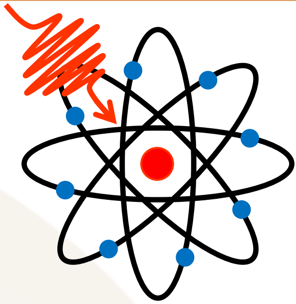

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Ionization of Rydberg atoms in Intense, Single-cycle THz field

4th year seminar of Sha Li
Advisor: Bob Jones
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April. 15th, 2013

Outline

Background

- Introduction of Rydberg atoms
- Brief review of several typical types of field ionization

My work

- Intense THz generation via optical rectification
- THz streak
- THz ionization of low-lying Rydberg atoms
- THz ionization of Rydberg stark states

Future Plan

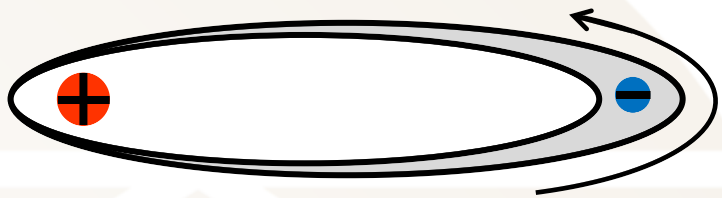
- Electron Scattering

Rydberg atoms

- Hydrogen-like atoms

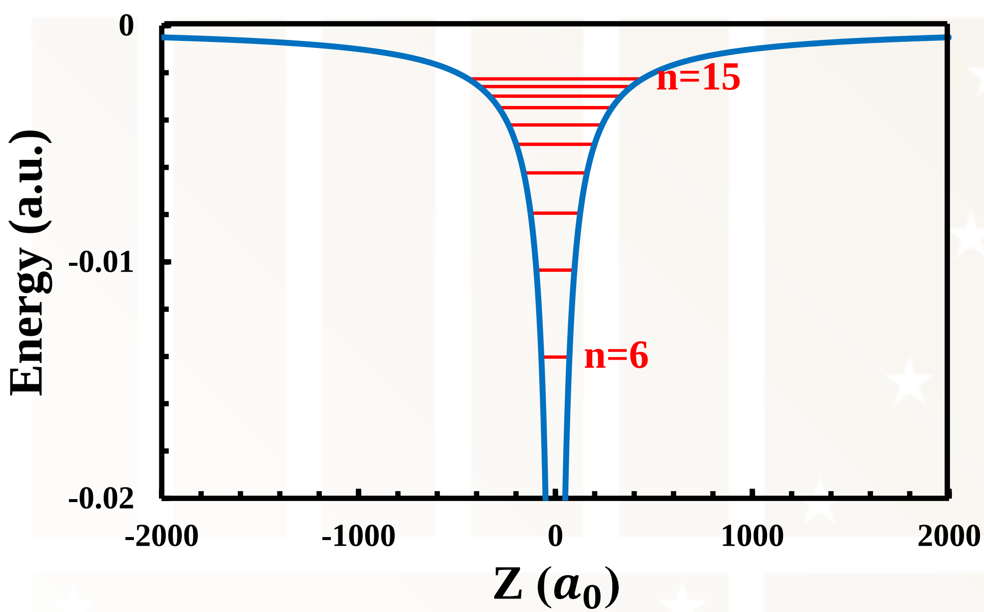
- Valance electron at highly excited orbit, with large principle quantum number n

- Experience effectively +1 net charge, can be considered as one electron system, but due to finite core size, QUANTUM DEFECT



Sketch of a Kepler orbit with low angular momentum

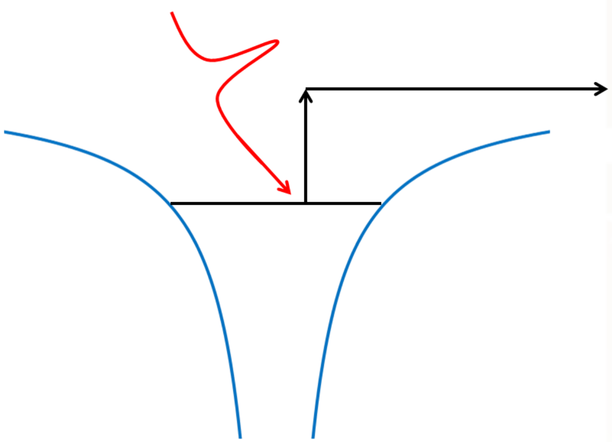
	n=6	n=15
$E_n = -\frac{1}{2(n-\delta_{n,l})^2}$	0.38eV	0.06eV
$E_{n+1} - E_n = \frac{1}{n^3}$	0.13eV	0.008eV
$r = \frac{3}{2}n^2$	$54a_0$	$338a_0$
$T = 2\pi n^3$	0.03ps	0.5ps
$\omega = \frac{1}{n^3}$	30THz	2THz

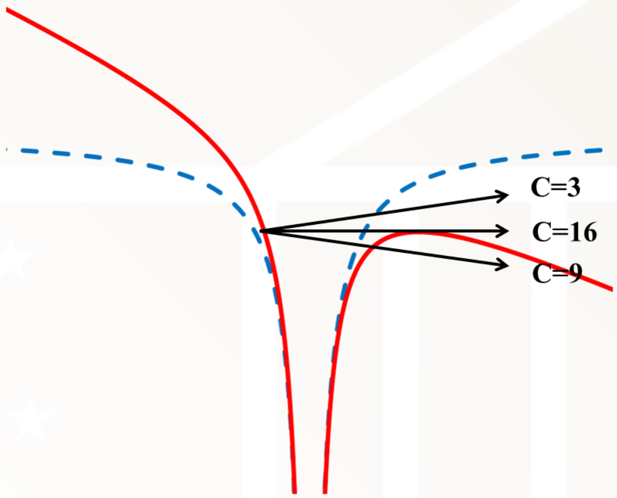


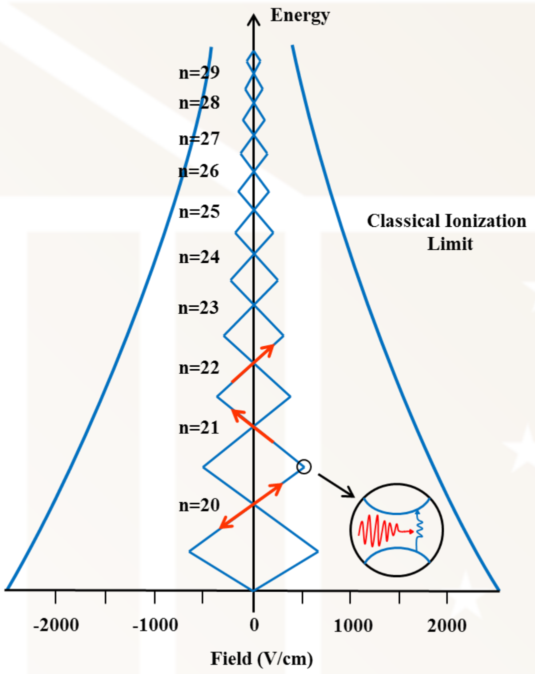
Hydrogen coulomb potential and energy diagram

Examples of Field ionization

$$\omega_{Field} \sim \omega_{atom}$$

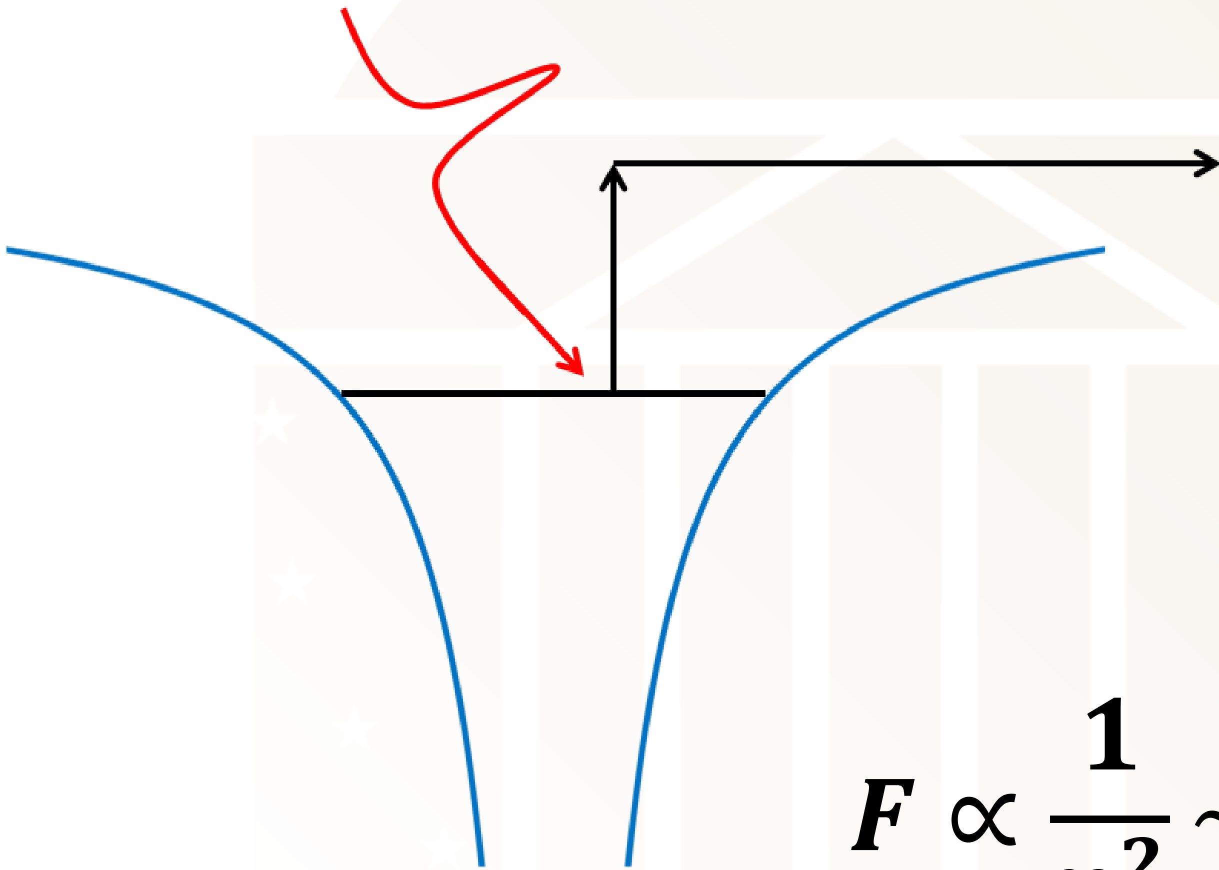


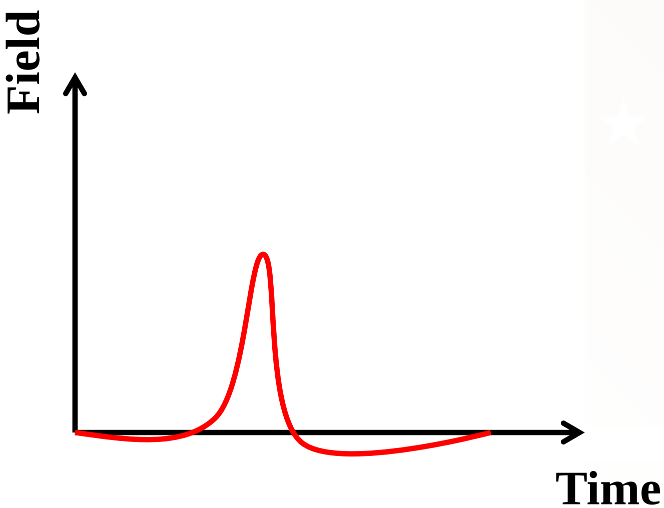




Examples of Field ionization

$\omega_F > \omega_{atom}$ Half Cycle Pulse: "impulsive" regime



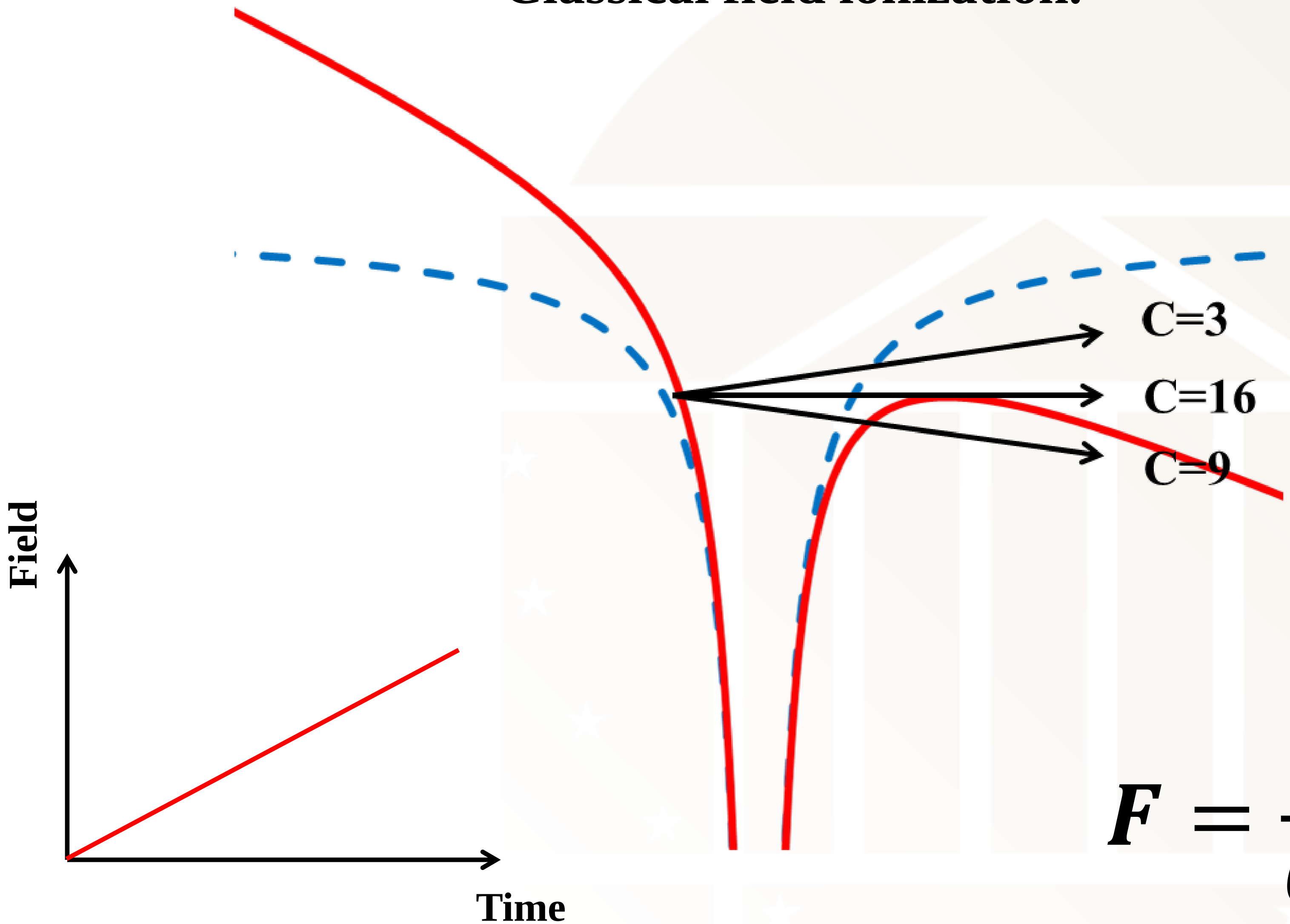


$$F \propto \frac{1}{n^2} \sim \frac{1}{n}$$

R. R. Jones, D. You, and P. H. Bucksbaum, Phys. Rev. Lett. 70, 12361239 (1993)

$\omega_F < \omega_{atom}$, static or quasi-static field.

Classical field ionization.

