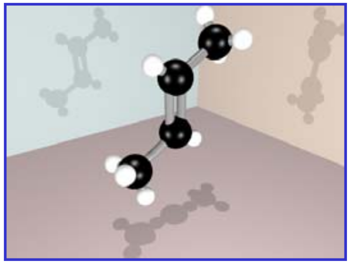
Quantenkontrolle

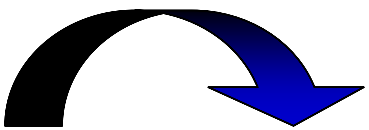
- Warum?
- Techniken
- Beispiele

Warum Quantenkontrolle?

$|i\rangle$

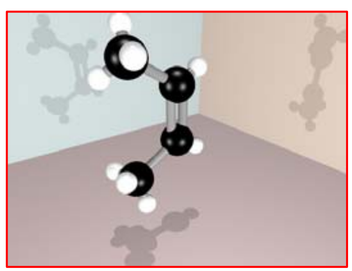


$-\vec{\mu}\,\vec{\mathcal{E}}(t)$



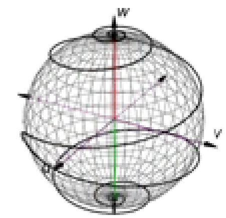
$|i\rangle$ $|f\rangle$

$|f\rangle$

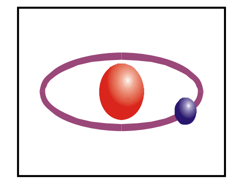


Anwendungen

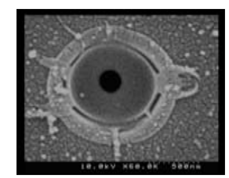
Quantencomputer



Attosekundenphysik



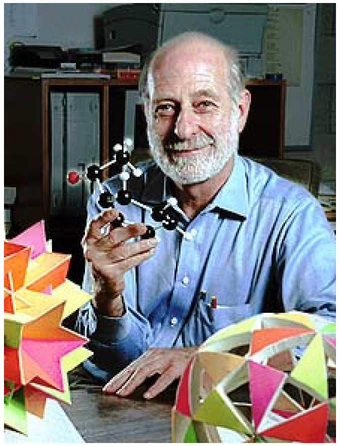
Materialbearbeitung



Kontrolle chemischer Reaktionen

Quantum control

“A most important point is that the operating principle for quantum control of any type is the manipulation of constructive and destructive quantum mechanical interferences“



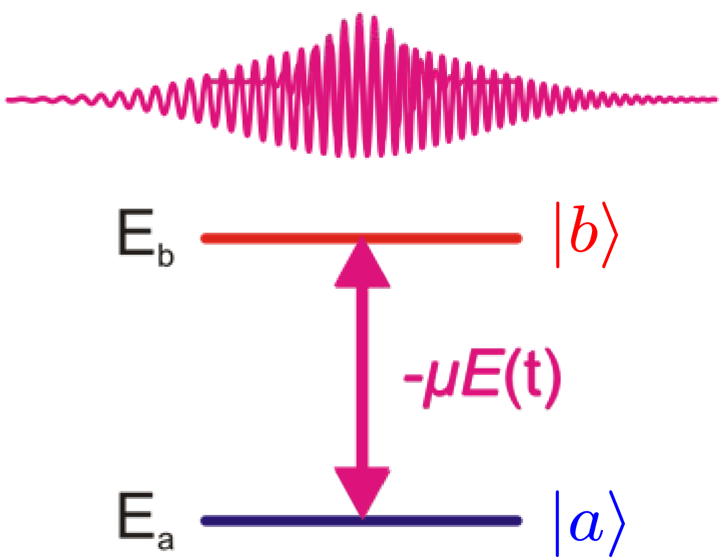
H. Rabitz

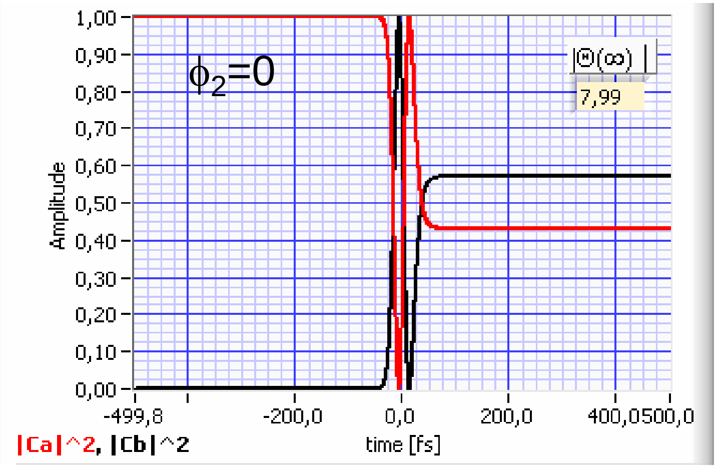
Quantenkontrolltechniken

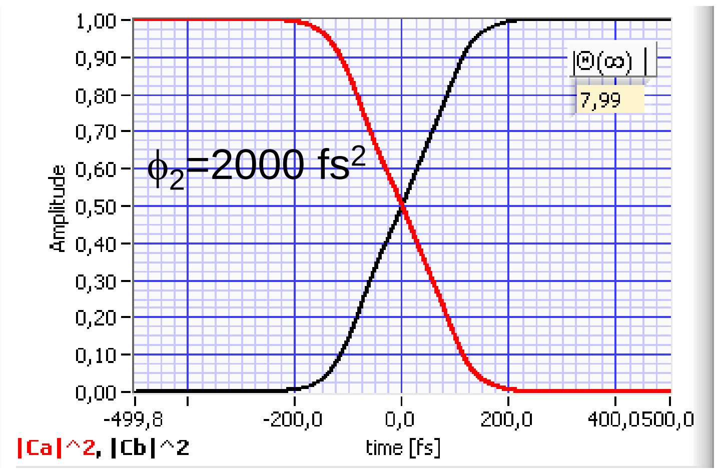
1. RAP (Rapid Adiabatic Passage)
2. STIRAP (Stimulated Raman Adiabatic Passage)
3. OCT (Optimal Control Theory)
4. Adaptive Methoden (Optimal Control Experiment, OCE)
5. Brumer – Shapiro
6. Tannor-Kosloff-Rice
7. Spektrale Interferenz
8. Control PES (Potential Energy Surfaces)
9. SPODS (Selective Population of Dressed States)

RAP

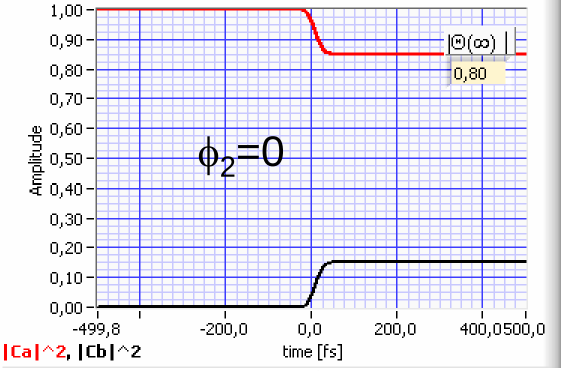
- **RAP** (Rapid Adiabatic Passage)
- Zwei Niveau System
- Intensive Laserfelder
- Chirp



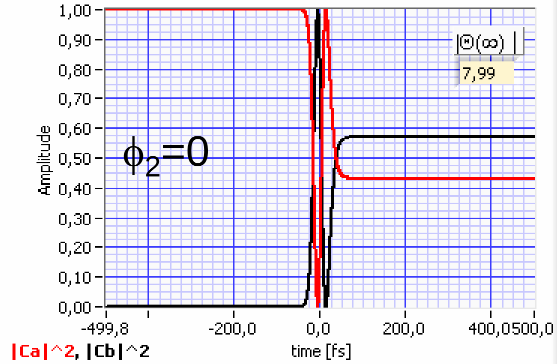




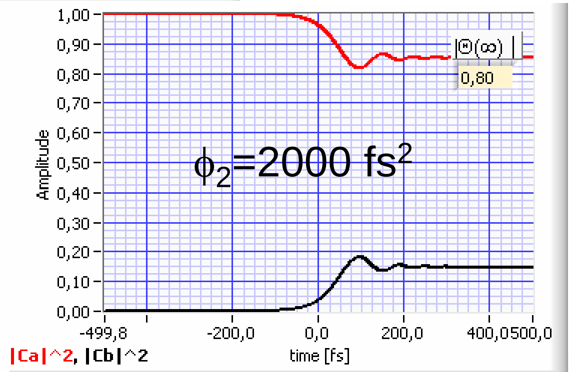
RAP



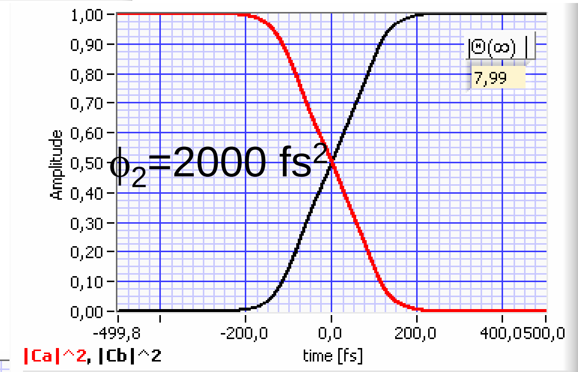
ϕ_2=0
|Θ(∞)|
0,80
Amplitude
time [fs]
|Ca|^2, |Cb|^2



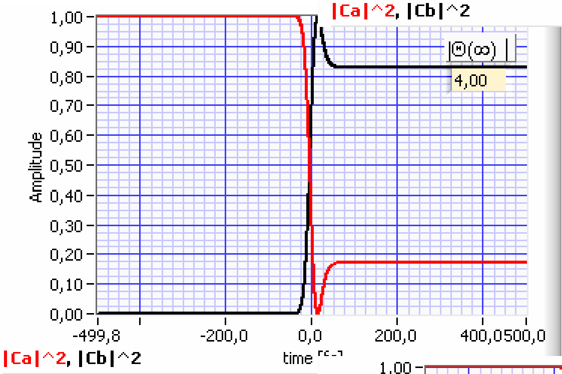
ϕ_2=0
|Θ(∞)|
7,99
Amplitude
time [fs]
|Ca|^2, |Cb|^2



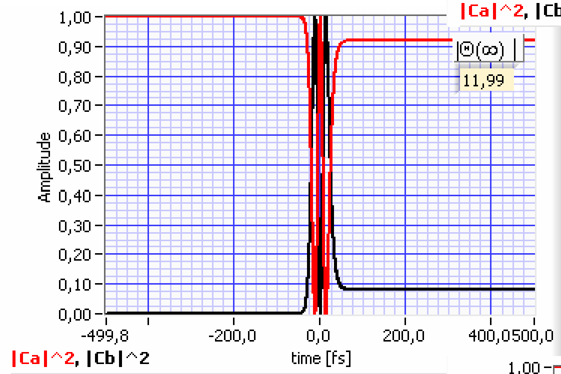
ϕ_2=2000 fs^2
|Θ(∞)|
0,80
Amplitude
time [fs]
|Ca|^2, |Cb|^2



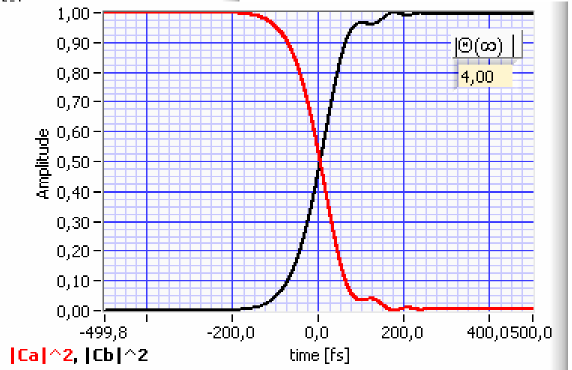
ϕ_2=2000 fs^2
|Θ(∞)|
7,99
Amplitude
time [fs]
|Ca|^2, |Cb|^2



