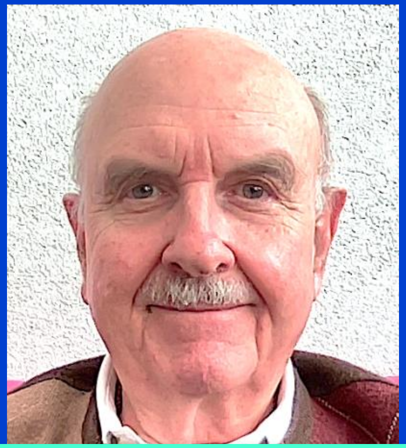
The Abdus Salam
ICTP International Centre for Theoretical Physics

School on Synchrotron Light Sources and their Applications

(1) Fundamentals of Synchrotron Radiation from Storage Rings
(2) Fundamentals of X-ray Interaction with Matter
(3) Bonus: X-ray Free Electron Lasers



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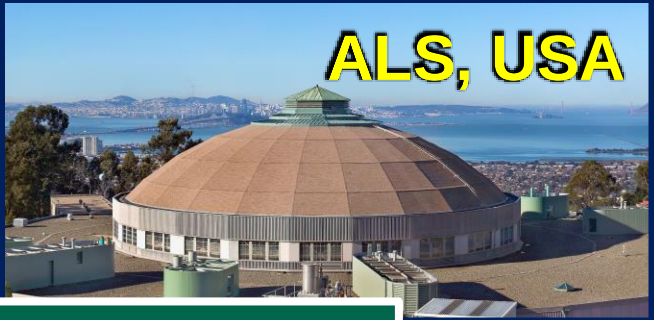
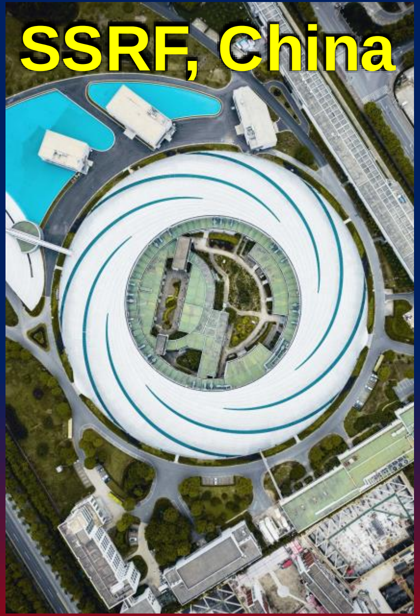
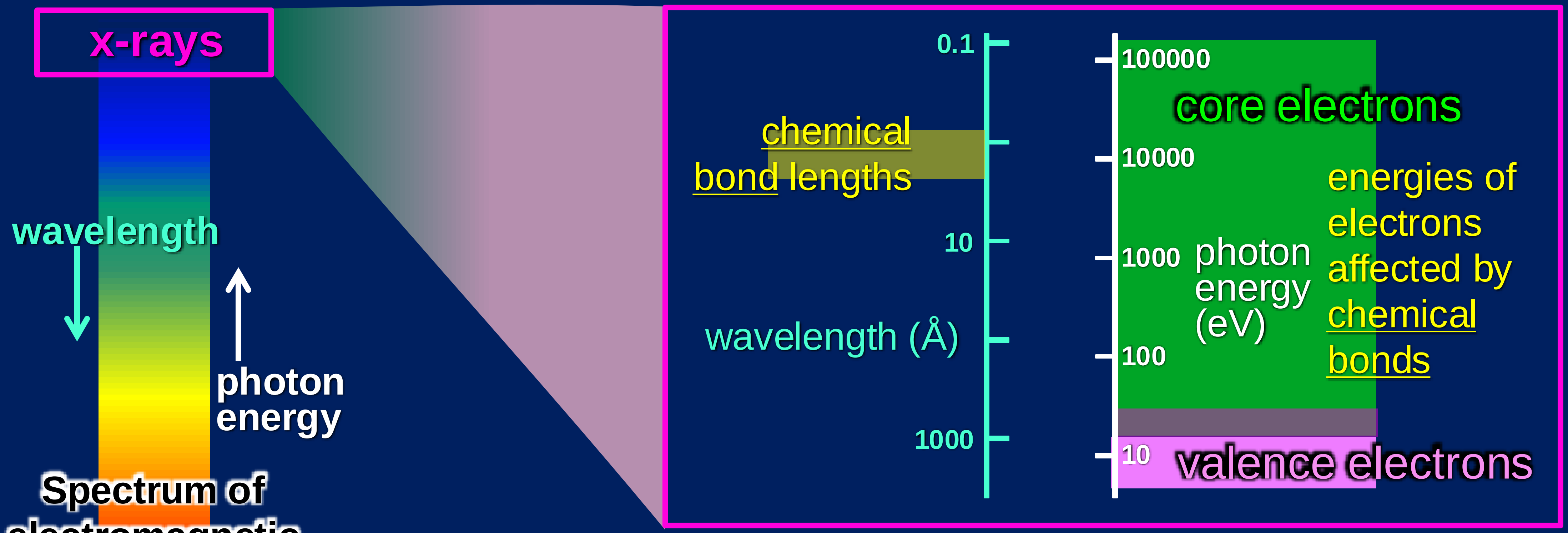
Synchrotron radiation: the biggest research network in the world!



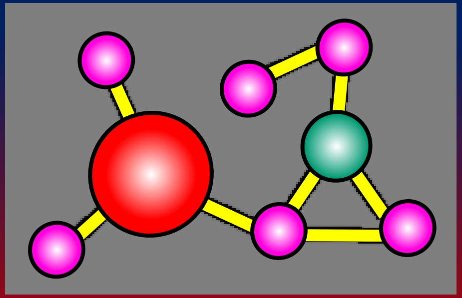


Tens of thousands of researchers
Over 60 active centers, more underway
Research articles: over 225,000
Expenditures of over 100 billion dollars
A production factory of Nobel prizes:
Agre, Baker, Boyer, Kornberg,
Mackinnon, Ramakrishnan, Steitz,
Yonath, Walker…

Synchrotrons notably emit x-rays, very important because of what their wavelengths and photon energies can investigate

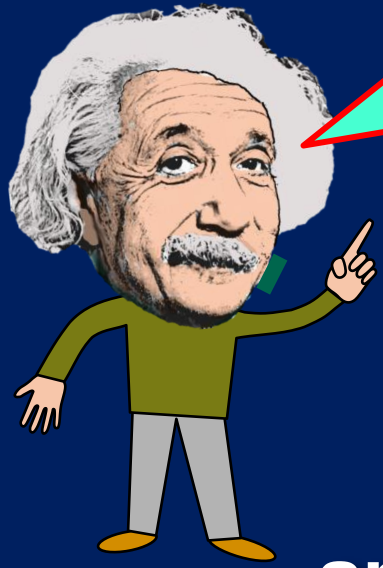


…x-rays are the best probes of chemical bonds, foundation of most of science and technology: we need excellent x-ray sources!



How can we get excellent x-ray sources? Using six tools from relativity

"gamma factor"

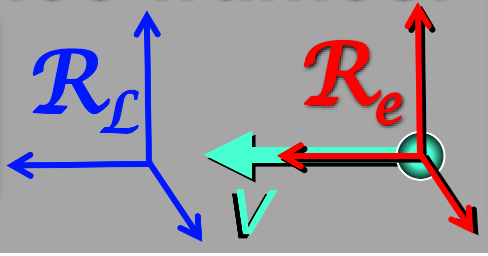


$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

NOTE:
$\gamma = m_L c^2/(m_e c^2)$
= energy/rest energy

Two reference frames:

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

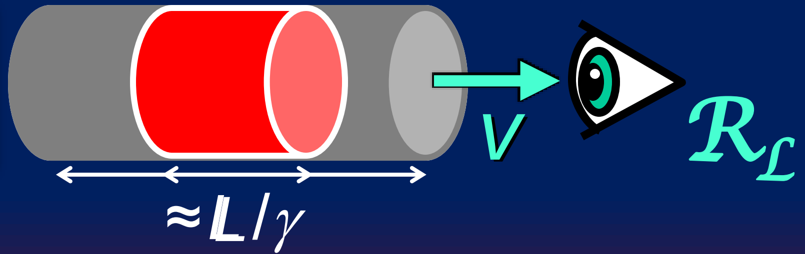


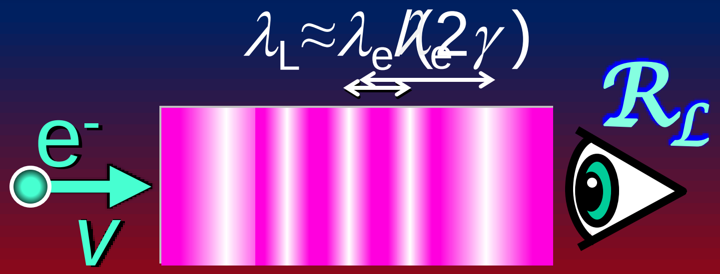
"Electron" frame $\mathcal{R}_e$, speed = v

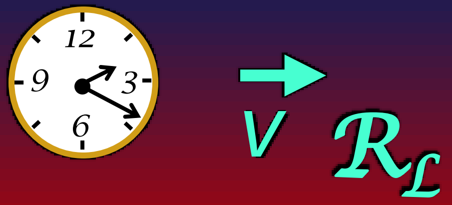
…and three effects:

(1) Lorentz contraction: measured by a motionless observer, the intrinsic length L of an object moving at speed v decreases to $\approx L/\gamma$

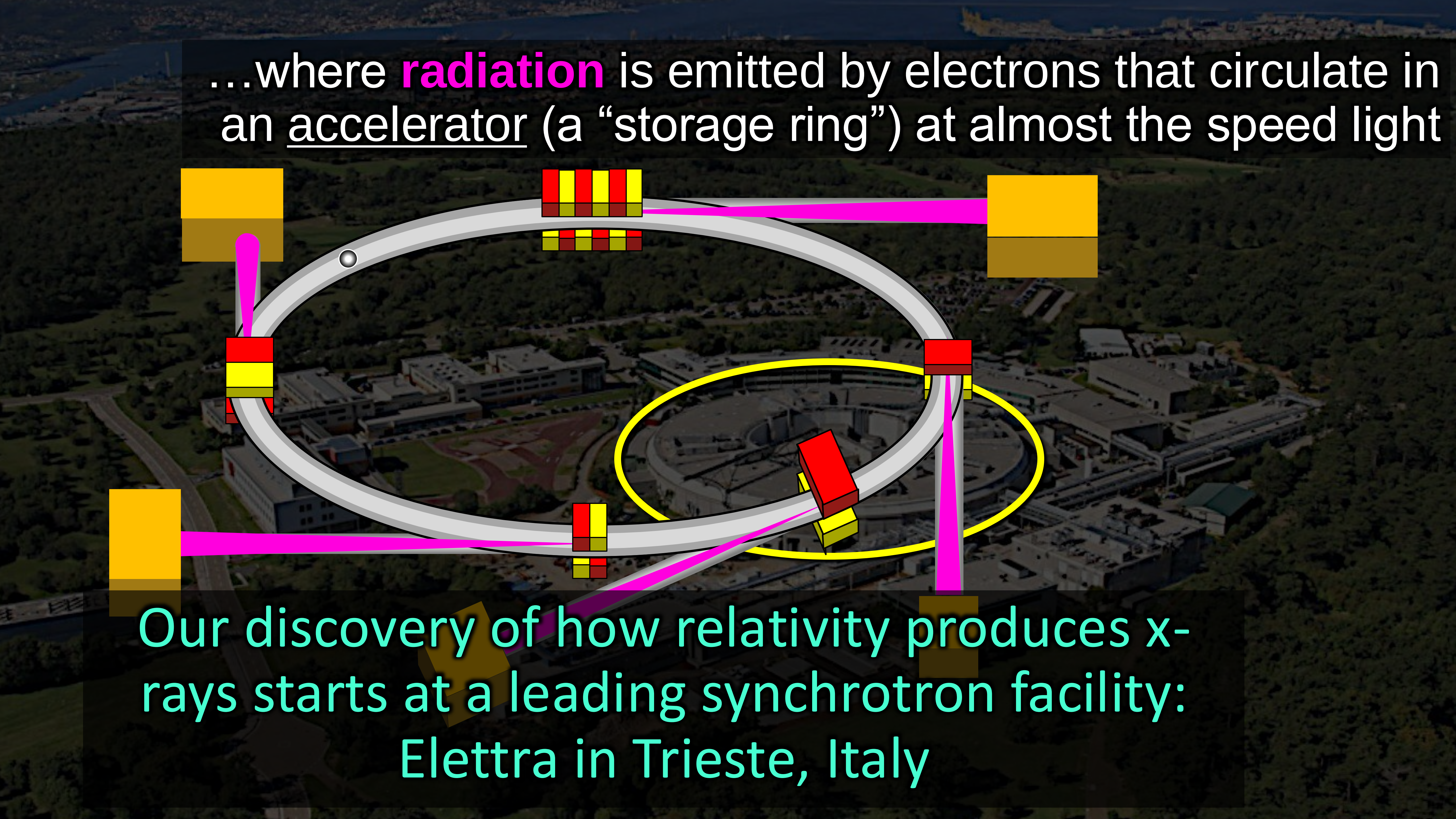
(2) Doppler effect: a wavelength λ_e emitted in $\mathcal{R}_e$ by a moving source shrinks to $\approx \lambda_e/(2\gamma)$ when measured in $\mathcal{R}_\mathcal{L}$





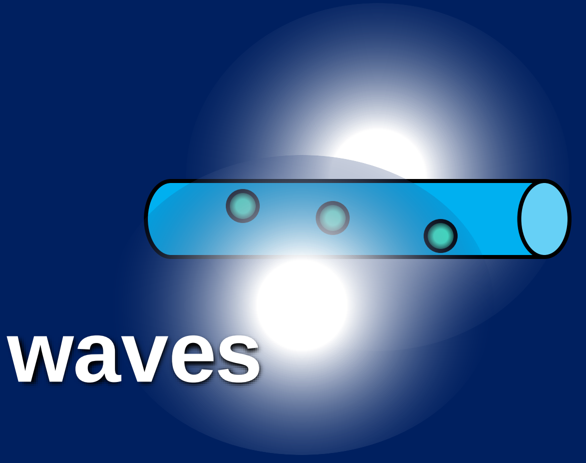


(3) Time dilation: an interval Δt_e in $\mathcal{R}_e$ becomes $\Delta t_L = \gamma \Delta t_e$ in $\mathcal{R}_\mathcal{L}$


…where **radiation** is emitted by electrons that circulate in an accelerator (a "storage ring") at almost the speed light
Our discovery of how relativity produces x-rays starts at a leading synchrotron facility:
Elettra in Trieste, Italy

Before seeing how, A REASONABLE QUESTION: why do we use big, costly accelerators instead of getting x-rays, as radio waves, from electrons oscillating in an antenna?

…indeed, oscillating electrons are accelerated electric charges, thus they do emit electromagnetic waves

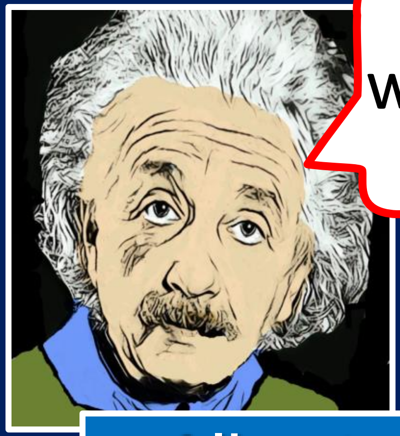


…and the electron mass is small: this enhances the acceleration and the emission

however, antennas are good for producing long-wavelength radio waves, but not short-wavelength x-rays!

Why not? Because the electronic devices inducing the oscillations cannot reach the required high frequencies (say, 10^{18} hertz)

To get x-rays, we use another strategy, combining oscillating electrons with two relativistic effects that shorten the wavelengths!

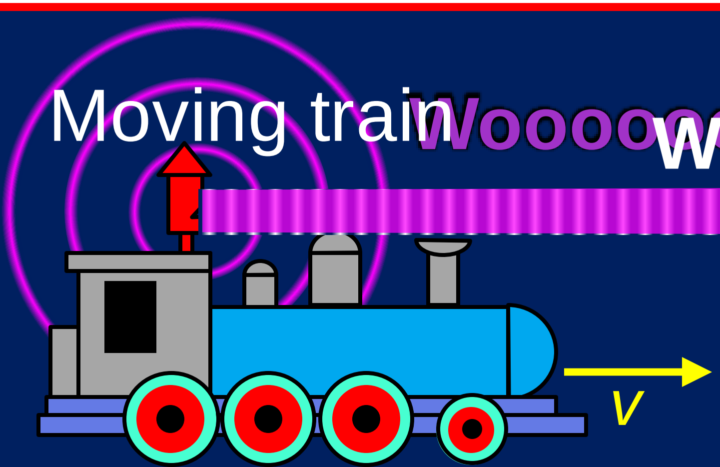


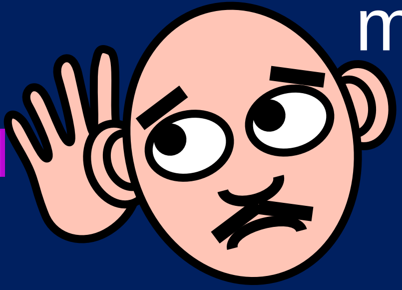
Albert Einstein

Yes indeed folks: my relativity can shorten wavelengths and produce x-rays… somewhat, but not entirely, like train sound

"Doppler effect":

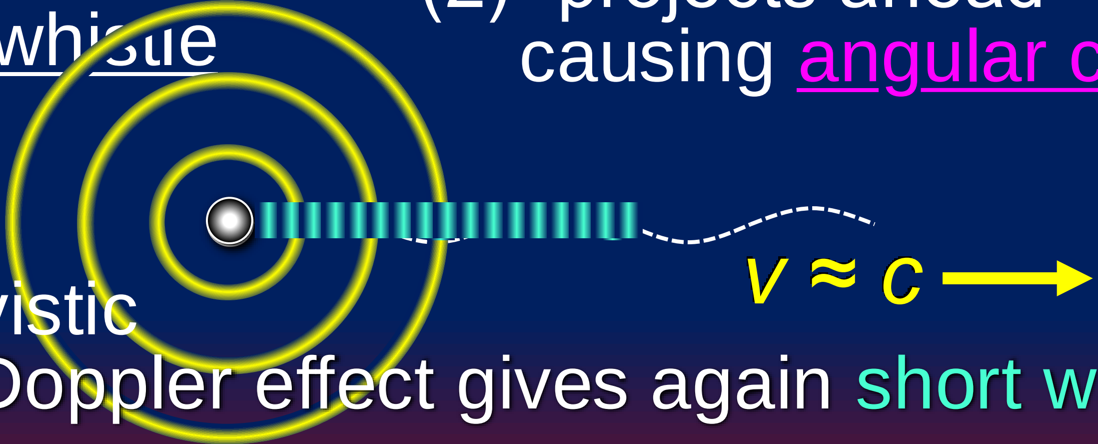
the source (train) motion: (1) shifts the detected sound to high frequencies (<u>short wavelengths</u>), and (2) "projects ahead" the sound causing <u>angular collimation</u>

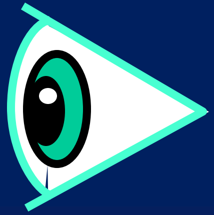




Stationary train: <u>low-frequency whistle</u>

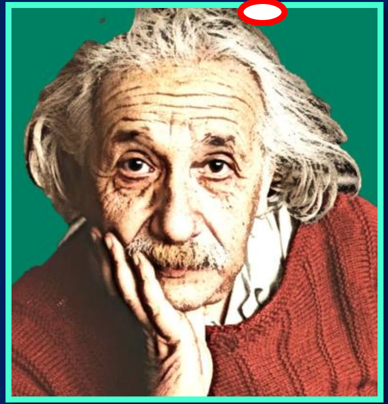
Consider now an electron that emits radiation of wavelength λ_e because of its transverse oscillations… then add a relativistic longitudinal speed $v \approx c$: the Doppler effect gives again short wavelengths and collimation



