Coherent Control and Attosecond Science

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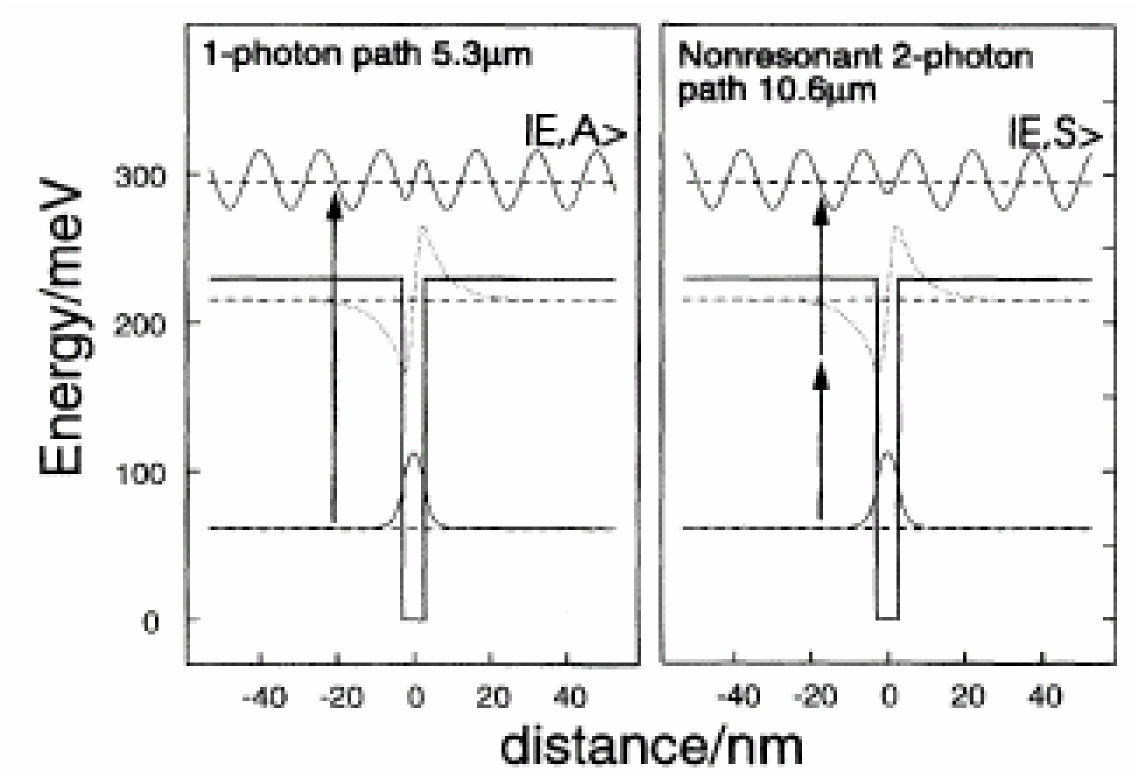
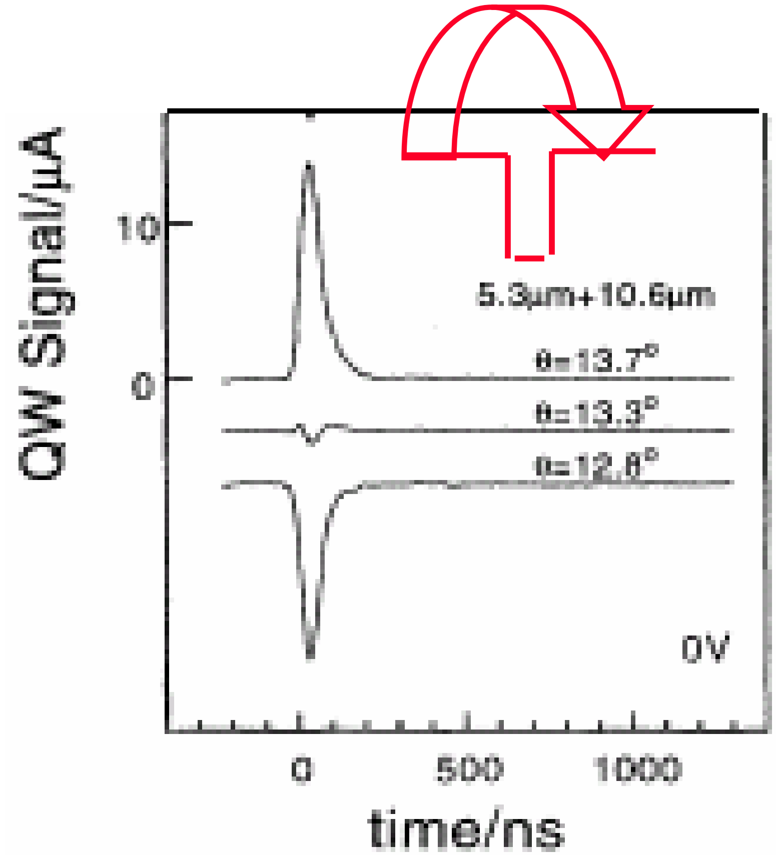
Quantum Interference --- the essence of Coherent Control





