International School
of Synchrotron Radiation
“Gilberto Vlaic”:
Fundamentals, Methods and Applications

Characteristics and Properties of Synchrotron Radiation:

Free Electron Lasers and Coherence

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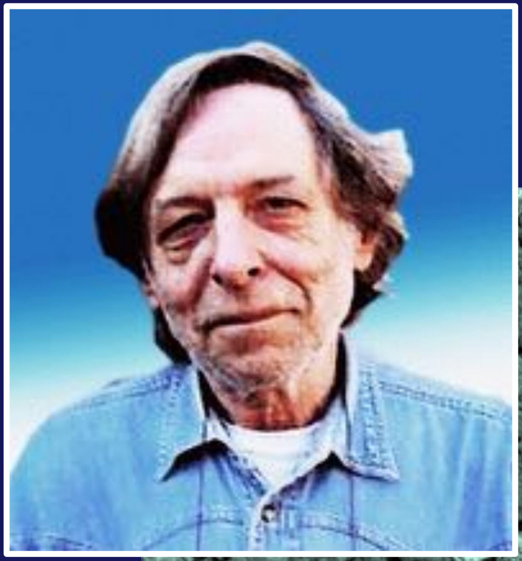


Gilberto Vlaic

…a friend, a pioneer, a wonderful person:
this school demonstrrates that we will never forget him!

Summary: the amazing properties of synchrotron emission

Short, tunable wavelengths

Linear or elliptical polarization

Time structure

Very high flux

High brightness

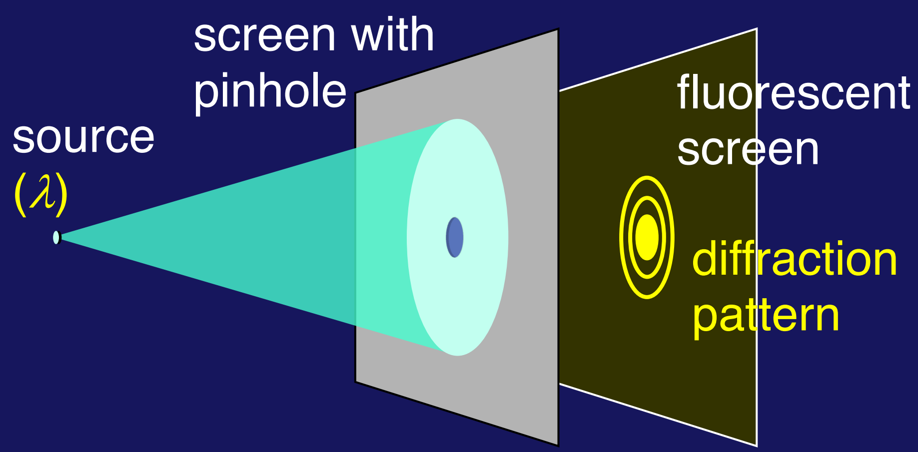
Small source area

Coherence

Narrow angular spread

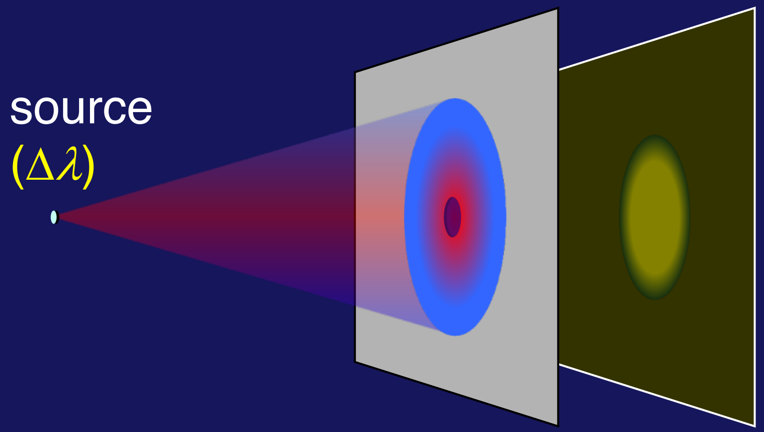
COHERENCE: a key aspect of synchrotron light!

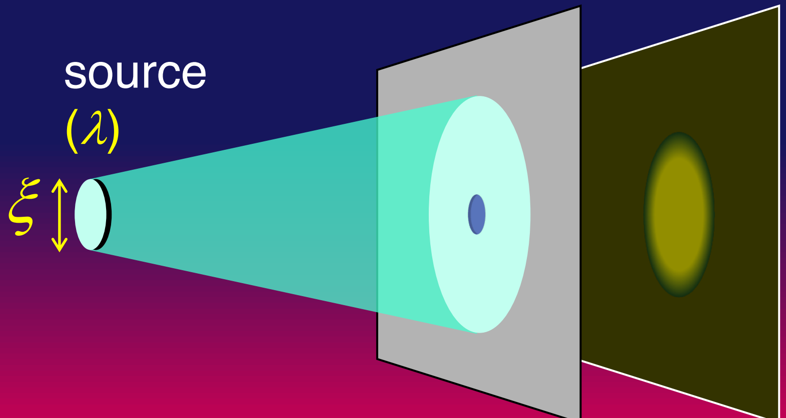
"The property that enables radiation to produce visible wave-like (diffraction or interference) effects"



Analyzing more realistic sources, we find TWO kinds of coherence: "time" and "spatial"

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

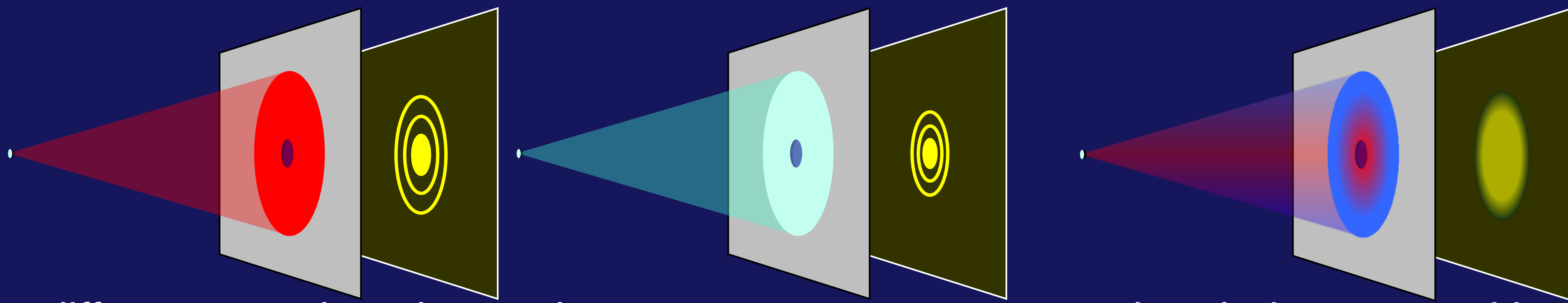




…if the source emits a band of wavelengths, the pattern may no longer be visible: this leads to the notion of "time coherence"

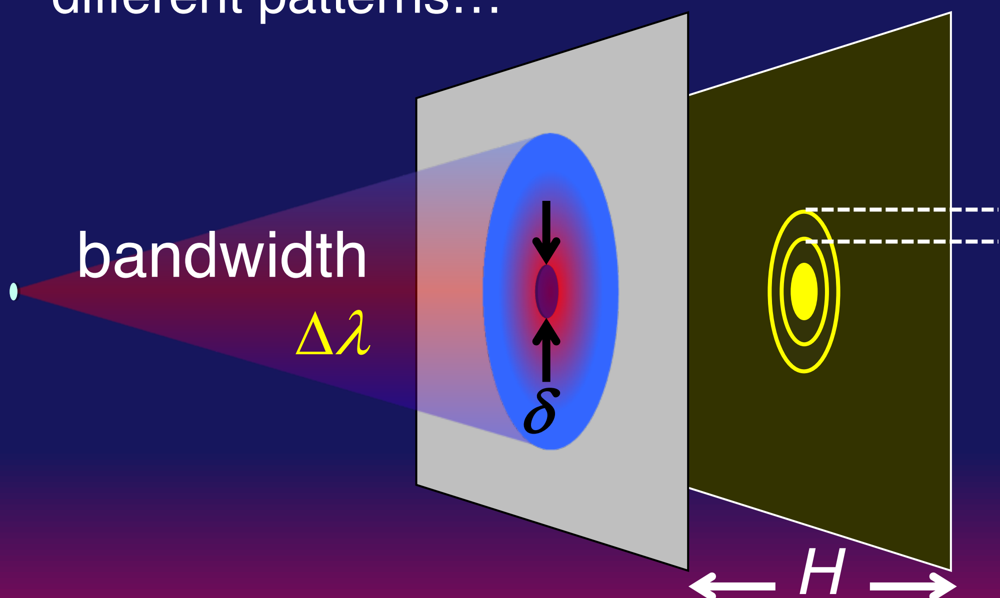
Likewise, if the source has a finite size the pattern may become impossible to see: this leads to "spatial coherence"

