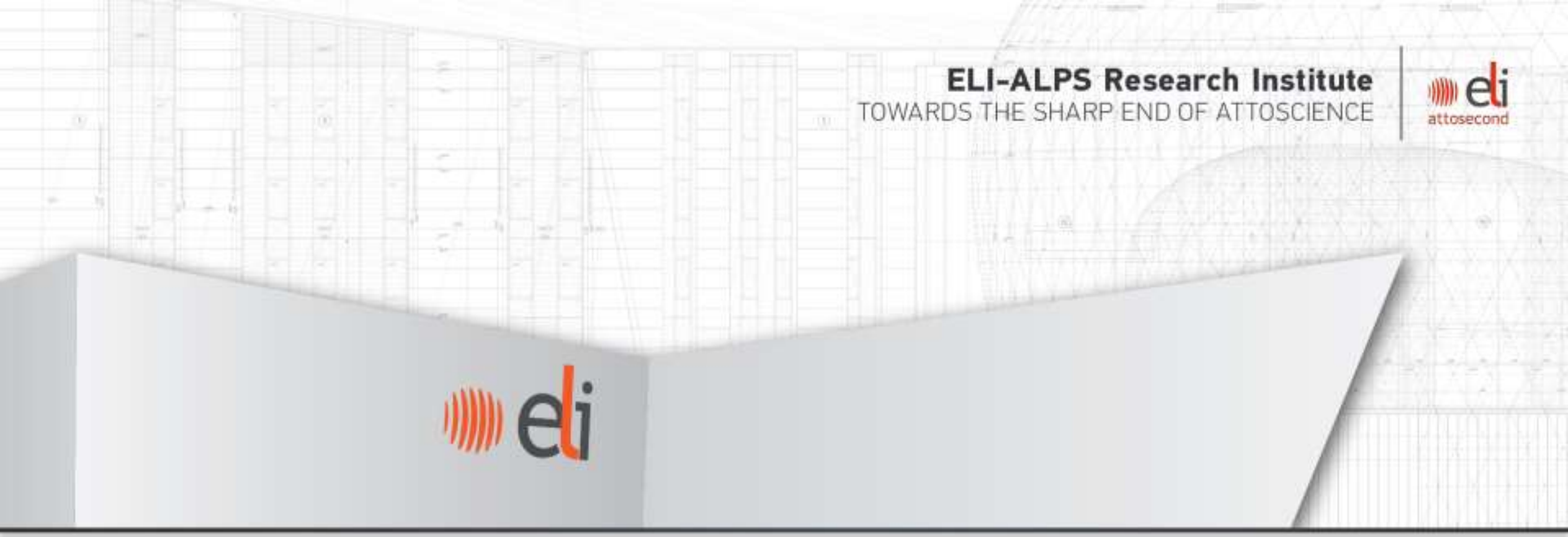


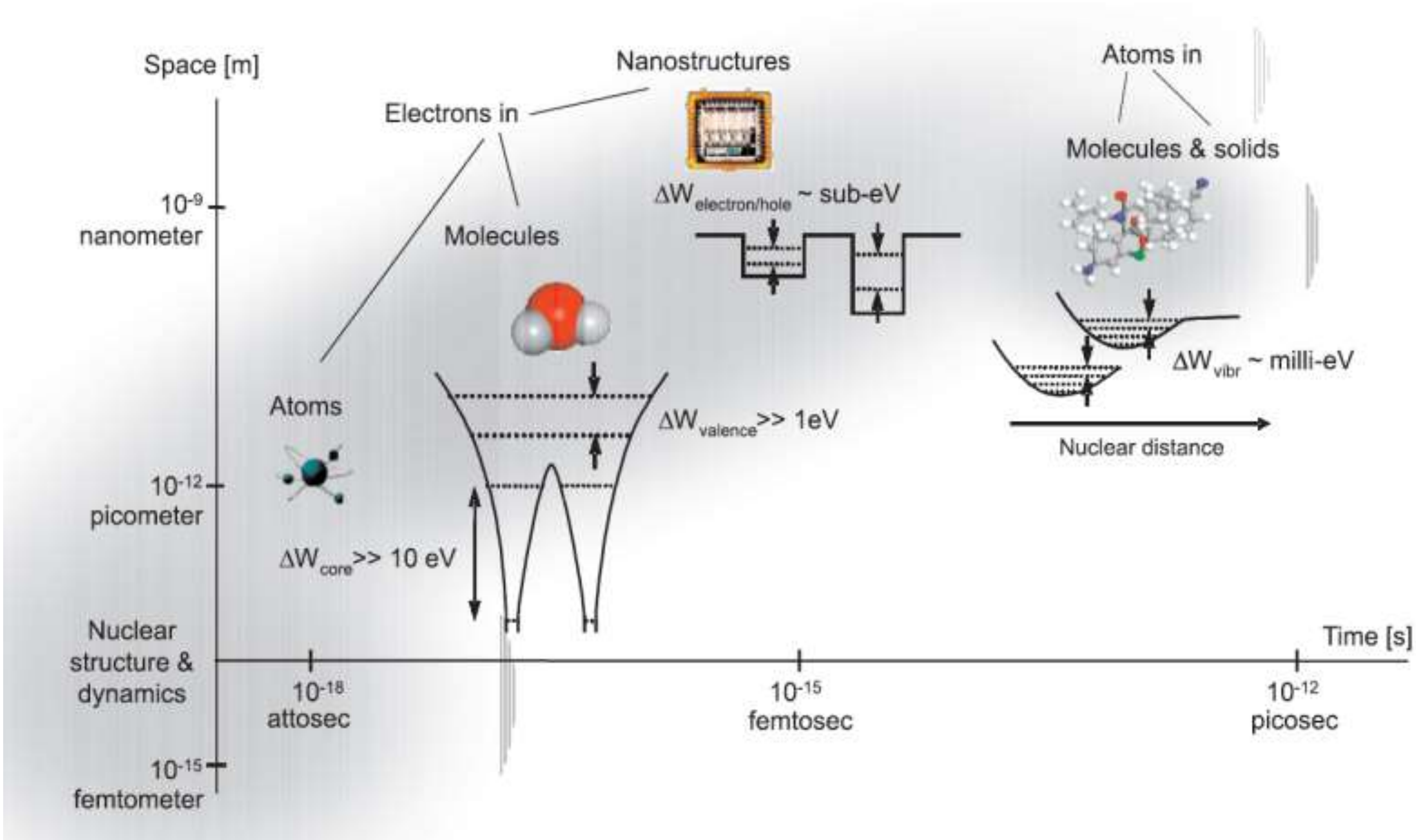
Generation of ultrashort XUV femtosecond to attosecond pulses

Katalin Varjú
ELI-ALPS

2nd MOLIM Training School
6 – 10 March, 2017
Paris-Saclay

SZÉCHENYI 2020
HUNGARIAN GOVERNMENT
European Union
European Regional Development Fund
INVESTING IN YOUR FUTURE

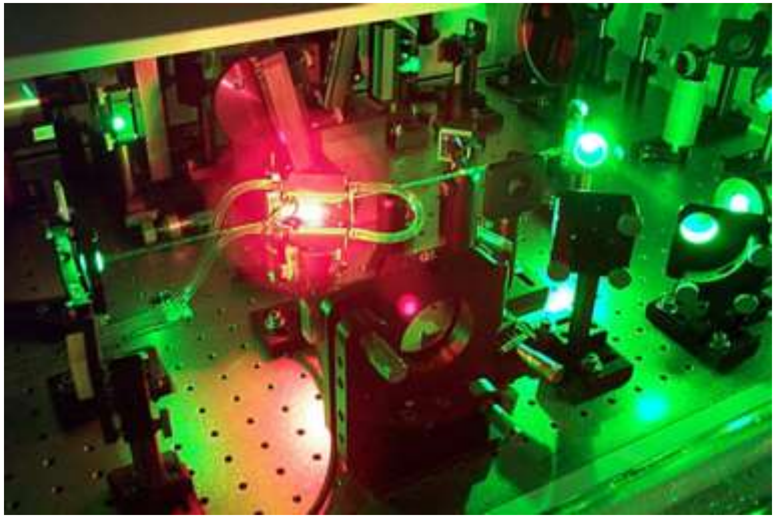
Characteristic times



Krausz: RevModPhys 81, 163 (2009)

Fs light sources

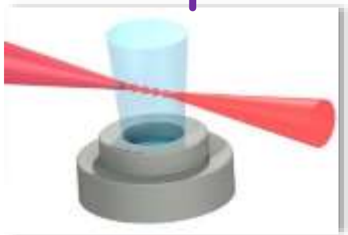
LASER mechanism ⇒ temporal and spatial coherence
oscillator, phase locking, broad bandwidth gain medium ⇒
⇒ ultrashort pulse duration



Can we build an XUV laser to transfer these properties to the XUV domain?

Mechanisms leading to fs-scale XUV generation

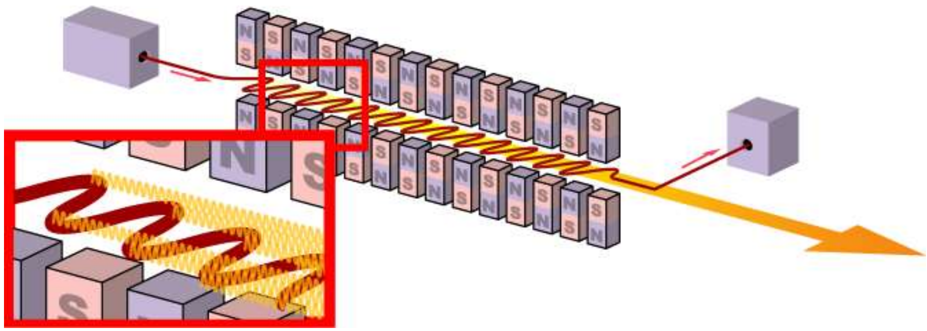
Intense laser pulse + nonlinear phenomenon



gas HHG

surface plasma HHG

Accelerated e- based schemes



synchrotron, FEL, seeded FEL

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- High order harmonic generation in gaseous media
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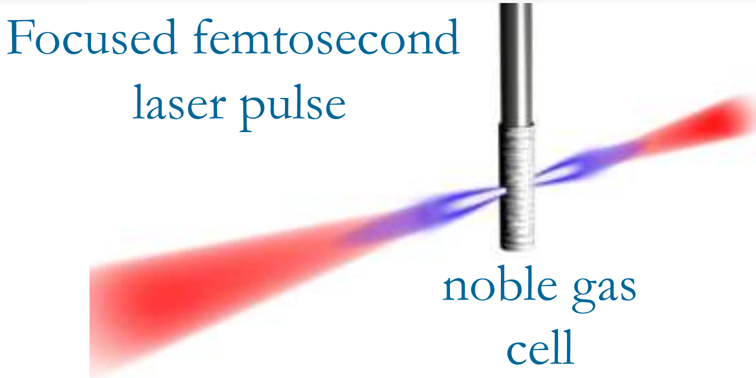
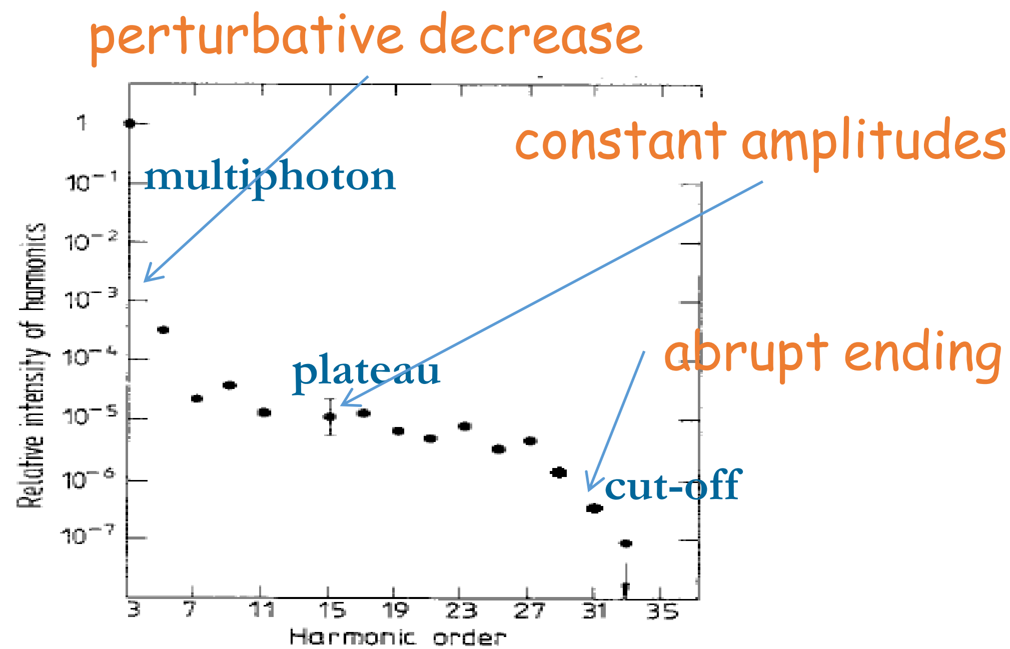
Experimental observation of HHG



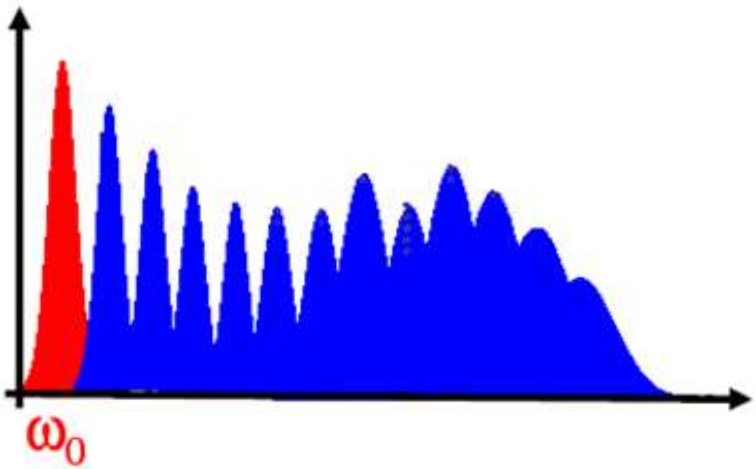


Ferray: J. Phys. B, 21, L31 (1988)

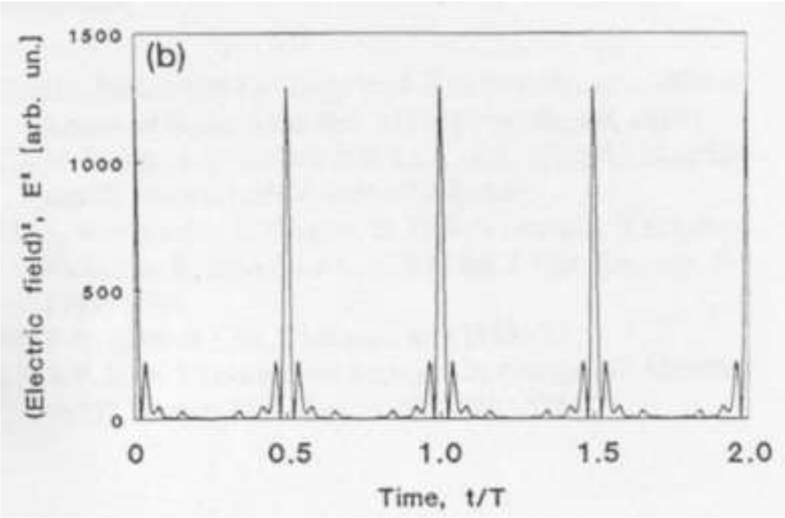
„Generating high order harmonics is experimentally simple."

Anne L'Huillier

The „birth" of attosecond science



FT



Farkas, Phys. Lett. A (1992)

Atoms in a strong laser field

atomic electron: $E(r) = -\frac{1}{4\pi\varepsilon_0}\frac{e}{r^2}$ $\quad r \approx 10^{-10}\,\mathrm{m}$ $\quad E \approx 10^{11}\,\frac{\mathrm{V}}{\mathrm{m}}$

intensity = |Poynting vektor|

$$I = 2\cdot\frac{5\,\mathrm{mJ}}{\pi\cdot(100\,\mu\mathrm{m})^2\cdot 20\,\mathrm{fs}} = 1.6\times10^{19}\,\frac{W}{m^2} = 1.6\times10^{15}\,\frac{W}{cm^2}$$

$$I_0 \approx \frac{E}{\pi\cdot w_0^2\cdot\tau}\cdot 2$$

$$I = S = \frac{1}{2\mu_0}E_{\max}B_{\max} = \frac{1}{2}\varepsilon_0 c E_{\max}{}^2$$

$$E_{\max} = \sqrt{\frac{2\cdot I}{\varepsilon_0 c}} = \sqrt{\frac{2\cdot 1.6\times10^{19}\,\frac{\mathrm{W}}{\mathrm{m}^2}}{8.8\times10^{-12}\,\frac{\mathrm{As}}{\mathrm{Vm}}\cdot 3\times10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}}} \approx 1.1\times10^{11}\,\frac{\mathrm{V}}{\mathrm{m}}$$

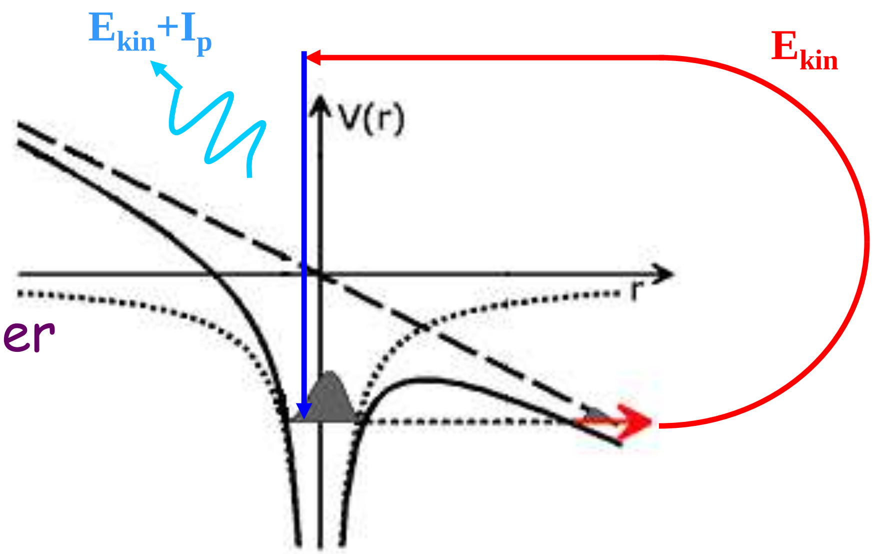
Field intensities $\sim 10^{14}\,\frac{W}{cm^2}$ correspond to the border between perturbative nonlinear optics and extreme NLO (where HHG occurs).

Three-step model

I Optical ionization through the distorted potential barrier

II Free electron propagating in the laser field, return to parent ion

III Electron captured by parent ion, photon emitted



Schafer: PRL, 70, 1599 (1993)
Corkum: PRL, 71, 1994 (1993)

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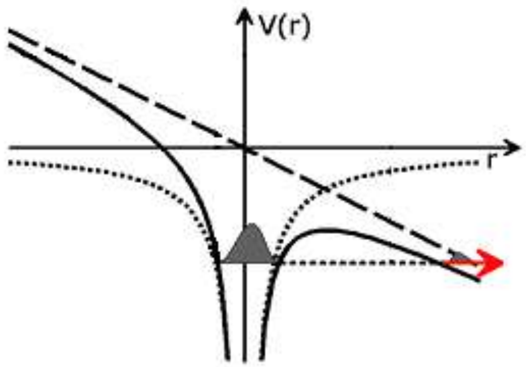
Classical description: Free electron in an oscillating E-field

$$E(t) = E_0 \sin(\omega t)$$ monochromatic field

$$F = -eE = m\ddot{x}$$ Newton's law of motion



P. B. Corkum, Phys Rev Lett 71, 1994 (1993)
K. Varjú, Am. J. Phys. 77, 389 (2009)

$$\mathrm{x_i} = 0 \text{ and } \mathrm{v_i} = 0 \quad \text{at} \quad t_i$$

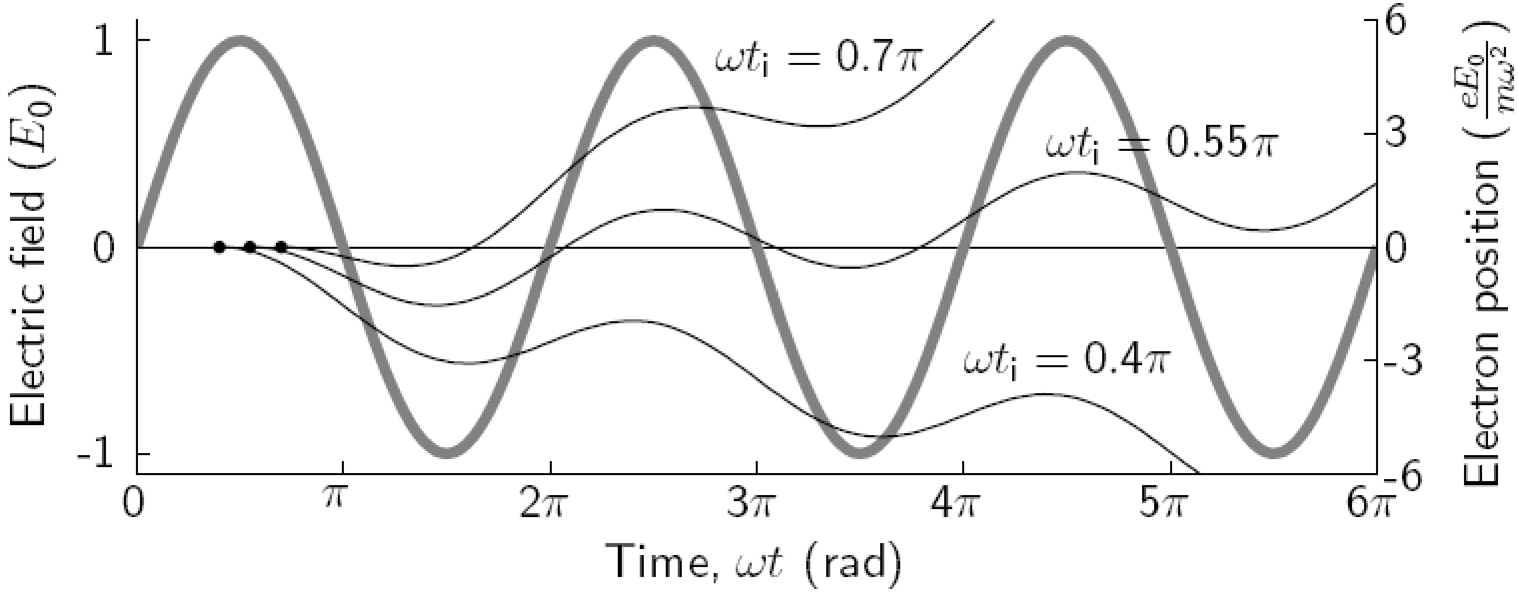
$$v(t) = -\frac{eE_0}{m\omega}\left[\cos(\omega t) - \cos(\omega t_i)\right]$$

$$x(t) = \frac{eE_0}{m\omega^2}\left[\sin(\omega t) - \sin(\omega t_i) - \omega(t - t_i)\cos(\omega t_i)\right]$$

analytic solution

Assumptions:
- 1-dim case
- the electron is ionized into the vicinity of the ion with zero velocity, and recombines if its path returns to the same position (no quantum effects!)
- while in the laser field, the effect of the Coulomb field is neglected
- if the electron recombines, a photon is emitted with energy Ekin+ Ip

$$x(t) = \frac{eE_0}{m\omega^2}\left[\sin(\omega t) - \sin(\omega t_i) - \omega(t - t_i)\cos(\omega t_i)\right]$$



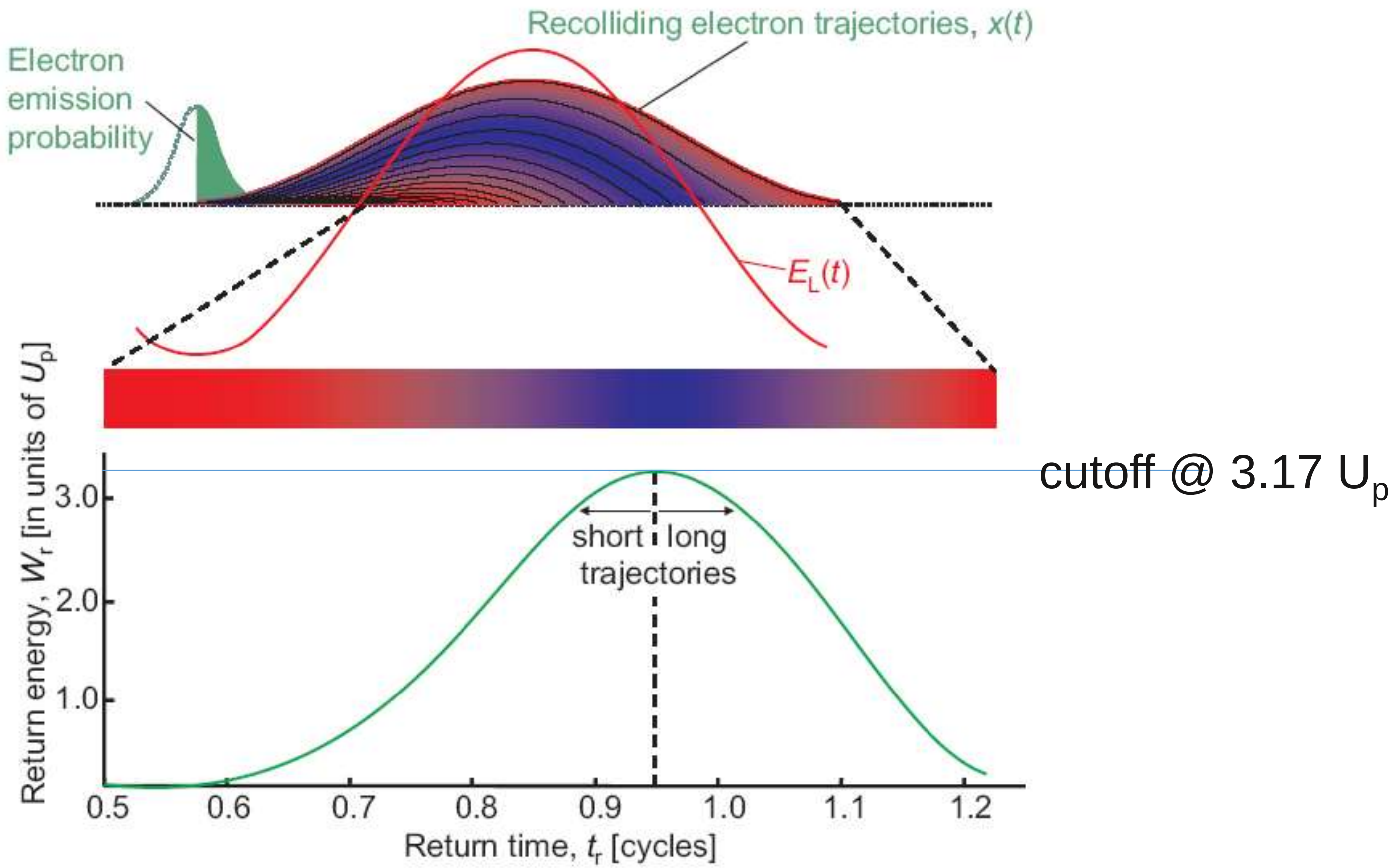
1, the electron may return

2, return of the electron depends on ionization time

3, energy gained in the laser field (~ velocity squared ~ slope of trajectory) depends on ionization time

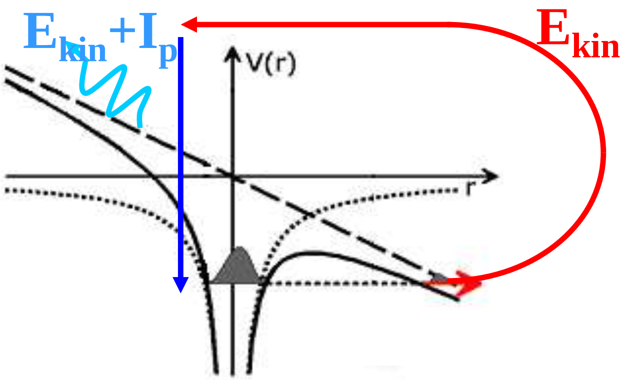
Chirp of attosecond pulses

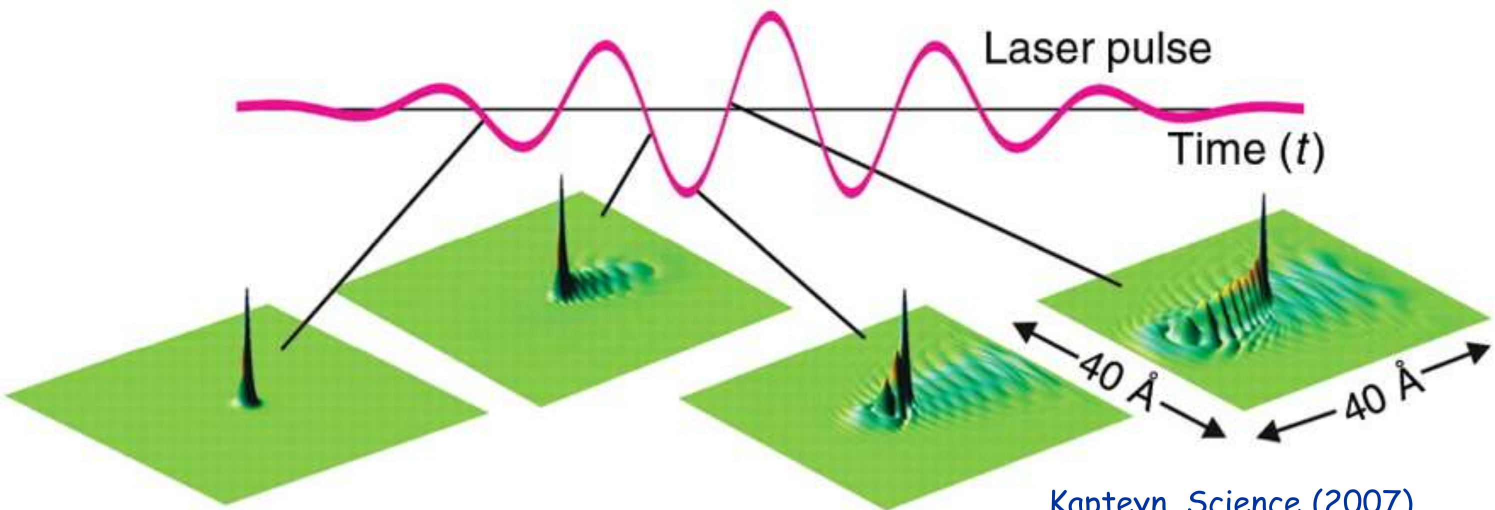
E_{kin} depends on return time → photon energy / frequency will vary with time → chirped pulses



Varjú, Laser Phys 15, 888 (2005)
Krausz, Ivanov, Rev Mod Phys 81, 163 (2009)

HHG in the quantum picture





Kapteyn, Science (2007)
Lewenstein, Phys Rev A (1994)

low efficiency!!!

