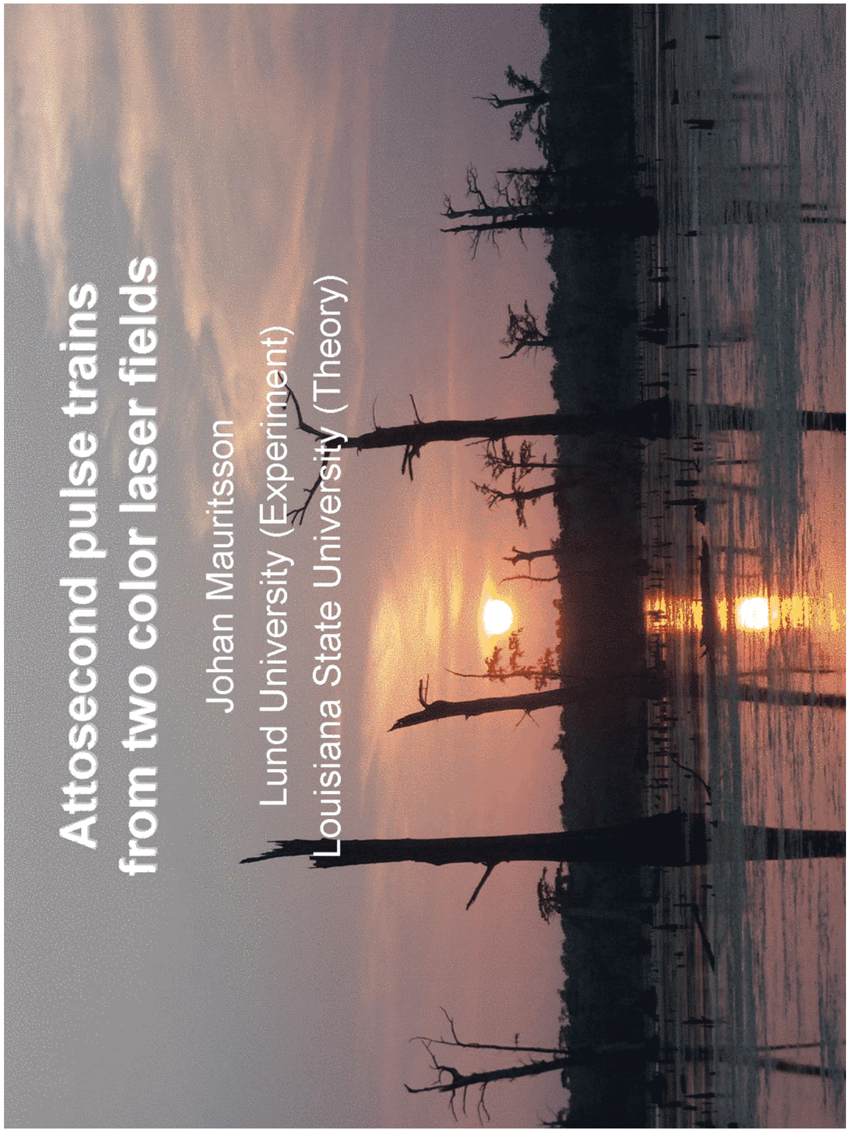

Outline

- APTs from 1ω-2ω source
  - *One pulse per IR cycle*
  - *phase stabilized few cycle XUV pulses*
- 3D electron wave packet control
- Strong field physics in a new regime

Acknowledgements

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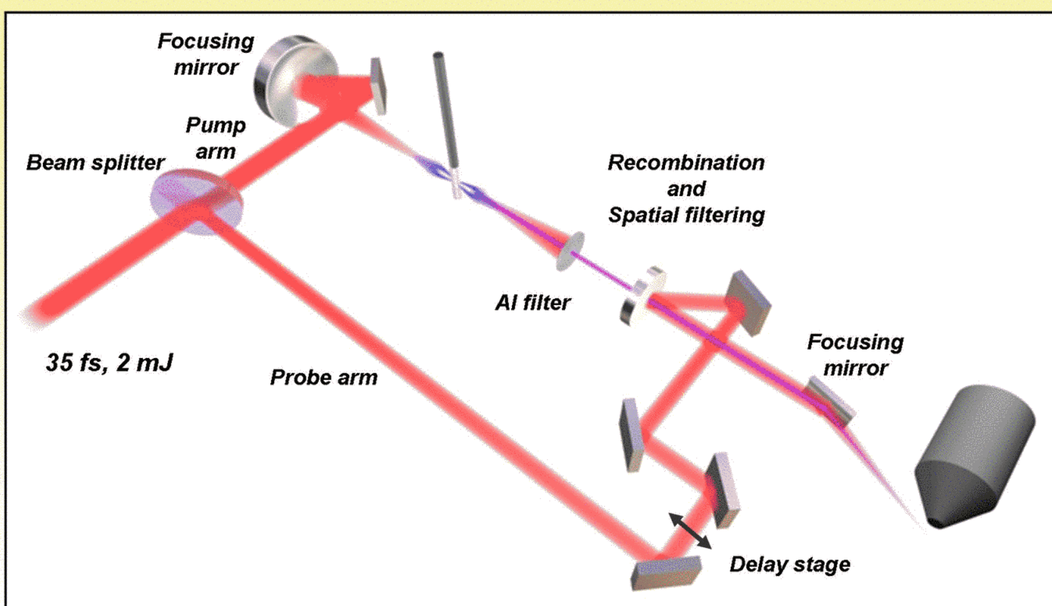
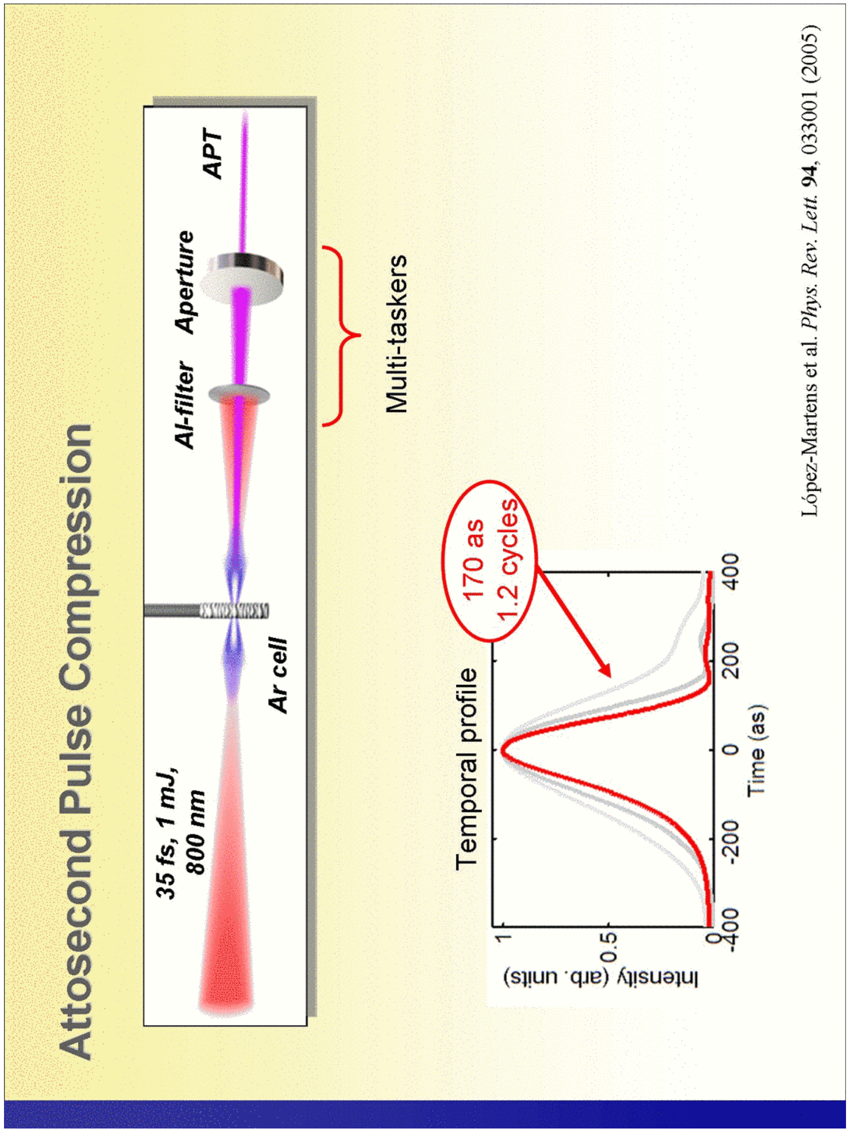
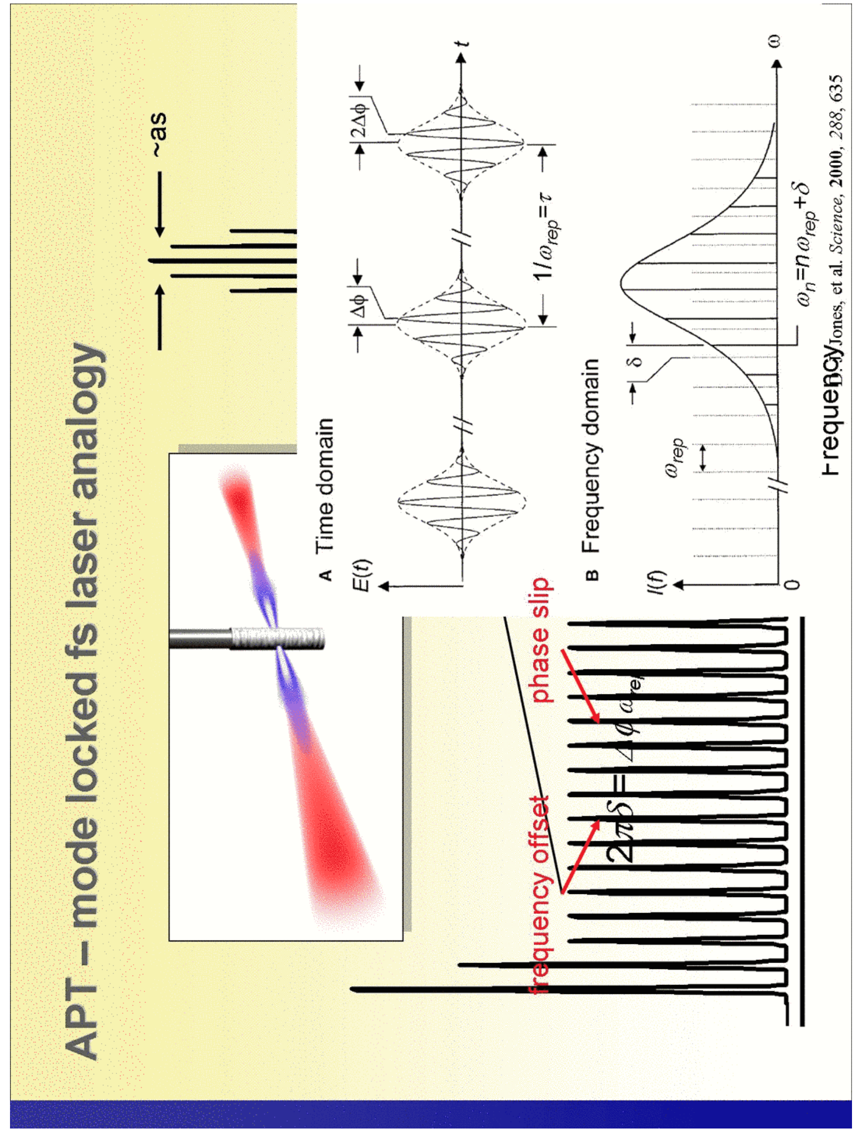
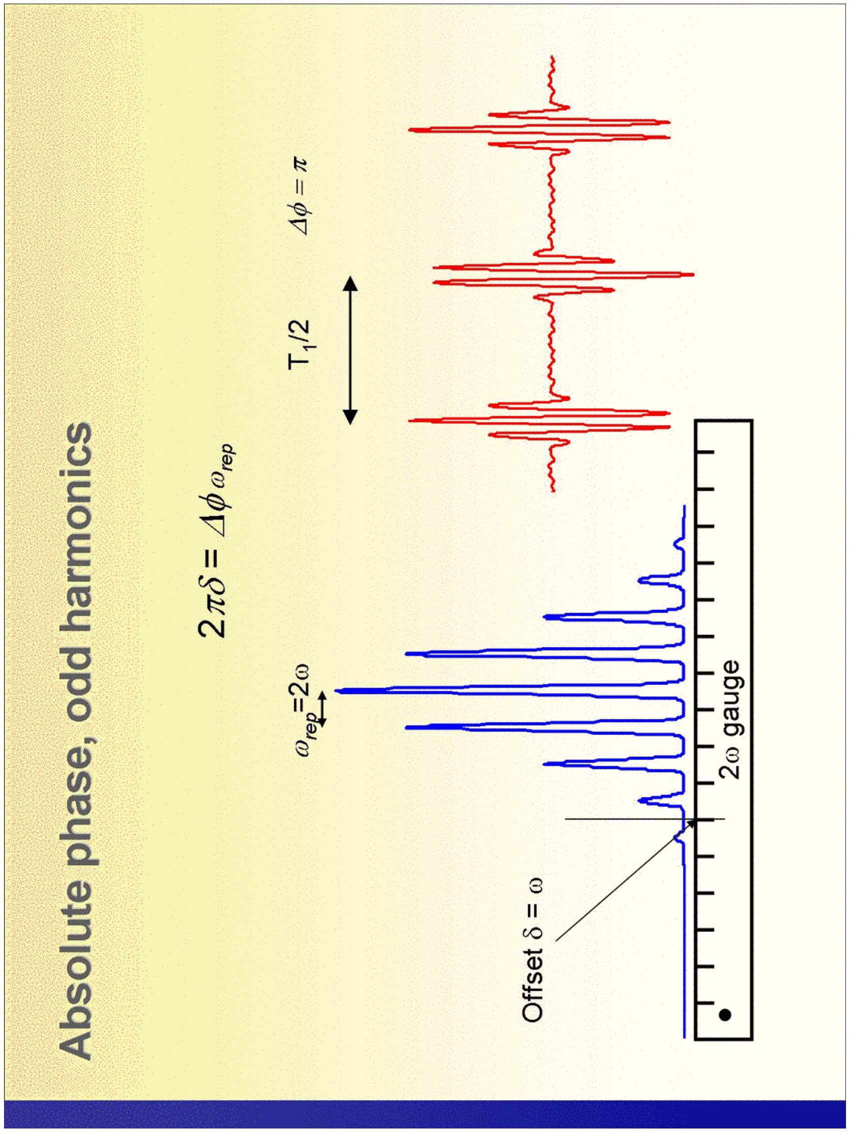
Marc Vrakking