Consequences of a finite wavelength band: time (longitudinal) coherence



different wavelengths produce different patterns…

…but their superposition may blur the pattern features



spacing between fringes:

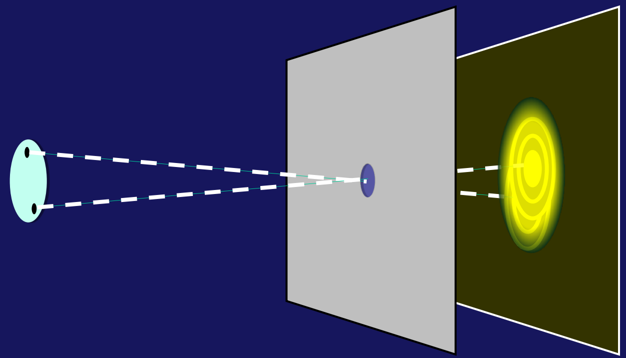
$x \approx (H/\delta)\lambda$

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

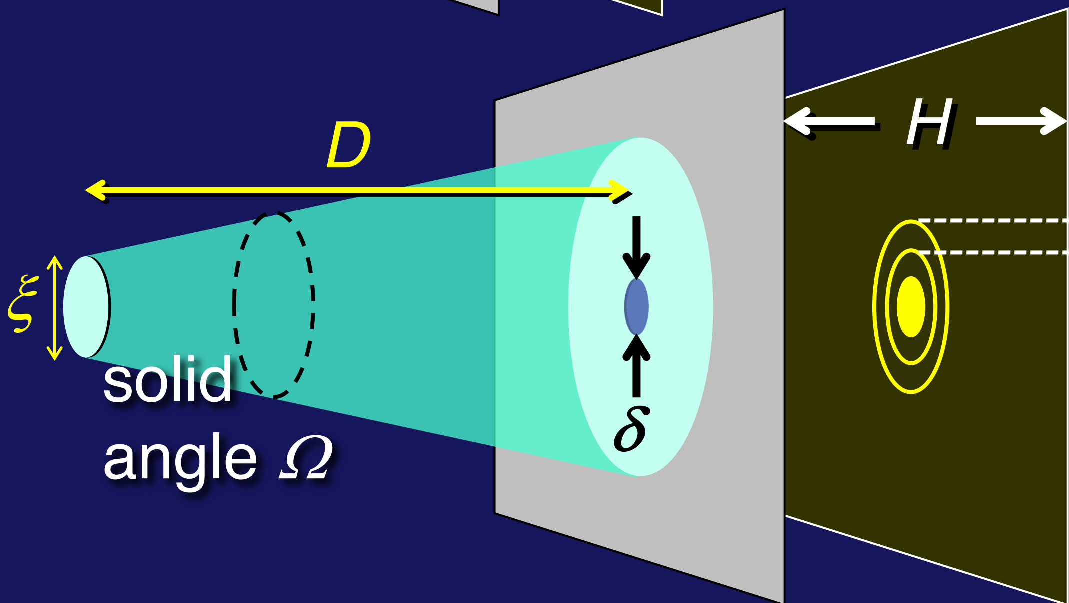
to see the pattern: $\Delta x < x$, $\Delta\lambda/\lambda < 1$

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

Source geometry: spatial (lateral) coherence



Each point in the source produces a diffraction pattern – but the superposition may blur the pattern features



When are such features visible?

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

$x \approx (H/\delta)\lambda$ = fringe spacing

To see the pattern features:

$\xi H/D \leq x \rightarrow$ $\delta \leq \lambda D/\xi$

condition for lateral coherence

Another way to describe lateral coherence:

Illuminated screen area: ΩD^2; pinhole area $\approx \delta^2$; portion of waves that contribute to diffraction:

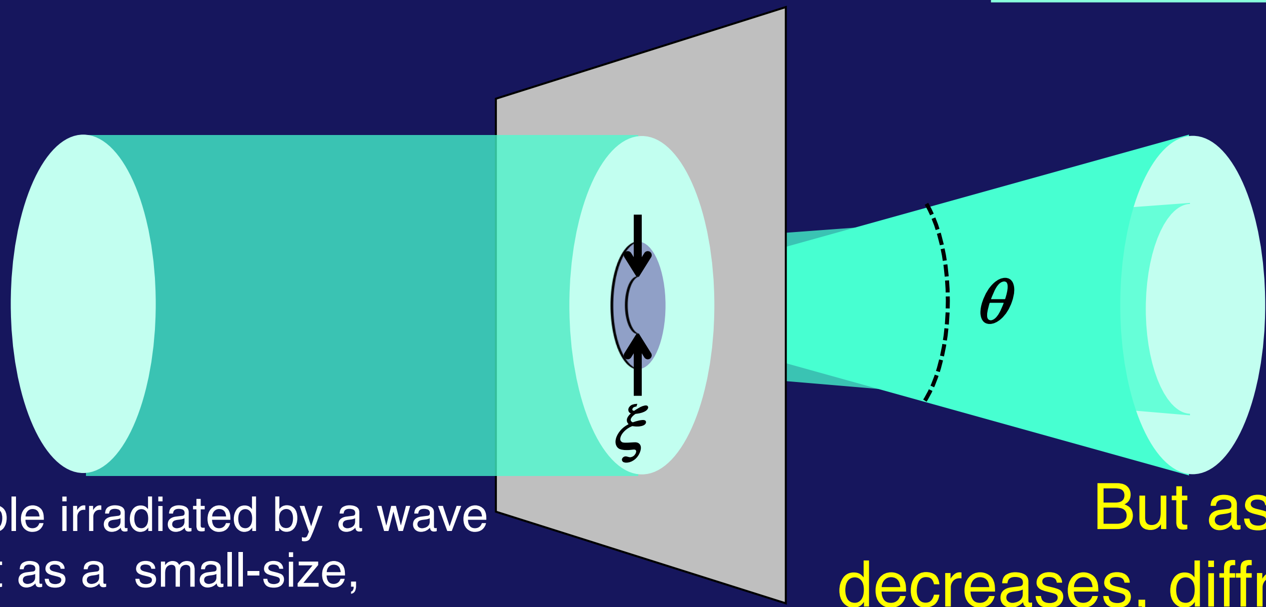
$\approx \delta^2/(\Omega D^2) \leq (\lambda D/\xi)^2/(\Omega D^2) = \lambda^2/(\xi^2\Omega)$

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

Coherence — summary:

- Time (longitudinal) coherence requires a large coherence length $\lambda^2/\Delta\lambda$
- Spatial (lateral) coherence requires a large coherent power factor $\lambda^2/(\xi^2\Omega)$
- Due to the λ^2 terms, both are difficult to achieve for small-wavelength x-rays
- The brightness is proportional to $F/(\xi^2\Omega)$; increasing the brightness by improving the geometric parameters also increases the spatial coherence, since the conditions are the same: small ξ^2 and small Ω

Full lateral coherence: diffraction limit



Solid angle $\Omega \approx \theta^2$

A pinhole irradiated by a wave can act as a small-size, spatially coherent source

But as the pinhole size decreases, diffraction increases the angular divergence

The diffraction theory gives $\xi\theta \approx \lambda$, thus $\xi^2\Omega \approx \lambda^2$

This defines the "diffraction limit" for the coherent power factor:

$$\frac{\lambda^2}{\xi^2\Omega} \approx 1$$

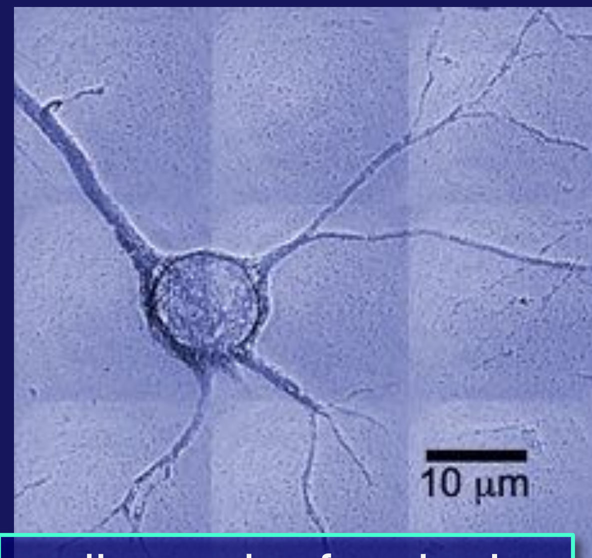
…corresponding to full spatial coherence

