Time and Length Scales in X-Ray Science

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Overview

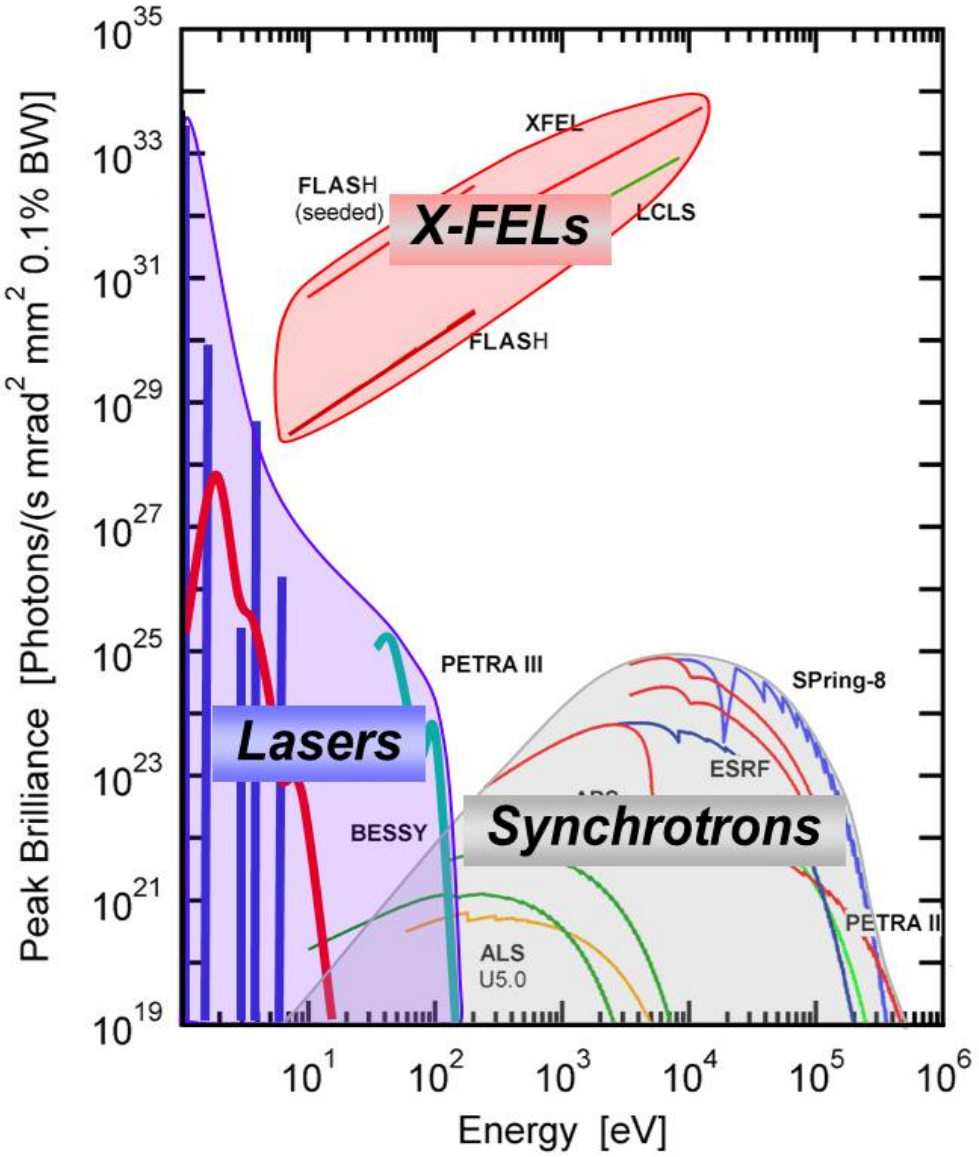
- **Production and Characteristics of X-rays**
  - Electrons, Fields, Radiation, Photons
  - Radiation spectra: synchrotron & X-FEL
  - Brightness/coherence: diffraction and transform limit

- **X-Ray Interactions – Length and Time Scales**
  - First and second order x-ray processes
  - Polarization effects – “dichroism”
  - Importance of ***E*** versus ***B*** fields

Part 1:

Production and Characteristics of X-rays

Categories of Lightsources

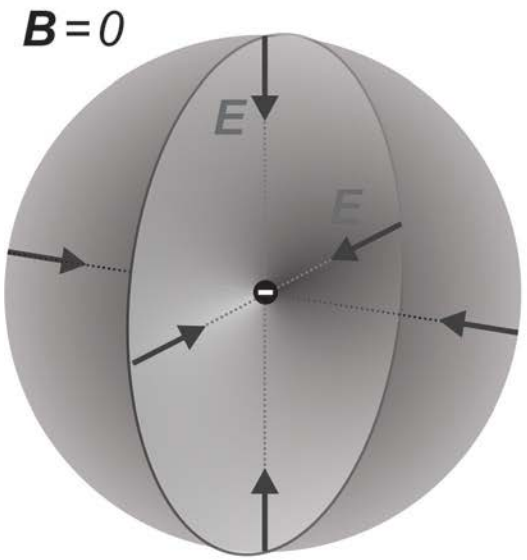


Synchrotron & X-FEL sources are based on electron accelerators

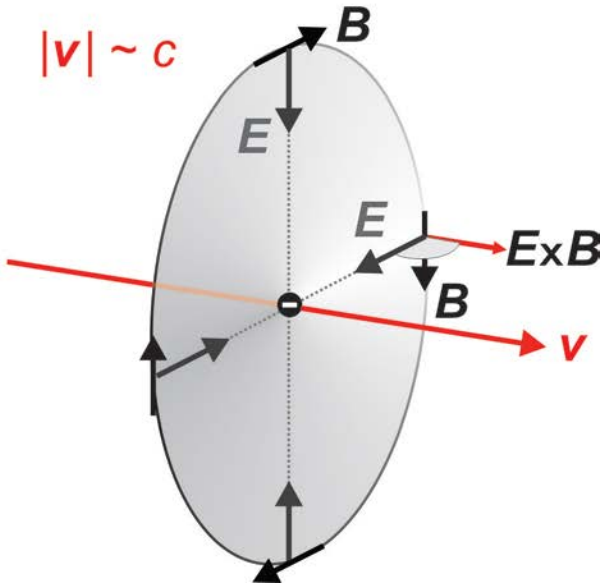
J. Ullrich, A. Rudenko, R. Moshammer
Ann. Rev. Phys. Chem. 63, 635 (2012)

Energy of electron beam is contained in its fields

Fields in frame of charge



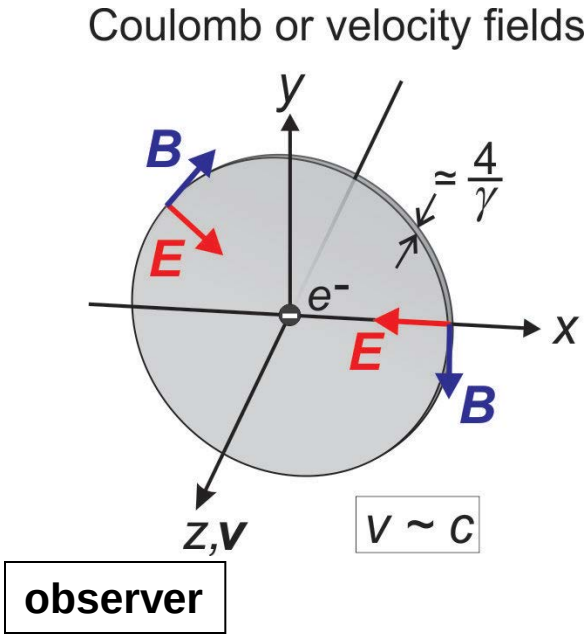
Fields in frame of observer



For moving charge, energy in *E* and *B* fields is the same

$$\text{Energy}: \quad \mathcal{U} = \frac{V}{2}\left(\epsilon_0|\boldsymbol{E}|^2 + \frac{1}{\mu_0}|\boldsymbol{B}|^2\right) = \epsilon_0 V\,|\boldsymbol{E}|^2$$

To an observer the approaching Coulomb fields look like an EM wave



The **Weizsäcker-Williams theory**

converts the energy in the field pulse $E(t)$, B(t)

