ROBUST COHERENT WAVEPACKET CREATION BY MEANS OF DISSIPATION

Alejandro Saenz

AG Moderne Optik
Institut für Physik
Humboldt-Universität zu Berlin

(QSIM19 at KITP Santa Barbara, 24.04.2019)

Overview

- Strong-field / attosecond physics in a (very tiny) nutshell.

Overview

- Strong-field / attosecond physics in a (very tiny) nutshell.
- Bond-softening and *Lochfraß*:
  coherent wave-packet formation in intense laser fields.

Overview

- Strong-field / attosecond physics in a (very tiny) nutshell.
- Bond-softening and *Lochfraß*:
  coherent wave-packet formation in intense laser fields.
- An ultracold-atom based quantum simulator for attosecond science.

Overview

- Strong-field / attosecond physics in a (very tiny) nutshell.
- Bond-softening and *Lochfraß*:
  coherent wave-packet formation in intense laser fields.
- An ultracold-atom based quantum simulator for attosecond science.
- Toward (interacting?) many-body systems . . .

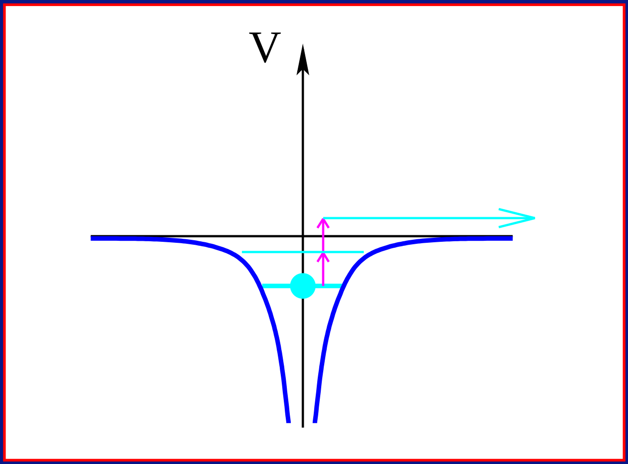
Overview

- Strong-field / attosecond physics in a (very tiny) nutshell.
- Bond-softening and *Lochfraß*:
  coherent wave-packet formation in intense laser fields.
- An ultracold-atom based quantum simulator for attosecond science.
- Toward (interacting?) many-body systems . . .

Disclaimer:

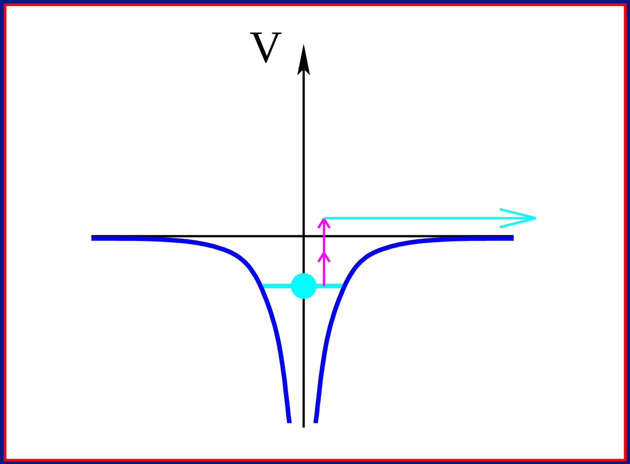
This talk tries to invoke discussions (and leaves many questions unanswered . . .).

Qualitative strong-field ionization models



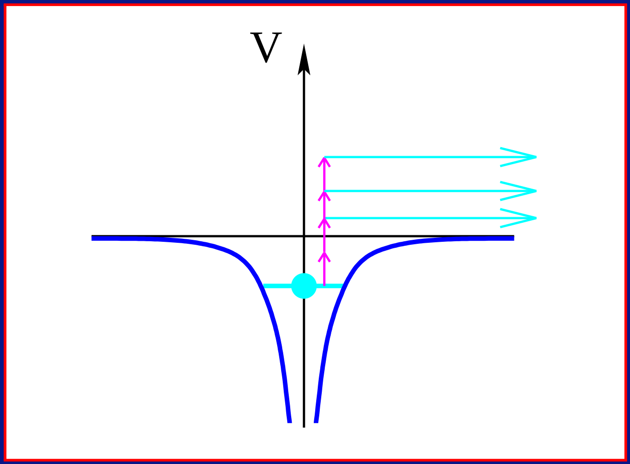
REMPI

Resonance-enhanced multiphoton ionization



Multiphoton Ionization

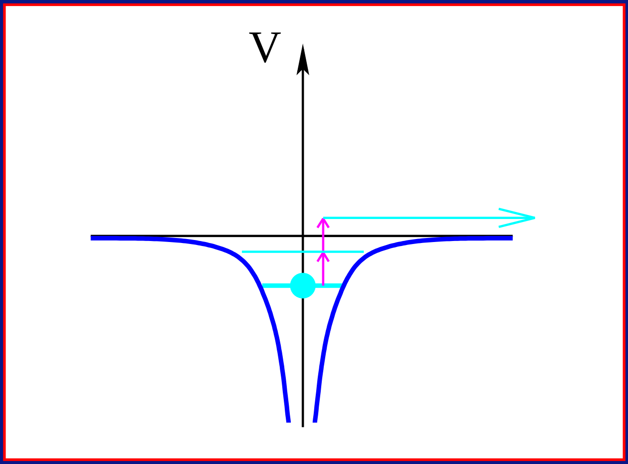
Non-resonant multiphoton ionization



ATI

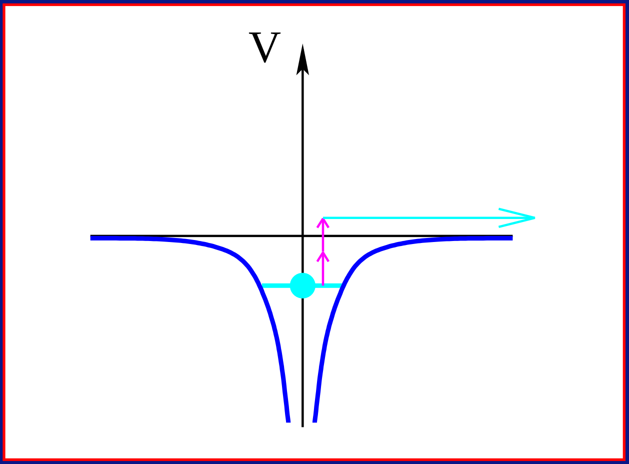
Above-threshold ionization

Qualitative strong-field ionization models



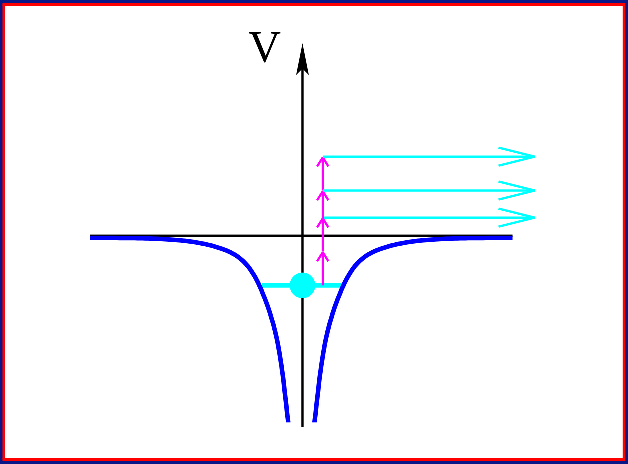
REMPI

Resonance-enhanced multiphoton ionization



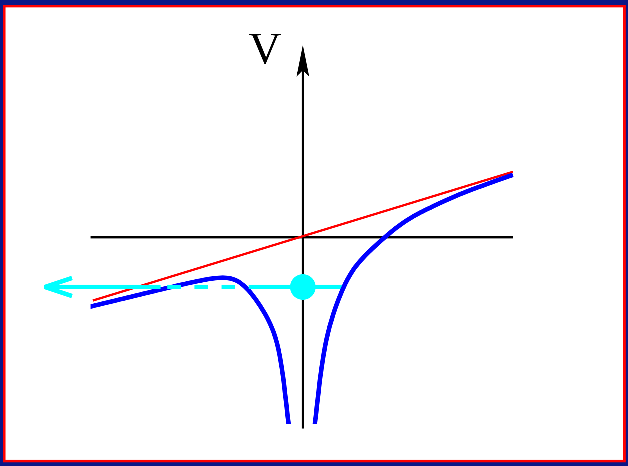
Multiphoton Ionization

Non-resonant multiphoton ionization

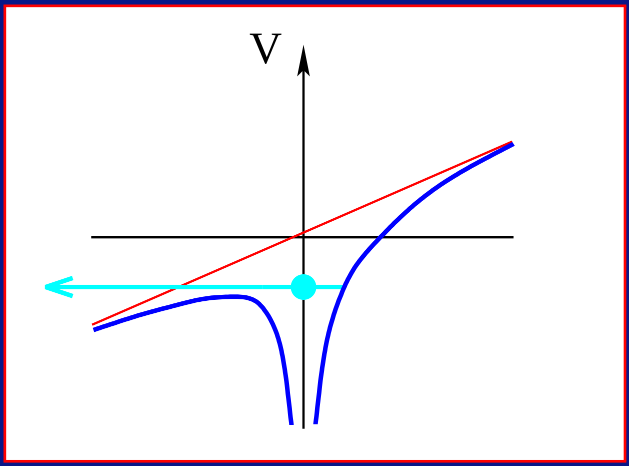


ATI

Above-threshold ionization



Tunnel ionization



Over-the-barrier ionization

Multiphoton regime

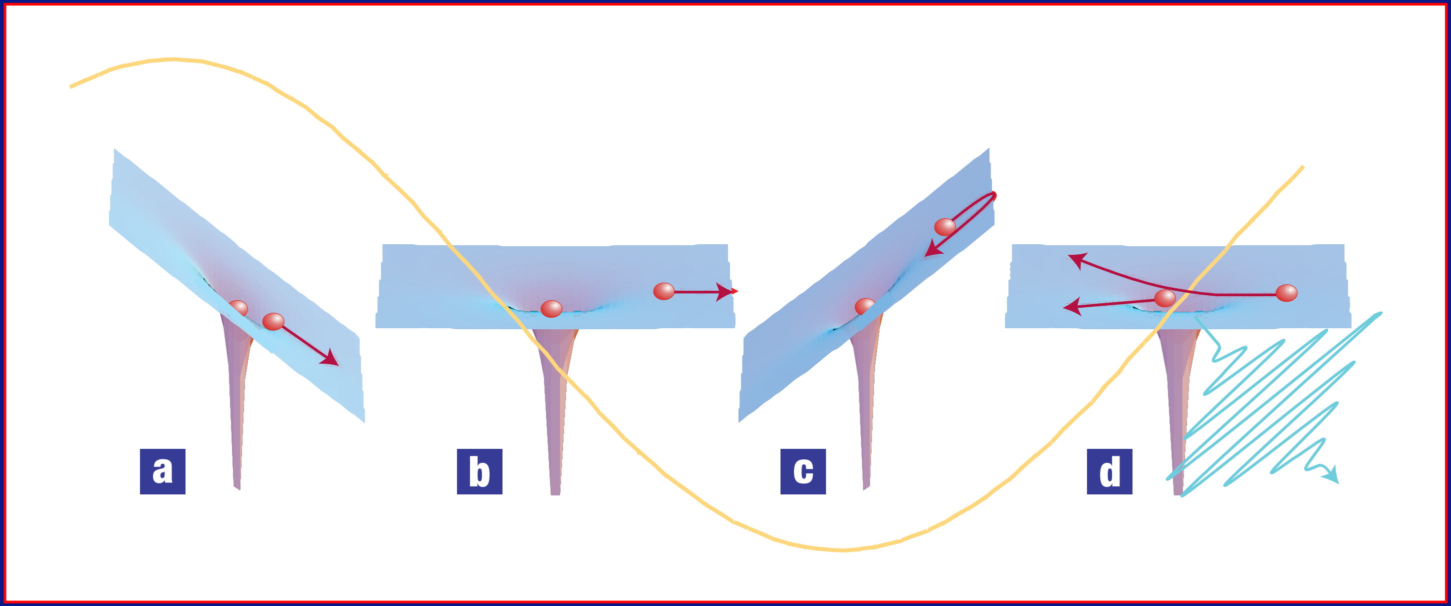
(upper row)

vs.

Quasi-static regime

(lower row)

Corkum's 3-step model:

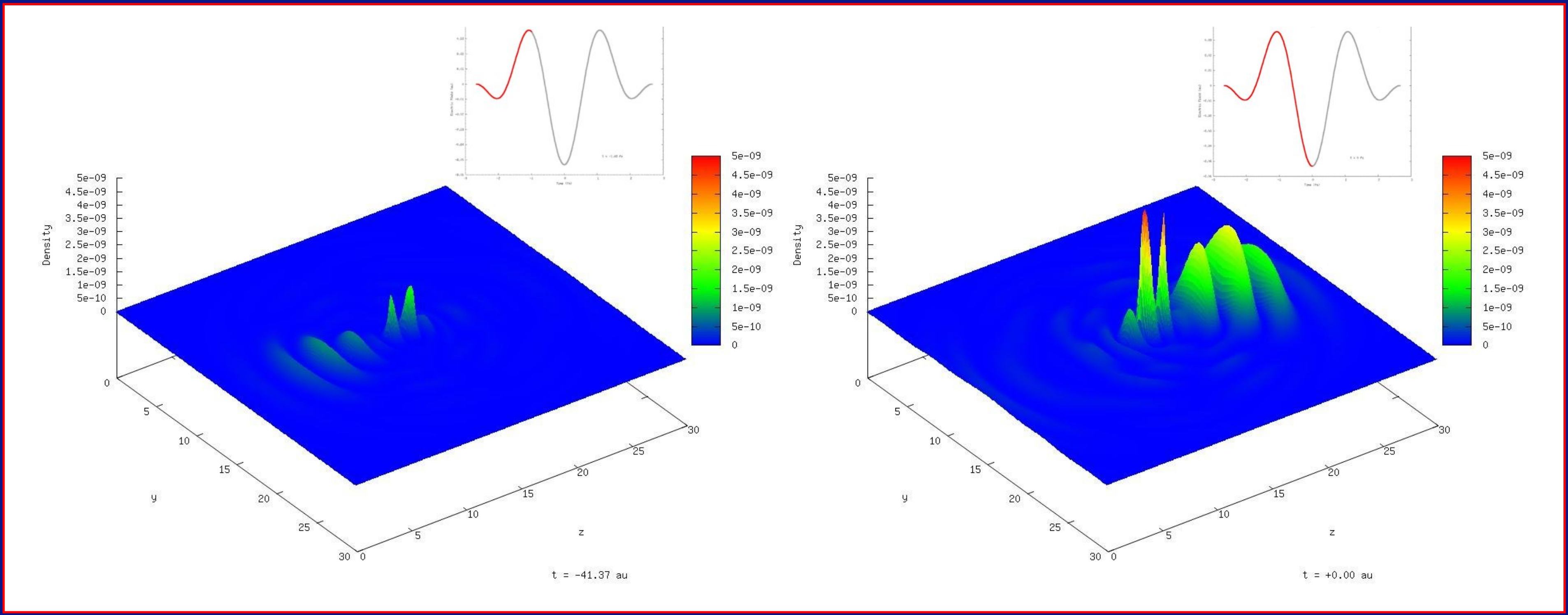


review: P. B. Corkum and F. Krausz, *Nature Phys.* **3**, 381 (2007)

1. Electron escapes through or over the electric-field lowered Coulomb potential (a).
2. Electronic wavepacket moves away until the field direction reverses (b) and is (partly) driven back to its parent ion (c).
3. The returning electron may (d)
   - scatter elastically (electron diffraction)
   - scatter inelastically (excitation, dissociation, double ionisation, . . .)
   - recombine radiatively (high-harmonic radiation).

⟶ **time-resolved imaging, attosecond pulses, . . .**

Example electronic wavepacket (H_2^+)

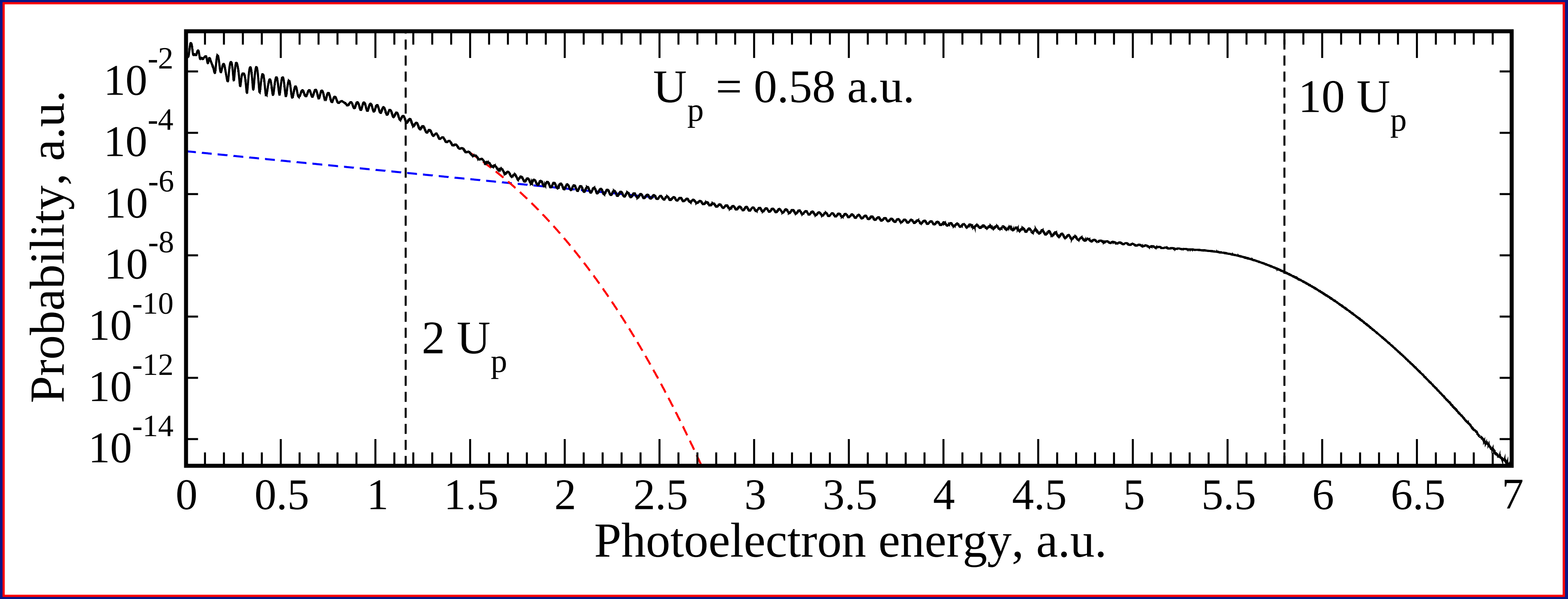


Electronic wavepacket at two different times within a 2-cycle laser pulse.