some synchrotrons now reach this limit – and so do x-ray FEL's

Using coherence for radiology, the main application of x-rays

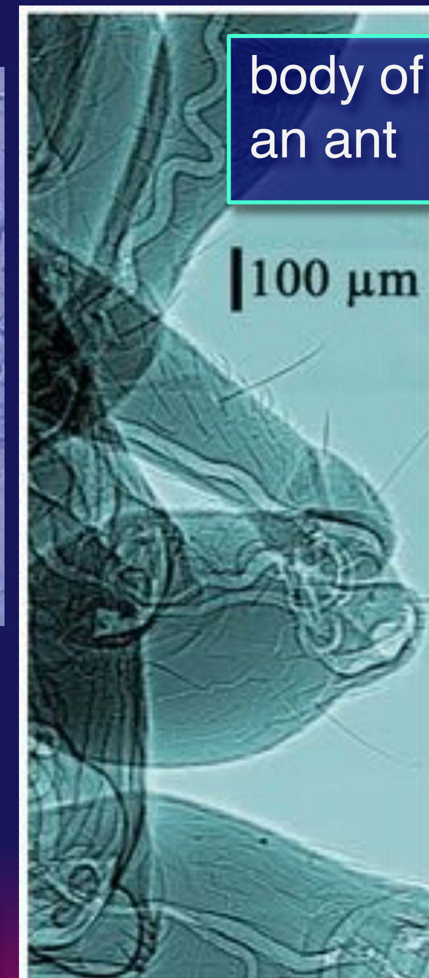
cancer microvasculature

[H. R. Wu et al., J. Phys. **D 45**, 242001 (2012)]



radiograph of a single neuron: world record of spatial resolution

body of an ant



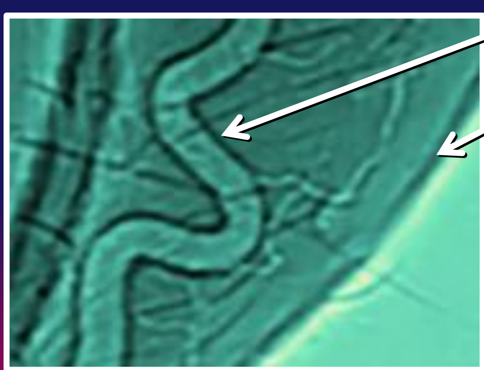
excellent contrast, detection of very small details: what causes them?

Basically, coherence produces holograms – but we can think more simply: how we "see" a glass of red wine

we detects the wine because it absorbs certain colors and looks red

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

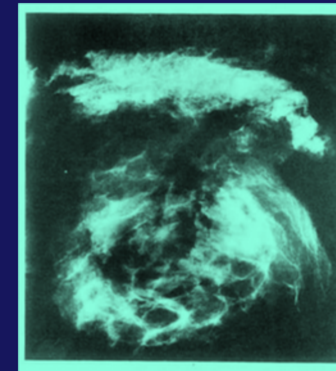
likewise, "phase contrast" (refraction/scattering) causes sharp, highly visible <u>edges</u> in synchrotron radiographs



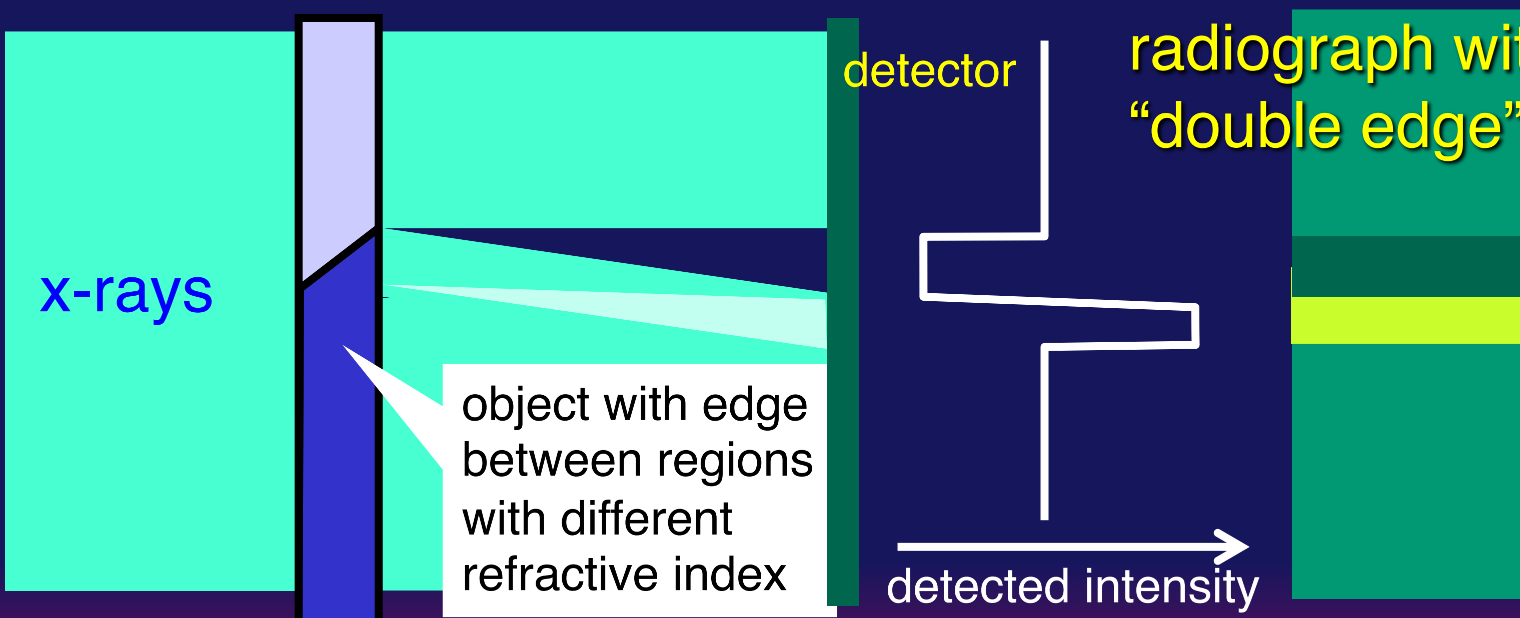
…this requires x-rays with <u>a well-defined direction</u>: fortunately, this is guaranteed by the high spatial coherence of synchrotron sources, which implies <u>angular collimation</u>

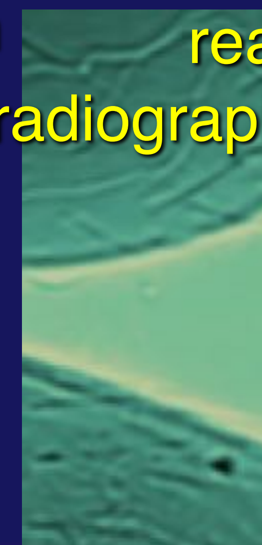
Early history:

Coherence-based phase contrast was already present in the synchrotron radiology results of the 1970's, notably those of Burattini and co-workers in Frascati... but it took some time to recognize their nature



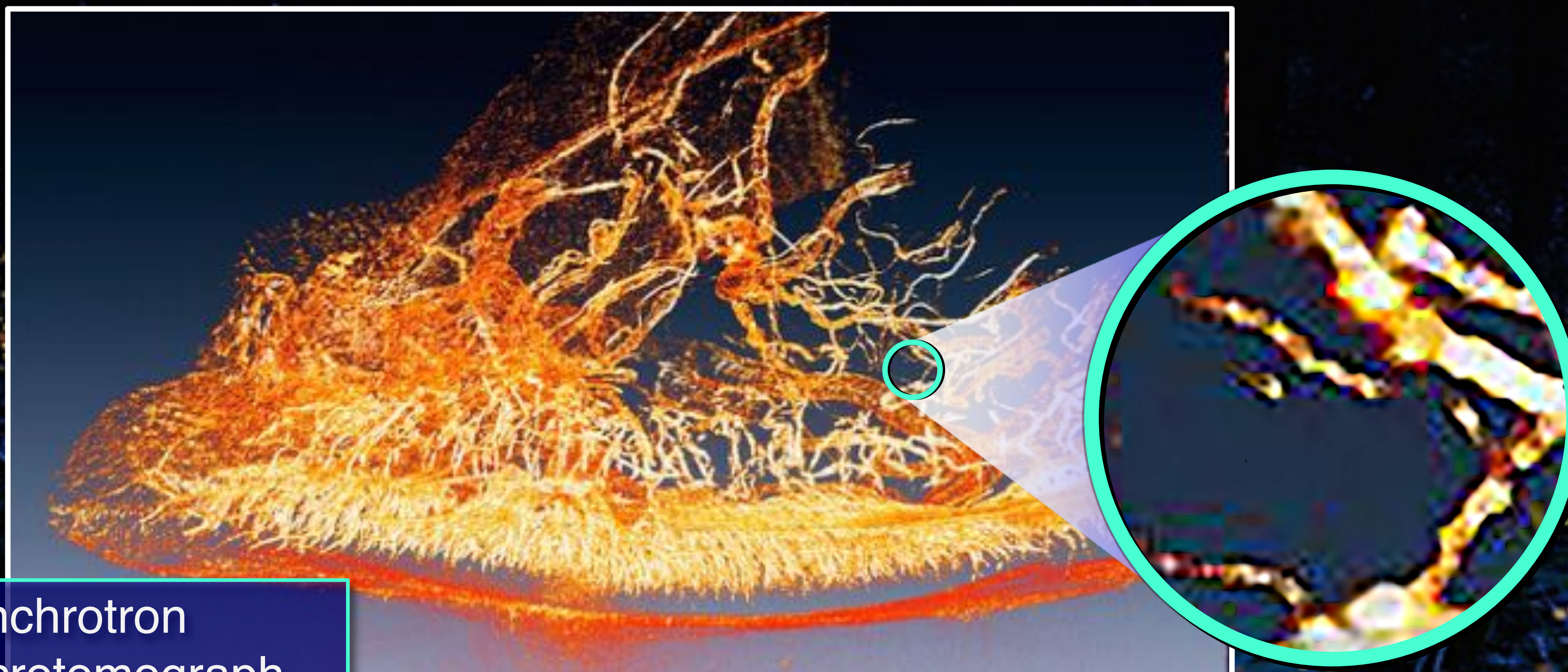
...this was achieved in the late 1990's with a very simple model by Hwu, Tromba and Margaritondo:





...this requires x-rays with a well-defined direction (lateral coherence) – but high longitudinal (time) coherence is not needed

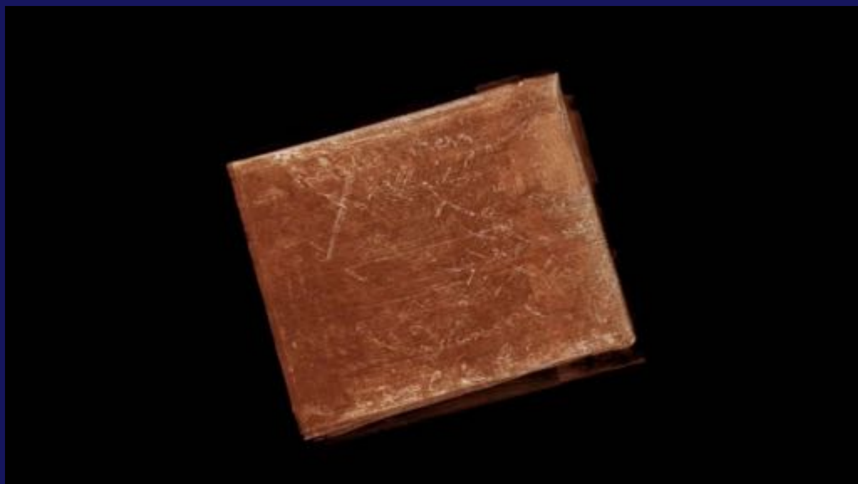
No time coherence required → no monochromator needed. The full source intensity is used, boosting the signal. This allows solving fundamental problems – such as the “magic” luminescence of fireflies



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

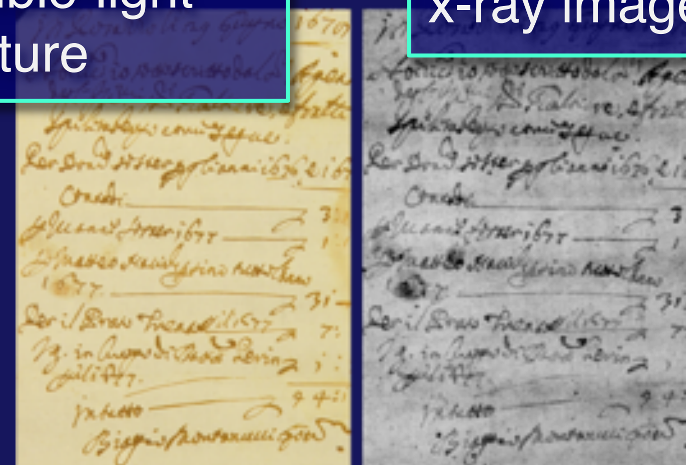
…by detecting all vessels, including the smallest ones, we clarified the extremely effective emission mechanism

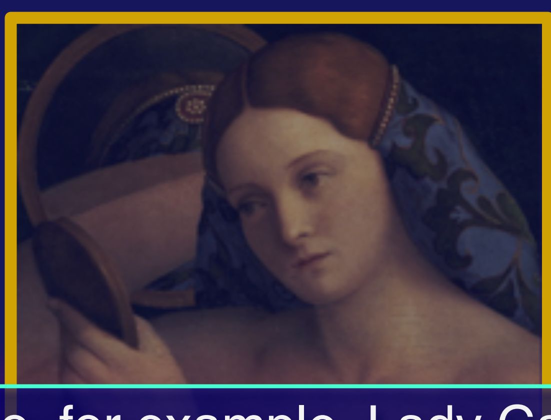
Synchrotron tomography reads ancient manuscripts even under seal:



visible-light picture

x-ray image

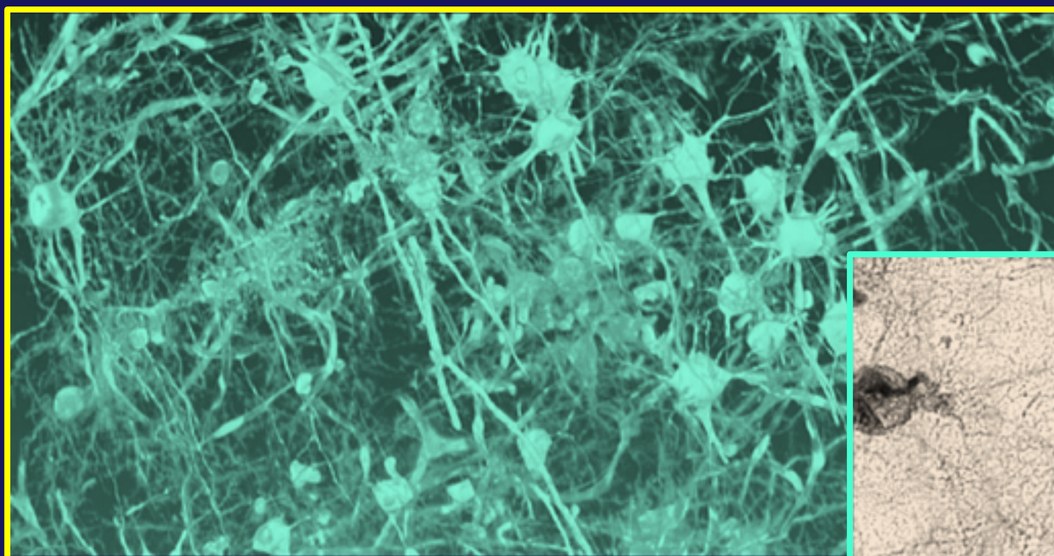


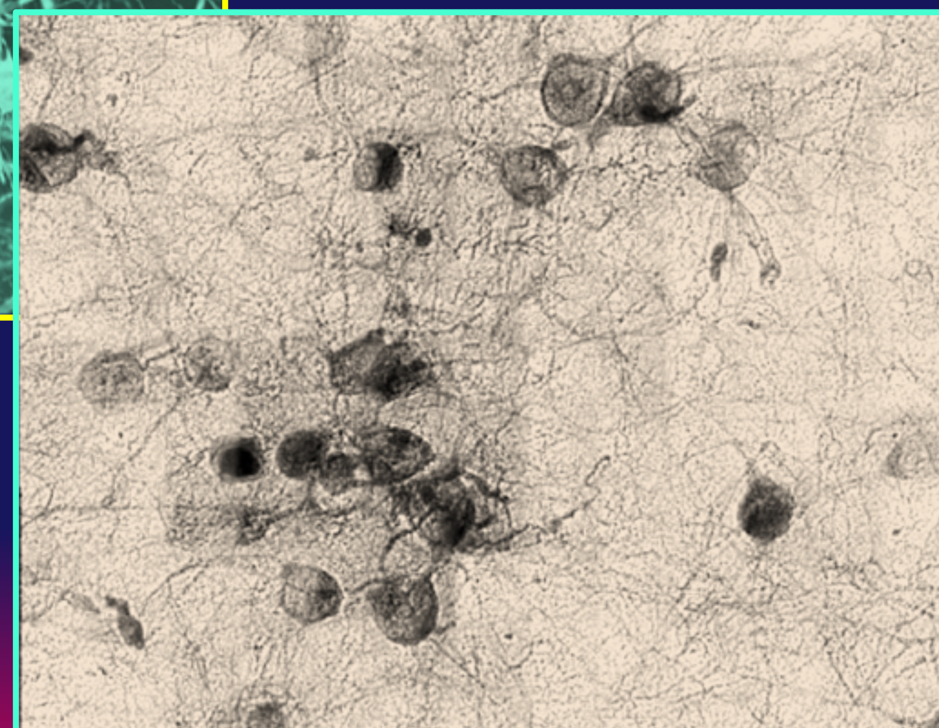


so, for example, Lady Cataruçia Savonario of Venice could speak to us after 7 centuries