Harmonic radiation

is a result of oscillation of the quasi-bound electron.
Desciption: quantum mechanics

TDSE:

$$i\,\frac{\partial}{\partial t}\,|\Psi(\vec{x},t)\rangle = [-\tfrac{1}{2}\nabla^2 + V(\vec{x}) - \vec{E}(t)\cdot\vec{x}]\,|\Psi(\vec{x},t)\rangle.$$

- one-electron approximation (initially in the bound ground state)
- classical laser field (high photon density)
- dipole approximation (we neglect the magnetic field and the electric quadrupole)
- laser field is assumed to be linearly polarized

SOLUTION: numerical integration
long computational time

Strong field approximation (SFA)

- the ionized electron is under the influence of the laser field, only (Coulomb potential neglected)
- only a single bound state is considered
- neglect depletion of the bound state

Dipole moment:

$$\vec{x}(t) = \langle \Psi(t) | \vec{x} | \Psi(t) \rangle$$

$$\vec{x}(t) = i \int_0^t dt' \int d^3\vec{p} \;\; \vec{d}^*(\vec{p} - \vec{A}(t)) \times \exp[-iS(\vec{p},t,t')] \;\; \vec{E}(t') \cdot \vec{d}(\vec{p} - \vec{A}(t')) + \text{c.c.},$$

capture of electron

electron propagation in the laser field

ionization transition

Lewenstein integral

M. Lewenstein Phys.Rev.A 49, 2117 (1994)

Harmonic spectrum

Harmonics are emitted as a result of the dipole oscillations

Fourier transform of the dipole moment:

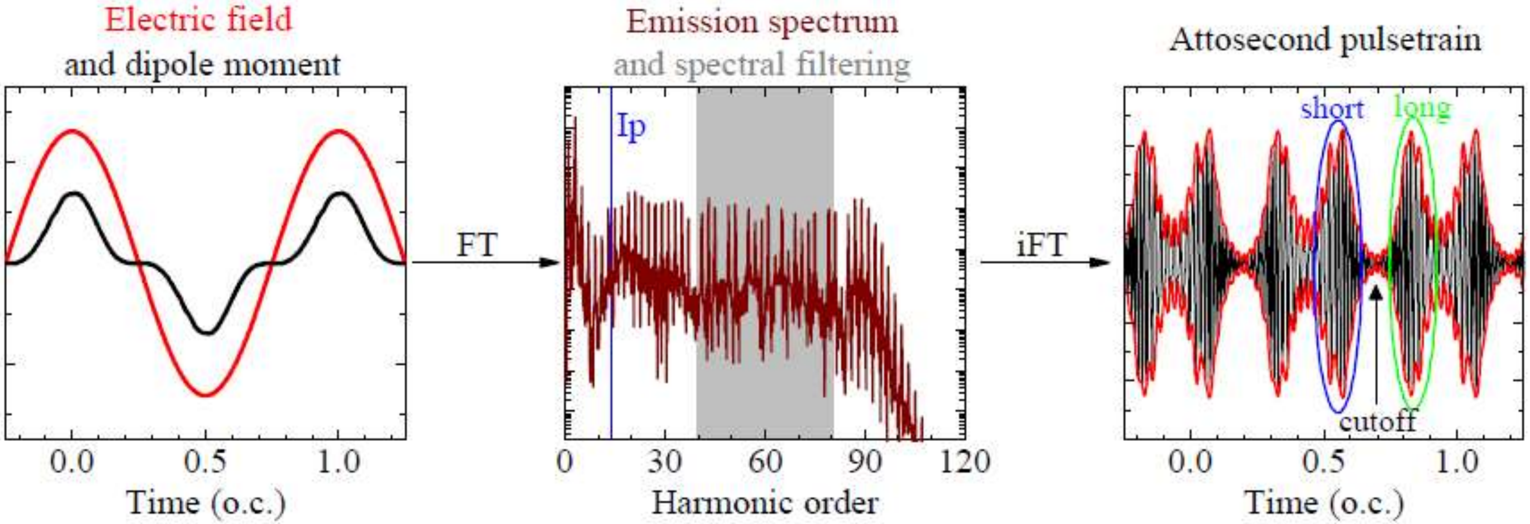
$$x(\omega) = \int_{-\infty}^{+\infty} dt\; x(t)\exp(i\omega t)$$

can be decomposed as

$$x(\omega) = \sum_s |x_s(\omega)|\exp[i\Phi_s(\omega)]$$

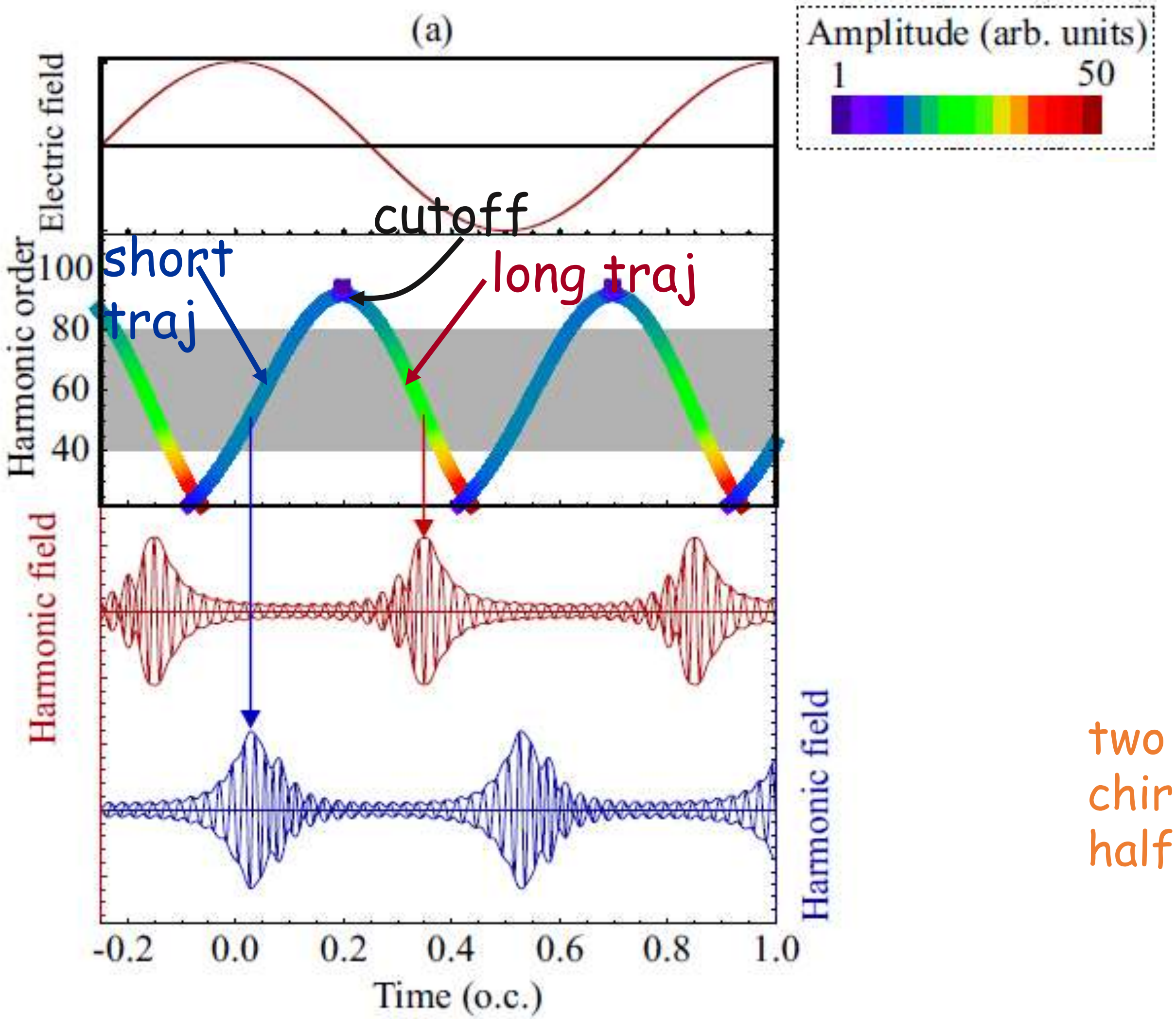
harmonic emission rate

$$W(\omega) \propto \omega^3 |x(\omega)|^2$$



λ = 800 nm,
$h\nu$=1.55 eV
$I_0 = 6\cdot10^{14}$ W/cm^2
I_p = 21.5 eV (Ne)

Half-cycle periodicity
separation of short and long traj components

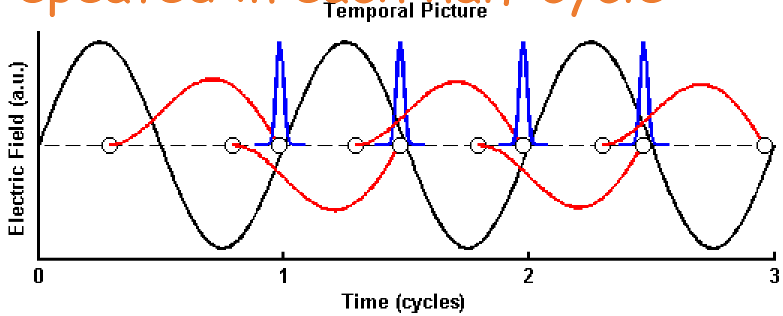


corresponding to emission in each halfcycle

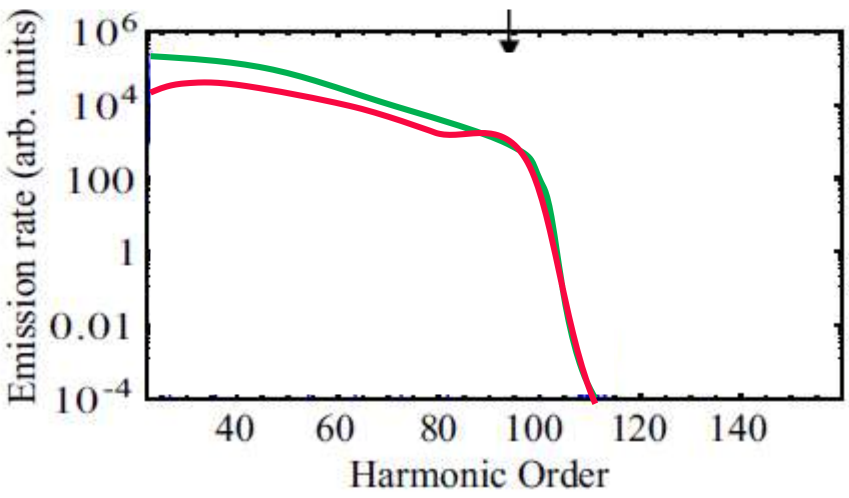
two delayed, oppositely chirped pulses in each half-cycle

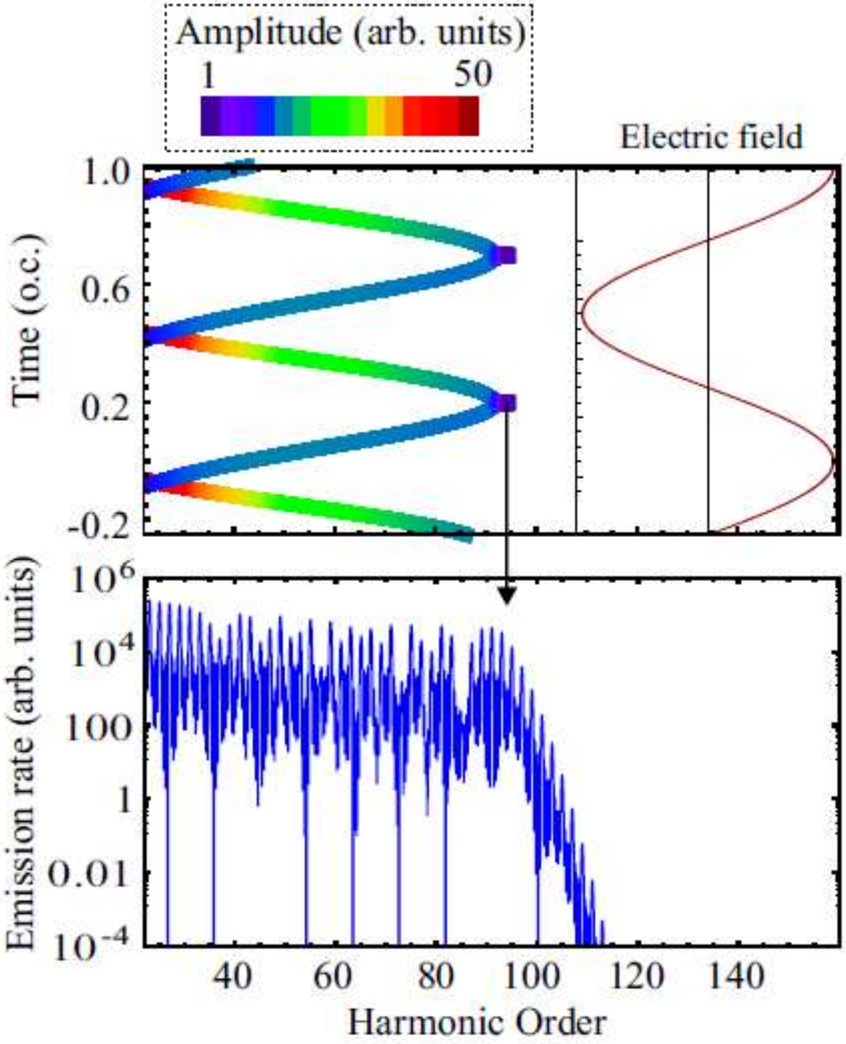
Periodicity

harmonic emission process
repeated in each half cycle



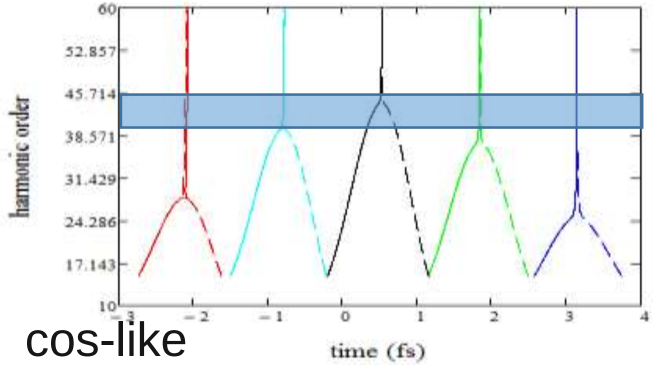
radiation emitted in each half cycle



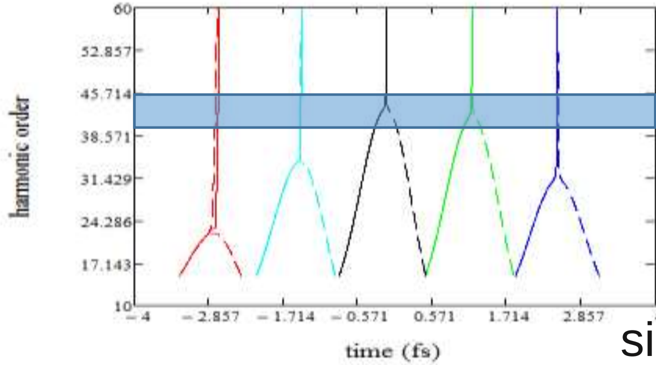


HHG by a short IR pulse

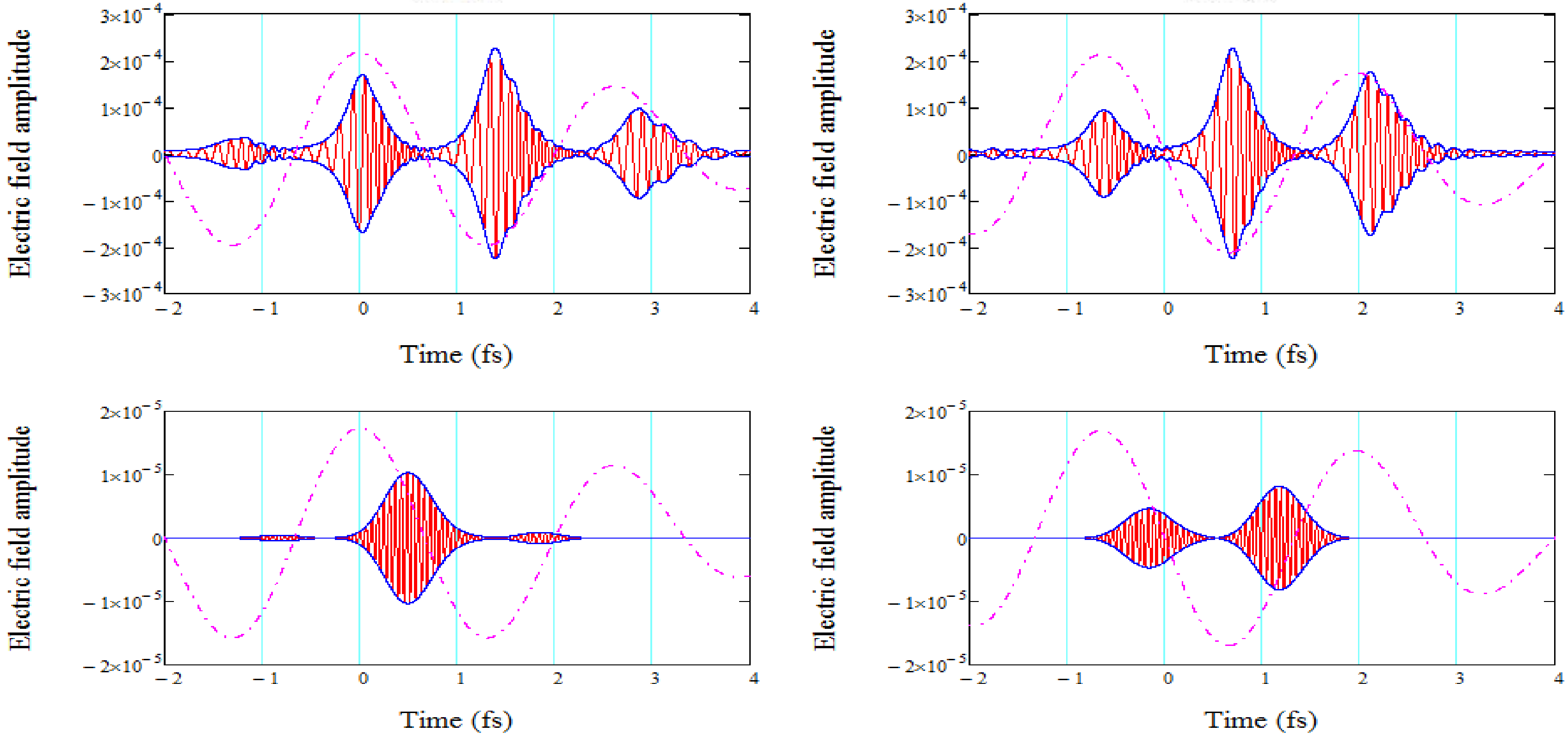
5 fs laser pulse,
800 nm,
$2.5*10^{14}$ W/cm^2
argon gas



cos-like



sin-like

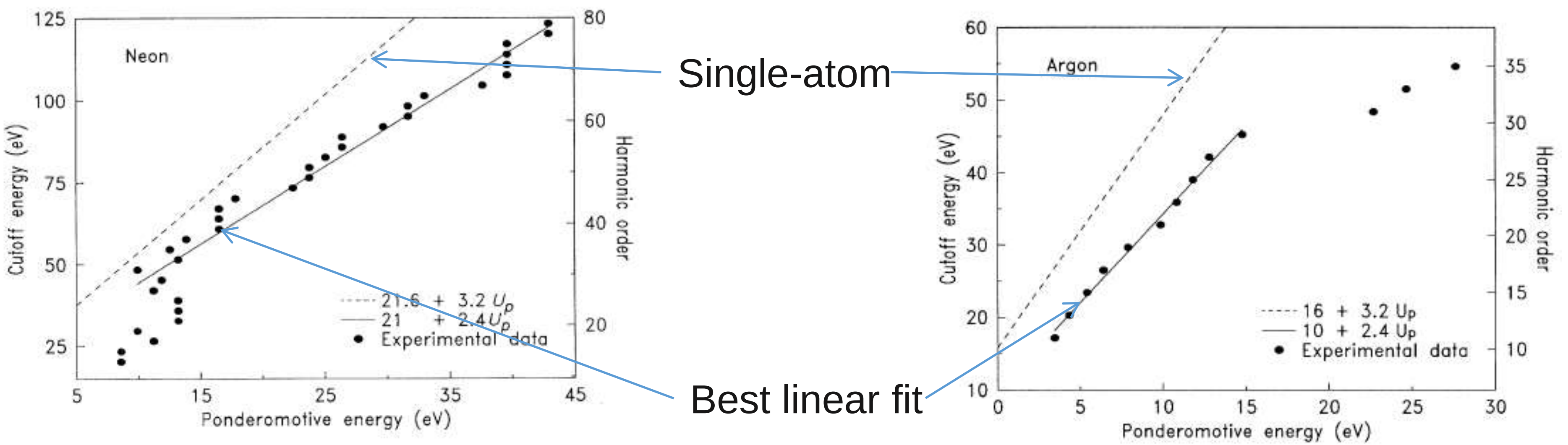


using a narrow spectral window (FWHM 3 harmonic orders), a single attosecond pulse can be selected - only short trajectories are considered!

The cutoff law - macroscopic

At high intensities saturation effects restrict the maximum photon energy to below cutoff, when the medium gets fully ionized before the peak (especially for long driving pulses)

- depletion of ground state
- prevents phasematching due to high concentration of electrons
- contributes to defocusing of the laser pulse



Macroscopic effects play an important role!!

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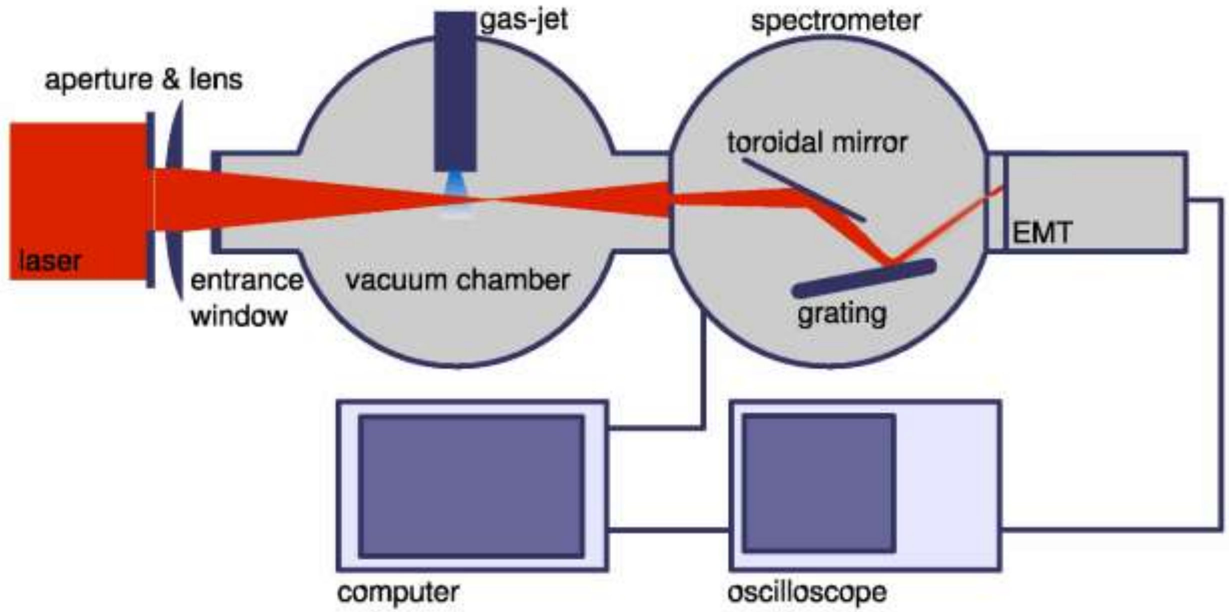
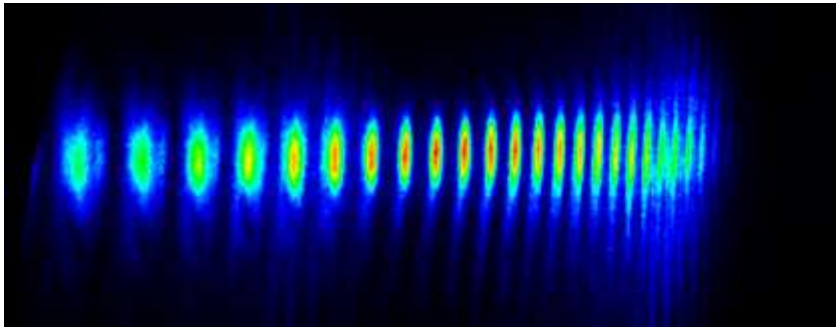
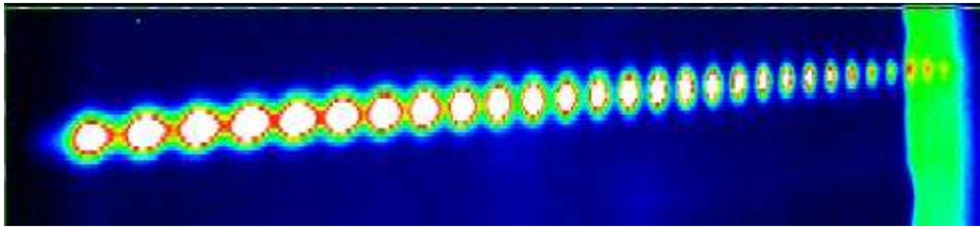
Photon detection





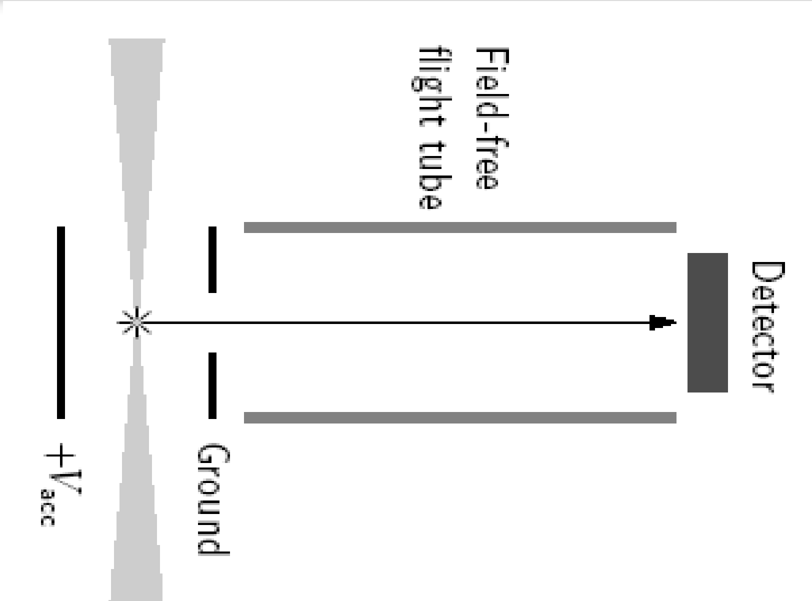
Nisoli et al., 2002



Kazamias et al.

