Attosecond Free Electron Lasers

Vitaliy Goryashko

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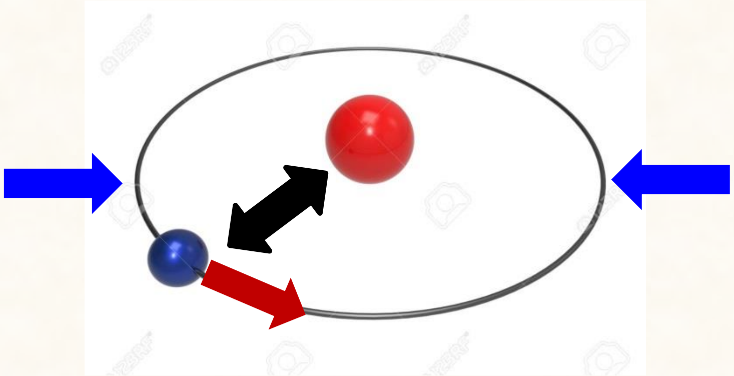
Part I: a taste of attosecond science

Hydrogen atom

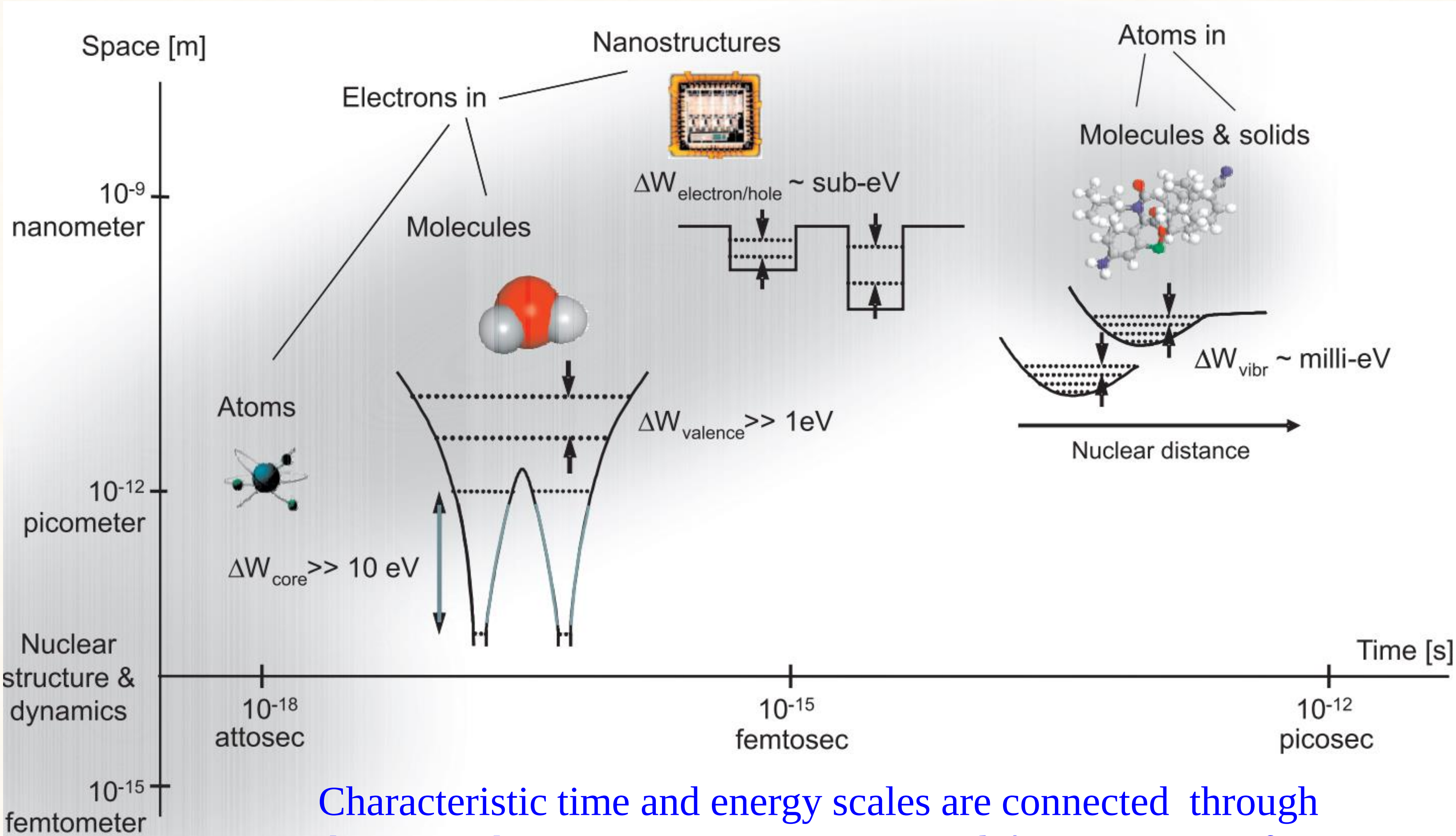


Energy scale ~ 10 eV

