Attosecond pulse generation & application:

Theoretical perspectives from strong field physics

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What do we mean by strong field physics?

Phenomena:

- Above threshold ionization
- High harmonic generation
- Seq. & non-seq. multiple ionization
- Coulomb explosion of molecules
- X-rays from clusters

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Attributes:

- Ionization driven processes
- Non-perturbative: $H_I \sim H_{at}$
- Electron wave packet dynamics (non-trivial!)

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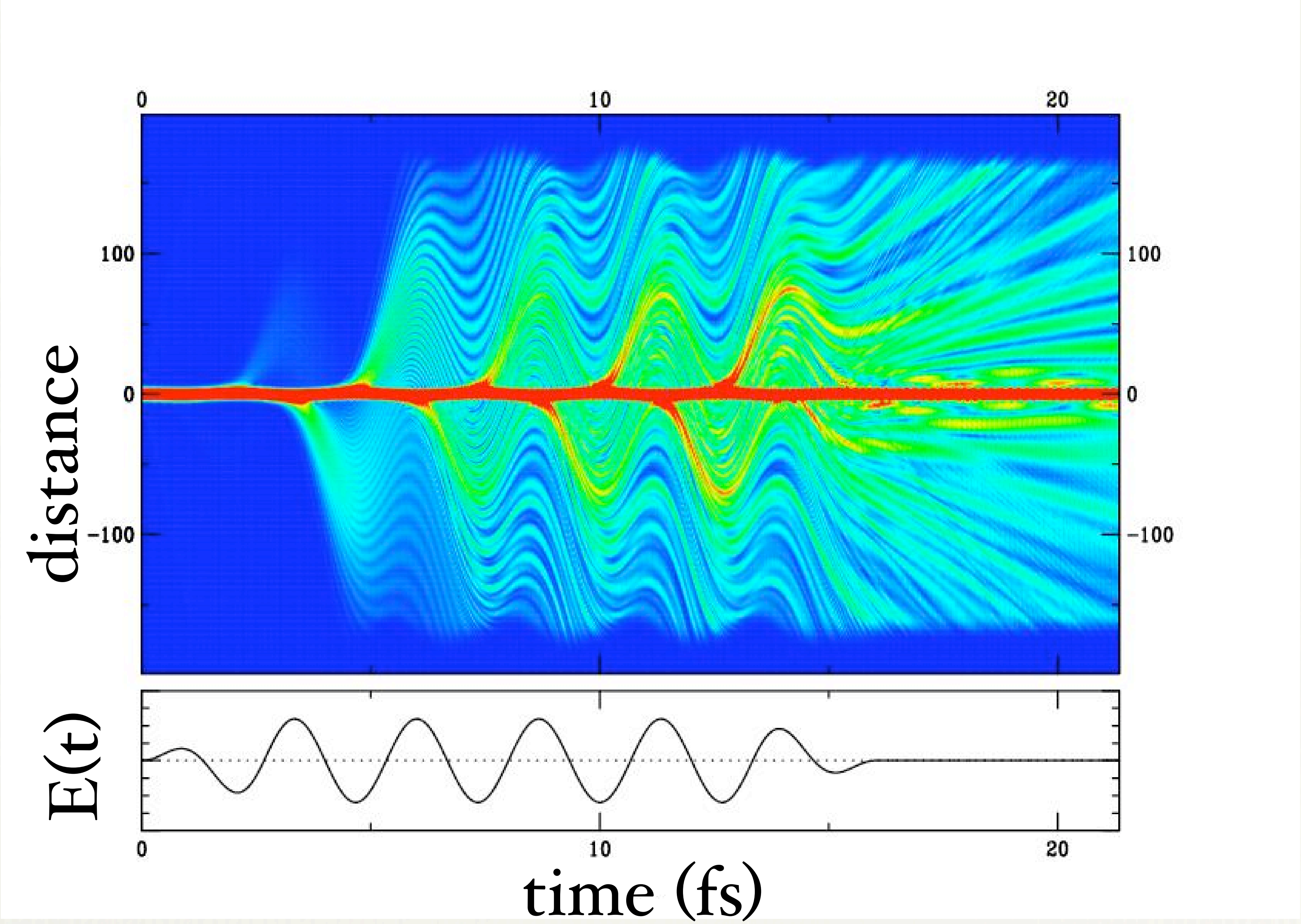
  - Quantum orbits

$$d_q(I) = \sum_{traj} A_\tau(I) \exp[-iS_\tau(I)]$$

Sum over paths

Visualizing quantum orbits



1-d quantum model

Strong field physics in attoscience

- Generation
- Metrology
- Applications

Strong field physics in attoscience

- Generation
  - Single atto pulses from cutoff harmonics
  - Trains of atto pulses from plateau harmonics
  - Compression of APT pulses

Strong field physics in attoscience

- Generation
  - Single atto pulses from cutoff harmonics
  - Trains of atto pulses from plateau harmonics
  - Compression of APT pulses
    - New paradigm for single pulse production
    - Trains of atto pulses with one pulse per IR cycle

Strong field physics in attoscience

- Metrology
  - SAPs - Pondermomotive streaking
  - APTs - Two color interference - RABBIT

Strong field physics in attoscience

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    - Absolute phase effects in few cycle XUV pulses

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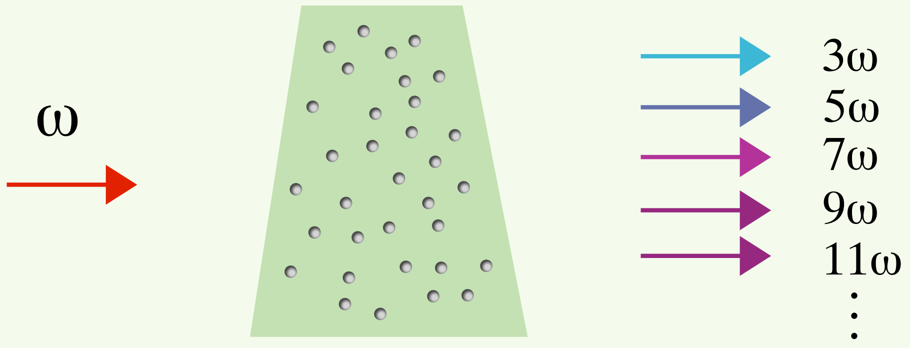
- Applications
  - Combine attosecond pulse with strong IR field.
  - Above threshold attosecond electron wave packets.

Strong field physics in attoscience

- Applications
  - Combine attosecond pulse with strong IR field.
  - Above threshold attosecond electron wave packets.
    - Attosecond electron wave packet interferometry
    - Near threshold AEWPs - quantum path selection.

How are attosecond light pulses made?

High harmonic generation



Up conversion of IR laser light to coherent, short pulsed XUV light

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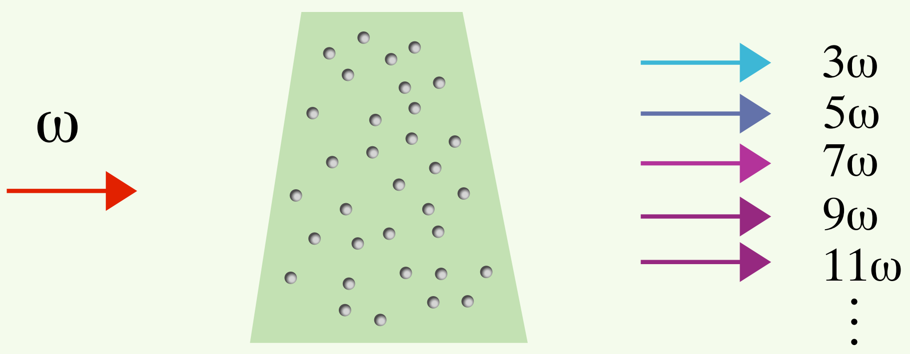
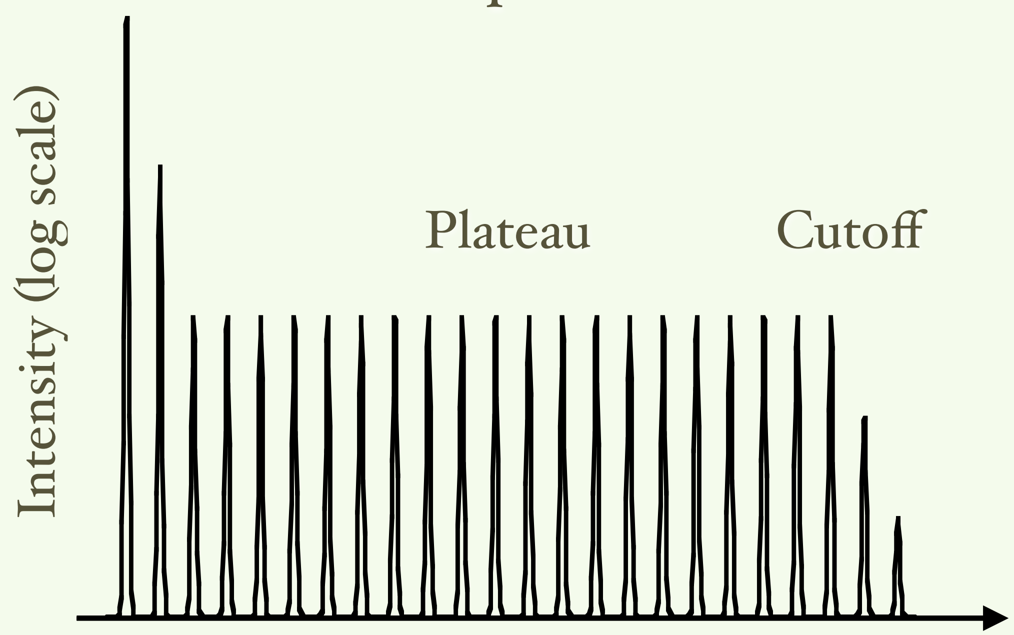


Up conversion of IR laser light to coherent, short pulsed XUV light

Harmonic spectrum



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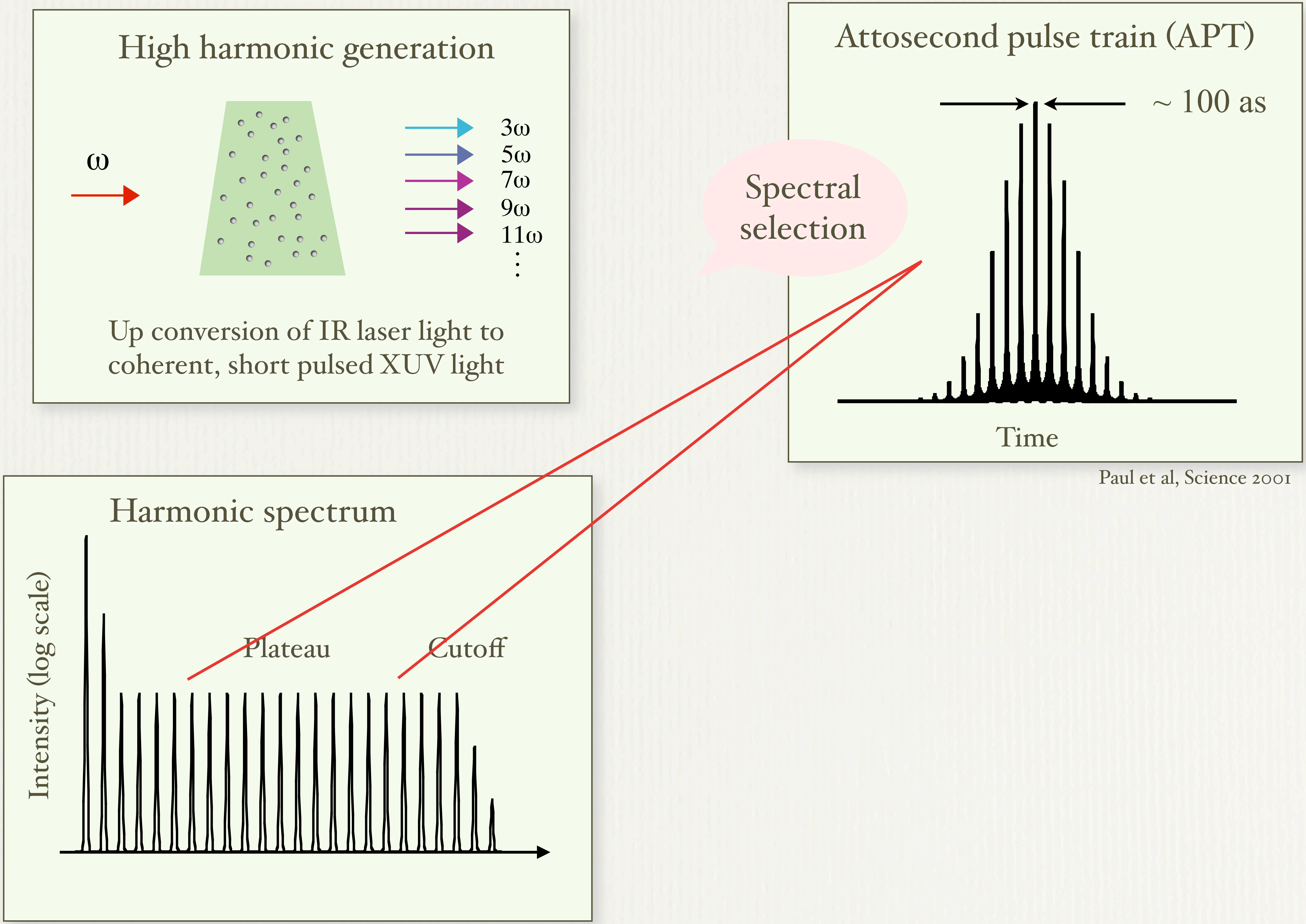

Paul et al, Science 2001

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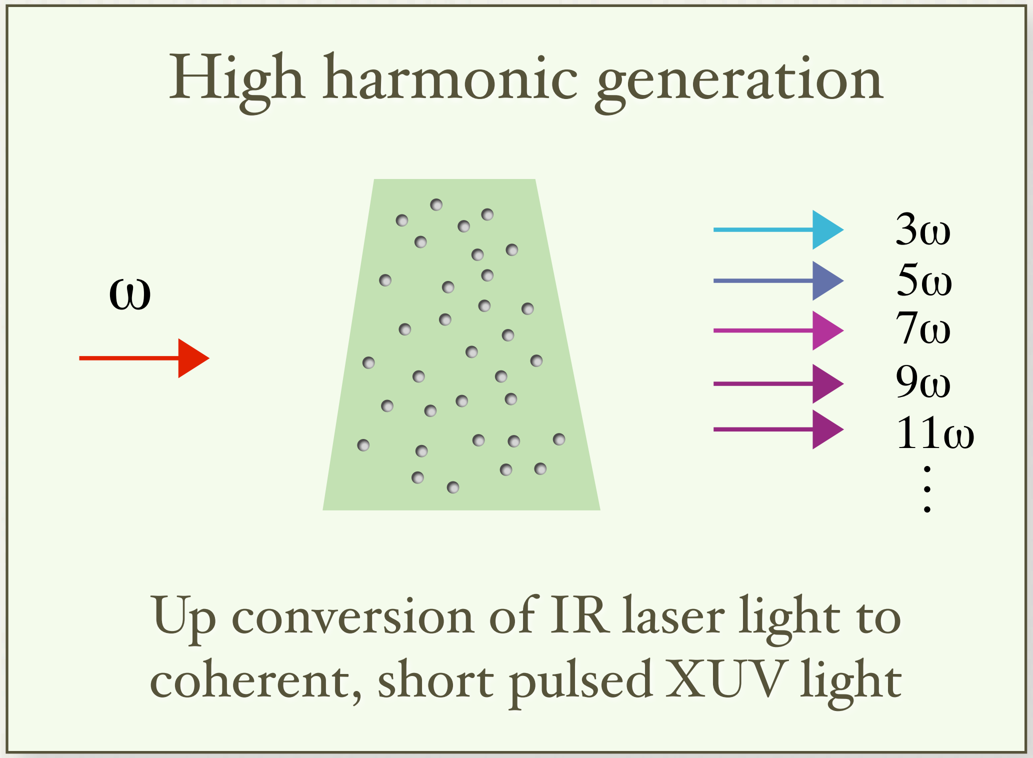

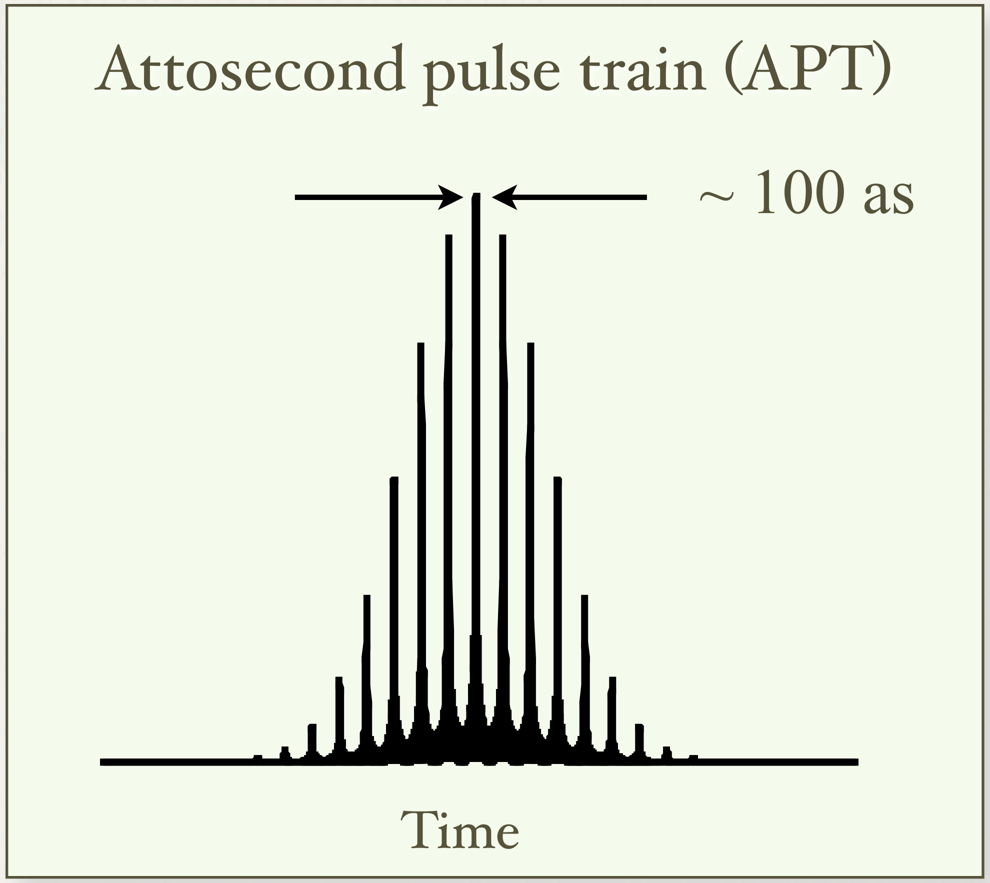

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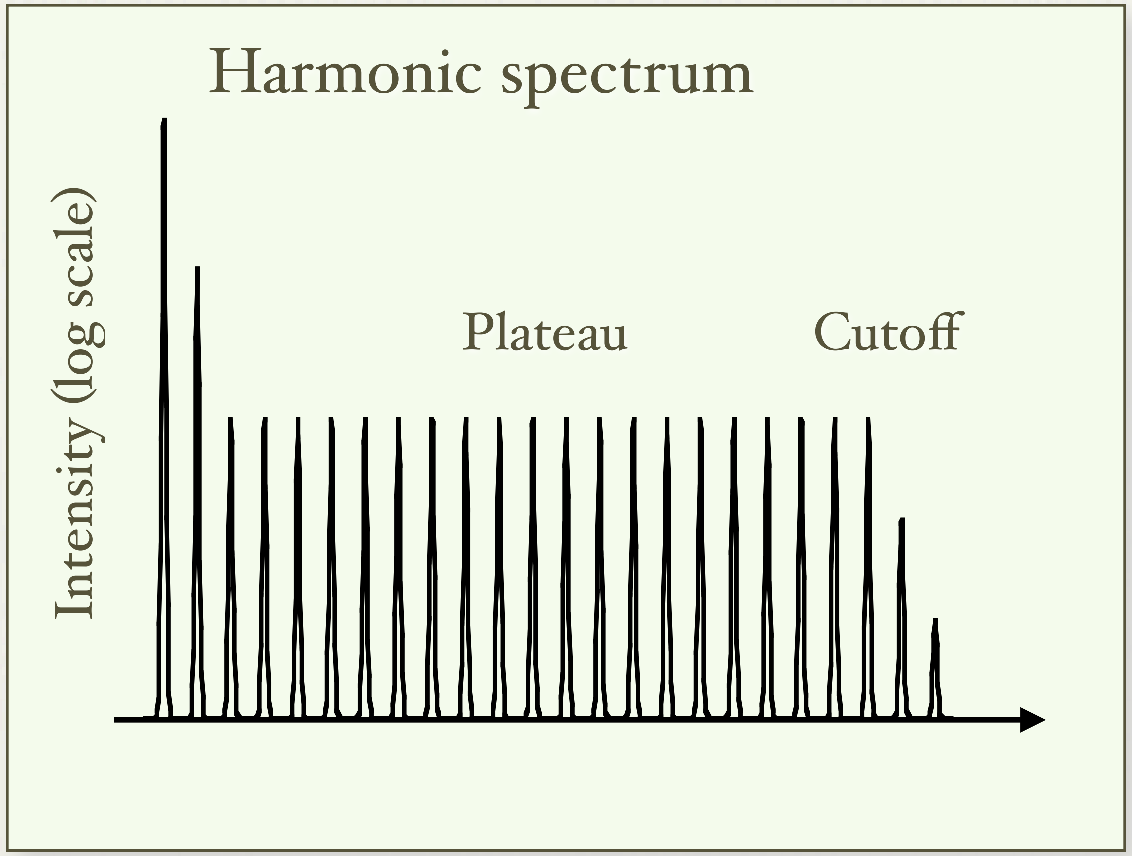