The relative phase of the light, controls the electron's phase

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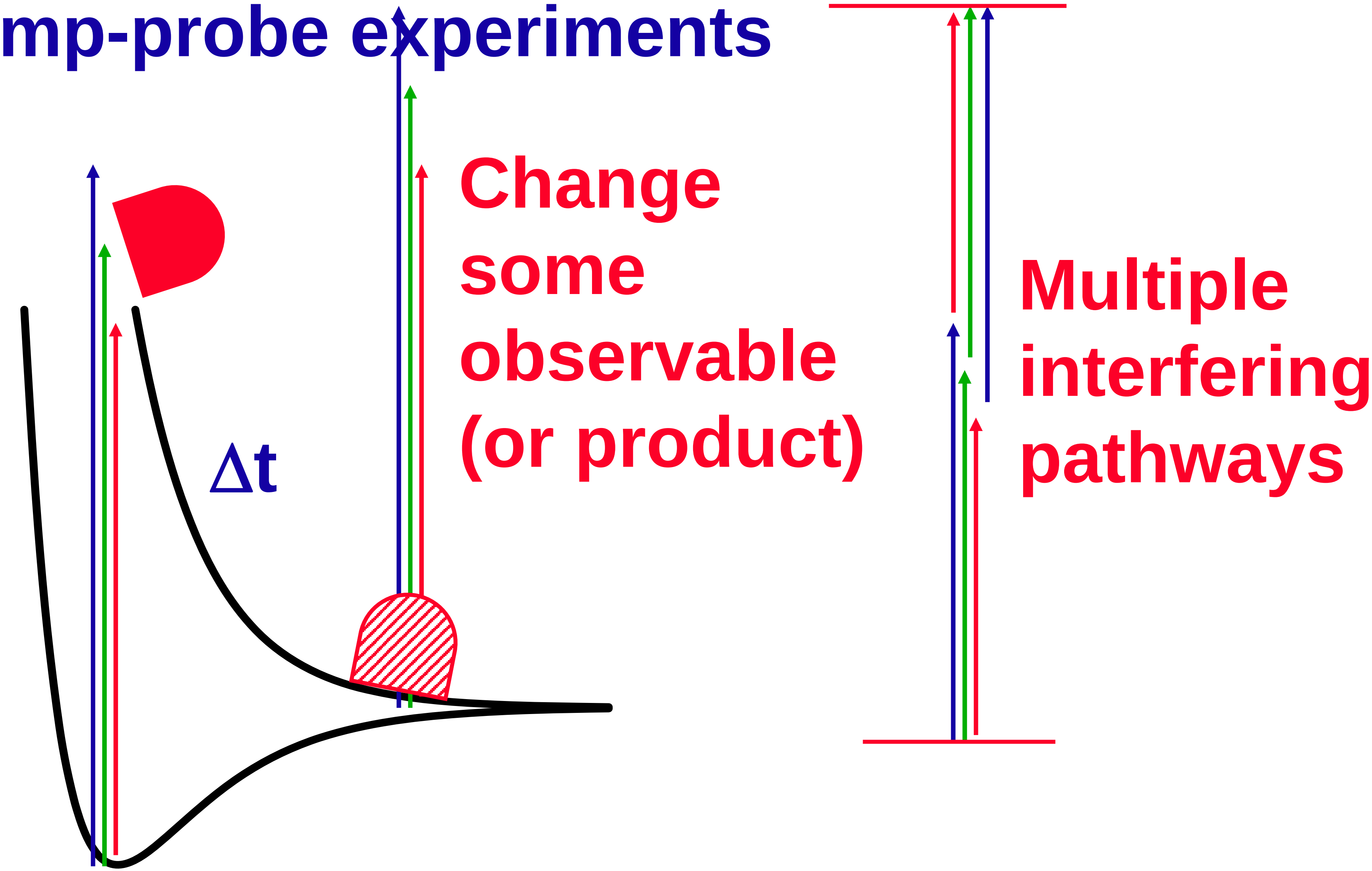
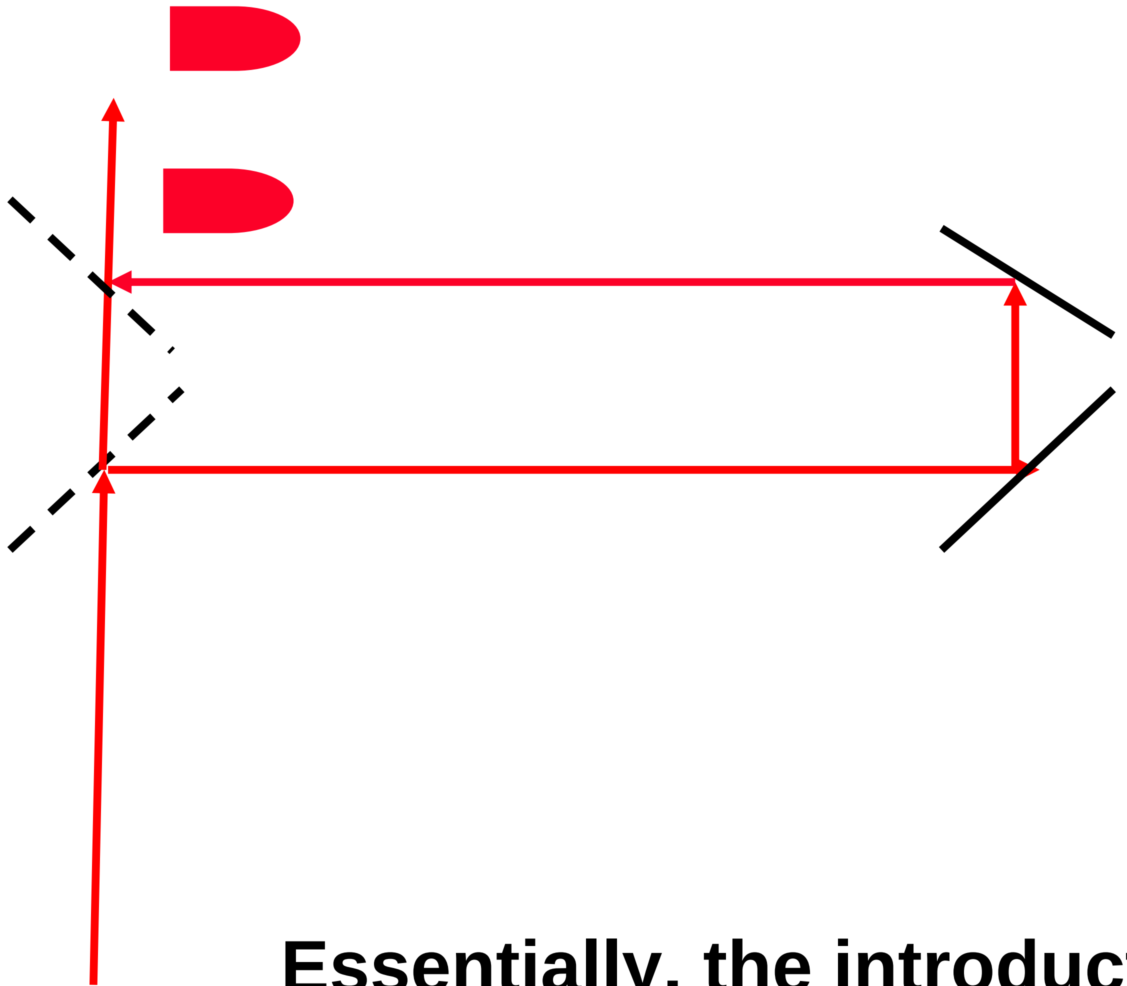
PRL 74, 3596 (1995)

Quantum interference – the essence of pump-probe experiments



Every pump-probe experiment is a "coherent control" experiment in disguise

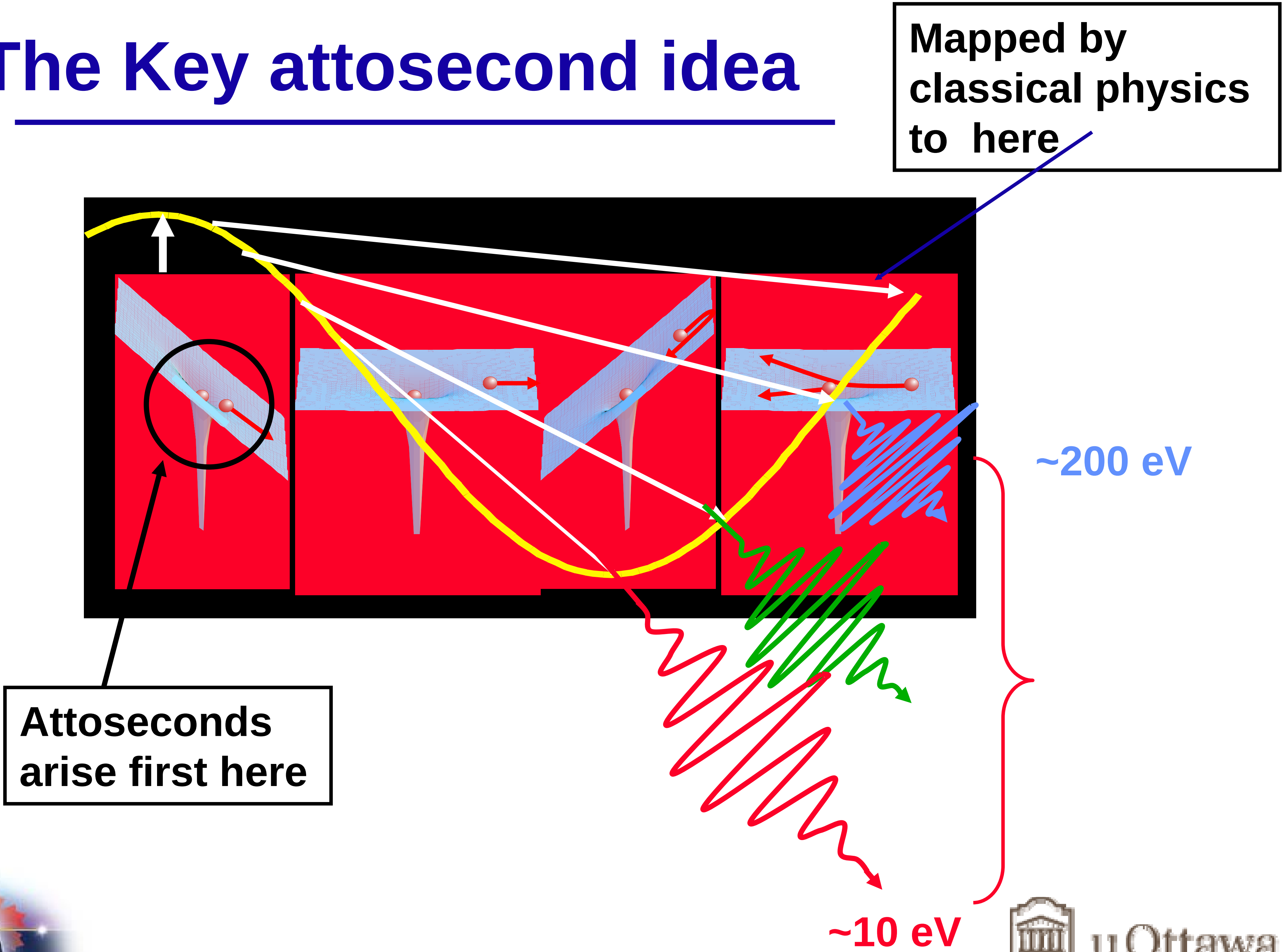
A pump-probe experiment for measuring ultrafast dynamics



Path length controls the pump probe delay

Essentially, the introductory slide from many coherent control presentations

The Key attosecond idea



A synthesis of optical and collision science

Offering:

- **Angstrom-scale *spatial resolution* to optical science**
- ***Time resolution and control* to collision science – *including dynamics in the nucleus***

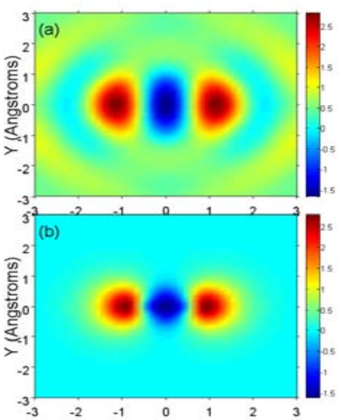
Attosecond science is sub-laser cycle science.