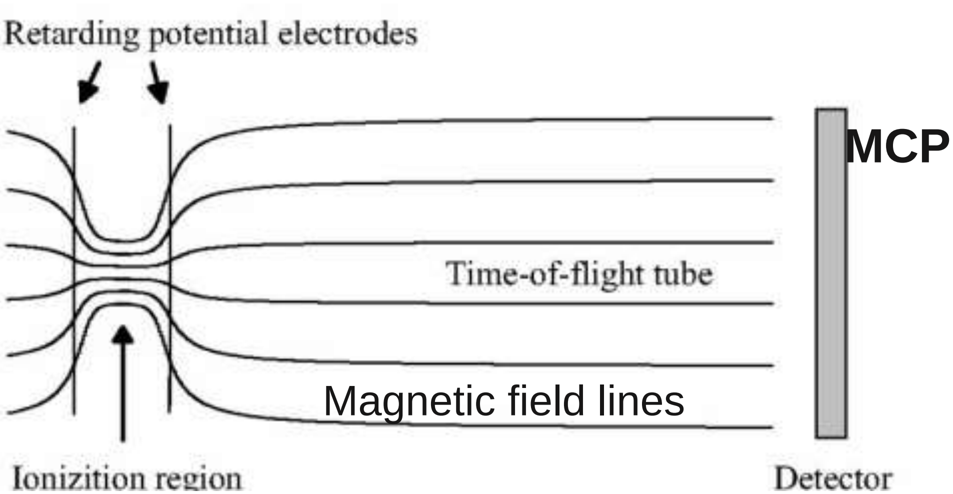
Spectral amplitude – no information about temporal features

Electron / ion detection



Time-of-flight spectrometer

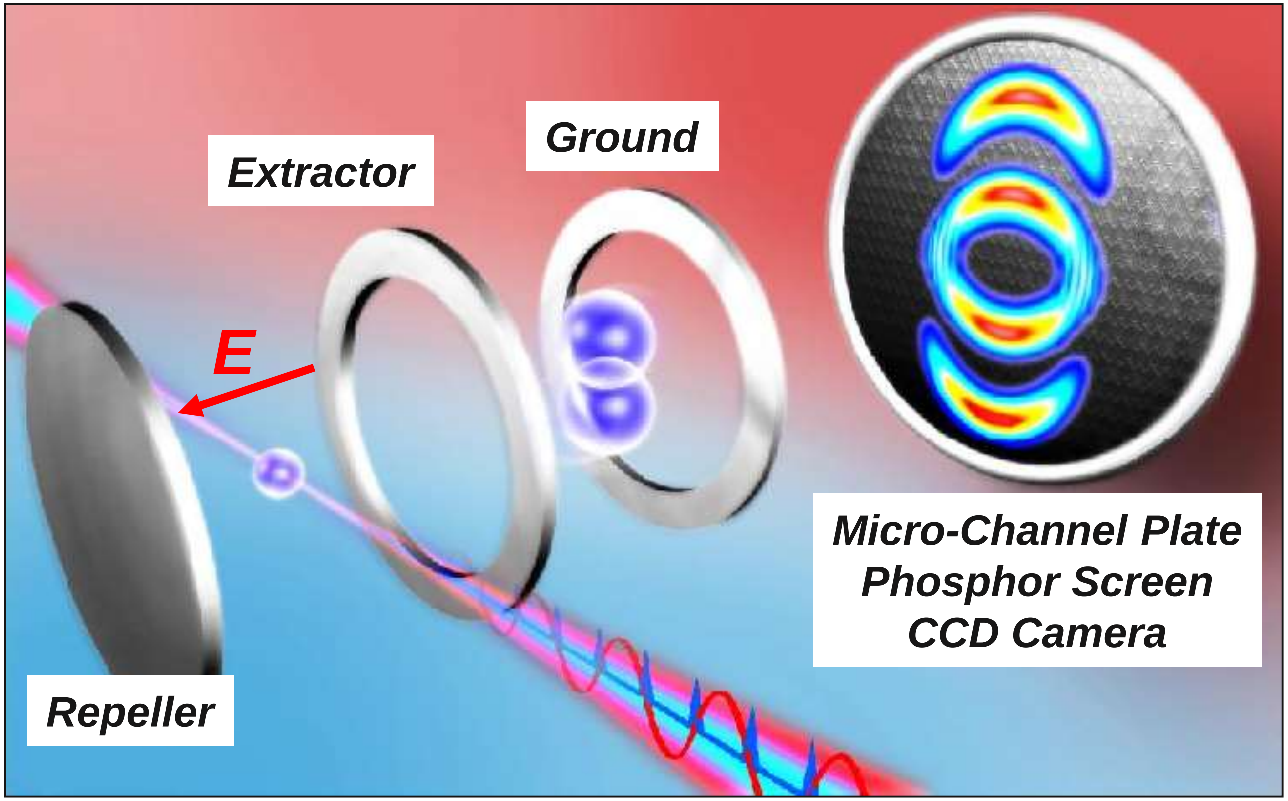
$$t \propto \frac{1}{v} \propto \sqrt{\frac{m}{q}}$$



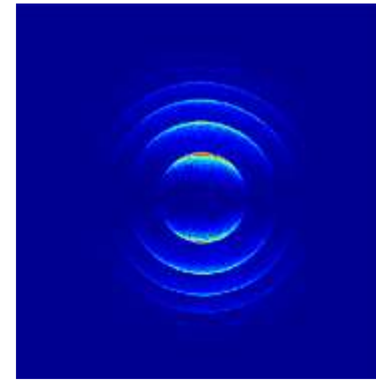
Magnetic Bottle Electron Spectrometer
photoionisation in a strong magnetic field (1T), reduced gradually towards the end of flight tube enables 2π collection of electrons

Velocity map imaging (VMI)

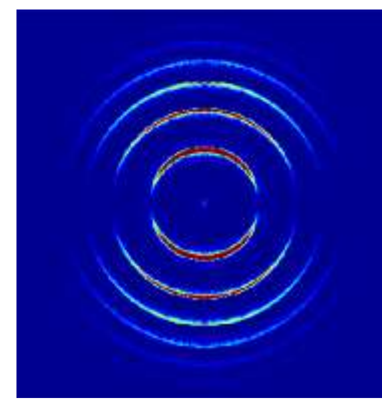
Eppink and Parker, Rev. Sci. Instr., 68, 3477 (1997)
Vrakking, Rev. Sci. Instrum., 72, 4084 (2001)



2D projection



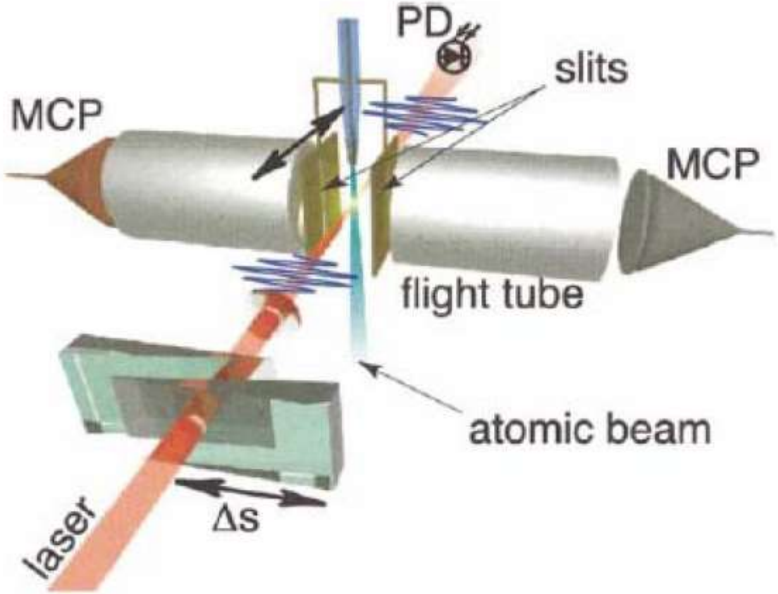
3D reconstruction



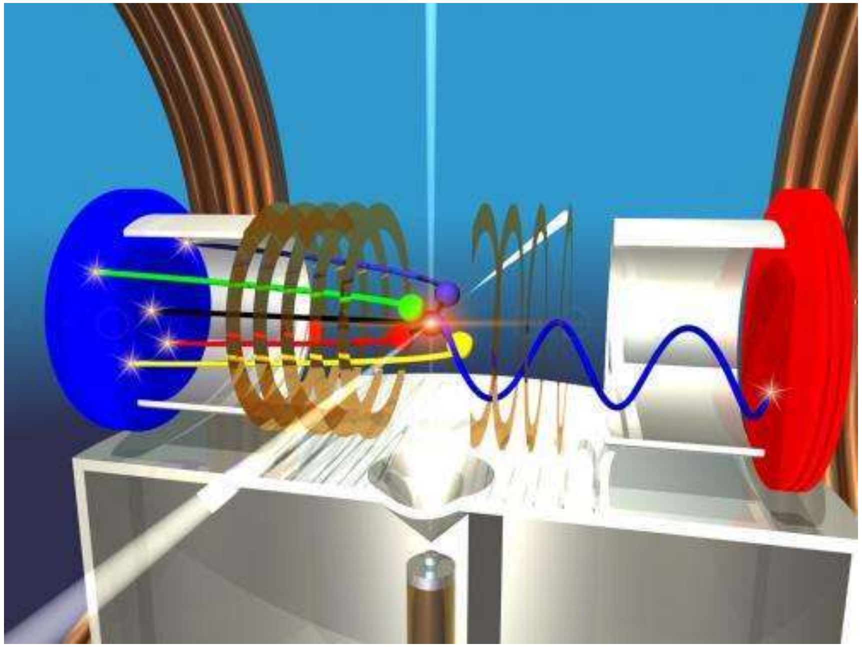
Detector captures the 2D projection of electron momentum distribution
+ assume symmetry around the E-field
Abel inverson → reconstruction of the full distribution

Stereo-machines

Coincidence measurements



Reaction Microscope / COLTRIMS



Temporal characterization

ultrashort laser pulses:

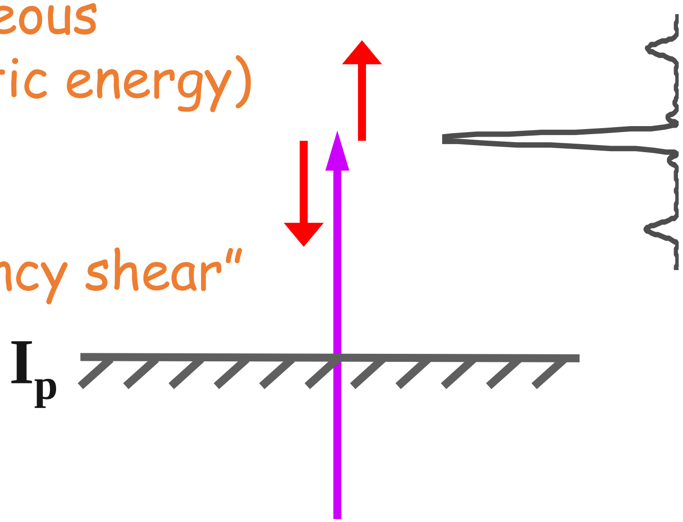
- autocorrelations (second/third order)
- SPIDER (spectral shear)
- FROG (second/third order)

} nonlinear effect

in the XUV regime???

photoionization can be considered an instantaneous process, conserving time-frequency (time-kinetic energy) properties

+ electron in the laser field undergoes „frequency shear"



in most cases we measure the electron/ion replicas

Temporal characterisation schemes

Autocorrelation

- 2nd order intensity volume autocorrelation (IVAC)

XUV SPIDER

Cross-correlation

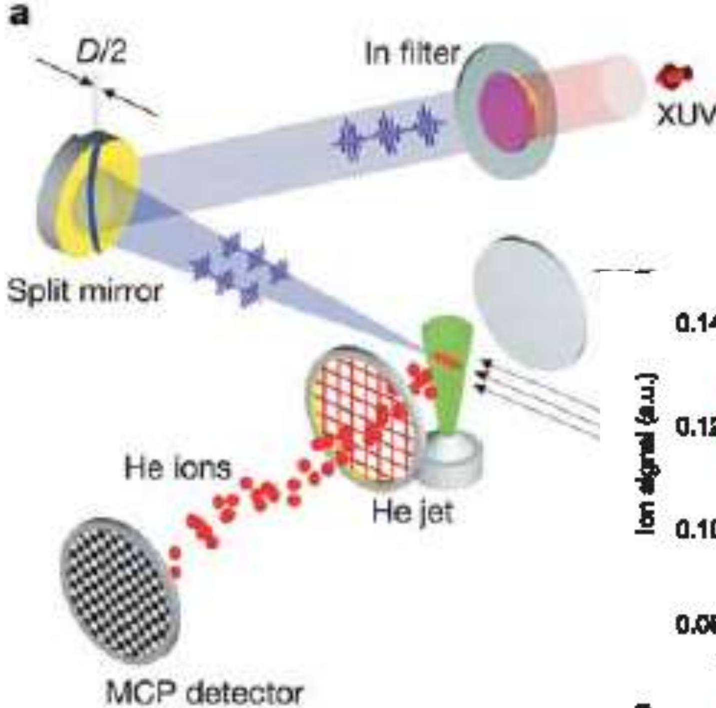
- X-FROG
- RABITT
- Asec streak camera
- FROG – CRAB

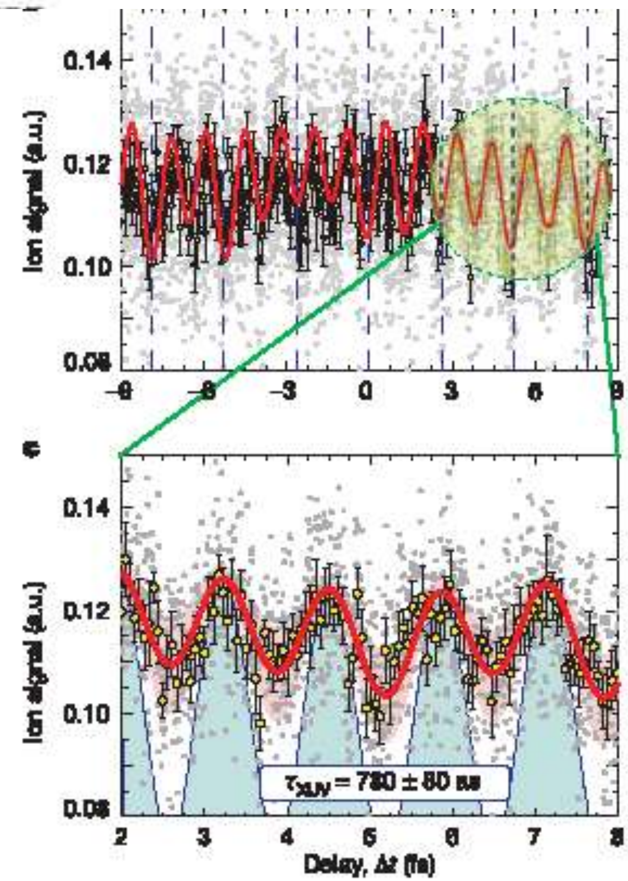
2nd order autocorrelation

Direct measurement of pulse duration

Requires:

- high XUV intensity
- nonlinear XUV detector (2-photon ionization of He)



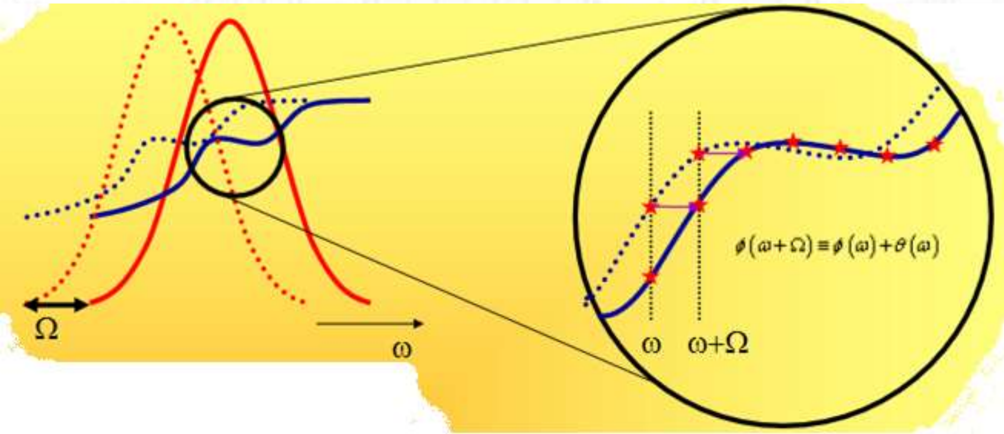


Status:

- spectral range: up till 30 eV
- pulse duration: 320 as

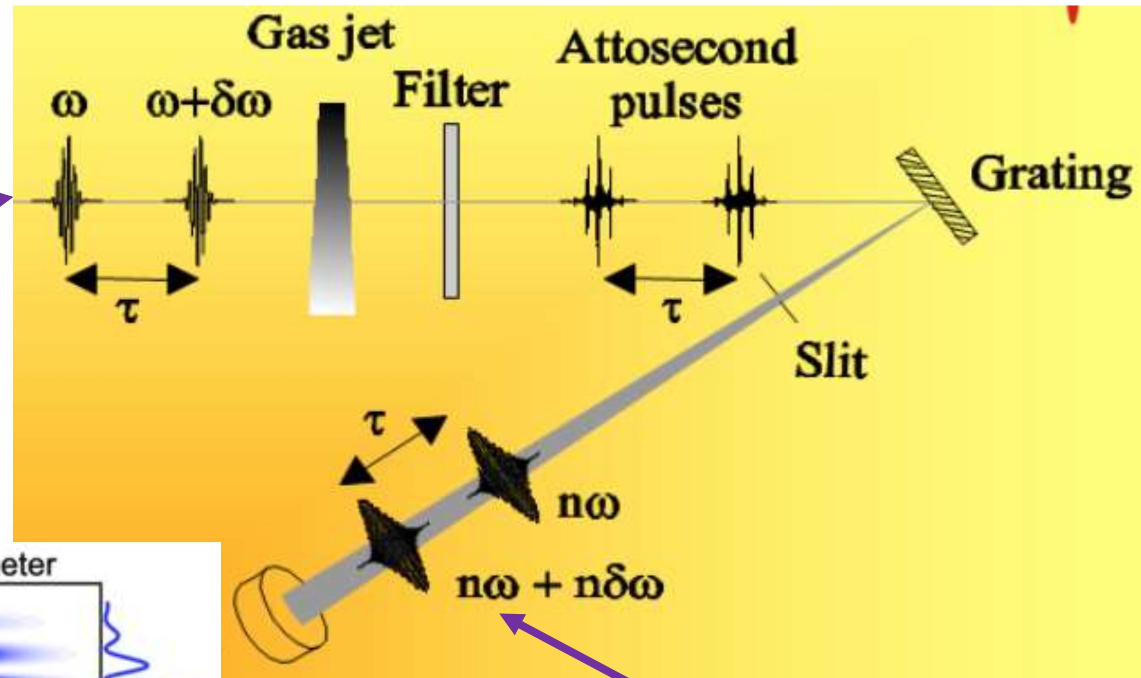
Tzallas: Nature, 426, 267 (2003)
Nabekawa: PRL 96, 083901 (2006)

XUV (SEA) SPIDER

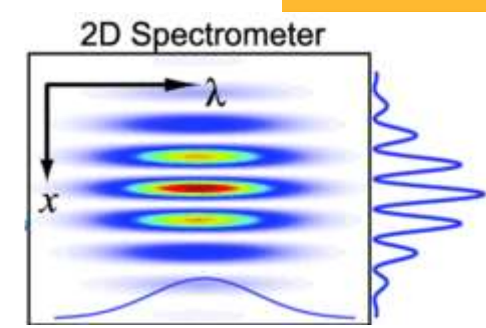


principle: spectral shear + delay interference

generating the spectral shear in the IR (Dazzler)



spectral shear in the XUV



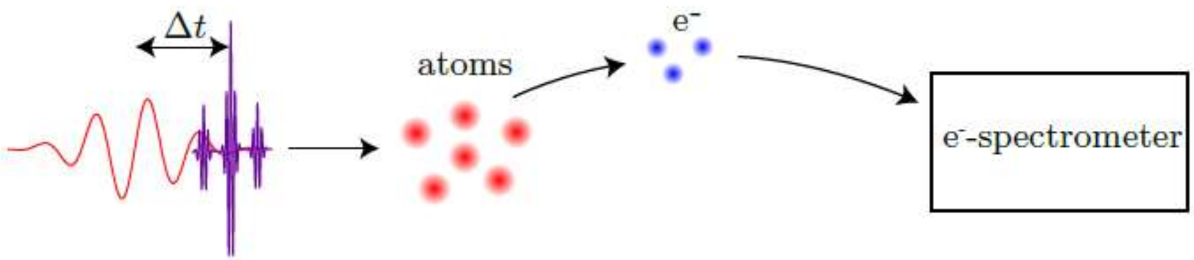
SPIDER fringes

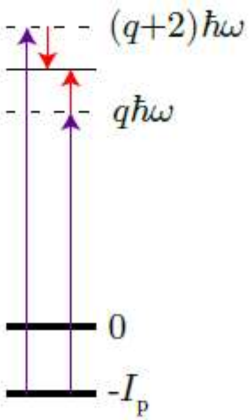
Cormier: PRL 94, 033905 (2005)
Mairesse: PRL 94, 173903 (2005)

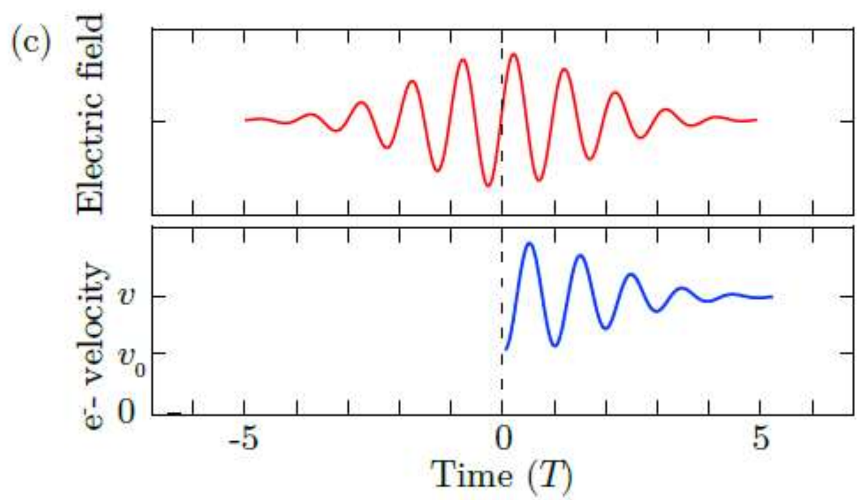
Cross-correlation

Low intensity of the high-harmonic radiation makes auto-correlation techniques less practical.