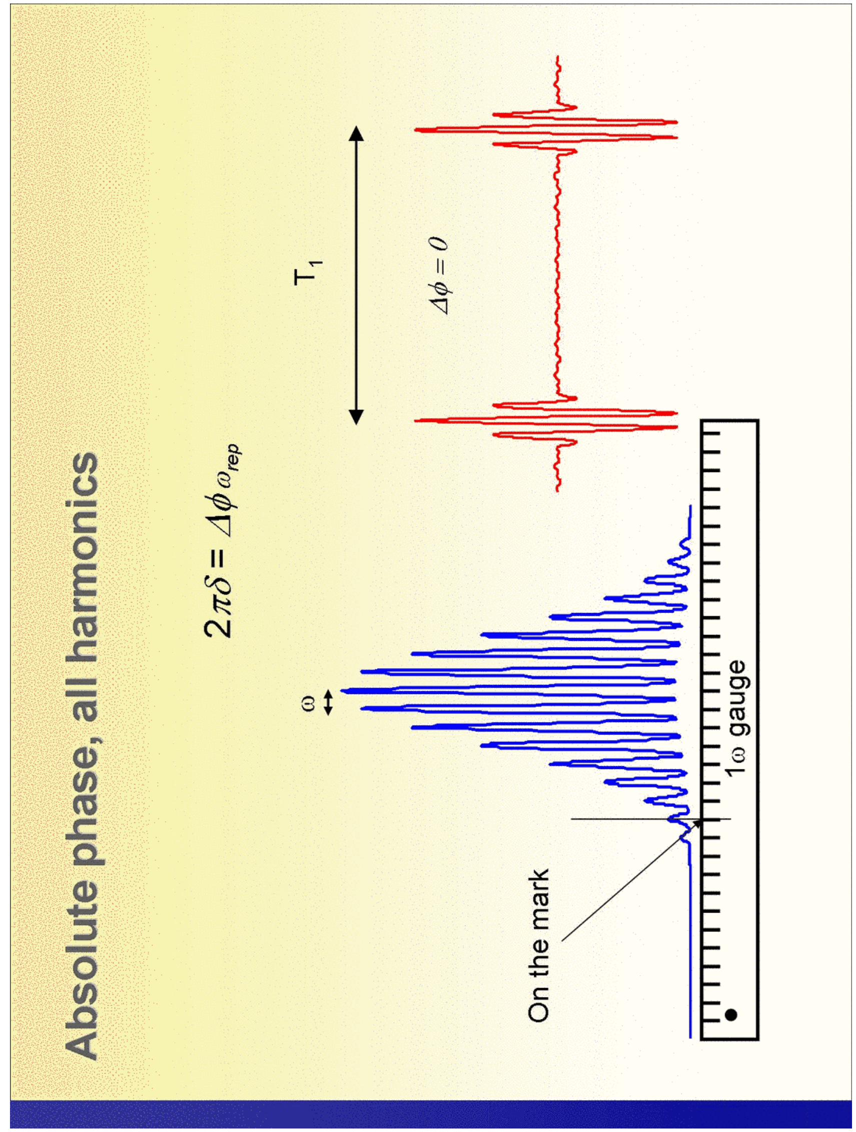
Experimental set-up



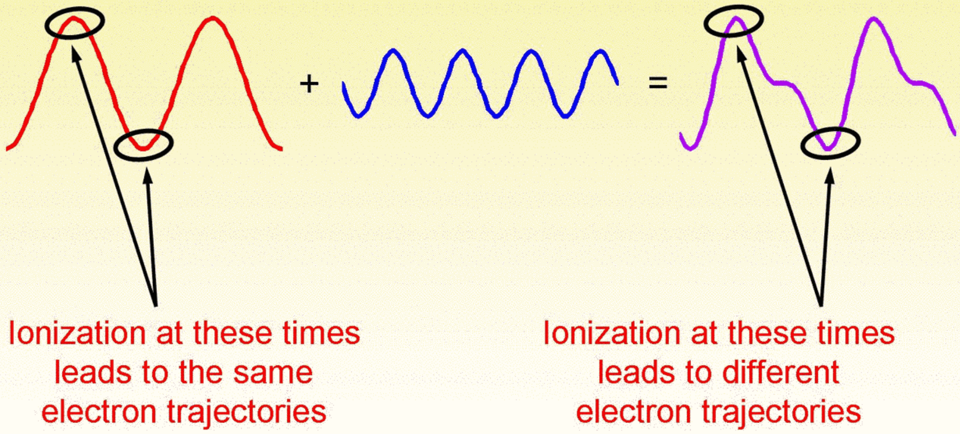

Attosecond Pulse Compression
35 fs, 1 mJ, 800 nm
Ar cell
Al-filter
Aperture
APT
Multi-taskers
Temporal profile
170 as
1.2 cycles
Intensity (arb. units)
Time (as)
López-Martens et al. Phys. Rev. Lett. 94, 033001 (2005)


APT – mode locked fs laser analogy
~as
A Time domain
E(t)
Δϕ
2Δϕ
$1/\omega_{rep}=\tau$
B Frequency domain
I(f)
ω_{rep}
δ
$\omega_n=n\omega_{rep}+\delta$
Jones, et al. Science, 2000, 288, 635
Frequency
frequency offset
phase slip


Absolute phase, odd harmonics
$2\pi\delta = \Delta\phi\,\omega_{rep}$
$\omega_{rep}=2\omega$
$T_1/2$
$\Delta\phi = \pi$
Offset $\delta = \omega$
2ω gauge


Absolute phase, all harmonics
$2\pi\delta = \Delta\phi\,\omega_{rep}$
ω
T_1
$\Delta\phi = 0$
On the mark
1ω gauge

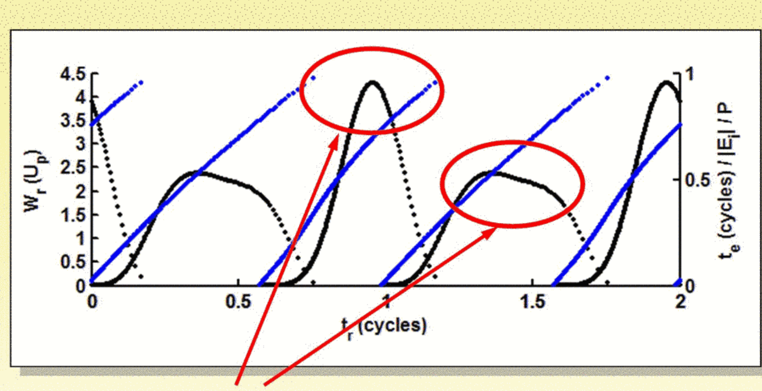
Breaking inversion symmetry adds control



M. D. Perry et al., *Phys. Rev. A* ***48***, *R4051 (1993)*
H. Eichmann et al., *Phys. Rev. A* ***51***, *R3414 (1995)*
I. J. Kim et al., *Phys. Rev. Lett.* ***94***, *243901 (2005)*

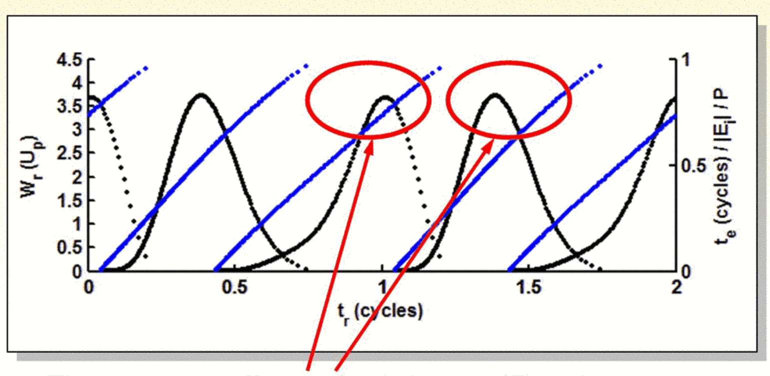
Classical Trajectories

IR/Blue
phase difference
φ=0

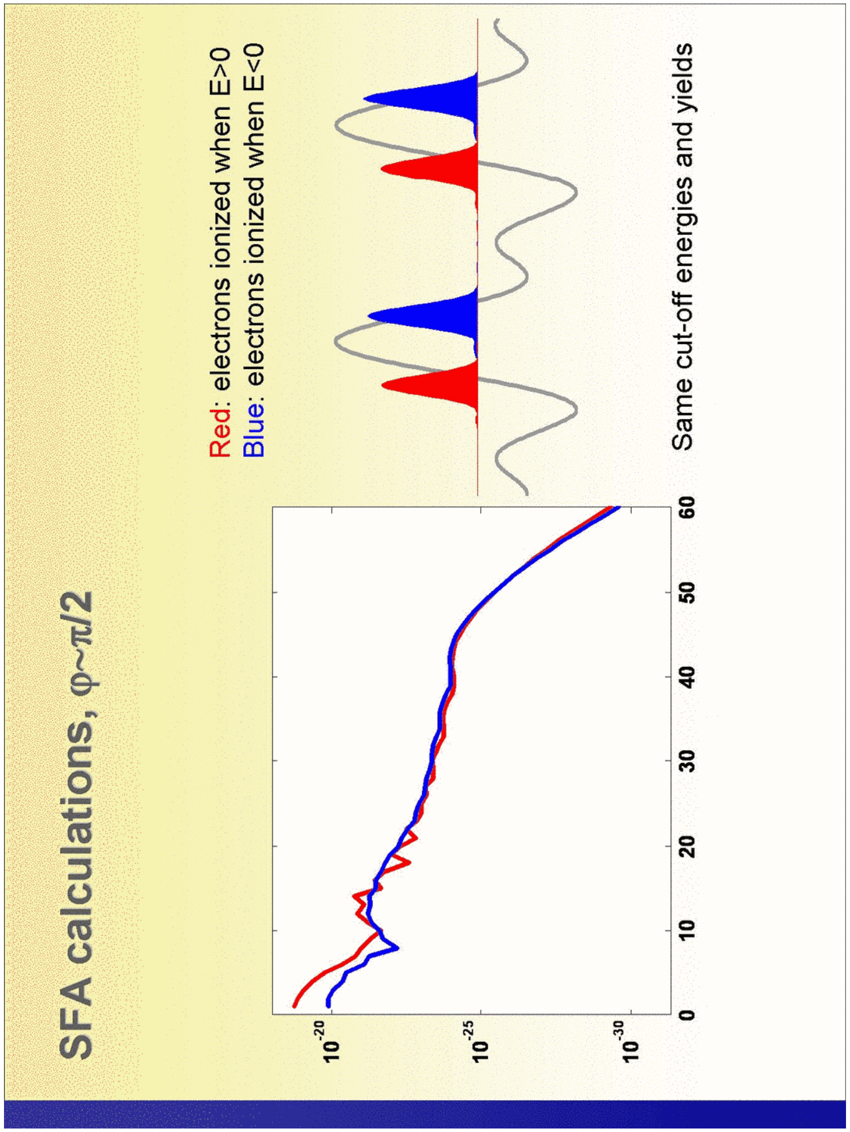


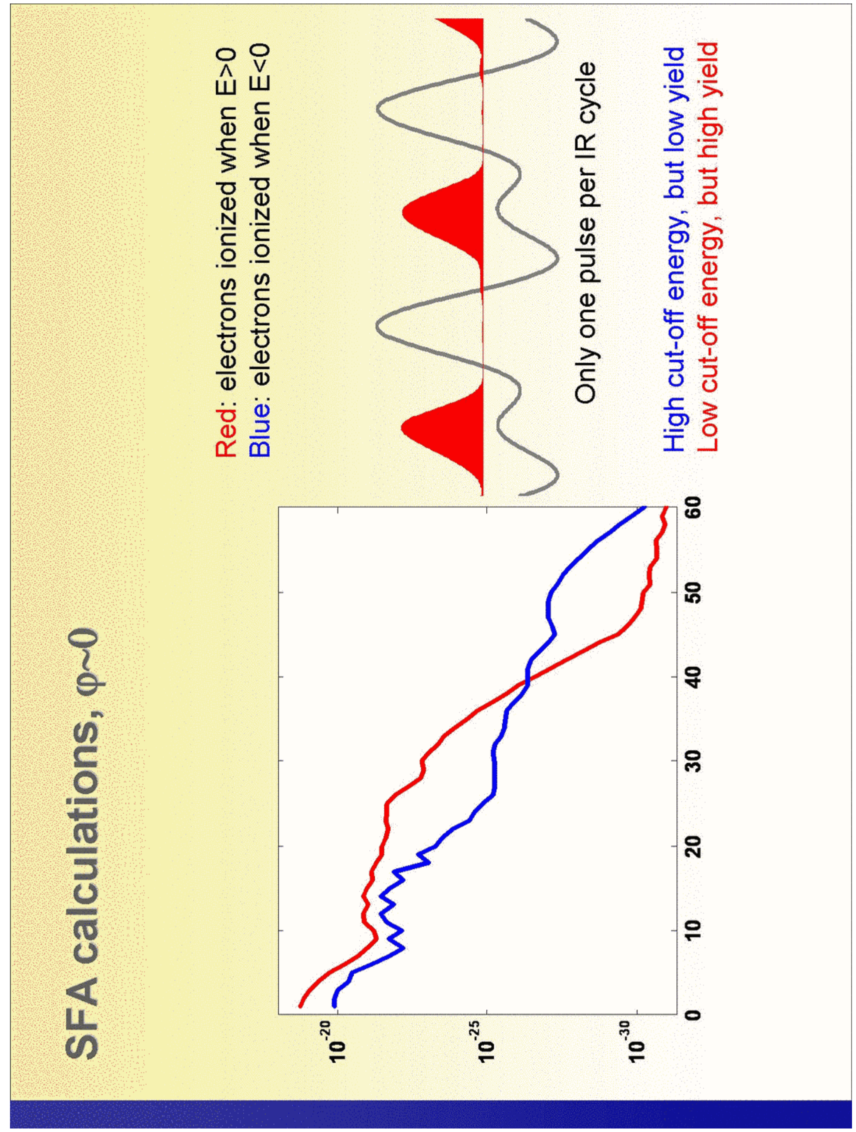
Two different cut-off energies per IR cycle

