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Advanced Plasma and Laser Science
プラズマ・レーザー特論E

attosecond laser pulse
アト秒レーザーパルス

attosecond pulse train (APT)

アト秒パルス列

と

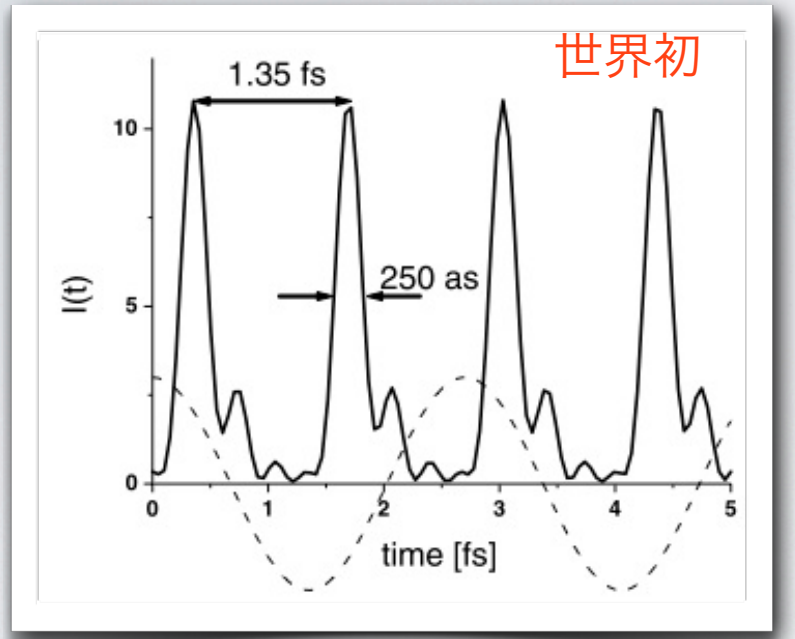
単独アト秒パルス

isolated attosecond pulse (IAP)

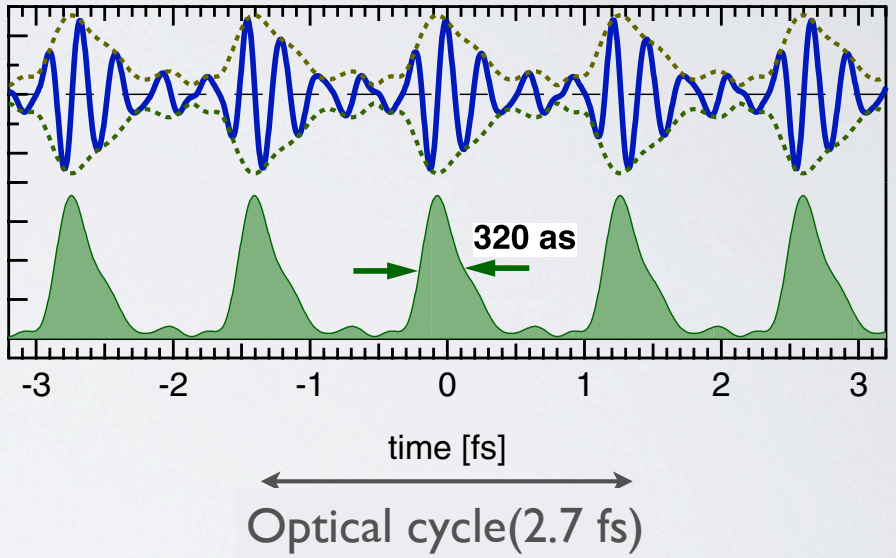
High-order harmonics are generated as attosecond bursts repeated each half cycle of the fundamental laser (attosecond pulse train)

高次高調波は、基本波レーザーの半周期ごとにアト秒のバーストとして発生する（アト秒パルス列）

Paul et al., Science 292, 1689 (2001)



Nabekawa et al., Phys. Rev. Lett. 97, 153904 (2006)



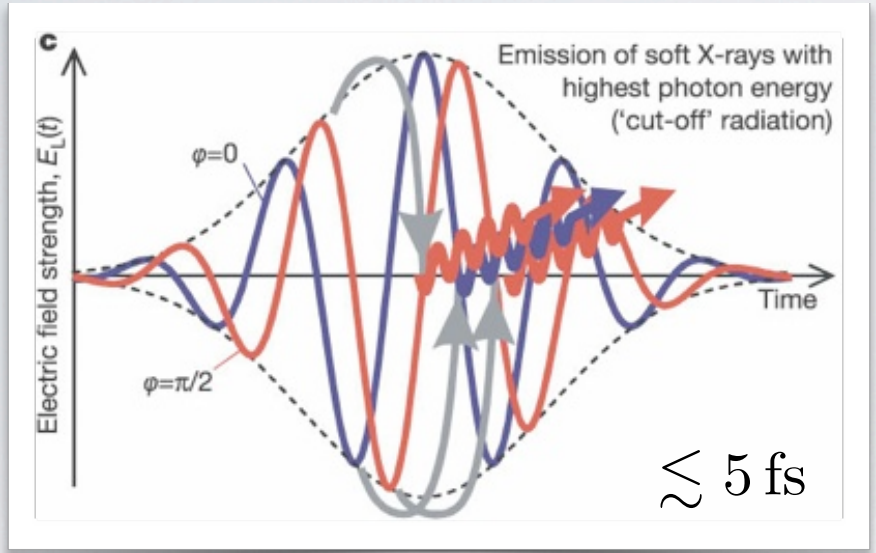
Only one burst → Isolated attosecond pulse (IAP)