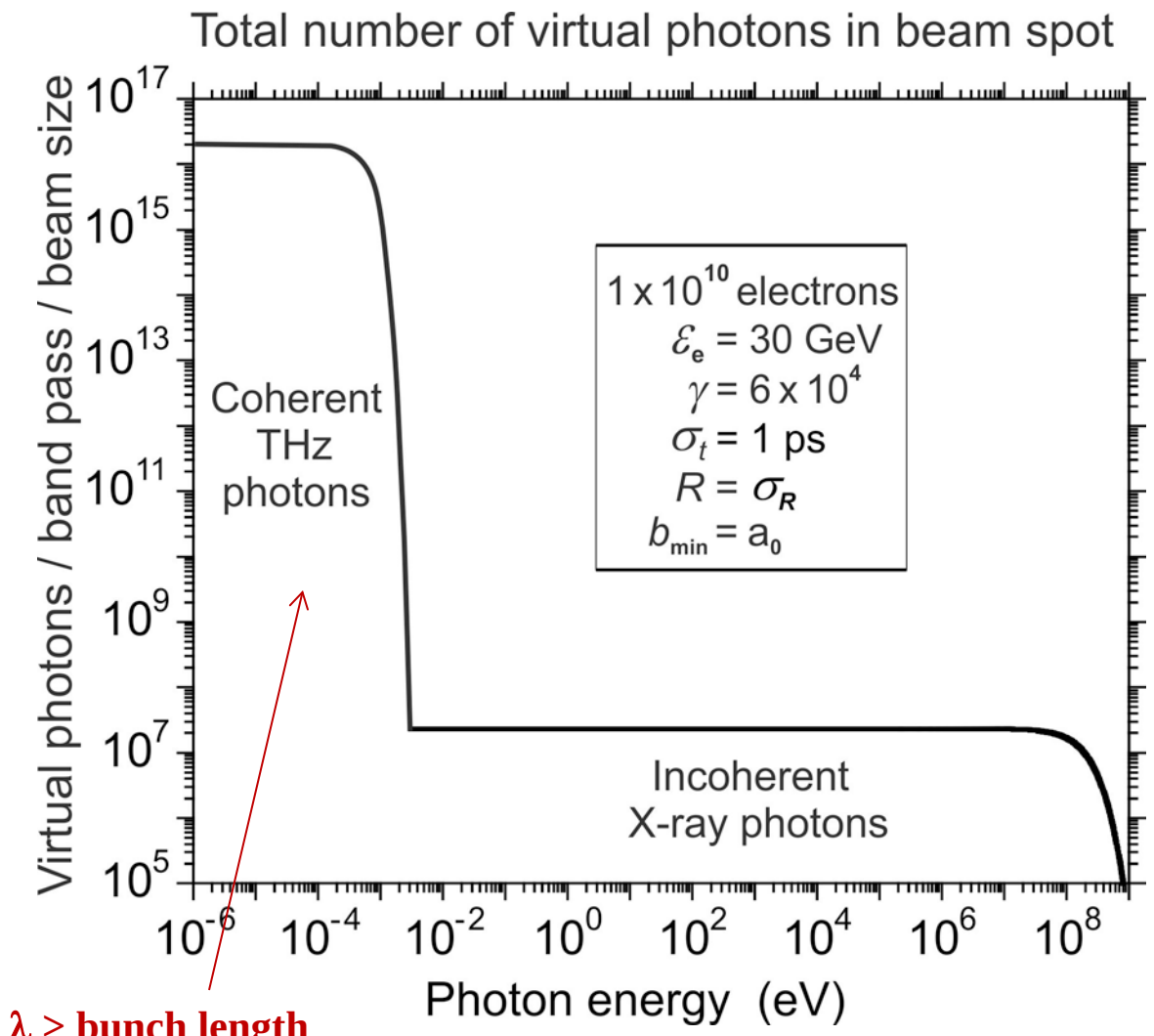
through Fourier transformation into

the "virtual photon" spectrum $E(\omega)$, $B(\omega)$

- The virtual photon cloud is attached to the charge
- All interactions are through the virtual photons

The Weizsäcker-Williams virtual photon spectrum

30GeV, 1ps electron bunch with 10^{10} electrons



λ > bunch length

1ps = 300μm

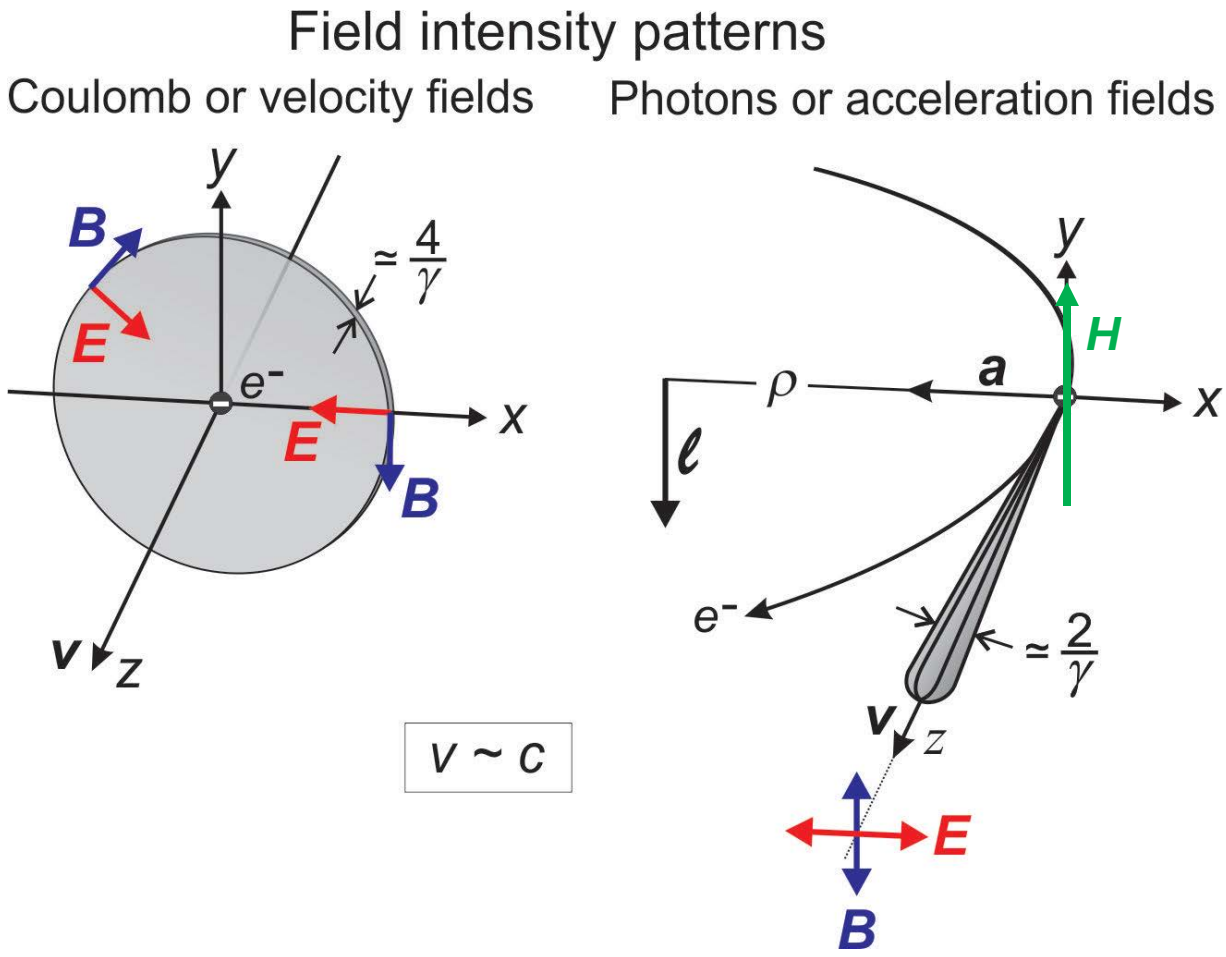
“Interactions” can turn Virtual Photons into real photons

Examples of conversions of VPs into real photons:

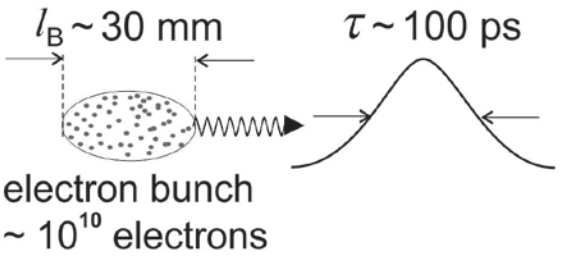
- “Bremsstrahlung”: scatt. of VPs on the nuclear Coulomb field
- “transition radiation”: scatt. of VPs on electric boundary field
- “Annihilation photons”: scatt. of electron on positron VPs
- “synchrotron radiation”: scatt. of VPs on a magnetic field

Synchrotron Radiation

magnetic field ***H*** accelerates electrons: converts VPs to “radiation”

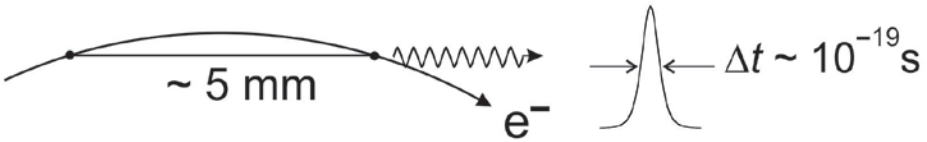


Synchrotron radiation “spectrum”

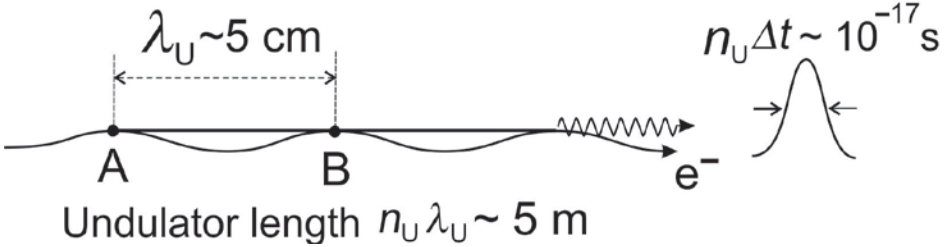


all electrons in bunch radiate independently

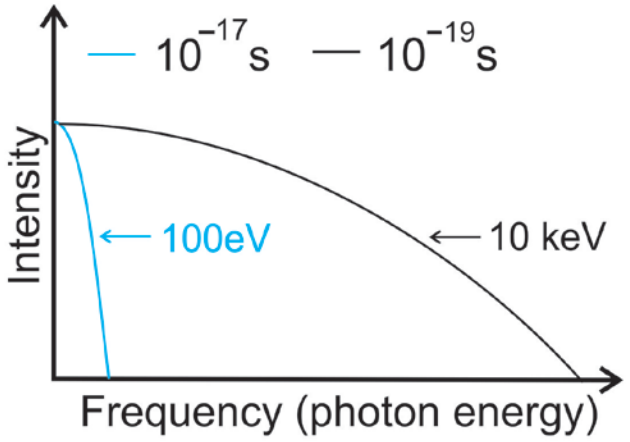
Single electron x-ray pulse from **bending magnet**