…all this, thanks to another remarkable Italian lady: Fauzia Albertin

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



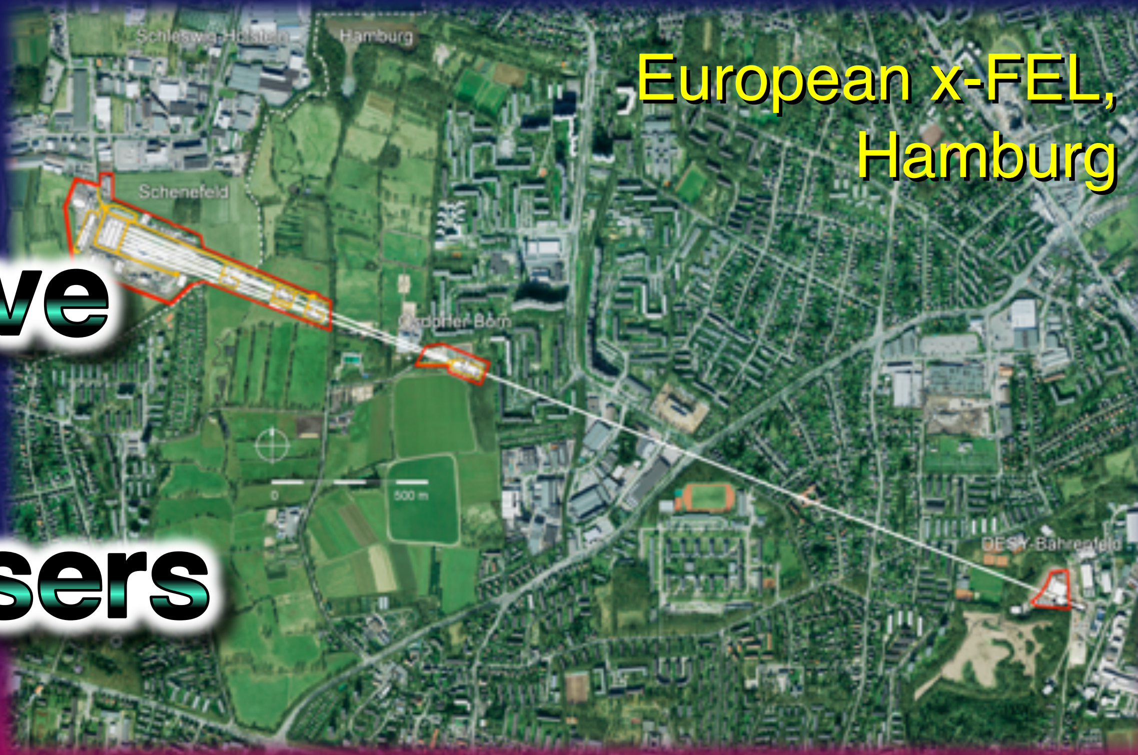


Synchrotron sources:

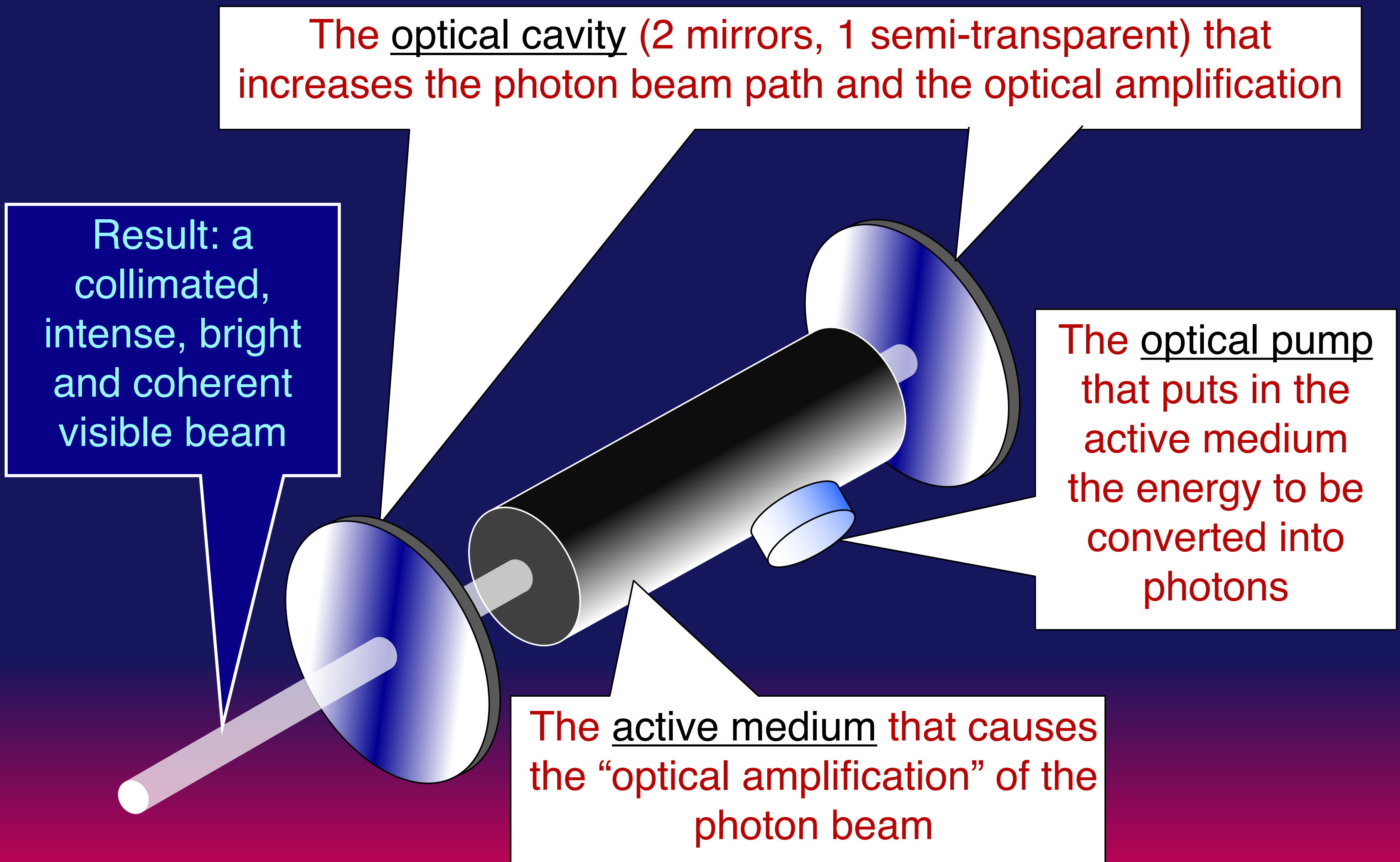
very <u>intense</u> and <u>bright</u>, <u>collimated</u>, <u>coherent</u>, <u>polarized</u>:

are they lasers?

...no, but now we have x-ray free electron lasers (x-FEL's)



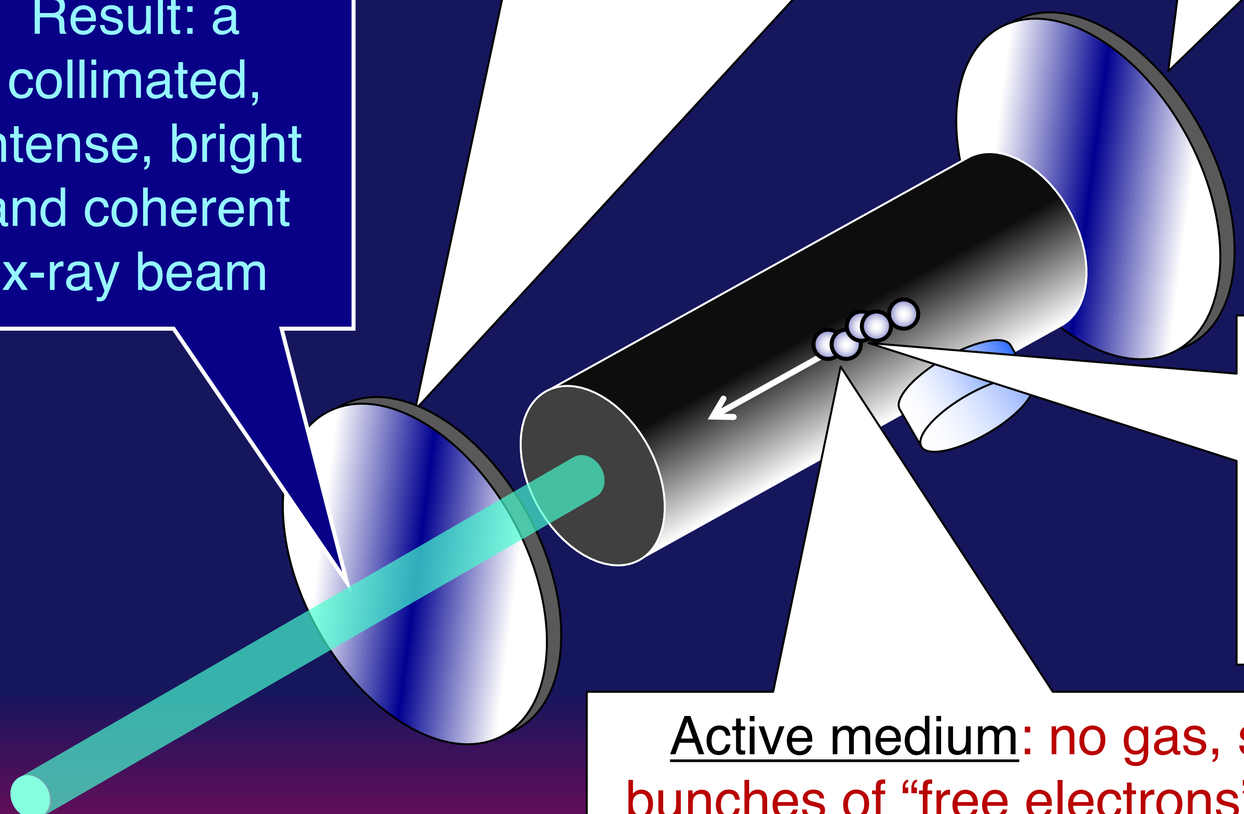
To understand x-FEL's, we start from a normal laser for visible light:



From a normal laser to an x-FEL:

Mirrors do not reflect x-rays ⇒ no optical cavity ⇒ enough amplification needed for **one-pass lasing**

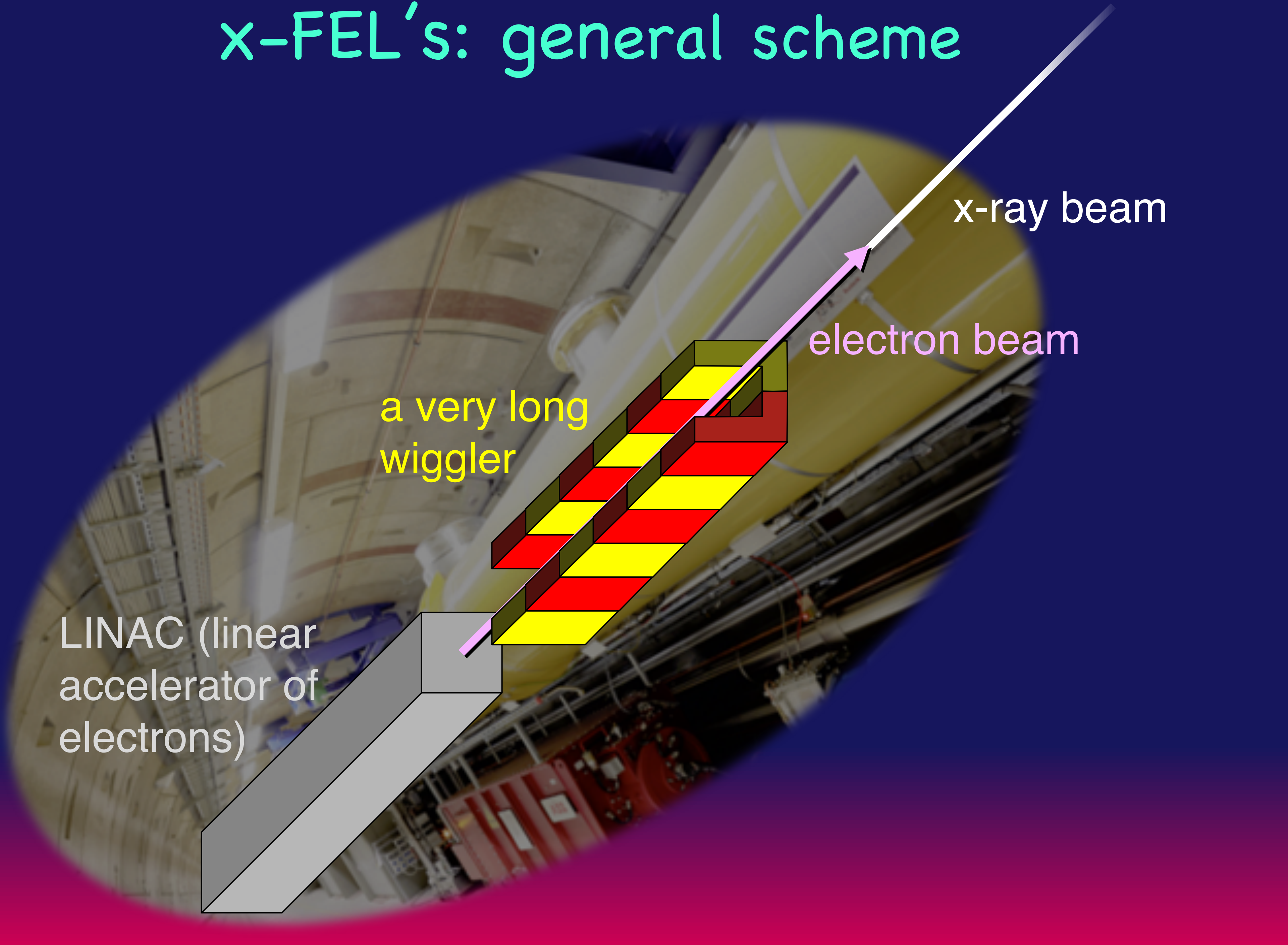
Result: a collimated, intense, bright and coherent x-ray beam



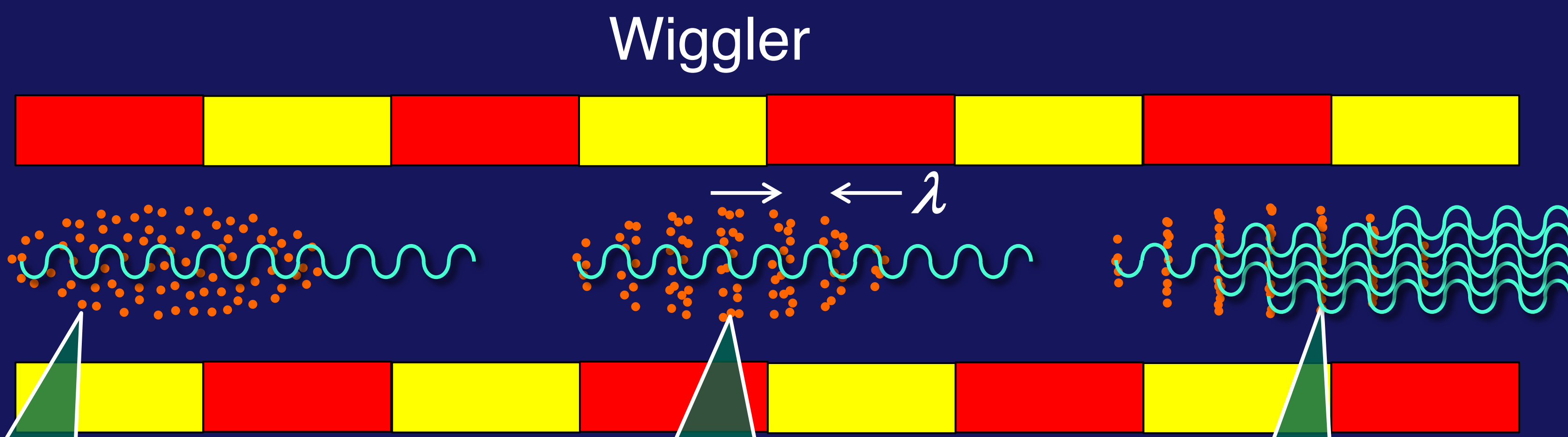
Optical pump: the free electrons themselves carry the energy and transfer it to the photons

Active medium: no gas, solid or liquid but bunches of “free electrons” in an accelerator: high power possible without damage

x-FEL's: general scheme



“sliced Italian salami”: the FEL optical amplification mechanism



A bunch of electrons enters the wiggler: an electron emits a wave

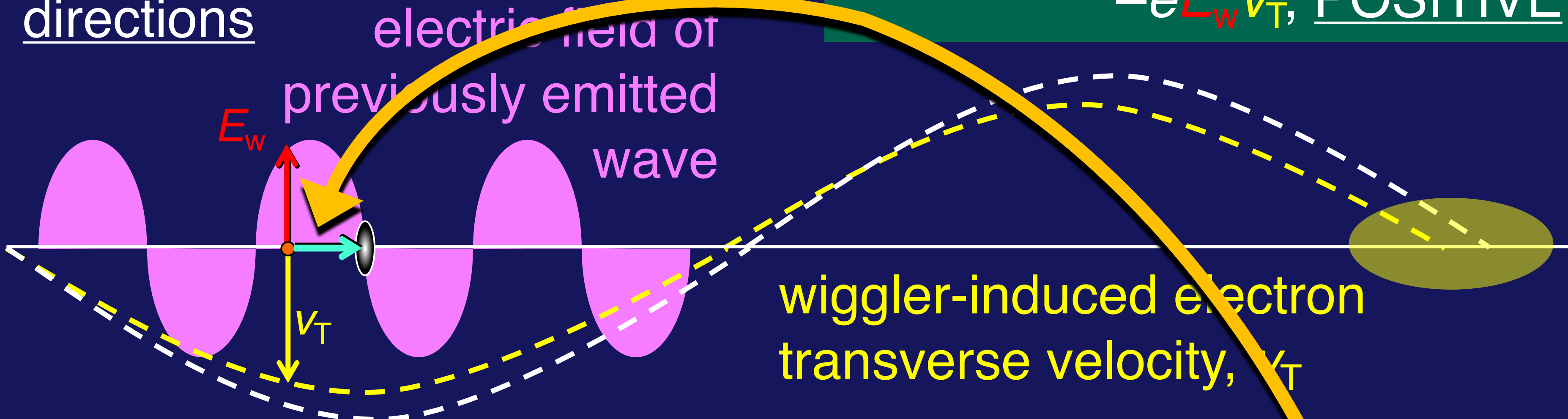
Interacting with the bunch, the wave creates a (sliced) microbunch structure with period equal to the wavelength