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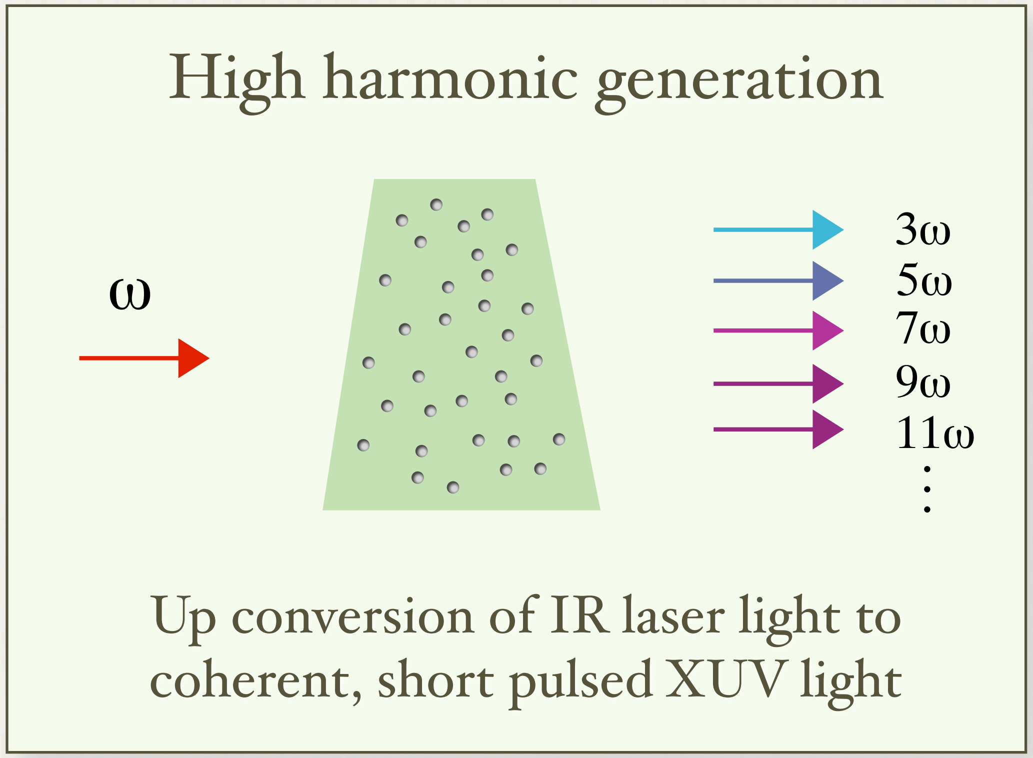

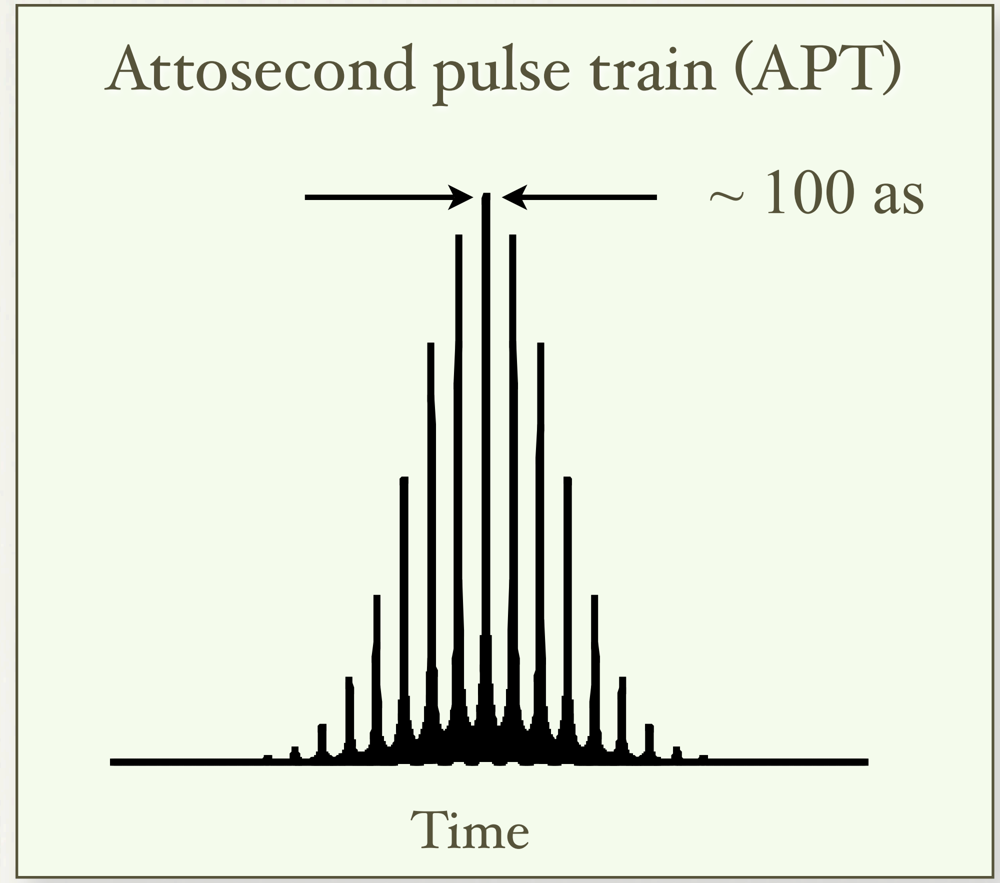

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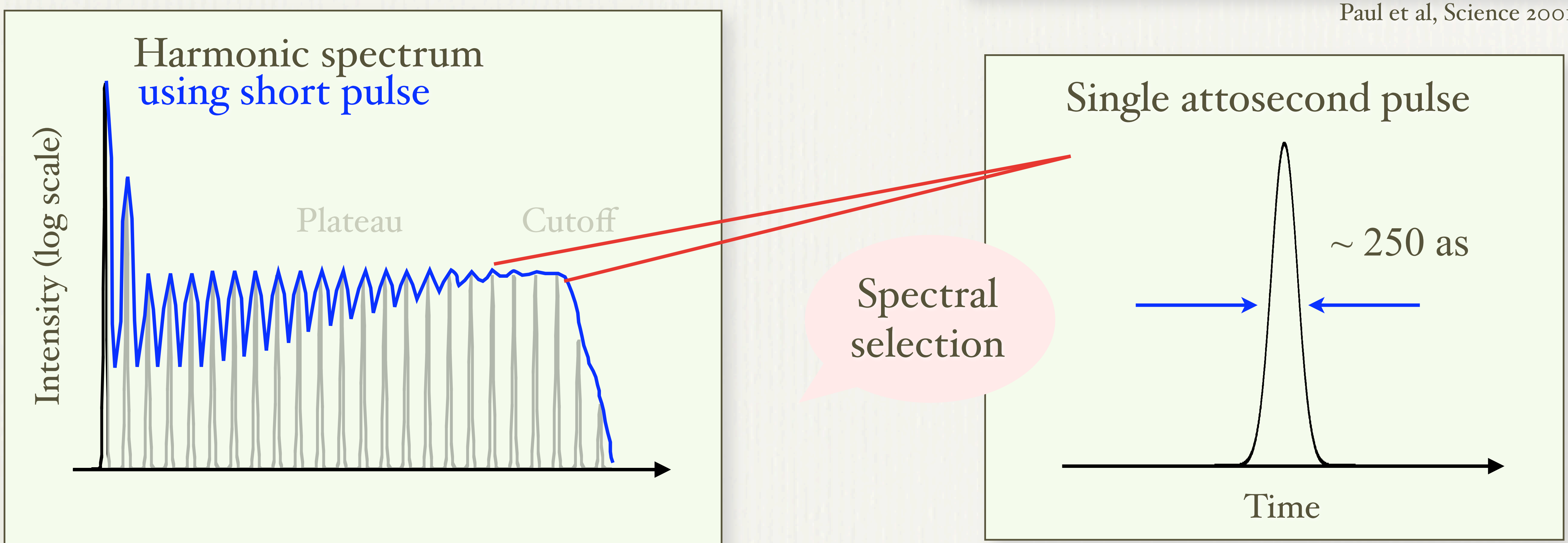
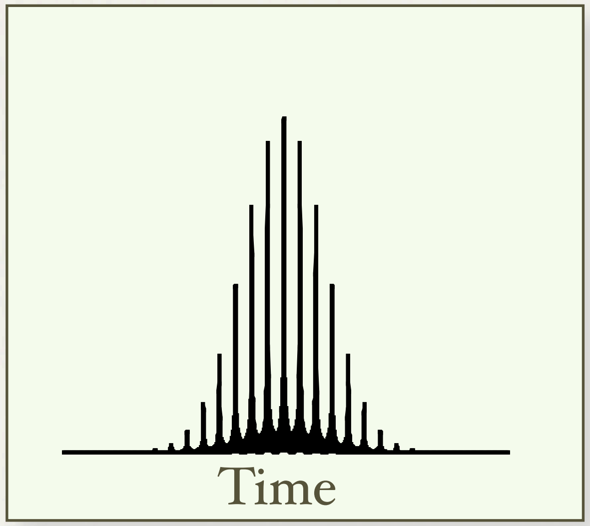


Krausz, et al.

APTs: Phase locking



$$\mathcal{E}_x(t) = \sum_q \mathcal{E}_q \sin\left(q[\omega_1 t - \phi_q] + \varphi\right)$$

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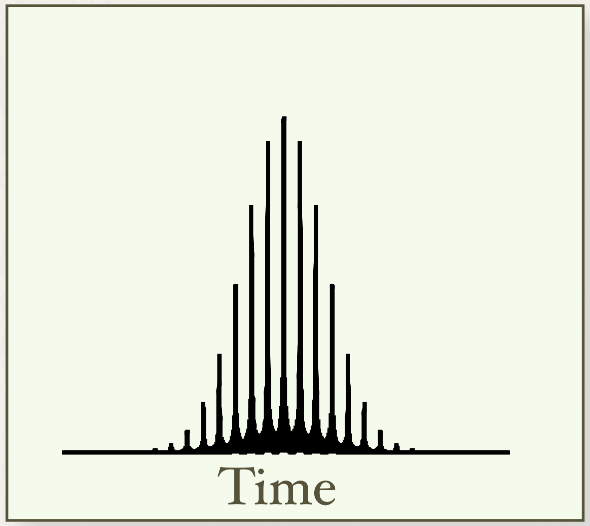

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q-dependent phase

C-E phase

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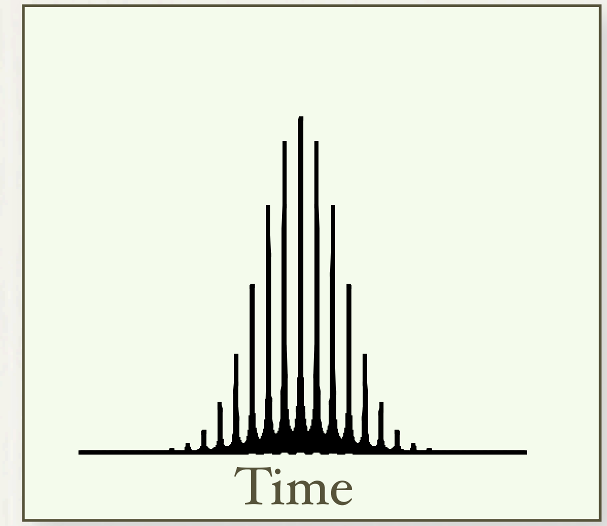

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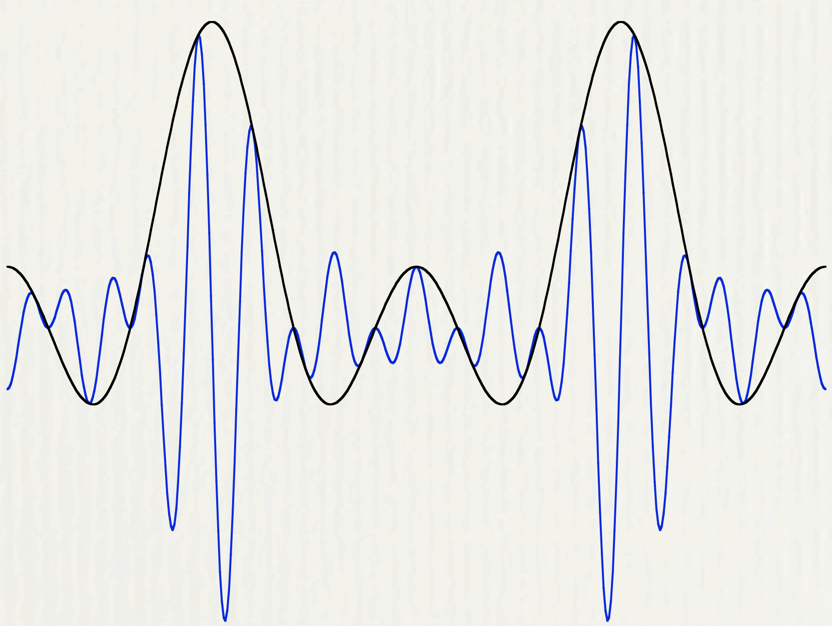
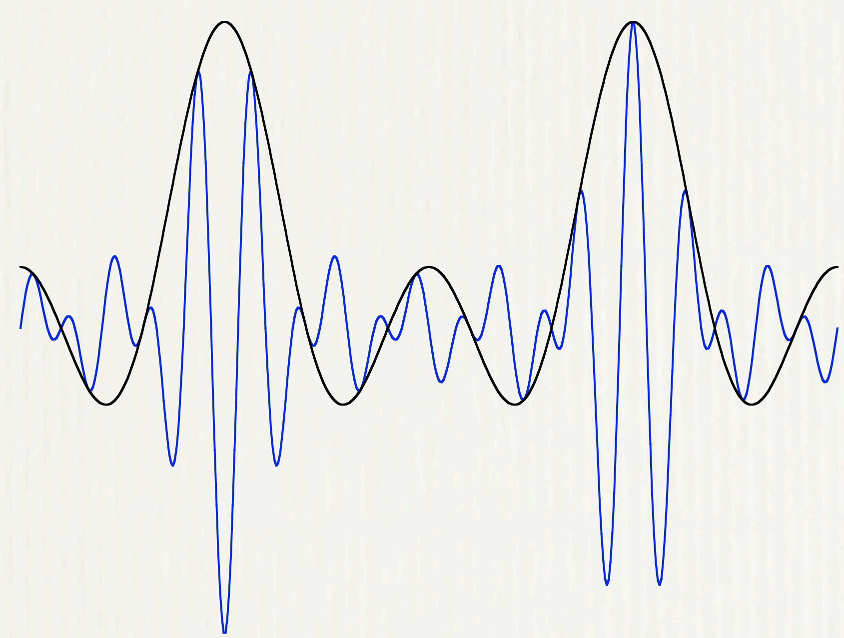
APT electric fields



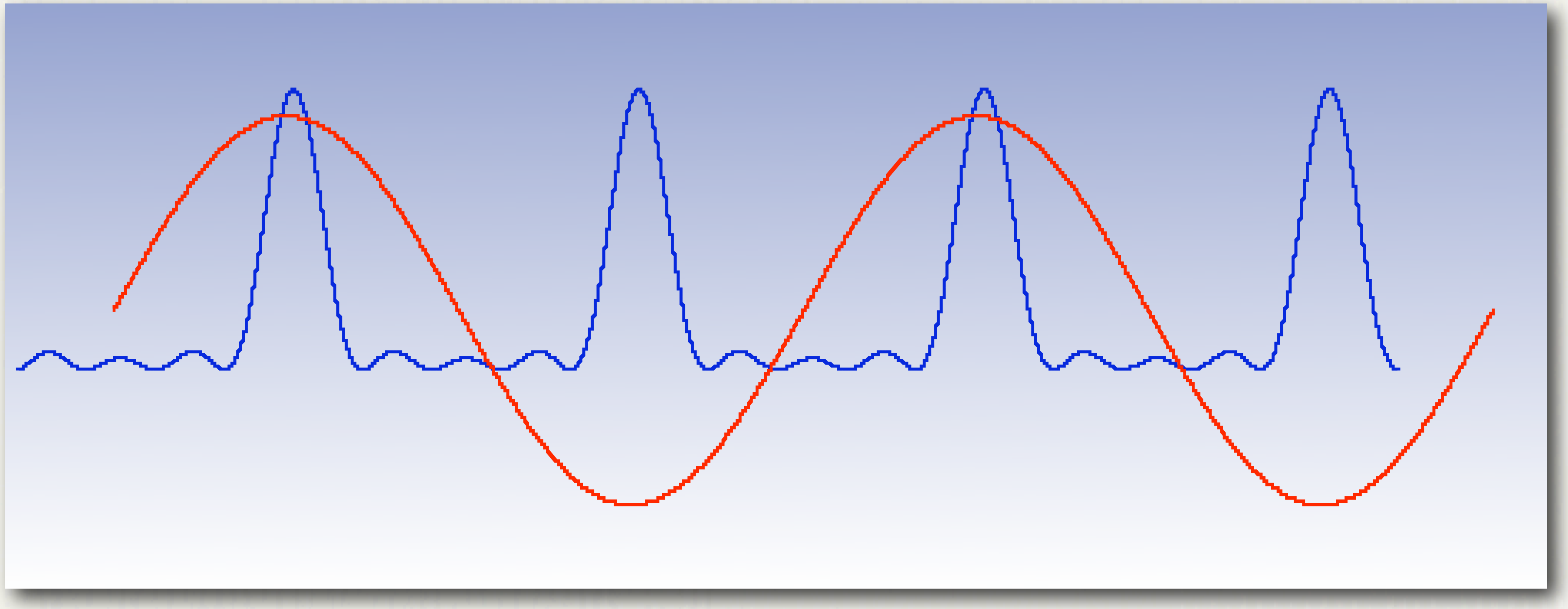
$\varphi = 0$



$\varphi = \pi/2$

Example: Quantum Path Selection

Idea = By controlling the time of ionization, we can choose one of several interfering contributions to a strong field process.



In general, we can hope to better understand and perhaps control strong field processes via this method.

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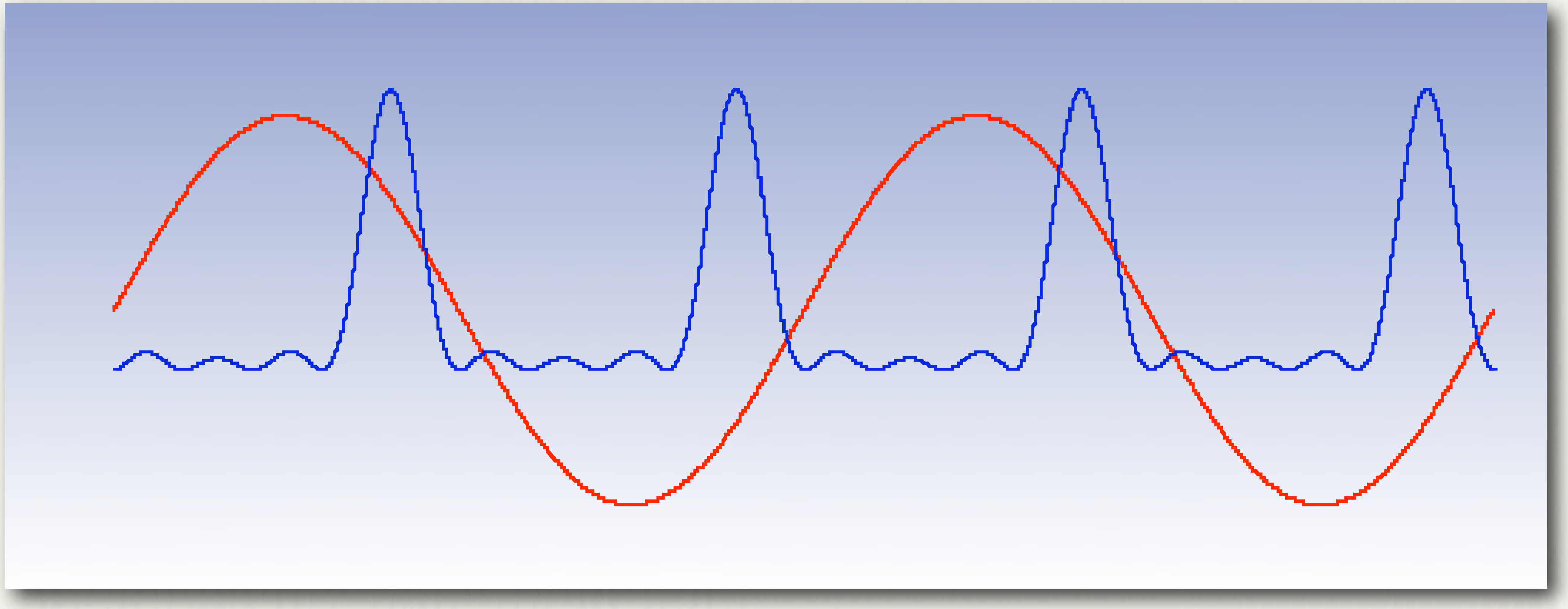

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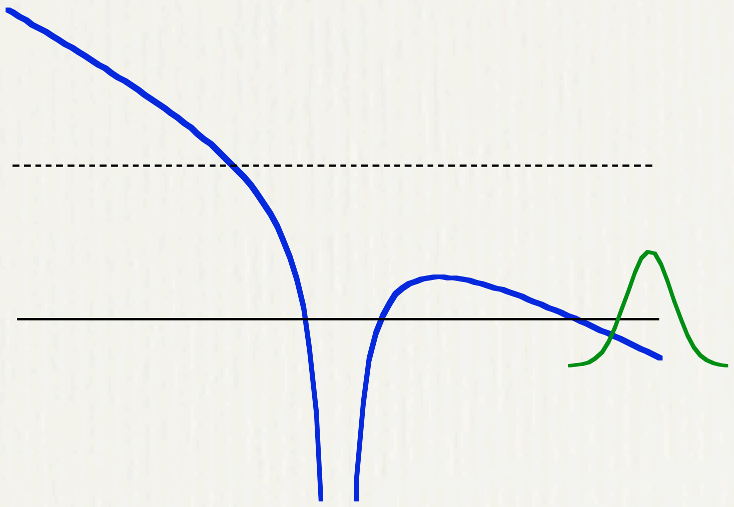
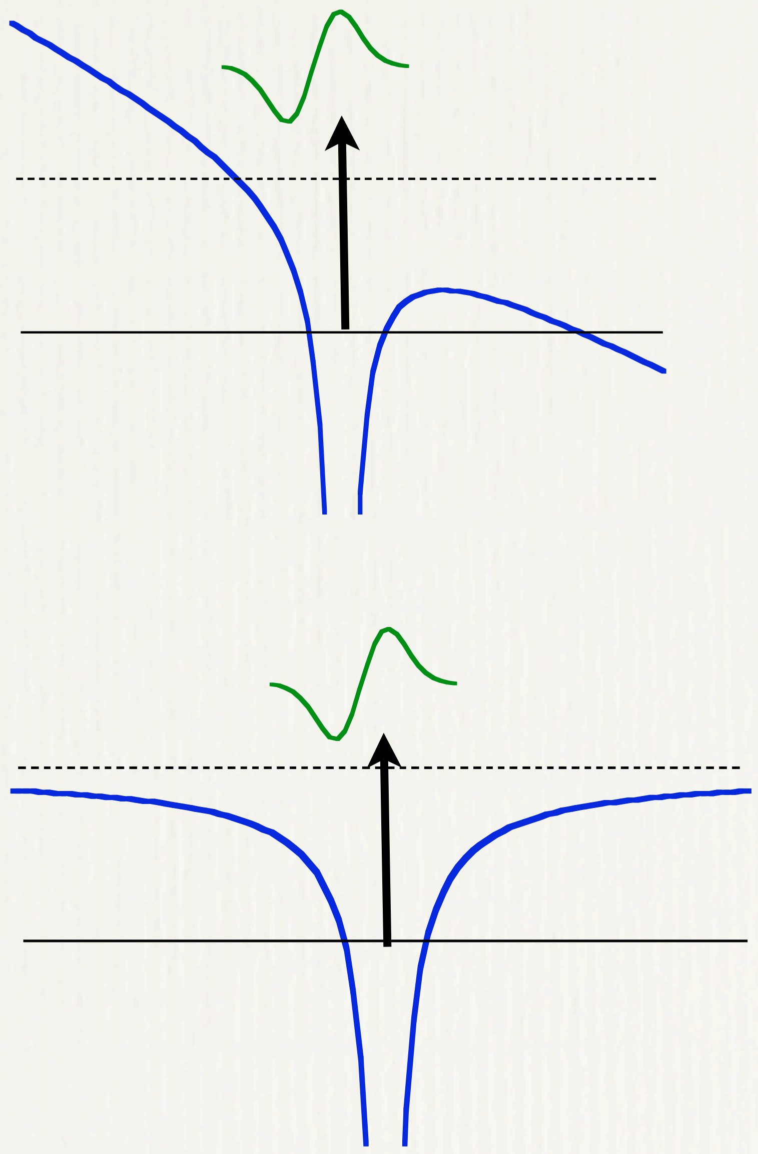
Tunneling electron wave packets