Spatial scale ~ 0.1 nm

Time scale ~ 150 as

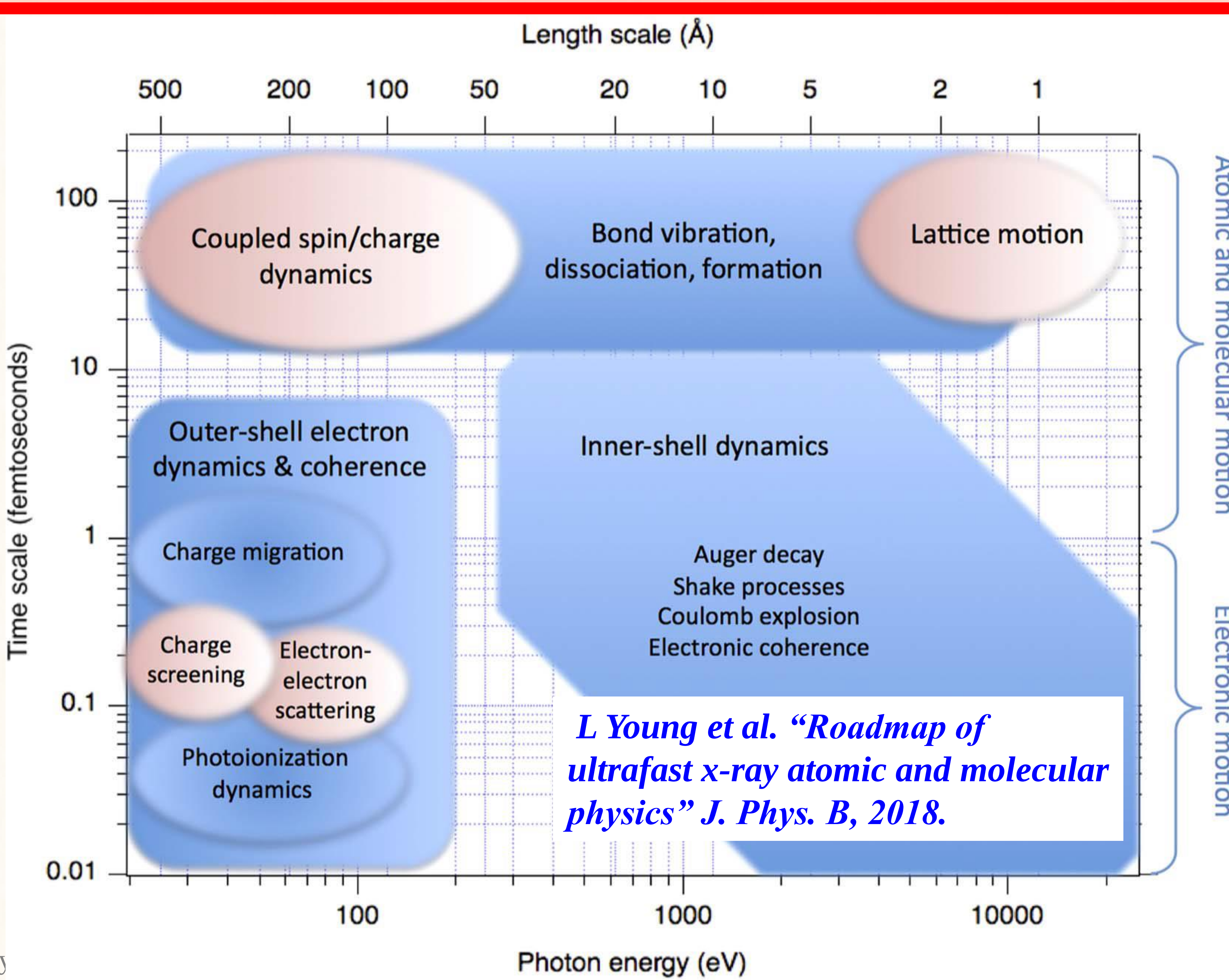
Characteristic time and space scales in physics



Characteristic time and energy scales are connected through the Heisenberg uncertainty as $\Delta t\ \Delta E \geq \hbar/2$: 1 eV => 42 fs