Strongly microbunched electrons emit coordinated waves

What causes the microbunching? (top view)

Electron charge: $-e$ (negative)
Wave electric field force: $-eE_w$
Work per unit time:
$-eE_wv_T$, POSITIVE

Here, E_w and v_T are in opposite directions

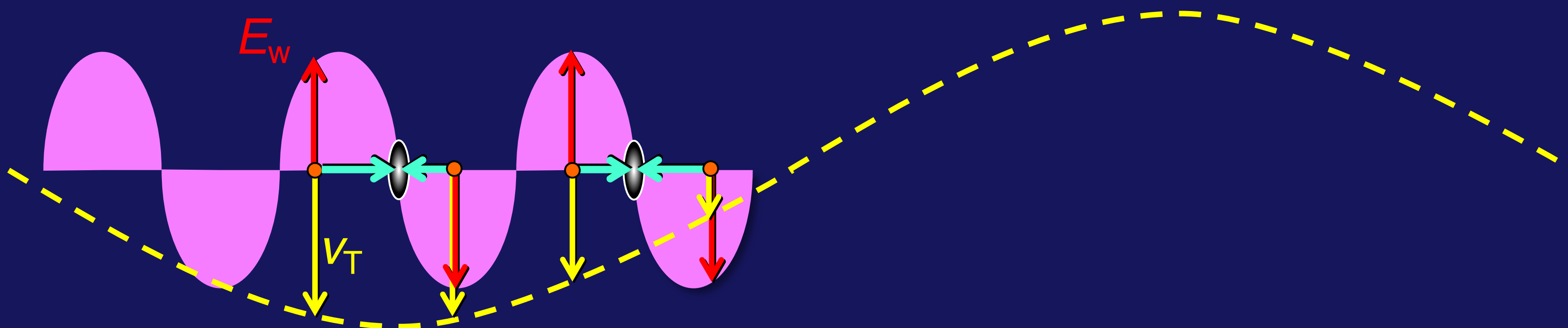


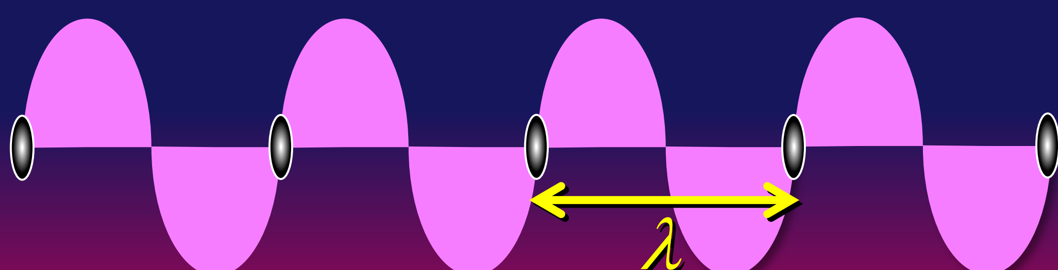
This slightly increases the electron energy and causes small changes in the electron trajectory.

Longitudinally, the effect is equivalent to a force that "pushes forward" the electron towards a wave node

What happens to other electrons?

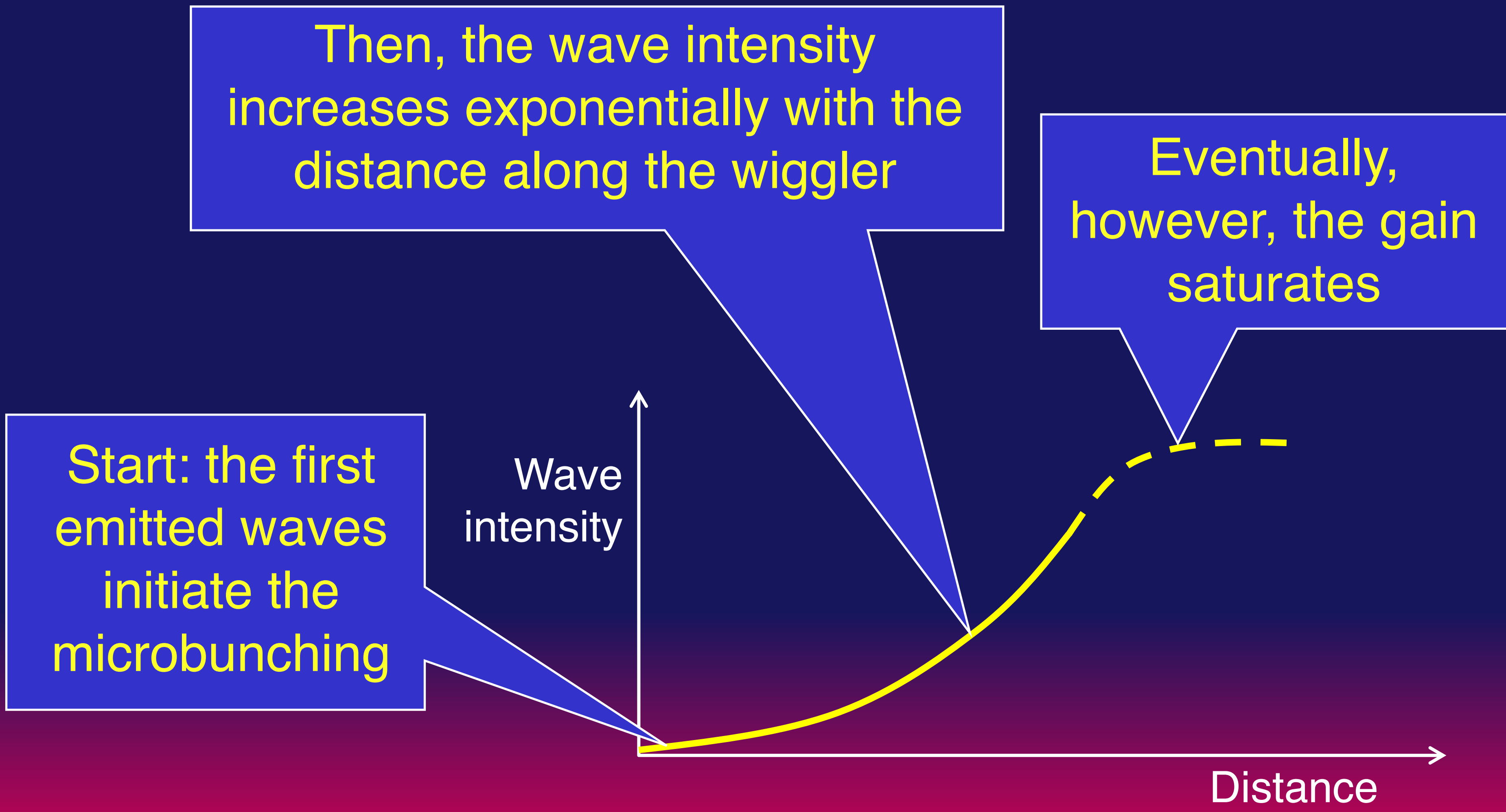
Look at the directions of E_w and v_T: the electrons are pushed towards every other wave node





This creates the microbunches, with period equal to the wavelength

Microbunching and coordinated emission produce a progressive increase of the wave (Self-Amplified Spontaneous Emission, SASE)

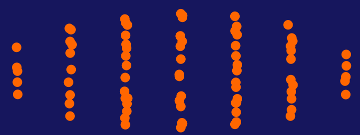


What causes the exponential intensity increase along the wiggler?

- Define: I = wave intensity; E_w = wave E-field, proportional to $\sqrt{I}$
- v_T = electron transverse velocity
- dI/dt = energy transfer rate (electrons→wave), determined by: (1) the transfer rate for one electron, (2) the microbunching
- The one-electron transfer rate is given by the (negative) work, proportional to $E_w v_T$
- The microbunching is proportional to E_w

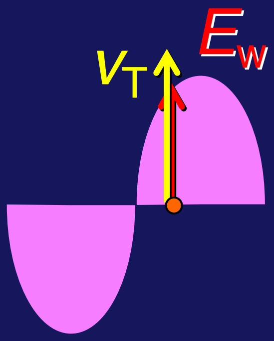
- **dI/dt is proportional to $E_w E_w$ and therefore to $\sqrt{I}\,\sqrt{I} = I$**
- **$dI/dt = C\,I$, with C = constant corresponds to $I = I_o \exp(Ct)$, an exponential increase of I with t, and also with the distance = vt**

Why does the intensity increase saturate?