1 回だけバーストが発生するようにすれば、単独パルスになる。

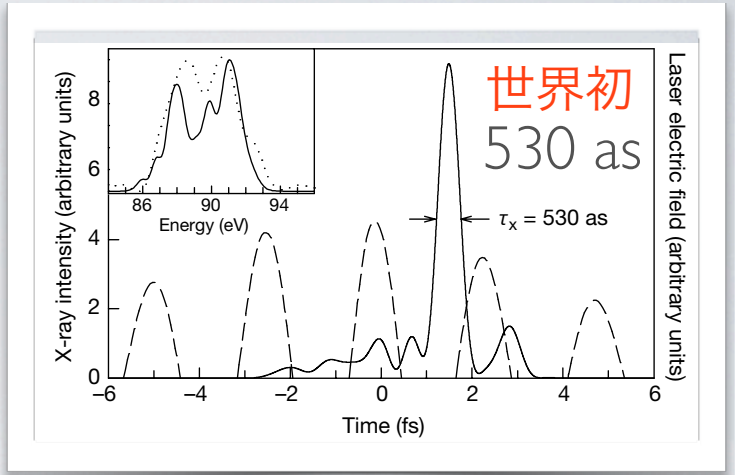
Isolated attosecond pulse generation
by a few-cycle laser pulse

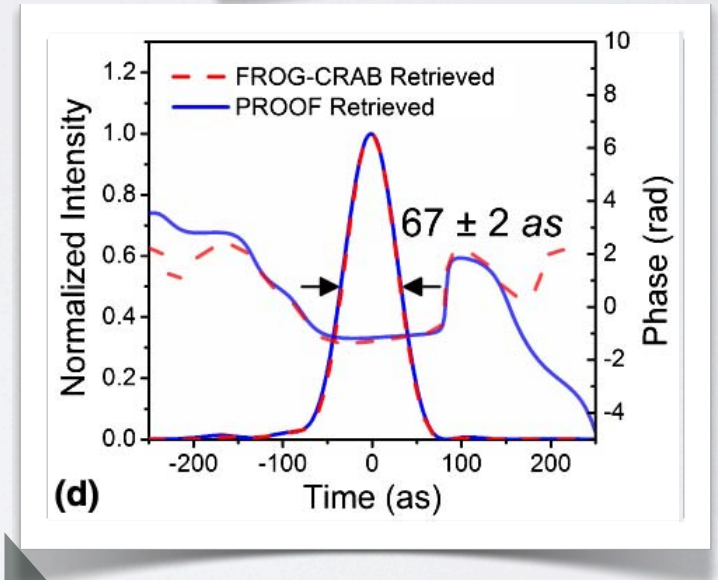
単独アト秒パルス

Baltuska et al. Nature 421, 611 (2003)



Hentschel et al. Nature 414, 509 (2001)





Zhao et al. (2012)

Light emission takes place only once.

光の放出は 1 回だけ

Attosecond (10^{-18} sec) pulse

アト秒パルス

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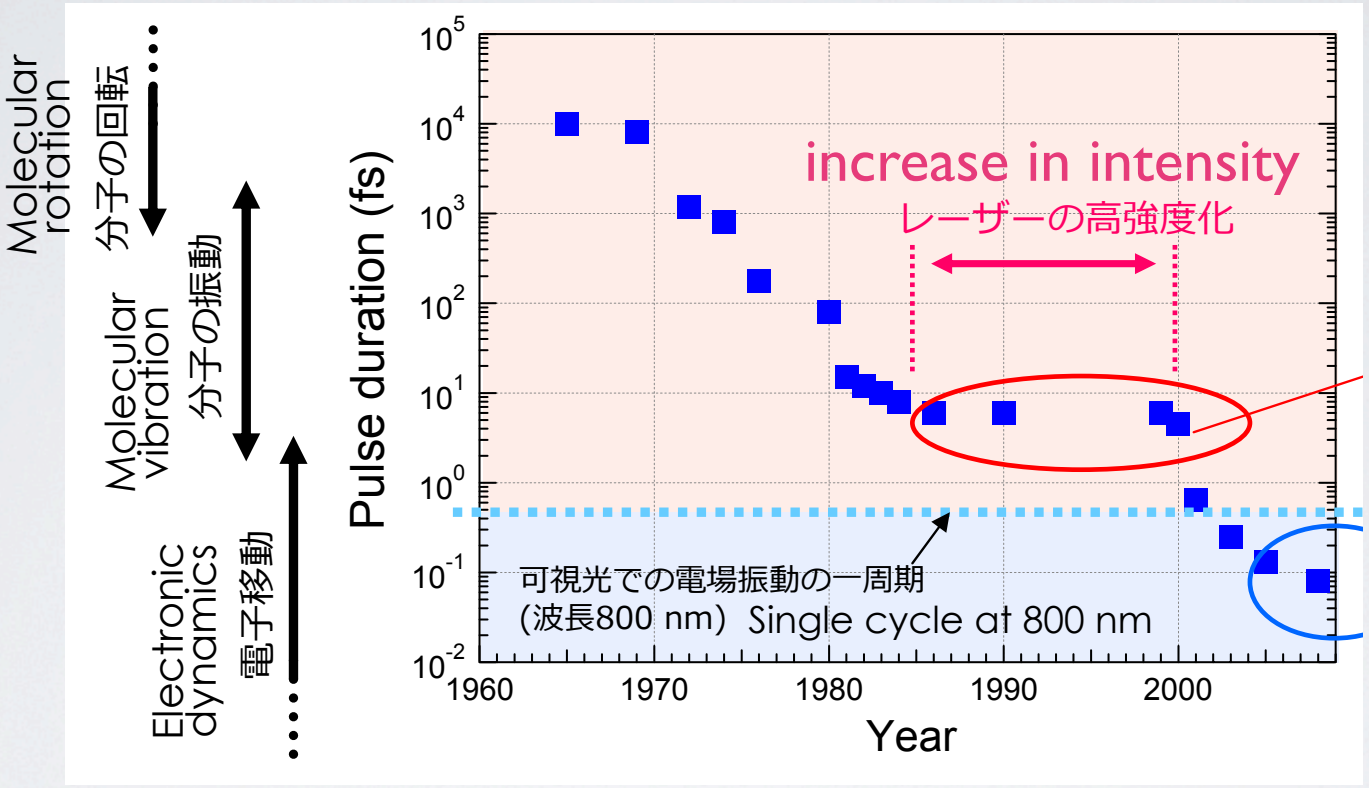
From femtosecond to attosecond