F. Krausz and M. Ivanov: Attosecond physics. Rev. Mod. Phys. 2009

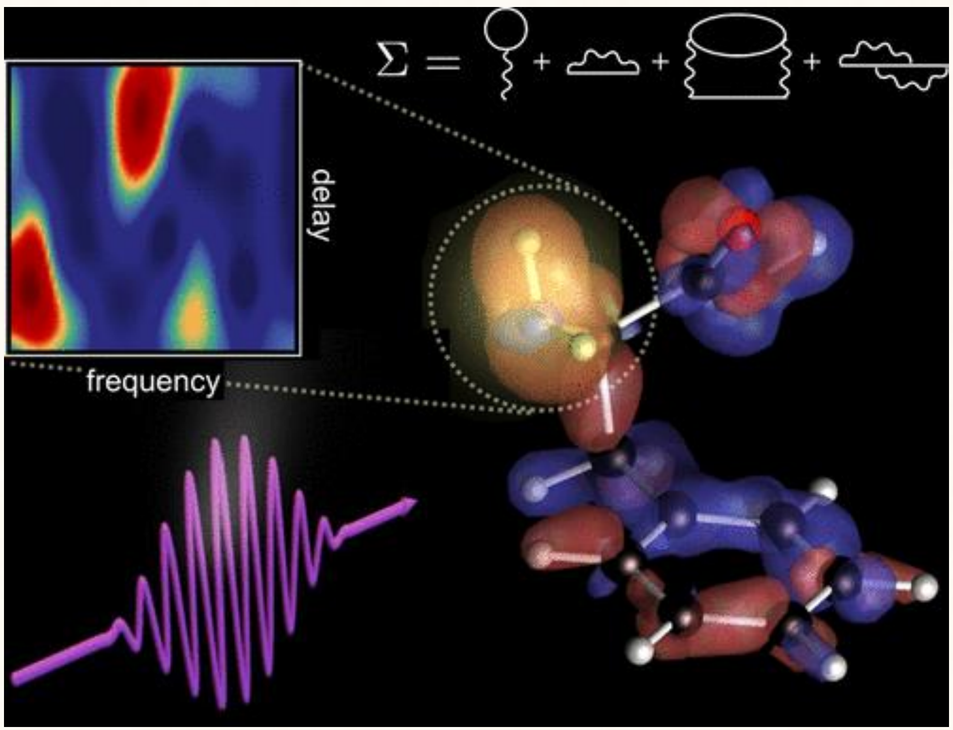
Science drivers for attosecond science



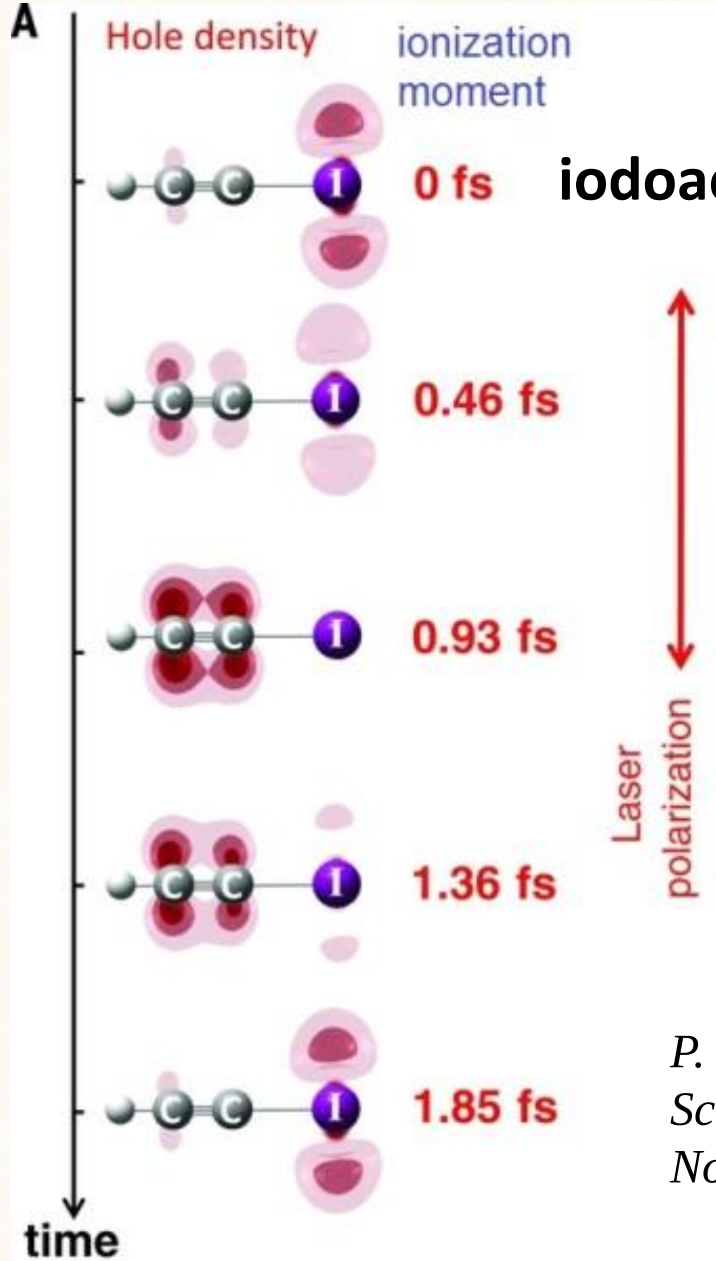
L Young et al. "Roadmap of ultrafast x-ray atomic and molecular physics" J. Phys. B, 2018.

Example of measured charge migration

- Processes at the atomic level are governed by electronic behavior.
- What happens if we remove an electron (ionize atom)?
- How does the electron hole migrate?



