi's Golden Rule:
$\Gamma_1 = 2\pi|\langle\alpha|\mu E|\beta\rangle|^2\rho_f$

$$\Gamma_2 = 2\pi\left|\frac{\langle\gamma|\mu E|\alpha\rangle\langle\alpha|\mu E|\beta\rangle}{\Delta W}\right|^2$$

Fermi's Golden Rule



Fermi's Golden Rule:

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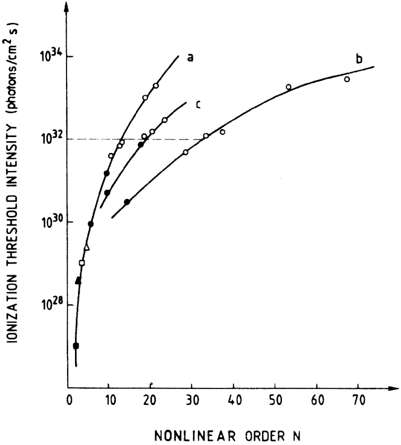
$$\Gamma_N \propto E^{2N}$$

Fermi's Golden Rule



l'Huillier *et al.*, *PRA* 27 (1983).

Fermi's Golden Rule:

$$\Gamma_1 = 2\pi |\langle \alpha | \mu E | \beta \rangle|^2 \rho_f$$

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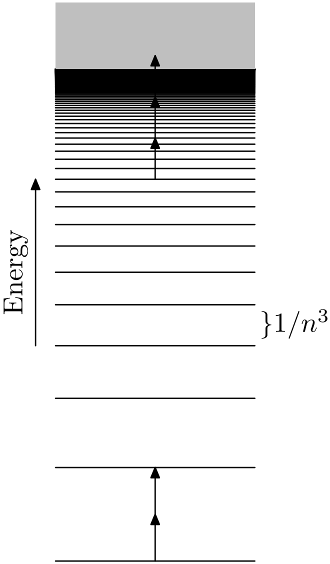
$$\Gamma_N \propto E^{2N}$$

Where does Microwave Ionization fit?



Scaled Microwave Units:

$$\Omega = \frac{\omega}{\omega_{Kepler}} = \omega n^3$$

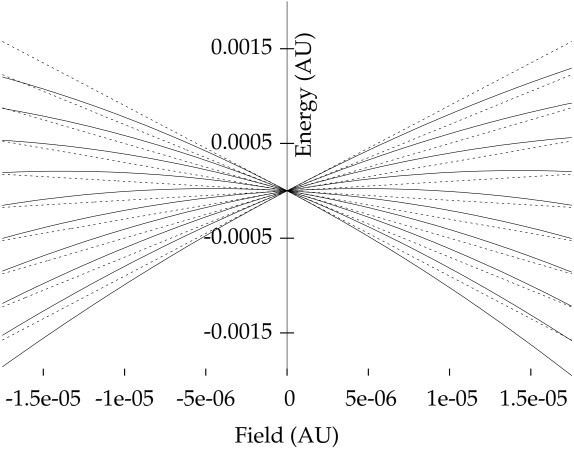
$$E_0 = \frac{E}{E_{Coulomb}} = En^4$$

Hydrogenic Microwave Ionization

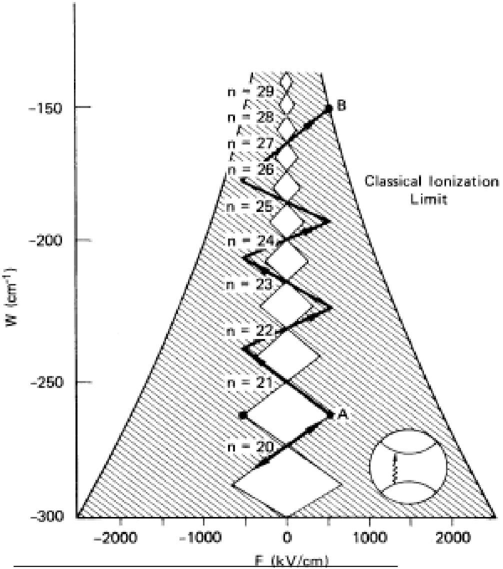
First experiments by Bayfield and Koch:

Non-constant $\frac{dW}{dE}$ projects (n, k) state onto Stark manifold

$$E = \frac{1}{9n^4}$$



Non-Hydrogenic Microwave Ionization

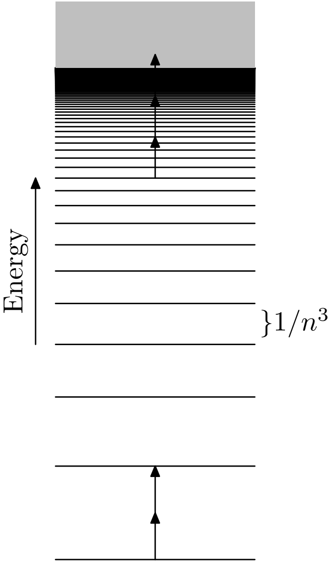


Pillet *et al.*, *Phys. Rev. Lett.* 50, 1983.

Ladder-climbing mechanism for ionization:

$$E = \frac{1}{3n^5}$$

Where Does Microwave Ionization Fit?