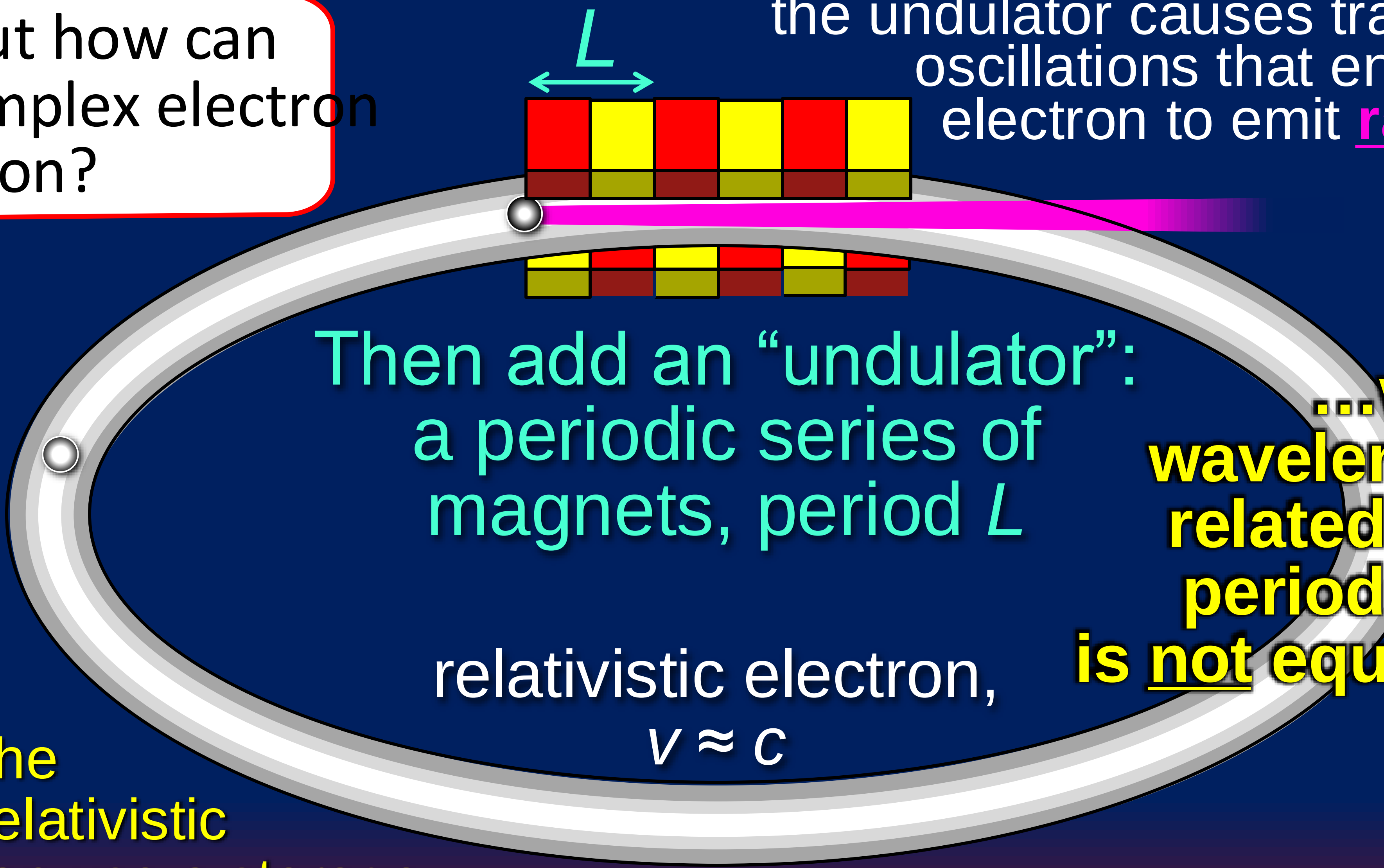


…and we shall see that relativity <u>boosts the emission</u> and further shortens the wavelength with a second effect, <u>length contraction</u>

…great! But how can we get that complex electron motion?



the undulator causes transverse oscillations that enable the electron to emit **radiation**



Then add an "undulator": a periodic series of magnets, period L

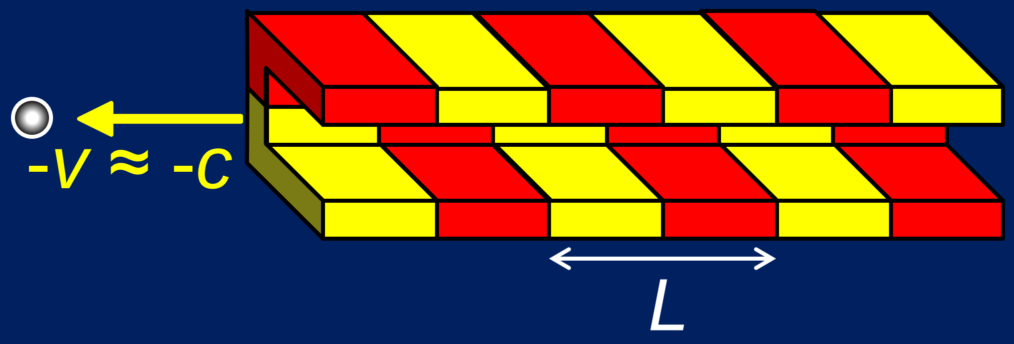
…whose wavelength is related to the period L, but is not equal to L

relativistic electron, $v \approx c$

A good solution: for the longitudinal relativistic motion, we can use a storage ring, with a system (not shown) of magnets and electric devices that forces electrons to circulate in vacuum at almost the speed of light

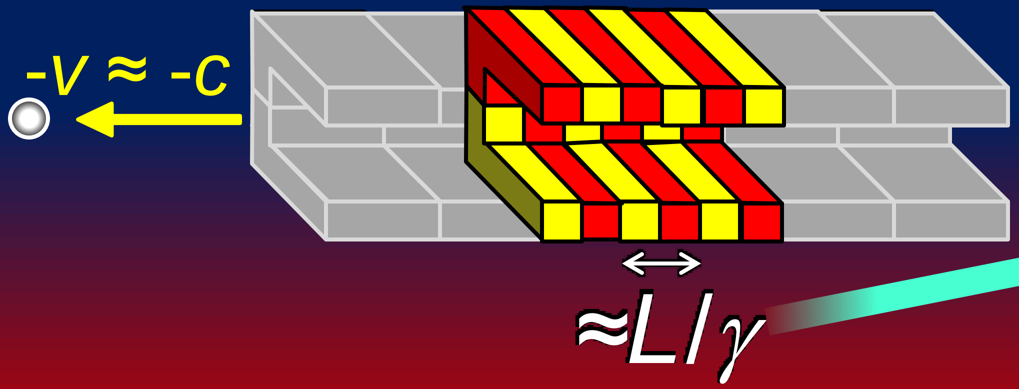
Why not? To understand, you must <u>think</u> like an electron!

From its own point of view, the electron "sees" the undulator arriving with velocity $-v \approx -c$



…so, the electron "sees" the undulator period L shrunk to $\approx L/\gamma$

…and in relativity a moving object is subject to the famous "**<u>Lorentz contraction</u>**": as we have seen, its length appears shortened by $\approx\gamma$



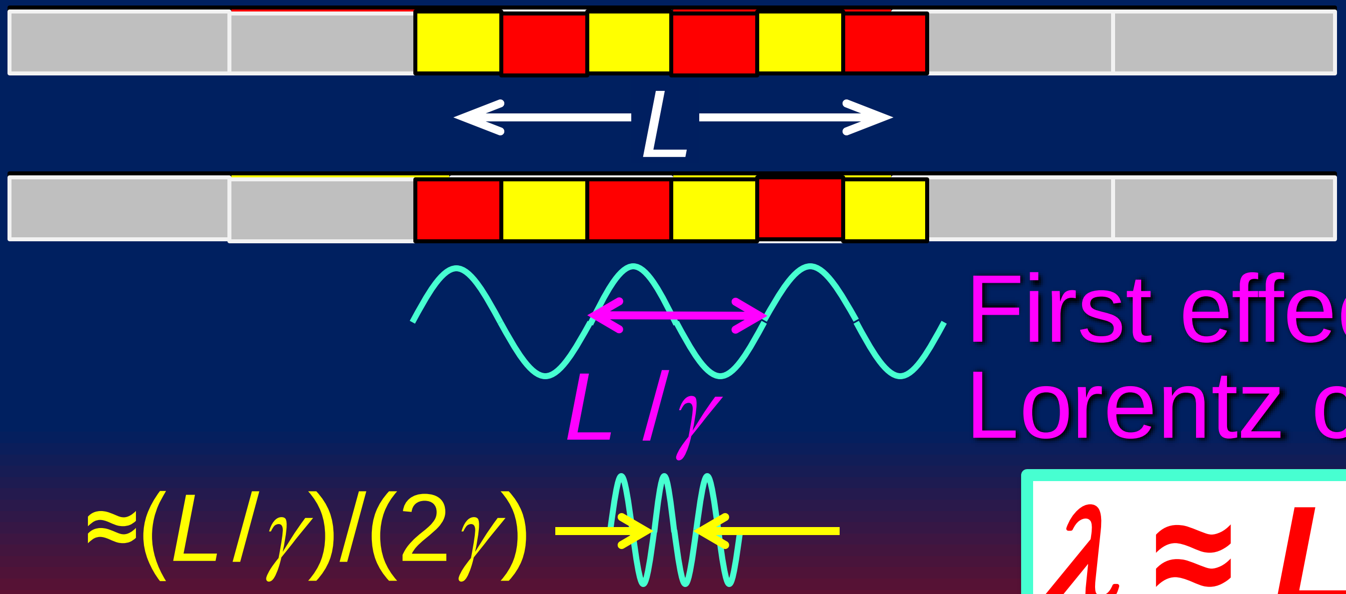
this equals the emitted wavelength as "seen" by the electron, $\lambda_e = L/\gamma$

…but λ_e is not the wavelength seen in the laboratory!

Why not? We already know the answer: the electron motion also causes the Doppler shift, further reducing the wavelength by $\approx 2\gamma$

So, short wavelengths are produced by two combined relativistic effects:

NOTE: in relativity, γ = energy/($m_o c^2$): high energy $\rightarrow$ large $2\gamma^2 \rightarrow$ short λ



First effect: Lorentz contraction

Second: Doppler shift

$$\boxed{\lambda \approx L/(2\gamma^2)}$$

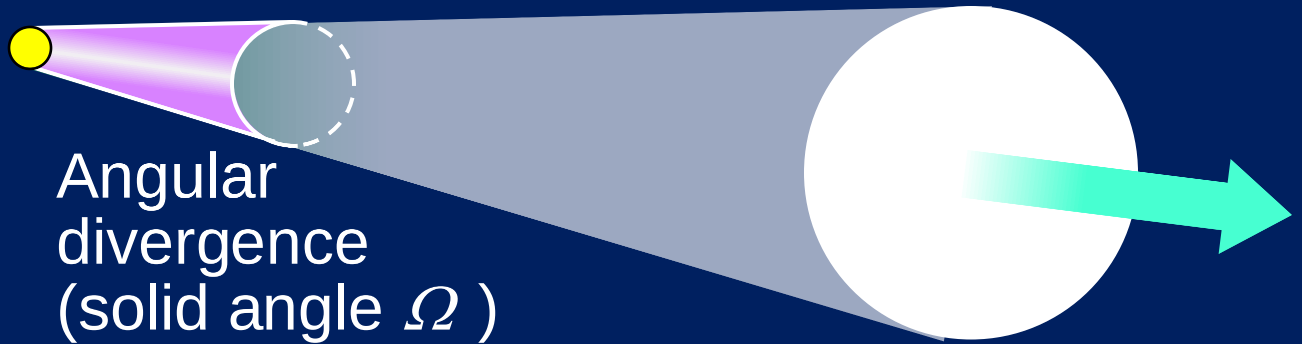
Example:
L = 1 cm,
γ = 5000
$\lambda \approx 2\times10^{-10}$ m
x-rays!!!

OK, relativity gives x-rays… but are we reaching our real goal, not generic x-ray sources but very good ones?

First, what is a "good source"?

To quantify this notion, consider the source parameters:

a flashlight is "good" if its flux is large but also because its emission is spatially concentrated



…and define the

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

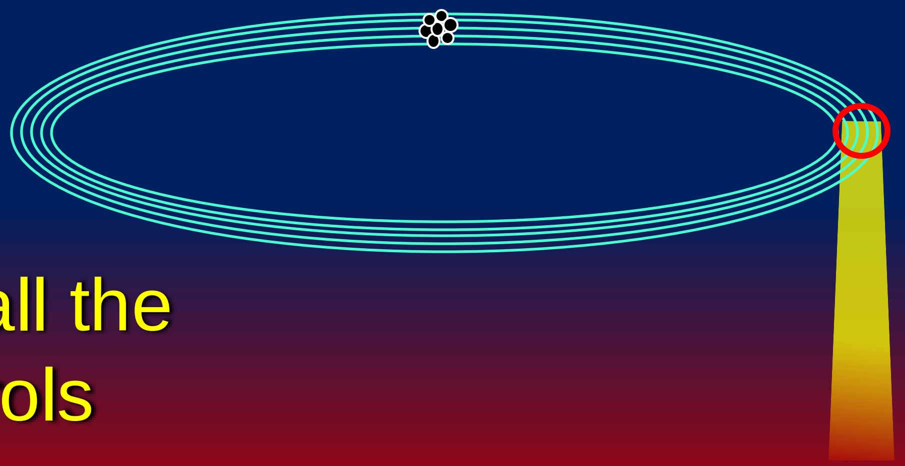
A source is "good" if it has high brightness: large flux, small area, small divergence

Do synchrotron sources reach high brightness?

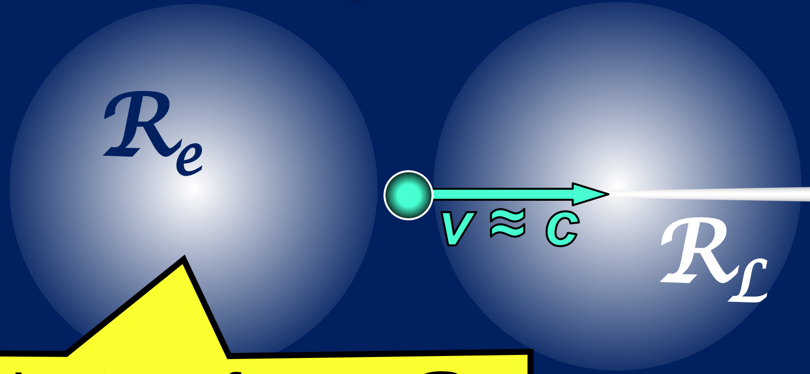
YES INDEED: over one million billion times more than conventional x-ray sources!

How? Thanks to four factors:

1. We shall see that relativity sharply reduces the angular divergence
2. And that relativity also boosts the emitted power
3. Electrons in a storage ring under vacuum can handle more emitted power than those in a solid, since the solid can be damaged
4. The electrons travel in the ring in bunches (we shall see why), along slightly different paths; the source size is the transverse cross section of the bunch, determined by all the paths and kept small by very effective controls



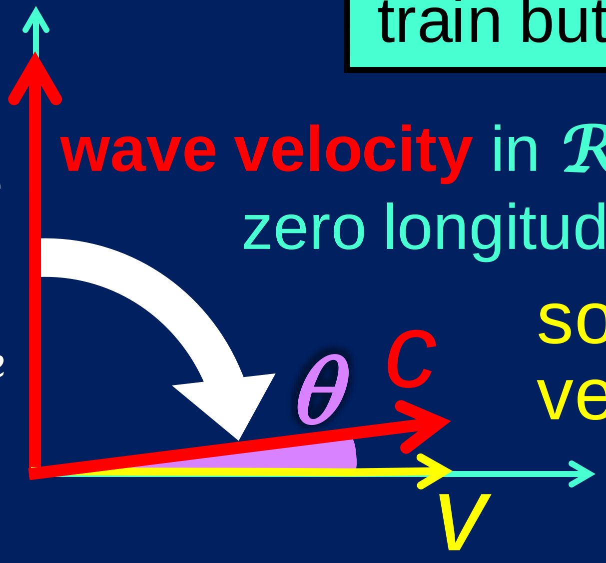
Relativity at work: extreme angular collimation



…but in $\mathcal{R}_\mathcal{L}$ it shrinks to a small forward cone, as the sound of a moving train but much narrower

…in the electron frame $\mathcal{R}_e$, the angular range of the emission is broad, like radio waves from an antenna

Why? Take the extreme case of an **x-ray wave** emitted in a transverse direction in $\mathcal{R}_e$



wave velocity in $\mathcal{R}_e$: magnitude c, zero longitudinal component

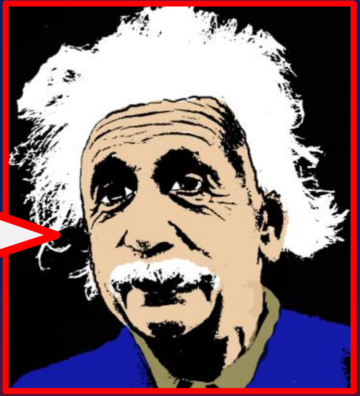
so, from $\mathcal{R}_e$ to $\mathcal{R}_\mathcal{L}$ the velocity vector rotates

In $\mathcal{R}_\mathcal{L}$, the electron motion with relativistic speed v "projects ahead" the emission: the forward wave velocity is $\approx v$ and, since θ is small:

$$\theta \approx \sin\theta = \sqrt{c^2 - v^2}/c = \sqrt{1 - v^2/c^2}$$

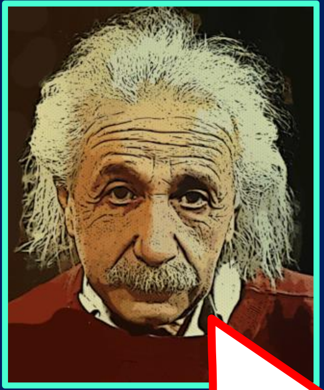
$$\boxed{\theta \approx 1/\gamma}$$

Relativity requires the magnitude c to be invariant



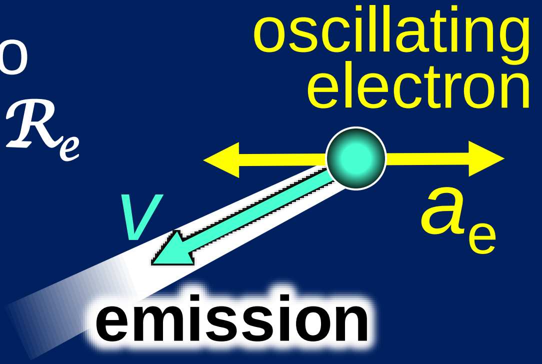
Very small angular spread $\approx 1/\gamma$: milliradians!!!

Relativity at work again: huge emitted power



"Larmor law": the emitted power is proportional to a_e^2, the square of the transverse acceleration in $\mathcal{R}_e$

If v = zero, $a_e = a_L$, the transverse acceleration in $\mathcal{R}_{\mathcal{L}}$ – and the power is proportional to a_L^2



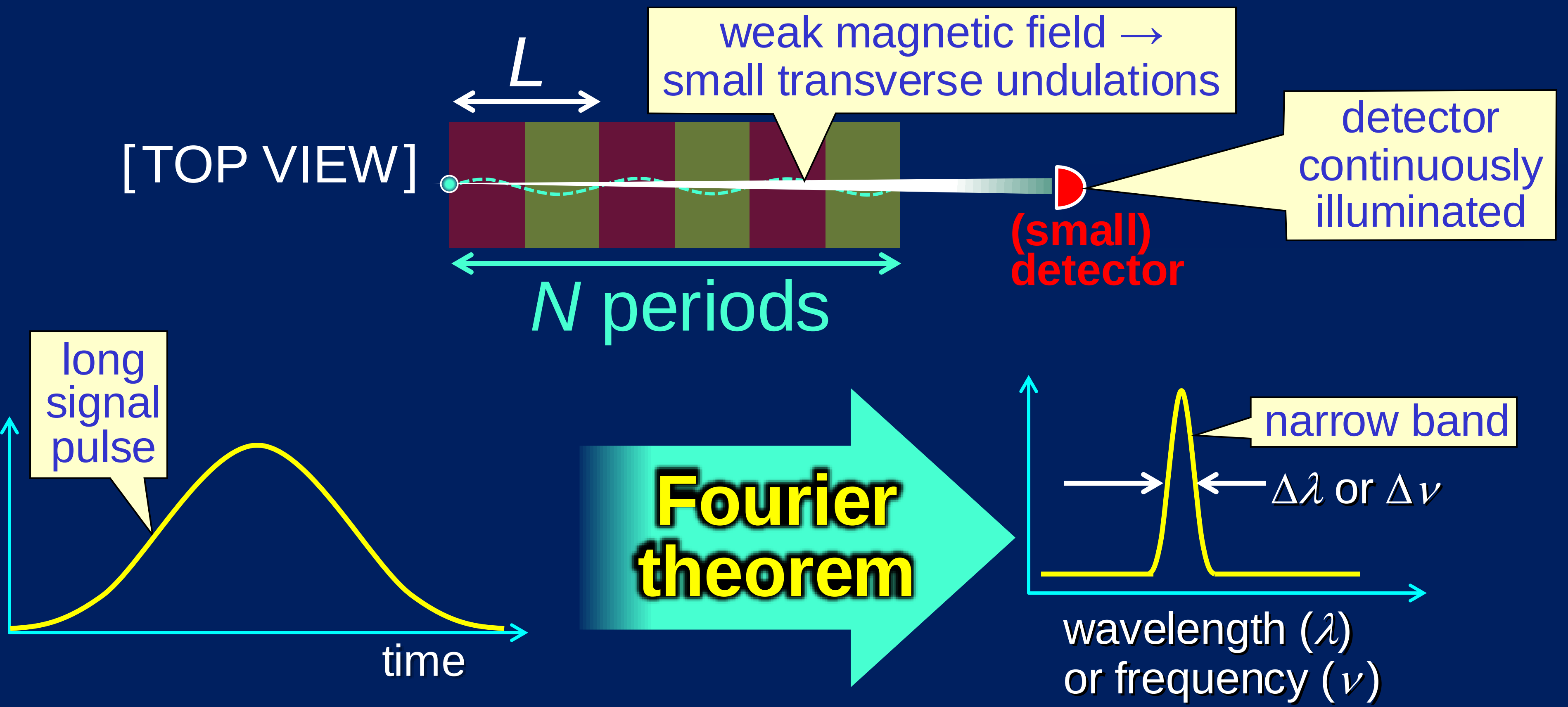
but, if $v \neq$ zero: going from $\mathcal{R}_e$ to $\mathcal{R}_{\mathcal{L}}$ the time is multiplied by γ while the transverse coordinate is invariant; the acceleration = coordinate/time^2 is divided by γ^2: $a_L = a_e/\gamma^2$, and $a_e = \gamma^2 a_L$

…the power is proportional to $a_e^2 = (\gamma^2 a_L)^2$, 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 decreases as $1/m_o^4$: electrons emit a lot, protons much less

Let us find more about relativistic electrons in an undulator: they behave as very collimated flashlights, causing their emitted wavelength spectrum

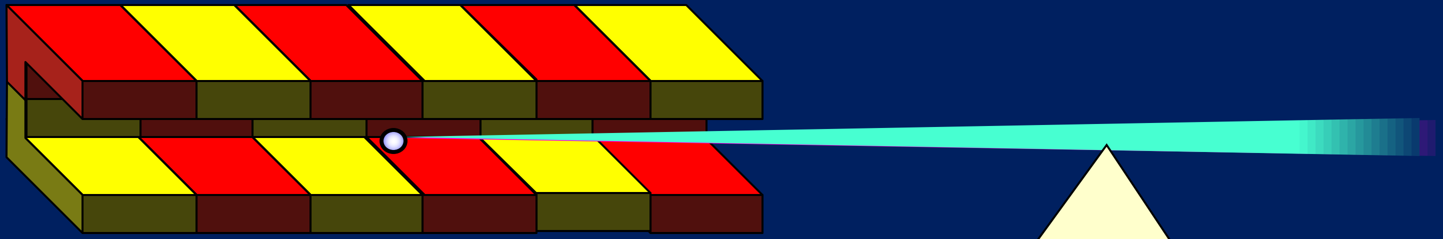


Bandwidth: going through the N undulator periods, the electron emits a wave with N wavelengths, of length $N\lambda_L$. Pulse duration: $\Delta t_L = N\lambda_L/c$. Fourier: $\Delta\nu_L = 1/\Delta t_L = c/(N\lambda_L)$. $\lambda_L = c/\nu_L$ so $\Delta\lambda_L/\lambda_L = |\Delta\nu_L/\nu_L| = [c/(N\lambda_L)]/(c/\lambda_L) = 1/N$

Other wonderful properties of undulators:

(1) They can emit different wavelengths; (2) their angular spread is very small; (3) they have very high brightness -- all such properties that can be explained with simple approaches, for example:

what happens if we increase the magnetic field strength *B* by changing the magnet gaps?



the wavelength changes: why?