(Only the continuum part is shown.)

⟶ strongly driven dissipative quantum system.

Example electron spectrum (ATI)



Hydrogen atom (laser parameters: 1300 nm; 6 cycles; $\cos^2$; $I_{\max} = 10^{14}\,\mathrm{W/cm^2}$).

Direct electrons: 0 to about 2 times the ponderomotive energy $\mathrm{U_p} = I/(4\omega^2)$.

Rescattered electrons: dominate spectrum beyond 2 $\mathrm{U_p}$.

$\longrightarrow$ extremely highly non-linear process.

From atoms to molecules:

Atoms in ultrashort intense laser fields:

- Numerical solution of Schrödinger equation extremely demanding, even for very few particles.

From atoms to molecules:

Atoms in ultrashort intense laser fields:

- Numerical solution of Schrödinger equation extremely demanding, even for very few particles.
- Strongly driven open (dissipative) system: great!

From atoms to molecules:

Atoms in ultrashort intense laser fields:

- Numerical solution of Schrödinger equation extremely demanding, even for very few particles.
- Strongly driven open (dissipative) system: great!
- However: very "boring" (structureless) environment: bad!

From atoms to molecules:

Atoms in ultrashort intense laser fields:

- Numerical solution of Schrödinger equation extremely demanding, even for very few particles.
- Strongly driven open (dissipative) system: great!
- However: very “boring” (structureless) environment: bad!
- What about molecules (adding the nuclear degree of freedom)?

From atoms to molecules:

Atoms in ultrashort intense laser fields:

- Numerical solution of Schrödinger equation extremely demanding, even for very few particles.
- Strongly driven open (dissipative) system: great!
- However: very "boring" (structureless) environment: bad!
- What about molecules (adding the nuclear degree of freedom)?

Tunneling ionization rate: (see, e. g., Landau-Lifshitz)

$$\Gamma(F) \;\propto\; \exp\left[-\frac{2\,(2\,E_b)^{3/2}}{3F}\right]$$

with field electric strength F and electron's binding energy E_b.

From atoms to molecules:

Atoms in ultrashort intense laser fields:

- Numerical solution of Schrödinger equation extremely demanding, even for very few particles.
- Strongly driven open (dissipative) system: great!
- However: very "boring" (structureless) environment: bad!
- What about molecules (adding the nuclear degree of freedom)?

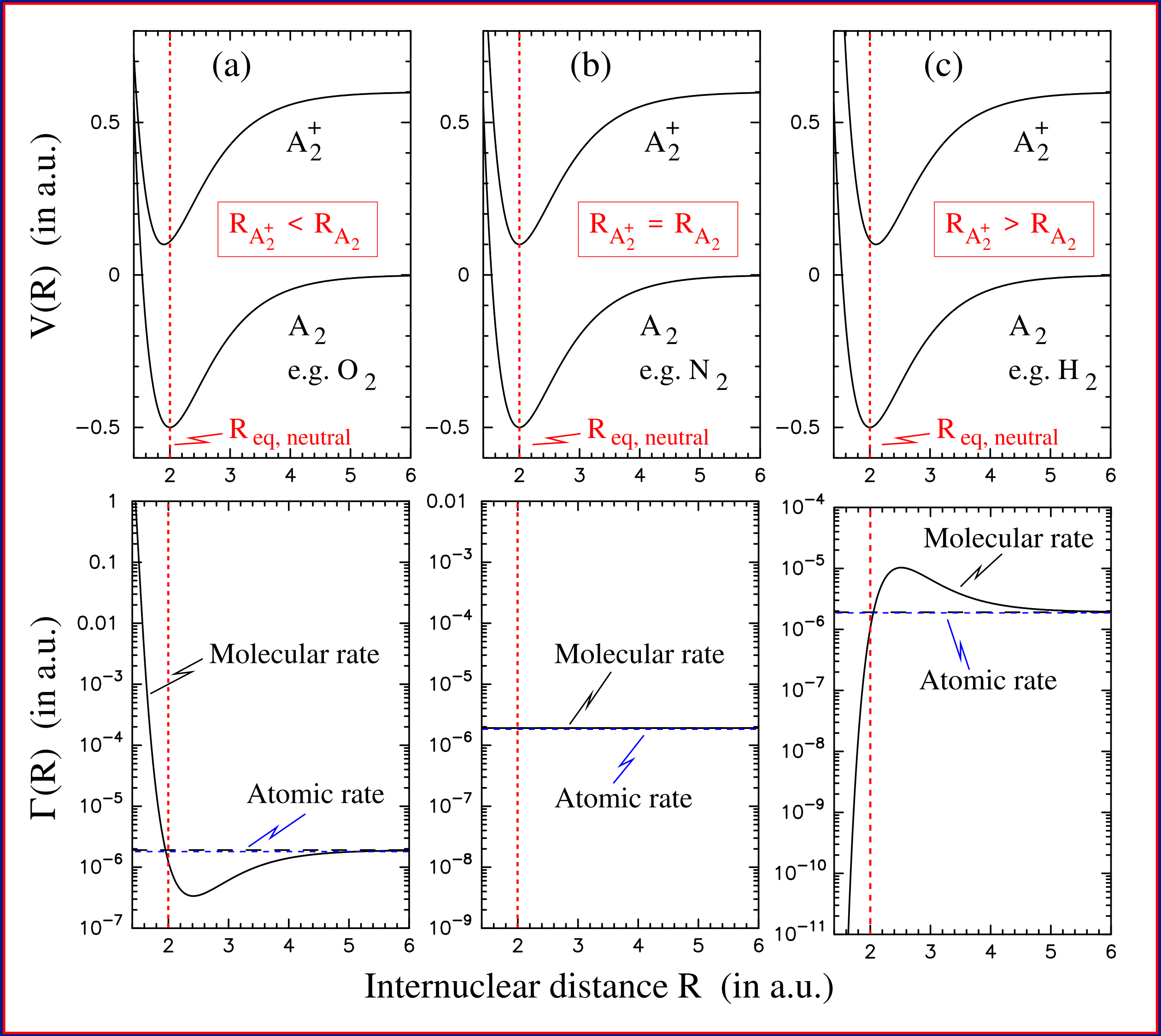
Tunneling ionization rate: (see, e. g., Landau-Lifshitz)

$$\Gamma(F) \;\propto\; \exp\left[-\frac{2\,(2\,E_b)^{3/2}}{3F}\right]$$

with field electric strength F and electron's binding energy E_b.

Molecules: Nuclear-geometry dependence of tunnel ionization?

Molecular effects: R-dependence (extnd. ADK model)



ADK model:

$$\Gamma_{\rm ADK} \propto \exp\left(-\frac{2\,(2\,I_P)^{3/2}}{3\,F}\right)$$

with

$\Gamma_{\rm ADK}$: ionization rate

F: field strength

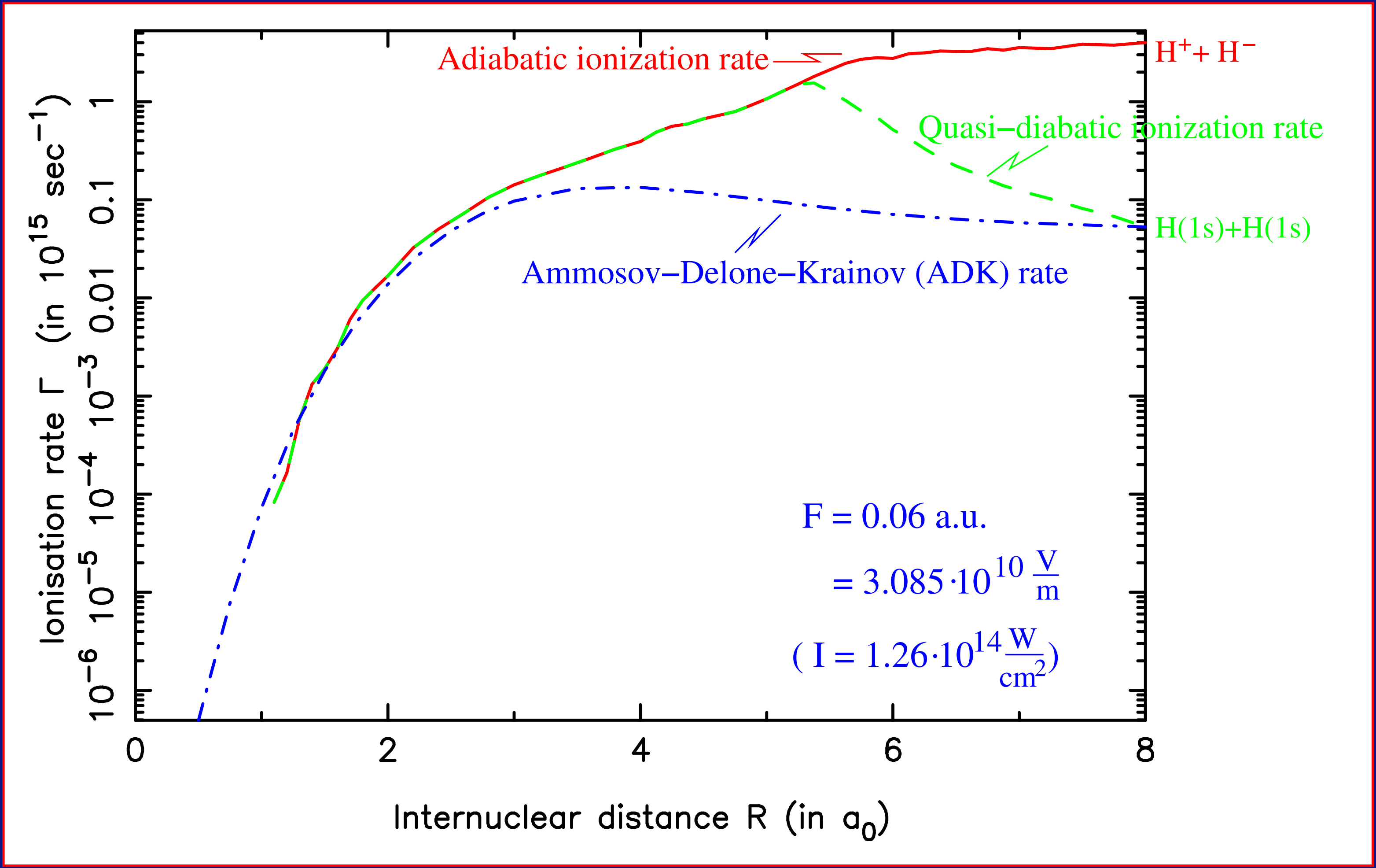
I_P: ionization potential

Extended ADK model:

Replace ionization potential I_P with $\boldsymbol{E}^{A_2^+}(R) - \boldsymbol{E}^{A_2}(R)$

No Franck-Condon distribution for, e. g., H_2 or O_2 [A. S., *J. Phys. B* **33**, 4365 (2000)].

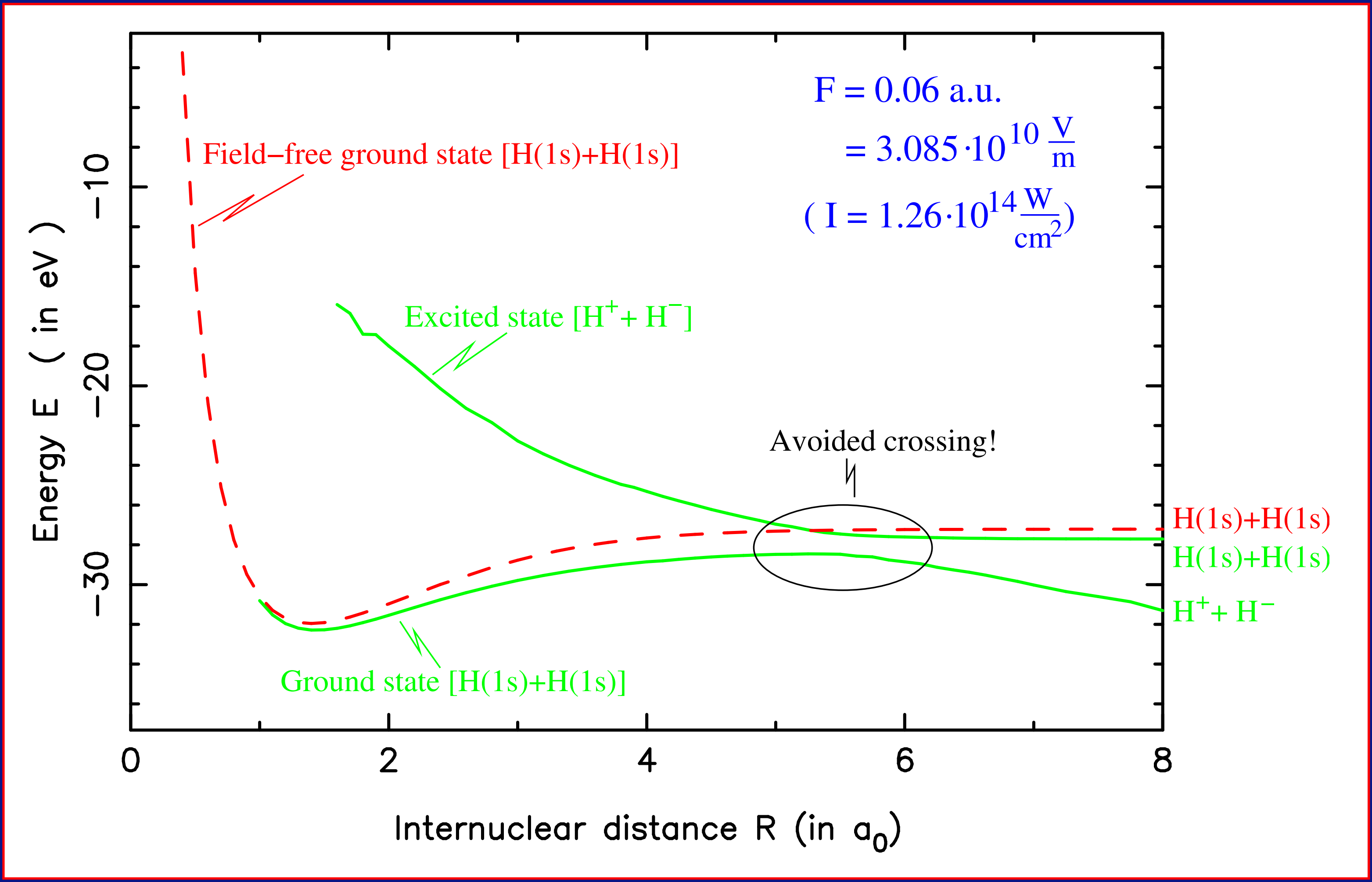
R-dependent ab initio dc ionization rate for H_2



Ab initio calculation (dc field) confirms: ionisation rate of H_2 strongly R dependent.

[A. S., *Phys. Rev. A* **61**, 051402 (R) (2000); *Phys. Rev. A* **66**, 063408 (2002).]

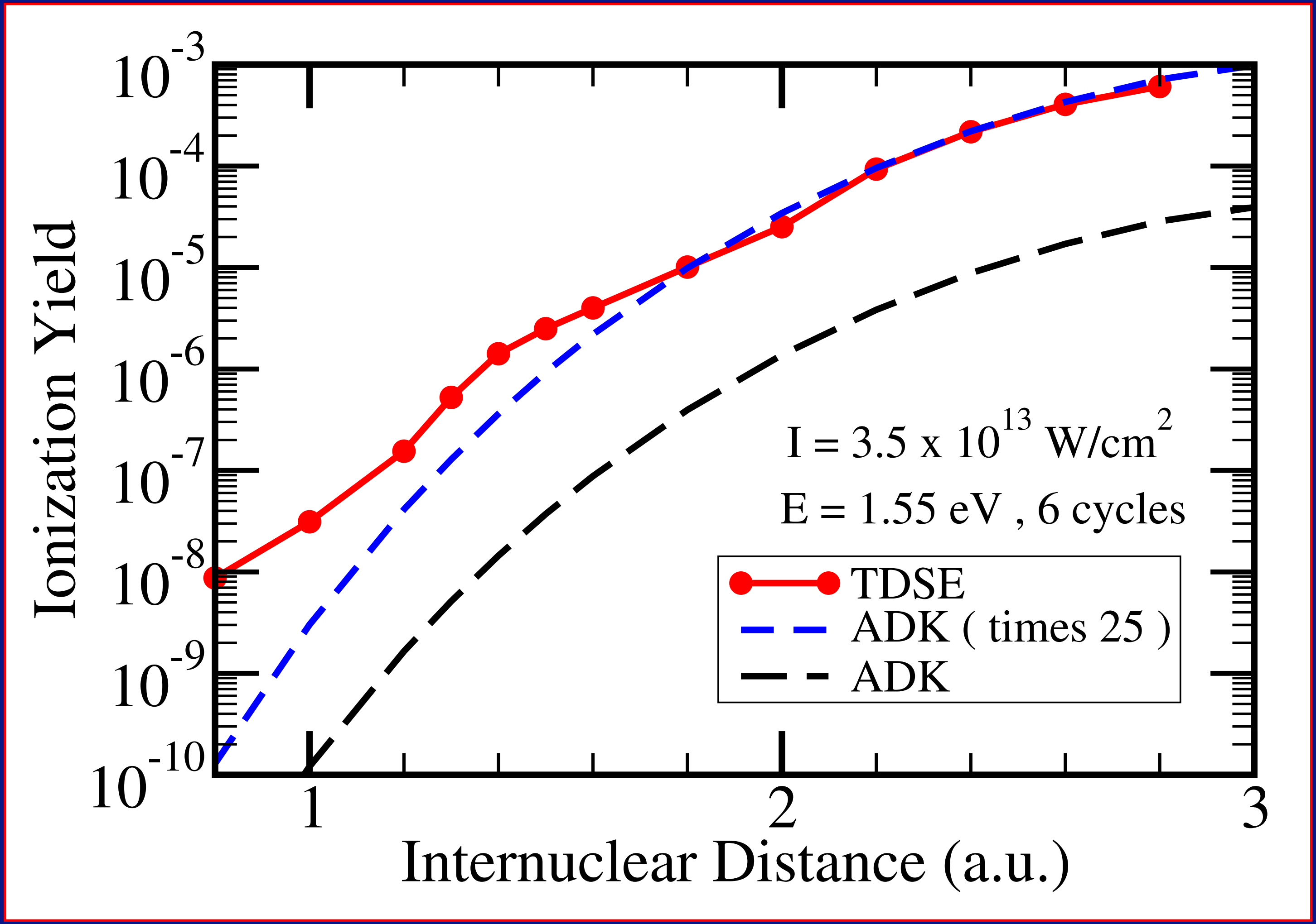
Furthermore: bond softening in neutral H_2



Ab initio complex-scaling calculation (dc field) of H_2 in an intense field.

