Metastable States in Microwave Ionization

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Outline

Introduction

- Rydberg Atoms
- Field Ionization and Photoionization
- MW Ionization
- Trapping in extremely high-lying Rydberg states

Experimental Setup

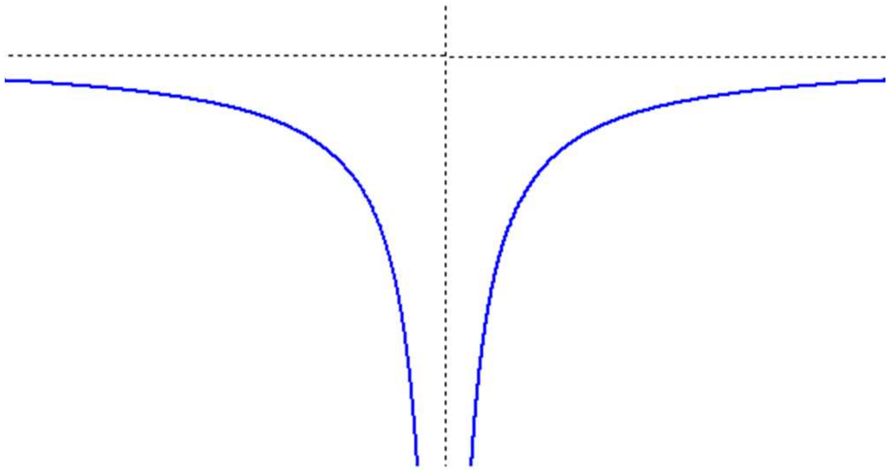
- Apparatus and Energy Levels of Li
- Timing Diagram

Observations

- Microwave fields required to ionize 50% and 10% of initial population
- Population trapping in metastable weakly-bound states
- Microwave assisted recombination and excitation to highly – excited states states

Conclusions and future work

Introduction – Rydberg atoms



$$V = -\frac{1}{|r|}$$

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

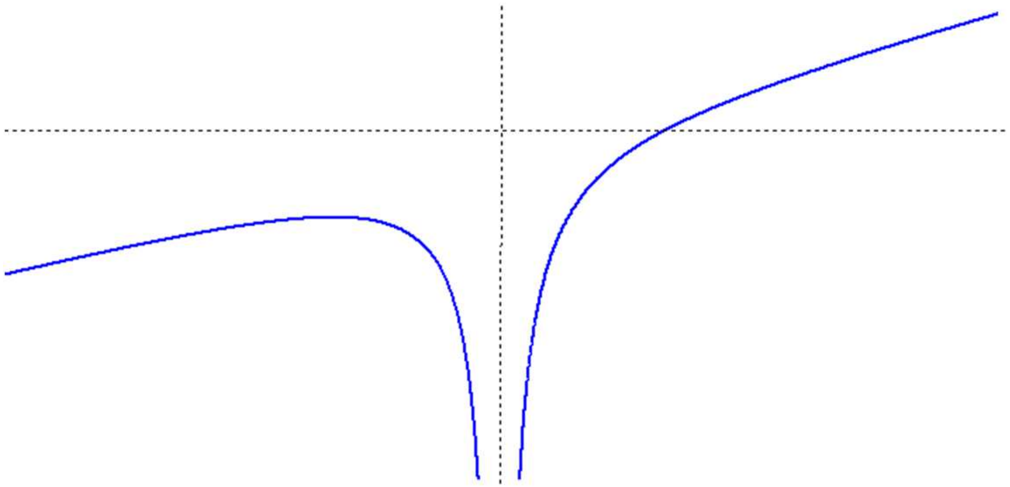
$$r \propto n^2$$

$$E_{ionization} \propto n^{-4}$$

$$w_k \propto n^{-3}$$

Rydberg atoms could be used as an important tool to study various physical phenomena such as: diamagnetism, astrophysics, plasmas, quantum computing, and interactions with strong electromagnetic fields

Introduction – Field Ionization



$$V = -\frac{1}{|r|} + rE$$

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

$$E = \frac{1}{16n^4}$$ - classical ionization

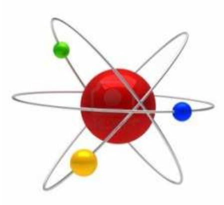
Stark shift increases binding energy, and, for m = 0,

$$W = -\frac{1}{2n^2} - \frac{3n^2 E}{2}.$$

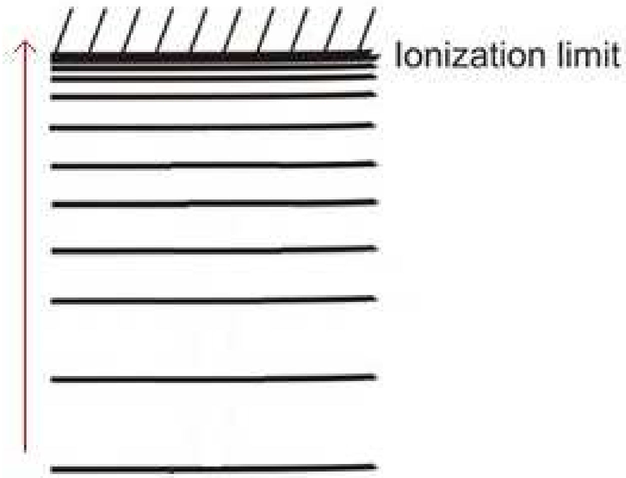
Field required to ionize the atom is higher due to the Stark shift

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

Introduction – PhotoIonization



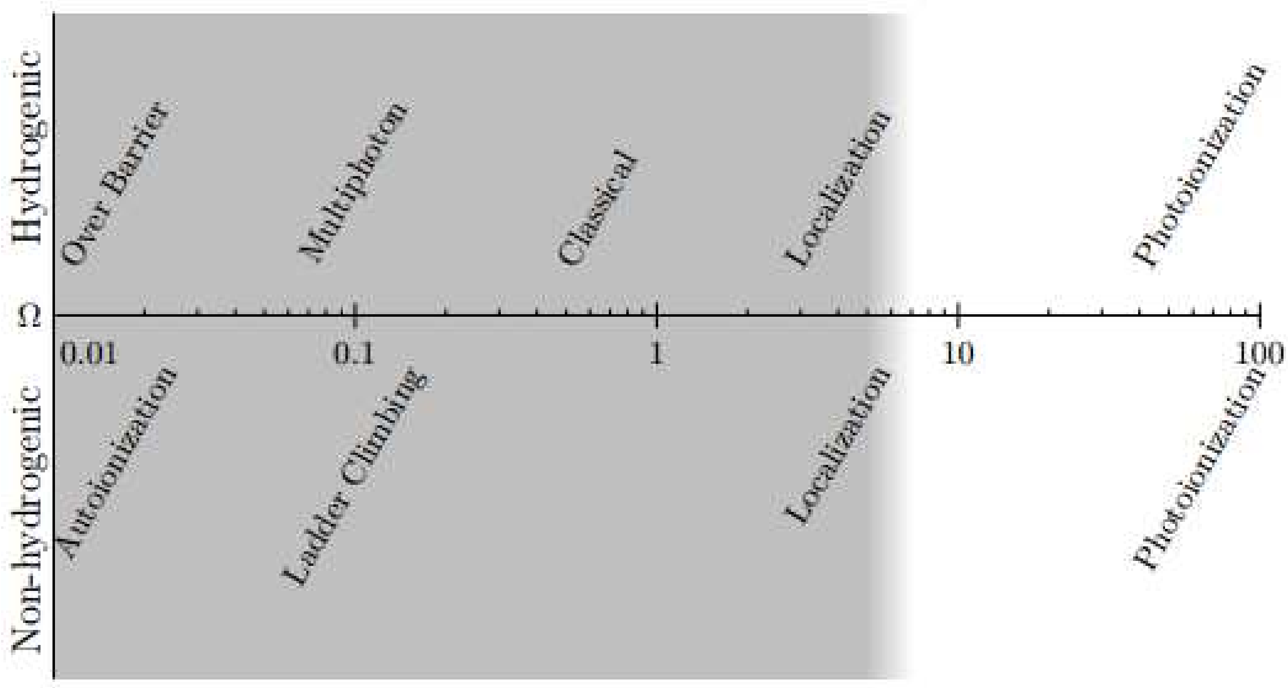
$$\hbar w > W$$



The atom can be ionized by absorbing one or more field photons

Introduction – Microwave Ionization

Scaled frequency: $$\Omega = \frac{w}{w_k} = wn^3$$



*picture updated from J.Gurian

Introduction – Metastable states in Microwave Ionization

Several-cycle 10-GHz microwave pulse can also redistribute initial population in energies and trap it in extremely high-lying states - Noel *et al*. (1999).

Similar effect was observed by Zhao *et al*. (2005) with the use of trains of unipolar pulses in bias fields when starting from high lying states.

Shuman *et al*. (2008) and Gurian *et al*. (2010) observed microwave assisted recombination 300 GHz below and above the ionization limit.

What is next?