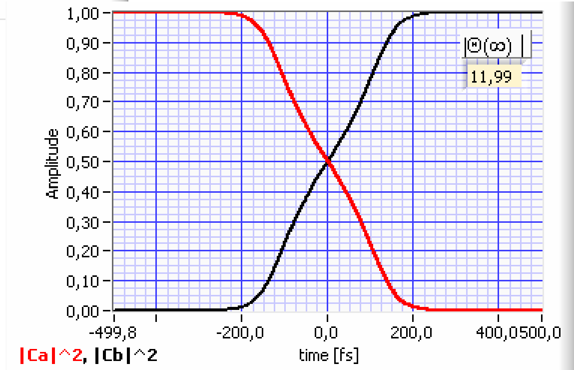
|Θ(∞)|
4,00
Amplitude
|Ca|^2, |Cb|^2



|Θ(∞)|
11,99
Amplitude
time [fs]
|Ca|^2, |Cb|^2



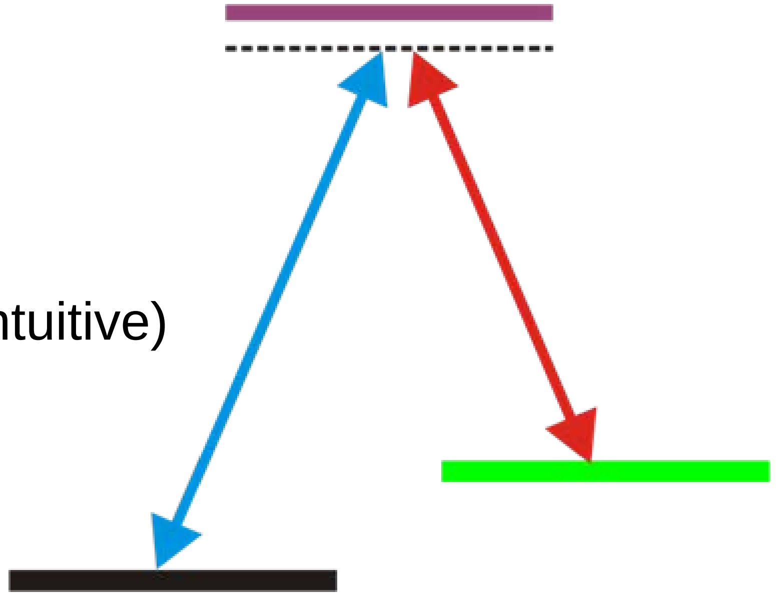
|Θ(∞)|
4,00
Amplitude
time [fs]
|Ca|^2, |Cb|^2



|Θ(∞)|
11,99
Amplitude
time [fs]
|Ca|^2, |Cb|^2

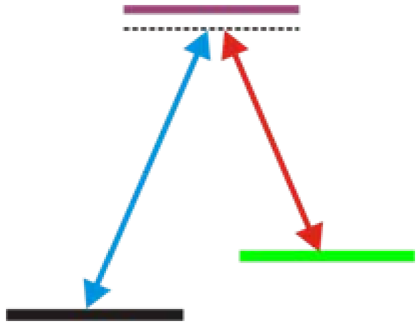
STIRAP

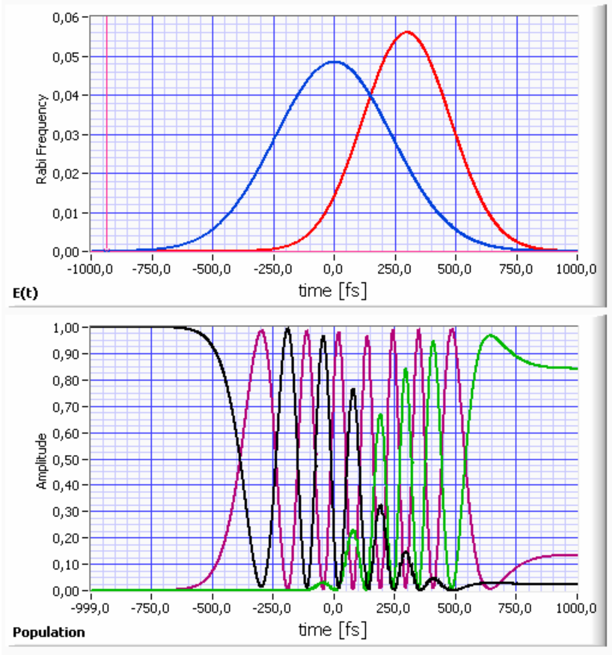
- **STIRAP** (Stimulated Raman Adiabatic Passage)
- Drei Niveau System
- Intensive Laserfelder
- Zwei Laserfelder
- Raman Übergänge
- Detuning
- Time Delay (counter-intuitive)



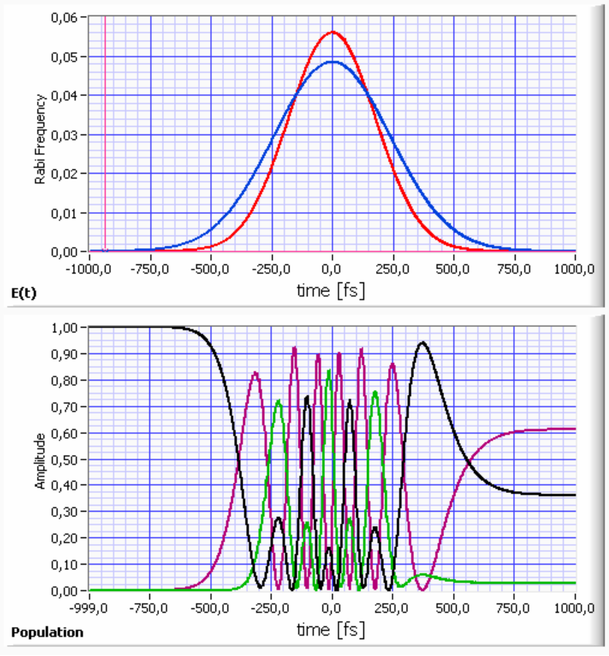
K. Bergmann

Resonant

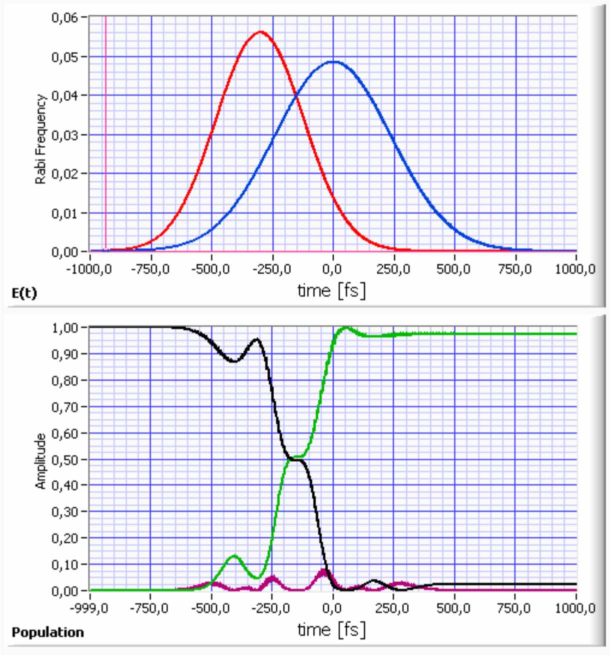




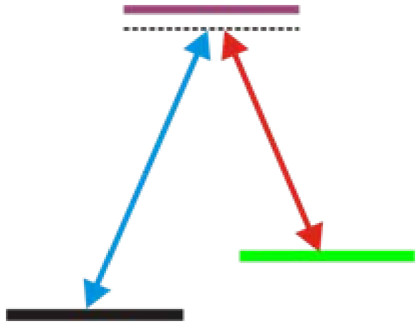
Δt = 300 fs



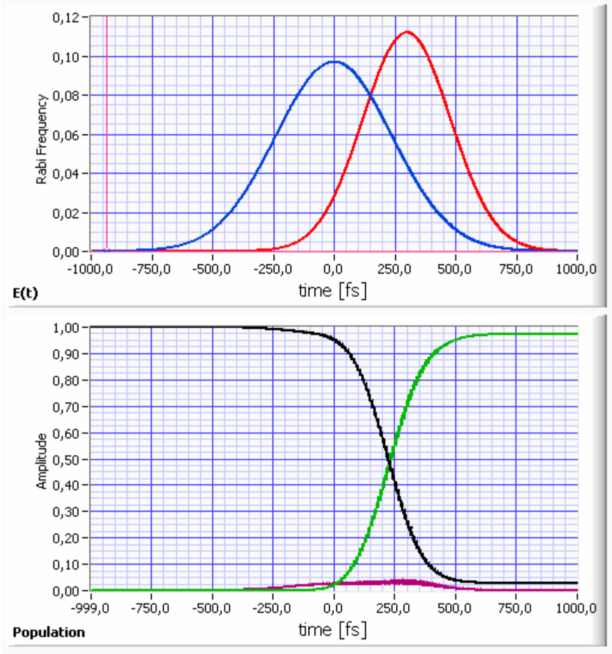
Δt = 0 fs



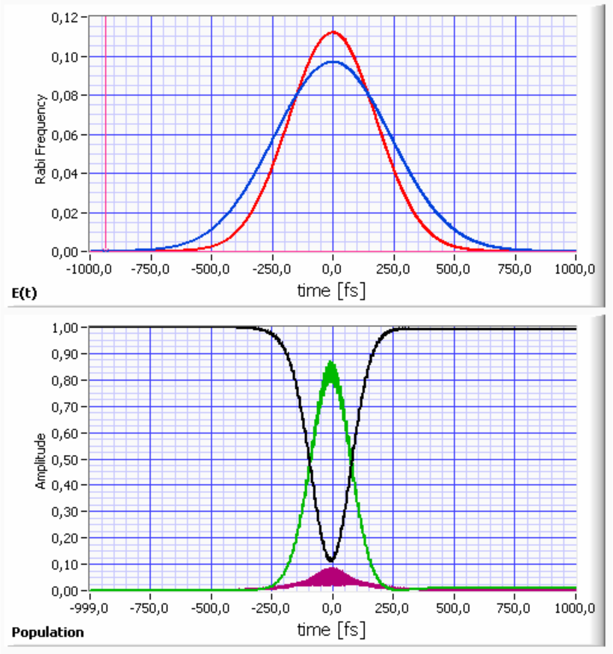
Δt = -300 fs



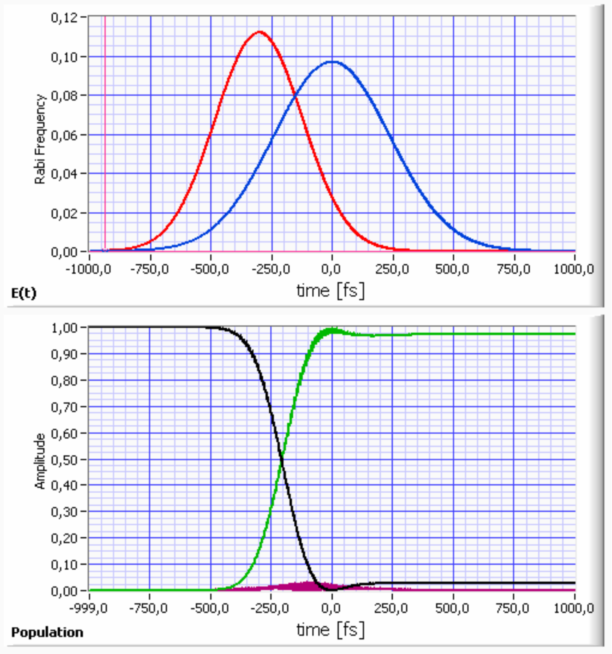
Nichtresonant



Δt = 300 fs



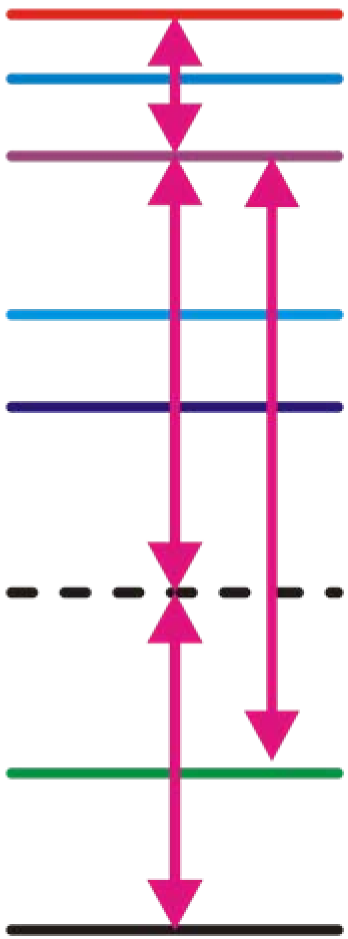
Δt = 0 fs



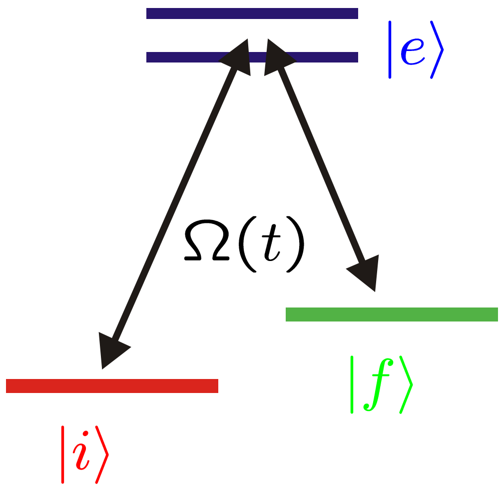
Δt = -300 fs

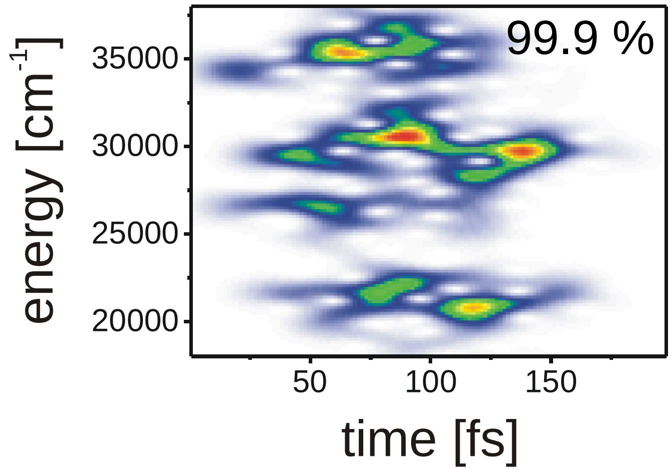
Optimal control theory (OCT)