E. Perfetto, J.Phys.Chem.Lett. 9, 1353, 2018.

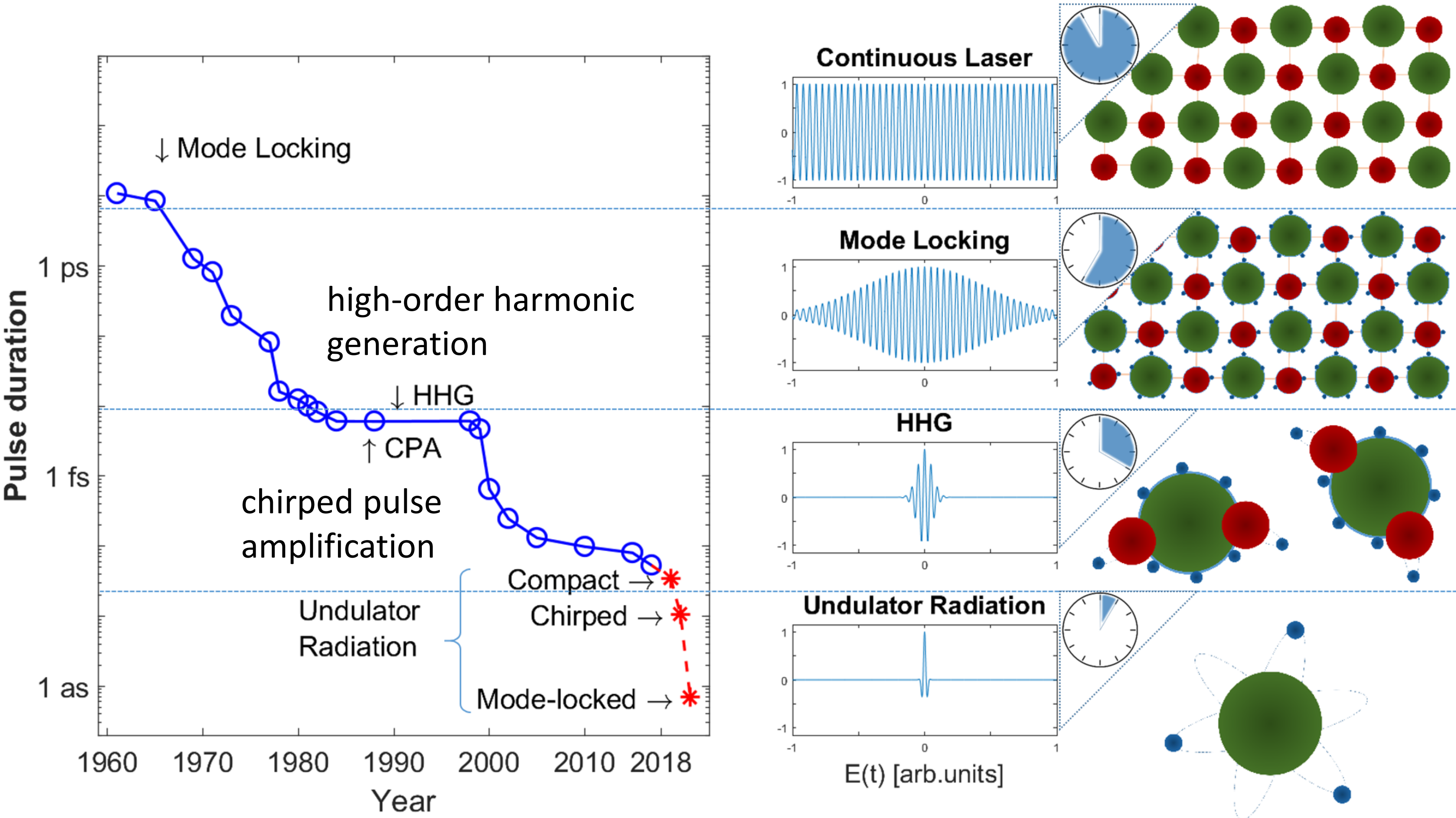


iodoacetylene

P. M. Kraus, Science 13, Nov 2015

Part II: present capabilities for the production of attosecond pulses

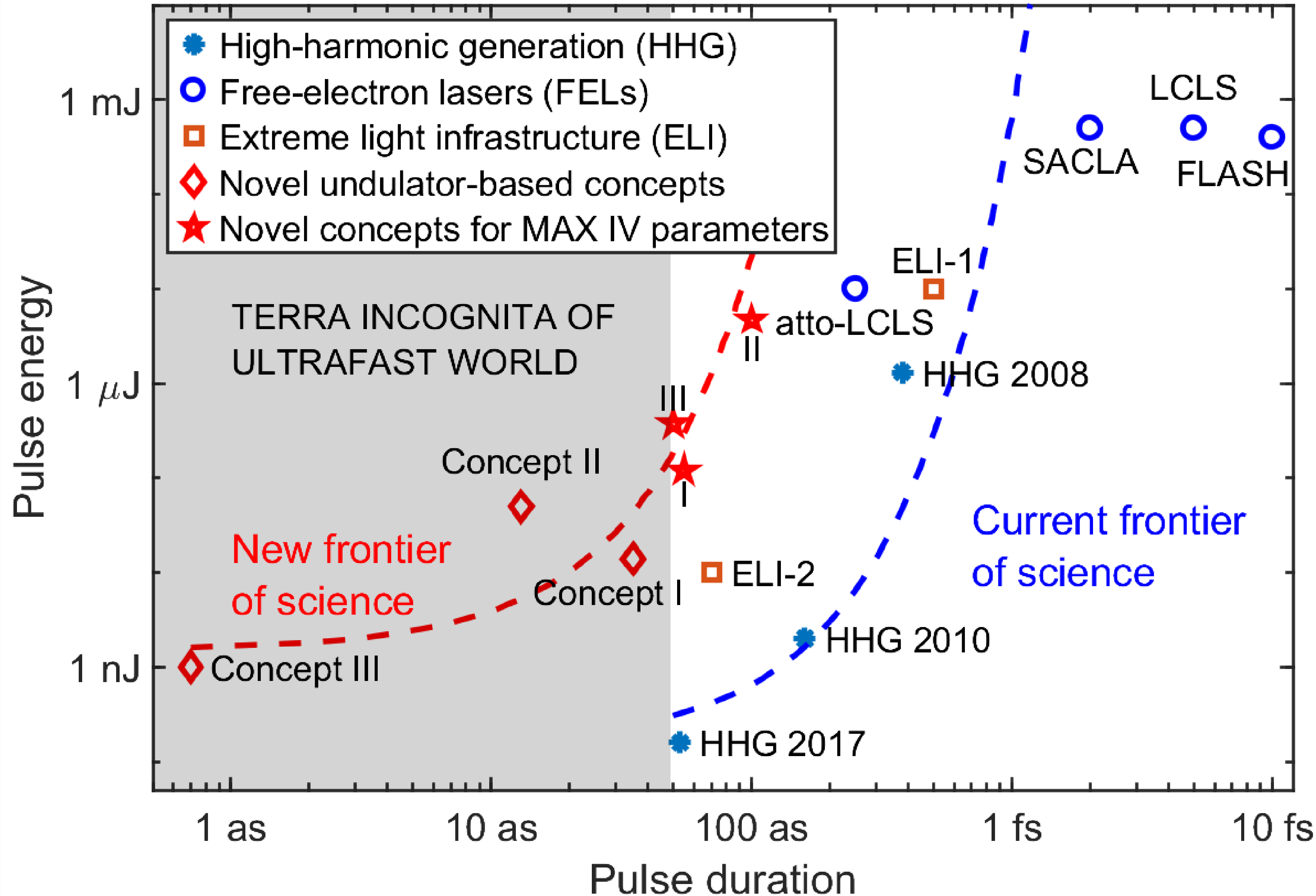
Progress on ultrashort generation



