Nondispersing Rydberg Wavepackets

Haruka Maeda
Donald Norum
Joshua Gurian
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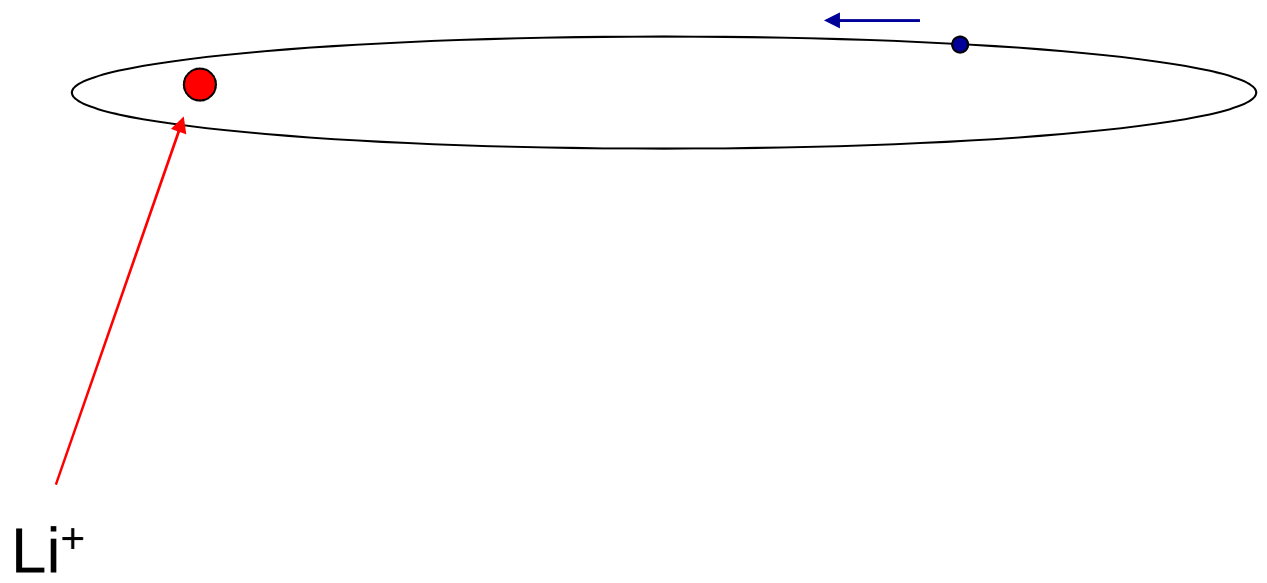
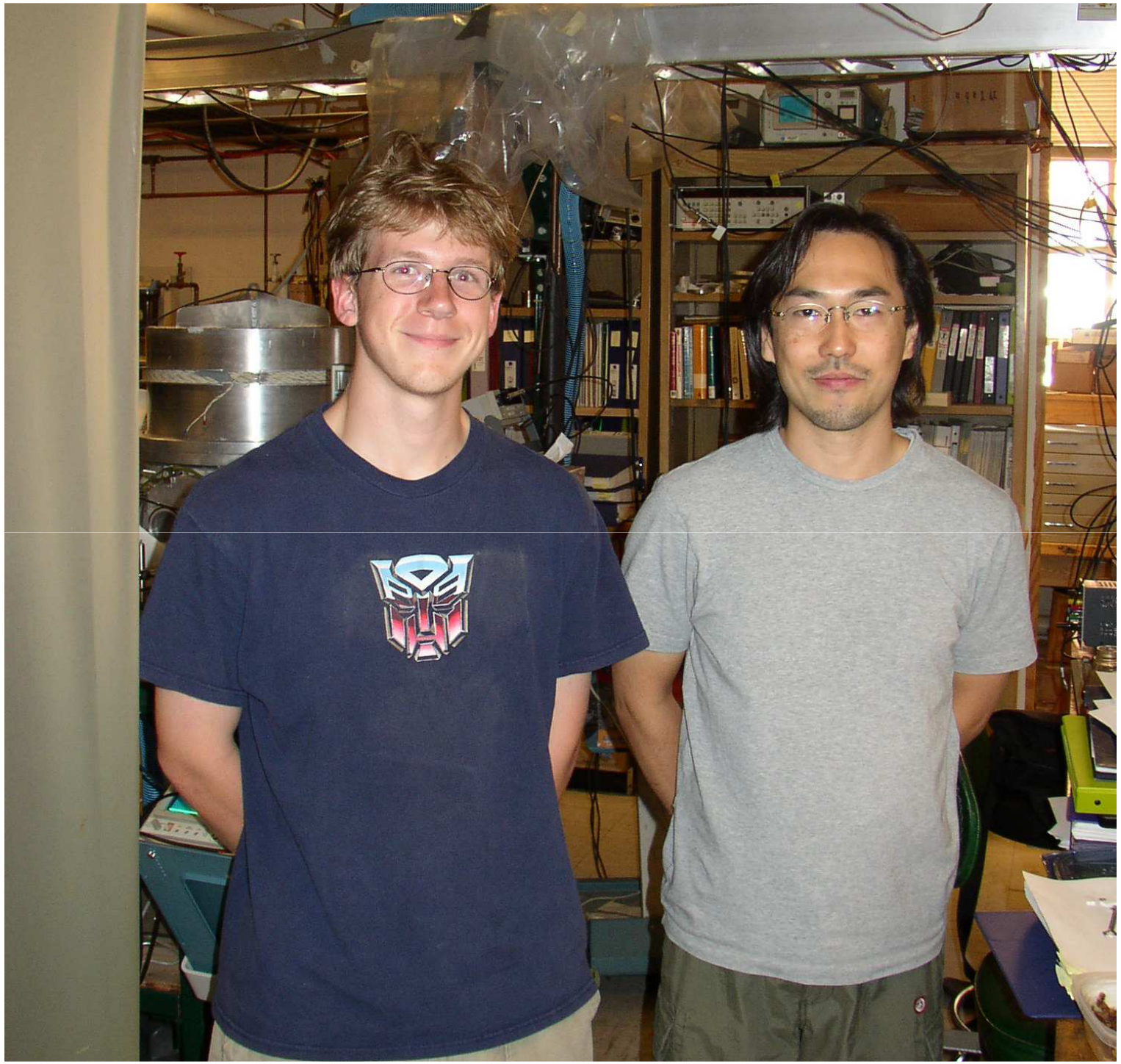
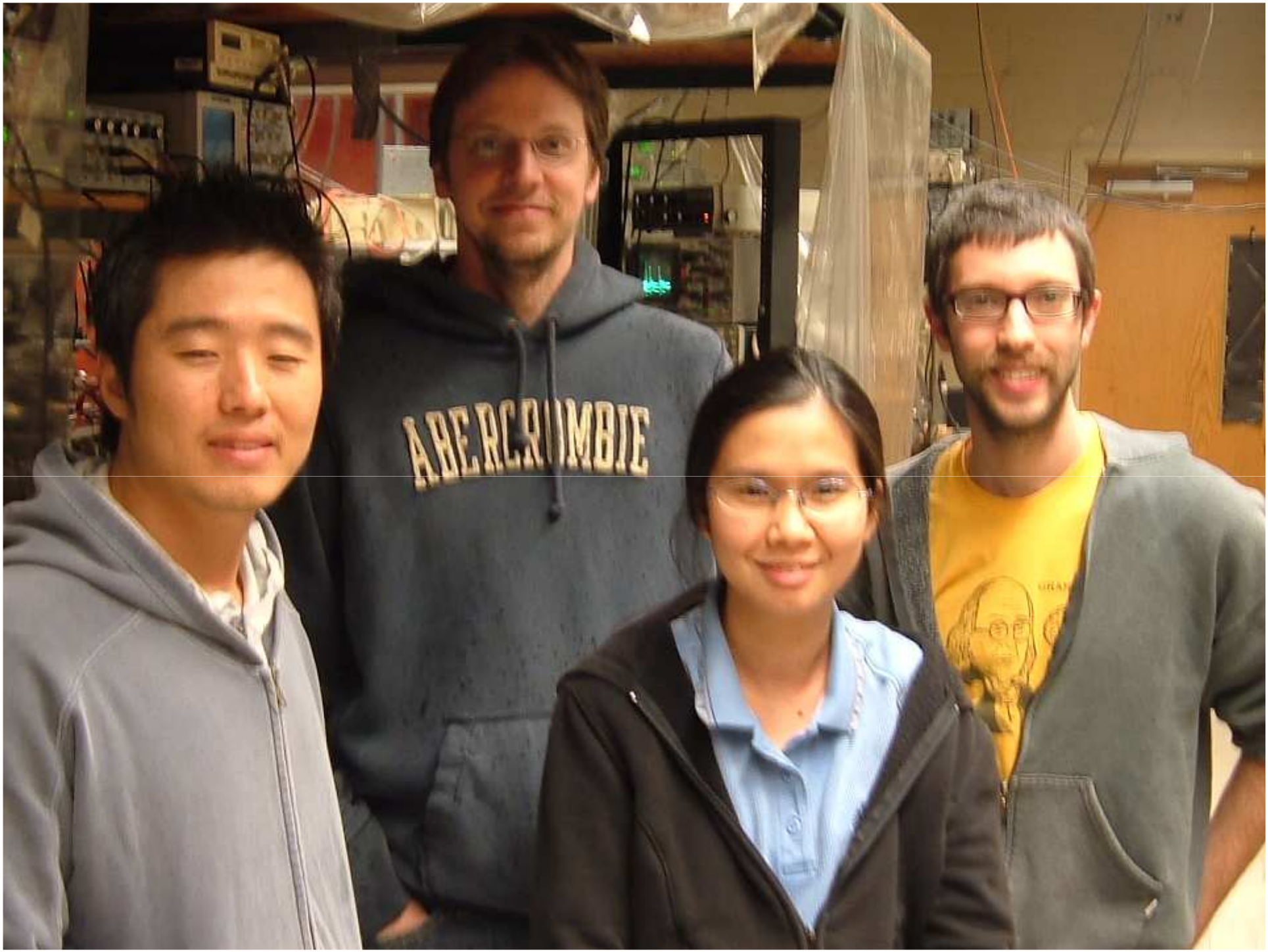
Making and manipulating classical Rydberg atoms






ABERCROMBIE

Rydberg atoms

Wavepackets

Making “classical” atoms which last more than a few orbits

Manipulating these atoms

Bohr wavepackets

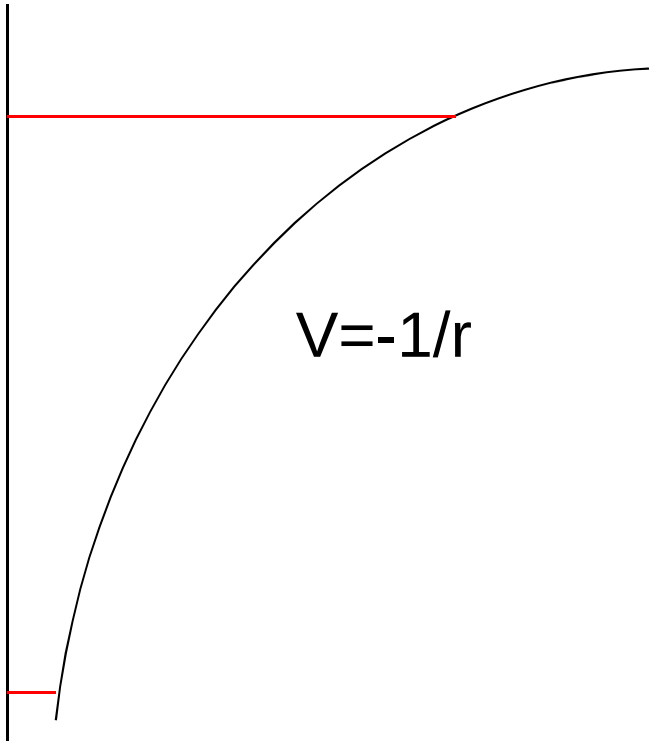
Atomic Units

(correspond roughly to the ground state of hydrogen)

Energy	2Ry=27.2 eV
Length	a_0 Bohr radius 0.53Å
Charge	e electron charge 1.6×10^{-19} C
Mass	m electron mass 9×10^{-31} kg
Field	5.14×10^{9} V/cm

Rydberg Atom

An atom in a state of high principal quantum number n



$W = -1/2n^2$

$\langle r \rangle = n^2$

$V = -1/r$

Large, weakly bound orbits

$n = 30$

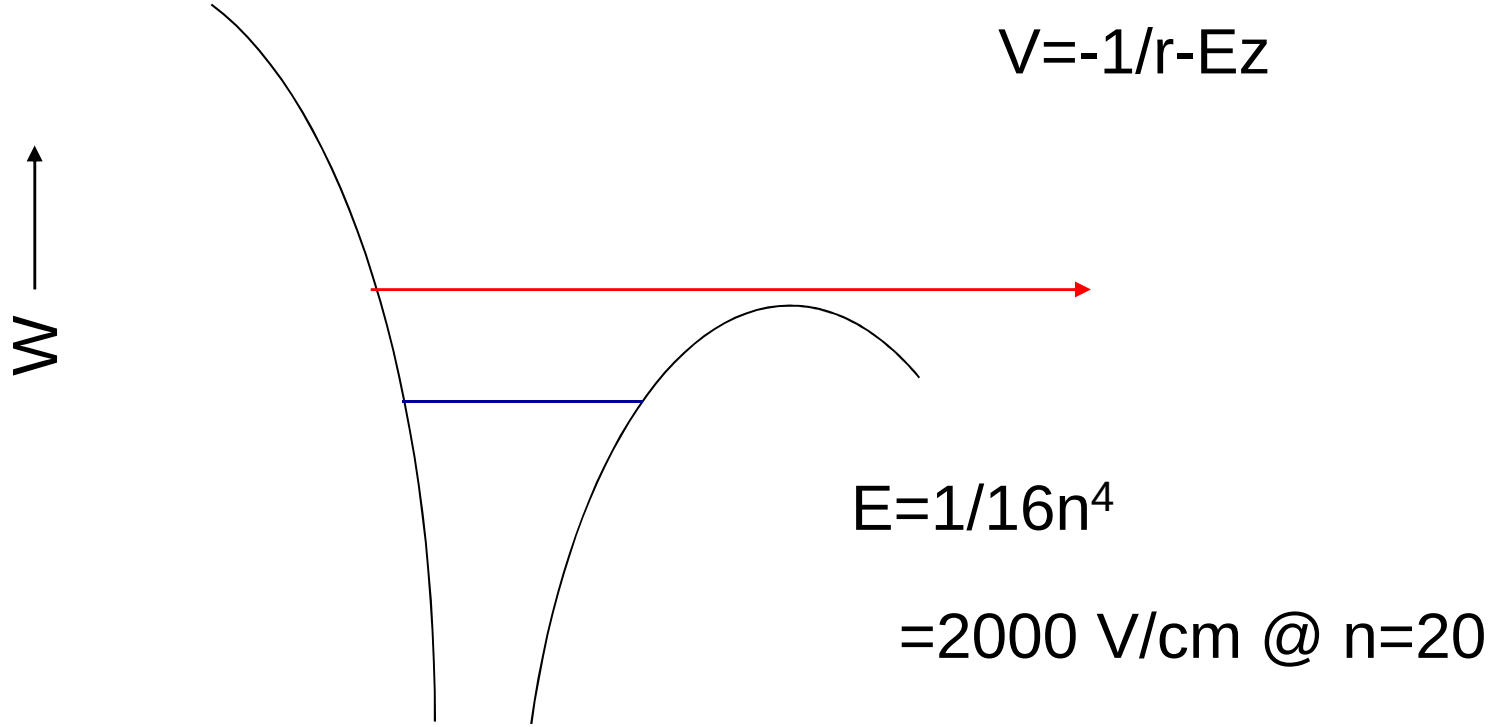
$\langle r \rangle = 900\ a_0$

$\mu = 900\ e a_0$

$W = -120\ cm^{-1} = -10\ meV$

Exaggerated properties allow the realization
Of gedanken experiments.