10^{-15} sec 10^{-18} sec



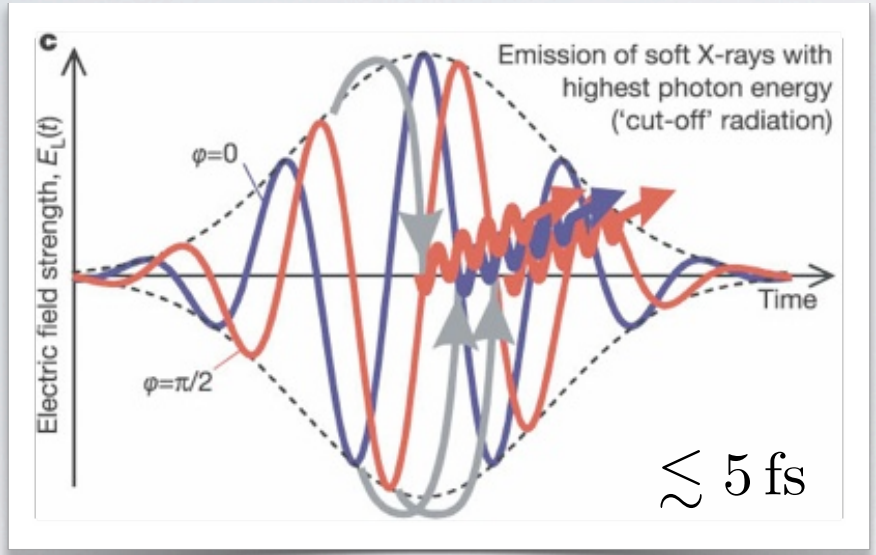
(courtesy of Prof. J. Itatani)

0.1 attosecond ! 0.1アト秒！

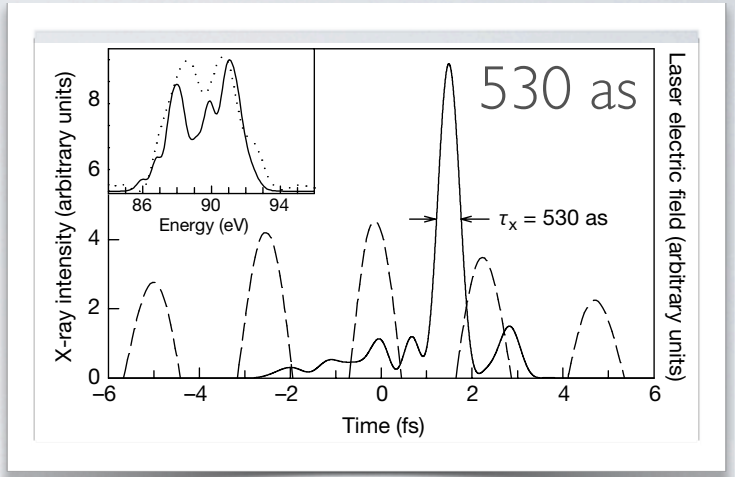
How to generate IAP

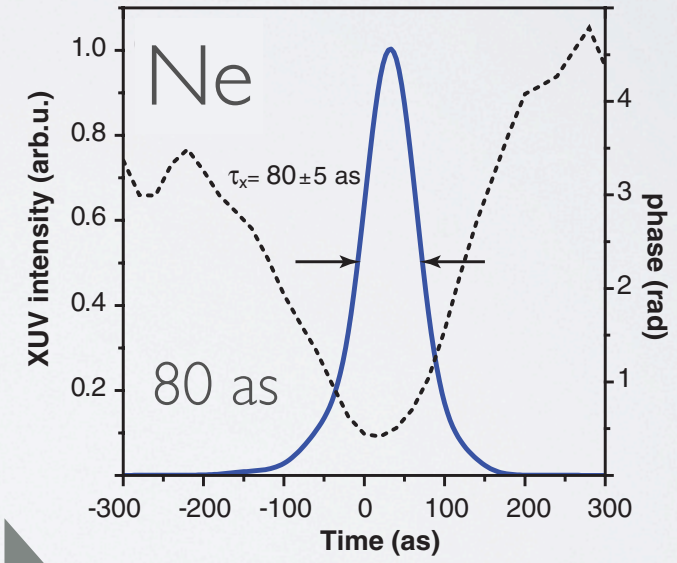
Isolated attosecond pulse generation by a few-cycle laser pulse

Baltuska et al. Nature 421, 611 (2003)



Hentschel et al. Nature 414, 509 (2001)





Goulielmakis et al. Science 320, 1614 (2008)

Light emission takes place only once.