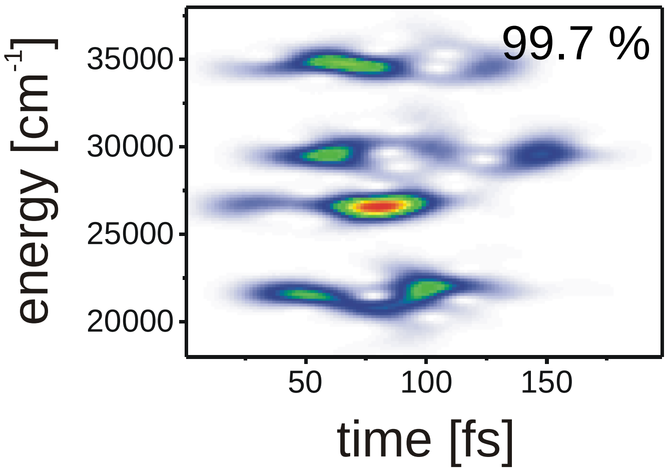
- **OCT**
- Multilevel Systeme / Moleküle
- Intensive Laserfelder
- Optimierungsziel vorgeben
- Optimierungsalgorithmus
- Komplexe Pulse / Komplexe Spektren

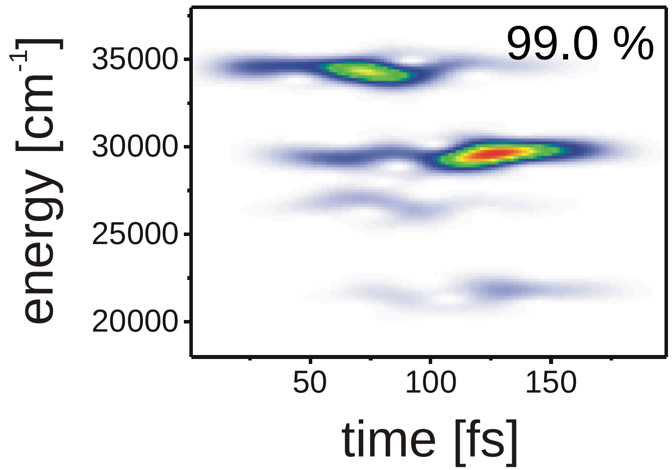


OCT Beispiel

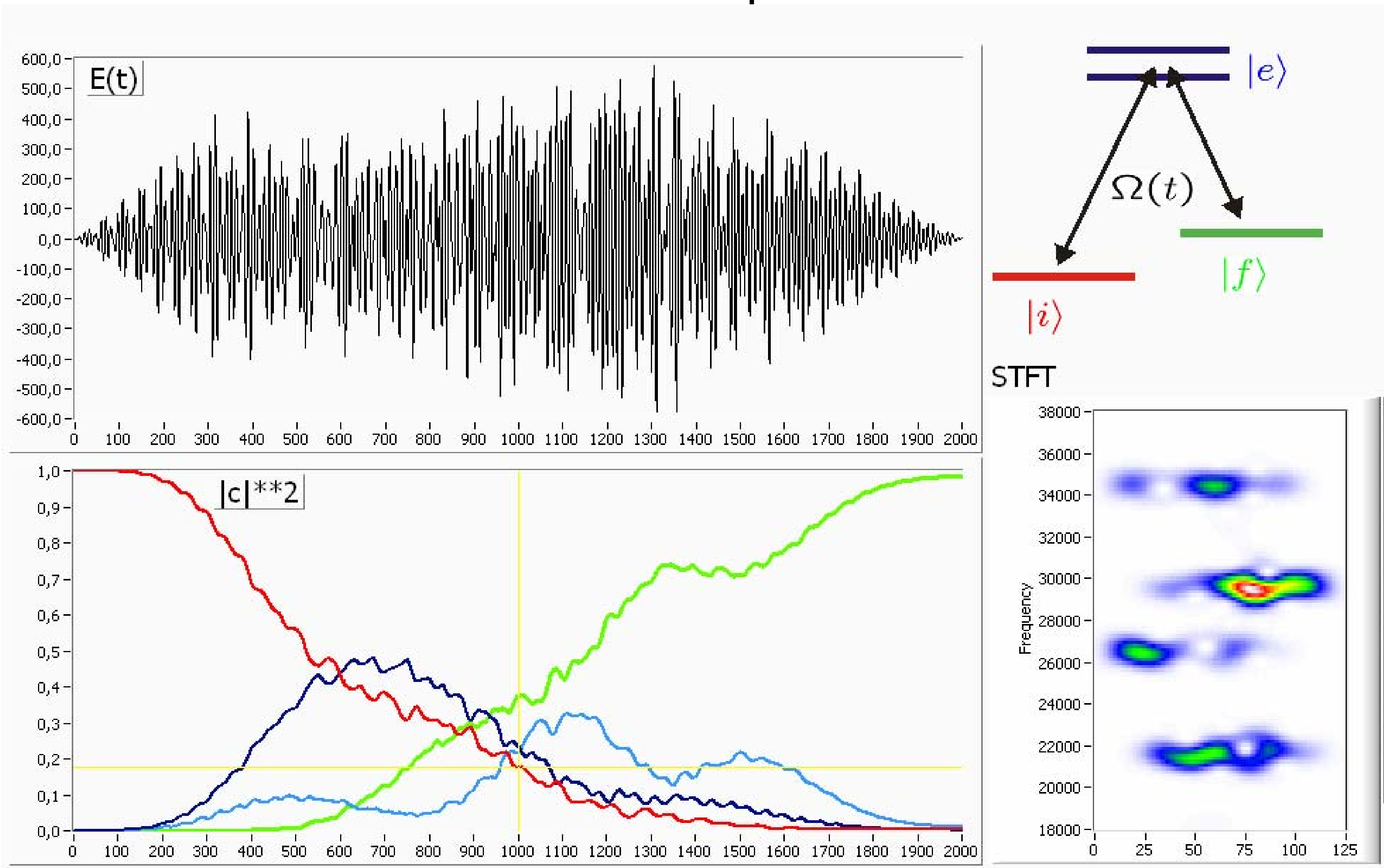






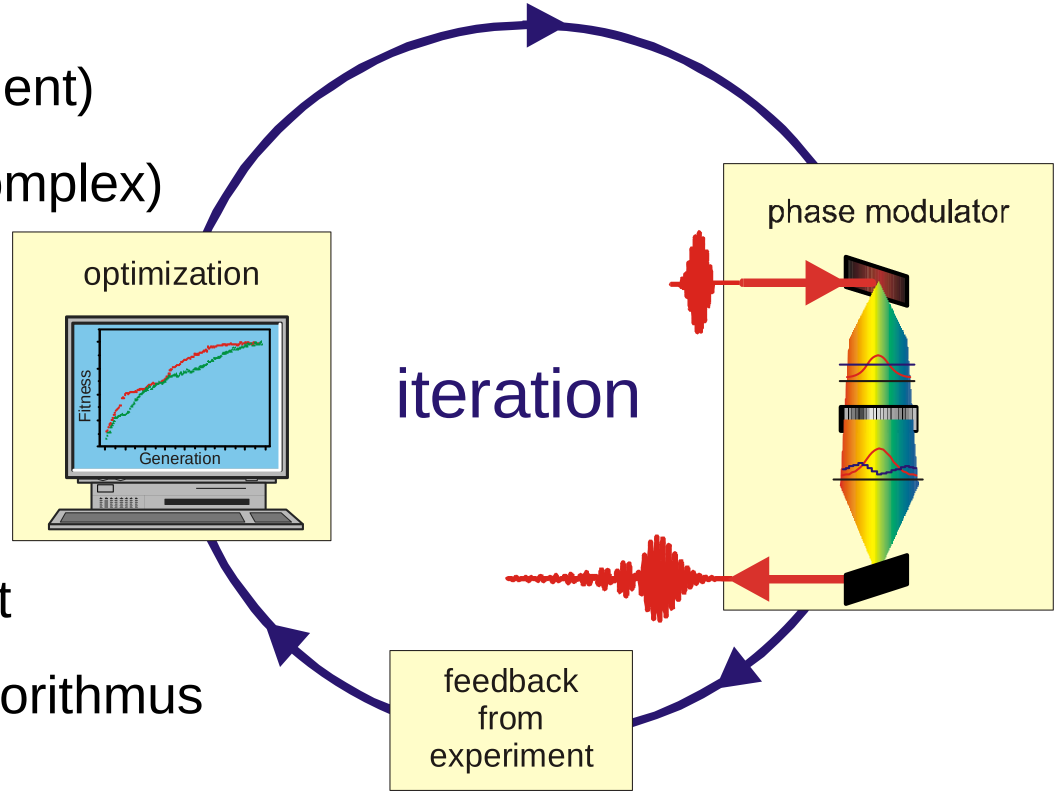


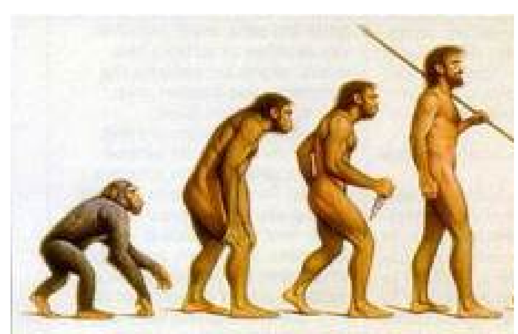
OCT Beispiel



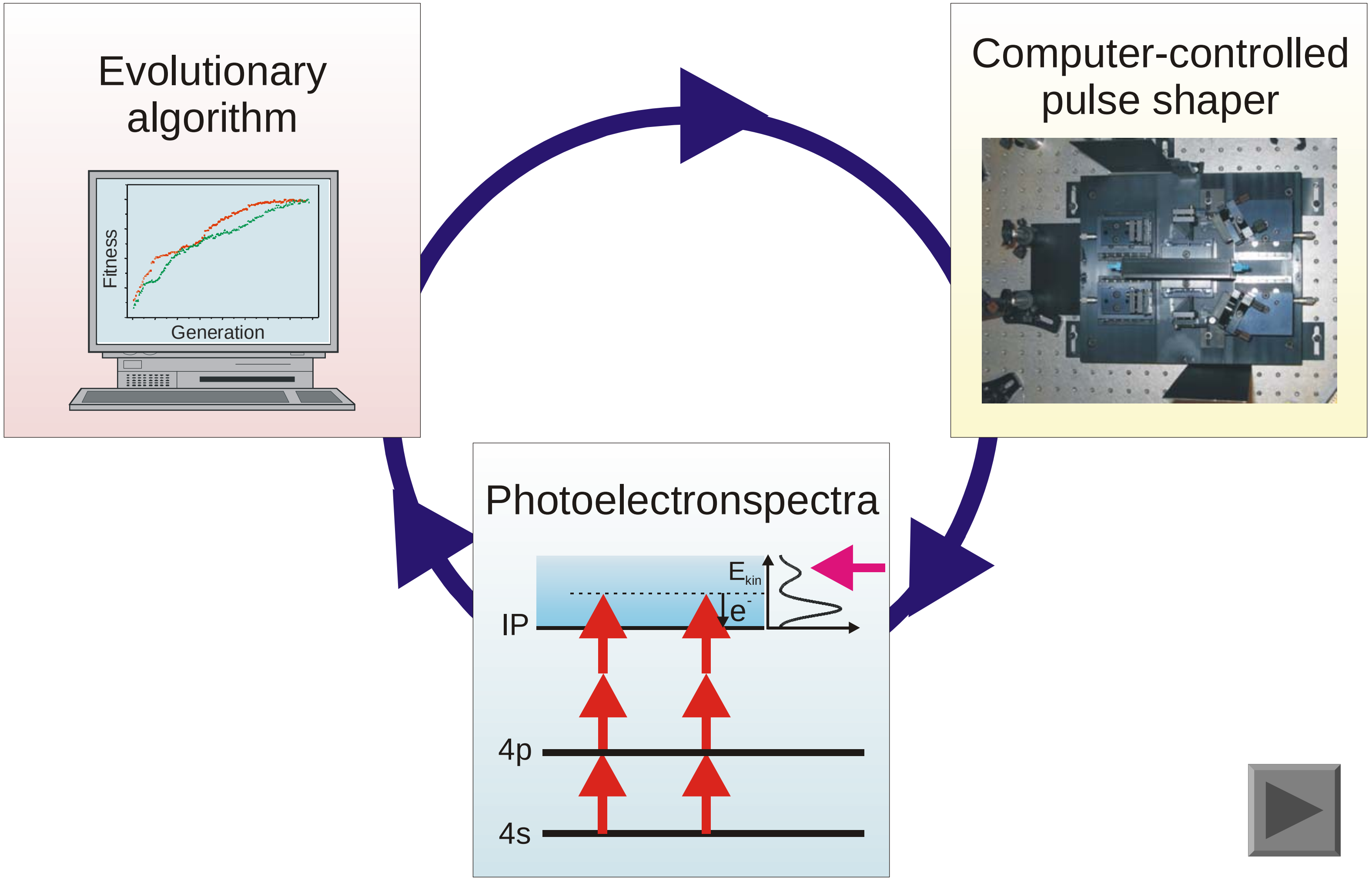
Rückkopplungsgesteuerte adaptive Optimierung

- **OCE** (Optimal Control Experiment)
- Beliebige Systeme (beliebig komplex)
- Keinerlei *a priori* Wissen über System notwendig
- Schwache oder intensive geformte Laserfelder
- Rückkopplung vom Experiment
- (Genetischer) Optimierungsalgorithmus
- Iterativ
- Komplexe Pulse kompatibel mit Laserspektrum
- Universell
- Interpretation ?