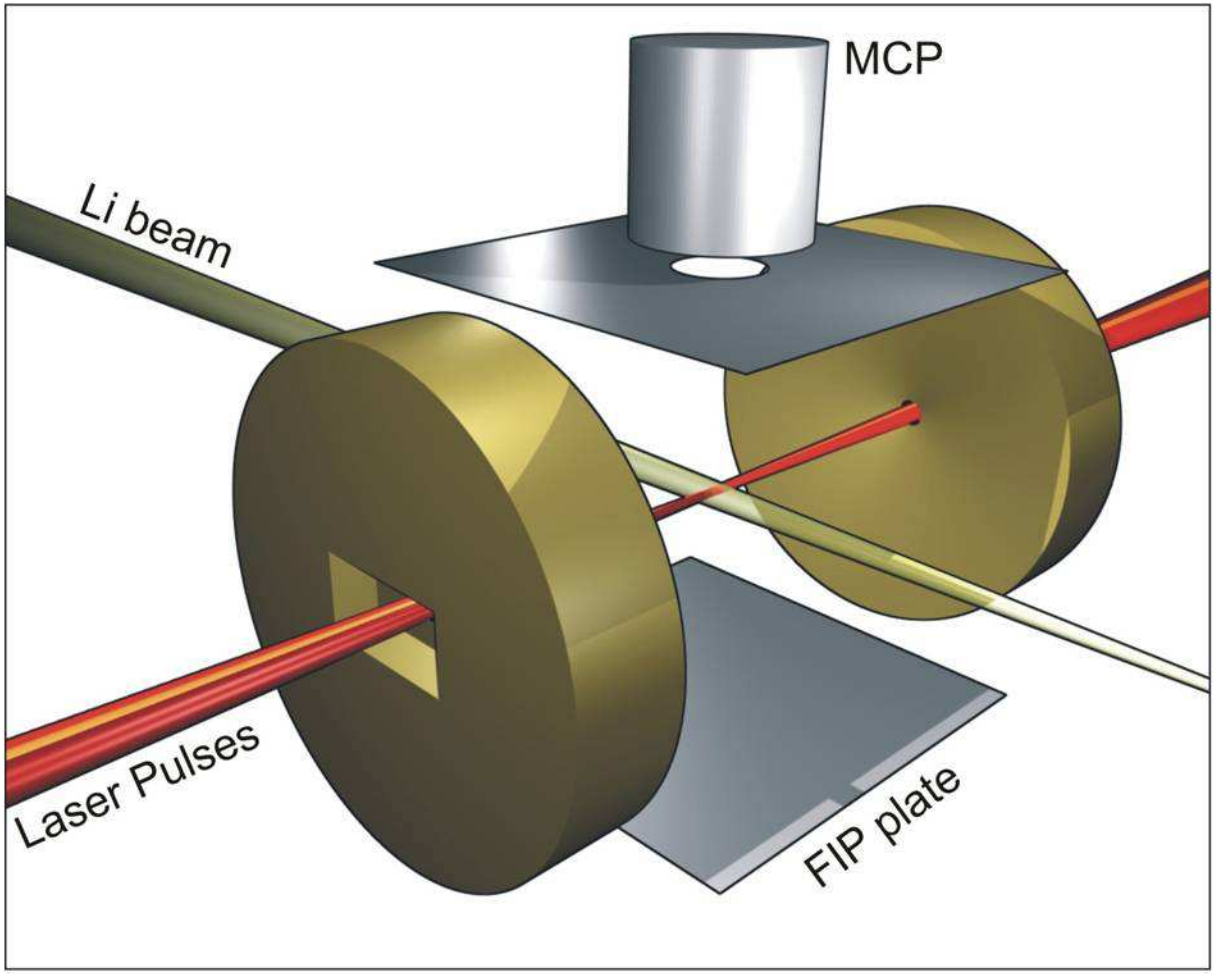
Introduction – Current discoveries

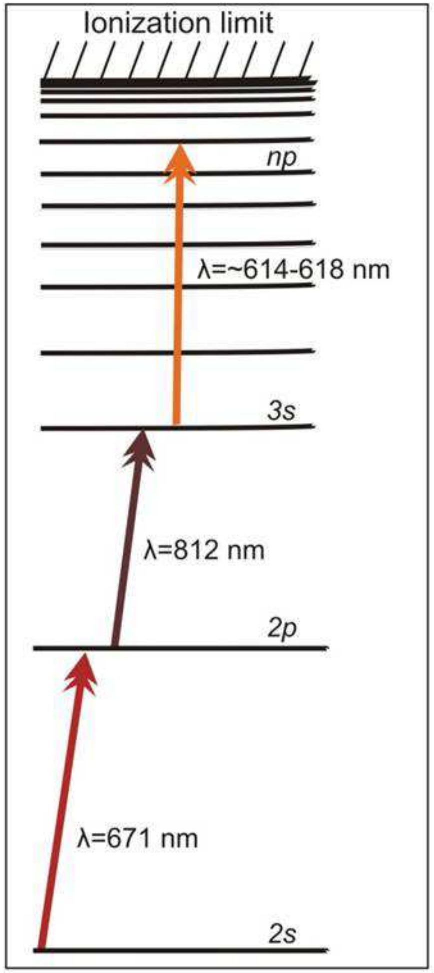
- Study of amplitude of 38-GHz microwave field required to ionize 50% and 10% of initially excited Li Rydberg atoms in the range of binding energies $0.3 < \Omega < \infty$.

- Trapping of initial population in extremely high-lying metastable states by strong 8000 cycle pulses for very wide range of initial binding energies

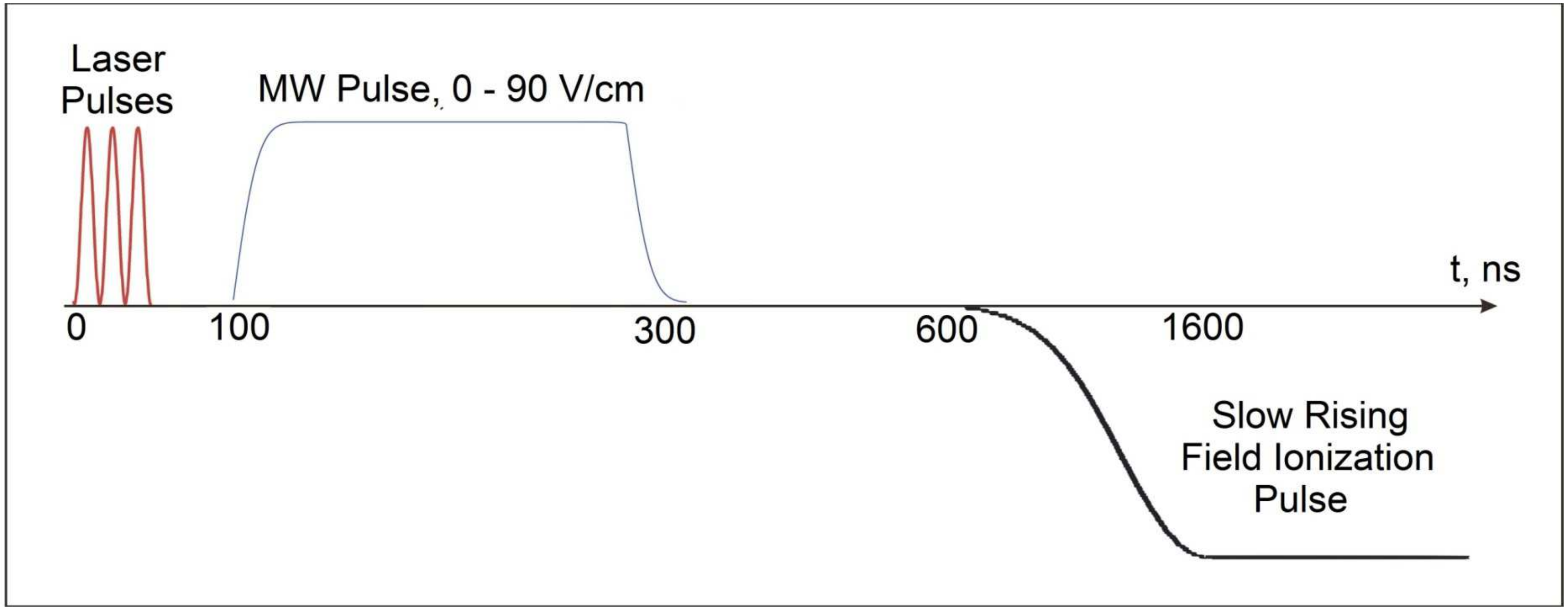
- Observation of regular microwave structure in energy spectrum for $\Omega < 1$, and a destructive effect of stray fields on it.

Experimental Setup – Excitation to a chosen Rydberg state

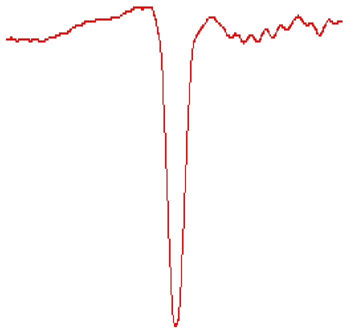




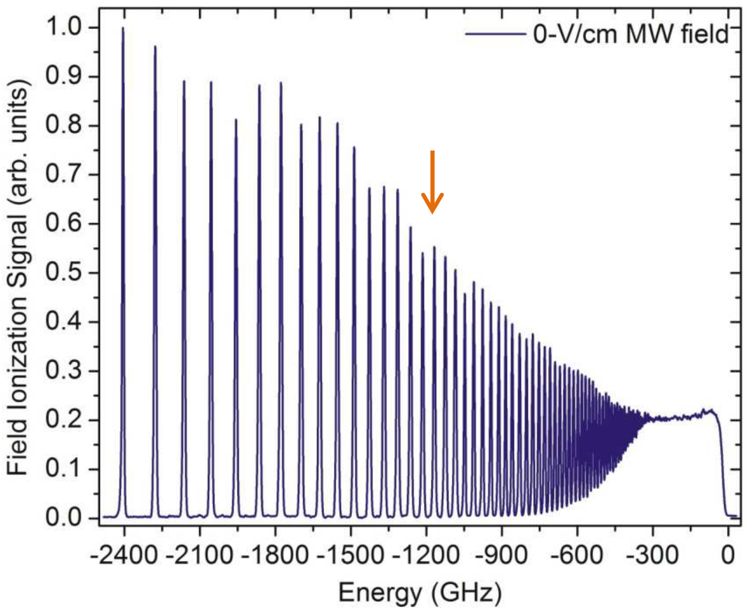
Experimental Setup – Timing Diagram



Oscilloscope trace:



Excitation to Rydberg states

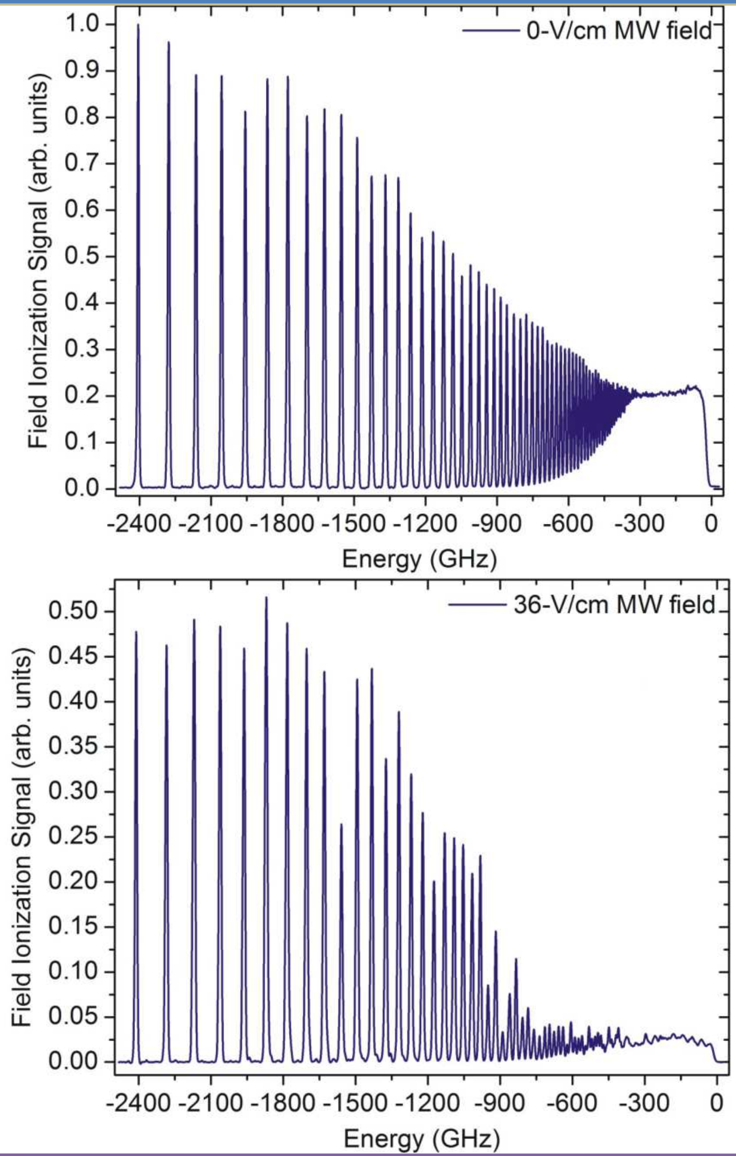


Ionization limit is depressed due to non-zero static field with shift $W = -2\sqrt{E}.$

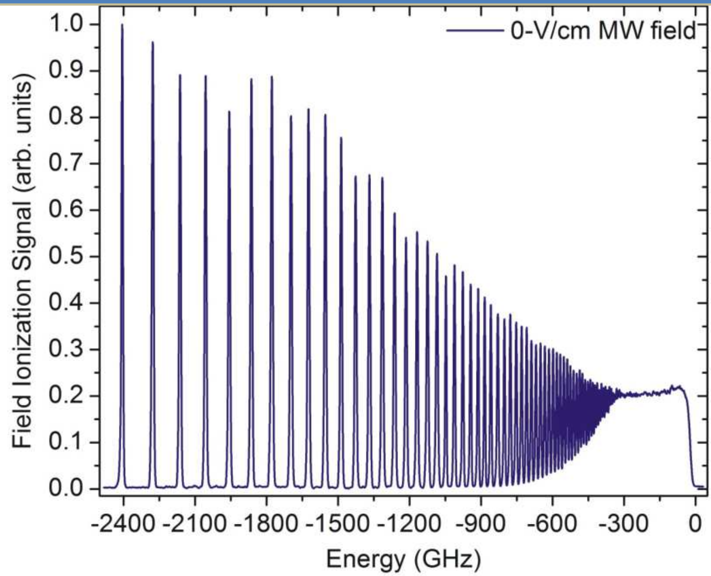
Here the depressed ionization limit is 25 GHz, so the static field must be 18 mV/cm.