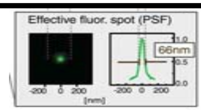
-- permitted by high nonlinearity.

- *All highly nonlinear interactions hold the promise. Tunneling and re-collision are just the first methods to develop.*

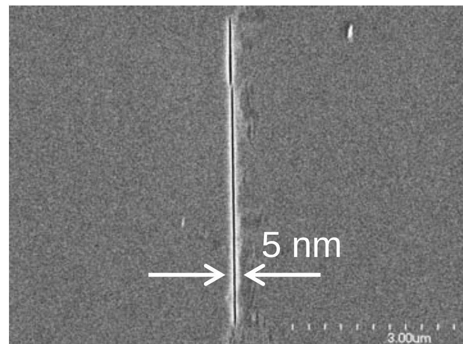
If we can sub-divide the period, we can also sub-divide the wavelength.

- ***A new approach to nano-technology***

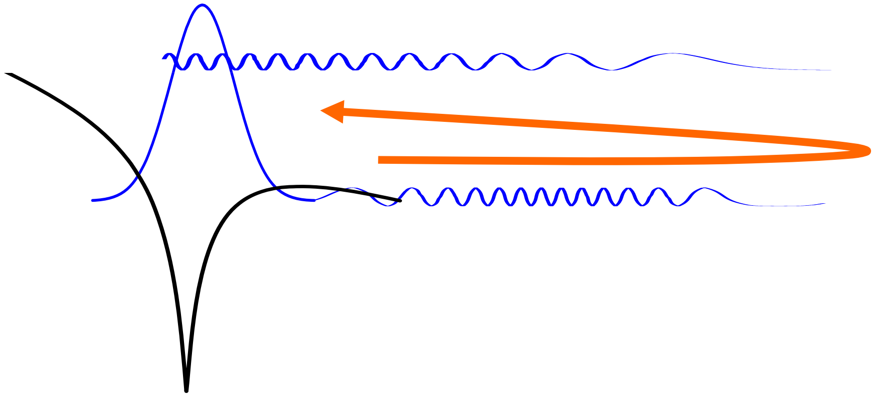




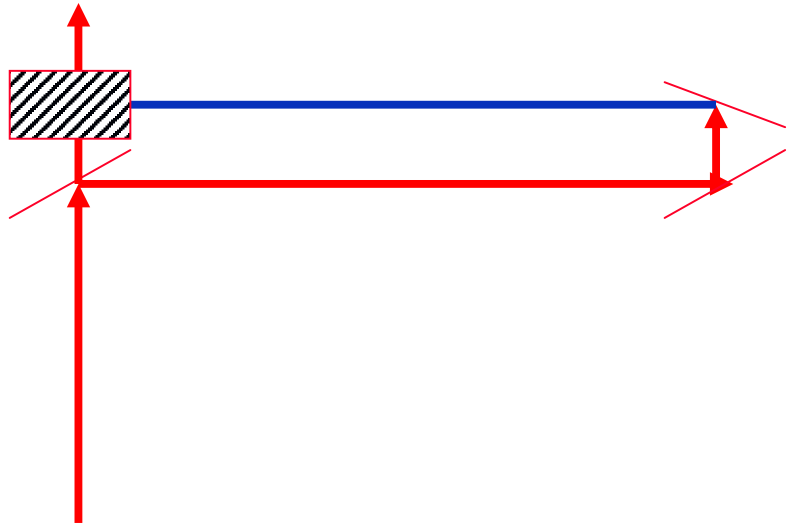
Group of S. Hell, Nature, **440**, 04592, 2006



Quantum Interference: the essence of Atto-science



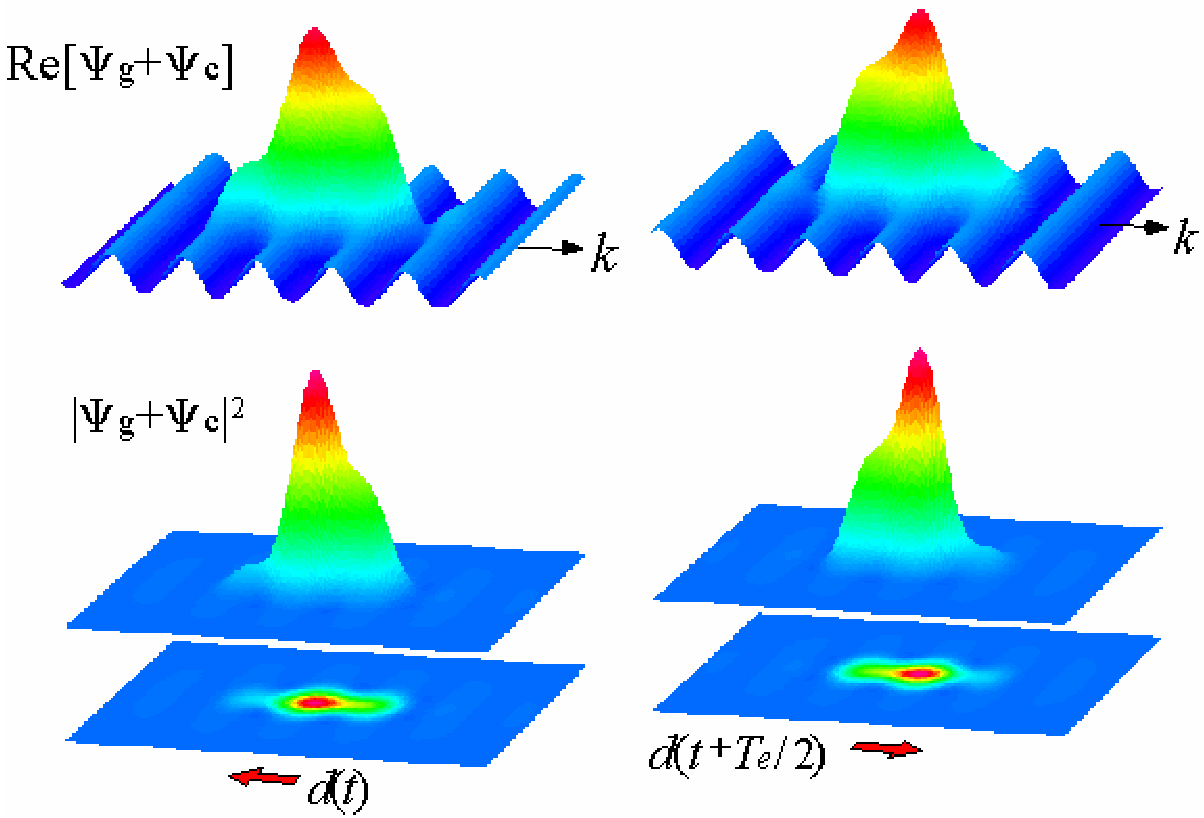
Electron interferometer



Optical interferometer

Interferometers allow us to determine everything about the waves involved AND TO CONTROL THEM.

Reading the interferometer-
High Harmonics/Attoseconds pulses



Modifying the Amplitude or phase of the re-collision electron modifies the light *through d(t).*