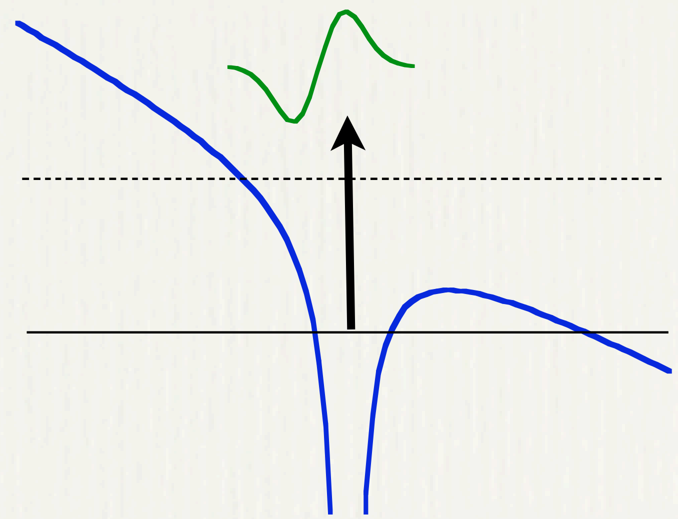


- All tunneling WPs are "identical"
- Born near peak of IR cycle
- Duration depends on IR intensity
- Born outside potential well, with initial velocity $v_0 = 0$
- Ionization step is highly non-linear
  - limits "low-IR" experiments

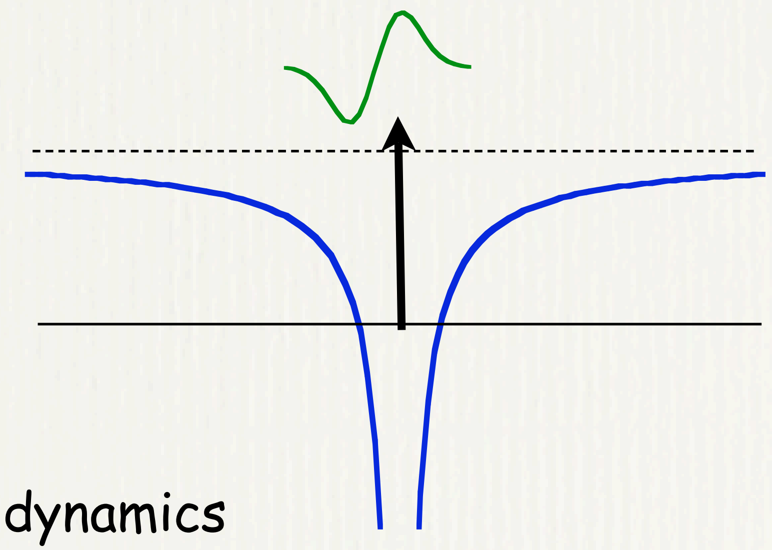
APT electron wave packets



APT electron wave packets



- Time of release determined by APT
- Properties can be tailored by APT
  - Duration
  - Non-zero v_0 - can be left or right
  - Chirp (on attosecond scale)

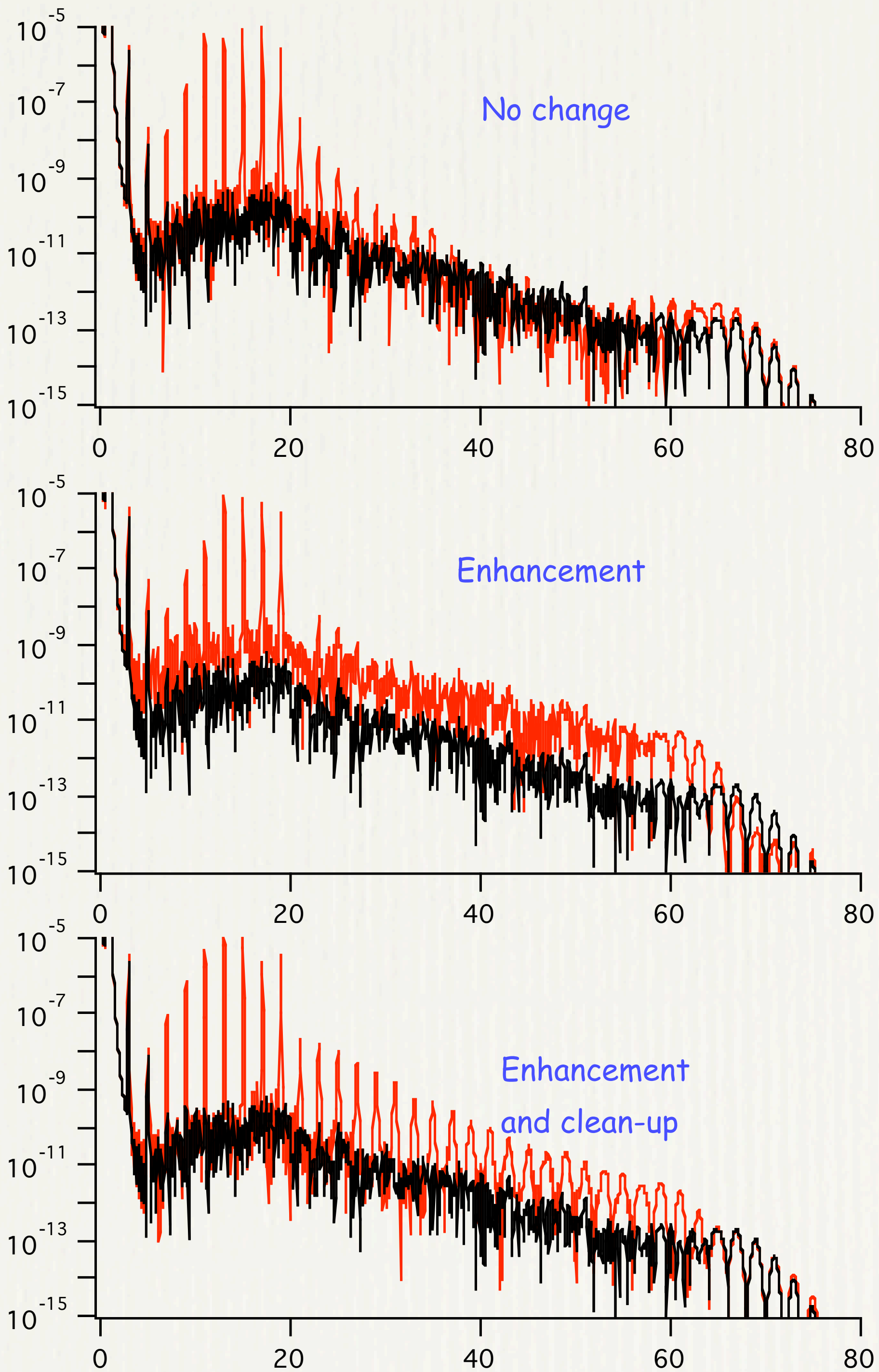


- Can be born near or even below threshold
- Ionization step separate from (IR) strong field dynamics
  - study "weak" IR or "strong" IR dynamics

Quantum Path Selection

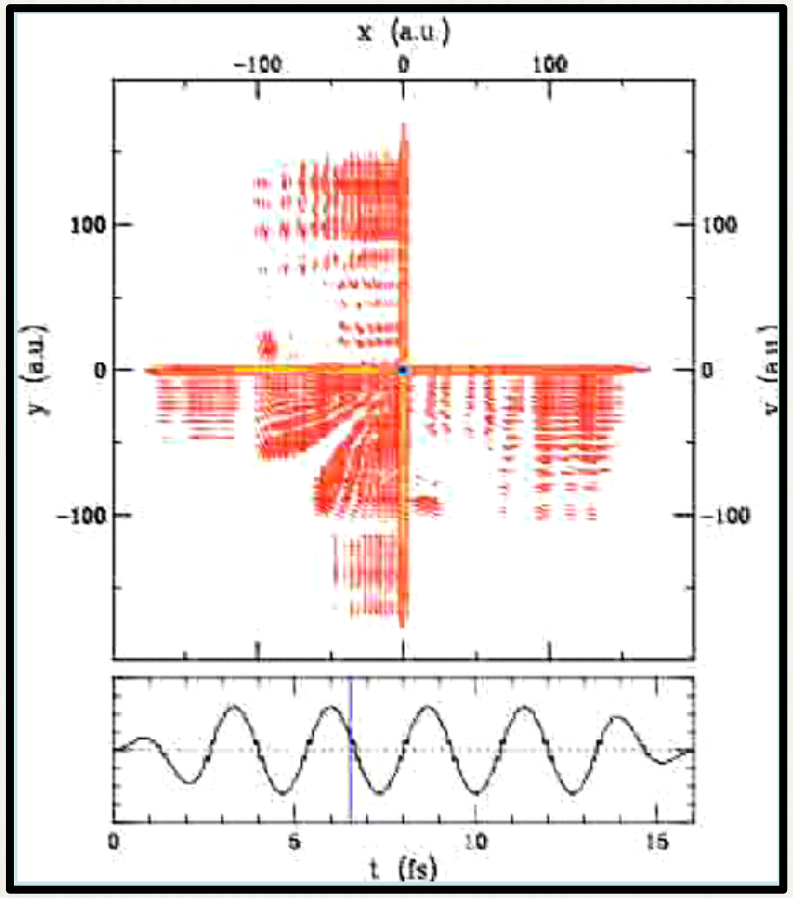
A previous theoretical study showed that QPS via APT driven ionization could be used to select a single contribution to the high harmonic spectrum.

Schafer et al, PRL 2004



Example: Non-sequential double ionization

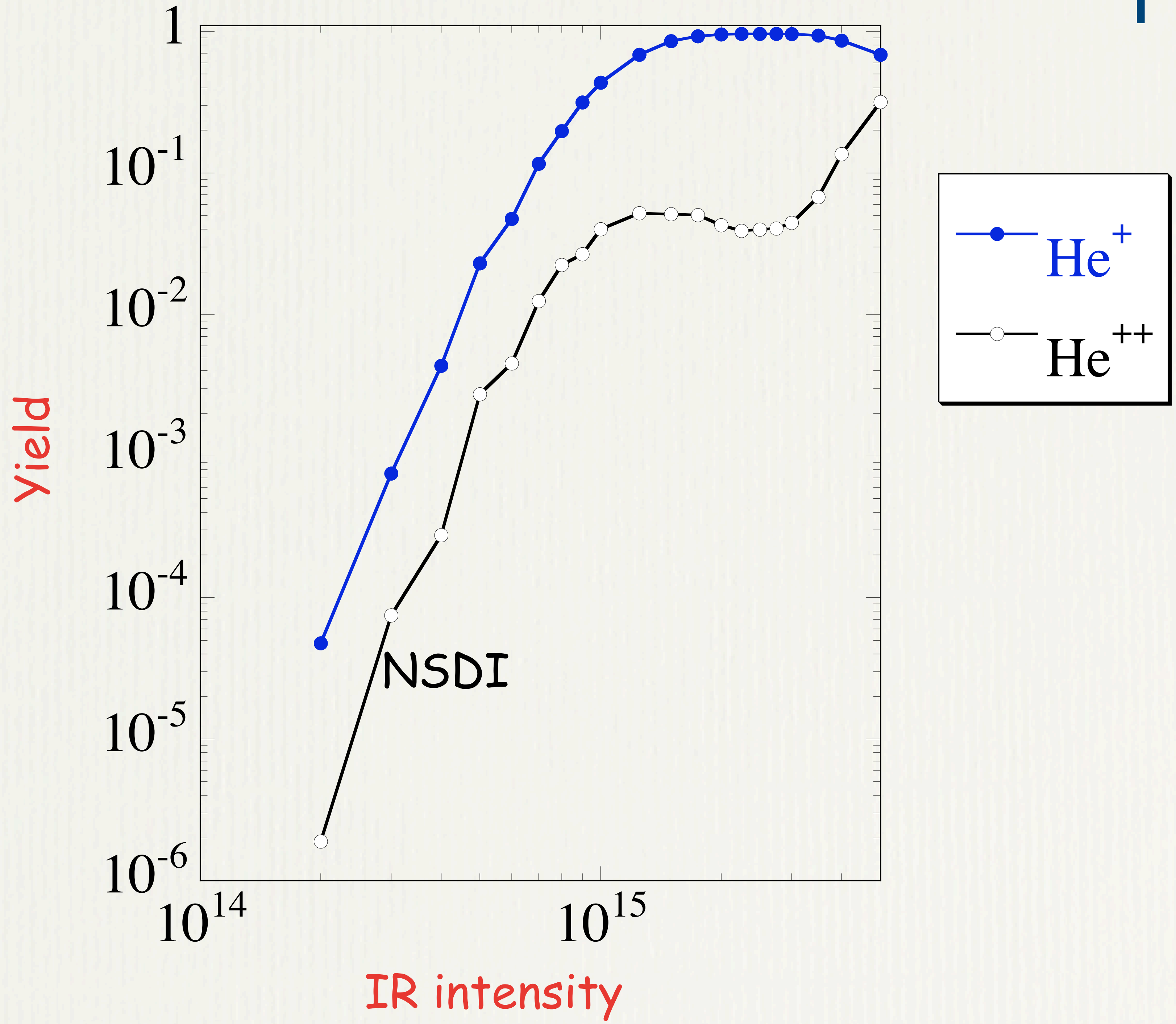
The “Aligned” Helium Atom



	2-d He	6-d He
E_0 neutral	-2.898 au	-2.902 au
E_0 ion	-1.920 au	-2.000 au
1st I.P.	0.978 au	0.904 au

Example: Non-sequential double ionization

The AEM reproduces the NSDI "knee" structure



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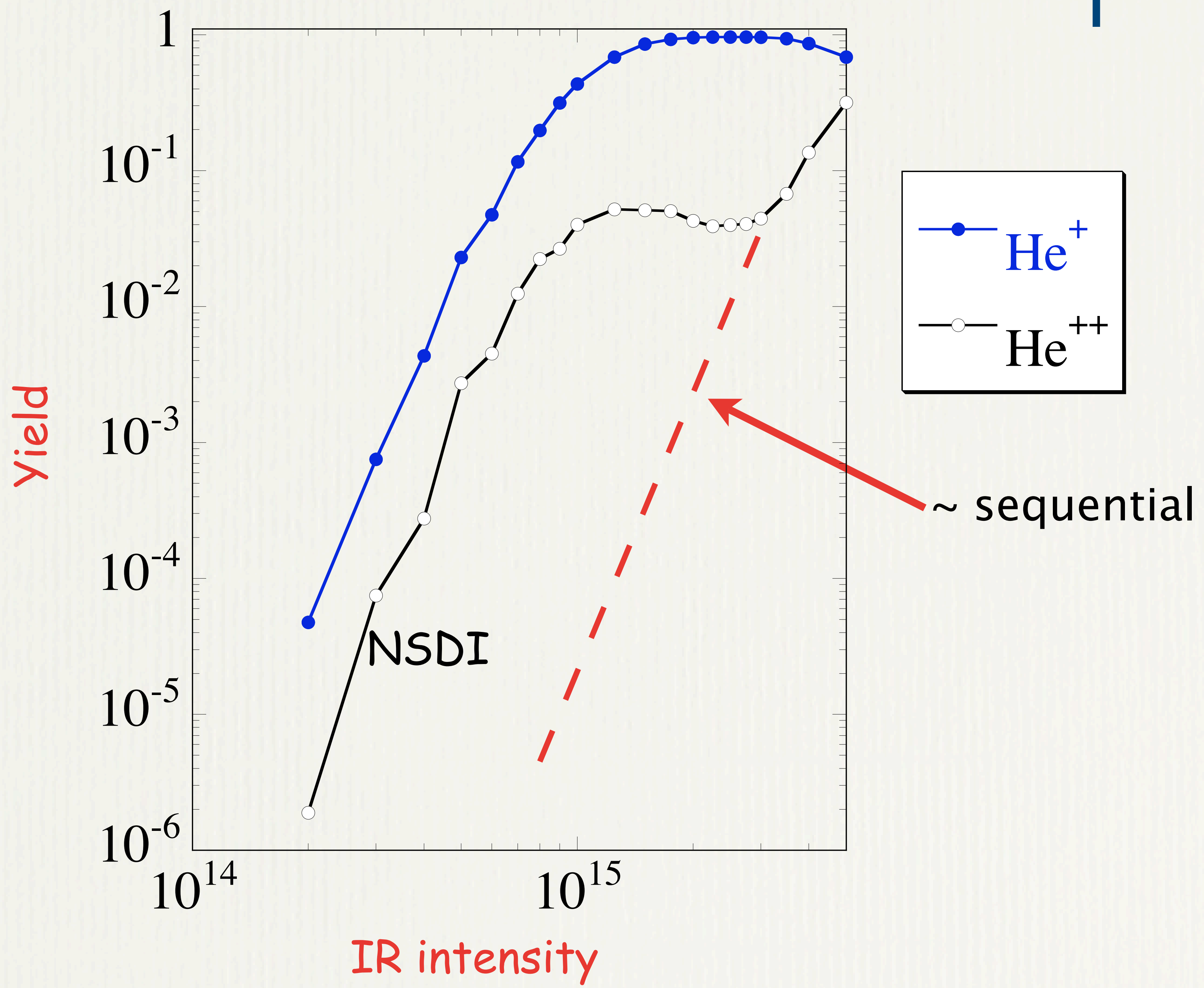

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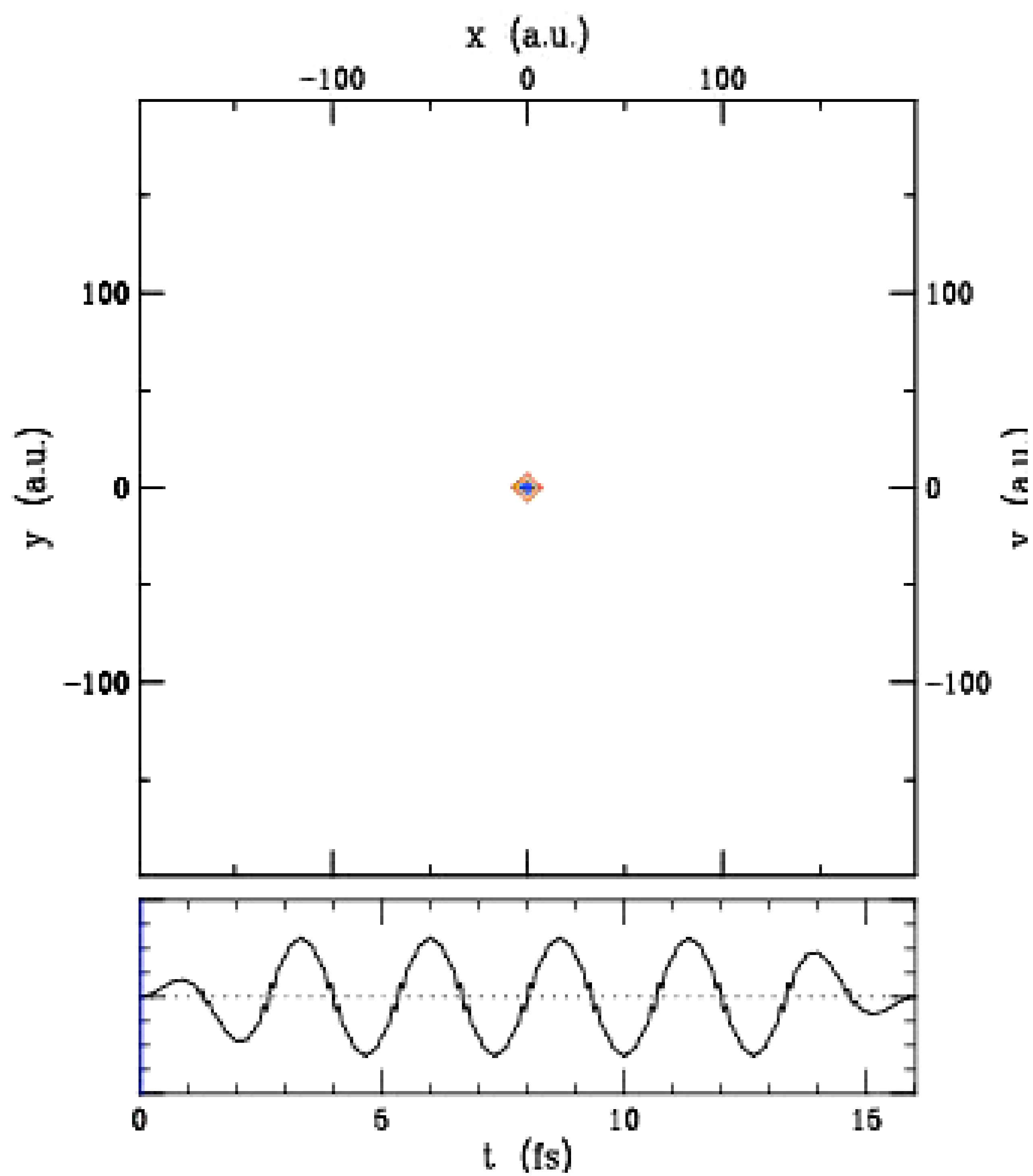