Detection by field Ionization



Wavepackets

A question undoubtedly posed to Schrodinger:

How do these time independent wavefunctions reduce to classical motion?

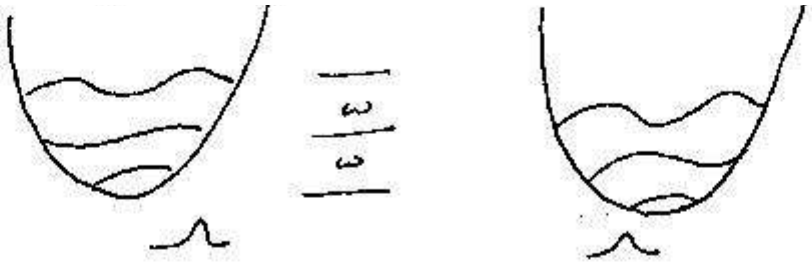
His reply: wavepackets

The Continuous Transition from Micro- to Macro-Mechanics

(*Die Naturwissenschaften*, 28, pp. 664-666, 1926)

Schrodinger's reply: Construct wave packets, coherent superpositions of energy eigenstates. His example was the harmonic oscillator.

$\omega t = 0$ $\omega t = \pi$



$$\omega_1 = 0$$
$$\omega_2 = \omega$$
$$\omega_3 = 2\omega$$

$$\Psi(r,t) = a_1\psi_1 e^{-i\omega_1 t} + a_2\psi_2 e^{-i\omega_2 t} + a_3 e^{-i\omega_3 t} \ldots$$

Motion occurs at the frequency equal to the level spacing.

Lorentz – Only in the harmonic oscillator are the levels evenly spaced. In all other systems the dispersion in the energy level spacings destroys the localization of the wavepacket.

Classical Limit of the Hydrogen Atom*

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University of Washington
Seattle, Washington 98195
(Received 20 November 1972; revised 15 December 1972)

A wavepacket solution for the hydrogen atom in the region of large principal quantum number n is constructed. This wavepacket follows a classical circular orbit. It has a width on the order of $n^{-1/2}$ times the size of the orbit.

servation of energy and angular momentum forbid any transverse spreading of the wavepacket as time passes. On the other hand, there is no constraint to it spreading out along the orbit. Indeed, an optimally prepared packet will spread along a fraction of the orbit that is on the order of (number of revolutions/n)$^{1/2}$. For microscopic systems (such as the hydrogen atom itself) excited to macroscopic dimensions, $n \sim 10^4$, and the width and spreading of the wavepacket are

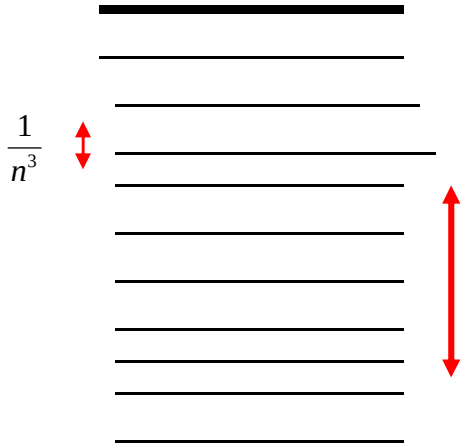
It is possible to make wave packets with negligible dispersion
Using high n Rydberg states.

The level spacings are approximately constant.

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

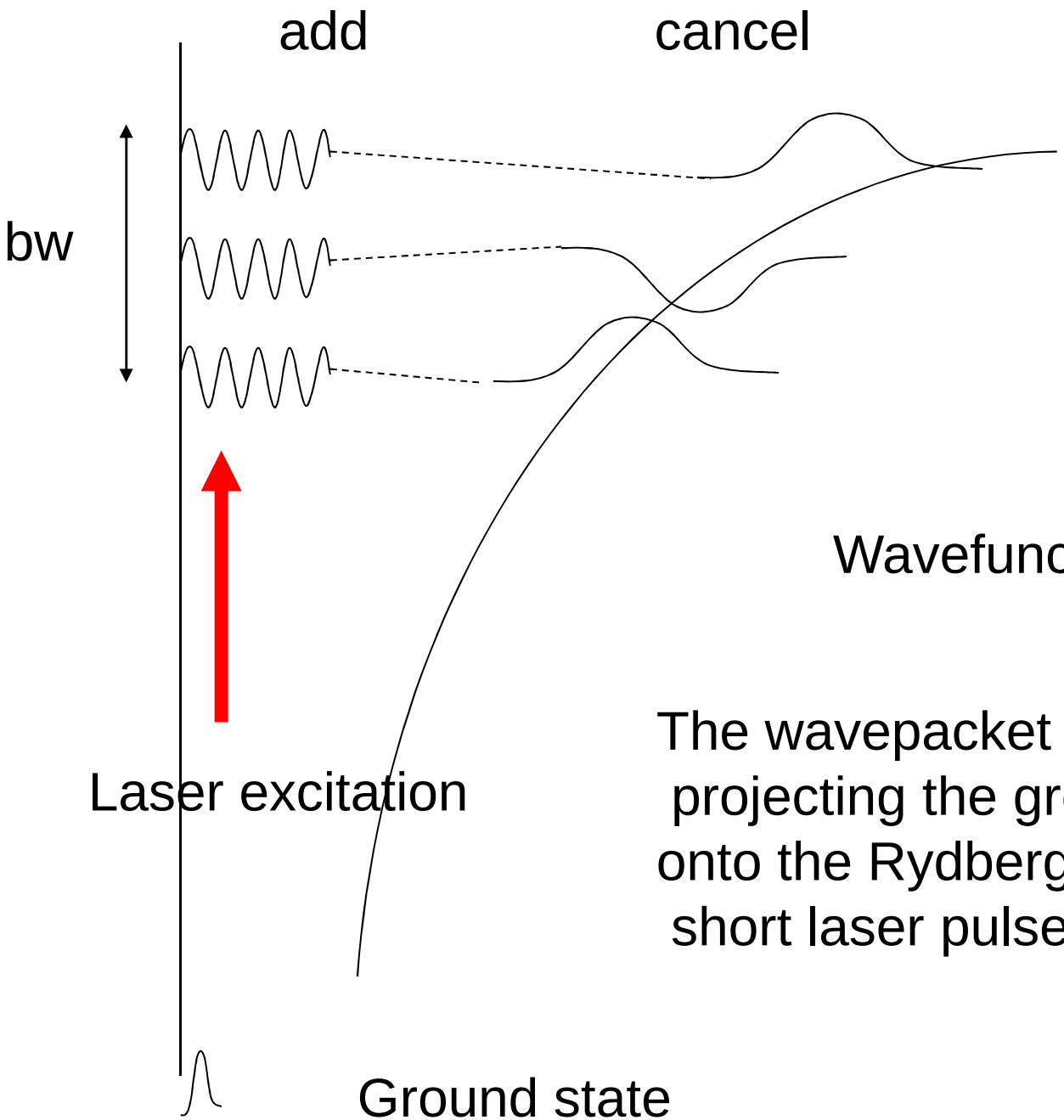
$$\frac{dW}{dn} = \frac{1}{n^3}$$

$$\frac{d(1/n^3)}{dn} = \frac{3}{n} \bullet \frac{1}{n^3}$$



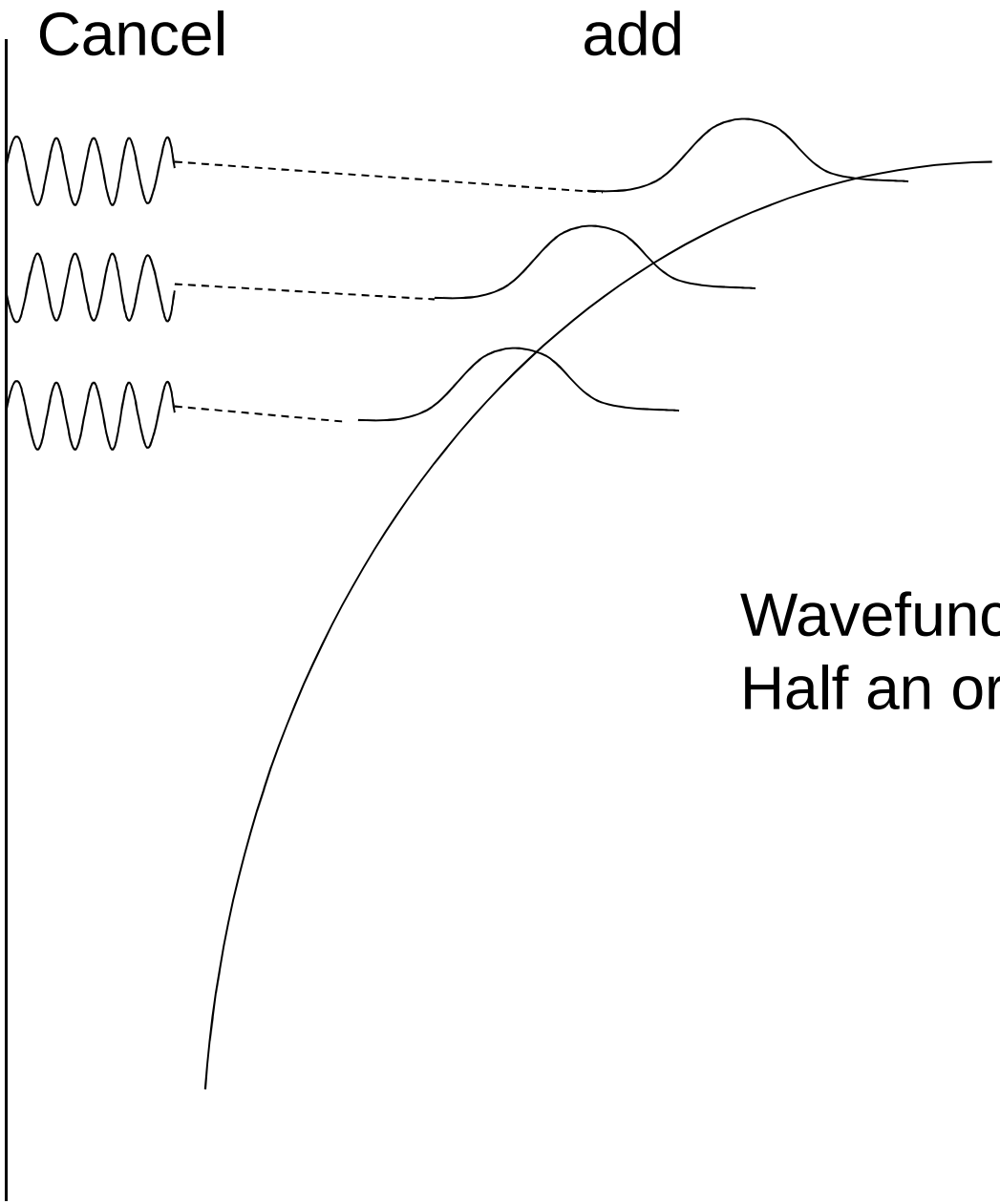
At n=60 3/n=5%, so a wavepacket containing 5 states should remain localized for about 5 orbits.

The superposition is made with a short laser pulse.

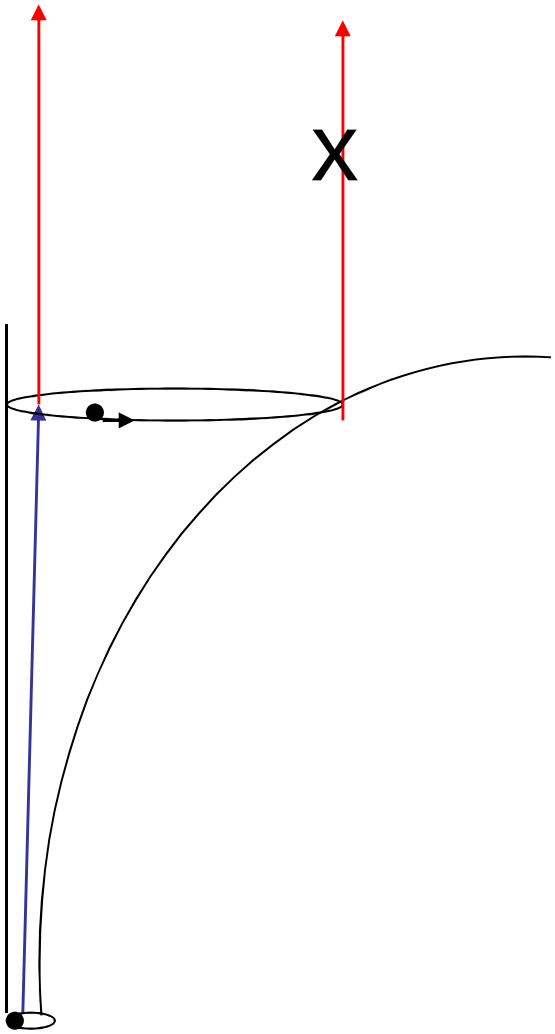


Wavefunctions at t=0

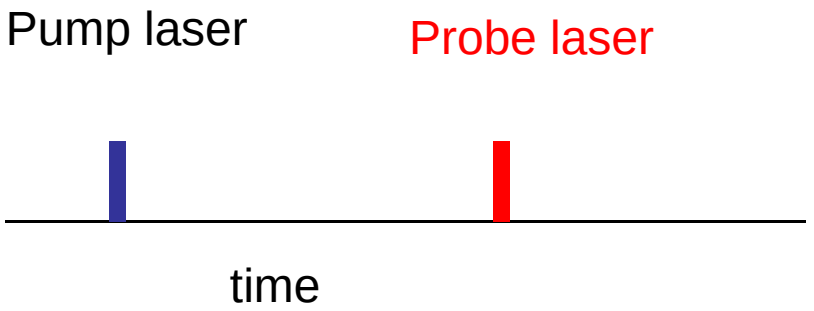
The wavepacket is made by projecting the ground state onto the Rydberg states with a short laser pulse.



Wavefunctions at $t=\pi/n^3$
Half an orbital period later



Pump –Probe Experiments with a ps Laser
Stroud, Rochester 1989
van Linden van den Heuvell, Amsterdam 1988
Typically 5 state wavepackets



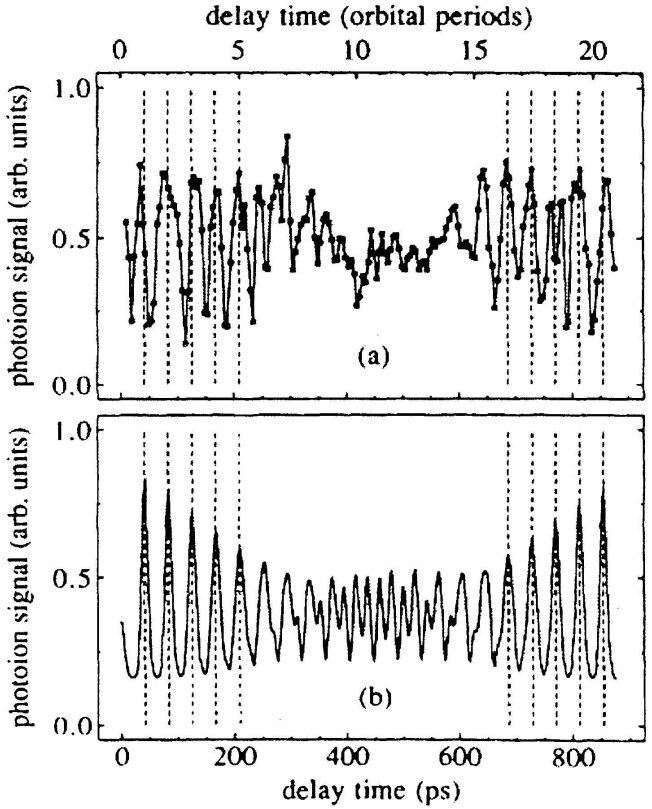
Photoionization of the wavepacket only occurs
At the ion core.