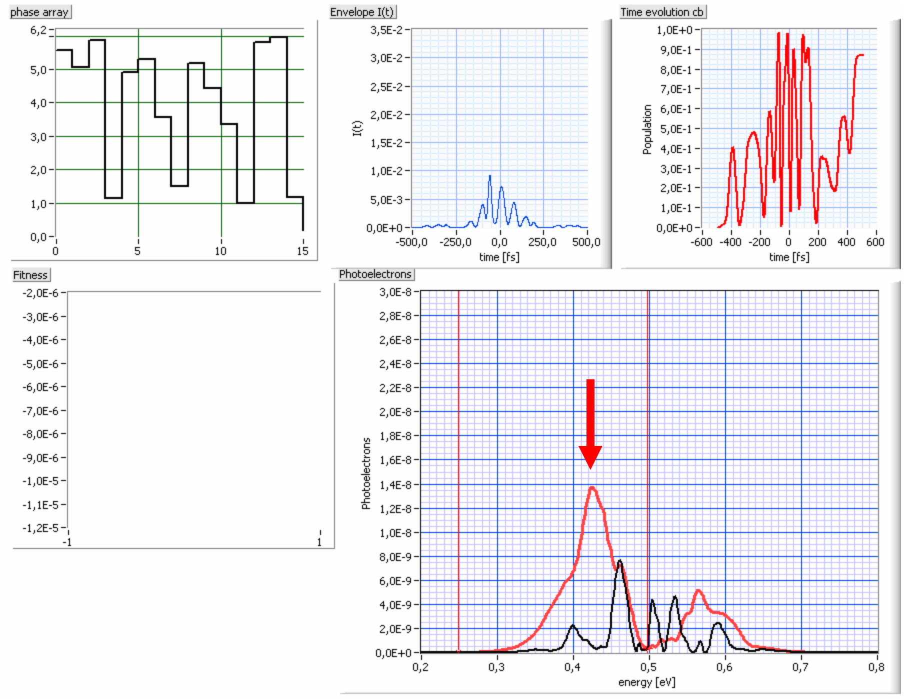


Simulation: adaptive Optimierung eines Photoelektronenspektrums

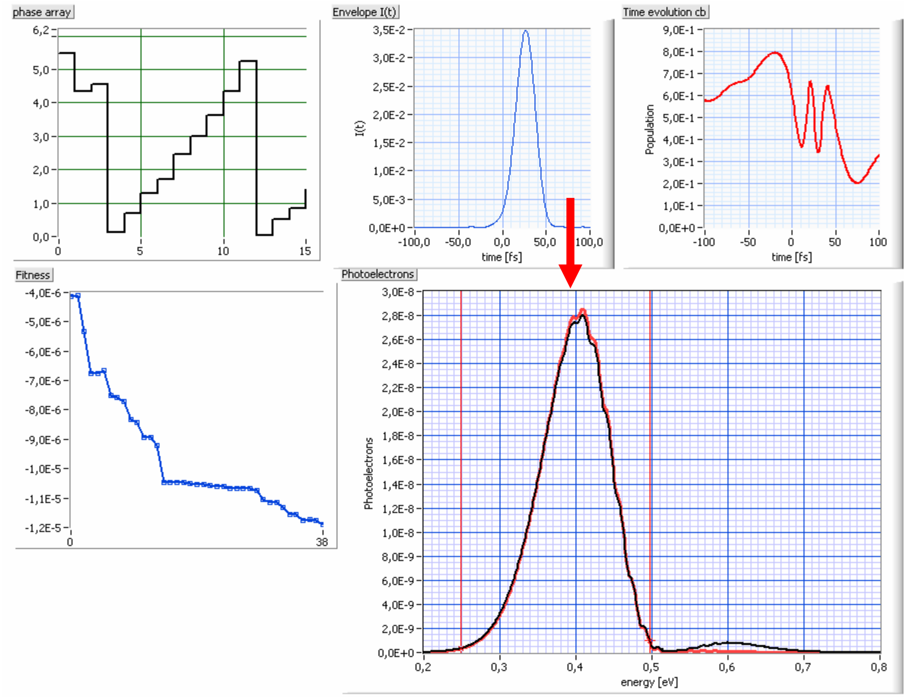


Simulation: adaptive Optimierung eines Photoelektronenspektrums

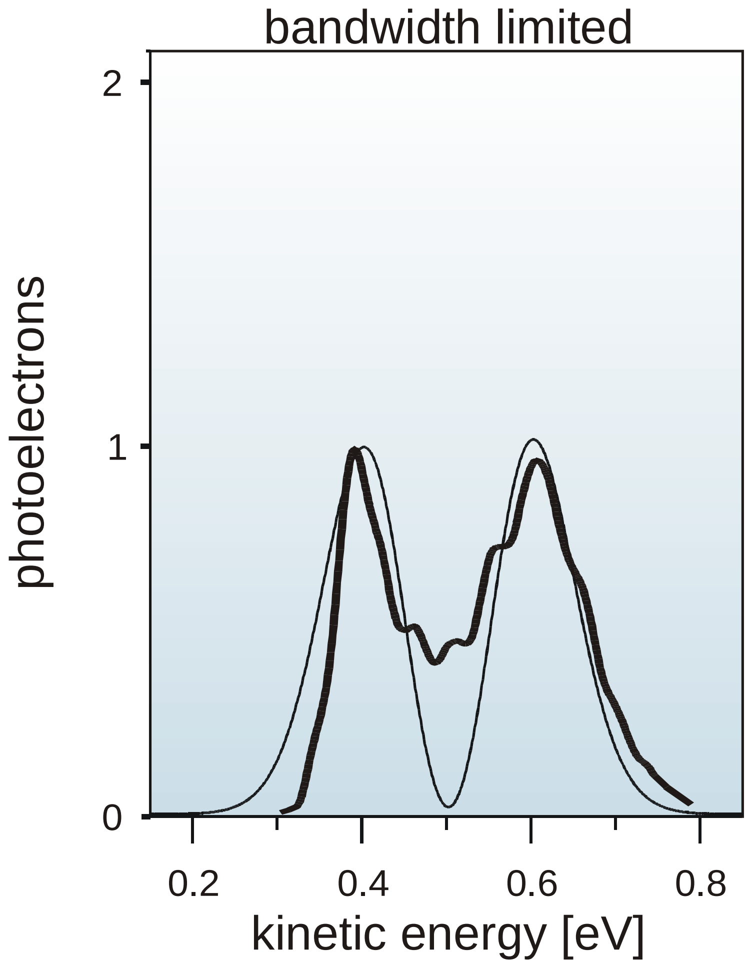
Initial photoelectron spectra

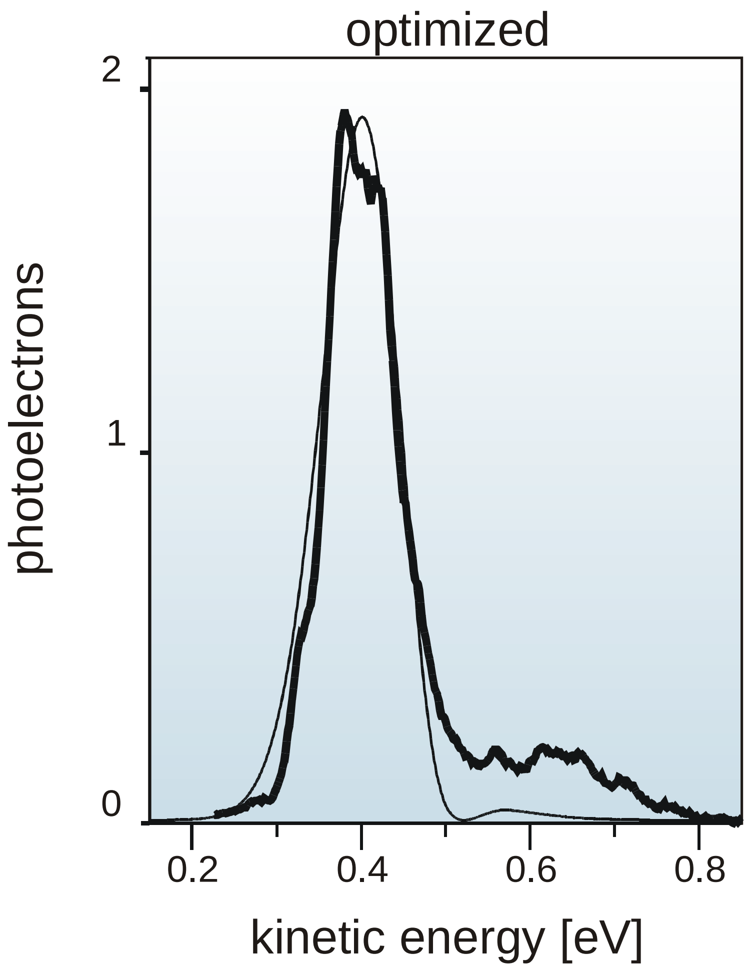


Optimized photoelectron spectra

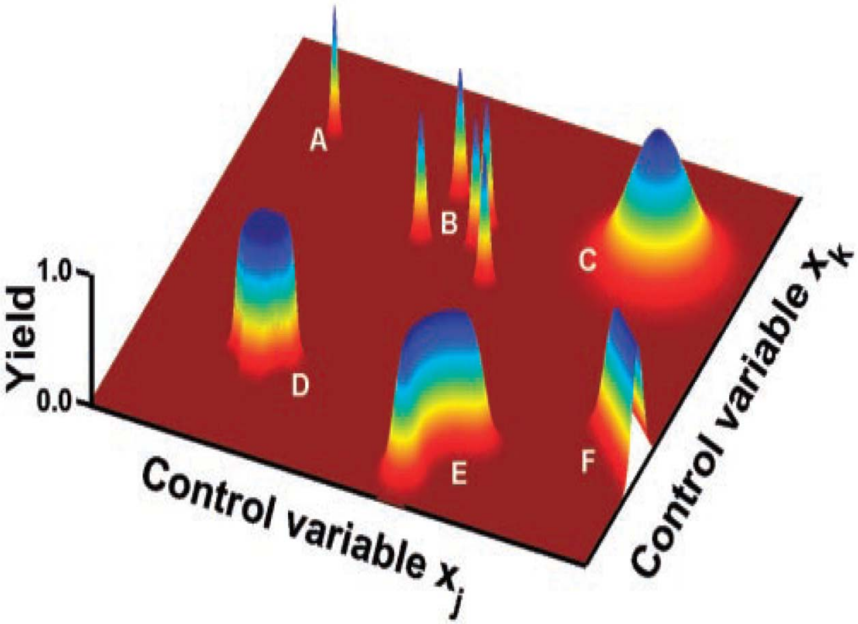


Experiment: adaptive Optimierung eines Photoelektronenspektrums

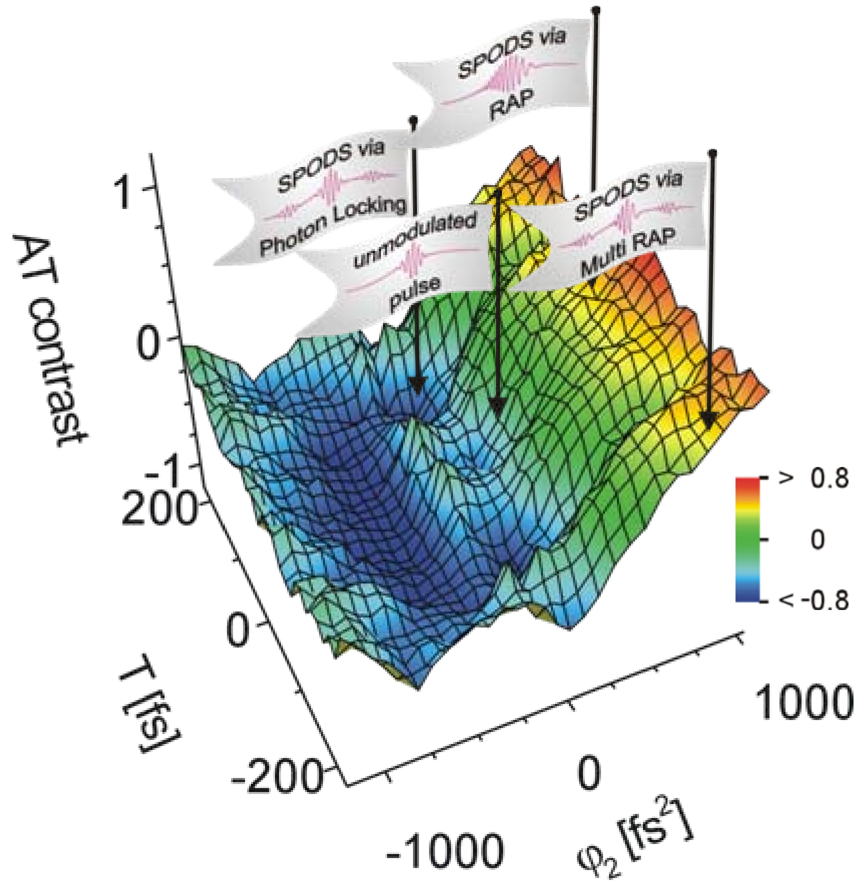




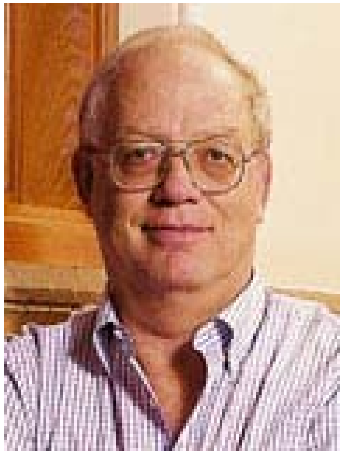
Quantum Control Landscapes



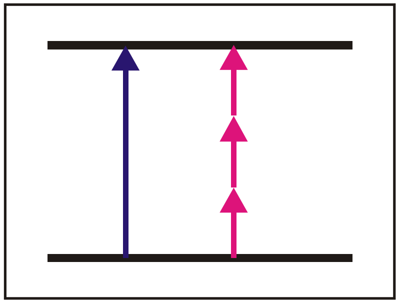
H. A. Rabitz et al., Science **303**, 1998 (2004)



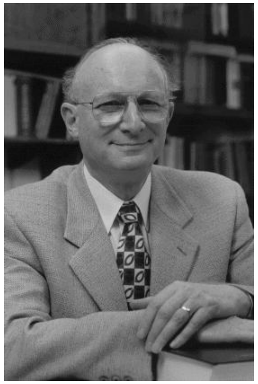
Brumer - Shapiro