A stronger magnetic field *B* increases the transverse electron oscillations and their transverse speed, proportional to *B*

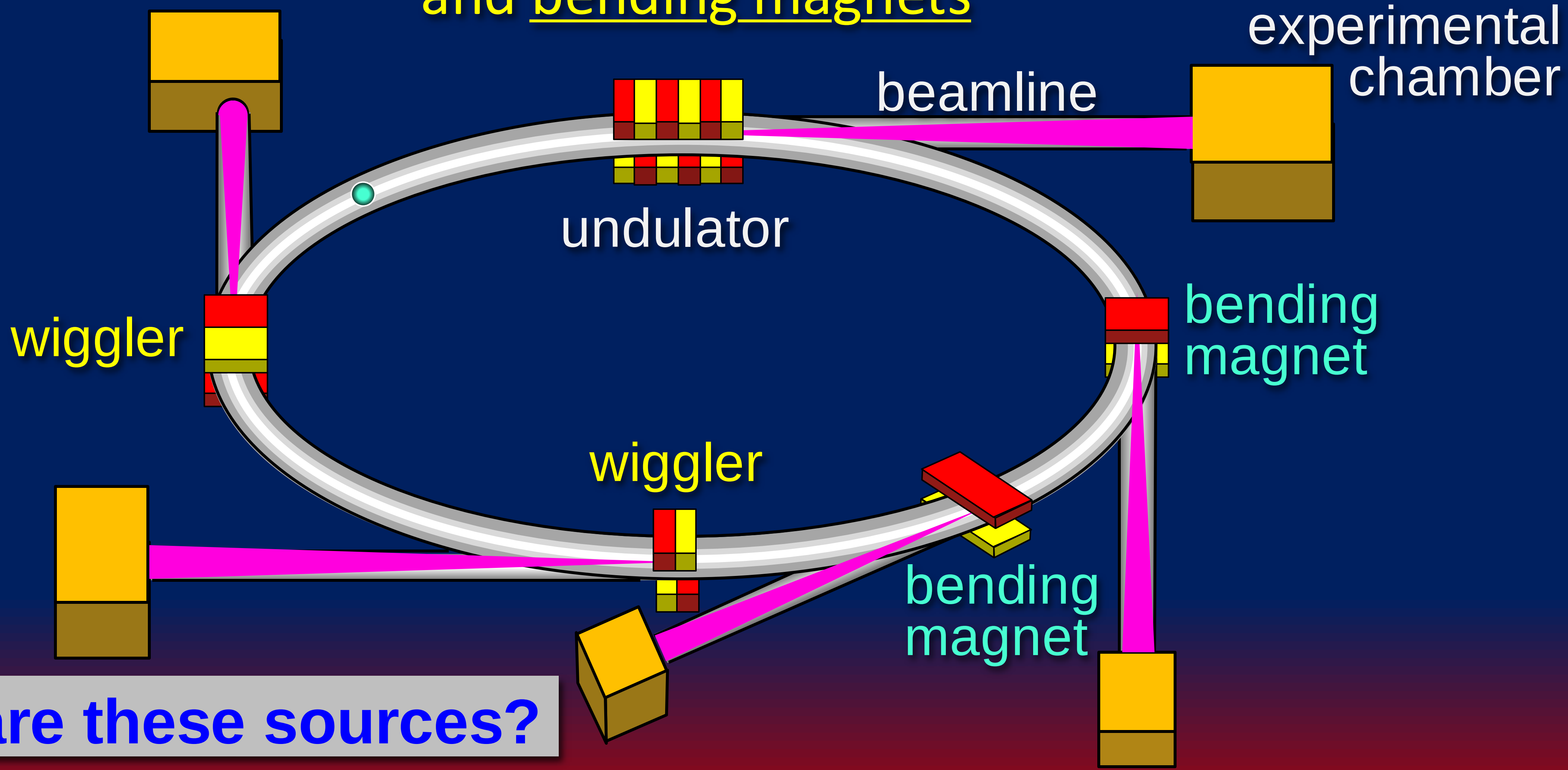
The magnetic (Lorentz) force of the undulator *B*-field on the electrons does not do work and cannot change the kinetic energy, so the longitudinal speed *v* decreases

This changes the γ-factor in the Doppler shift, modifying λ_L from $L/(2\gamma^2)$ to

$$\lambda_L = [L/(2\gamma^2)](1 + \text{constant} \times B^2)$$

We can <u>tune</u> the wavelength!

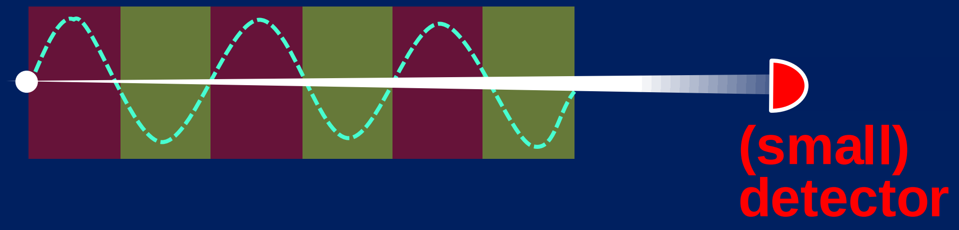
Around the storage ring of a synchrotron facility, there are other x-ray sources besides undulators: wigglers and bending magnets

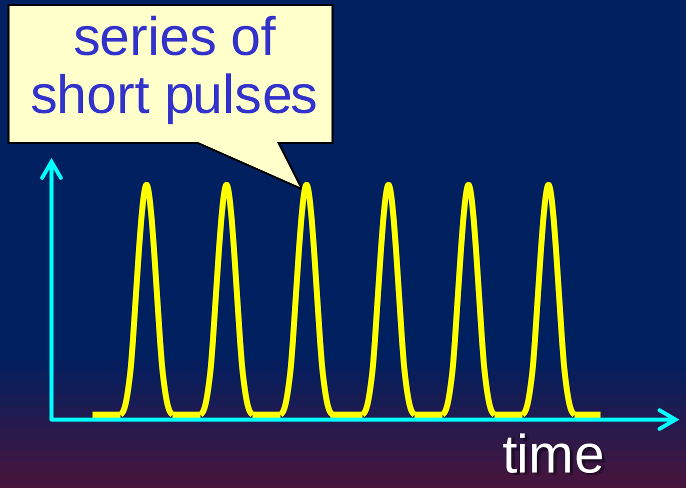


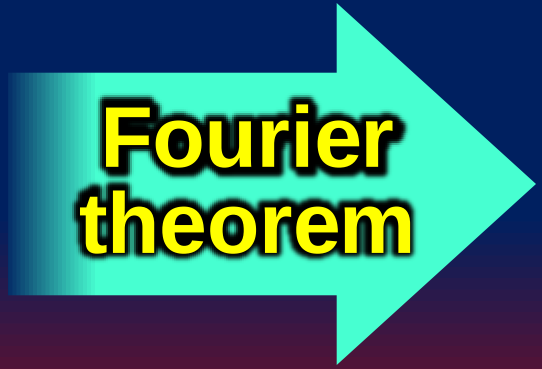
What are these sources?

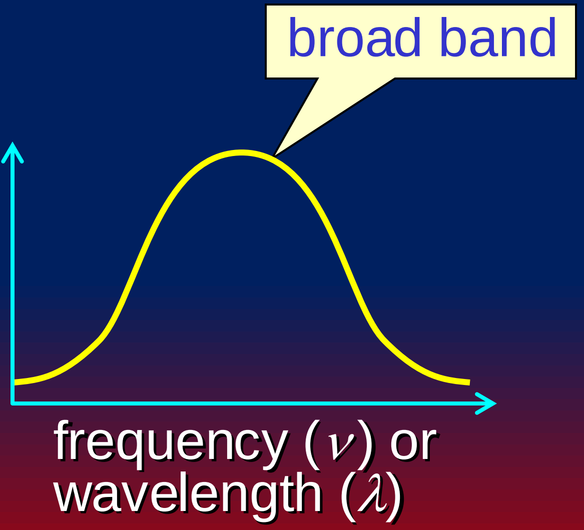
A wiggler, as an undulator, is a periodic magnet array -- but its magnetic field is stronger and causes larger transverse oscillations of the electrons:

[TOP VIEW]



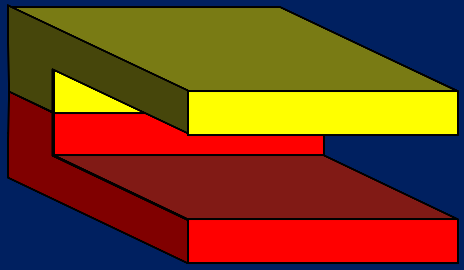


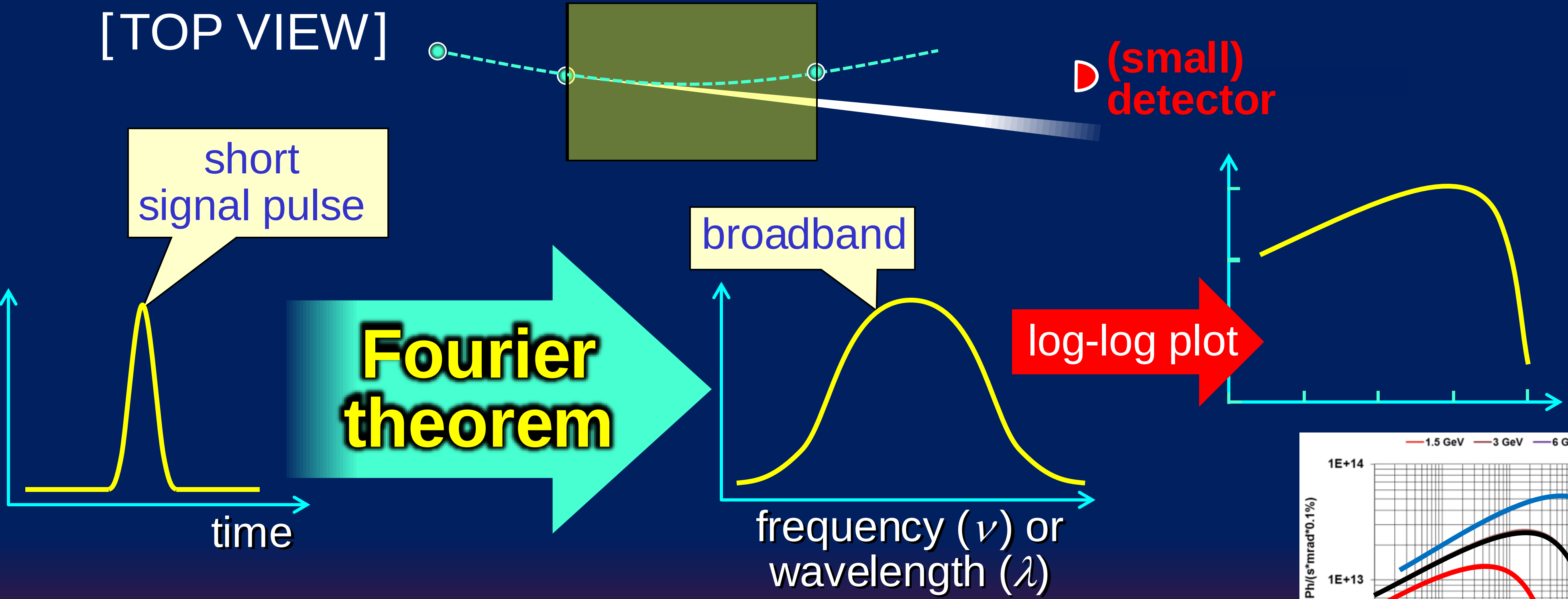


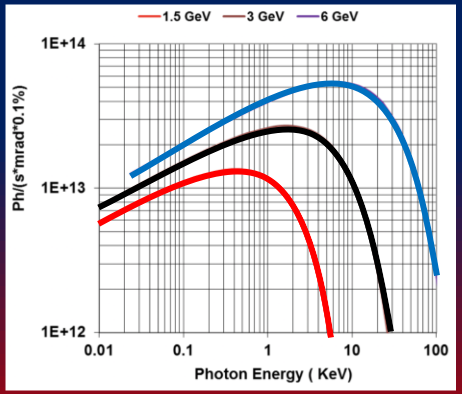


Multiple pulses → stronger emission

The third type of synchrotron sources: bending magnets, the dipoles that force the electrons to circulate in the storage ring



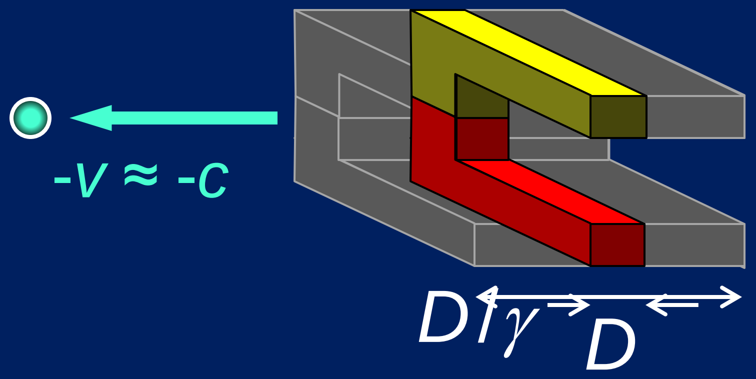




This explains the famous synchrotron radiation spectrum of bending magnets: the log-log plot of a peak!

Note -- bending magnets emit very short x-ray wavelengths: why?

…because of the same effects present for undulators (and wigglers): Lorentz contraction and Doppler shift



Intuitively, the emitted wavelengths are related to the longitudinal size *D* of the magnet …which in the electron frame $\mathcal{R}_e$ is Lorentz-contracted to $\approx D/\gamma$

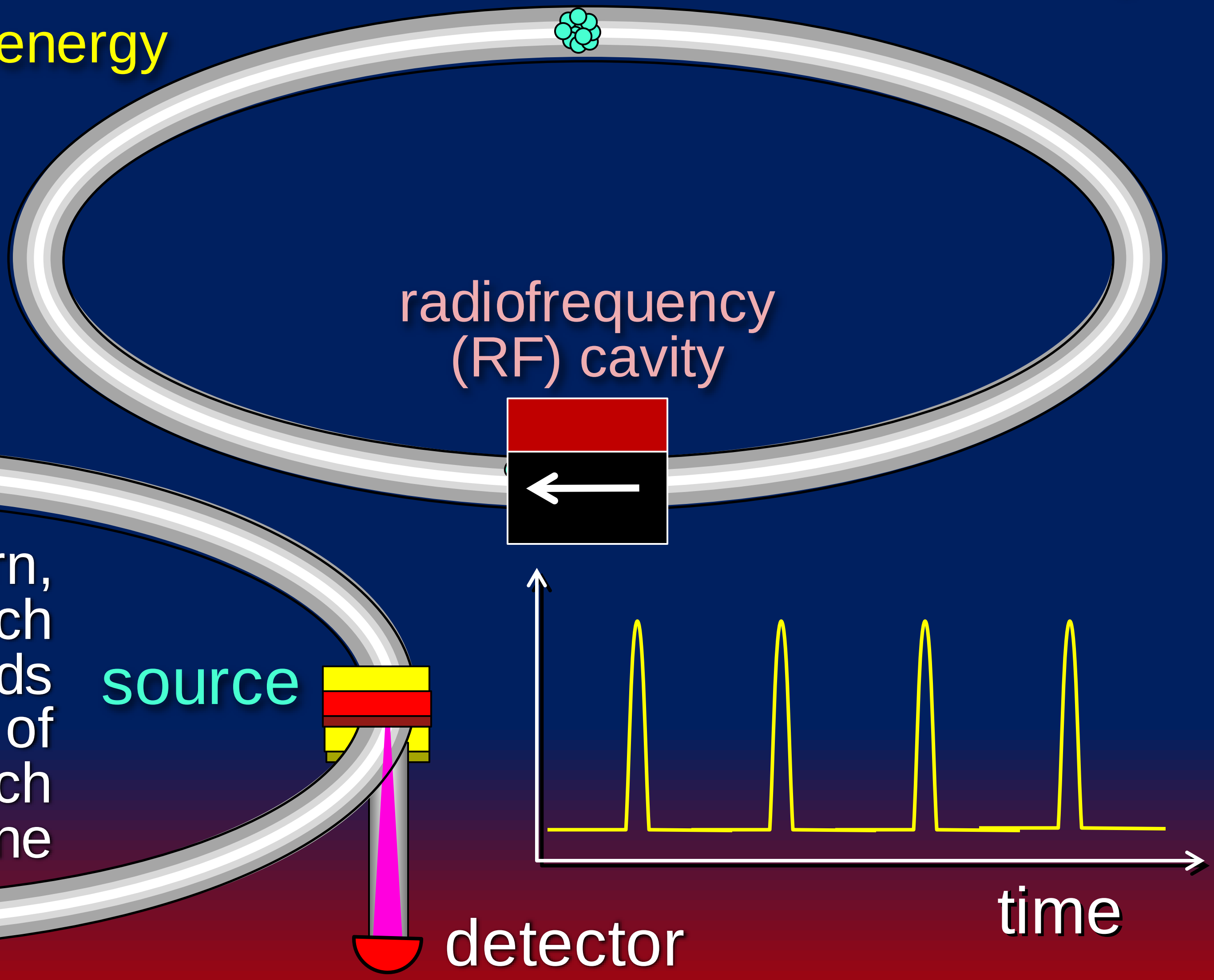
And in the laboratory frame $\mathcal{R}_\mathcal{L}$ the wavelengths are Doppler-shifted by a factor $\approx 2\gamma$, so they are related to $\approx (D/\gamma)/(2\gamma) = D/(2\gamma^2)$

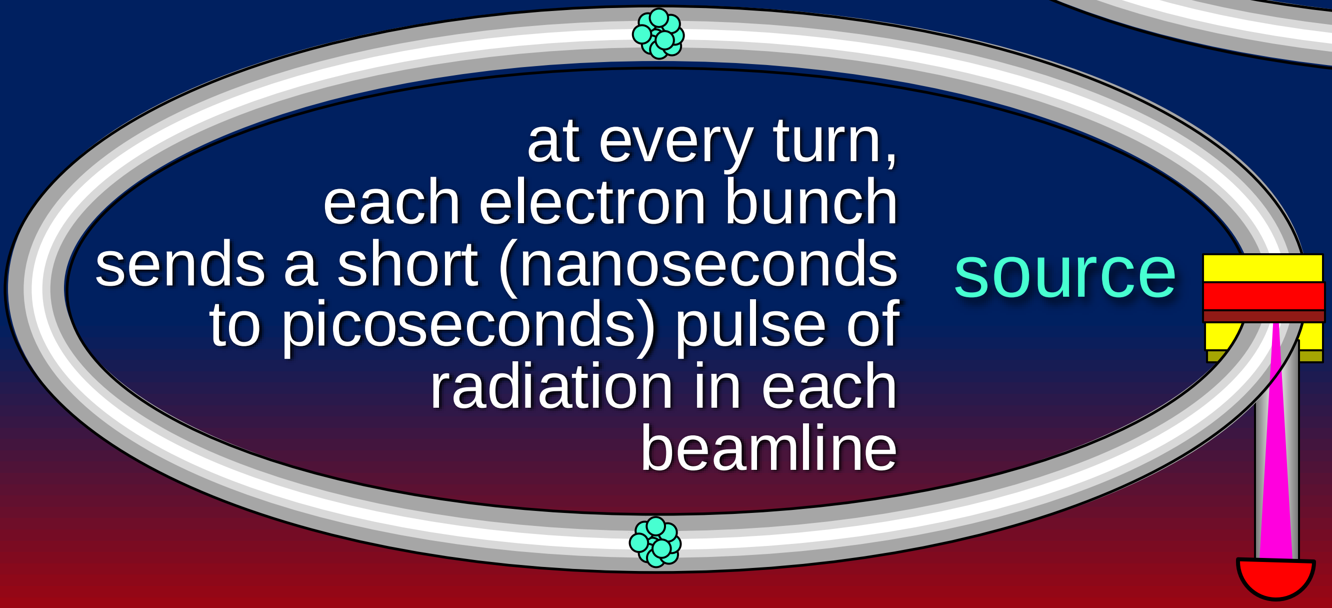
The $2\gamma^2$ factor again!