Scaled Microwave Units:

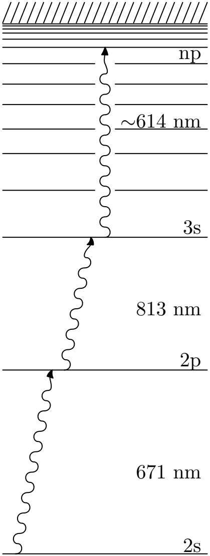
$$\Omega = \frac{\omega}{\omega_{Kepler}} = \omega n^3$$

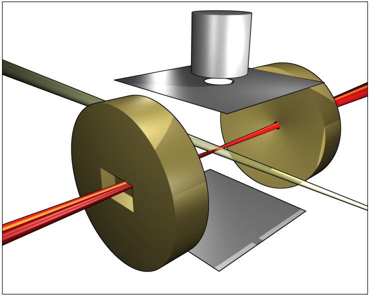
$$E_0 = \frac{E}{E_{Coulomb}} = En^4$$

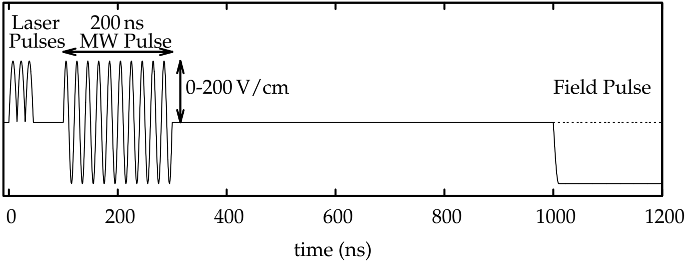
Experimentally, what happens as we approach the photoionization limit?

Outline

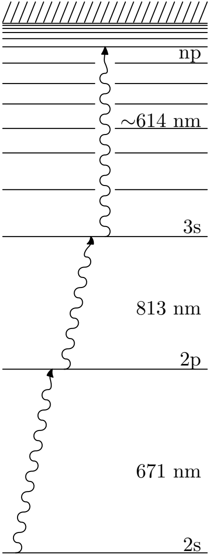
Experimental Setup

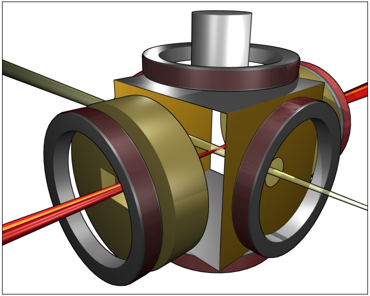


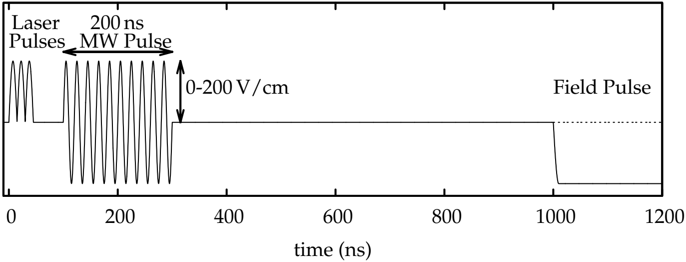




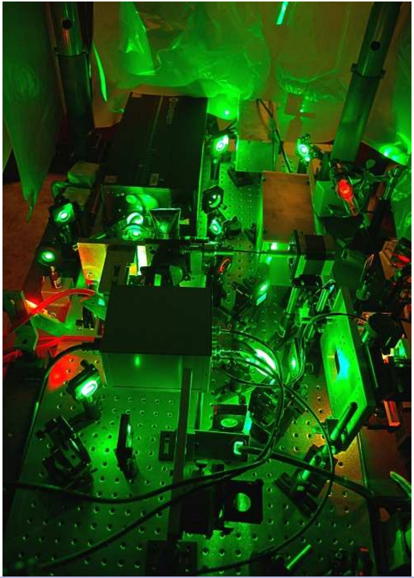
Experimental Setup

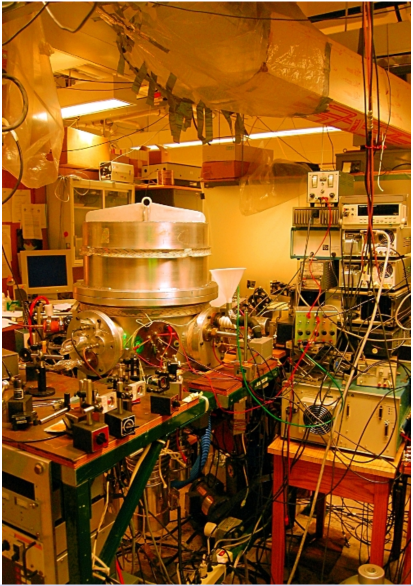






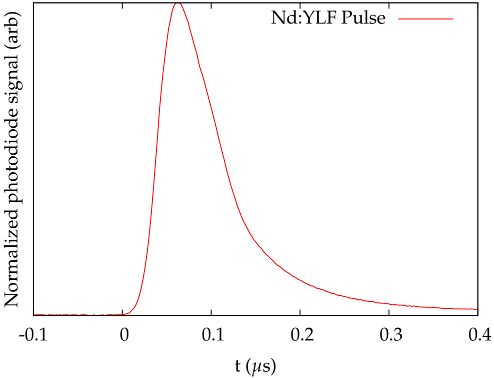
Pictures



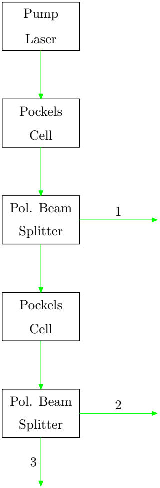


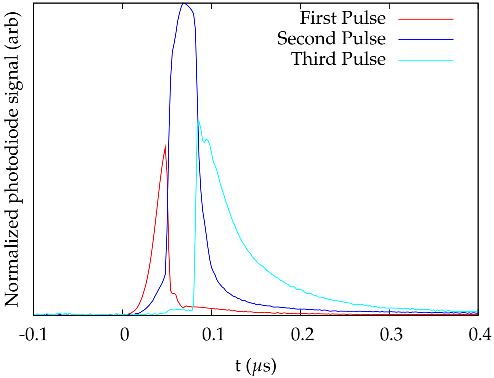
A New Laser System

- Coherent Evolution-30
- Nd:YLF @ 527 nm
- 20 mJ/pulse w/ 1 kHz Pulse Repetition Frequency