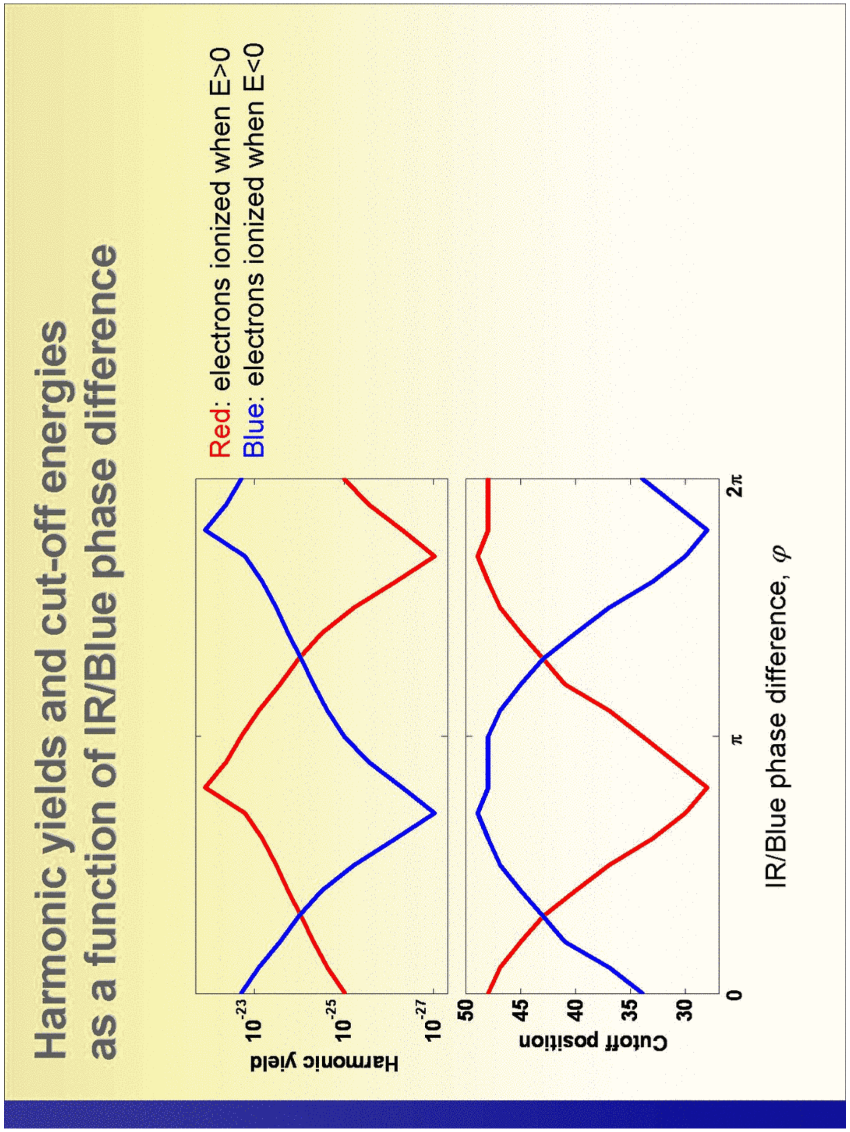
IR/Blue
phase difference
φ=π/2

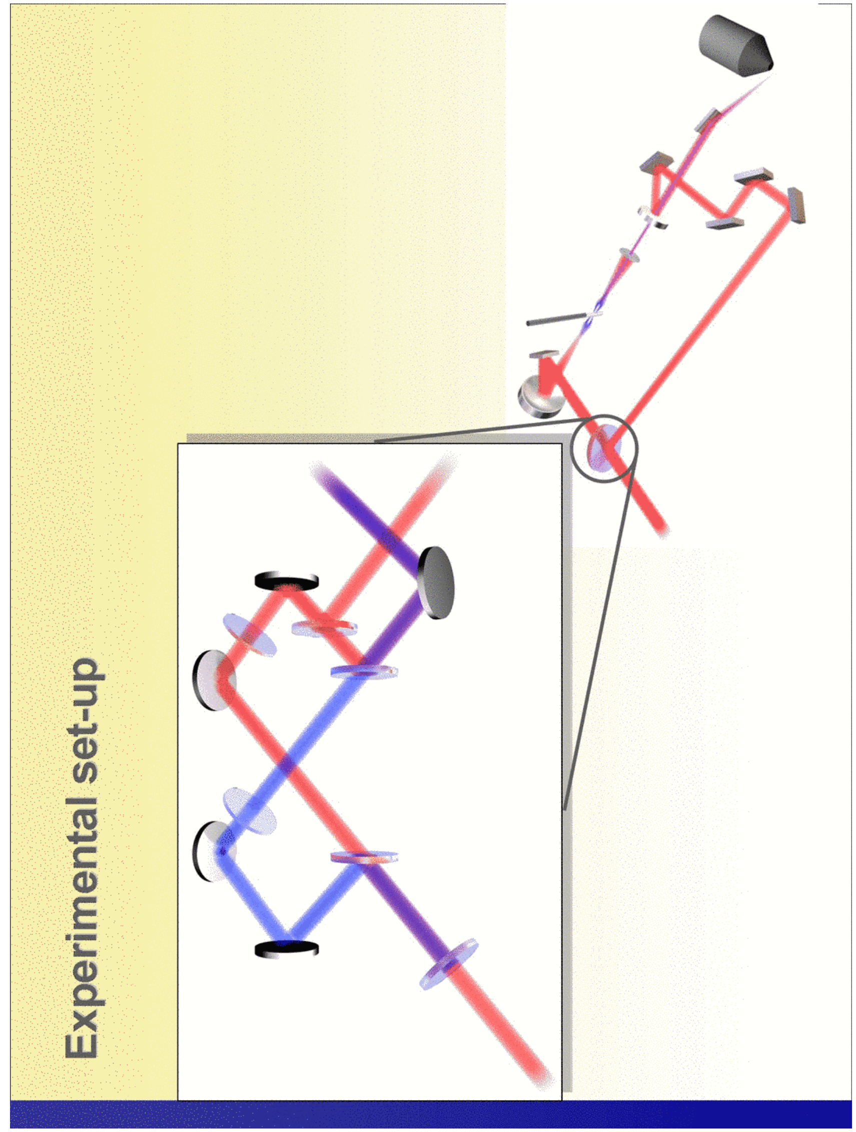


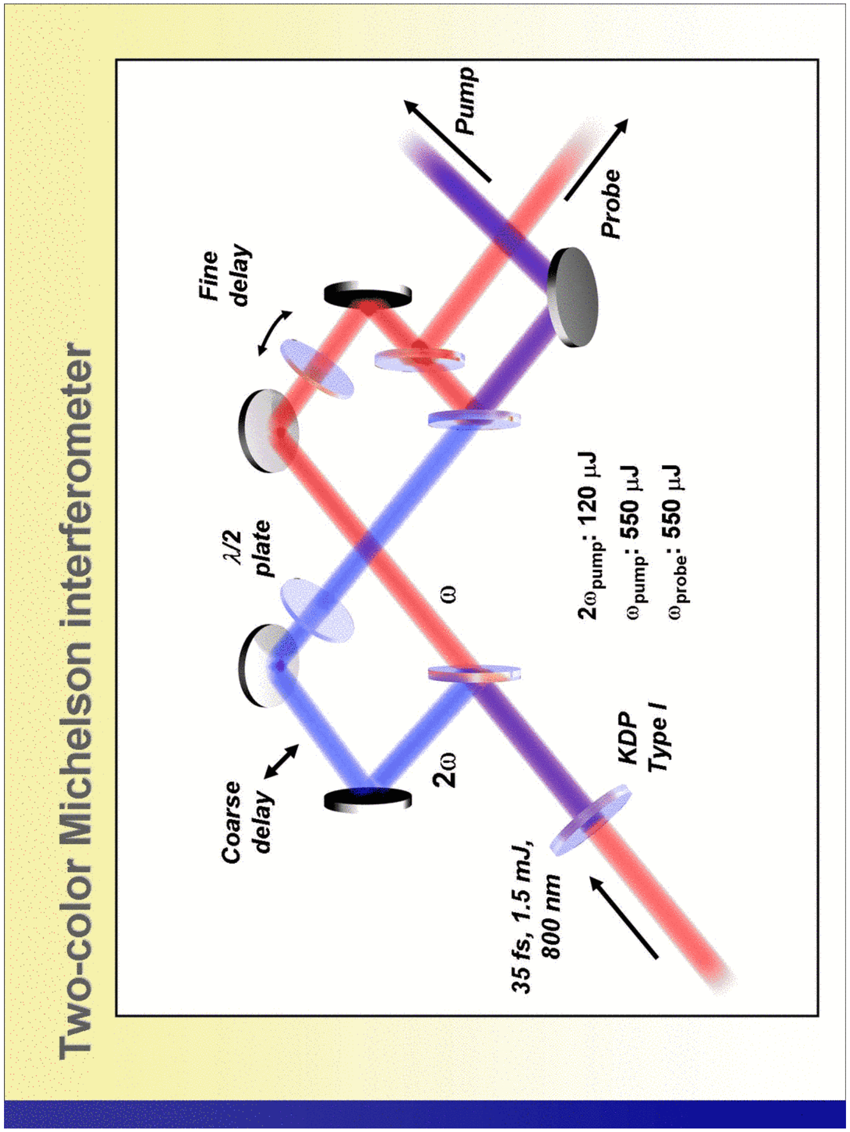
The same cut-off energies twice per IR cycle

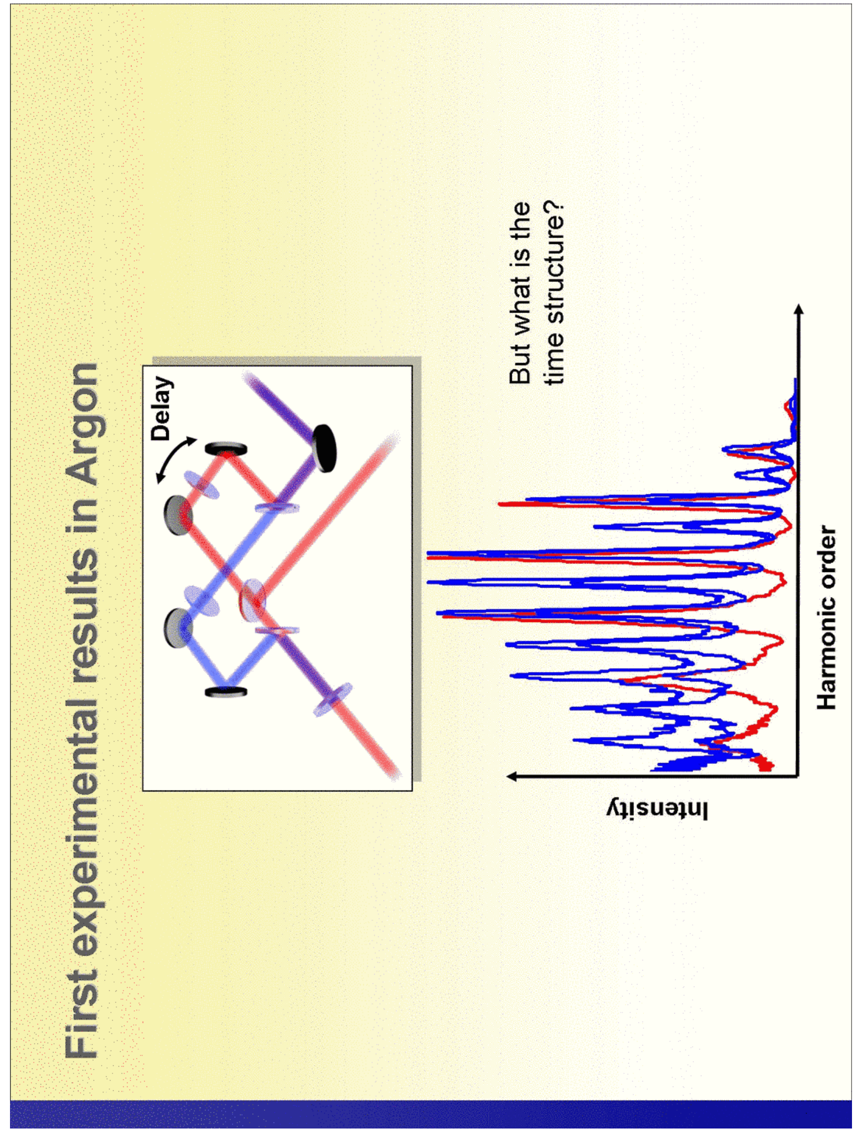

SFA calculations, φ~π/2
Red: electrons ionized when E>0
Blue: electrons ionized when E<0
Same cut-off energies and yields
10-20
10-25
10-30
0
10
20
30
40
50
60