Single electron x-ray pulse from **undulator**

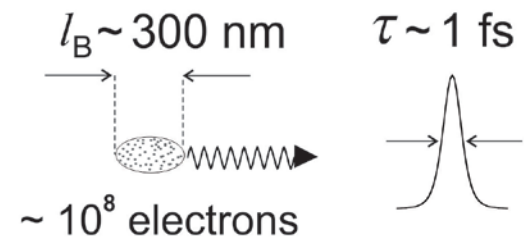


Fourier transform of pulse = synchrotron radiation spectrum



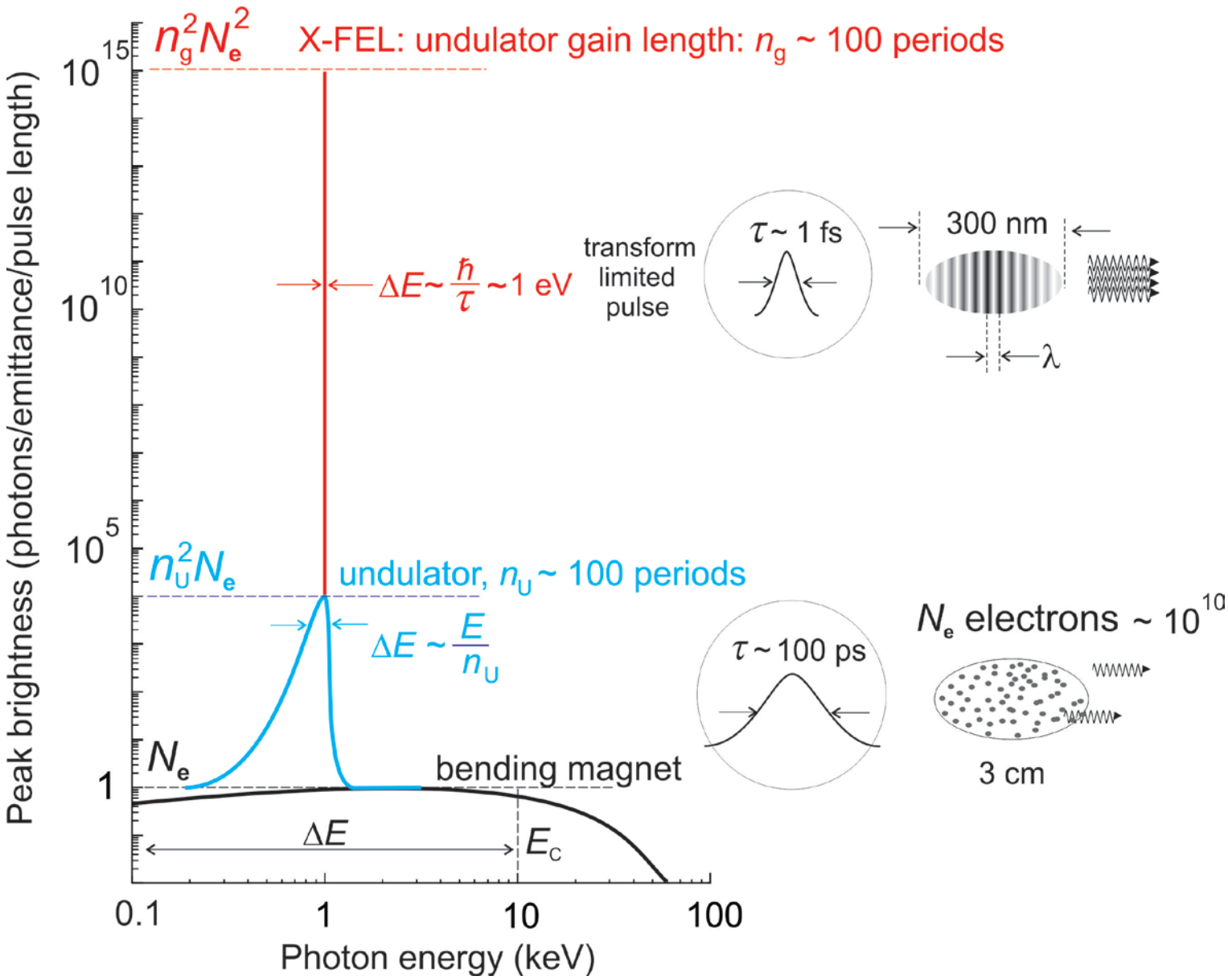
X-FEL spectrum

Short pulse X-FEL spectrum

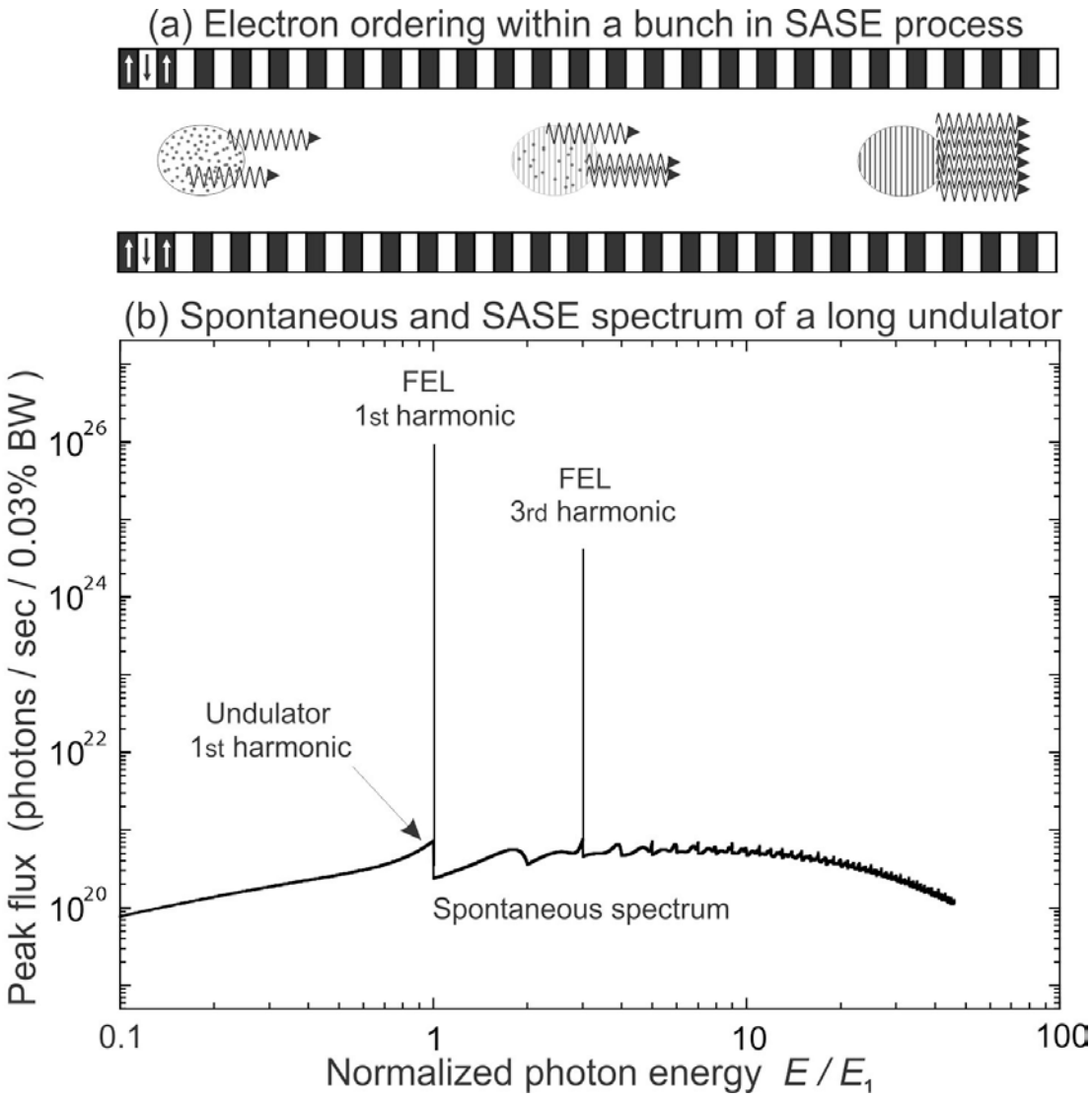


electrons in bunch are arranged in sheets and radiate coherently in phase

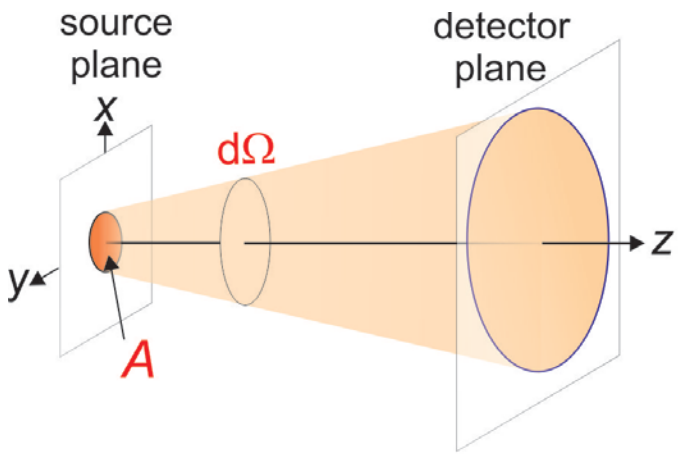
Summary of x-ray source spectra



Calculated X-FEL spectrum



Source brightness (or brilliance)

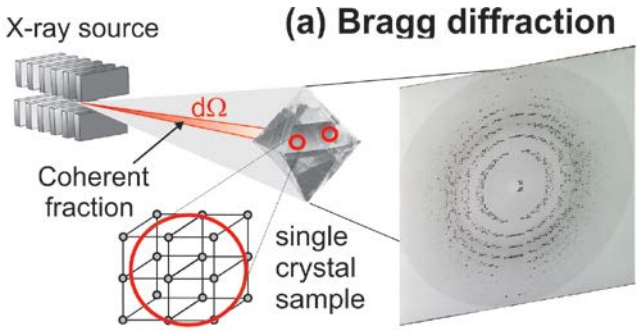


$$\text{peak brightness} = \frac{\text{number of photons}}{\underbrace{A\,d\Omega}_{\Delta r\,\Delta p \geqslant \hbar} \quad \underbrace{\tau_{pulse}\Delta\omega/\omega}_{\Delta t\,\Delta \mathcal{E} \geqslant \hbar}}$$

