2023 School on Synchrotron Light Sources and their Applications

1. Fundamentals of Synchrotron Radiation from Storage Rings

2. Fundamentals of X-ray Interactions with Matter

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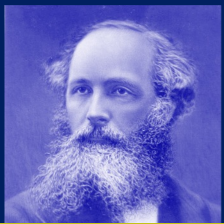
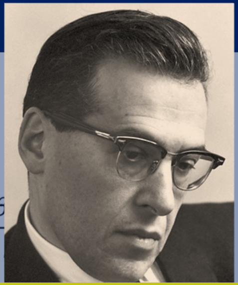
Two ways to understand synchrotron radiation:



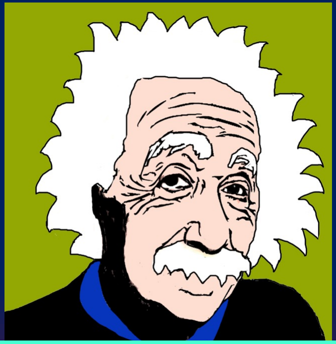
1865-1973: Maxwell's equations

1898: Liénard's retarded potentials



1945-49: Schwinger's full radiation emission theory

(1) The hard way, with a complete theory:
8 decades of development, complex formalism



(2) Considering only the pure relativistic case

Simple analysis, elementary math

Synchrotron radiation and X-ray free-electron lasers (X-FELs) explained to all users, active and potential

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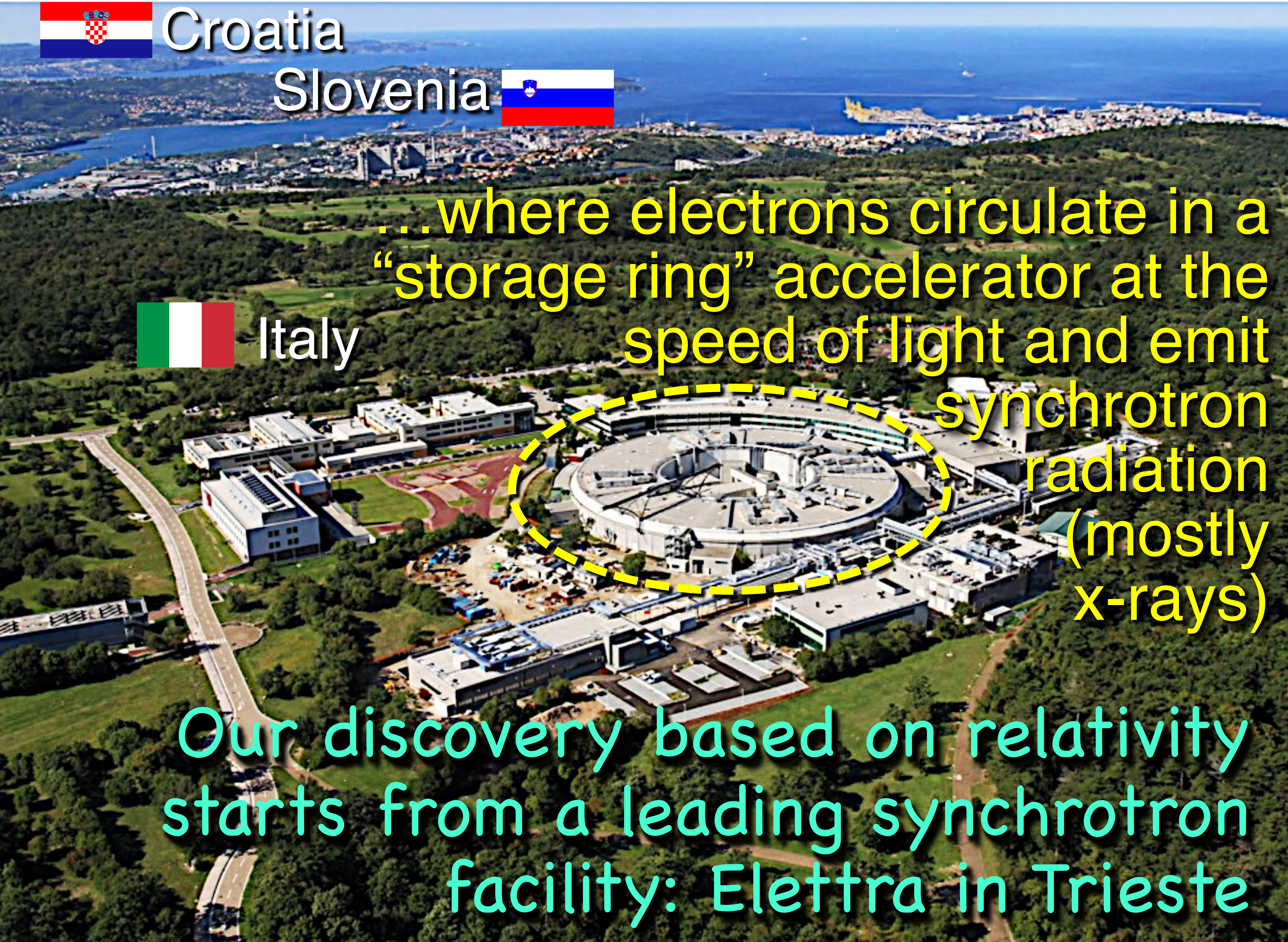
JSR JOURNAL OF SYNCHROTRON RADIATION (2021). **28**, 1014–1029

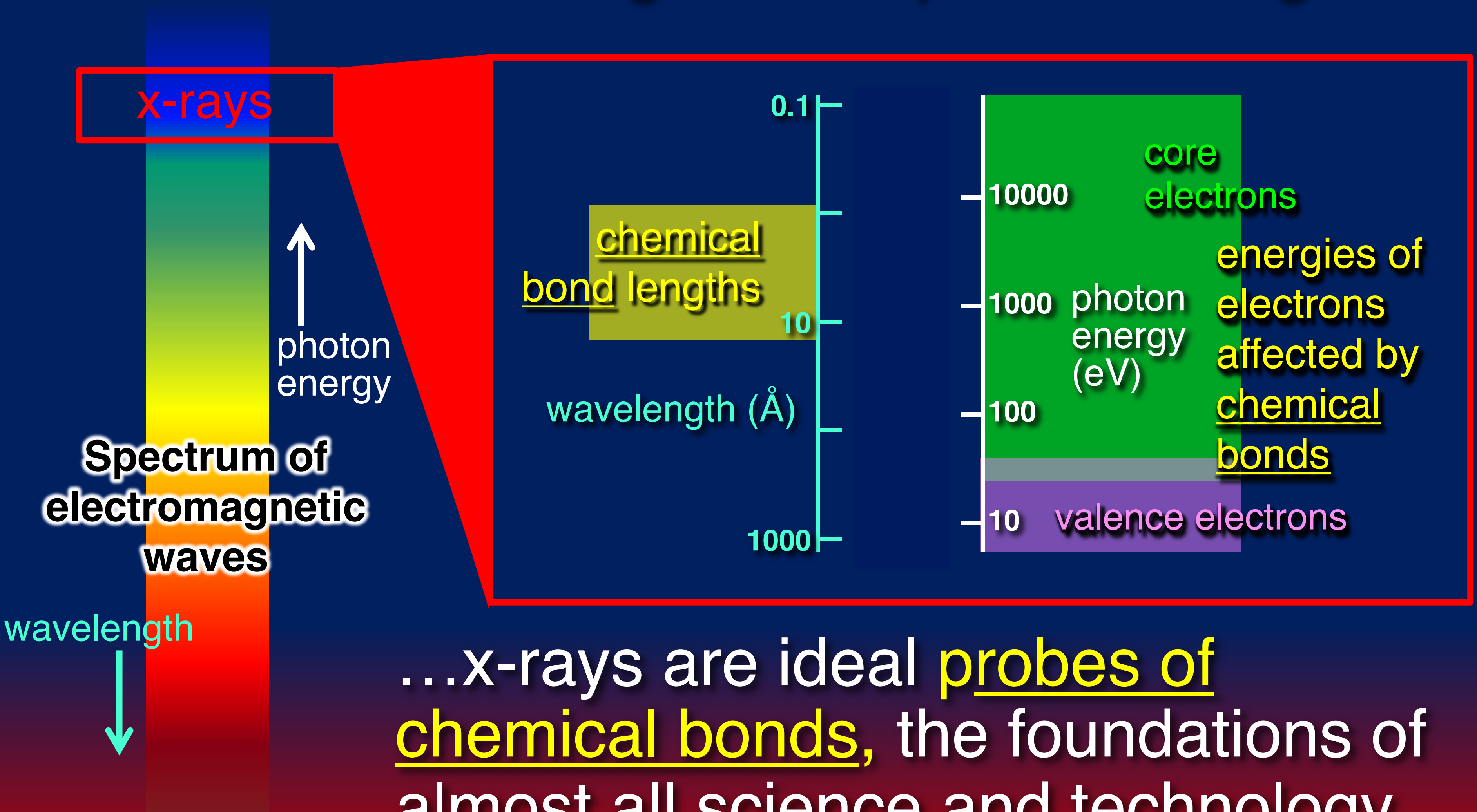
...ctron lasers

...Primoz Rebernik Ribic

...ron Radiation **18**, 101 (2011)


Croatia
Slovenia
Italy
…where electrons circulate in a "storage ring" accelerator at the speed of light and emit synchrotron radiation (mostly x-rays)
Our discovery based on relativity starts from a leading synchrotron facility: Elettra in Trieste

Why are x-rays from electron accelerators so important? In other words, what can we probe with their wavelengths and photon energies?

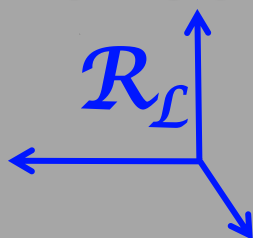


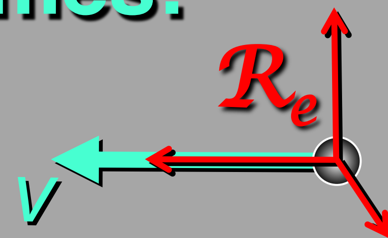
…x-rays are ideal probes of chemical bonds, the foundations of almost all science and technology

So, we need excellent x-ray sources: how can we build them with relativity?

Using two reference frames:

"Laboratory" frame, $\mathcal{R}_\mathcal{L}$

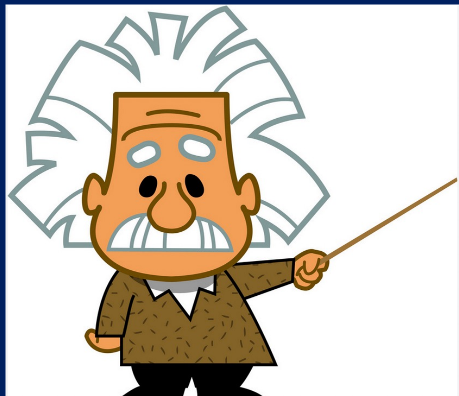




"Electron" frame $\mathcal{R}_e$, speed = v

...and five relativistic ingredients

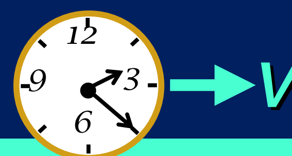
The five relativistic ingredients:



(1) "gamma factor":

$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}} = \frac{m_L}{m_e} = \frac{m_L c^2}{m_e c^2} = \frac{\text{energy}}{m_e c^2}$$

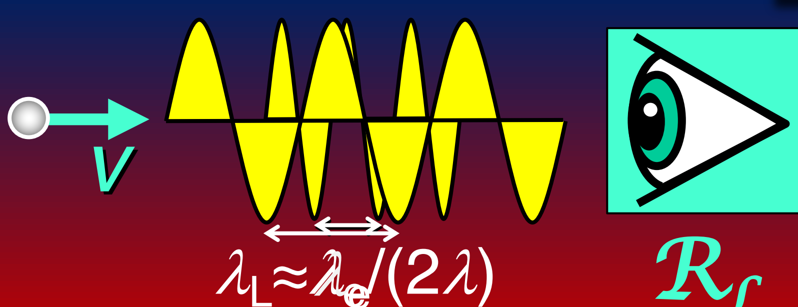
(5) **Relativistic mass**: the electron mass m_e in $\mathcal{R}_e$ (rest mass) changes in $\mathcal{R}_\mathcal{L}$ to $m_L = \gamma\, m_e$

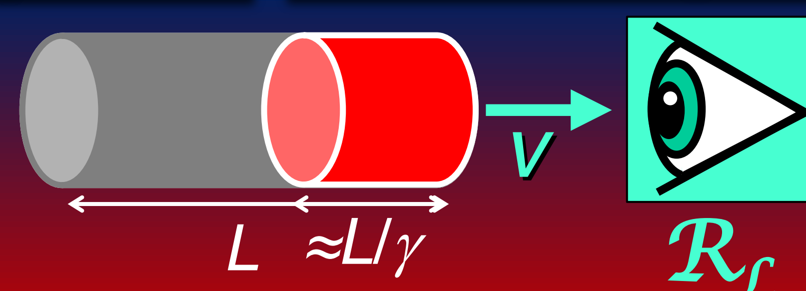


(2) **Doppler shift**: due to the source motion (speed v), the wavelength λ_e emitted by an electron in $\mathcal{R}_e$ decreases to $\lambda_L \approx \lambda_e/(2\gamma)$ when seen in $\mathcal{R}_\mathcal{L}$

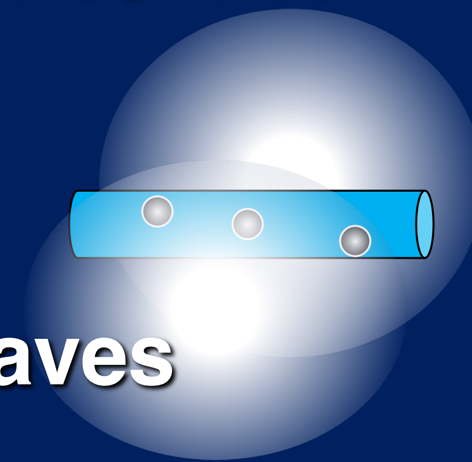
(4) **Time Dilation**: a time interval Δt_e in $\mathcal{R}_e$ increases in $\mathcal{R}_\mathcal{L}$ to $\Delta t_L = \gamma\,\Delta t_e$

(3) **Lorentz contraction**: the length L of an object moving with speed v decreases to $\approx L/\gamma$ when seen in $\mathcal{R}_\mathcal{L}$





To understand how a synchrotron source works, we start from electrons oscillating in an antenna

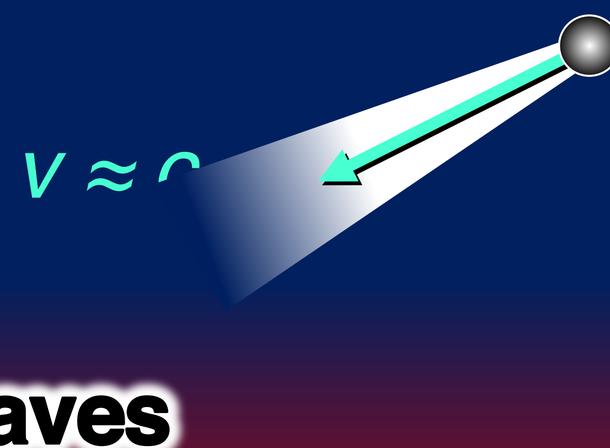


…they are accelerated electric charges, thus they emit electromagnetic waves

But the typical emission is long-wavelength radio waves, not short-wavelength x-rays!

The electron mass is small: this enhances the acceleration and the emission

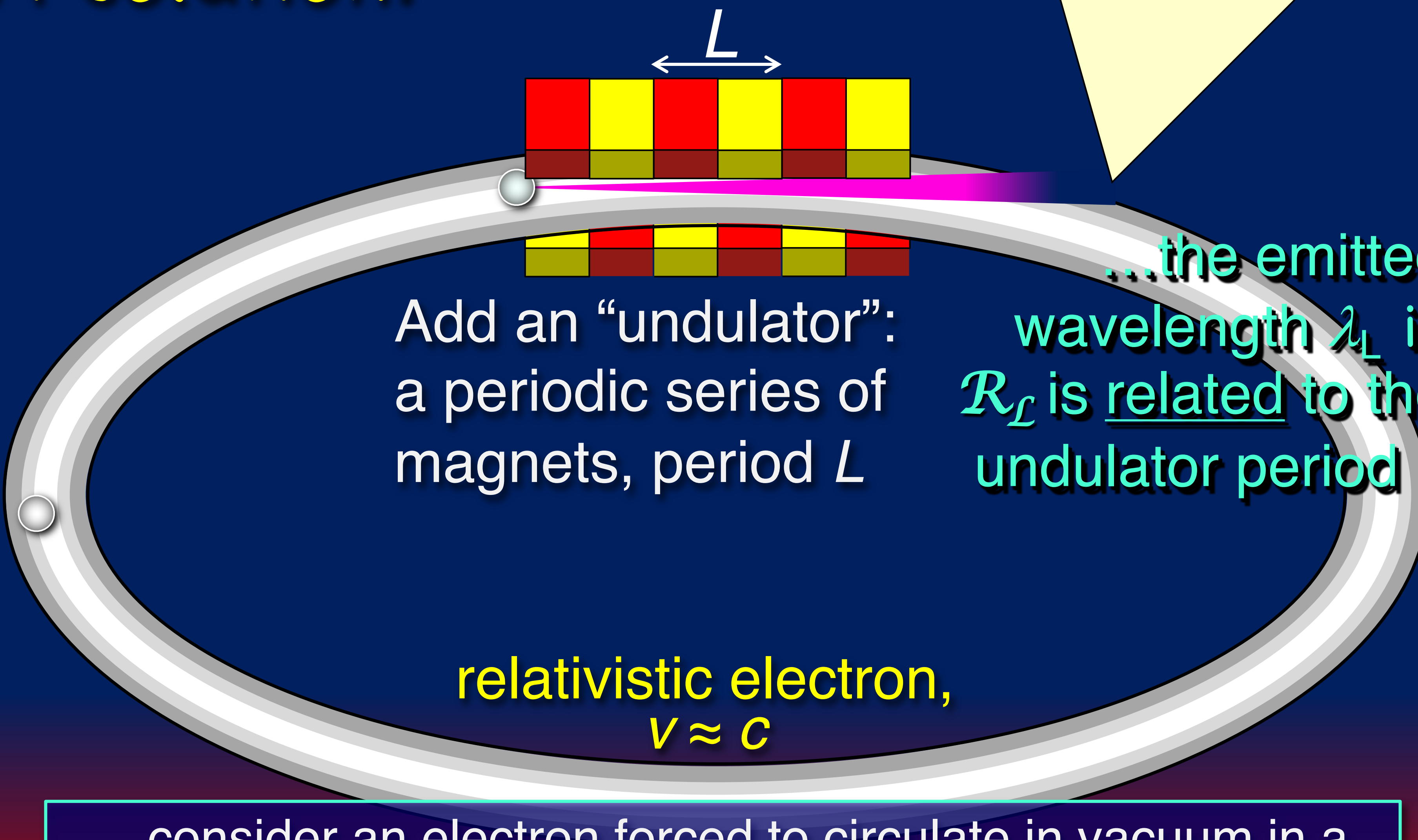
To get x-rays, we need relativity: consider an electron oscillating transversally, but also moving longitudinally with speed $v \approx c$



How can we obtain this complex motion?

A solution:

The undulator forces the electron to oscillate in a transverse direction: being accelerated, it emits electromagnetic waves – “synchrotron radiation”



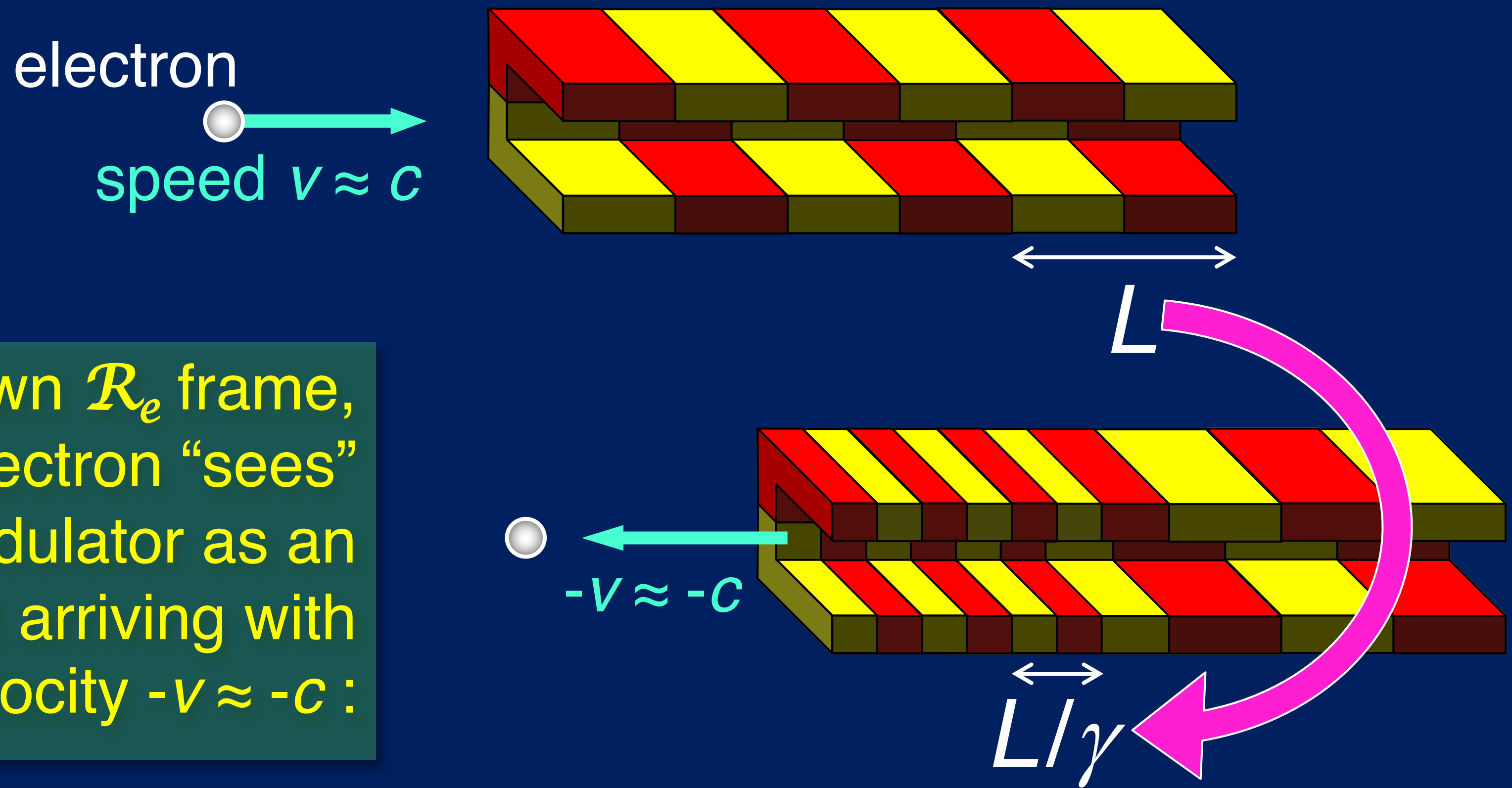
Add an “undulator”: a periodic series of magnets, period L

…the emitted wavelength λ_L in $\mathcal{R}_\mathcal{L}$ is <u>related</u> to the undulator period L

relativistic electron, $v \approx c$

…consider an electron forced to circulate in vacuum in a <u>storage ring</u> by a special system of magnets (not shown)

...but λ_L is not simply equal to L! Why? You must think like an electron!