[A. S., *Phys. Rev. A* **61**, 051402 (R) (2000); *Phys. Rev. A* **66**, 063408 (2002).]

Validity of quasi-static approximation for H_2



Full dimensional solution of TDSE: M. Awasthi, Y. V. Vanne, A. S., *J. Phys. B* **38**, 3973 (2005) [method];
M. Awasthi and A. S., *J. Phys. B:* **39**, S389 (2006) [R dependence].

Strong-Field Control: “Lochfrass” (Proposal)

- **Pronounced R-dependent ionization yield**

  $\longrightarrow$ **fast** ionization process (pump) should **deplete** the large R component of the wavefunction.

Strong-Field Control: “Lochfrass” (Proposal)

- **Pronounced R-dependent ionization yield**
  $\longrightarrow$ **fast** ionization process (pump) should **deplete** the large R component of the wavefunction.

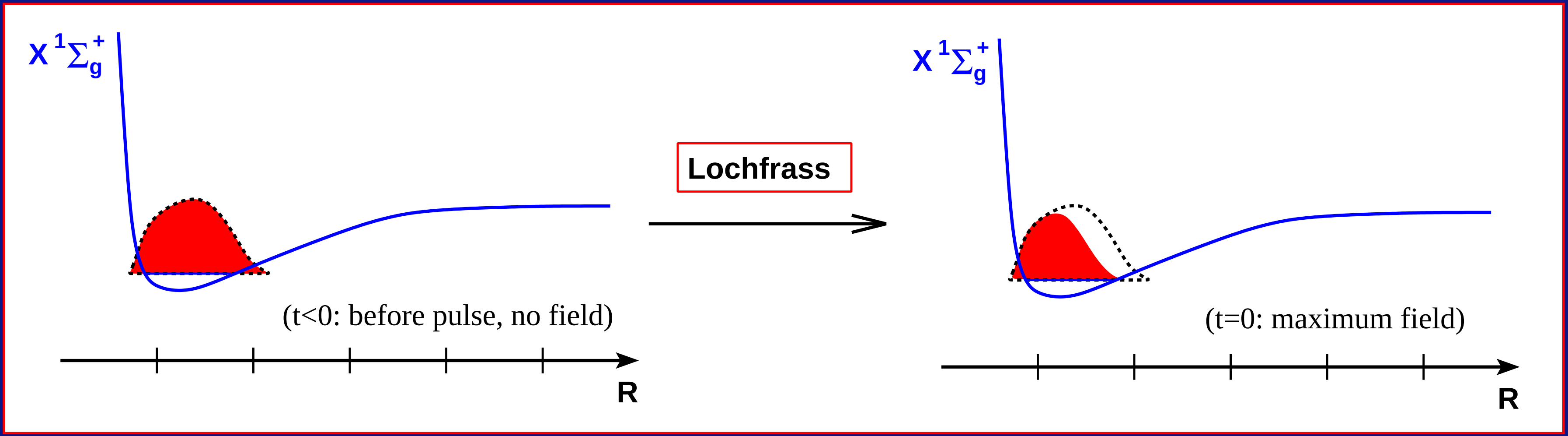
- A coherent vibrational wavepacket in the electronic ground state of the **neutral(!)** molecule is created.

Strong-Field Control: “Lochfrass” (Proposal)

- Pronounced R-dependent ionization yield

  ⟶ **fast** ionization process (pump) should **deplete** the large R component of the wavefunction.

- A coherent vibrational wavepacket in the electronic ground state of the **neutral(!)** molecule is created.



Strong-Field Control: “Lochfrass” (Proposal)

- **Pronounced R-dependent ionization yield**
  $\longrightarrow$ **fast** ionization process (pump) should **deplete** the large R component of the wavefunction.

- A coherent vibrational wavepacket in the electronic ground state of the **neutral(!)** molecule is created.

Strong-Field Control: “Lochfrass” (Proposal)

- **Pronounced R-dependent ionization yield**
  $\longrightarrow$ **fast** ionization process (pump) should **deplete** the large R component of the wavefunction.

- A coherent vibrational wavepacket in the electronic ground state of the **neutral(!)** molecule is created.

- **Purely quantum-mechanical effect:**
  A **superposition state** of the **ionized** and the **neutral** molecule!

Strong-Field Control: "Lochfrass" (Proposal)

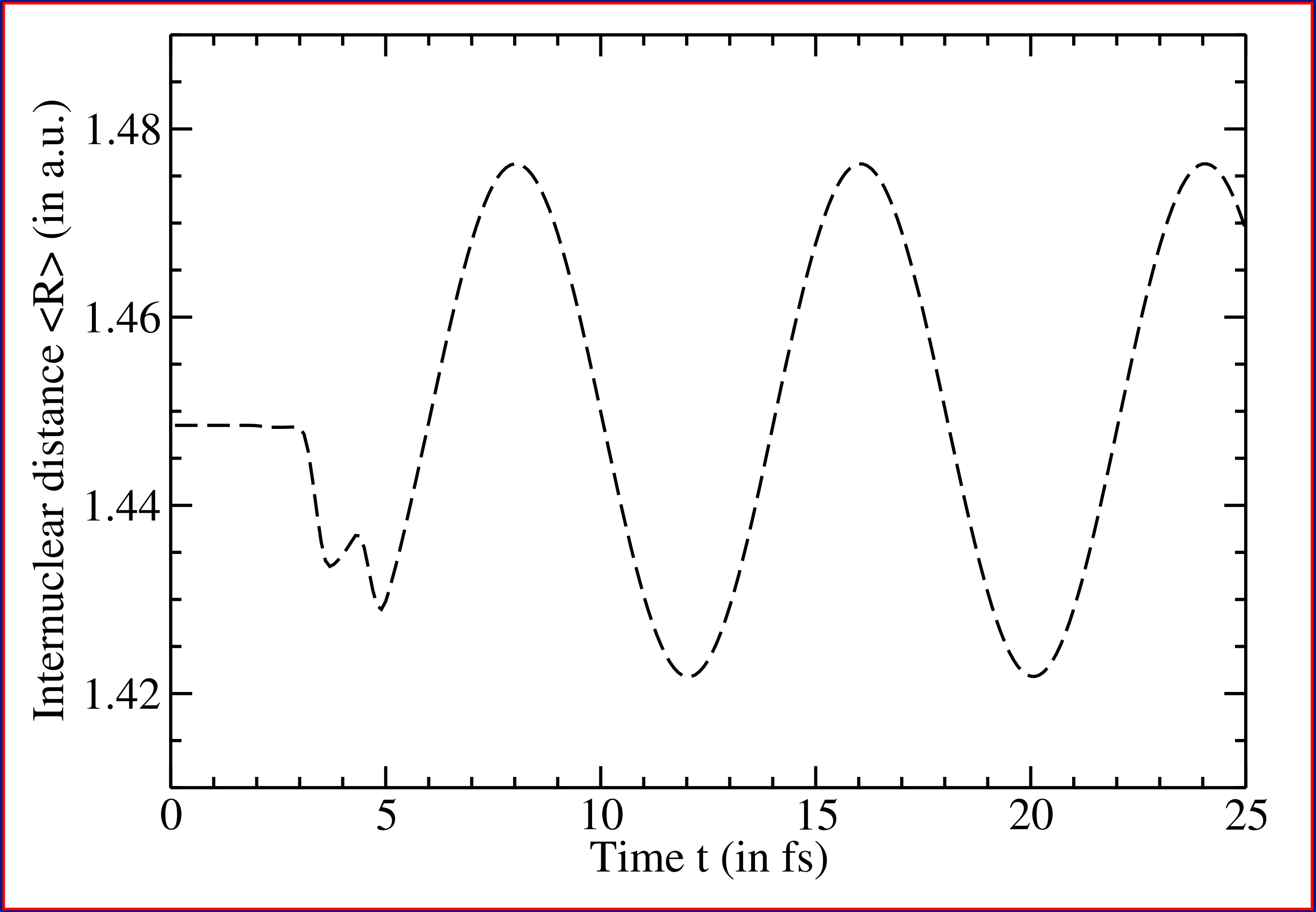
- **Pronounced R-dependent ionization yield**
  $\longrightarrow$ **fast** ionization process (pump) should **deplete** the large R component of the wavefunction.

- A coherent vibrational wavepacket in the electronic ground state of the **neutral(!)** molecule is created.

- **Purely quantum-mechanical effect:**
  A **superposition state** of the **ionized** and the **neutral** molecule!

- **Highly non-linear process:**
  A second (probe) pulse should detect a time-dependent ionization signal.

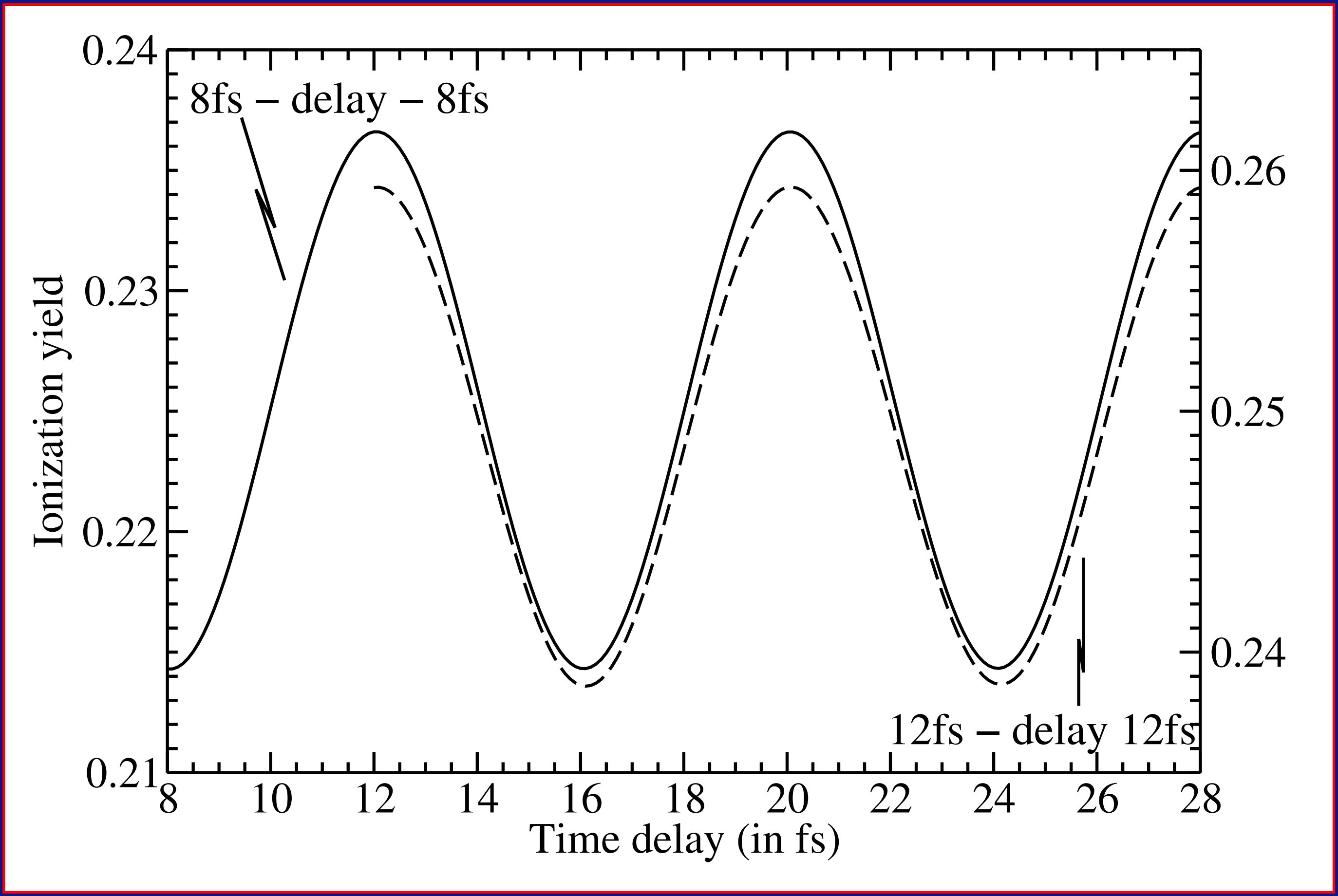
Wave-packet study (results)



Peak intensity: $I = 6 \cdot 10^{14}\,\mathrm{W/cm^2}$, Wavelength: $\lambda = 800\,\mathrm{nm}$, Length: 8 fs.

Formation of a H_2 wavepacket by “Lochfrass” (“eating a hole”).

Wave-packet detection: Pump-probe



Identical pulses, Peak intensities: $I = 6 \cdot 10^{14}$ W/cm^2, Wavelength: $\lambda = 800$ nm.

[E. Goll, G. Wunner, and A. S., *Phys. Rev. Lett.* **97**, 103003 (2006)]

Pump-probe experiment (MPI Heidelberg)

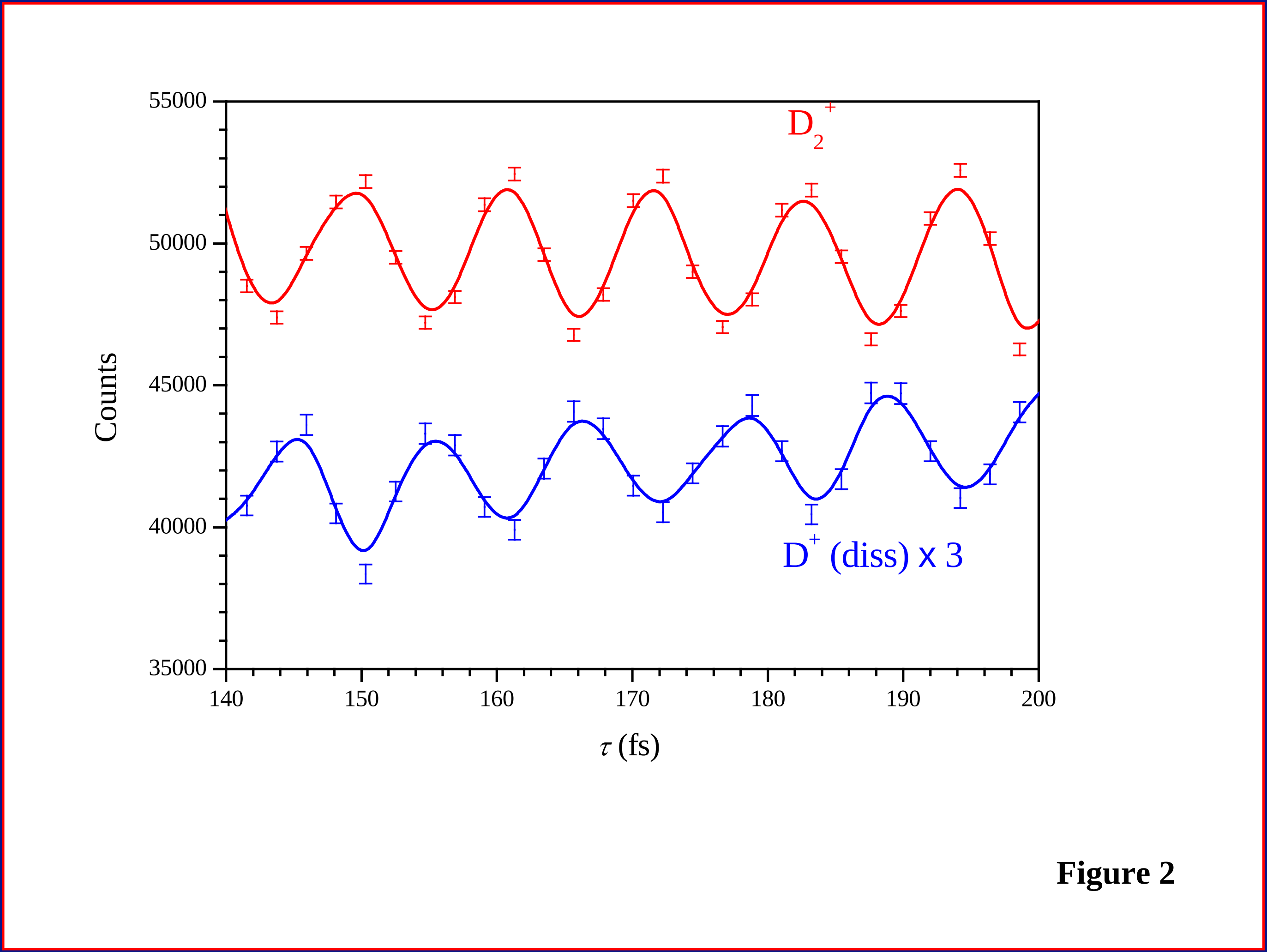


Figure 2

Parameters:

Two identical pulses,

$I = 4(1) \cdot 10^{14}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$,

$\lambda = 795\,\mathrm{nm}$,

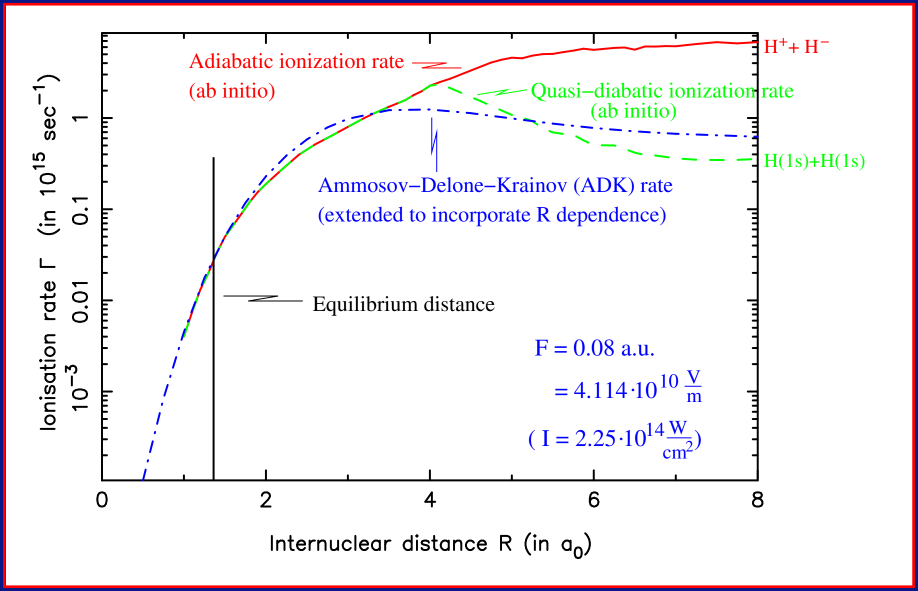
7 fs (FWHM).