Attosecond (10^{-18} sec) pulse

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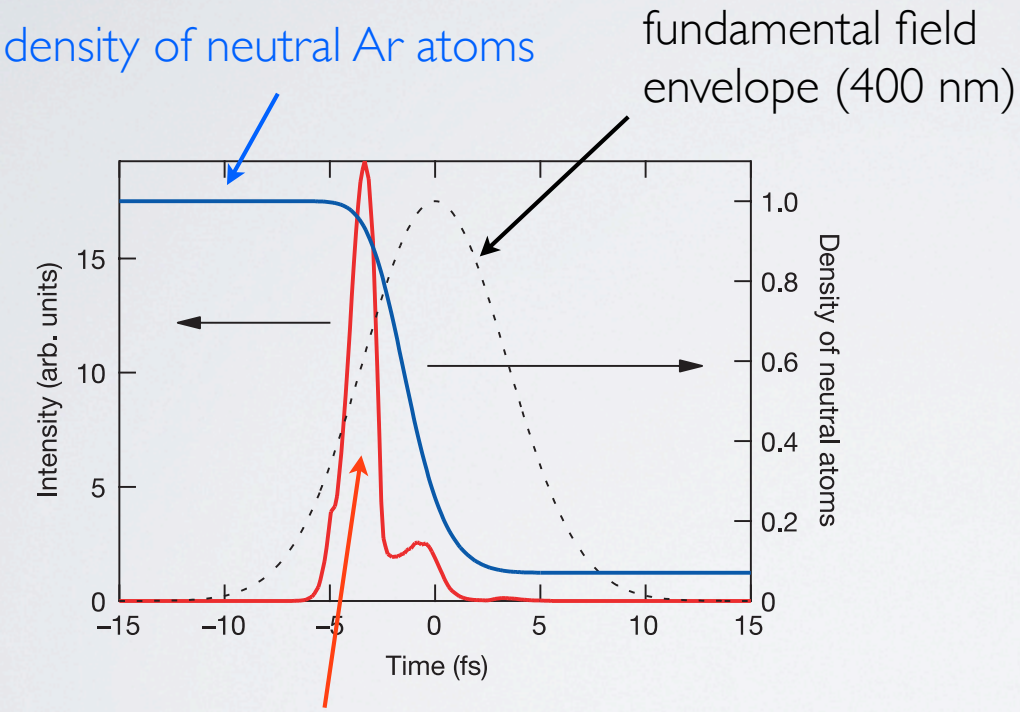
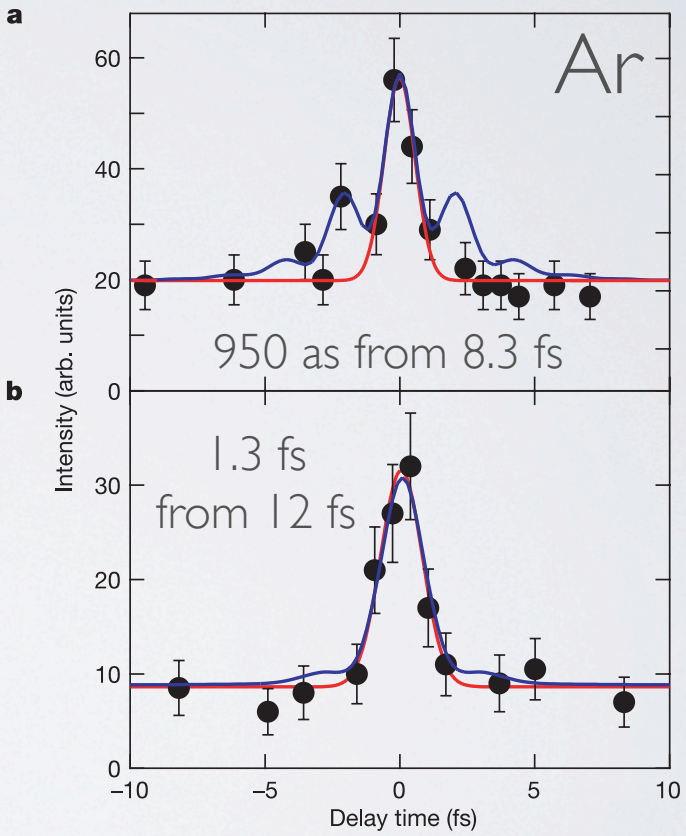
IONIZATION SHUTTER

HHG is suppressed when neutral atoms are depleted





Isolated sub-fs pulse generation from a ~10 fs pulse

Sekikawa *et al.*, Nature 432, 605 (2004)