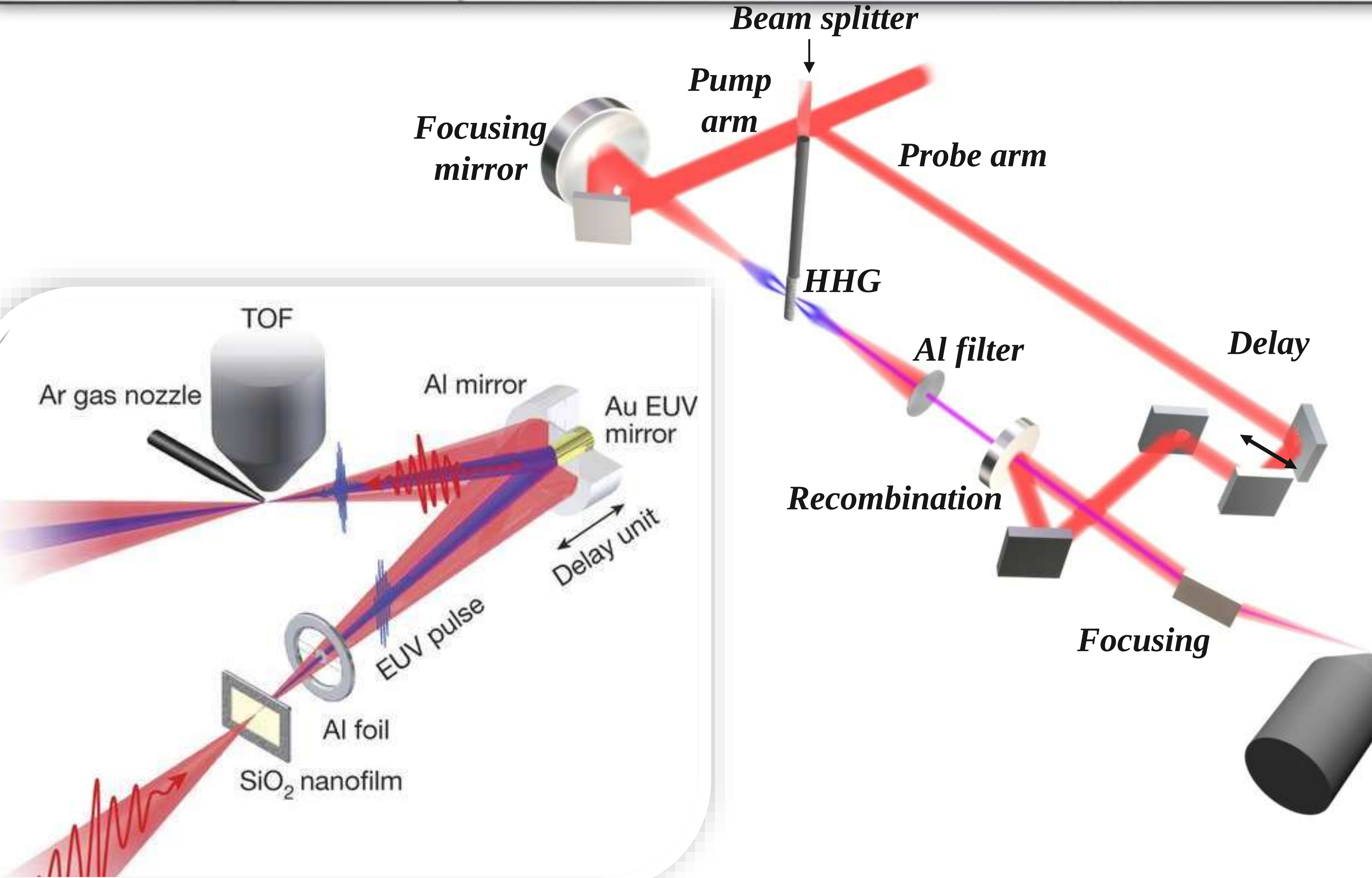
Scheme: XUV photoionization in the presence of the IR field



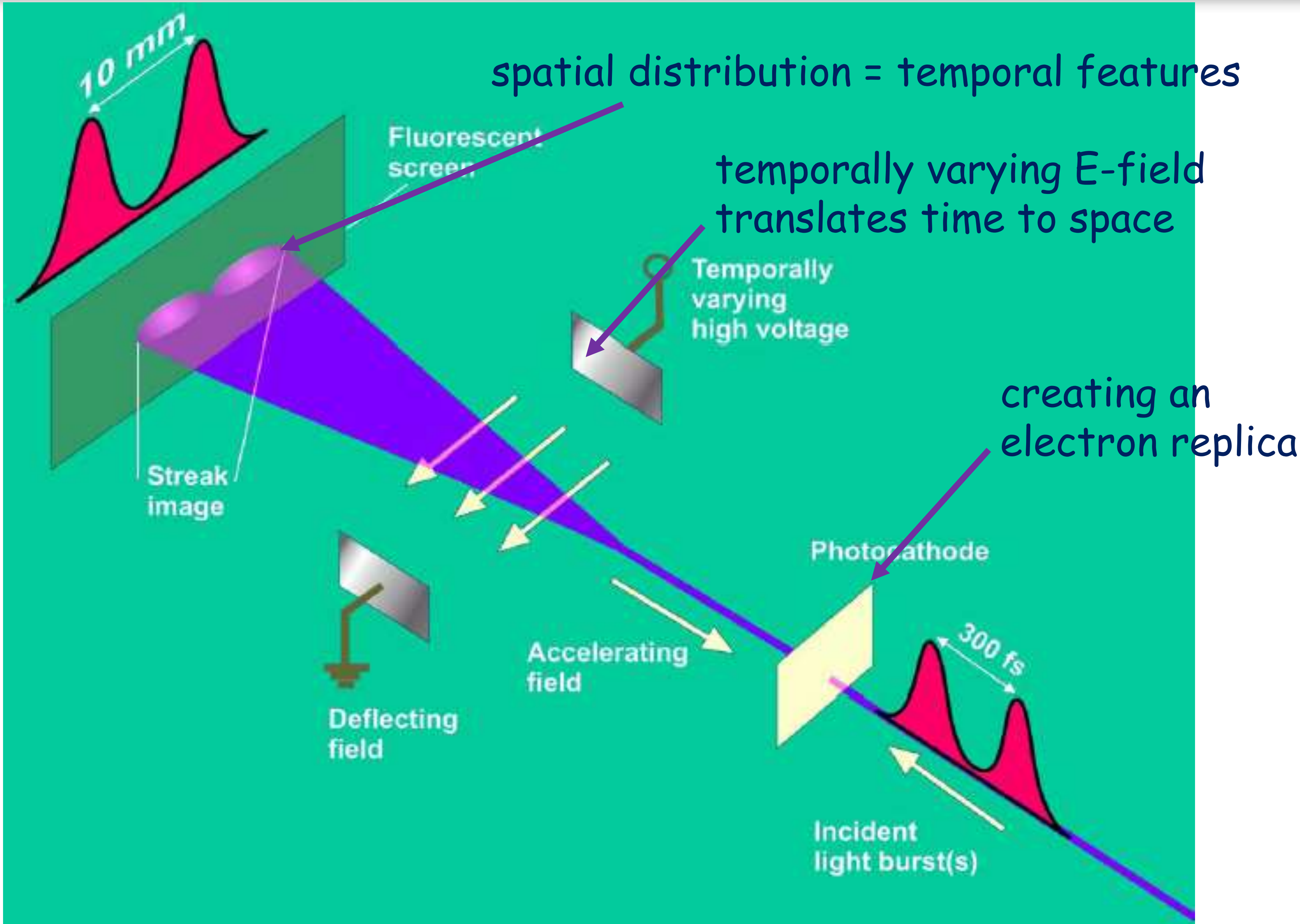




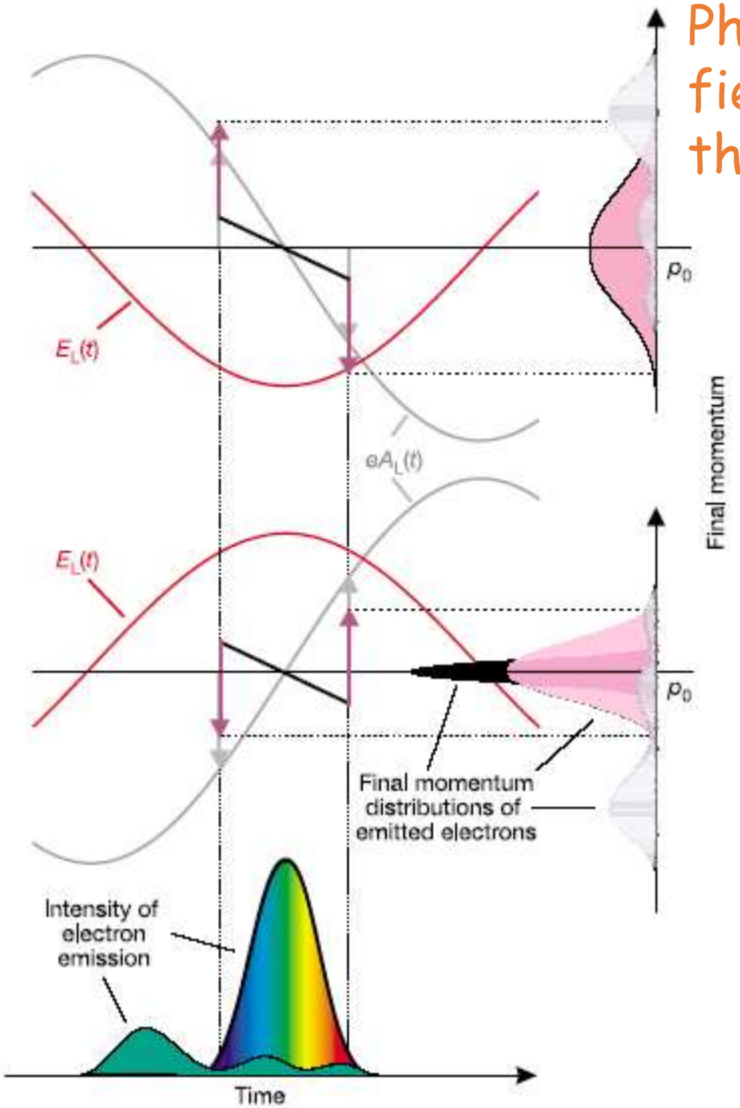
Experimental arrangement



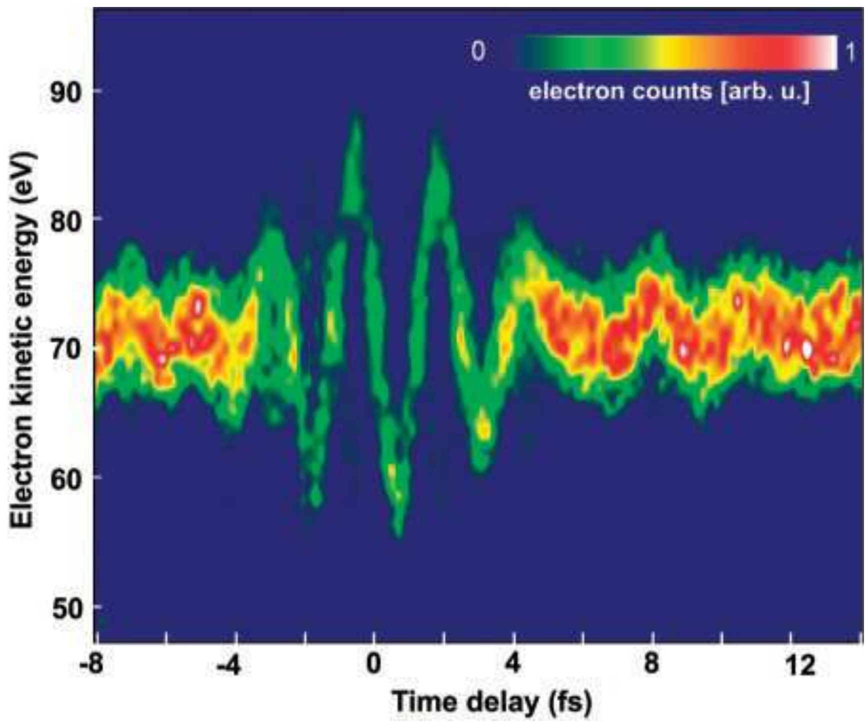
Conventional streak camera (ps)



Attosecondstreak camera (strong IR)



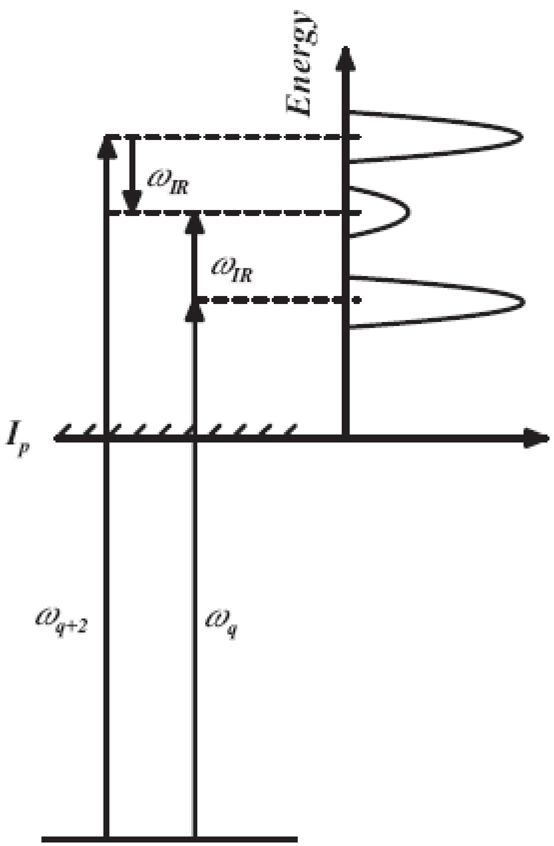
Photoionization in the presence of the IR field:
the IR E-field provides the fast streaking



Drescher: Science 291, 1923 (2001)
Itatani: PRL 88, 173903 (2002)
Kitzler: PRL 88, 173904 (2002)
Gouliemakis: Science 305, 1267 (2004)

Creation of sidebands (weak IR)

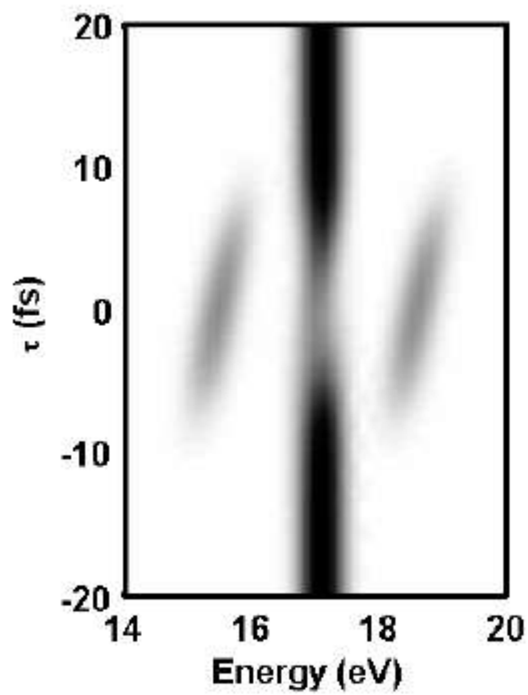
$$A_{SB}(\omega) = \int_{-\infty}^{\infty} dt\, e^{i(\omega - I_p/\hbar)t} \tilde{\varepsilon}_{XUV}(t)\, \varepsilon_{IR}(t-\Delta t) e^{i\Phi_{IR}(t-\Delta t)}$$



$$\tilde{\varepsilon}_{IR}(t) = \tilde{\varepsilon}^{+}_{IR}(t) + \tilde{\varepsilon}^{-}_{IR}(t),$$
$$\tilde{\varepsilon}^{+}_{IR}(t) = \tilde{A}_{IR}(t)\, e^{-i\omega_0 t},$$
$$\tilde{\varepsilon}^{-}_{IR}(t) = \tilde{A}^{*}_{IR}(t)\, e^{+i\omega_0 t}.$$

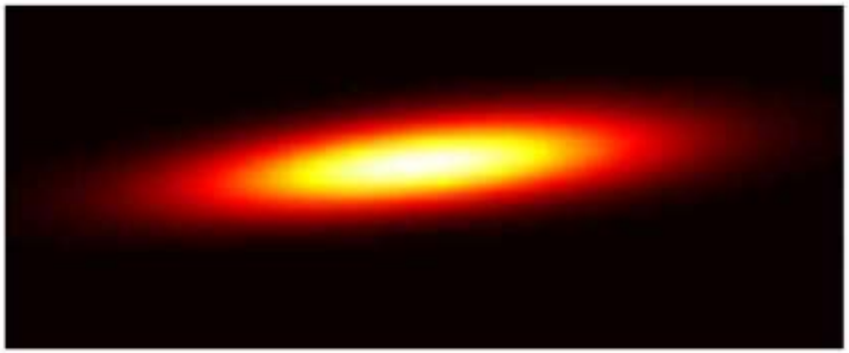
absorption, emission

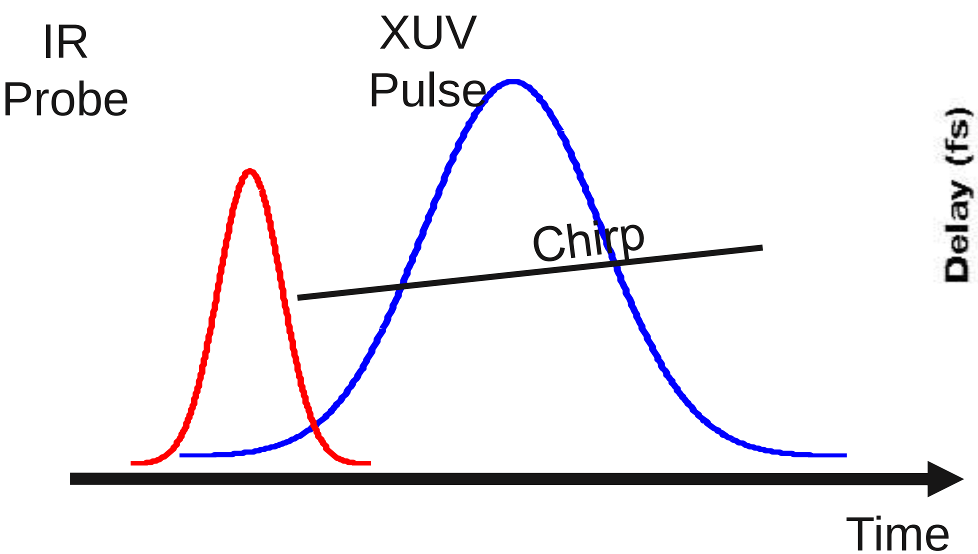
$$\tau^2_{XUV} = \tau^2_{SB} - \tau^2_{IR}$$

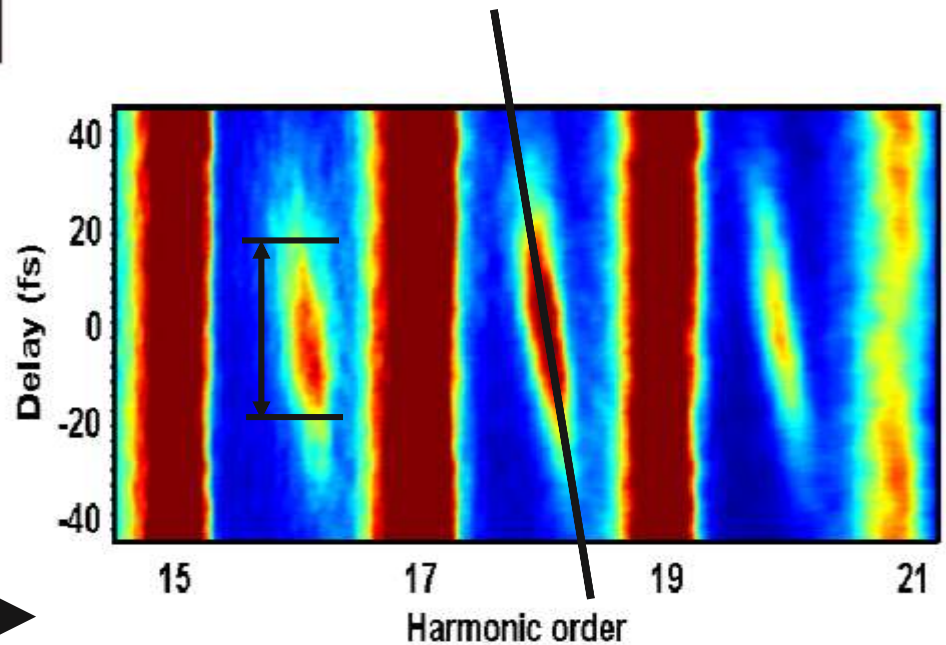


Femtosecond characteristics: XFROG

MAURITSSON: Phys. Rev. A. 70 021801R (2004)







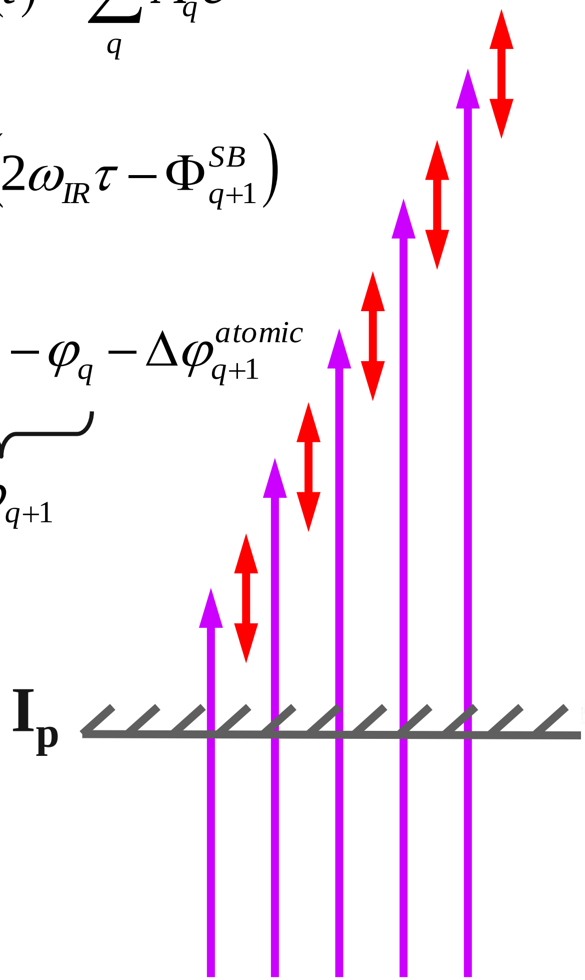
Attosecond characteristics: RABITT

Reconstruction of Attosecond Beating by Interference of Two-photon Transitions (RABITT)

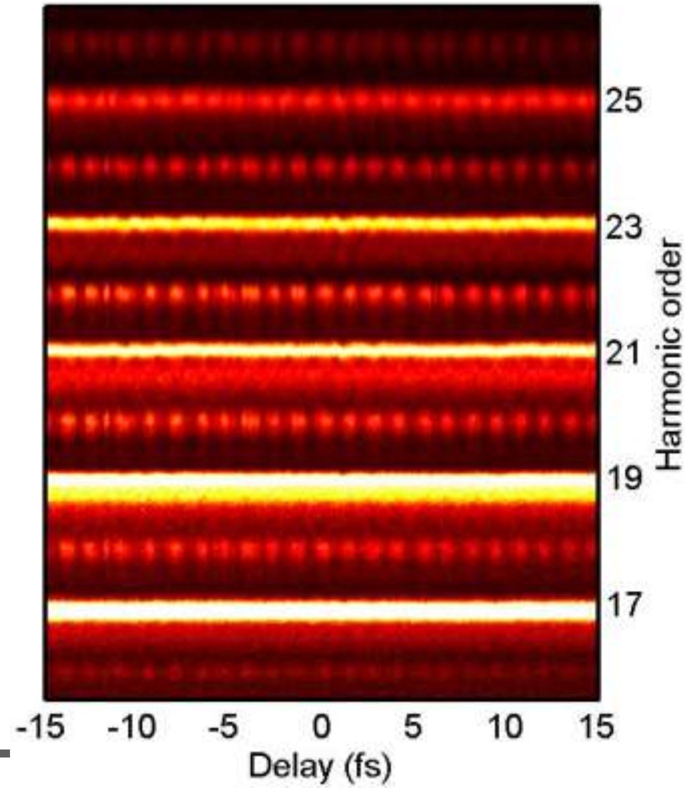
Harmonic field: $E(t) = \sum_q A_q e^{i\varphi_q}$

Sidebands: $I_{q+1}^{SB} \propto \cos\left(2\omega_{IR}\tau - \Phi_{q+1}^{SB}\right)$

phase-diff: $\Phi_{q+1}^{SB} = \underbrace{\varphi_{q+2} - \varphi_q}_{\Delta\varphi_{q+1}} - \Delta\varphi_{q+1}^{atomic}$



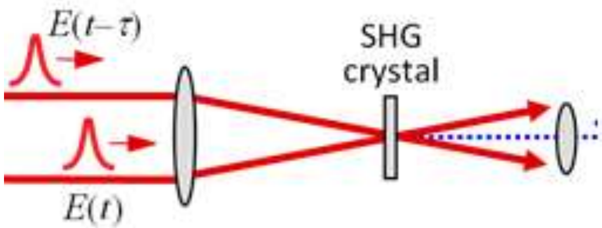
Photoelectron spectrum

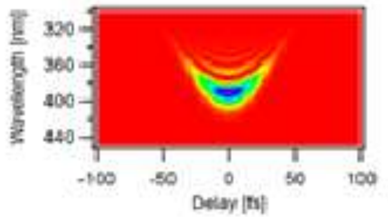


Paul: Science, 292, 1689 (2001)
Muller: Appl. Phys. B74, S17 (2002)
Mairesse: Science 302, 1540 (2003)

FROG CRAB

Frequency Resolved Optical Gating for Complete Resolution of Attosecond Bursts



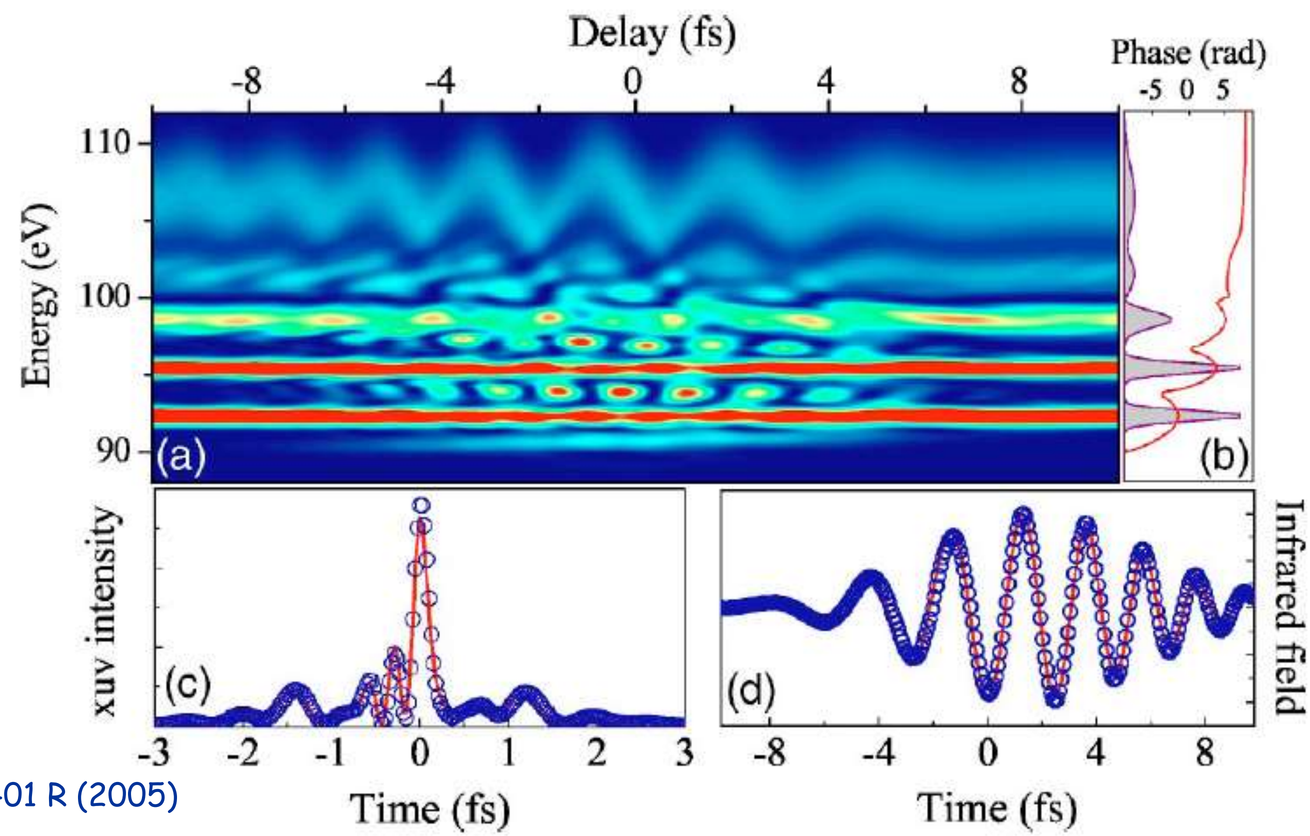


FROG:

- gate pulse
- delay resolved spectrogram
- iterative reconstruction proc.