In its own $\mathcal{R}_e$ frame, the electron "sees" the undulator as an object arriving with velocity $-v \approx -c$:

Furthermore, it "sees" the undulator period shrunk to $\approx L/\gamma$ by the relativistic Lorentz contraction. This is also the emitted wavelength λ_e as detected in $\mathcal{R}_e$: $\lambda_e \approx L/\gamma$

…however, in the laboratory frame $\mathcal{R}_\mathcal{L}$ the motion of the source (the electron) causes the (relativistic) Doppler shift -- further decreasing the detected wavelength by a factor $\approx 1/(2\gamma)$

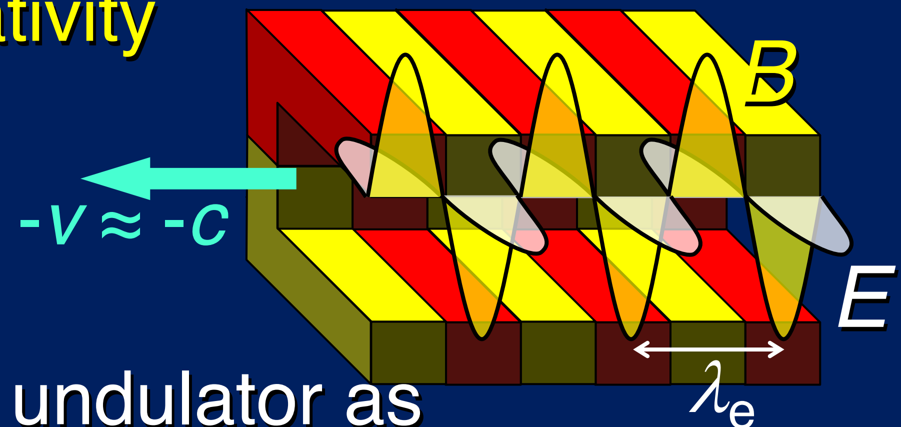
Together, the Lorentz contraction and the Doppler effect decrease the wavelength in $\mathcal{R}_\mathcal{L}$ to:

$$\lambda_L \approx \frac{L/\gamma}{2\gamma} = \frac{L}{2\gamma^2}$$

Example: $L = 1$ cm,
$\gamma = 5000$,
$\rightarrow \lambda_L \approx 2$ Å: **x-rays!!!**

An alternate, intriguing look at how an undulator produces synchrotron radiation:

In the electron frame $\mathcal{R}_e$, relativity adds to the periodic B-field of the undulator a periodic, perpendicular electric field:

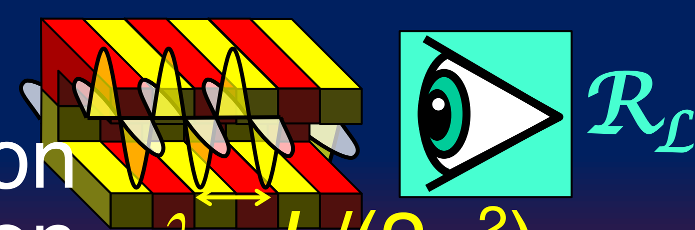


Thus, the electron "sees" the undulator as a pseudo <u>electromagnetic wave</u> of wavelength $\lambda_e \approx L/\gamma$

…and it backscatters this wave. The backscattered wave is synchrotron radiation:

electron

synchrotron radiation

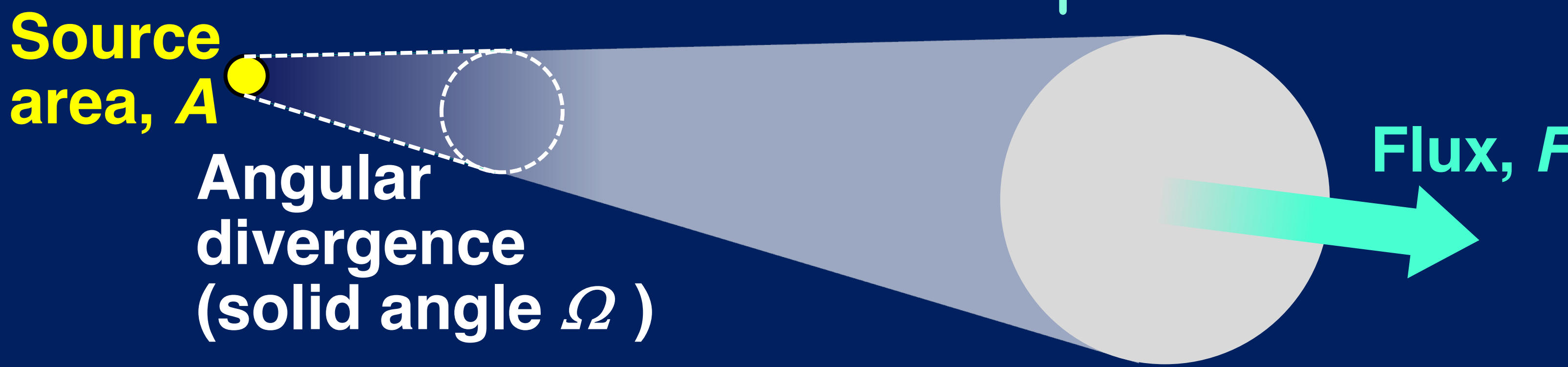


$\lambda_L \approx L/(2\gamma^2)$

…whose wavelength in the laboratory frame $\mathcal{R}_{\mathcal{L}}$ is Doppler-shifted to $\lambda_L \approx \lambda_e/(2\gamma) \approx (L/\gamma)/(2\gamma) = L/(2\gamma^2)$

Question: are we getting closer to good x-ray sources? First, what is a "good" source?

Consider the source parameters:



a flashlight is effective ("good") because its emission is geometrically concentrated

To quantify this notion, we use the:

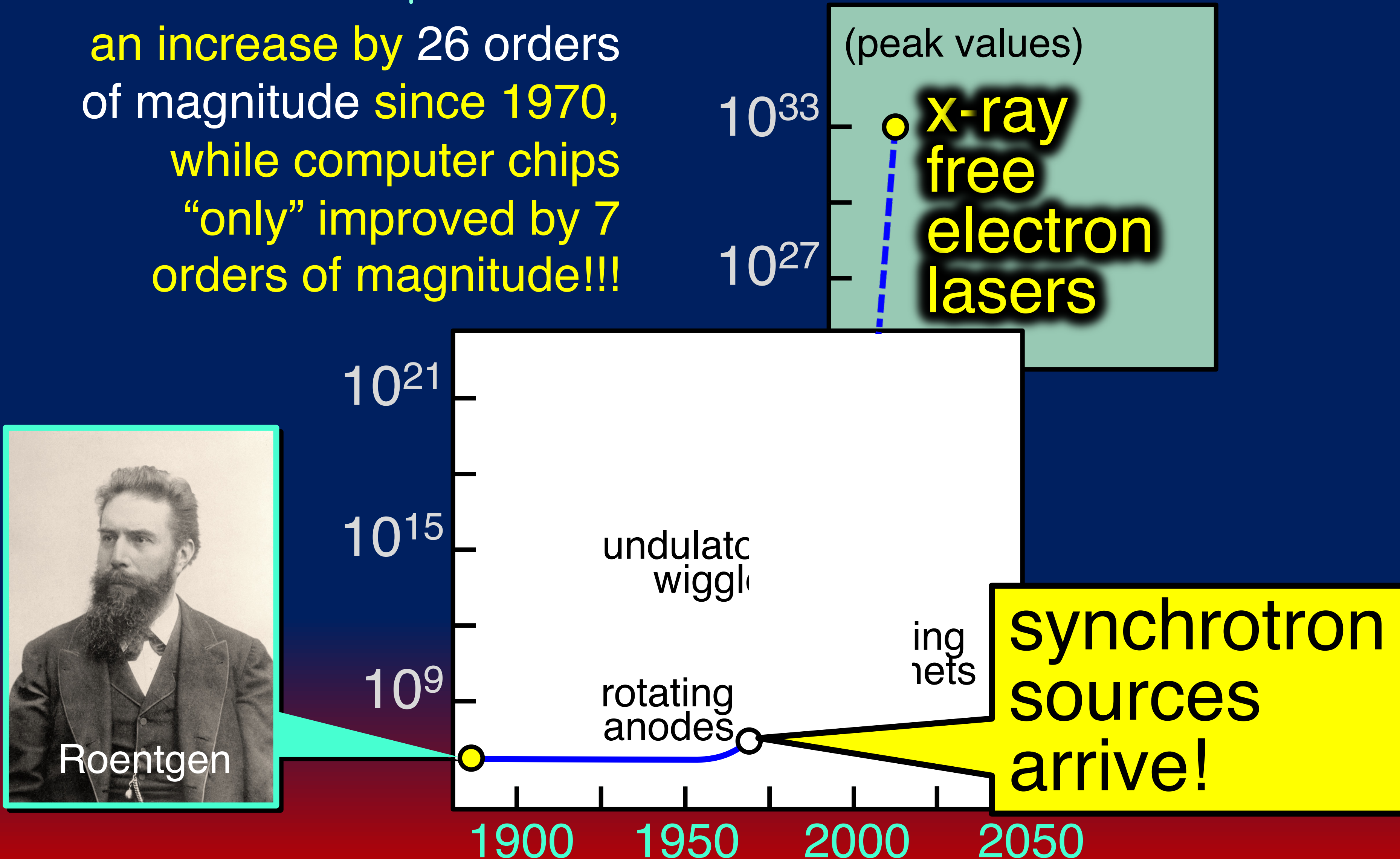
$$\text{"Brightness"} = \text{constant}\ \frac{F}{A\,\Omega}$$

A "good" source has high brightness: large flux, small area, small divergence

This is how the brightness of x-ray sources evolved in history: synchrotrons boosted it!

(units: photons/mm^2/s/$mrad^2$, 0.1% bandwidth)

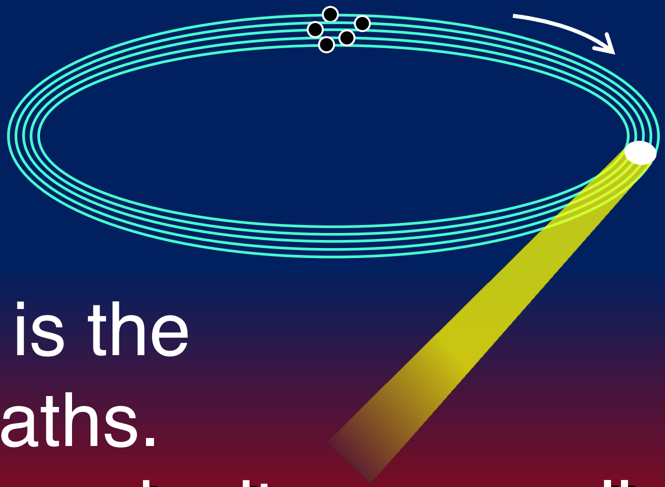
an increase by 26 orders of magnitude since 1970, while computer chips "only" improved by 7 orders of magnitude!!!



Synchrotron sources reach very high brightness levels (some 10^{15} times more than conventional x-ray sources) -- how?

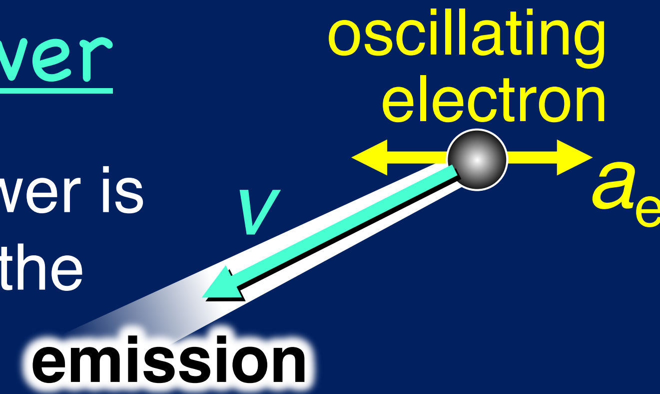
Thanks to four factors:

1. Relativity drastically boosts the emitted power
2. Relativity sharply reduces the angular divergence
3. Electrons in vacuum can handle more emitted power than those in a solid since the power does not damage their environment



2. Different electrons circulate in the accelerator along slightly different paths. The source size is the transverse cross section of all paths. Effective electron beam controls make it very small

Relativity at work: emitted power



"Larmor law": the emitted power is proportional to the square of the transverse acceleration, a_e^2

If v = zero, $a_e = a_L$: the power is proportional to a_L^2

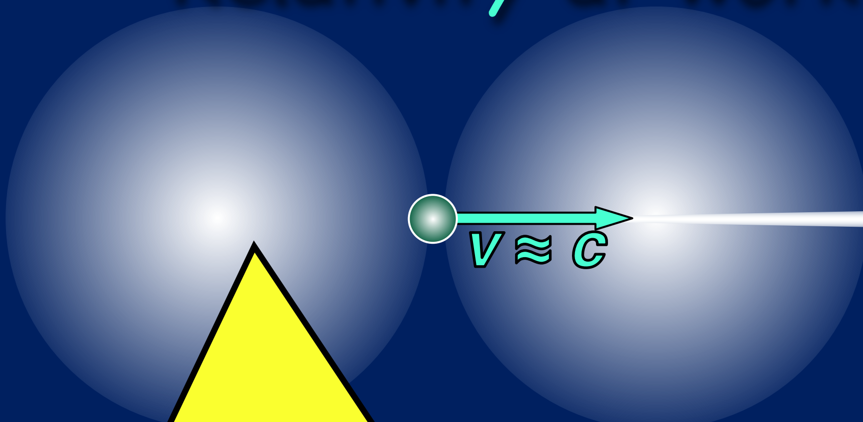
If $v \neq$ zero: from $\mathcal{R}_e$ to $\mathcal{R}_L$ the time is dilated by γ and the transverse coordinate remains invariant; the acceleration = coordinate/time^2 is divided by γ^2: $a_L = a_e/\gamma^2$, and $a_e = \gamma^2 a_L$

…the power is proportional to $a_e^2 = \gamma^4 a_L^2$, thus to $\gamma^4 = (\text{energy})^4/(m_o c^2)^4$

The emission increases as the 4th power of the electron energy, to very high levels

…and it decreases as $1/m_o^4$: electrons emit a lot, protons much less

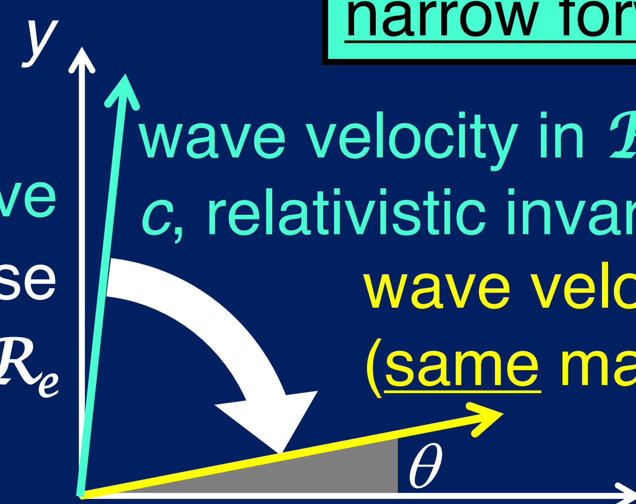
Relativity at work again: angular collimation of synchrotron radiation



…but seen in $\mathcal{R}_\mathcal{L}$ the range shrinks to a <u>very</u> <u>narrow forward cone</u>

in the electron $\mathcal{R}_e$ frame, x-rays are emitted in a wide angular range, like the waves from an antenna

Why? Consider a wave emitted in a transverse direction in $\mathcal{R}_e$



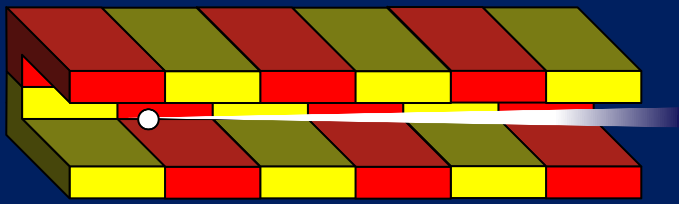
wave velocity in $\mathcal{R}_e$ (magnitude c, relativistic invariant)

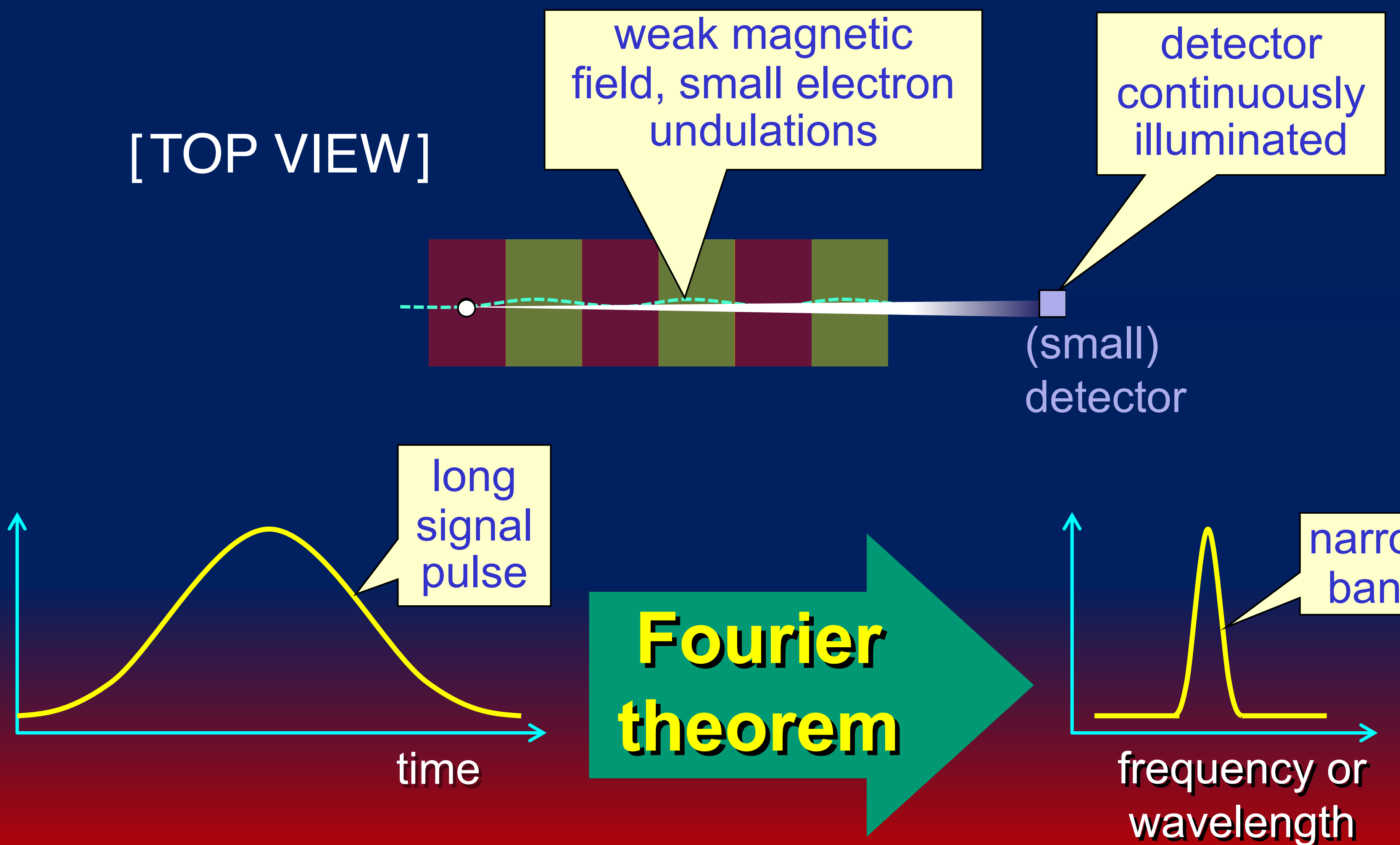
wave velocity in $\mathcal{R}_\mathcal{L}$ (<u>same</u> magnitude c)

$\mathcal{R}_e \rightarrow \mathcal{R}_\mathcal{L}$: the time is dilated by γ; the transverse coordinate is invariant; the transverse velocity, proportional to 1/time, changes from c_{ye} to $c_{yL} = c_{ye}/\gamma \approx c/\gamma$. The vector velocity <u>rotates</u> to $\theta \approx c_{yL}/c \approx 1/\gamma$

Small angular spread $\approx 2\theta \approx 2/\gamma$: milliradians!!!

…so, accelerated relativistic electrons emit radiation like super-narrow flashlights: let us see the consequences for undulators

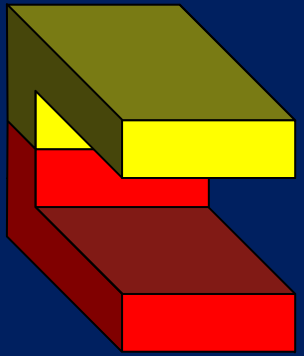


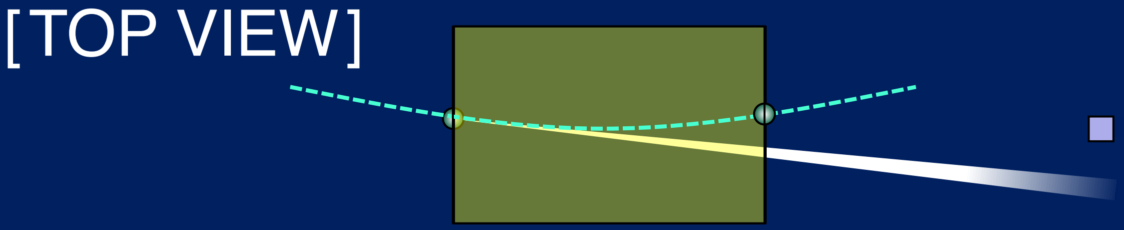


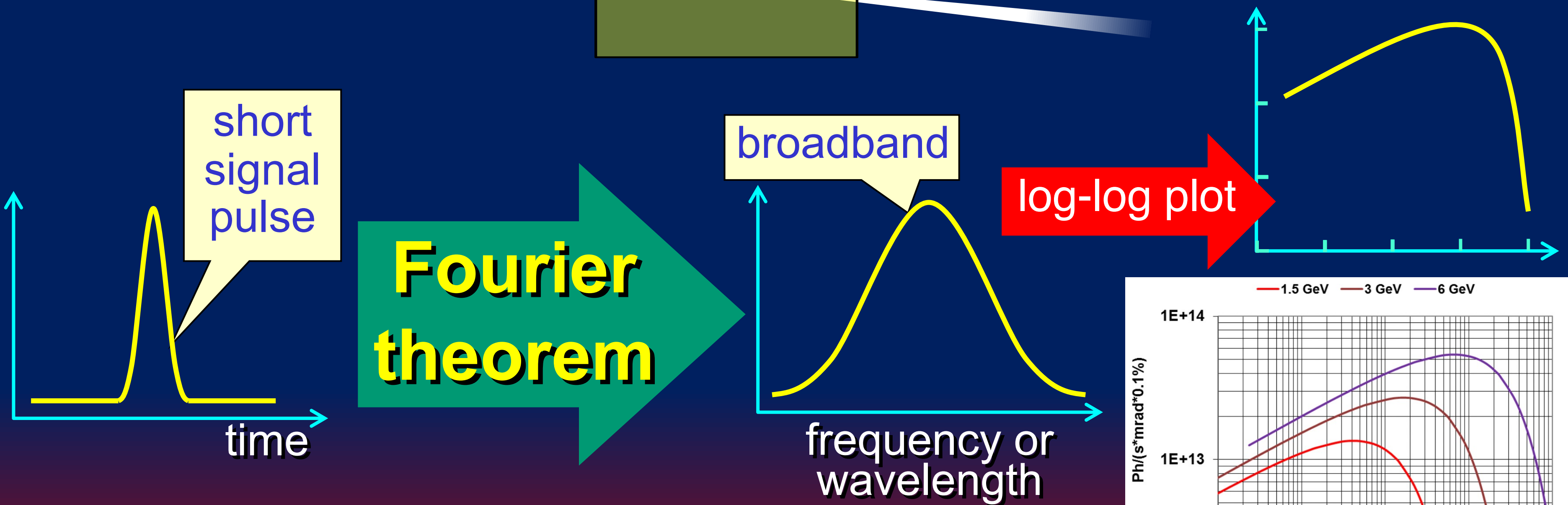
Around a storage ring, there are other types of x-ray sources besides undulators

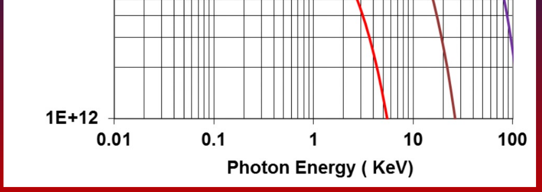
...let us see what they are

Bending magnets:
the dipole magnets that also keep the electrons circulating in the storage ring