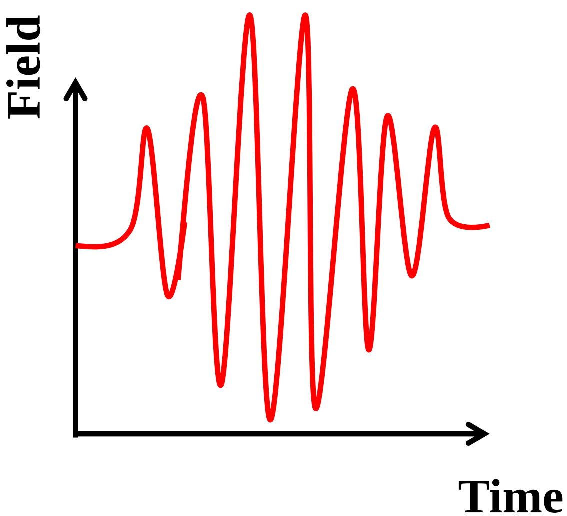


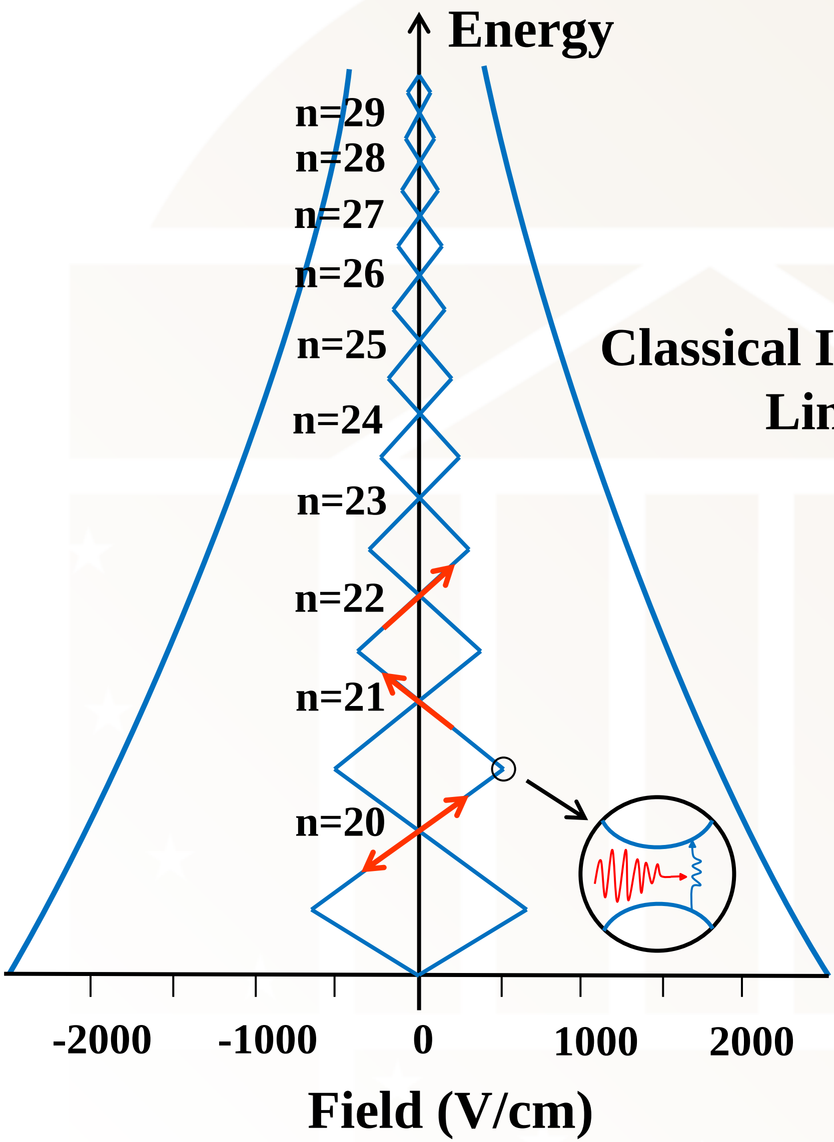
$$F = \frac{1}{Cn^4}$$

T. F. Gallagher, Rydberg Atoms, Cambridge University Press (1994)

Examples of Field ionization

$\omega_F < \omega_{atom}$, Multi-cycle Microwave ionization.



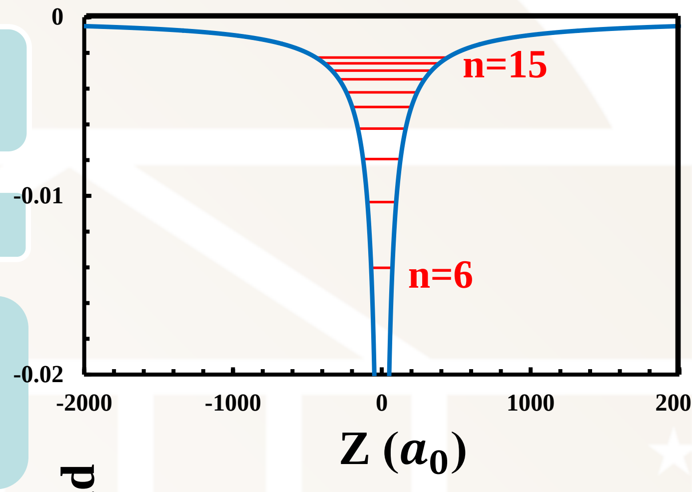


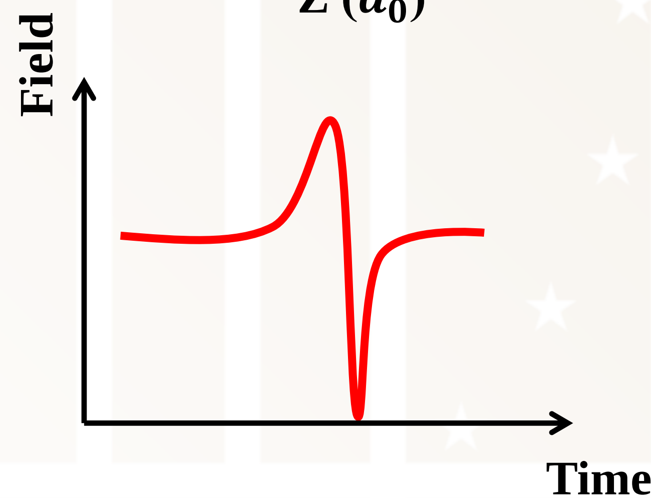
$$F = \frac{1}{3n^5}$$

P. Pillet, T. F. Gallagher, et.al Phys. Rev. A 30, 280294 (1984)

Our Experiment

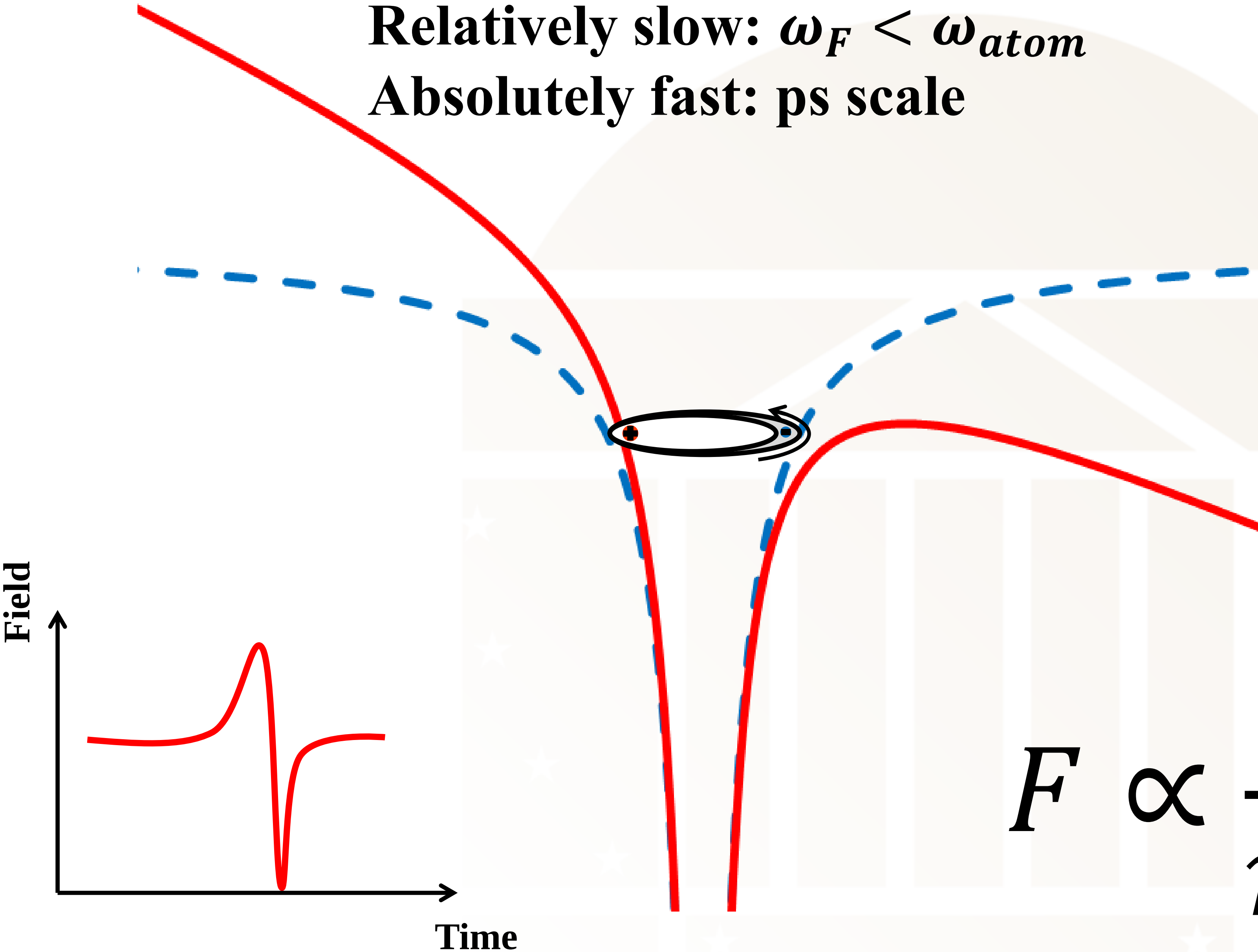
- Low-lying n levels (n=6-15), which require very high field for ionization
- Oscillating field, but single cycle
- Very fast pulsed field $T \sim 4ps$ compared to ns or µs scale pulsed field usually used. And very strong peak field strength $\sim 500\ kV/cm$
- But still relatively slow ($\boldsymbol{\omega_F < \omega_{atom}}$) compared to the Kepler period of the Rydberg atoms studied: T (n=6-15) range from 0.03ps~0.5ps





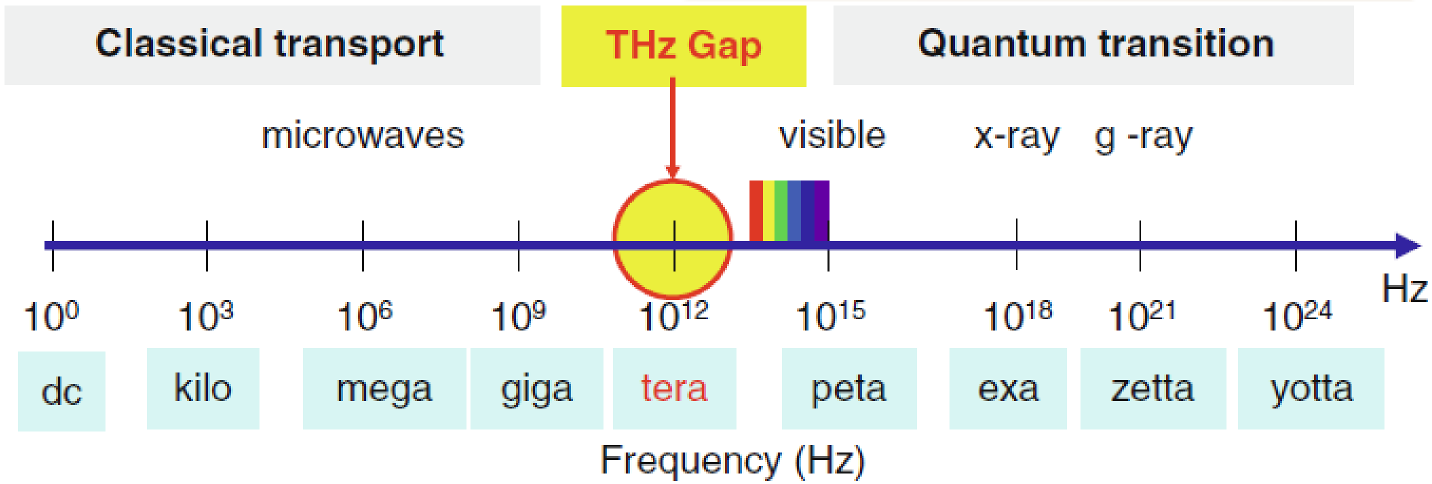
Relatively slow: $\omega_F < \omega_{atom}$

Absolutely fast: ps scale



$$F \propto \frac{1}{n^?}$$

Characteristics of THz radiation



- **Frequency: $\nu = 1$ THz $= 10^{12}$ Hz**
- **Period: $\tau = 1/\nu = 1$ ps $= 10^{-12}$ s**
- **Wavelength: $\lambda = c/\nu = 0.3$ mm $= 300$ μm**
- **Wavenumber: $1/\lambda = 33.3\ cm^{-1}$**
- **Photon energy: $\hbar\omega = 4.14$ meV**
- **Temperature: $T = h\nu/kB = 48$ K**

Xi-Cheng Zhang, Jingzhou Xu, Introduction to THz Wave Photonics, Springer (2009)
Yun-Shik Lee, Principles of Terahertz Science and Technology, Springer (2008)

THz generation via Optical Rectification

χ^2

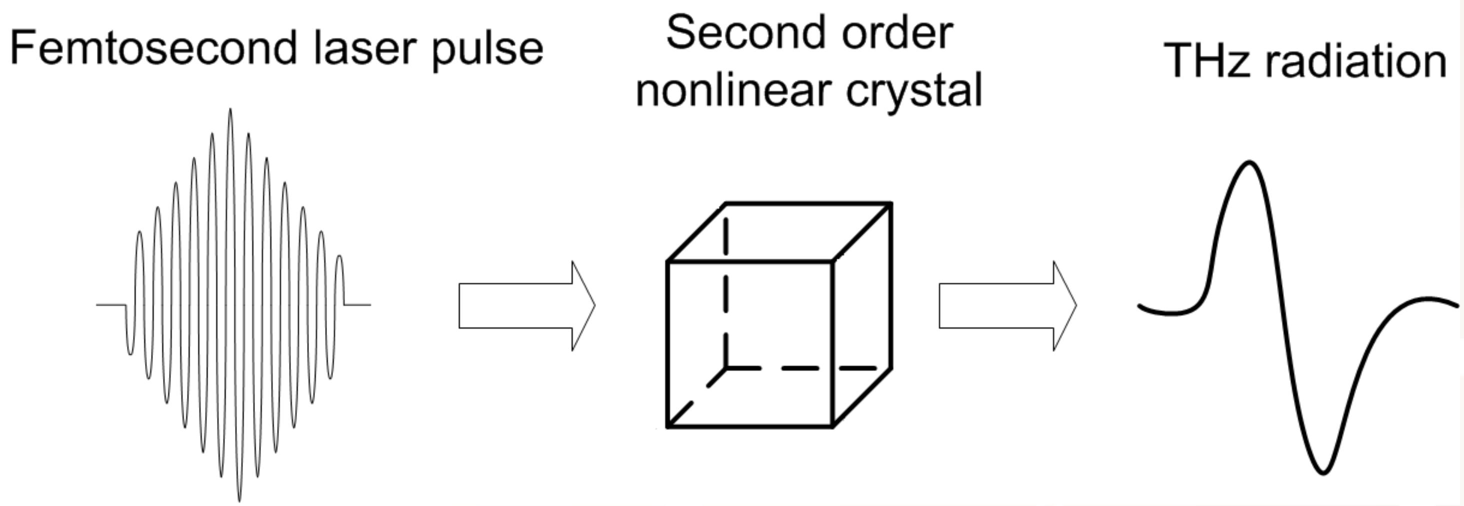
- **Second order nonlinear effect**
- **Difference-frequency mixing among the spectral components contained within the ultrashort pulse bandwidth**