APT = harmonics 11-19

Ir = 5×10^{14} W/cm^2

APT = 1×10^{13} W/cm^2

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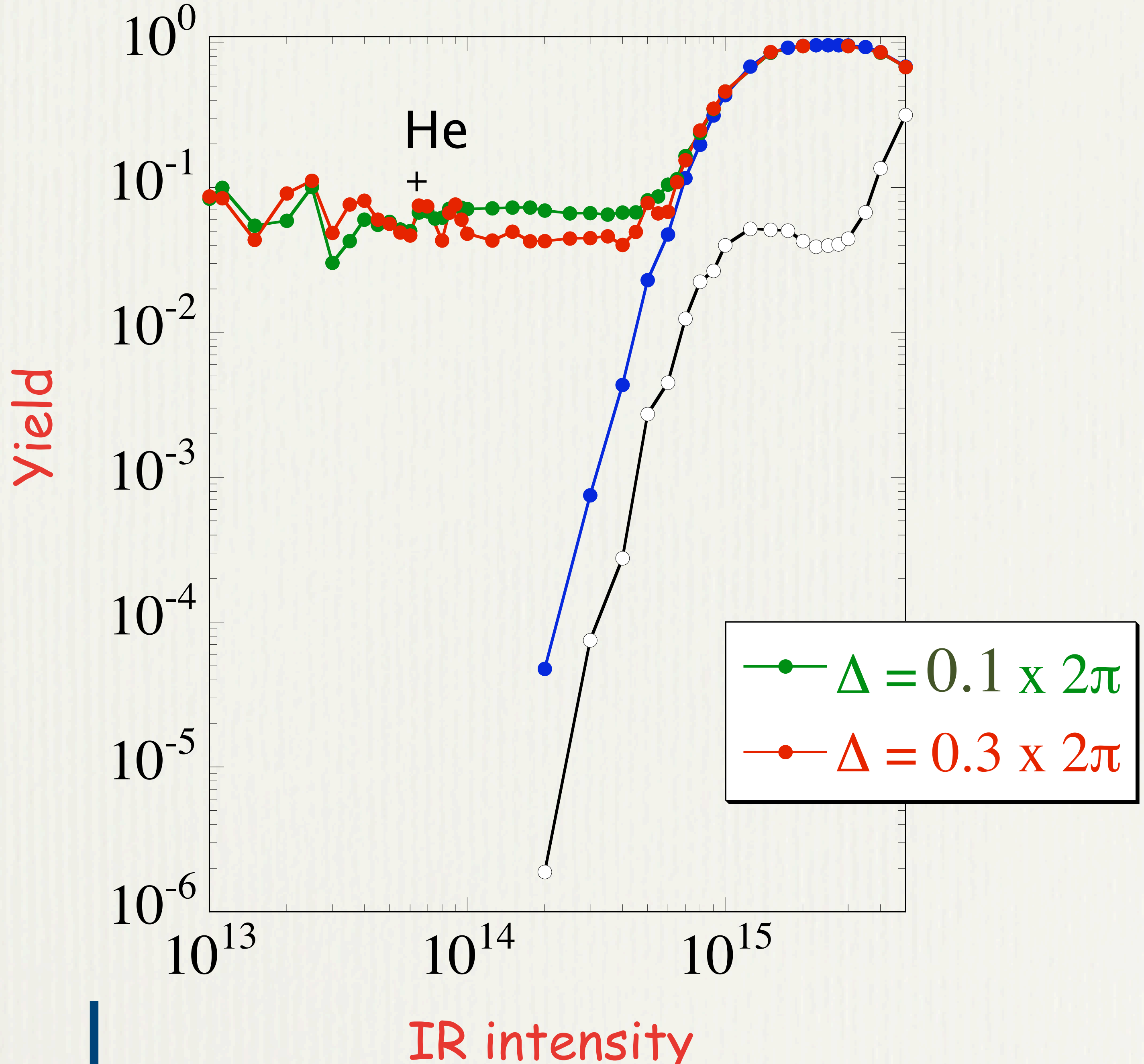

Combined
IR+ APT

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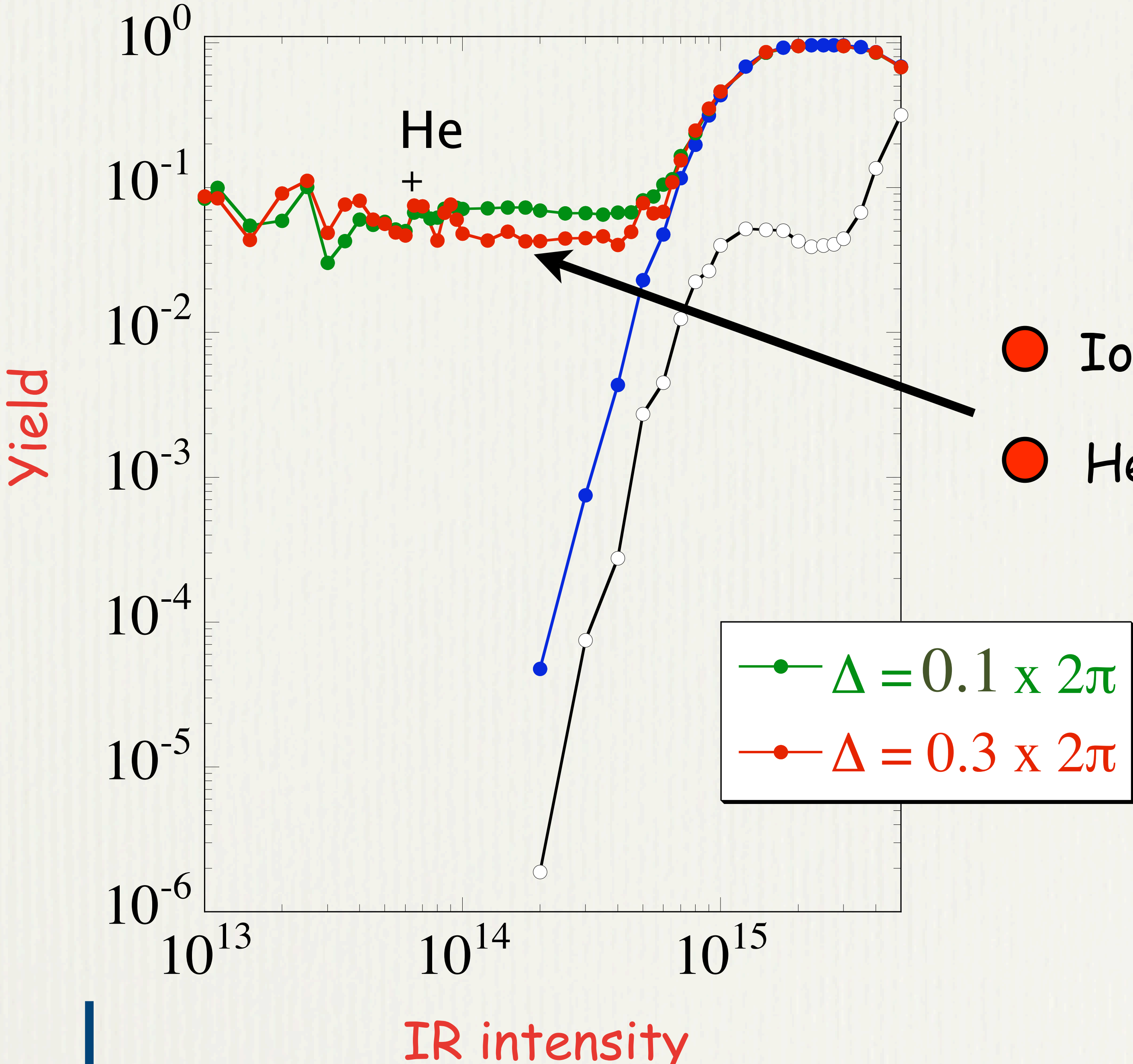
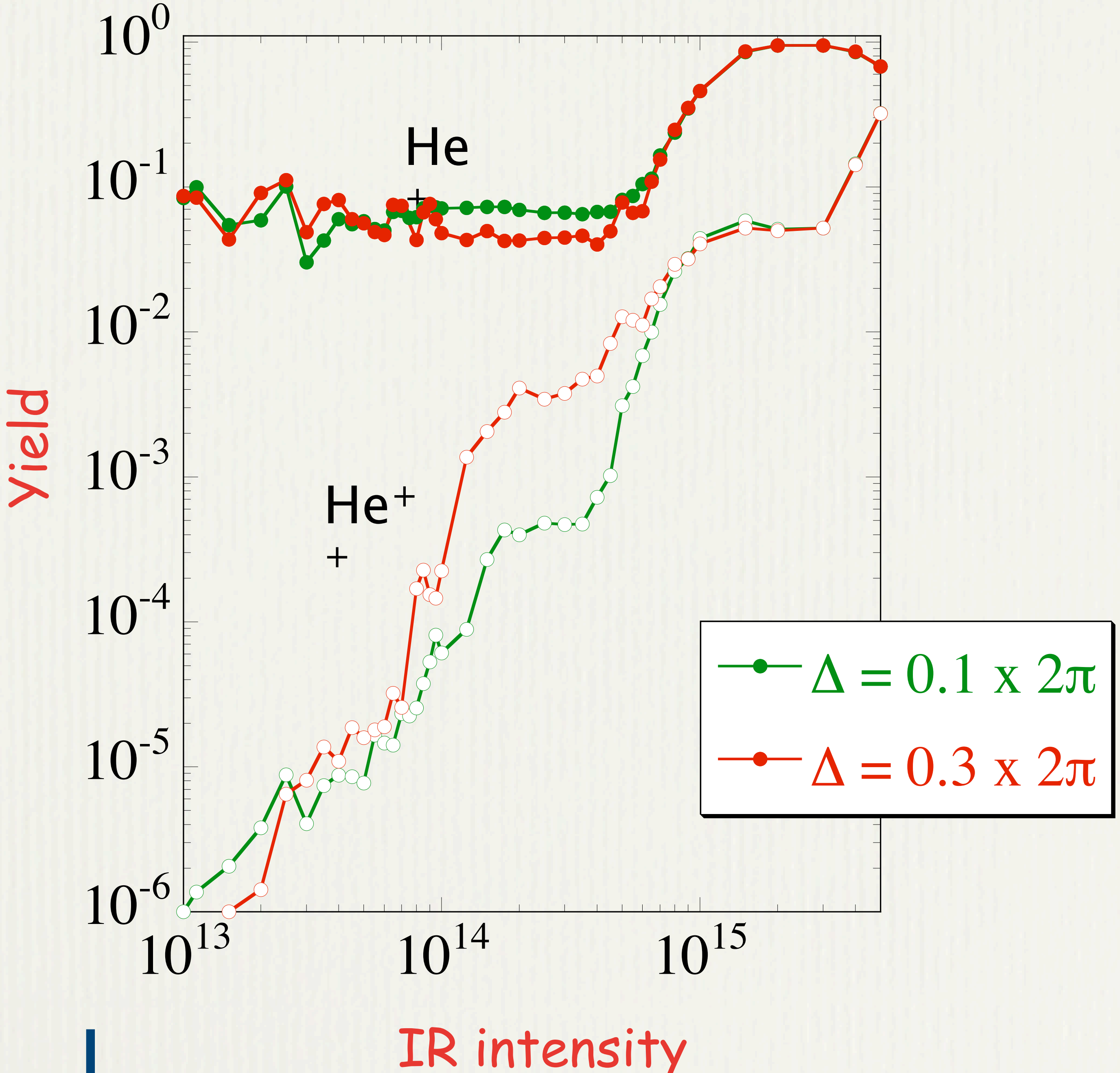


- Ionization is APT-driven
- He^+ yield is delay dependent

Example: Non-sequential double ionization



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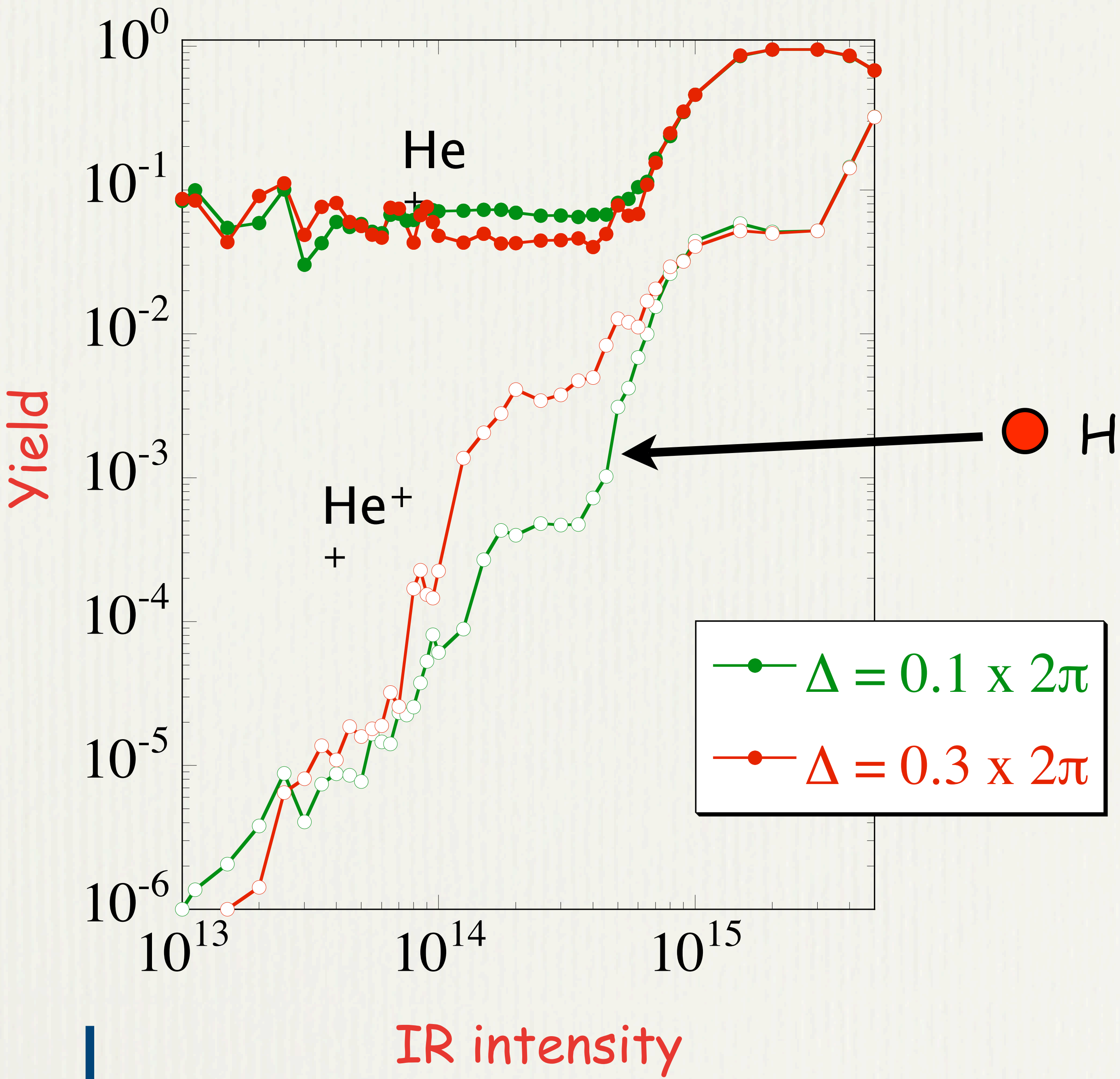
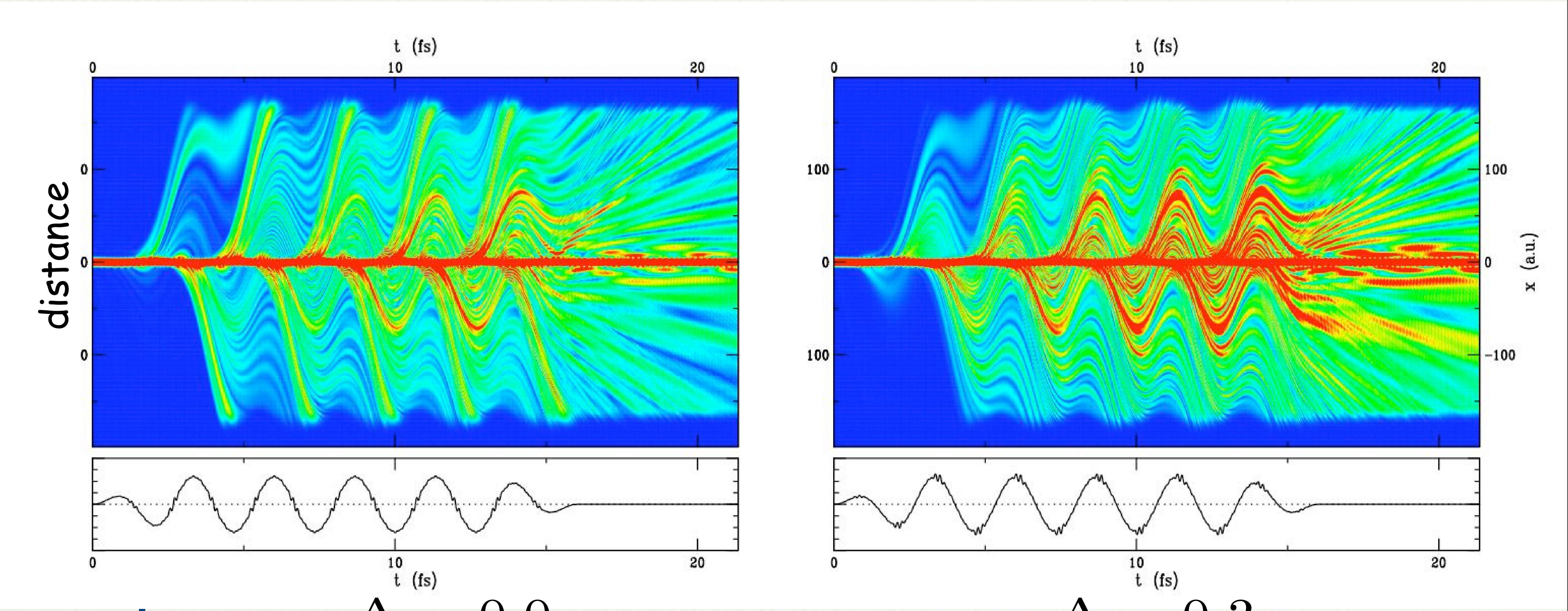


He++ yield delay dependent

Example: Non-sequential double ionization

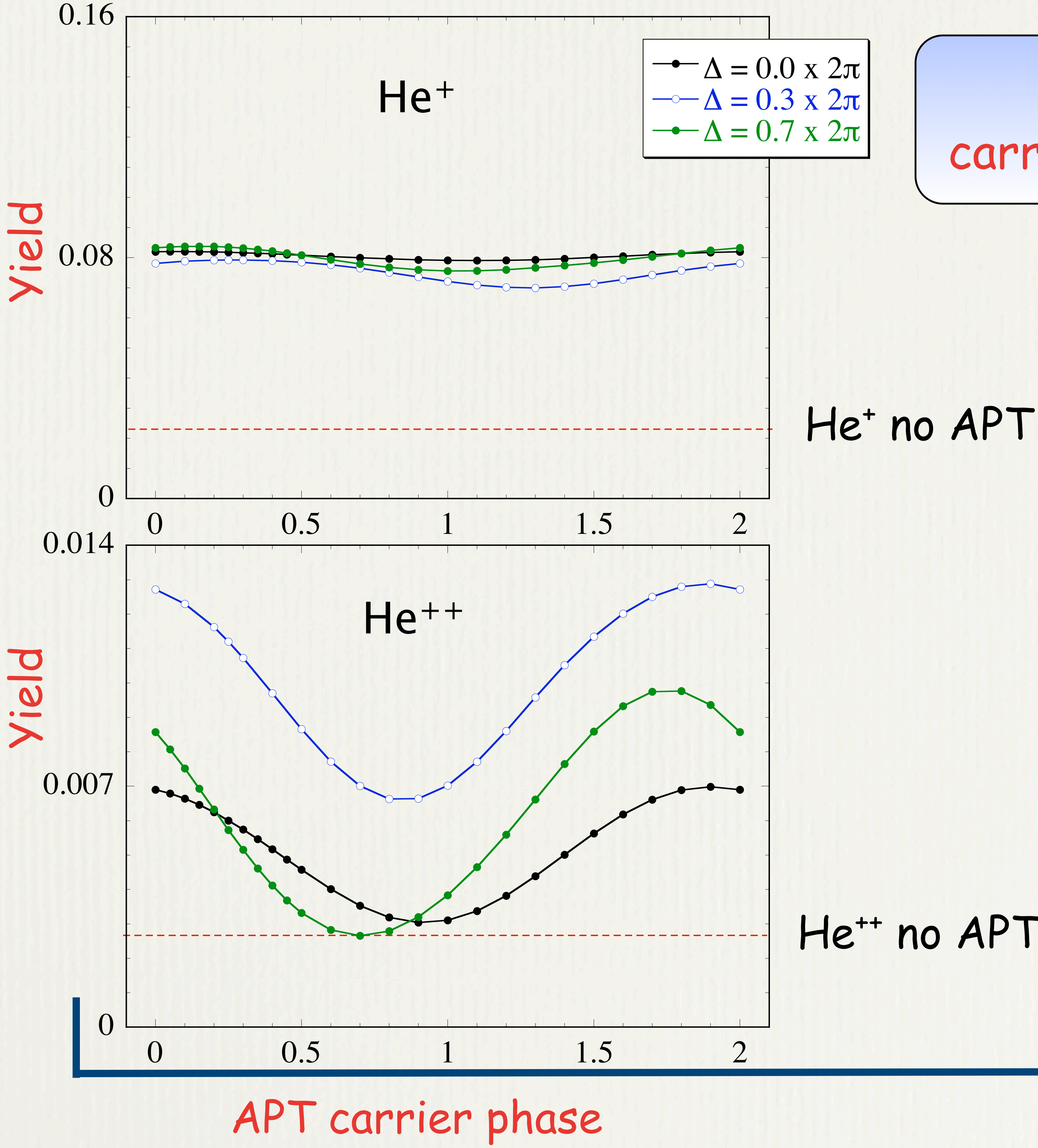
Comparing electron trajectories from 2 different IR-APT delays



$\Delta = 0.0$ $\Delta = 0.3$

Example: Non-sequential double ionization

Effect of
carrier envelope phase



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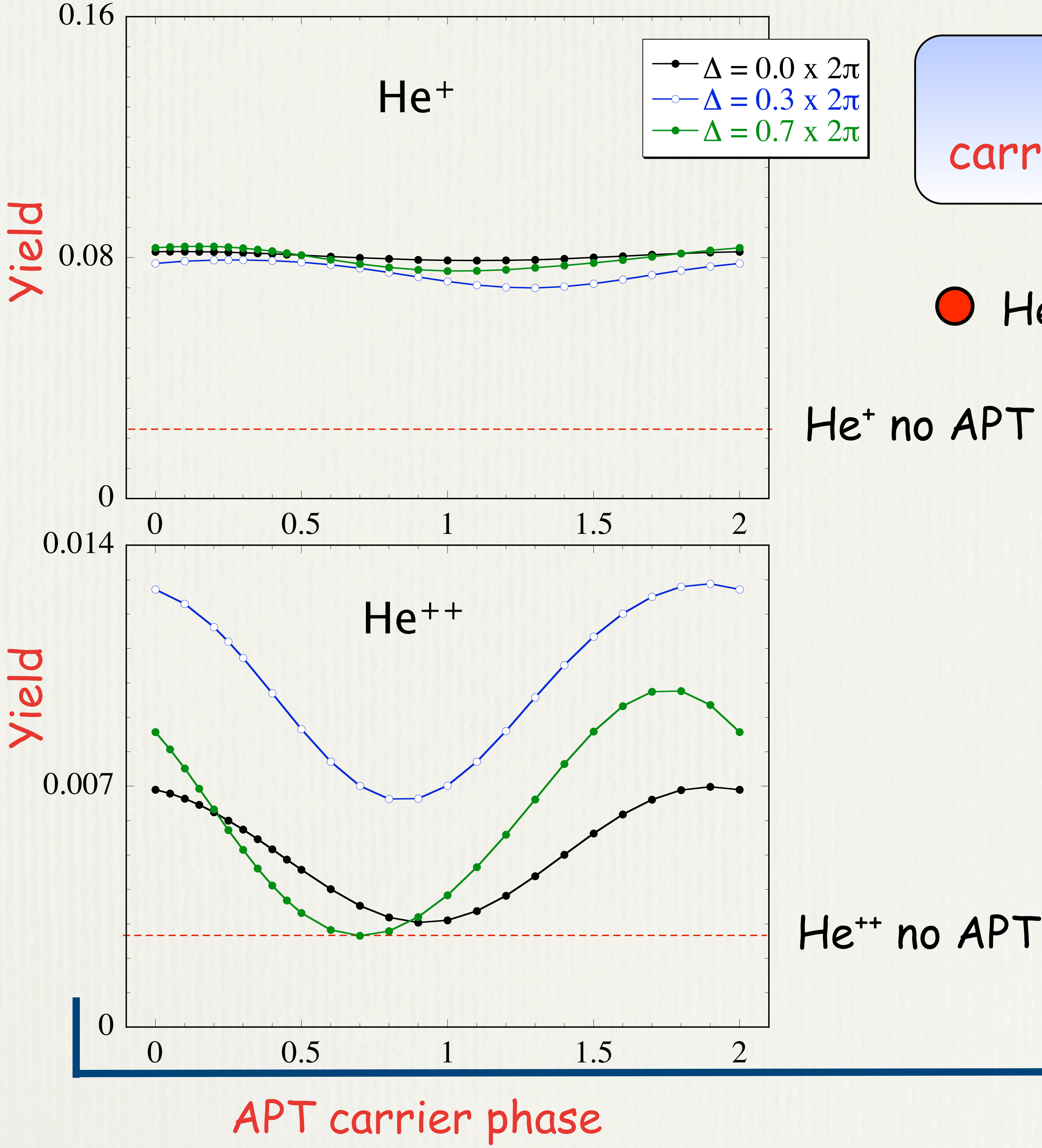