The time structure of synchrotron radiation

The cause: electrons travel around the ring <u>in bunches</u> -- why?

To keep the electrons in the ring, the energy they lose by emitting synchrotron radiation must be restored by the periodic force of an “RF cavity”: but this only works for <u>bunched</u> electrons passing through the cavity in synchrony with the force

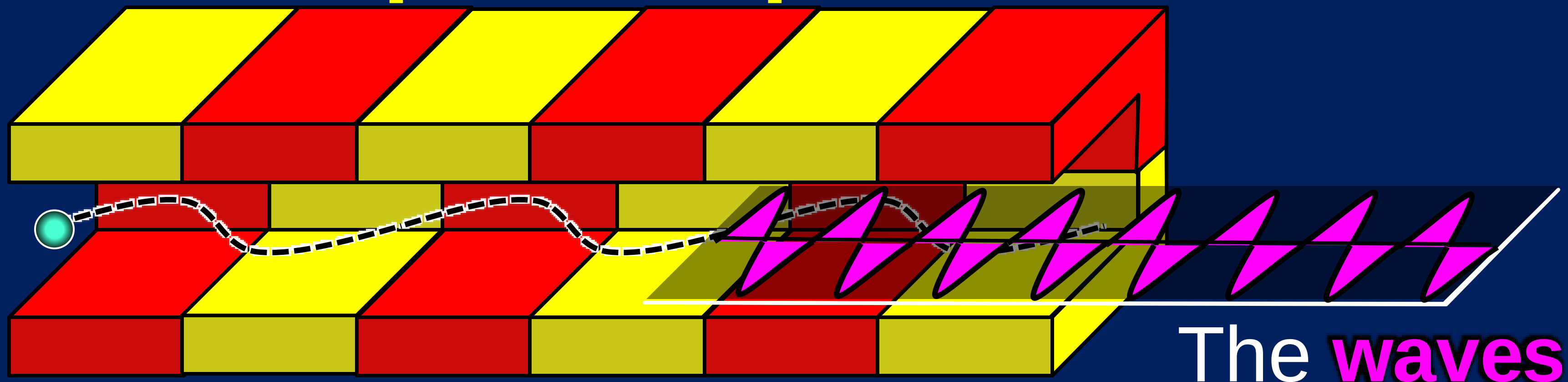




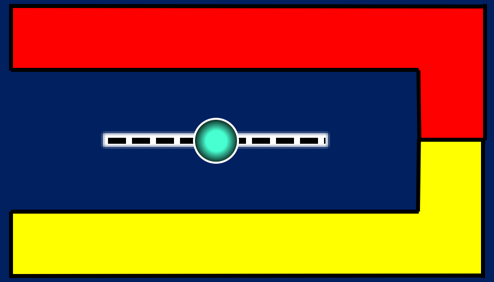
Another key synchrotron property: polarization

Consider an electron traveling through an undulator or a wiggler:

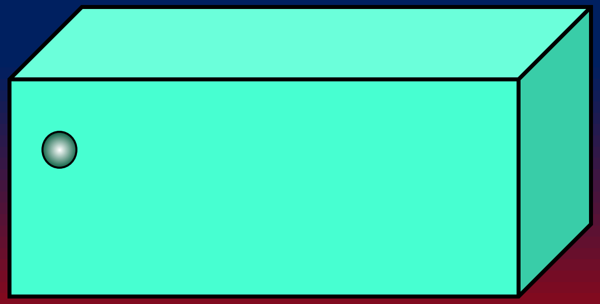
[SIDE VIEW]



[FRONT VIEW]



The **waves** emitted along the undulator axis correspond to electric field perturbations in the horizontal plane: they are linearly polarized



…likewise, on-axis waves from bending magnets are linearly polarized in the horizontal plane

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

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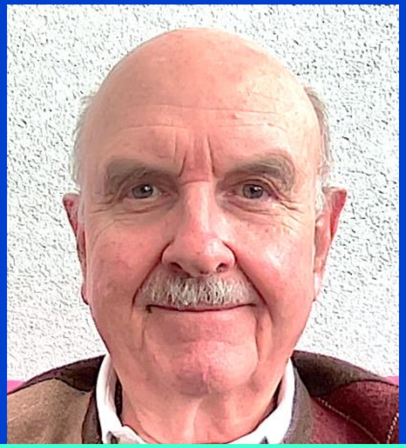

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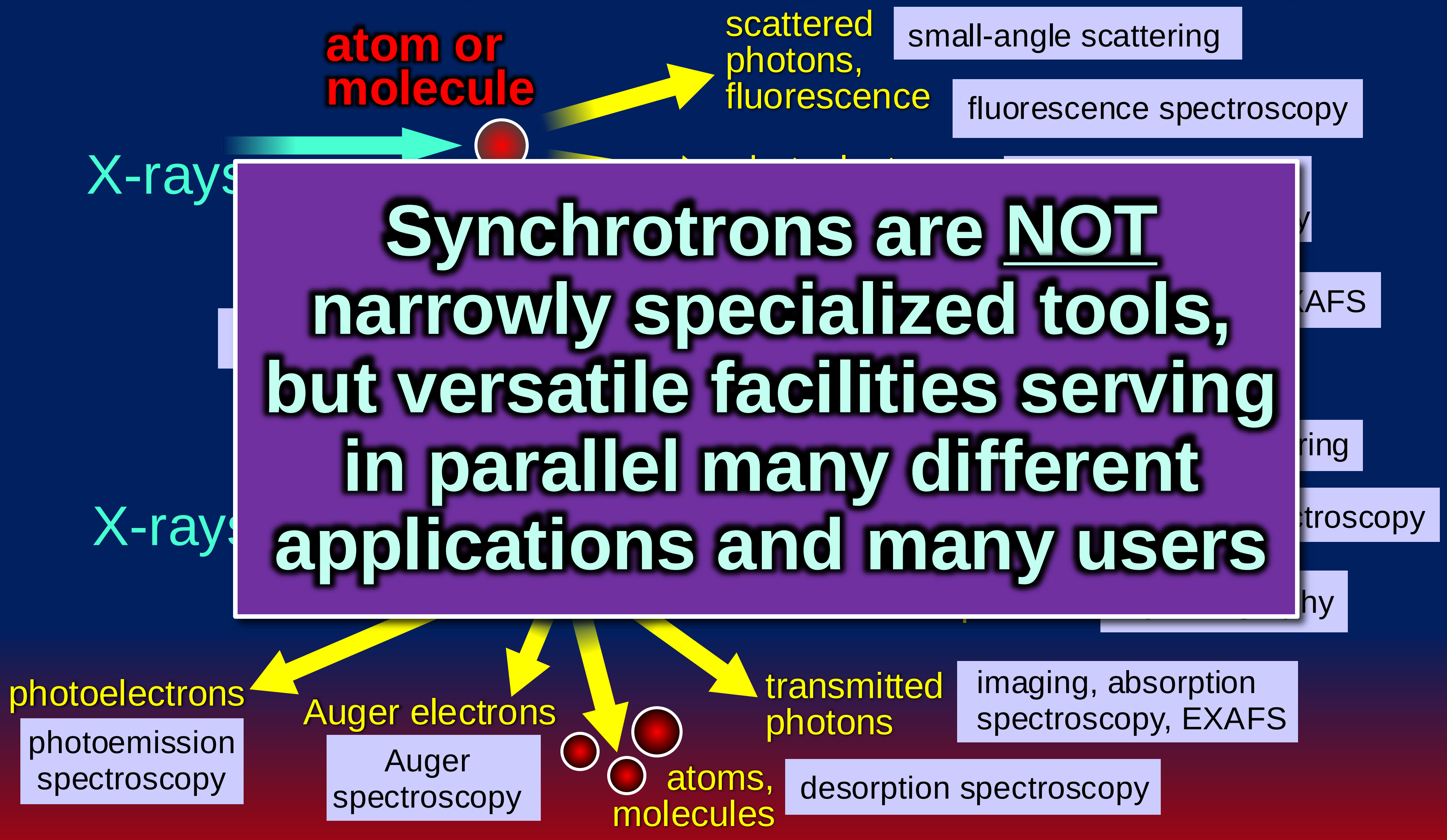
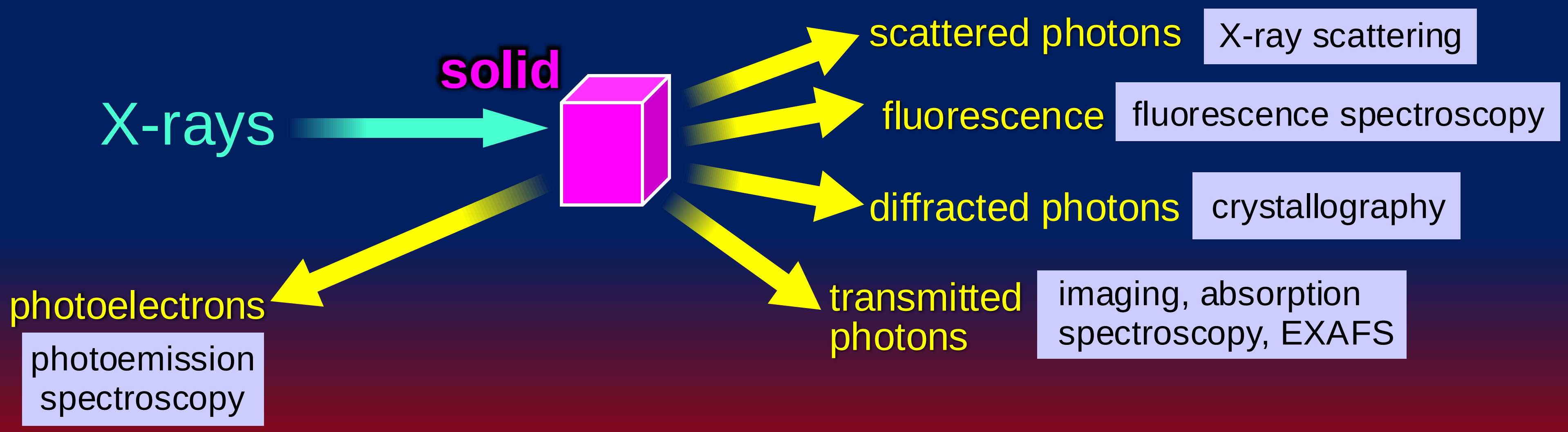
Using synchrotron radiation: different interactions of x-rays with matter lead to many different experimental techniques



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

…let us focus now on the interactions between x-rays and solids that are most important for synchrotron applications



First, the interactions used for <u>imaging</u>, the first application of x-rays, and still the most common

Originally, x-ray imaging was based on <u>absorption</u>. But synchrotron sources have a property that now leads to novel and very powerful imaging techniques: let us discover it!

In everyday life, we occasionally see wave-like effects like oil-film interference… but they are rare

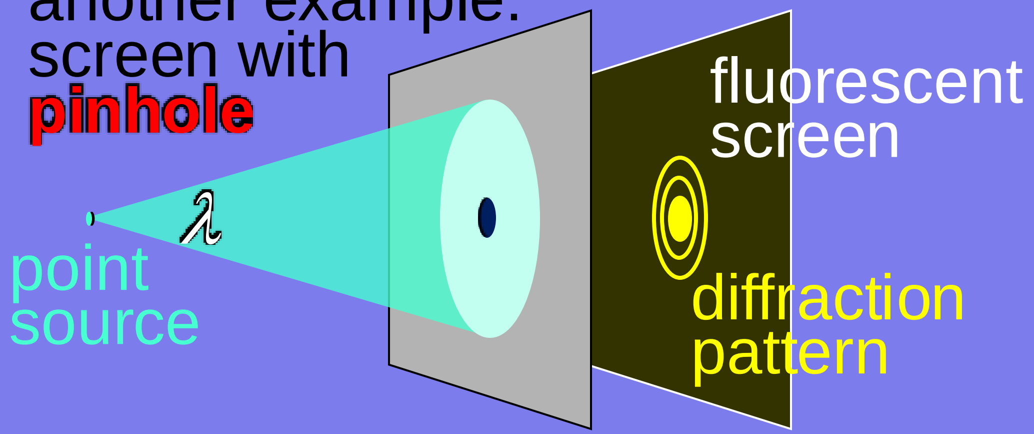
Why? Because to see them the radiation source must have "coherence" = "what allows radiation to produce visible wave-like effects like interference and diffraction"

X-rays from synchrotron sources have high coherence, which is now exploited for a revolutionary new radiology!

A simple description of coherence:

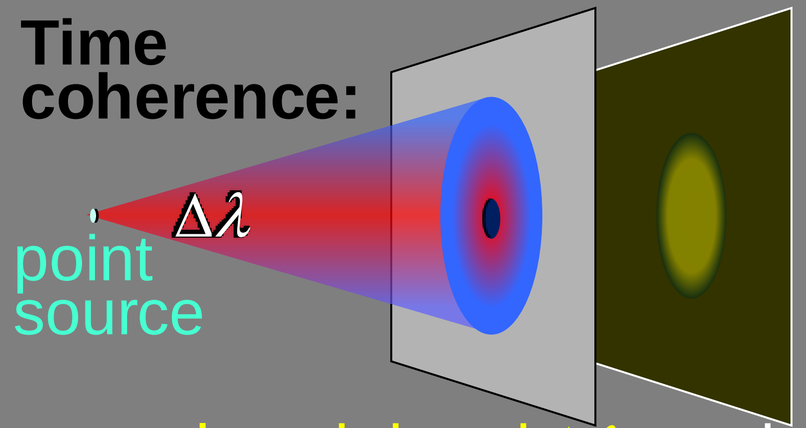
Take a double-slit screen and a fluorescent

another example: screen with **pinhole**



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

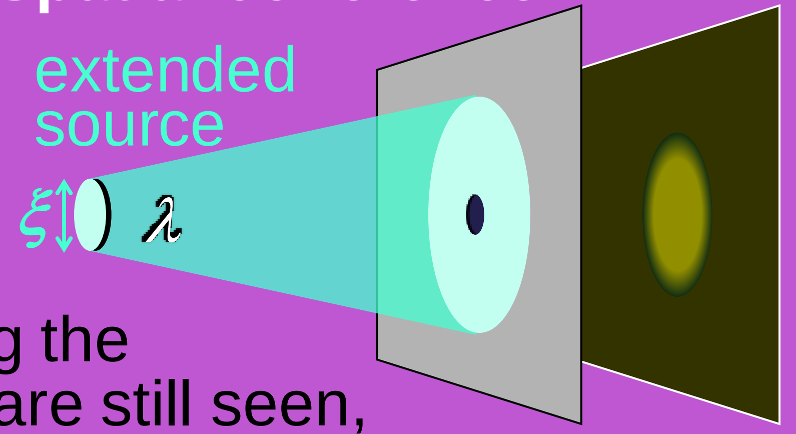
Time coherence:



if the source emits a wavelength band $\Delta\lambda$, each λ gives a fringe pattern; the superposition blurs the fringes: they may not be visible; if they are, there is time ("longitudinal") coherence

Spatial coherence:

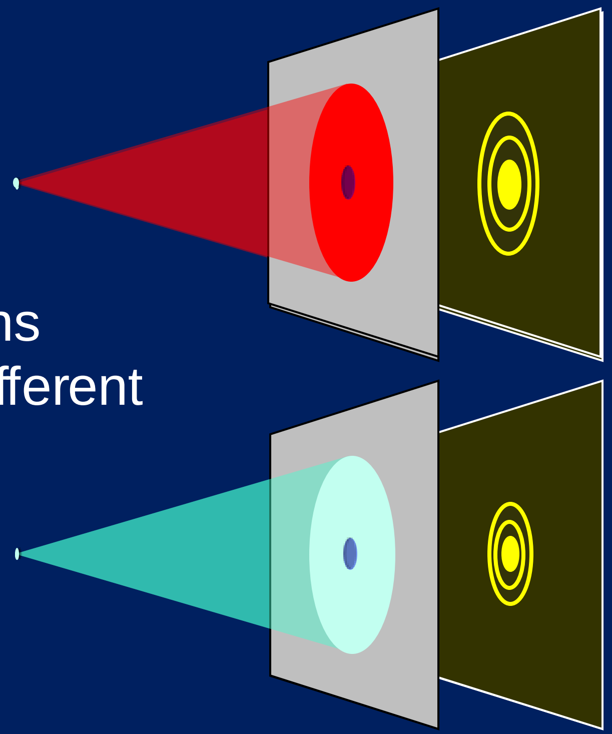
Each point of a source with finite size ξ produces a different pattern, blurring the fringes: if they are still seen, there is "spatial" ("lateral") coherence

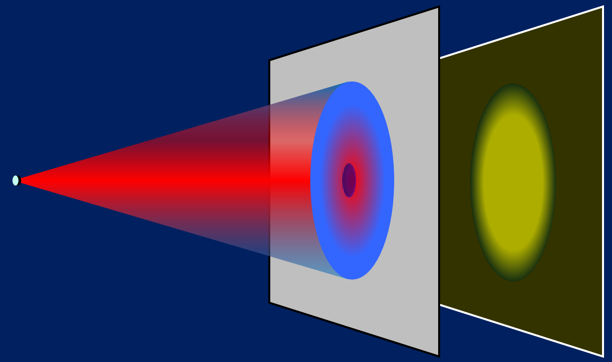


More realistic sources reveal TWO kinds of coherence: "time" and "spatial"

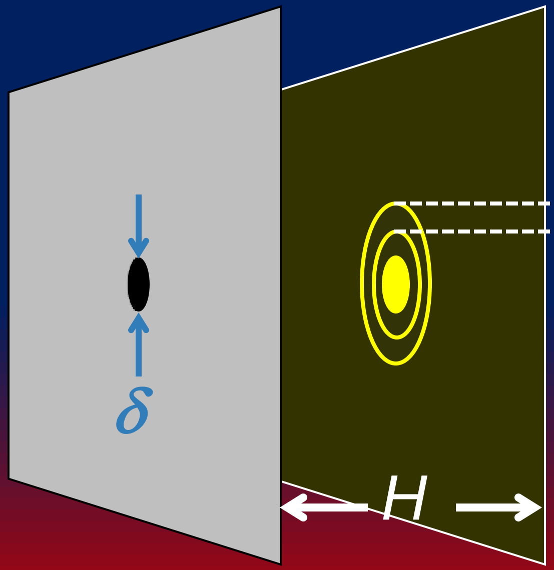
Multiple wavelengths: longitudinal (time) coherence

different wavelengths produce different patterns…





…whose superposition blurs the fringes



when is the fringe pattern still visible?