Wavepacket Collapse and Revival
Yeazell, Mallalieu, and Stroud

As predicted by Lorentz, the dispersion in the energy level spacings destroys the localization of the wavepacket after six orbits, but since there is a finite number of states, it revives.

Even in the best of cases, though, there are only a few revivals, due to other forms of dephasing.

Once the phase coherence is lost there is no motion of the probability.



How can we make the wavepacket last for many orbits?

Add a weak field oscillating synchronously with the orbit

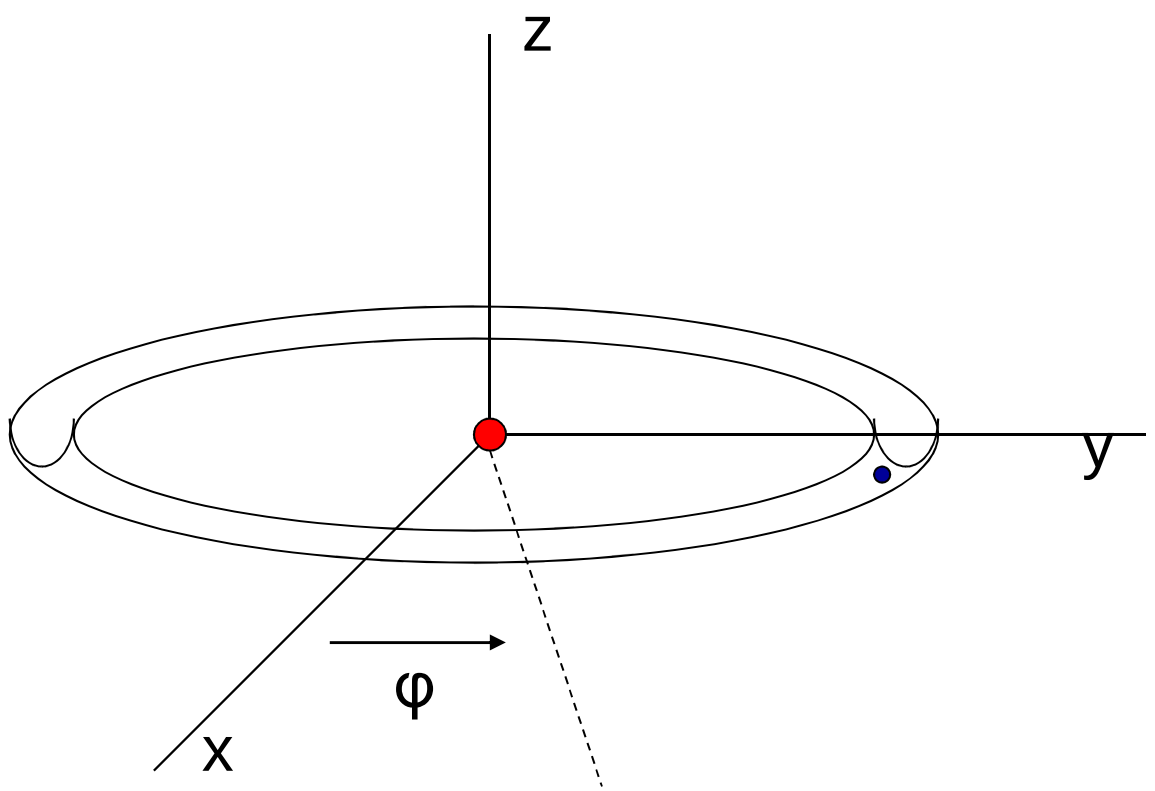
Proposals
Circularly polarized microwaves
Bialynicki-Birula, Kalinsky, and Eberly 1994
Farrelly and Uzer 1995

Linearly polarized microwaves
Buchleitner and Delande 1995

Trains of half cycle pulses
Reinhold and Burgdorfer
realization by Dunning 2004

Such wavepackets are called non dispersing wavepackets.

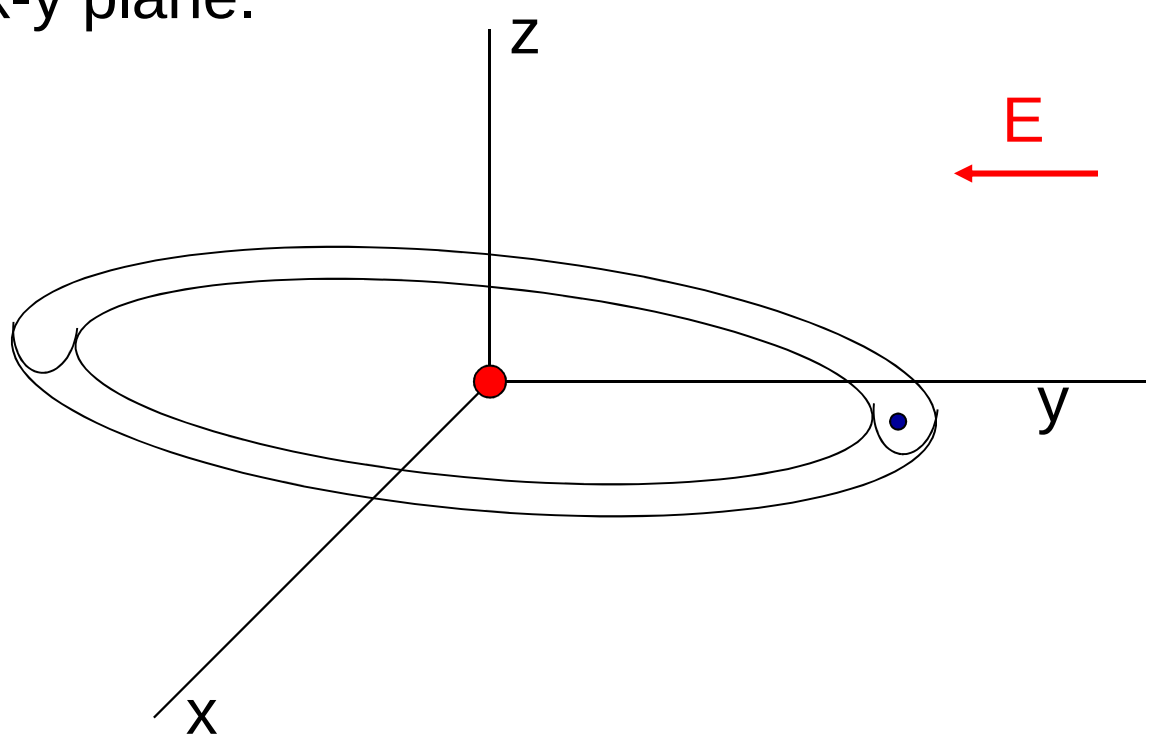
Recipe of Bialynicki-Birula, Kalinsky, and Eberly



Start with a circular eigenstate.

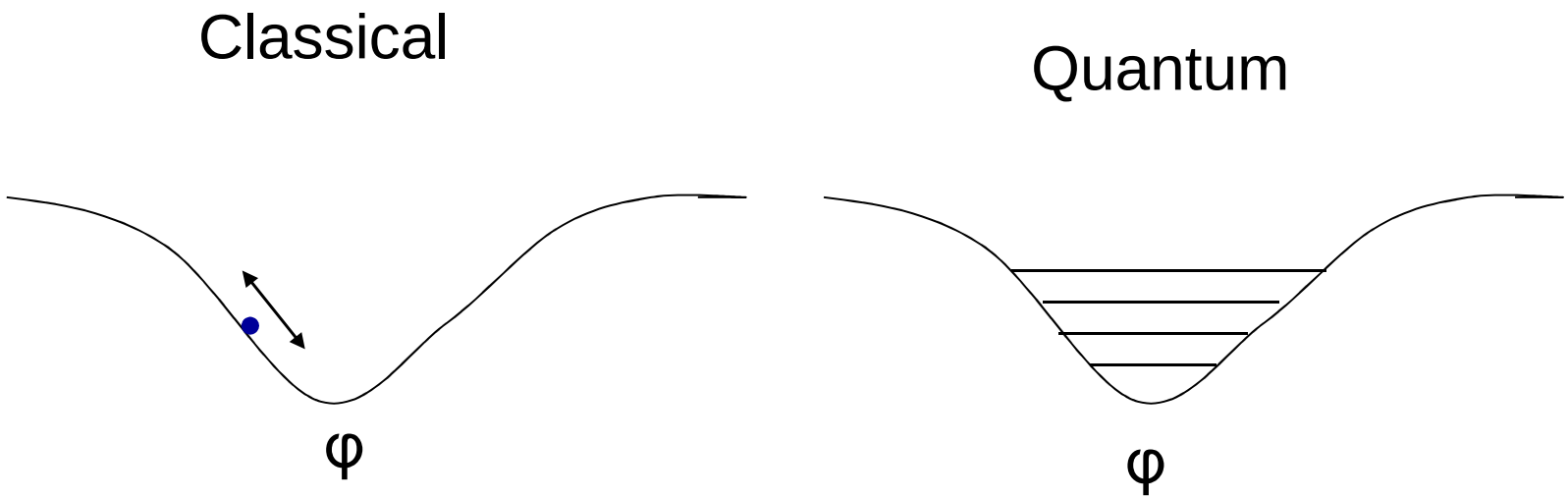
The electron is confined to a trough,
but with no φ localization

Add a circularly polarized field rotating at $\omega=1/n^3$ in the x-y plane.



There is a circulating minimum in the potential.

In the frame rotating at ω there is a static potential well.

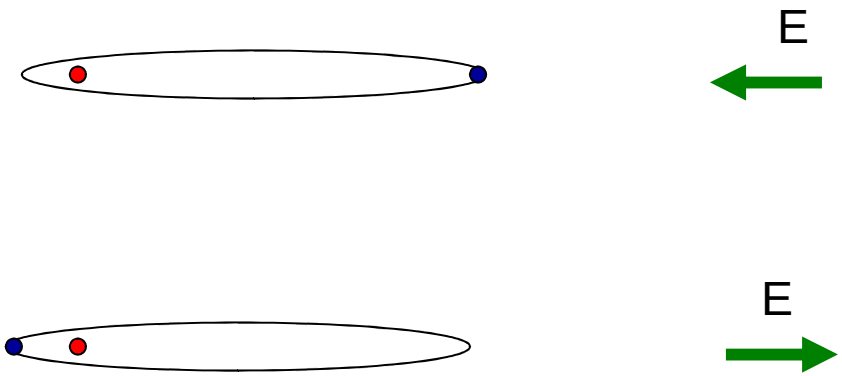


Classically, the electron oscillates between leading and lagging the field.
The quantum states are like harmonic oscillator states.

The problem….

Start with a circular state (high ℓ, high m)

Making nondispersing wavepackets with linearly polarized microwaves
a one dimensional problem-Buchleitner and Delande



For both circular and linear polarization the electron's
Motion is phase locked to the field.

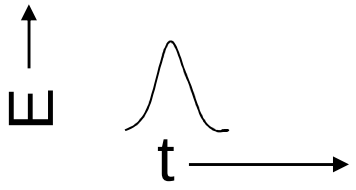
How do you detect that the electron's motion is phase locked?

Detect the time varying momentum using a half cycle field pulse (HCP)
Jones and Bucksbaum

Momentum analysis with a unipolar HCP - Jones

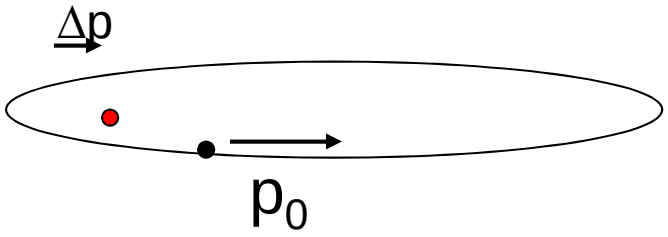
Ionization occurs by energy transfer, not field ionization!

$T_{HCP} << T_{orbit}$



$$\Delta p = \int E dt$$

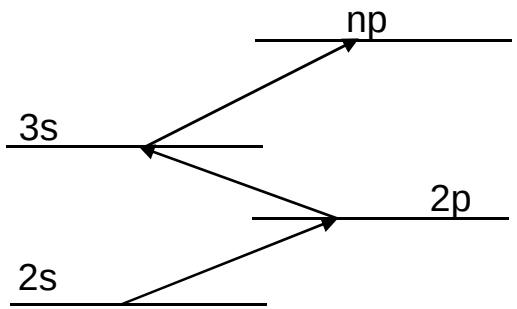
Ionization occurs if the energy transfer from the HCP exceeds the binding energy.



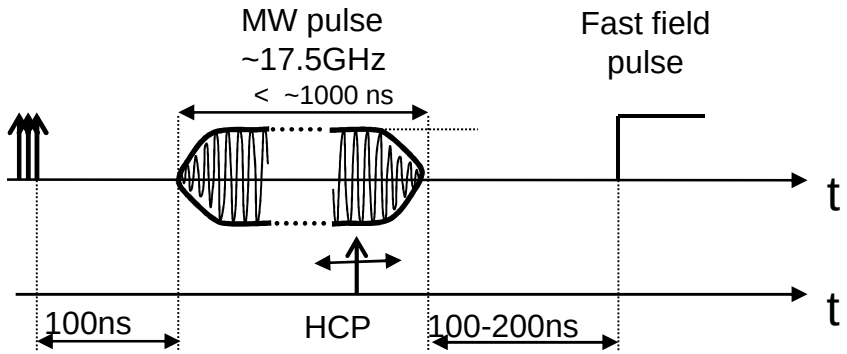
$$\Delta W = \frac{(p_0 + \Delta p)^2}{2} - p_0^2$$

$$\Delta W = \overline{p}_0 \cdot \Delta\overline{p} + (\Delta p)^2$$

Choose HCP so ionization occurs when the electron is moving in the direction of Δp.