Effect of carrier envelope phase

- He+ insensitive to APT CEP

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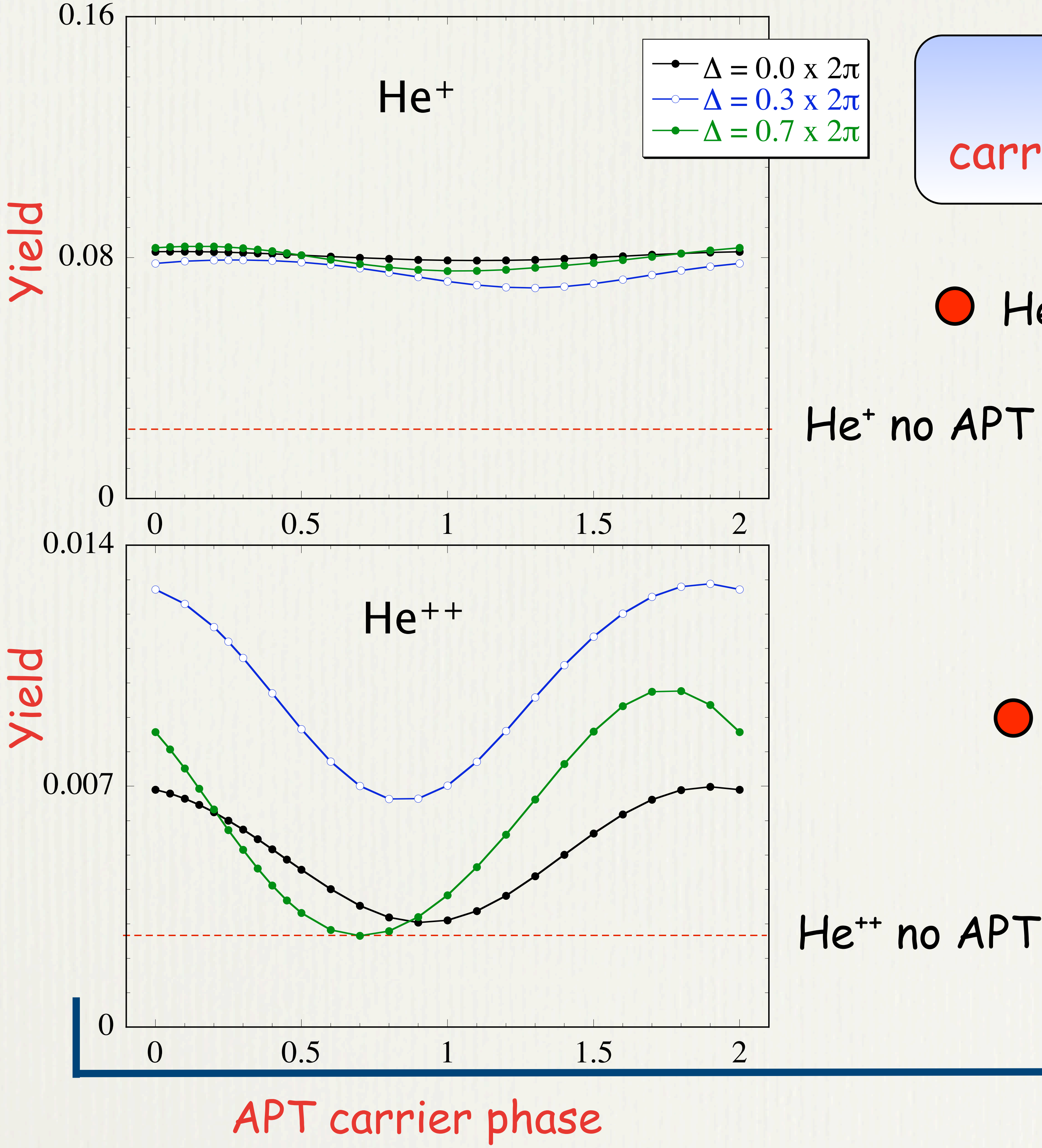
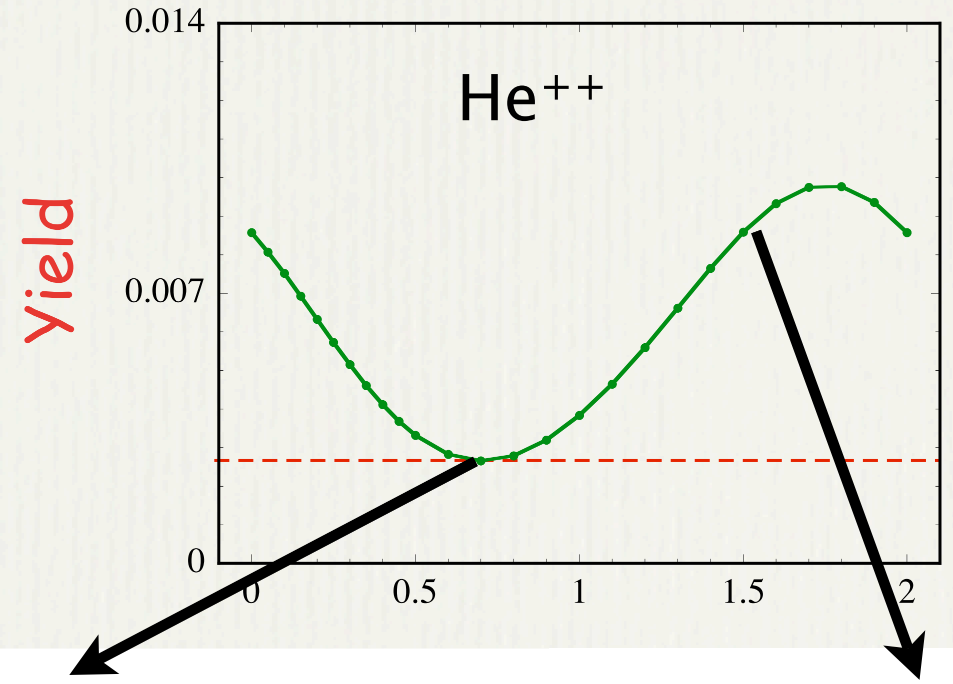


Effect of carrier envelope phase

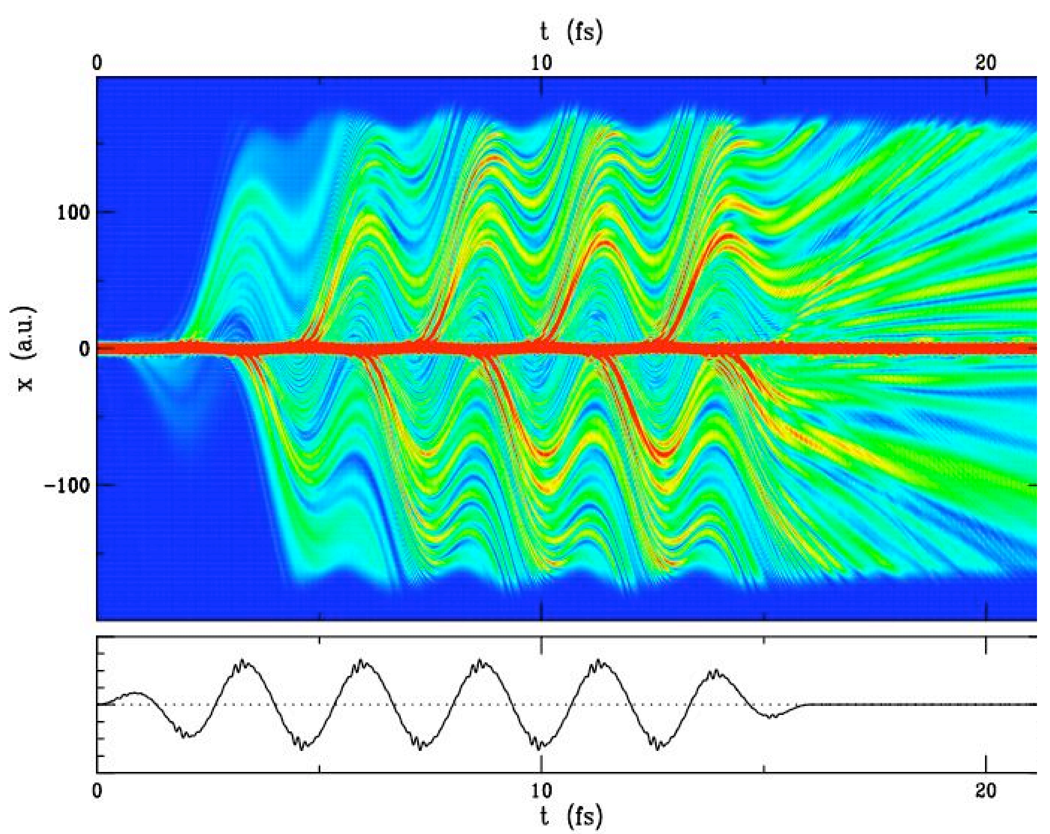
- He+ insensitive to APT CEP
- He++ very sensitive to APT CEP

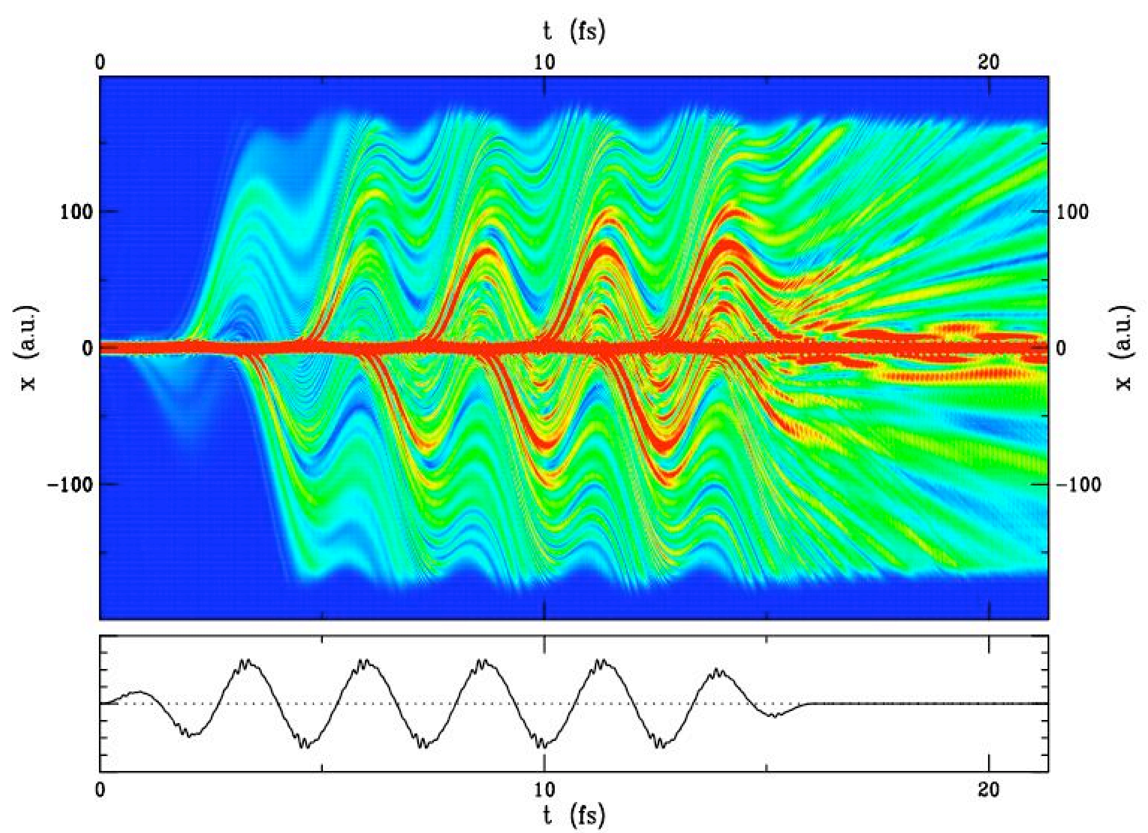
Example: Non-sequential double ionization

$\Delta = 0.7$



Single ionization





$\varphi = 0.7\pi$ $\varphi = 1.7\pi$

Ionization drives HHG

Single atom response

- Electron WP must return to core:
  - Ellipticity dependence
  - Saturation

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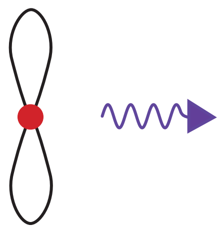
Propagation

- Free electrons reduce the refractive index.
  - Happens in space: fundamental defocused.
  - Happens in time: frequency modulation.

Calculating the single atom and macroscopic response

One atom, strong field



Dipole radiation
Ionization probability

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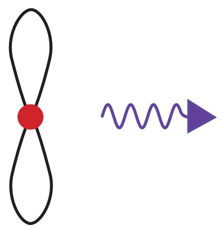

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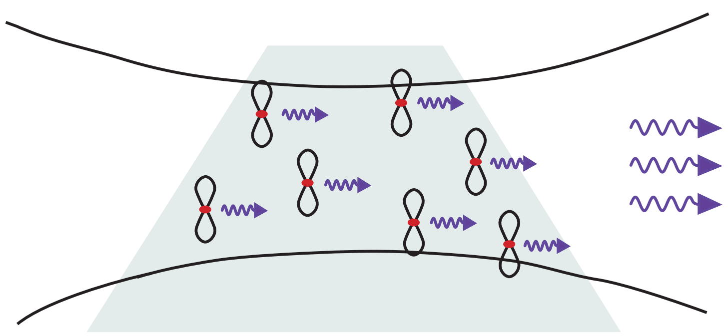
Many atoms, focused laser beam



Propagation

Phase matching

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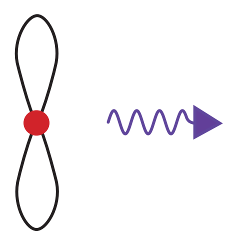

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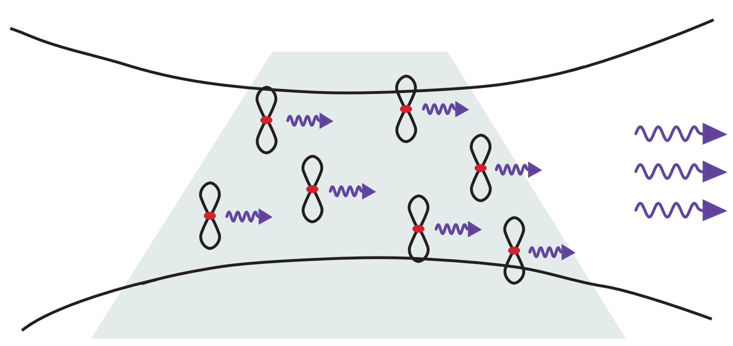

Propagation
Phase matching

Calculating the single atom and macroscopic response

Non-adiabatic, coupled solutions of wave equation and time-dependent Schrödinger equation.

$$\nabla_\perp^2 E_1(\omega, \mathbf{r}) + \frac{2i\omega}{c}\frac{\partial E_1(\omega, \mathbf{r})}{\partial z} = G(\omega, \mathbf{r})$$

$$\nabla_\perp^2 E_h(\omega, \mathbf{r}) + \frac{2i\omega}{c}\frac{\partial E_h(\omega, \mathbf{r})}{\partial z} = -\omega^2 \mu_0 P_{nl}(\omega, \mathbf{r}) - \frac{i\omega}{c}\alpha(\omega, \mathbf{r}) E_h(\omega, \mathbf{r})$$

SEWA: Brabec and Krausz, Rev. Mod. Phys 2001

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Laser field: $G(\omega,\mathbf{r})$ from ionization

- Free electrons change refractive index in space and time. Leads to defocusing and self-phase modulation (frequency shift).
- Loss of energy to ionization process
- Use ADK rates, scale ionization probability to fit numerical solution of TDSE

Gaarde et al, PRL submitted

Harmonic fields

$$P_{nl}(t,\mathbf{r}) = N_{atom}(t,\mathbf{r})d(t,\mathbf{r})$$

- Use SFA, non-adiabatic
- Absorption $\alpha(\omega,\mathbf{r})$

Single attosecond pulse production

SAP production is usually understood as a single atom effect.

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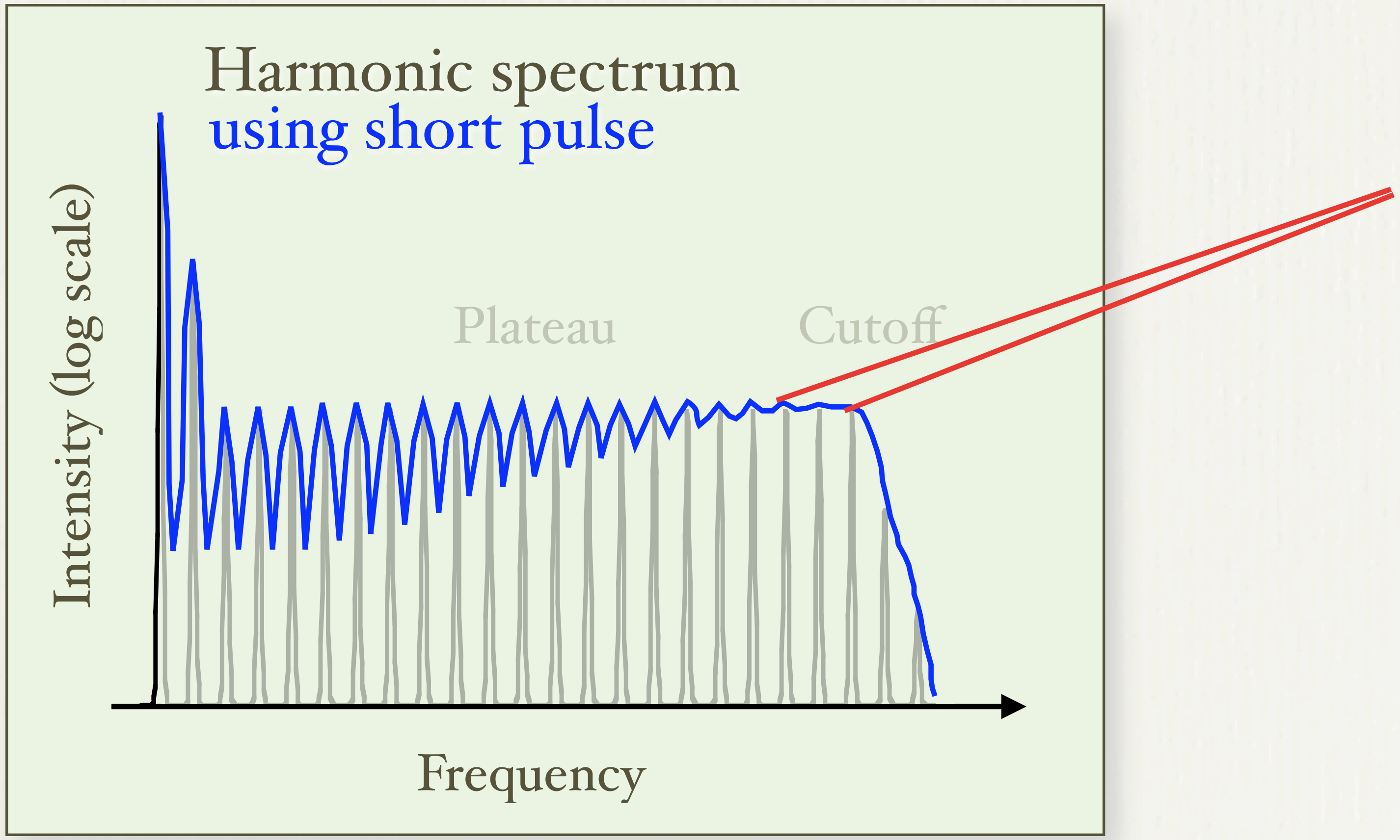