[Fig. from Ergler et al. *Phys. Rev. Lett.* **97**, 103004 (2006)]

$\longrightarrow$ Experiment observes the theoretically predicted oscillation!!!

[**Note:** expected oscillation period for $\mathbf{D_2}$: 11 fs ($\mathbf{H_2}$: 8 fs).]

Is it really Lochfraß?



“Lochfraß”

(R-dependent depletion by ionization)

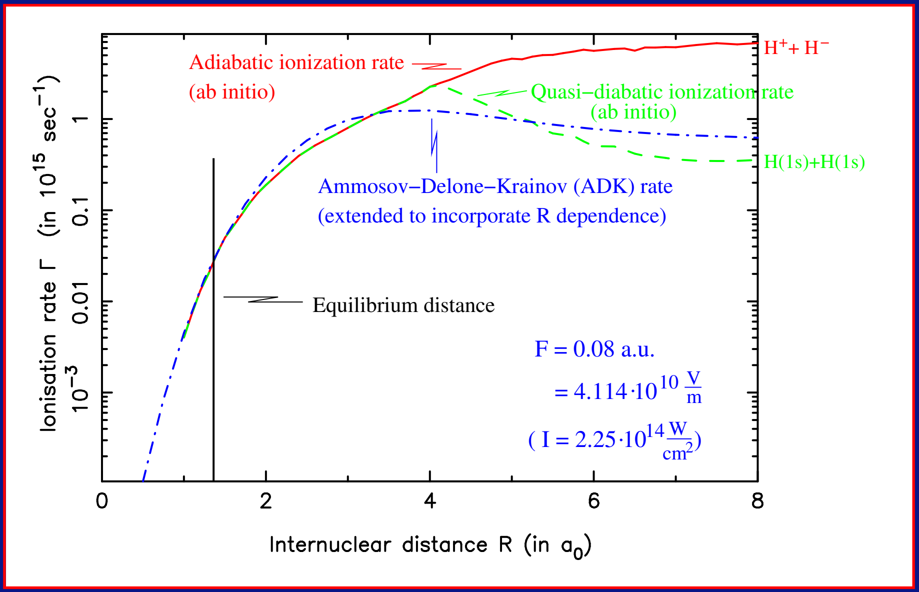
[E. Goll et al., *PRL* **97**, 103003 (2006)]

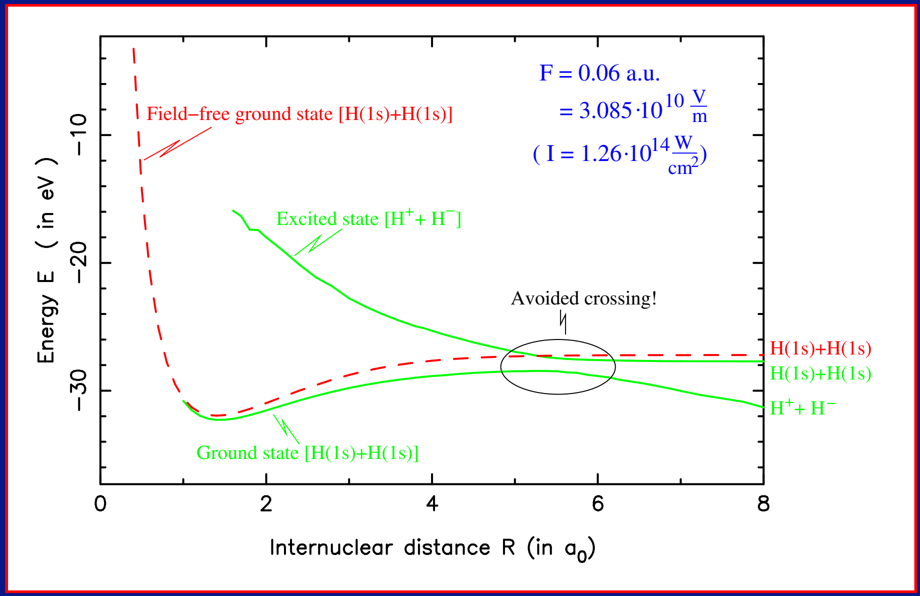
Preferential ionization at large R:

If ionisation is fast enough,

a hole is carved into the wavefunction.

Is it really Lochfraß?





“Lochfraß”

(R-dependent depletion by ionization)

[E. Goll et al., *PRL* **97**, 103003 (2006)]

Preferential ionization at large R:

If ionisation is fast enough,

a hole is carved into the wavefunction.

Bond Softening

(caused by potential-curve distortion)

[A. S., *PRA* **61**, 051402(R) (2000)]

Field-induced lowering of potential curve:

The nuclear wavefunction escapes

over the suppressed barrier.

Modelling bond softening and Lochfraß

Full solution of the time-dependent Schrödinger equation:

- Beyond reach at the time of the proposal.

Modelling bond softening and Lochfraß

Full solution of the time-dependent Schrödinger equation:

- Beyond reach at the time of the proposal.
- Now, in principle possible, but still extremely demanding.

Modelling bond softening and Lochfraß

Full solution of the time-dependent Schrödinger equation:

- Beyond reach at the time of the proposal.
- Now, in principle possible, but still extremely demanding.
- Not of interest for QSIM19: no environment . . .

Modelling bond softening and Lochfraß

Full solution of the time-dependent Schrödinger equation:

- Beyond reach at the time of the proposal.
- Now, in principle possible, but still extremely demanding.
- Not of interest for QSIM19: no environment . . .

Model Hamiltonian (nuclear motion with dissipation):

$$\hat{\mathrm{H}}(R,t) \;=\; \hat{\mathrm{H}}_0(R) \;+\; \Delta\hat{\mathrm{V}}(R,F(t)) \;-\; \frac{i}{2}\,W(R,F(t))$$

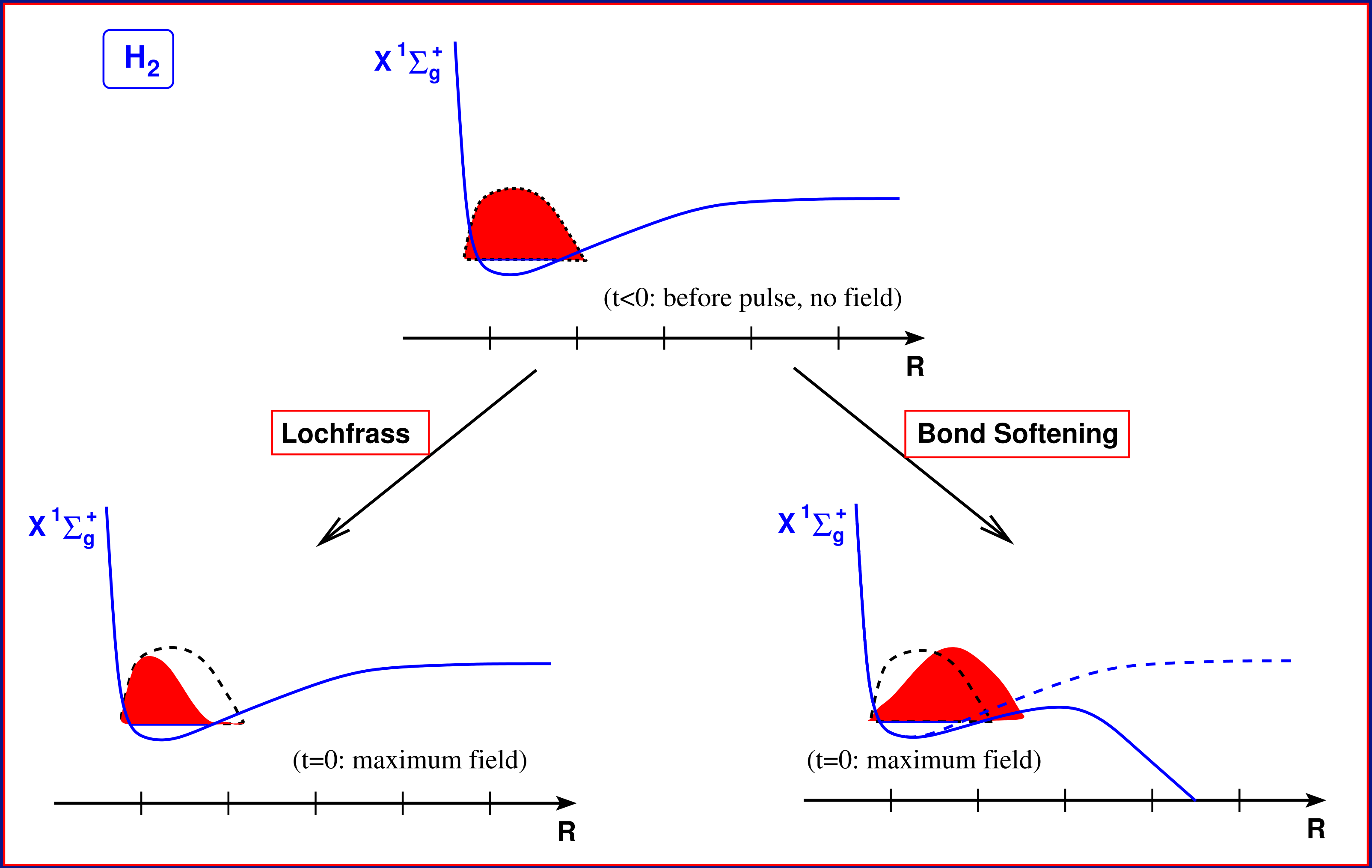
$\hat{\mathrm{H}}_0(R)$: field-free time-independent Hamiltonian.

$\Delta\hat{\mathrm{V}}(R,F(t))$: field-induced distortion of the potential curve.

$W(R,F(t))$: field-induced (quasi-static) ionization rate.

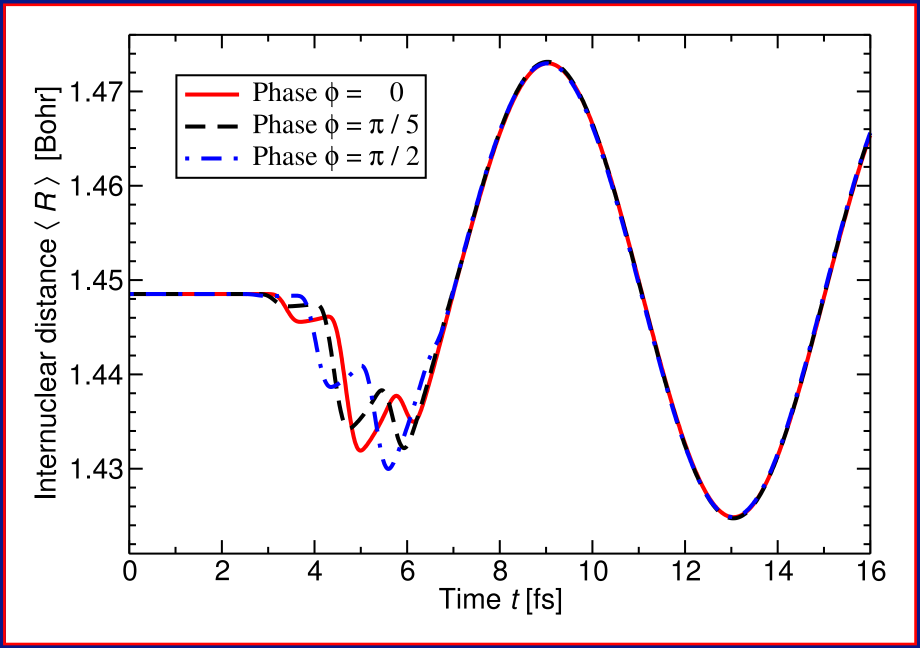
$F(t)$: time-dependent electric field component of the laser pulse.

How to experimentally determine the mechanism?

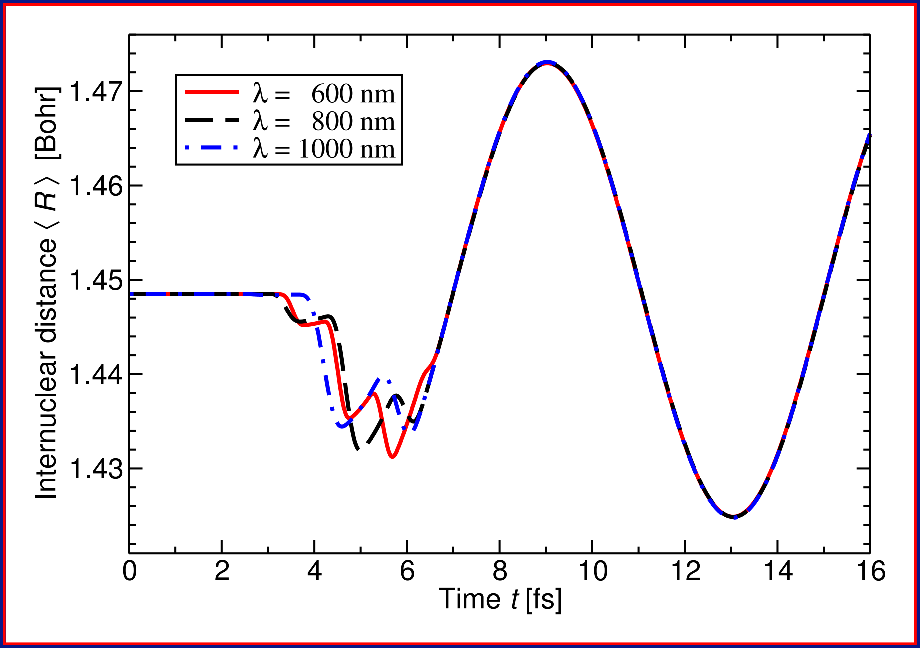


Lochfrass and Bond Softening may be distinguished by the absolute phase!!!

Robustness of Lochfraß



Variation of the **absolute** (carrier-envelope) **phase ϕ** of the ultrashort laser pulse.



Variation of the laser **wavelength λ**.

⟶ Lochfraß is extremely robust!

Determination of the mechanism

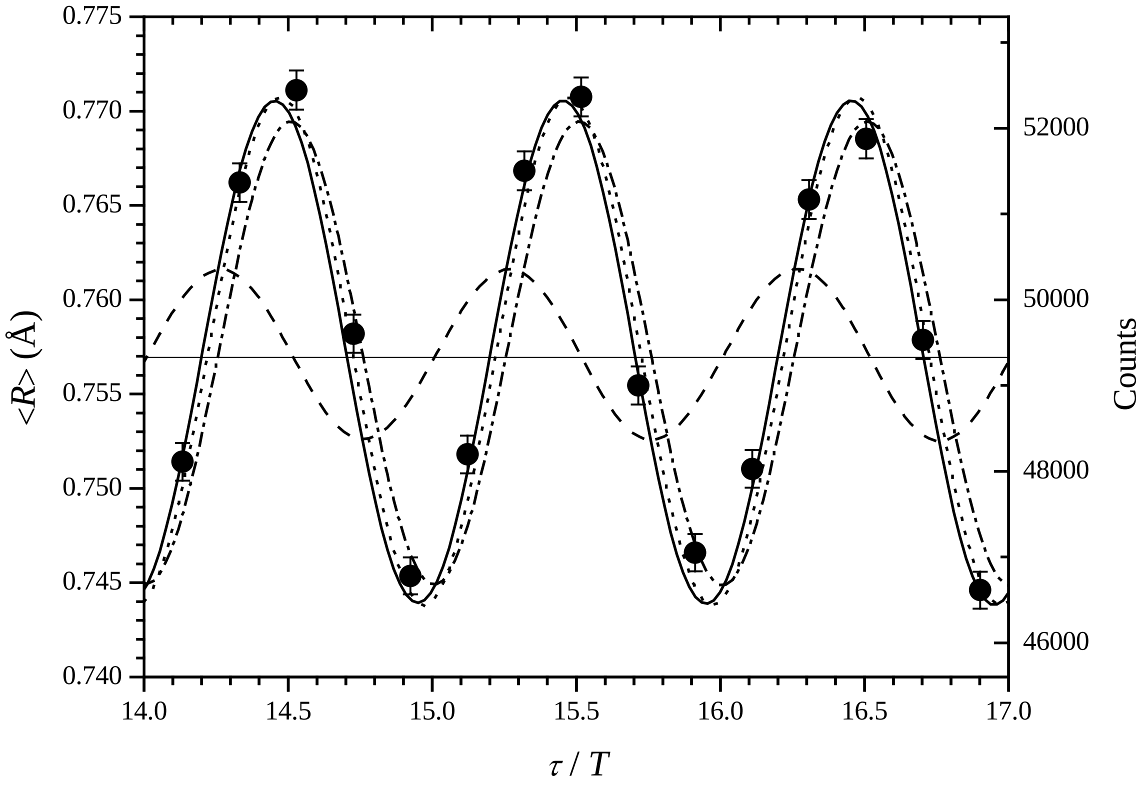


Figure 3

Dashed:
Bond Softening

Chain:
Lochfrass.