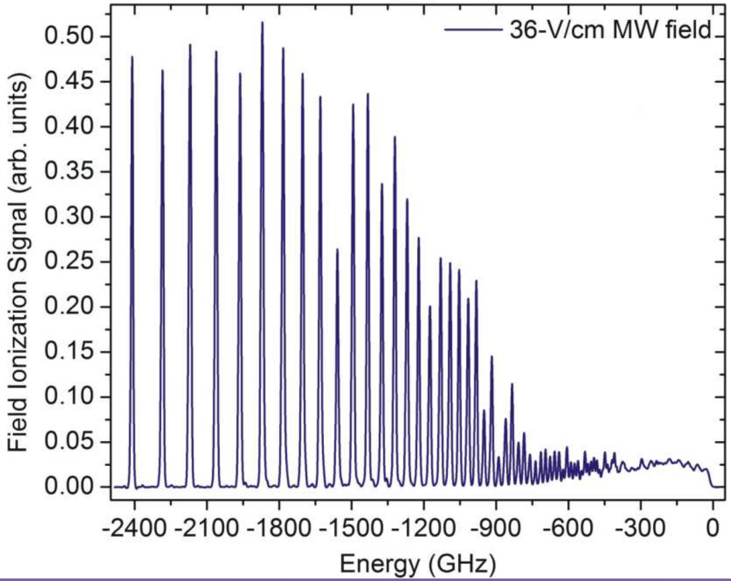
The first peak here is n =37, Ω=0.32
At n=56, Ω=1 for 38-GHz MW field

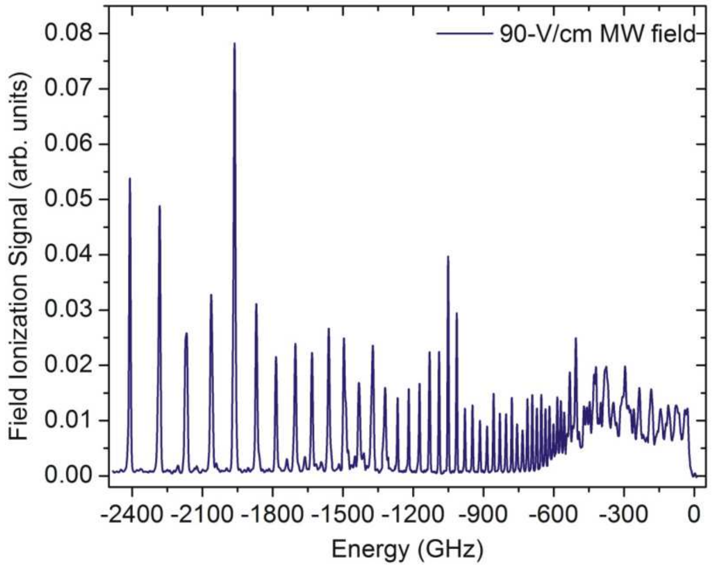
Microwave ionization of Rydberg states



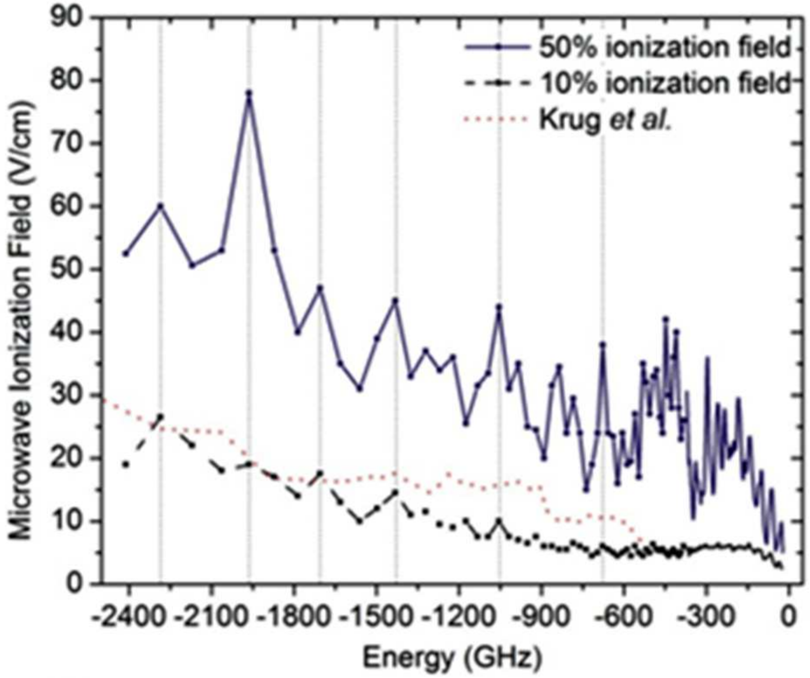
Microwave ionization of Rydberg states

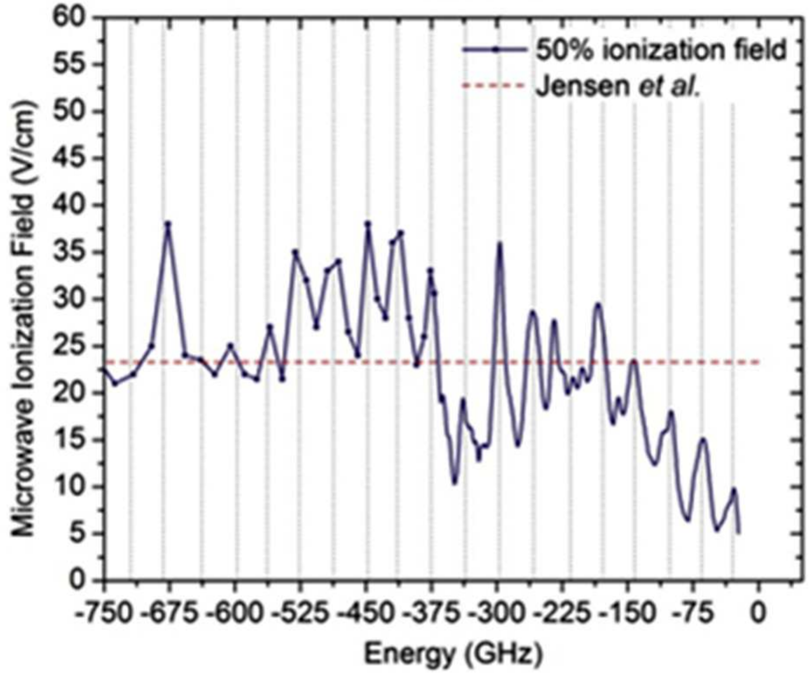






MW Ionization Thresholds

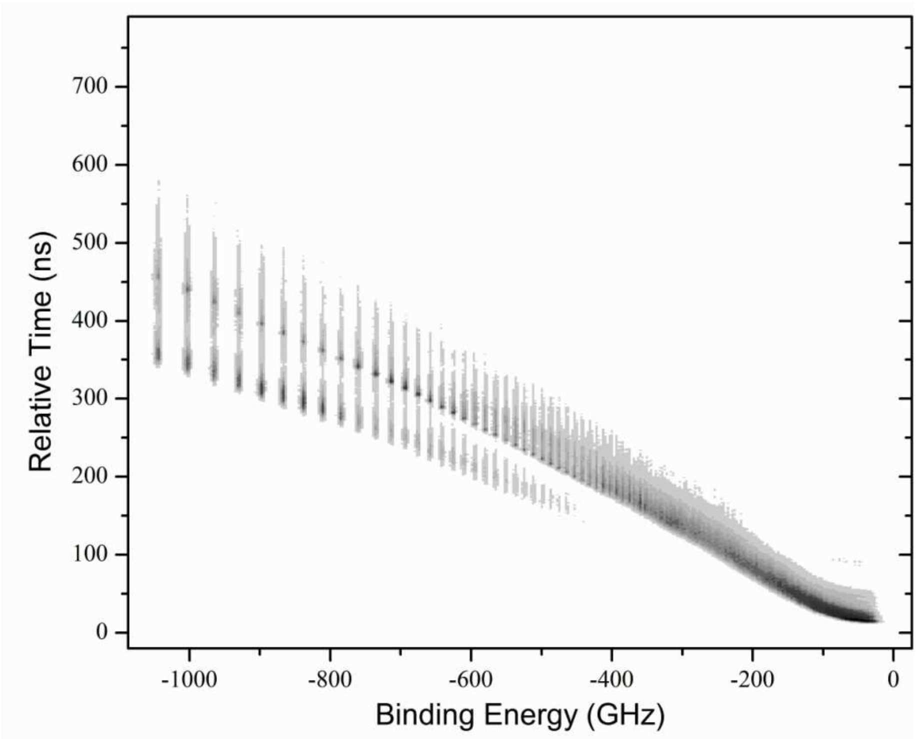




Vertical lines correspond to energies where Kepler frequency equals *3ω, 2.5ω, 2ω, 1.5ω, ω, and 0.5ω*