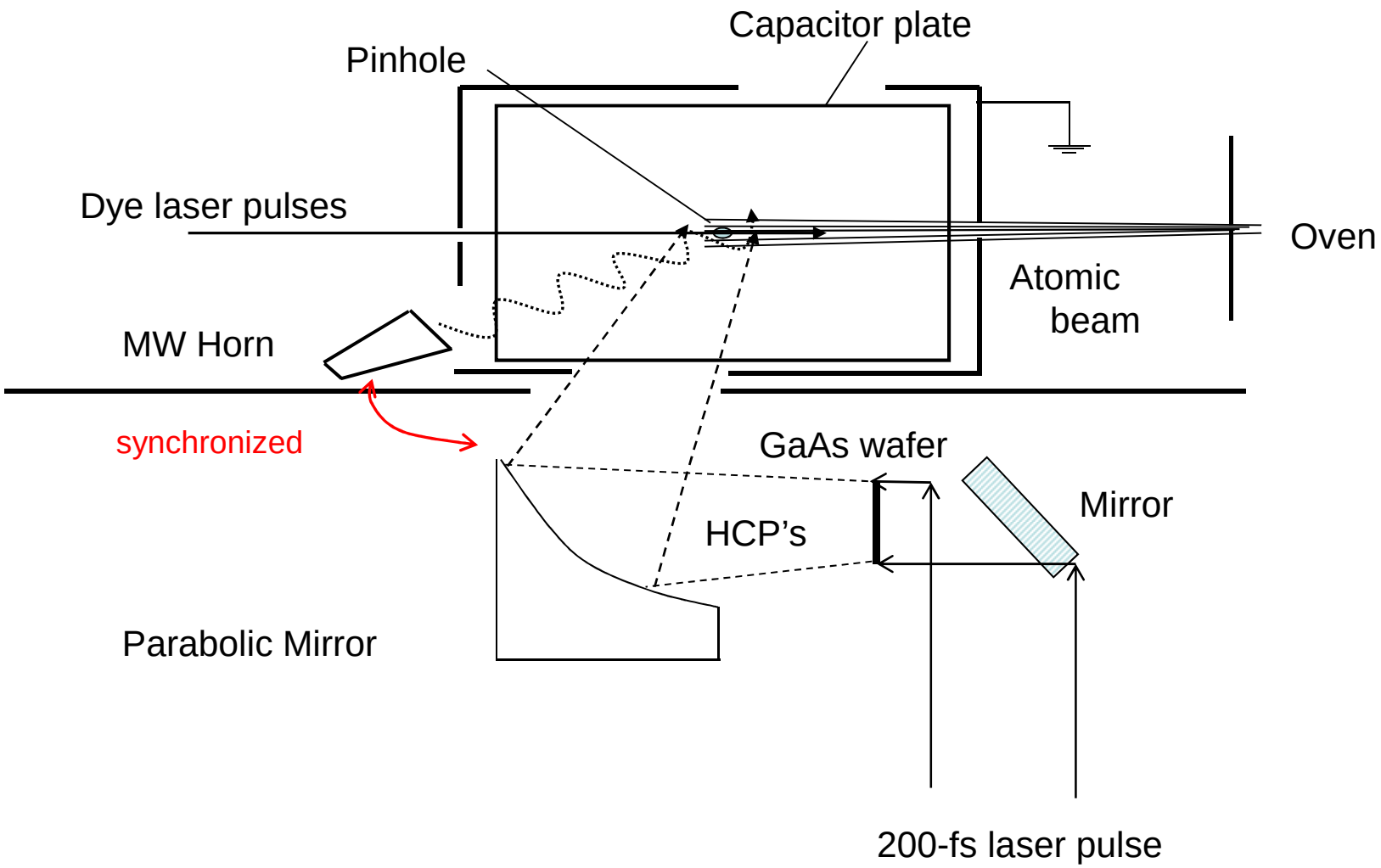


Li

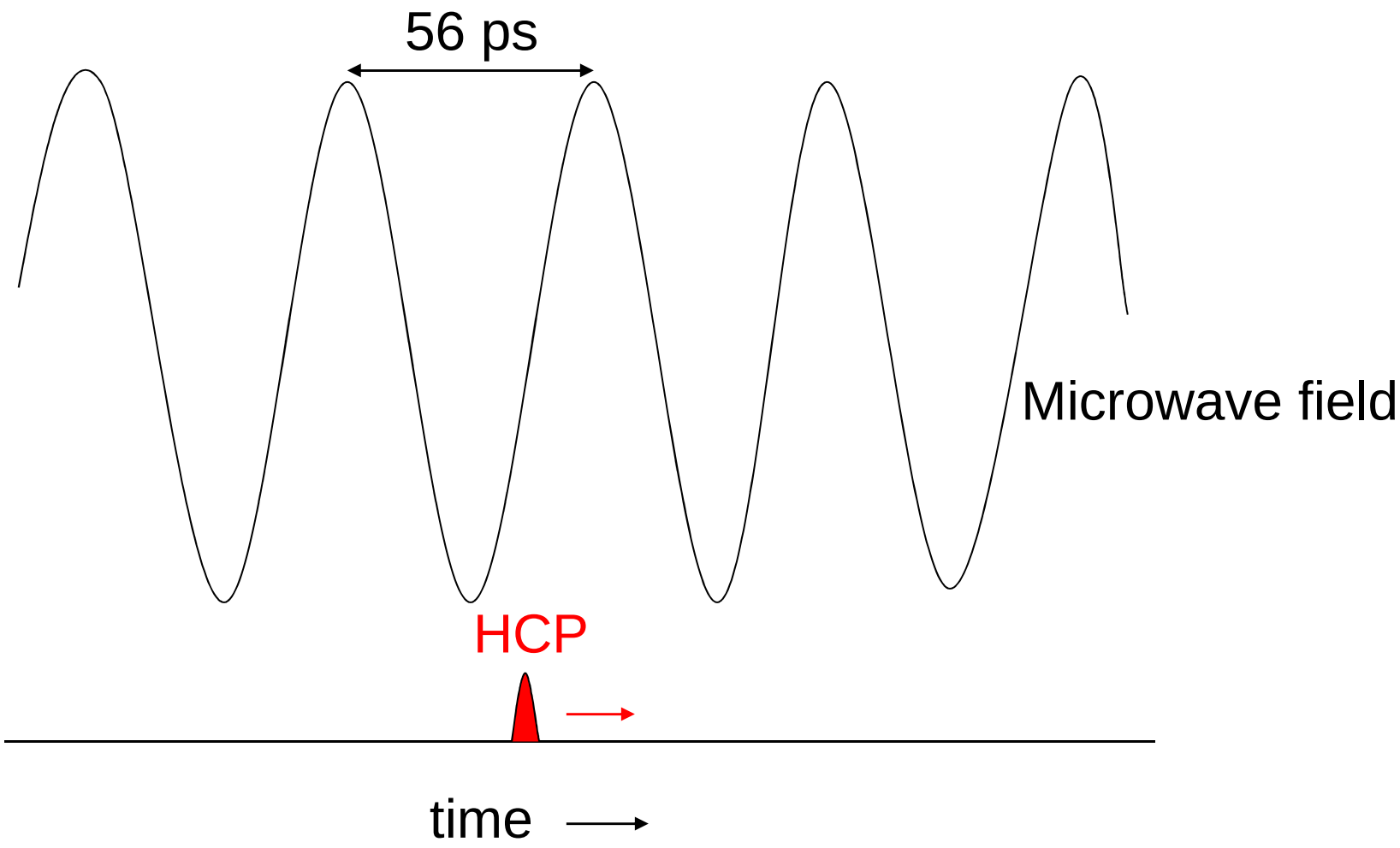


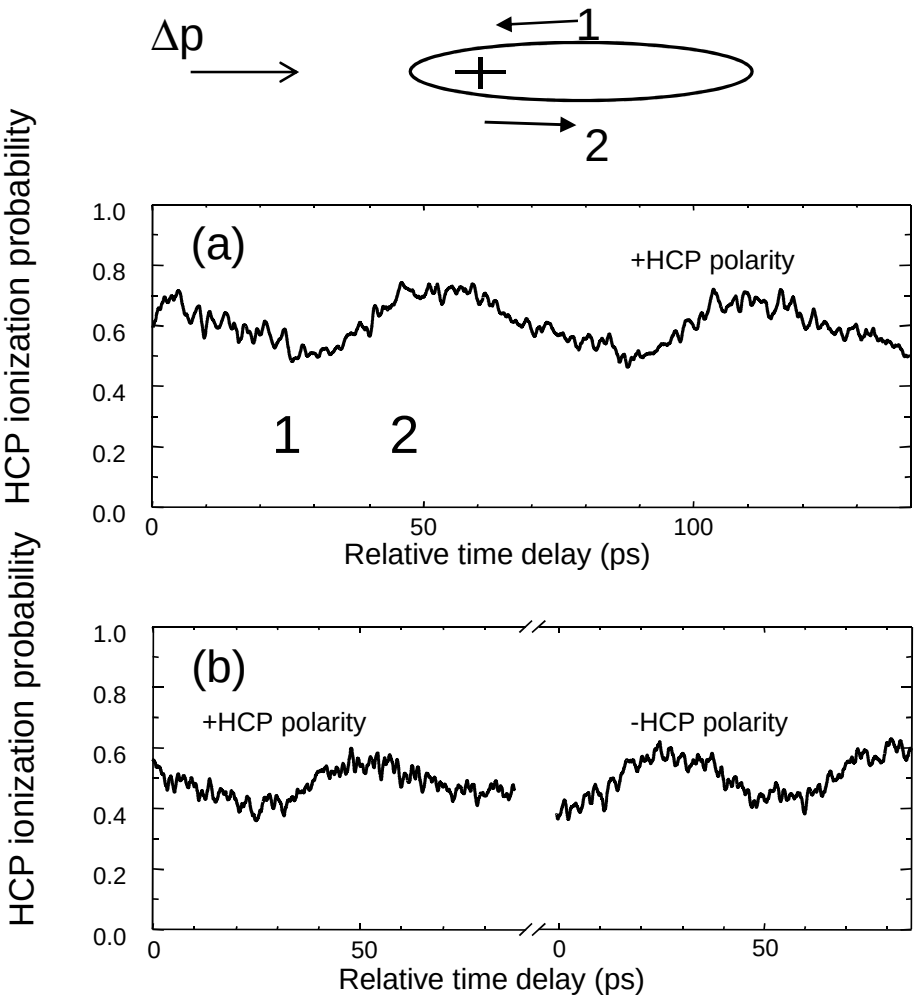
Preferential ionization by half cycle pulse (HCP) depending on electron's momentum (Jones)

collect ions vs time of HCP relative to microwave field


Capacitor plate
Pinhole
Dye laser pulses
Oven
Atomic
beam
MW Horn
synchronized
GaAs wafer
Mirror
HCP's
Parabolic Mirror
200-fs laser pulse

Detect ionization vs HCP delay



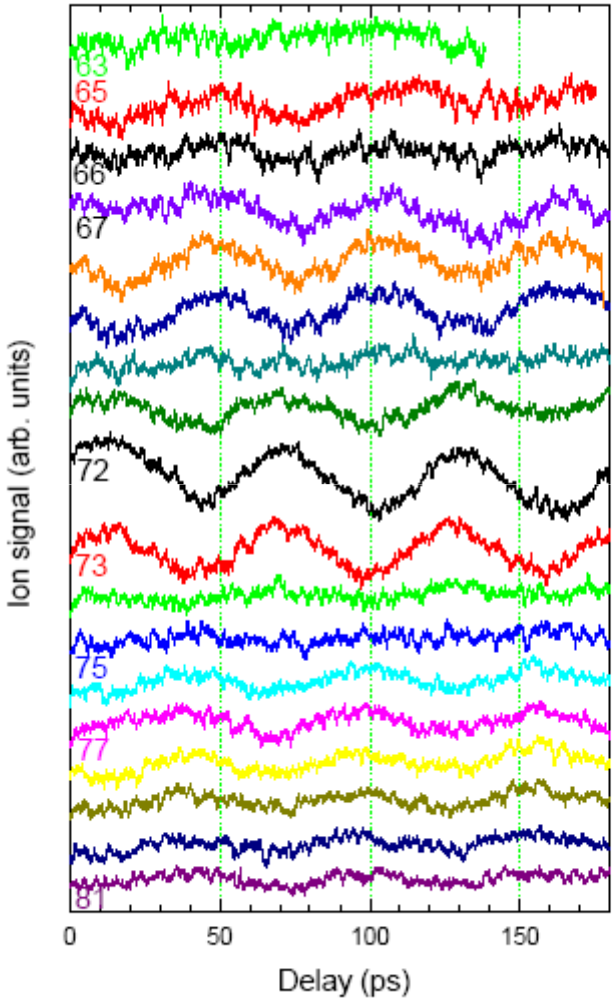


17.528 GHz (56 ps) 1 V/cm

100 ns after MW pulse $E = 0.005/n^4$

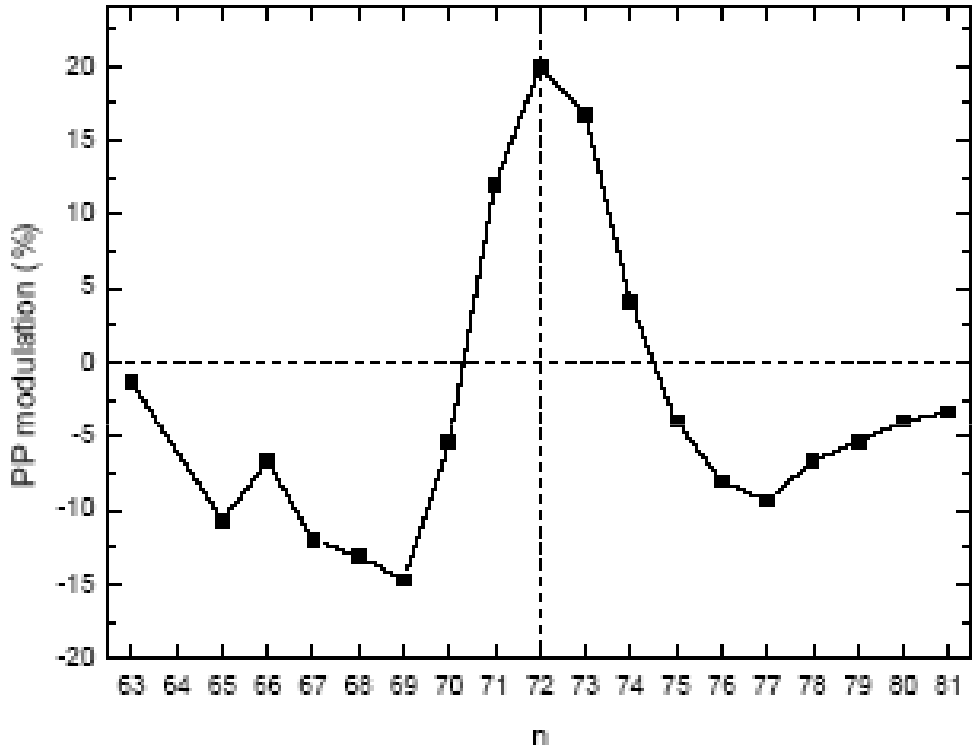
10 times reduction in signal with HCP $\perp$ E_{MW}

Ionization signals vs n with a 17.5 GHz field of 4 V/cm resonant at n=72



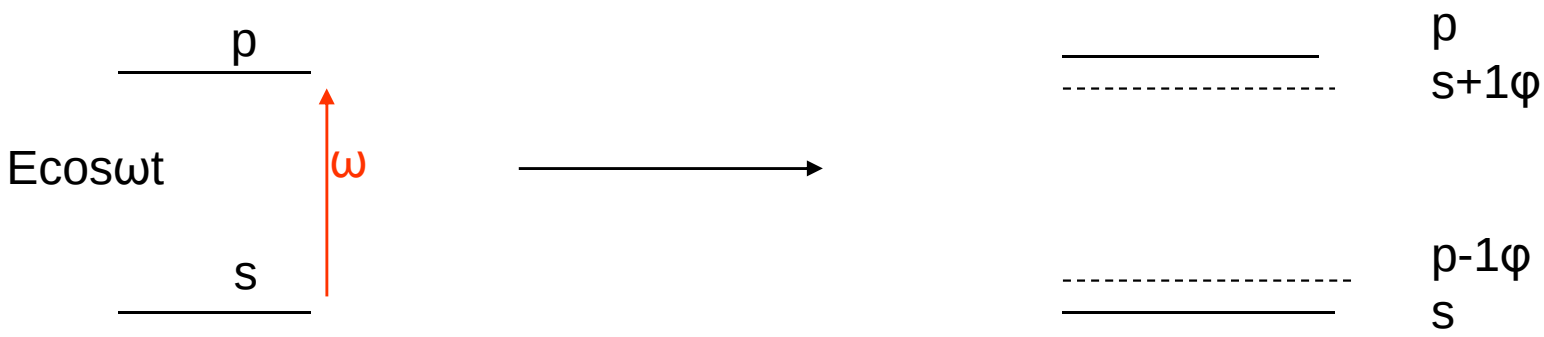
A phase reversal with n!