FROG CRAB

- gated by the generating IR pulse
- reconstruction of both IR and XUV pulses



Mairesse: PRA 71, 011401 R (2005)

FROG CRAB - examples

isolated attosecond burst

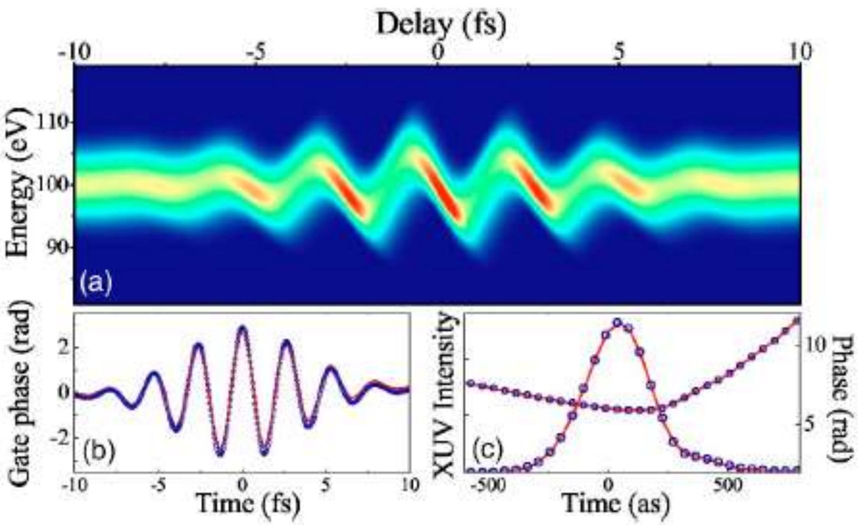


FIG. 1. (a) CRAB trace of a single 315 as pulse [full width at half maximum (FWHM) of intensity], having second- and third-order spectral phases (Fourier limit=250 as), gated by a Fourier-limited 6-fs 800 nm laser pulse, of 0.5 TW/cm^2 peak intensity. The electrons are collected around $\theta=0$ with an acceptance angle of ±30°. (b), (c) A comparison of the exact as pulse and the laser-induced gate phase $\phi(t)$ (full line) with the corresponding reconstructions (dots) obtained from the CRAB trace after 100 iterations of the PCGPA algorithm [20]. The gate modulus $|G(t)|$ is constant and equals to 1.

attosecond pulse train

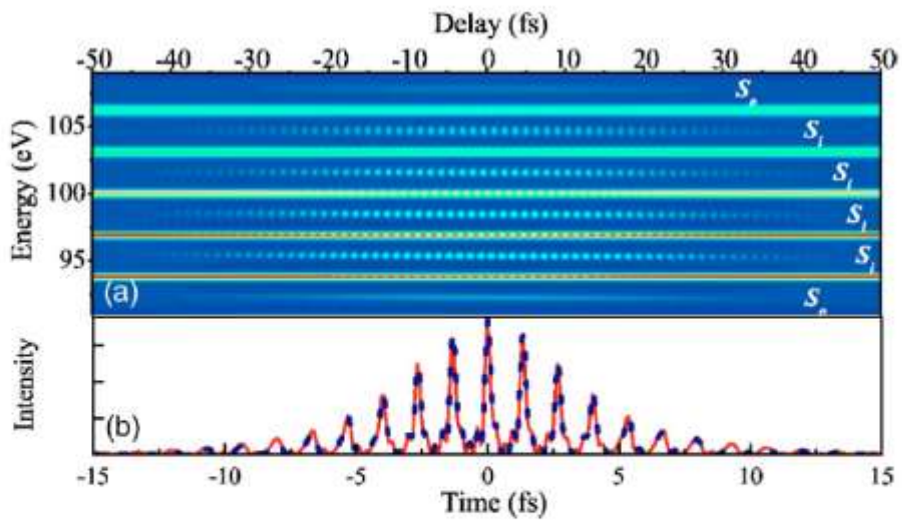
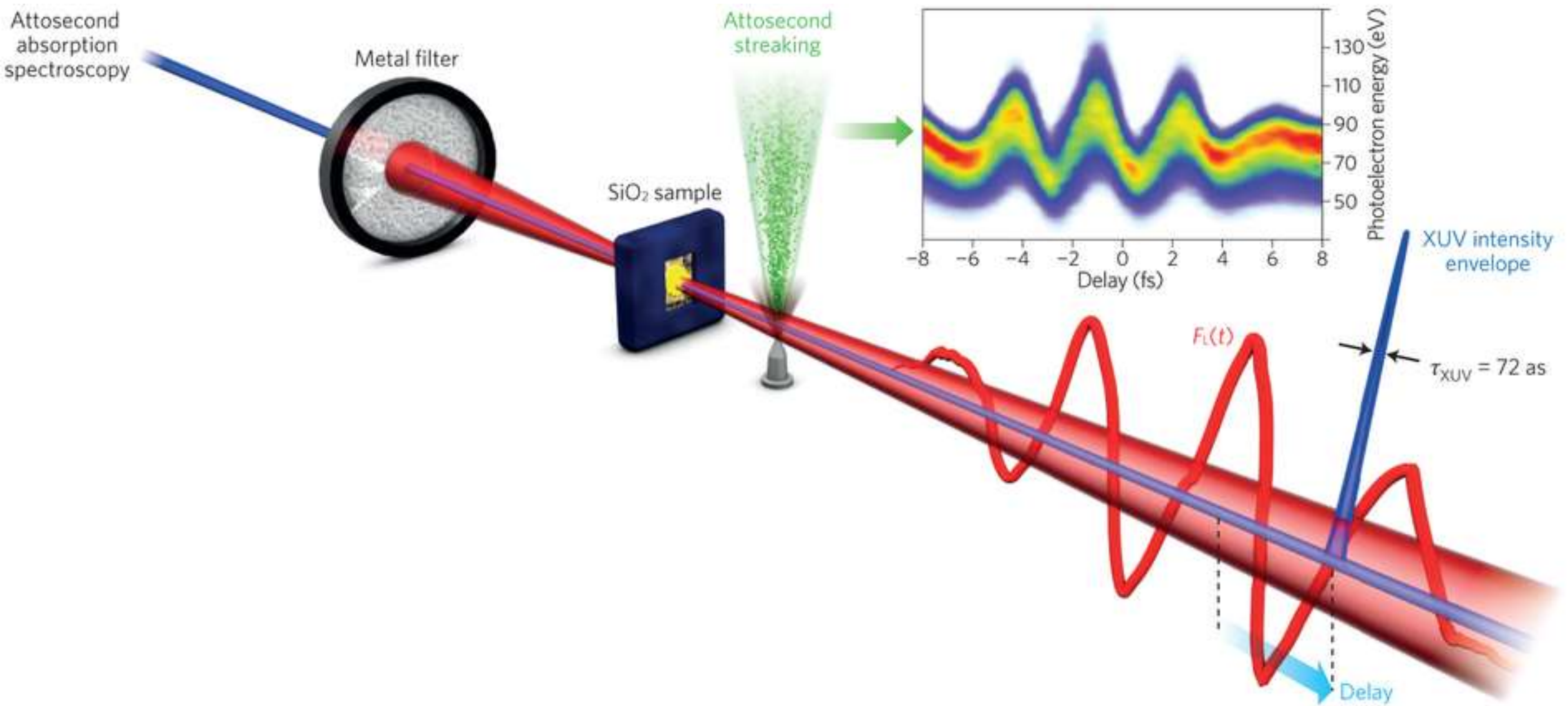


FIG. 2. (a) CRAB trace at $\theta=0$ of a 12-fs-train of nonidentical as pulses, of period $T/2=1.3$ fs, gated by a 30-fs-800 nm- ($T=2.6$ fs) laser pulse, of 0.05 TW/cm^2 peak intensity, assuming a spectrometer resolution of 100 meV. The as pulses are shorter in the center of the train (≈250 as), than in the edges (≈400 as). The outer and inner sidebands are respectively labelled S_o and S_i. (b) A comparison of the exact as train (red line) and the reconstruction (dotted blue line) obtained from the CRAB trace after 750 iterations of the PCGPA algorithm.

Mairesse: PRA 71, 011401 R (2005)

On-line characterisation



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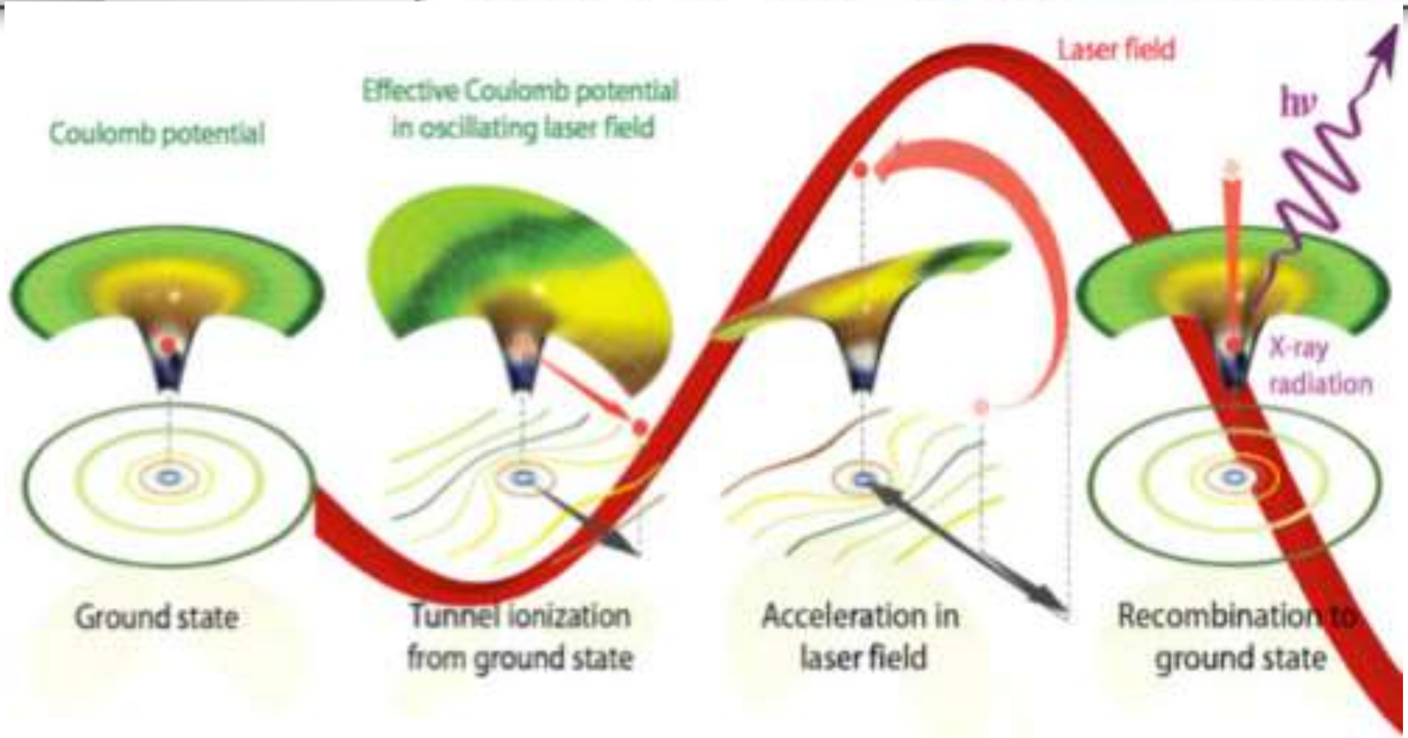
„Delay" of the HHG process



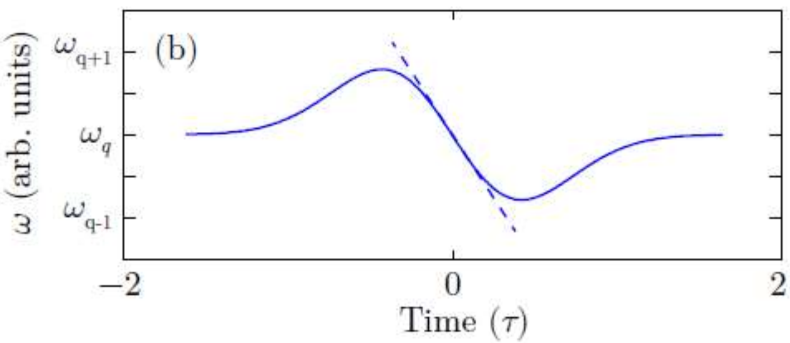
HHG is a non-instantaneous process: electron travels in the continuum, ie the harmonics are shifted in phase relative to the fundamental: phase of the dipole moment.

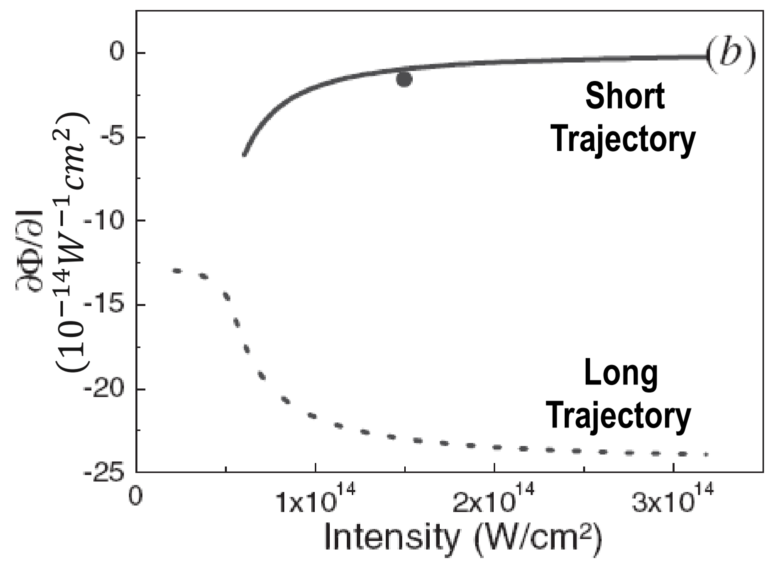
Phase depends on harmonic order and intensity and trajectory type (short/long)!
Short andlong trajectory components can be distinguished based on spectral and spatial characteristics.

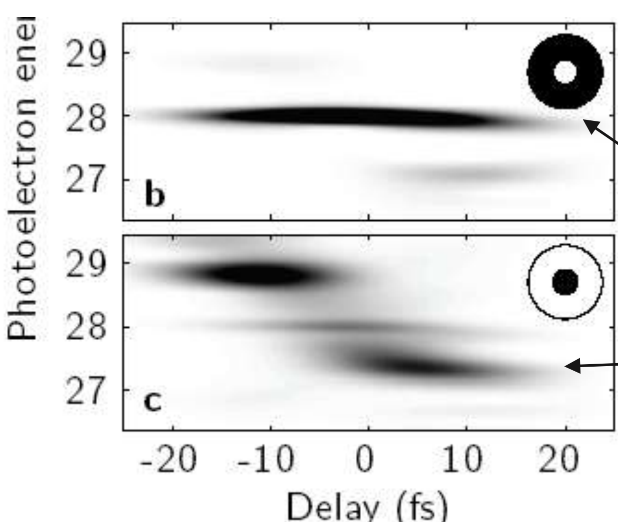
Multicycle phase modulations: harmonic chirp

The intensity of the driving pulse varies on the multicycle timescale
+ dipole phase depends on intensity $\Rightarrow$ time-dependent phase

$$\omega_q(t) = q\omega_0 + \frac{\partial \Phi_j}{\partial t} = q\omega_0 + \alpha(q)\frac{\partial I}{\partial t} \approx q\omega_0 - \alpha(q)\frac{8\ln(2)I_0}{\tau^2}t$$





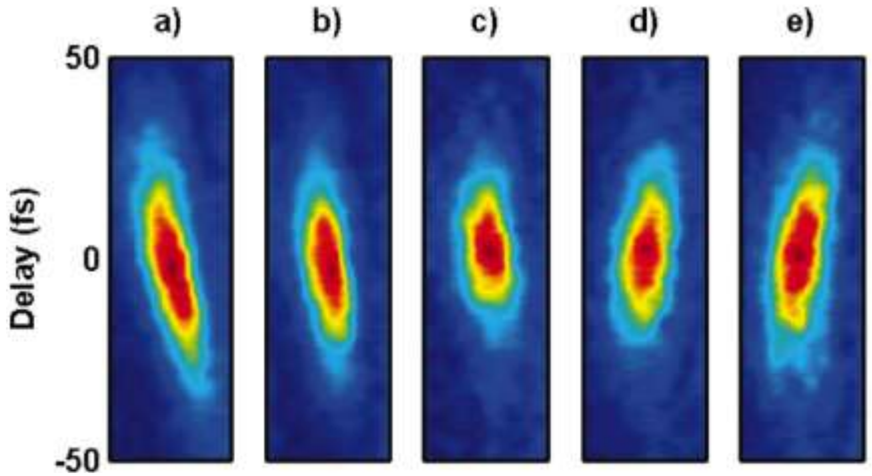


short trajectories
long trajectories
possess chirp of different magnitudes

Generating harmonics with a chirped fundamental

varying the chirp of the fundamental

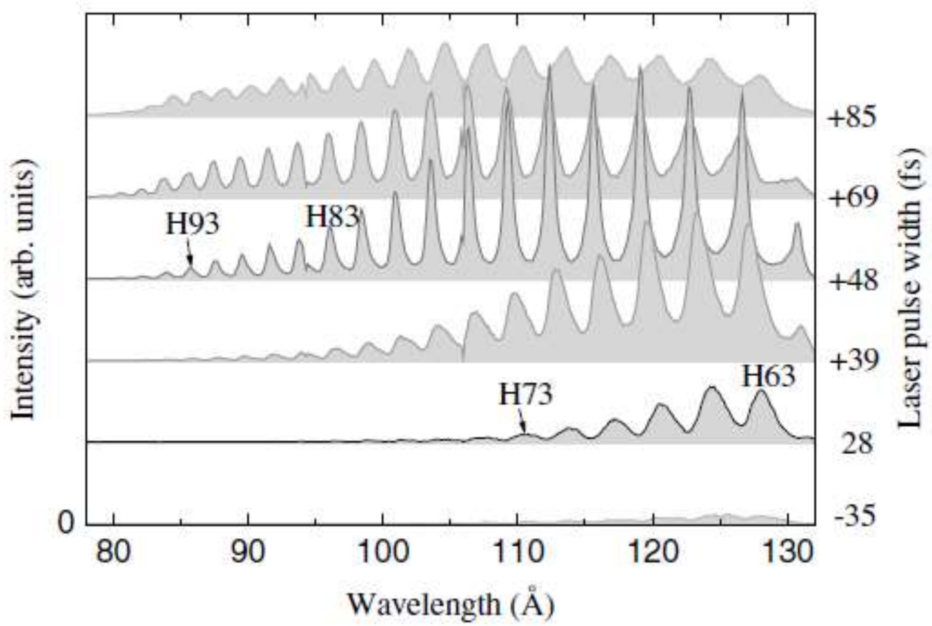
$$b_j^q = q\,b_{\text{fund}} + 8\,\ln(2)\frac{I_0}{\tau_0^2}\frac{\partial \Phi_j^q}{\partial I}$$



	(a)	(b)	(c)	(d)	(e)
GDD_{fund} (s^2)	−1	−0.6	0	0.3	0.6×10^{-27}
τ_{fund}(fs)	90	44	37	42	57

MAURITSSON: Phys. Rev. A. 70 021801R (2004)

adding a suitable positive chirp to the fundamental can compensate the chirp resulting from the intensity dependence of the atomic phase:



Lee, PRL 87, 243902

Subcycle phase modulations: attosecond structure

Determined by the frequency dependence of the harmonic phase

$$\Phi = \Phi_q$$

$$\Phi_q = \Phi_{q0} + \frac{\partial \Phi}{\partial q}(q - q0) + \frac{1}{2}\frac{\partial^2 \Phi}{\partial q^2}(q - q0)^2 + \ldots$$

group delay

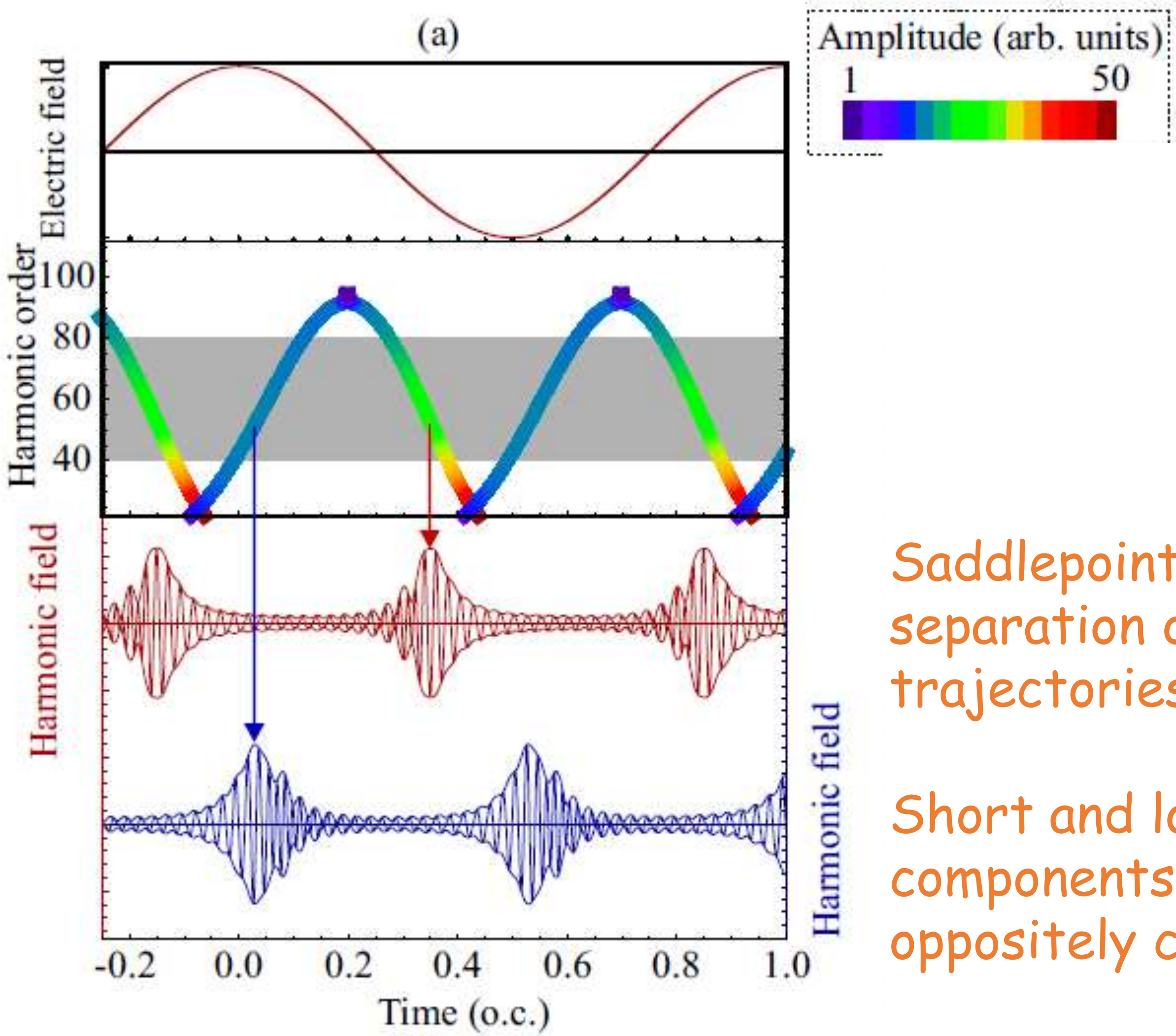
group delay dispersion
related to chirp

$$\frac{\partial}{\partial q} \quad \to \quad \frac{1}{\omega 0}\frac{\partial}{\partial q} = \frac{\partial}{\partial \Omega}$$

emission time or group delay

$$t_{e,j}^q = \frac{1}{\omega}\frac{\partial \Phi_j^q}{\partial q}$$

Attochirp for short and long trajectory components

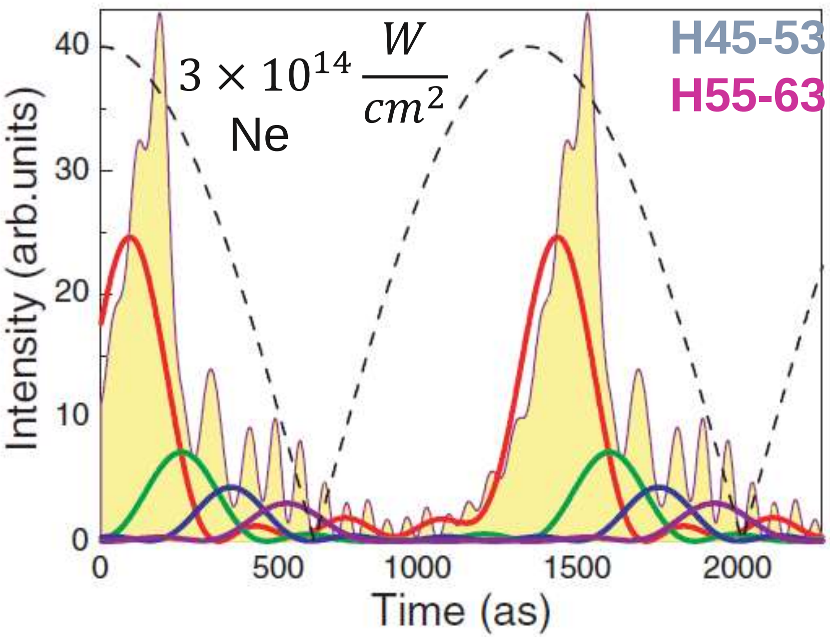


corresponding to emission in each halfcycle

Saddlepoint analysis enables separation of short and long trajectories.

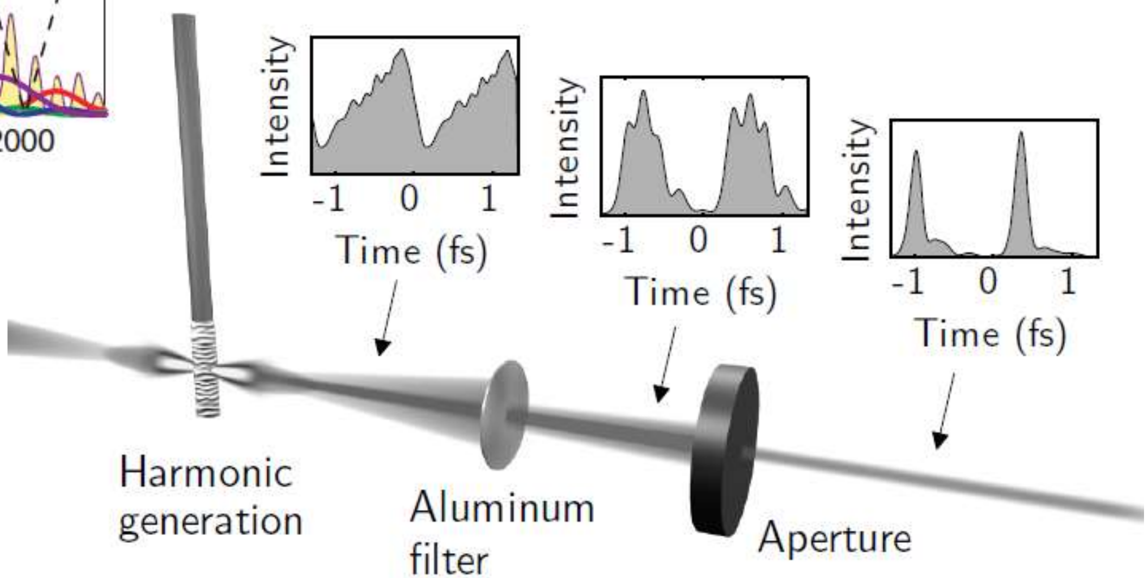
Short and long trajectory components are delayed and oppositely chirped: attochirp.