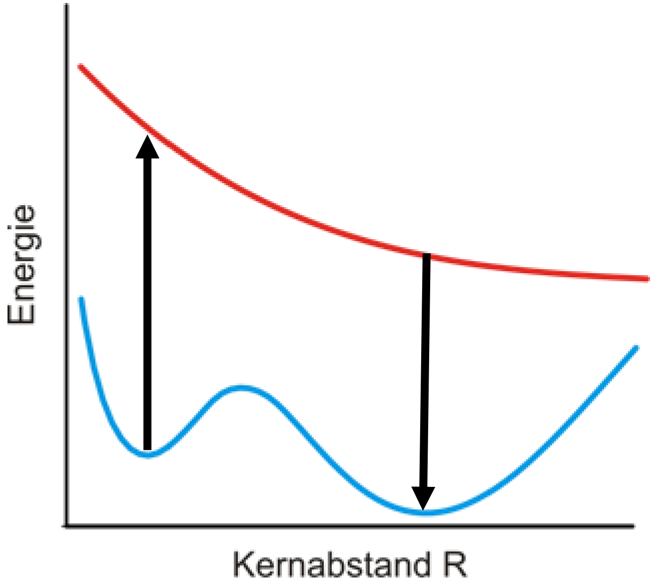
• **Brumer-Shapiro** (N-Photon vs. M-Photon)



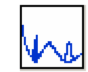
Tannor – Kosloff - Rice

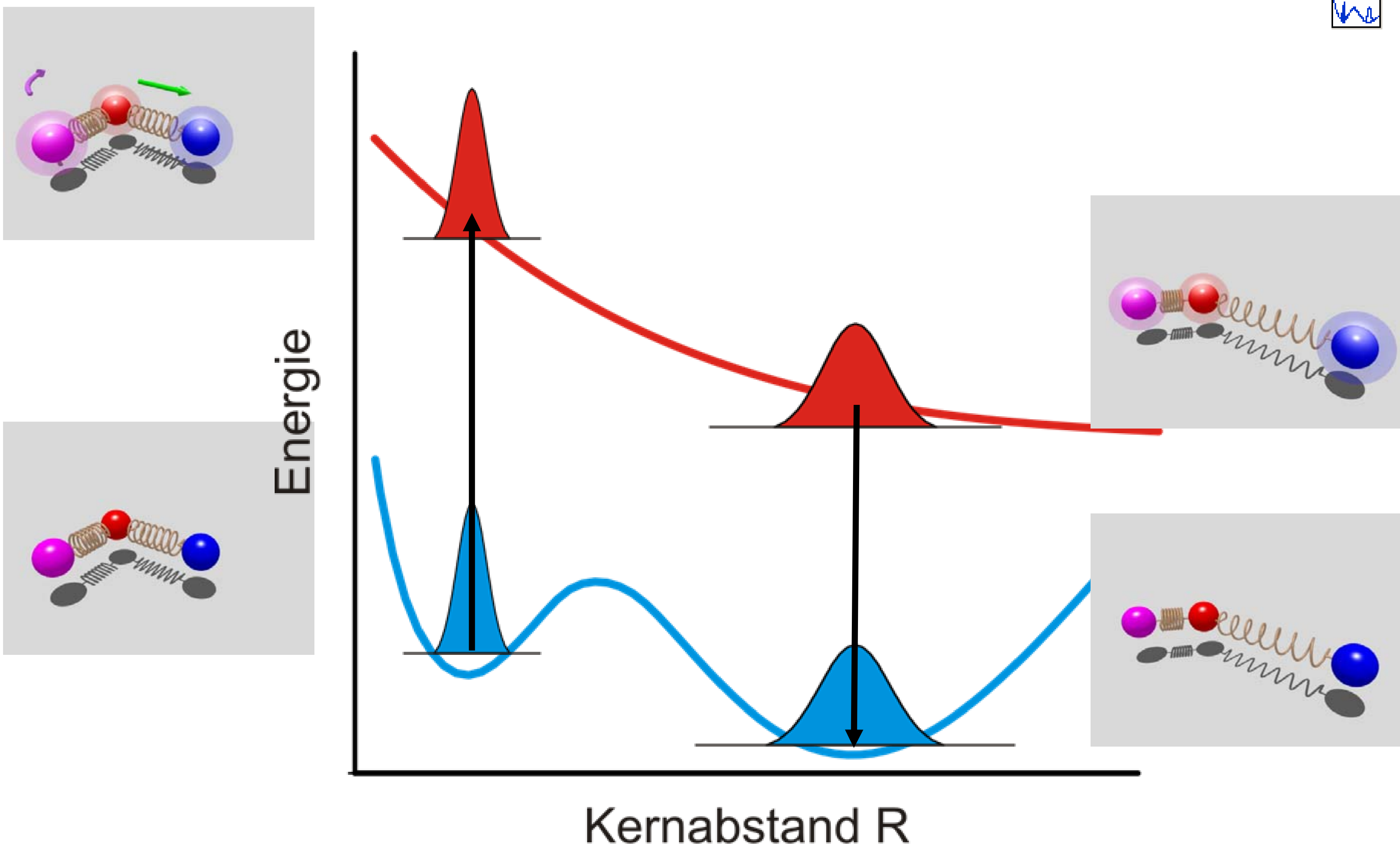
  

- **TKR** (Tannor – Kosloff - Rice)
- Kontrolle durch Pump – Probe Pulse
- Zwei Laserfelder
- Zwei Potentialflächen
- Raman Übergänge
- Time Delay: Synchronisation mit Moleküldynamik



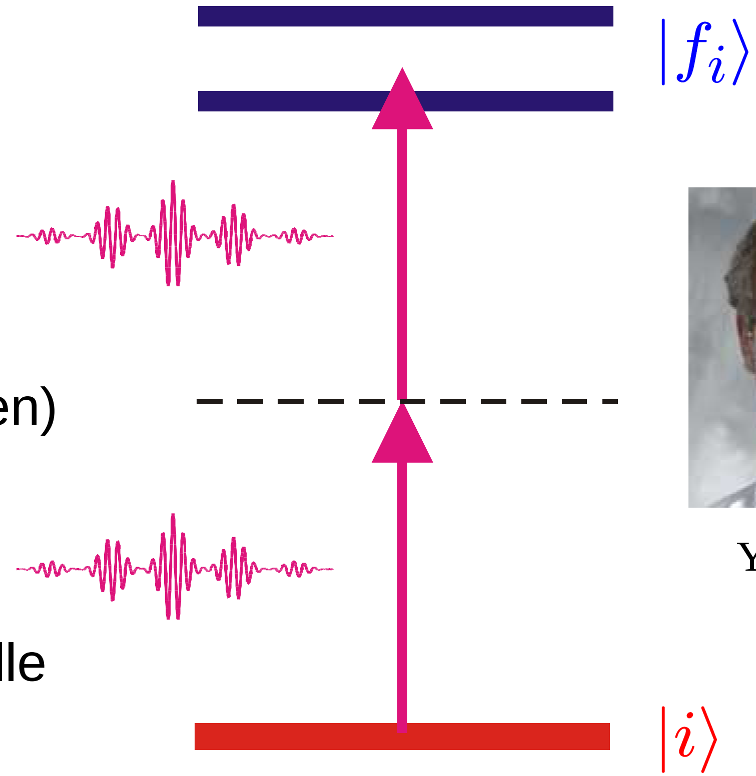
Quantenkontrolle mit Wellenpaketen





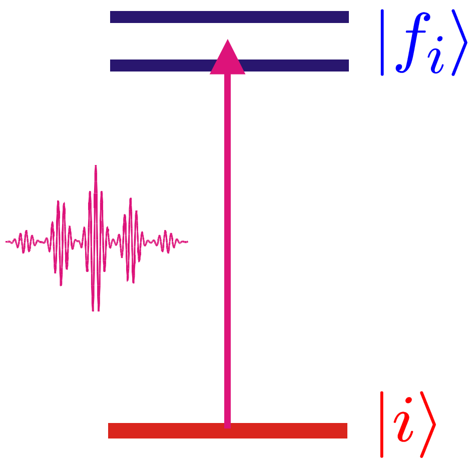
Spektrale Interferenz

- **SI (**Spektrale Interferenz)
- Schwache Laserfelder
- Geformte Laserpulse
- Multiphotonenübergänge (keine intermediären Resonanzen)
- „Kontrolle des Multiphotonenspektrums“
- Verständnis von Quantenkontrolle mit geformten Laserpulsen