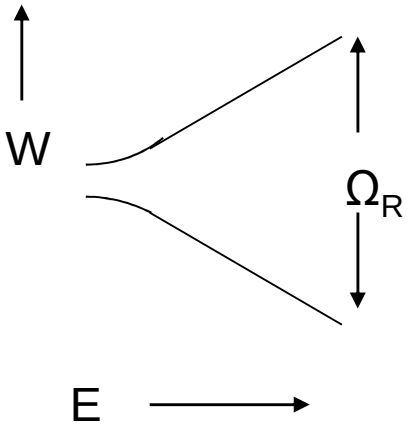
HCP ionization signal vs n at 17.5 GHz 4 V/cm



Quantum Floquet approach and classical phase locking

Floquet eigenstates are periodic (2π/ω) and by definition nondispersing.





(s+1φ) + p μ aligned opposite E

(s+1φ) – p μ aligned with E

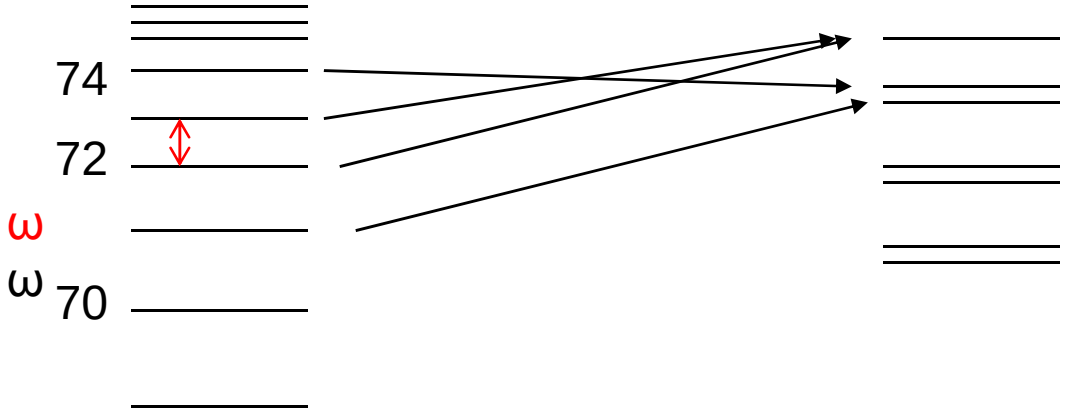
•In both states the dipoles are phase locked!

Floquet energies of the one dimensional Rydberg atom in a 17 GHz field

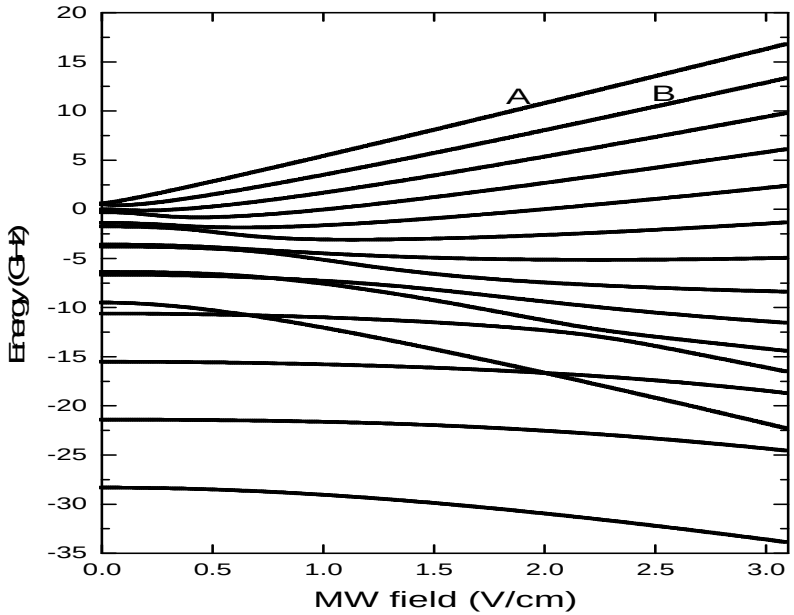
$W_{Fn}=W_n-(n-72)\omega$

Normal energies

Floquet energies

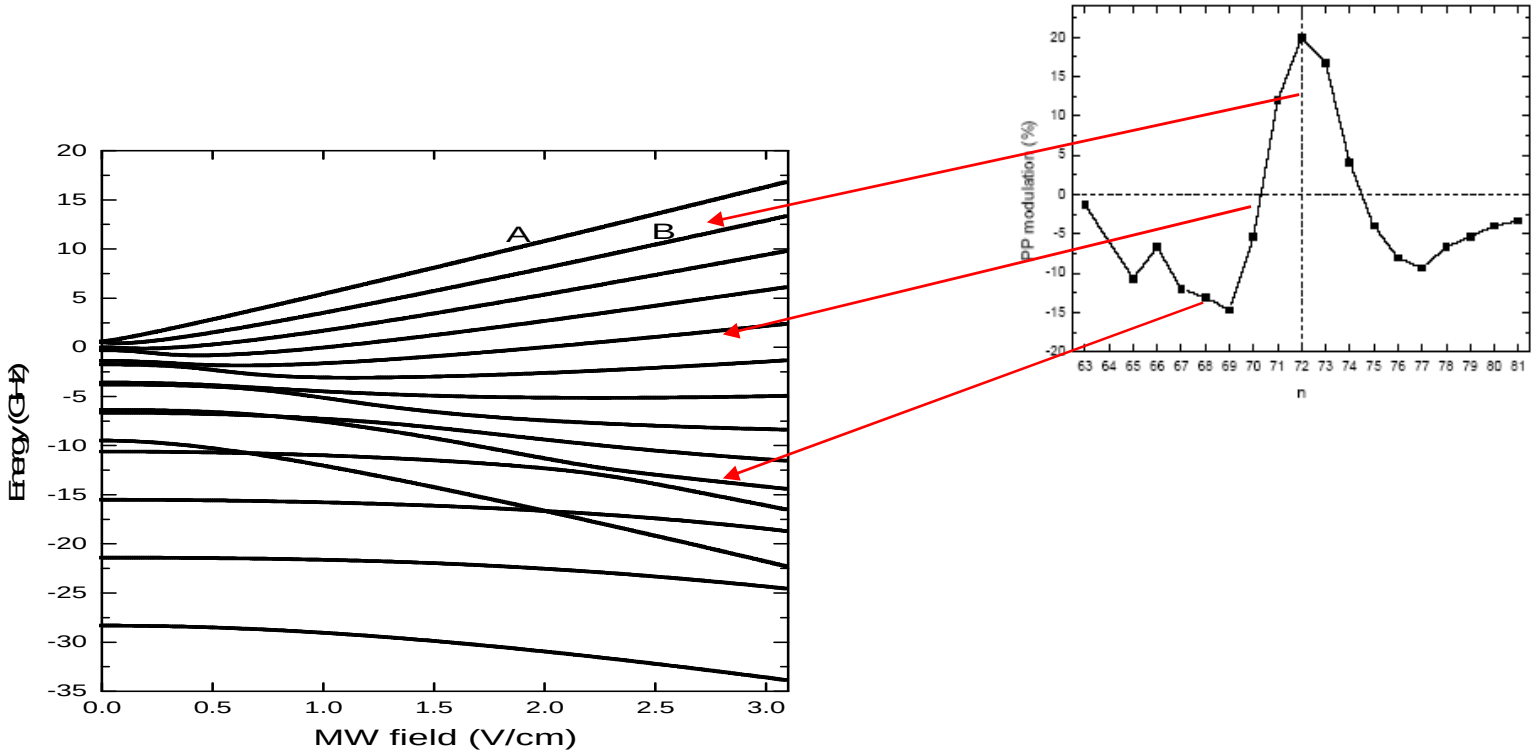


Floquet Energies of the States near n=72



Different initial states lead to Floquet states with different dipoles.
All oscillate at the microwave frequency.

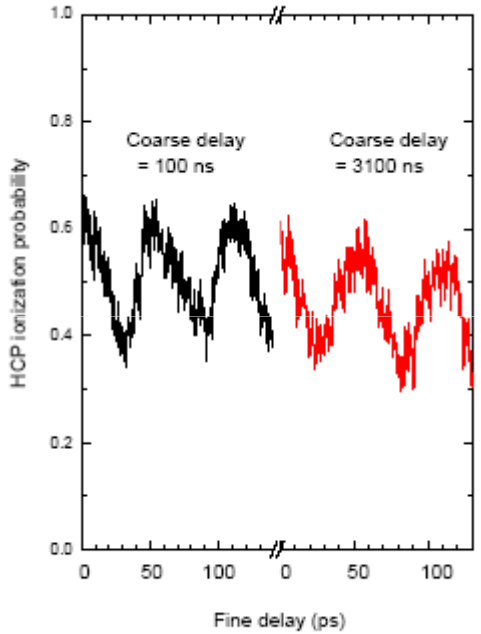
Floquet Energies of the States near n=72



Different initial states lead to Floquet states with different dipoles

These “classical” atoms are “eternal” Buchleitner and Delande

55,000 orbits, 3.1 μs

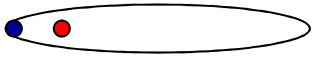


The atoms are impervious to dispersion and technical dephasing.

Why do these wavepackets live so long?

Normal radial wavepacket

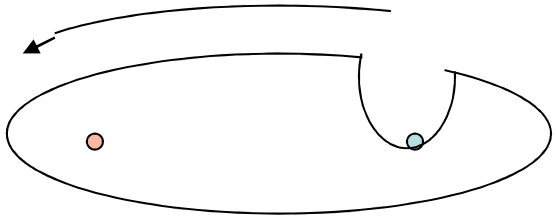
$\Psi = a\Psi e^{-i\omega at} + b\Psi e^{-i\omega bt} + c\Psi e^{-i\omega ct} \ldots$



The difference is only in the phases!

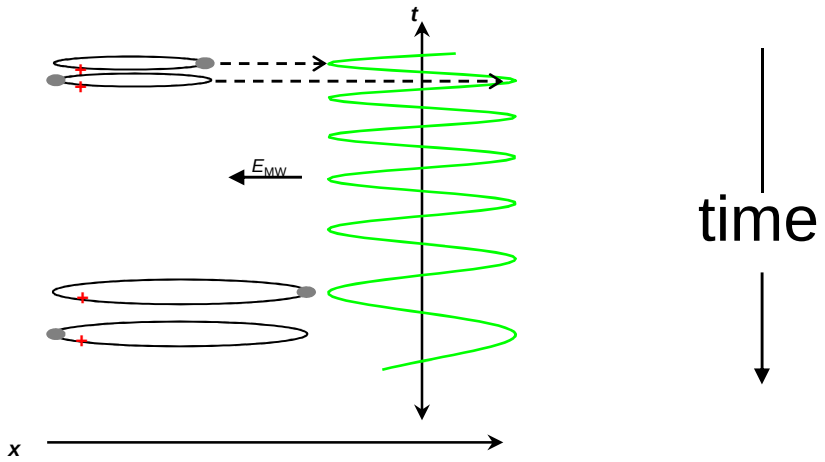
For nondispersing wavepackets there is a difference in the energies since μ is aligned with or against the field.

If the electron is phase locked to the microwave field, can we speed it up or slow it down by chirping the microwave frequency ω?
first suggested by Kalinski and Eberly



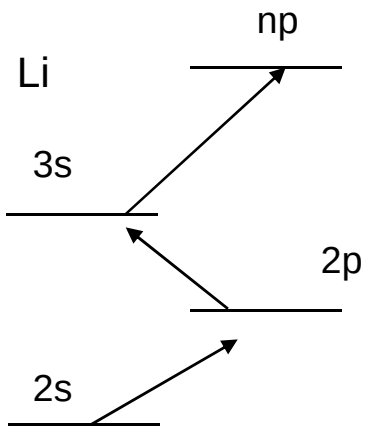
Since $\omega = 1/n^3$, this amounts to changing n or the binding energy.

Realization with linearly polarized microwaves
Moving n=70 atoms to n=80

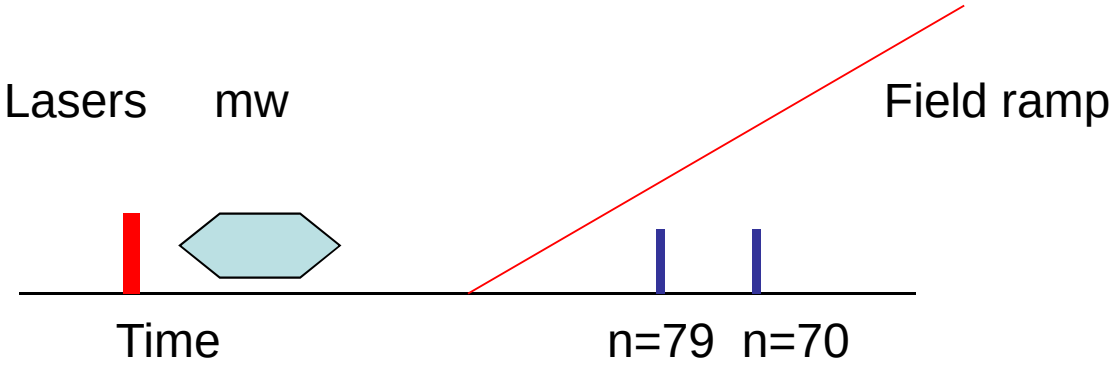


The orbital frequency decreases, n increases, and the orbit becomes larger and more weakly bound.