Vertical lines spaced by $\omega/2\pi$ = *38.3GHz*

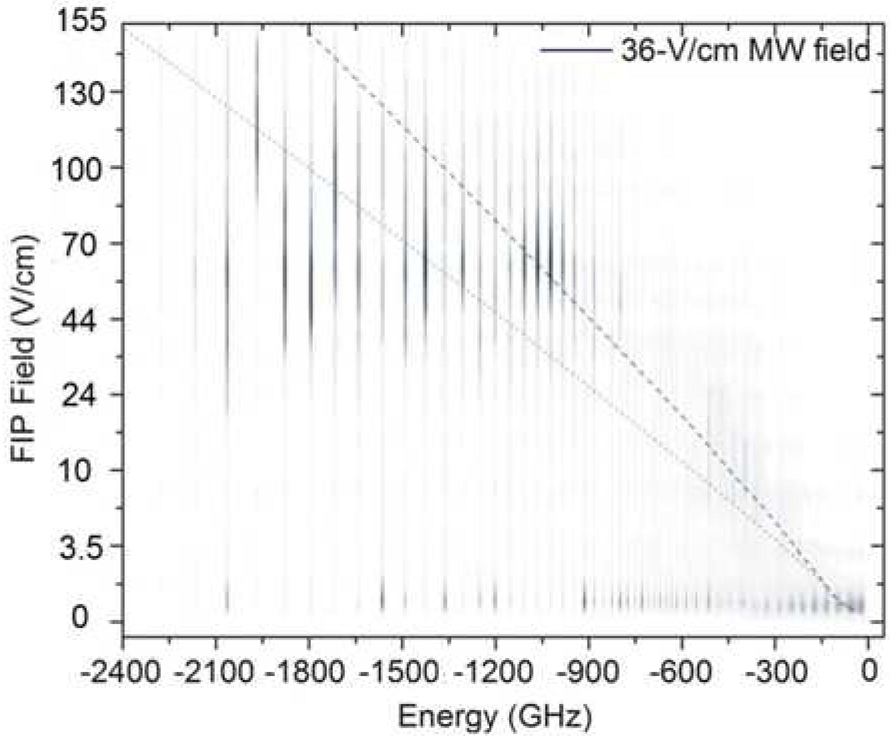
Final State Distribution



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

adiabatic ionization: $$E = \frac{1}{16n^4}$$

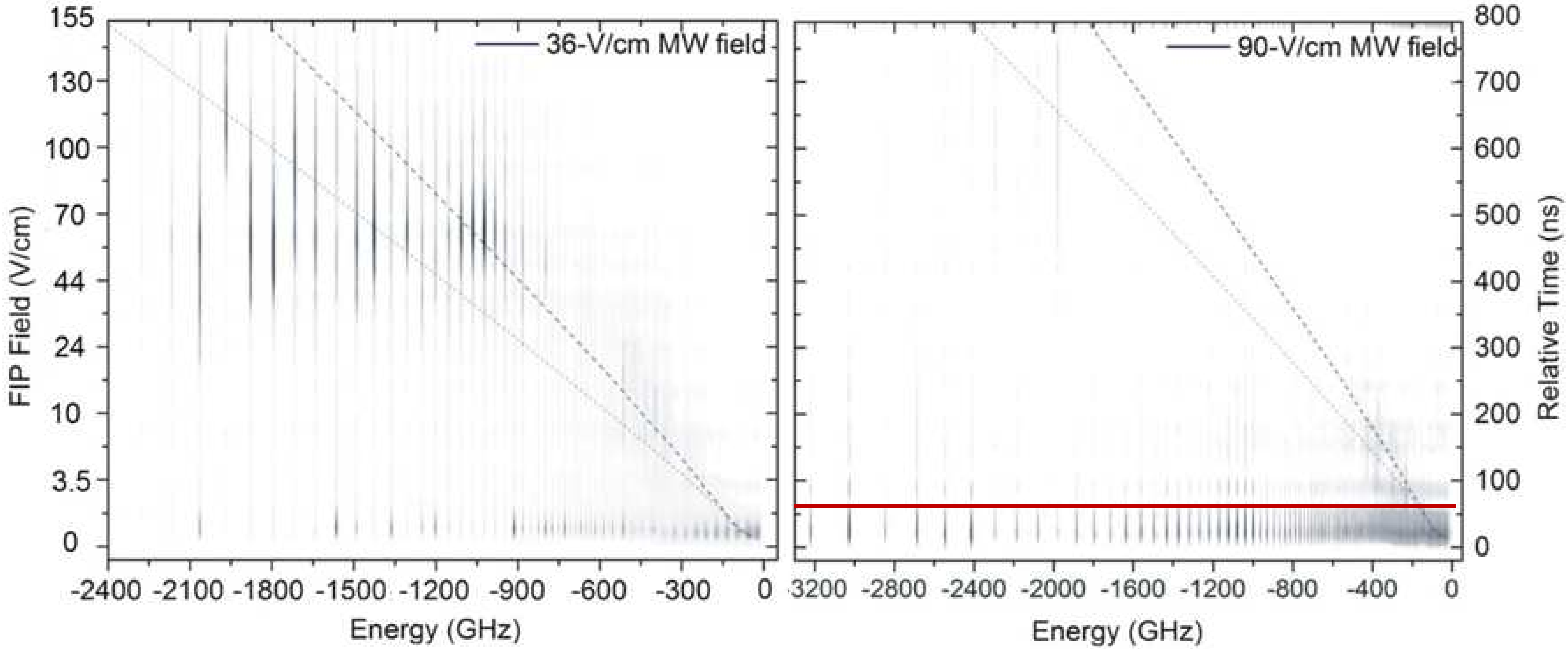
Final State Distribution



The dashed lines show diabatic ionization field $E = \dfrac{1}{9n^4}$,

the dotted lines correspond to adiabatic ionization field $E = \dfrac{1}{16n^4}$.

Final State Distribution



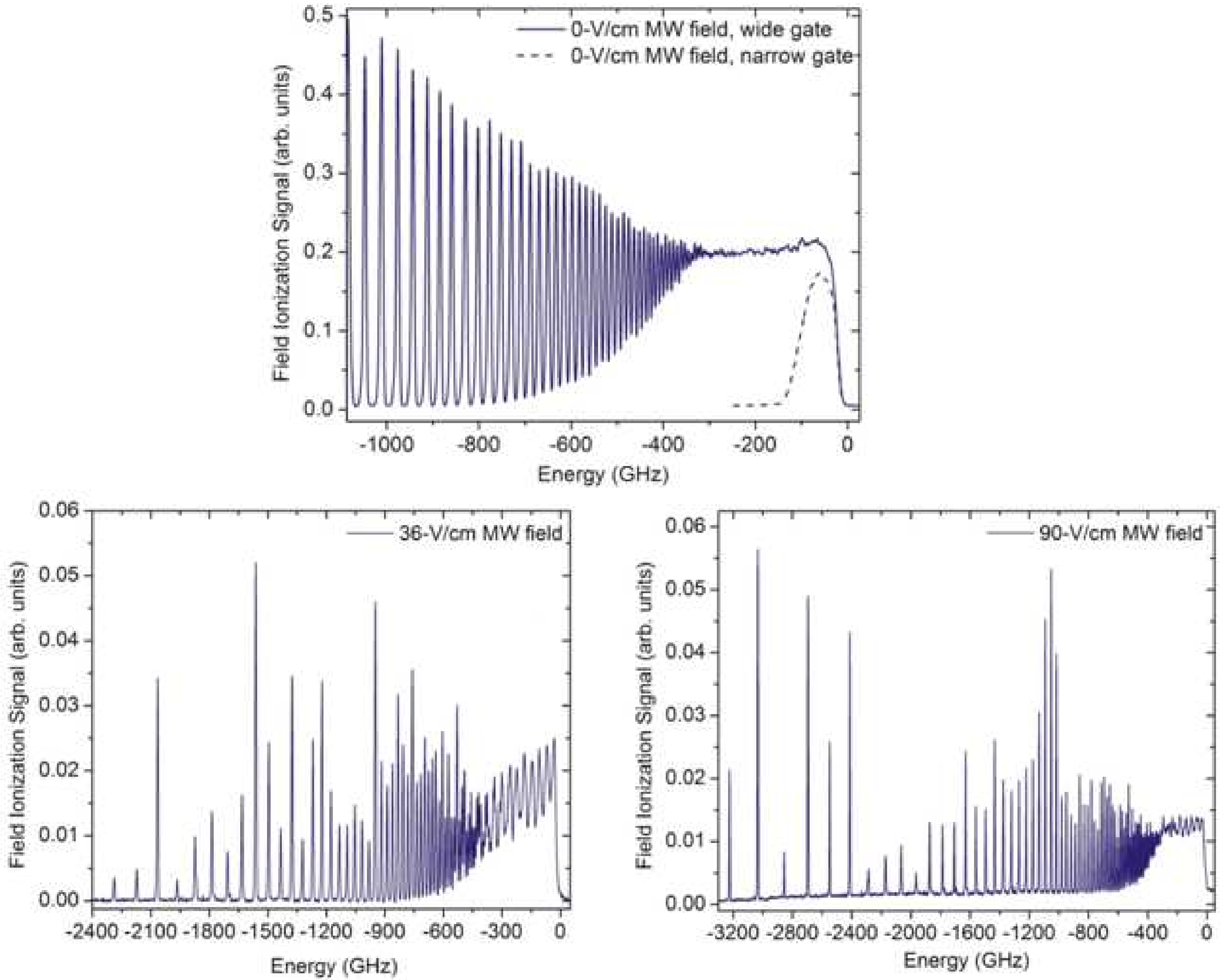
The dashed lines show diabatic ionization field