$$d(t)=\{\int \Psi e r\, a(k) e^{ikx}\, d^3r\} e^{(IP+KE)t}$$

ω

Photoelectron spectroscopy in reverse

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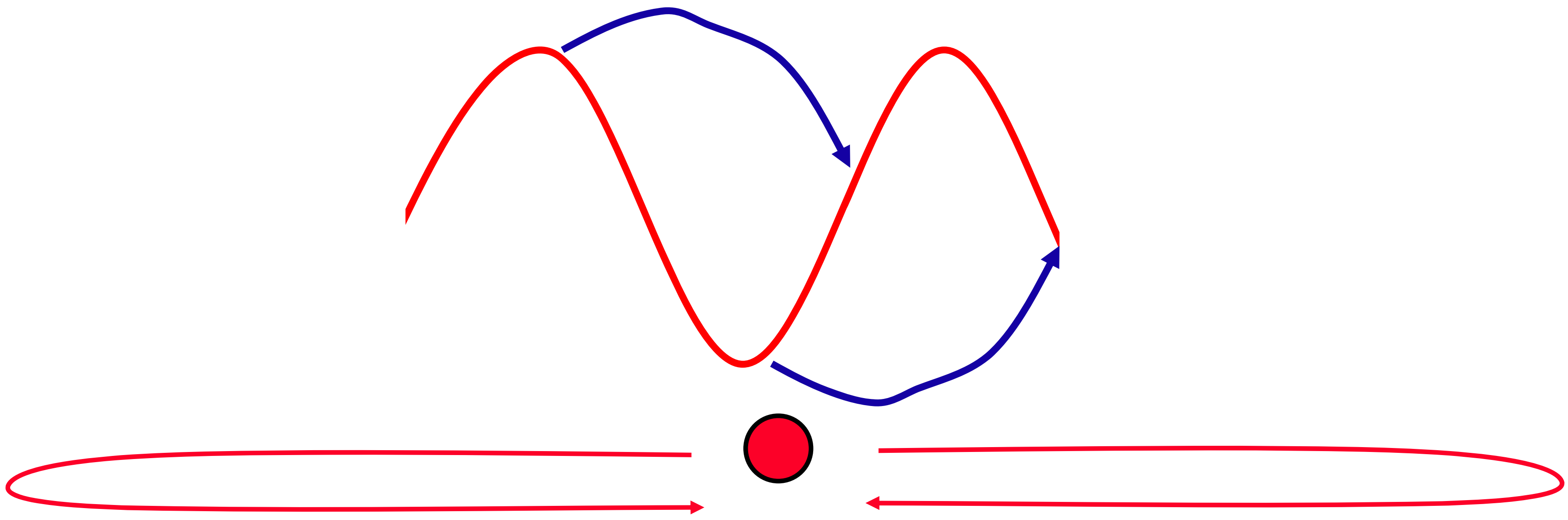
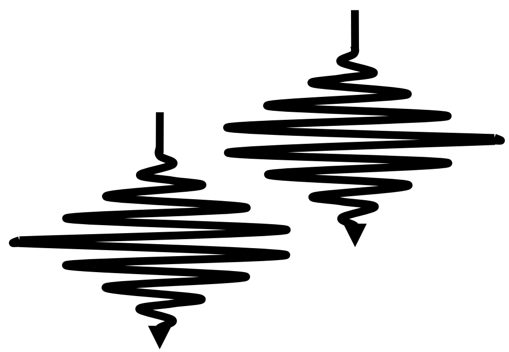
A multi-cycle laser pulse produces a train of attosecond pulses



If one:

Single attosecond pulse

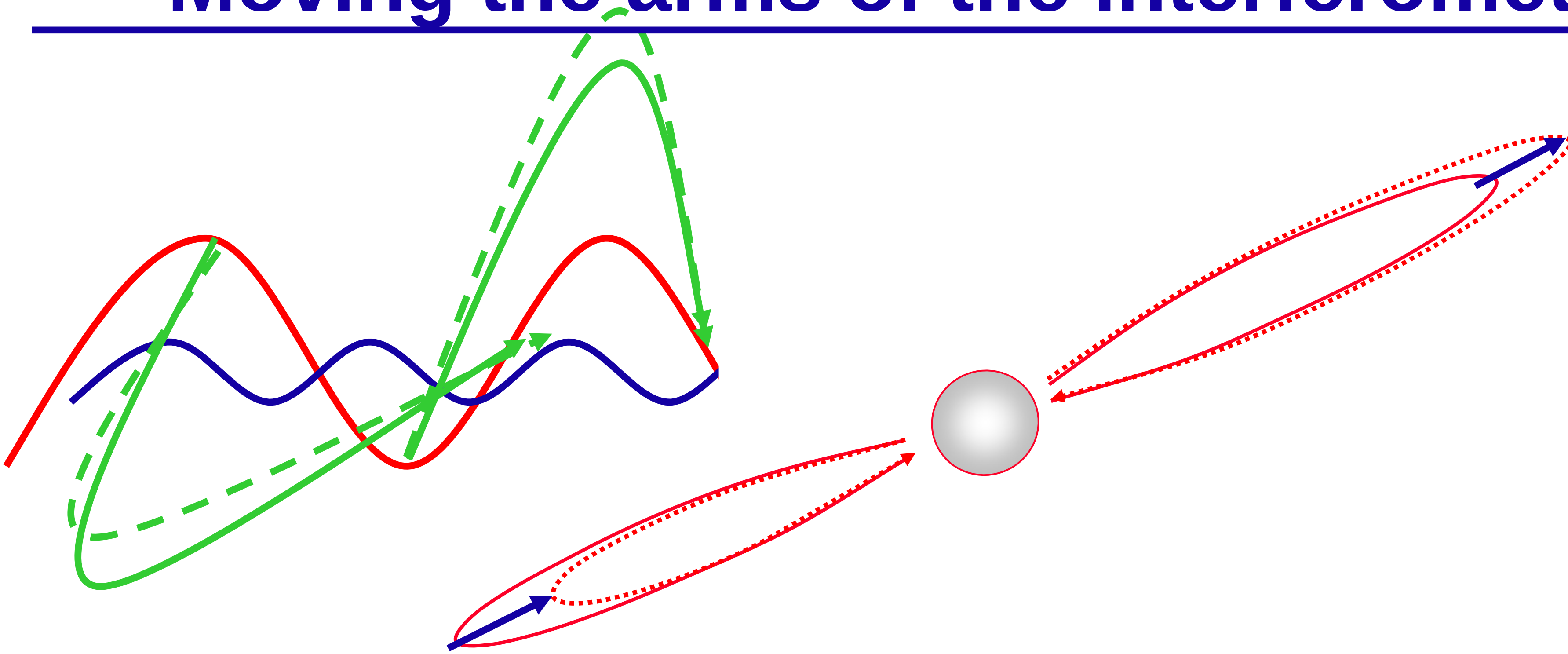


If more than one:

Train of attosecond pulse

Quantum Interferometers are everywhere

Measuring the duration of attosecond pulses --- Moving the arms of the interferometer



A (weak) 2ω field breaks symmetry, generating even harmonics

Each moment of birth (re-collision) has an optimum phase difference (θ) between ω and 2ω