space-momentum uncertainty

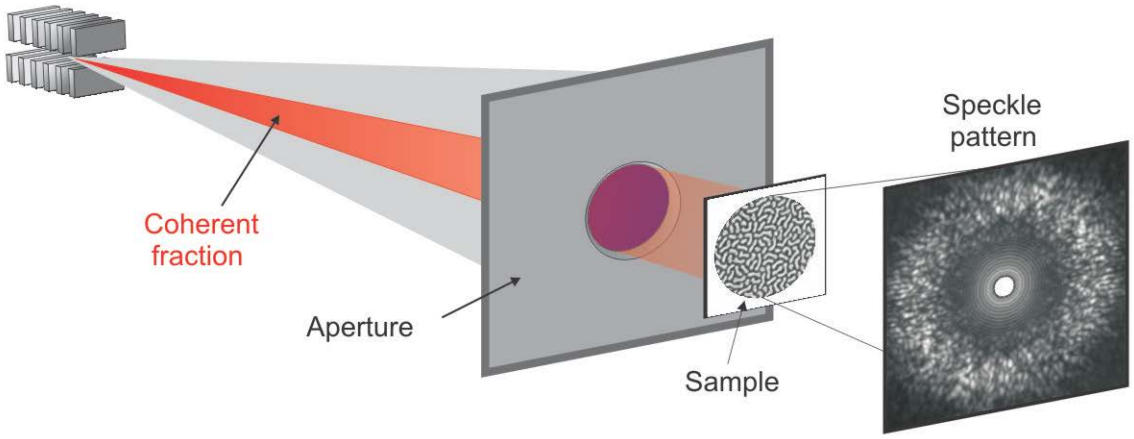
time-energy uncertainty

Importance of a “diffraction limited source” or laterally coherent source

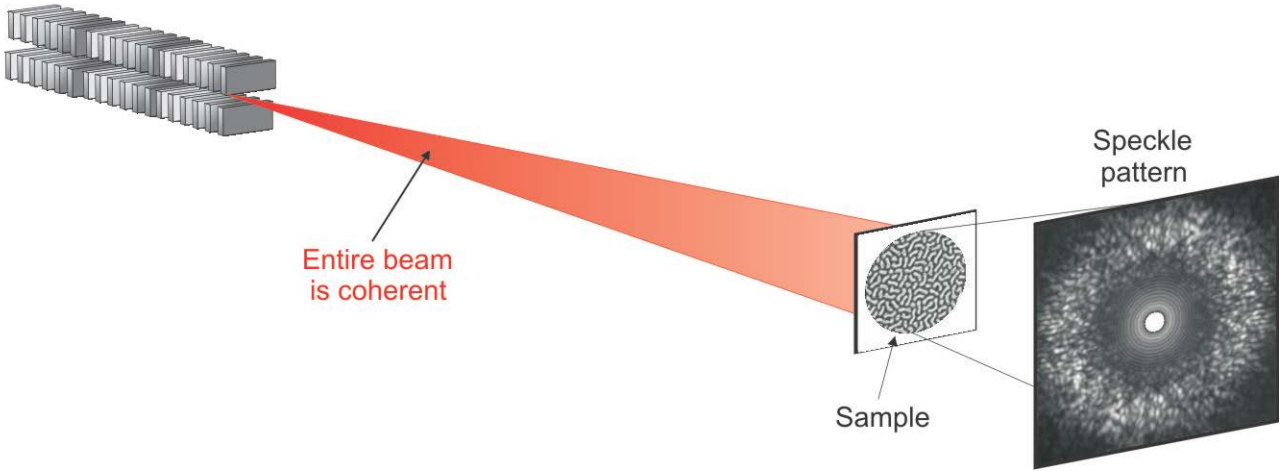


X-FEL x-rays are diffraction limited allow single shot diffraction imaging

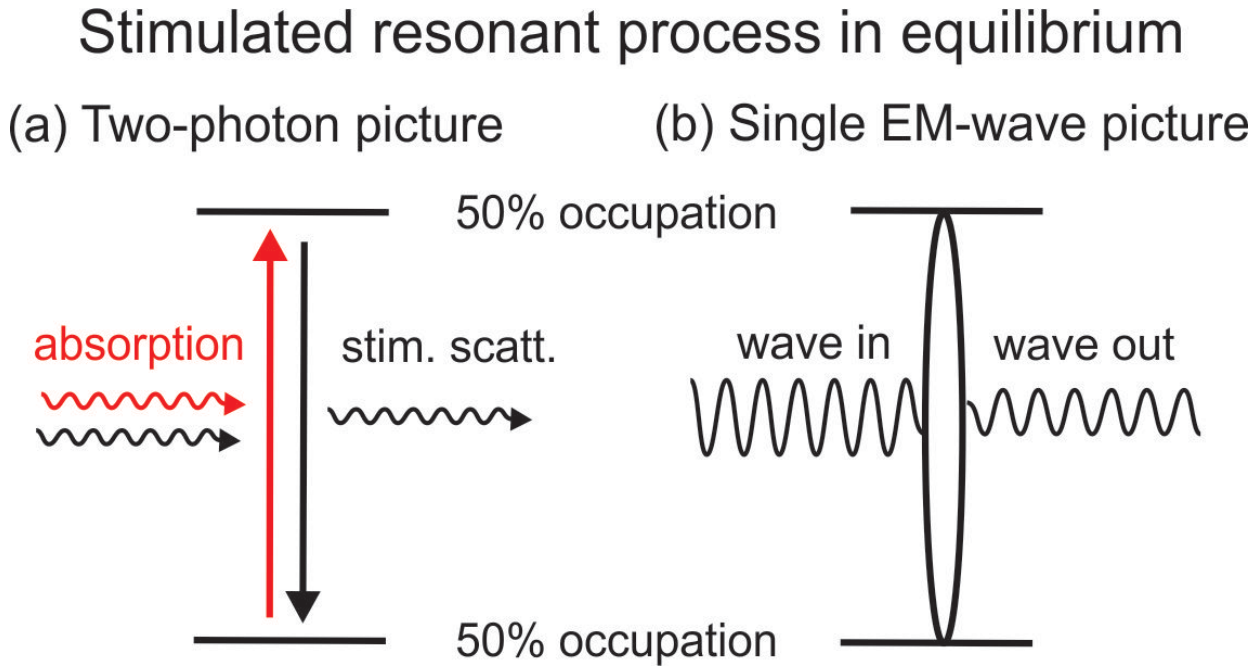
Storage ring: undulator



X-ray Free Electron Laser



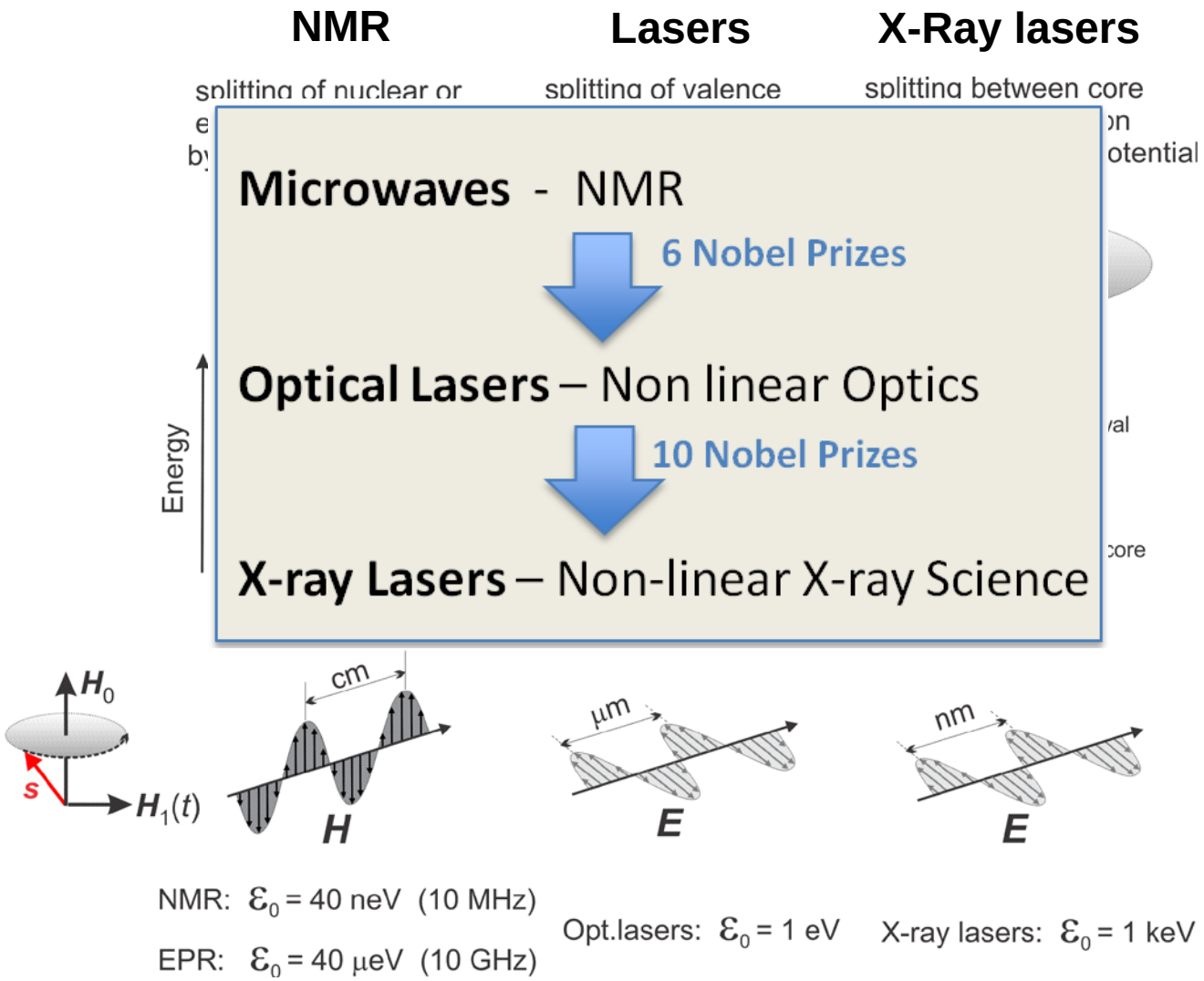
Importance of a “transform limited” source or longitudinally coherent source



More than one photon at-a-time = strong classical field

offers complete “up-down” control

From NMR to X-Ray Lasers:
controlling transitions with coherent EM radiation

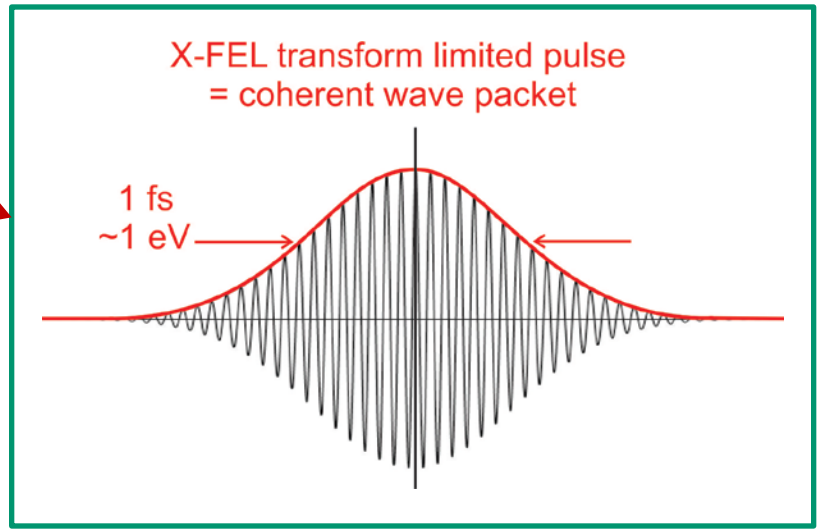


Number of simultaneous coherent x-rays: storage ring versus XFEL

"simultaneous" is defined by atomic decay clock ~ 1 fs

Storage ring:
10^{14} phot./eV/s ⇨ **10^{-1} phot./eV/fs** **"one photon at a time"**