Spacing of adjacent fringes (from elementary optics):

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

if λ is replaced by a band $\Delta\lambda$, x is "blurred" to:

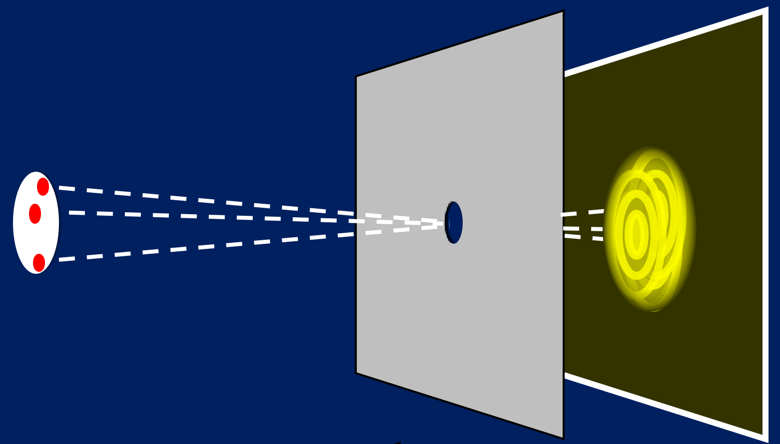
$\Delta x \approx (H/\delta)\Delta\lambda$

Condition to see the pattern:

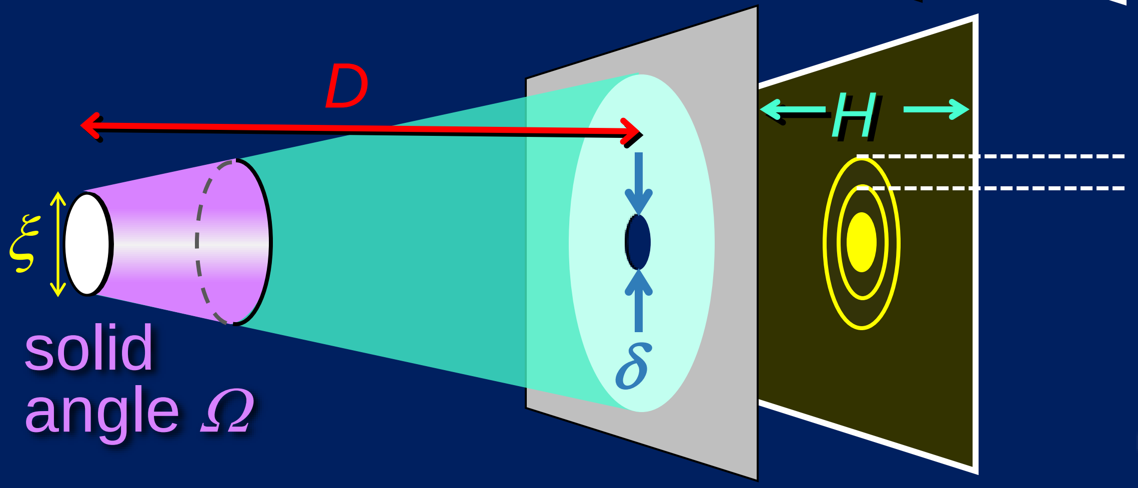
$\Delta x < x \longrightarrow$ $\boxed{\Delta\lambda/\lambda < 1 \text{ (time coherence)}}$

defining the "<u>coherence length</u>" as $L_c = \lambda^2/\Delta\lambda$, time coherence requires $L_c > \lambda$

Spatial coherence:



Each point of an extended source produces a diffraction pattern
→ blurring



when is a pattern still visible?

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

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

Fringes can be seen if $M \le x$:

$\xi H/D \le (H/\delta)\lambda \rightarrow \boxed{\delta \le \lambda D/\xi}$

condition for spatial coherence

Another way to look at this condition: the radiation contributing to diffraction is that reaching the pinhole, emitted in the solid angle $\approx \delta^2/D^2 \boxed{\le (\lambda D/\xi)^2/D^2} = \lambda^2/\xi^2$ – which corresponds to a fraction of the total emission

$\approx(\lambda^2/\xi^2)/\Omega = \boxed{\lambda^2/(\xi^2\Omega)}$ This is the "coherent power factor": it is large if there is spatial coherence

Are synchrotron sources spatially coherent?

YES! Their small size ξ and small angular spread Ω give a large coherent power factor $\lambda^2/(\xi^2\Omega)$

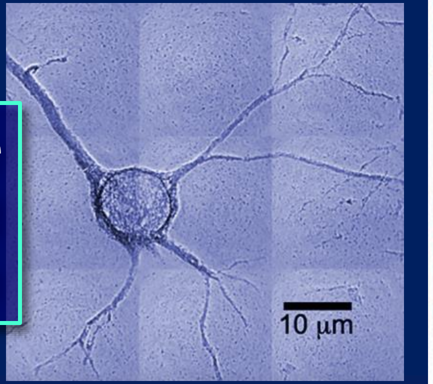
Note, however: λ^2 in this factor makes spatial coherence very difficult to obtain for the short λ's of x-rays: synchrotron sources are required

…and λ^2 is also present in the (time) coherence length causing a similar problem!

Also note: the brightness is proportional to $1/(\xi^2\Omega)$

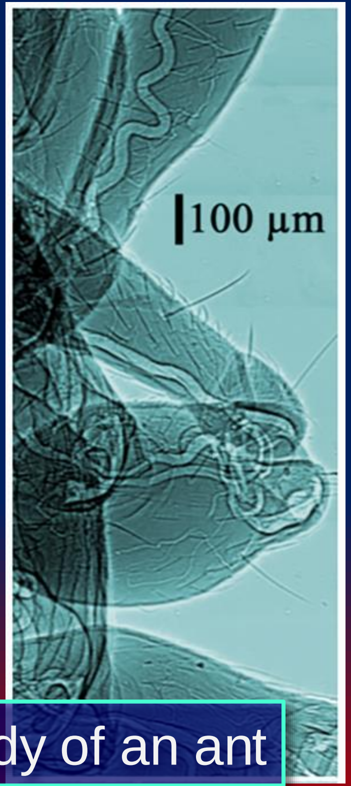
thus, the historical efforts to enhance the brightness by decreasing ξ and Ω also boosted the spatial coherence

Synchrotron x-ray coherence is very beneficial for imaging: it notably produce phase-contrast radiographs, with sharp features and very small details



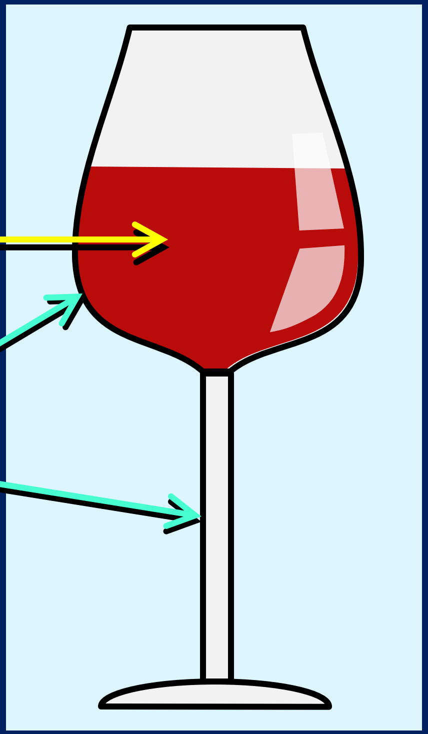
radiograph of a single neuron: world record of spatial resolution

cancer microvasculature



body of an ant

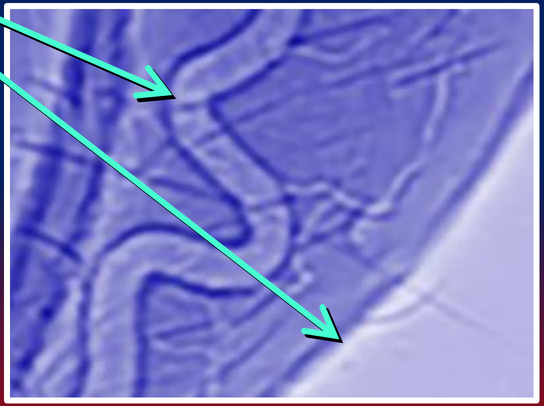
Phase-contrast imaging: the mechanism is complex, but we can grasp key features with a simple analogy: "seeing" a glass of wine



we see the wine because it absorbs and/or scatters certain wavelengths and looks colored

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

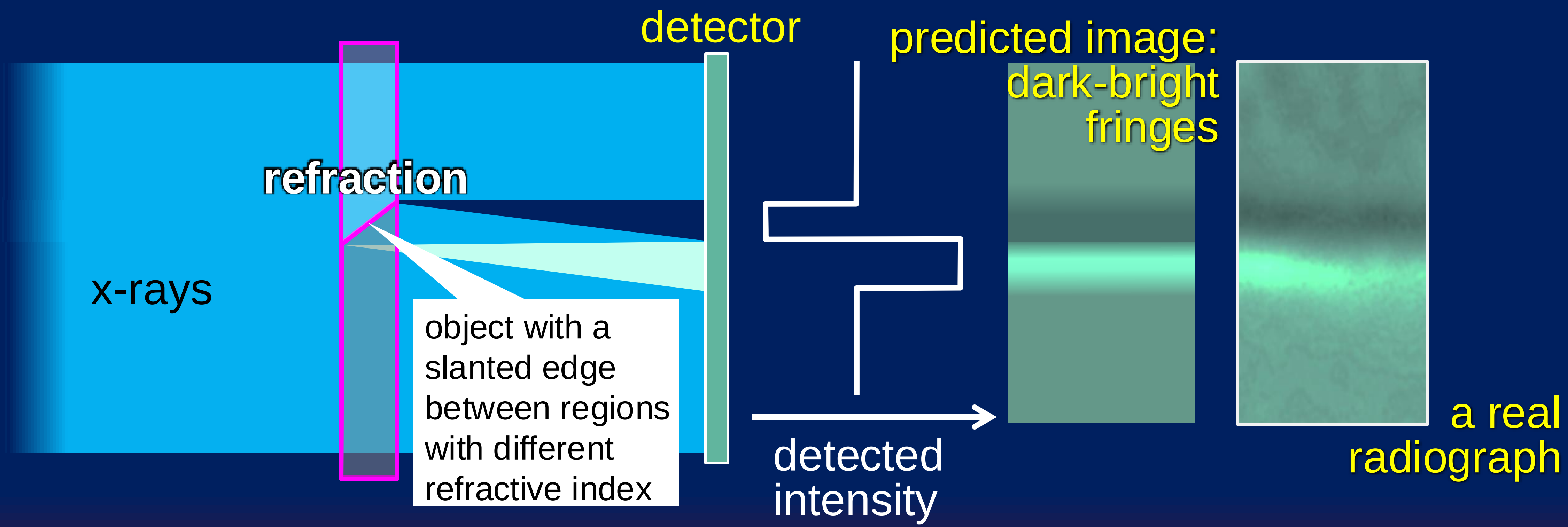
likewise, phase contrast (refraction/scattering of x-rays) can cause sharp, highly visible edges in synchrotron radiographs



…however, to create such edges x-rays must have a well-defined direction: this is guaranteed by the spatial coherence of synchrotron radiation, which implies angular collimation

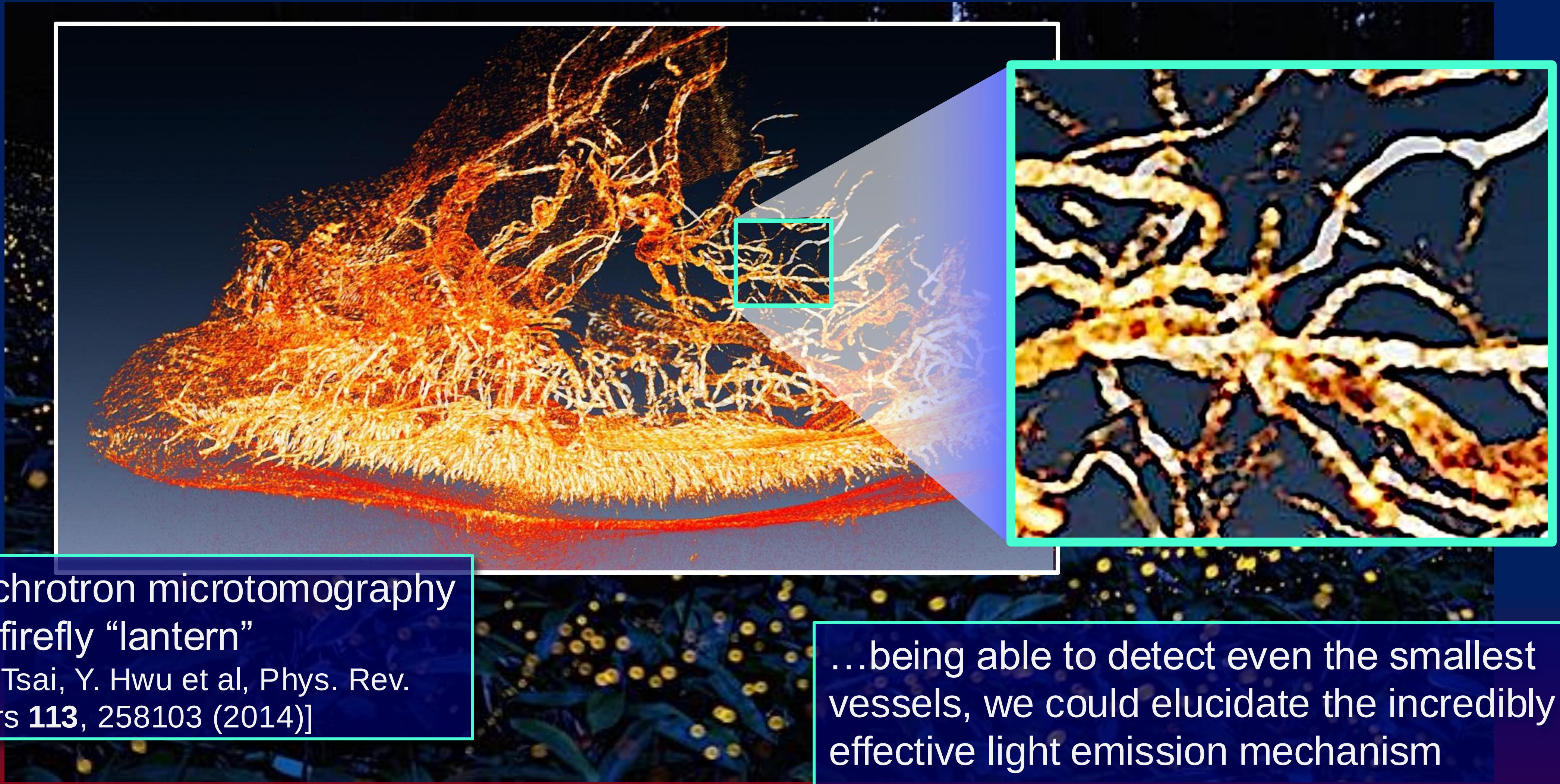
A simple model of x-ray imaging by phase contrast

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



Note: high lateral coherence is required for phase contrast, but high longitudinal (time) coherence is not needed

An example of what can be done with phase contrast imaging: explaining the miracle of fireflies

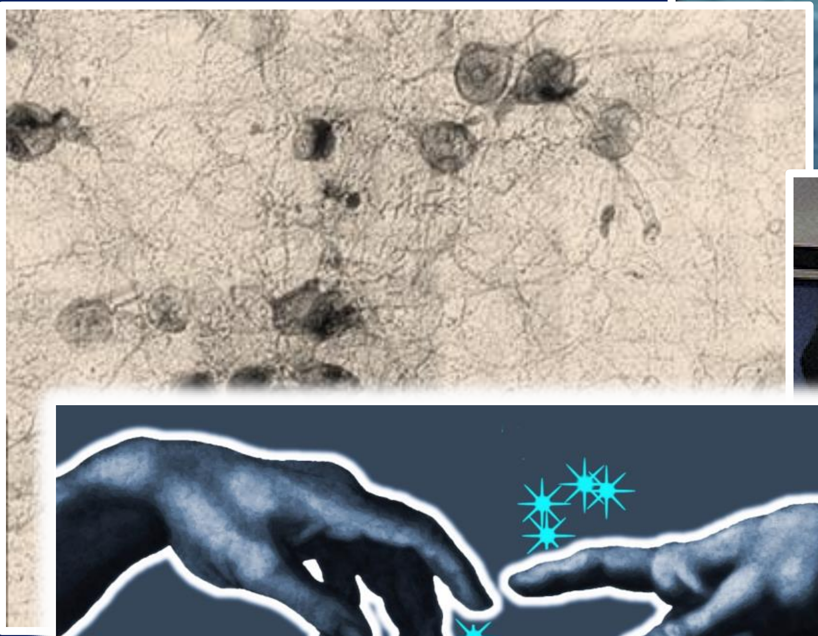


Synchrotron microtomography of a firefly “lantern”
[Y. L. Tsai, Y. Hwu et al, Phys. Rev. Letters **113**, 258103 (2014)]

…being able to detect even the smallest vessels, we could elucidate the incredibly effective light emission mechanism

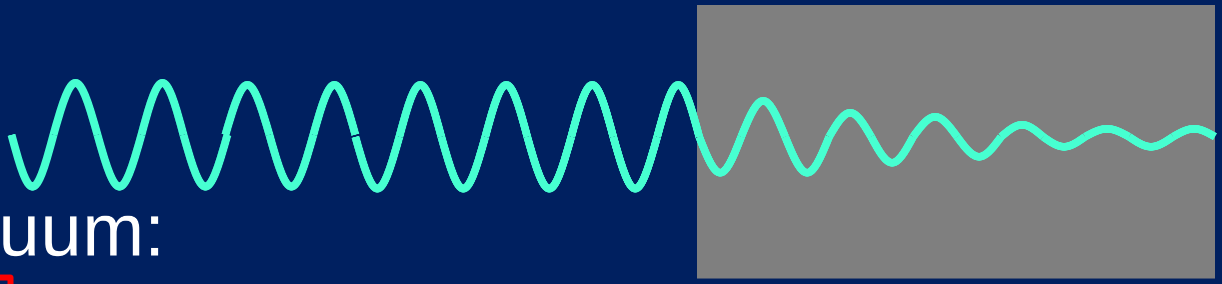
Microscopy with coherent x-rays: exploring the brain, neuron by neuron

SYnchrotrons for Neuroscience – an Asia-Pacific Strategic Enterprise (SARI/SSRF-China, PAL-Korea, AS-Taiwan, RIKEN/Spring8-Japan, NUS/SSLS-Singapore, ANSTO-Australia, SLRI-Thailand, SESAME-Jordan)



Goal: mapping a human brain

The general formal background of the interactions of x-rays with solids:



Wave function in vacuum:

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

"PHASE"

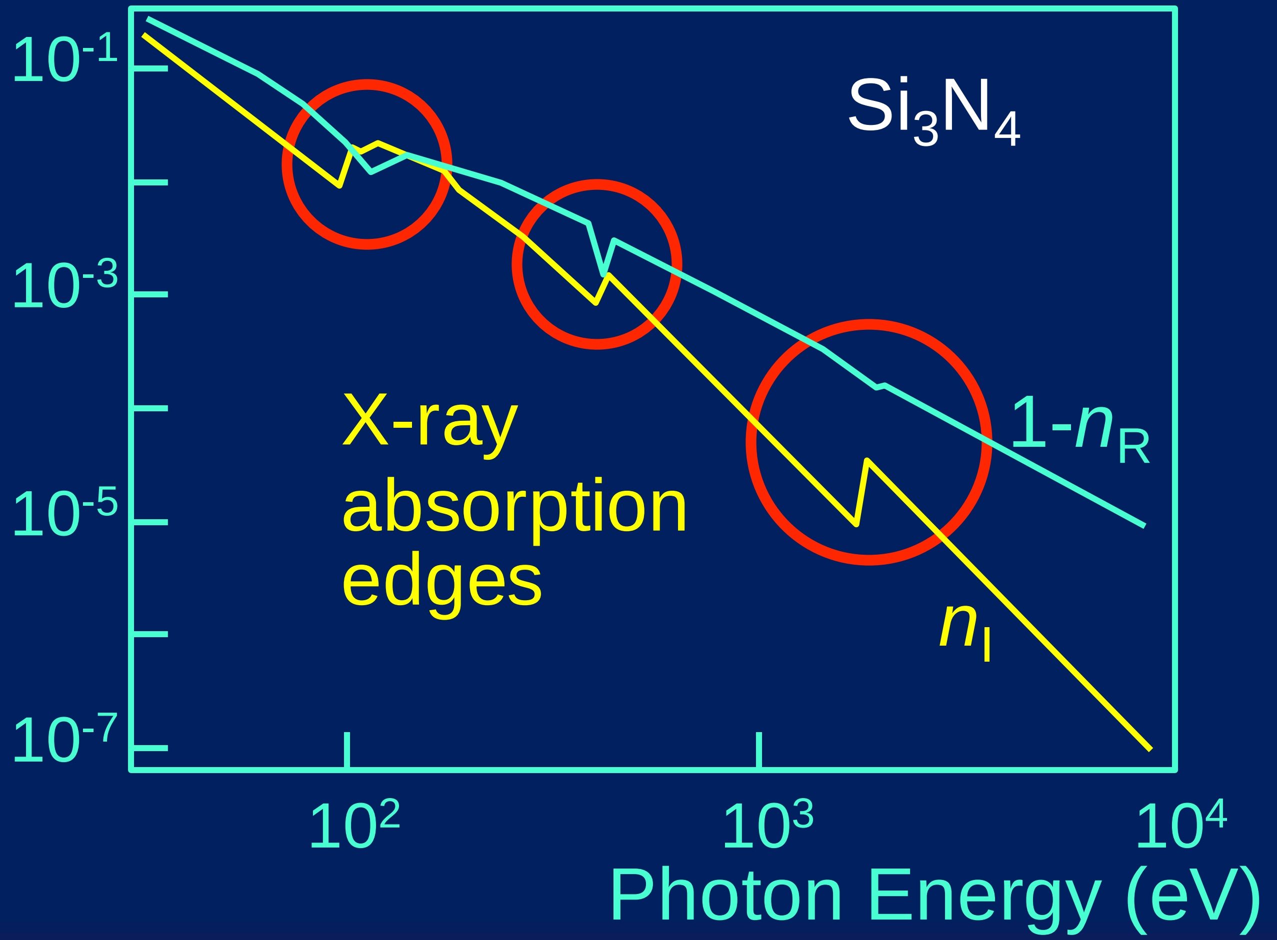
In the solid: k changes to nk ,
where $n = n_R + i n_I$
(<u>compl</u>e<u>x</u> refractive index)
Wave function: $W_o \exp[i\,(nkx - \omega t\,)]$
$= W_o\,\boxed{\exp(-n_I kx\,)}\,\exp[i\,\boxed{(n_R kx - \omega t}\,)]$