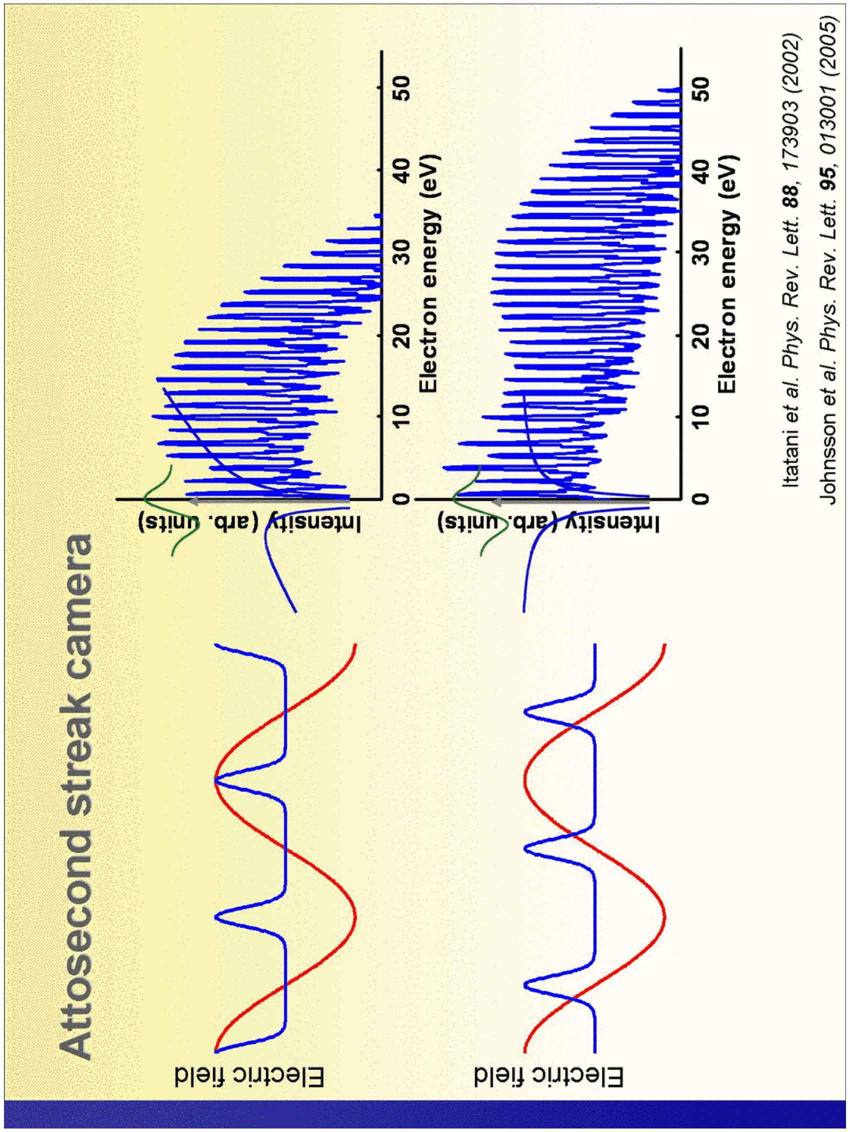

SFA calculations, φ~0
Red: electrons ionized when E>0
Blue: electrons ionized when E<0
Only one pulse per IR cycle
High cut-off energy, but low yield
Low cut-off energy, but high yield
10-20
10-25
10-30
0
10
20
30
40
50
60

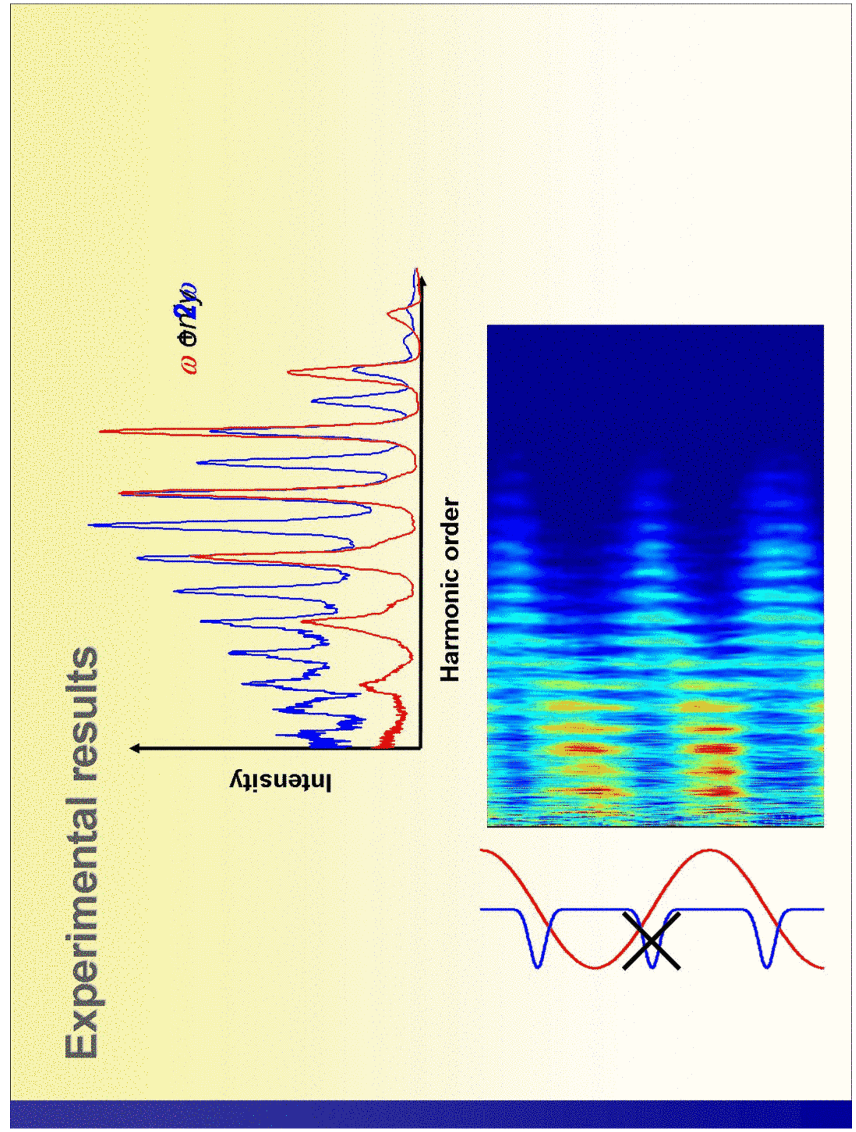

Harmonic yields and cut-off energies as a function of IR/Blue phase difference
Red: electrons ionized when E>0
Blue: electrons ionized when E<0
Harmonic yield
10^-23
10^-25
10^-27
Cutoff position
50
45
40
35
30
0
π
2π
IR/Blue phase difference, φ

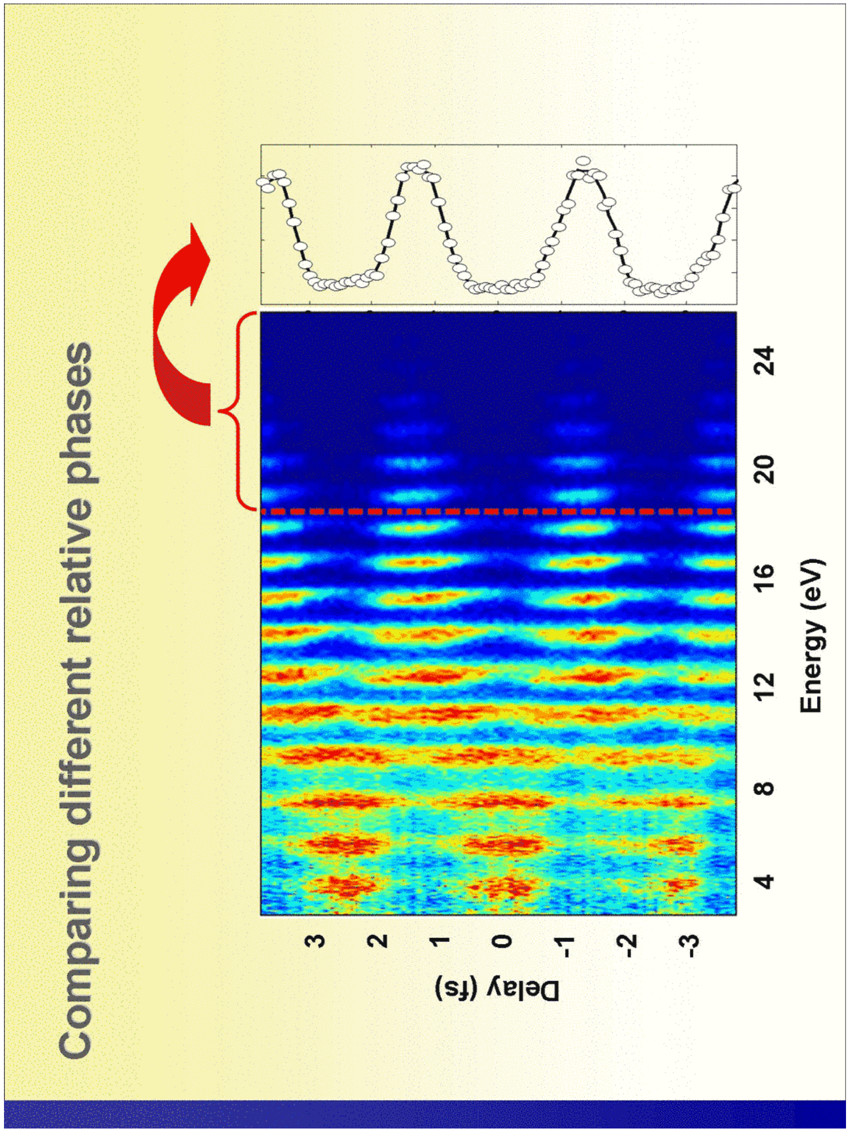

Experimental set-up

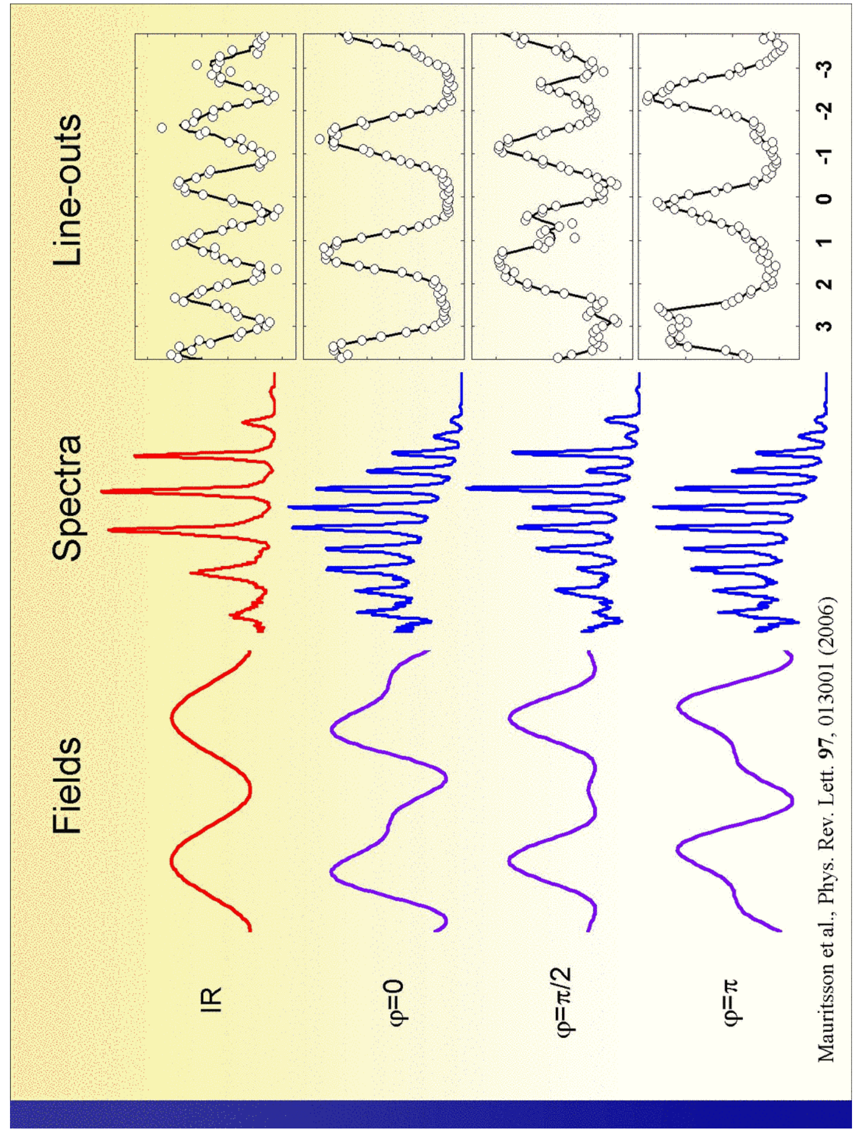

Two-color Michelson interferometer
Coarse delay
Fine delay
λ/2 plate
2ω
ω
Pump
Probe
KDP Type I
35 fs, 1.5 mJ, 800 nm
2ω_pump: 120 µJ
ω_pump: 550 µJ
ω_probe: 550 µJ