The electron's motion should remain phase locked.



n ~ 70

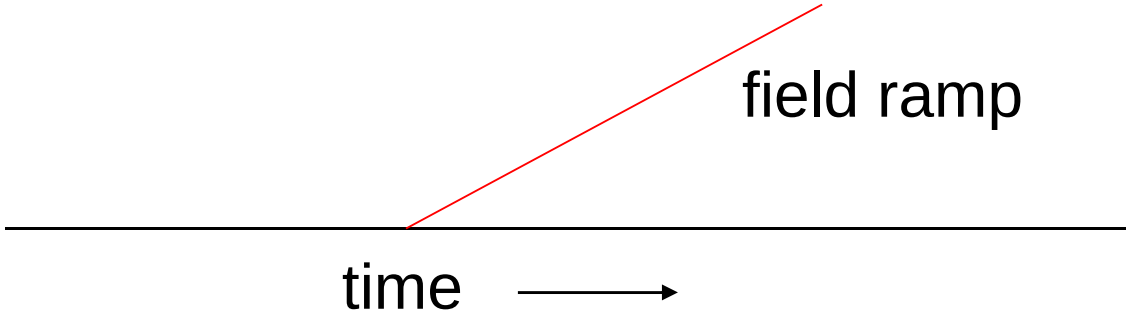


19 GHz
n=70

13 GHz
n=79

500 ns long pulse
-12 GHz/μs

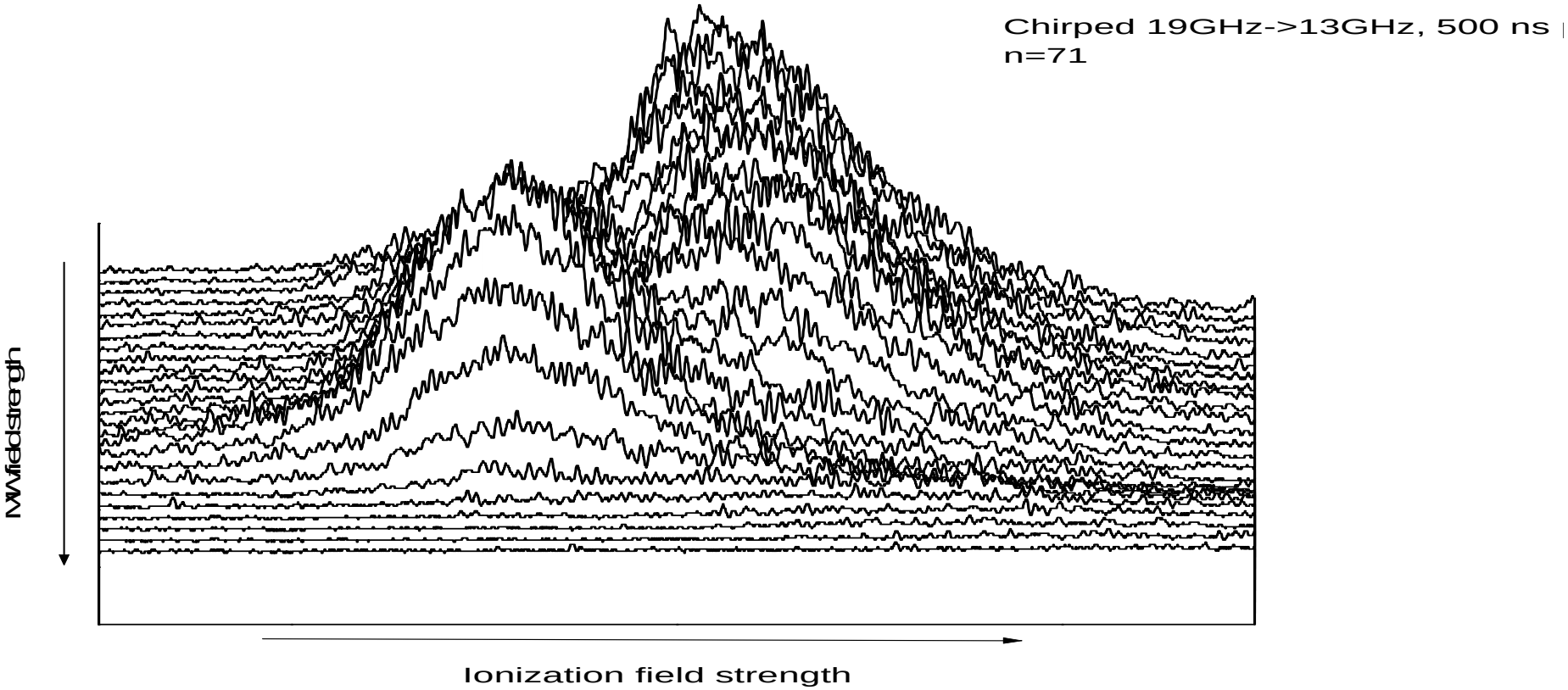
Time resolved field ionization signals



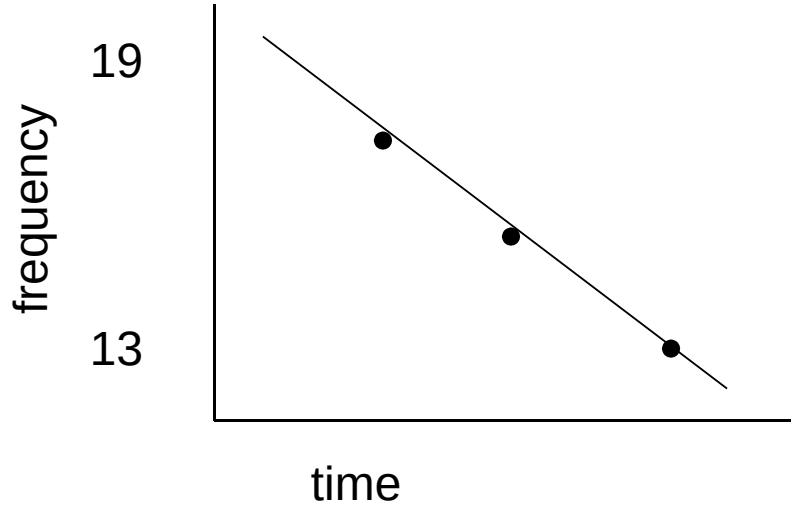
excite n=70

low mw power

high power


Chirped 19GHz->13GHz, 500 ns
n=71
MW field strength
Ionization field strength

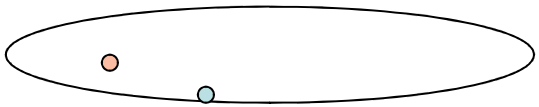
Does the electron remain phase locked as the frequency is chirped?



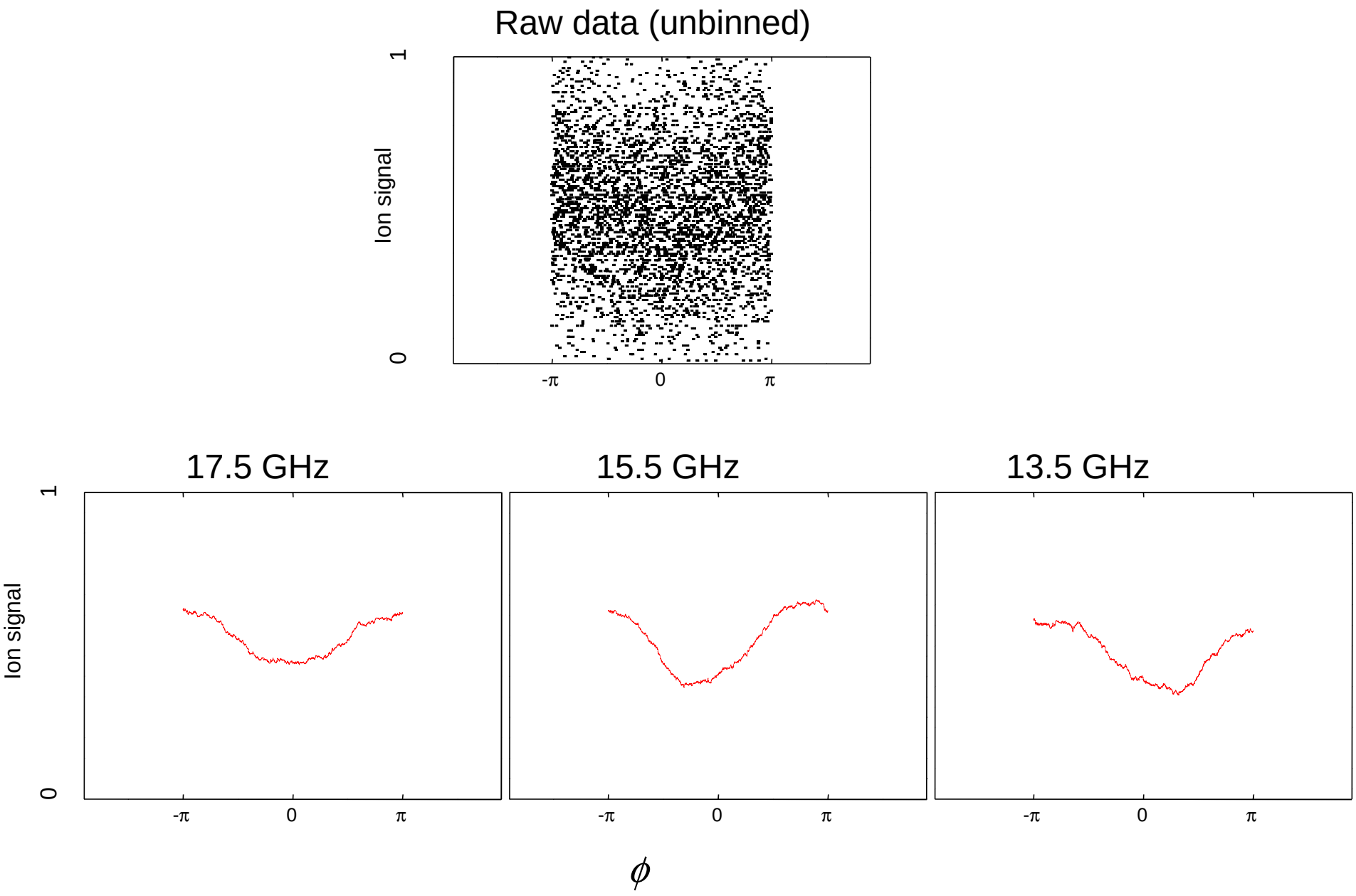
Sample
1. microwave field & derivative
2.HCP ionization signal

1. 

$$\Rightarrow E\cos\varphi$$

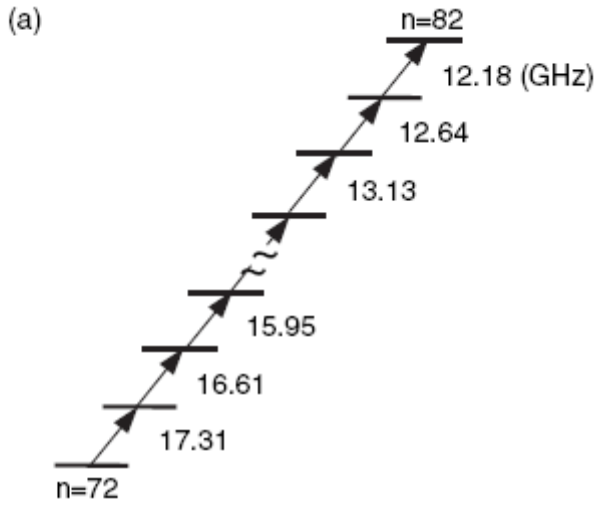
2. 

$$\Rightarrow p(\varphi)$$



The electron is phase locked !

Quantum mechanical population transfer from n=72 to n=82

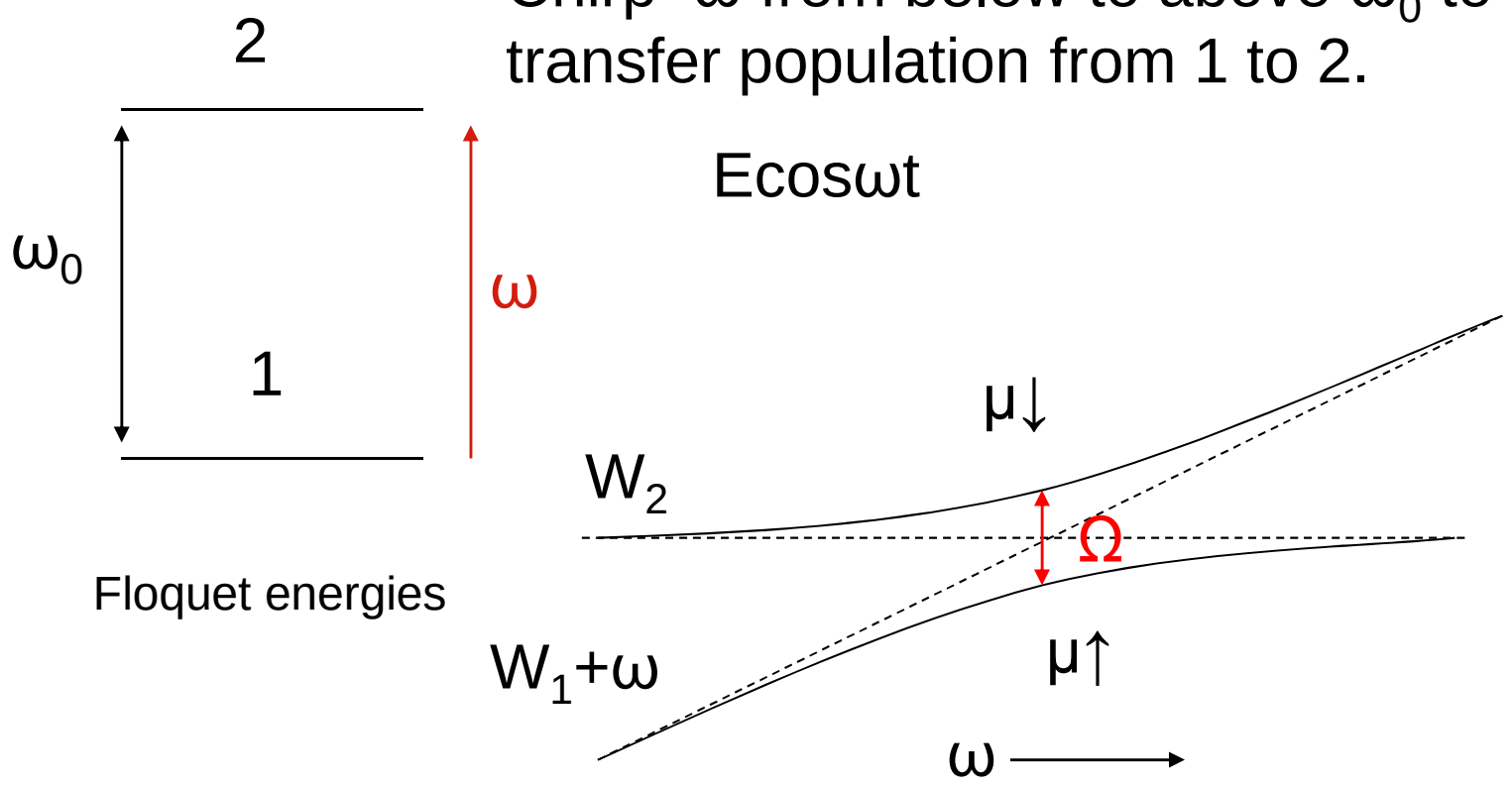


Chirping from 19 to 13 GHz is a sequence of single photon adiabatic passages

Adiabatic Rapid Passage

(through a one photon avoided level crossing)

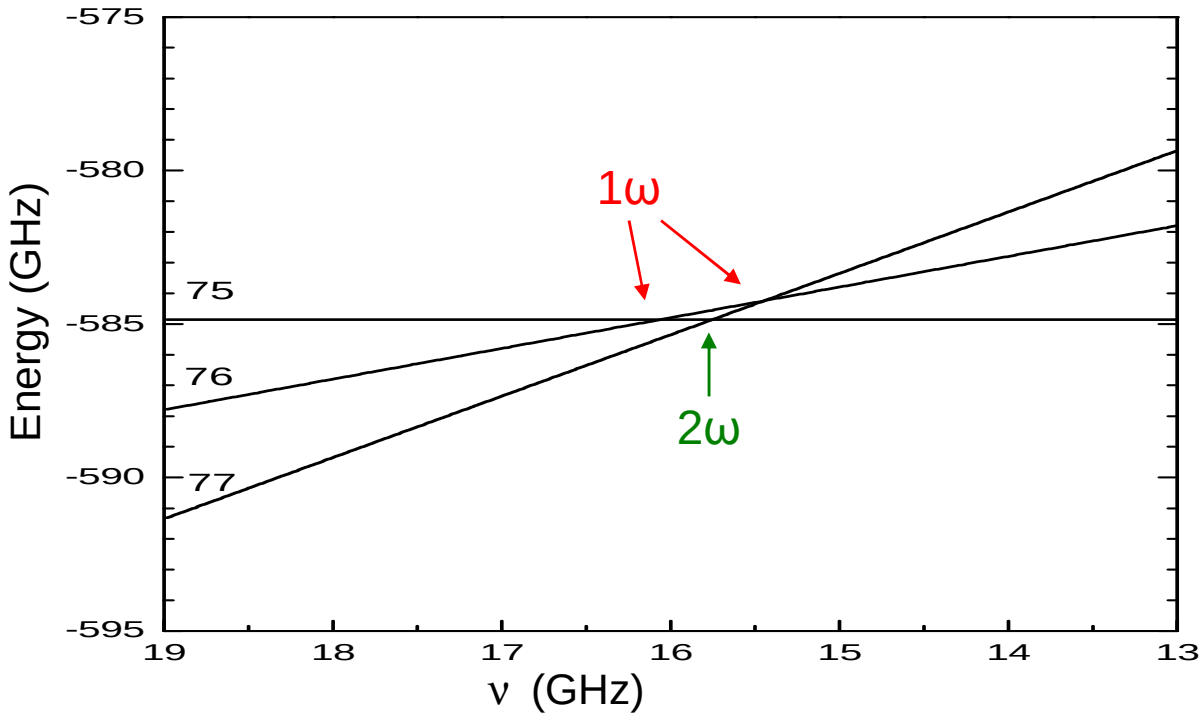
Chirp ω from below to above ω_0 to transfer population from 1 to 2.