Factor decreasing with the distance, corresponding to absorption

$n_R k$ determines the phase and corresponds to phase effects: refraction, diffraction, interference…

The real and imaginary parts of the refractive index, n_R and n_I, are not independent

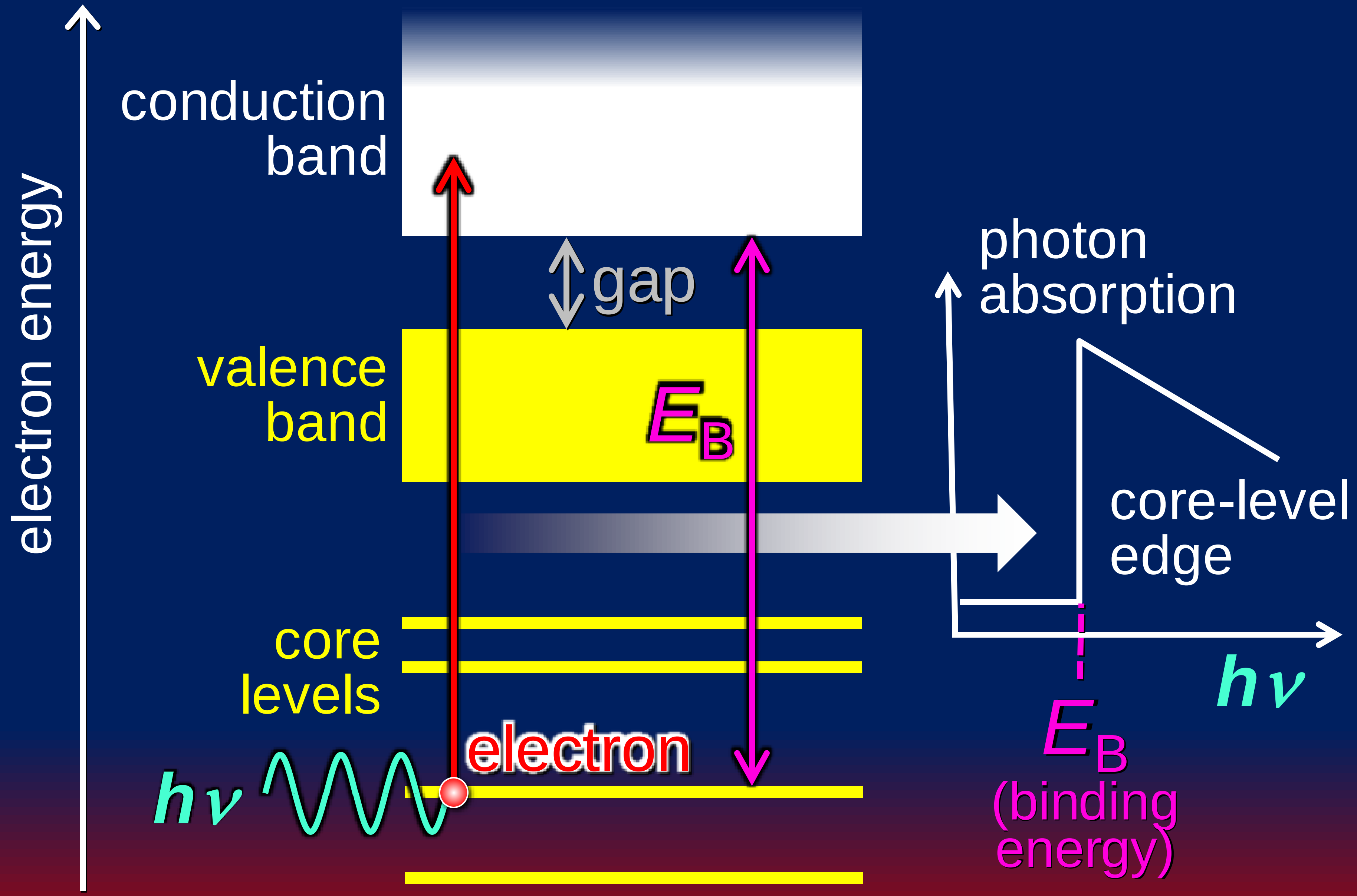
- They are <u>linked</u> by the so-called <u>"Kramers-Kroenig equations"</u>
- This explains the relations between different phenomena:
  - strong reflection corresponds to strong absorption (think about a metal-coated mirror)
  - phase and absorption features occur for the same wavelengths



…when "something" happens for absorption (n_I), "something" else also happens for refraction (n_R)

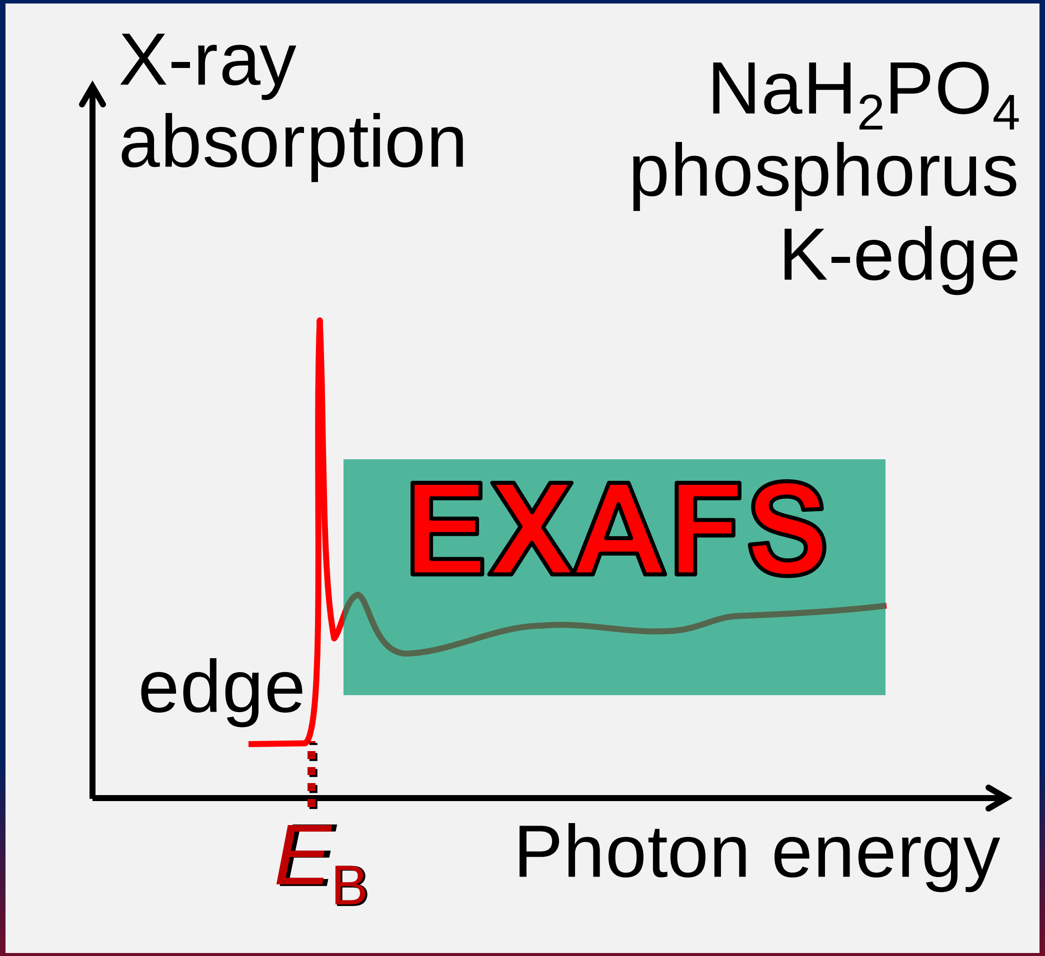
What causes the x-ray core-level absorption edges?

...consider the electron energies in an (insulating) solid

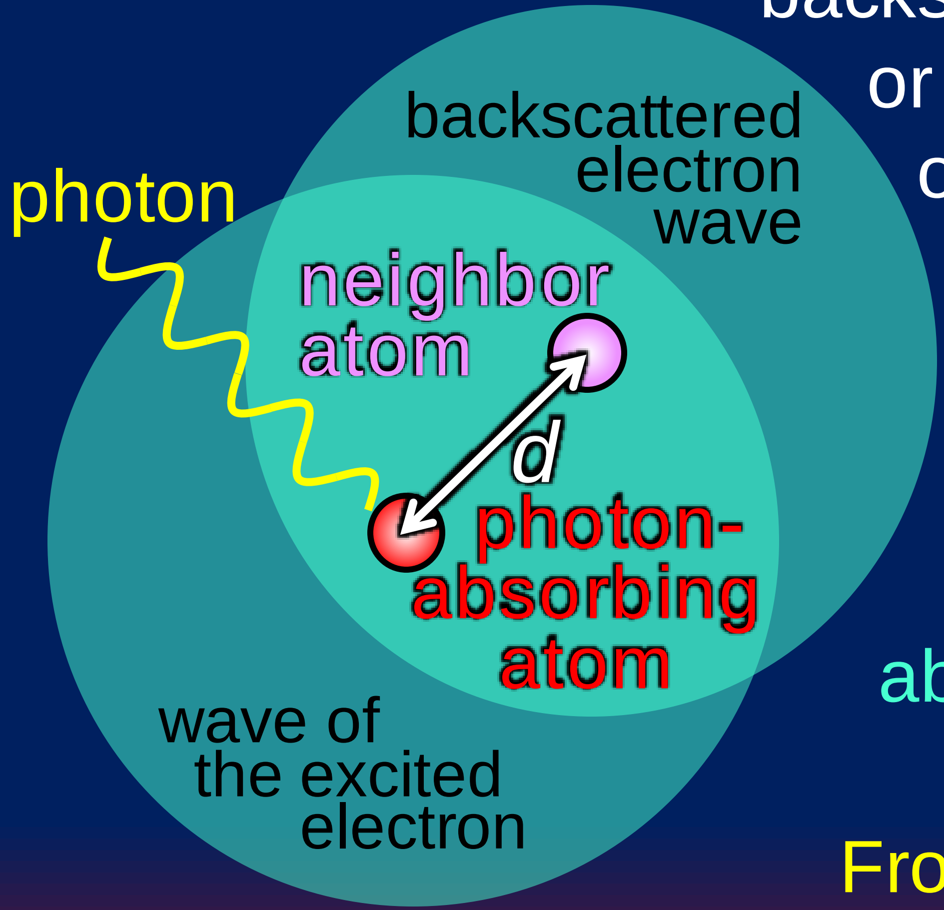


A core-level edge in an x-ray absorption spectrum reveals the presence of the corresponding element, its chemical status …and more

In particular, the "**EXAFS**" = **E**xtended **X**-ray **A**bsorption **F**ine **S**tructure above each edge yields precious information on the local microscopic environment of the x-ray absorbing atom

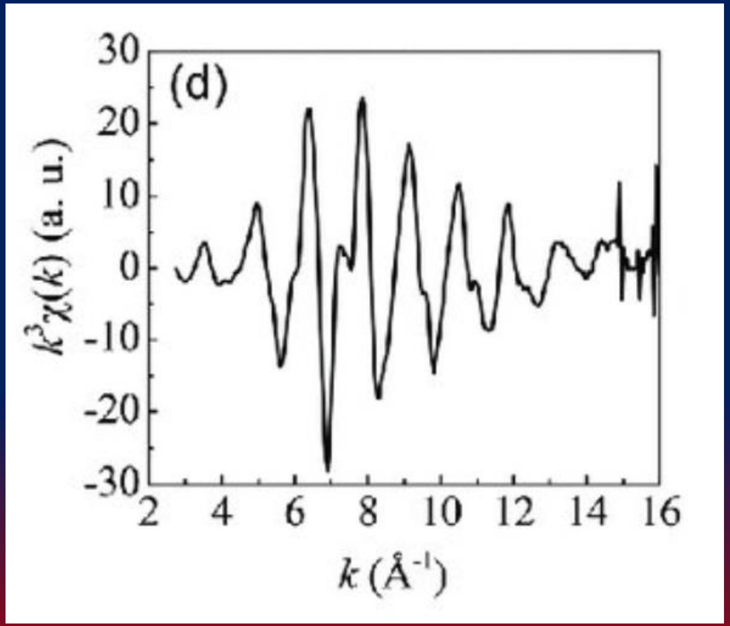


EXAFS mechanism:



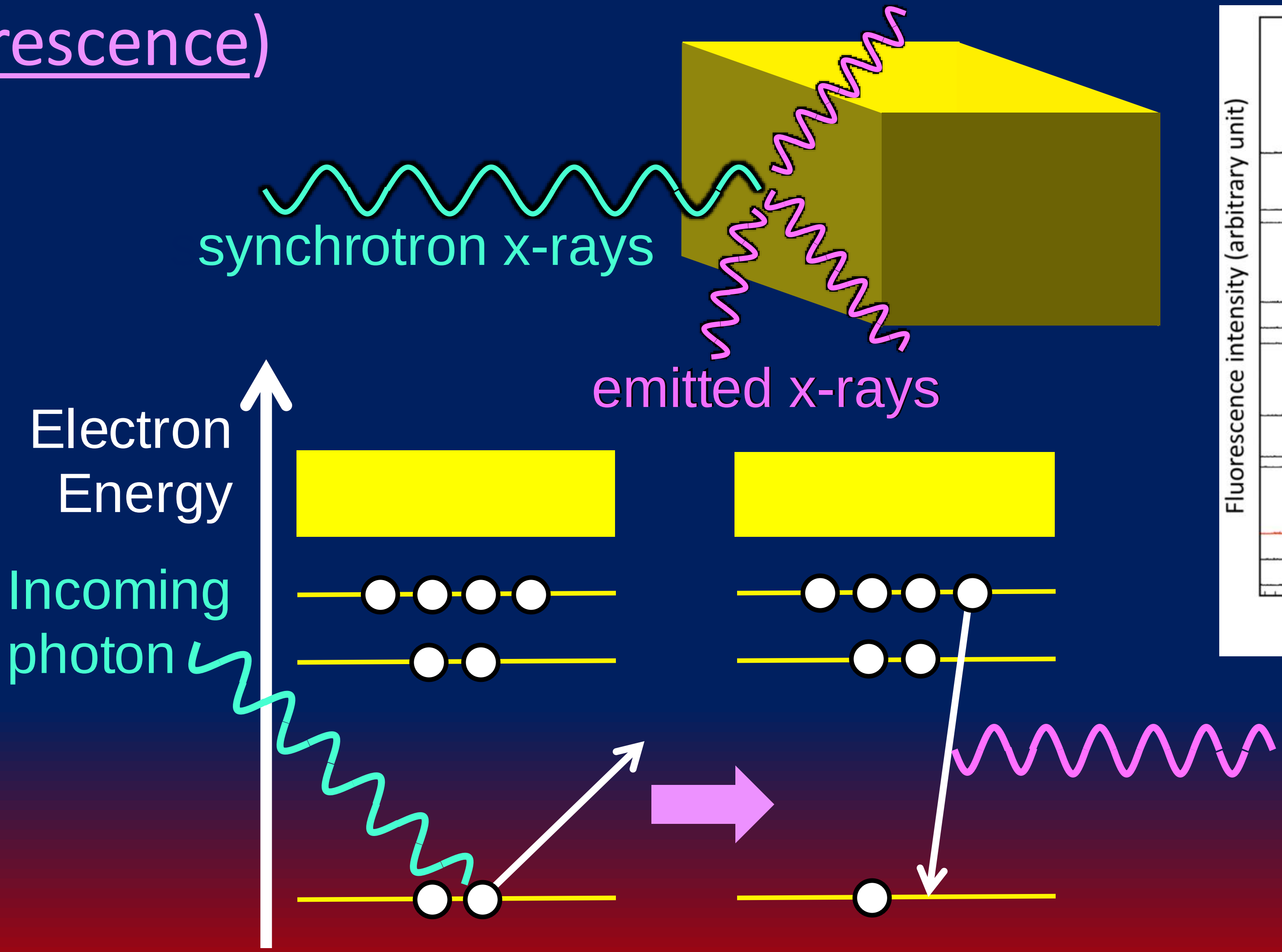
The outgoing excited-electron wave and the backscattered electron wave interfere constructively or destructively <u>depending on the distance *d*</u> and on the electron wavelength, which corresponds to the electron energy and therefore to the photon energy $h\nu$

This causes <u>oscillations</u> in the absorption vs. $h\nu$ plots

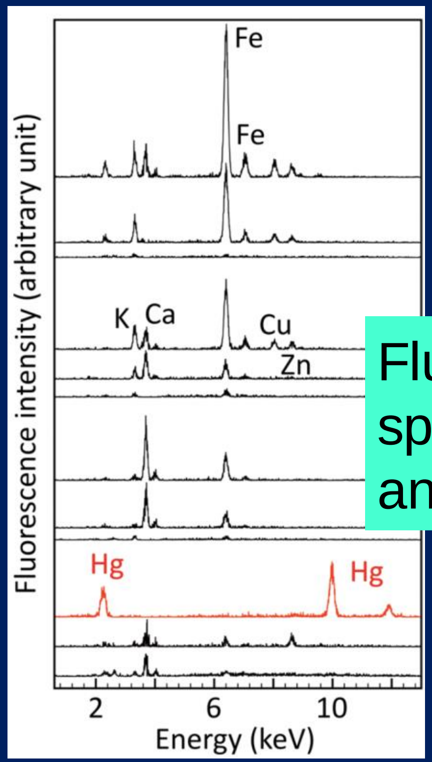


From these oscillations (EXAFS), one can derive the <u>local interatomic distance *d*</u>, a very valuable piece of information

What happens to the energy of x-ray photons absorbed by a solid? One possibility is to cause the emission of other photons (x-ray fluorescence)



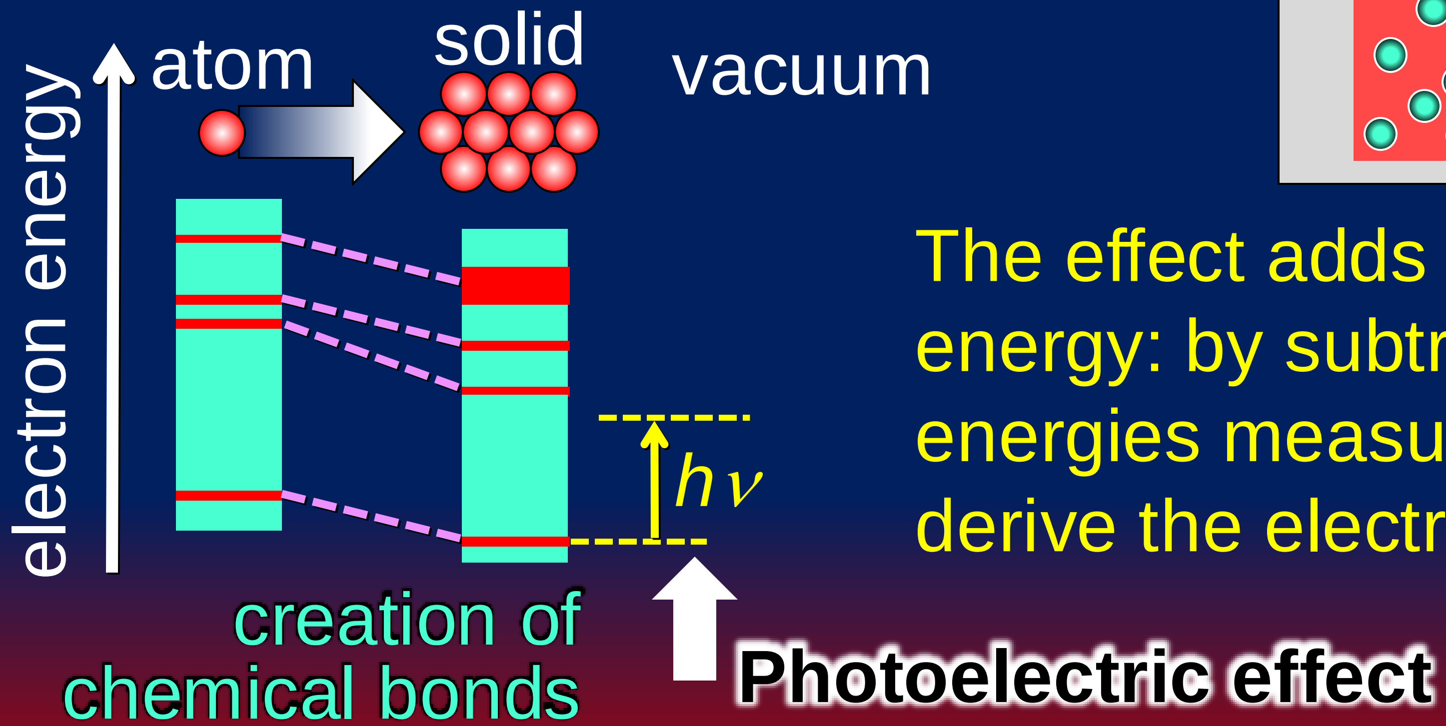
emitted x-ray photon that reveals the presence of the element corresponding to the core levels