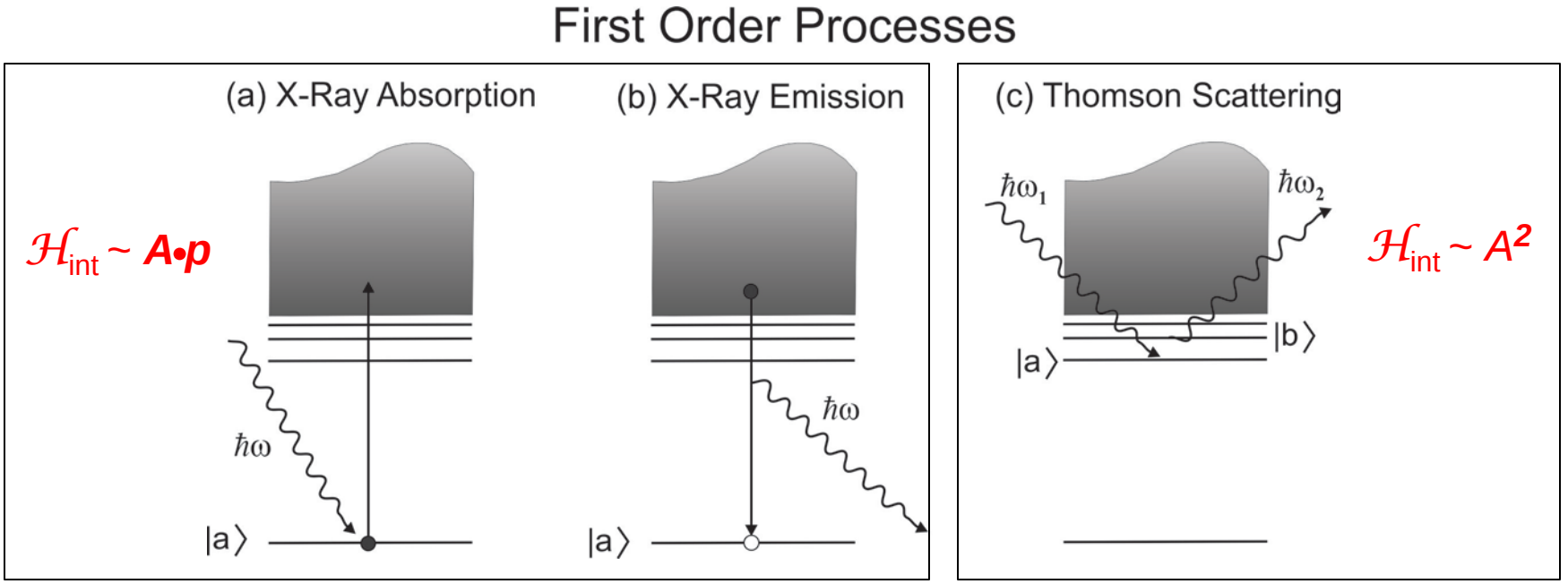
X-Ray laser: 10^{9} phot./eV/fs



Part 2:

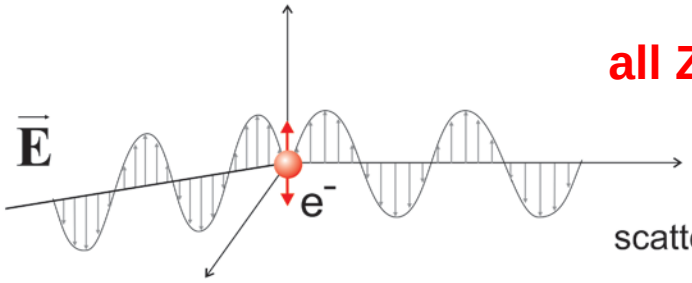
X-Ray Interactions – Length and Time Scales

Basic x-ray interaction processes



First Order X-Ray Scattering: “Thomson Scattering”

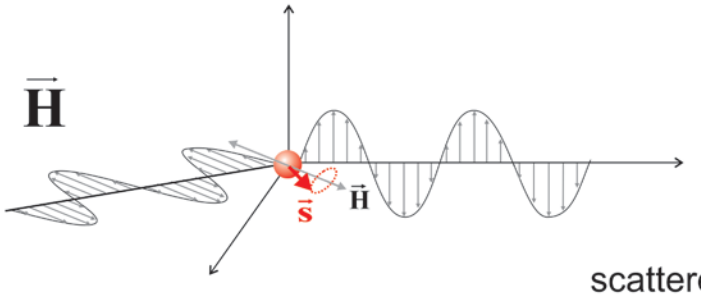
Scattering by charge



all Z atomic electrons “wiggle”

scattered intensity: 1

Scattering by spin



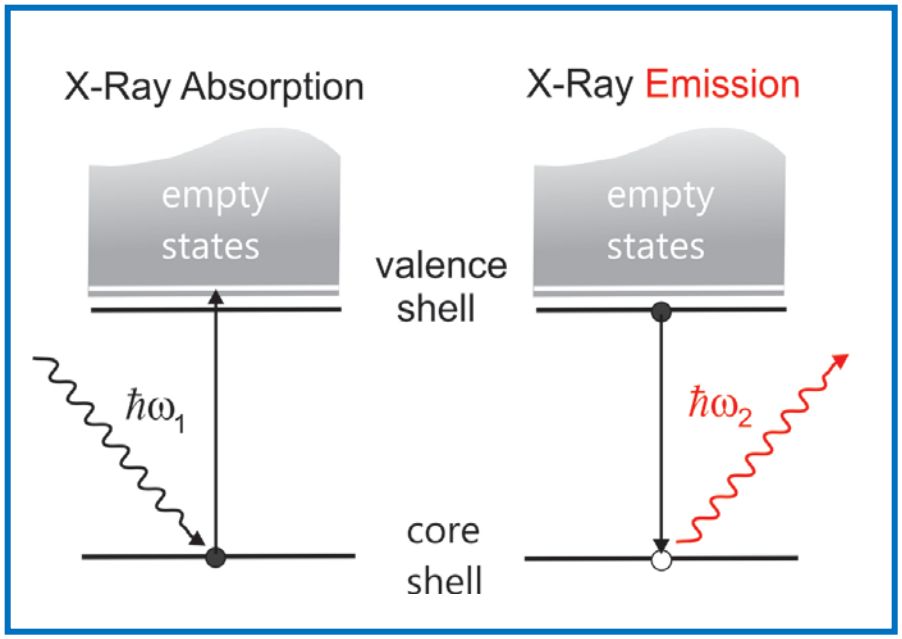
very weak

scattered intensity: $(h\nu/mc^2)^2$

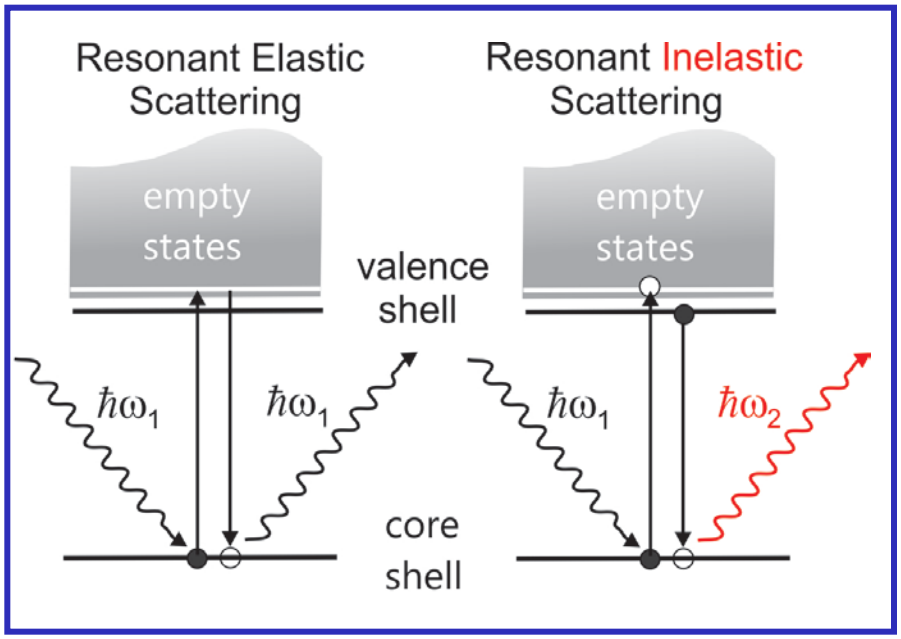
mc^2 ~ 500 keV

“Bragg diffraction” = interference of Thomson scattered fields

The four basic Resonant X-Ray Processes

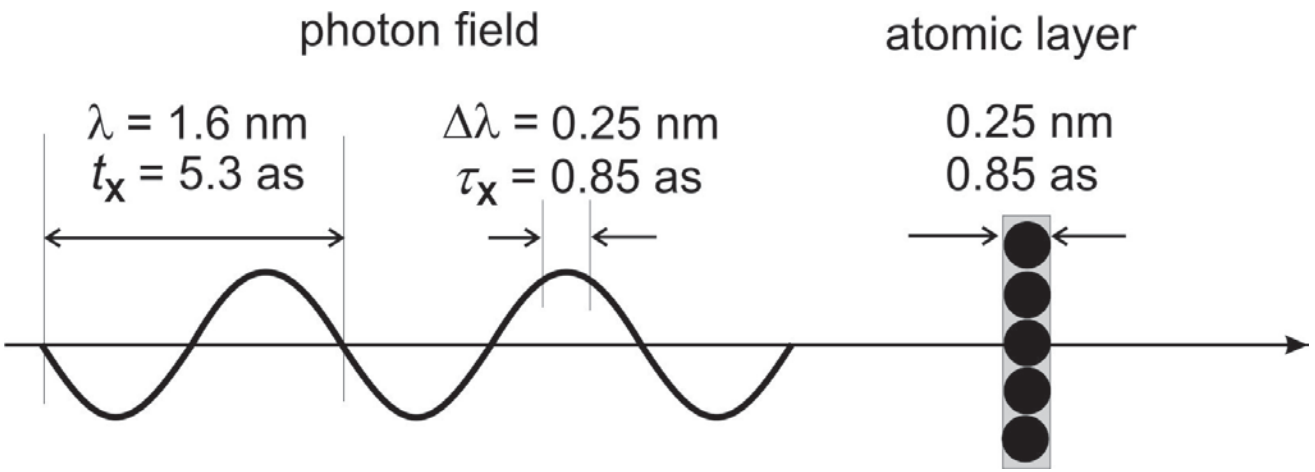


First order: “Fermi's golden rule”