Attosecond pulse train synthetised from a broad sectrum



Mairesse, Science 302, 1540

postcompression is required for short pulse generation

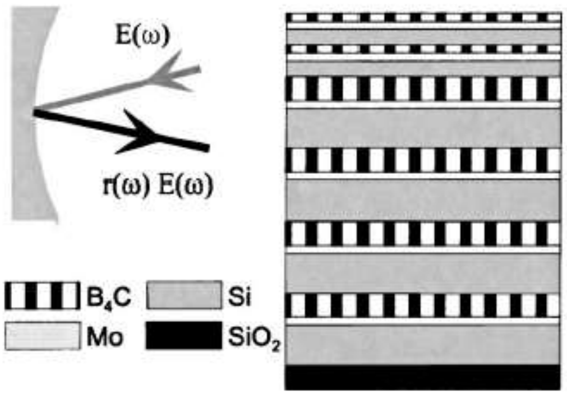


López-Martens PhysRevLett (2005)

Postcompression of attosecond pulses

XUV chirped mirror

aperiodic multilayer structure



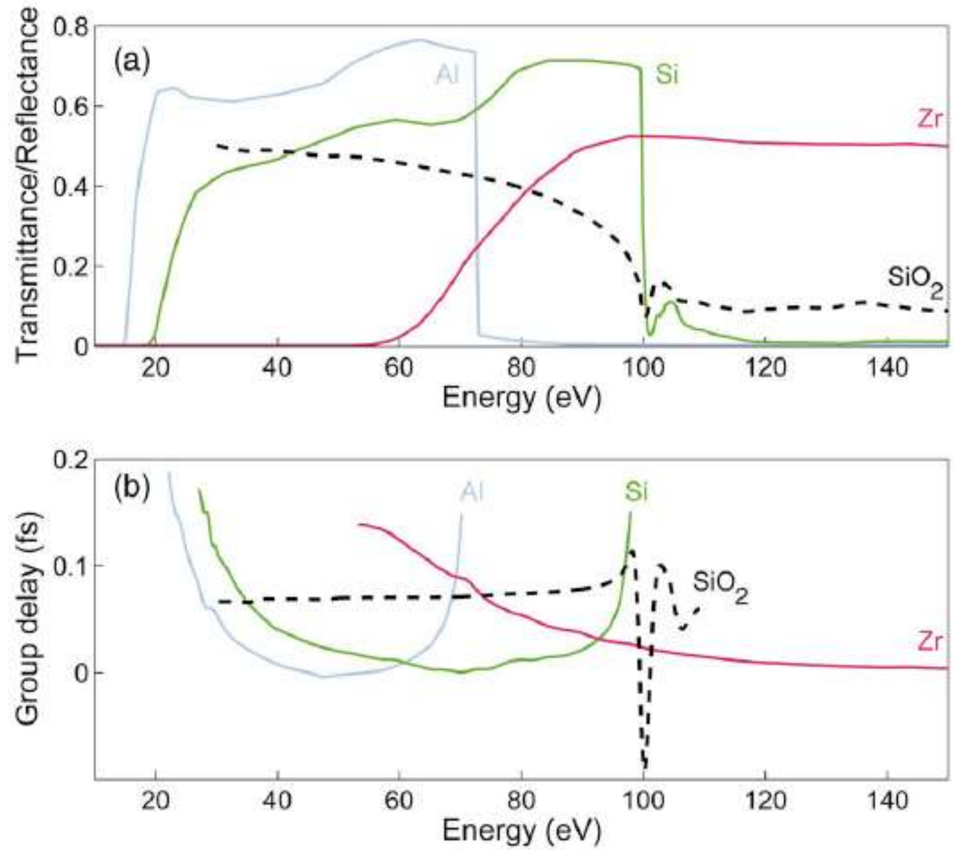
uncertainty in refractive indices

very severe conditions on layer thickness precision

Morlens: Opt Lett 31, 1558 (2006)

Metallic films

anomalous dispersion just above the absorption band

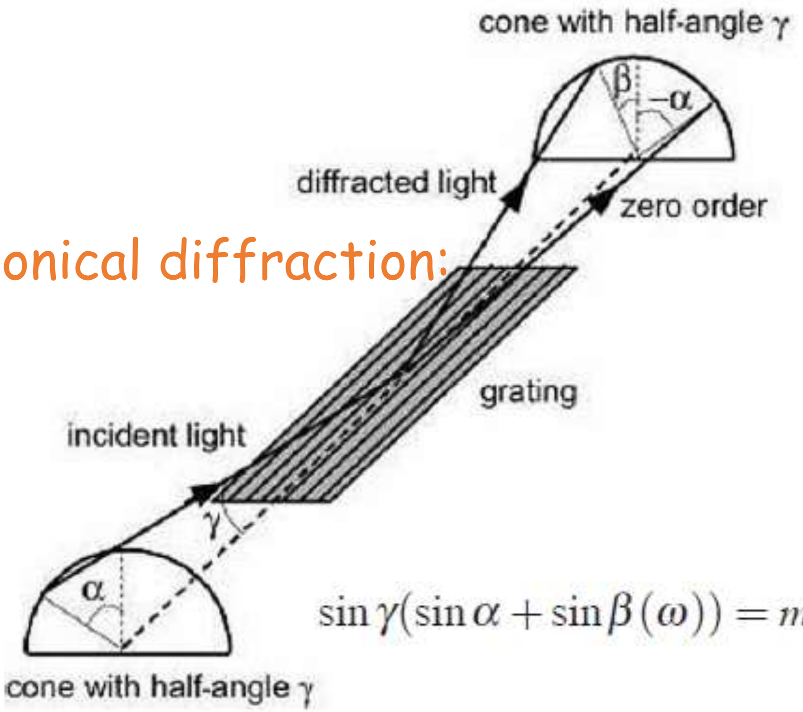


200 nm thick filters

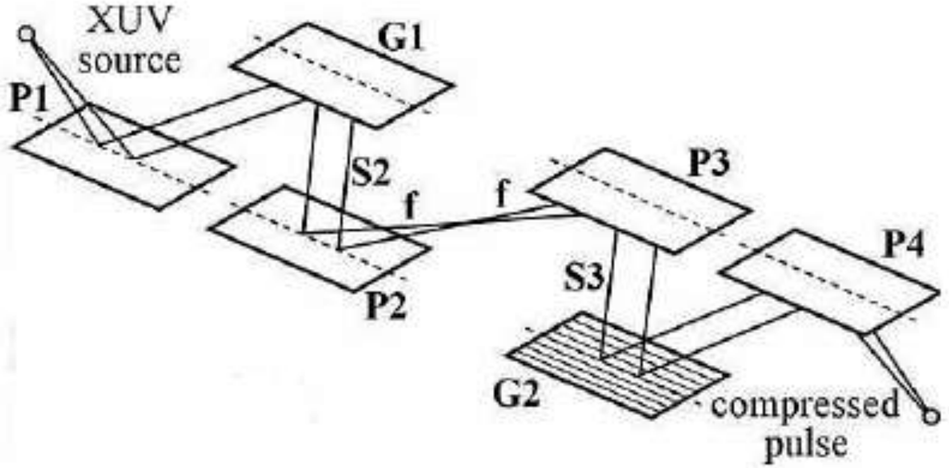
Gustafsson: Opt Lett 32, 1353 (2007)

Grazing incidence grating compressor

conical diffraction:

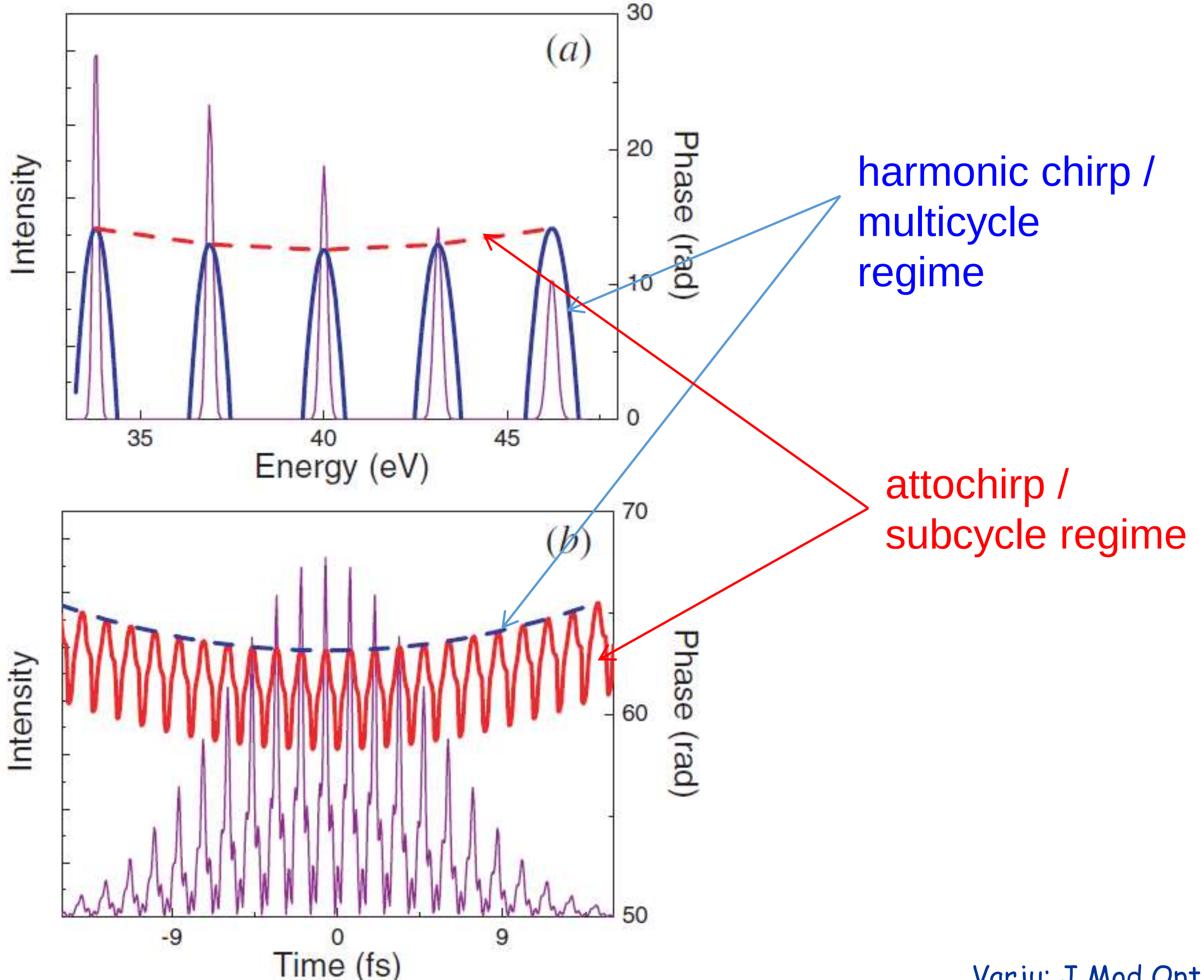


$$\sin\gamma(\sin\alpha+\sin\beta(\omega))=m\lambda(\omega)\sigma$$



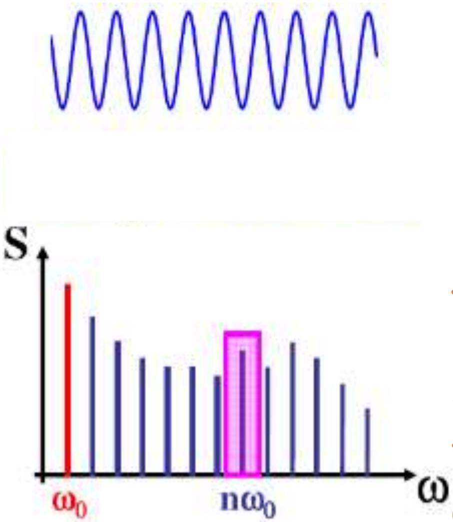
Mero: Opt Exp 19, 23420 (2011)

Spectral and temporal phase of the high harmonic radiation

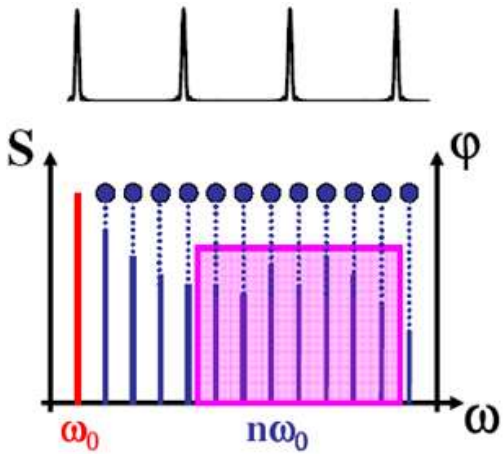


Varju: J Mod Opt 20, 379 (2005)

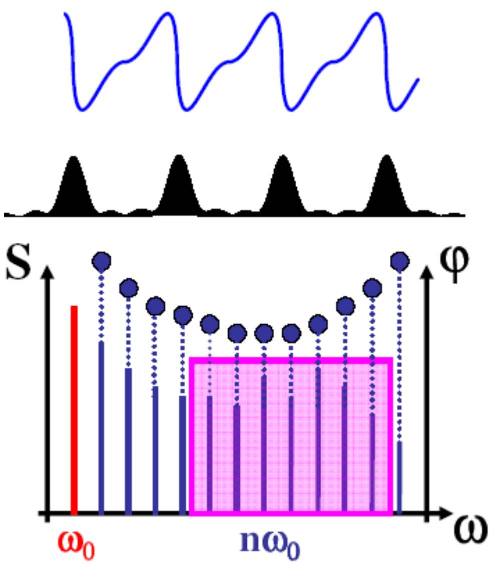
Complete characterization of the spectral phase



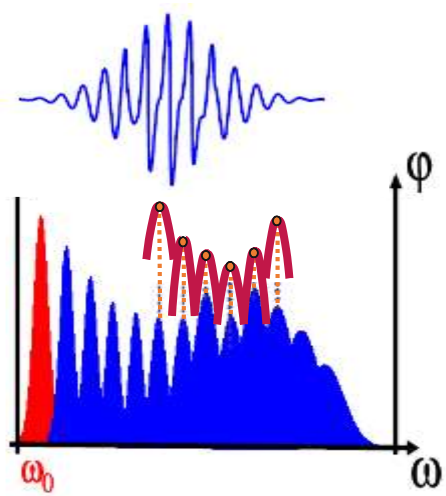
single harmonic corresponds to a cw emission



multiple harmonics phaselocked corresponds to an attosecond pulse train



multiple harmonics with quadratic spectral phase corresponds to chirped attosecond pulses in the train



chirped individual harmonics correspond to broader harmonics and pulse-to-pulse variations in the attosecond pulse train

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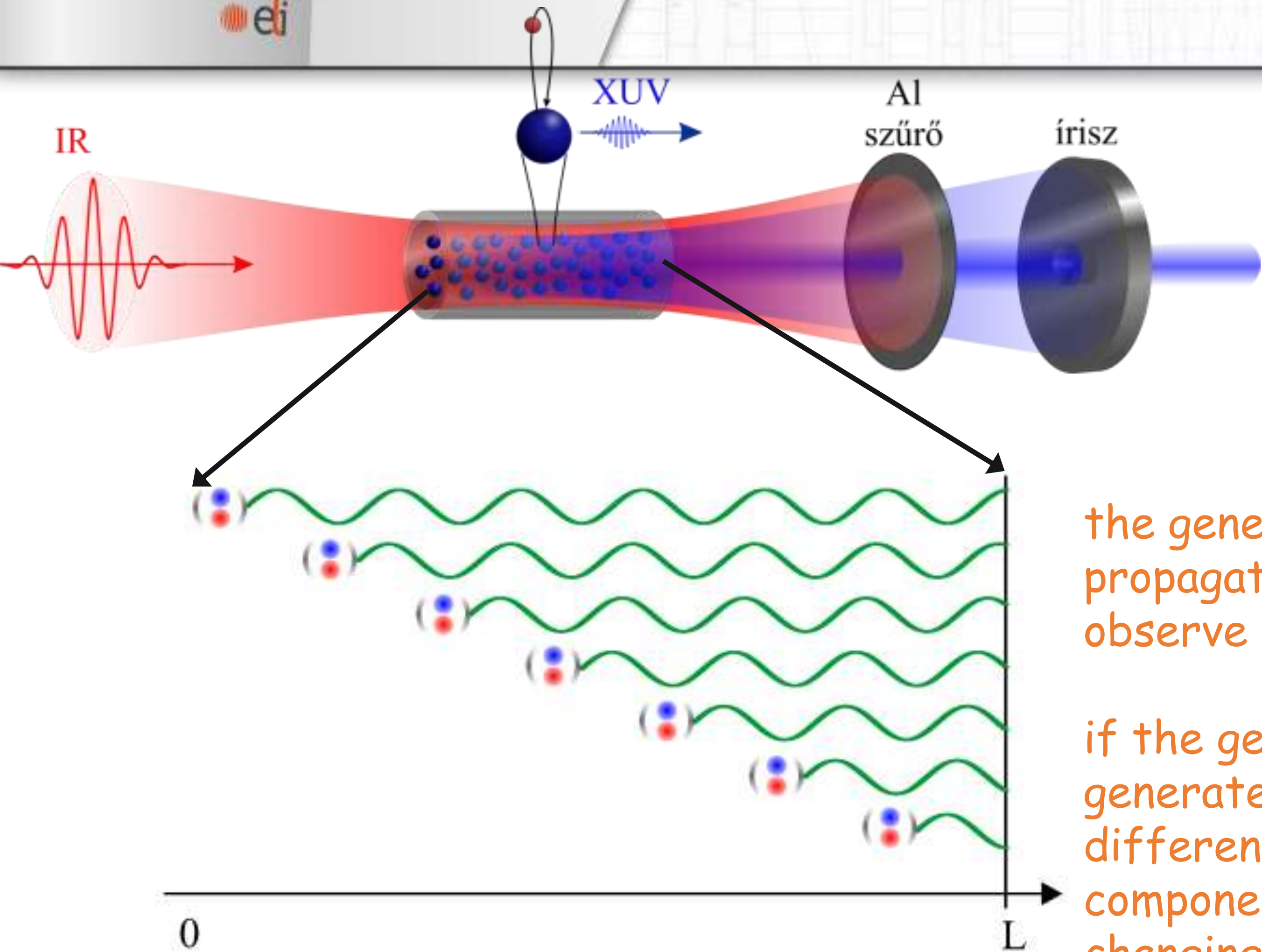
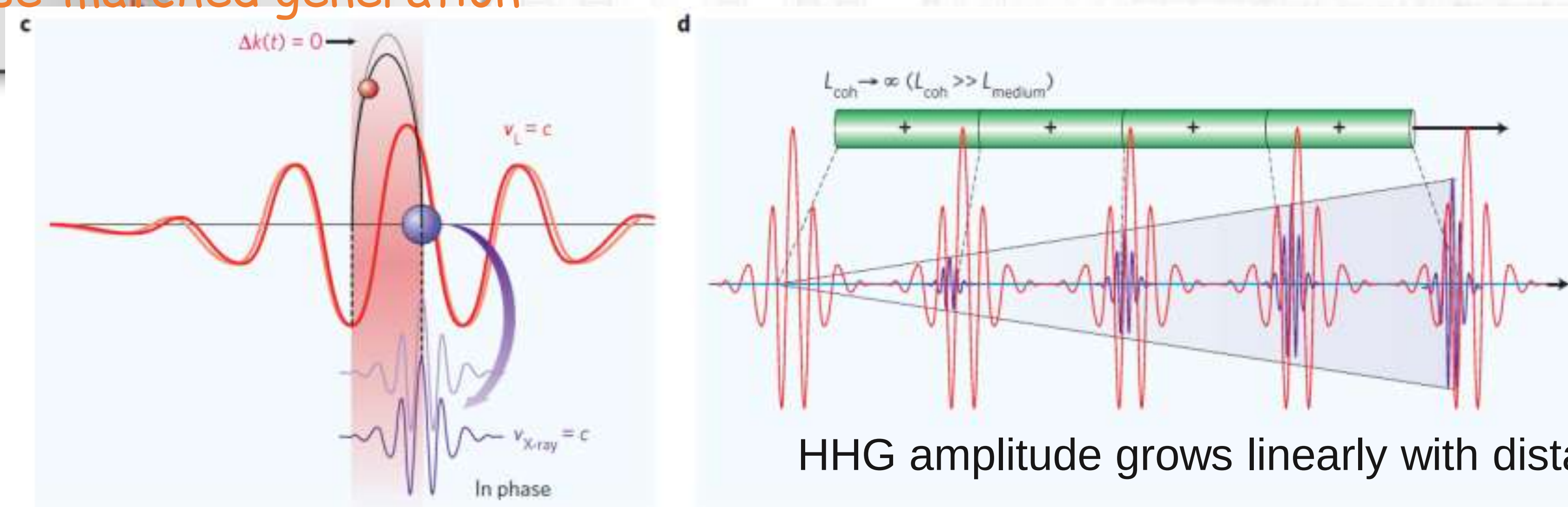
The role of phase-matching



the generated elementary waves propagate in the medium, and we observe their superposition

if the generating field and the generated component has a different velocity, the components add with a spatially changing phase: the harmonic signal oscillates with medium thickness

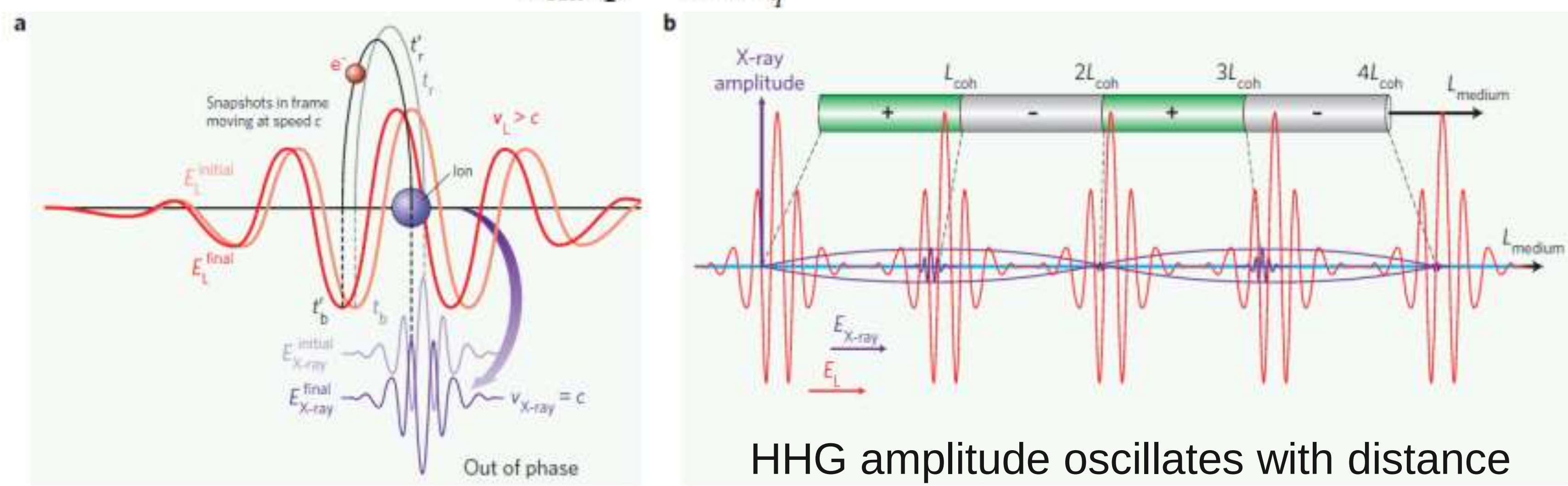
Phase-matched generation



HHG amplitude grows linearly with distance

Non-phase-matched generation

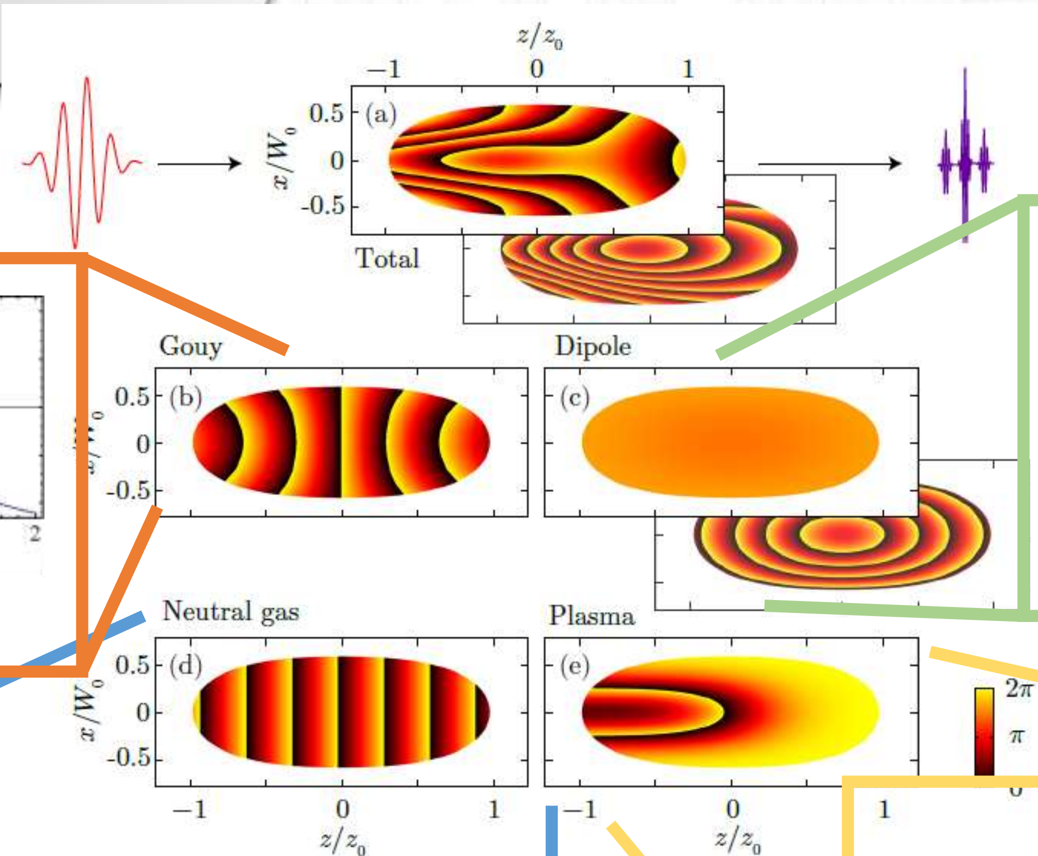
$$L_{\mathrm{coh}}(q) = \pi/\Delta k_q$$

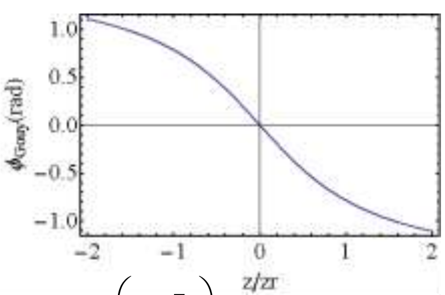


HHG amplitude oscillates with distance

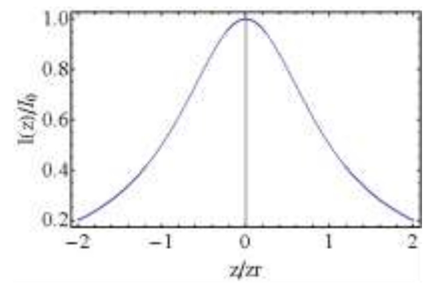
Popmintchev: Nphot 4, 822 (2010)

Components of phase-mismatch





$$arctg\left(-\frac{z}{z_R}\right)$$



$$\varphi_d = -\alpha\, I$$

$$\sqrt{1-\frac{\omega_p^2}{\omega^2}} \cong 1-\frac{1}{2}\frac{e^2 N_e}{\omega^2 \varepsilon_0 m_e}$$

Plasma contribution always < 0
Scales as λ^2

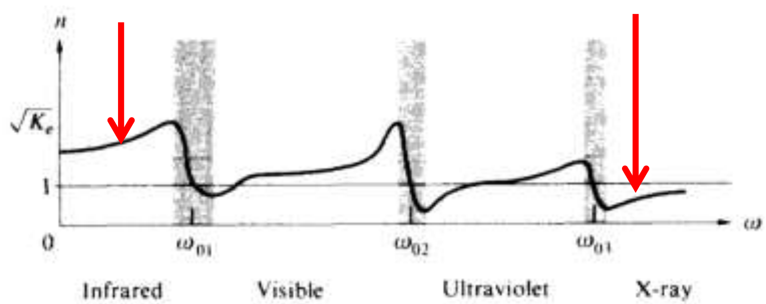
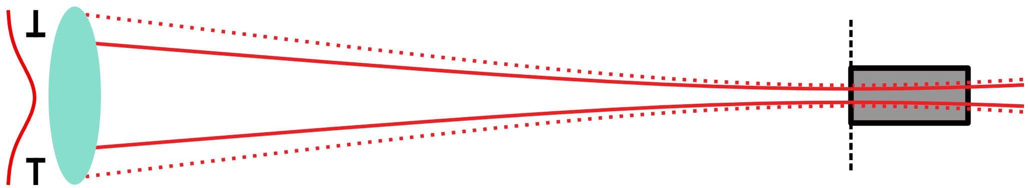


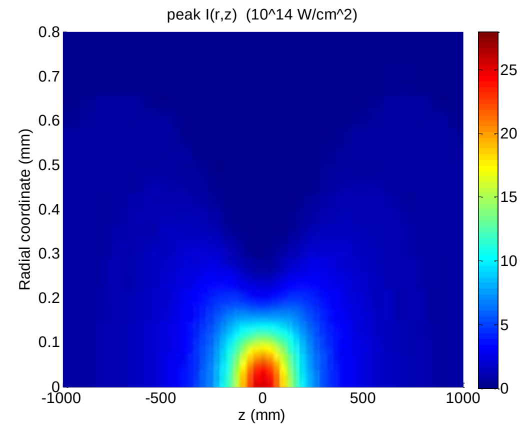
Figure 3.41 Refractive index versus frequency.