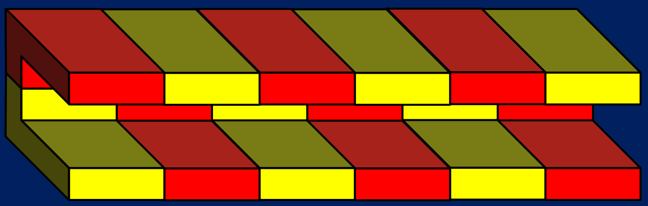


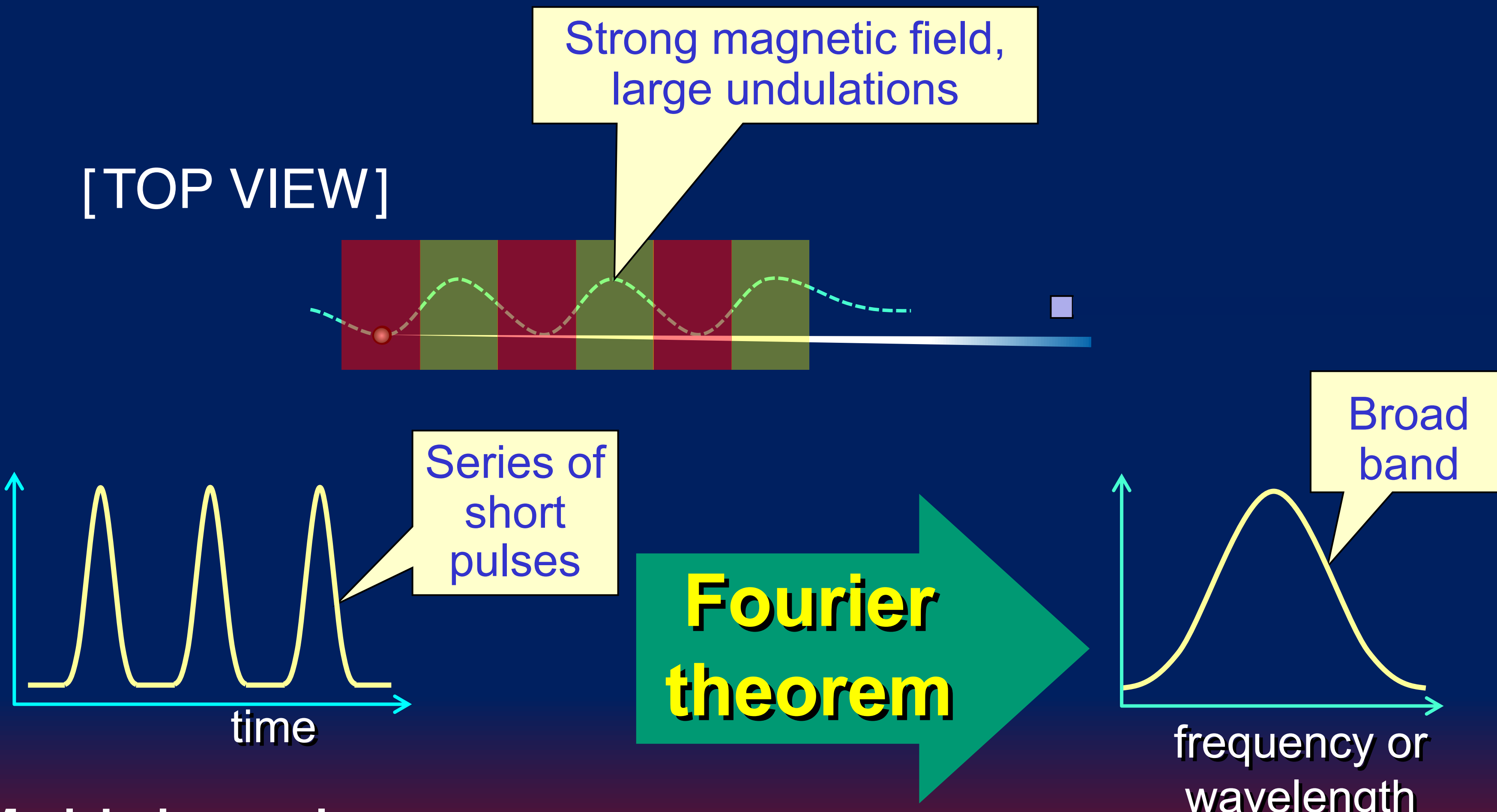




…not too far from reality!

A third type of sources: “wigglers”



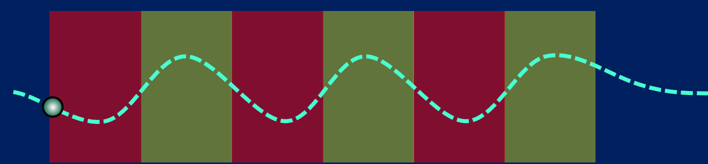


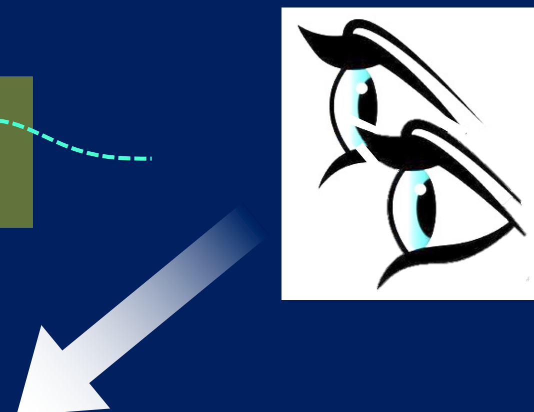
Multiple pulses → more brightness than from bending magnets

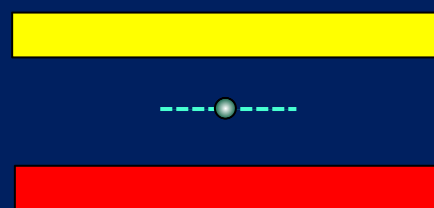
Synchrotron emission is also polarized!

Why? Imagine an electron
in an undulator or a wiggler:

[TOP VIEW]



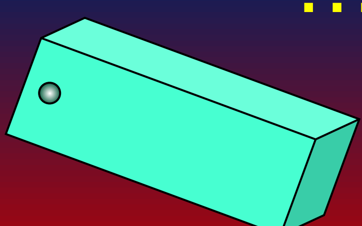




[FRONT VIEW]

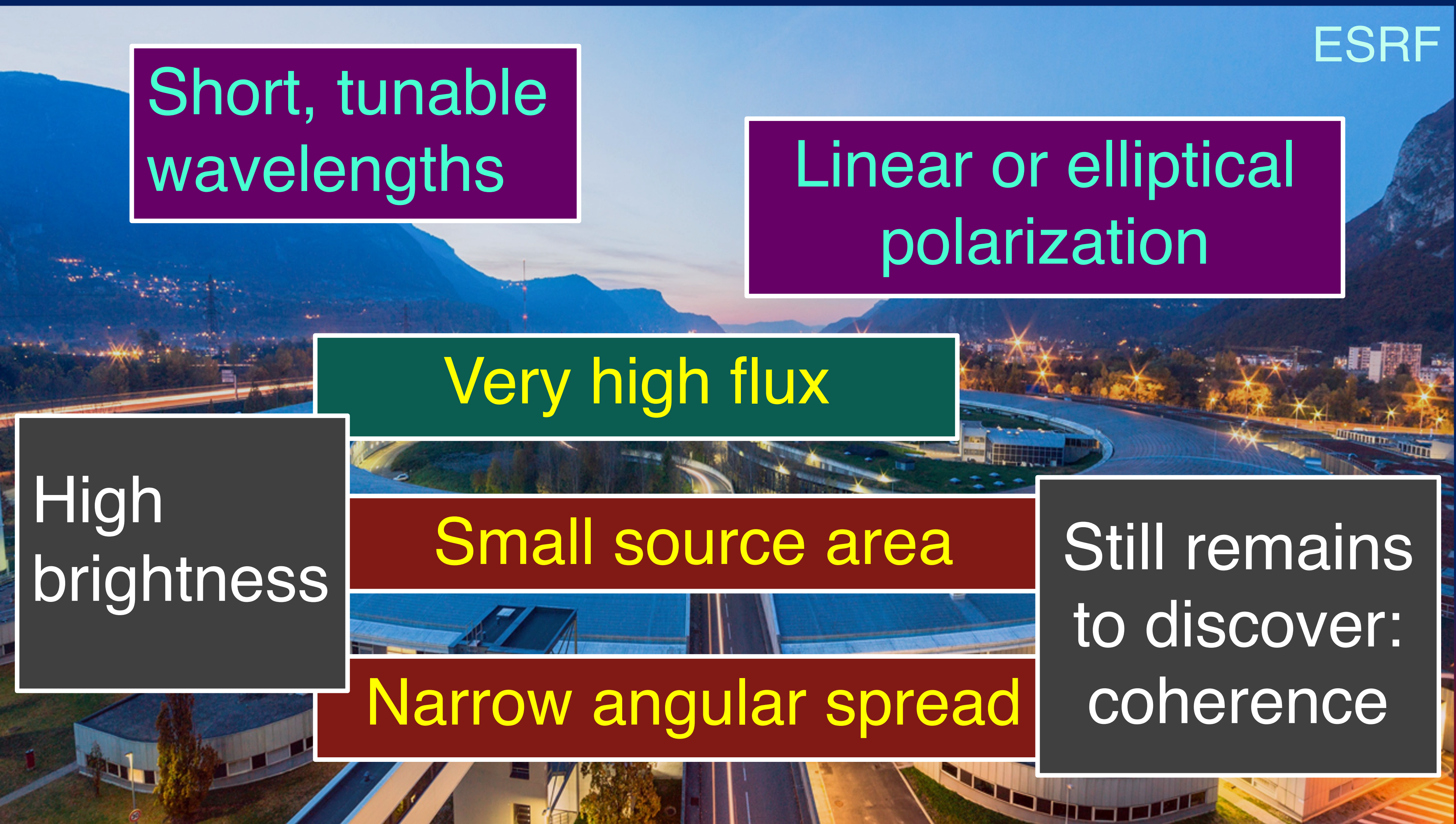
Linear polarization
in the horizontal
plane, where the electric field perturbations by the wave occur

…same conclusion for bending magnets



and special (elliptical) wigglers/undulators can produce intense elliptically polarized radiation

Summary of the amazing properties of synchrotron sources discovered so far:



Short, tunable wavelengths

Linear or elliptical polarization

Very high flux

High brightness

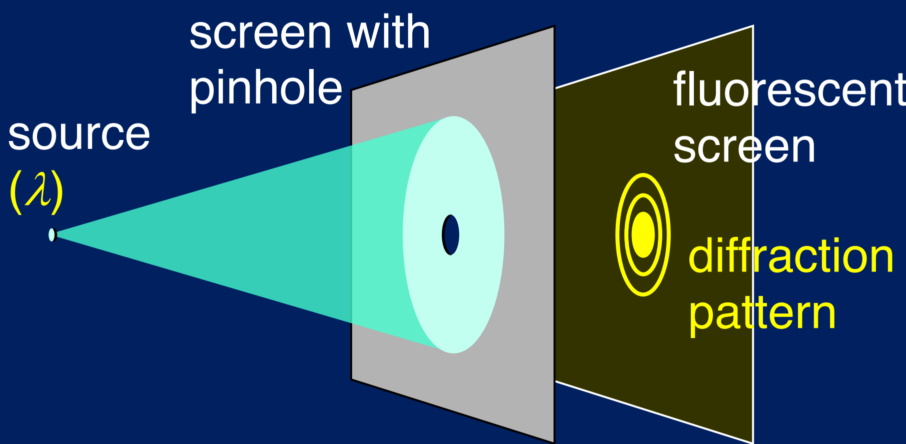
Small source area

Narrow angular spread

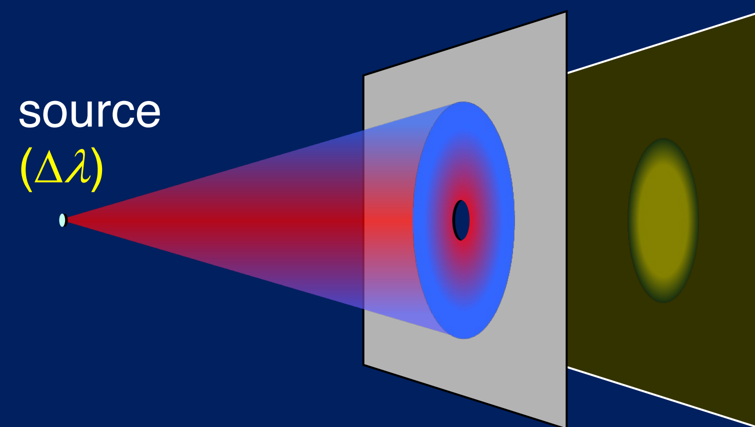
Still remains to discover: coherence

COHERENCE is "what enables radiation to produce visible wave effects (e.g., diffraction or interference)"

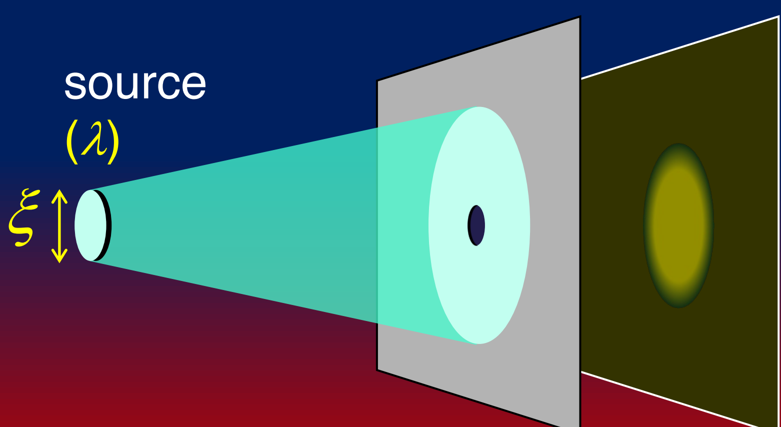
With a more realistic source, we discover TWO kinds of coherence: "time" and "spatial"



Example: pinhole diffraction - a point source emitting only one wavelength always produces a visible diffraction pattern: it has full coherence

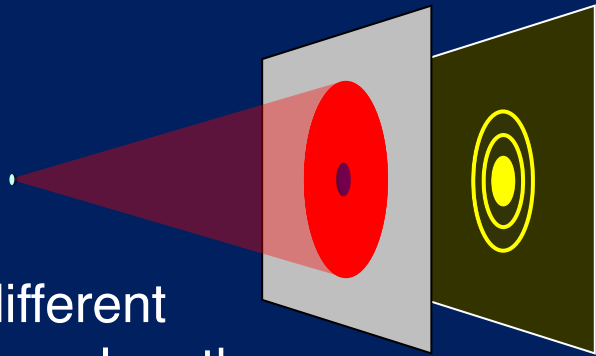


…if the source emits a band of wavelengths, each one of them produces a pattern; in the superposition of patterns the fringes may be too blurred to be visible: this leads to the notion of "time (or longitudinal) coherence"

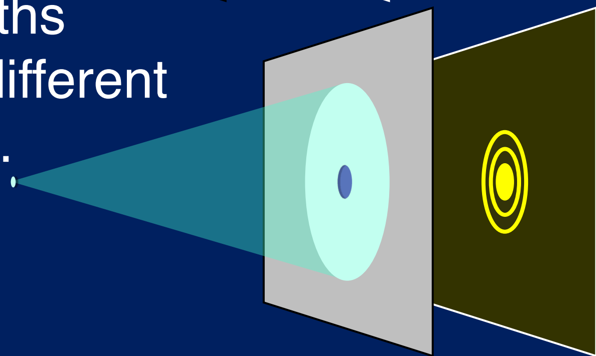


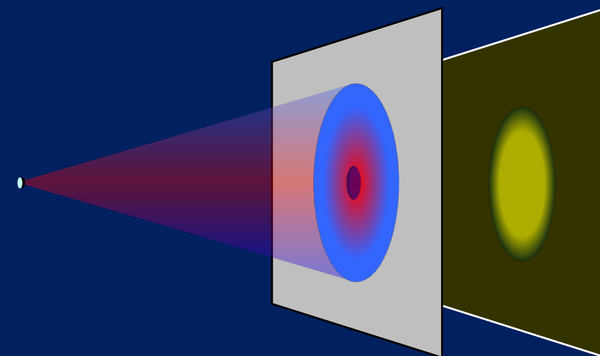
Likewise, if the source is not a point but has a finite size the pattern may become impossible to see: this leads to "spatial (or lateral) coherence"

Effects of multiple wavelengths: longitudinal (time) coherence

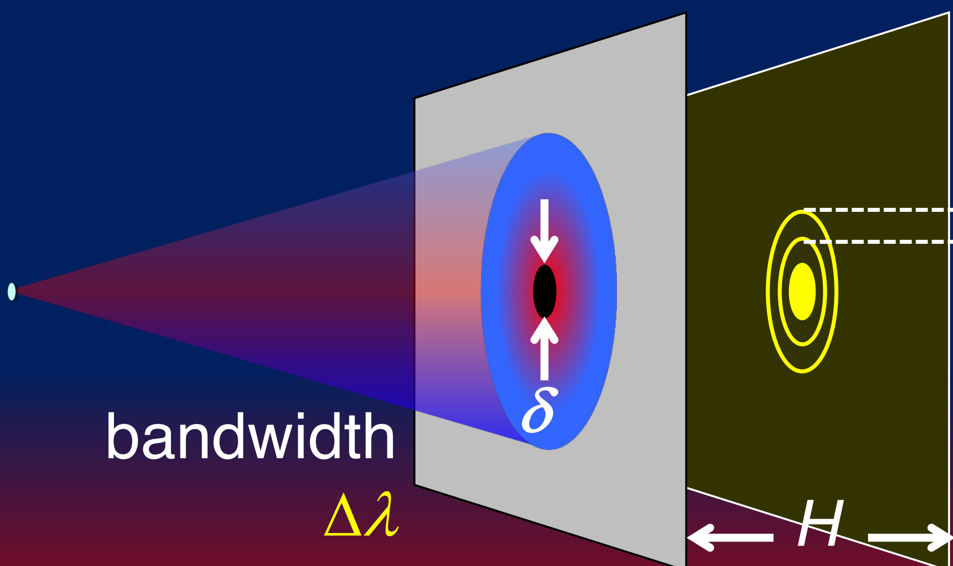


different wavelengths produce different patterns…





…and their superposition blurs the pattern features



bandwidth $\Delta\lambda$

spacing between fringes:

$x \approx (H/\delta)\lambda$

$\Delta\lambda$ "blurs" x to $\Delta x \approx (H/\delta)\Delta\lambda$

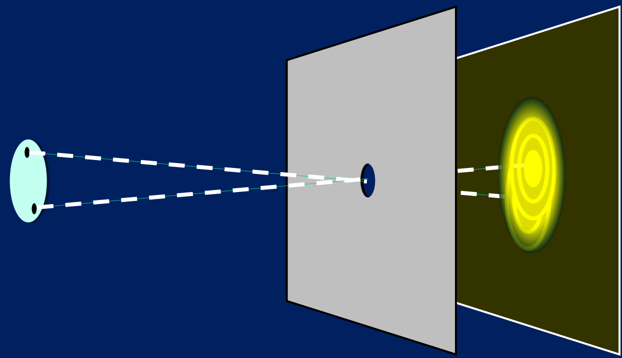
<u>Condition to see the pattern:</u>

$\Delta x < x$, $\Delta\lambda/\lambda < 1$ (time coherence)

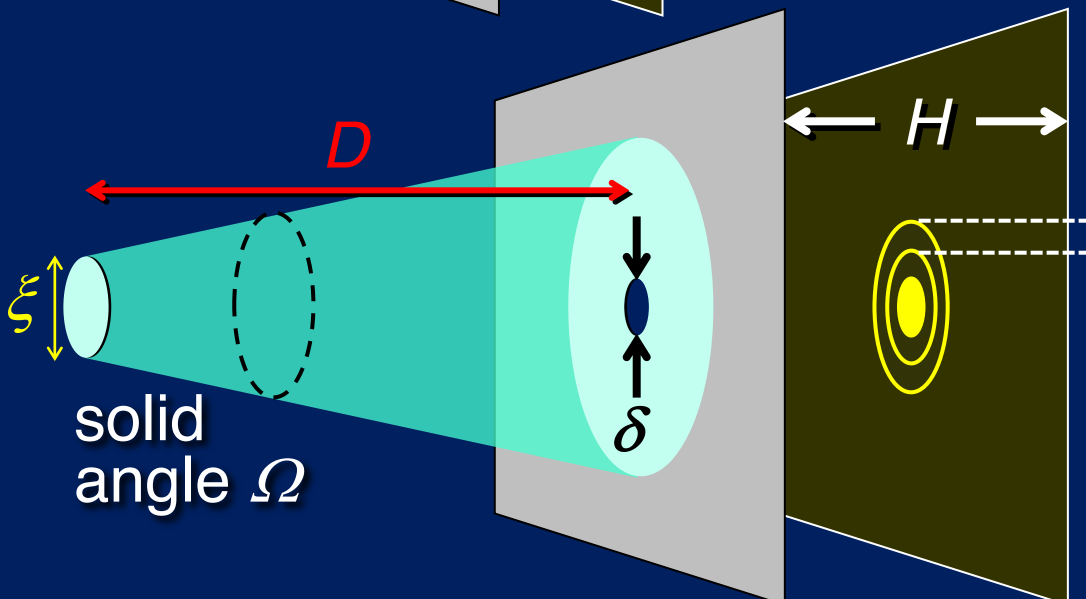
Using the "<u>coherence length</u>"

$L_c = \lambda^2/\Delta\lambda$, the condition for time coherence is: $L_c > \lambda$

Source geometry: spatial (lateral) coherence



Each point in the source produces a diffraction pattern – and the superposition blurs the pattern fringes



When are such fringes visible?