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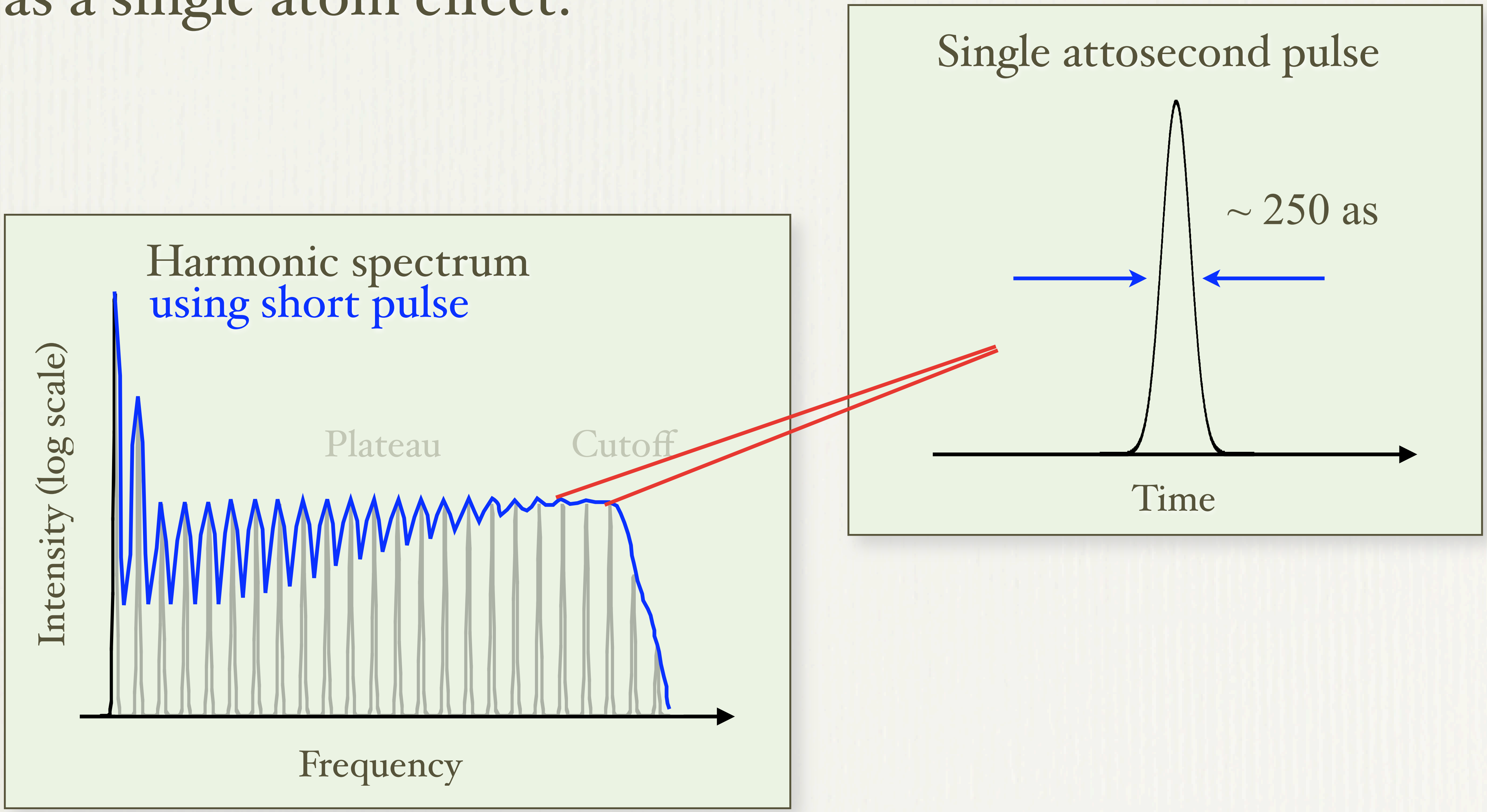

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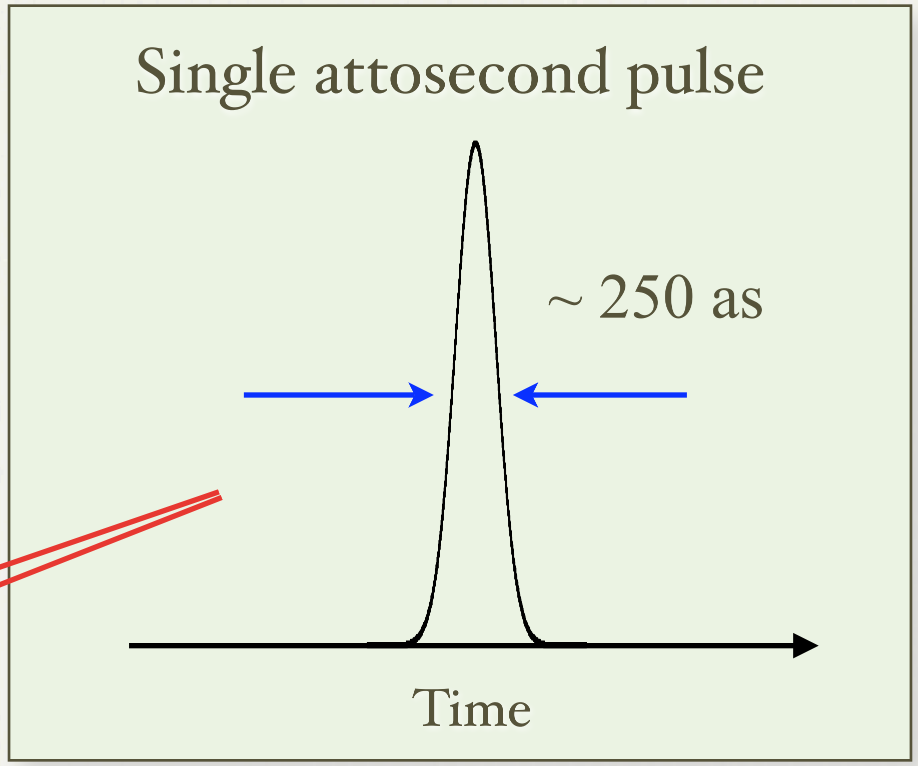

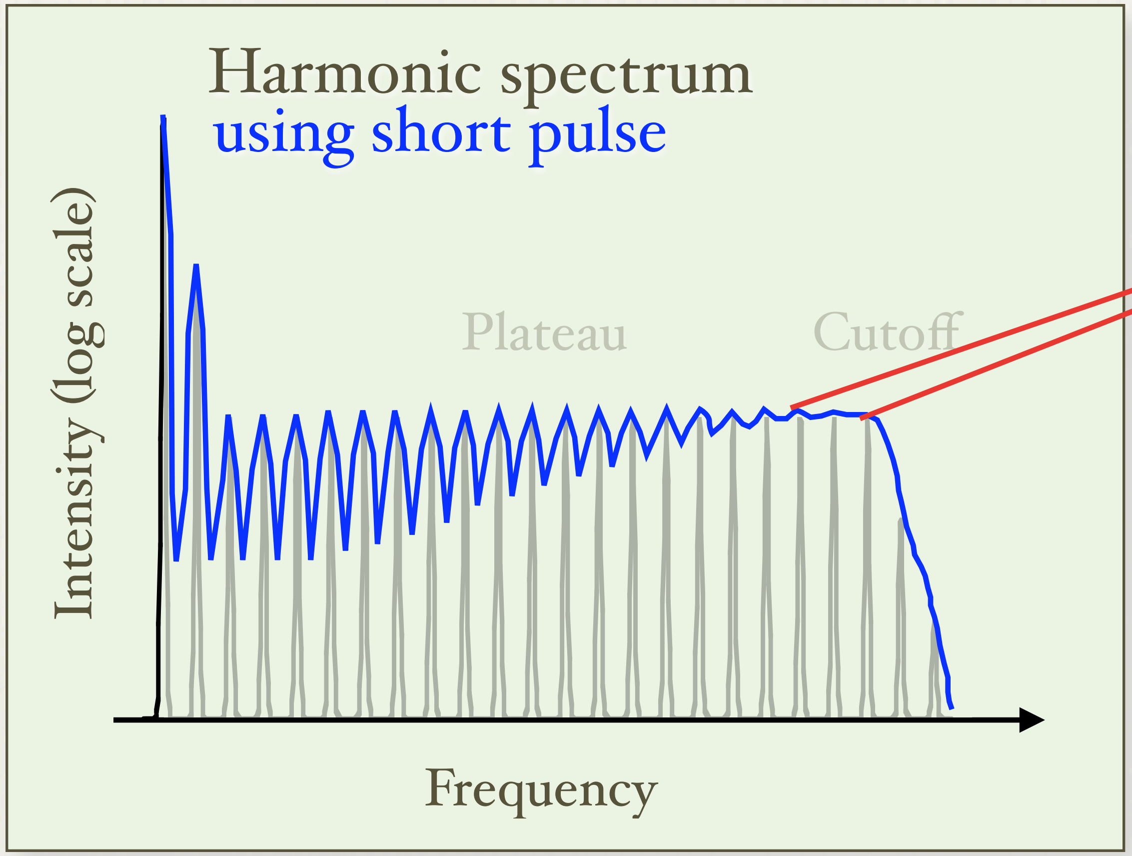

- Two cycle (5-6 fs) driving pulse.
- Spectral selection.
- Carrier envelope phase control.

Few cycle C-E control of HHG

$$E(t) = f(t)\cos(\omega_o t + \phi)$$

Krausz Group, Nature 2003

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Carrier envelope phase

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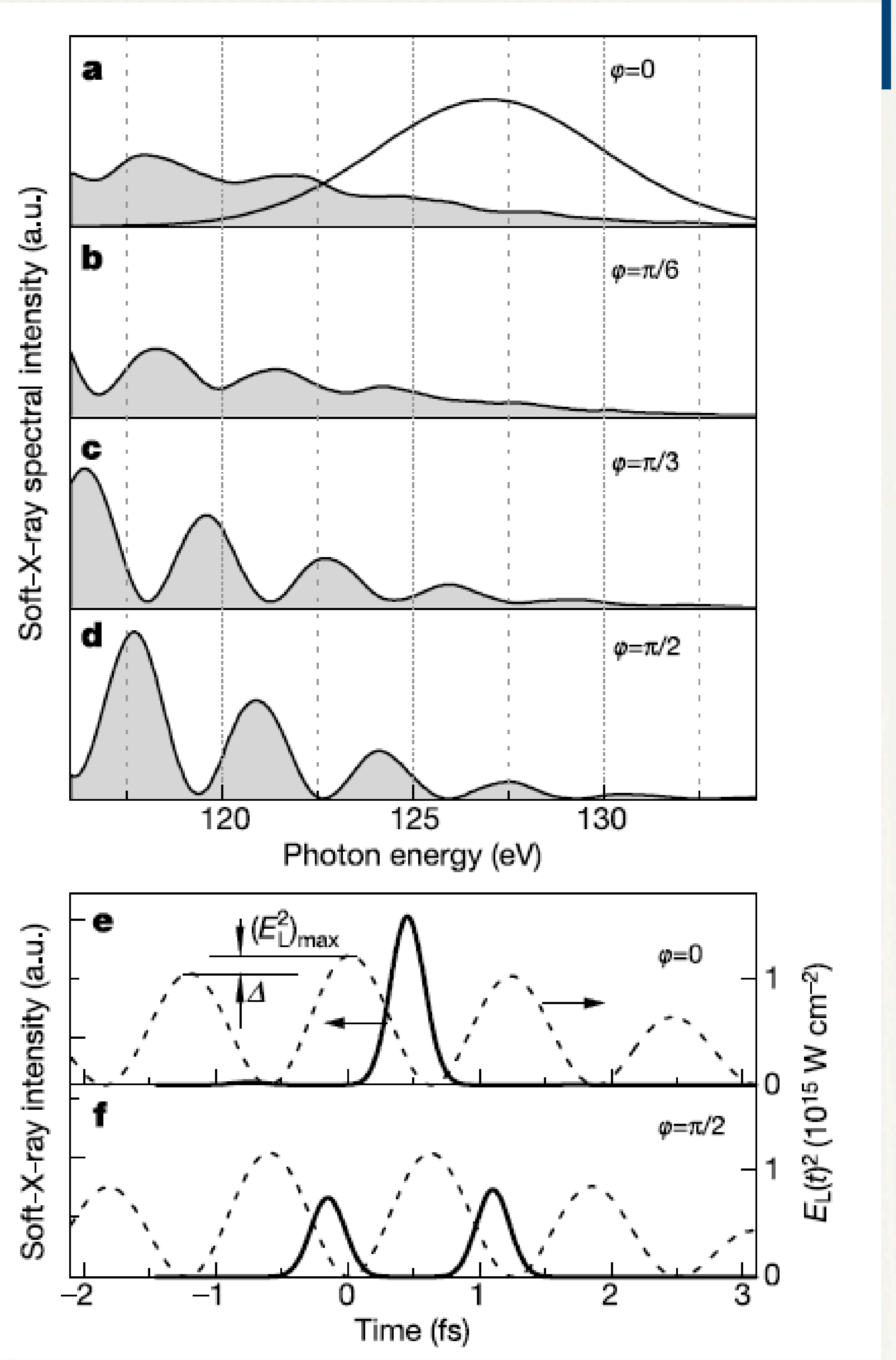

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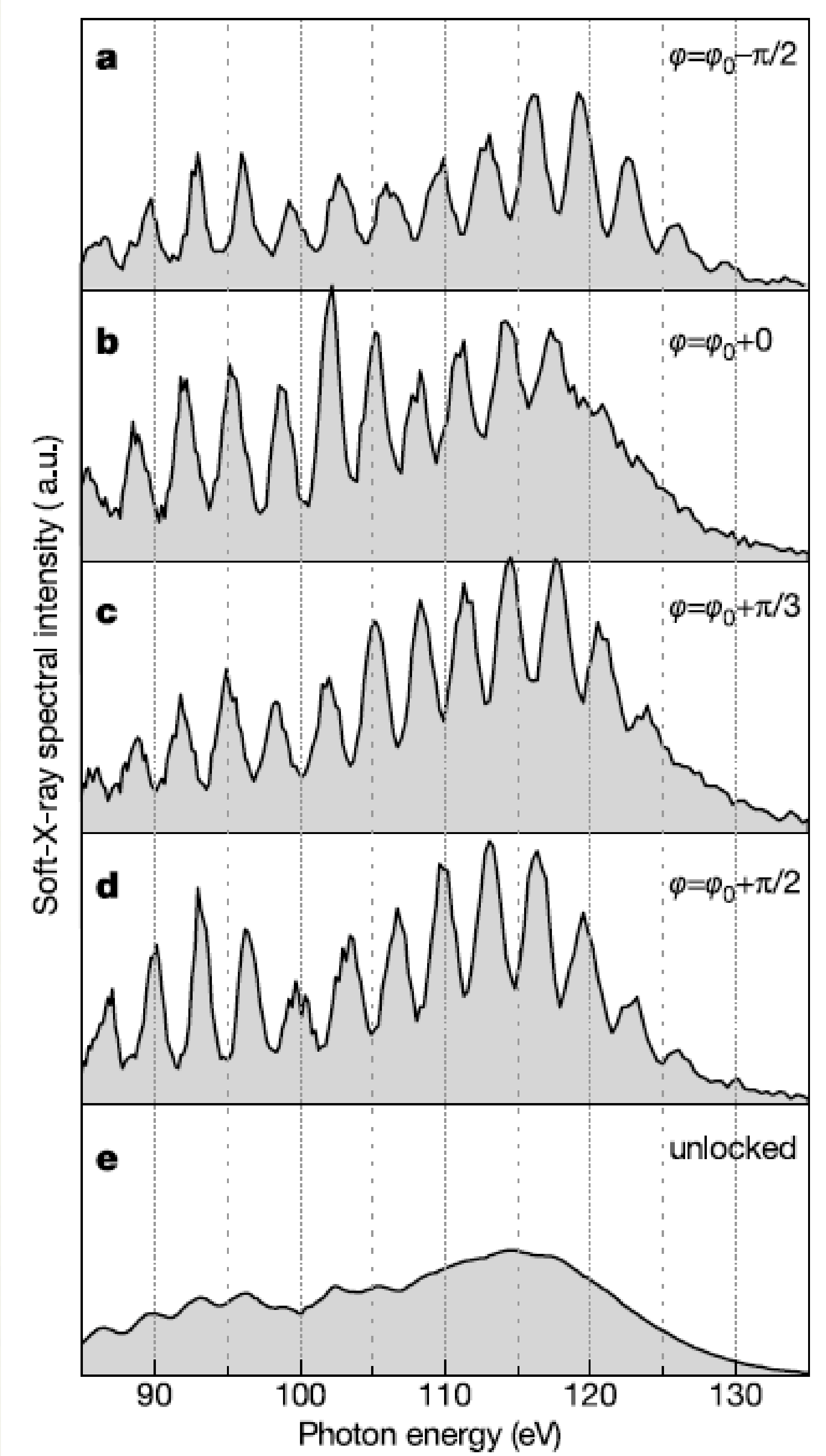
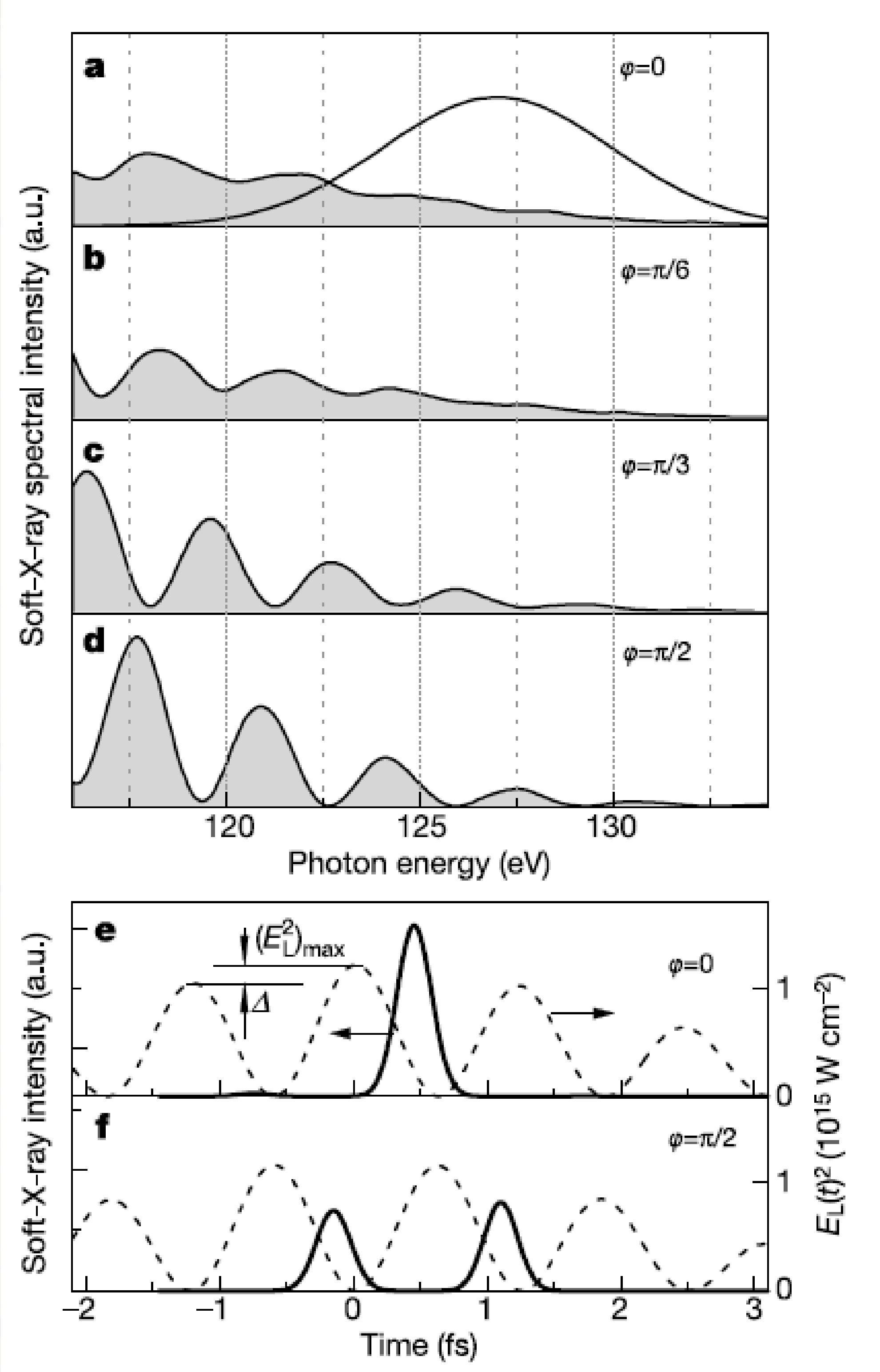
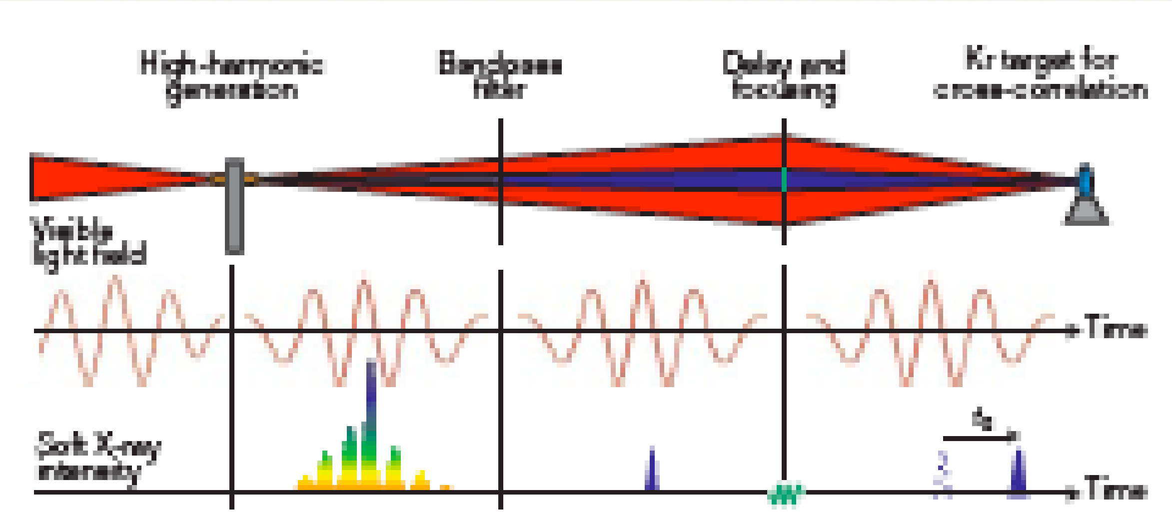
Few cycle C-E control of HHG





Krausz Group, Nature 2003

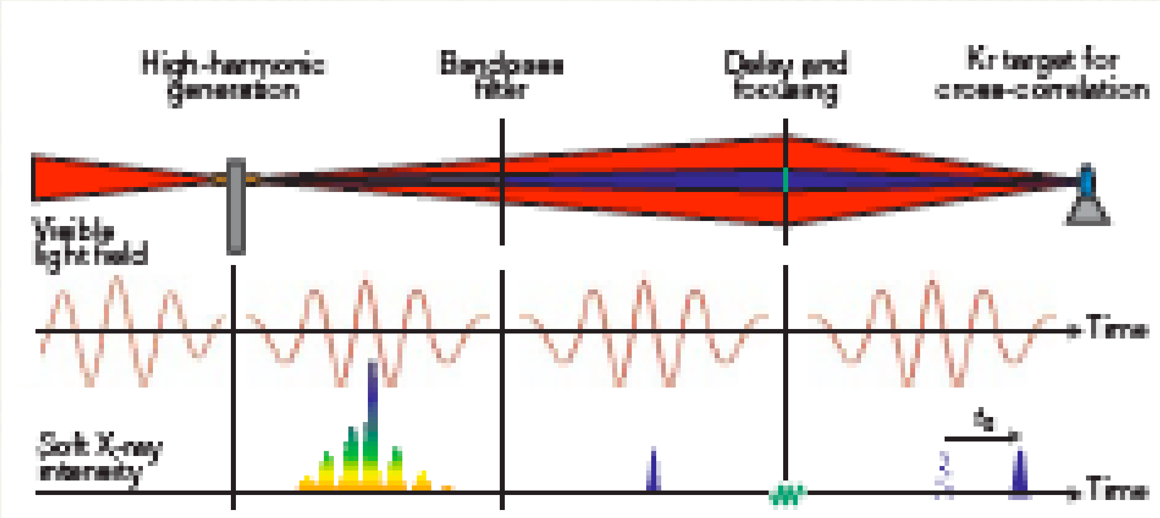
Attosecond pulse selection



- The pulse is too long (3 cycles).
- The C-E phase was not controlled.

Hentschel, *et al*, Nature 2001.