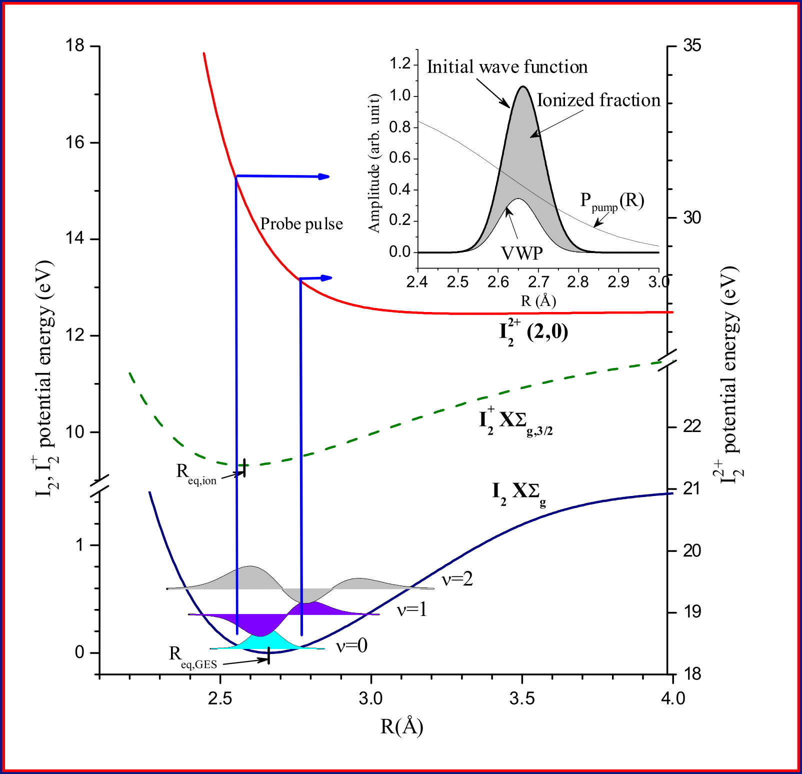
Solid:
Both effects,

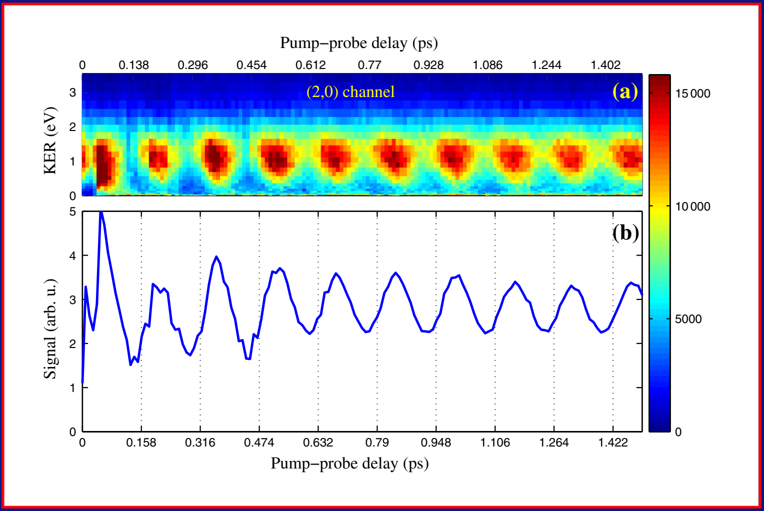
Circles:
Experiment.

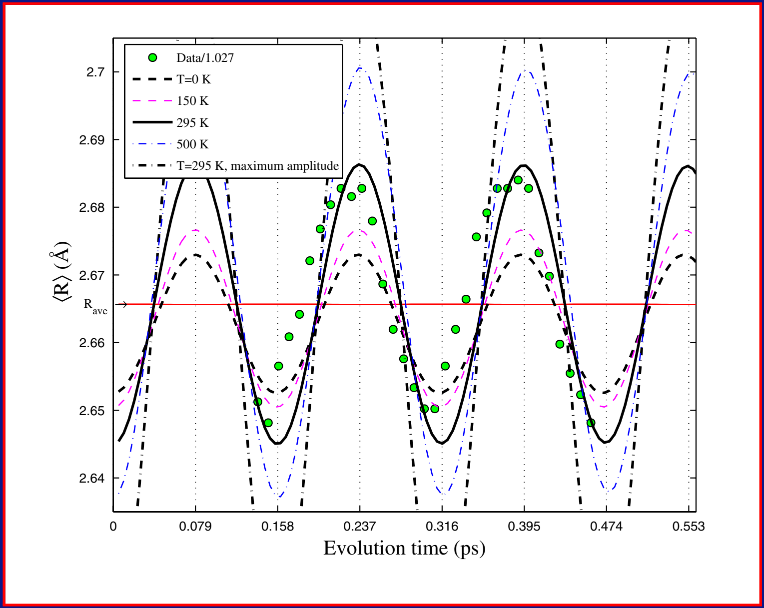
[Fig. from Ergler et al.]

⟶ Lochfrass is the clearly dominating mechanism!!!

Lochfrass in I_2





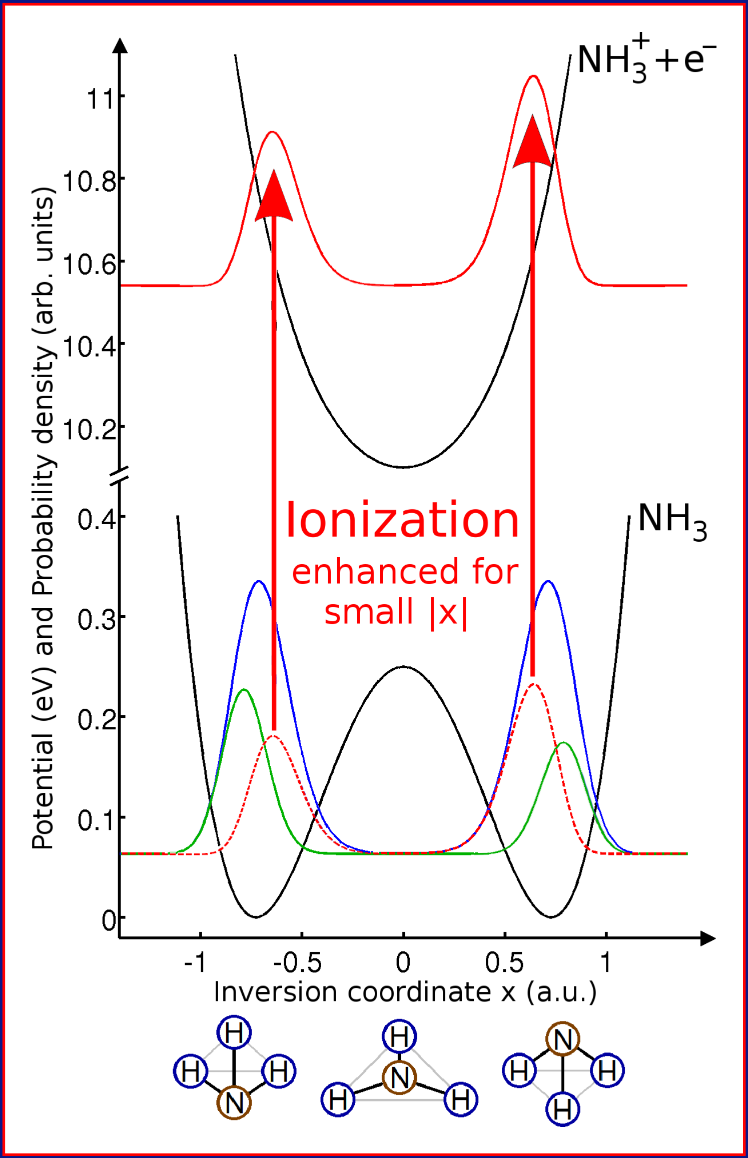


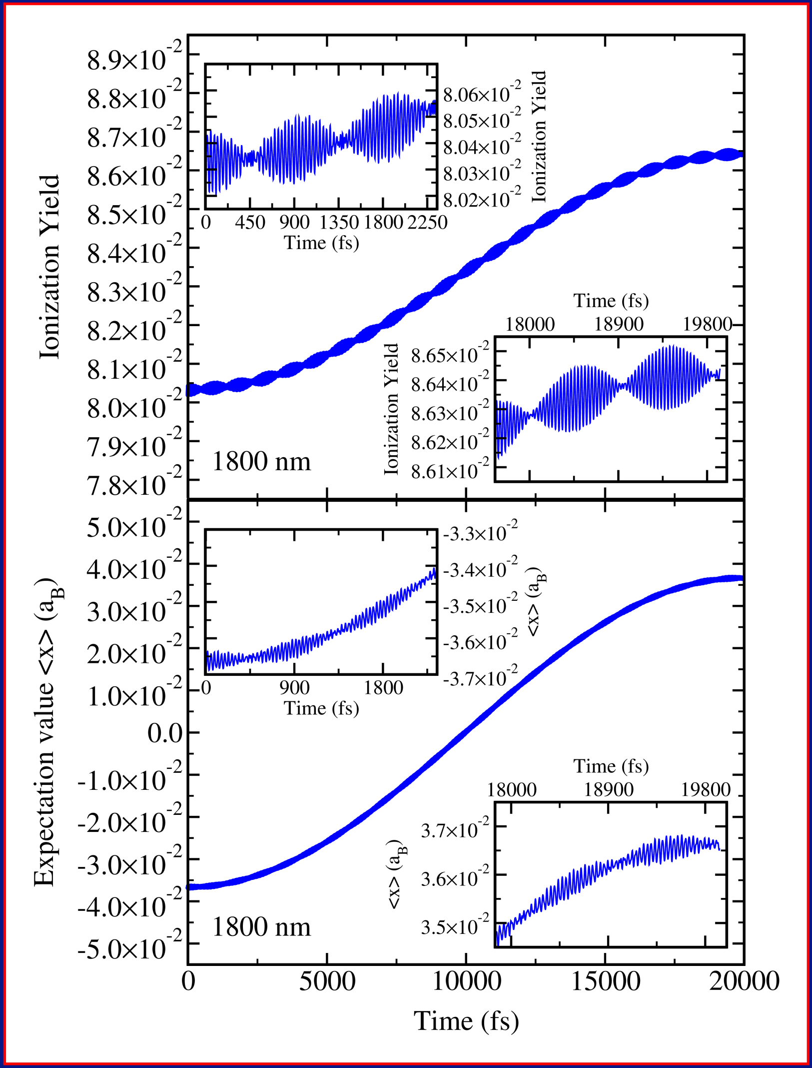
Lochfrass is again seen.

More incoherence in initial state improves coherent control scheme!

[L. Fang and G. N. Gibson,
Phys. Rev. Lett. **100**, 103003 (2008)]

Beyond diatomics: Lochfraß in ammonia (NH_3)





2 cycles (pump+probe), 1800 nm, 10^{14} W/cm^2

Real-time imaging of nuclear motion and tunneling possible [Förster et al., *Phys. Rev. A* **94**, 043405 (2016)].

Questions:

Why did the *Lochfraß* experiment work at all?

Questions:

Why did the *Lochfraß* experiment work at all?

- no carrier-envelope-phase stabilisation

Questions:

Why did the *Lochfraß* experiment work at all?

- no carrier-envelope-phase stabilisation
- short pulse → large spectral width (wavelength distribution)

Questions:

Why did the *Lochfraß* experiment work at all?

- no carrier-envelope-phase stabilisation
- short pulse → large spectral width (wavelength distribution)
- variation of pulse length from shot to shot expected.

Questions:

Why did the *Lochfraß* experiment work at all?

- no carrier-envelope-phase stabilisation
- short pulse $\longrightarrow$ large spectral width (wavelength distribution)
- variation of pulse length from shot to shot expected.

Why can *Lochfraß* and bond softening be distinguished by the absolute phases?

Questions:

Why did the *Lochfraß* experiment work at all?

- no carrier-envelope-phase stabilisation
- short pulse → large spectral width (wavelength distribution)
- variation of pulse length from shot to shot expected.

Why can *Lochfraß* and bond softening be distinguished by the absolute phases?

Why can a more incoherent initial state lead to a more coherent wavepacket?

Questions:

Why did the *Lochfraß* experiment work at all?

- no carrier-envelope-phase stabilisation
- short pulse → large spectral width (wavelength distribution)
- variation of pulse length from shot to shot expected.

Why can *Lochfraß* and bond softening be distinguished by the absolute phases?

Why can a more incoherent initial state lead to a more coherent wavepacket?

Note: All results in perfect agreement with theoretical simulation!

More questions:

- How universal is the robust formation of coherent wavepackets by time- and position-dependent dissipation?

More questions:

- How universal is the robust formation of coherent wavepackets by time- and position-dependent dissipation?

- Can this phenomenon be transferred to many-body systems?

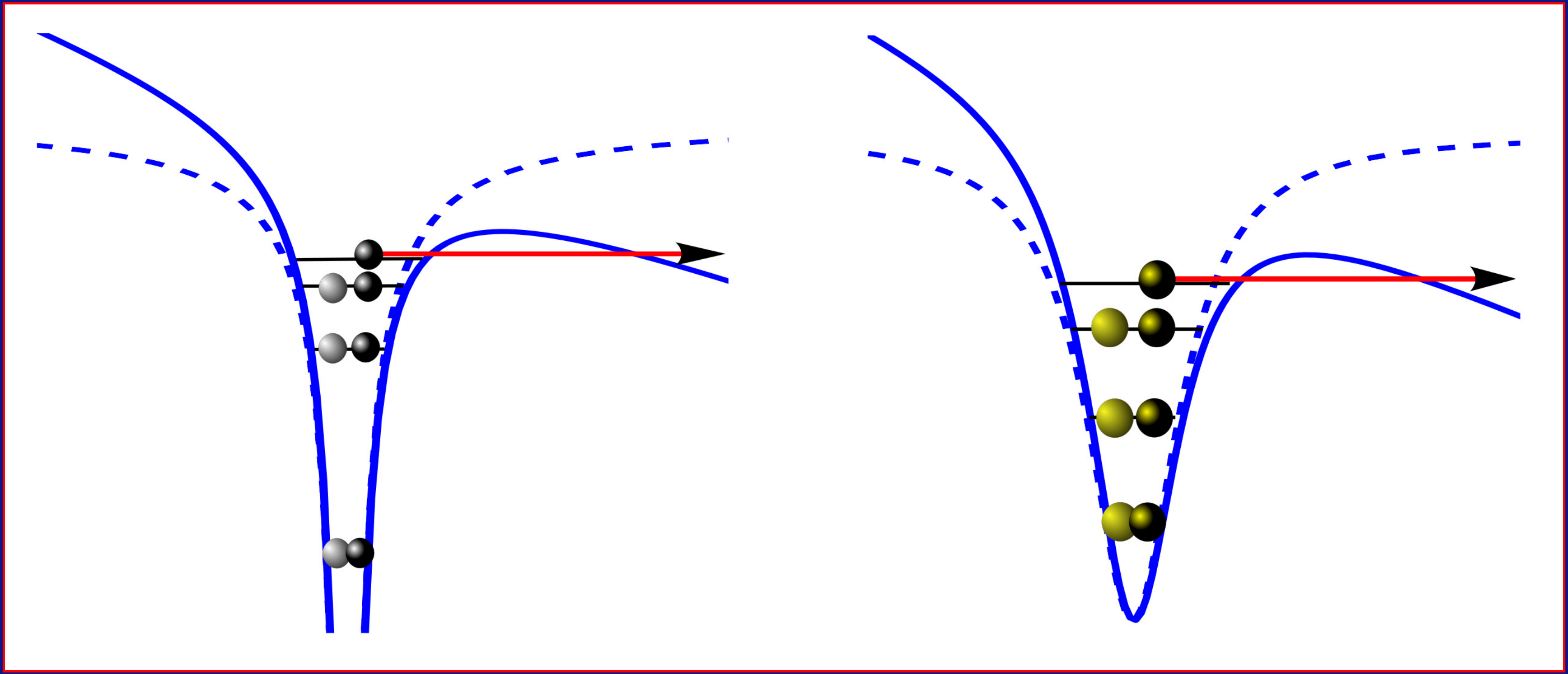
More questions:

- How universal is the robust formation of coherent wavepackets by time- and position-dependent dissipation?
- Can this phenomenon be transferred to many-body systems?
- Especially, also to (strongly) interacting many-body systems?