$\xi H/D \approx$ maximum distance between centers of patterns given by different source points

fringe spacing $\approx (H/\delta)\lambda$;

To see the pattern features:

$\xi H/D \leq (H/\delta)\lambda \rightarrow$ $\delta \leq \lambda D/\xi$

condition for lateral coherence

Another way to look at lateral coherence:

Illuminated screen area: ΩD^2; pinhole area $\approx \delta^2$;

portion of waves contributing to diffraction $\approx \delta^2/(\Omega D^2) \leq (\lambda D/\xi)^2/(\Omega D^2) =$

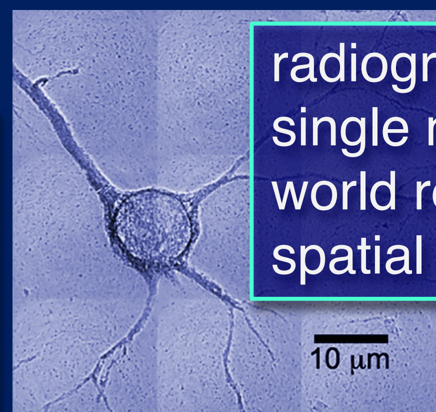
$\lambda^2/(\xi^2\Omega)$

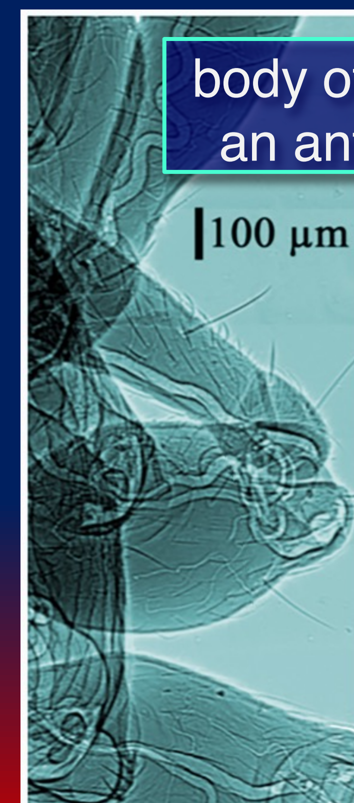
"coherent power factor": if it is large, there is lateral coherence

Spatial coherence — summary:

- It requires a large coherent power factor $\lambda^2/(\xi^2\Omega)$: we need a synchrotron source with small ξ^2 and Ω
- Due to the λ^2 term, it is difficult to achieve for small x-ray λ's (by the way: a λ^2 term is also present for longitudinal coherence)
- NOTE: the brightness is proportional to $1/(\xi^2\Omega)$ the efforts to enhance the brightness by decreasing ξ and Ω also increased the spatial coherence

Coherent x-rays allow phase-contrast imaging, a powerful radiology that produces pictures with sharp contrast and very small details: we shall see later how



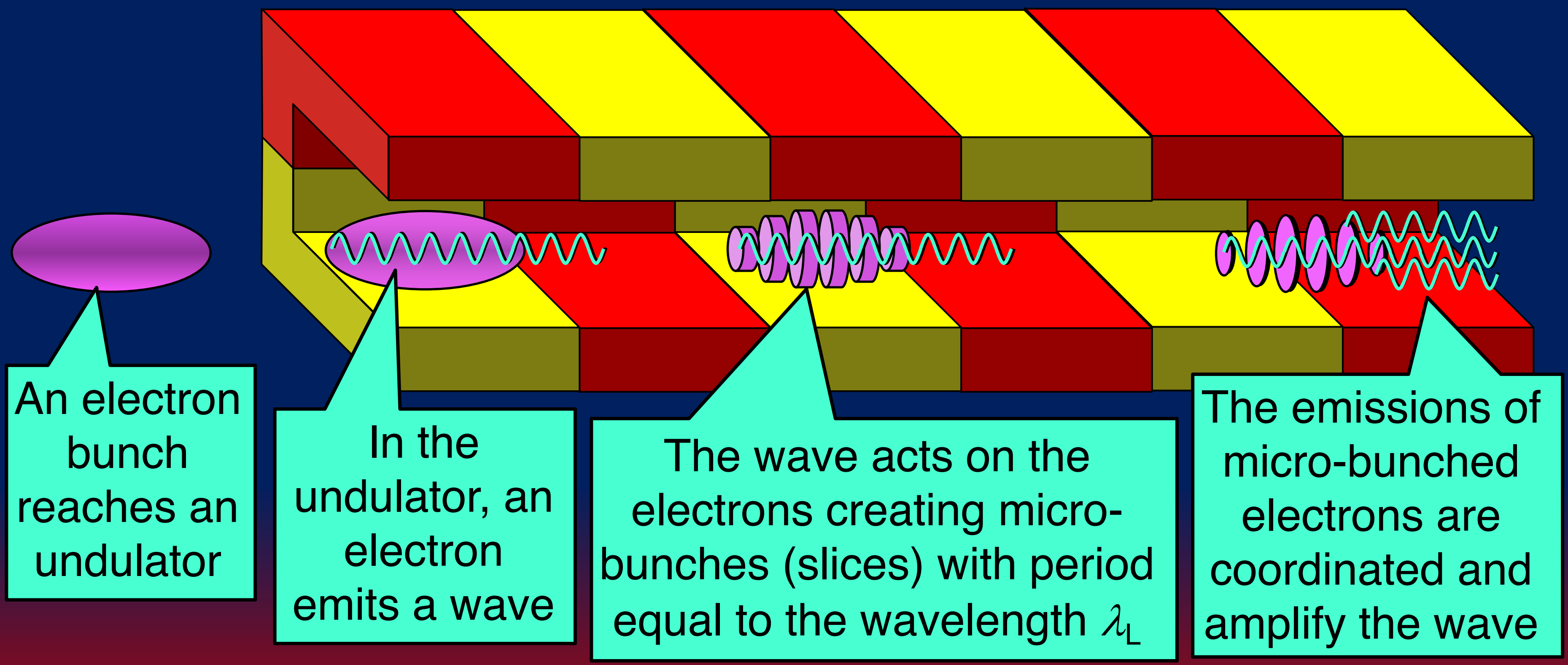


From storage rings to X-ray Free Electron Lasers (X-FELs)

Synchrotron sources have several laser-like properties: collimation, high intensity, coherence... are they lasers?

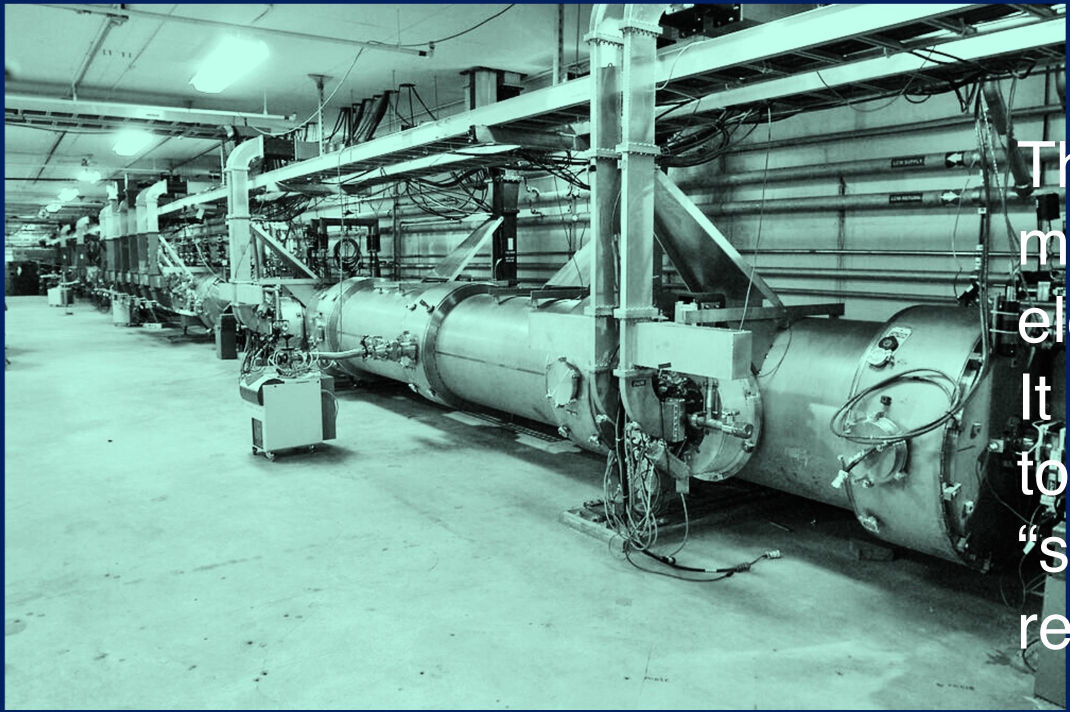
NO: the emission mechanism is different!

But there is now a new class of x-ray sources more similar to lasers: the FELs (Free Electron Lasers) – with optical amplification caused by the interaction of electrons with their emitted waves



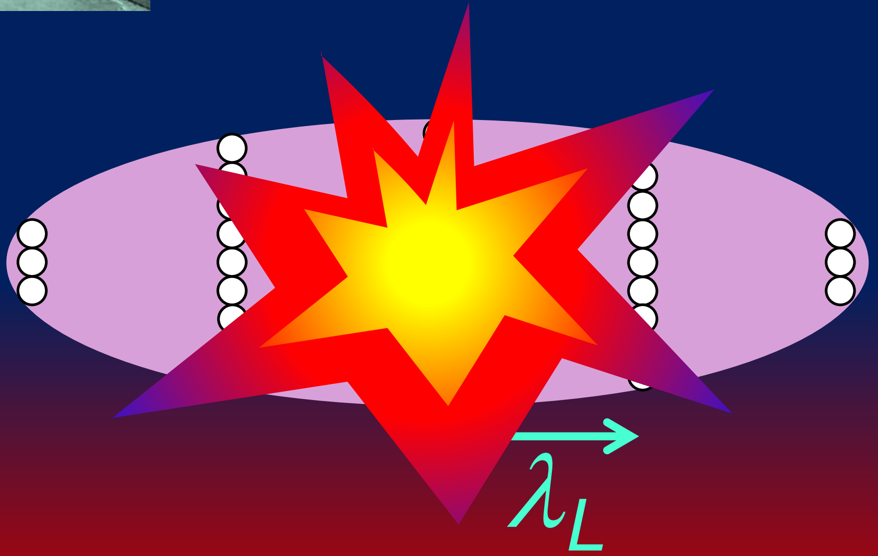
...this is the FEL optical amplification mechanism

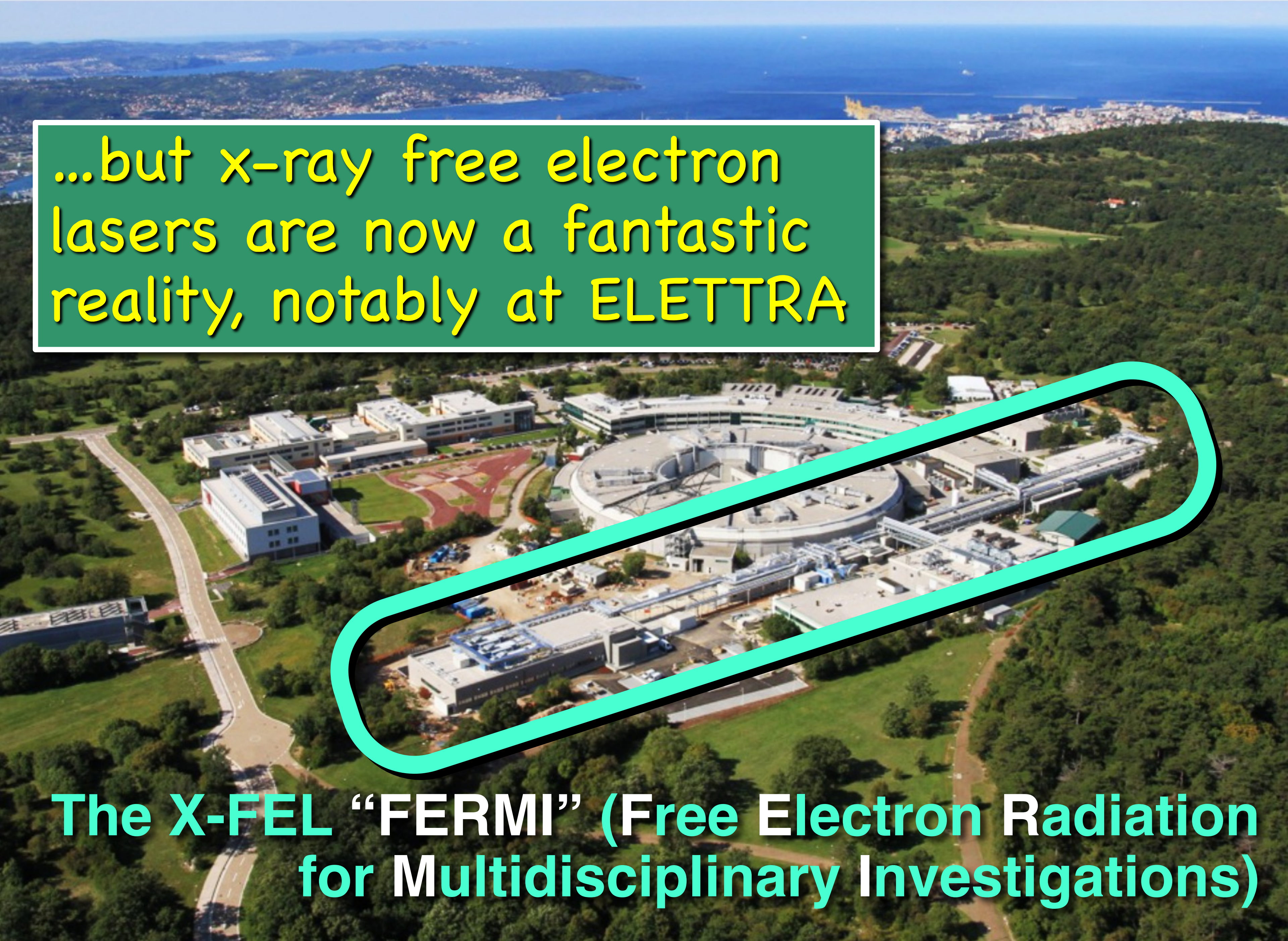
Why are not all undulators behaving like FELs?



The relativistic “longitudinal mass” of high-speed electrons, $\gamma^3 m_e$, is very heavy. It takes a (relatively) long time to move the electrons to the “slices”: micro-bunching requires very long undulators

…and the microbunching period is very short (x-ray wavelengths): the structure is delicate and easily destroyed





...but x-ray free electron lasers are now a fantastic reality, notably at ELETTRA

The X-FEL "FERMI" (Free Electron Radiation for Multidisciplinary Investigations)

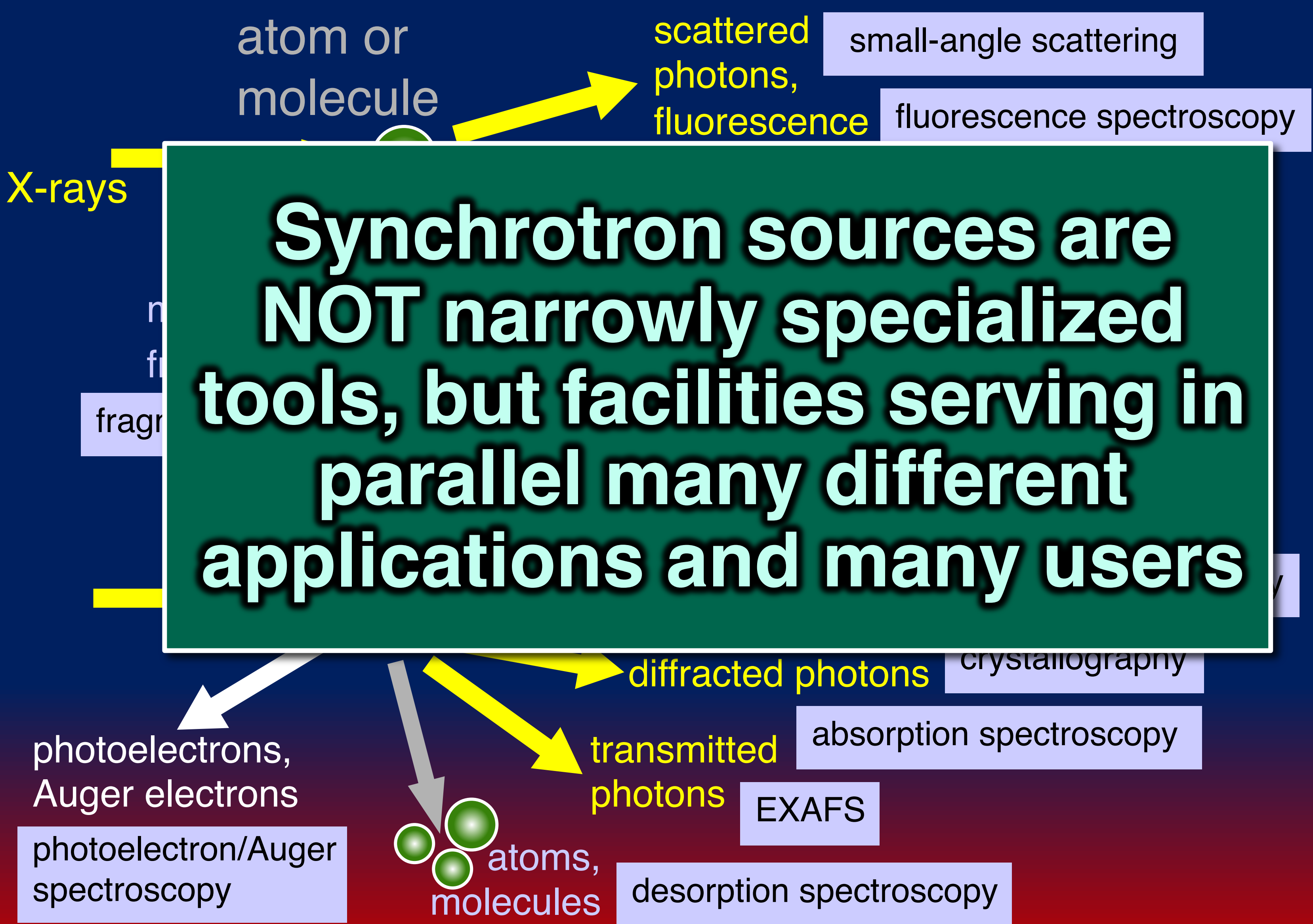
2023 School on Synchrotron Light Sources and their Applications

1. Fundamentals of Synchrotron Radiation from Storage Rings

2. Fundamentals of X-ray Interactions with Matter

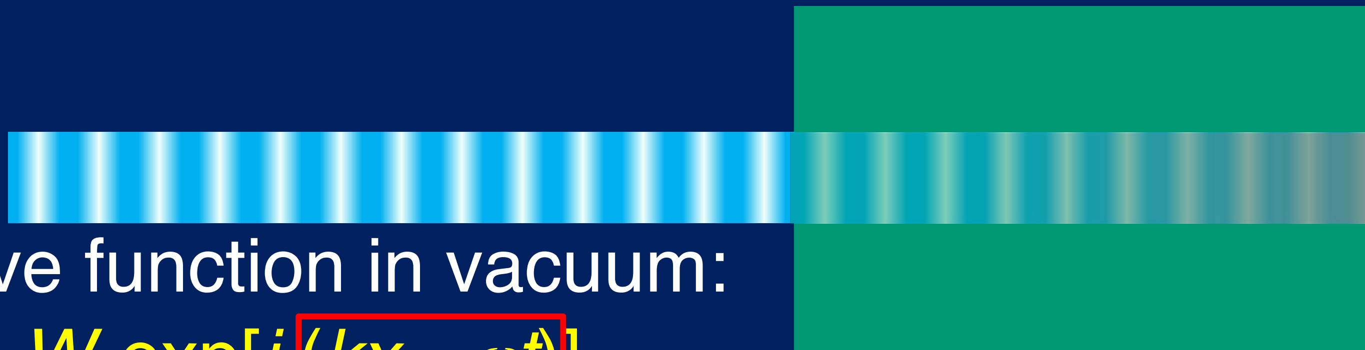
Giorgio Margaritondo
Ecole Polytechnique Fédérale de Lausanne
EPFL

General view of synchrotron research: many x-ray interactions with matter lead to many applications



Synchrotron sources are NOT narrowly specialized tools, but facilities serving in parallel many different applications and many users

Interactions between x-rays and solids: general formal background



Wave function in vacuum:

$W_o \exp[i\,(kx - \omega t)]$

"PHASE" → $(kx - \omega t)$

In the solid: k changes to nk,

where $n = n_R + in_I$ (complex refractive index)

Wave function: $W_o \exp[i\,(nkx - \omega t)]$

$= W_o \exp(-n_I kx) \exp[i\,(n_R kx - \omega t)]$

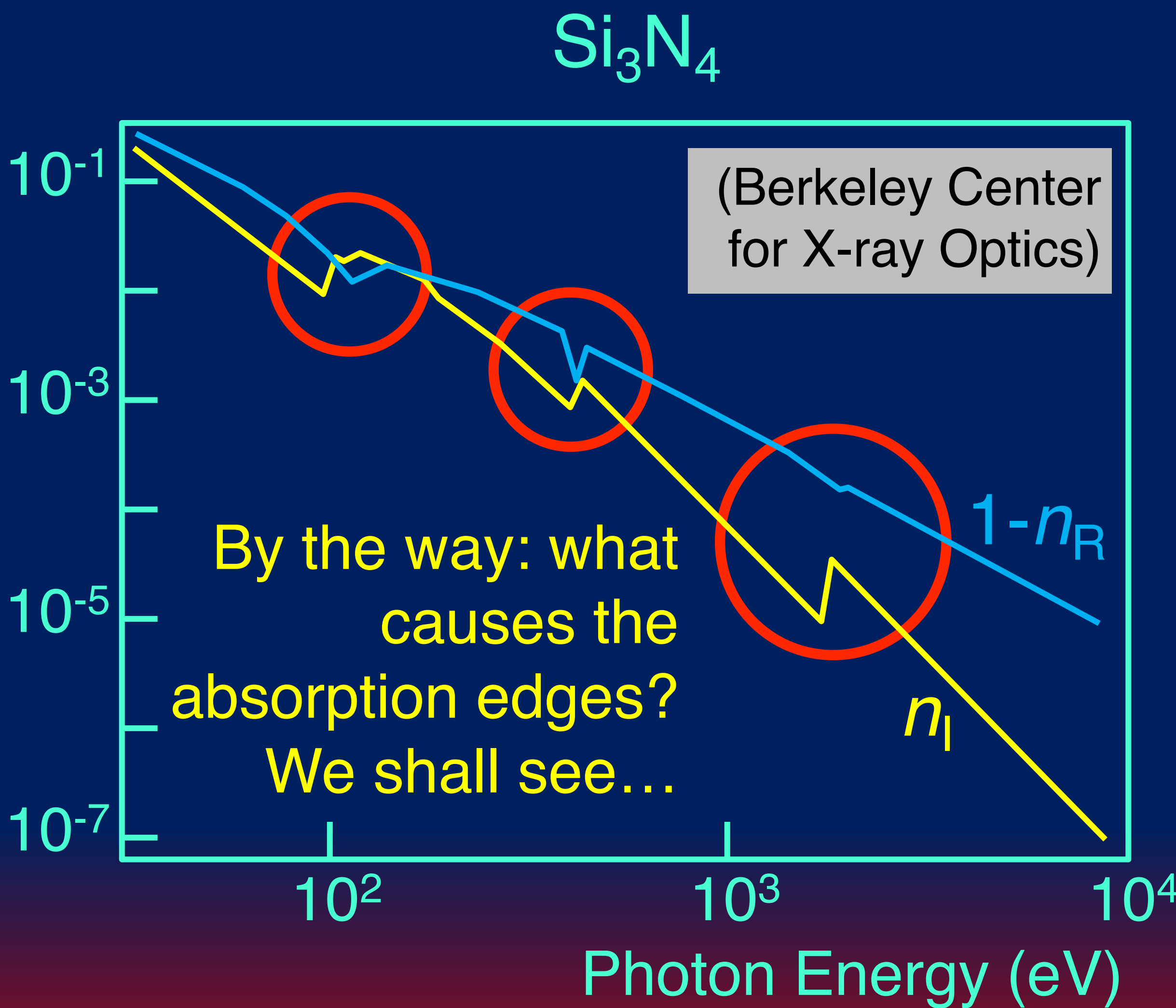
Factor decreasing with the distance: absorption → $\exp(-n_I kx)$

$n_R k$ determines the phase, causing phase effects: refraction, diffraction, interference… → $(n_R kx - \omega t)$

The real and imaginary parts of the refractive index, n_R and n_I, are linked to each other

- $n = n_R + in_I$ is the "response function" describing how the system interacts with photons
- General rule for complex response functions: the real and imaginary parts are not independent but linked by relations like the "Kramers-Kroenig" (KK) equations
- This explains the relations between different types of phenomena:
  - strong reflection corresponds to strong absorption (think about a mirror)
  - refraction and absorption phenomena occur for the same wavelengths
  - Faraday rotation is linked to circular dichroism
  - Hi-fi systems: the amplification is linked to the phase changes