External Pulse Splitting





Dye Laser Output: $\approx 20\mu$J/pulse

Outline

Rydberg Atoms and How They Ionize

- Rydberg Atoms
- Field Ionization
- Photoionization
- MW Ionization

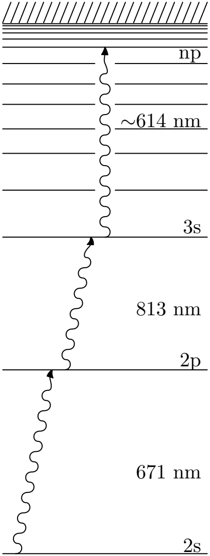
Experimental Setup

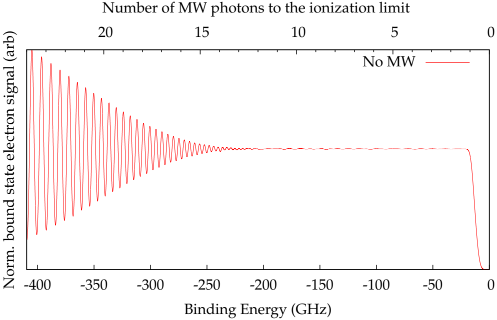
- Experimental Apparatus
- kHz Laser

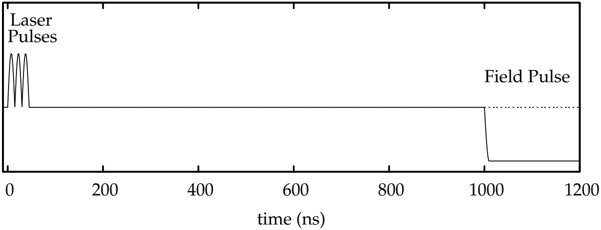
Experimental Results

- Multiphoton MW Ionization
- Single Photon Ionization Rates
- Above-Threshold Bound States

Expected Results







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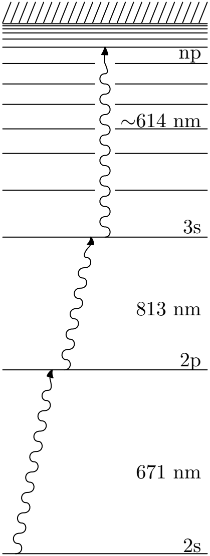
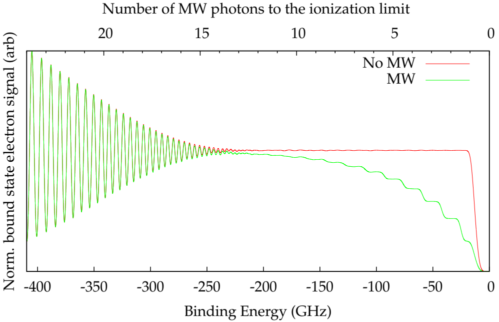
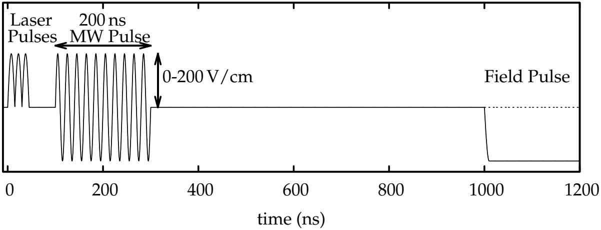
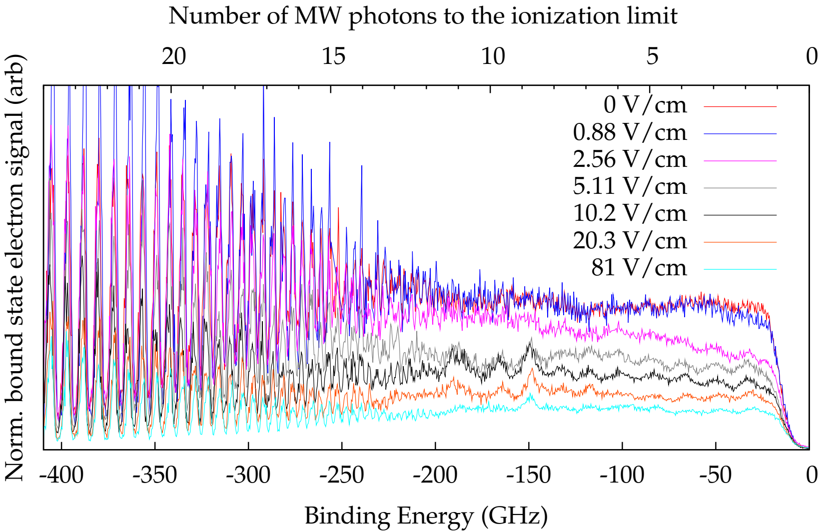