Attosecond pulse selection



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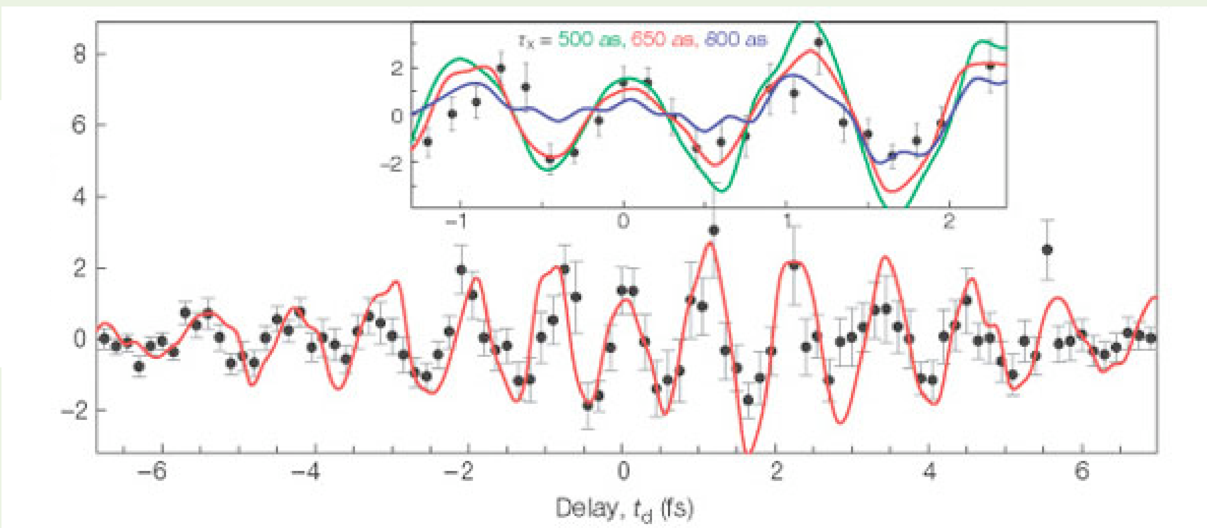
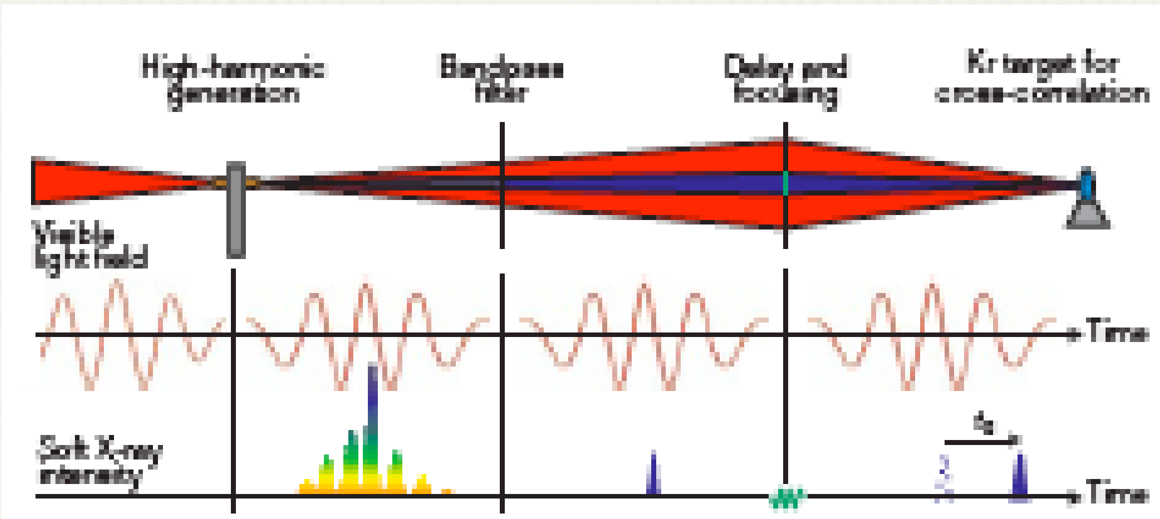


- 750 nm, 7 fs pulses, I = 9e14 W/cm^2
  → Isolated 630 as pulses at 90 eV
- Measured absolute phase of laser field:
  Large dynamical blue shift, up to 35%

  Result of rapid ionization dynamics?

Attosecond pulse selection



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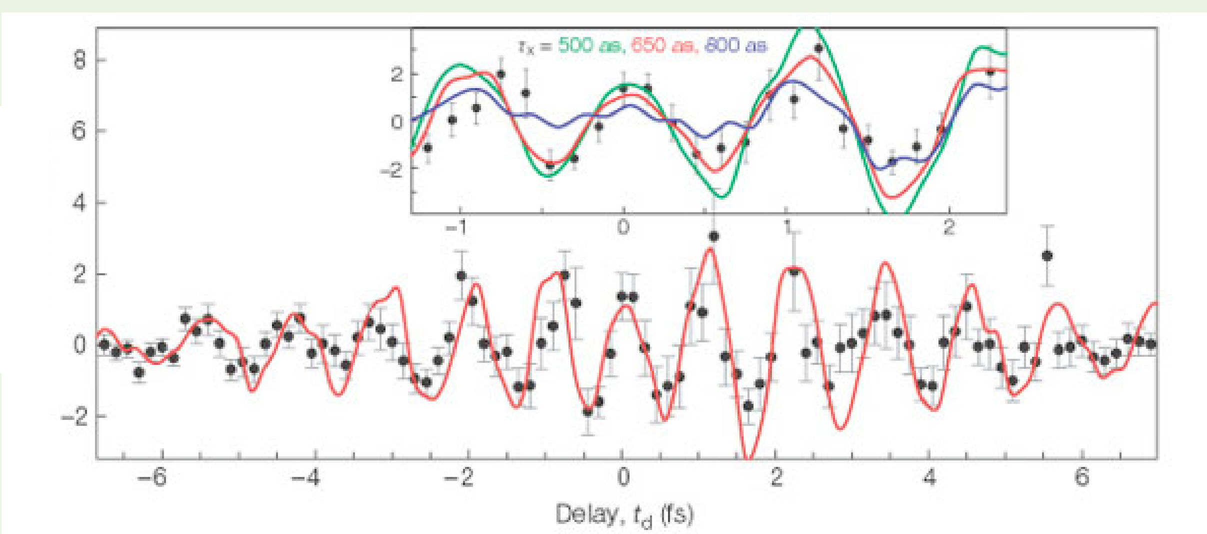

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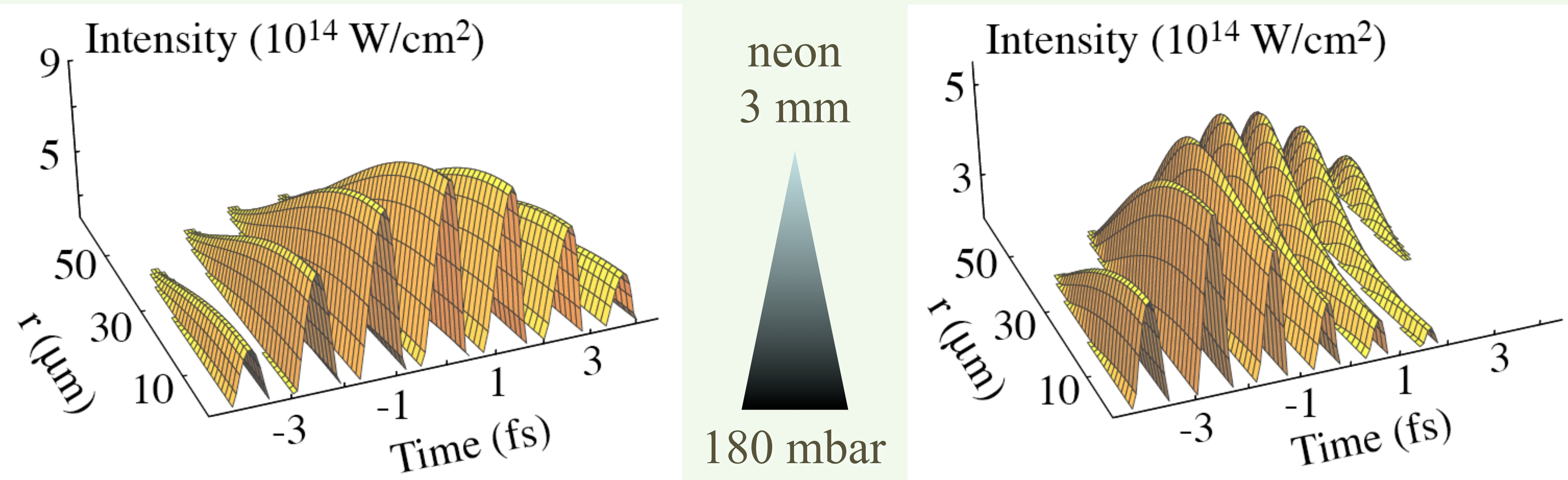
Selection of single attosecond pulse in farfield

Ionization-driven spatiotemporal reshaping

Initial laser pulse

After propagation



Calculation

using parameters from 2001 exp.

- (Much) lower peak intensity
- Strongly divergent wave front
  Intensity peaks at different times for different radial pos.

Gaarde et al, PRL submitted

Ionization-driven spatiotemporal reshaping

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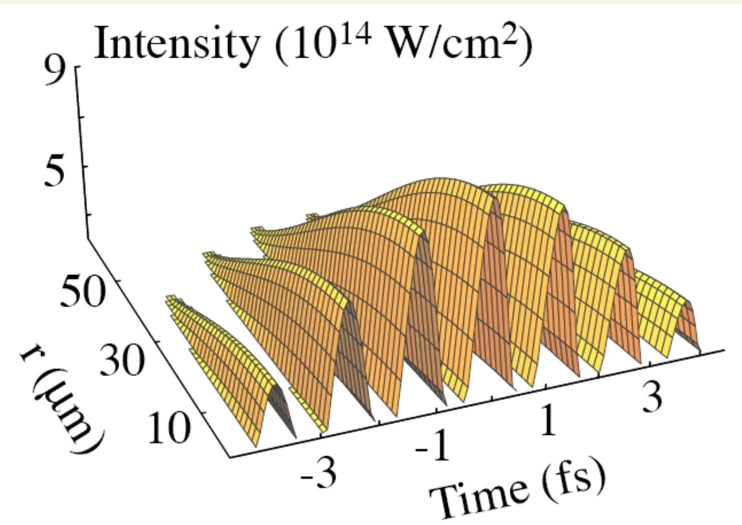
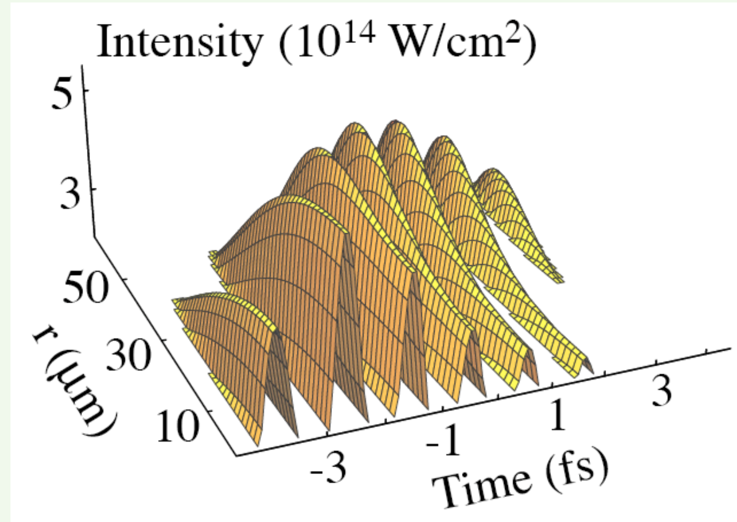
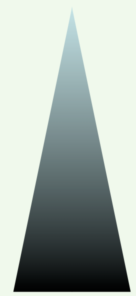


After propagation



neon
3 mm



180 mbar

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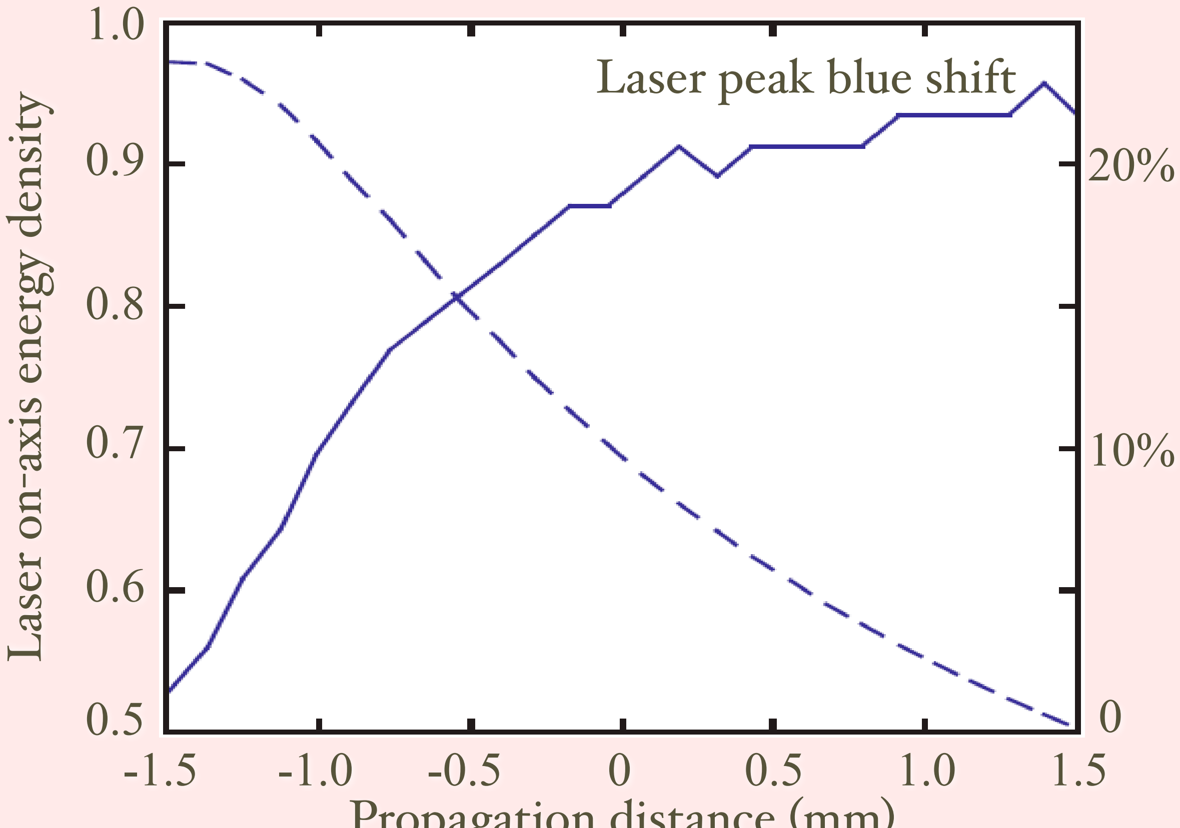
Gaarde et al, PRL submitted

Defocusing and frequency modulation

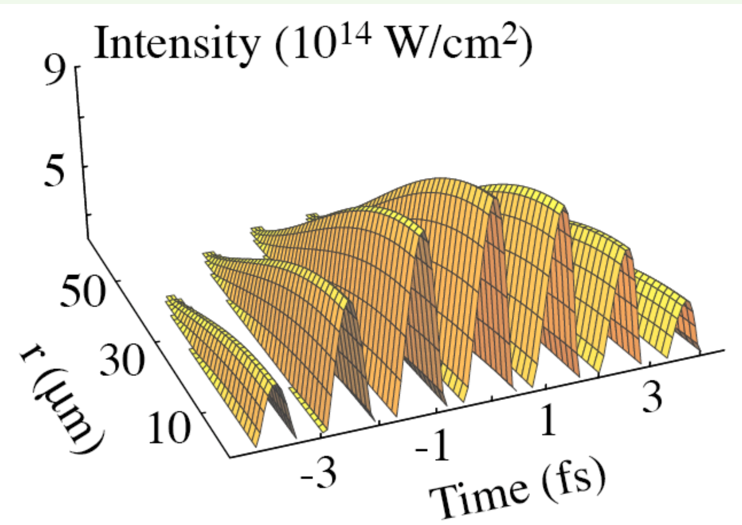


- Blue shift builds up rapidly in first half of gas while intensity is still high
- Defocusing reduces on-axis intensity
  Consistent with 90 eV cutoff energy

Slightly different laser focusing reproduces 35% frequency shift and 90 eV cutoff

Ionization-driven spatiotemporal reshaping

Initial laser pulse



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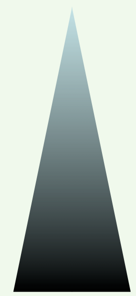
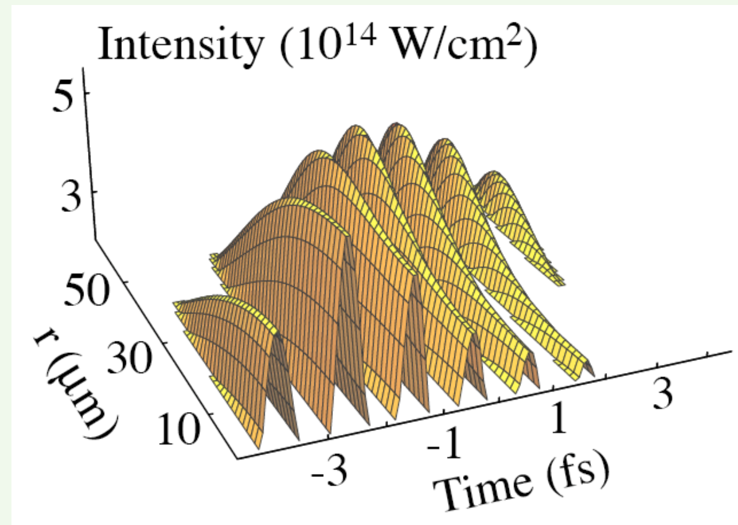


180 mbar

After propagation



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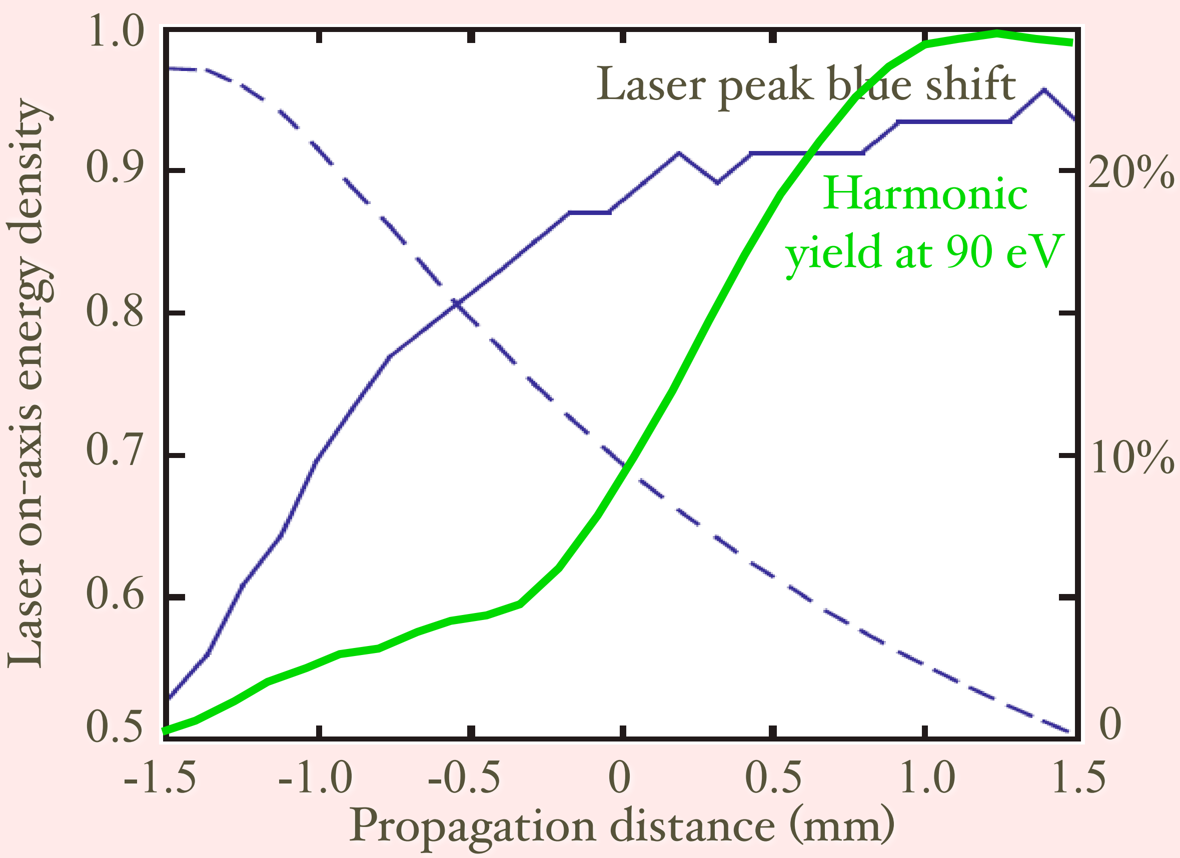

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- Harmonics around 90 eV are generated in second half of medium

Ionization-driven spatiotemporal reshaping

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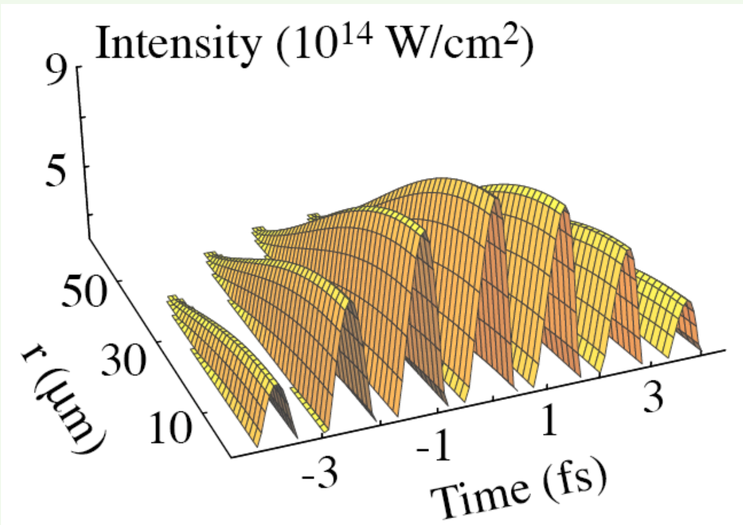

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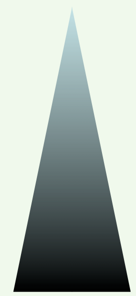