Kramers-Kroenig relations for x-rays: example



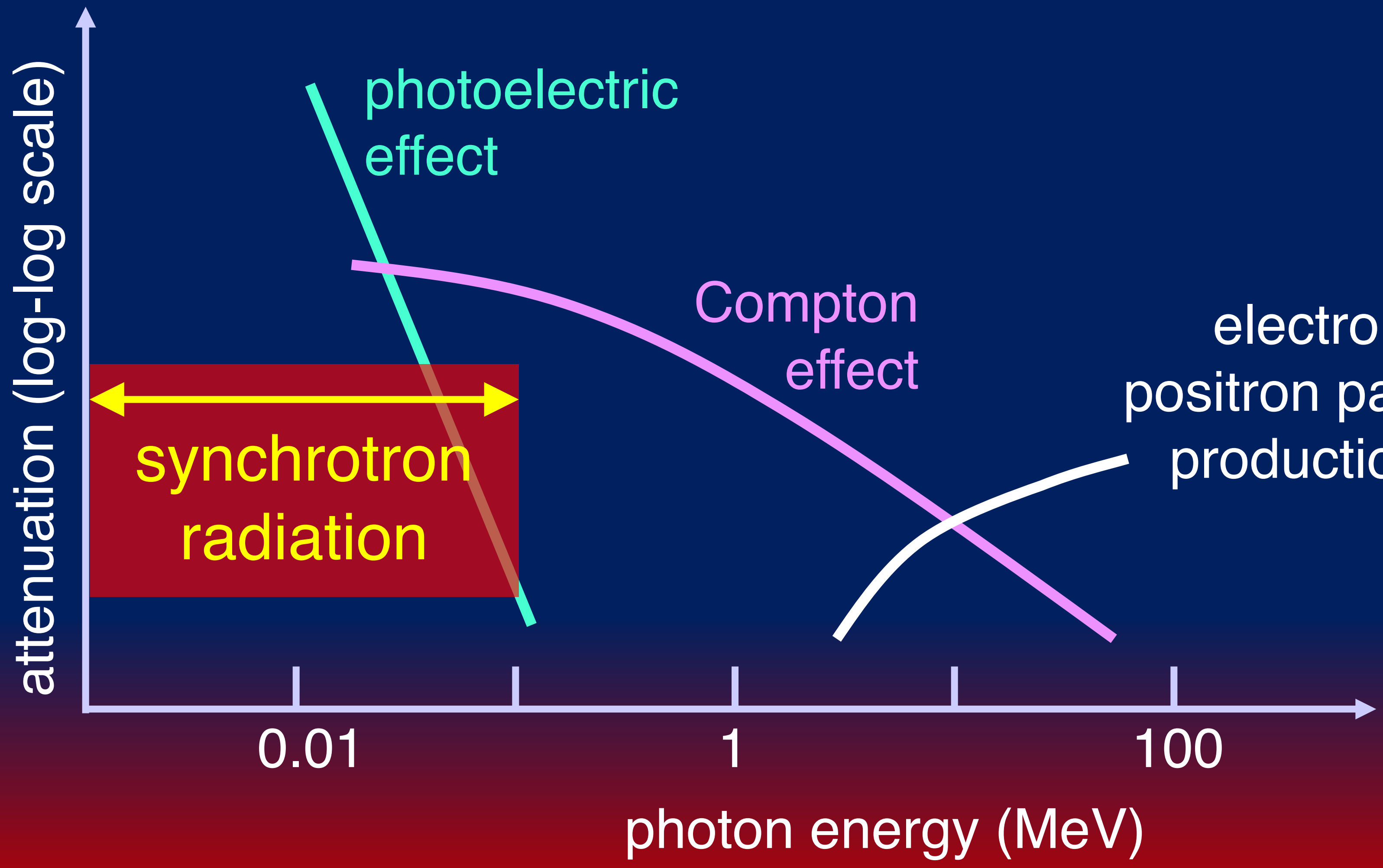
…if something happens for absorption, something also happens for refraction

The mathematical forms of the Kramers-Kroenig relations include integrals over the entire ν frequency range, from zero to infinity

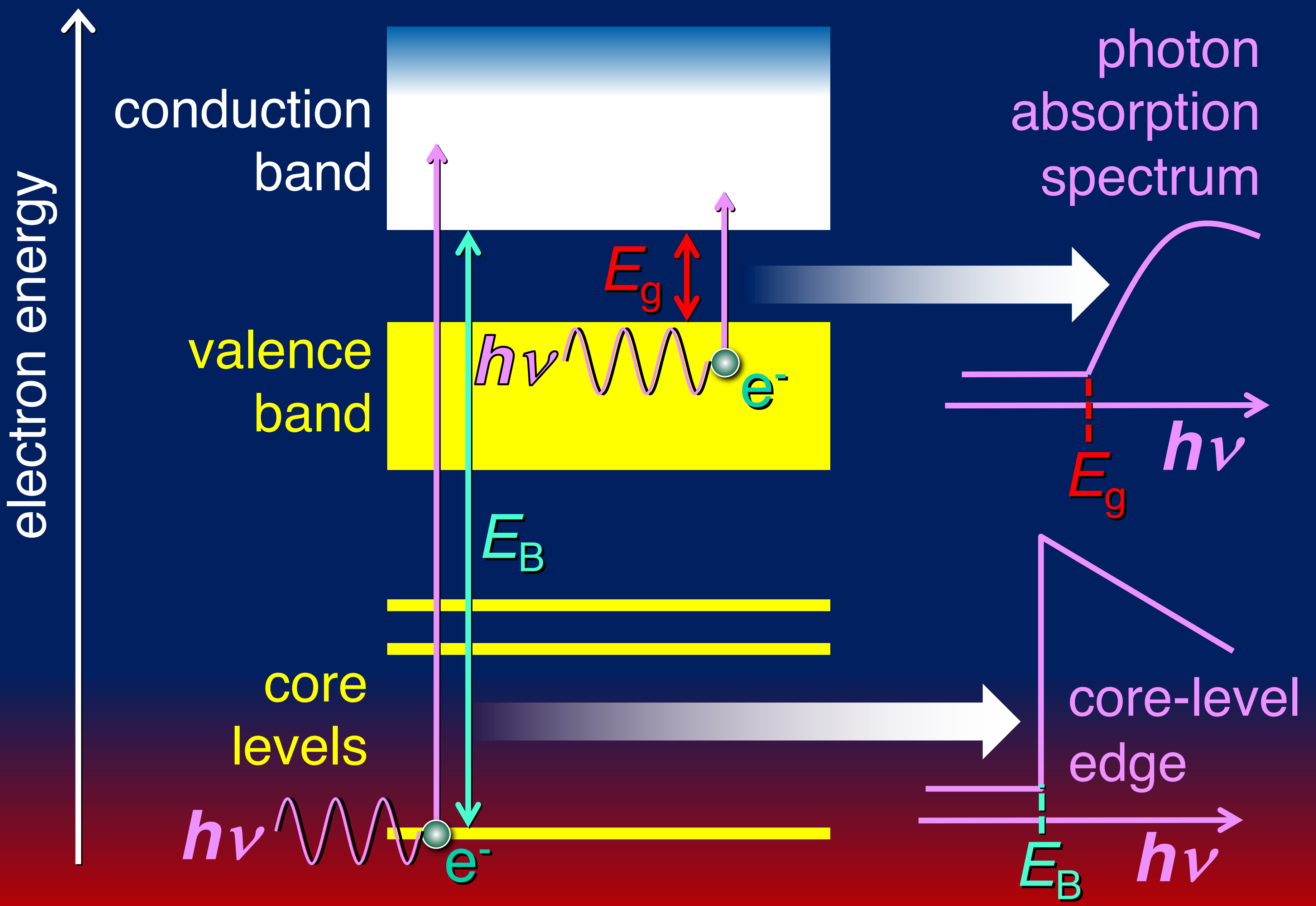
Thus, if one measures n_R over the entire ν spectral range, one can derive n_I mathematically avoid measuring it -- and vice-versa

Realistically, however, one cannot measure n_R or n_I for all frequencies, but over a frequency range as wide as possible: broadband synchrotron sources are helpful!

We shall now explore effects linked to the imaginary part n_I of the complex refractive index, "inelastic" phenomena in which x-ray waves lose energy. The three most important ones are (plots for water):



Photon absorption in an (insulating) solid:



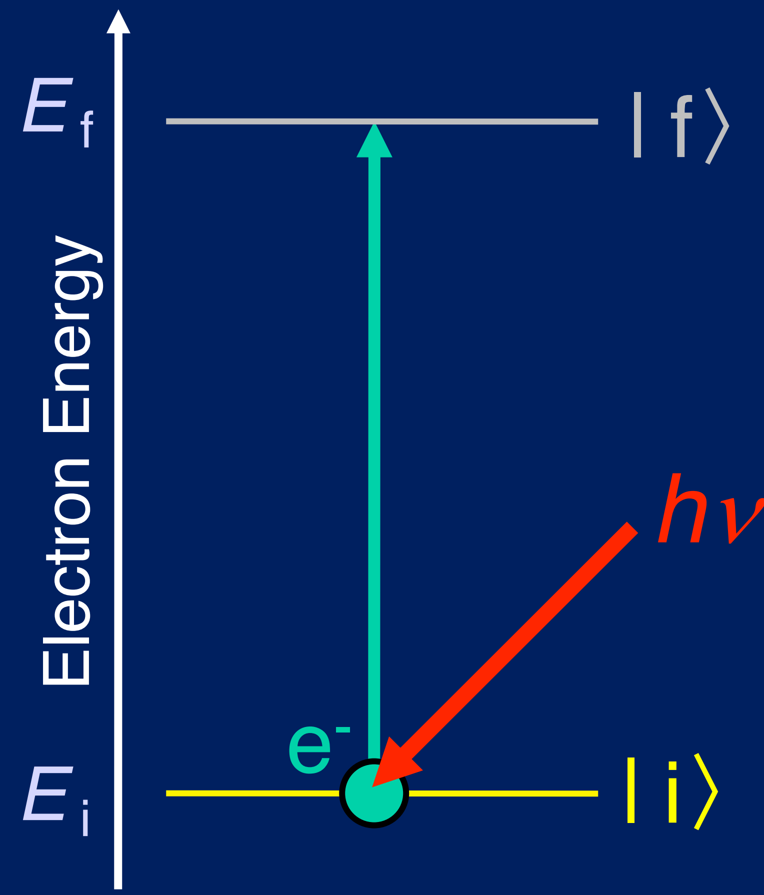
Photon absorption: theory

Transition probability: proportional to

$$|\langle i|\vec{A}\cdot\vec{p}|f\rangle|^2$$

photon vector potential

electron momentum

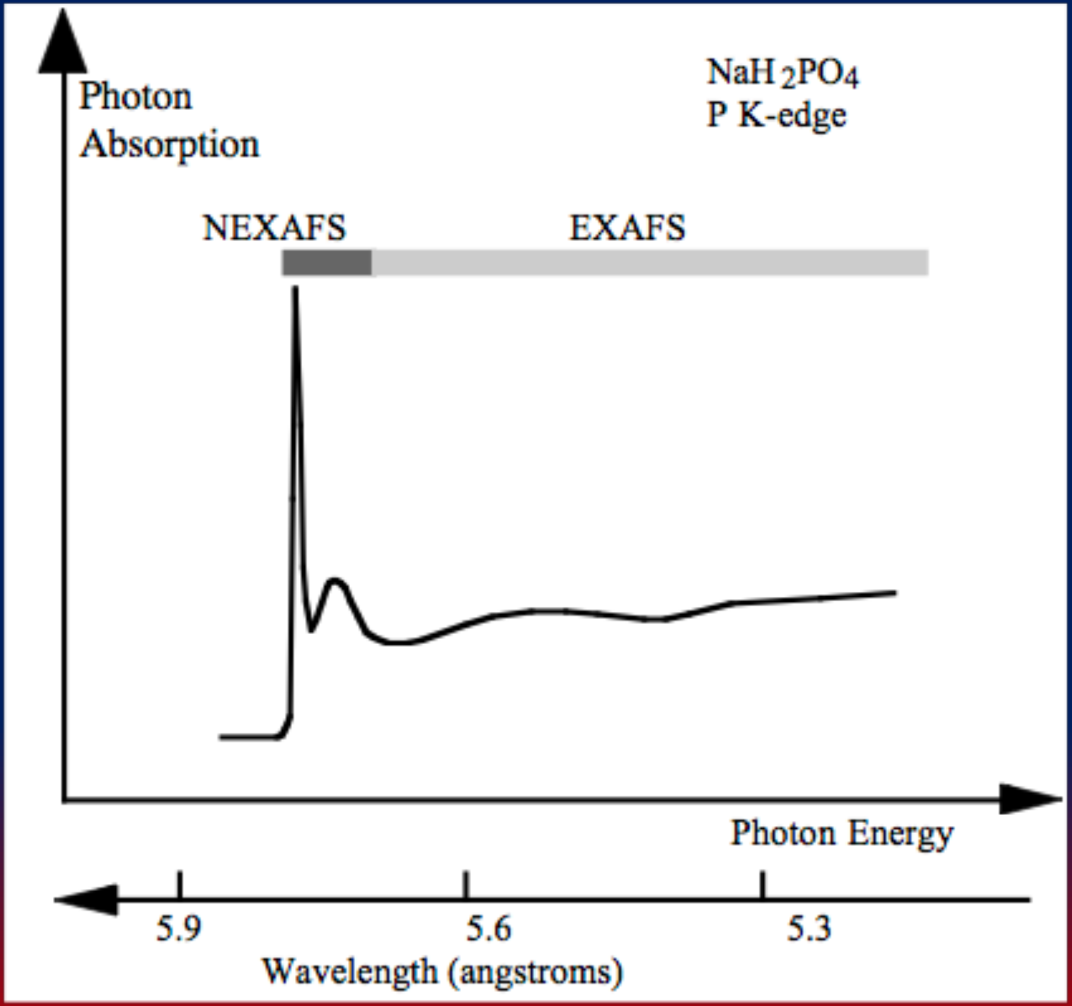


The direction of $\vec{A}$ is that of the photon polarization: polarized synchrotron radiation can explore the electronic state symmetry (parity)

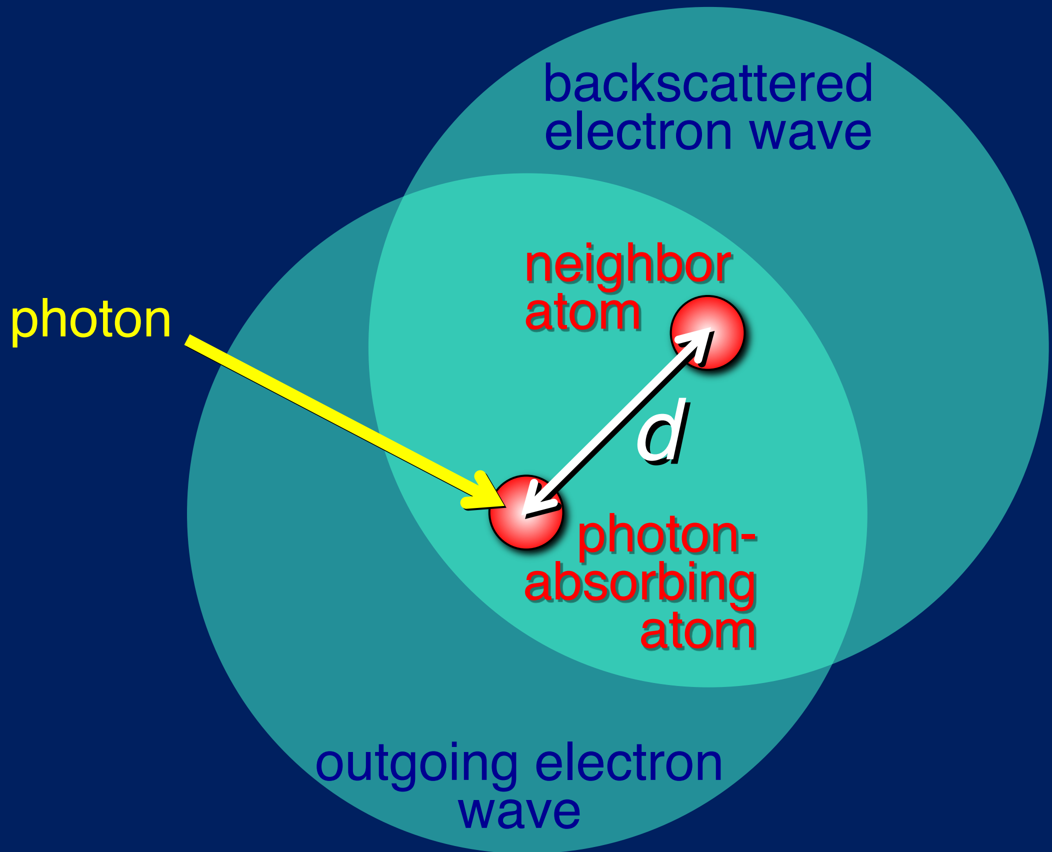
A core-level absorption edge reveals the presence of the corresponding element and its chemical status -- plus more information

EXAFS = Extended X-ray Absorption Fine Structure

NEXAFS = Near-Edge X-ray Absorption Fine Structure

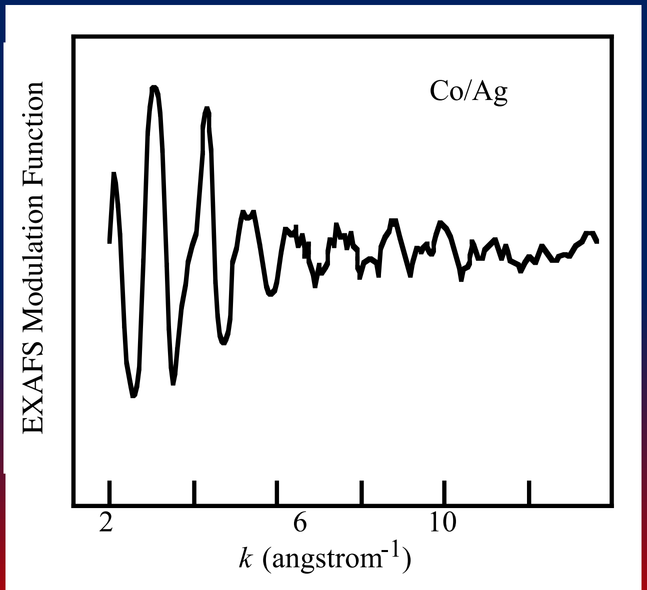


EXAFS mechanism:

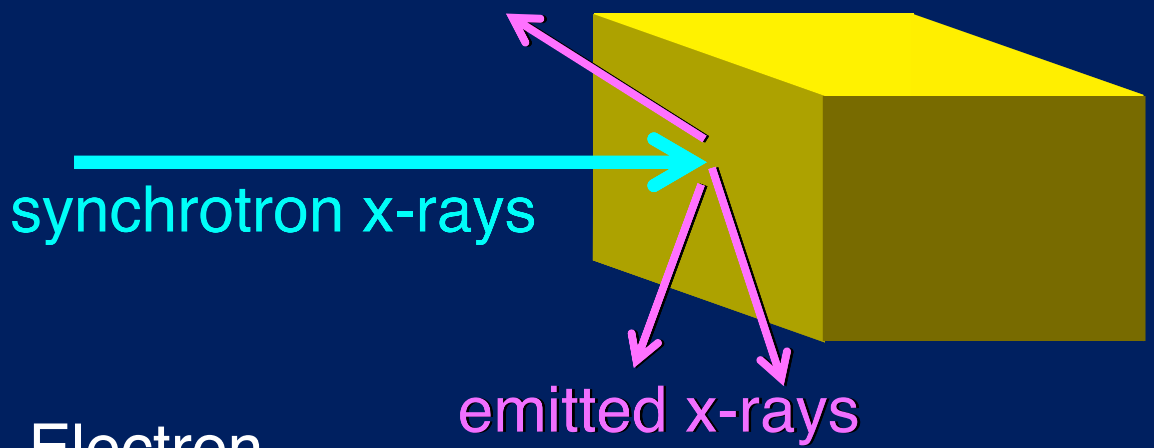


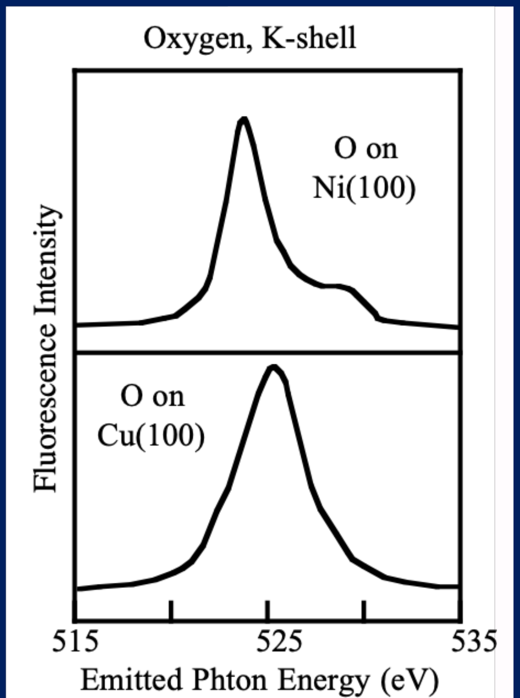
The outgoing and backscattered electron waves interfere constructively or destructively depending on the distance *d* and on the electron wavelength -- which in turn depends on the electron energy and therefore on the photon energy $h\nu$. This produces oscillations in the absorption vs. $h\nu$ plots

From the oscillations, one can derive the local interatomic distance *d*, a very valuable piece of information

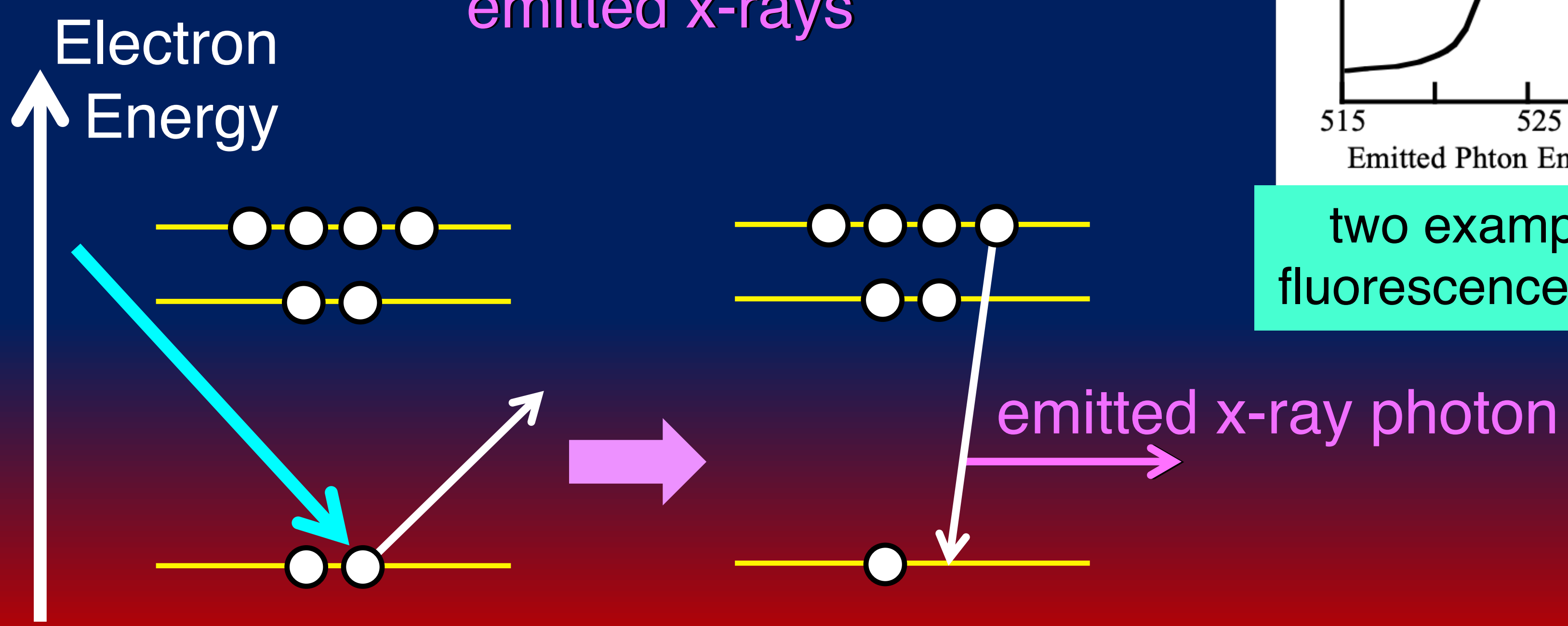


What happens to the energy of a photon absorbed by a solid? It can cause the emission of another photon (**fluorescence**)