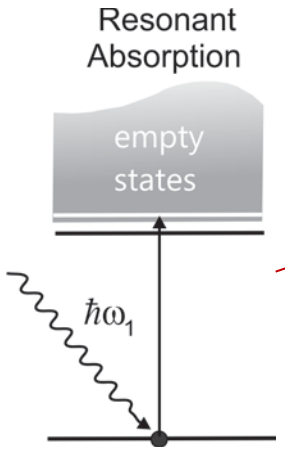


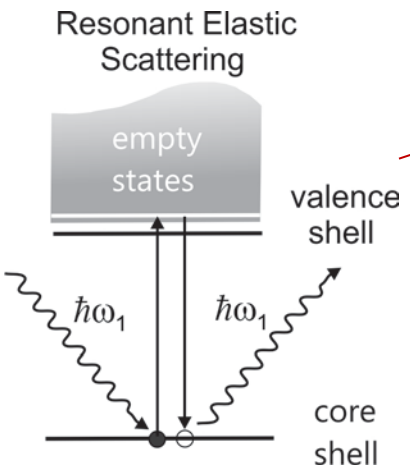
Second order: “Kramers-Heisenberg”

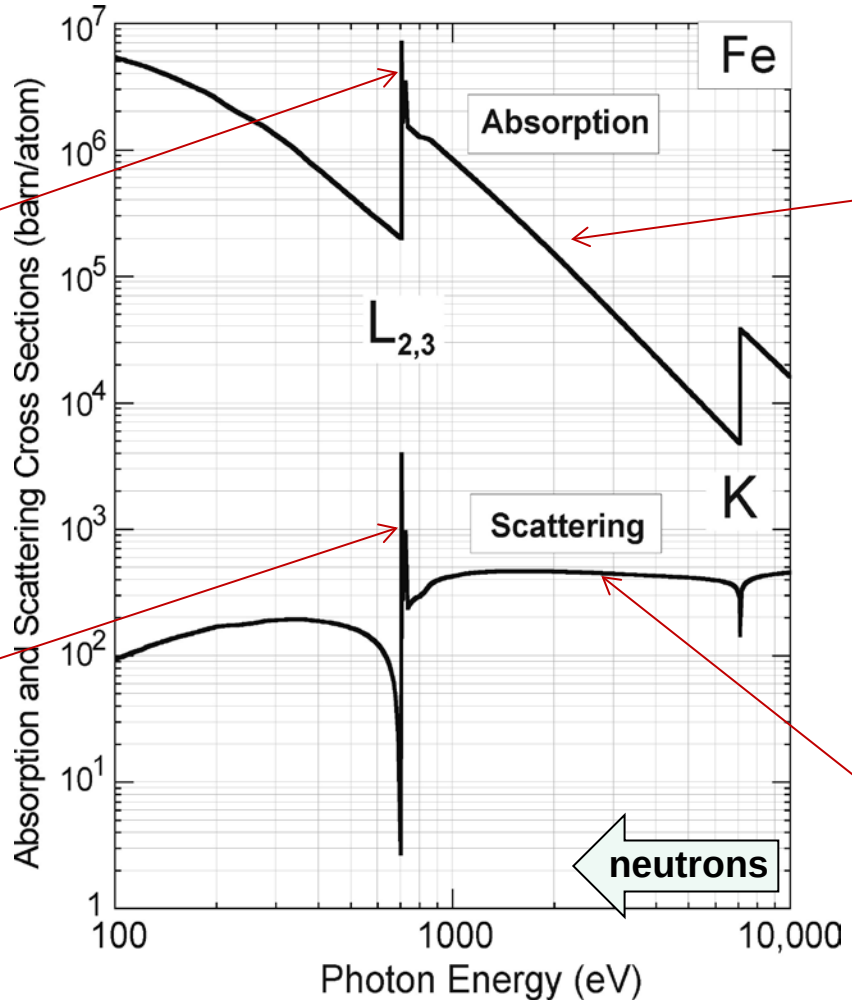
Length and time scales of (soft) x-rays

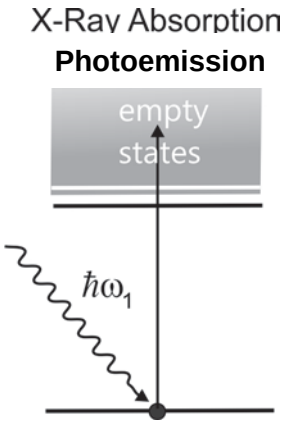


Photon energy dependence of cross sections

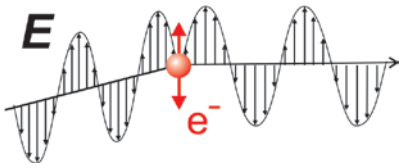








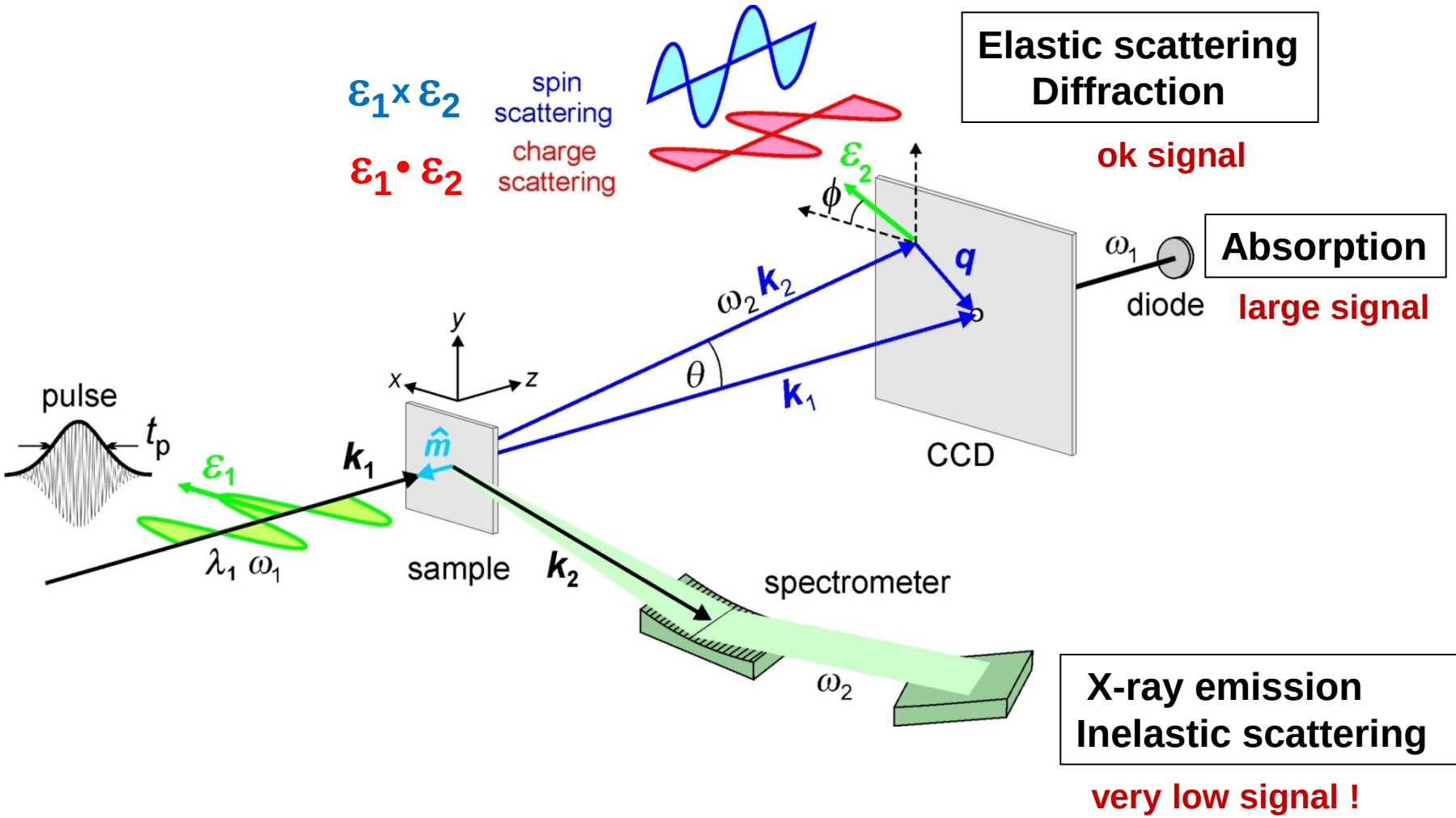
Thomson scattering



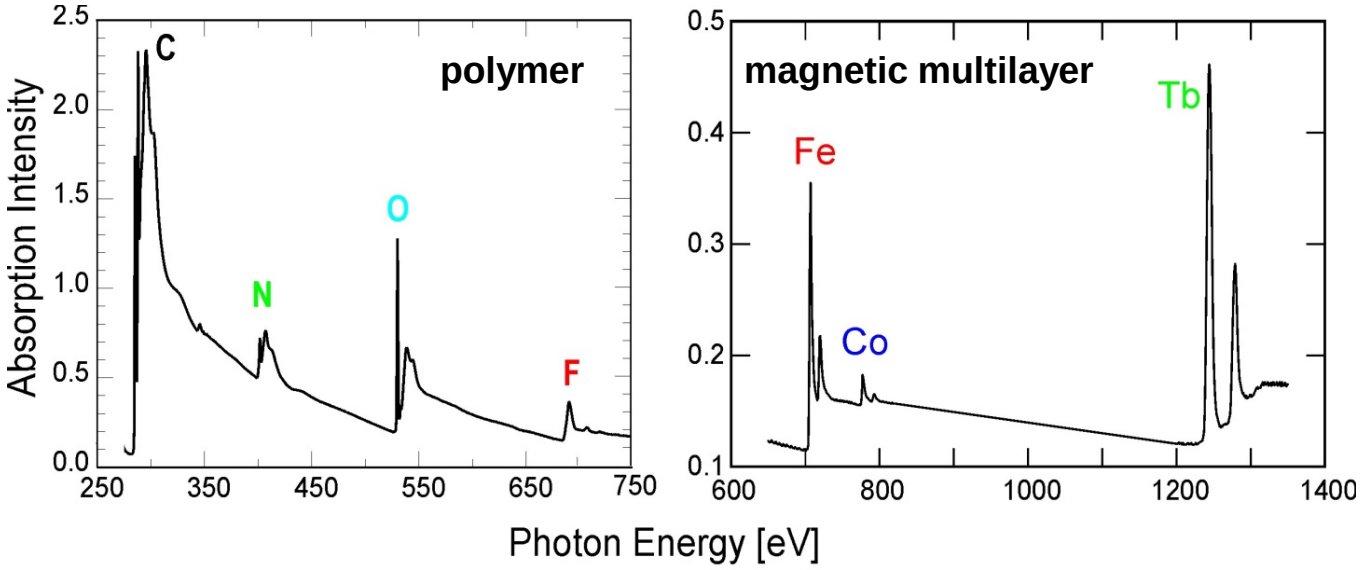
✪ **Z, electrons/atom**

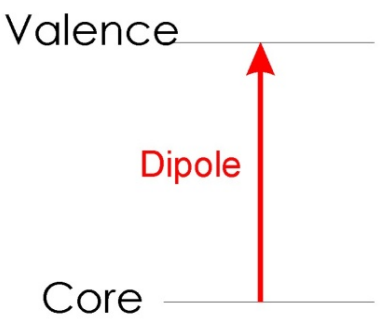
Resonant processes give orders of magnitude signal enhancements

Measurement of X-Ray Processes