HHG sources are facing saturation. New methods are needed.

A. Mak et al. & V. Goryashko, Reports on Progress in Physics, 2018.

State-of-the-art of short pulse generation

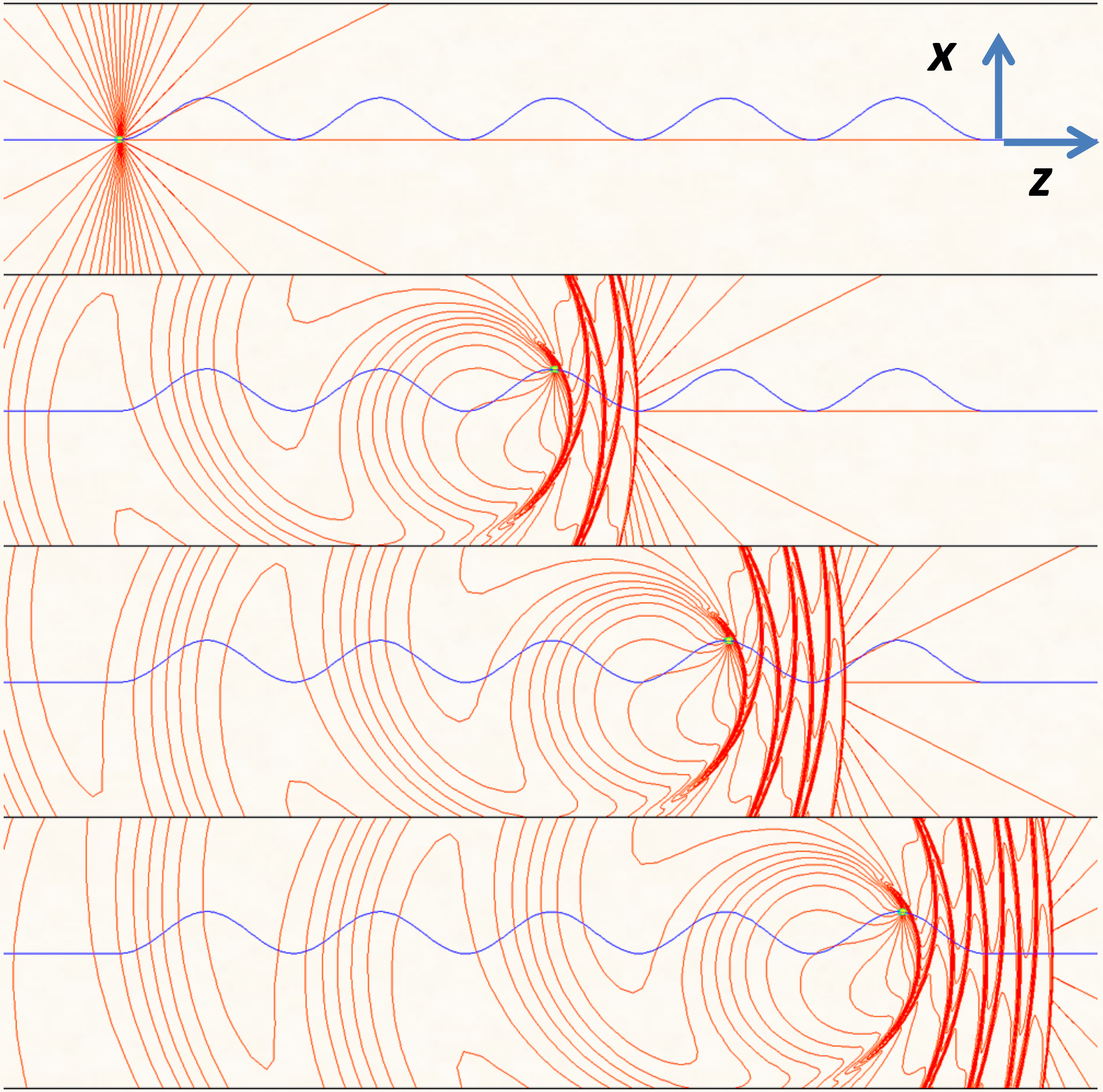


Undulator light source is a promising way to the attosecond region.