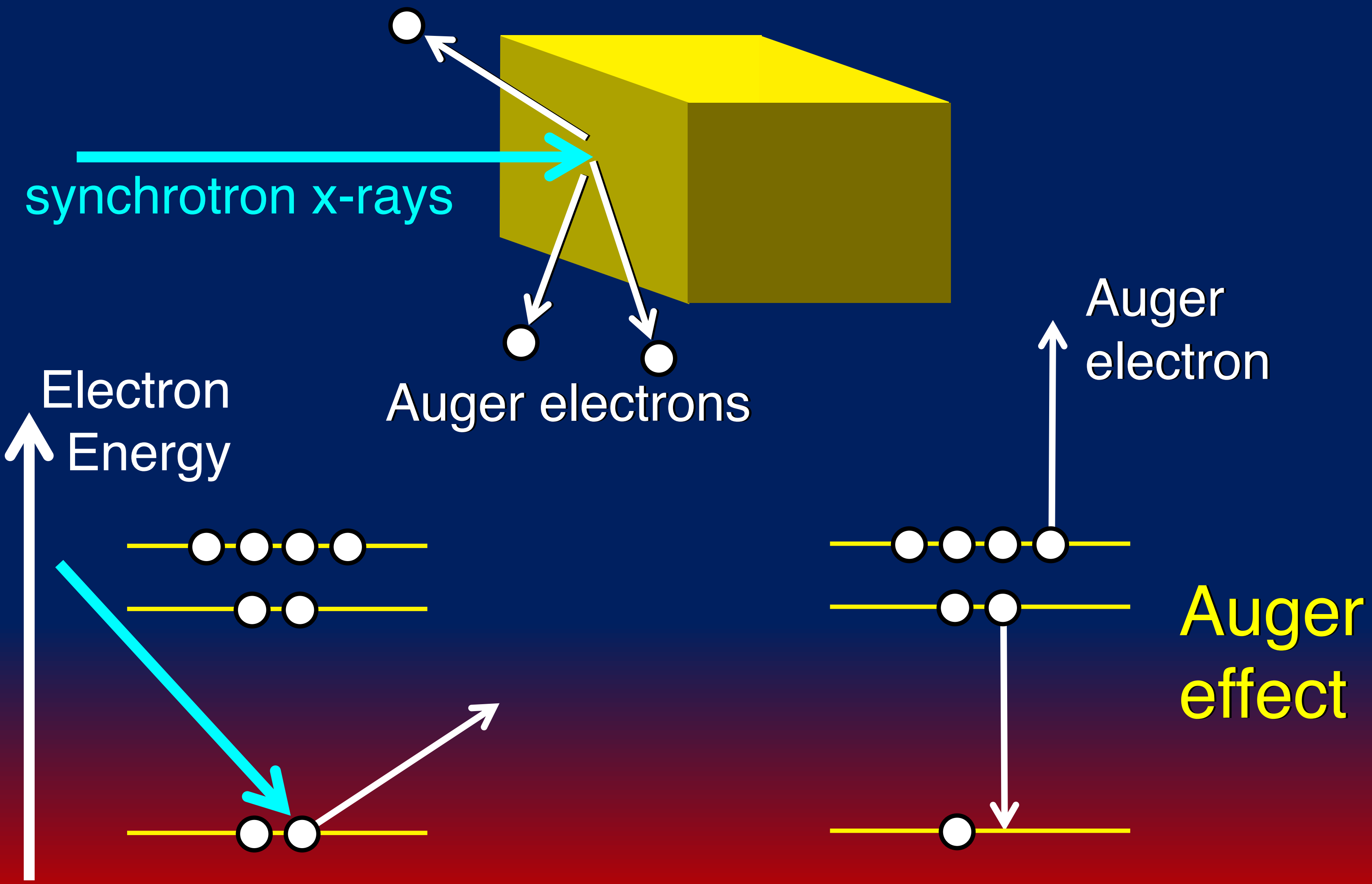




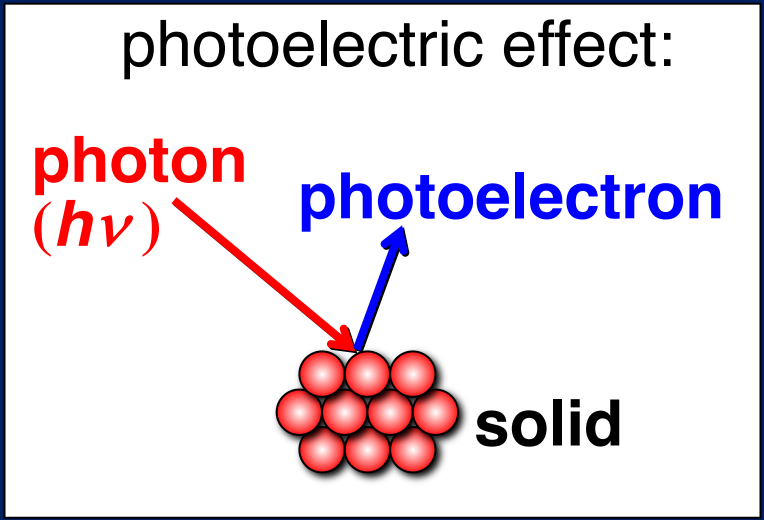
two examples of fluorescence spectra

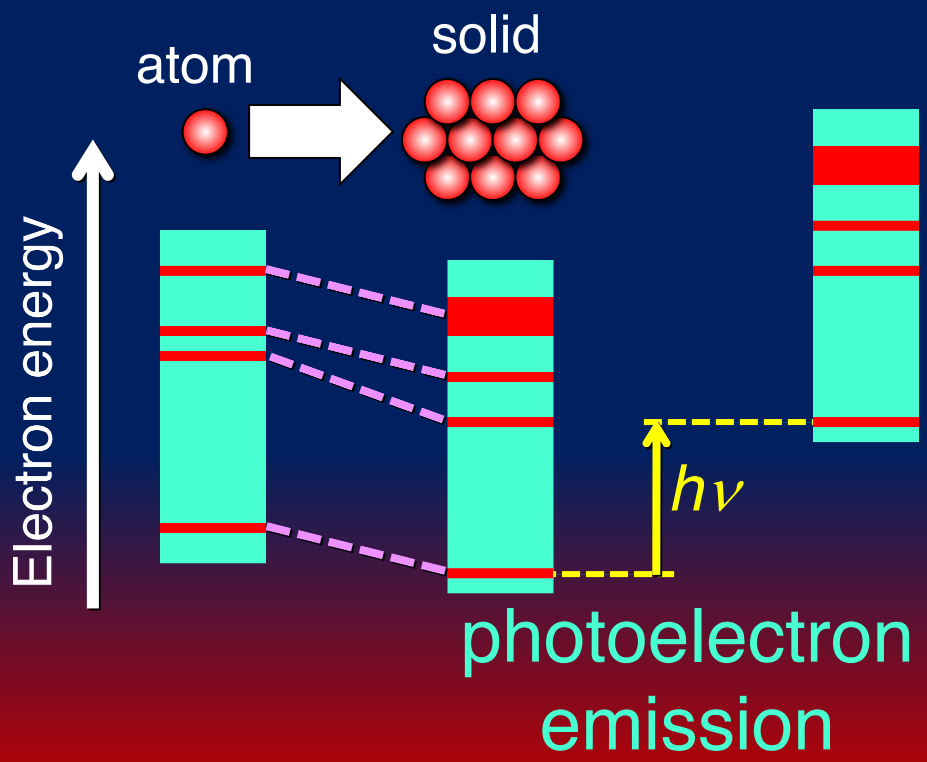


The Auger effect: another way for a solid or a molecule to lose energy after absorbing a photon



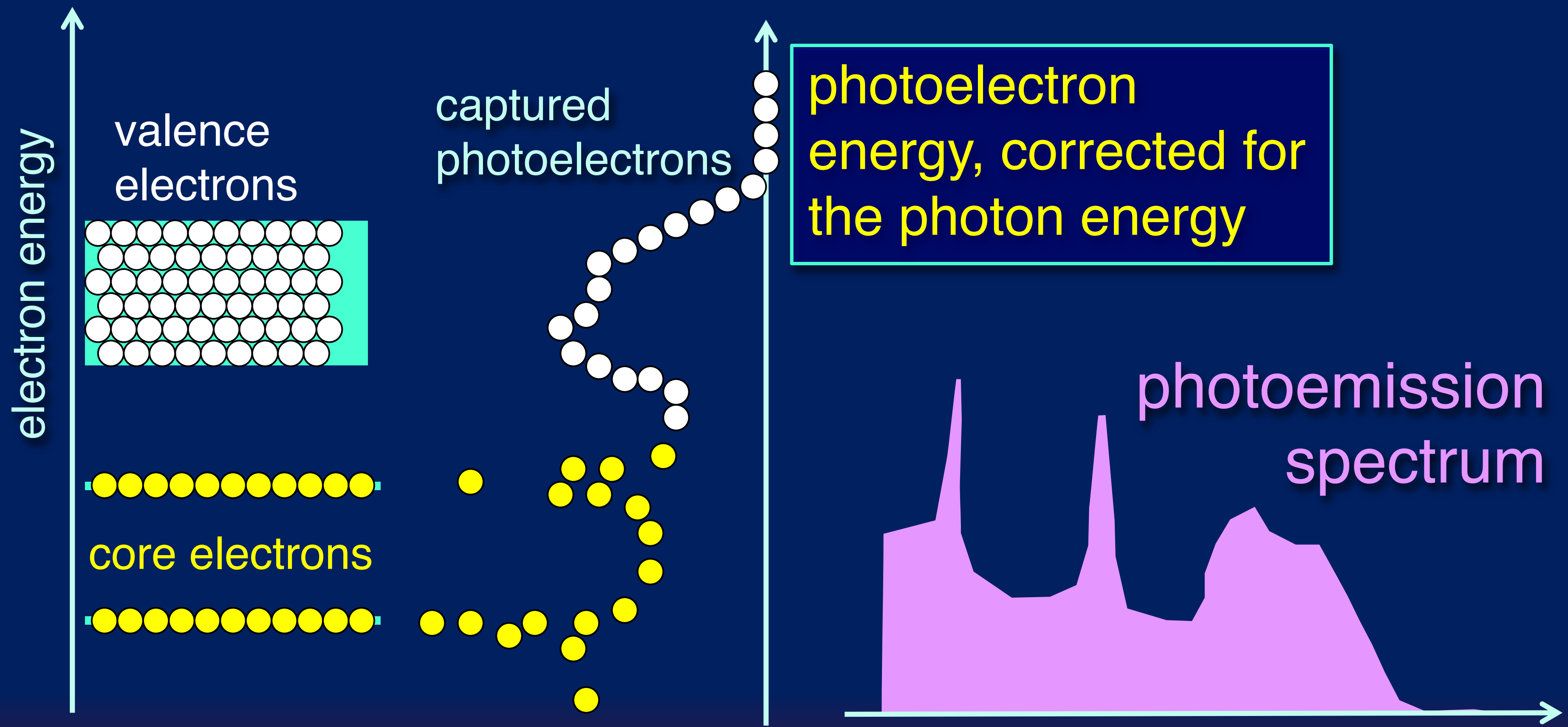
Photoemission, a leading synchrotron technique based on x-ray absorption





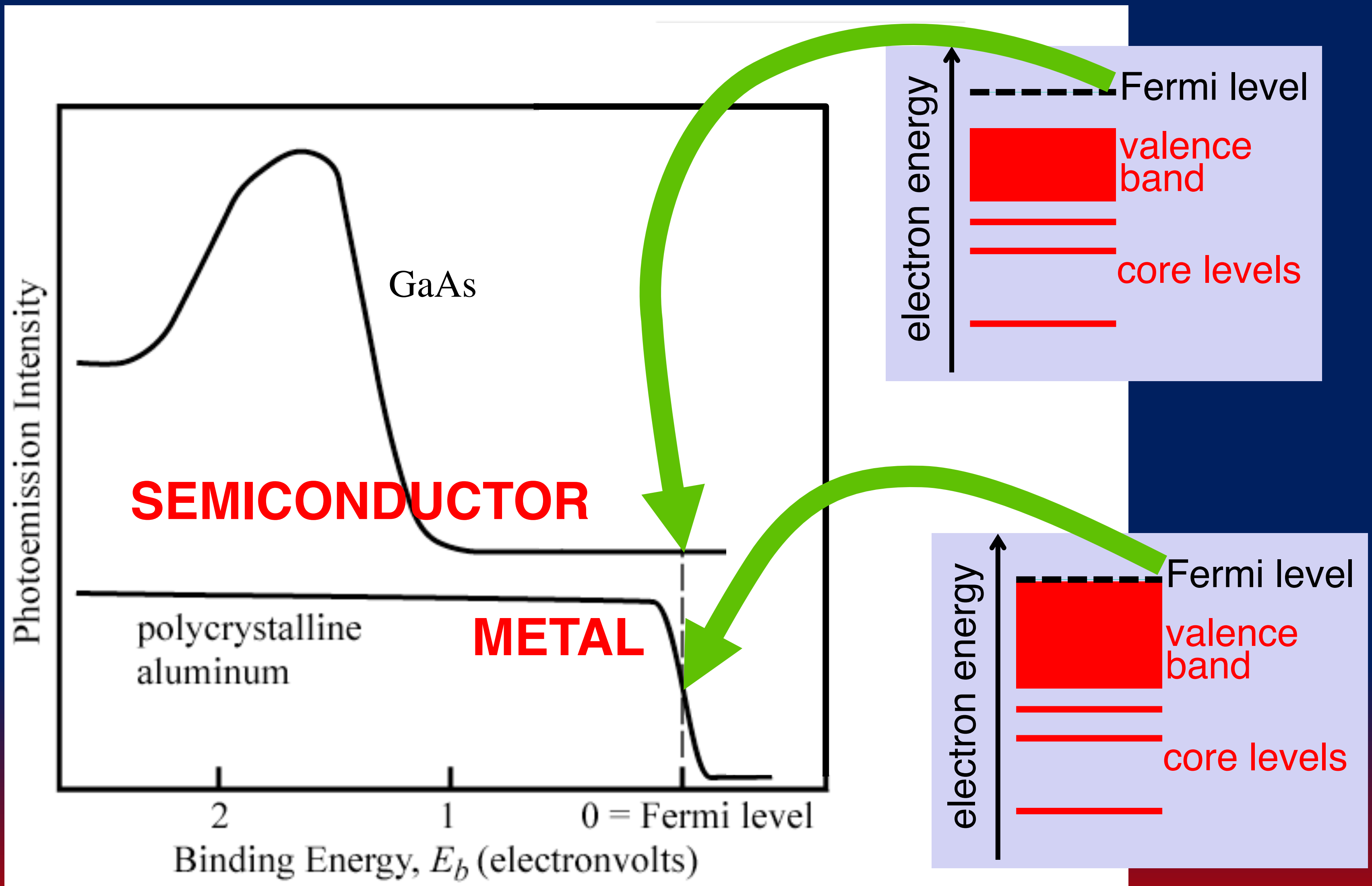
The photoelectric effect increases the electron energy by $h\nu$: one can derive from measured photoelectron energies the electron energies in the solid

Photoemission detects valence electrons and core electrons

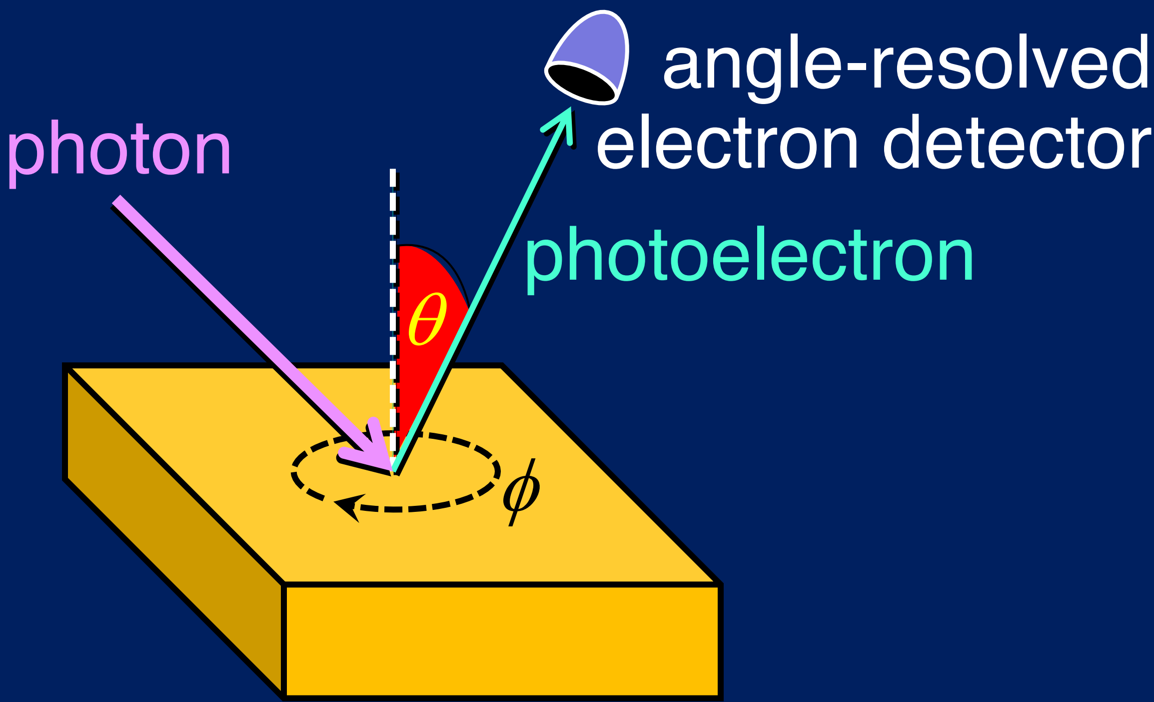


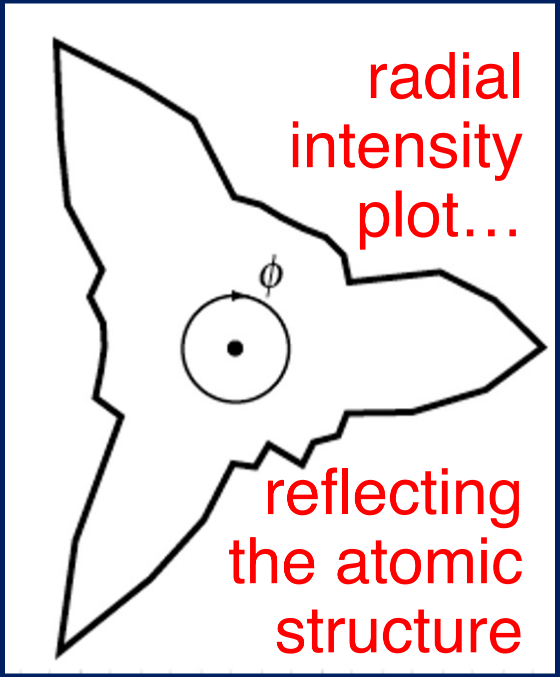
…synchrotron photoemission actually transformed my bookish quantum notions into very tangible realities!

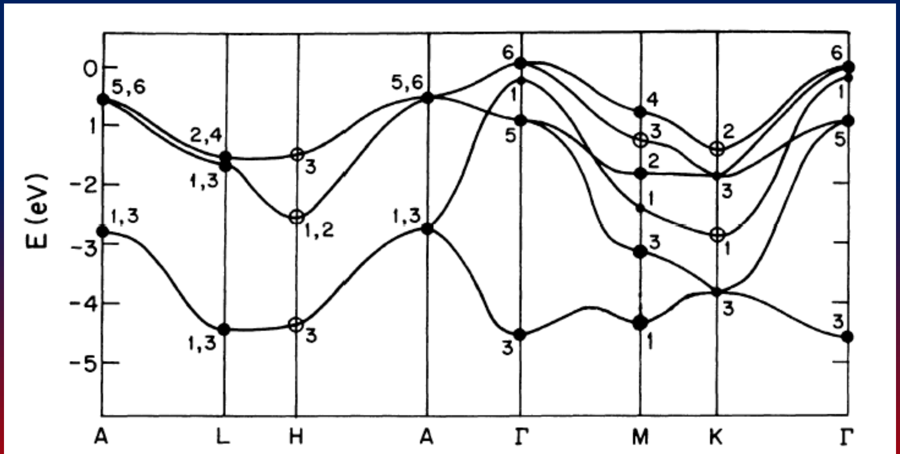
Photoemission: a metal compared to a semiconductor



Angle-resolved photoemission

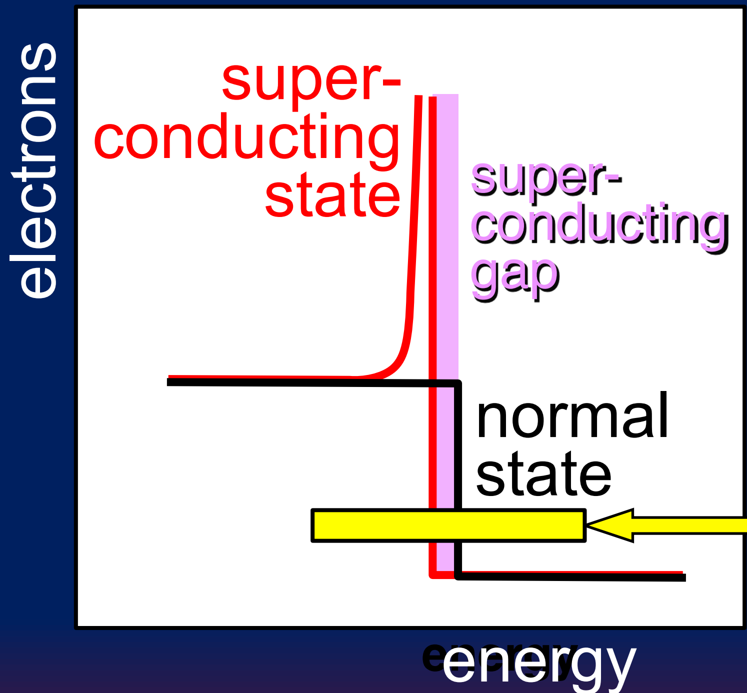






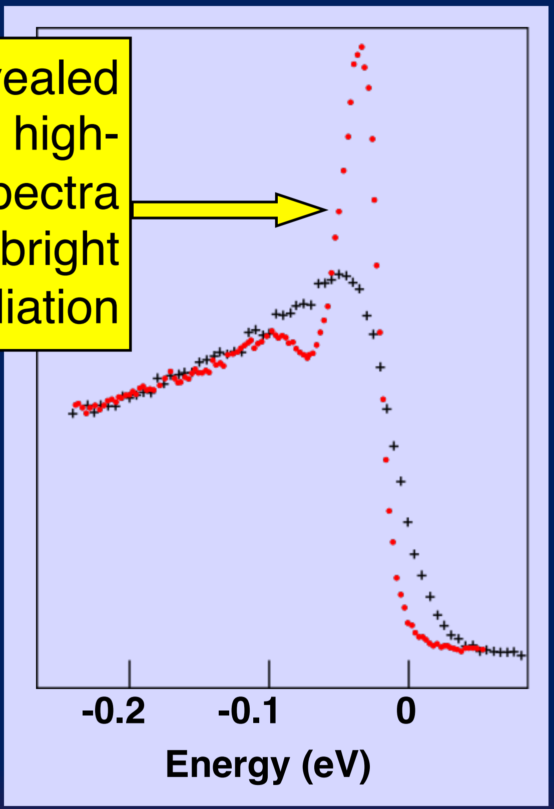
by detecting the energy and direction of a photoelectron, one can obtain its ***k***-vector and derive the experimental band structure $E(\boldsymbol{k})$ – here the results for CdS

Photoemission of a (high-temperature) superconductor



With the limited energy resolution of conventional photoemission, it was impossible to detect the gap

…which was revealed instead by high-resolution spectra taken with ultrabright synchrotron radiation



From photoemission spectroscopy to spectromicroscopy:

Spectroscopy (energy and momentum resolution)

↓

Chemical information

Microscopy (spatial resolution)

↓

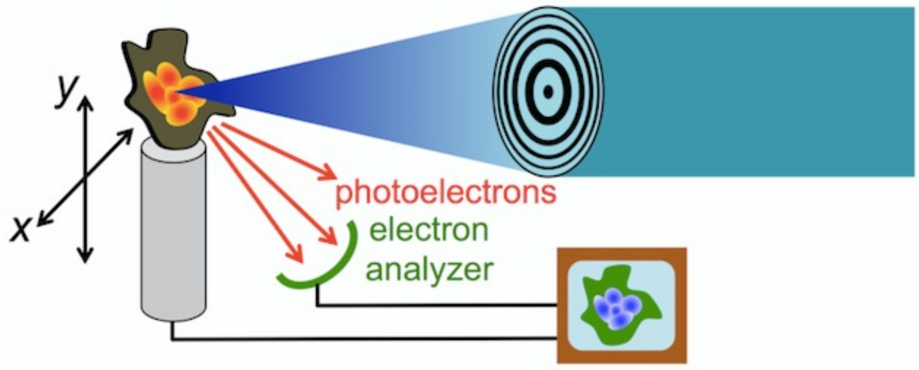
Structural information

↓

Spectromicroscopy

But, as the probed area decreases, the signal is lower: one needs a bright synchrotron source!