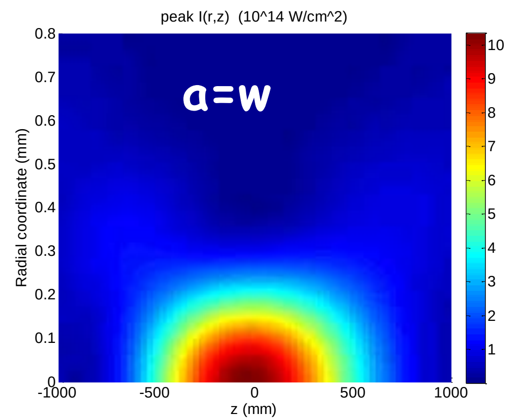
Hecht, Optics (2002)

Ch Heyl, PhD dissertation

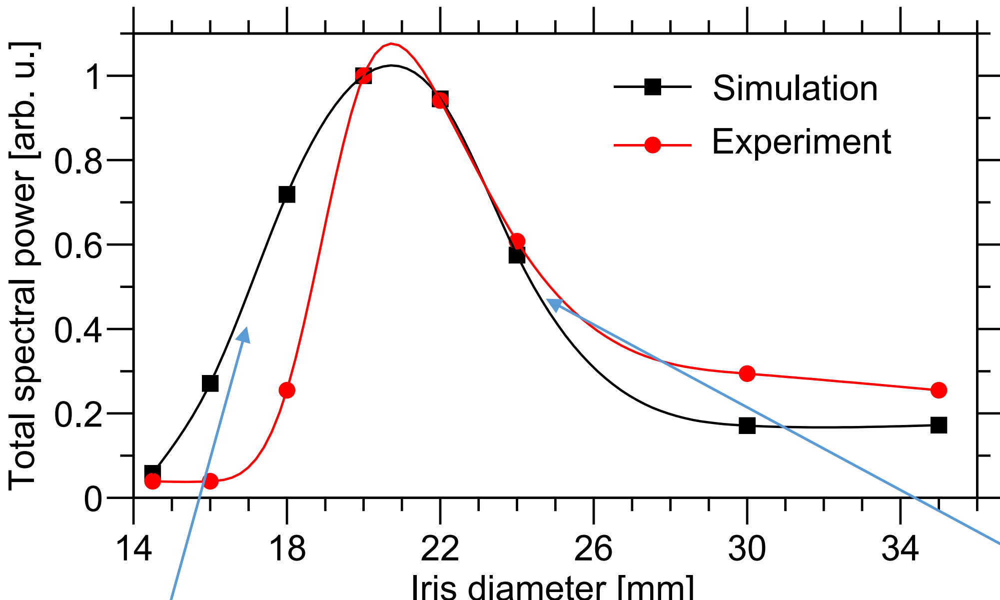
Phase-matching in the laboratory: via aperturing the laser beam







With 86% of the energy the peak intensity is only 40% of the untruncated value



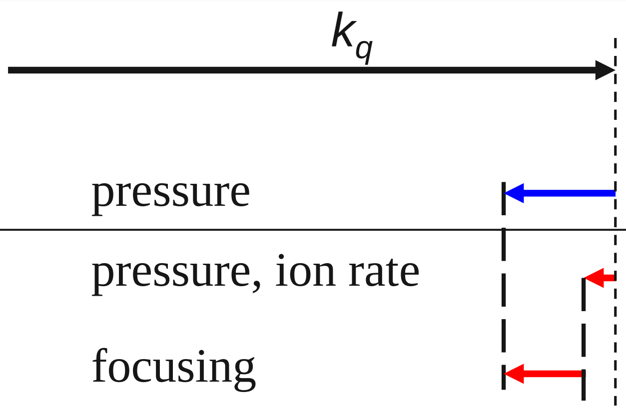
Closing the aperture the pulse energy is decreased and the Rayleigh range is increased, finely tuning phase-matching conditions.
+ focal spot size increases, ie higher number of photons contribute to HHG.

When the iris is too small, the intensity in the focus falls below the HHG threshold.

Pressure-tuned phase-matching

Phase velocity c for harmonic q

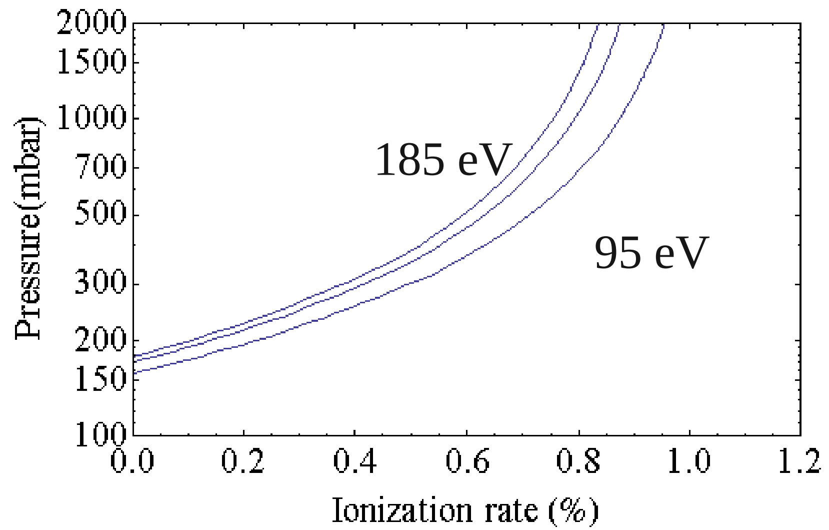
- neutral dispersion for the XUV
- neutral + plasma dispersion for the IR
- Gouy phase-shift



For a given focusing geometry and ionization rate, there is an optimal pressure:

$$p_{match} = \frac{-\Delta k_G}{\frac{\partial \Delta k_n}{\partial p} + \frac{\partial \Delta k_p}{\partial p}}$$

Has to be positive!



Critical ionization rate: $\Delta k_n = \Delta k_p$

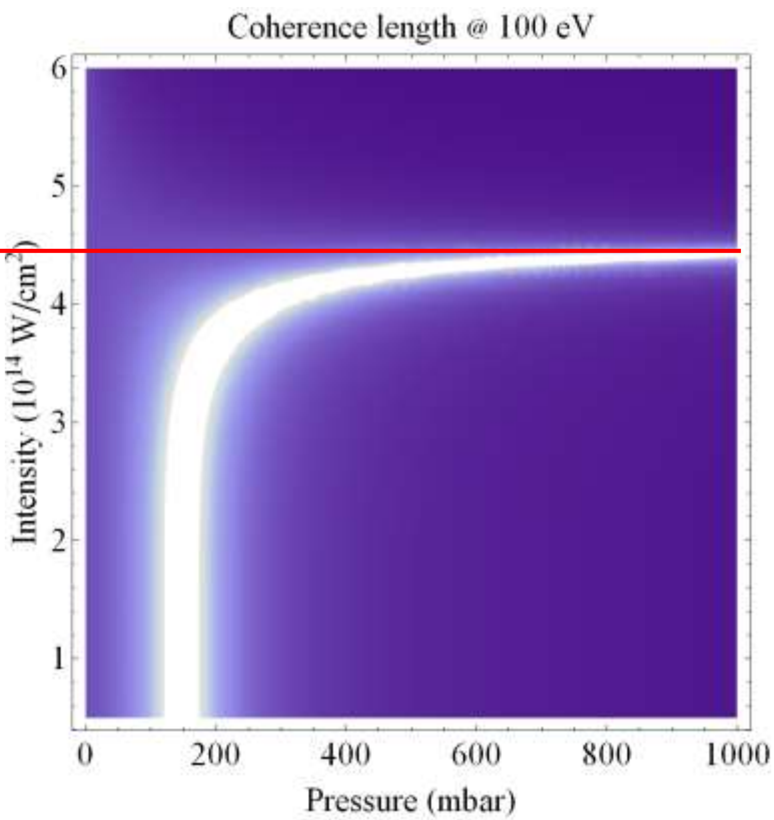
Balogh E, PhD dissertation

Pressure-tuned phase-matching

Using the ionization rate at the peak of the pulse (i.e. where cutoff harmonics are generated)

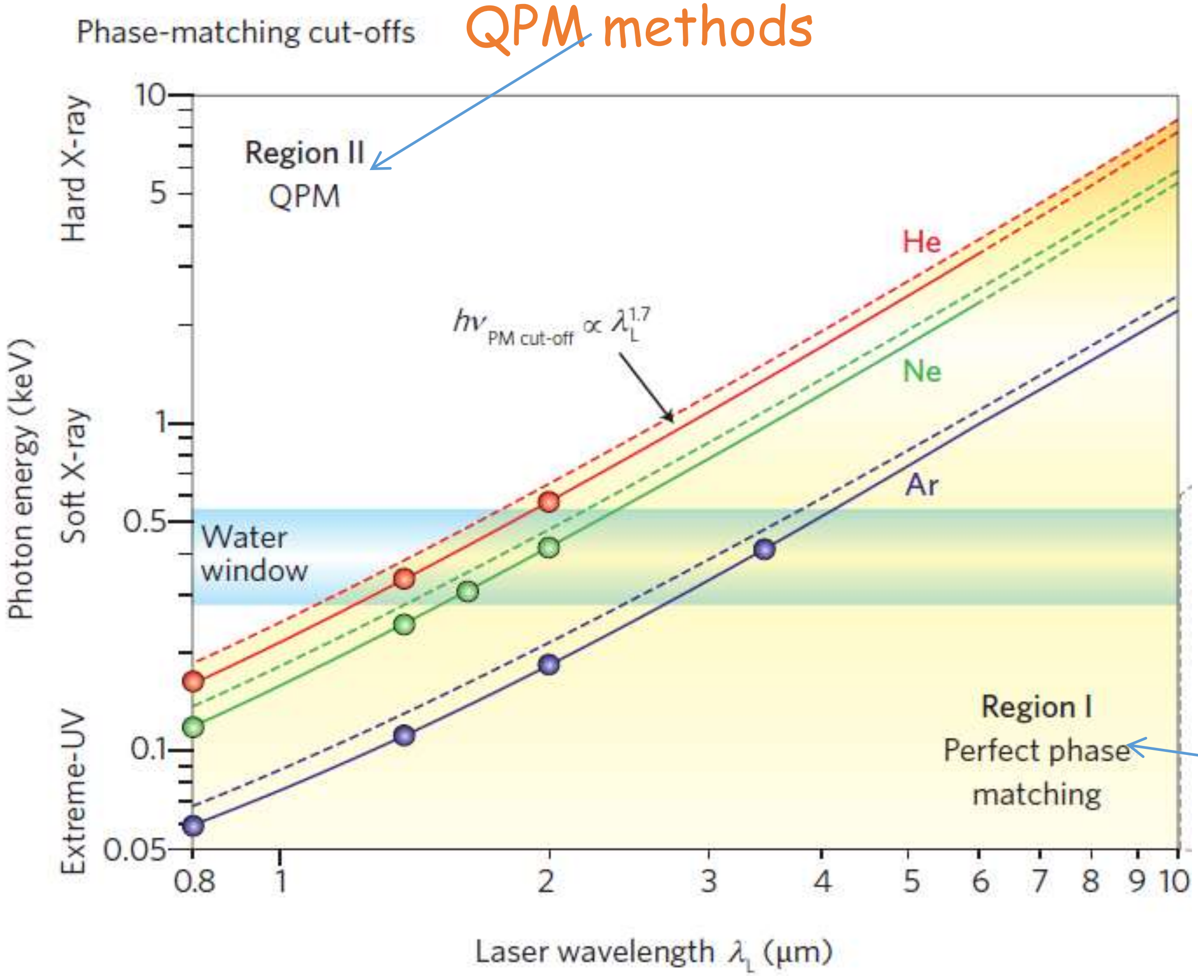
At this intensity the cutoff is at 105 eV:
highest achievable photon energy is limited

Coherence length as a function of pressure and intensity



Pressure-tuned phase-matching

phase-matching not possible:
QPM methods



phase-matching cutoffs for an 800 nm driver field (8 cycles):

in Ar 60 eV H39
in Ne 110 eV H71
in He 180 eV H117

phase-matching possible with pressure-tuning

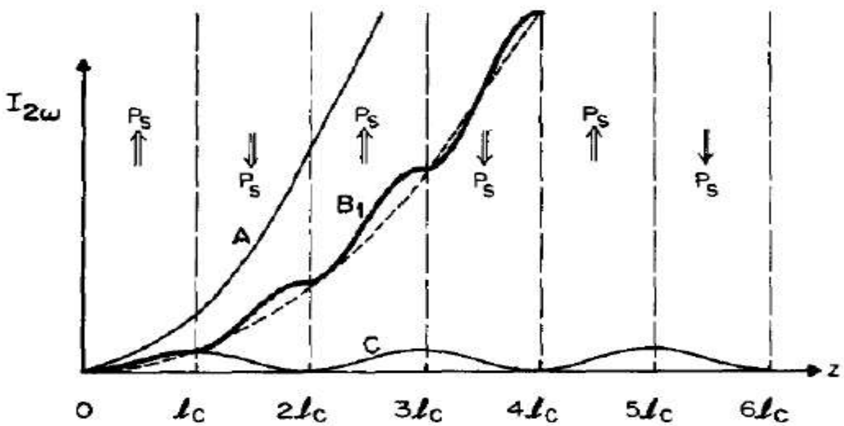
Popmintchev: Nphot 4, 822 (2010)

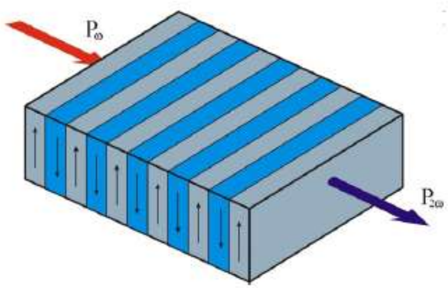
When phase-matching is not possible: Quasi phase-matching

PHYSICAL REVIEW VOLUME 127, NUMBER 6 SEPTEMBER 15, 1962

Interactions between Light Waves in a Nonlinear Dielectric*

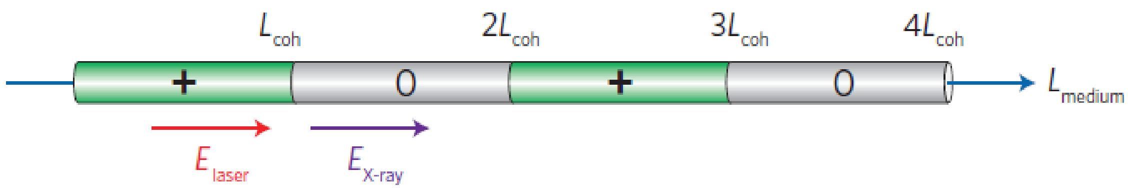
J. A. Armstrong, N. Bloembergen, J. Ducuing,† and P. S. Pershan
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts
(Received April 16, 1962)





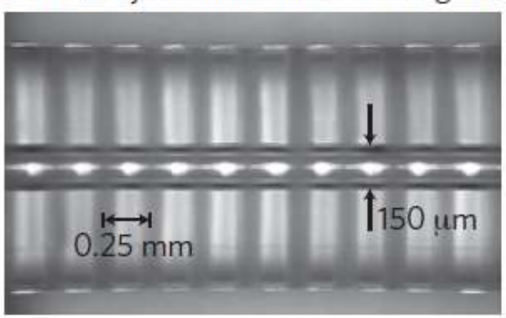
QPM techniques in HHG

to periodically switch off HHG in destructive zones

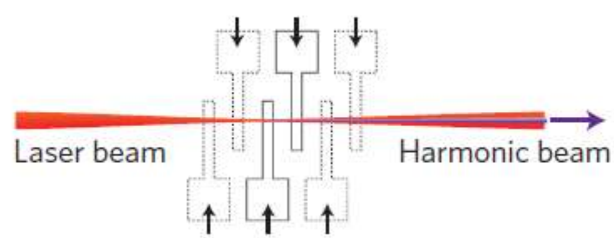


a

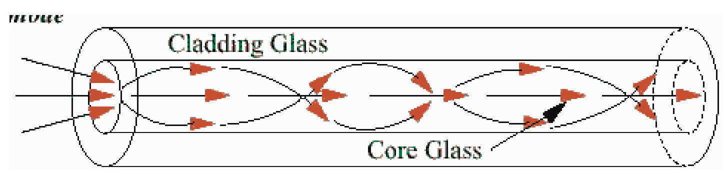
Periodically modulated hollow waveguide



Successive gas jets

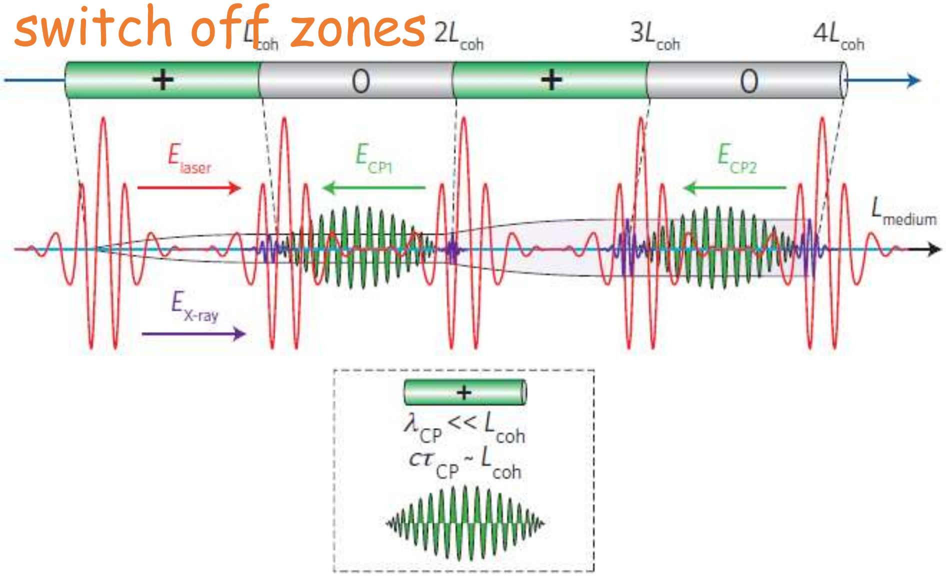


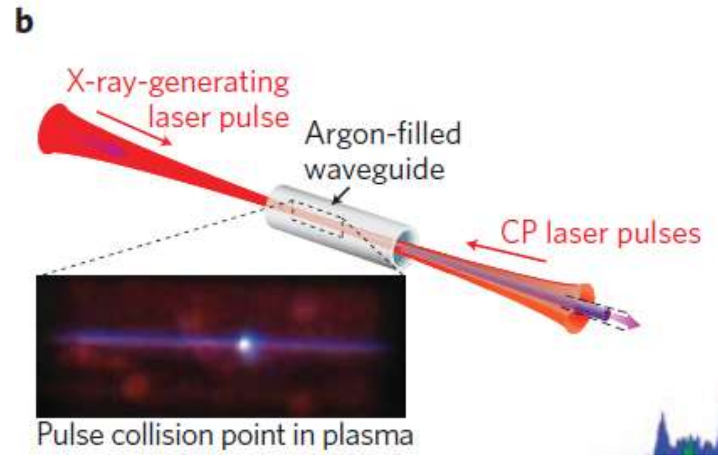
multimode waveguide



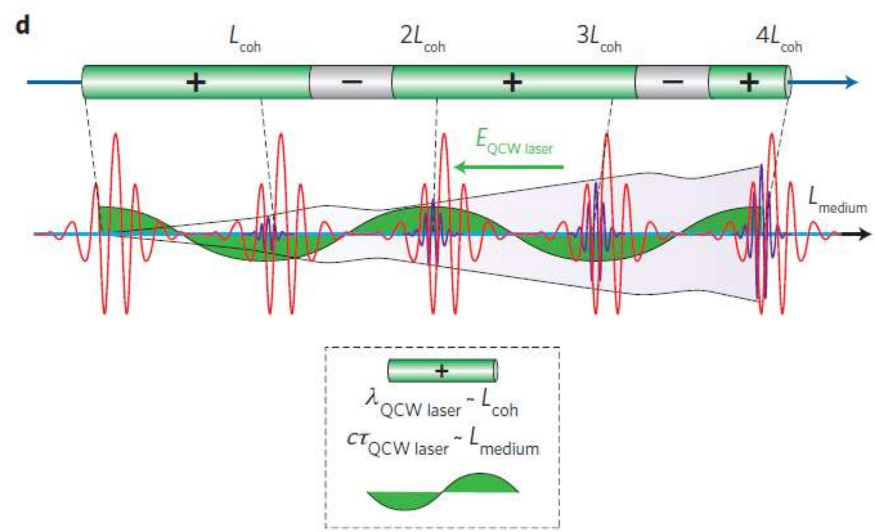
QPM techniques in HHG

counter-propagating pulses scramble the phase of high-harmonic emission to switch off zones





counter-propagating or perpendicularly propagating quasi-CW laser shifts the phase of the emission to increase constructive zones



Contents

- High order harmonic generation in gaseous media
- Description of the generated radiation
- „Measuring" the radiation
- Chirp of the harmonic radiation
- Phasematching in HHG
- Optimizing HHG

Optimizing the HHG source

1, increasing the achievable photon energy („water-window”)

2, increasing the XUV photon flux (up-scaling)

3, producing a Single Attosecond Pulse (gating)

Spectral extension

$$\hbar\omega_{max} = I_p + 3.17\, U_p$$

$$U_p \propto I\, \lambda^2$$

typical values:

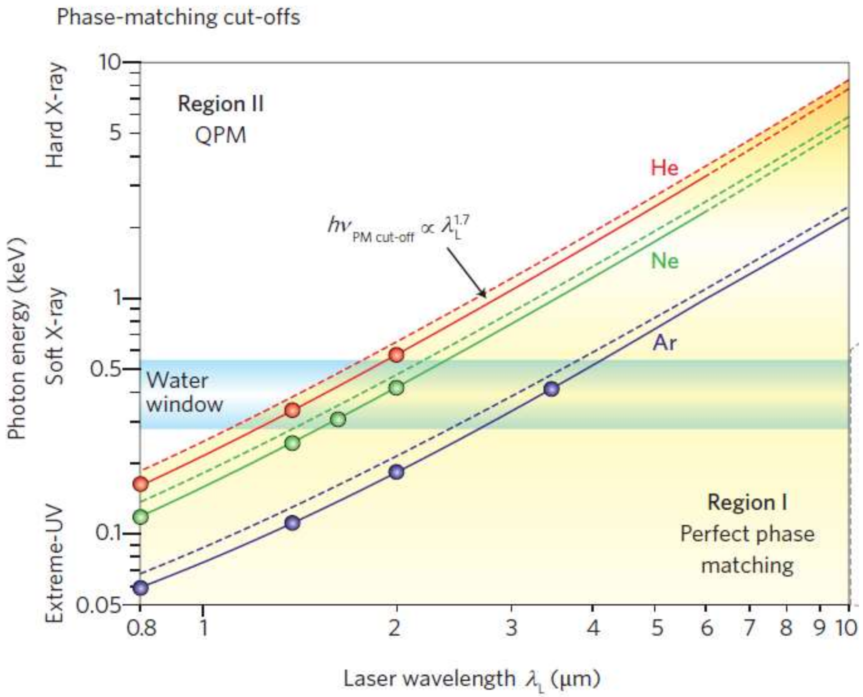
$I_p = 10..24$ eV

$I = 10^{15}$ W/cm^2 @ 800 nm gives $U_p = 60$ eV

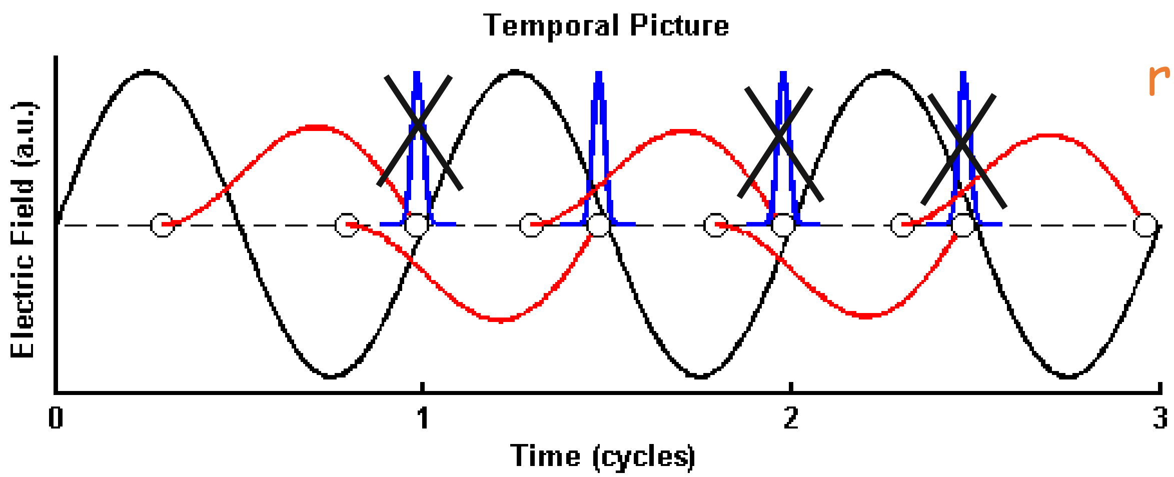
$I_p + 3.17\, U_p \approx 200$ eV

How to increase the cutoff?

- increase laser intensity
  limit: ionization of the medium
  (phase matching, depletion)
  avoid: short pulses, QPM
- increase laser wavelength
  limit: laser technology
- increase ionization potential
  e.g. generate with ions
  limit: phase matching