Phase matching

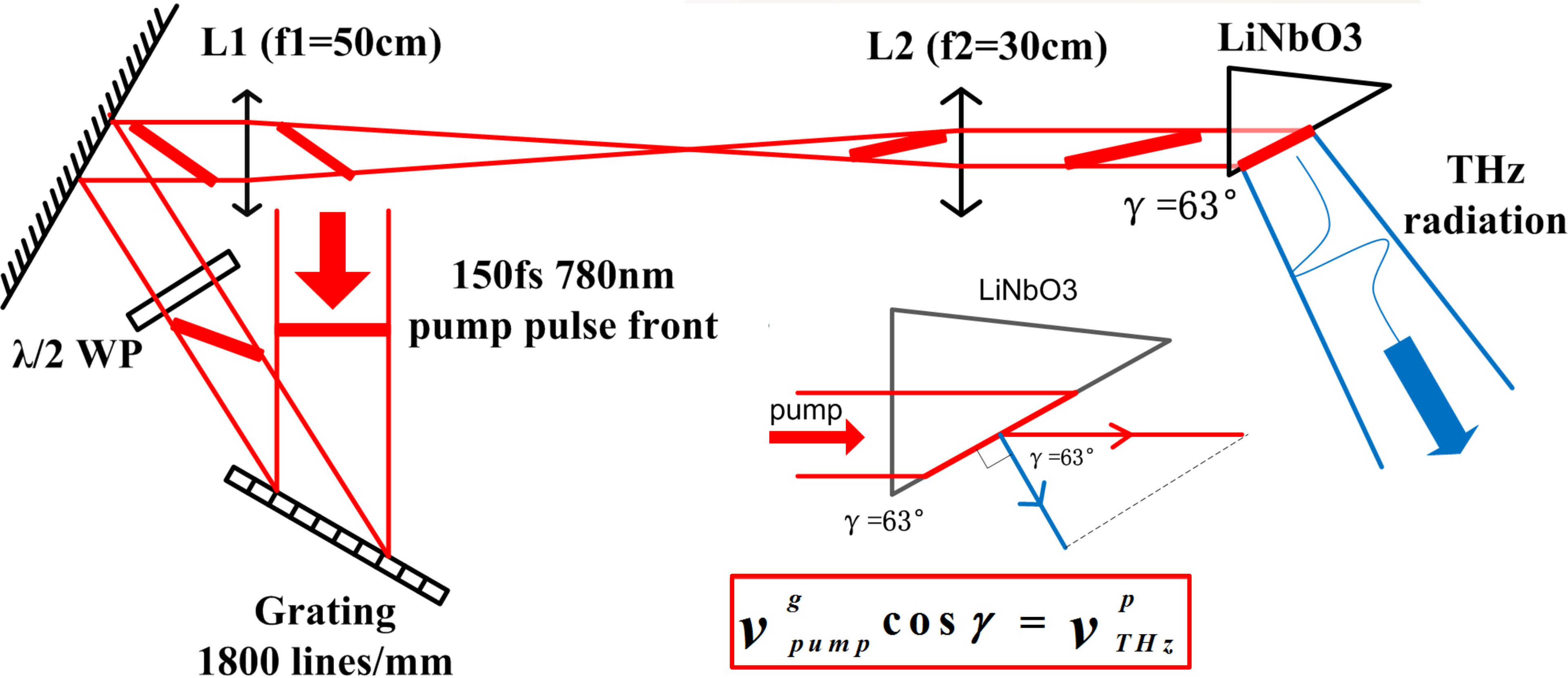
$$v^{g}_{pump} = v^{phase}_{THz}$$

LiNbO3

- **Large nonlinear coefficient**
- **Less THz absorption**



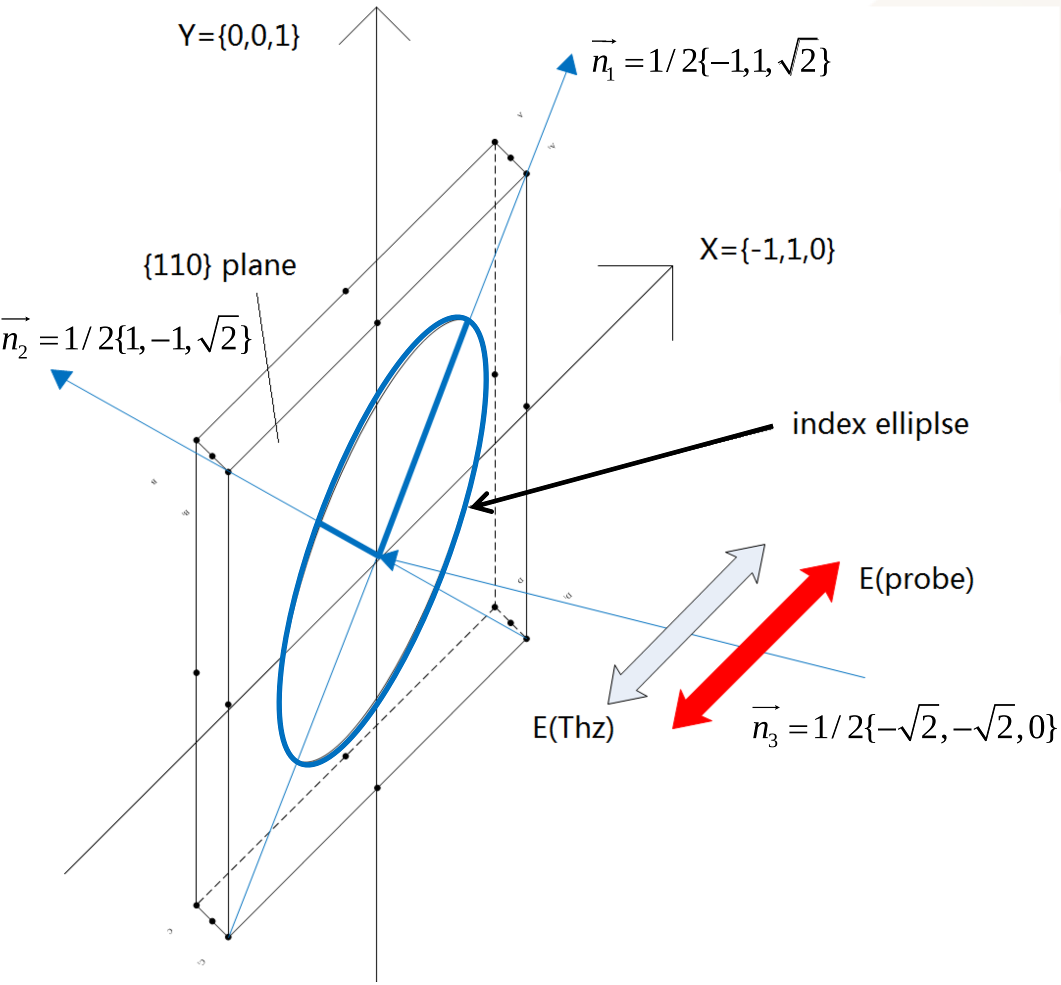
Tilted-Pulse-Front Pumping



$$v^{g}_{pump}\cos\gamma = v^{p}_{THz}$$

J. Hebling, Keith A. Nelson, et.al JOSA B, Vol. 25, Issue 7, pp. B6-B19 (2008)

Electro-Optic Sampling

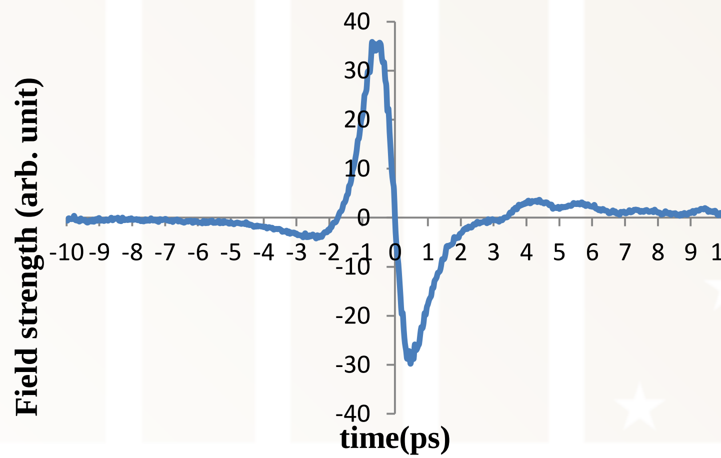


$$n_1 = n_0 + \frac{n_0^3 \gamma_{41} E_{THz}}{2}$$

$$n_2 = n_0 - \frac{n_0^3 \gamma_{41} E_{THz}}{2}$$

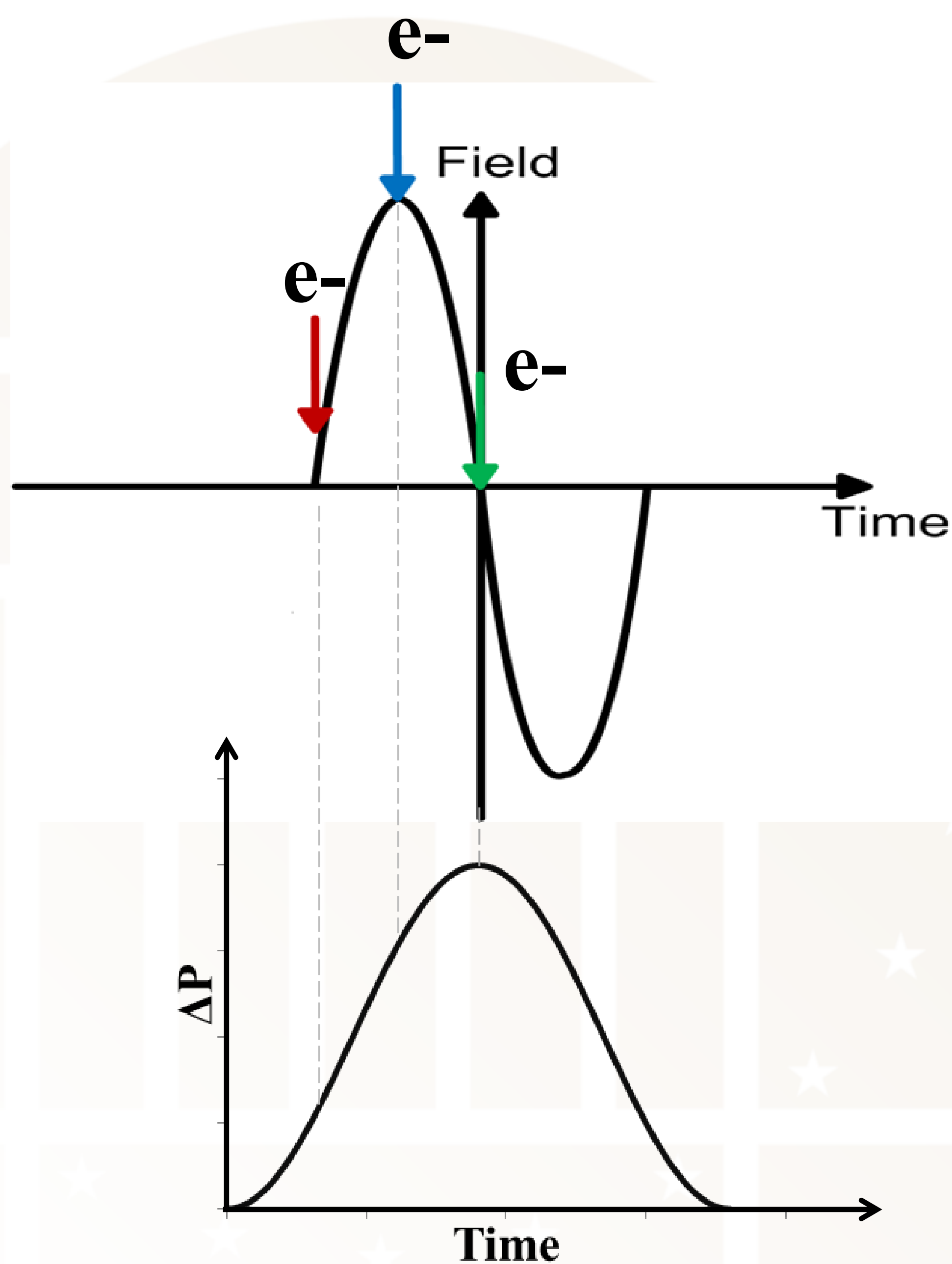
$$n_3 = n_0$$

$$\Delta\varphi = \frac{\omega d}{c}(n_1 - n_2) \propto E_{THz}$$

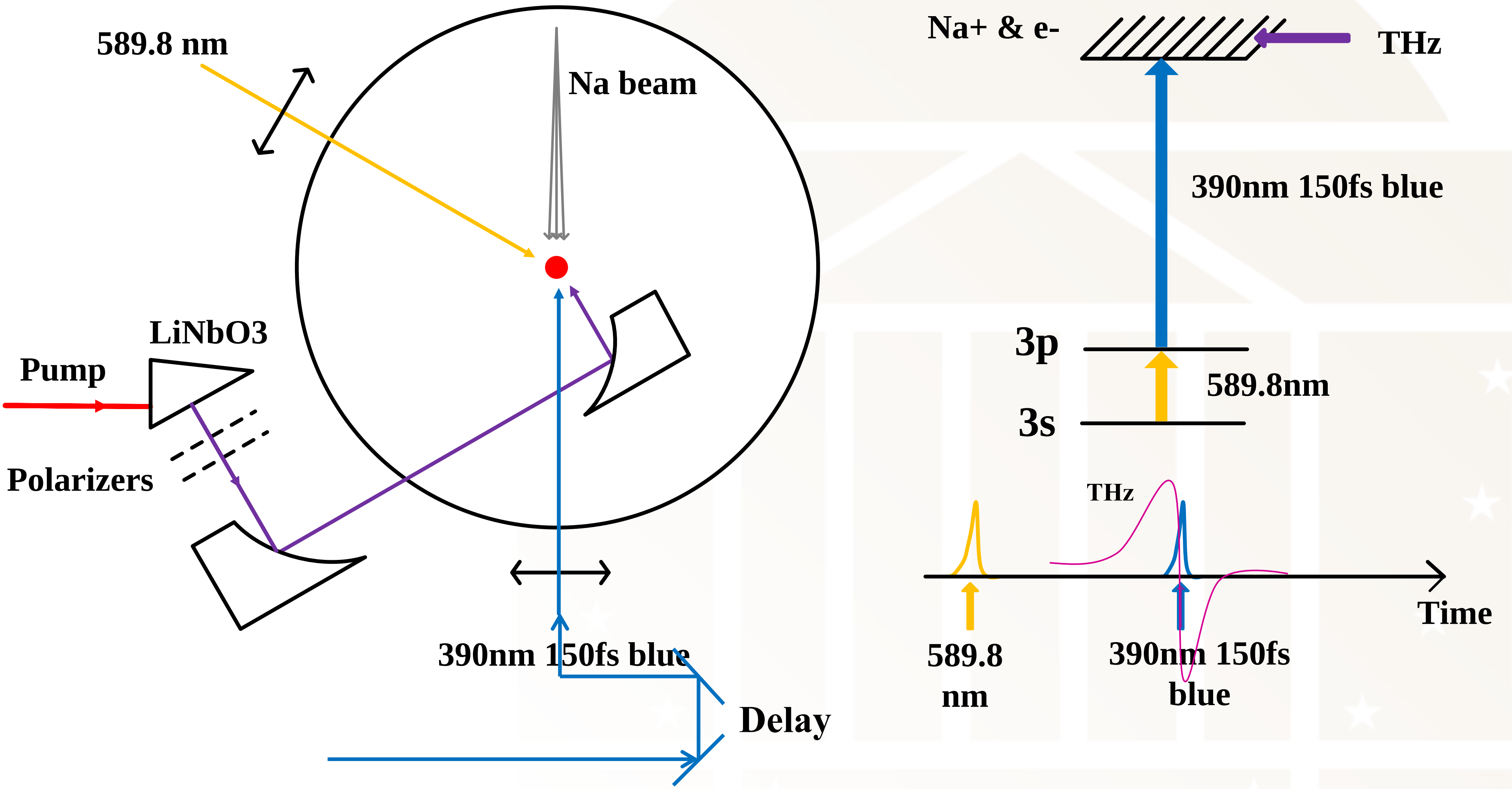


THz Streak

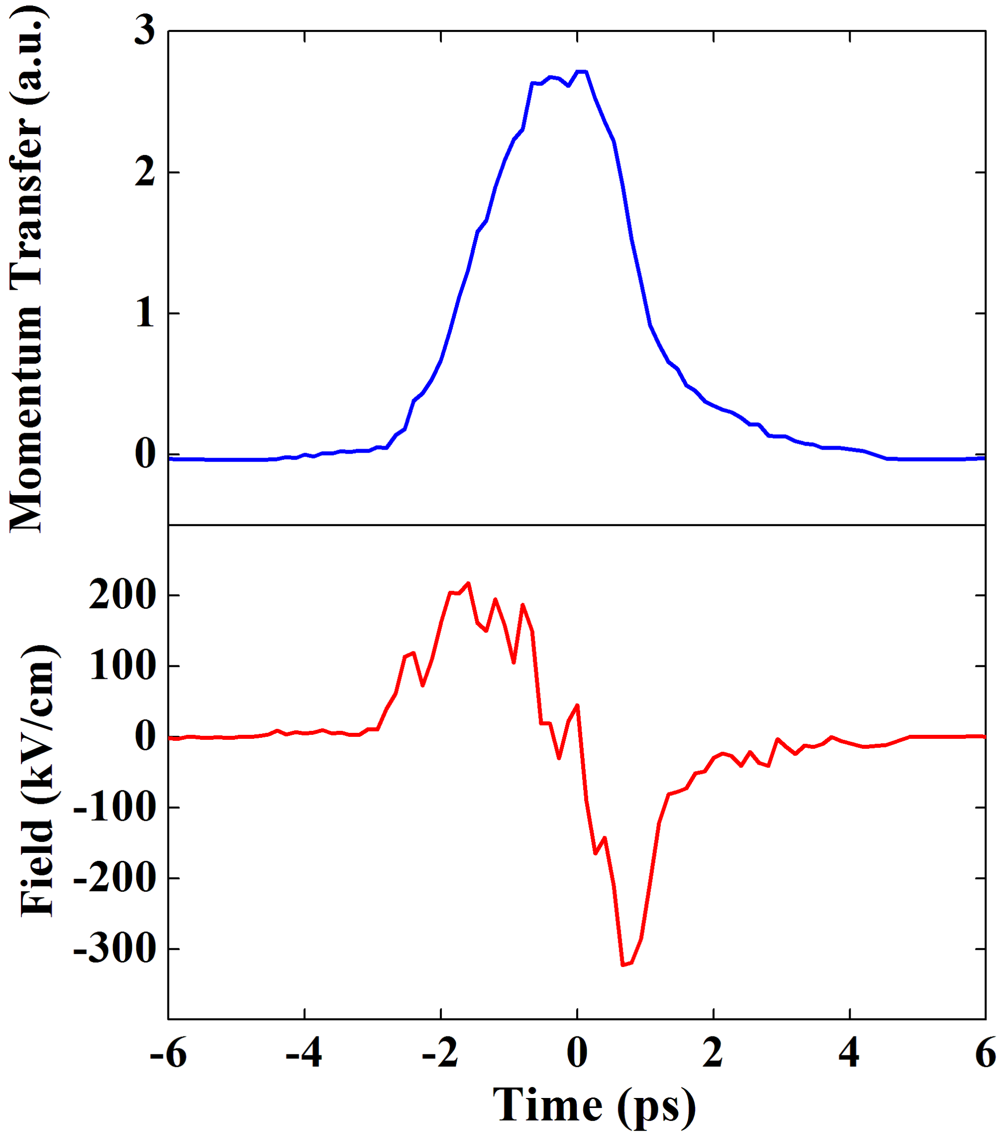
$$\Delta p = -\int_{t}^{\infty} F(t)\,dt$$