More questions:

- How universal is the robust formation of coherent wavepackets by time- and position-dependent dissipation?
- Can this phenomenon be transferred to many-body systems?
- Especially, also to (strongly) interacting many-body systems?
- **This is QSIM19: where is the quantum simulator?**

Quantum-simulator for attosecond physics (I)



Atom in electric field

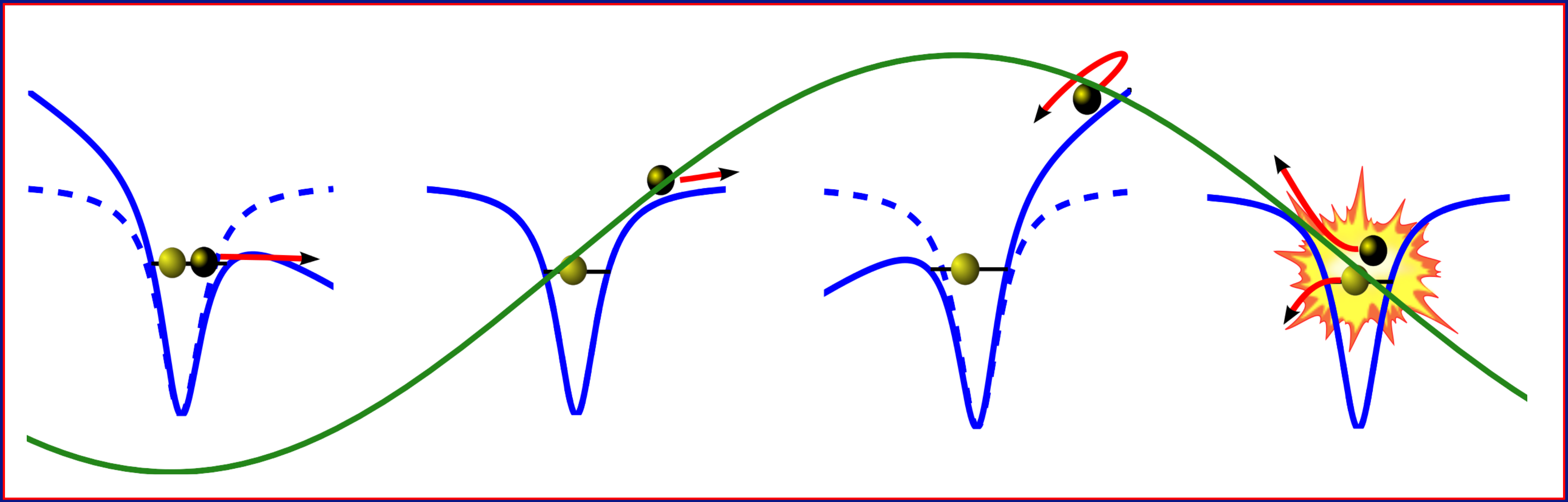
$$\hat{H}^{\mathrm{LG}}(t) = \hat{H}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot e\mathbf{E}$$

Atoms in dipole trap

$$\hat{\mathcal{H}}^{\mathrm{LG}}(t) = \hat{\mathcal{H}}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot \mu\boldsymbol{\mathcal{B}}'$$

Mapping of electric field $\mathbf{E}$ on magnetic-field gradient $\mathcal{B}'$.

Quantum-simulator for attosecond physics (II)



Atom in electric field

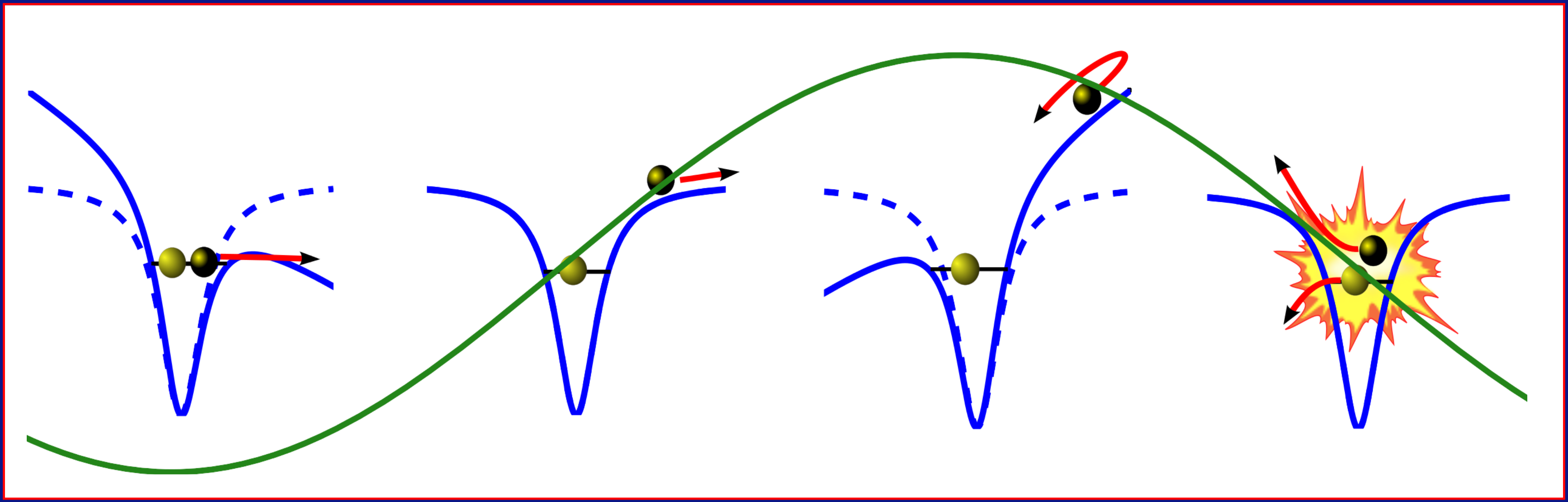
$$\hat{H}^{\mathrm{LG}}(t) = \hat{H}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot e\mathbf{E}(t)$$

Atoms in dipole trap

$$\hat{\mathcal{H}}^{\mathrm{LG}}(t) = \hat{\mathcal{H}}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot \mu\boldsymbol{\mathcal{B}}'(t)$$

Mapping of electric field $\mathbf{E}(t)$ on magnetic-field gradient $\mathcal{B}'$(t).

Quantum-simulator for attosecond physics (II)



Atom in electric field

$$\hat{H}^{\mathrm{LG}}(t) = \hat{H}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot e\mathbf{E}(t)$$

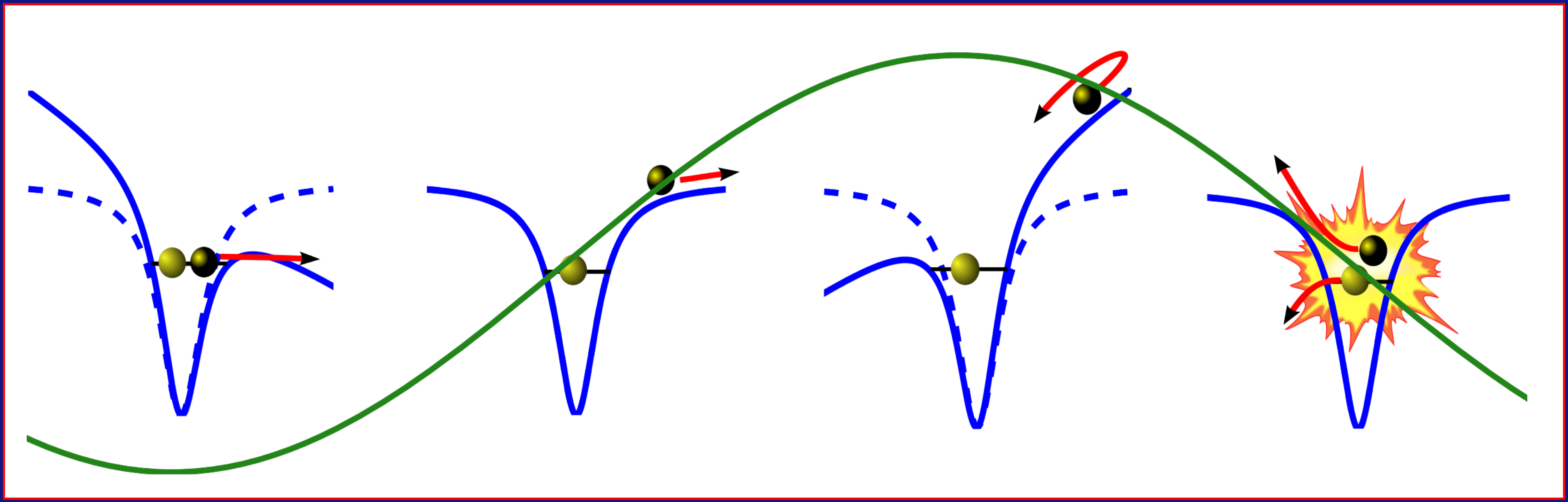
Atoms in dipole trap

$$\hat{\mathcal{H}}^{\mathrm{LG}}(t) = \hat{\mathcal{H}}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot \mu\boldsymbol{\mathcal{B}}'(t)$$

Mapping of electric field $\mathbf{E}(t)$ on magnetic-field gradient $\mathcal{B}'(\mathrm{t})$.

Time scales of field variation: femtoseconds vs. milliseconds.

Quantum-simulator for attosecond physics (II)



Atom in electric field

$$\hat{H}^{\mathrm{LG}}(t) = \hat{H}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot e\mathbf{E}(t)$$

Atoms in dipole trap

$$\hat{\mathcal{H}}^{\mathrm{LG}}(t) = \hat{\mathcal{H}}_0 + \sum_{i=1}^{N} \mathbf{r}_i \cdot \mu\boldsymbol{\mathcal{B}}'(t)$$

Mapping of electric field $\mathbf{E}(t)$ on magnetic-field gradient $\mathcal{B}'$(t).

Time scales of field variation: femtoseconds vs. milliseconds.

$\longrightarrow$ attoscience in slow motion!

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.
- Pulse shape easily controllable (and very flexible).

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.
- Pulse shape easily controllable (and very flexible).
- Distinguishable vs. indistinguishable atoms (role of exchange).

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.
- Pulse shape easily controllable (and very flexible).
- Distinguishable vs. indistinguishable atoms (role of exchange).
- Multi-well potentials (double and multiple wells already realized): "molecule" with fixed or classically moving nuclei.

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.
- Pulse shape easily controllable (and very flexible).
- Distinguishable vs. indistinguishable atoms (role of exchange).
- Multi-well potentials (double and multiple wells already realized): "molecule" with fixed or classically moving nuclei.
- Short-range potential: ideal test case for strong-field approximation.

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.
- Pulse shape easily controllable (and very flexible).
- Distinguishable vs. indistinguishable atoms (role of exchange).
- Multi-well potentials (double and multiple wells already realized): "molecule" with fixed or classically moving nuclei.
- Short-range potential: ideal test case for strong-field approximation.
- Controlled collisions between atoms (with variable dimension).

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.
- Pulse shape easily controllable (and very flexible).
- Distinguishable vs. indistinguishable atoms (role of exchange).
- Multi-well potentials (double and multiple wells already realized): "molecule" with fixed or classically moving nuclei.
- Short-range potential: ideal test case for strong-field approximation.
- Controlled collisions between atoms (with variable dimension).
- Attoscience imaging concepts may be applied to ultracold atoms.

Advantages of the quantum simulator

- Trap potential (confinement) experimentally tunable.
- Atom number variable and experimentally controllable.
- Atom-atom interaction experimentally tunable.
- Independent variation of trap and particle parameters.
- Pulse shape easily controllable (and very flexible).
- Distinguishable vs. indistinguishable atoms (role of exchange).
- Multi-well potentials (double and multiple wells already realized): "molecule" with fixed or classically moving nuclei.
- Short-range potential: ideal test case for strong-field approximation.
- Controlled collisions between atoms (with variable dimension).
- Attoscience imaging concepts may be applied to ultracold atoms.

Key question: does it work with realistic experimental parameters?

Possible experimental realization (cf. S. Jochim's set-up)

The experiment uses fermionic Li atoms.

The optical trap potential is **effectively one-dimensional**: aspect ratio 10:1.

Potential:

$$\mathcal{V}_L(z) = \alpha \mathcal{V}_0 \left[1 - \frac{1}{1+(z/z_r)^2}\right]$$

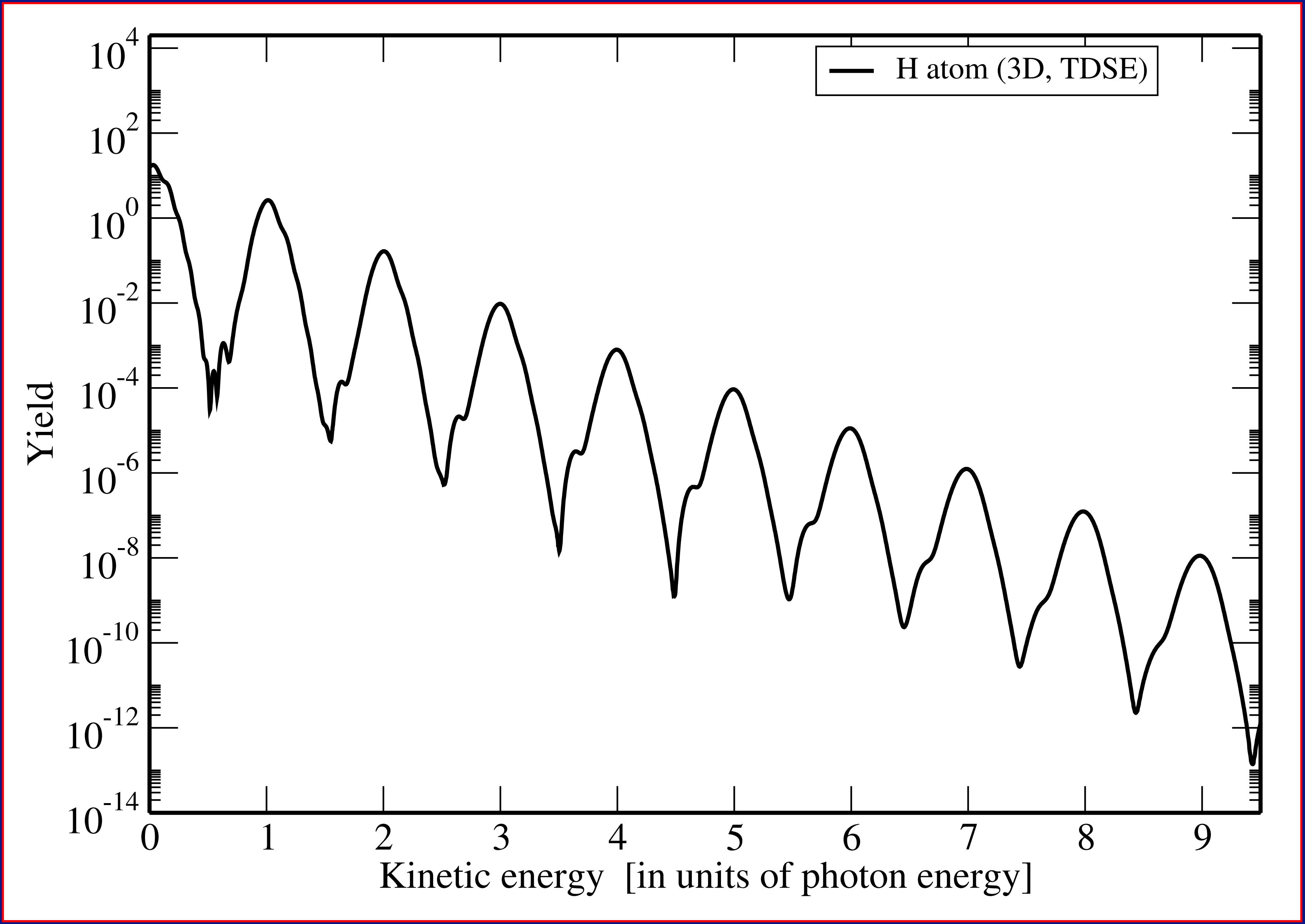
with variable parameter α, basic trap depth $\mathcal{V}_0/k_b = 3.33\ \mu\mathrm{K}$ (Boltzmann constant k_b), and the Rayleigh length $z_r = \pi w_0^2/\lambda$ ($\lambda = 1064\,$nm).

Mapping (equal Keldysh parameters and binding energies):

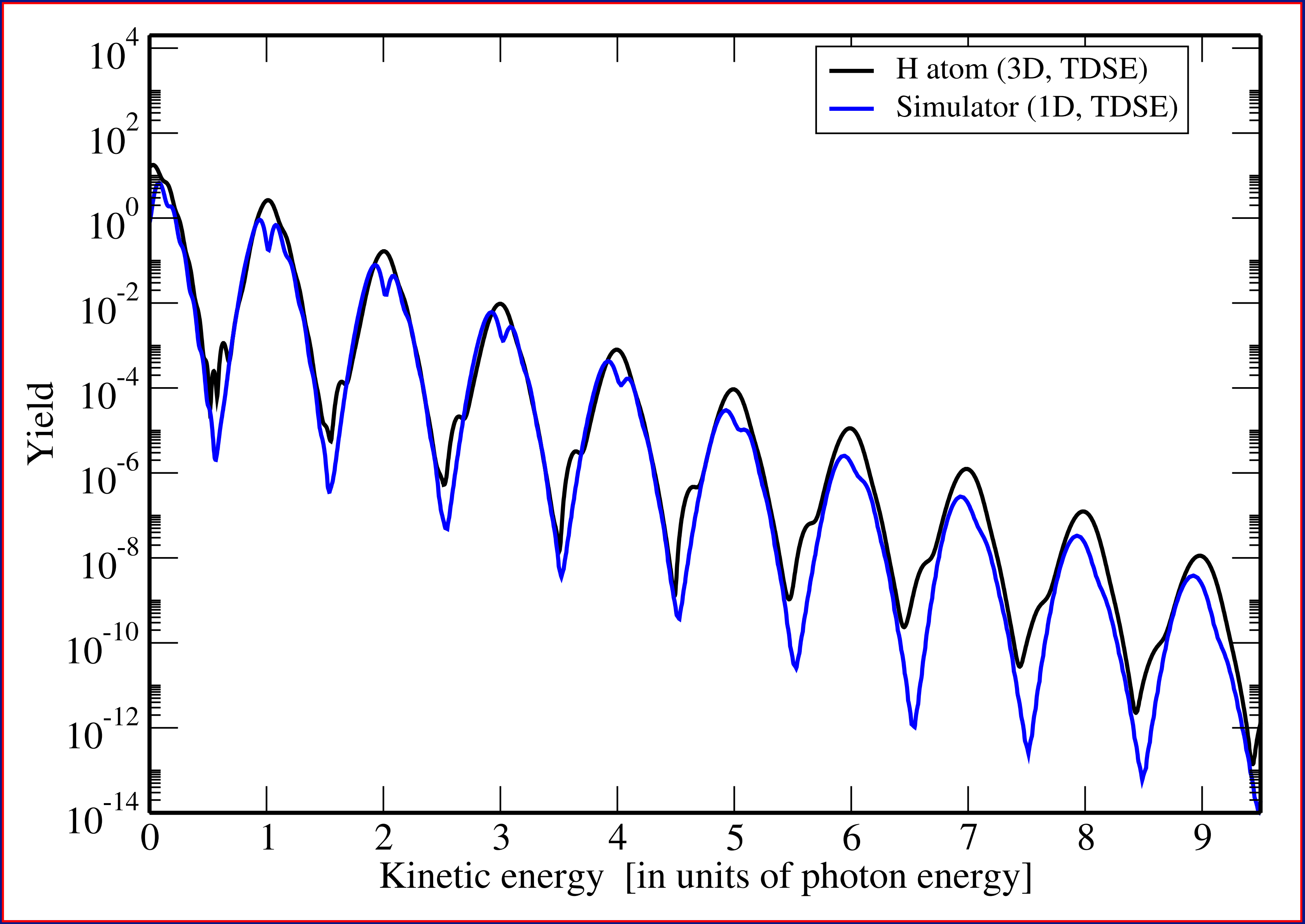
$$\gamma_\mathrm{e} := \omega_\mathrm{e} \frac{\sqrt{2m_\mathrm{e} I_p}}{eE_0} = \omega \frac{\sqrt{2m_\mathrm{a} E_\mathrm{b}}}{\mu \mathcal{B}_0'} =: \gamma_\mathrm{a} \qquad \beta_\mathrm{e} := \frac{I_p}{\hbar\omega_\mathrm{e}} = \frac{E_\mathrm{b}}{\hbar\omega} =: \beta_\mathrm{a} \quad .$$

where I_p and E_b are the binding energies of the ground states of the field-free Hamiltonians.