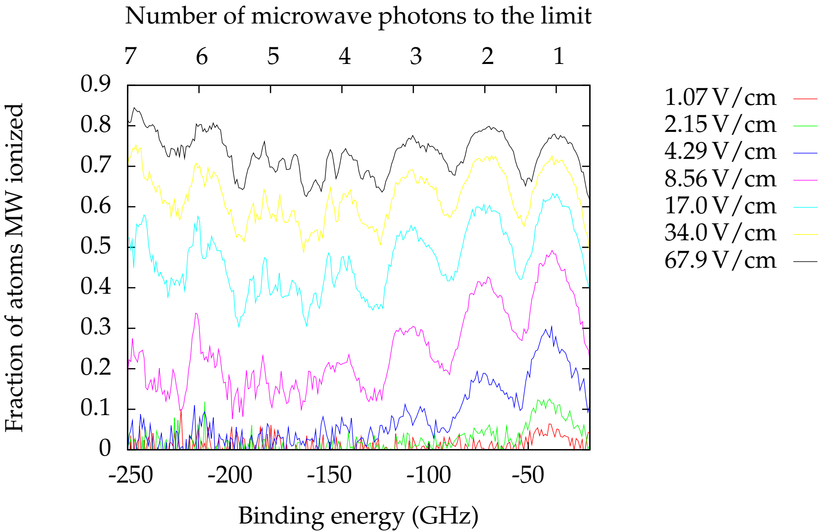




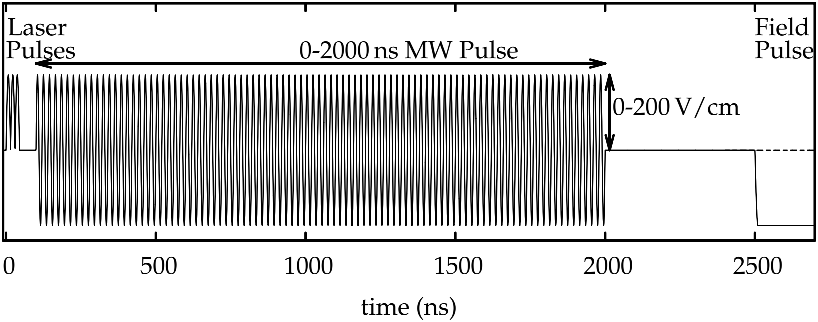
Microwave Ionization Steps - 17 GHz



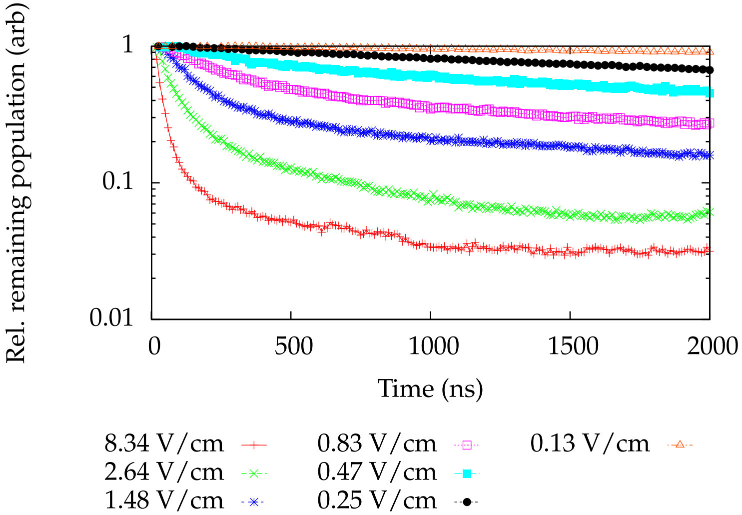
Microwave Ionization Steps - 36 GHz



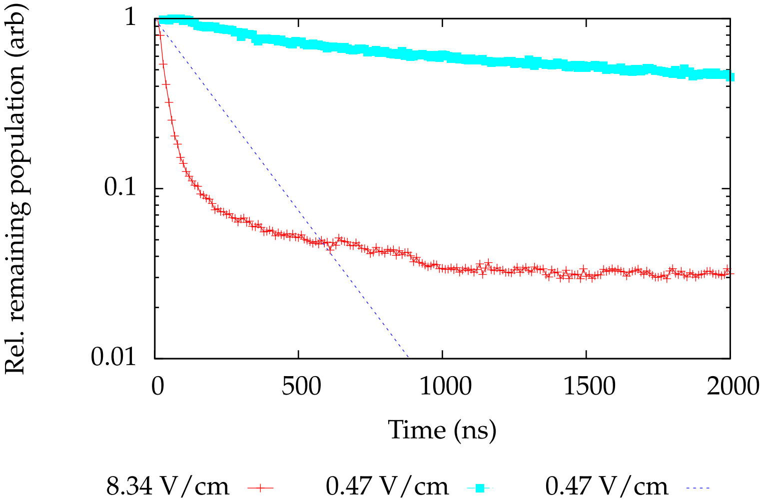
Photoionization - Timing



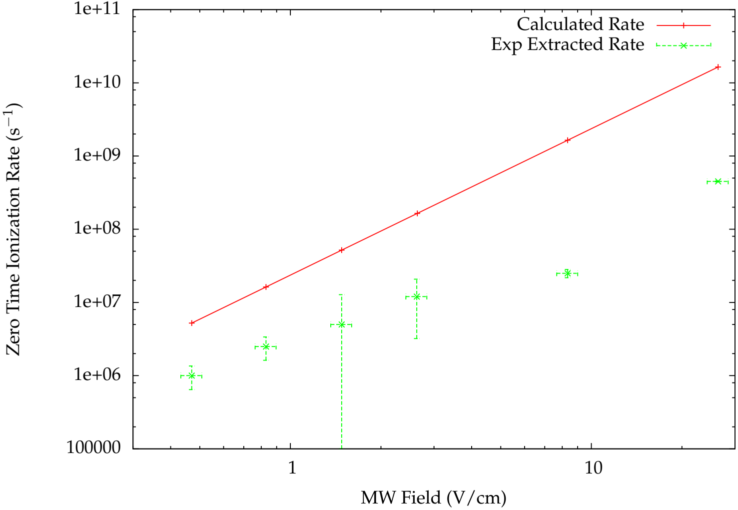
Single Photon Ionization



Single Photon Ionization

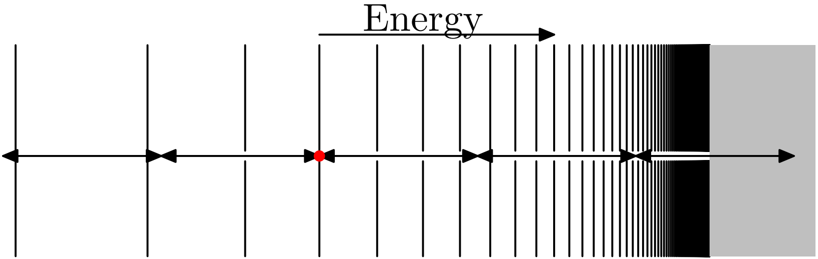


Fermi's Golden Rule Comparison



Dynamical Anderson Localization

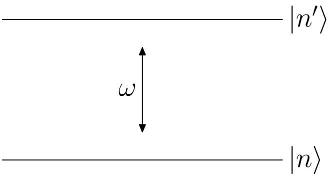
First work by Casati *et al.*