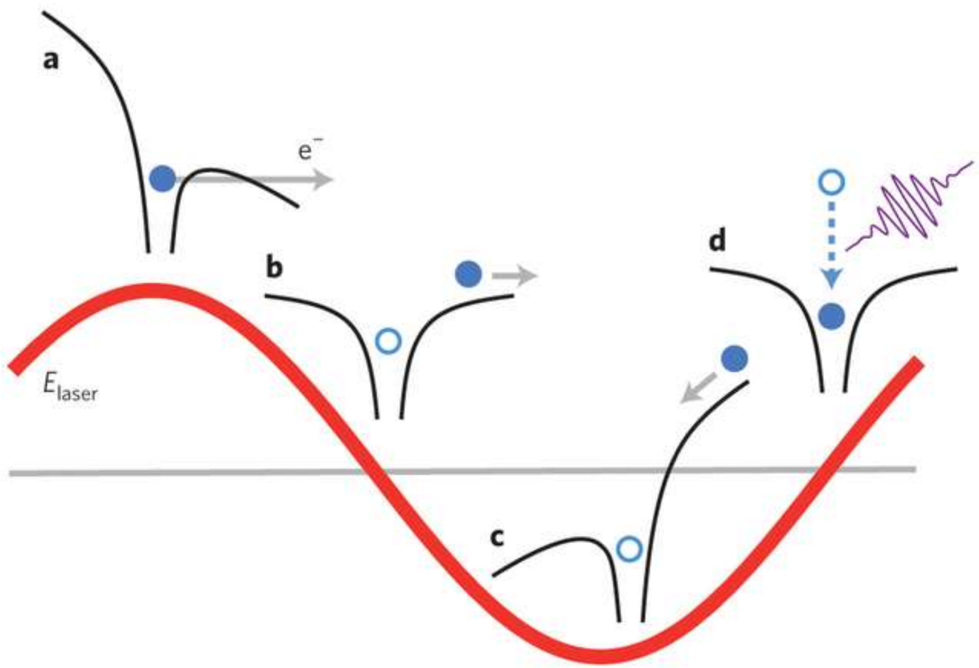


Temporal gating



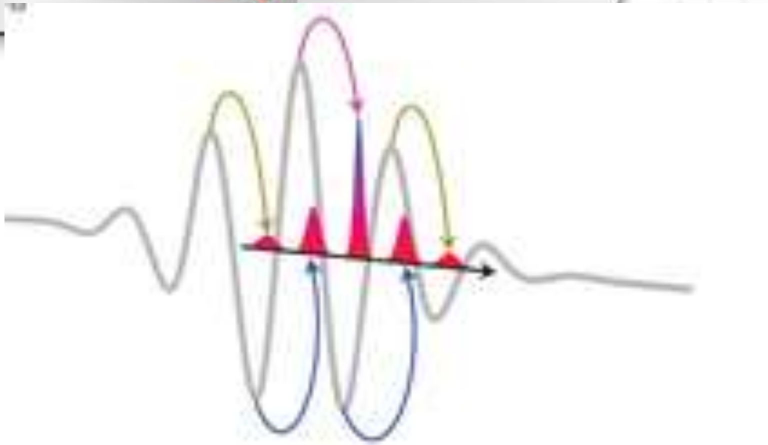
reduce the emission events

by avoiding ionization,
or recombination,
or shortening the generating pulse



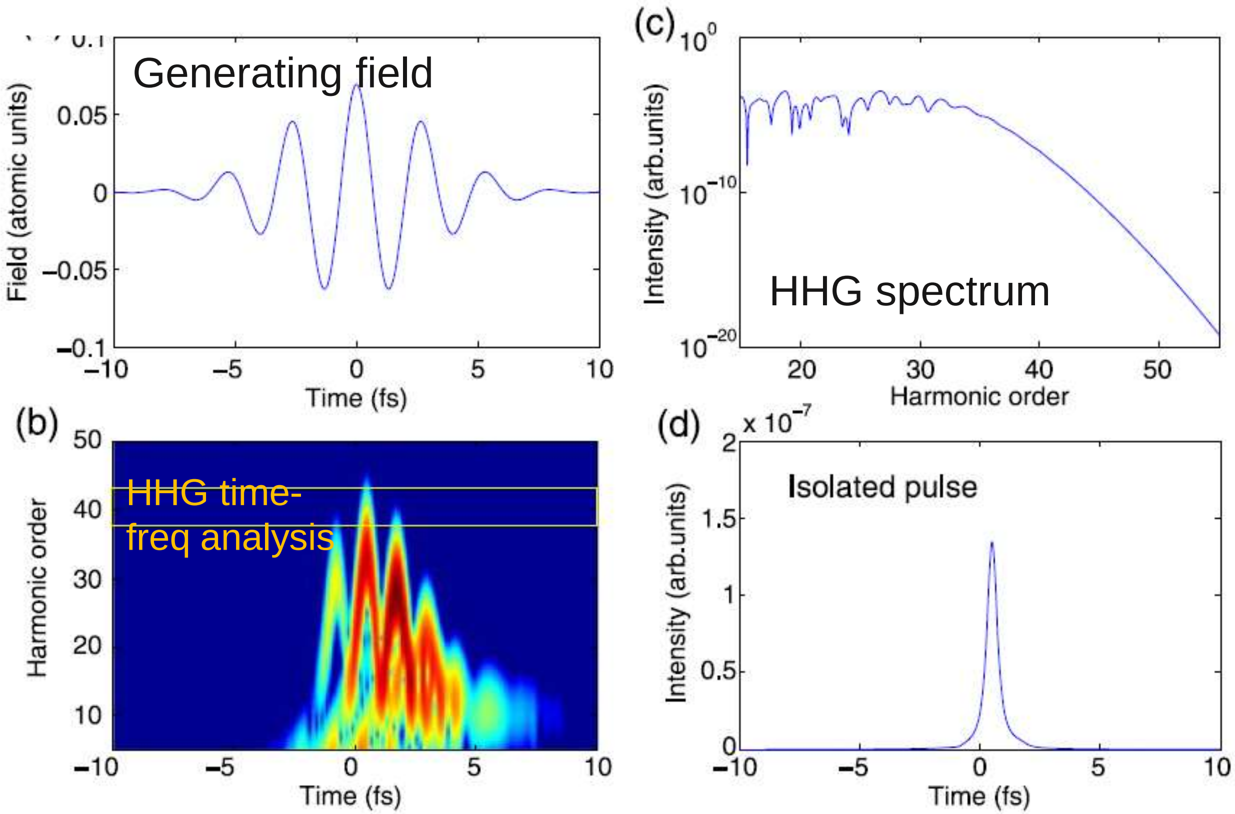
Amplitude/intensity gating

M. Hentschel et al., Nature (London) **414**, 509 (2001)
A. Baltuska et al., Nature **421**, 611 (2003)

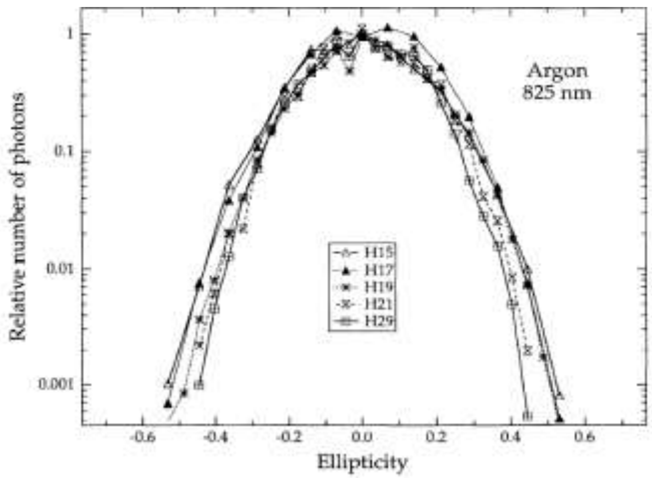


- spectrally filtering the cutoff
- small intensity
- small bandwidth

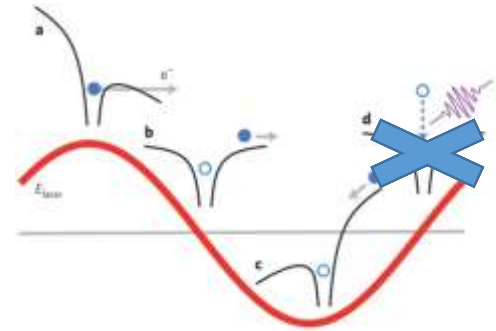
τ < 5 fs, CEP-stable driving laser

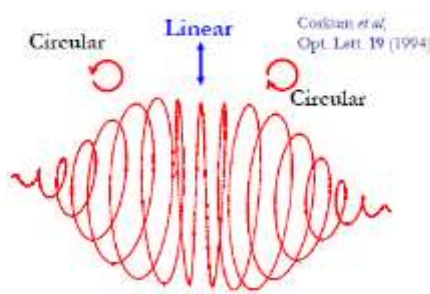


Ellipticity-gating

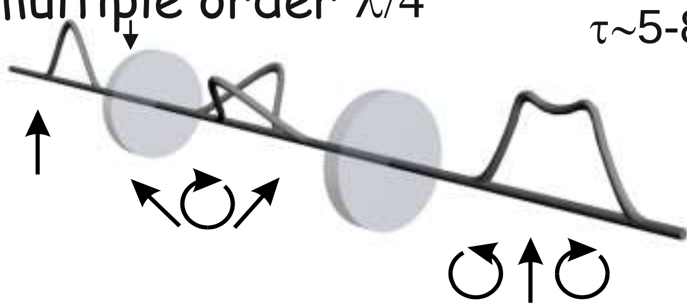


Budil et al., PRA 48, R3437 (1993)



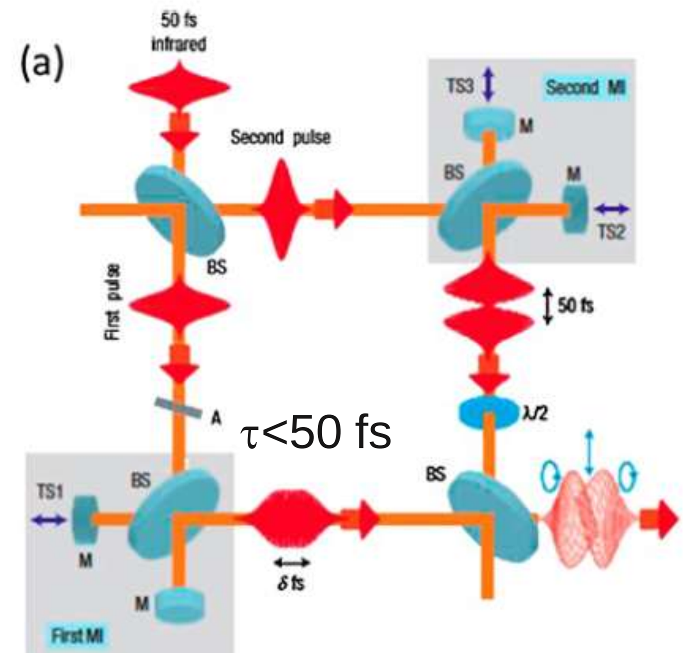


multiple order $\lambda/4$



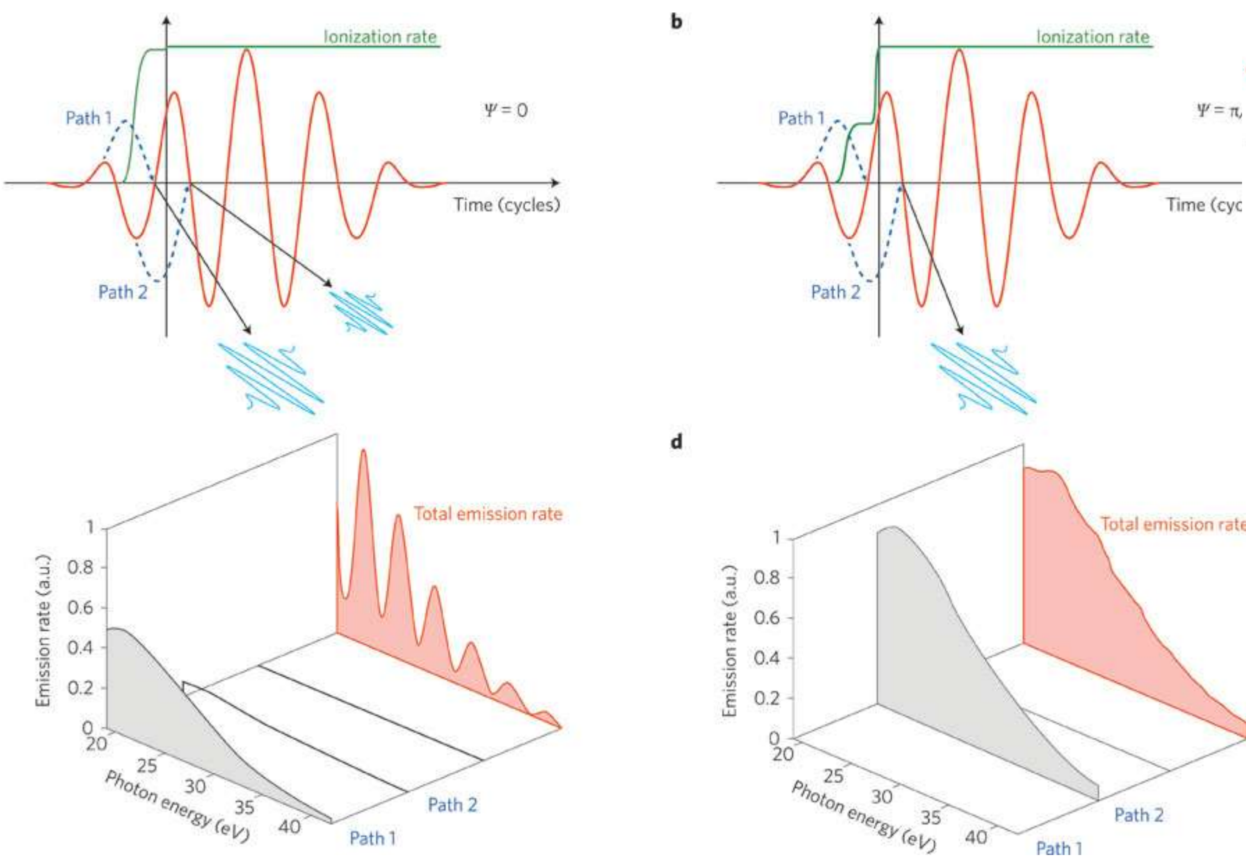
τ~5-8 fs

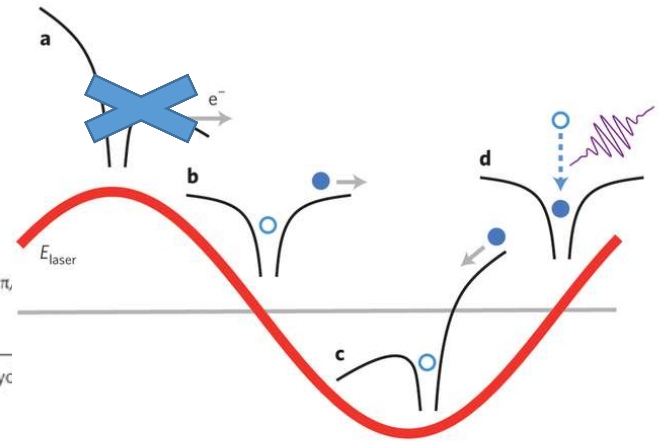
Sansone: Science 314 (2016)



Tzallas: Nature Physics 3, 846 - 850 (2007)

Ionisation gating I. single atom effect





complete depletion of neutral atom population on the pulse leading edge

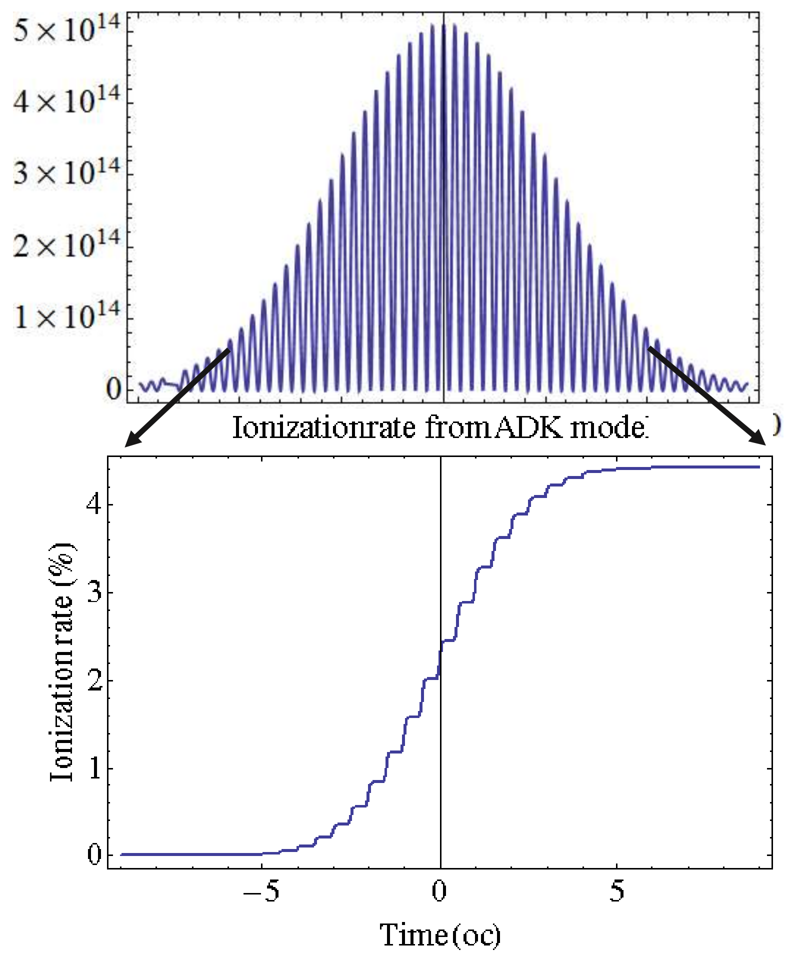
Sansone, Nphot 5, 655 (2011)

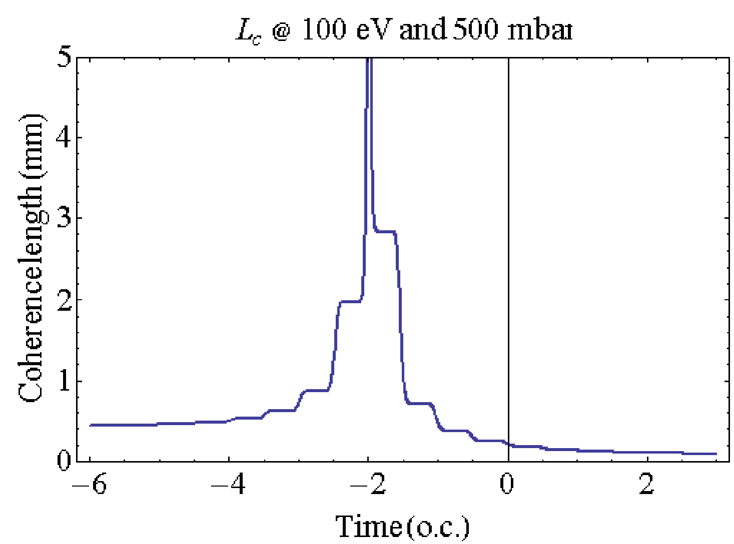
Ionisation gating II.

Macroscopic: time-dependent coherence length

Lcoh > 1 mm for only 1 optical cycle

Temporal gating:
isolation of a single attosecond pulse

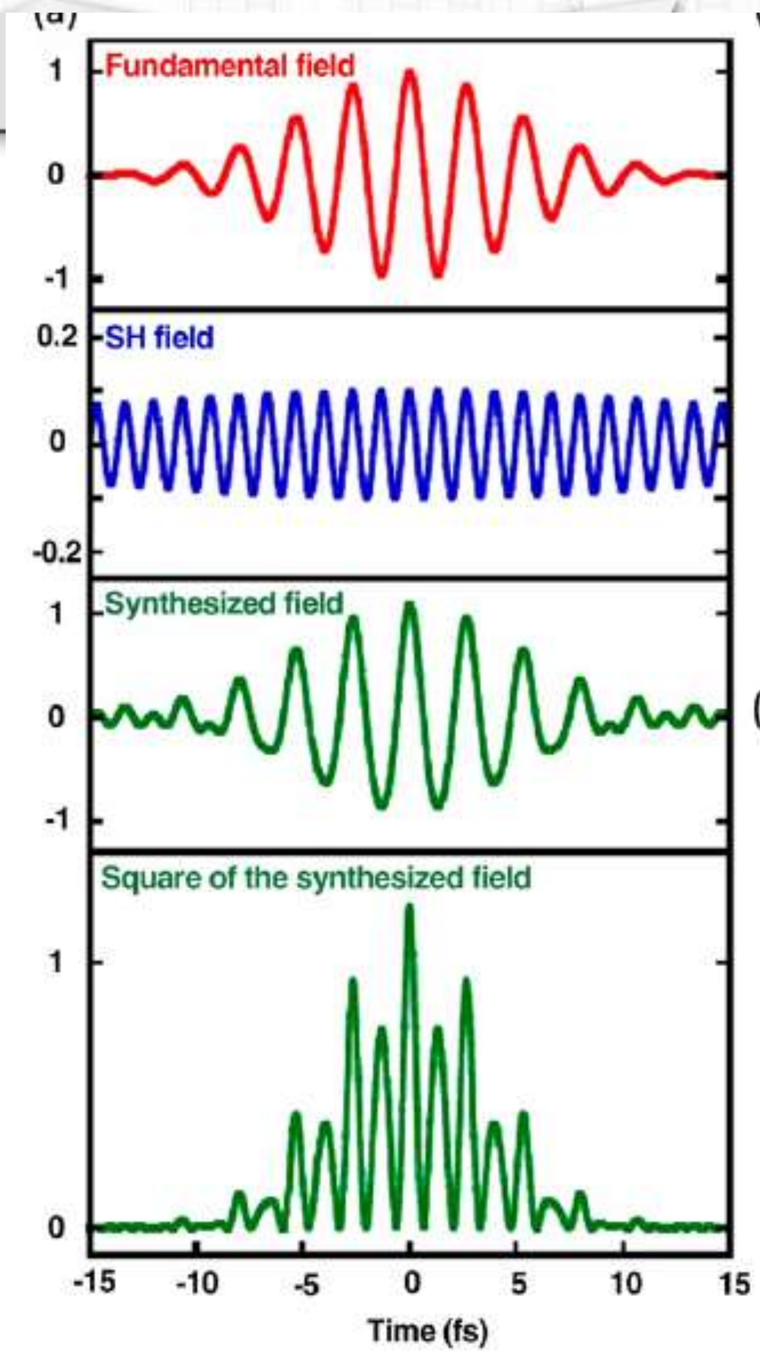




for ex.: $5.1*10^{14}$ W/cm^2, 35 fs pulse

Balogh E, PhD dissertation

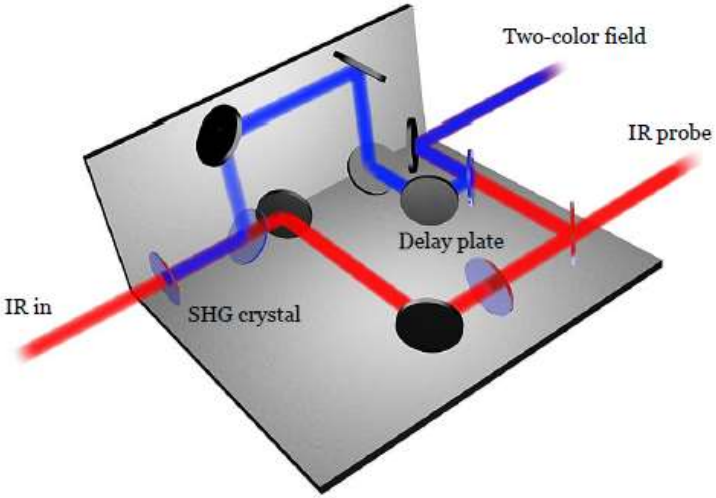
Two-color gating (with SH or MIR)



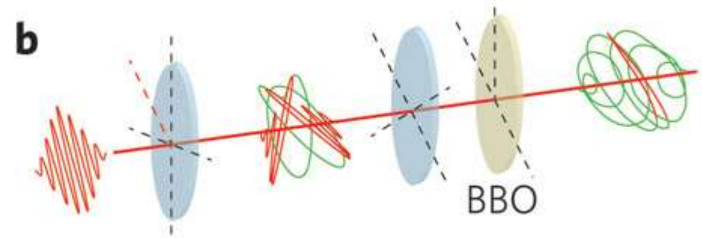
Tunable weak perturbing pulse (harmonic or longer wavelength)

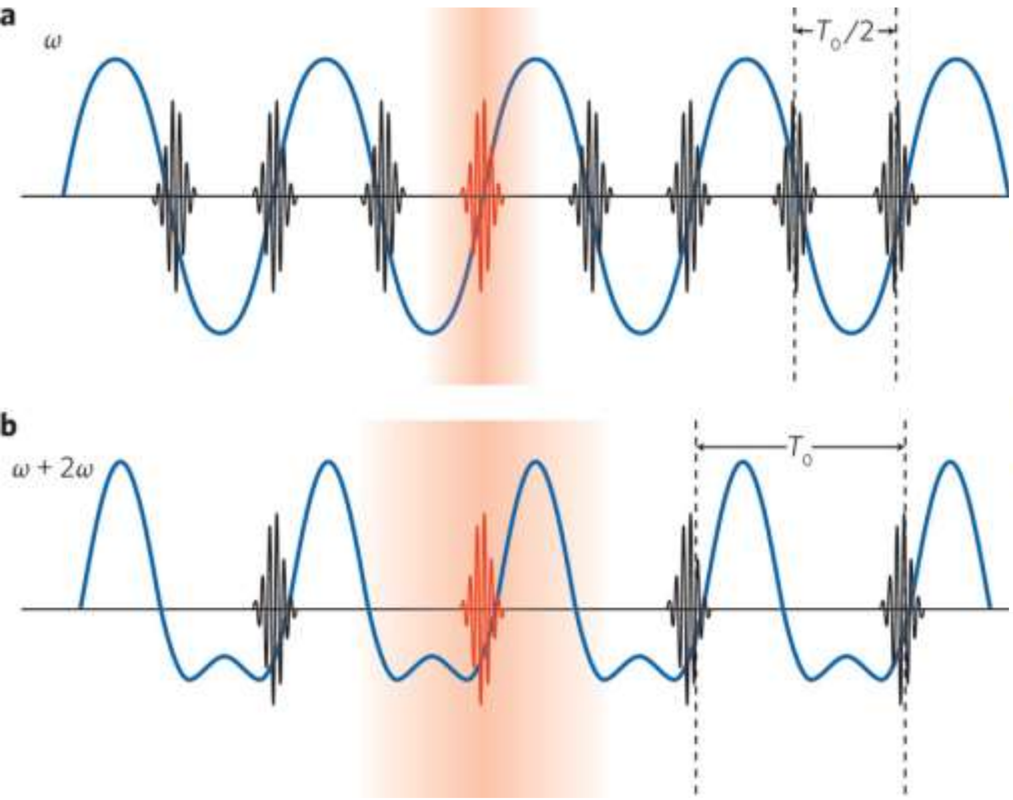
Increases the period of the process (least common multiple)

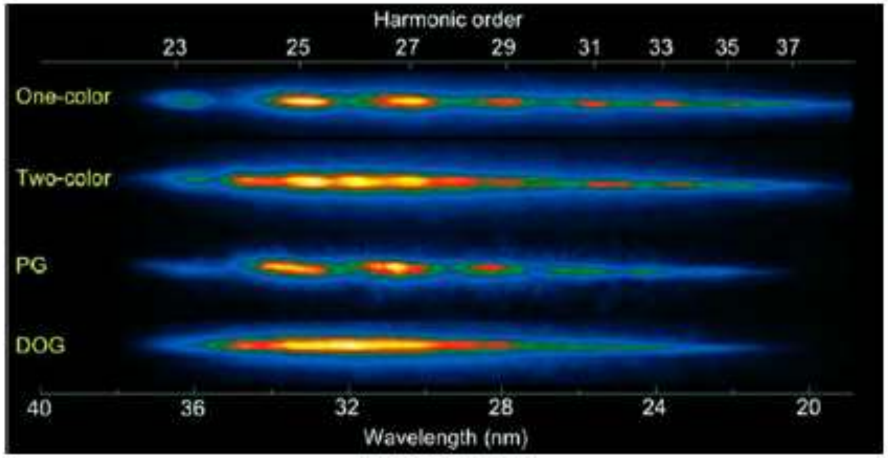
Can be combined with any other gating process



Polarization + two-color gating = Double Optical Gating (DOG)



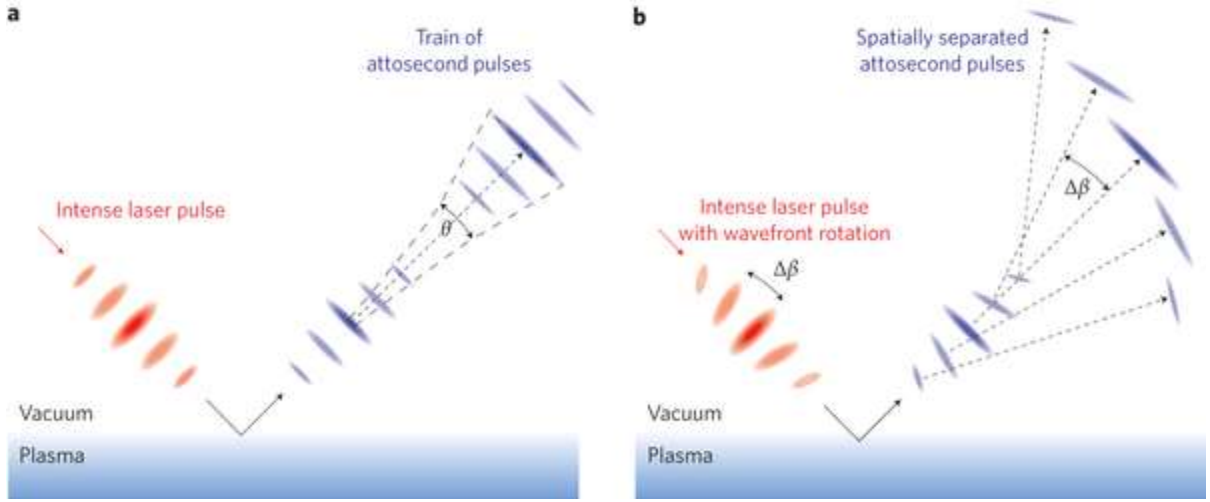




Mashiko: Phys. Rev. Lett. 100, 103906 (2008)

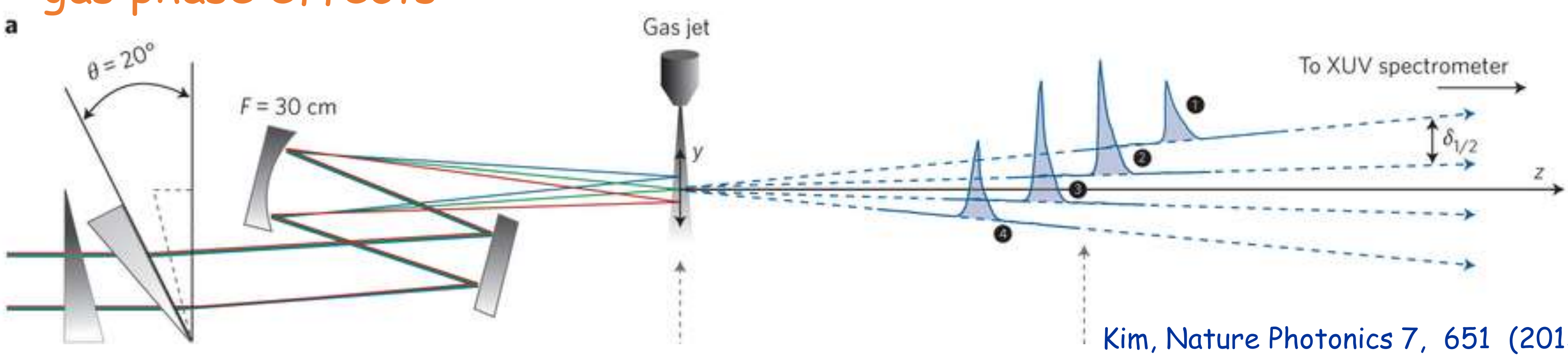
The attosecond lighthouse effect

surface plasma effect



Wheeler, Nat Phot 6, 829 (2012)

gas phase effects



Kim, Nature Photonics 7, 651 (2013)

Further reading

Boyd: Nonlinear Optics
Chang: Fundamentals of attosecond optics
Plaja (ed): Attosecond Physics
Vrakking (ed): Attosecond and XUV Physics

THANK YOU FOR YOUR ATTENTION!

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