Y. Silberberg

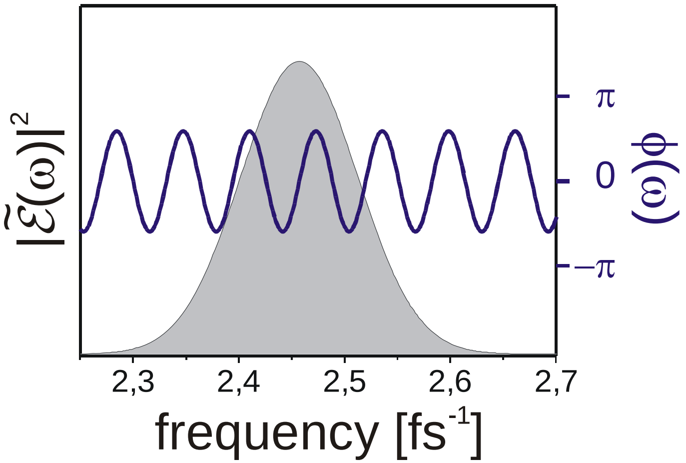
Spektrale Interferenz

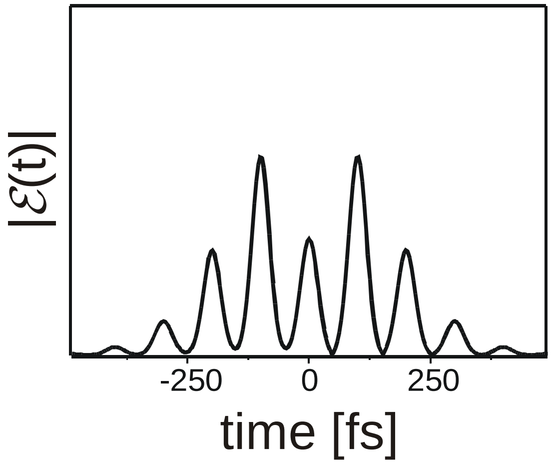


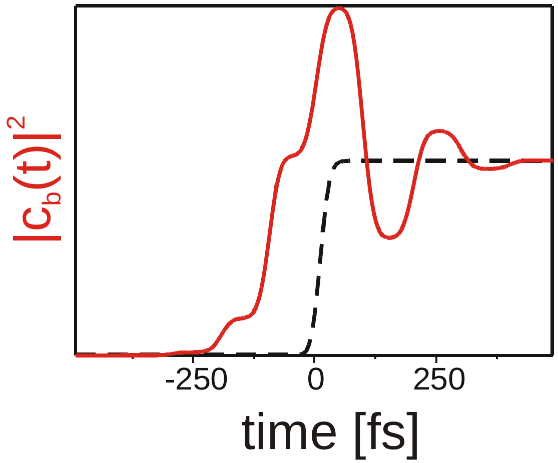
$$\tilde{\mathcal{E}}_{mod}(\omega) = \tilde{\mathcal{E}}(\omega)\tilde{M}(\omega)$$

$$\tilde{M}(\omega) = e^{-i\varphi(\omega)}$$

$$c_f(t) = -\frac{\mu_f}{i\hbar}\tilde{E}^*(\omega_f)$$







Spektrale Interferenz: 2-photonen Anregung

Amplitude nach der Laseranregung:

$$c_f^{(2)}(t) \propto \tilde{S}^*(\omega_f)$$

$$\tilde{S}(\omega) = \int_{-\infty}^{\infty} E^2(t)\, e^{-i\omega t}\, dt$$

„Zweiphotonen Spektrum“

Spektrum der zweiten Harmonischen

$$E(t) \circ\!\!-\!\!\bullet \tilde{E}(\omega)$$

$$E(t) \cdot E(t) \circ\!\!-\!\!\bullet \tilde{S}(\omega) = \tilde{E}(\omega) \otimes \tilde{E}(\omega)$$

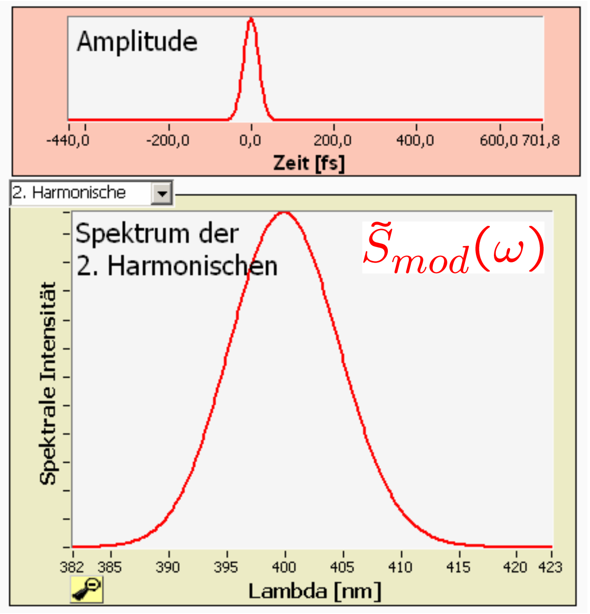
Phasenmodulation

$$E_{mod}(t) \circ\!\!-\!\!\bullet \tilde{E}(\omega) e^{-i\varphi(\omega)}$$

$$E_{mod}(t) \cdot E_{mod}(t) \circ\!\!-\!\!\bullet \tilde{S}_{mod}(\omega) = \tilde{E}(\omega) e^{-i\varphi(\omega)} \otimes \tilde{E}(\omega) e^{-i\varphi(\omega)}$$

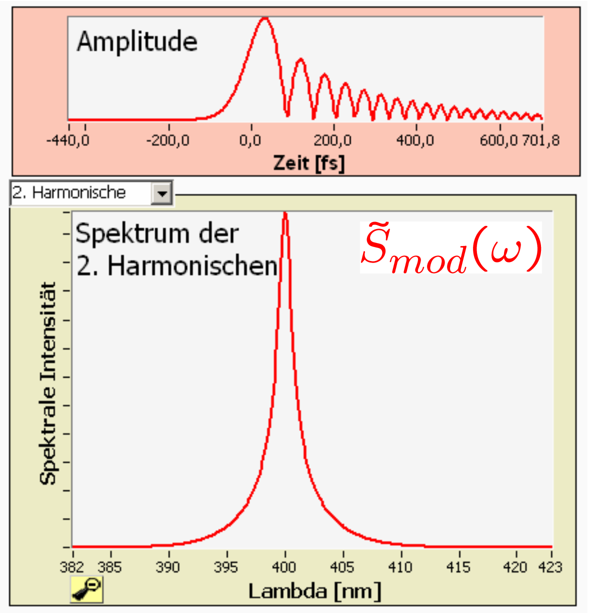
Modulation des Multiphoton Spektrums durch Phasenmodulation

unmoduliert



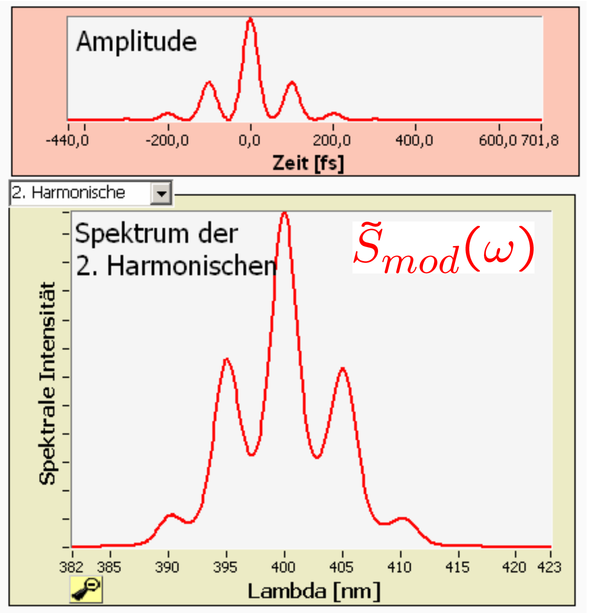
$$\tilde{E}(\omega)$$

TOD



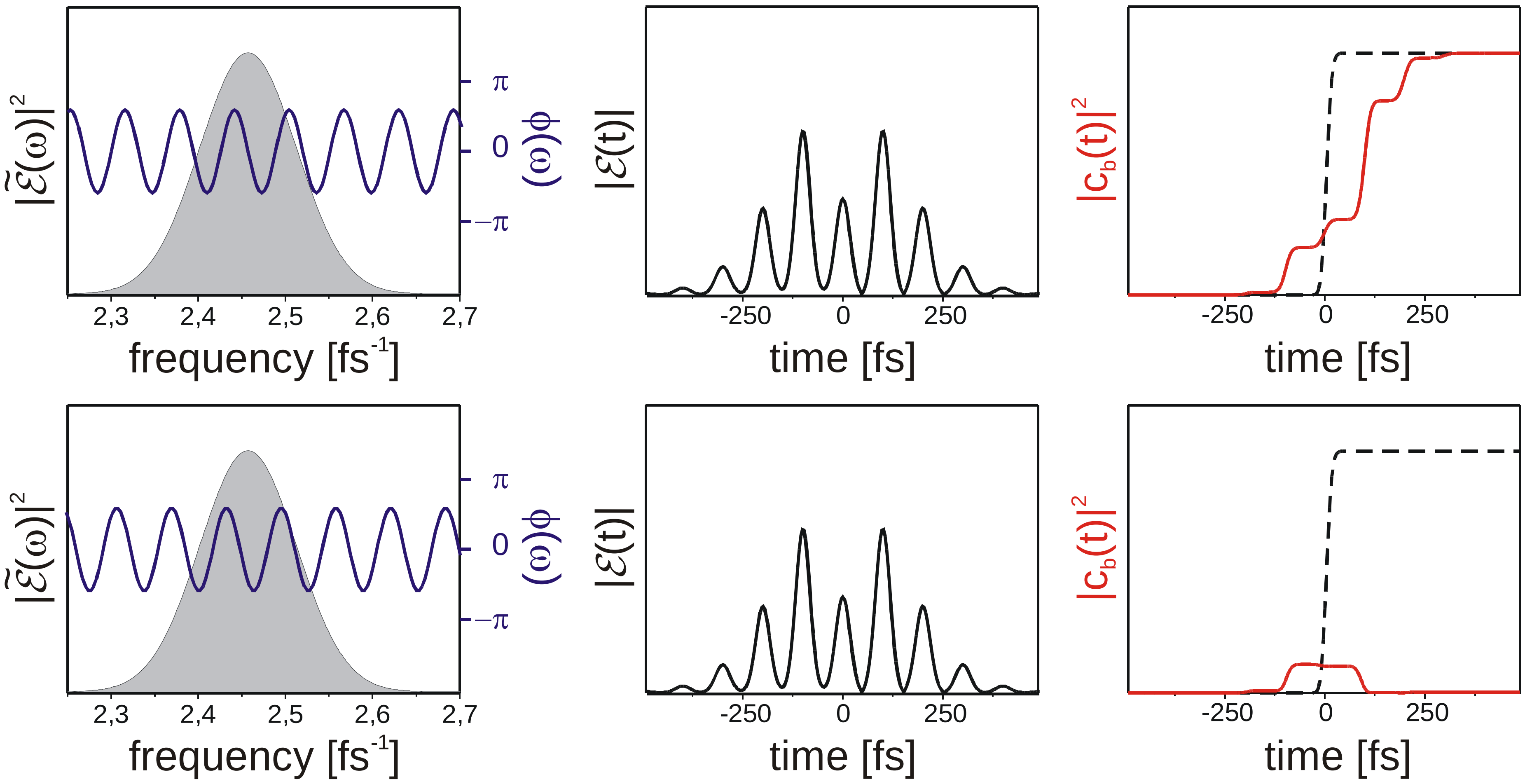
$$\tilde{E}(\omega)e^{-i\frac{\varphi 3}{3!}}$$