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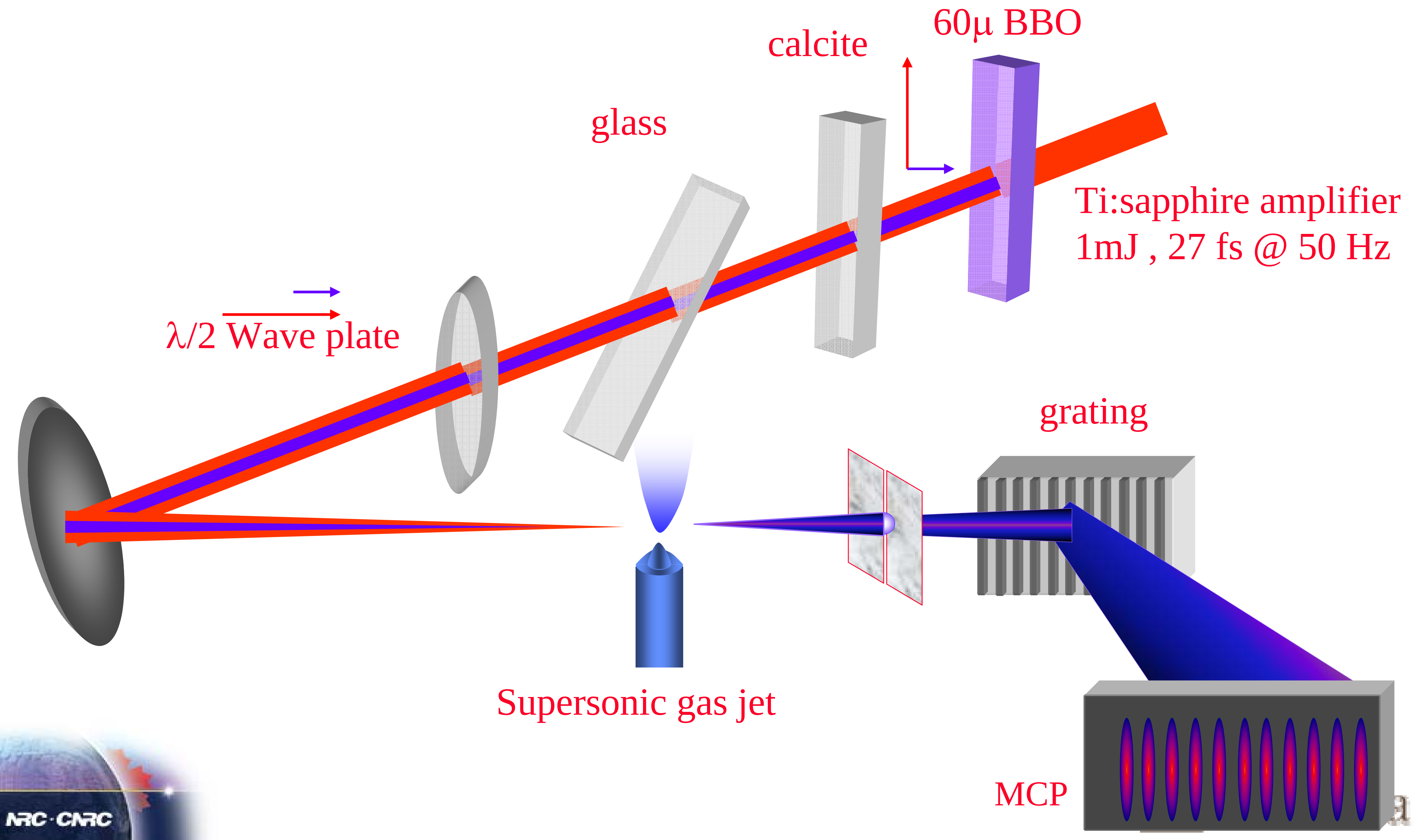
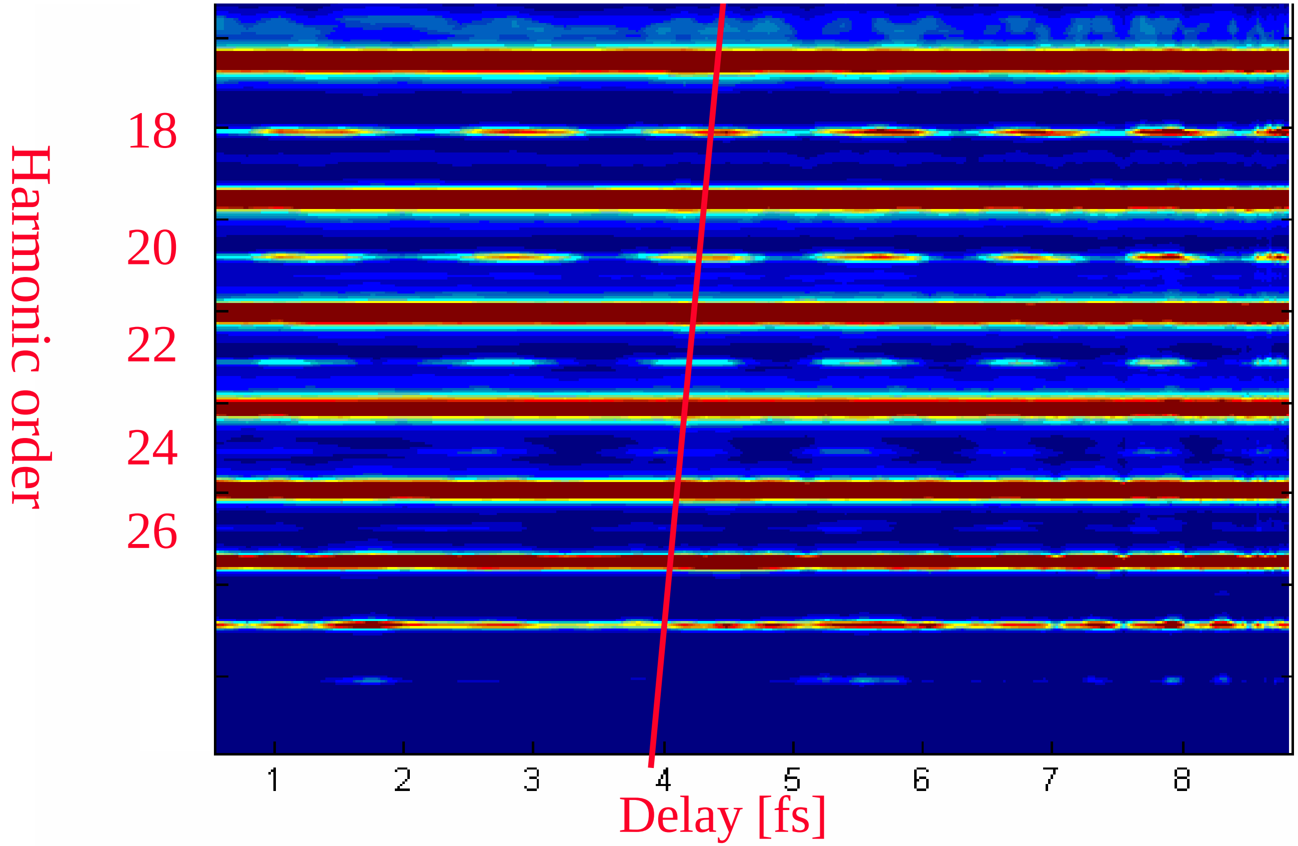
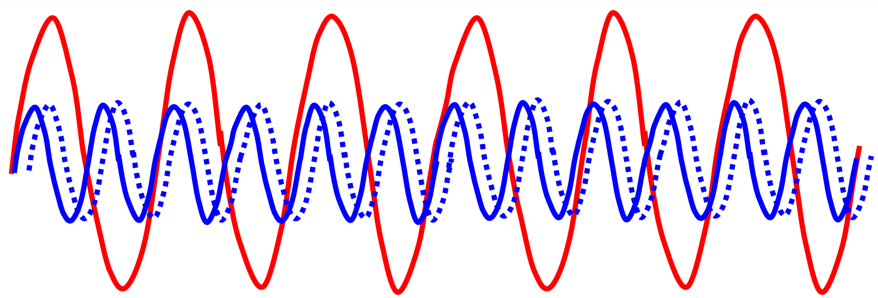
Experimental Set-Up

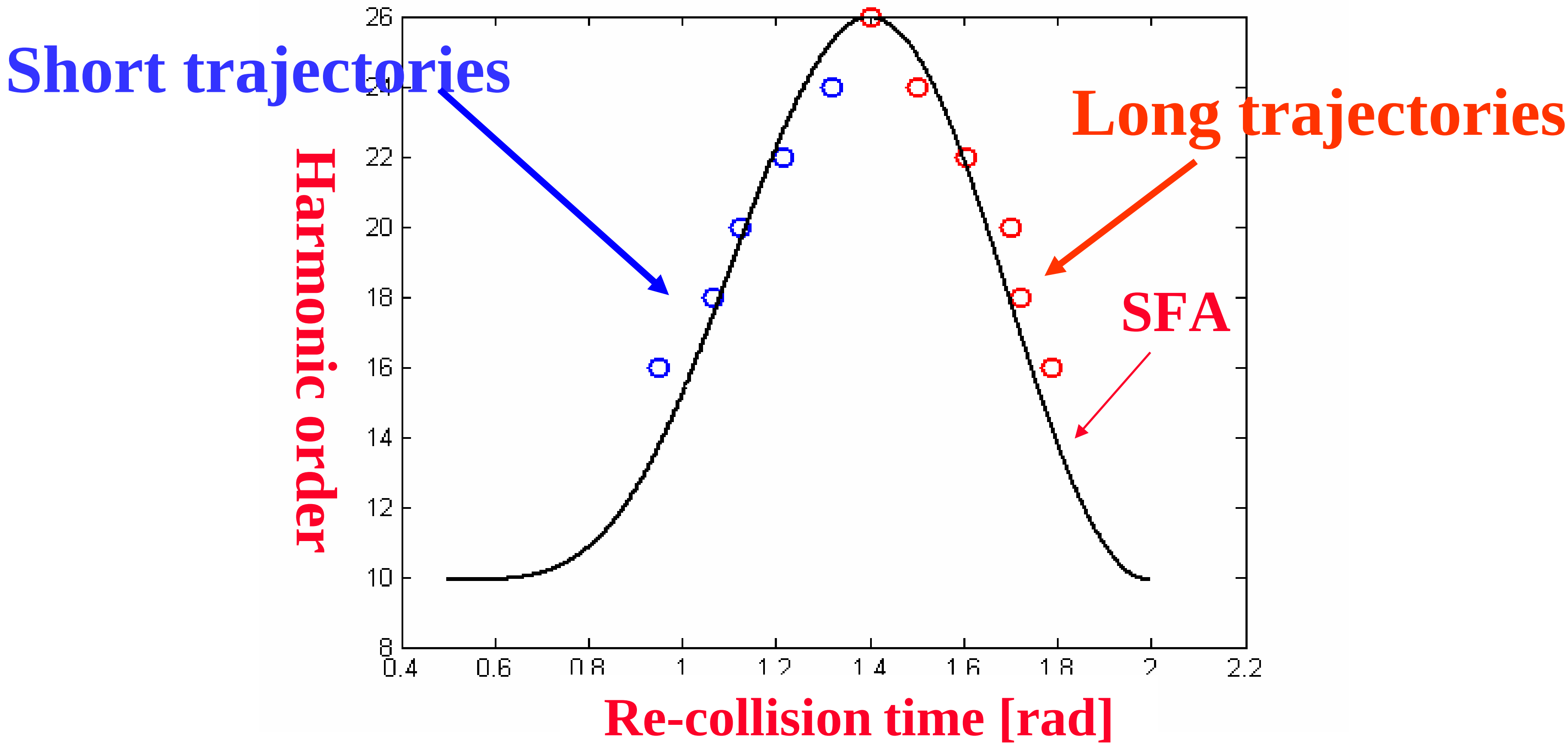


What Phase difference moves the interferometer arms optimally?





Attosecond Pulse Reconstruction



Electron wave packet measurement is equivalent to a ***xuv pulse measurement*** up to the transition dipole.