Strong resonances near absorption thresholds (edges)



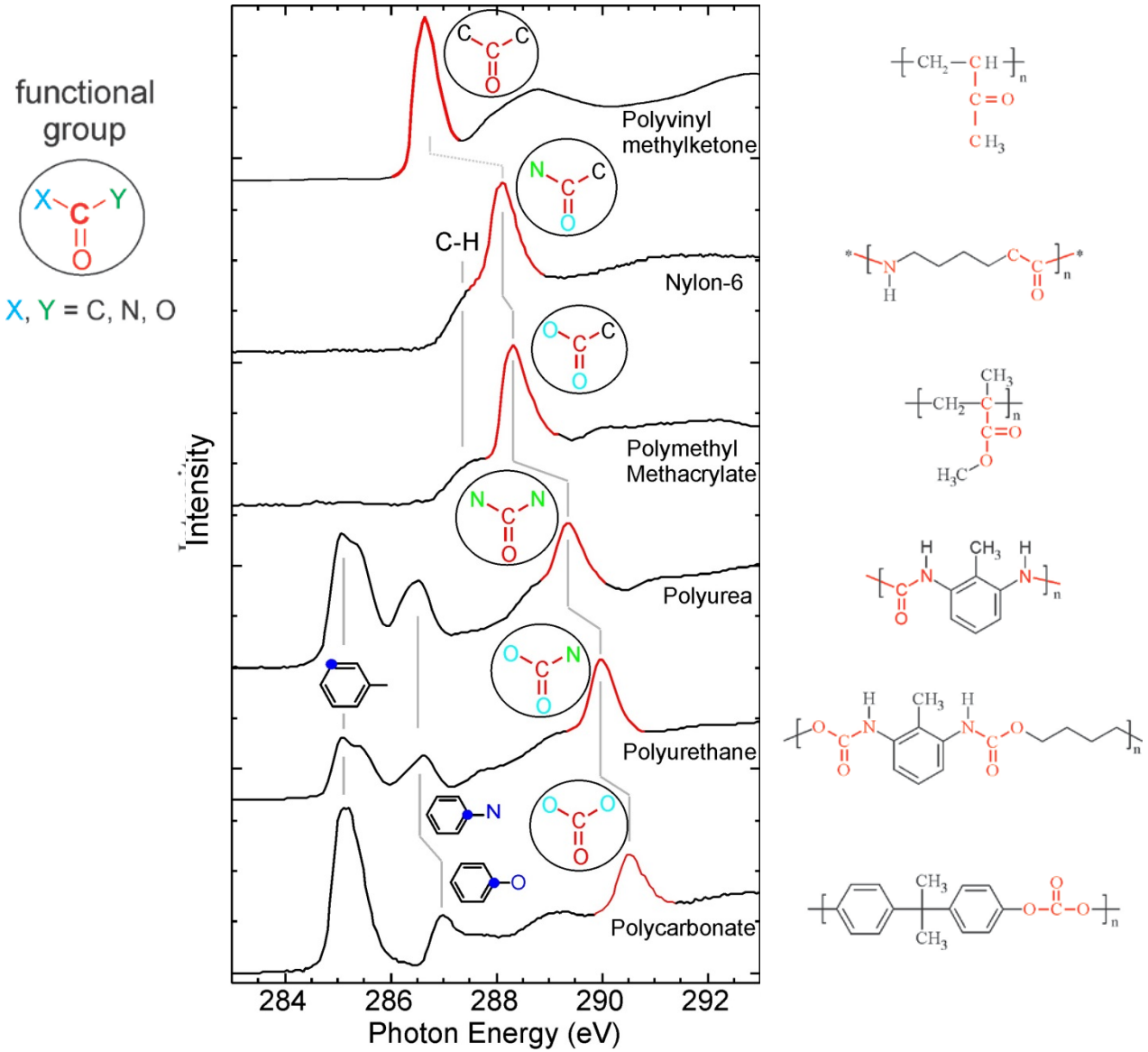


Molecules, Polymers: p-orbitals
Transition metals : d-orbitals
Rare Earths: f-orbitals

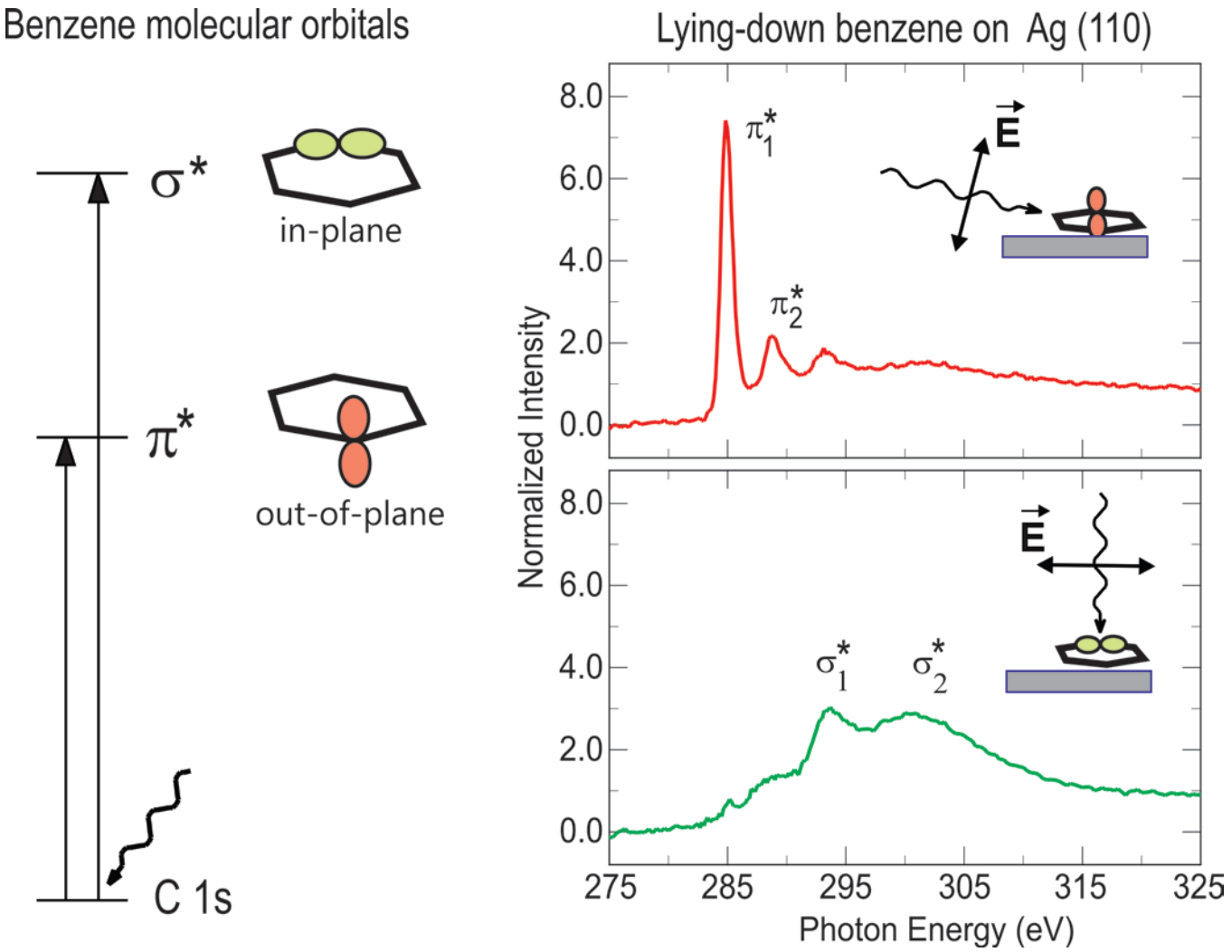
1s K-edge
2p L edge
3d M edge

Element specificity, Chemical specificity, Valence properties

Absorption spectra reveal local bonds around Carbon atoms



“Linear dichroism” reveals bond orientation

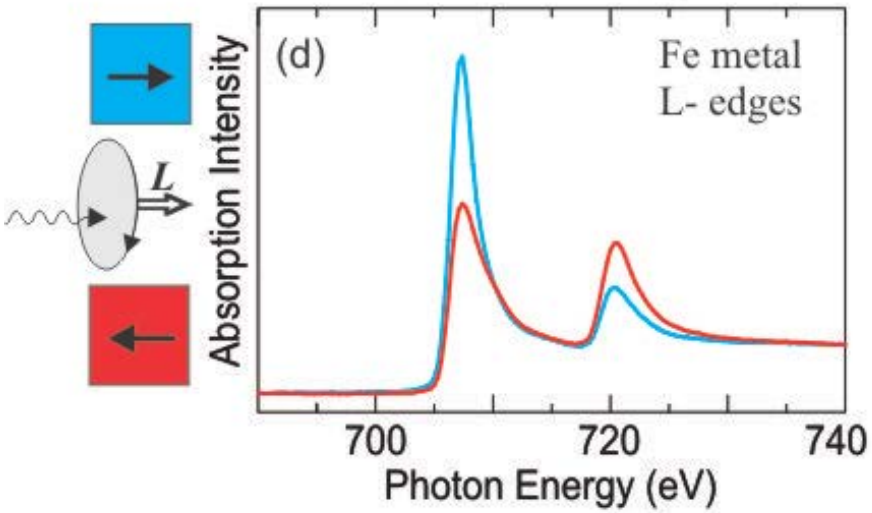


Circular dichroism is spin dependent

- **Circularly polarized photons have angular momentum**
- **Photon "spin" interacts with sample spin**