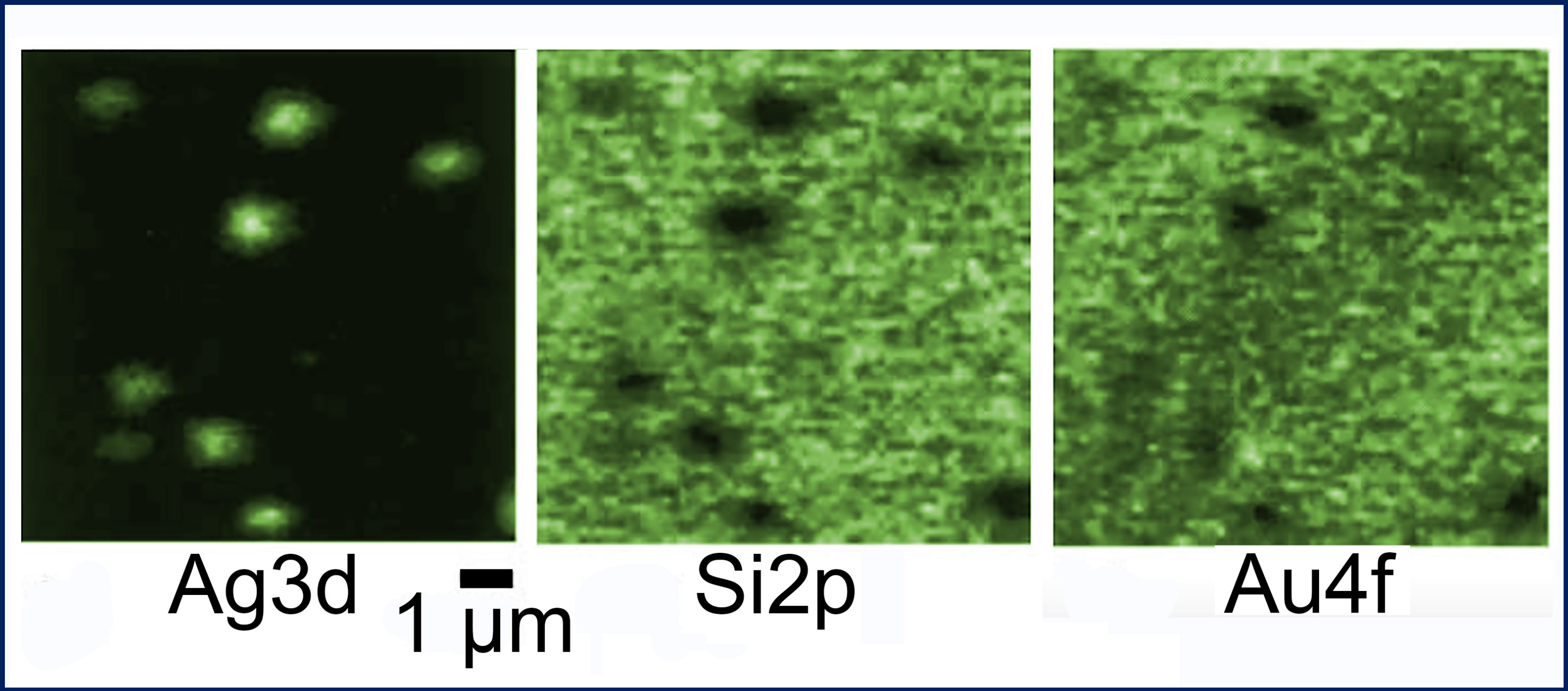
Two ways to implement photoemission spectromicroscopy:



Photon beam focusing

Photoelectron detection with magnifying electron lenses

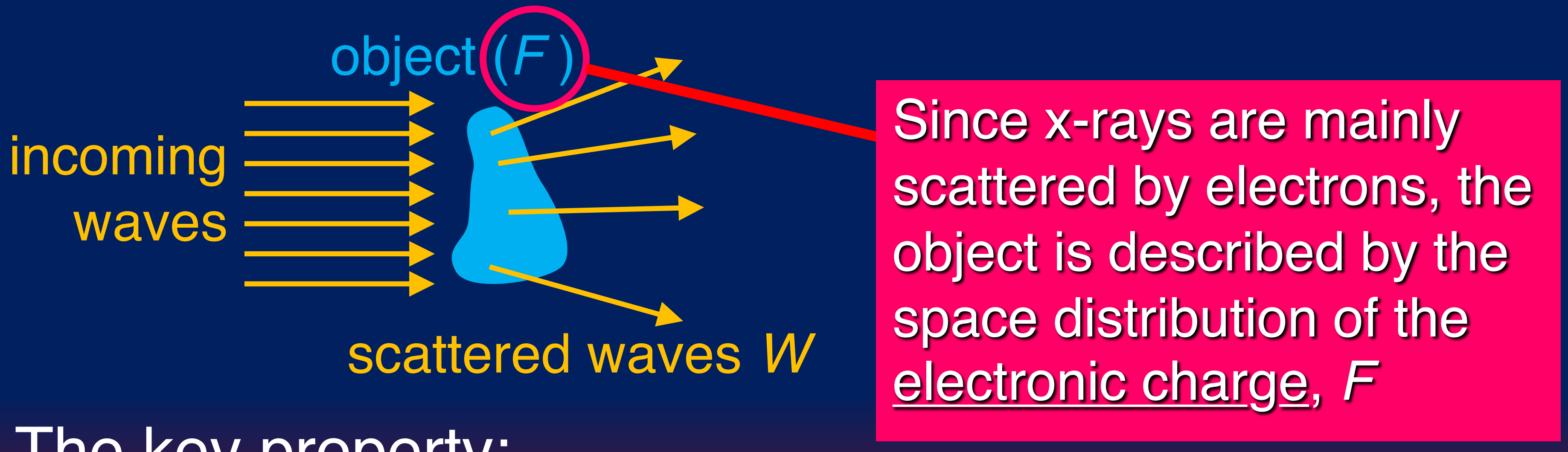
Photoemission spectromicroscopy results: "chemical maps":



Photoelectron images at three different photoelectron energies: note the chemical contrast inversion [M. Marsi et al., J. Electron Spectroscopy **84**, 73 (1997)]

We shall now describe elastic phenomena corresponding to the real part n_R of the refractive index, such as refraction or reflection (both very weak for x-rays), and:

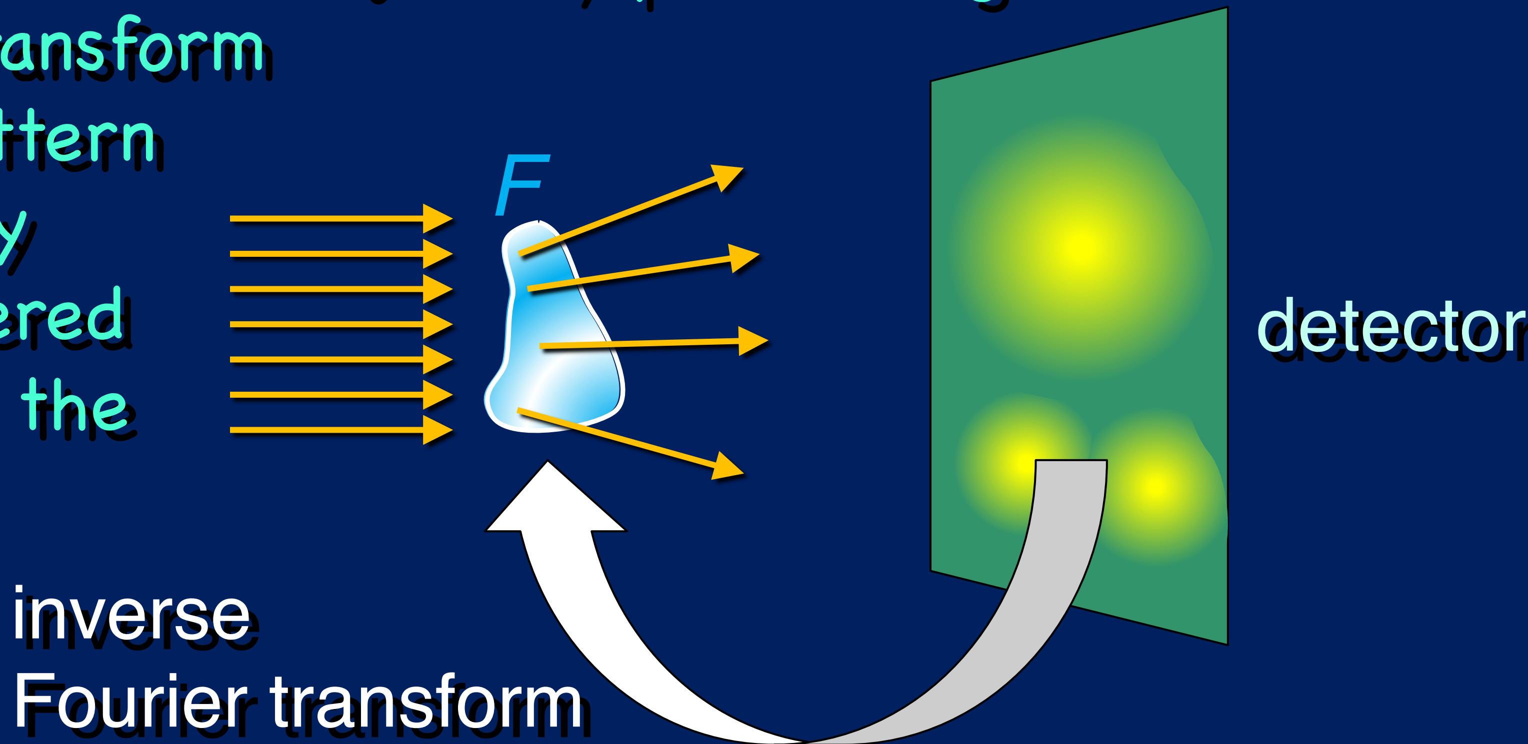
Elastic x-ray scattering: a tool to explore the microscopic structure of objects



The key property:

- *W* corresponds to the Fourier transform of *F*
- The inverse Fourier transform of *W* corresponds to *F*

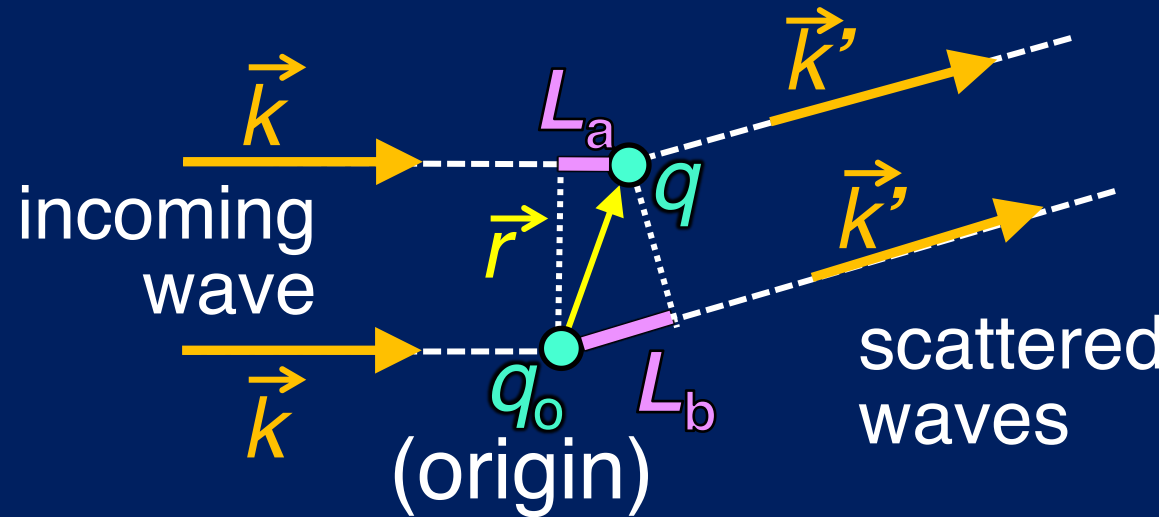
Thus, we can hope to retrieve the electronic charge distribution of an object by performing an inverse Fourier transform of the pattern created by the scattered x-rays on the detector



BUT: we do not measure the scattered wave $W = W_o \exp(i\vec{r}\cdot\vec{k}')$, only its intensity, $W^* W = W_o^* \exp(-i\,\vec{r}\cdot\vec{k}')\; W_o \exp(i\,\vec{r}\cdot\vec{k}') = W_o^* W_o$. Thus, we do not know its PHASE. This severely affects the inverse Fourier transforms, creating the PHASE PROBLEM. Special synchrotron-based methods are used to solve it

Grasping the role of Fourier transforms: x-ray scattering by a point-charge q

the k-vector magnitude is $2\pi/\lambda$, thus the unit vectors defining the directions are $(\lambda/2\pi)\vec{k}$ and $(\lambda/2\pi)\vec{k}'$



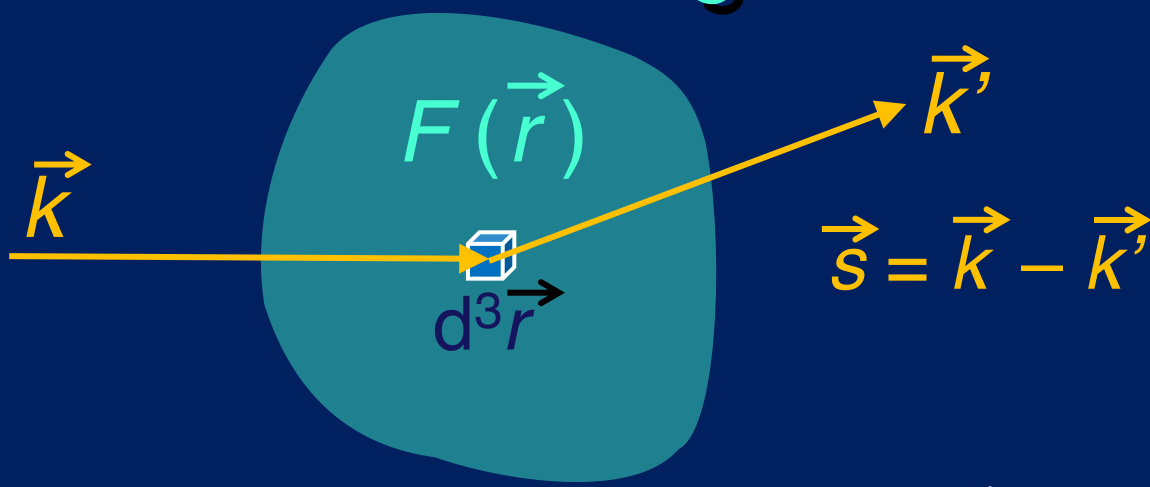
Using as a reference a wave scattered by a charge q_o at the origin, the path difference is:

$$L_a - L_b = \vec{r}\cdot(\lambda/2\pi)\vec{k} - \vec{r}\cdot(\lambda/2\pi)\vec{k}' = \vec{r}\cdot\vec{s}\,(\lambda/2\pi),$$

where $\vec{s} = \vec{k} - \vec{k}'$ = "scattering vector"

Phase difference = $(2\pi/\lambda)$(path difference) = $\vec{r}\cdot\vec{s}$: the wave scattered by q is proportional to $q\exp(i\vec{r}\cdot\vec{s})$

Now look at an entire charge distribution $F(\vec{r})$:



The charge in the infinitesimal volume $d^3\vec{r}$ is $F(\vec{r})d^3\vec{r}$

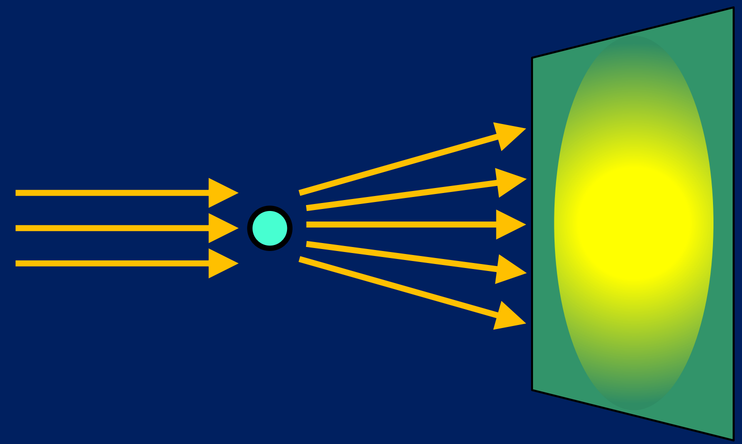
The wave scattered by this charge is proportional to $F(\vec{r})d^3\vec{r}\exp(i\vec{r}\cdot\vec{s})$

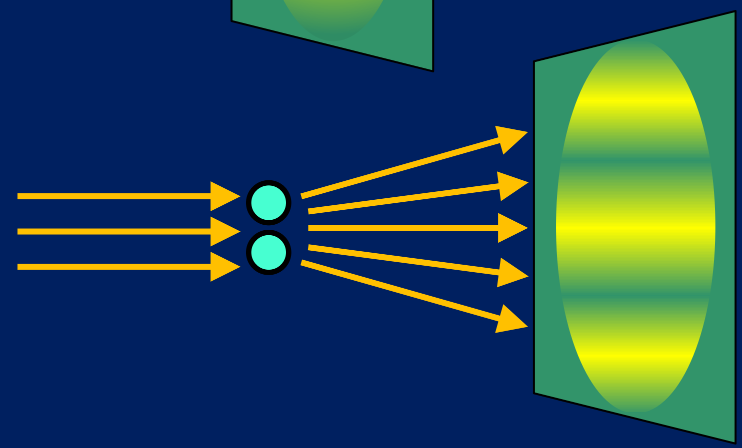
Thus, the total scattered wave $W(\vec{s})$ is proportional to $\int F(\vec{r})\exp(i\vec{r}\cdot\vec{s})d^3\vec{r}$

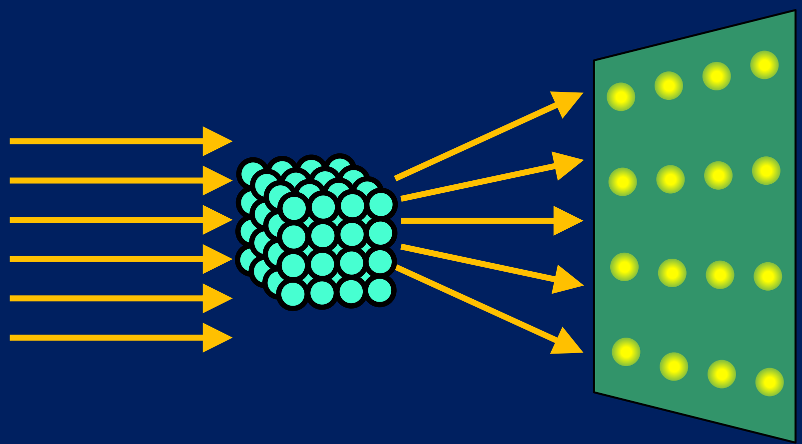
…indeed, the Fourier transform of the distribution F !

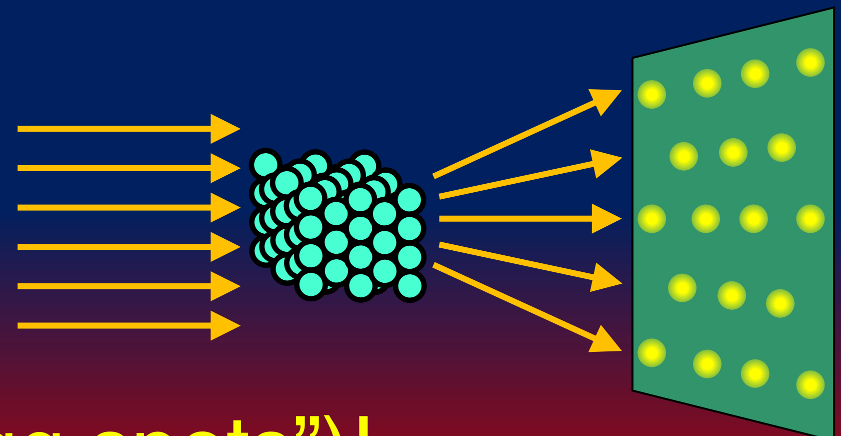
…and $F(\vec{r})$ is proportional to $\int W(\vec{s})\exp(-i\vec{r}\cdot\vec{s})d^3\vec{s}$ (inverse Fourier transform)

Fourier transform relation between some simple objects and their scattered waves:



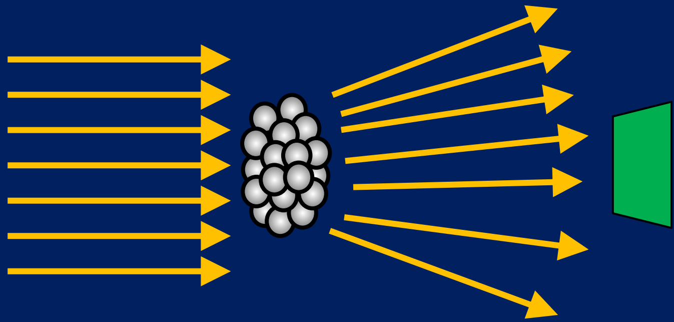






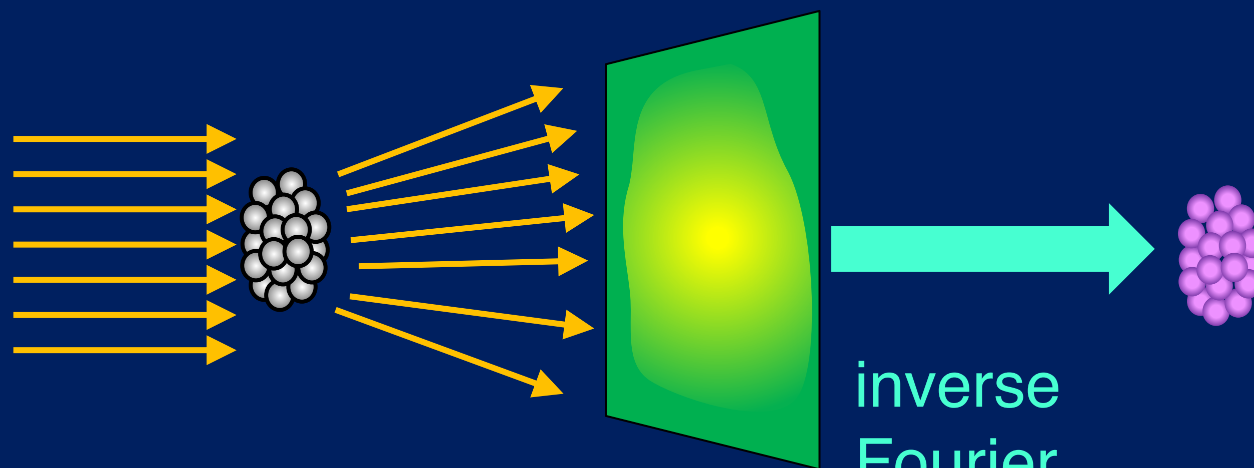
Note: periodic object
→ periodic *F*
→ <u>periodic pattern</u> (“Bragg spots”)!