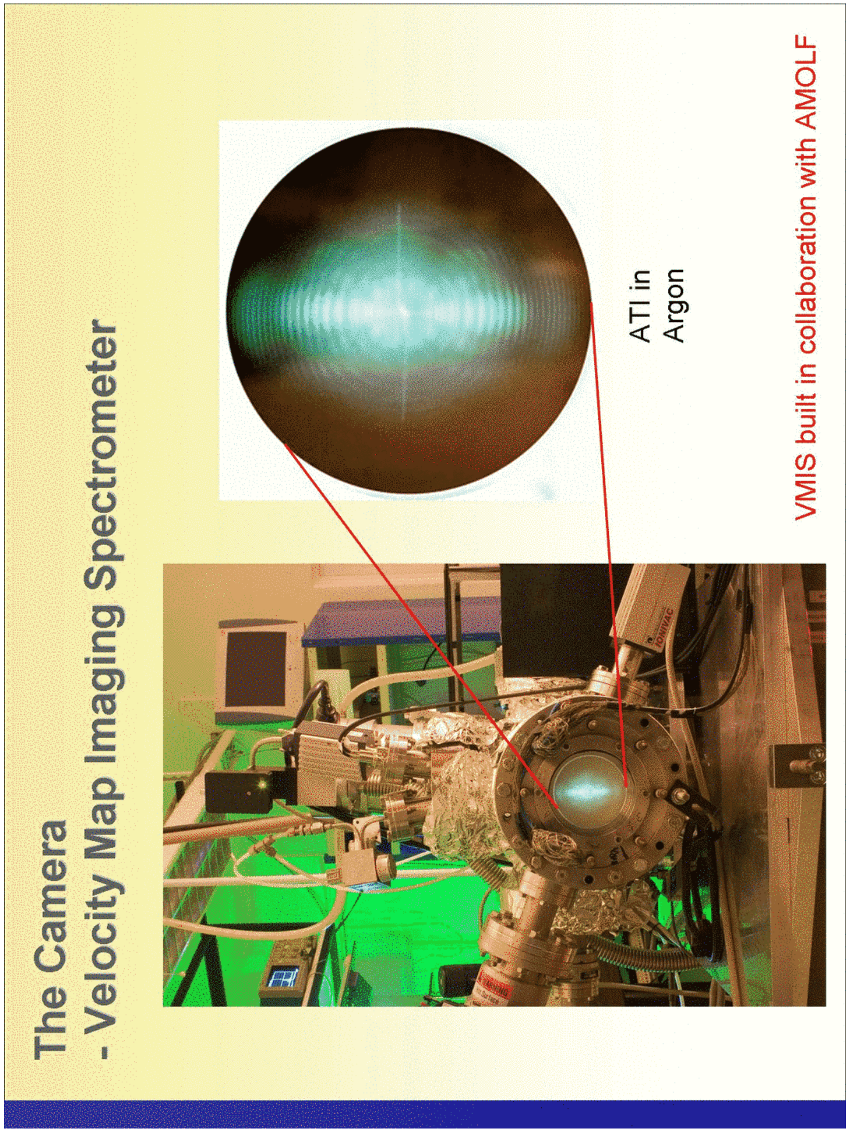

First experimental results in Argon
Delay
But what is the time structure?
Intensity
Harmonic order

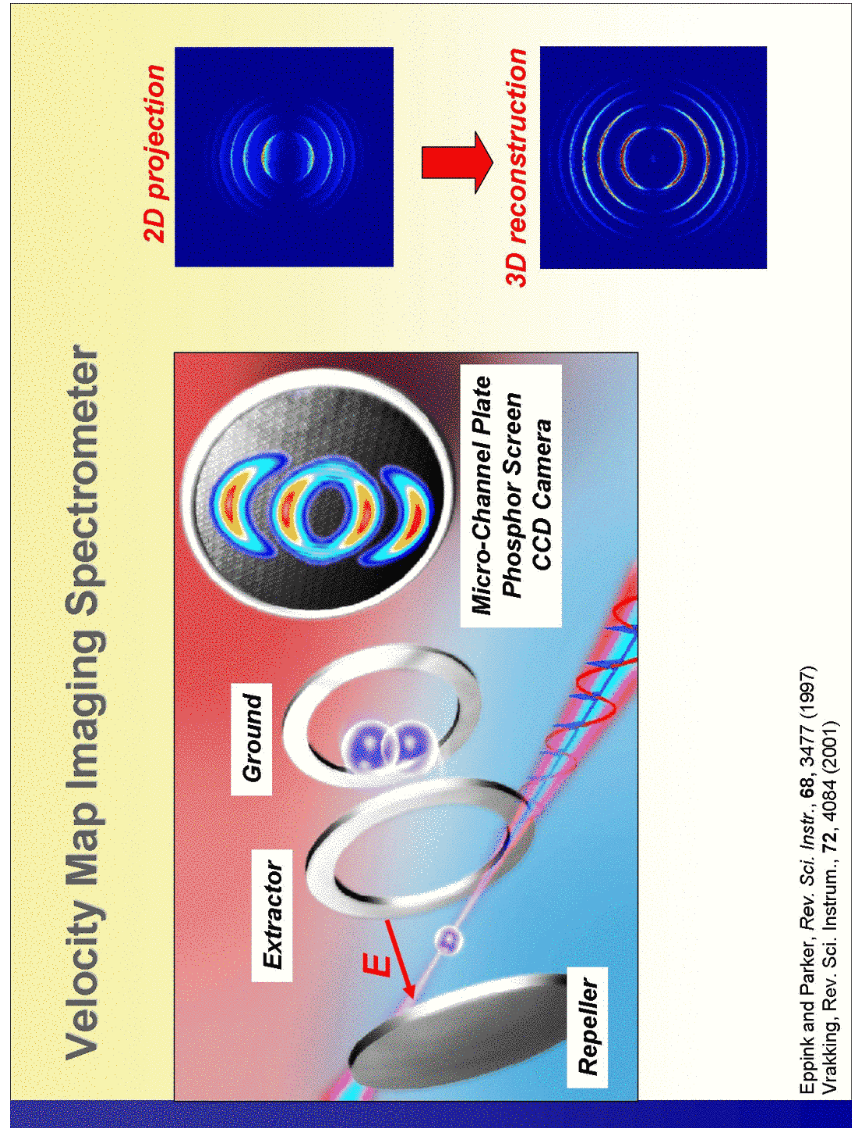

Attosecond streak camera
Electric field
Electric field
Intensity (arb. units)
Intensity (arb. units)
Electron energy (eV)
Electron energy (eV)
0
10
20
30
40
50
Itatani et al. Phys. Rev. Lett. 88, 173903 (2002)
Johnsson et al. Phys. Rev. Lett. 95, 013001 (2005)

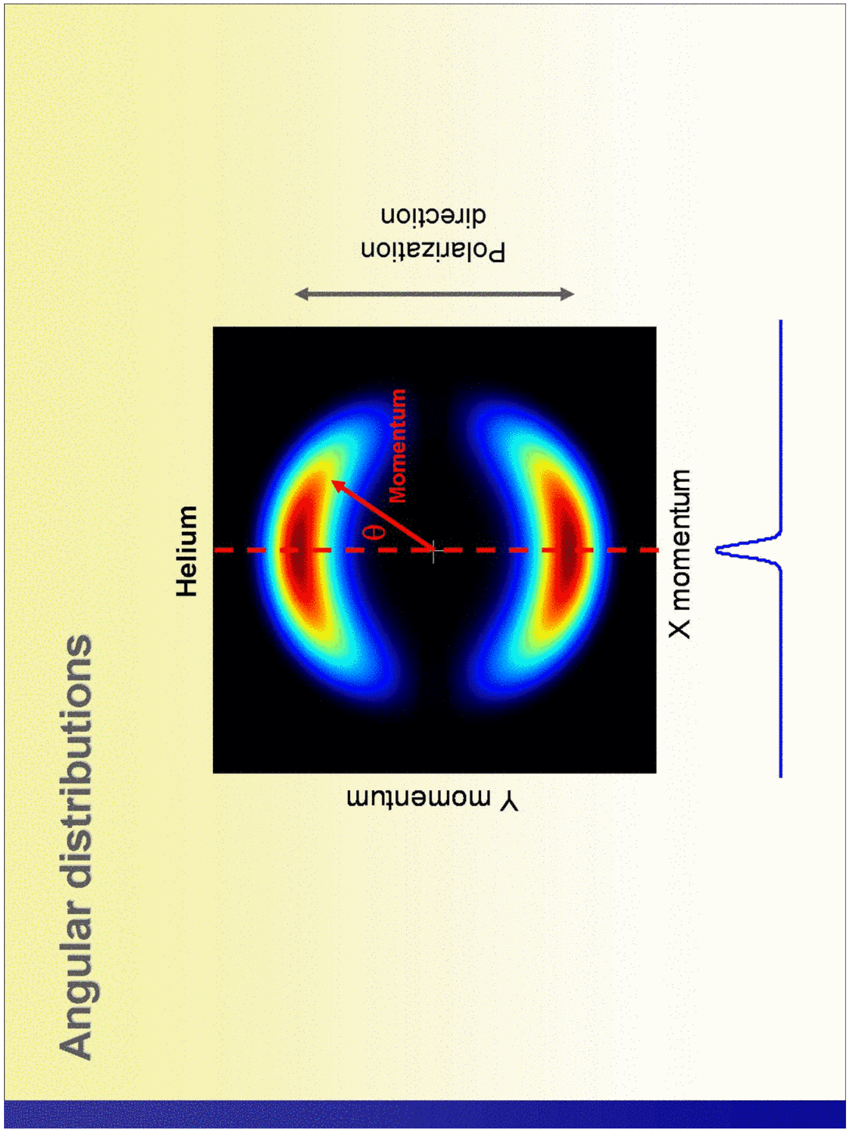

Experimental results
Intensity
Harmonic order

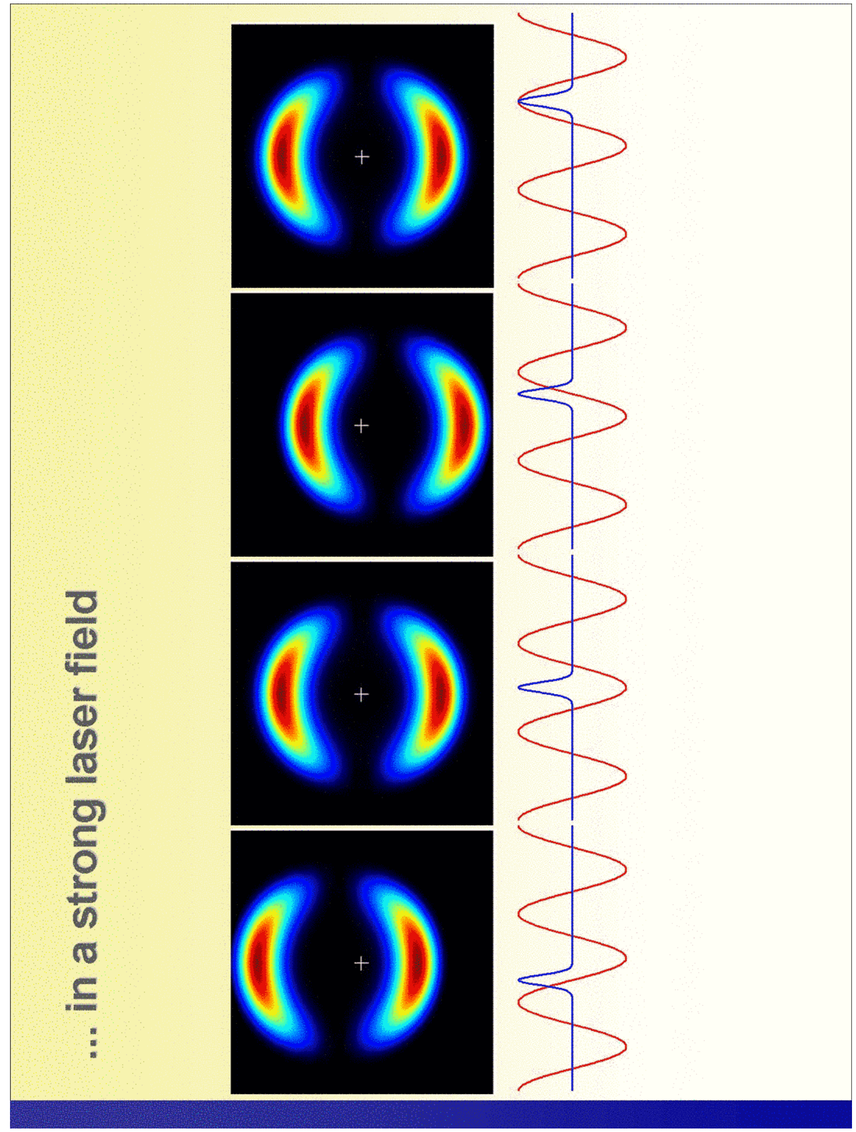

Comparing different relative phases
Delay (fs)
3
2
1
0
-1
-2
-3
4
8
12
16
20
24
Energy (eV)