Highly nonlinear processes are unique. They are hardly changed by adding another photon.

Yet, the second field can serve as a gate --- an amplitude or phase gate. eg

1. **Ellipticity.**
2. **2ω field or either polarization.**
3. **Another fundamental beam.**

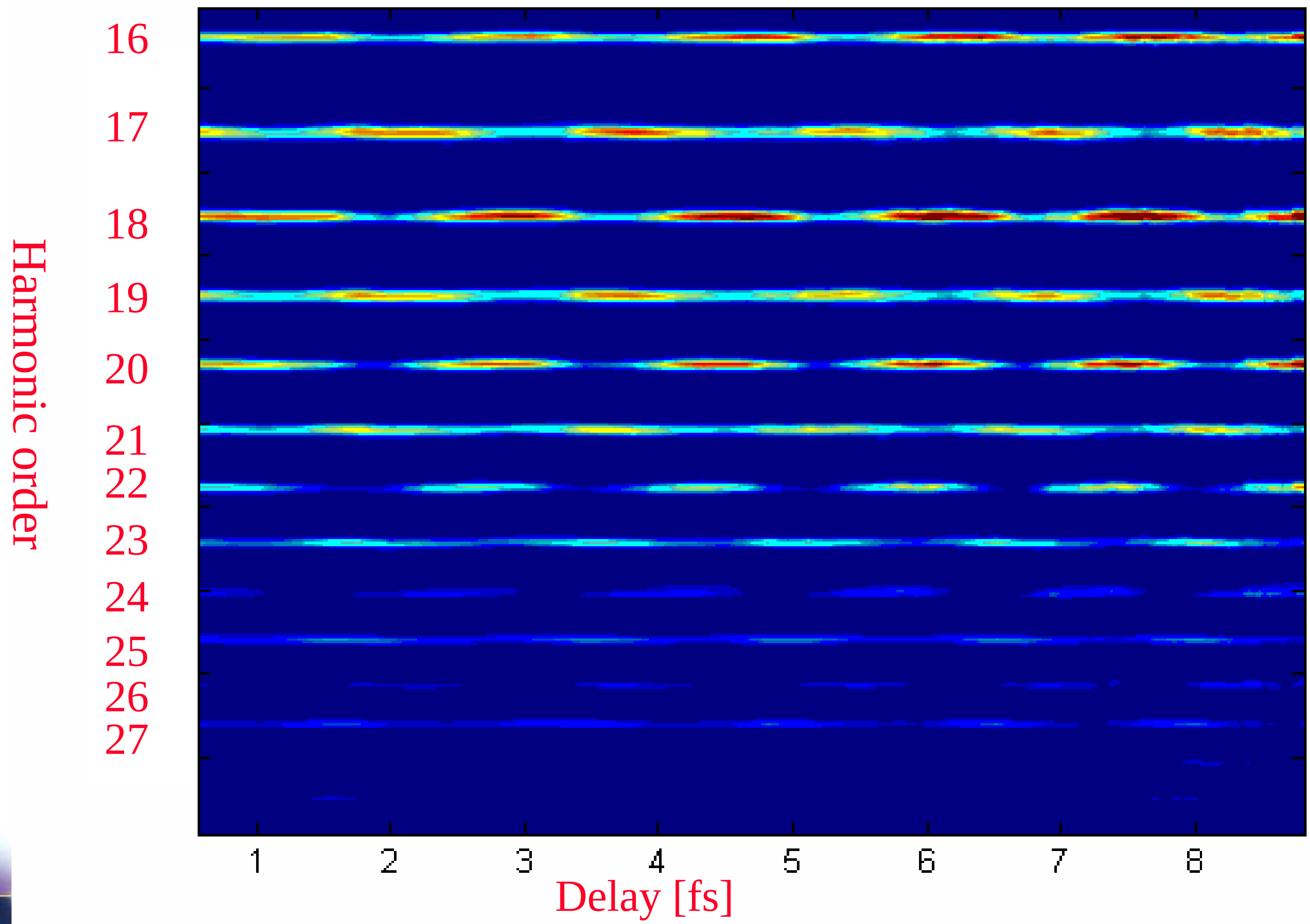
We can apply gating to re-collision physics –

Leading to optical-quality real-time *measurements.*

Even measuring dynamics of the nucleus

From measurement to control

Increasing 2ω intensity



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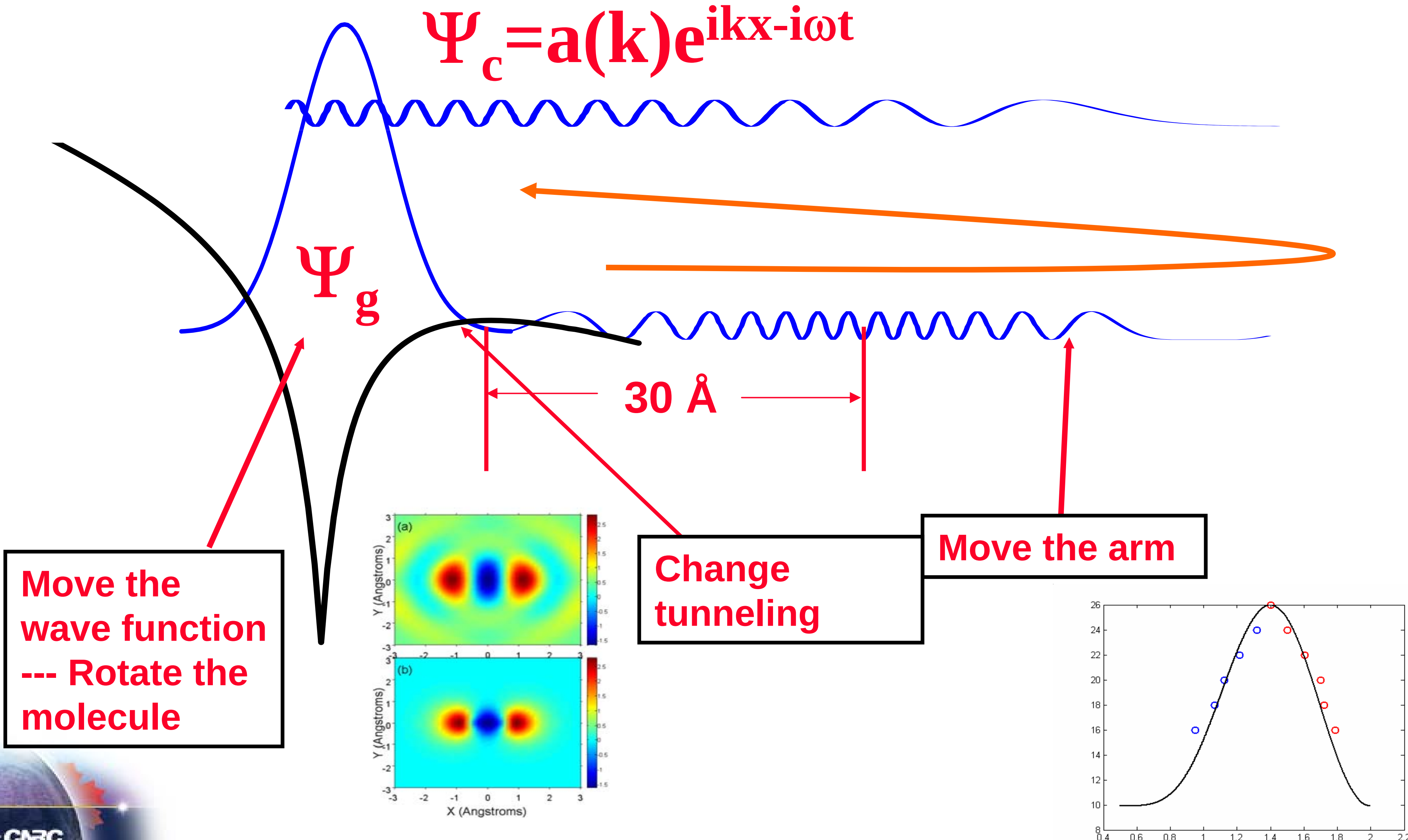
We can construct any device based on phase