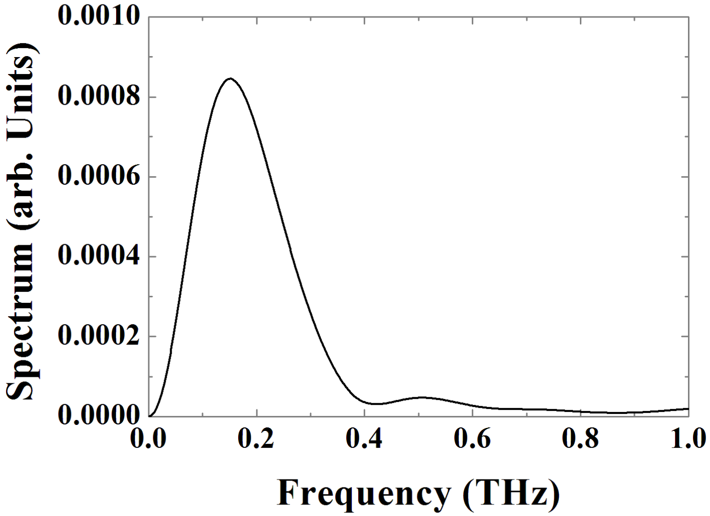


THz Streak: Experimental setup

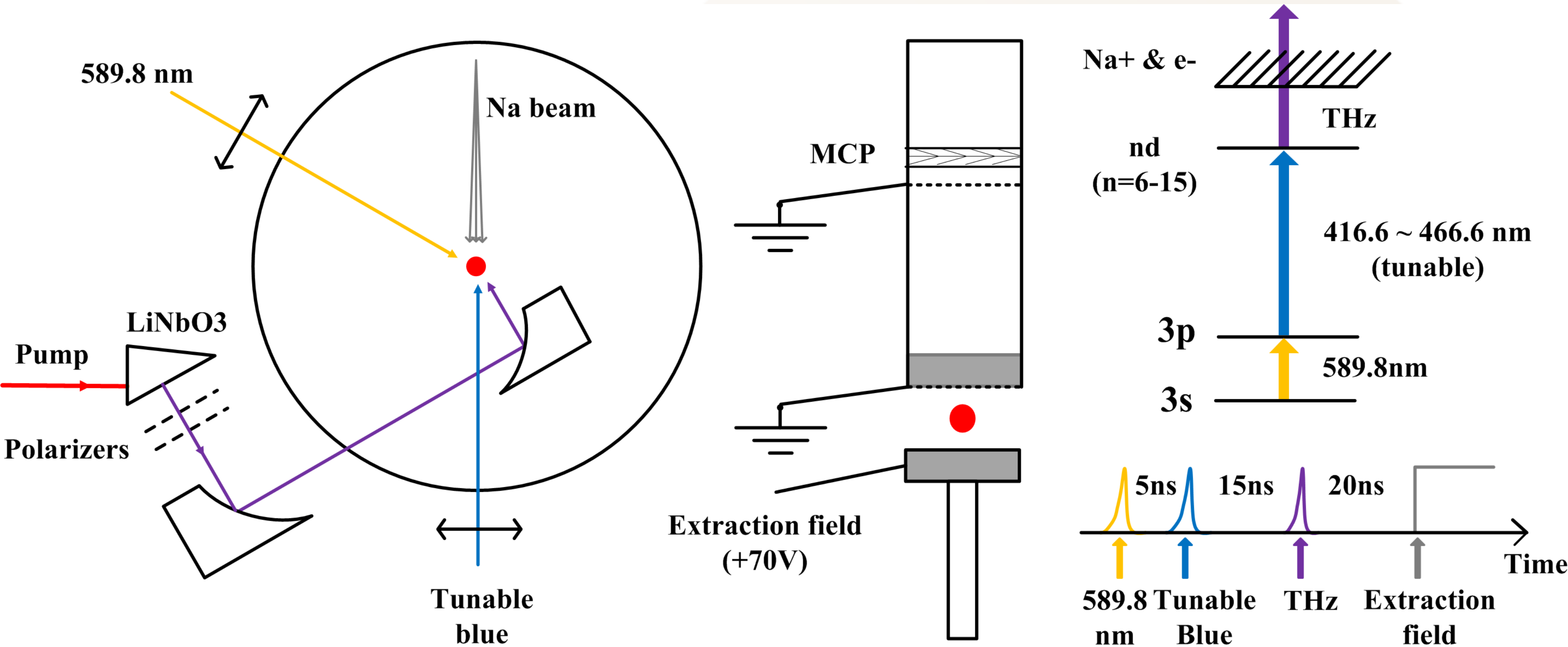


THz Streak: Result

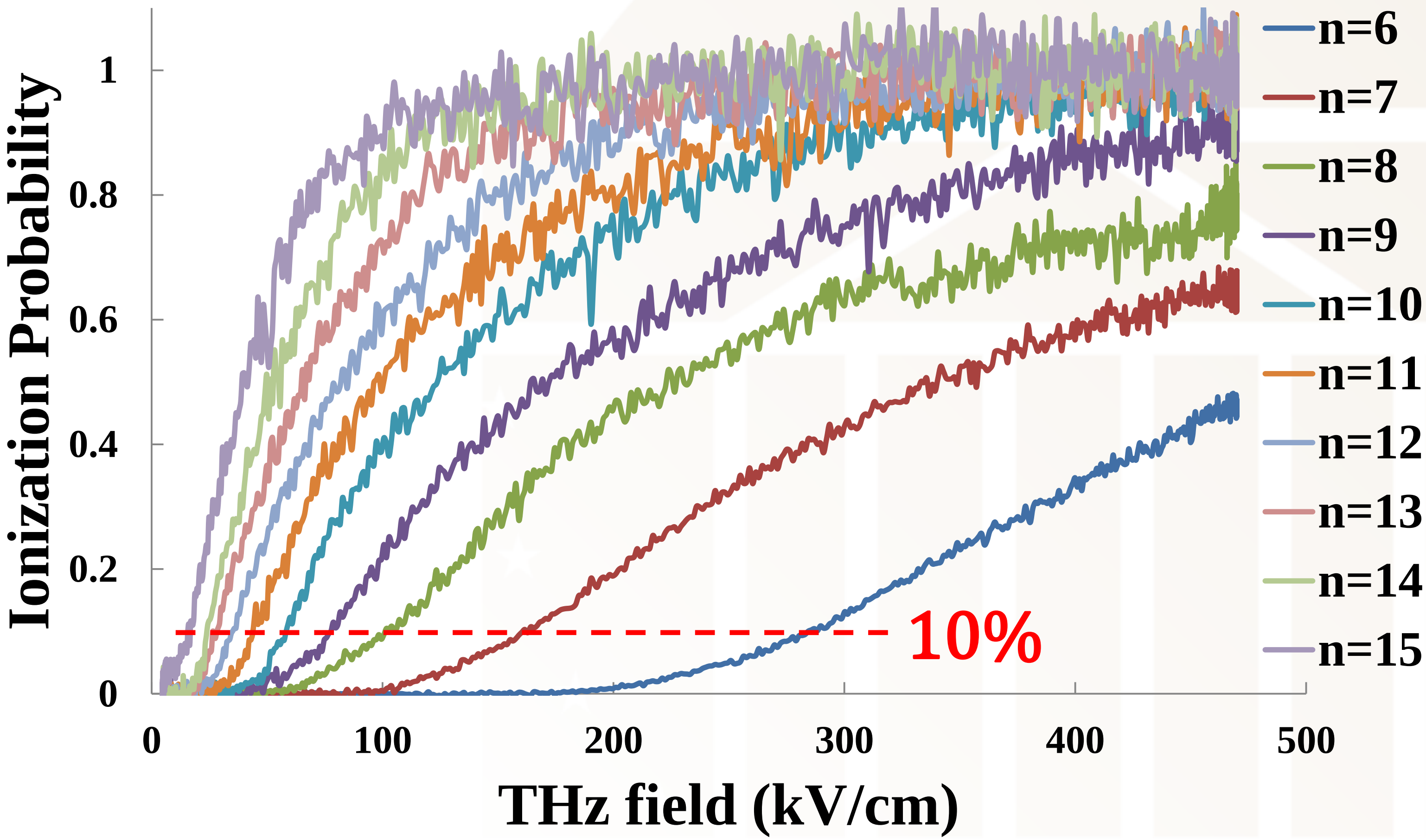




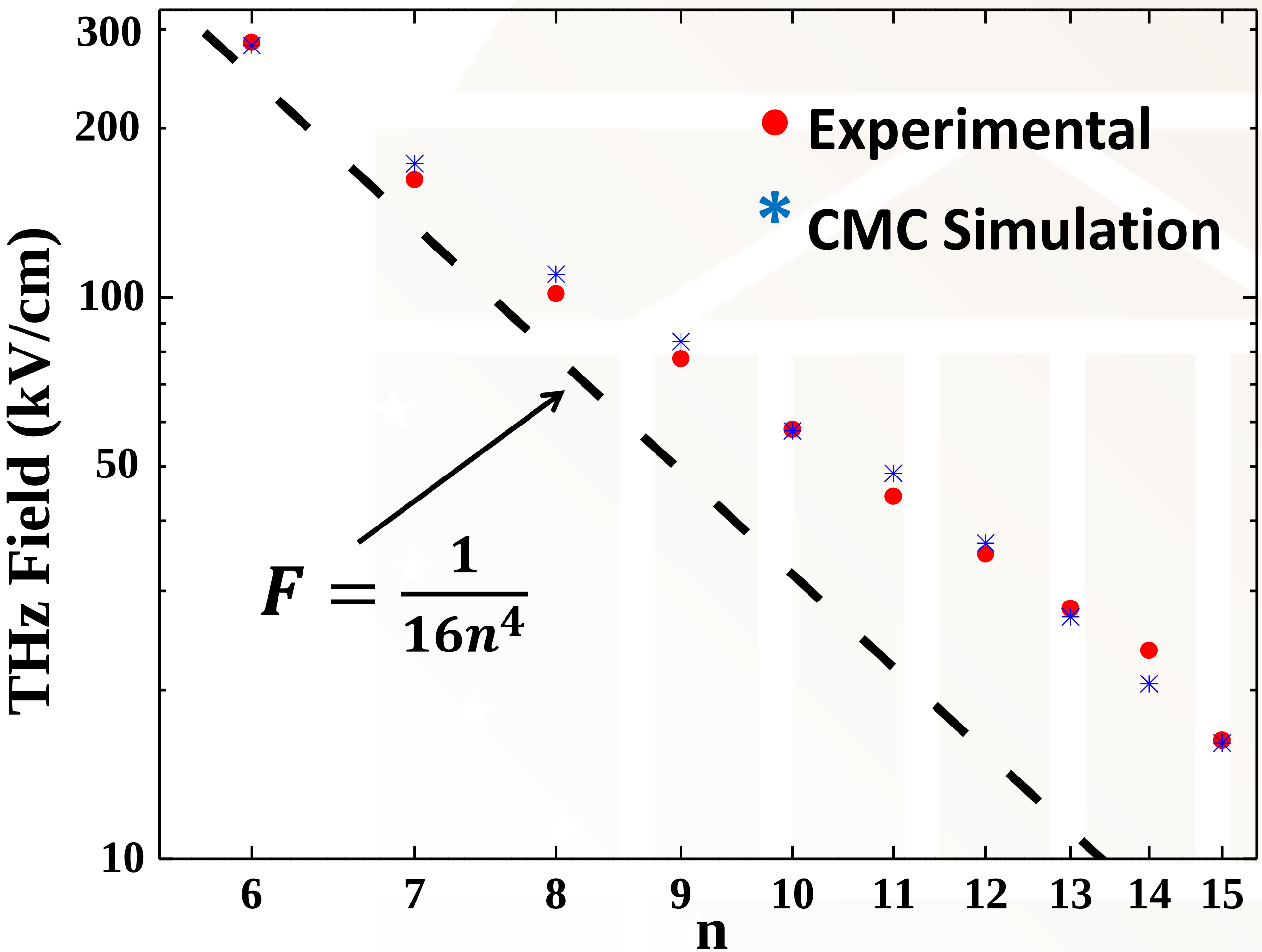
THz ionization: Experimental Setup



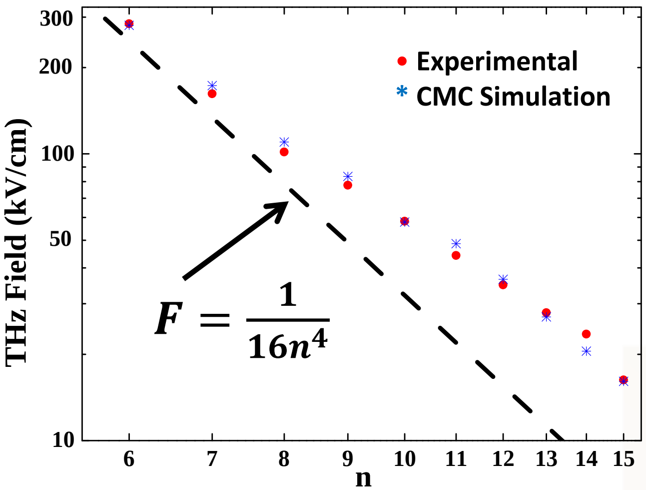
Ion yield curve

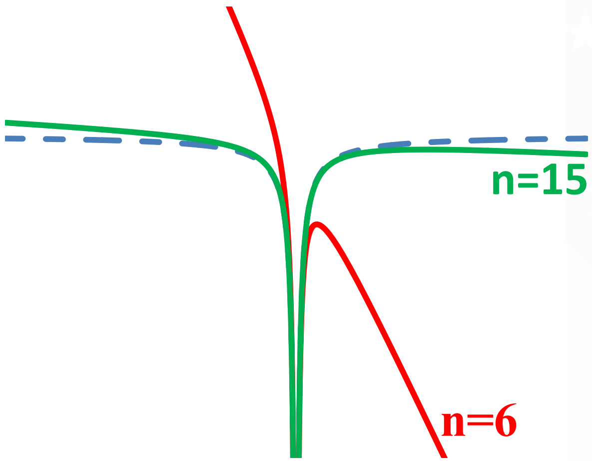