Destructive interference between many multiphoton paths localizes the electronic wave function, and ionization occurs when electron transport diffuses over the limit.

Casati *et al.*, *Phys. Rep.* 154 (1987).

Jensen *et al.* Model



Rabi width = $\mu \cdot E = \dfrac{0.4108E}{\omega^{5/3} n^3}$

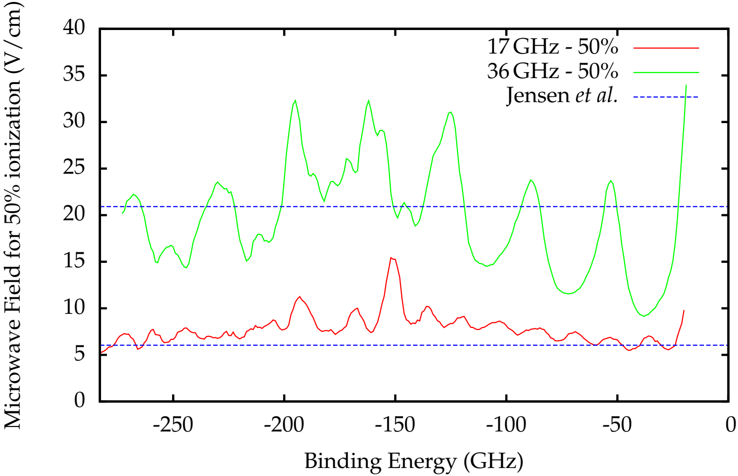
State spacing = $\dfrac{1}{n^3}$

MW ionization occurs when the Rabi width $\geq$ state spacing

$$\boxed{E = 2.4\omega^{5/3}}$$

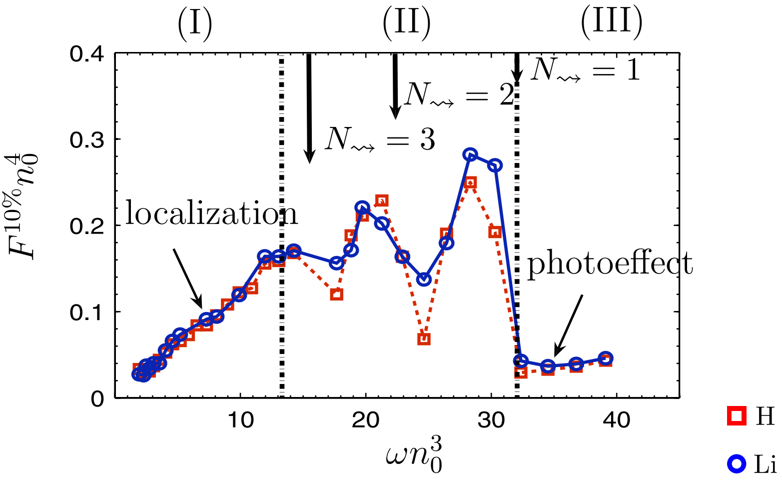
Jensen *et al.*, *Phys. Rev. Lett.* 62, (1989).

Jensen *et al.* Comparison



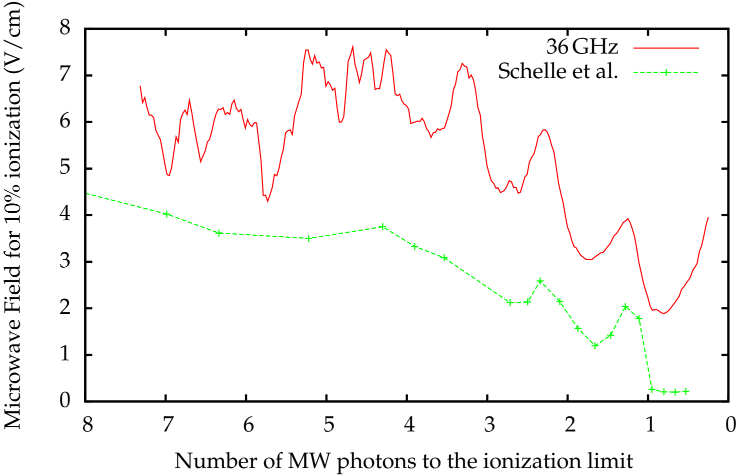
Jensen *et al.*, *Phys. Rev. Lett.* 62, (1989).