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

the dotted lines correspond to adiabatic ionization field

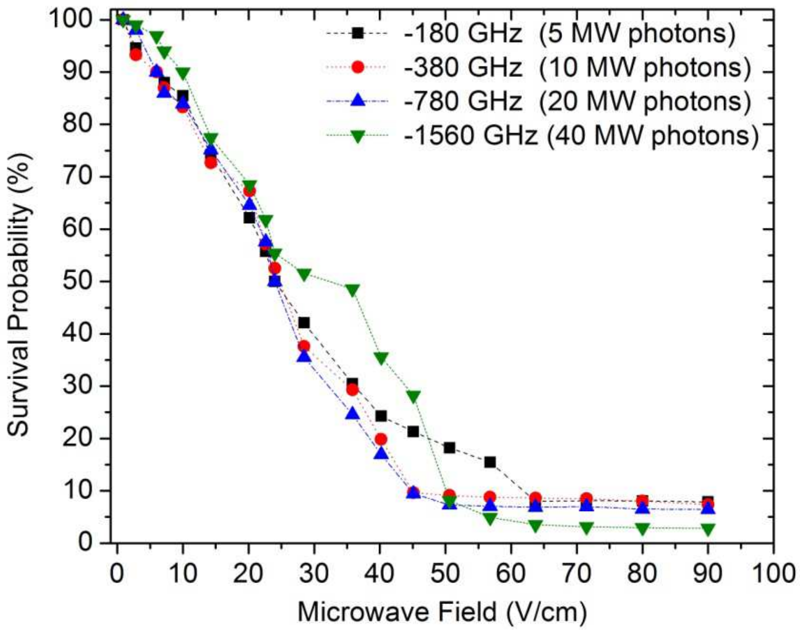
$$E = \frac{1}{16n^4}.$$

Extremely high-lying states

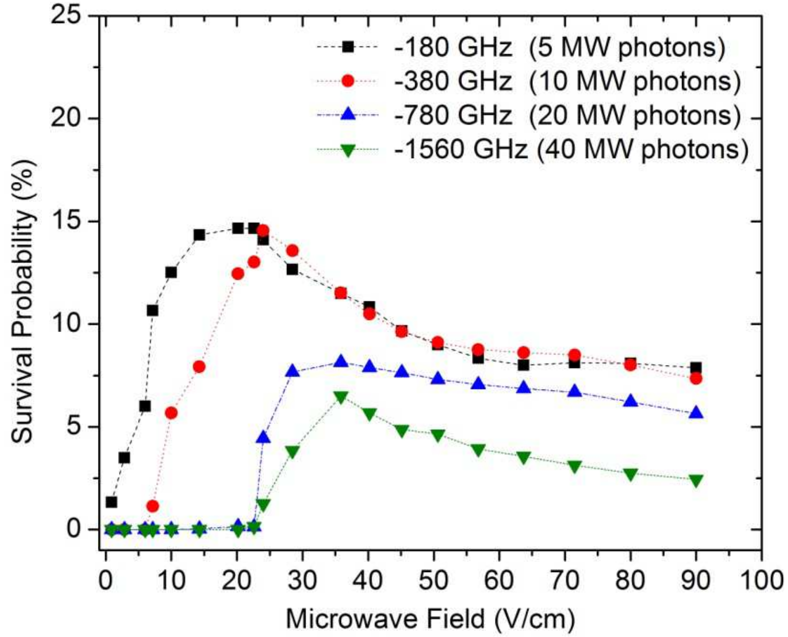


Survival Probability

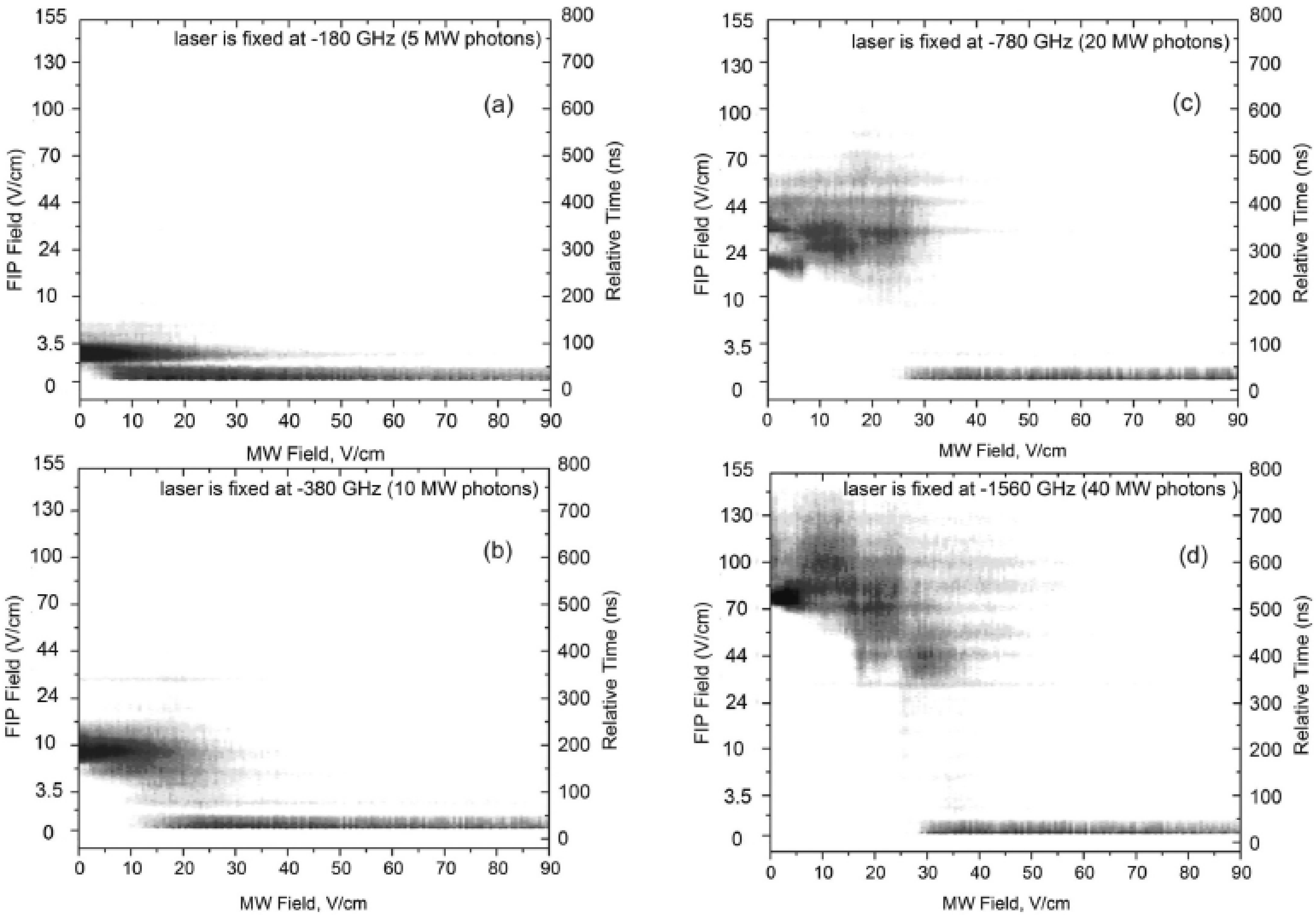
Wide gate to detect all bound states



Narrow gate to detect only states within 2 MW photons of the IL



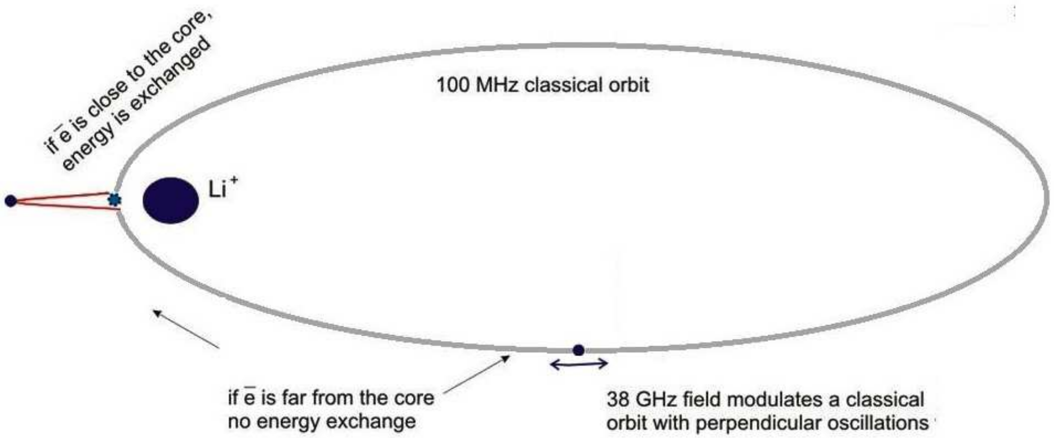
Final state distribution vs MW field



How do these states survive the field?

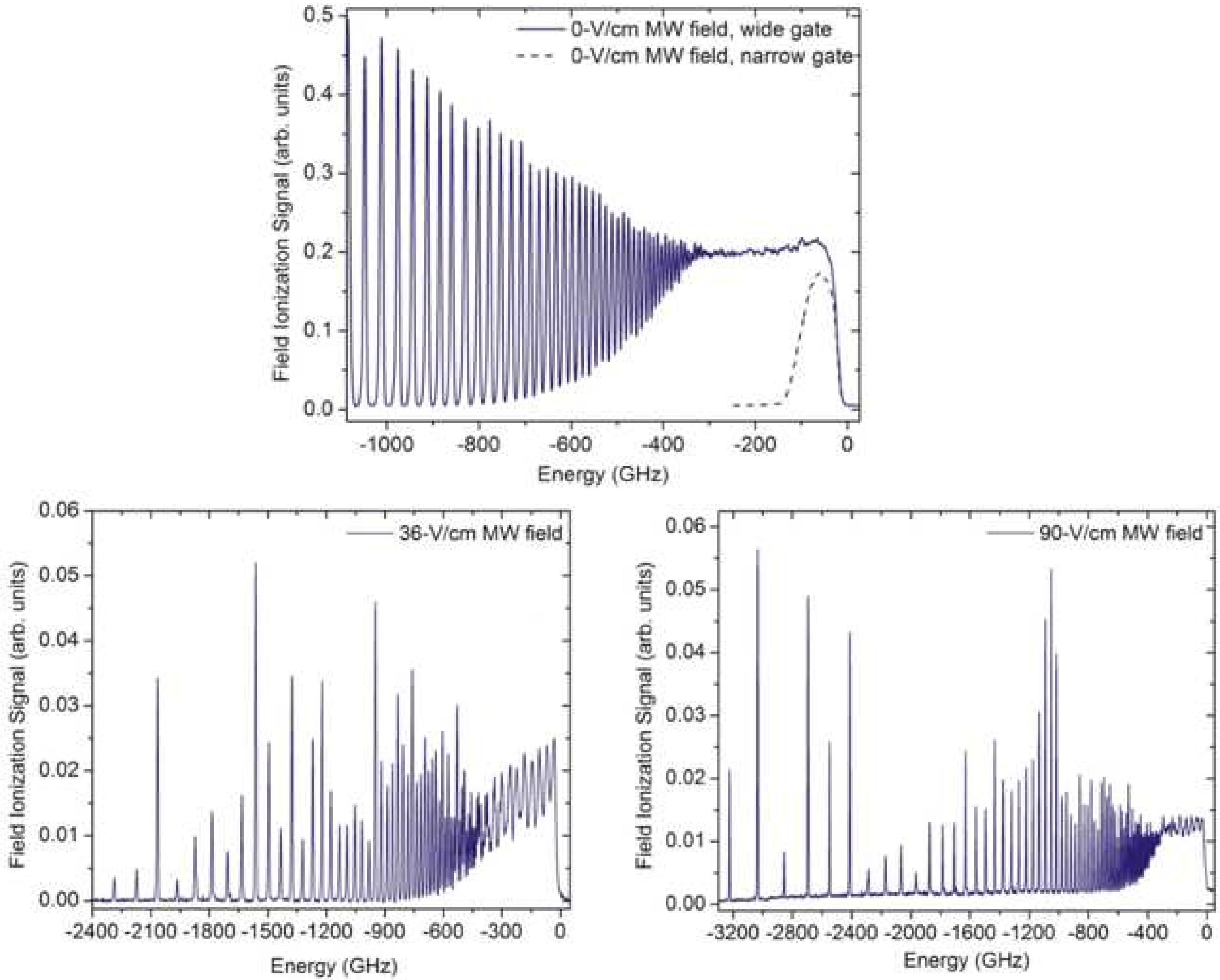
❖ In spite of the fact that the 90-V/cm MW pulse is 8000 cycles long, we detect approximately 5-7% of the initial population trapped in very-high-lying ($n > 215$) states, even though mostly all stronger bound states are ionized.

How do they remain stable in such a strong MW field?

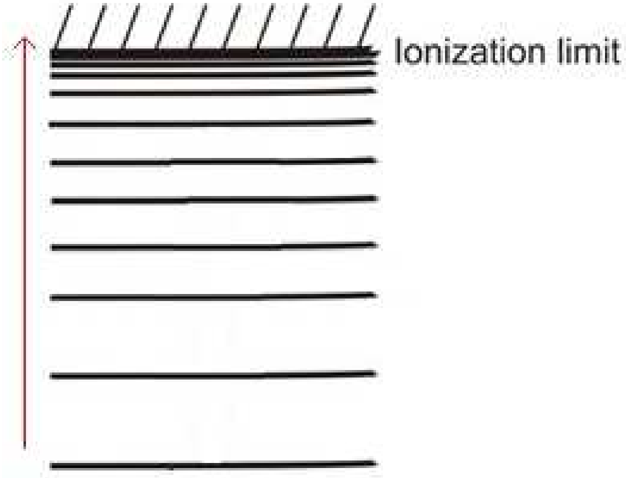


❖ Atoms are trapped in metastable atom-field states and relax to high-lying states at the end of the microwave pulse

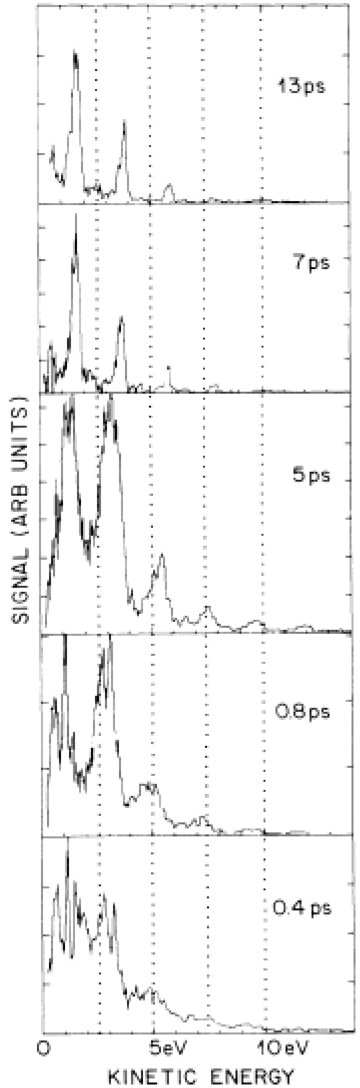
What is that regular structure near the IL?