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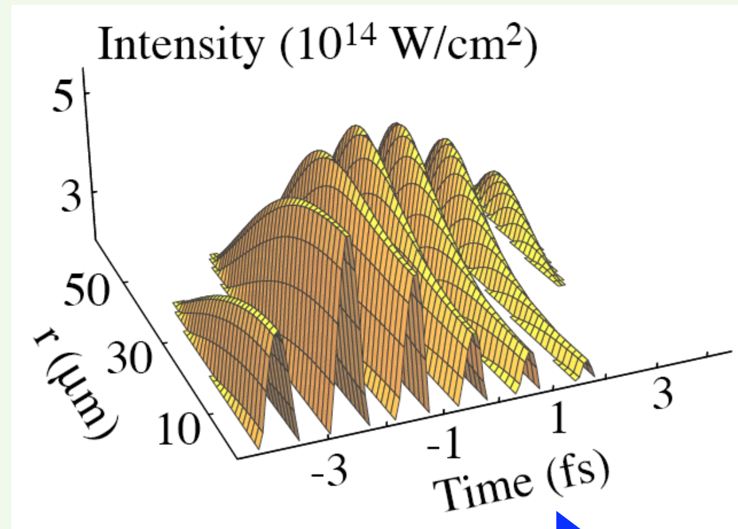

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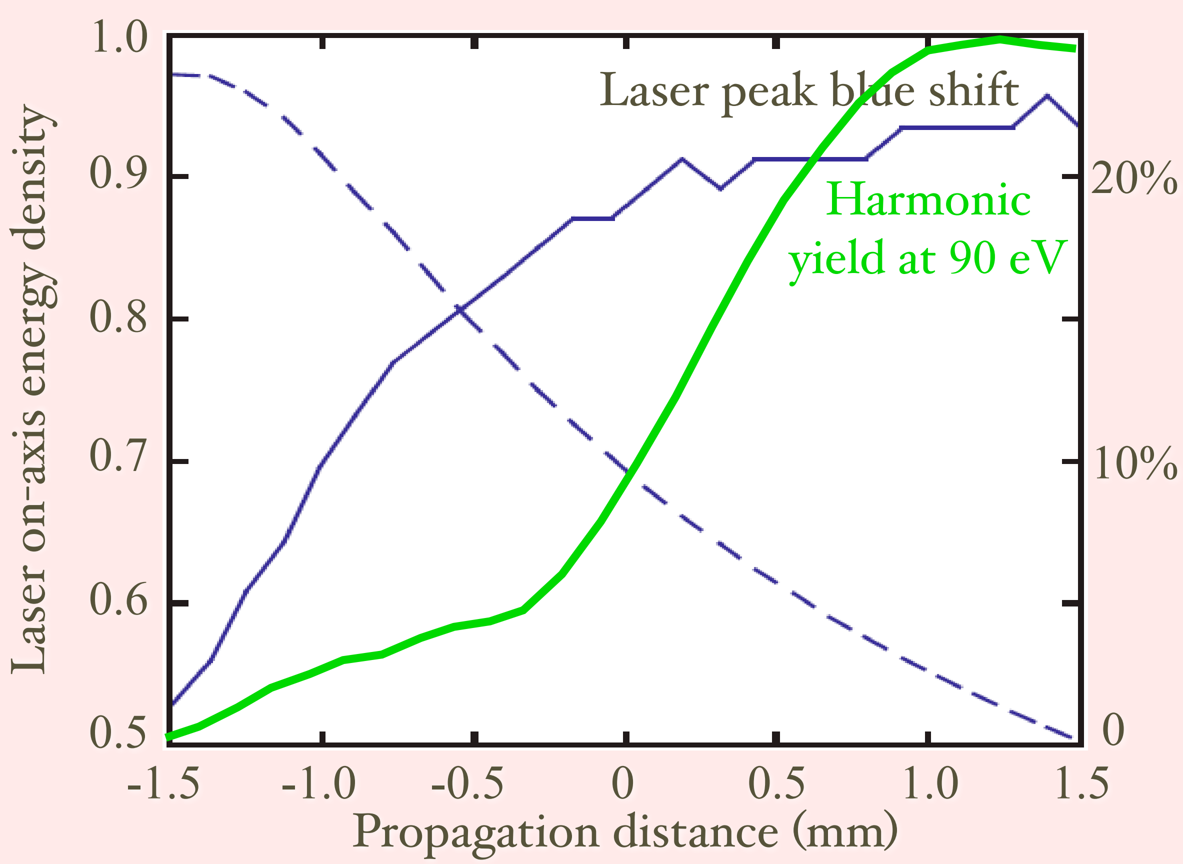

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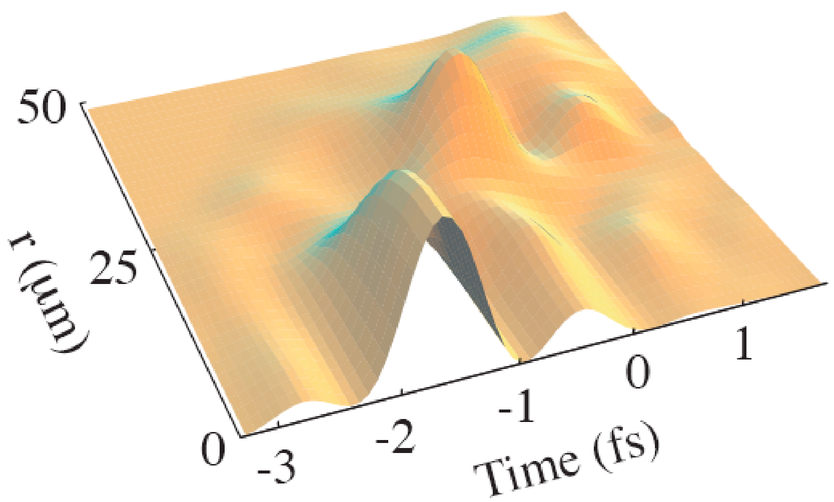
Harmonic generation and attosecond XUV pulses

Gaarde and Schafer, in preparation

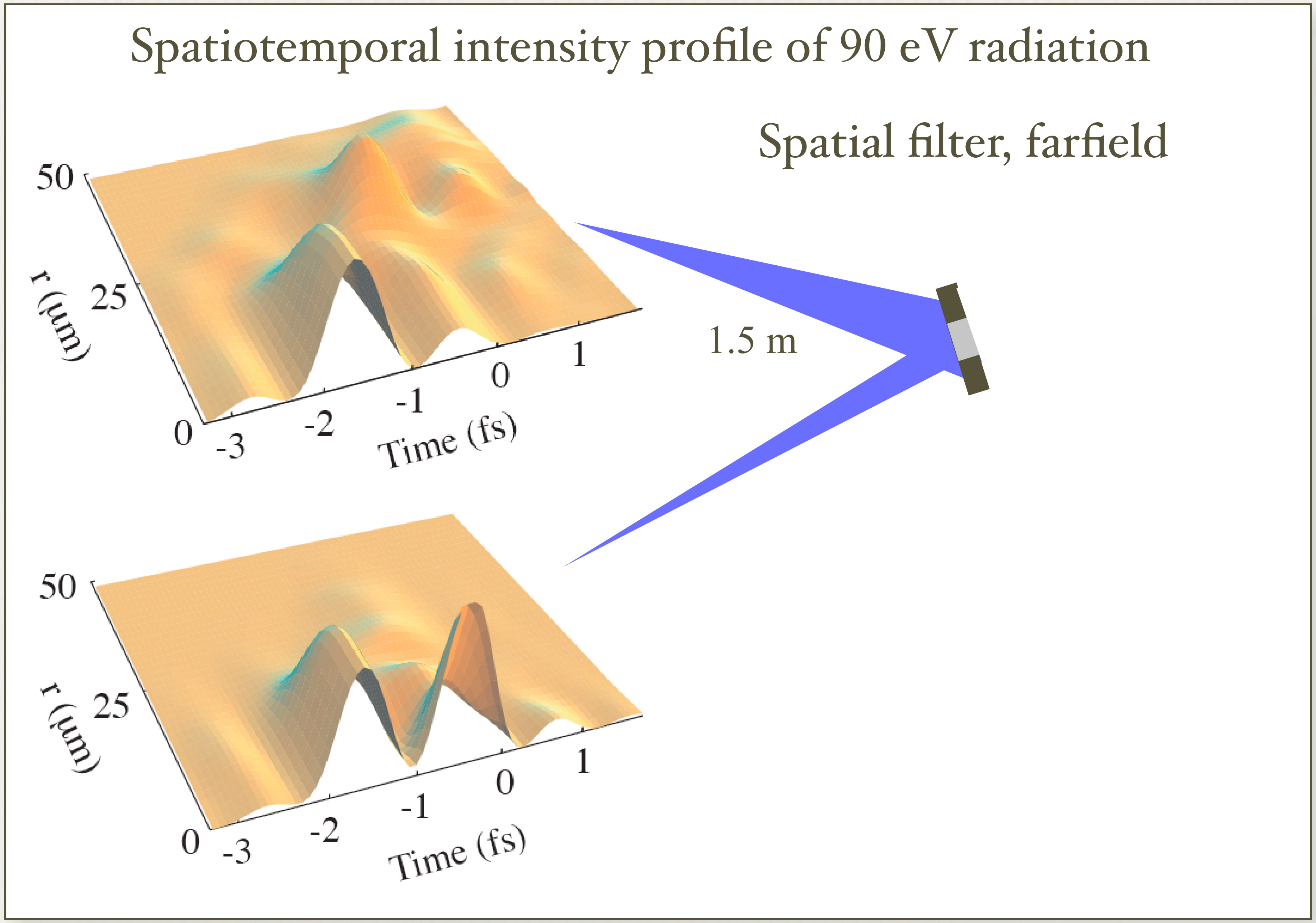
Spatiotemporal intensity profile of 90 eV radiation



- Multiple pulses in nearfield
- Reshaped driving laser pulse means they are generated with different divergences

Harmonic generation and attosecond XUV pulses

Gaarde and Schafer, in preparation



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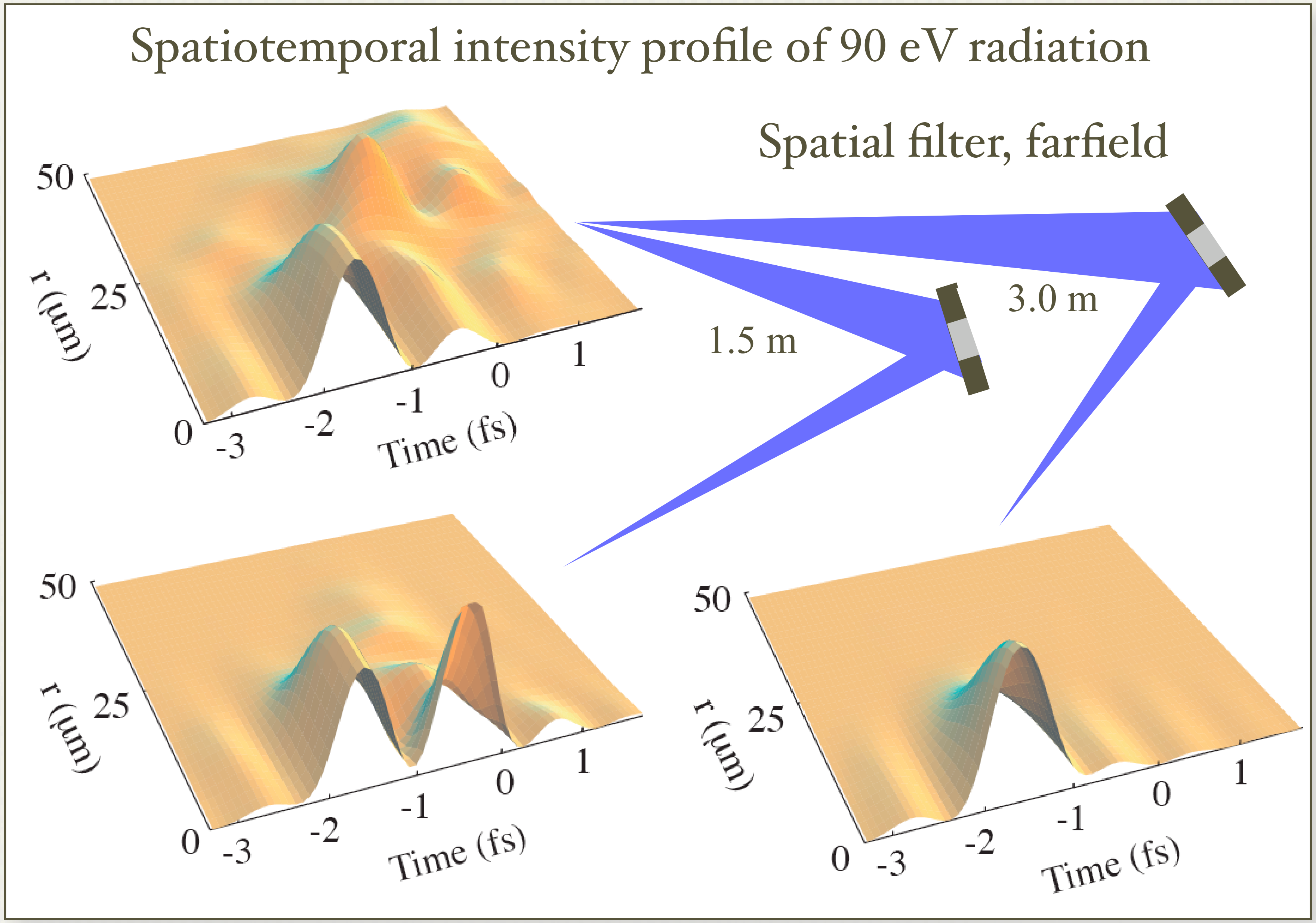

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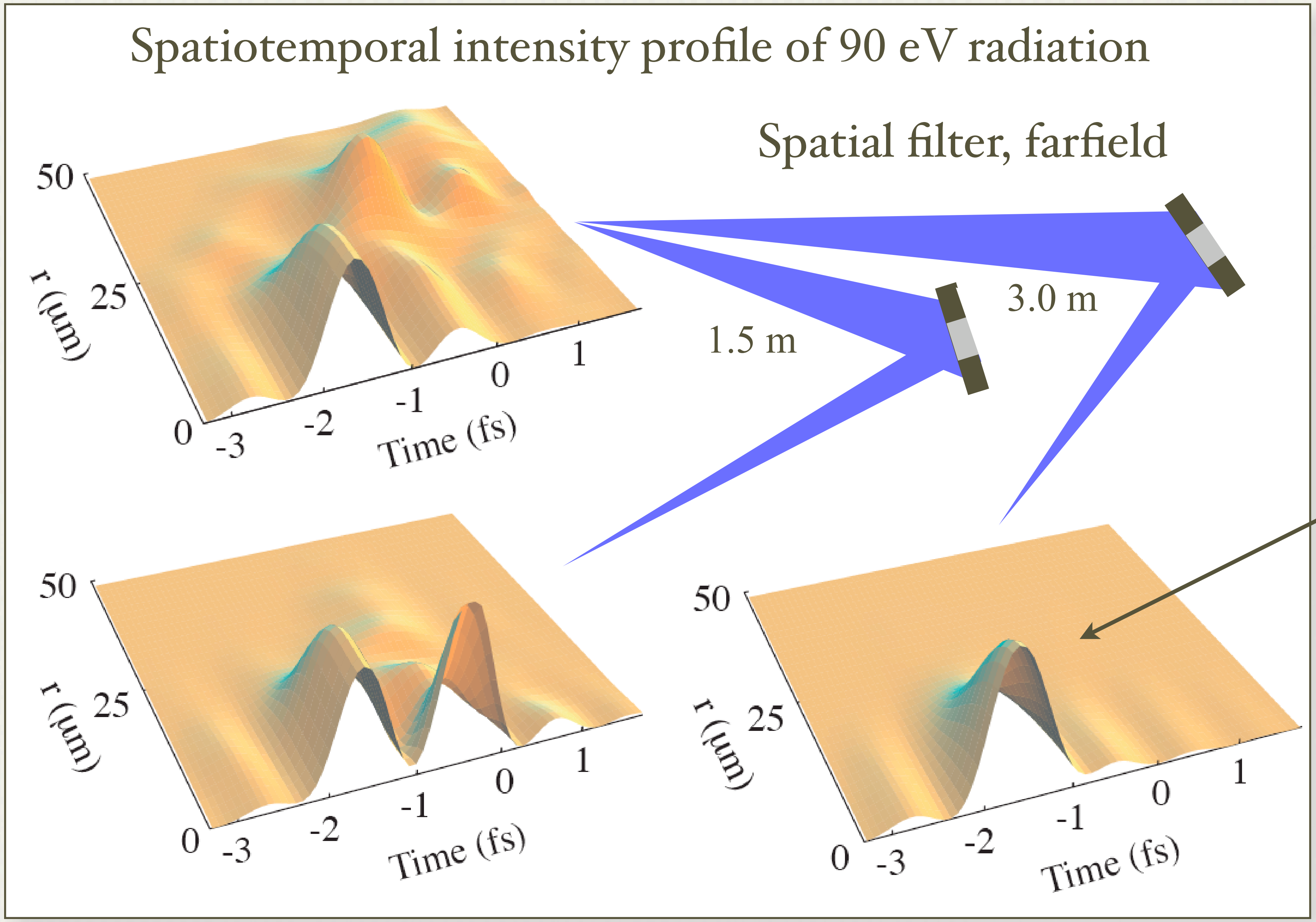

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- 630 as, 3 pJ

Spatial filter in farfield works as time gate
Isolate a single attosecond pulse among several

Spatial filter is XUV mirror with a 2 mm diameter, as in Hentschel *et al*, Nature 2001 (placed 2.5 m from source)

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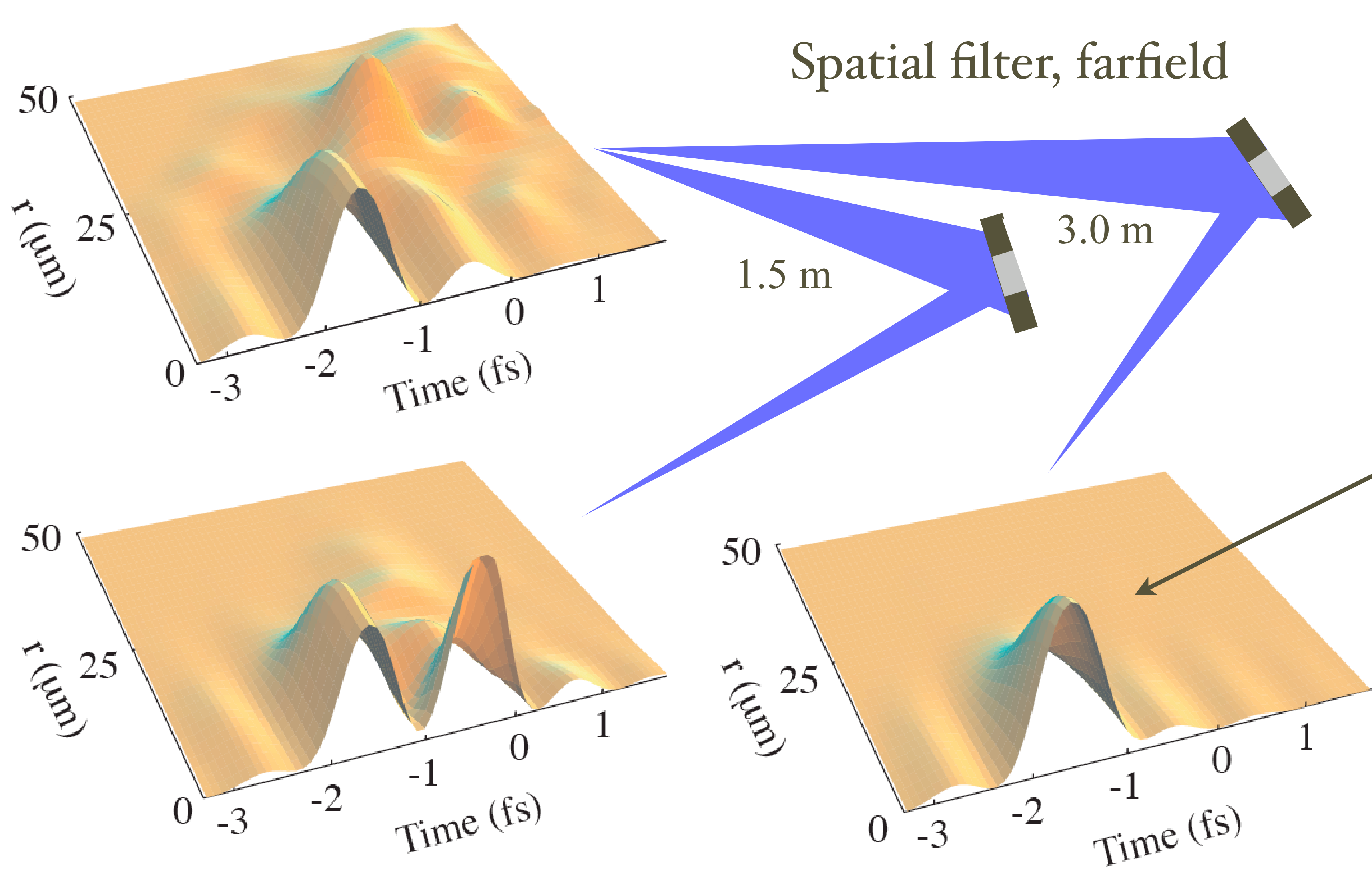

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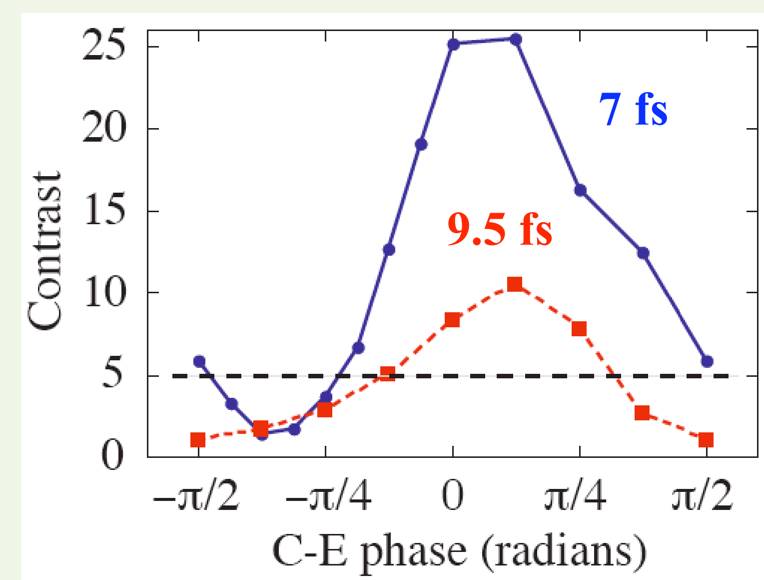
Works for even longer pulses:



- 9.5 fs driving pulse gives contrast ratio of 10:1
- 11 fs driving pulse gives contrast ratio of 6:1

Spatial filter in farfield works as time gate

Isolate a single attosecond pulse among several

Spatial filter is XUV mirror with a 2 mm diameter, as in Hentschel *et al*, Nature 2001 (placed 2.5 m from source)

Strong field physics in attoscience

- Theory challenges
  - What we know we don't know:
    Beyond single active electron model,
    multiple electrons in full dimensionality.
  - What we don't know:
    Where are multi electron effects important?
  - We need better TDSE/MWE solvers.

Strong field physics in attoscience

- Take home message:

Attosecond pulses are an exciting new tool to increase the precision with which we can study and control strong field processes. This, in turn, can lead to new attosecond sources and metrologies.