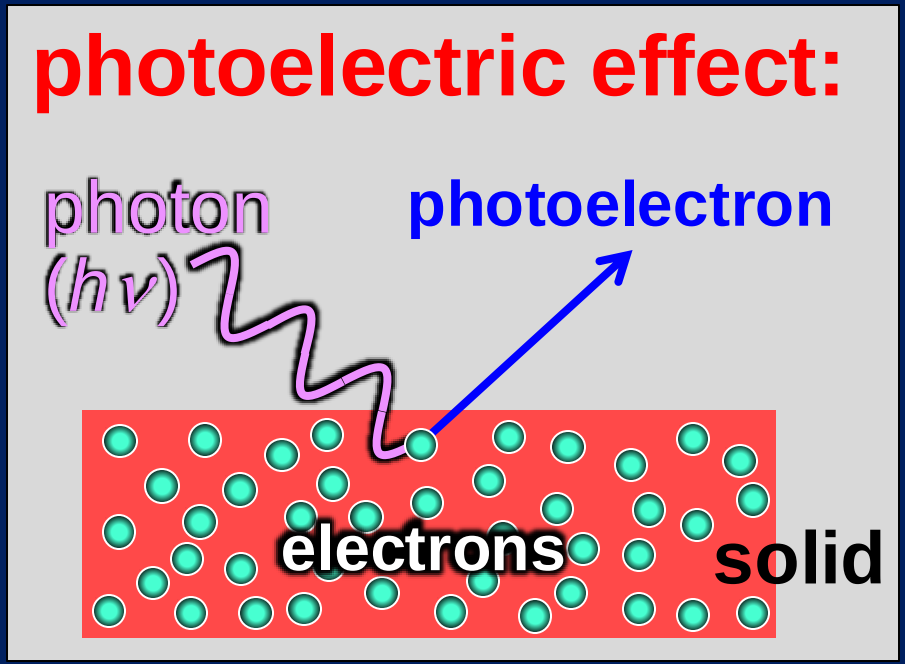


Fluorescence spectra of ancient inks

Photoemission, another fundamental class of synchrotron techniques

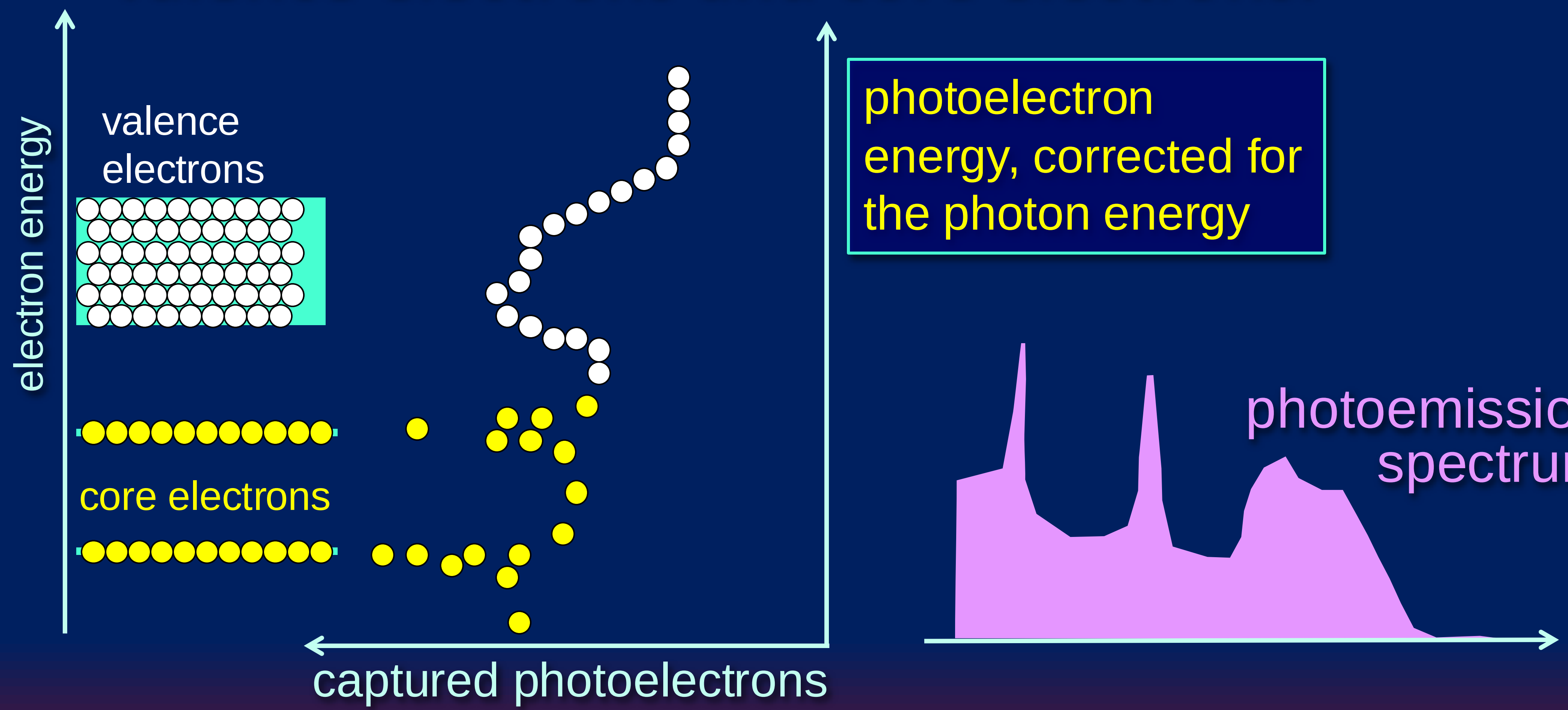
…photoemission explores the energies of electrons forming chemical bonds:





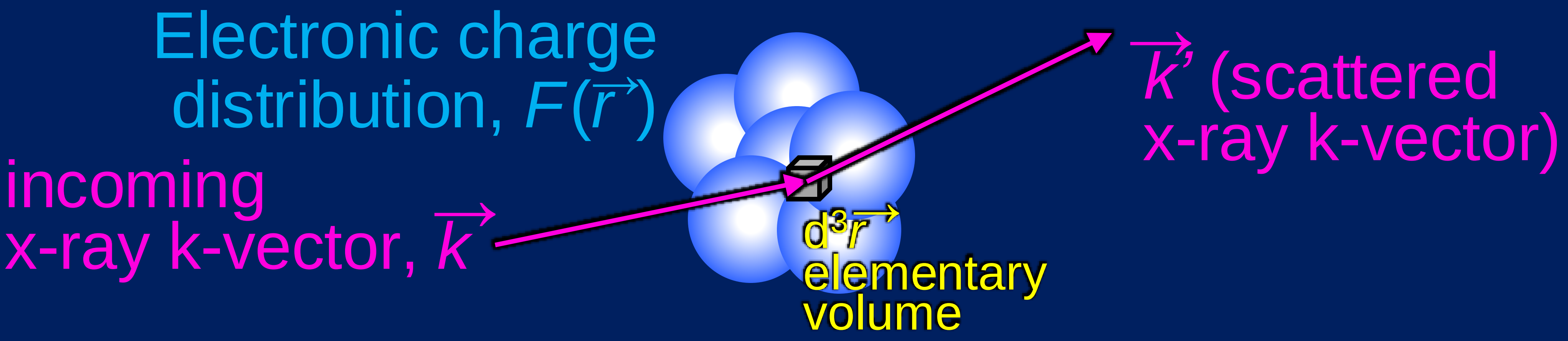
The effect adds $h\nu$ to the electron energy: by subtracting $h\nu$ from electron energies measured in vacuum, one can derive the electron energies in the solid

Solid-state photoemission detects valence electrons and core electrons:



…synchrotron photoemission transformed my bookish quantum notions like core levels into tangible realities!

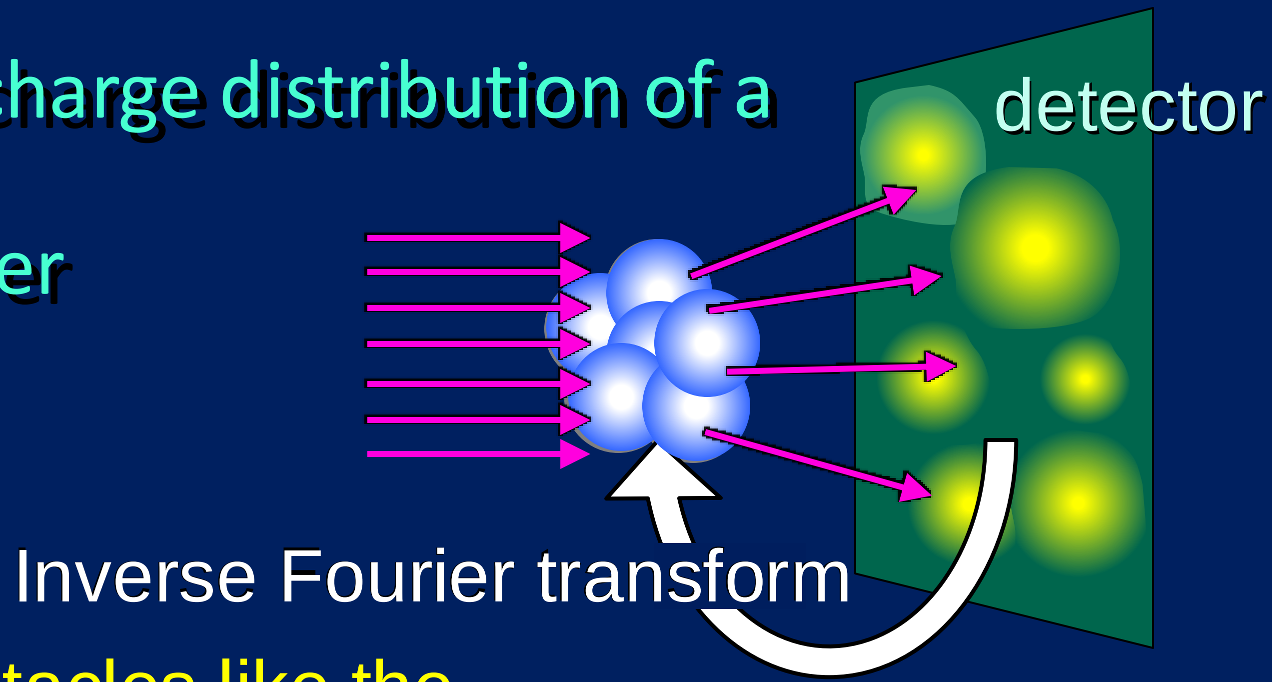
A key class of synchrotron techniques: x-ray scattering -- which reveals the electron charge distributions of microscopic structures



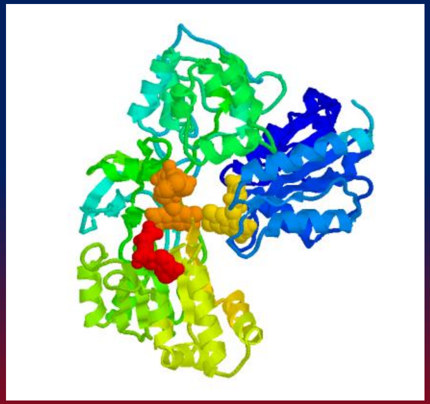
Theory: defining the scattering vector as $\vec{s} = \vec{k}' - \vec{k}$, the scattered wave $W(\vec{s})$ is proportional to $\int F(\vec{r})\exp(i\vec{r}\cdot\vec{s})d^3\vec{r}$, which is the Fourier transform of the charge distribution F

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

Thus, we can find the electron charge distribution of a microscopic object
by performing the inverse Fourier transform of scattered x-rays

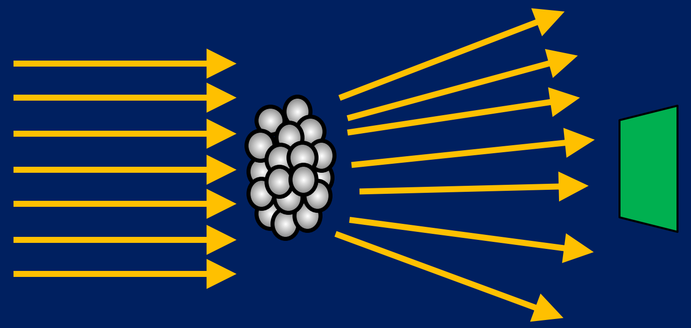


This strategy faces serious obstacles like the "phase problem", but leads to many powerful synchrotron techniques:



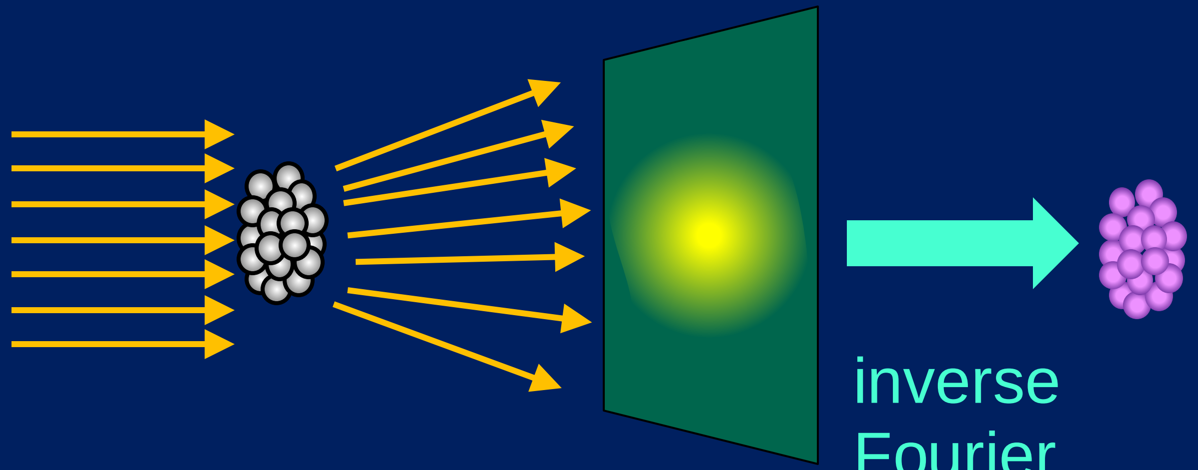
- Large-angle scattering
- Small-angle scattering
- Powder diffraction
- Crystallography
- Protein crystallography …and more

Small-angle and large-angle scattering



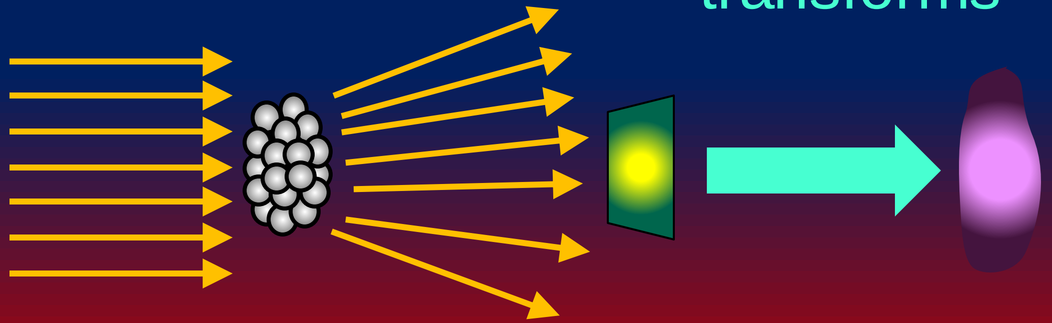
In a real experiment, the detector captures only a portion of the solid angle, i.e., only part of the scattered x-rays

Fourier transform properties: if scattered x-rays are only detected at small angles, the inverse transform gives the general shape of the object but not its fine details



inverse Fourier transforms

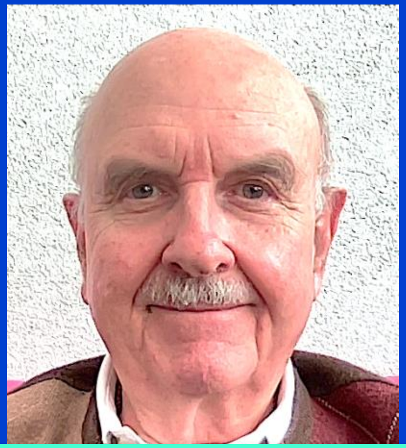
So, small-angle scattering is useful for a first look at microstructures



The Abdus Salam International Centre for Theoretical Physics

School on Synchrotron Light Sources and their Applications

(1) Fundamentals of Synchrotron Radiation from Storage Rings
(2) Fundamentals of X-ray Interaction with Matter
(3) Bonus: X-ray Free Electron Lasers



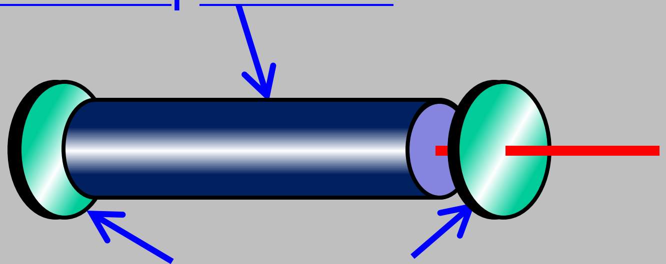
Giorgio Margaritondo
Ecole Polytechnique Fédérale de Lausanne (EPFL)
and Istituto Italiano di Tecnologia (IIT)

X-ray Free Electron Lasers (X-FELs): the New Generation of Synchrotron Radiation Sources

Storage-ring synchrotron sources have laser-like features: strong collimation, high intensity, high brightness and excellent coherence – are they lasers?

A visible/infrared laser:

Active medium, providing optical amplification

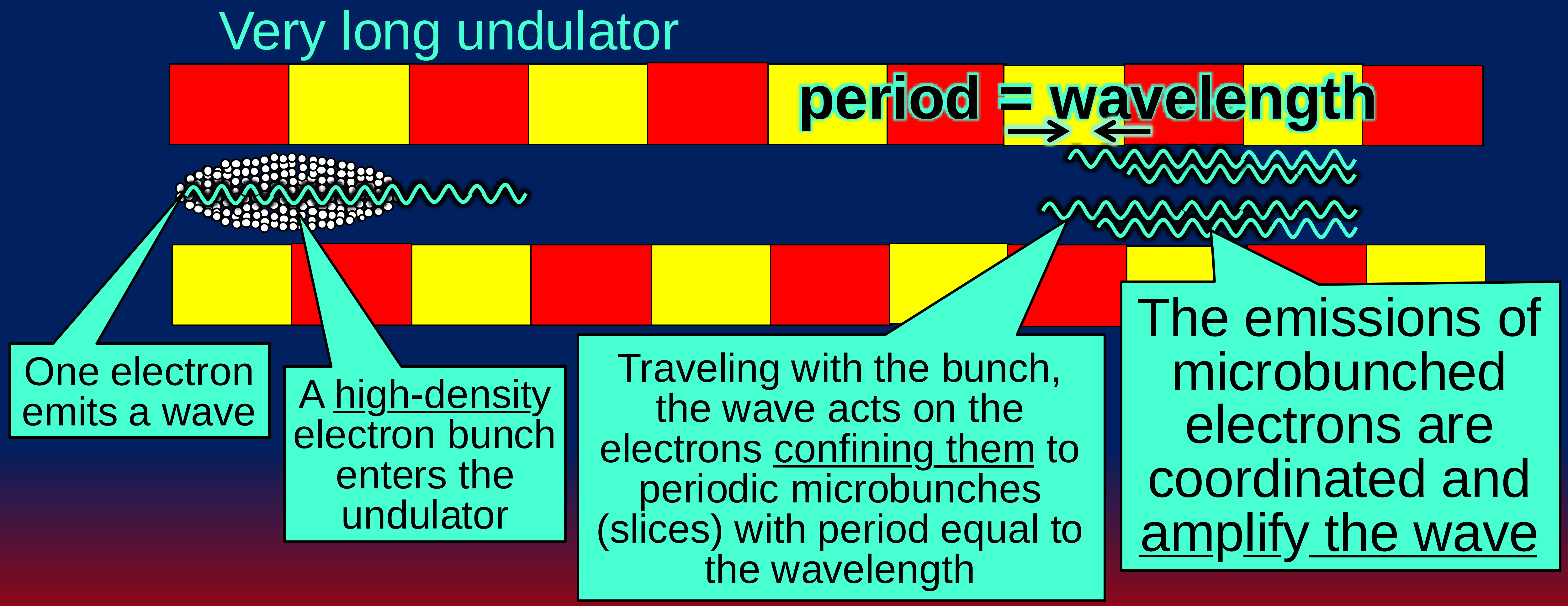


Two-mirror optical cavity, increasing the photon path and the optical amplification

Storage-ring synchrotron radiation sources:

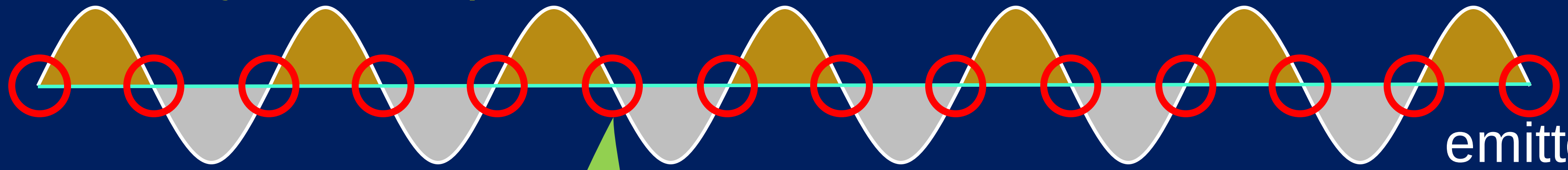
- NO optical amplification
- NO good mirrors for x-rays, thus NO optical cavities
- **They are NOT lasers**

But there is now a new class of laser-like synchrotron x-ray sources, the X-FELs, based on an optical amplification process due to the interaction of electron bunches with their emitted waves



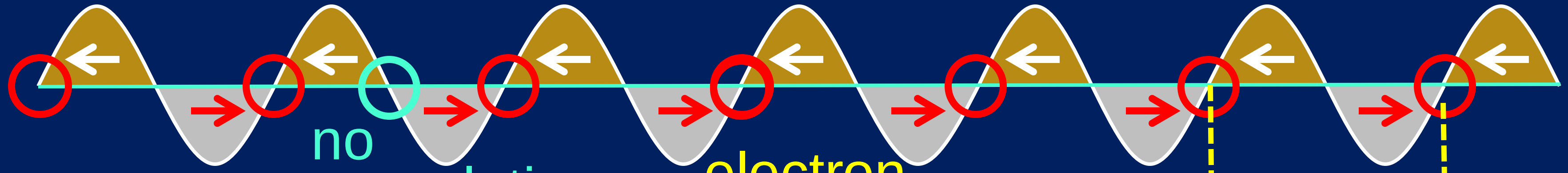
What pushes the electrons towards the “slices”?