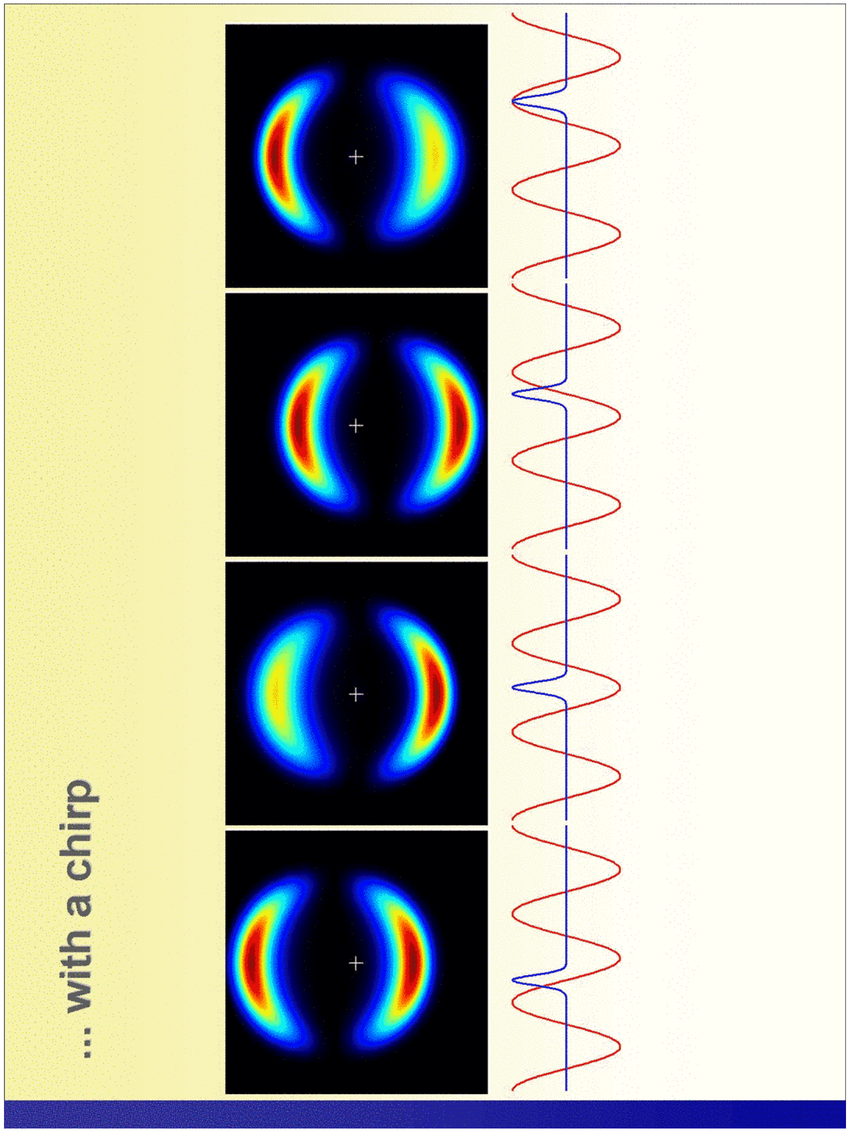

Fields
Spectra
Line-outs
IR
φ=0
φ=π/2
φ=π
3
2
1
0
-1
-2
-3
Mauritsson et al., Phys. Rev. Lett. 97, 013001 (2006)

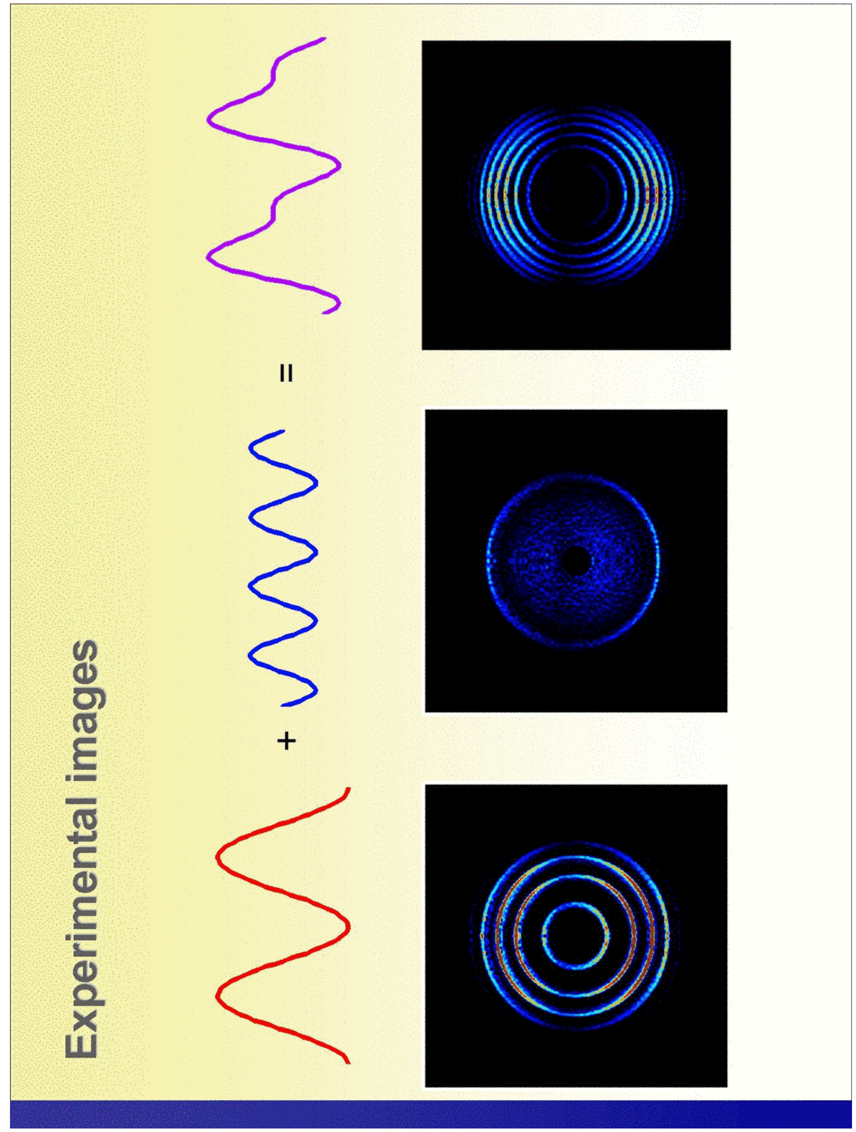

The Camera
- Velocity Map Imaging Spectrometer
ATI in
Argon
VMIS built in collaboration with AMOLF

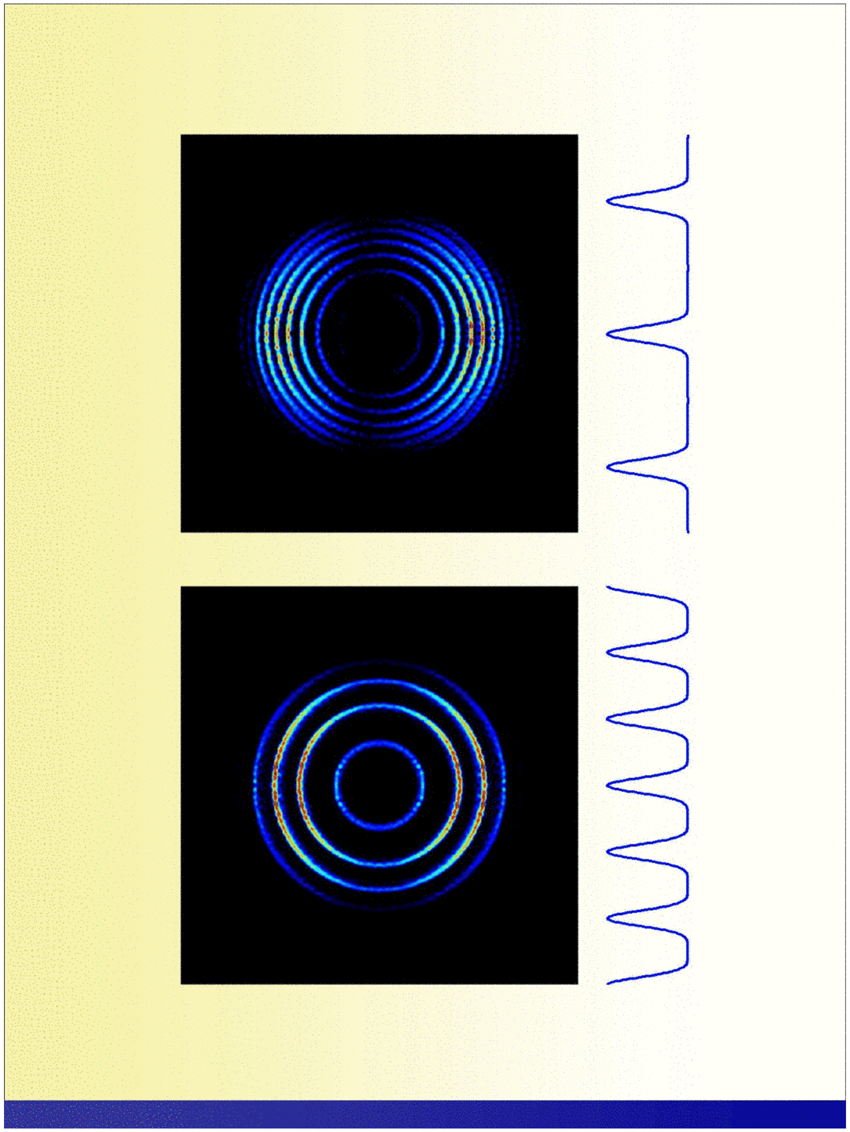

Velocity Map Imaging Spectrometer
2D projection
3D reconstruction
Micro-Channel Plate
Phosphor Screen
CCD Camera
Ground
Extractor
E
Repeller
Eppink and Parker, Rev. Sci. Instr., 68, 3477 (1997)
Vrakking, Rev. Sci. Instrum., 72, 4084 (2001)

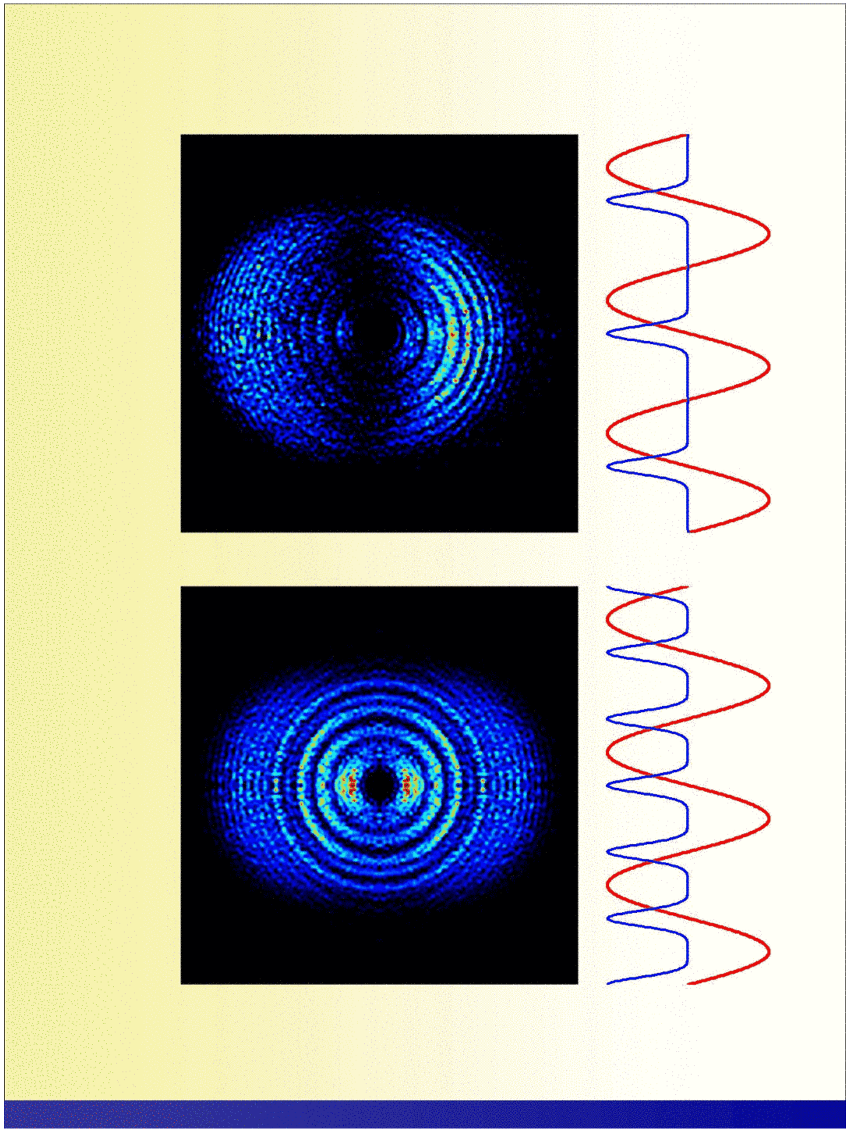

Angular distributions
Helium
Momentum
θ
X momentum
Y momentum
Polarization direction