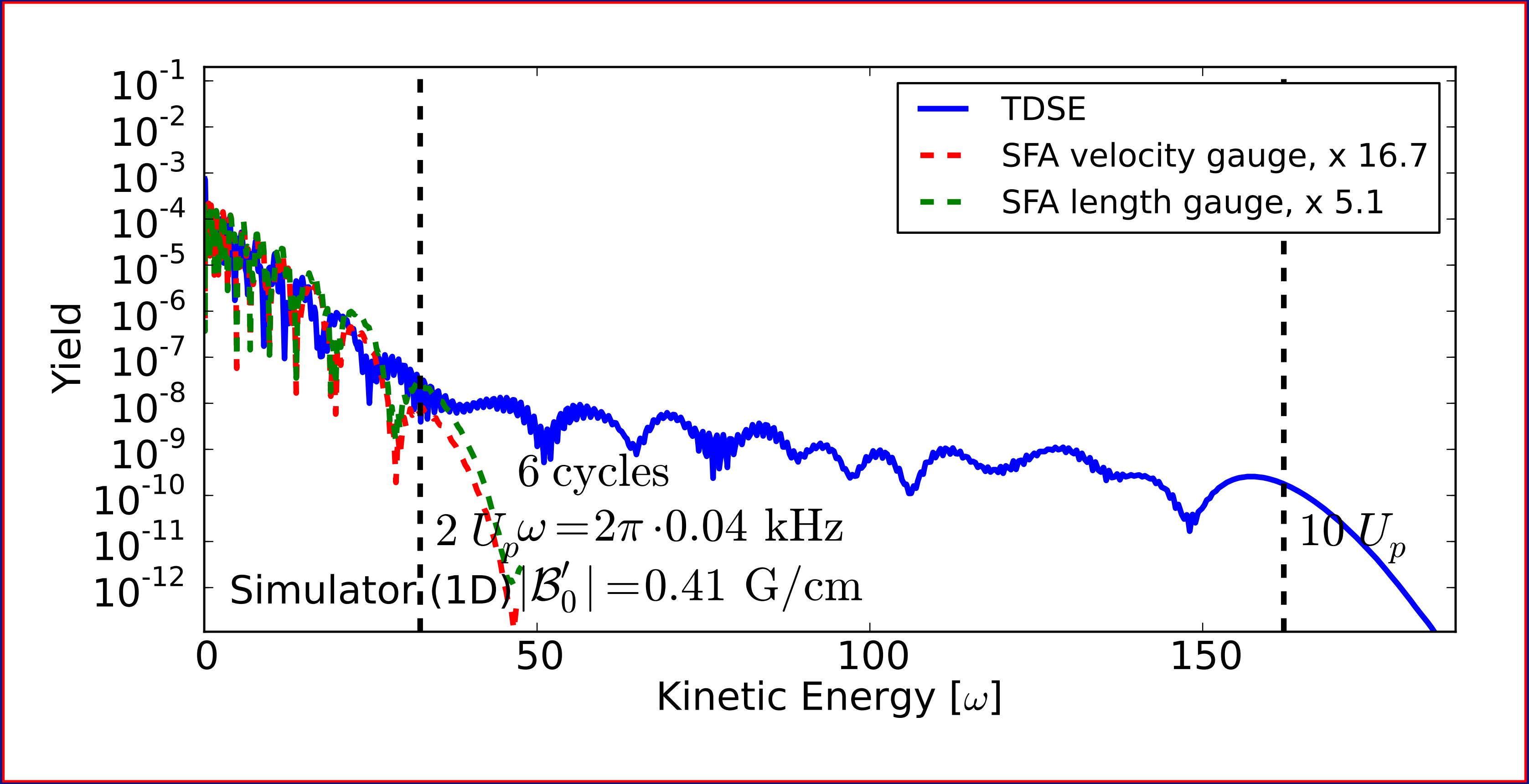
Quantum simulator in multiphoton regime (I)



Quantum simulator in multiphoton regime (II)



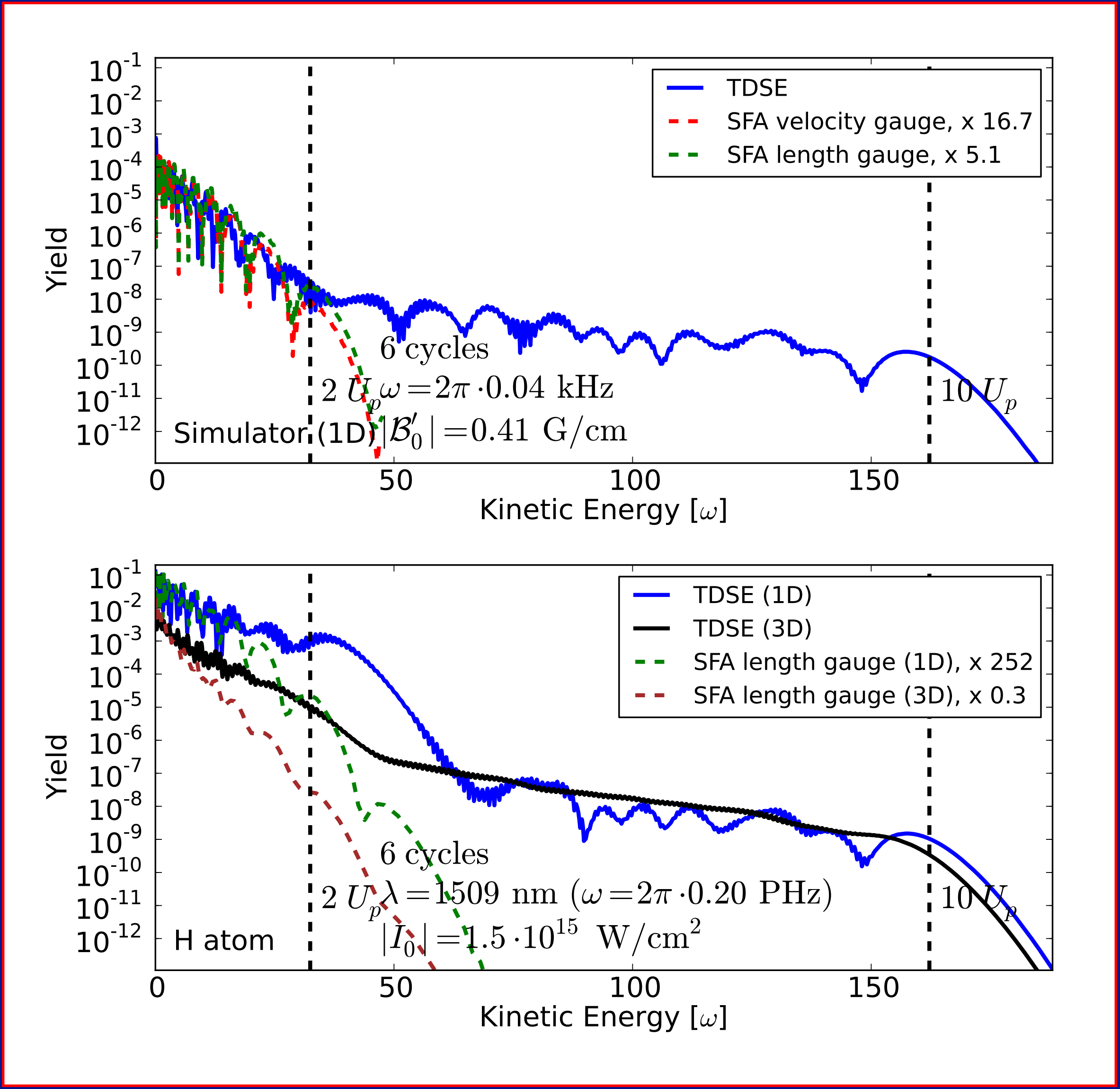
Quantum simulator in quasi-static regime (I)



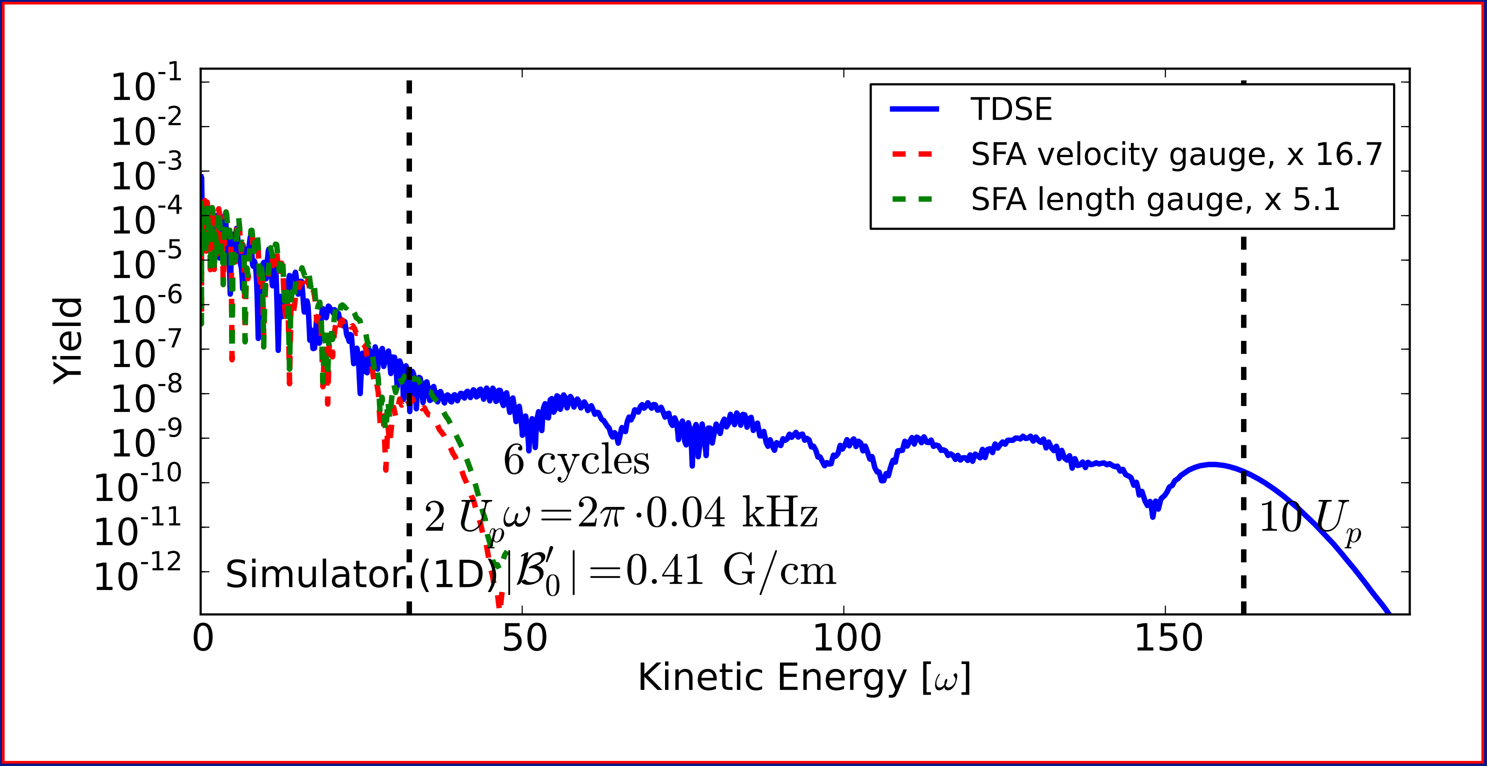
Characteristic features: direct emission ($< 2U_p$), plateau between 2 and 10 U_p.

SFA (strong-field approximation): very popular, **long-range Coulomb interaction between electron and remaining ion is ignored!**

Quantum simulator in quasi-static regime (II)

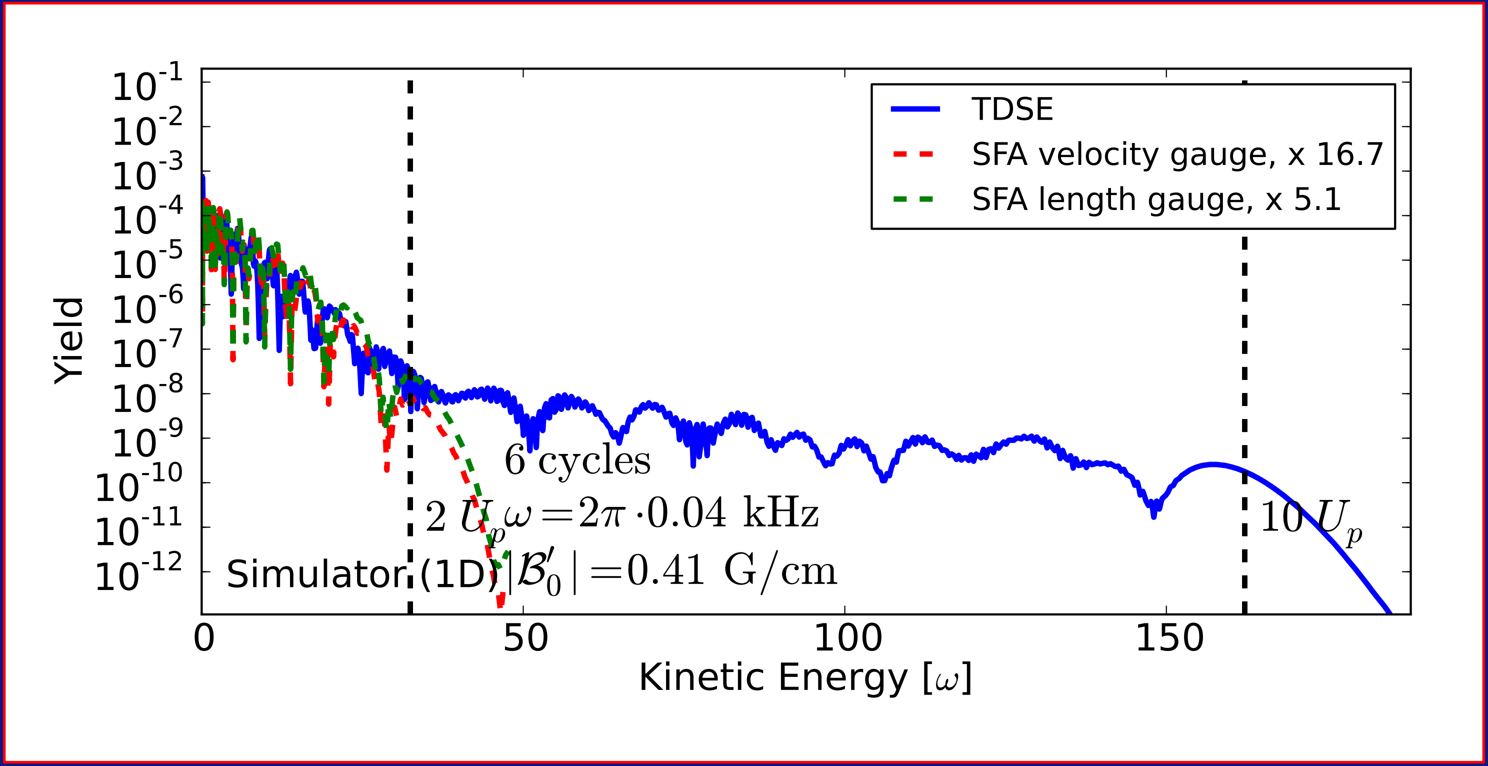


Measurement issues



Problem: in view of the **statistics** such **energy-resolved "ATI" spectra** are **hard to measure with few atoms**.