Part III: new concepts for reaching the 'terra incognita' of ultrashort pulses

- Example of an oscillating charge;
- Undulator;
- Free-electron laser;
- Generation of attosecond single-cycle pulses in an undulator.

Radiation from a single moving oscillating charge

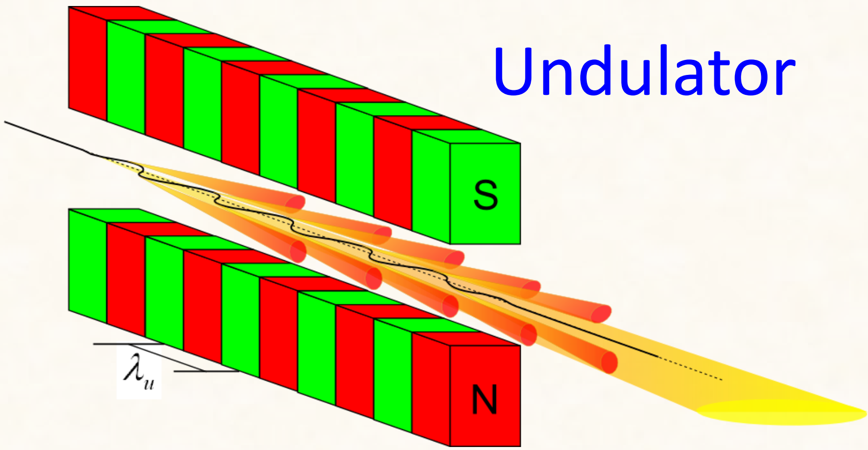


$$E_x = \frac{q}{c^2 r}\frac{d^2 x'}{dt^2}$$

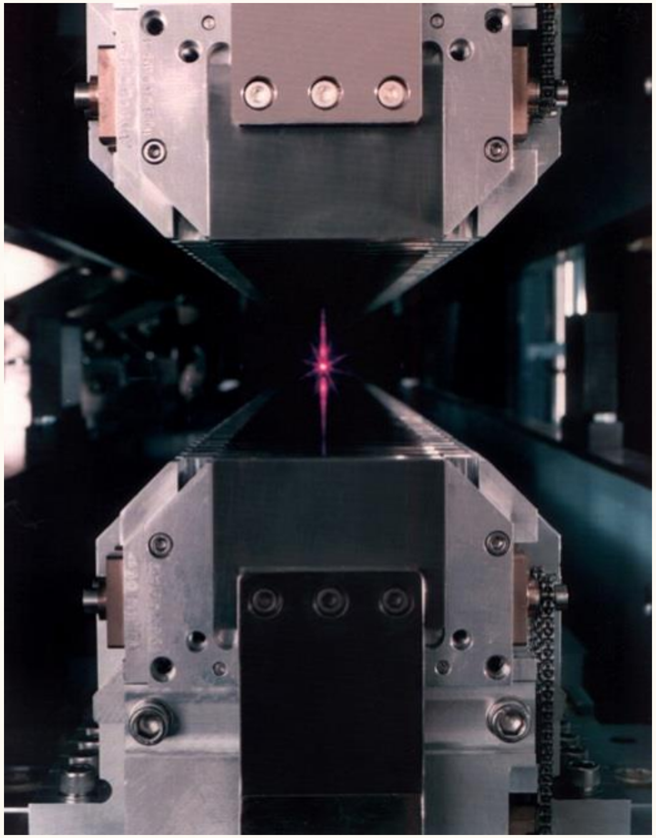
- $\bar{e}$ moves along z-axis
- $v_z \approx c$
- $\gamma_z = 1/\sqrt{1 - v_z^2/c^2}$
- $\bar{e}$ oscillates at ω_0 along x-axis
- in the frame moving at v_z, $\bar{e}$ emits a sin wave at frequency $\omega_0 \gamma_z$
- In the lab frame, the radiation frequency is Doppler upshifted

$$\omega = \gamma_z^2 \, \omega_0$$

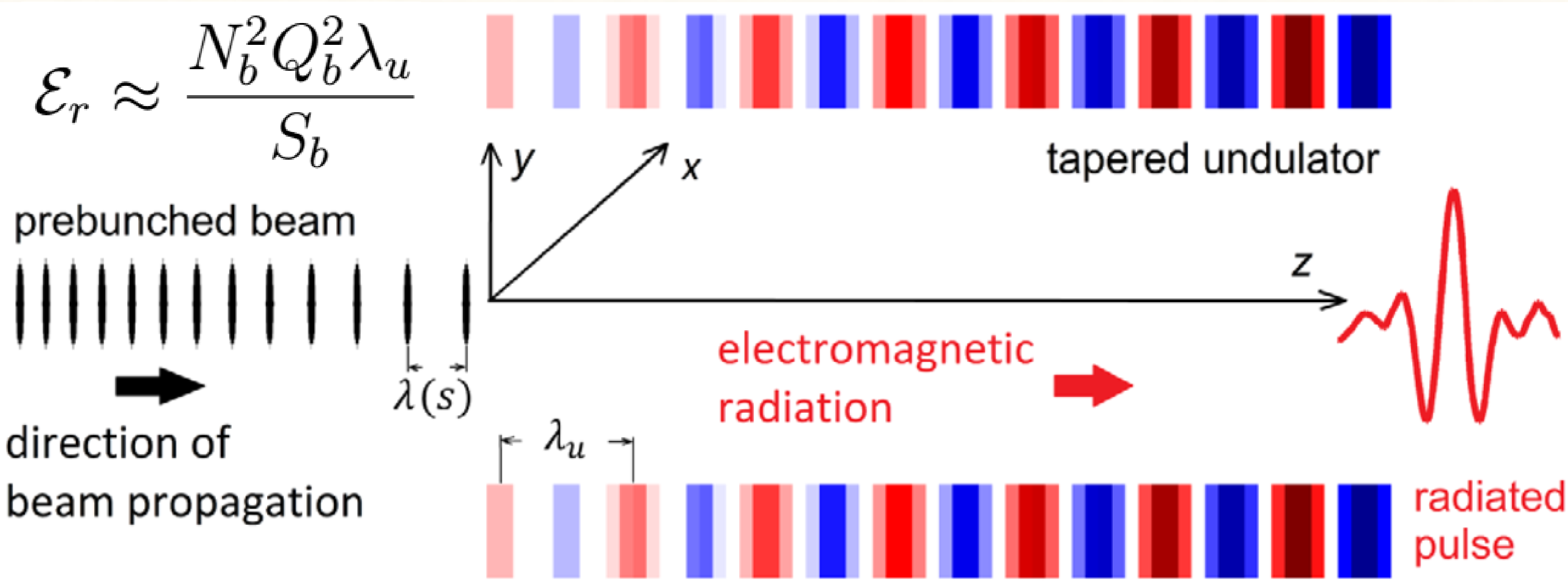
How to force electrons to wiggle?