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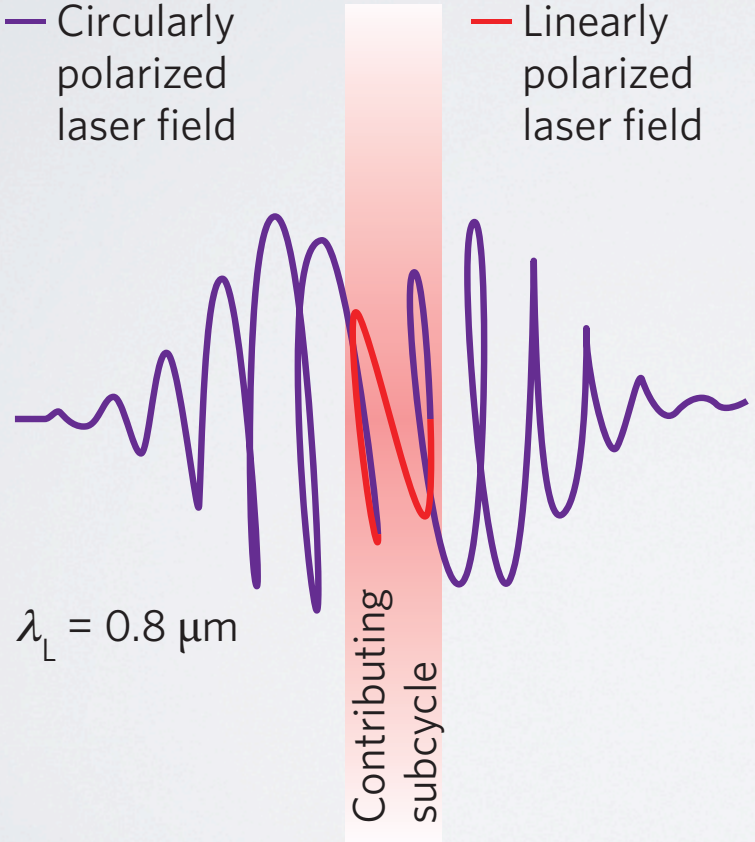
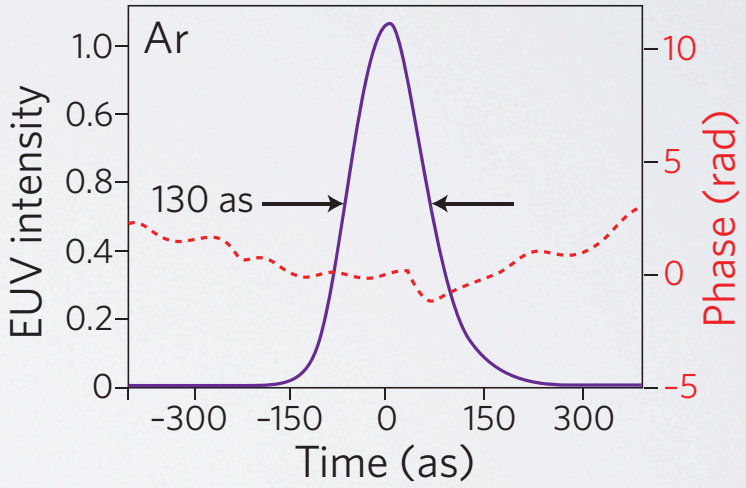
POLARIZATION GATING (PG)

HHG is suppressed when circular polarization is used

counter-rotating circularly polarized pulses with a delay





Sansone *et al.*, Science 314, 443 (2006)

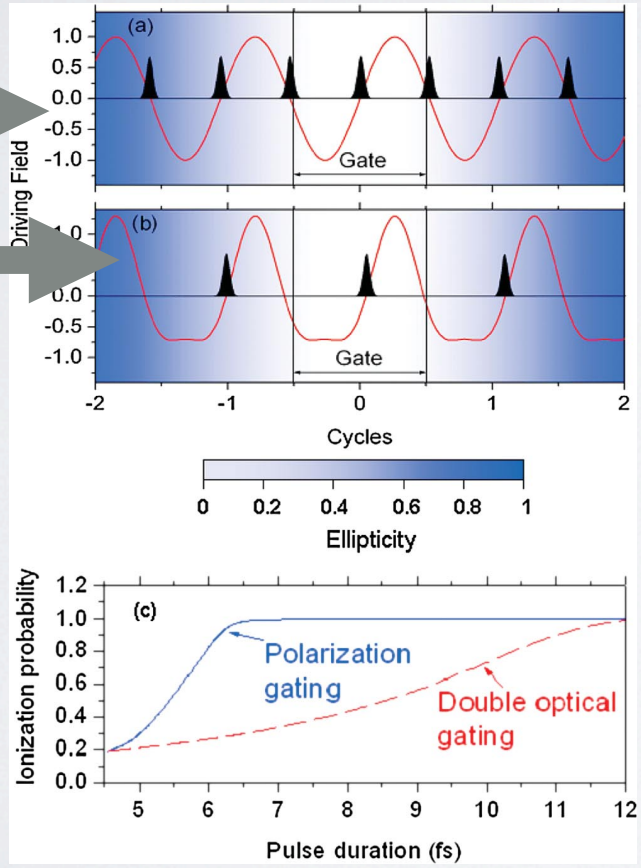
DOUBLE OPTICAL GATING (DOG)

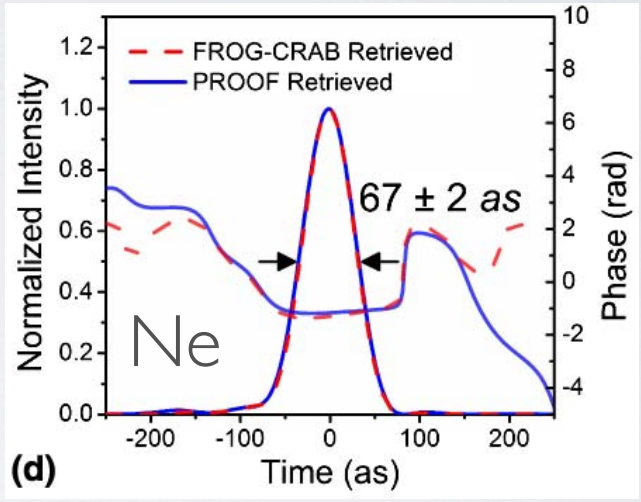
Polarization gating + two-color gating

ω

$\omega + 2\omega$

with second-harmonic field





IAP generation from a ~10 fs pulse

Mashiko et al., PRL 2008, 103906 (2008)

Zhao et al., Opt. Lett. 37, 3891 (2012)