Small-angle and large-angle scattering

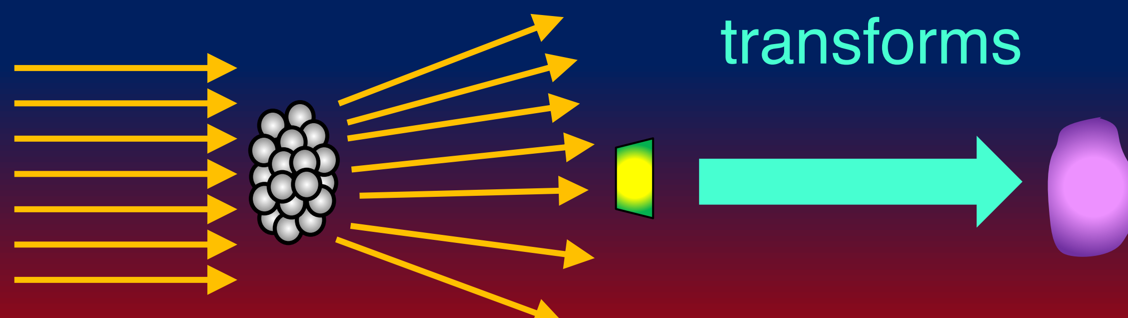


In a real experiment, the detector captures only a portion of the solid angle, i.e., only part of the scattered x-rays

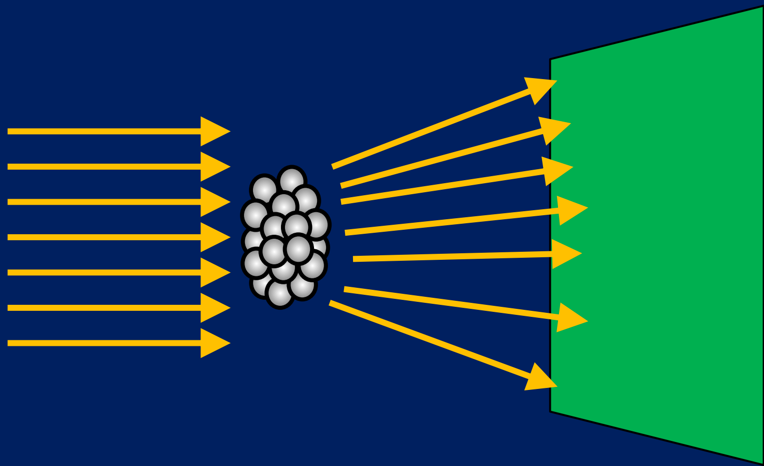
Because of the Fourier transform properties, when scattering is only detected at small angles the inverse transform gives the general shape of the object but not its fine details



inverse Fourier transforms



Small-angle and large-angle scattering



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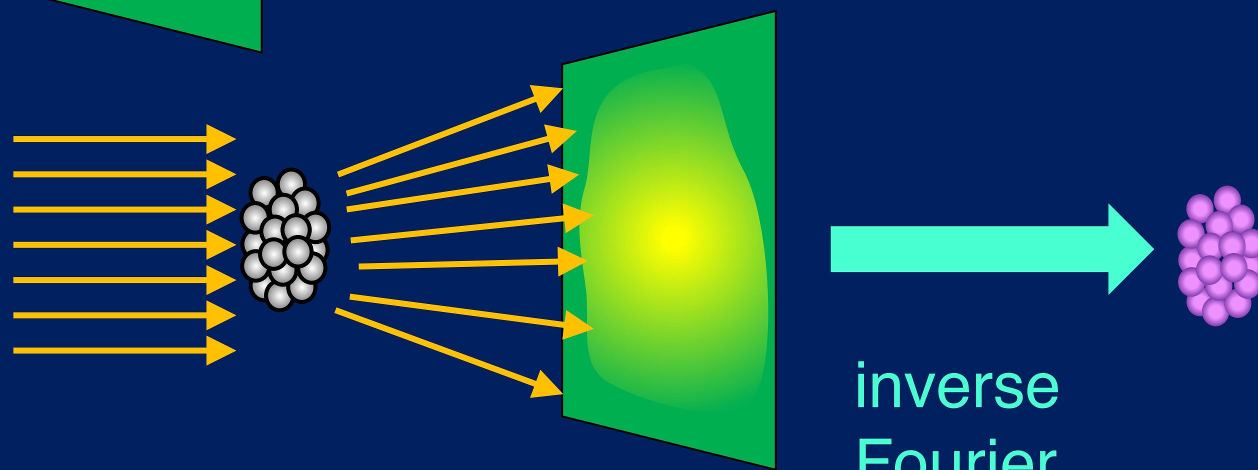
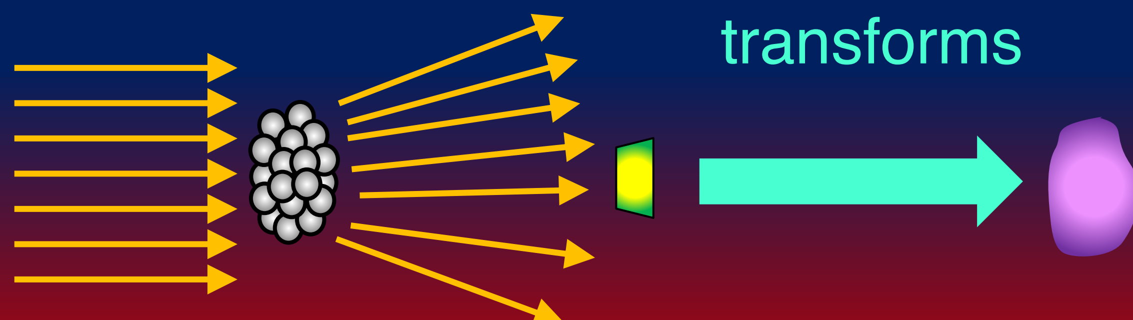
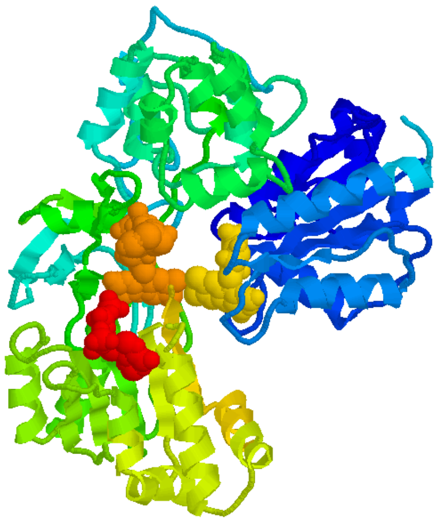


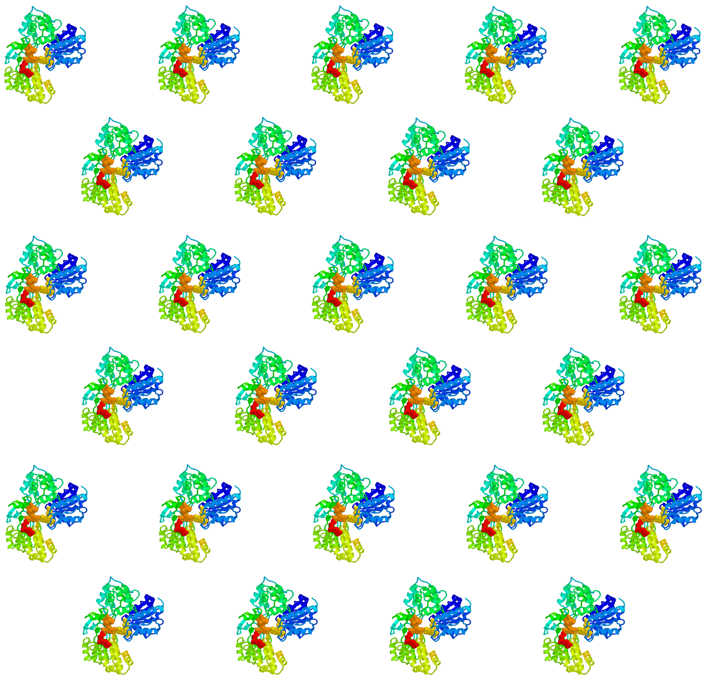
inverse Fourier transforms



Protein crystallography

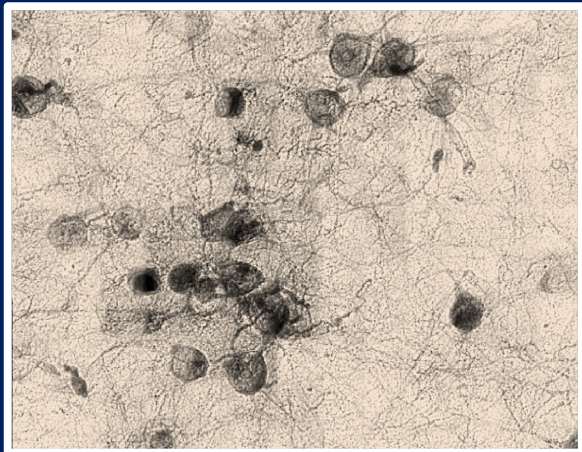


The accurate identification of protein structures with tens of thousands of atoms is one of the most important and challenging tasks for science today



However, damage induced by x-rays is a major problem. The standard solution is to measure simultaneously a large number of molecules organized in a "crystal"

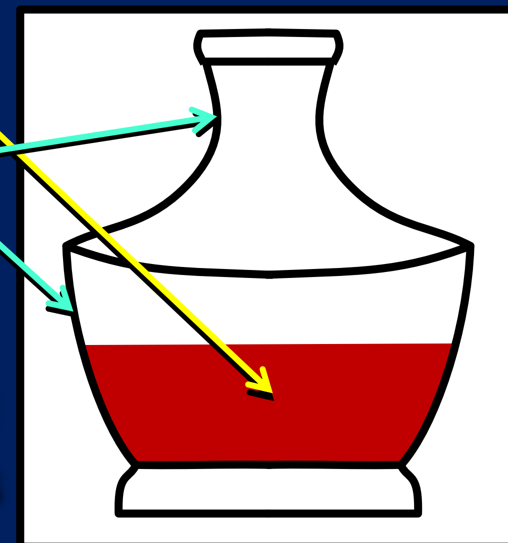
Problem: obtaining large stable crystals, in particular for hydrophobic molecules – for example, many membrane proteins



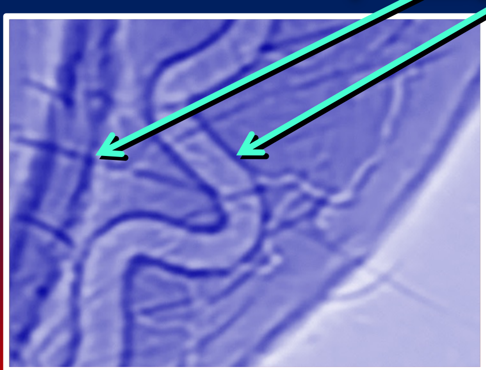
We must now look at phenomena in which the effects of n_R and n_I are both present, such as imaging with coherent x-rays. We can use a simple analogy: seeing a bottle of red wine

we see the wine because it absorbs certain wavelengths and looks red

but we also see the edges of the (transparent) glass bottle because they deviate the light by refraction/scattering



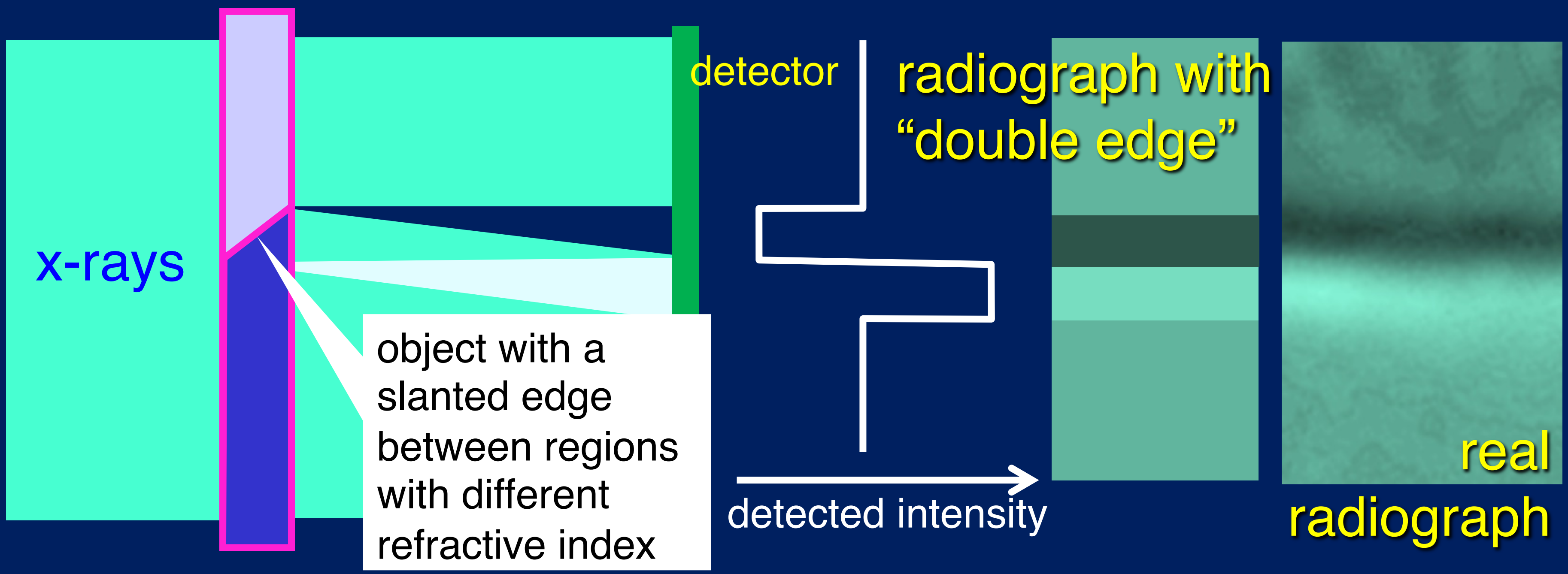
likewise, "phase contrast" (refraction/scattering) causes sharp edges in synchrotron radiographs



…to see the edges we need x-rays with a well defined direction: fortunately, the high spatial coherence of synchrotron sources implies angular collimation

A simple model of how edges are caused by refraction in phase-contrast radiology

[G. Margaritondo and G. Tromba, J. Appl. Phys. **85**, 3406 (1999); Y. Hwu et al., J. Appl. Phys. **86**, 4613 (1999)]



... high lateral coherence is required (x-rays with a well-defined direction); on the contrary, high longitudinal (time) coherence is not needed

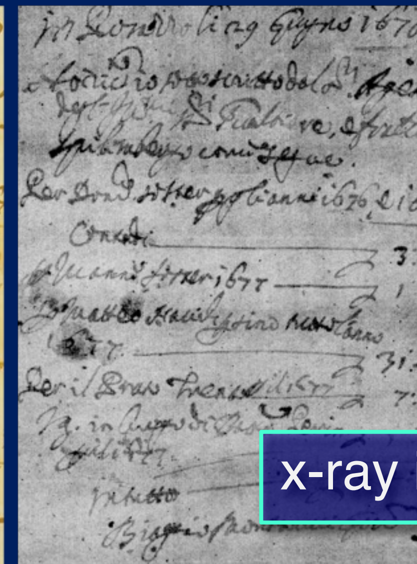
Example of study with phase contrast radiology: the magic light of fireflies

Synchrotron microtomography of a firefly “lantern” [Y. L. Tsai, Y. Hwu et al.]

…being able to detect all vessels, including the smallest ones, we could identify the incredibly effective emission mechanism

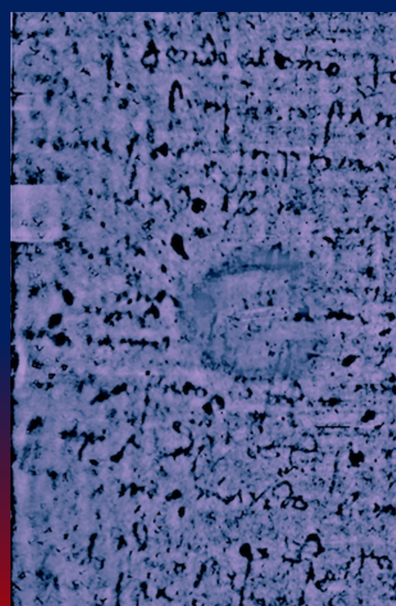
Synchrotron tomography reads ancient manuscripts:

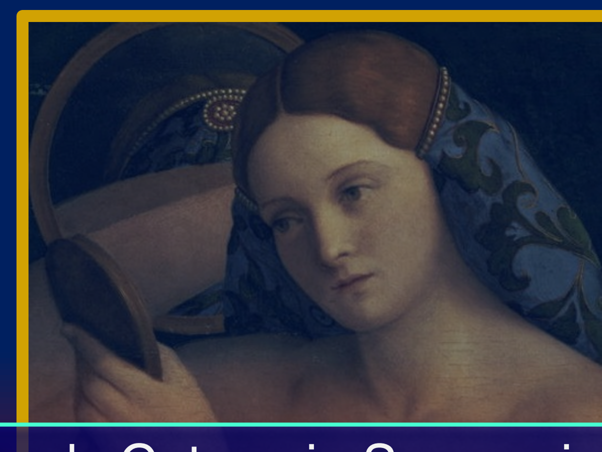
visible-light picture



x-ray image

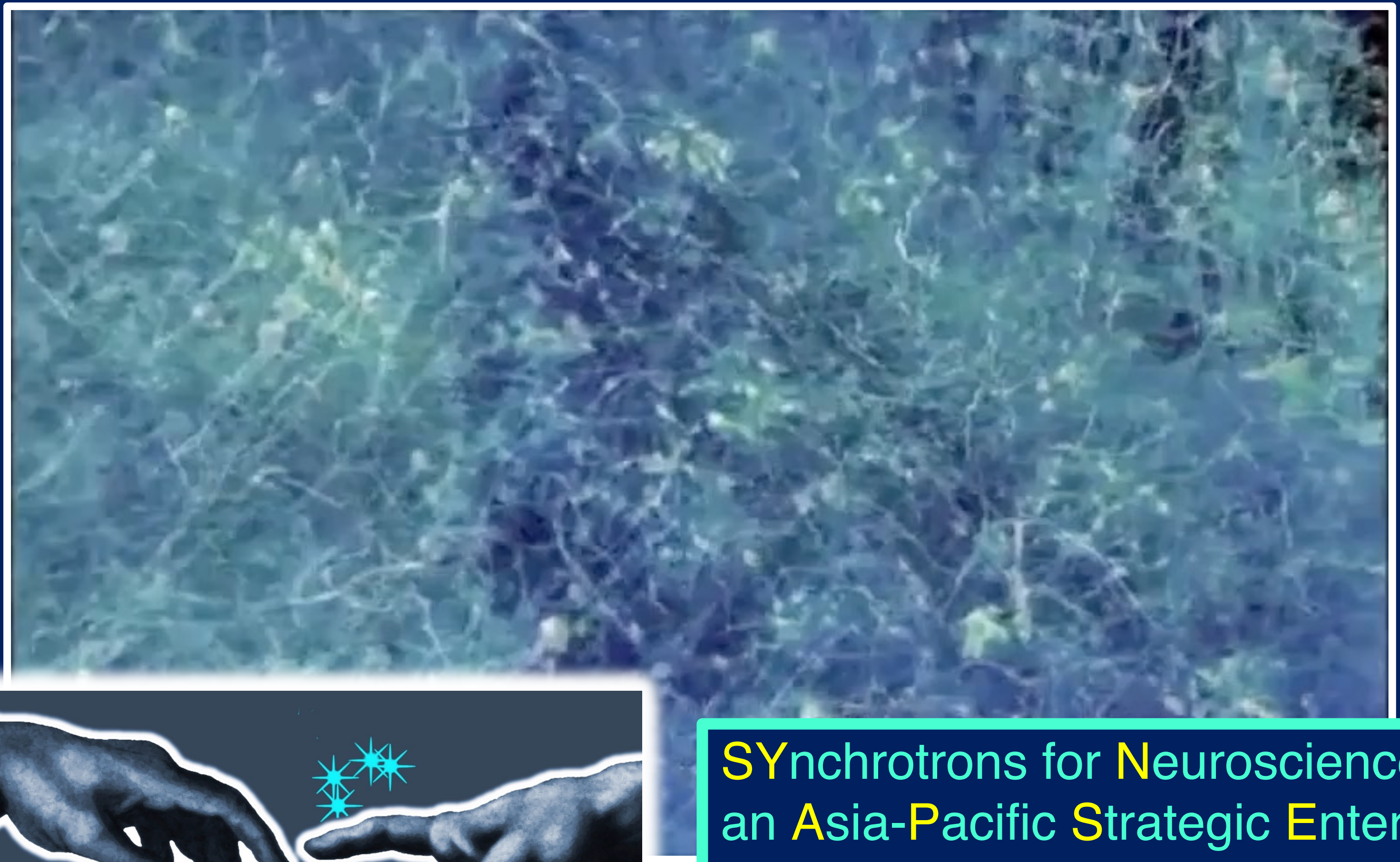
...even under seal:





so, Lady Cataruçia Savonario of Venice could speak to us after seven centuries [results of Fauzia Albertin]

Imaging with coherent x-rays: exploring the brain, neuron by neuron



SYnchrotrons for Neuroscience – an Asia-Pacific Strategic Enterprise

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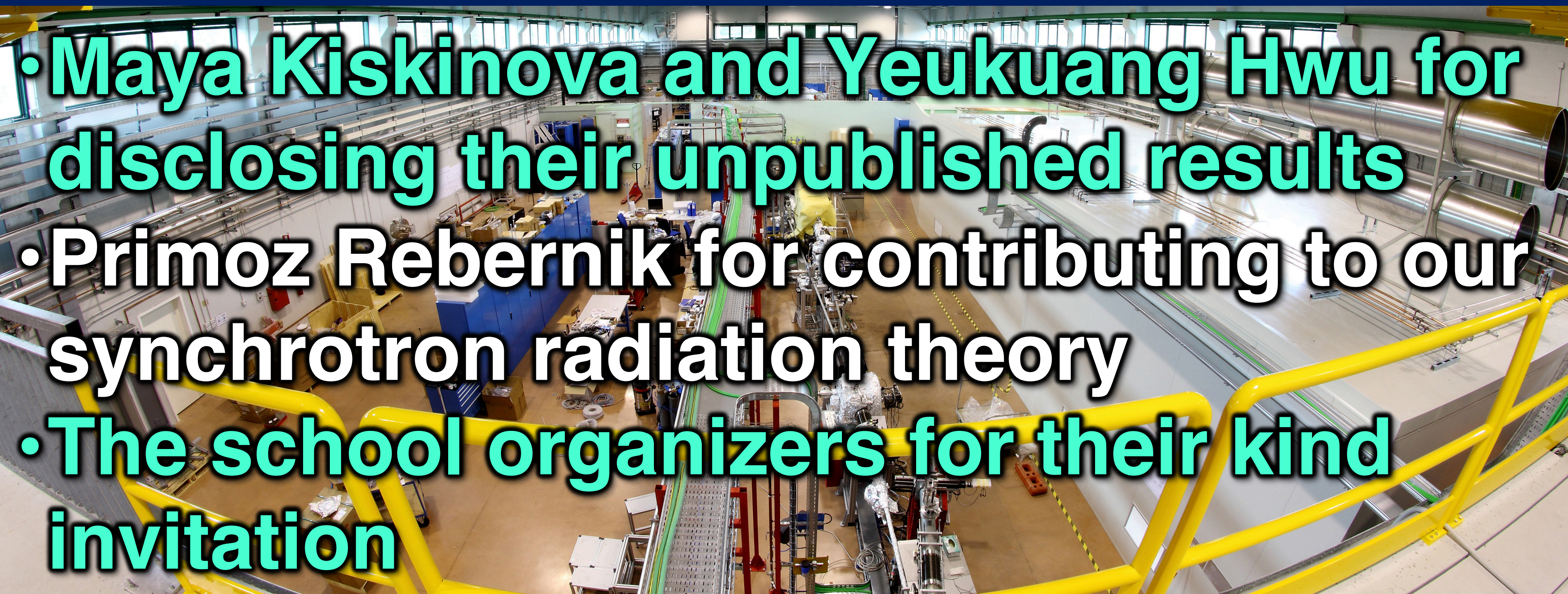
At the end of our journey, I would like to thank:



- Maya Kiskinova and Yeukuang Hwu for disclosing their unpublished results
- Primoz Rebernik for contributing to our synchrotron radiation theory
- The school organizers for their kind invitation

...and thank you, young folks, for attending my lectures: your future looks brighter than ever!

For further reading:

Y. Hwu and G. Margaritondo: "*Synchrotron Radiation and X-ray Free Electron Lasers (X-FELs) Explained to all Users, Active and Potential*", J. Synchrotron Radiation **28**, 1014 (2021)