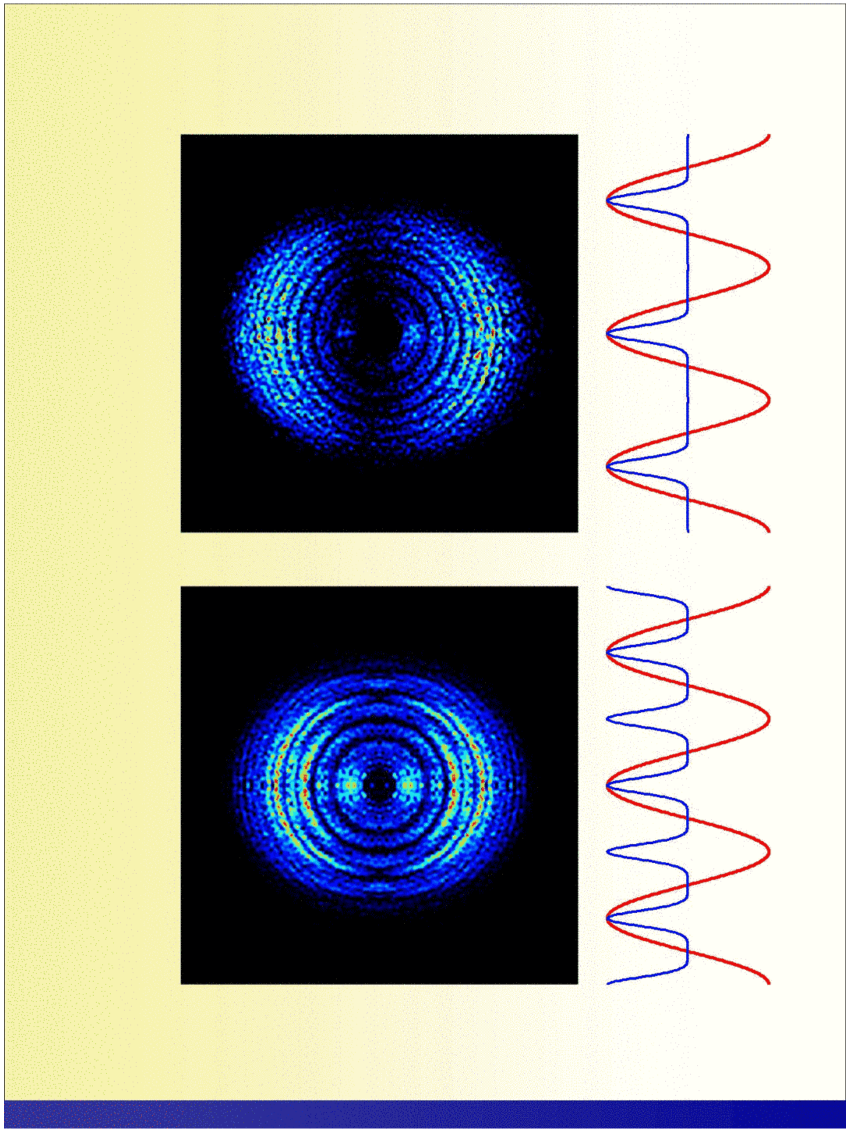

... in a strong laser field

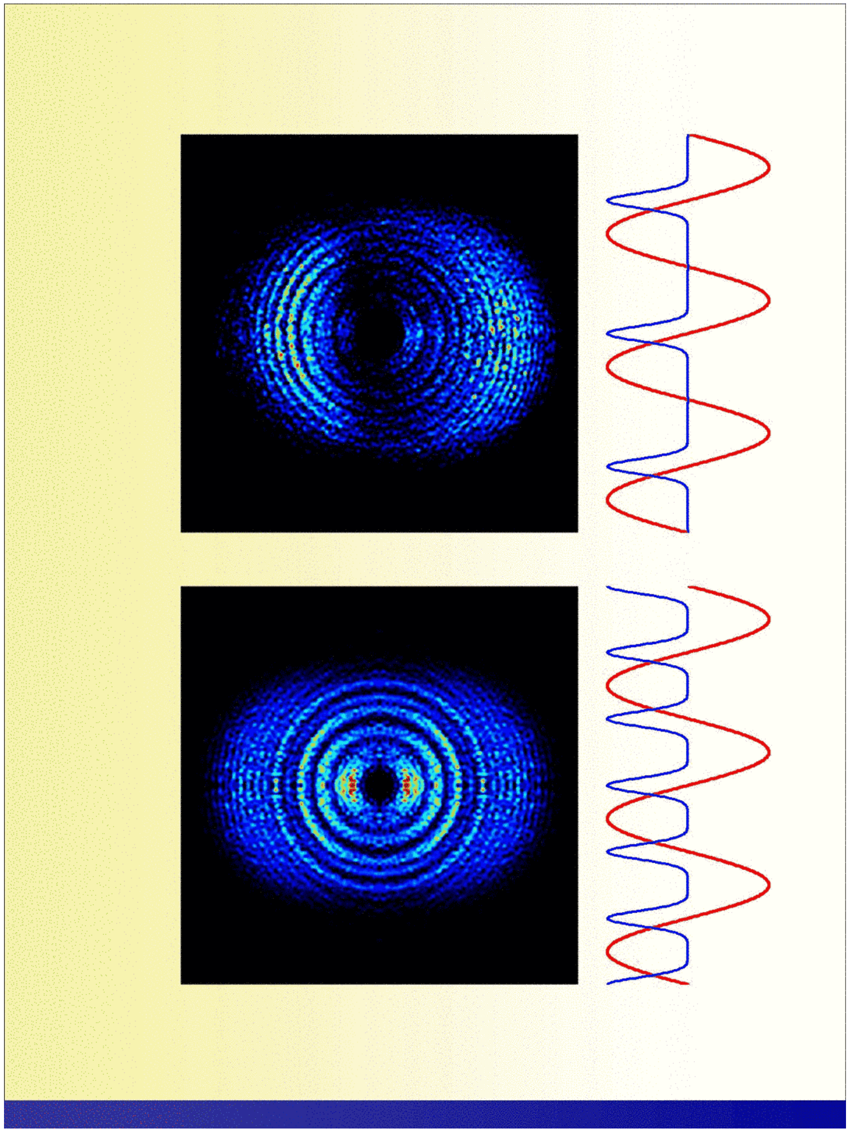

... with a chirp

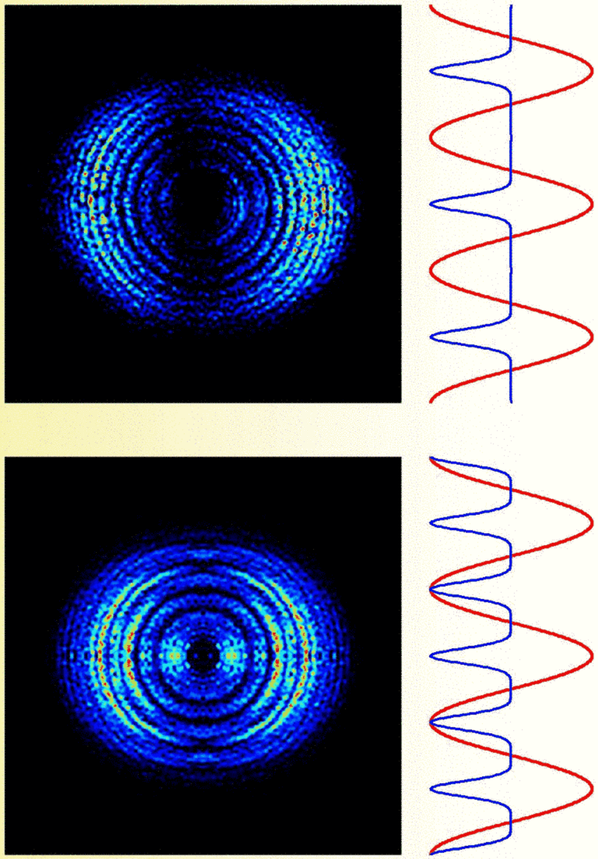

Experimental images
+
=

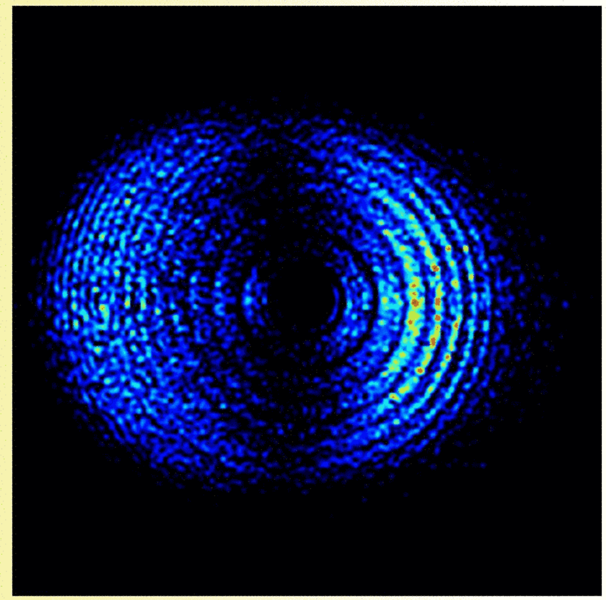




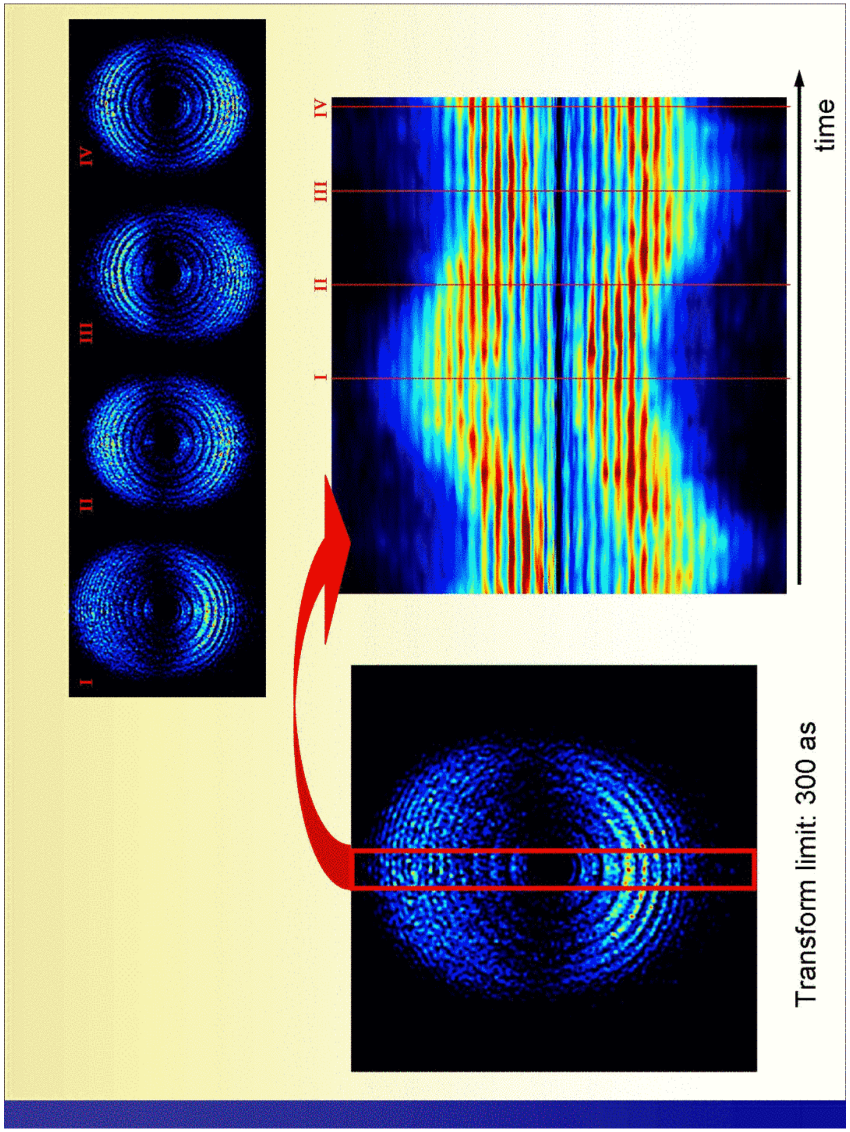


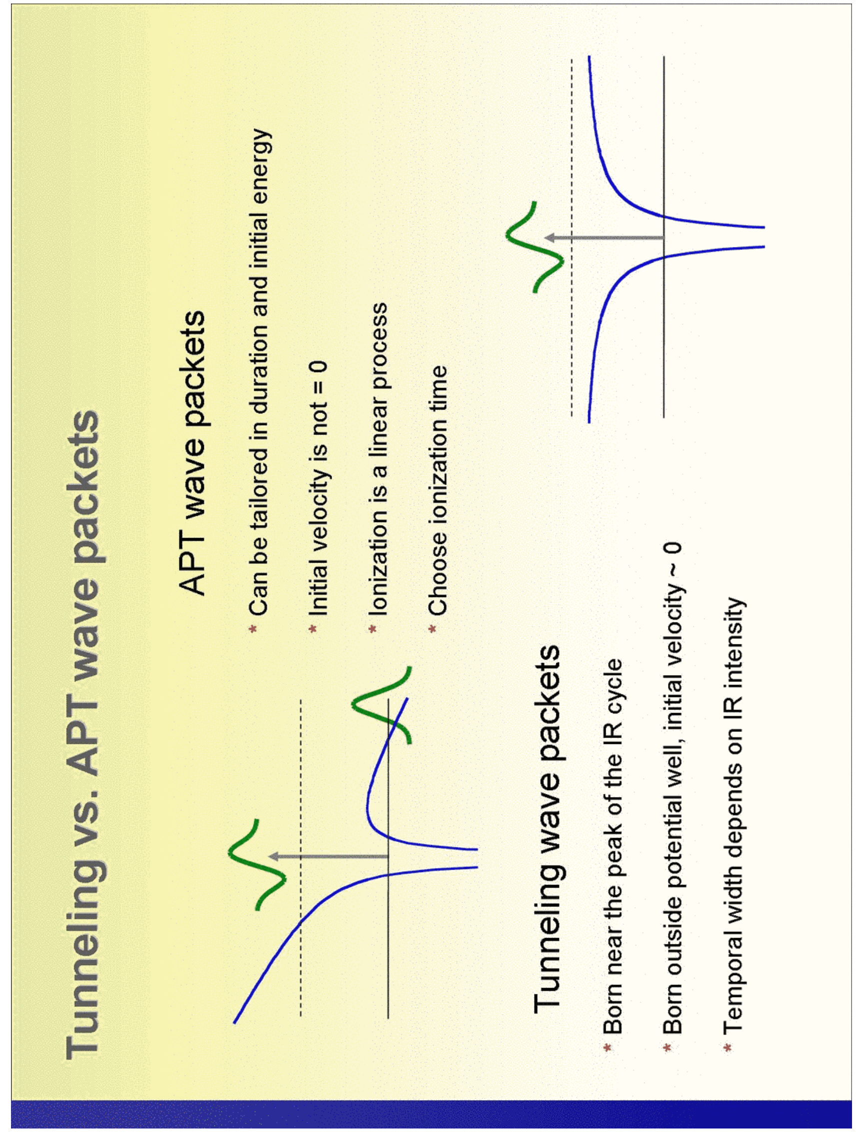




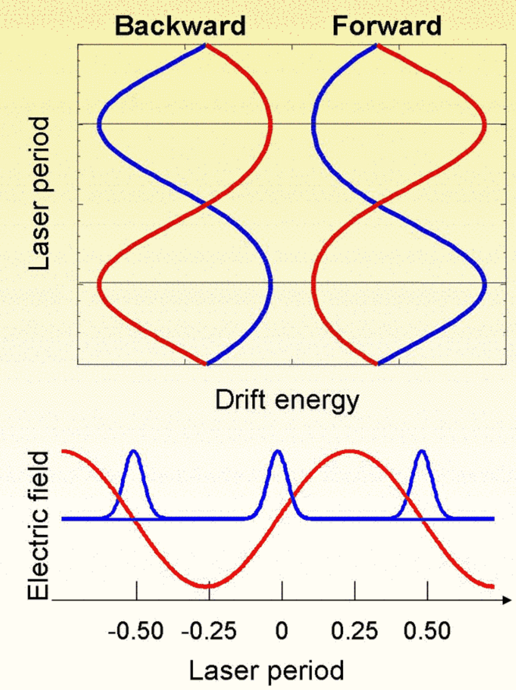


Movie


I
II
III
IV
time
Transform limit: 300 as


Tunneling vs. APT wave packets
APT wave packets
* Can be tailored in duration and initial energy
* Initial velocity is not = 0
* Ionization is a linear process
* Choose ionization time
Tunneling wave packets
* Born near the peak of the IR cycle
* Born outside potential well, initial velocity ~ 0
* Temporal width depends on IR intensity

Free electrons released into an IR field