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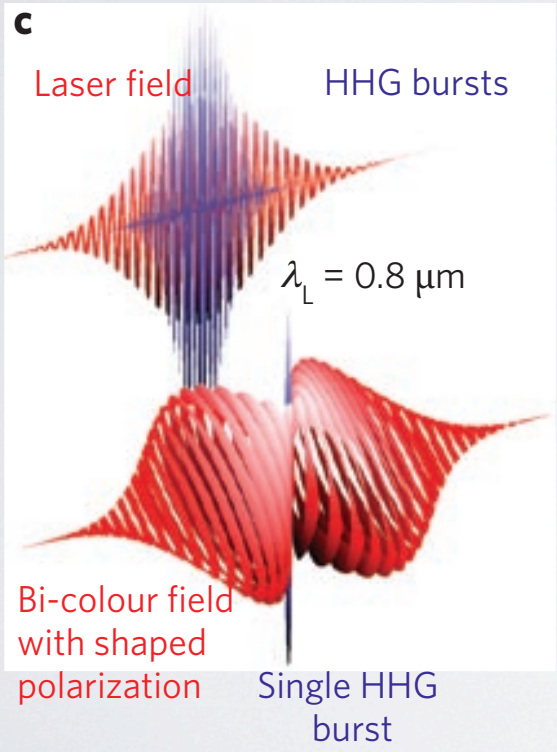
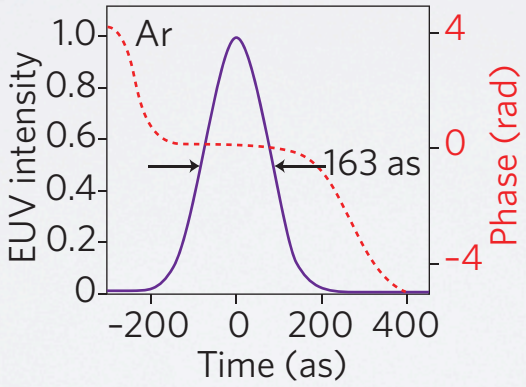
GENERALIZED DOUBLE OPTICAL GATING (GDOG)

Elliptical instead of circular polarization





IAP generation from a > 20 fs pulse without need of carrier-envelope stabilization

Gilbertson et al., PRL 105, 093902 (2010)
Gilbertson et al., PRA 81, 043810 (2010)

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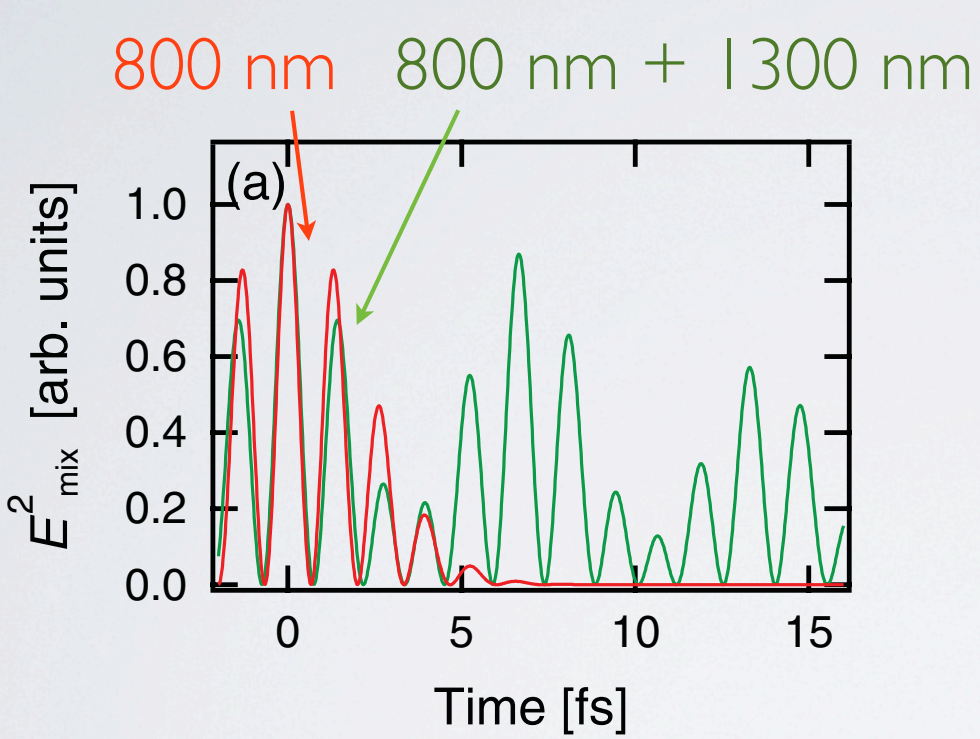
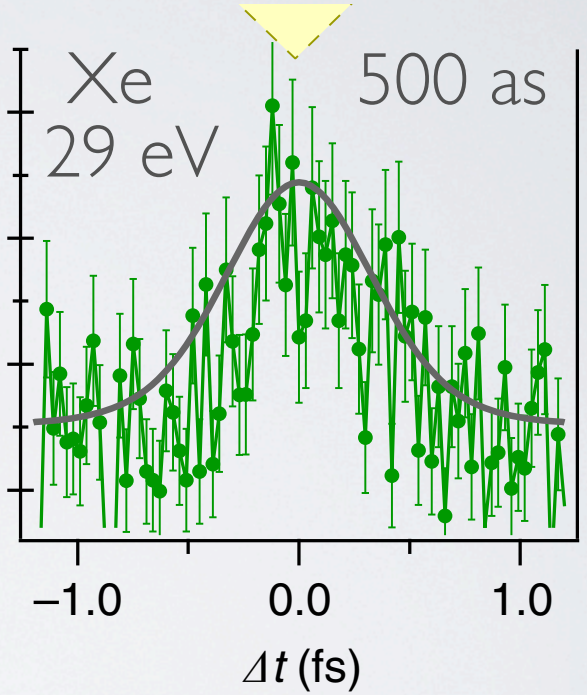
INFRARED TWO-COLOR SYNTHESIS