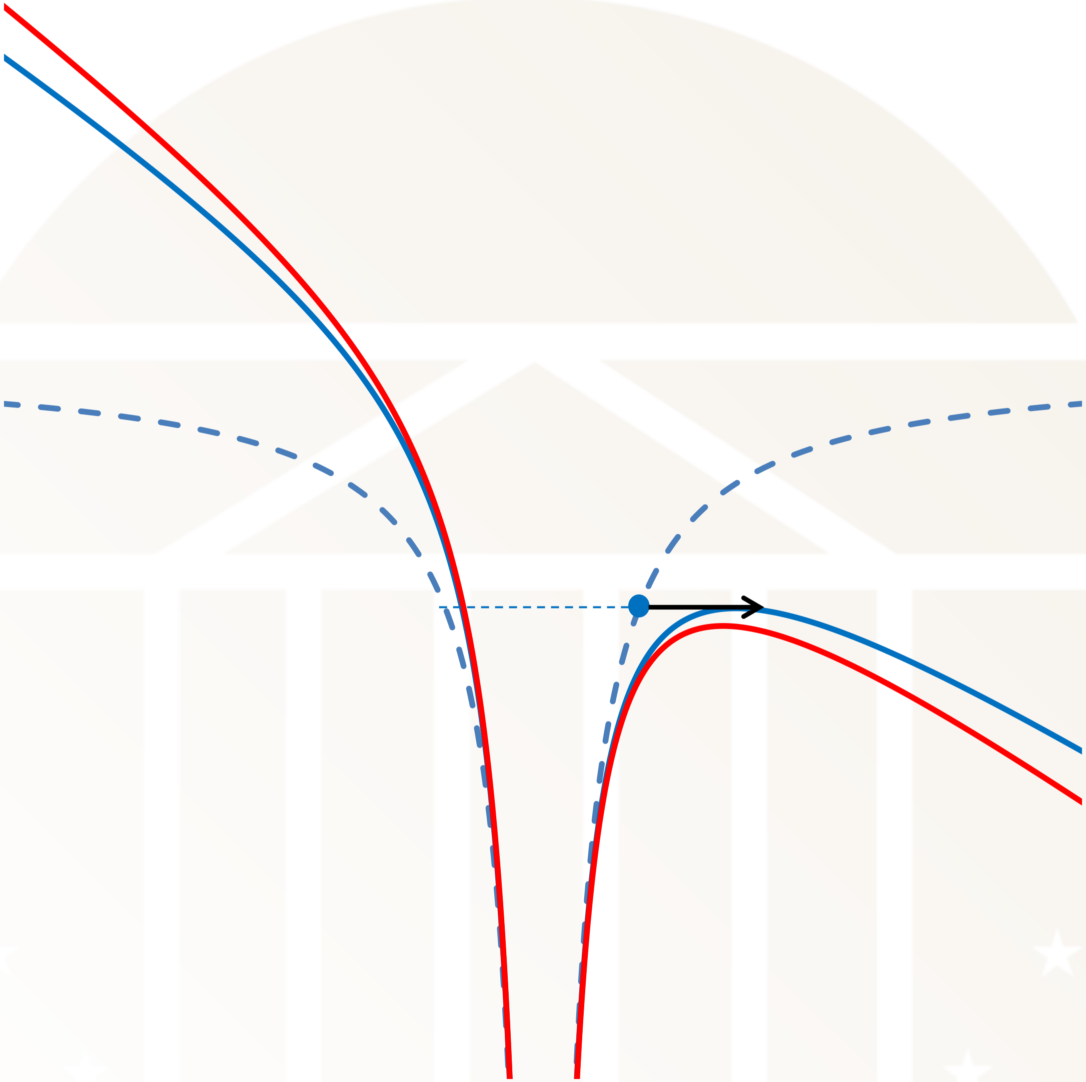
New Scale Law: $F \propto \frac{1}{n^3}$!!!



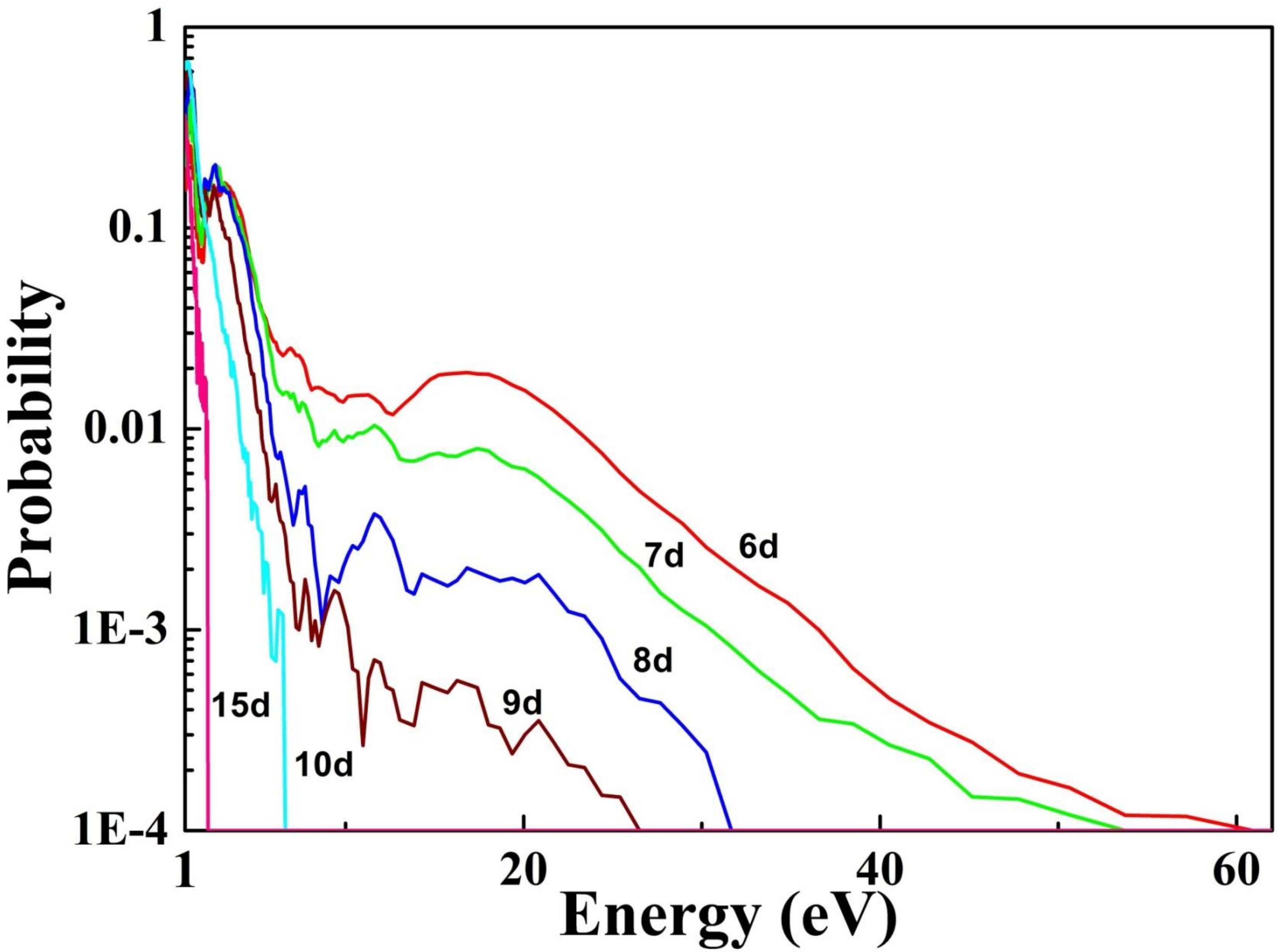
THz ionization of low-lying Rydberg atoms



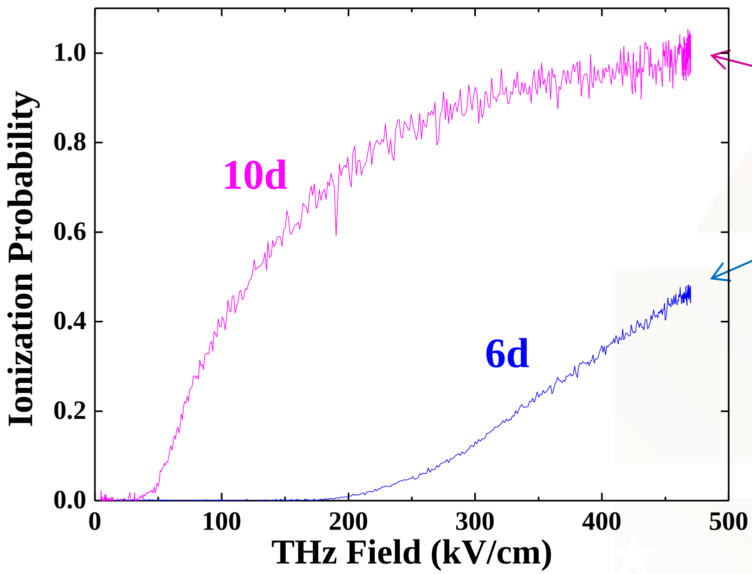


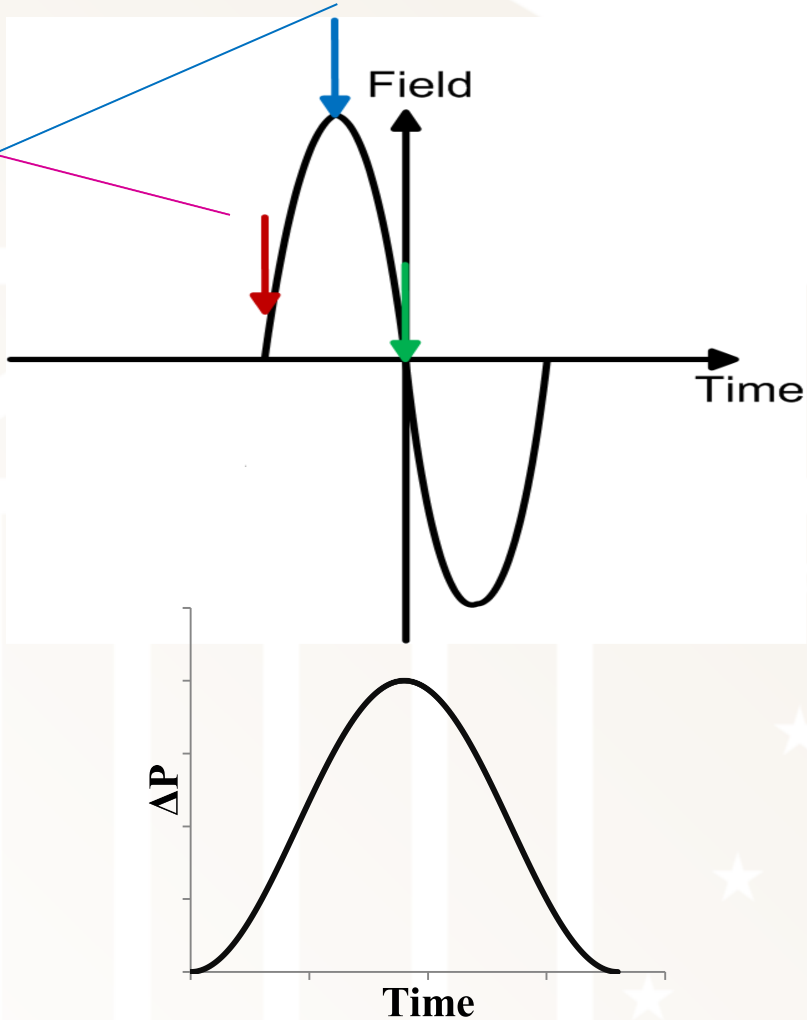


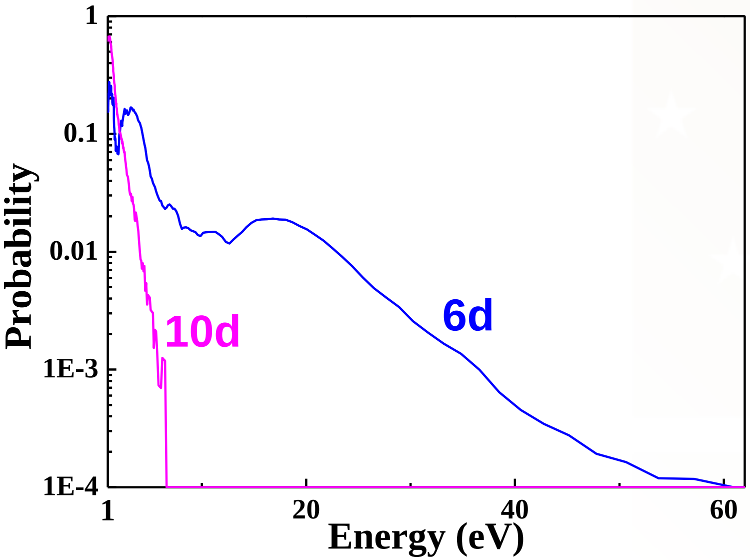
Electron energy distributions at Max THz field (470 kV/cm)