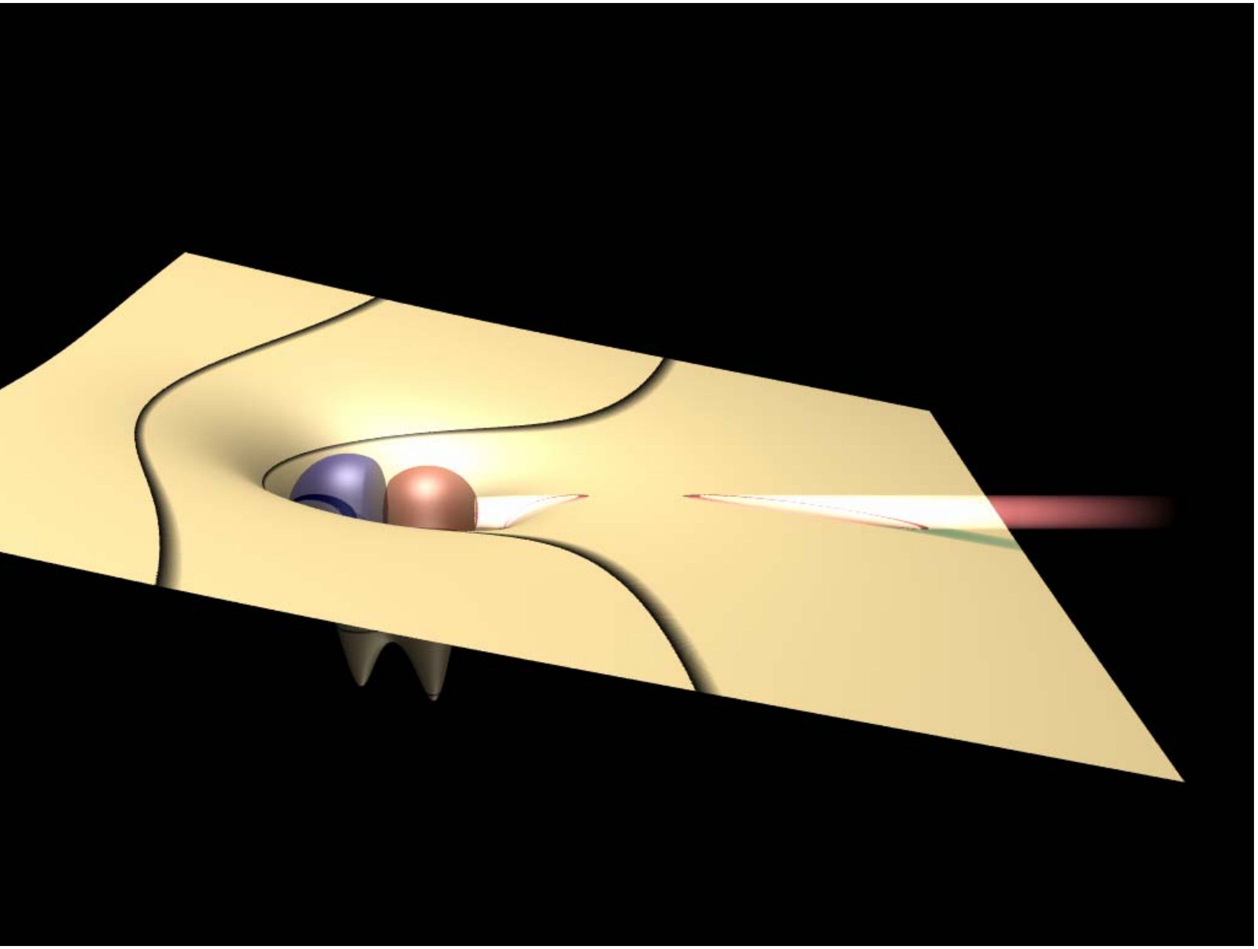
-Lenses
-prisms
-Digital optics

Controlled by fundamental or a harmonic

Ways to Control the interferometer



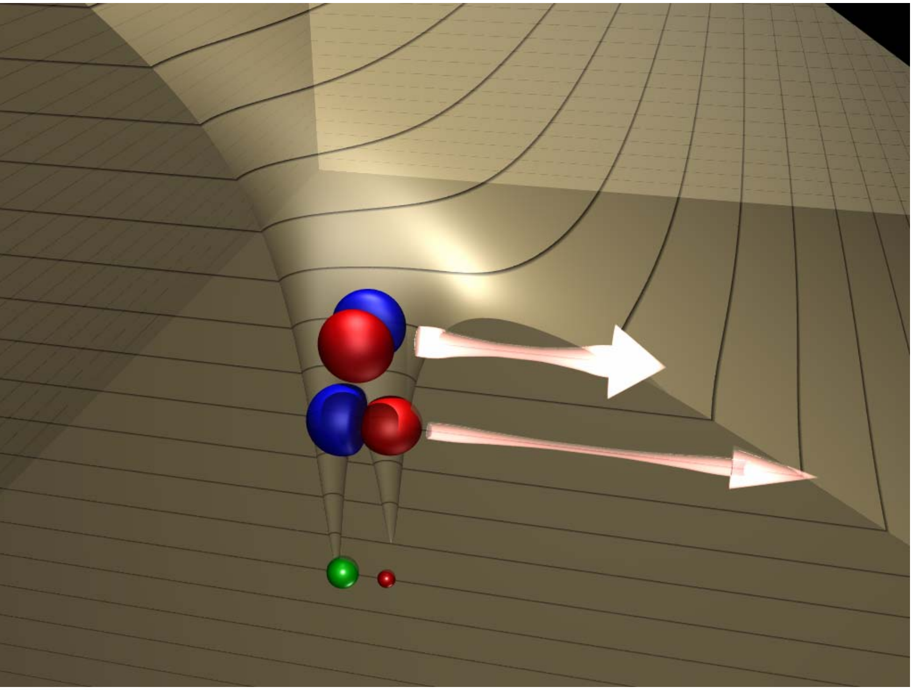
Change tunneling: Many optimal control experiments begin with ionization



- Multiple orbitals can contribute to ionization
- The probability of both ionization and recollision changes with angle

Implications of tunneling:

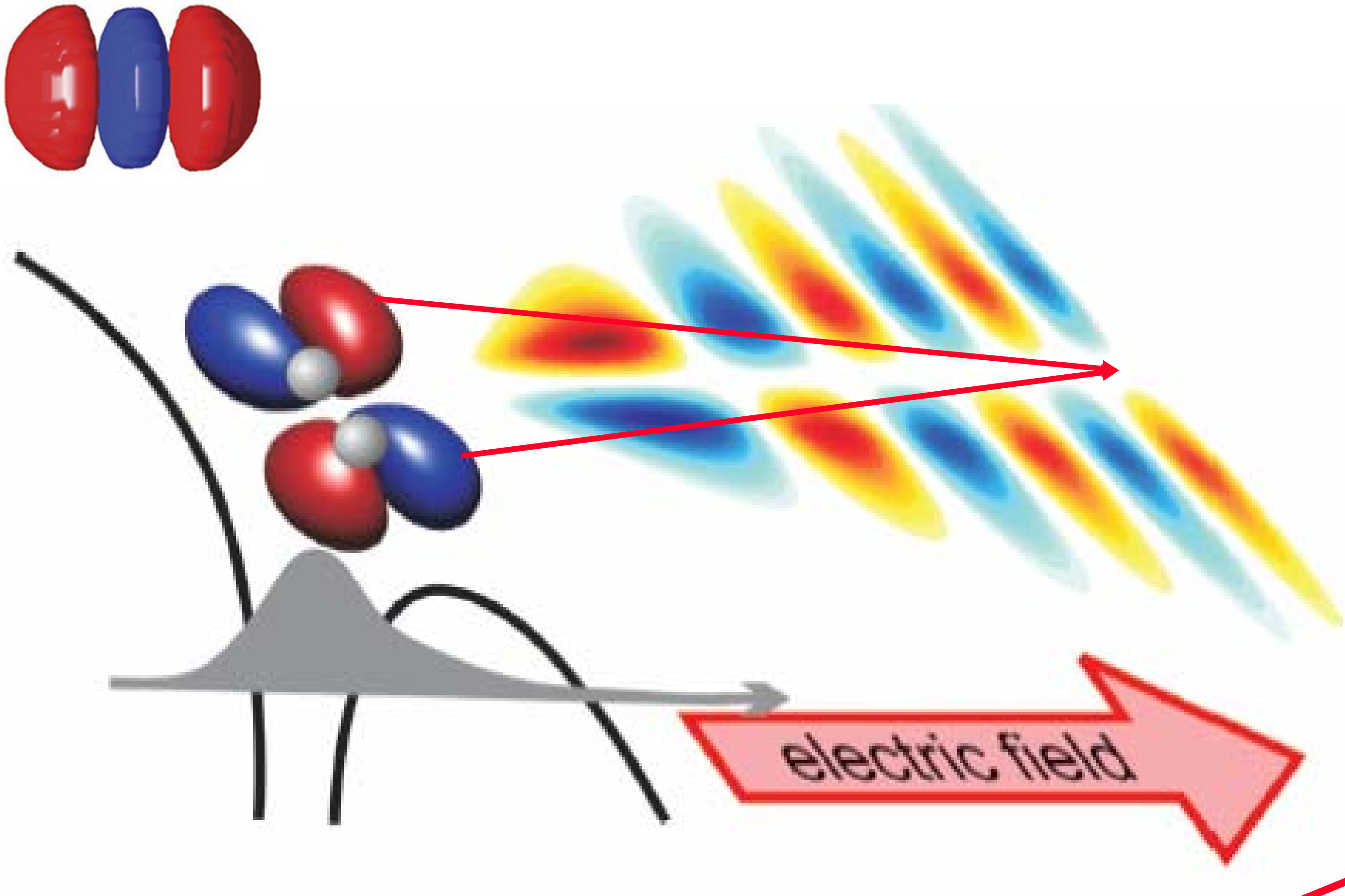
$$\omega(t) = 4\omega_0 \left[\frac{E_i}{E_h}\right]^{5/2} \frac{E_a}{E(t)} \exp\left[-\frac{2}{3}\left[\frac{E_i}{E_h}\right]^{3/2} \frac{E_a}{E(t)}\right]$$



The exponent is ~ 10 for 50 fs pulses.