Floquet energies

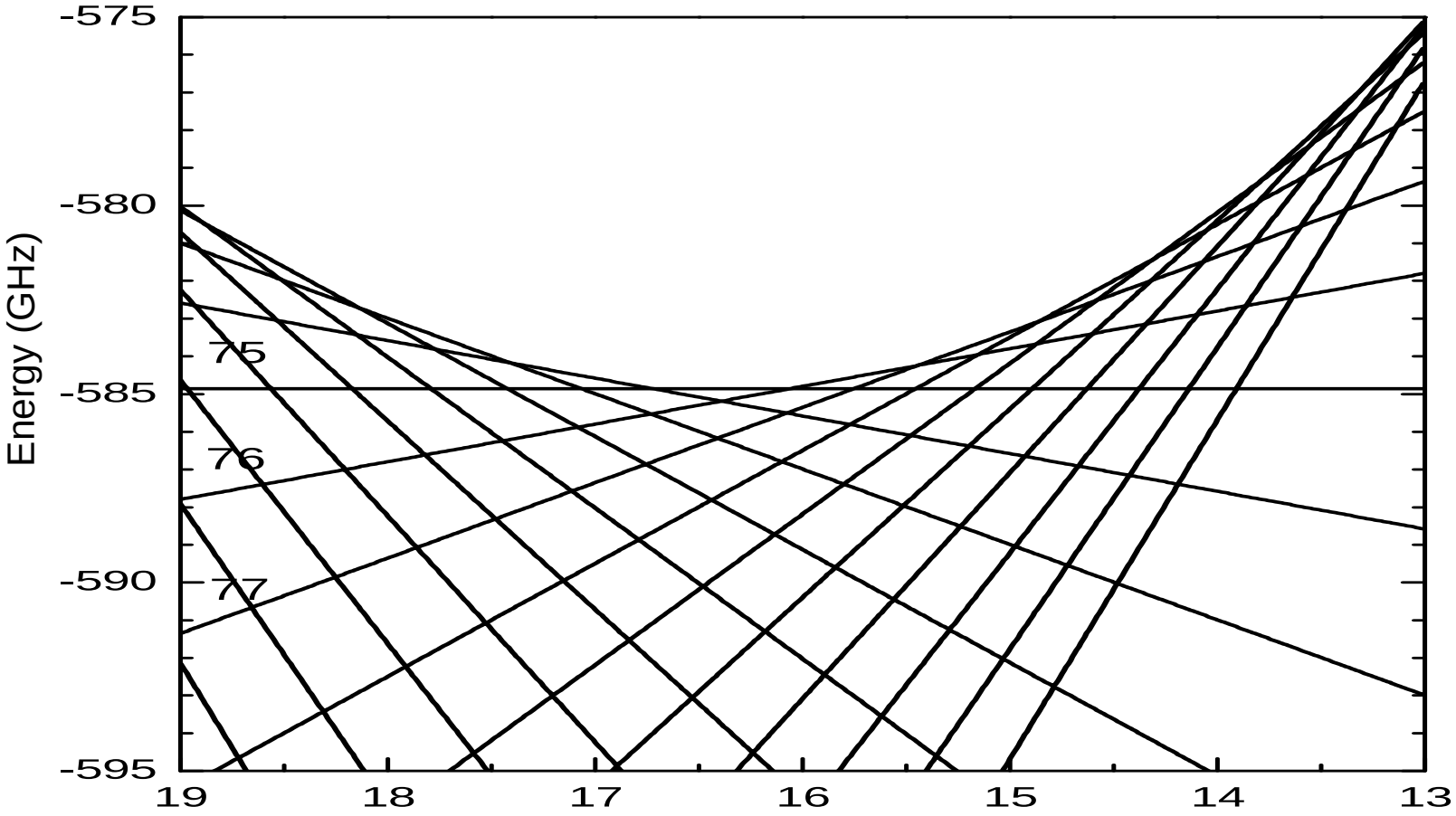
ARP condition: $d\omega/dt > \Omega^2$ $\Omega=\mu E$

n=75, 76, and 77 Floquet levels in no microwave field
W_{75}, W_{76}-ω, W_{77}-2ω

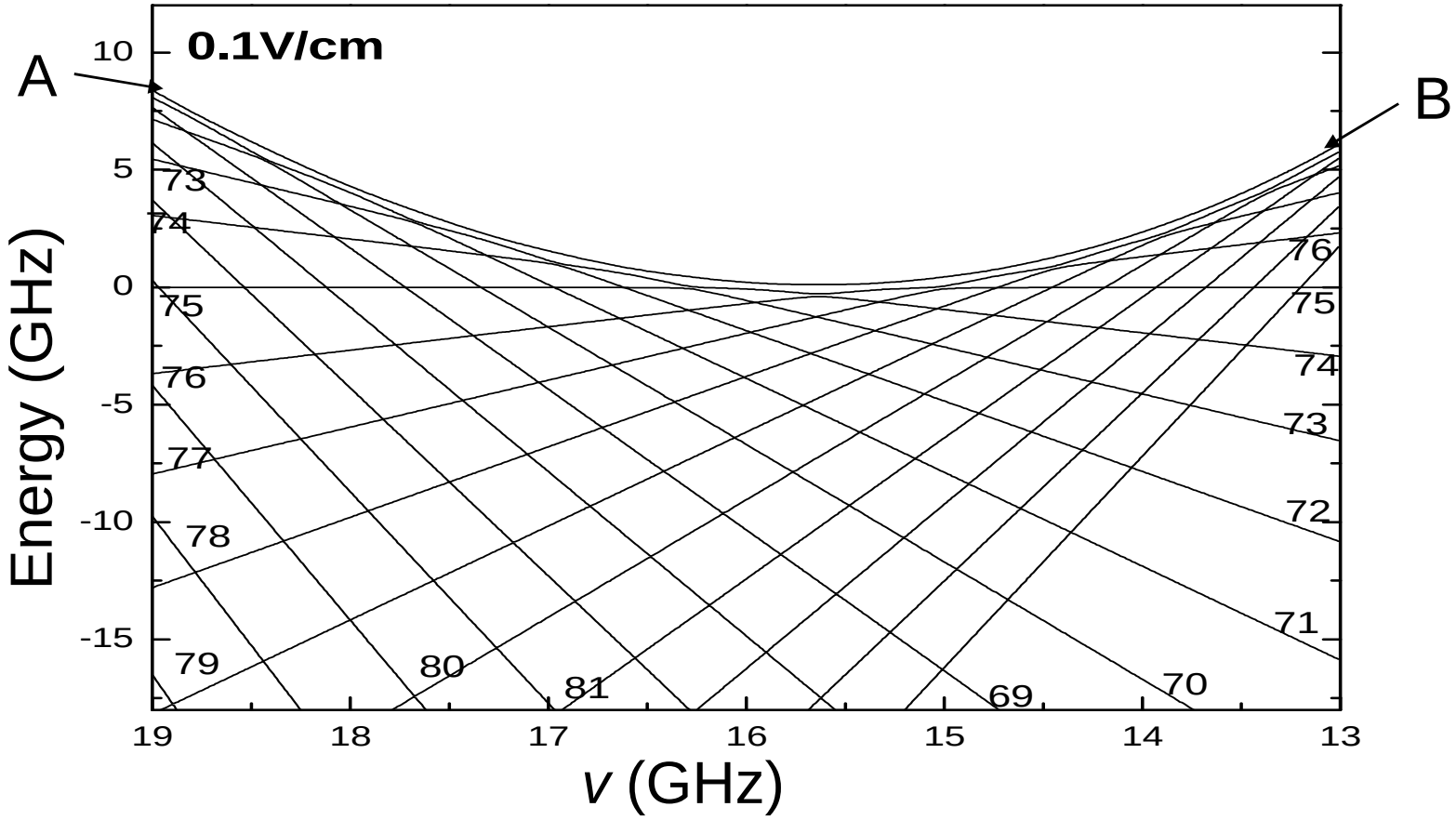


Chirping ω from 17 to 14 GHz transfers population from
n = 75 to n =77 by two one photon resonances.
Chirping from 14 to 17GHz does it by a two photon resonance
Oreg, Hioe, and Eberly; Noordam et al, Bergmann

N=68 to 84 levels no microwave field

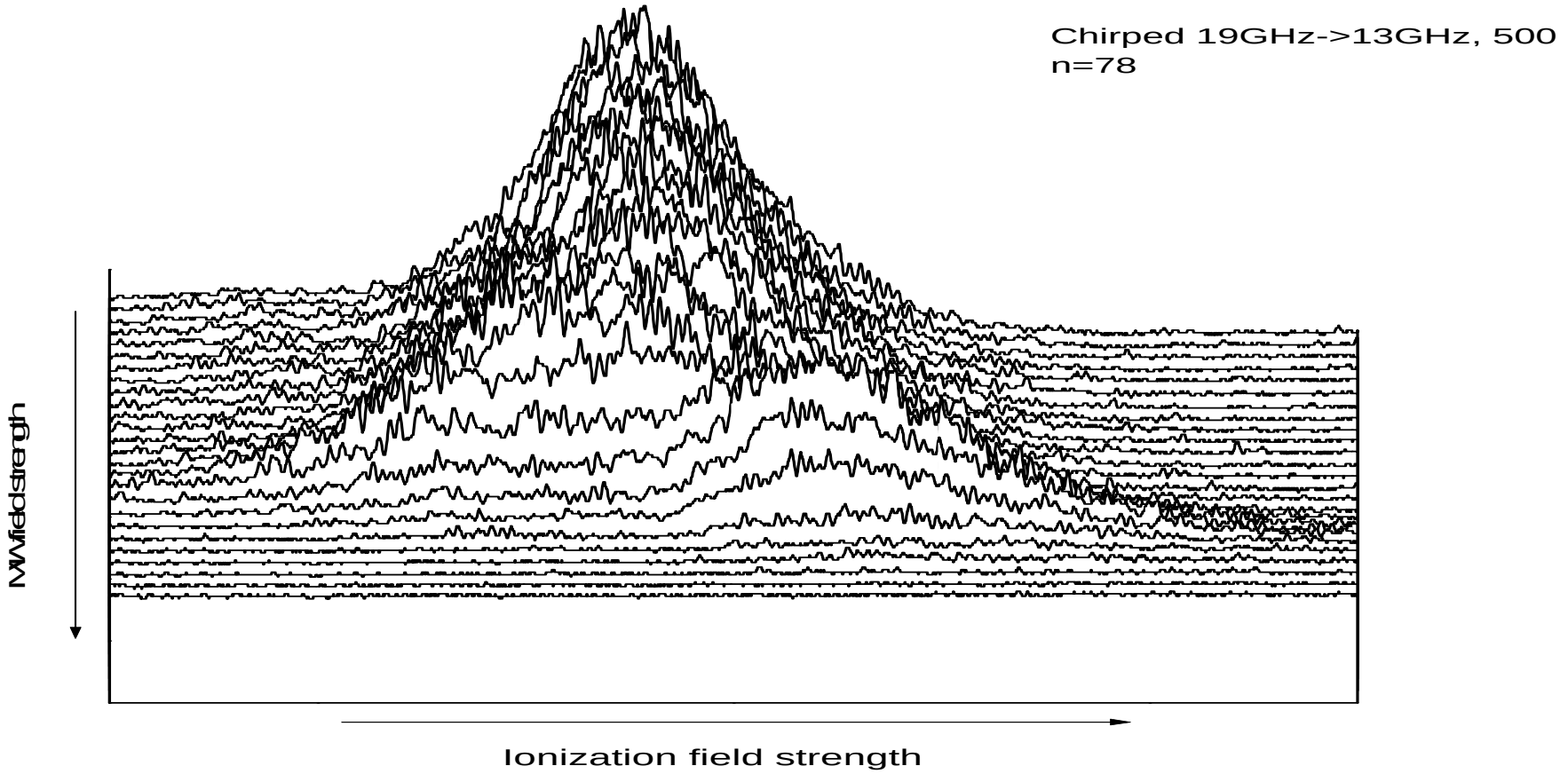


With a 0.1V/cm microwave field the single photon avoided crossings overlap and become a smooth curve.



Chirping the frequency from 19 to 13 GHz moves population from n = 71(A) to n=82 (B).

Chirping the wrong way works too! Population transfer from n=78 to n=72 with a 19 to 13 GHz chirp



We can change the frequency and the wave packet remains phase locked.

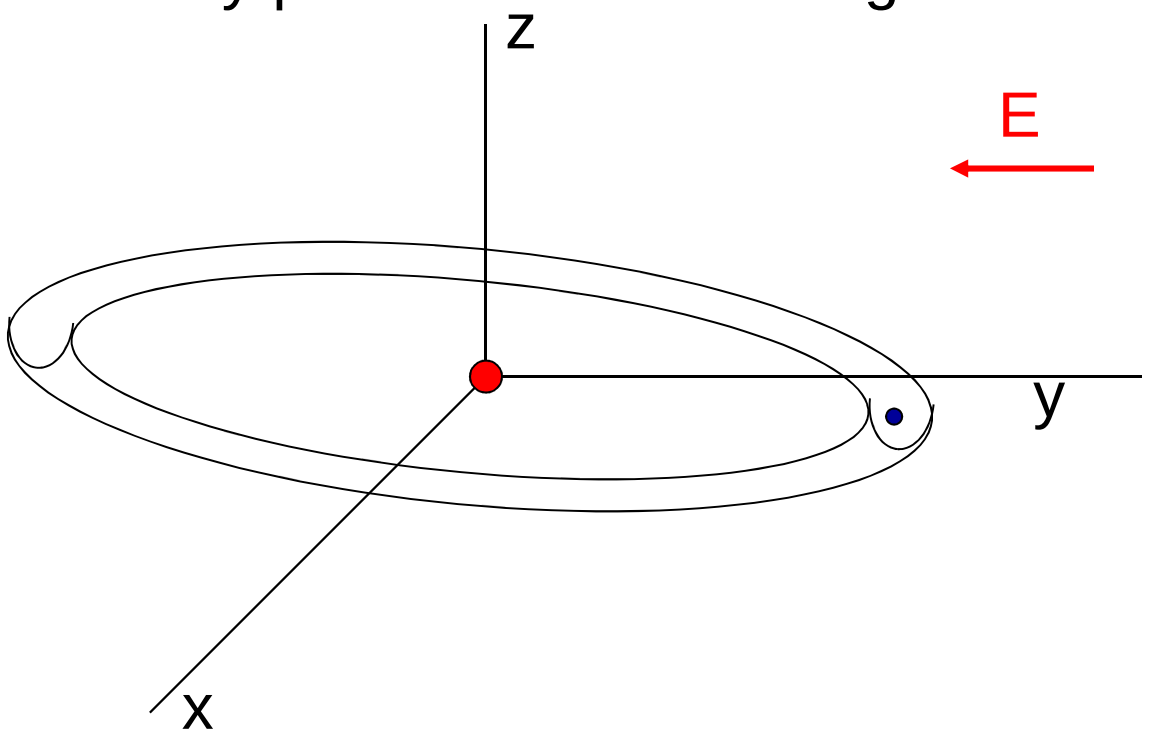
We can change the microwave field amplitude and the wave packet remains phase locked.