$$v(t) = \sqrt{4U_p}\,[\underbrace{(\cos(\omega t_0) \pm \tilde{\gamma})}_{\text{Drift velocity}} - \cos(\omega t)]$$

$$\tilde{\gamma} = \sqrt{\frac{W}{2U_p}}$$

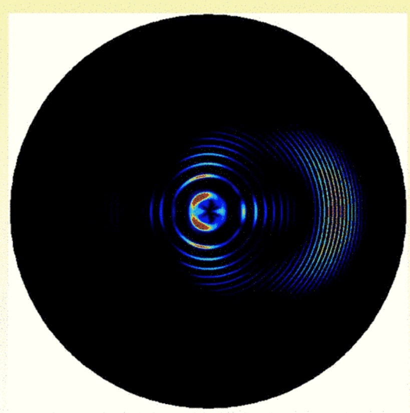
W is the initial kinetic energy.

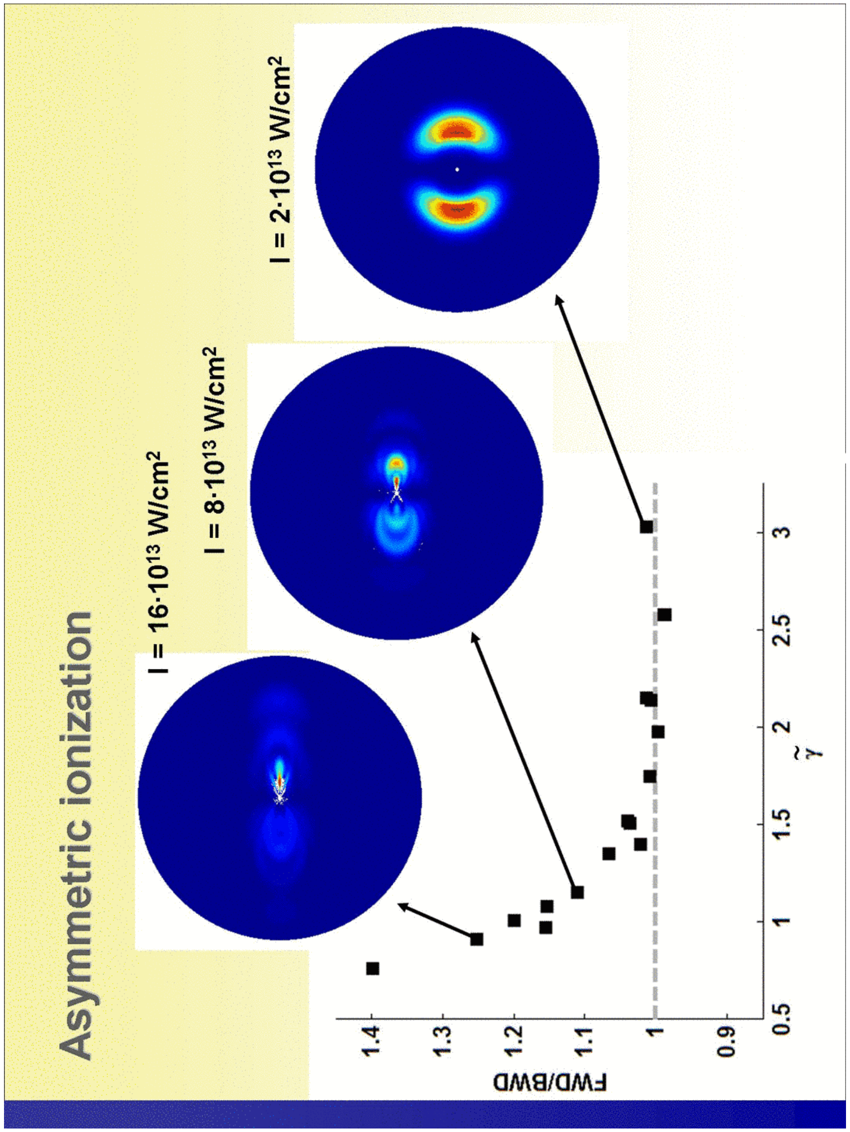
$\tilde{\gamma} < 1$ is the strong field regime in this simple model and some electrons return to the ion core.

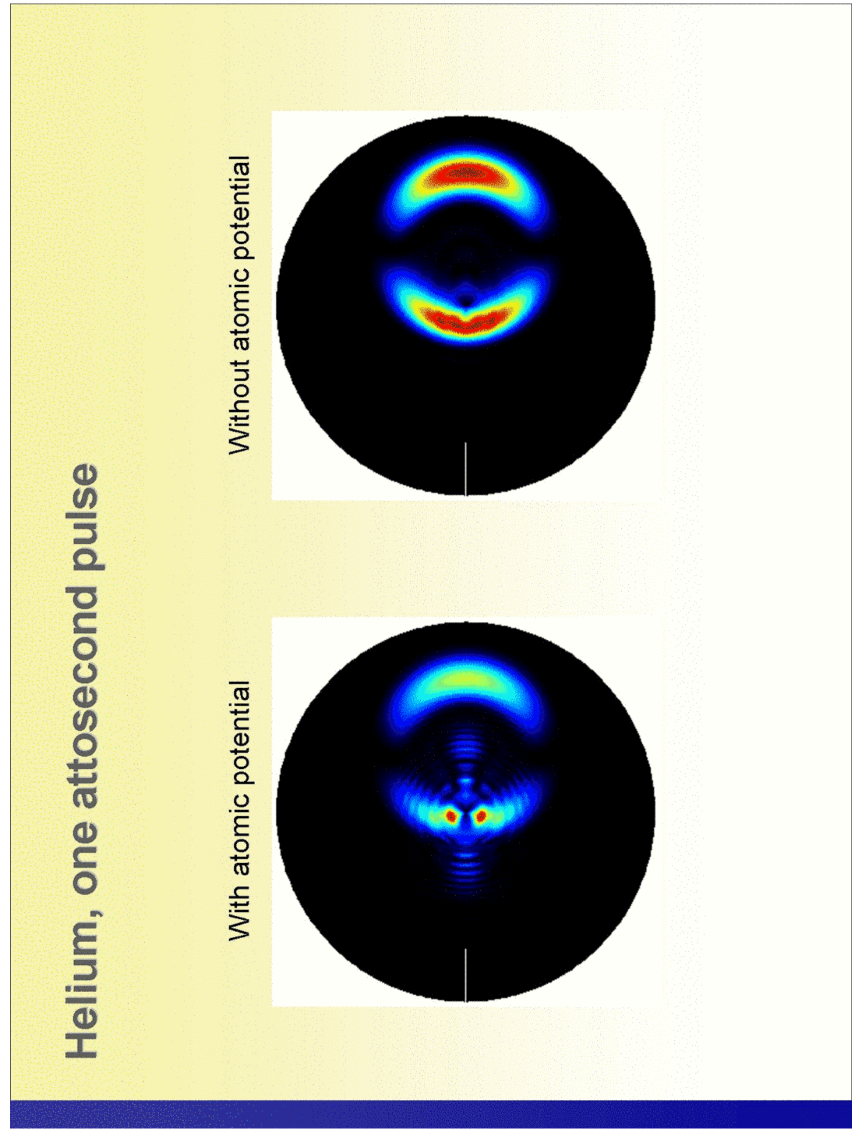
Argon, higher IR intensity

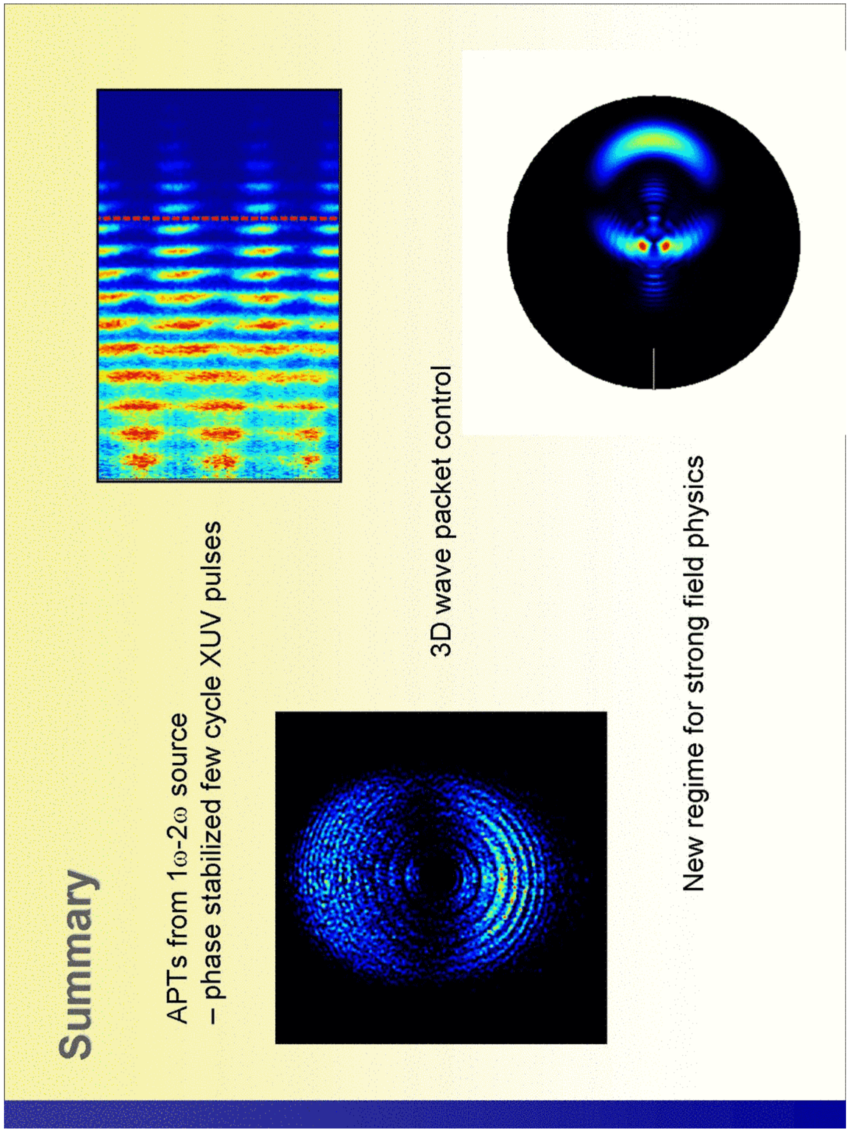
m=0

m=1




Asymmetric ionization
I = 16·10¹³ W/cm²
I = 8·10¹³ W/cm²
I = 2·10¹³ W/cm²
FWD/BWD
γ̃


Helium, one attosecond pulse
With atomic potential
Without atomic potential


Summary
APTs from 1ω-2ω source
– phase stabilized few cycle XUV pulses
3D wave packet control
New regime for strong field physics