800 nm + 1300 nm two-color driving field



Takahashi et al., PRL 104, 233901 (2010)

autocorrelation trace

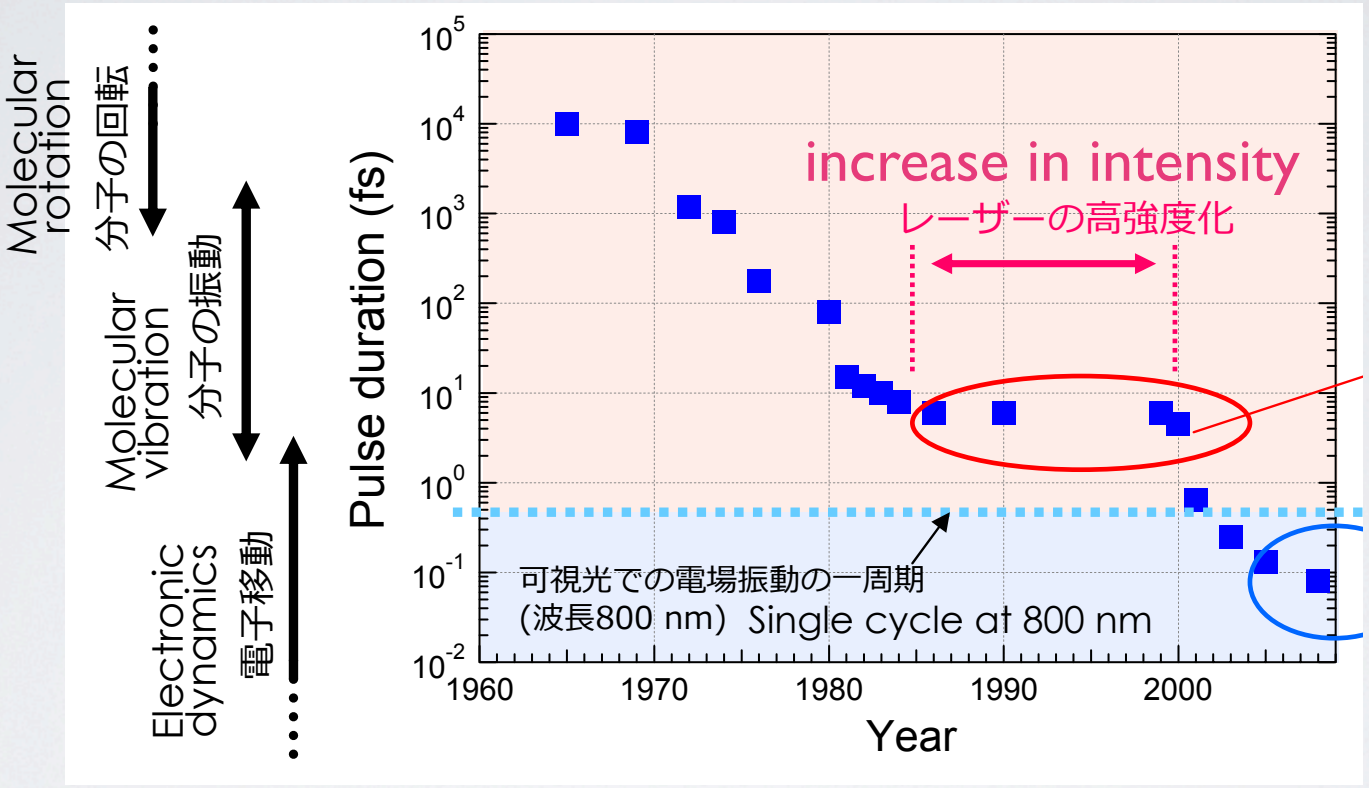


Takahashi et al., Nat. Commun. 4, 2691 (2013)

High-energy (1.3 micro J), high-power (2.6 GW) IAP

more than 100 times more energetic than previously reported

FROM FEMTOSECOND TO ATTOSECOND



(courtesy of Prof. J. Itatani)

Quest for higher photon energy (shorter wavelength)

cutoff $E_c = I_p + 3.17U_p$

$$U_p(\mathrm{eV}) = \frac{e^2 E_0^2}{4m\omega^2} = 9.3 \times 10^{-14} I(\mathrm{W/cm^2})\lambda^2(\mu\mathrm{m})$$

Longer fundamental wavelength is advantageous

Optical parametric chirped-pulse amplification (OPCPA)