Measurement issues

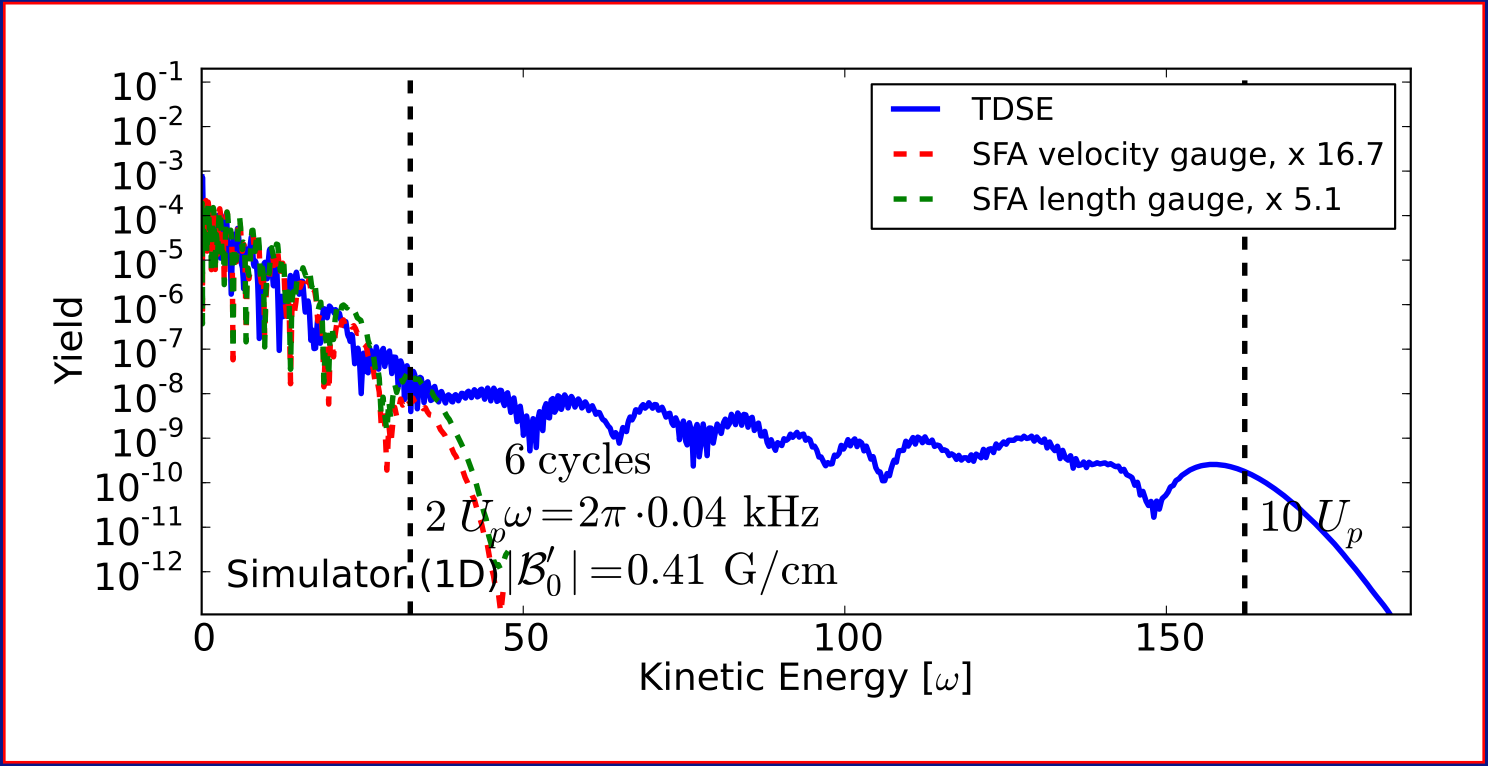


Problem: in view of the **statistics** such **energy-resolved "ATI" spectra** are **hard to measure with few atoms**.

Possible solutions:

other observables (e. g., excited states: "frustrated tunneling ionization")

Measurement issues



Problem: in view of the **statistics** such **energy-resolved "ATI" spectra** are **hard to measure with few atoms**.

Possible solutions:

other observables (e. g., excited states: "frustrated tunneling ionization")

or using **many atoms** (e. g., one BEC) per simulated electron!

Towards experimental realization

The possibility of strong-field simulations with ultracold atoms has been discussed earlier: Arlinghaus and Holthaus [*Phys. Rev. A* **81**, 063612 (2010)].

Idea: a periodically shaken lattice effectively generates a periodic linear force (in the frame co-moving with the lattice).

Towards experimental realization

The possibility of strong-field simulations with ultracold atoms has been discussed earlier: Arlinghaus and Holthaus [*Phys. Rev. A* **81**, 063612 (2010)].

Idea: a periodically shaken lattice effectively generates a periodic linear force (in the frame co-moving with the lattice).

Simulator: the atoms in the lattice represent electrons in a solid exposed to a periodic electromagnetic field.

Towards experimental realization

The possibility of strong-field simulations with ultracold atoms has been discussed earlier: Arlinghaus and Holthaus [*Phys. Rev. A* **81**, 063612 (2010)].

Idea: a periodically shaken lattice effectively generates a periodic linear force (in the frame co-moving with the lattice).

Simulator: the atoms in the lattice represent electrons in a solid exposed to a periodic electromagnetic field.

$\longrightarrow$ **"Floquet engineering"** [Holthaus, *J. Phys. B* **49**, 013001 (2016)]

Towards experimental realization

The possibility of strong-field simulations with ultracold atoms has been discussed earlier: Arlinghaus and Holthaus [*Phys. Rev. A* **81**, 063612 (2010)].

Idea: a periodically shaken lattice effectively generates a periodic linear force (in the frame co-moving with the lattice).

Simulator: the atoms in the lattice represent electrons in a solid exposed to a periodic electromagnetic field.

⟶ **"Floquet engineering"** [Holthaus, *J. Phys. B* **49**, 013001 (2016)]

Combination: Use a single- (or few-)site trap (instead of optical lattice) and shaking (instead of magnetic-field gradient) with many atoms (better statistics).

Towards experimental realization

The possibility of strong-field simulations with ultracold atoms has been discussed earlier: Arlinghaus and Holthaus [*Phys. Rev. A* **81**, 063612 (2010)].

Idea: a periodically shaken lattice effectively generates a periodic linear force (in the frame co-moving with the lattice).

Simulator: the atoms in the lattice represent electrons in a solid exposed to a periodic electromagnetic field.

⟶ **"Floquet engineering"** [Holthaus, *J. Phys. B* **49**, 013001 (2016)]

Combination: Use a single- (or few-)site trap (instead of optical lattice) and shaking (instead of magnetic-field gradient) with many atoms (better statistics).

Experiment: periodically shaken single-trap strontium BEC:
David Weld and his group at University of California Santa Barbara (UCSB).

Towards experimental realization

The possibility of strong-field simulations with ultracold atoms has been discussed earlier: Arlinghaus and Holthaus [*Phys. Rev. A* **81**, 063612 (2010)].

Idea: a periodically shaken lattice effectively generates a periodic linear force (in the frame co-moving with the lattice).

Simulator: the atoms in the lattice represent electrons in a solid exposed to a periodic electromagnetic field.

⟶ **"Floquet engineering"** [Holthaus, *J. Phys. B* **49**, 013001 (2016)]

Combination: Use a single- (or few-)site trap (instead of optical lattice) and shaking (instead of magnetic-field gradient) with many atoms (better statistics).

Experiment: periodically shaken single-trap strontium BEC: David Weld and his group at University of California Santa Barbara (UCSB).

Note: Magnetic-field gradient would allow for **larger laser-paramter regime** (multiphoton/quasistatic).

Streaking ultrashort laser fields

A time-delayed (weak) attosecond pulse ionizes an atomic system dressed by an ultrashort intense femtosecond pulse (observed: kinetic energy of emitted electrons).

Streaking ultrashort laser fields

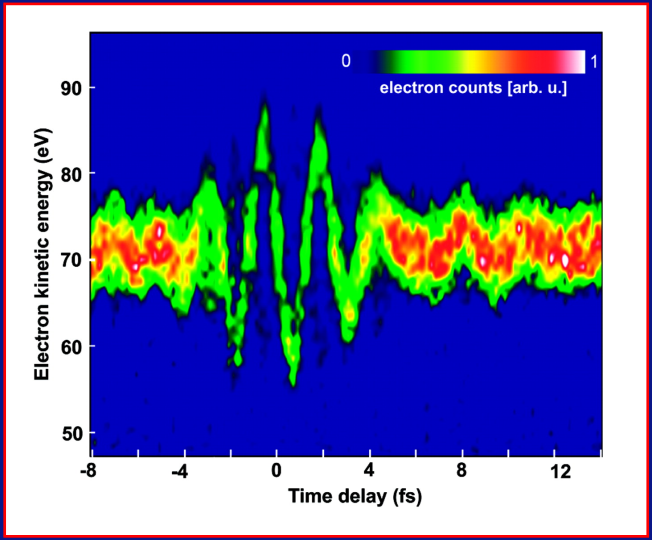
A time-delayed (weak) attosecond pulse ionizes an atomic system dressed by an ultrashort intense femtosecond pulse (observed: kinetic energy of emitted electrons).

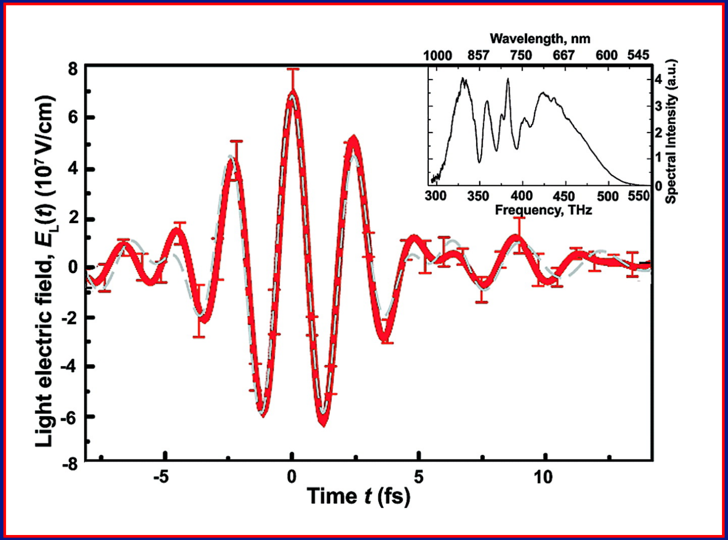
Mapping of the time-dependent vector potential (of the femtosecond pulse) due to mechanical/canonical momentum $p \longrightarrow p + A(t)$.

Streaking ultrashort laser fields

A time-delayed (weak) attosecond pulse ionizes an atomic system dressed by an ultrashort intense femtosecond pulse (observed: kinetic energy of emitted electrons).

Mapping of the time-dependent vector potential (of the femtosecond pulse) due to mechanical/canonical momentum $p \longrightarrow p + A(t)$.

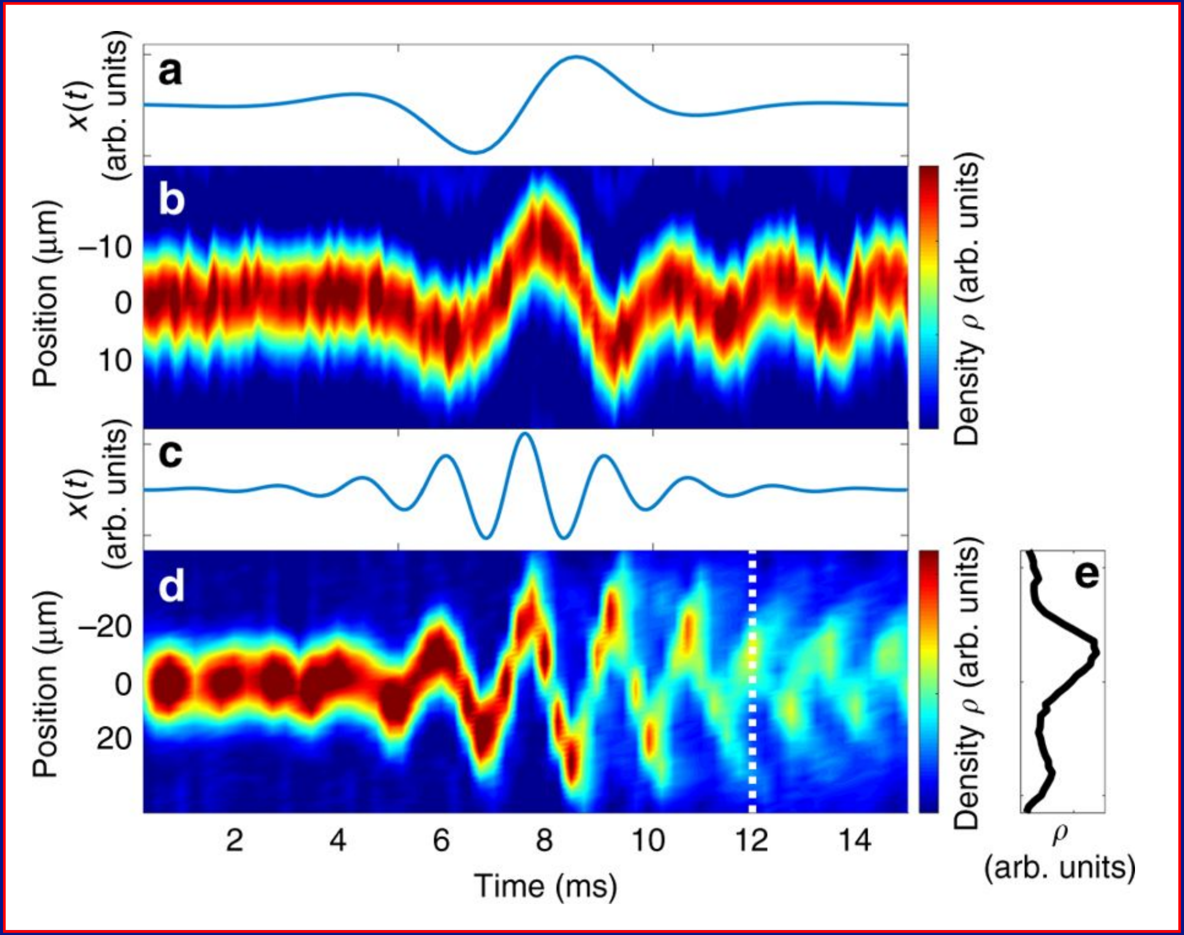




[Goulielmakis *et al.*, *Science* **305**, 1267 (2004)]

.

Streaking using ultracold atoms



Experiment: periodically shaken single-trap strontium BEC.

[Senaratne *et al.*, *Nature Comm.* **9**, 2065 (2018)]

Summary

- *Lochfraß*: robust coherent wavepacket formation by means of time and spatially varying dissipation.
- The proposed ultracold-quantum simulator for strong-field physics [“attosecond science in slow motion”, *Phys. Rev. A* **95**, 011403 (*Rapid Comm.*) (2017)] works for realistic experimental parameters.

Summary

- *Lochfraß*: robust coherent wavepacket formation by means of time and spatially varying dissipation.
- The proposed ultracold-quantum simulator for strong-field physics [“attosecond science in slow motion”, *Phys. Rev. A* **95**, 011403 (*Rapid Comm.*) (2017)] works for realistic experimental parameters.
- Experimental realisation(s) in progress.

Summary

- *Lochfraß*: robust coherent wavepacket formation by means of time and spatially varying dissipation.
- The proposed ultracold-quantum simulator for strong-field physics ["attosecond science in slow motion", *Phys. Rev. A* **95**, 011403 (*Rapid Comm.*) (2017)] works for realistic experimental parameters.
- Experimental realisation(s) in progress.
- The quantum simulator is extremely flexible (potential, particle number and interactions, pulse shapes, . . .) and "clean".

Summary

- *Lochfraß*: robust coherent wavepacket formation by means of time and spatially varying dissipation.
- The proposed ultracold-quantum simulator for strong-field physics [“attosecond science in slow motion”, *Phys. Rev. A* **95**, 011403 (*Rapid Comm.*) (2017)] works for realistic experimental parameters.
- Experimental realisation(s) in progress.
- The quantum simulator is extremely flexible (potential, particle number and interactions, pulse shapes, . . .) and “clean”.
- Multiple wells (molecules with fixed or classically moving nuclei) recently realised.

Summary

- *Lochfraß*: robust coherent wavepacket formation by means of time and spatially varying dissipation.
- The proposed ultracold-quantum simulator for strong-field physics [“attosecond science in slow motion”, *Phys. Rev. A* **95**, 011403 (*Rapid Comm.*) (2017)] works for realistic experimental parameters.
- Experimental realisation(s) in progress.
- The quantum simulator is extremely flexible (potential, particle number and interactions, pulse shapes, . . .) and “clean”.
- Multiple wells (molecules with fixed or classically moving nuclei) recently realised.
- May test all kind of “tunnelling (delay) times”.

Summary

- *Lochfraß*: robust coherent wavepacket formation by means of time and spatially varying dissipation.
- The proposed ultracold-quantum simulator for strong-field physics ["attosecond science in slow motion", *Phys. Rev. A* **95**, 011403 (*Rapid Comm.*) (2017)] works for realistic experimental parameters.
- Experimental realisation(s) in progress.
- The quantum simulator is extremely flexible (potential, particle number and interactions, pulse shapes, . . .) and "clean".
- Multiple wells (molecules with fixed or classically moving nuclei) recently realised.
- May test all kind of "tunnelling (delay) times".
- **Really of interest:** not H atom (used here for validation), but simulations of many-particle systems beyond the reach of classical computers.

Summary

- *Lochfraß*: robust coherent wavepacket formation by means of time and spatially varying dissipation.
- The proposed ultracold-quantum simulator for strong-field physics [“attosecond science in slow motion”, *Phys. Rev. A* **95**, 011403 (*Rapid Comm.*) (2017)] works for realistic experimental parameters.
- Experimental realisation(s) in progress.
- The quantum simulator is extremely flexible (potential, particle number and interactions, pulse shapes, . . .) and “clean”.
- Multiple wells (molecules with fixed or classically moving nuclei) recently realised.
- May test all kind of “tunnelling (delay) times”.
- **Really of interest:** not H atom (used here for validation), but simulations of many-particle systems beyond the reach of classical computers.

New perspective: strongly (periodically) driven (few or many) ultracold atoms, possibly with (strong) interaction and structured dissipative environment.