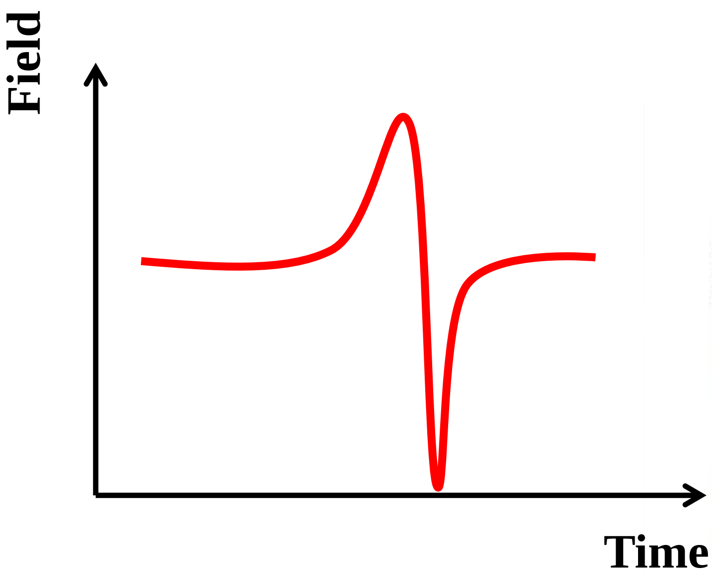
Qualitative analysis

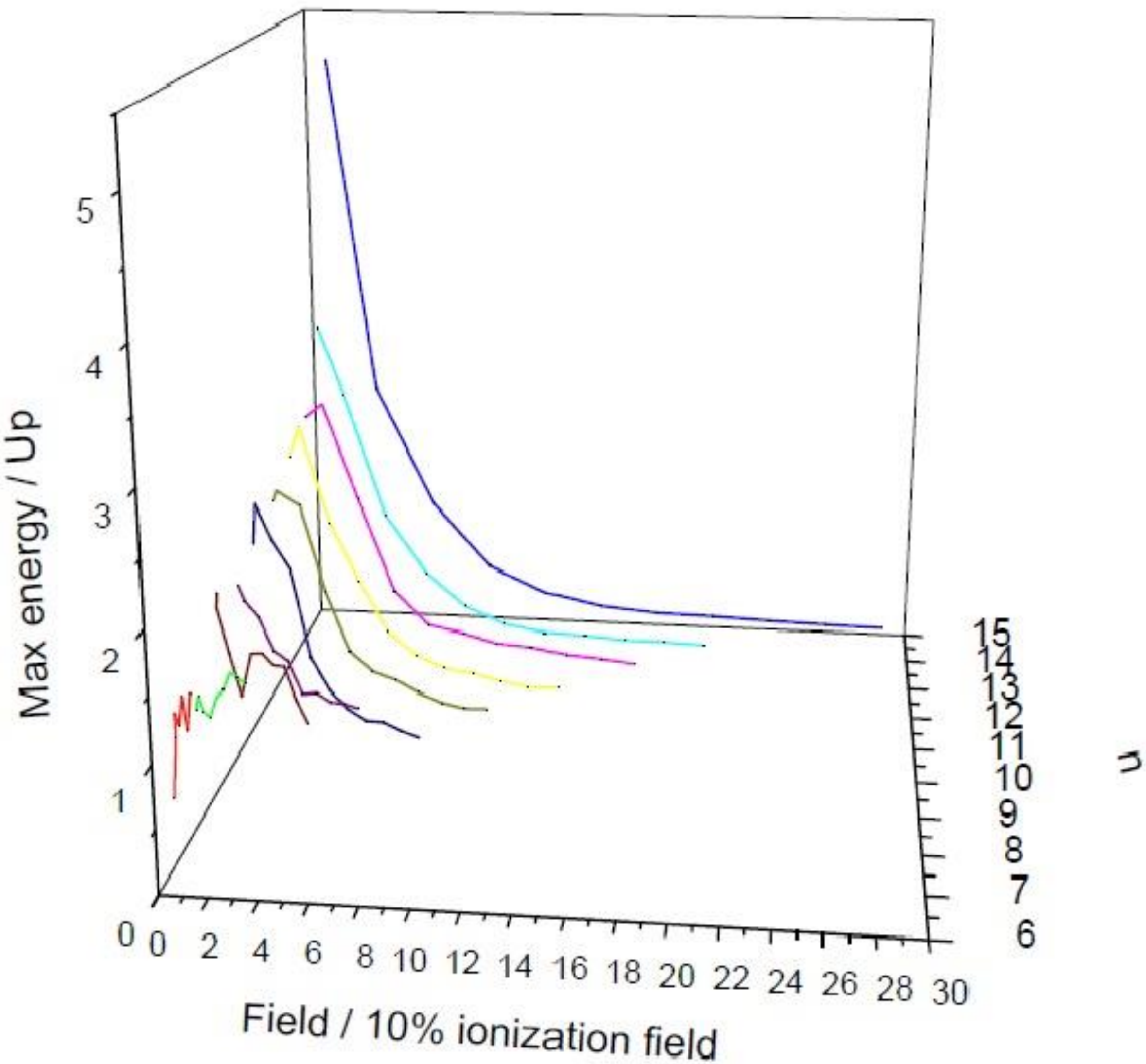






$$\Delta p = -\int_{t}^{\infty} F(t)dt$$


Field
Time


Max energy / Up
Field / 10% ionization field
n
0
1
2
3
4
5
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
6 7 8 9 10 11 12 13 14 15

Ponderomotive Energy

Up: The cycle averaged quiver energy of a free electron in an oscillating electric field:

$$Up = \frac{e^2F^2}{4m\omega^2} = \frac{F^2}{4\omega^2}\ \text{(a.u.)}$$

2Up: The max energy a free electron can get from a oscillating electric field that slowly decreases in aptitude:

Max energy=2Up

What if the field have only a few cycles, or even one single cycle?

Analyze electron energy distributions

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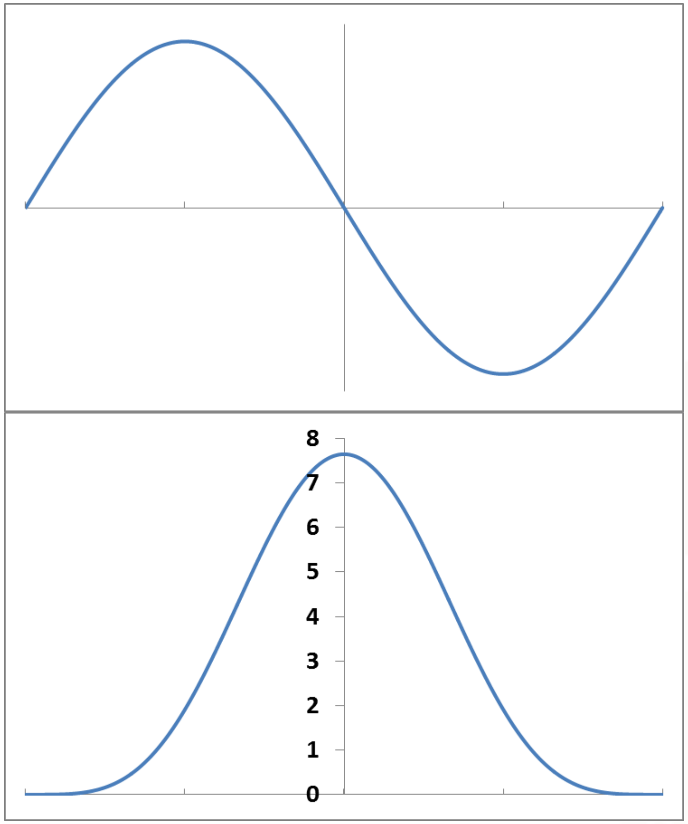
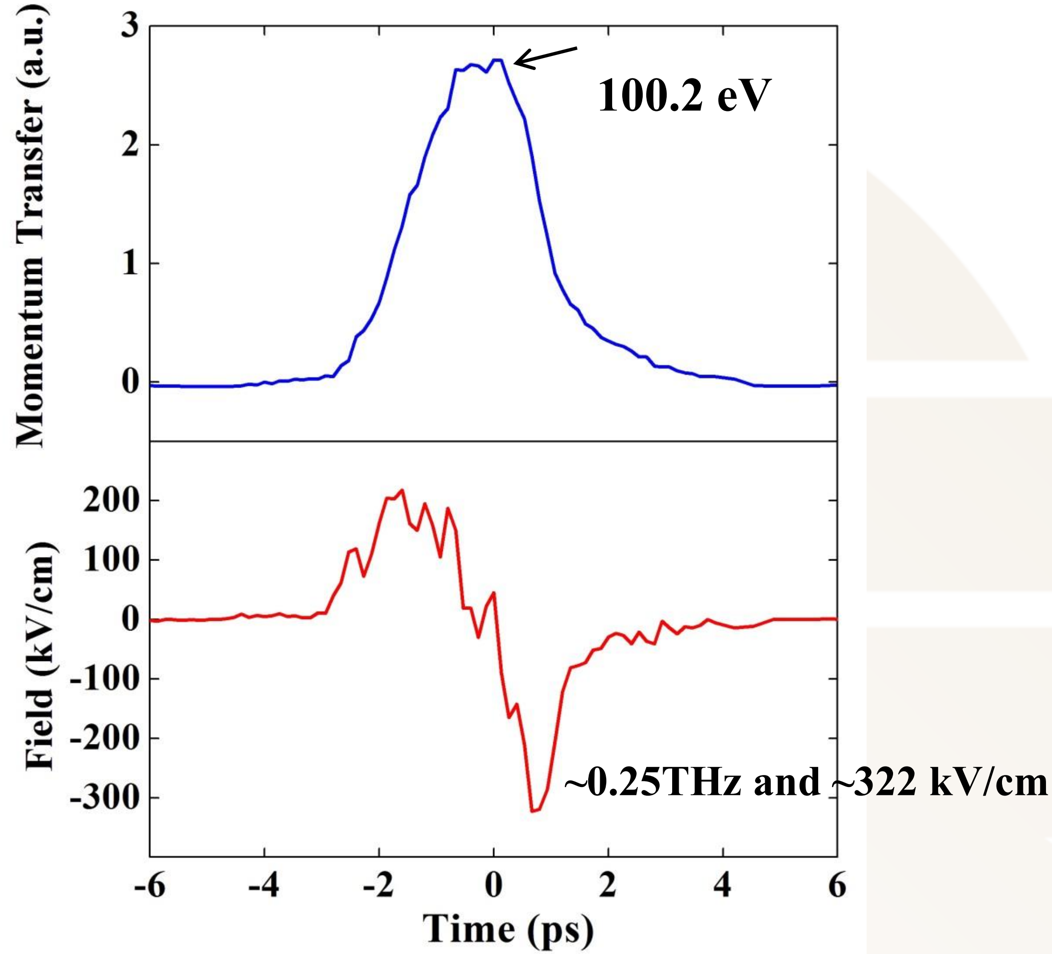




$$F(t) = F_0 \sin(\omega t)$$

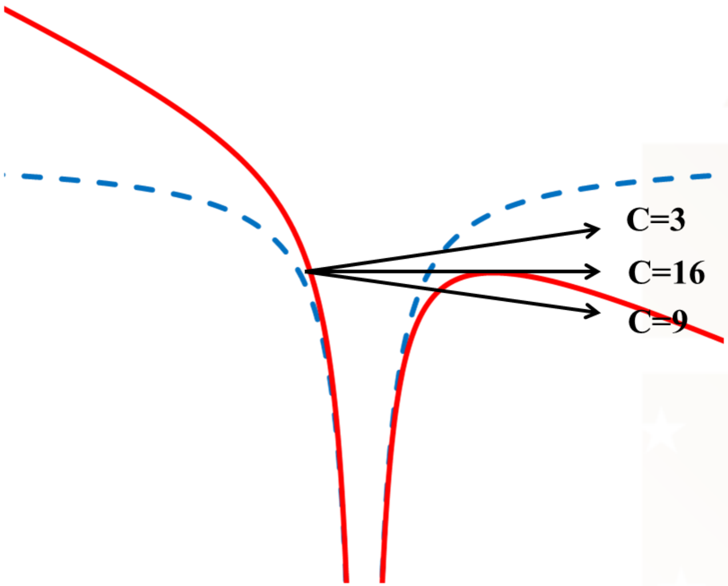
$$\Delta P = -\int_{t0}^{\infty} F(t)dt$$

$$\Delta E = (2P_0 \Delta P + (\Delta P)^2)/2$$

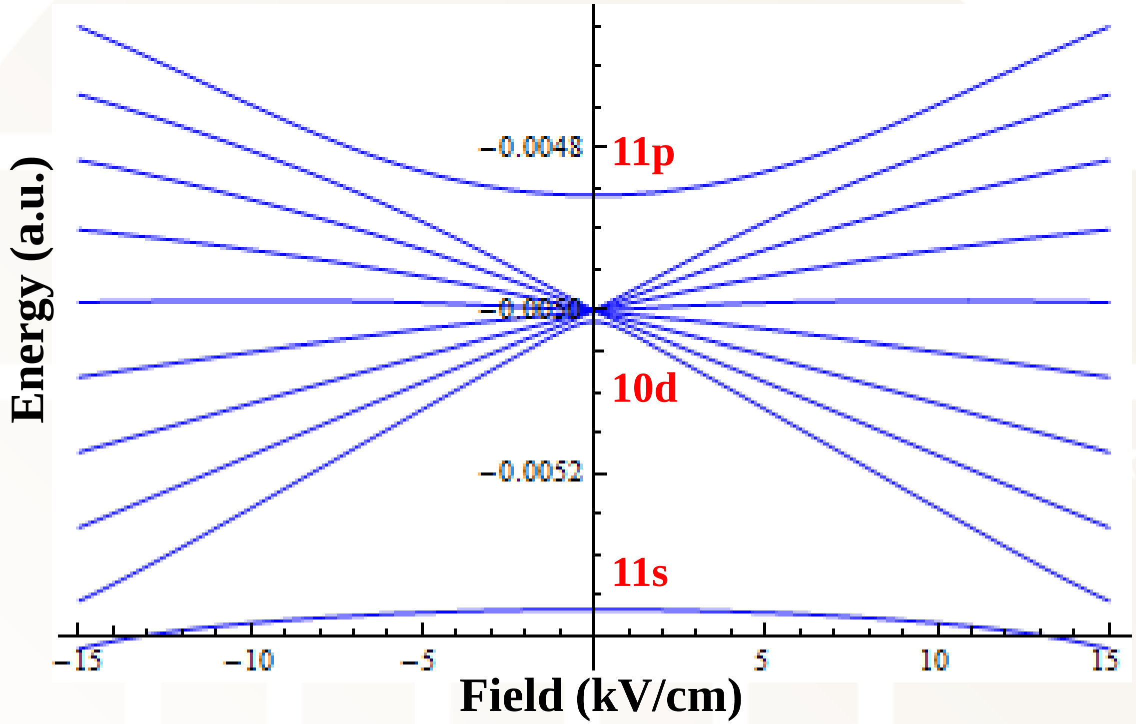
$$Up = \frac{F^2}{4\omega^2} \approx 18.5\ eV$$

Max energy~ $5.4\ Up$!!!

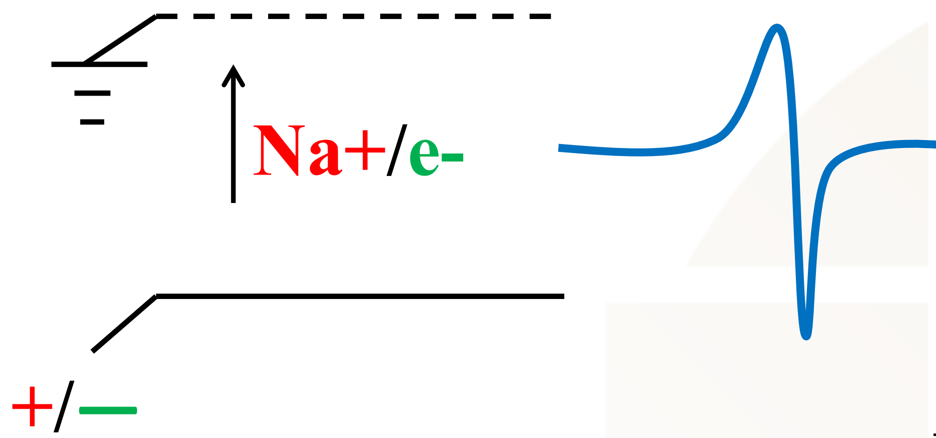
What if the Rydberg atoms are initially prepared in Stark states?

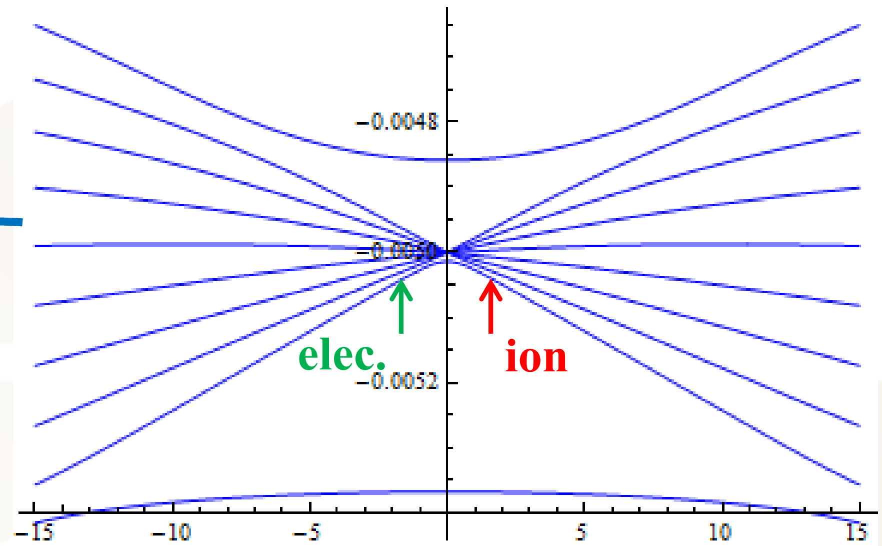


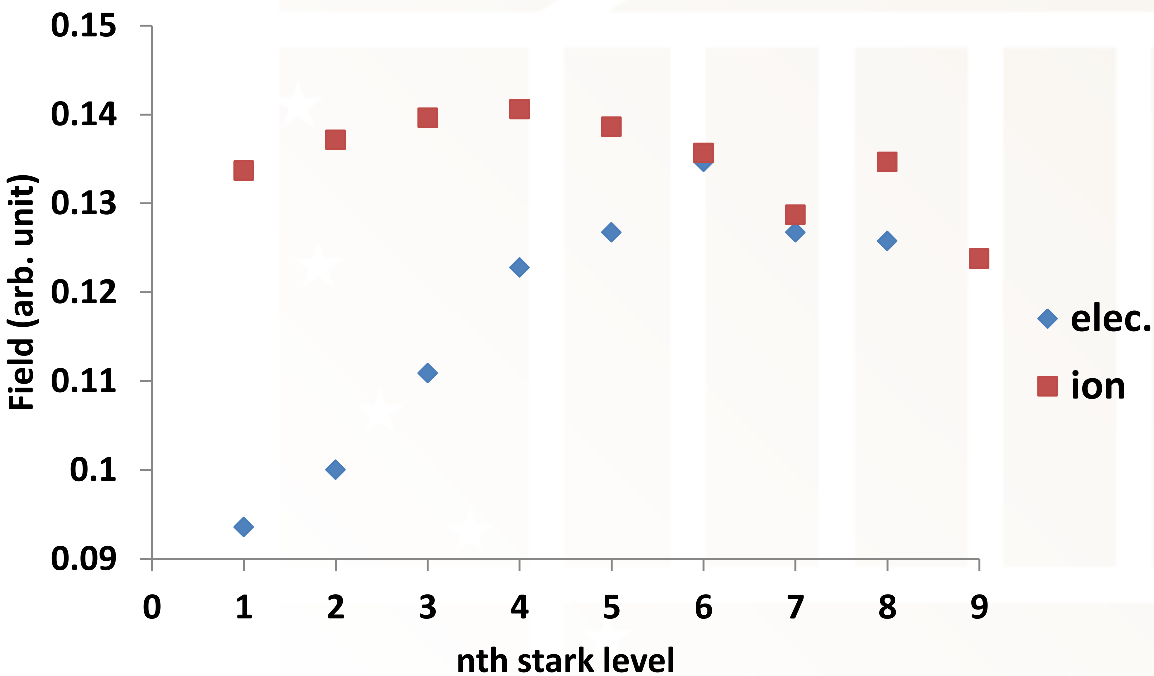
$$F = \frac{1}{Cn^4}$$



Na n=10, m=0 Stark manifold


Na+/e-
+/—


−0.0048
−0.0050
−0.0052
elec.
ion
−15
−10
−5
5
10
15


Field (arb. unit)
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0
1
2
3
4
5
6
7
8
9
nth stark level
elec.
ion