- A set of alternating magnetic poles
- Planar or helical geometry
- Characterized by period λ_u
- and by undulator parameter
  $K = 0.934\, B_0[\text{Tesla}]\, \lambda_u[\text{cm}]$



Single-cycle pulses from a tapered undulator

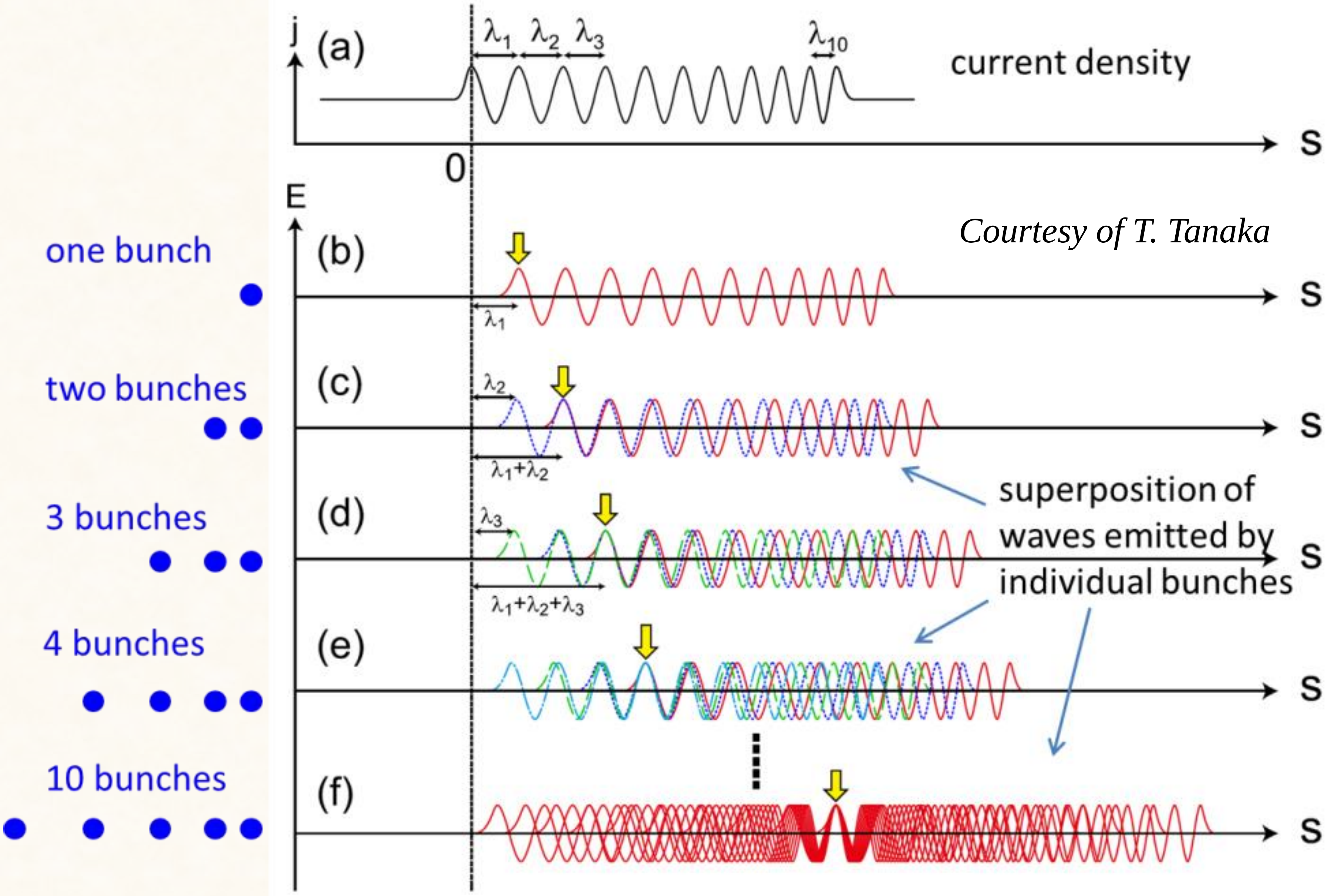


- Periodic undulator field with varying strength $B_0(z)\cos(2\pi z/\lambda_u)$
- A train of electron bunches (prebunched beam)
- Radiation wavelength changes along the pulse

$$\lambda(z) = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{\mathcal{K}(z)^2}{2}\right], \qquad \mathcal{K}(z) \propto B_0(z).$$