Sinus

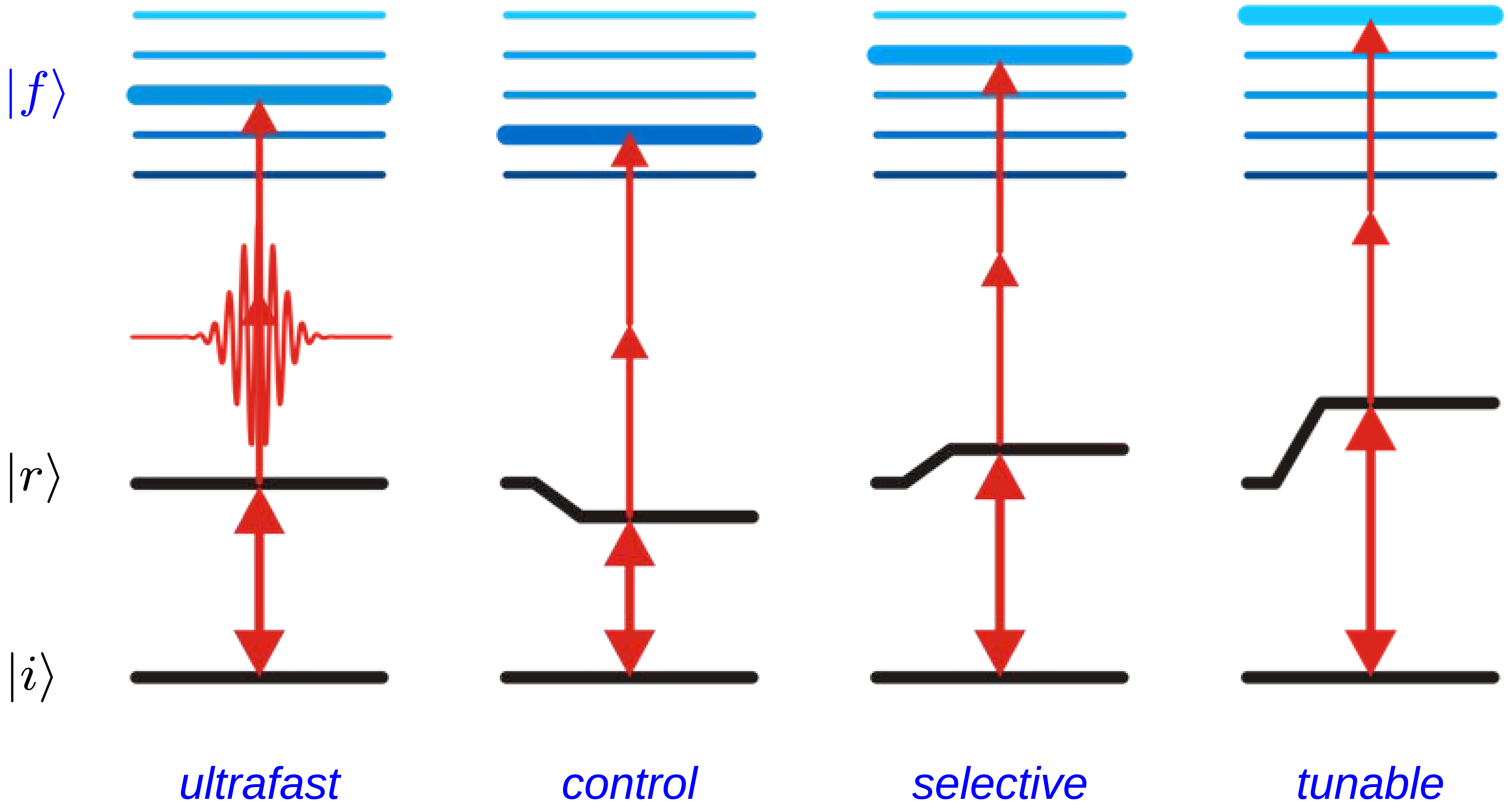


$$\tilde{E}(\omega)e^{-i[A\sin(\omega T)+\phi_0]}$$

Multi-photonen Anregung atomarer Übergänge mit phasenmoduiertem Licht: zeitabhängig