Will the wavepacket stay locked if we change the polarization?

Can we convert our linearly oscillating wave packet to a Circular Bohr wave packet?

Can we realize this idea?

Add a circularly polarized field rotating at ω in the x-y plane.



There is a circulating minimum in the potential.

Li np

↓

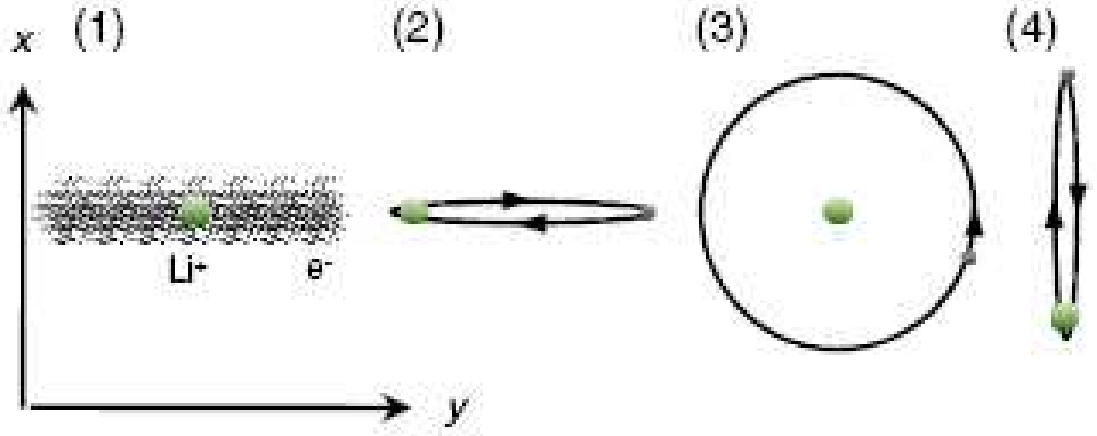
Add y polarized mw field — y linear wavepacket?

↓

Slowly change polarization to circular by adding x polarized mw field (π/2 phase) — Bohr wavepacket?

↓

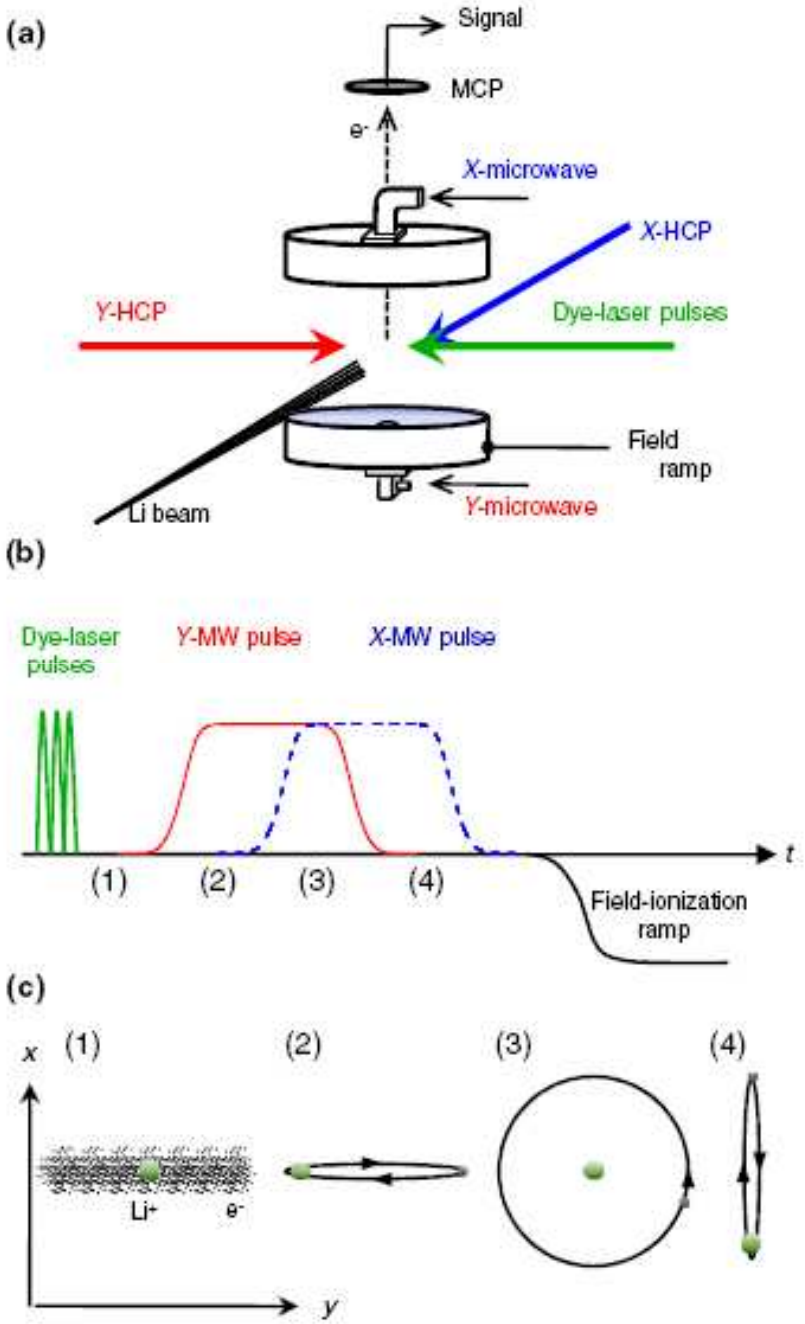
Remove y polarized field — x linear wavepacket?

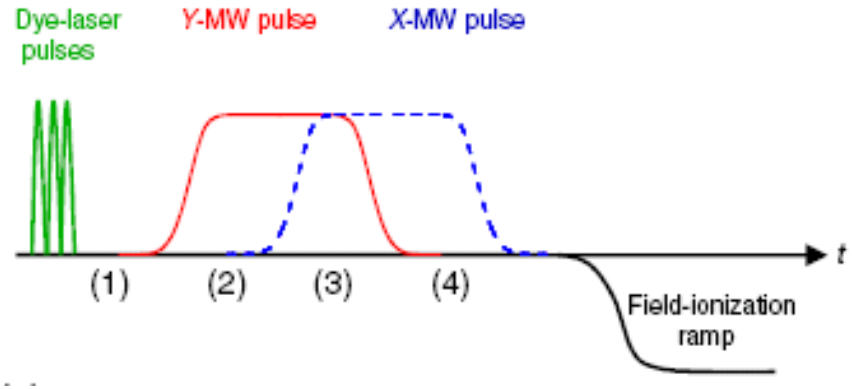


Apparatus

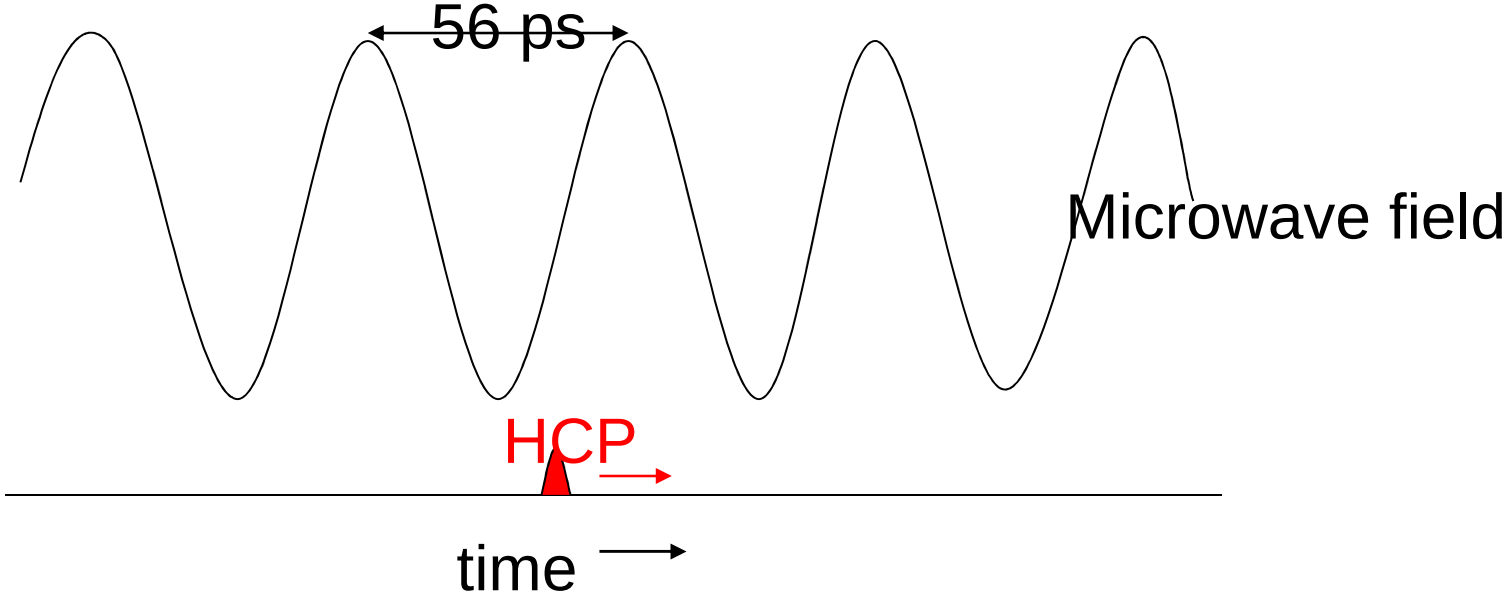
Timing

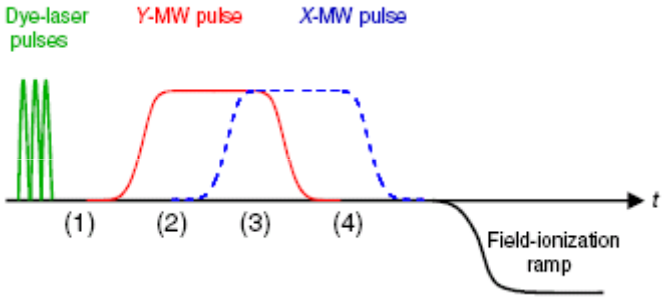
Expectation





Detect ionization vs HCP delay



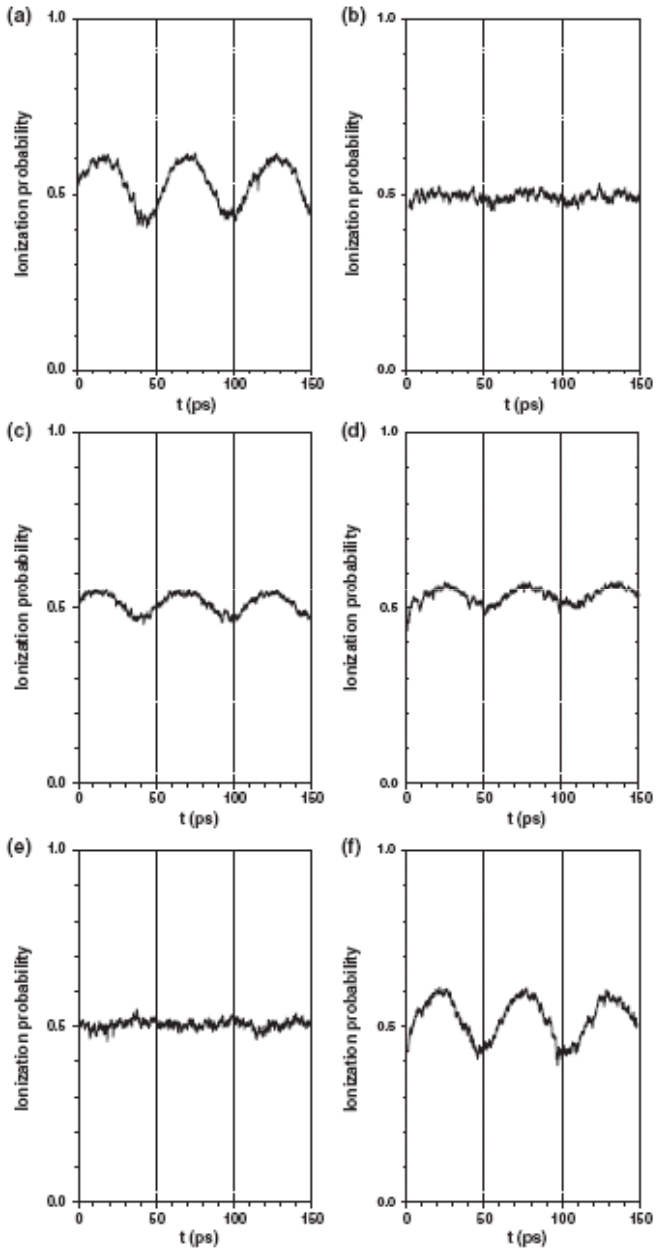


Y HCP X HCP

2

3

4



The difference between left and right cp wavepackets probed with x HCP.

X polarized mw field phase shifted by 90°

X polarized mw field phase shifted by -90°

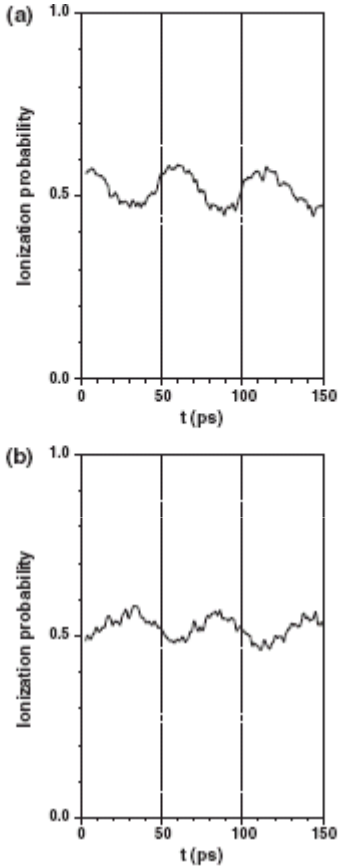


FIG. 4. Signals observed in right- and left-circularly polarized fields, time (3) of Fig. 2(b), when scanning the fine delay of the x-polarized HCP. (a) x-polarized MW field phase shifted by 90°. (b) x-polarized field phase shifted by $-90°$.

Summary

We can make and manipulate arbitrarily long lived "classical atoms.

They can be useful:
Samples of synchronously oscillating dipoles as targets
Interacting phase locked dipoles for quantum gates.

The ideas can be applied to real problems, e.g. the "wrong way" chirp is interesting for laser manipulation.

Quantum physics becomes classical through coherence.