Landau-Zener Transition

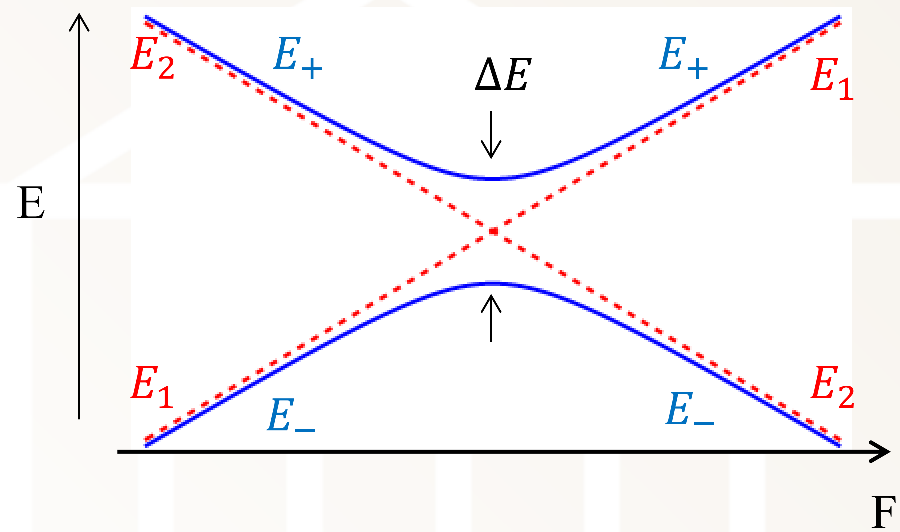
Simplest case: 2-level

$$\mathbf{H(F)}=\begin{pmatrix} E_1(F) & \frac{1}{2}\Delta E \\ \frac{1}{2}\Delta E & E_2(F) \end{pmatrix}$$

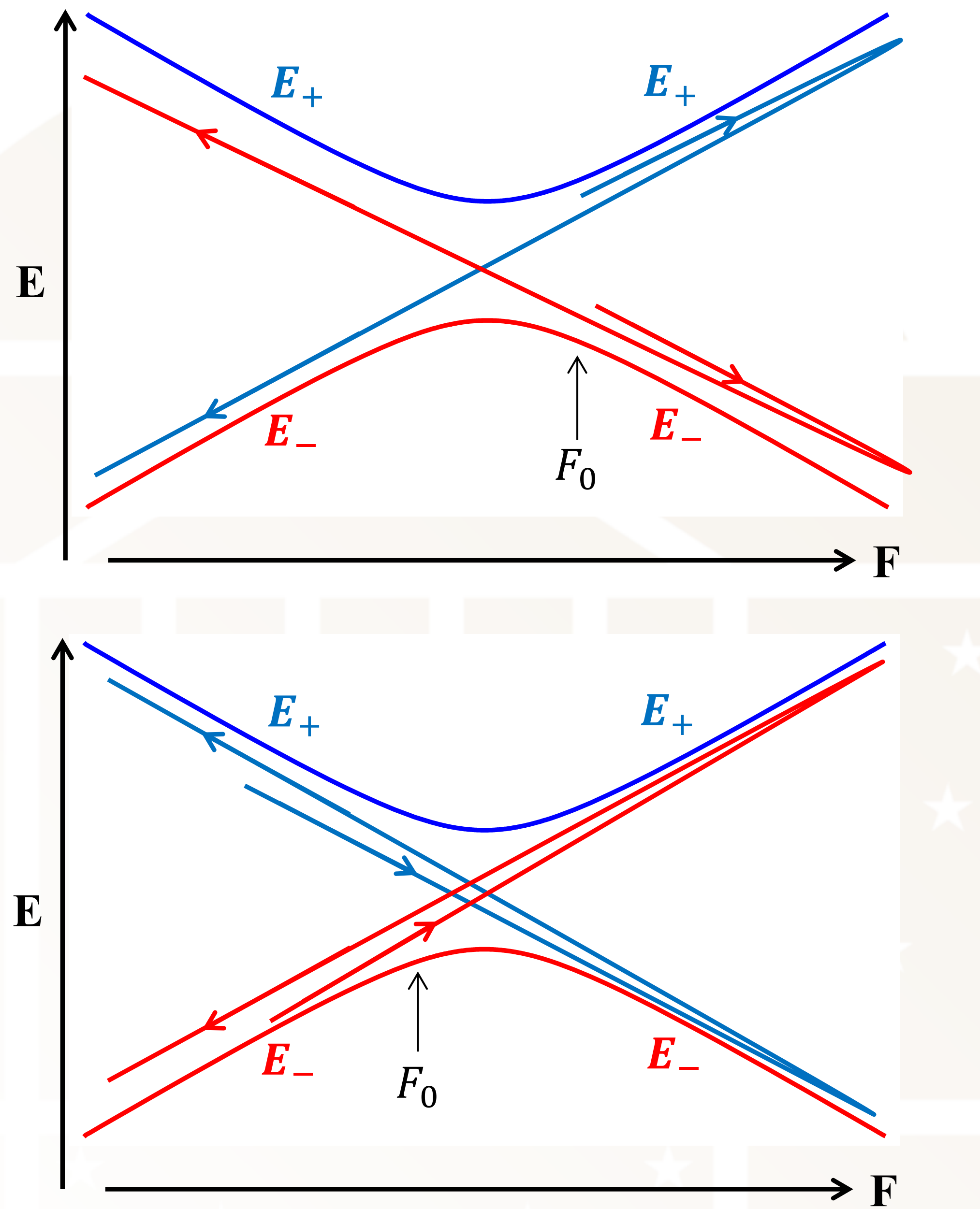
ΔE: coupling/quantum defect

$$P^{dia}=e^{-2\pi\Gamma}$$

$$\Gamma=\frac{(\frac{1}{2}\Delta E)^2}{\left|\frac{dE1}{dt}-\frac{dE2}{dt}\right|}=\frac{(\frac{1}{2}\Delta E)^2}{\left|\dot{F}\left(\frac{dE1}{dF}-\frac{dE2}{dF}\right)\right|}$$

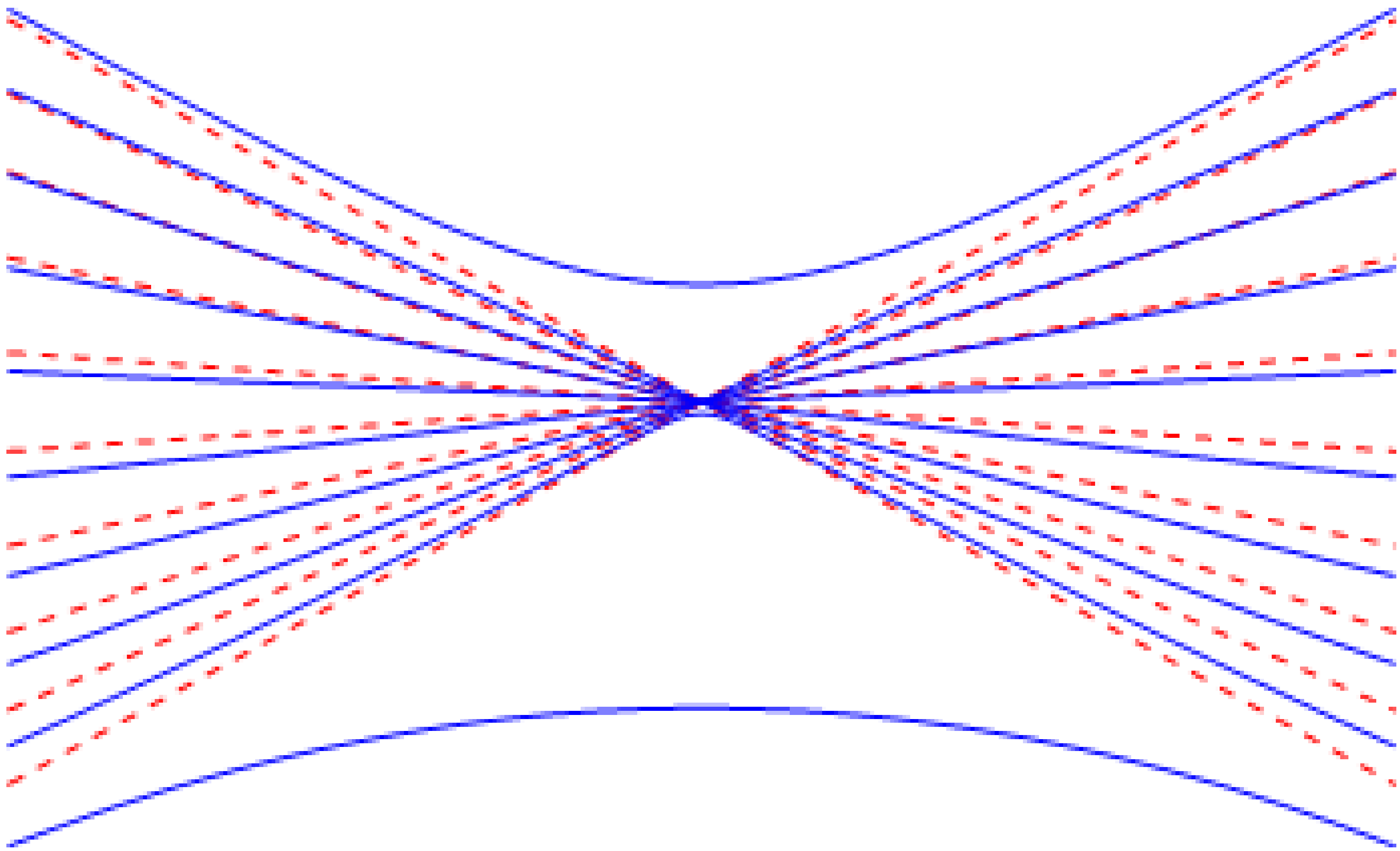



THz field
t


E
E_+
E_+
E_-
E_-
F_0
F
E
E_+
E_+
E_-
E_-
F_0
F

What may influence the result ?

- Aptitude of static field
- Direction of static field (Relative to THz)
- Initial stark level
- Asymmetry of THz and THz slew rate



Multi-level Landau-Zener Transitions

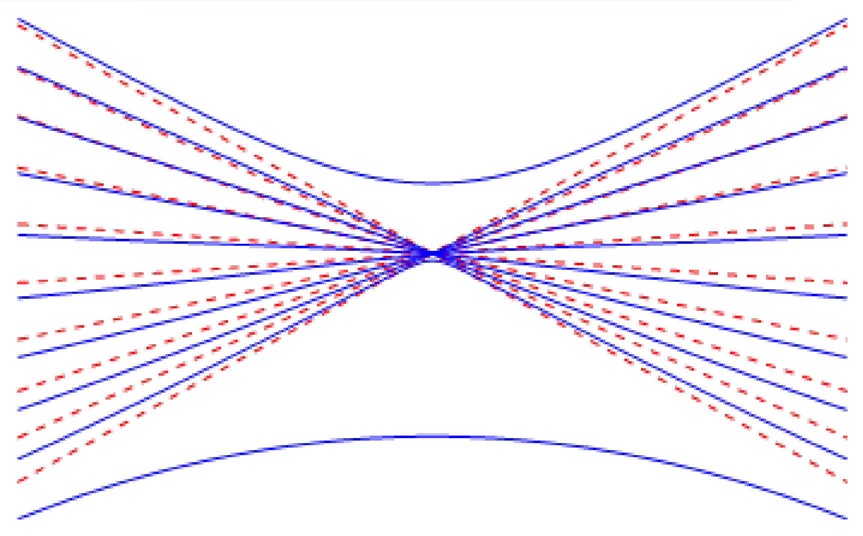
$$i\frac{\partial\psi(t)}{\partial t} = H(t)\psi(t)$$

$$\psi(t) = \sum_n C_n(t)\psi_n(t)e^{-iE_n(t)t}$$

Spherical basis $|n,l,m>$: Ψ_n , E_n

$$i\dot{C}_f(t) = \sum_n C_n(t)H_{fn}(t)e^{i\Delta E_{fn}t}$$

Parabolic/Diabatic basis $|n,k,m>$: Ψ_n , $E_n(t)$



$$i\dot{C}_f(t) = \sum_n C_n(t)H_{fn}(t)e^{\int_0^t i\Delta E_{fn}(t)dt}$$

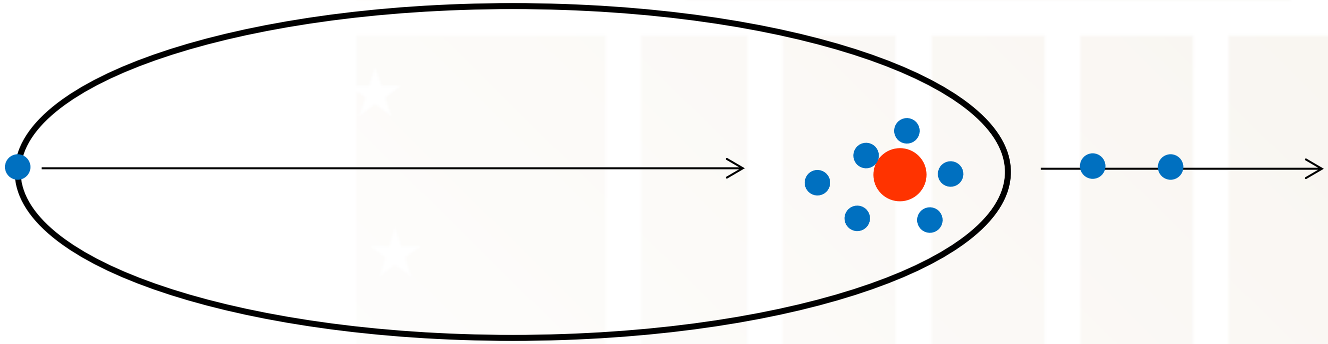
Adiabatic/Local basis :
(no good quantum #) $\Psi_n(t)$, $E_n(t)$

Still working on numerical simulation codes !

Future plan

Electron Scattering

- Electron been "dragged back" by THz to the nucleus and "knocks off" more electrons.