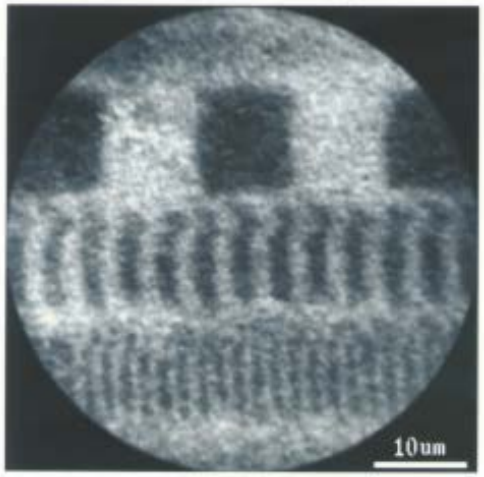
X-ray Magnetic Circular Dichroism

Spectroscopy:



Schütz *et al.*, Phys. Rev. Lett. **58**, 737 (1987)

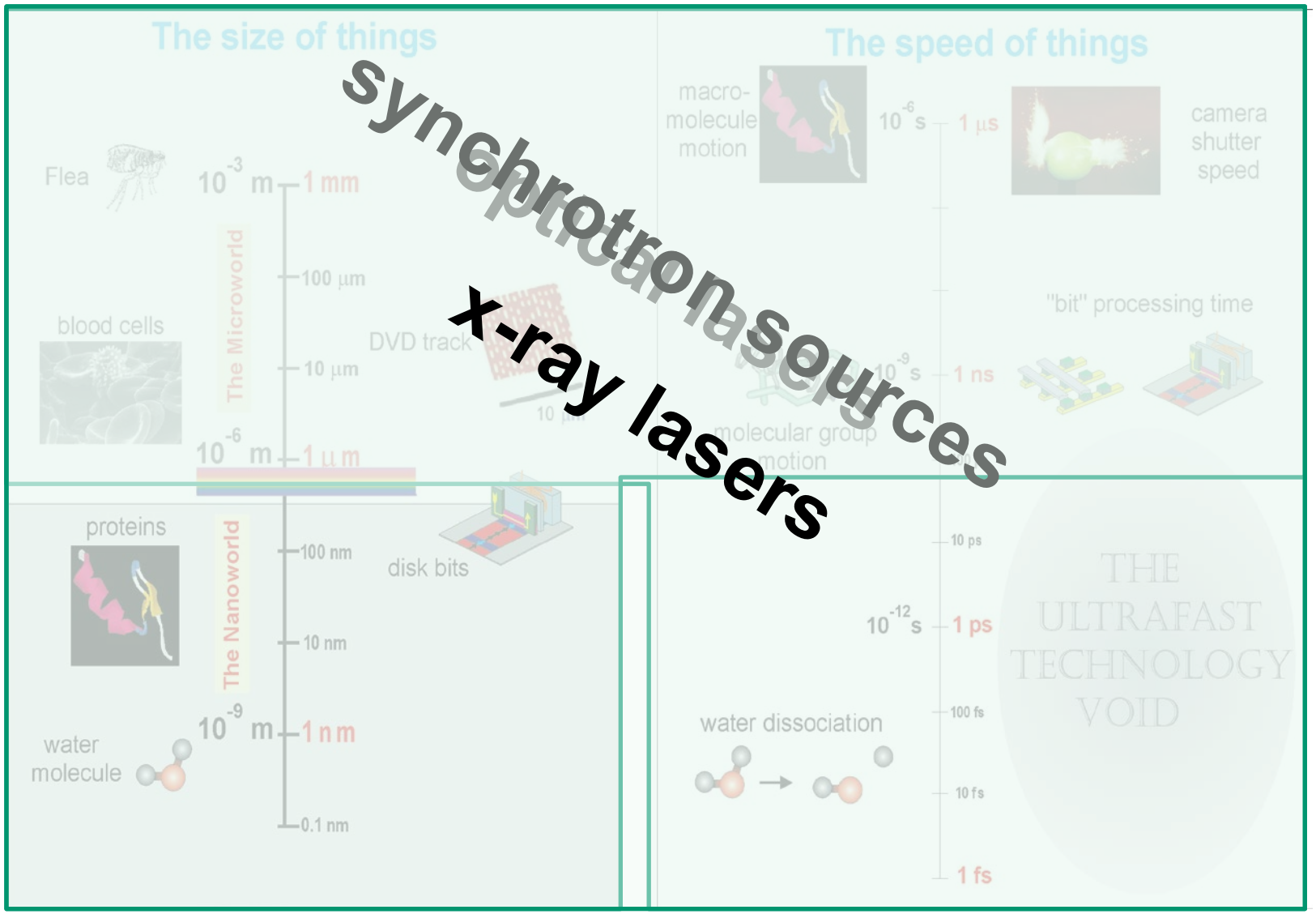
Microscopy:



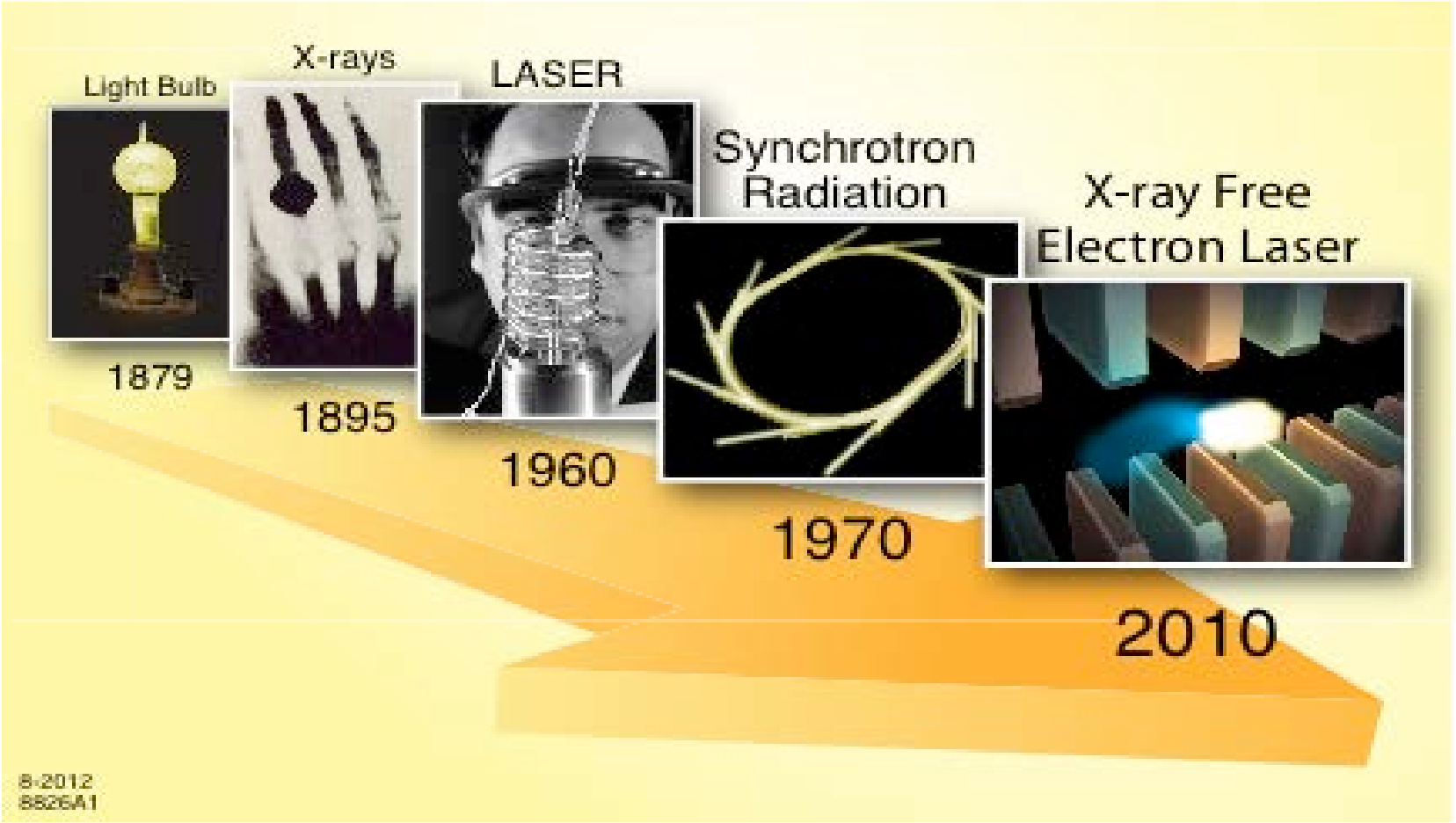
Stöhr *et al.*, Science **259**, 658 (1993)

Dichroism effect is large at atom-specific resonances

The size and speed of things:
-- from “structure” to “function” --



Light revolutions



Interaction Strength of Electromagnetic Fields with Matter