Schelle, Delande, and Buchleitner Model



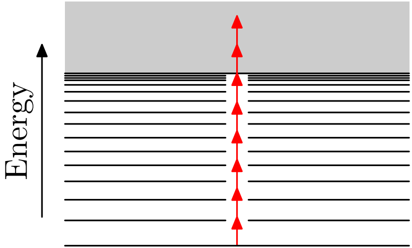
Schelle, Delande, and Buchleitner, *Phys. Rev. Lett.* 102, (2009).

Schelle, Delande, and Buchleitner Comparison



Schelle, Delande, and Buchleitner, *Phys. Rev. Lett.* 102, (2009).

Dressed Atom Picture



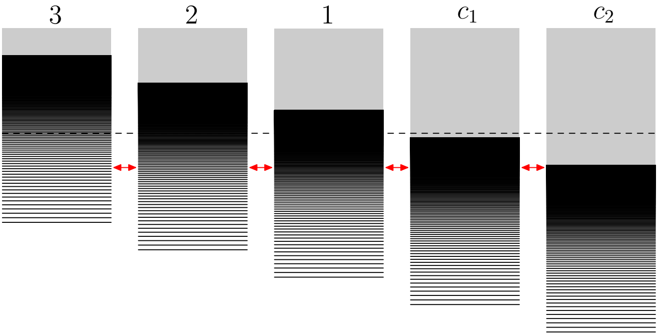
Can we simply use a Floquet picture to describe system?

How do we choose the correct levels to include?

How do we include the above-threshold continuum states?

MQDT-Floquet Model

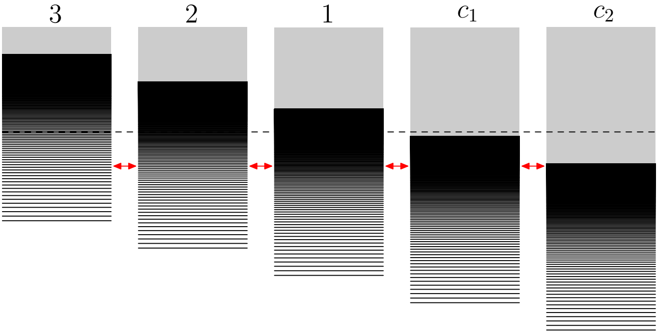
Giusti-Suzor and Zoller proposed a Floquet-MQDT model for Rydberg atoms in laser fields where the couplings between channels are radiative dipole couplings. The Rydberg electron is in a Coulomb potential, and can only scatter to other states near the core.



Giusti-Suzor and Zoller, *Phys. Rev. A* 36, (1987).

MQDT-Floquet Model

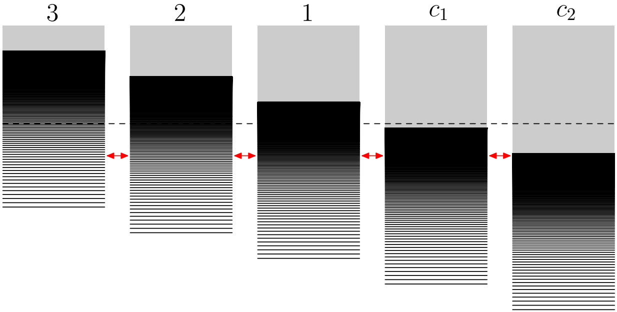
We can define a series of channels, each separated by one microwave photon.



The coupling between channels are radial dipole couplings - the same as the level coupling used by Jensen *et al.*

MQDT-Floquet Model

Following the method of Cooke and Cromer, we can easily calculate the time-dependent transfer of the bound channel populations to the continuum along the dashed line.



By iterating the binding energy (the dashed line) we can compute the ionization spectrum

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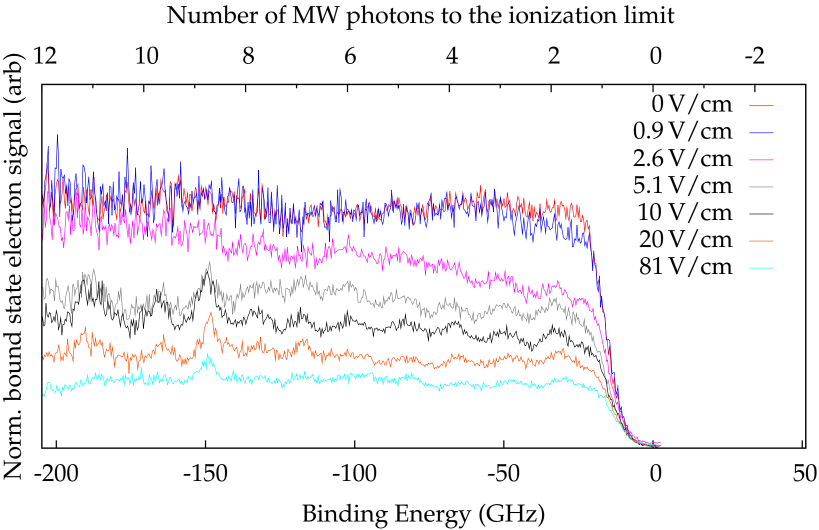
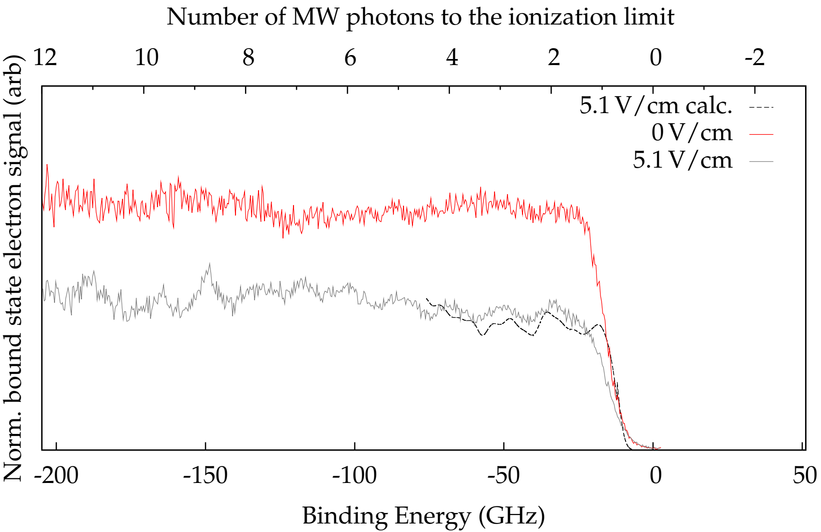
Cooke and Cromer, *Phys. Rev. A* 32, (1985).