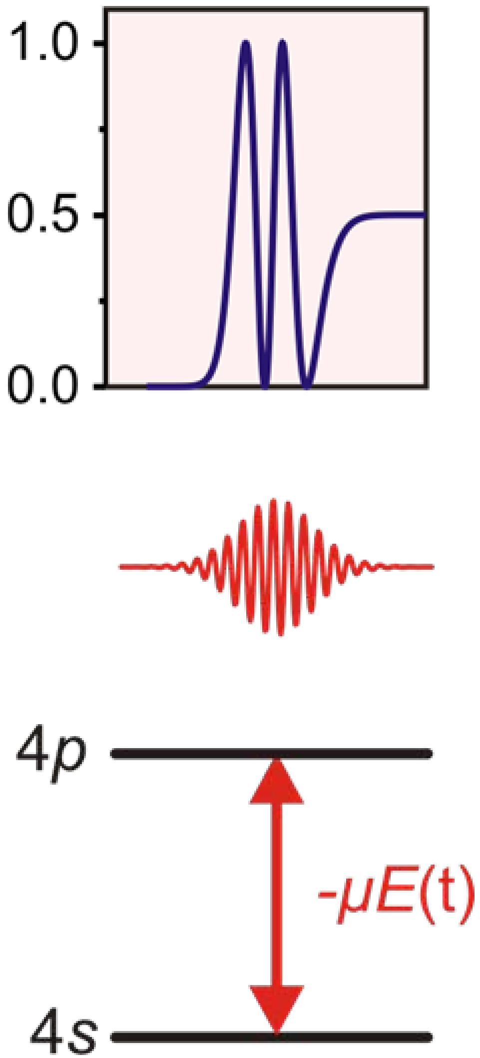


Strong field coherent control scenario



The physical model: dressed state control

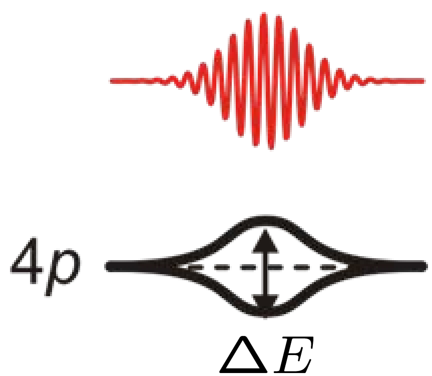
Bare states



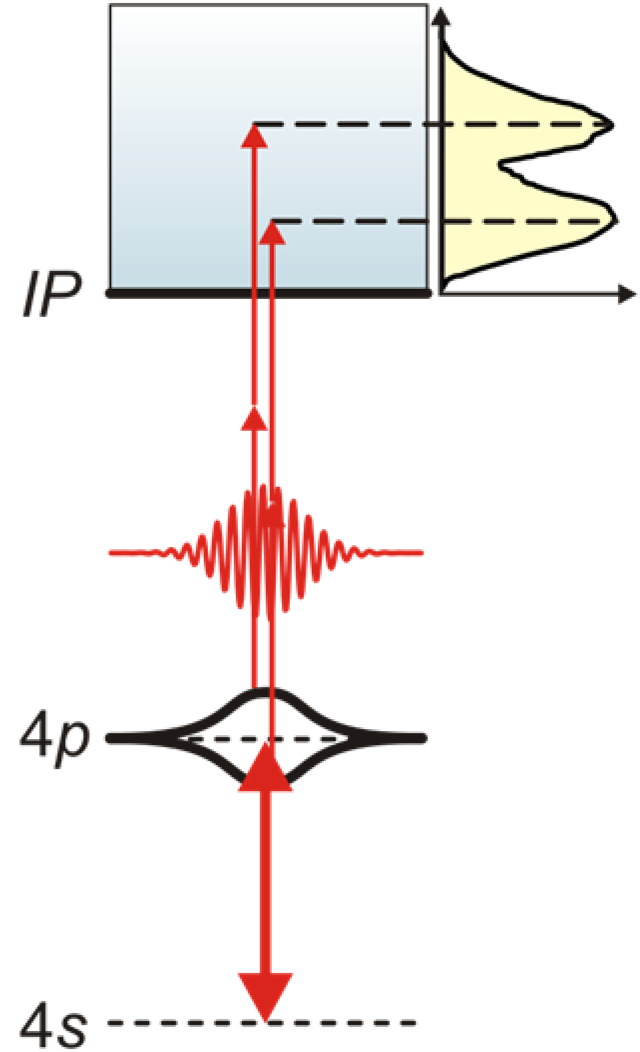
Dressed states

$$\Delta E = \hbar\Omega(t) = \mu E(t)$$

$$\Delta E[\text{eV}] = \frac{4.14}{T_R[\text{fs}]}$$

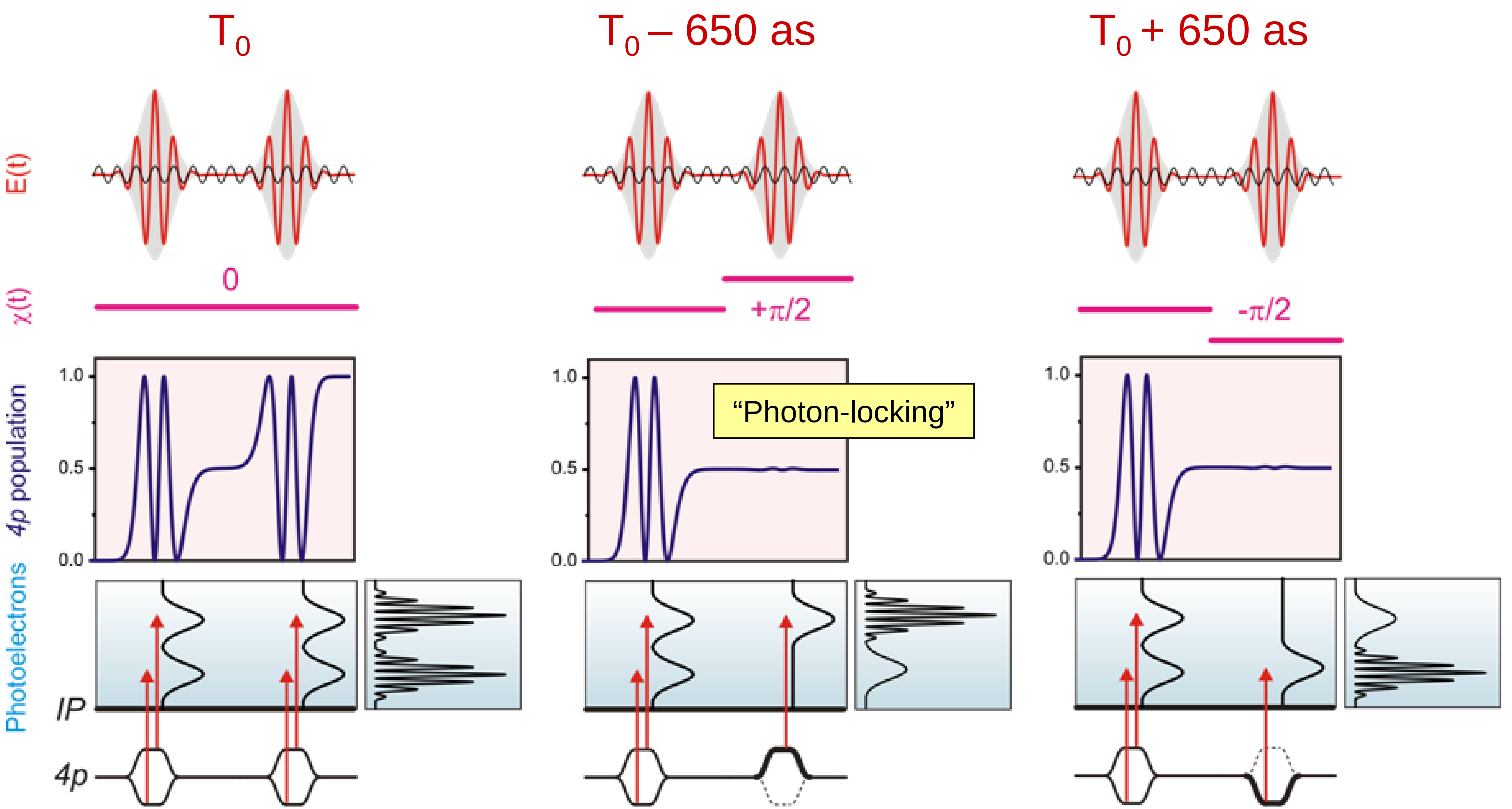


Photoelectrons



Annu. Rev. Phys. Chem, ***56***, *25, (2005)*

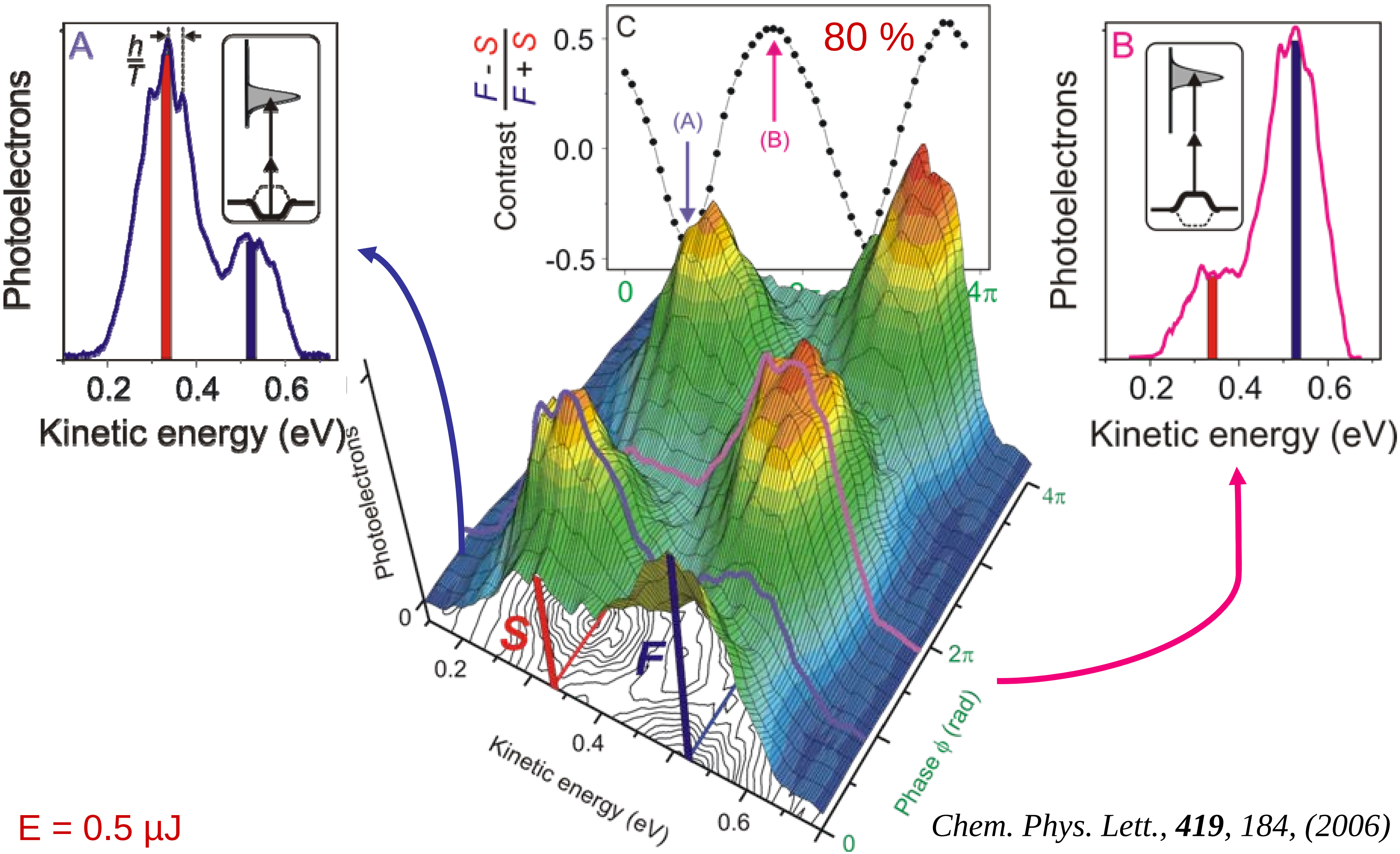
Quantum control by Selective Population Of Dressed States



Young's double slit in time

J. Opt. B, ***7***, *S270, (2005)*

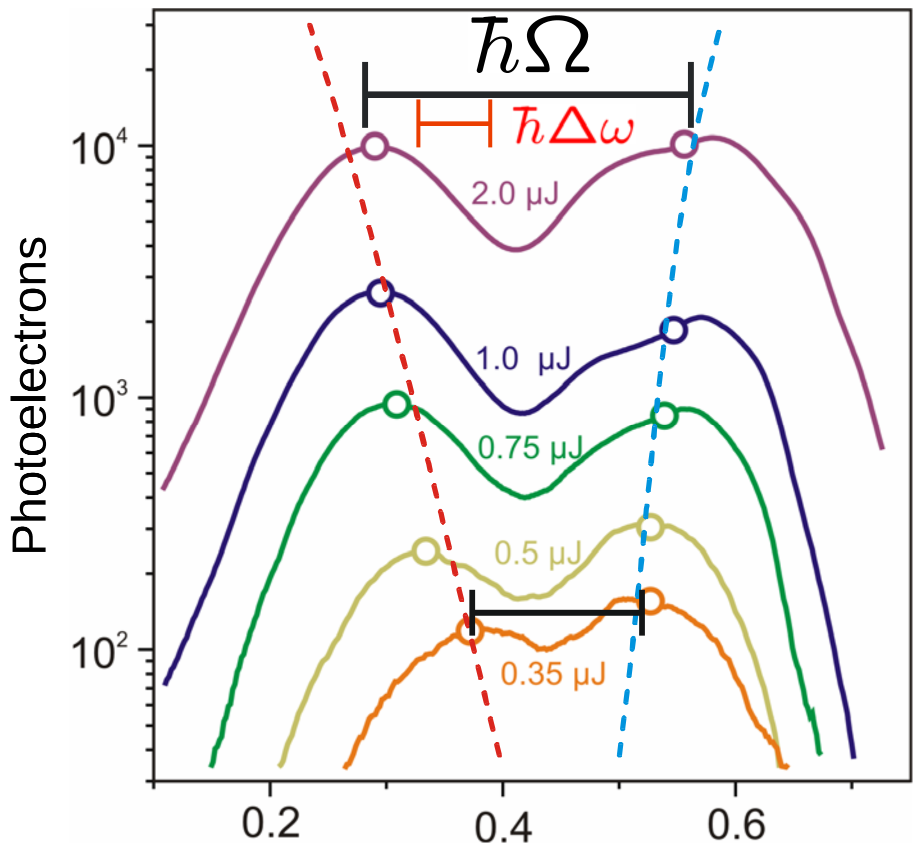
Experimental results on atoms: selectivity

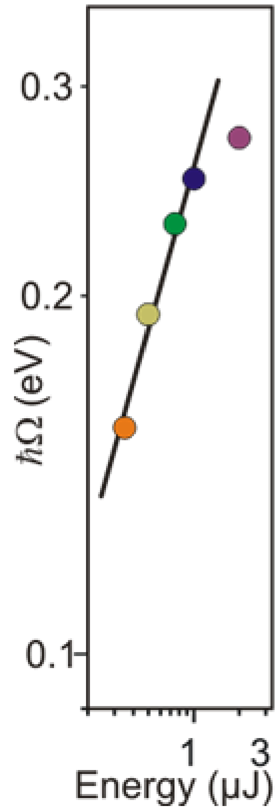


E = 0.5 µJ

Chem. Phys. Lett., ***419***, *184, (2006)*

Experimental results on atoms: tunability



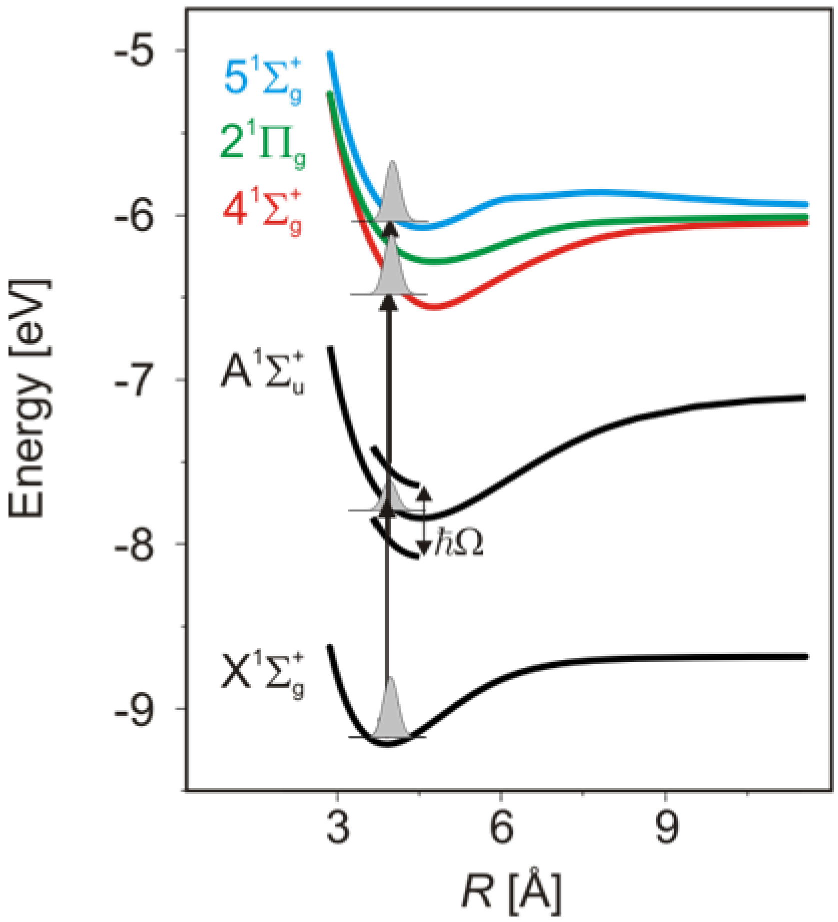


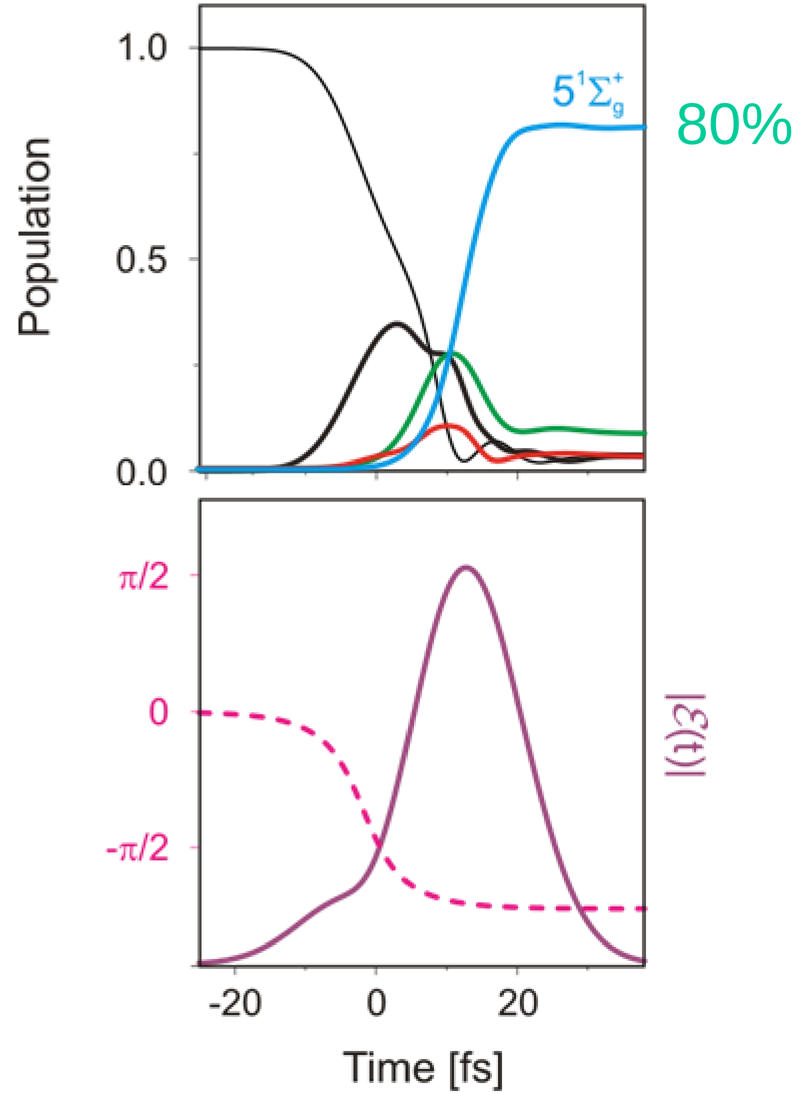
$\Delta\nu > 2000\ cm^{-1}$

$\hbar\Omega \propto I^{0.46\pm0.04}$

Chem. Phys. Lett., ***419***, *184, (2006)*

SPODS on molecules: wave packet calculations on K_2





J. Photochem. Photobiol. A, ***180***, *248, (2006)*

Femtochemie

- Fourier – Techniken
- Erzeugung ultrakurzer Laserpulse
- Pulsformung
- Pulscharakterisierung
- Materie (Atome und Moleküle)
- Licht und Materie
- Wellenpakete
- Quantenkontrolle