Above Threshold Ionization



$$\hbar w(n+s) > W$$



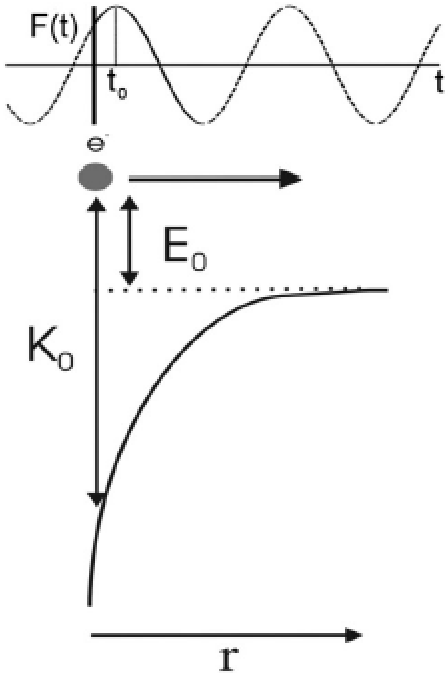
* Freeman *et al.* (1987)

A combination of high and low frequency fields can trigger that effect if they are in phase, for example:

ultraviolet attosecond pulses synchronous with an IR field (Johnsson *et al.* (1987))

ns dye laser and microwaves (Gallagher (1988)

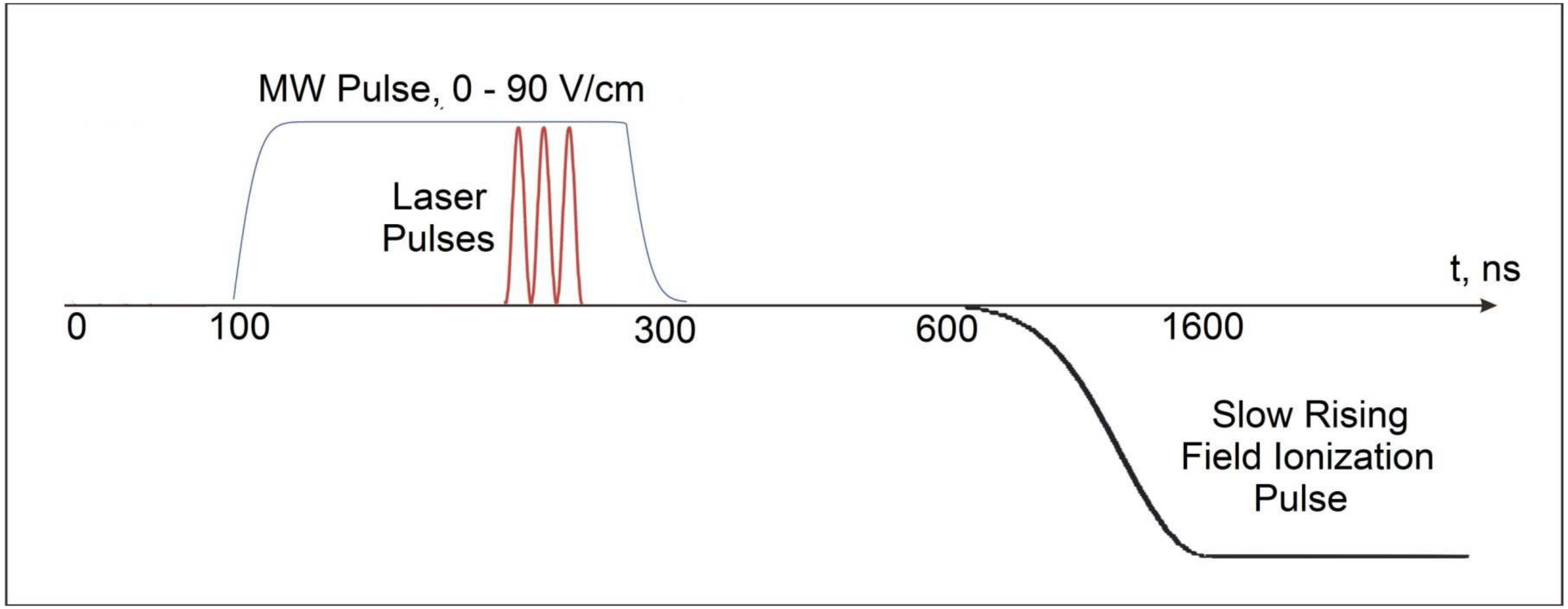
Above Threshold Recombination



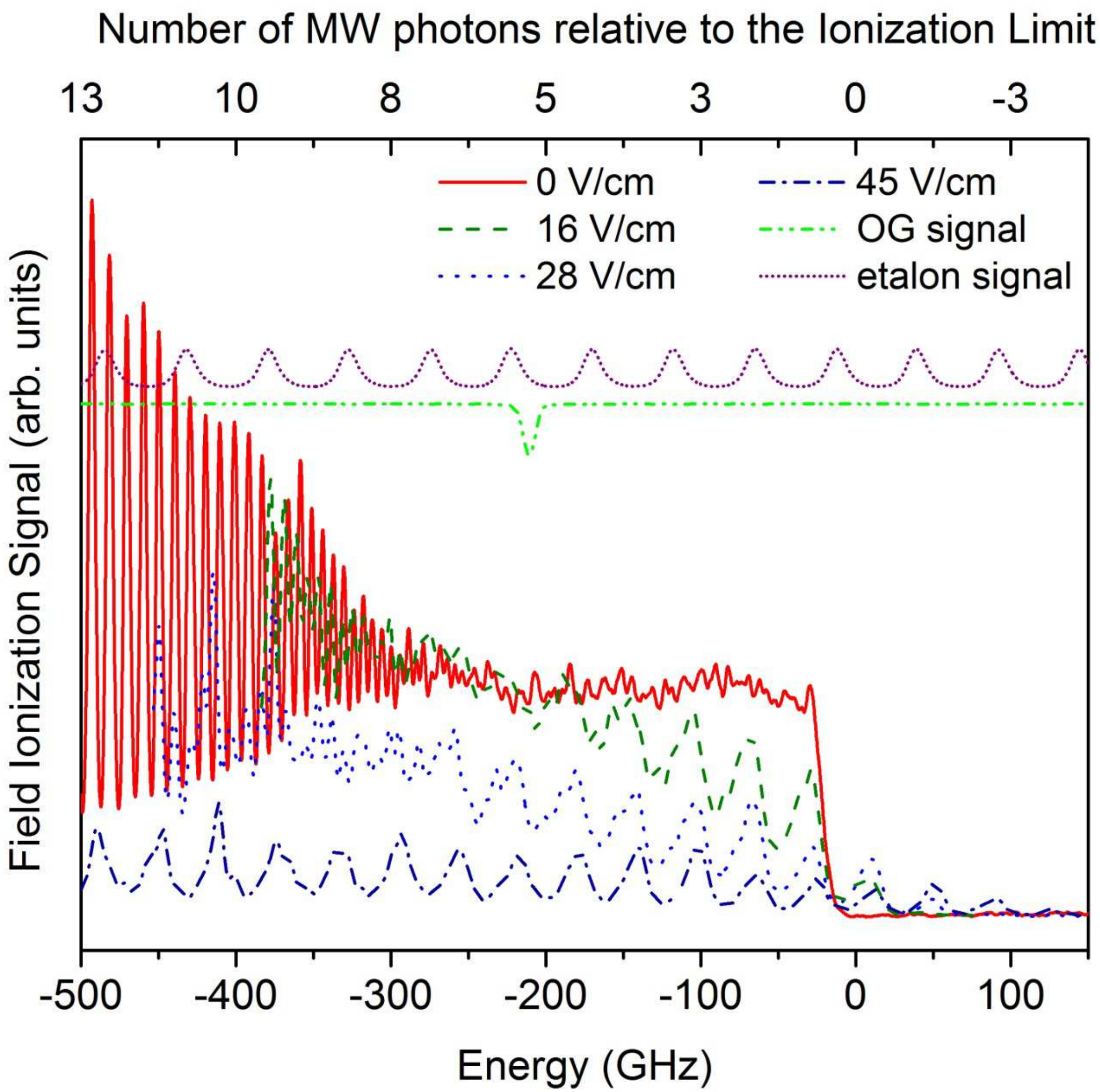
When the laser is tuned above the ionization limit,
the microwave field can recombine the ejected electron with the parent ion.

* Shuman *et al.* (2008)