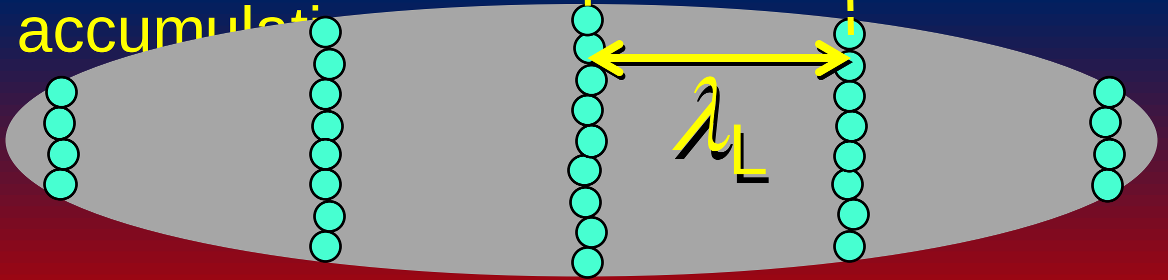
…the “ponderomotive forces”, due to the interaction of the electrons with the wave and the undulator: they are complicated, but their basic features can be easily grasped



The wave is zero at the nodes and so are the ponderomotive forces: the nodes are where the electrons could accumulate

But accumulation does not occur at all nodes since the wave field has two directions that cause forces with opposite orientations:



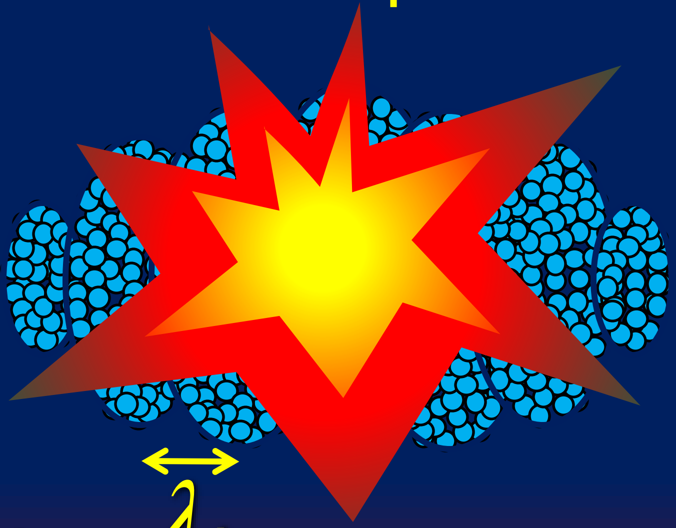


…so, electrons accumulate at every other node: the microbunch period is one wavelength

Why most undulators do not behave like x-FELs?

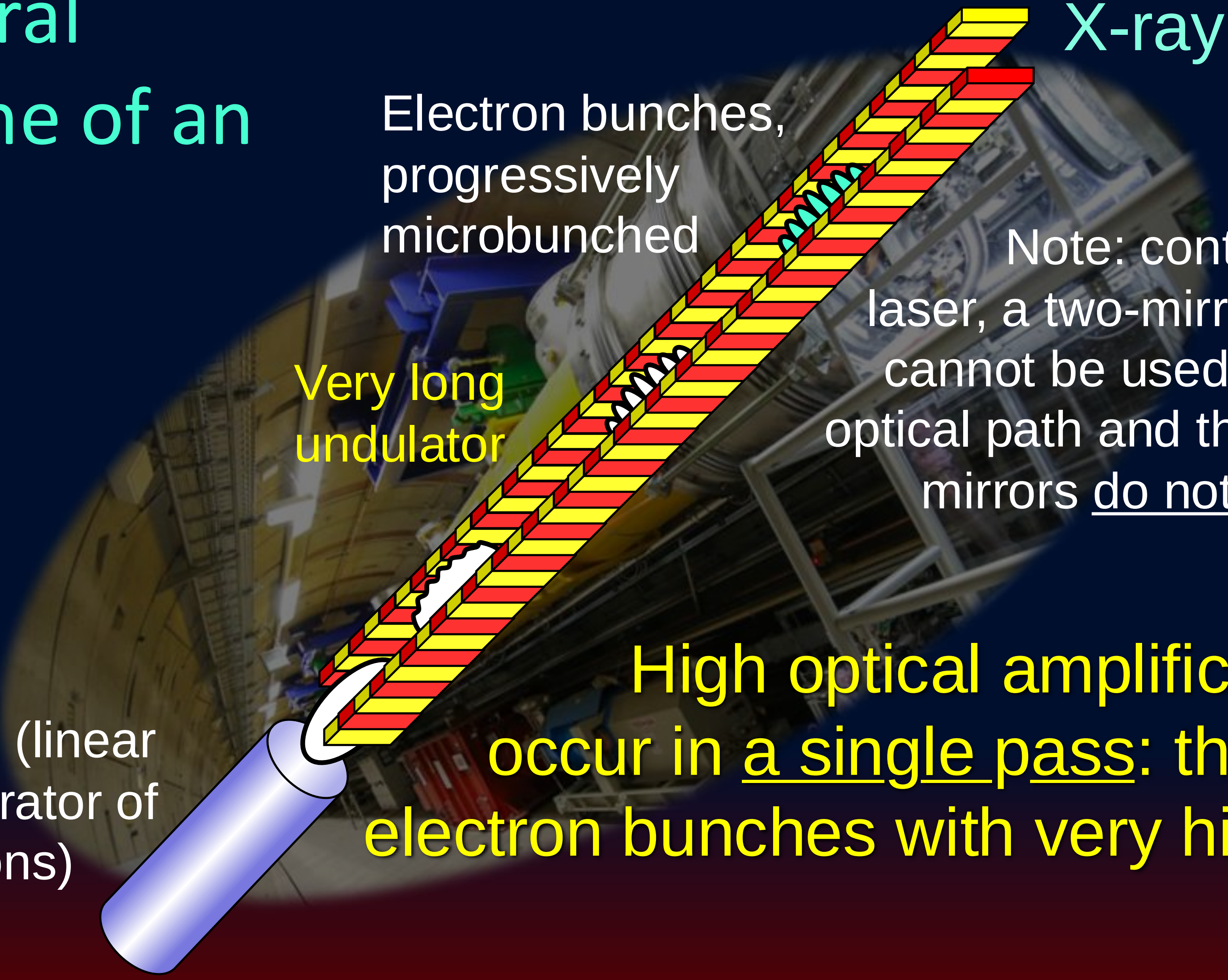
…to emit x-rays, high-energy electrons with large γ–values are required, whose relativistic "longitudinal mass" $\gamma^3 m_o$ is very heavy: it takes a (relatively) long time to shift them to the "slices", so a very long undulator is required for microbunching

…plus, the microbunching period is very short (x-ray wavelengths) -- the structure is delicate, easily destroyed: the undulator and the electron beam must be extremely accurate



NOTE: for infrared FELs the γ–factor is smaller, the longitudinal mass much lighter and the wavelength much longer, so the above problems do not exist: that is why infrared FELs arrived several decades before the x-FELs

General scheme of an X-FEL:

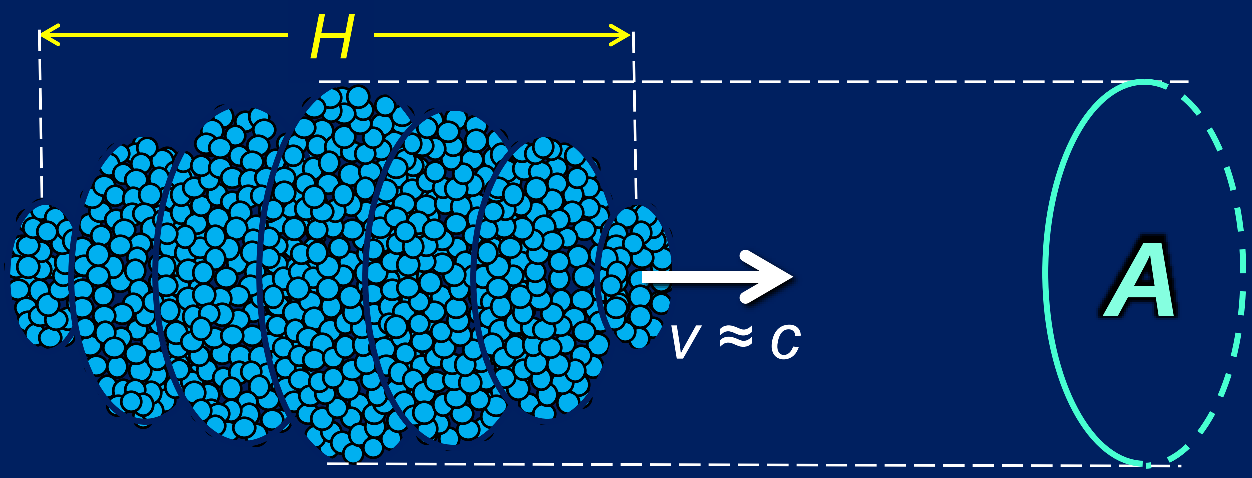


Note: contrary to a visible laser, a two-mirror optical cavity cannot be used to increase the optical path and the amplification: mirrors do not exist for x-rays

High optical amplification must occur in a single pass: this requires electron bunches with very high density

Duration and cross section of an x-FEL pulse:

A high electron density requires a very short electron bunch length *H*



Microbunched electron bunch

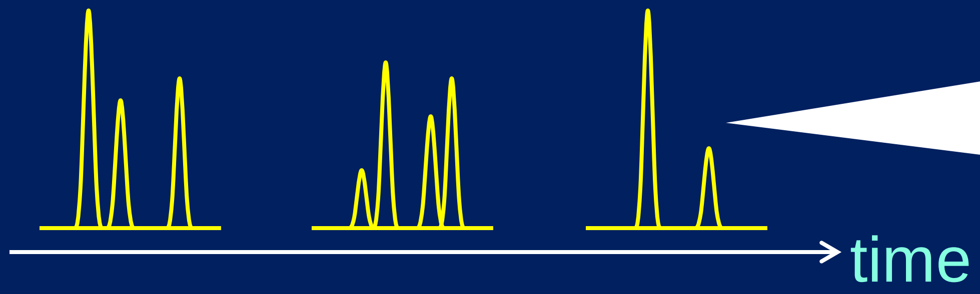
…causing a <u>very short</u> photon pulse $H/v \approx H/c$ (<u>femtoseconds</u> or less, shorter than the synchrotron radiation pulses from storage rings)

[Note: most x-FELs are not based on storage rings but on LINACs, which can produce smaller cross sections *A*]

Plus, a high electron density also requires a very small cross section *A* of the electron bunch and therefore of the photon pulse, producing high brightness

COHERENCE of x-FELs: <u>spatial</u> excellent, <u>time</u> problematic

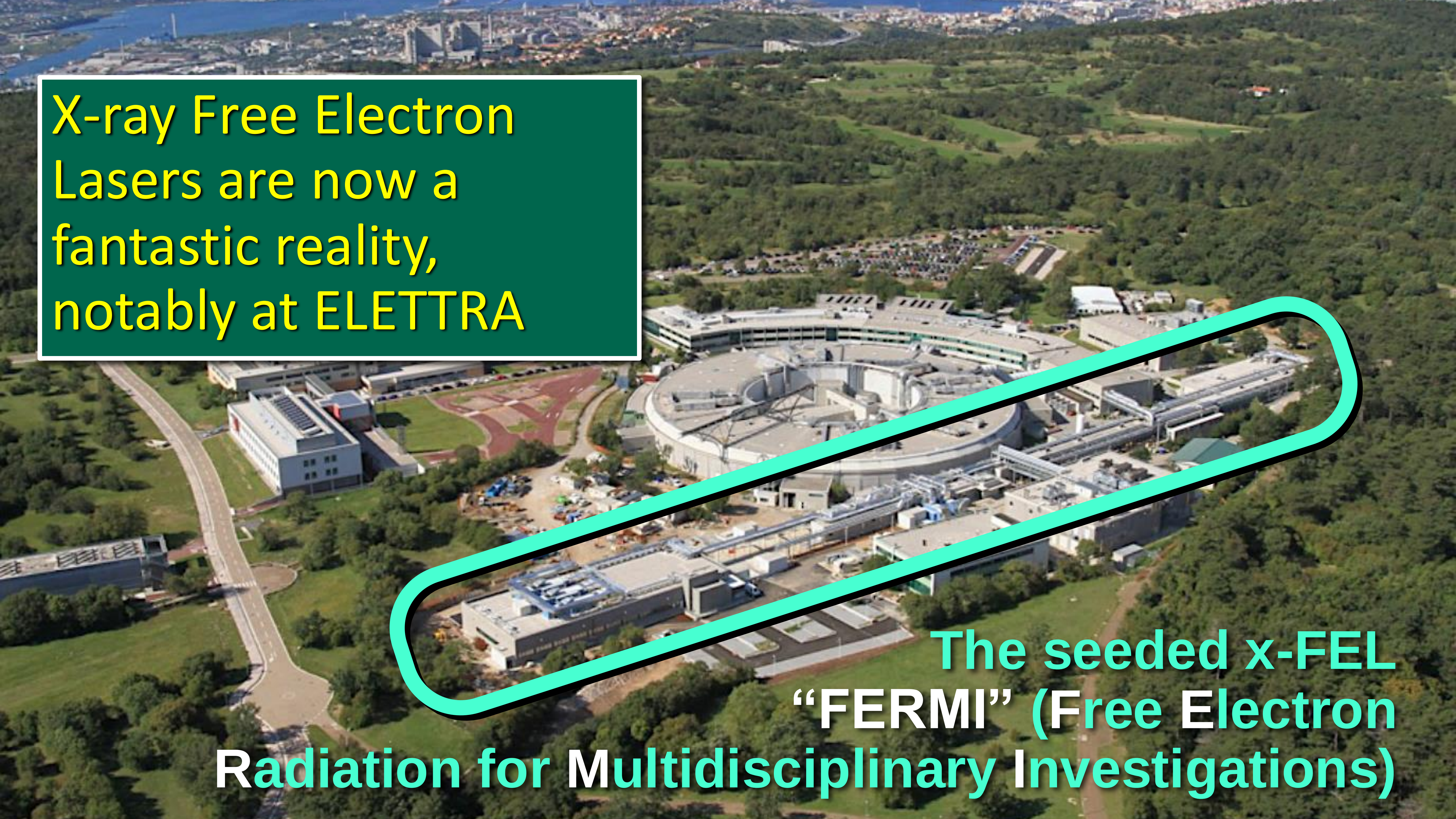
Why problematic? Because the waves that are amplified are emitted <u>at random</u> when the electron bunch enters the undulator (SASE = Self-Amplified Spontaneous Emission)



Thus, the time structure is different for different photon pulses: this broadens the wavelength spectrum $\Delta\lambda$ and limits the time coherence

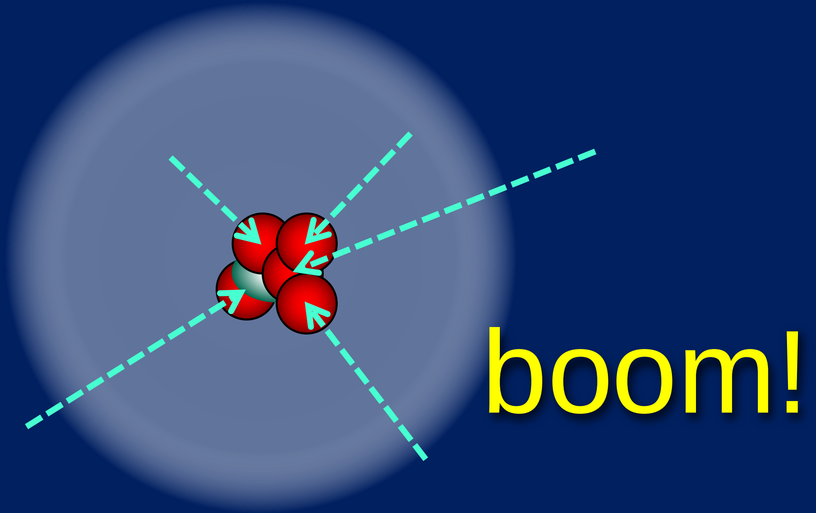
Possible solution: "seeding" -- i.e., using the x-FEL undulator to amplify waves with high time coherence produced by an external source

A complicated technology, recently realized


X-ray Free Electron Lasers are now a fantastic reality, notably at ELETTRA
The seeded x-FEL "FERMI" (Free Electron Radiation for Multidisciplinary Investigations)

Note: x-FELs emit femtosecond pulses of tens of gigawatts: how can we handle this tremendous concentrated power, and how can we use it?

…sent into a molecule or a nanoparticle, causes its explosion:



…but, with the ultrafast x-ray FEL pulses one can analyze the structure <u>during the explosion</u> and try to retrieve from the data the initial structure

Some examples of what happens at the femtosecond time scale of an x-FEL pulse:

Fast chemical reactions

In 100 femto

waves trave

emtoseconds

Photons p

Typica

emtoseconds

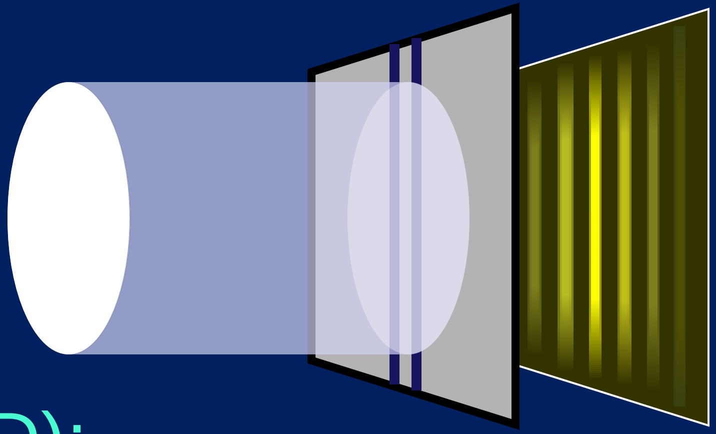
Laser surg

Novel micromachining techniques, etc…

X-FEL experiments on these and many other ultrafast phenomena open very exciting new opportunities in science and technology!

A fascinating final aspect: X-ray FELs and the quantum foundations of physics

What causes the interference and diffraction of photons?



First-order Quantum Electrodynamics (QED):

(1) Wave effects like interference and diffraction are caused by interactions of each photon only with itself (indeed, they happen even when, on the average, there is only one photon in the apparatus)

(2) Multiple-photon effects are negligible

BUT: with ultrabright "seeded" x-FELs, multi-photon higher-order QED effects are detected, leading to new techniques! [J. Stöhr, Synchrotron Radiation News **32** , 48 (2019)]

Thanks to the school organizers for inviting me!

...and thank you for your attention: 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)

G. Margaritondo: "*An Enlightening Procedure to Explain the Extreme Power of Synchrotron Radiation*", J. Synchrotron Radiation **26**, 2094 (2019)

G. Margaritondo: "*The Simple Physics of the Bending Magnet Spectrum*", J. Synchrotron Radiation **25**, 1271 (2018)

G. Margaritondo: "*Synchrotron Light: a Success Story over Six Decades*", Rivista Nuovo Cimento **40**, 411 (2017)

G. Margaritondo and J. Rafelski: "*The Relativistic Fundations of Synchrotron Radiation*", J. Synchrotron Radiation **24**, 898 (2017)

G. Margaritondo: "*Who Were the Founders of Synchrotron Radiation? Historical Facts and Misconceptions*", J. Vacuum Sci. Technol. **A40**, 033204 (2022)

G. Margaritondo: "*Teaching about the Birth of Synchrotron Light: the Role of Frascati and a Missed Opportunity*", J. Synchrotron Radiation **31**, 987 (2024)