Even orbitals with 30% greater IP than the HOMO ionize significantly.

Quantum interference: Tunnelling and re-collision are angle dependent

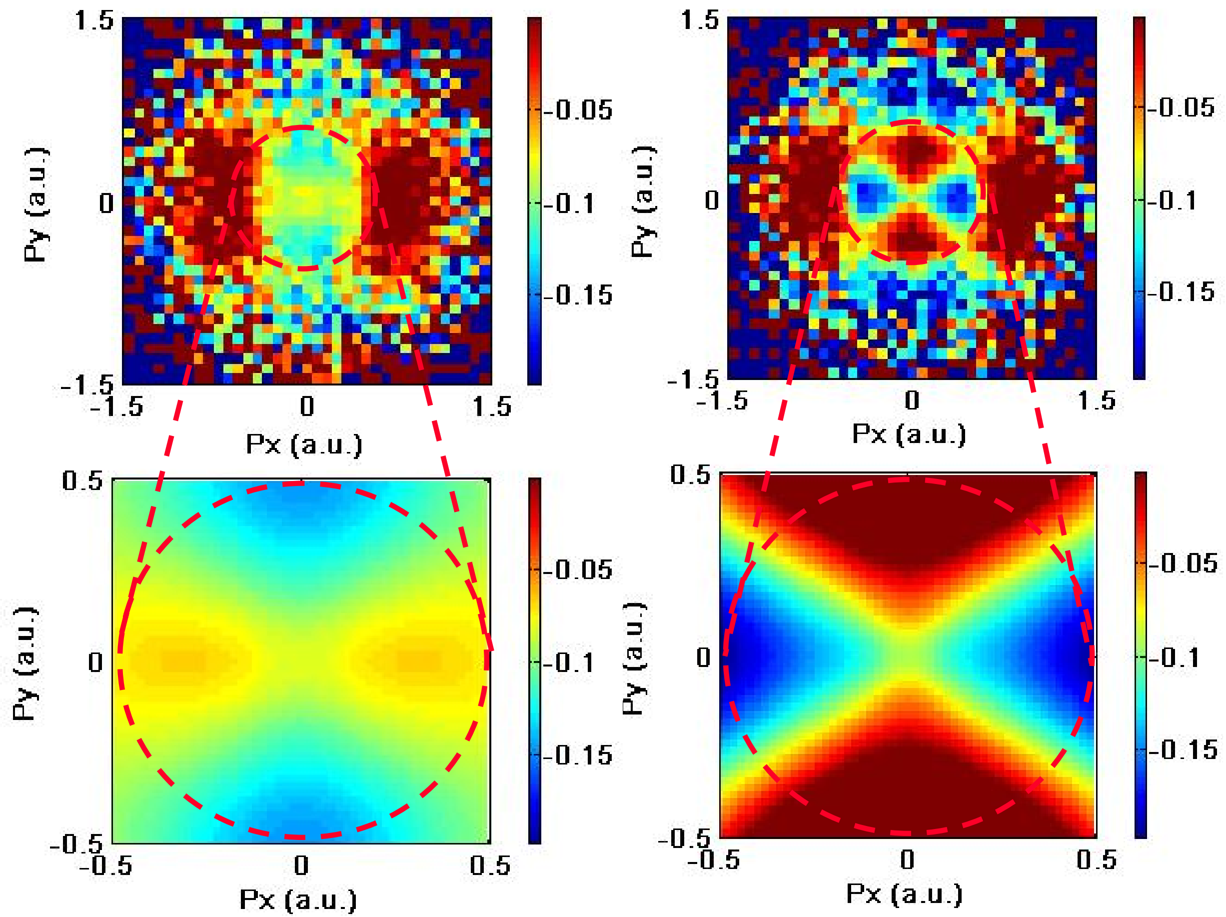


Perpendicular momentum Is "wasted"

$IP_{eff} = IP + p^2_{\perp}/2m$

$$\Psi_c(\theta) = \langle p_\perp | \Psi \rangle \exp\left[-\frac{p_\perp^2 \sqrt{IP}}{E\sqrt{2}} \right]$$

Low Lateral momentum electrons



The ionization and re-collision probability are strongly angle dependent.

Extreme Nonlinear Optics -- recollision:

A new frontier of spectroscopy

- A mixture of optical and collision science

- The mixture offers new opportunities for each

To optics -- *Angstrom spatial imaging.*

To collision physics -- *Time resolution*.

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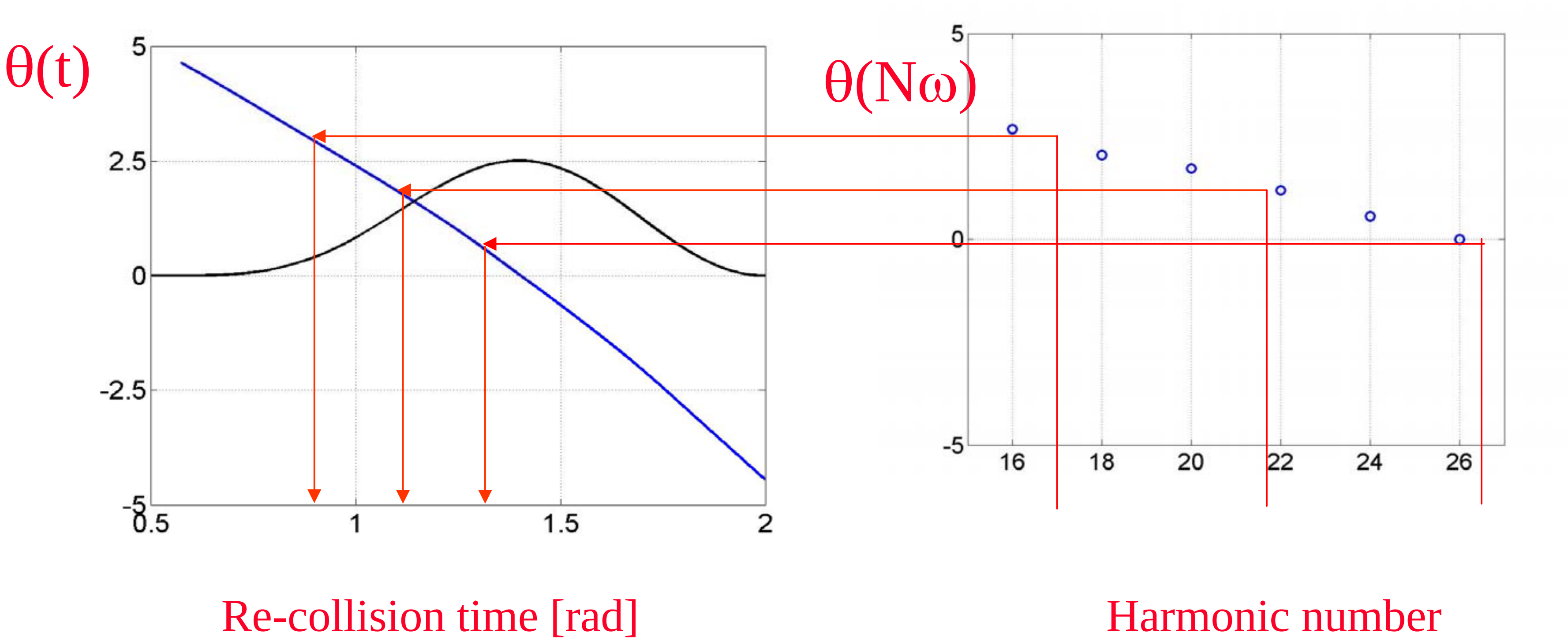
NRC's Atto-group 2008

Nirit Dudovich Yann Mairesse

Attosecond Temporal Phase Gate

$$d_{\omega,2\omega}(t) \sim d_{\omega}(t)\, \boxed{e^{\,i\sigma(t)}}$$

SFA



θ: two color delay which maximizes the even harmonic signal