Conclusion

Intense THz generation via optical rectification

- Can generate THz with peak field strength as high as 500 kV/cm

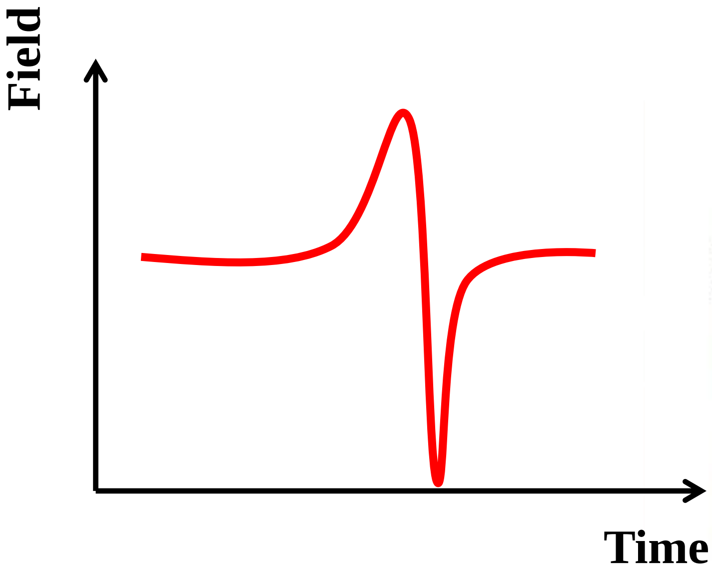
THz streak & Electron energy distributions

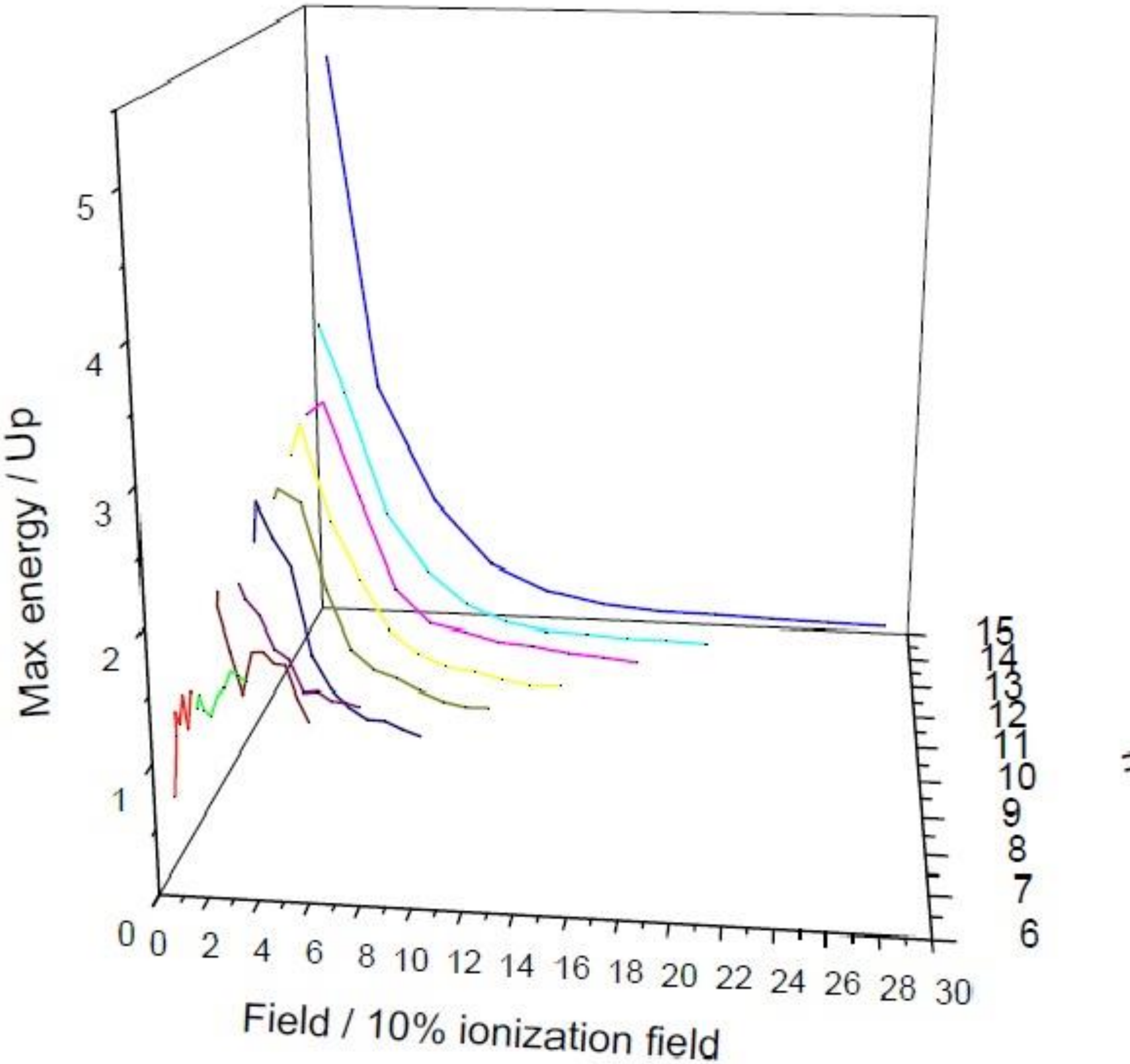
- Can measure THz waveform inside the chamber.
- Electrons from ionization of lower n states have higher energies
- Electron energy distribution shows the asymmetry of the field
- In THz streak, have electrons with energy exceed 2Up.

THz ionization of low-lying Rydberg atoms and Rydberg stark states

- Ionization of low-lying Rydberg atoms: Scales as 1/n^3
- Ionization of Rydberg stark states: Shows the asymmetry and fast property of THz field.

Thank you!

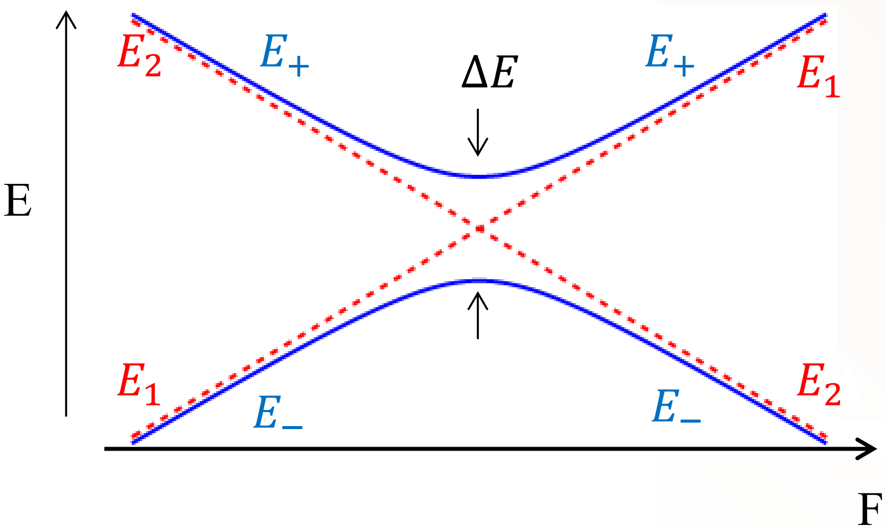

Field
Time

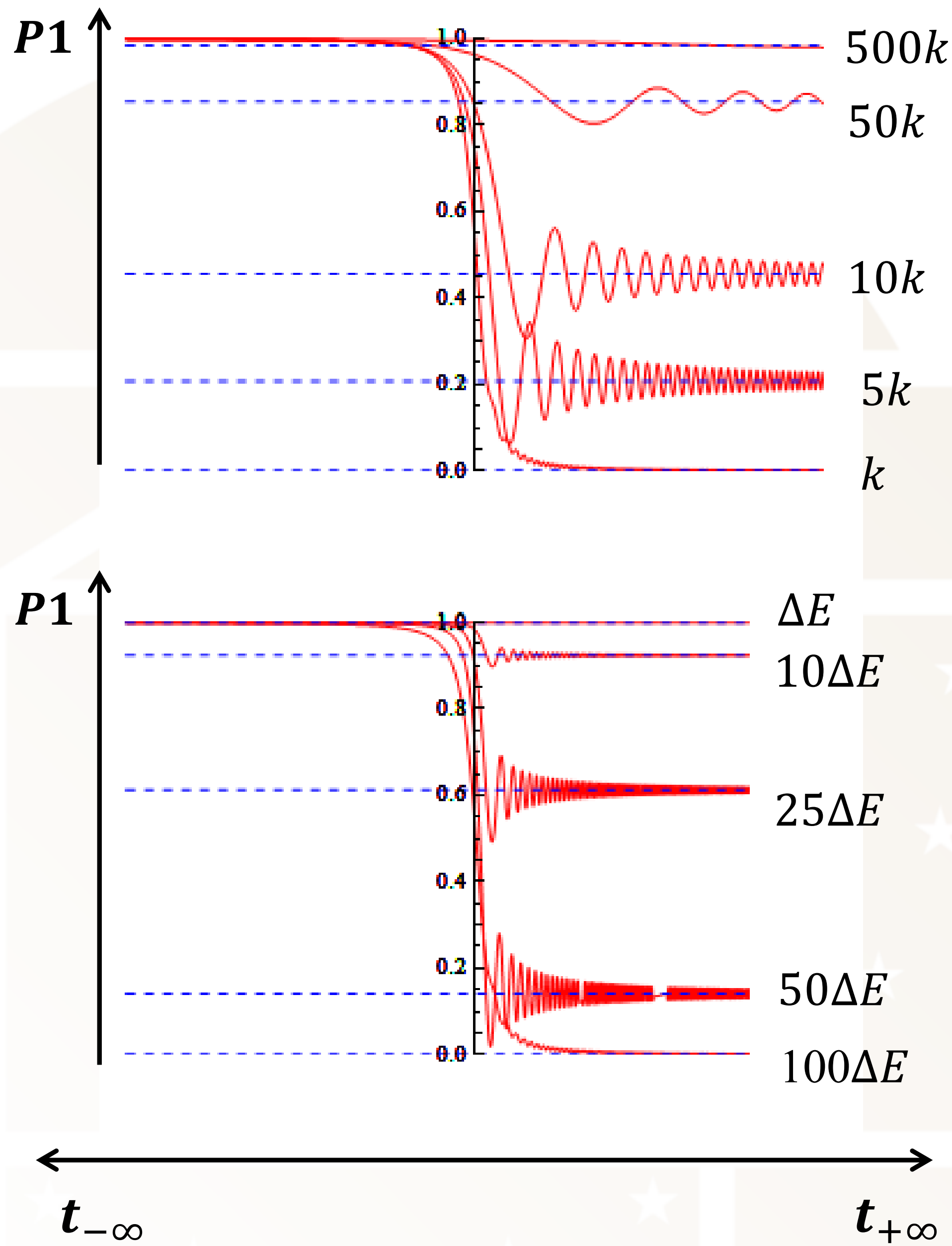

Max energy / Up
0
1
2
3
4
5
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Field / 10% ionization field
n
6 7 8 9 10 11 12 13 14 15

Numerical Simulation: 2 -Level

$$\Gamma = \frac{(\frac{1}{2}\Delta E)^2}{|\frac{dE1}{dt} - \frac{dE2}{dt}|} = \frac{(\frac{1}{2}\Delta E)^2}{|\dot{F}\left(\frac{dE1}{dF} - \frac{dE2}{dF}\right)|}$$

Initially in state "—", with a linear ramp $F = kt$ from very large negative time to very large positive time. work in |1>,|2> basis





THz ionization of low-lying Rydberg atoms

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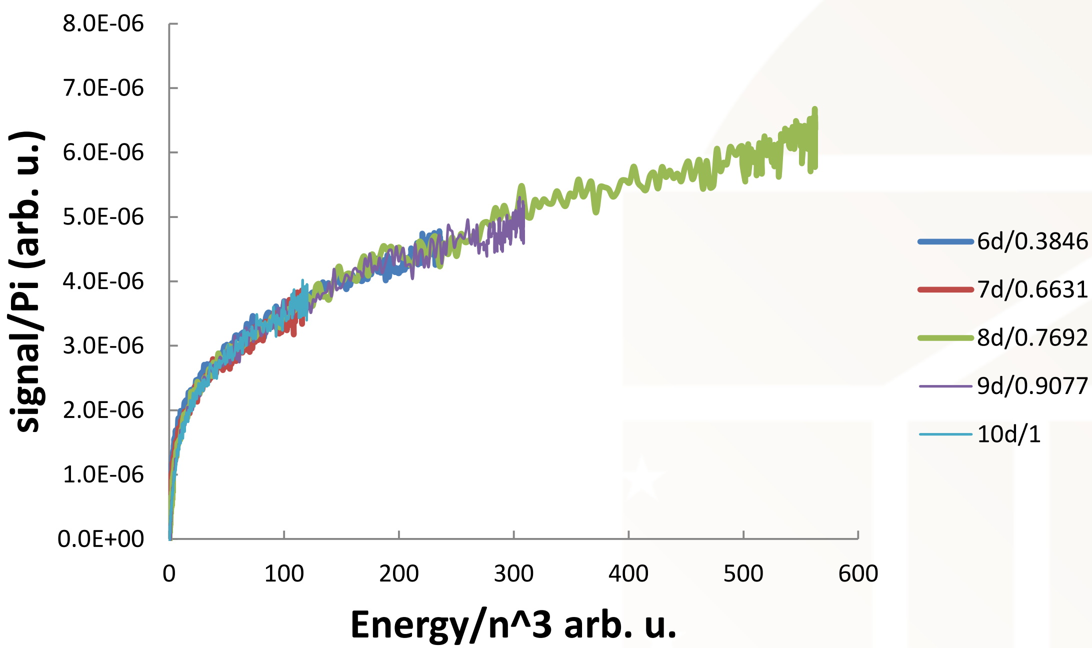


3s-nd excitation prob. curves

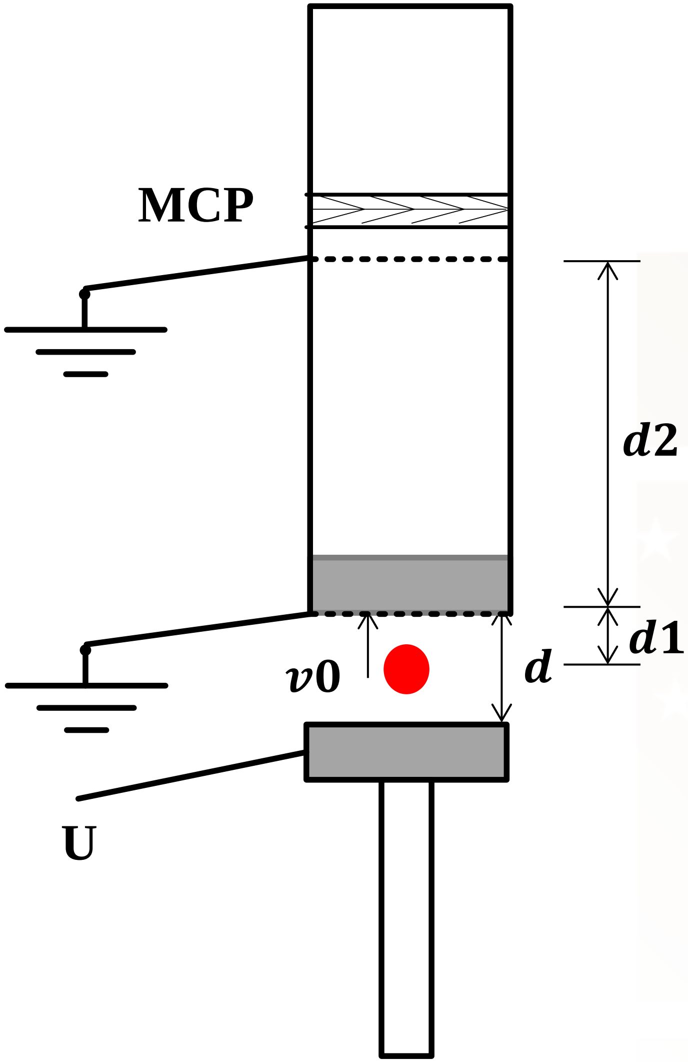
$$sig. \propto P_e P_i N_{3s}$$

$$P_e = \alpha \frac{E}{n^3}$$

$$\frac{sig}{P_i} \propto P_e N_{3s} = \alpha \frac{E}{n^3} N_{3s}$$

$$\frac{sig}{P_i} \propto \frac{E}{n^3}$$

Time of Flight (ToF) spectrometer



$$t - t_0 = \frac{md}{eU}\left(\sqrt{v_0^2 + \frac{2d_1 eU}{md}} - v_0\right) + \frac{d_2}{\sqrt{v_0^2 + \frac{2d_1 eU}{md}}}$$