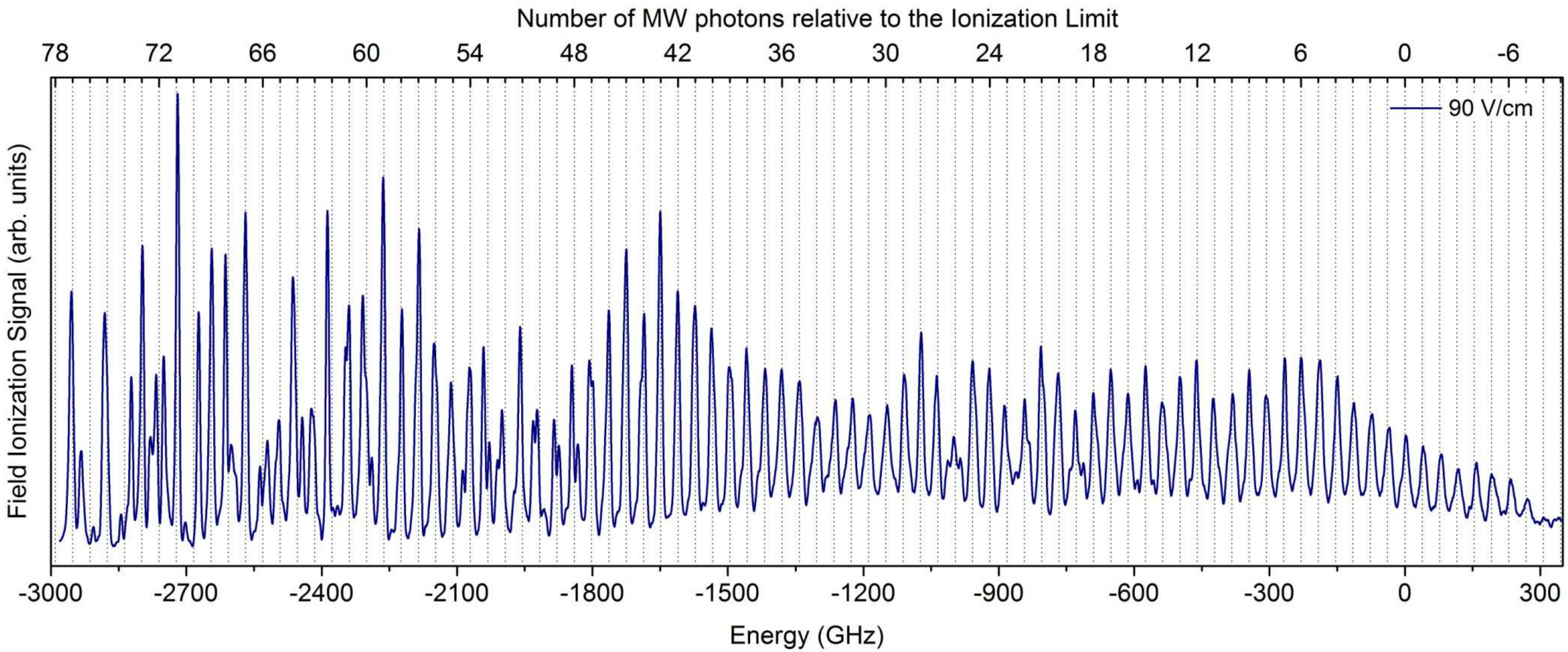
Experimental Setup – Timing Diagram



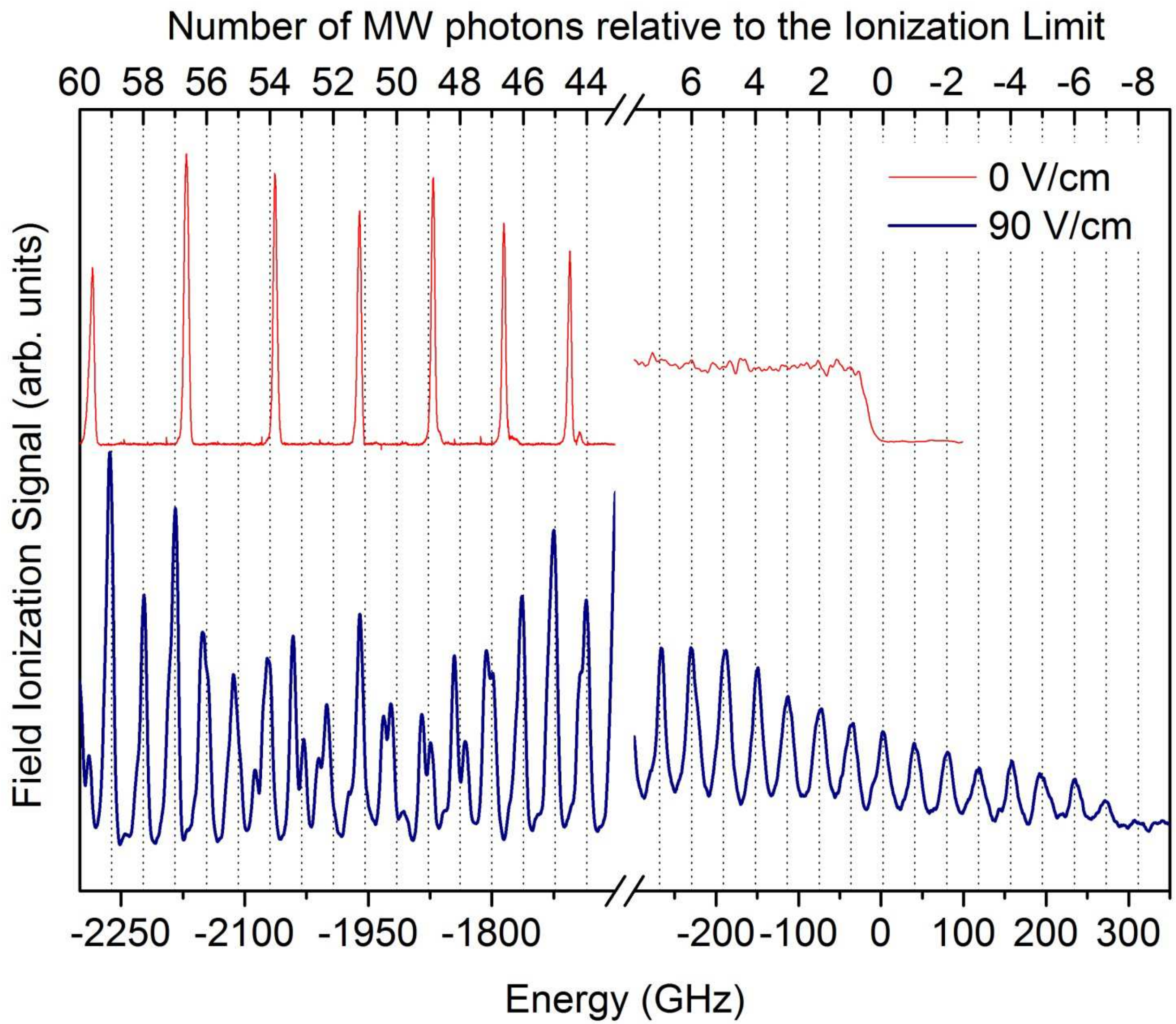
Microwave recombination



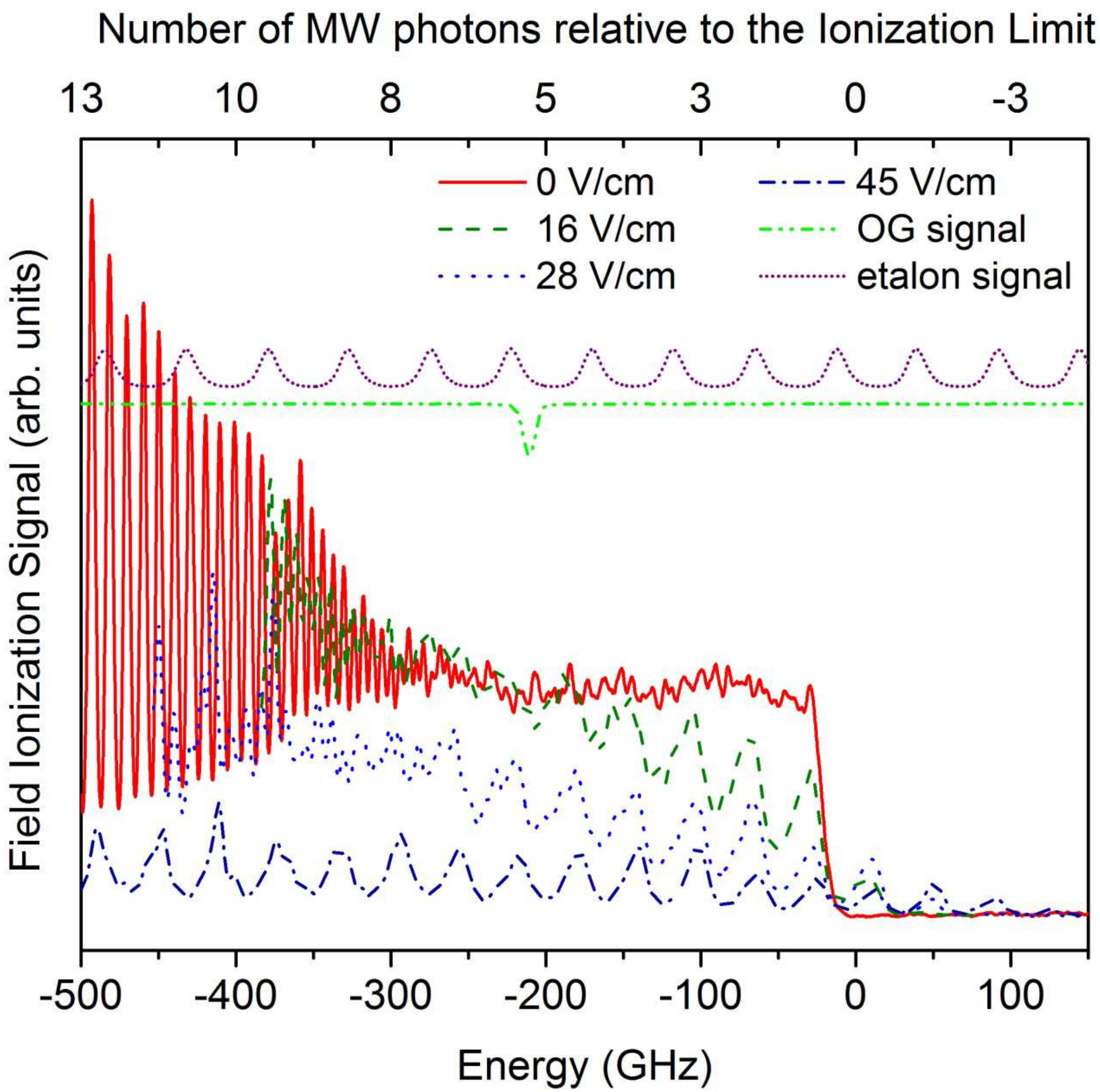
Microwave recombination



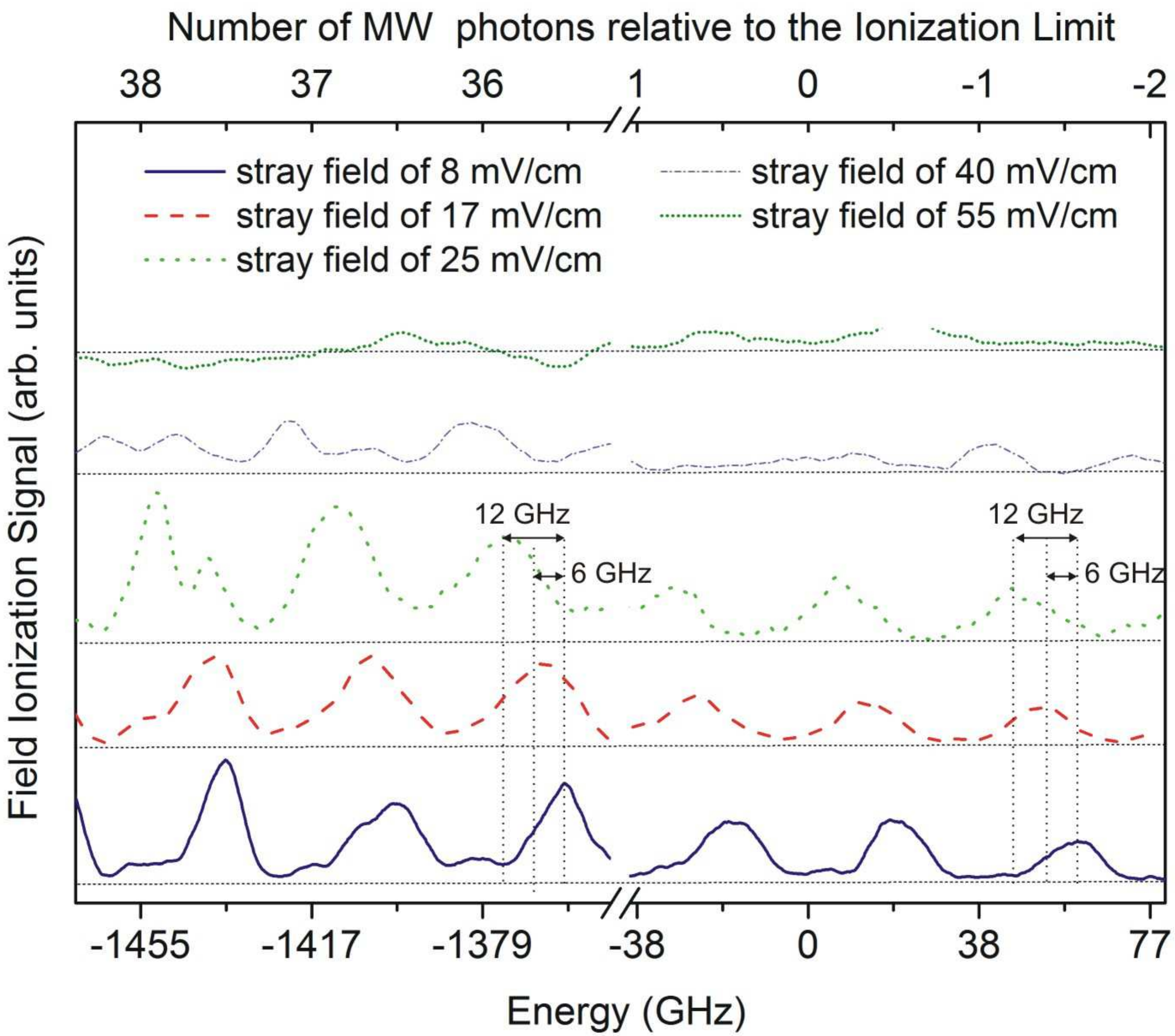
Microwave recombination



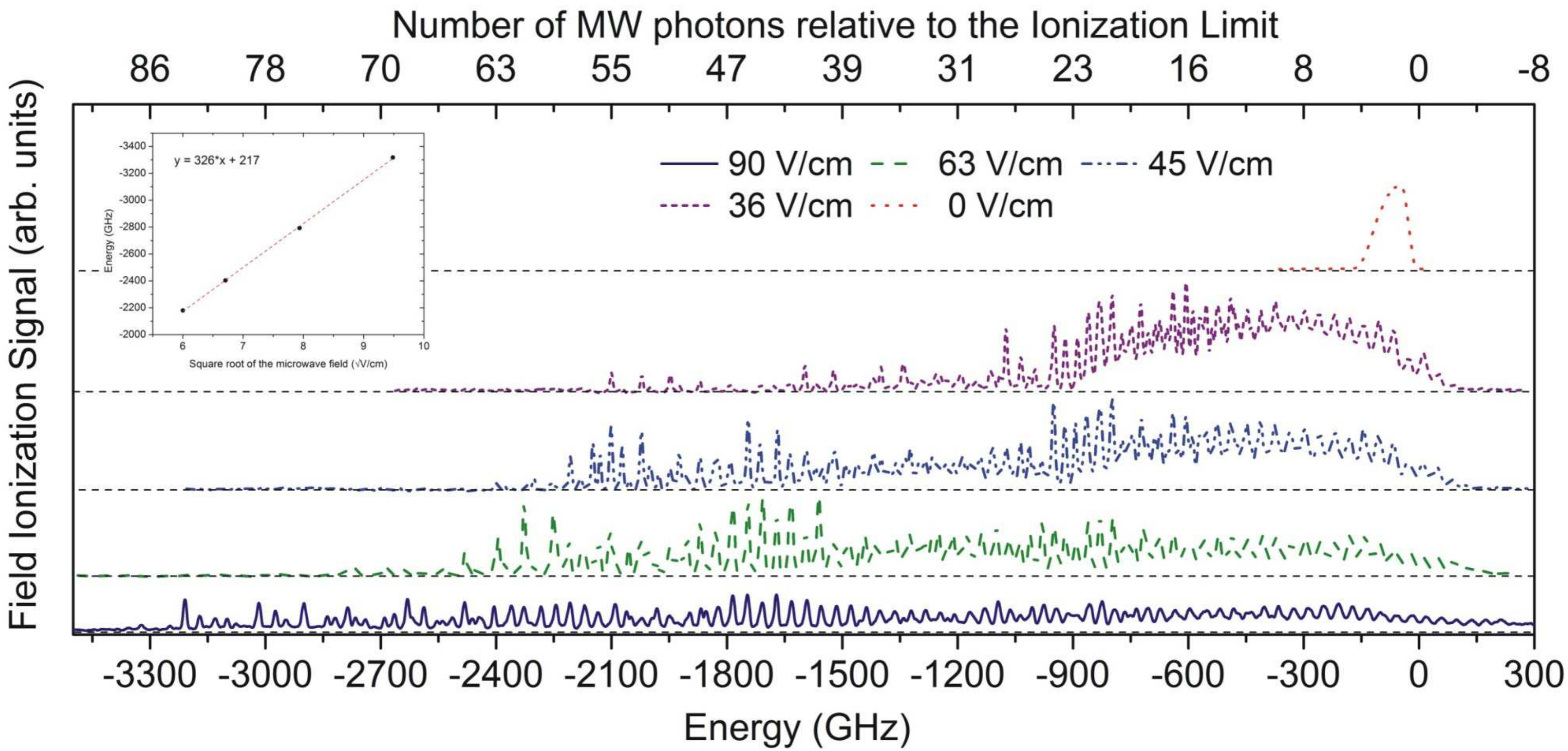
Microwave recombination



Response on stray fields

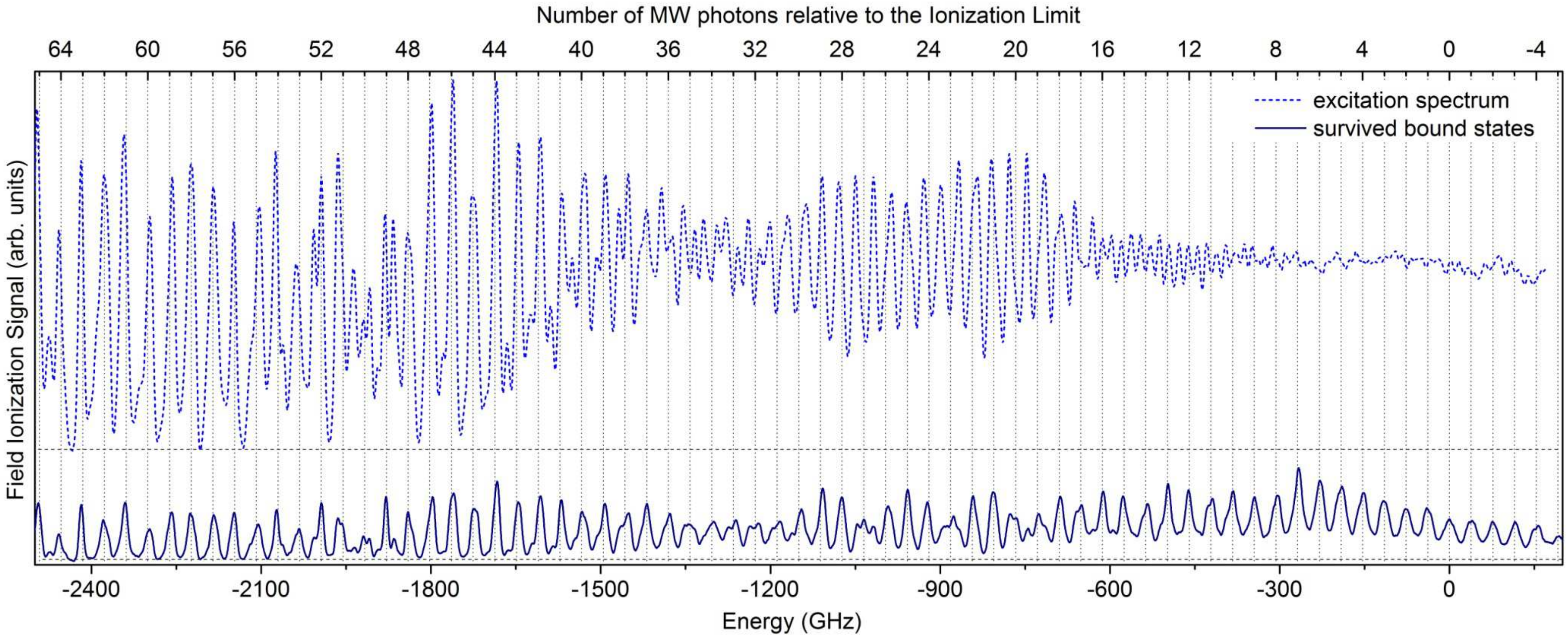


Integrating only over states within 70 GHz of the IL

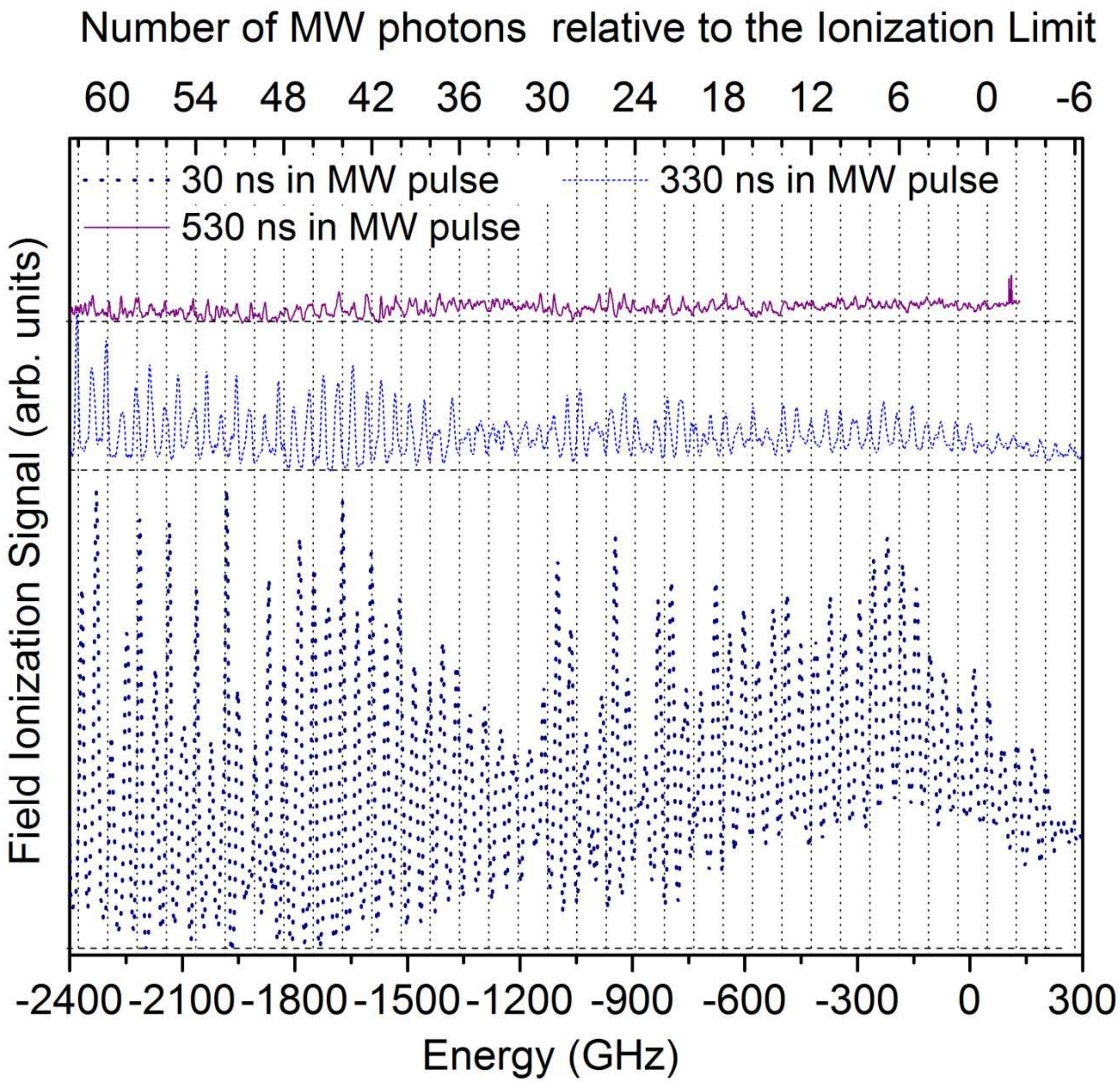


The onset of the MW structure corresponds to $W = 4\sqrt{E}$, twice the energy required to ionize an atom classically.

Total photoabsorption spectrum



Lifetime of the high-lying states



Summary

- We detect approximately 5-10% of the initial population in very high Rydberg states with $n>215$ after the microwave pulse for a wide range of initial binding energies.

- The surviving population of atoms displays a periodic comb structure in energy with a periodicity matching the structure of the 38.3 GHz microwave field.

- A small static field displaces the entire comb to lower energy along with the ionization limit, and the high lying states disappear when the static field exceeds 40 mV/cm.

- The same periodic comb is detected in the excitation spectrum, and the population trapped in the extremely high lying states remain stable in the MW field with a lifetime of 80 ns for a 90-V/cm pulse.

- More to explore: relative phase of microwave and laser fields, structure of each peak in the microwave structure, higher microwave frequency experiment

Thank you for your attention!