Model Comparison

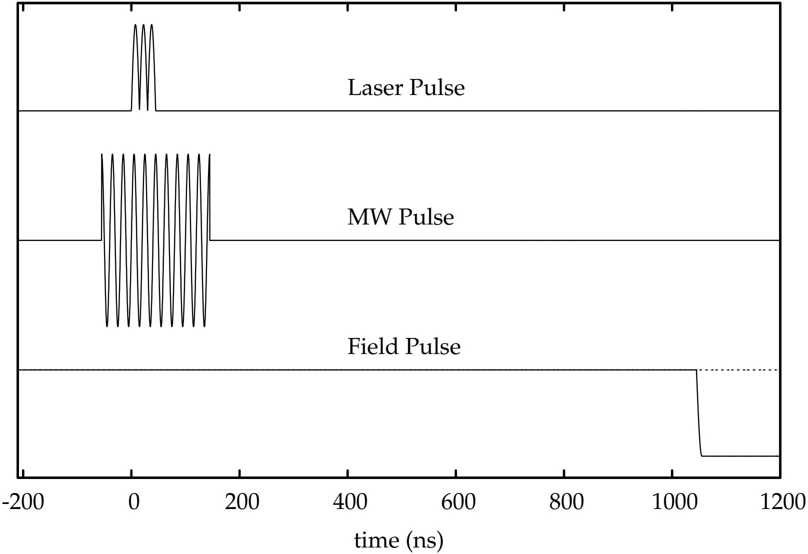


Model Comparison

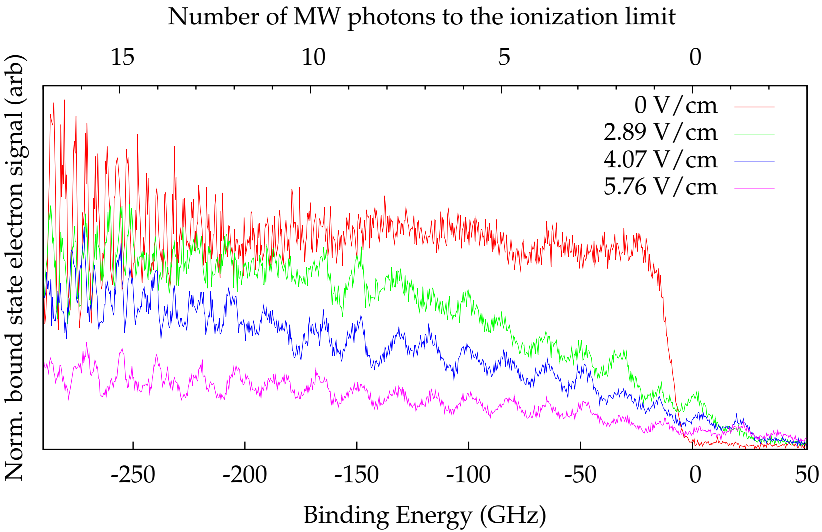


Outline

Above-Threshold Bound States - Timing



Above-Threshold Bound States



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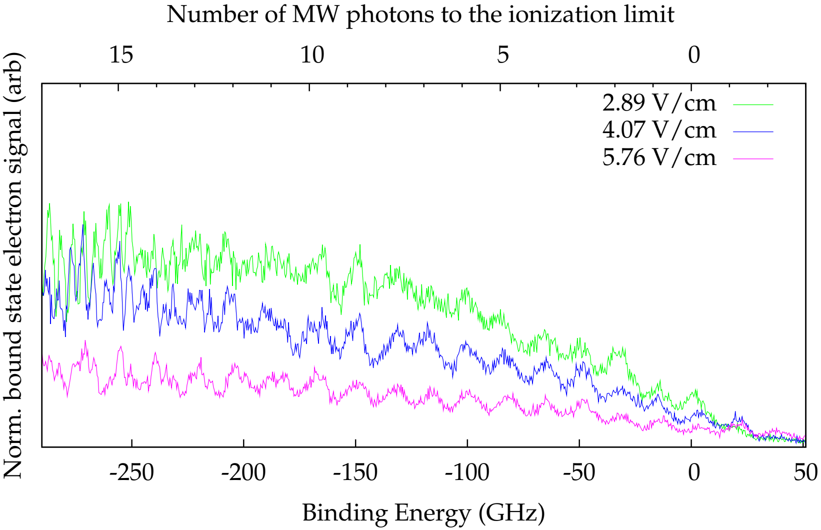