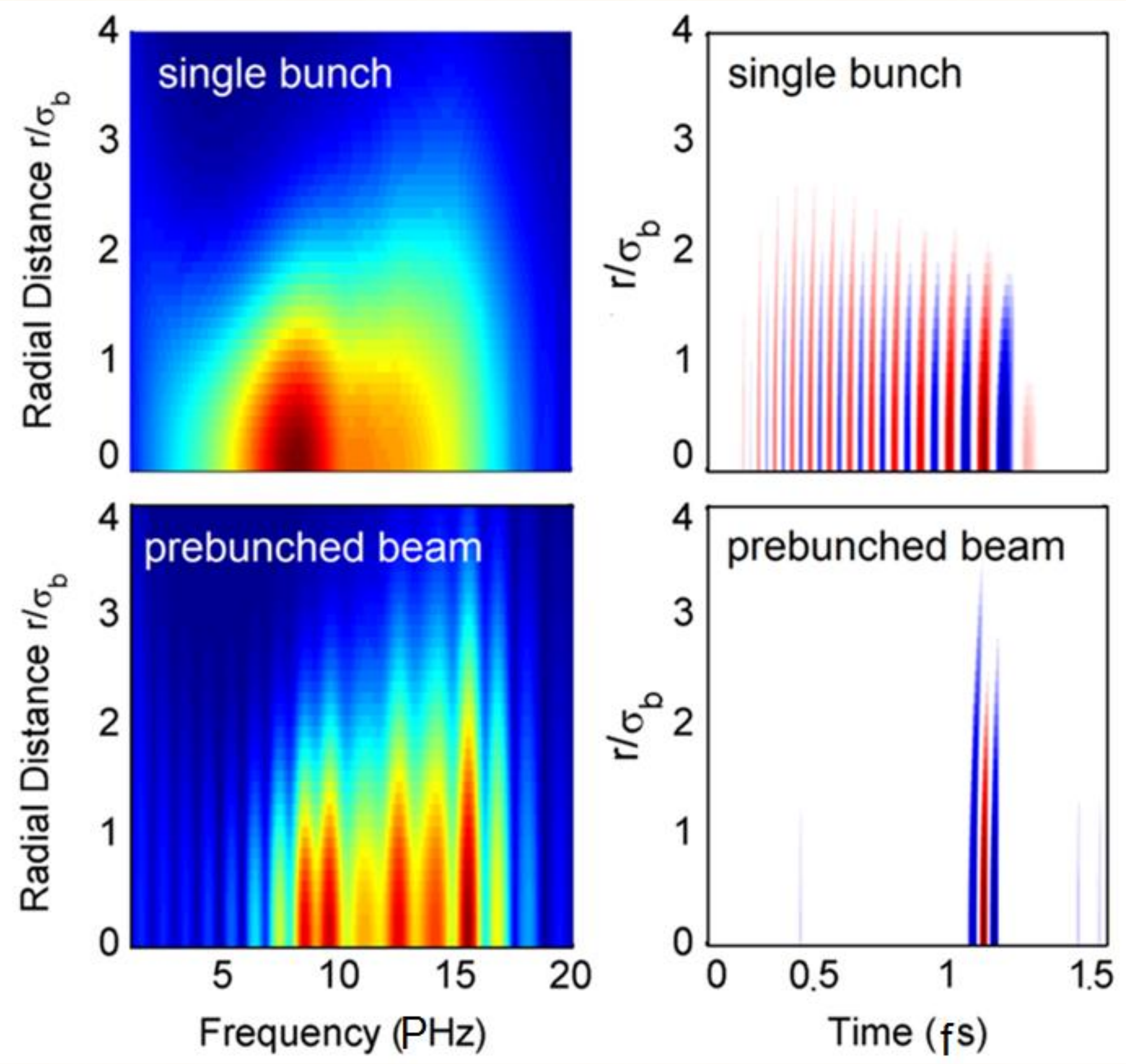
V. Goryashko "Quasi-half-cycle pulses of light from a tapered undulator," Phys. Rev. Acc. & Beams, 2017.

How it really works



Pulse waveform can be controlled by taper profile.

Pulse shape control: example of simulations



Take home messages

- In Bohr's model of the hydrogen atom, the electron in the ground state completes one cycle in 150 attoseconds.
- Dynamics of electrons in atoms and molecules occurs on the attosecond time scale. The energy scale is 10-1000 eV.
- Attosecond pulses of light can provide the resolution needed for studying and ultimately controlling the dynamics of electrons.
- The existing HHG sources are limited to ~ 100 eV => 100 as.
- Using coherent undulator radiation, it is feasible to push the limit to 1 keV region => 10 as.
- Electron bunch traversing a tapered undulator produces a chirped radiation pulse (wavelength varies along the pulse).
- Constructive interference of chirped pulses from a train of electron bunches gives a single-cycle wave packet.

Thank you for your attention!