WATER-WINDOW HHG

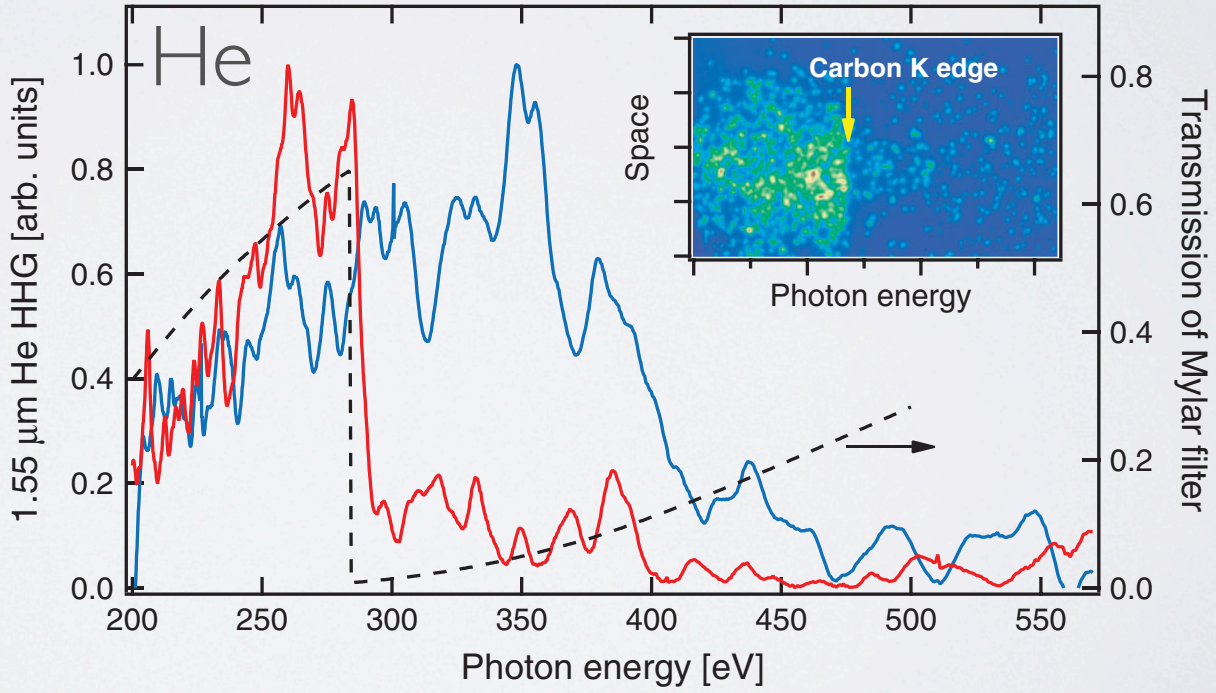
spectral range between the *K*-absorption edges of C (284 eV) and O (543 eV)

absorbed by biological samples but not by water

attractive for high-contrast biological imaging

$\lambda_0 = 1.55\,\mu\mathrm{m}$

$I = 5.5 \times 10^{14}\,\mathrm{W/cm^2}$



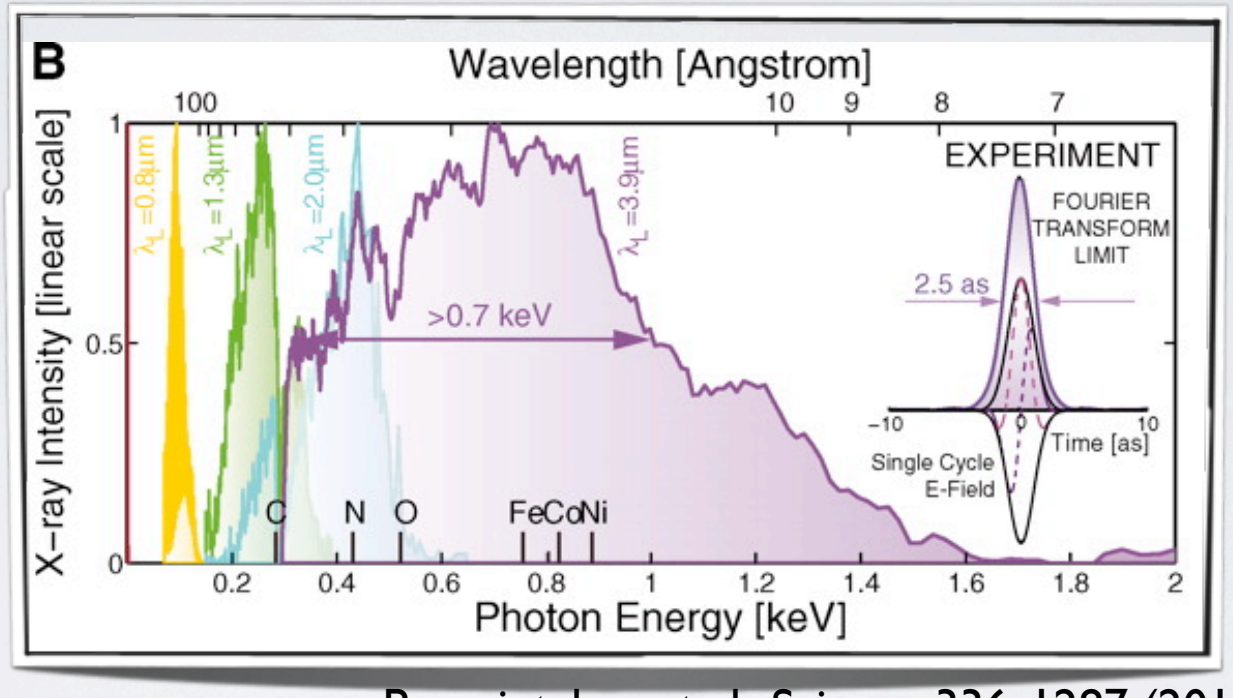
Takahashi et al., PRL 101, 253901 (2008)

keV HHG

Even up to 1.6 keV, > 5000 orders

almost x-ray!

$\lambda_0 = 3.9\,\mu\mathrm{m}$



Popmintchev et al., Science 336, 1287 (2012)

a new type of laser-based radiation source

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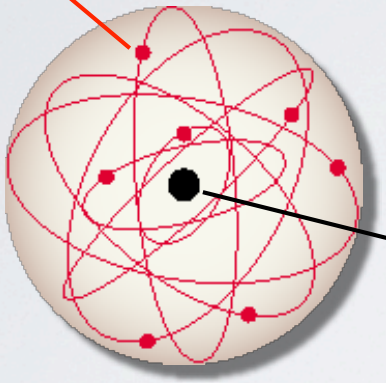
ATTOSECOND SCIENCE

atomic unit of time = 24 attoseconds

Electron



Nucleus

Orbital period of the Bohr electron

$$m\omega^2 r = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r^2}$$

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{4\pi\epsilon_0 m r^3}{e^2}} = 152\ \text{as} = 2\pi\ \text{a.u.}$$

real-time observation and time-domain control of **atomic-scale electron dynamics**

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