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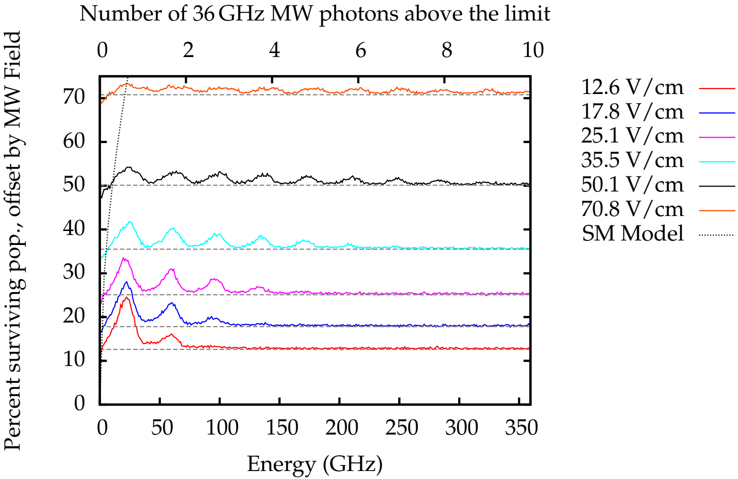
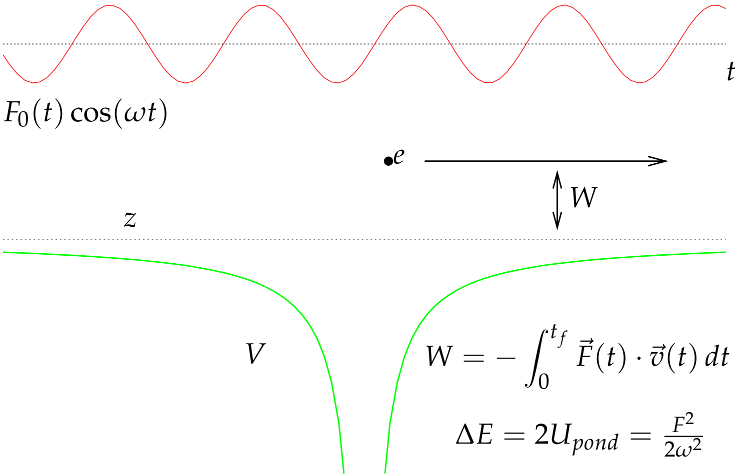


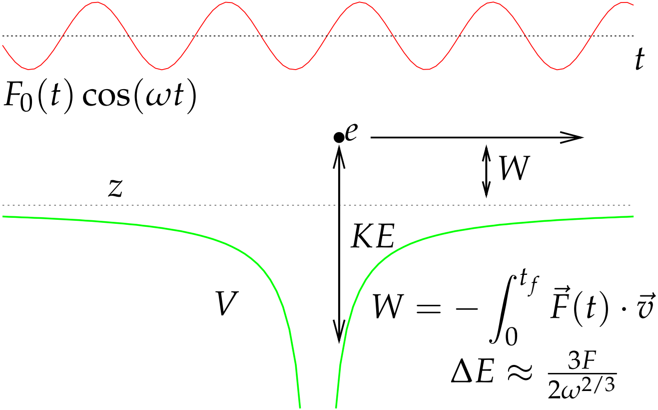
Simpleman's Model



$$W = -\int_0^{t_f} \vec{F}(t)\cdot\vec{v}(t)\,dt$$

$$\Delta E = 2U_{pond} = \frac{F^2}{2\omega^2}$$

New Classical Model

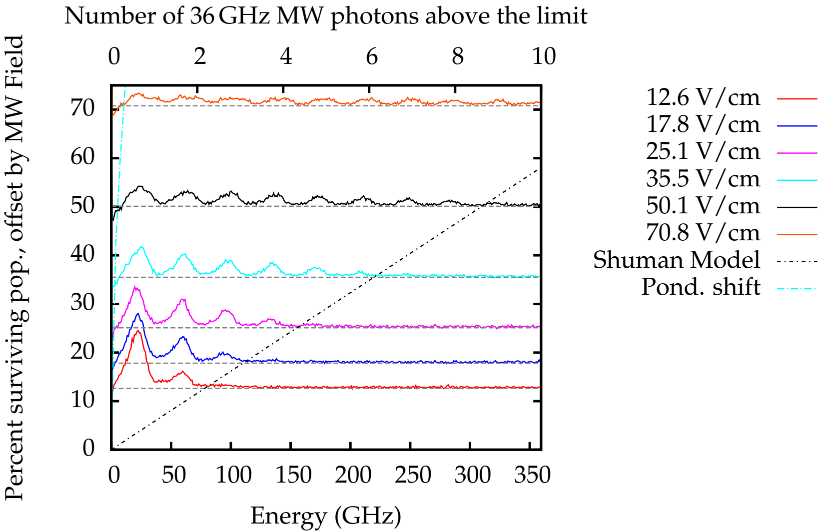


$$W = -\int_0^{t_f} \vec{F}(t)\cdot\vec{v}(t)\,dt$$

$$\Delta E \approx \frac{3F}{2\omega^{2/3}}$$

Shuman et al., *Phys. Rev. Lett.* 101, (2009).

Above-Threshold Bound States



Conclusions

- An Anderson Localization model crossing over to Fermi's Golden Rule does not match experimental results
- The coherent coupling of levels both above and below the ionization limit describes high scaled frequency microwave ionization
- A simple classical model illustrates population transfer from above the limit to bound states