After a certain distance, the microbunching is complete, and the amplification slows down

Plus, the electrons lose energy to the wave and their γ decreases, changing the emitted wavelength $L/(2\gamma^2)$: they no longer contribute to the wave intensity

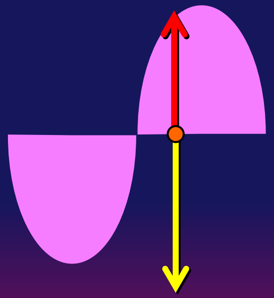


Also note: for electron→wave energy transfer, the directions of v_T and of the wave E-field must produce negative work: this is true here

But, as the electron gives energy to the wave, it slows down: the direction of v_T relative to E_w changes.

Eventually, this leads to wave → electron energy transfer

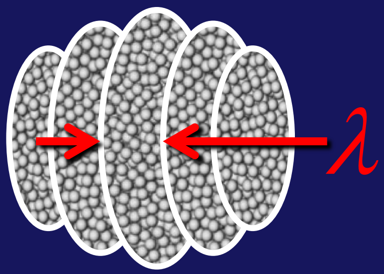
The electrons accelerate until they reach again the conditions for electron → wave energy transfer



The mechanism goes on and on, with electrons-wave energy oscillations rather than a continuous wave amplification

A paradox?

At short wavelengths, free electron lasing is very difficult: x-FEL's were realized only several decades after the infrared FEL's

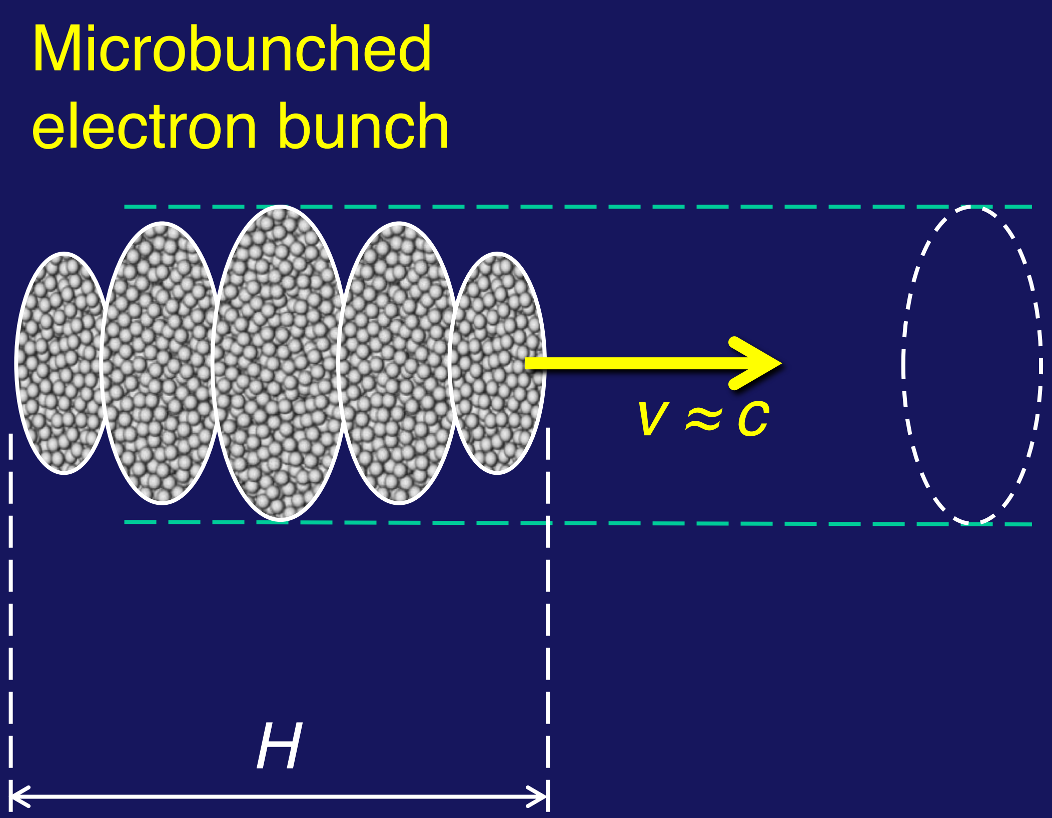


…but why? At short x-ray wavelengths the microbunches are close to each other and require short shifts of the electrons inside their bunches: should microbunching be easier?

NO, BECAUSE:

- A short wavelength $L/(2\gamma^2)$ requires a large γ
- A large γ boosts the longitudinal relativistic mass $\gamma^3 m_o$, making the electrons "heavy" and difficult to move to the microbunches
- **Furthermore, the small spacing between microbunches makes the microbunched structure very vulnerable to perturbations**
- Finally, one-pass lasing requires, besides a long wiggler, a very small, high-density electron bunch, i.e., an excellent electron beam control (this is why "normal" wigglers are not x-FEL's)

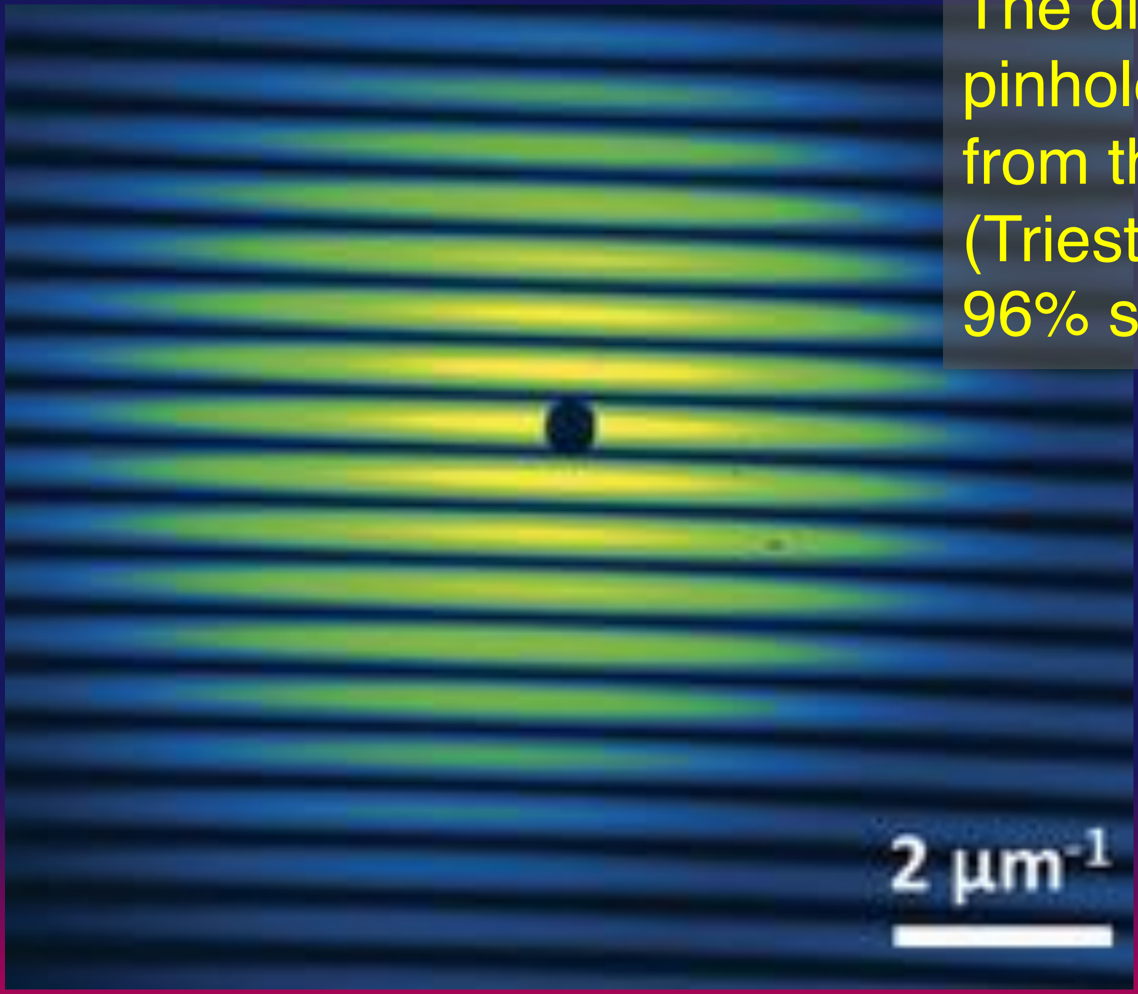
Geometry and duration of an FEL pulse:



One-pass lasing requires a very small electron bunch cross section, producing a small transverse size of the photon pulse

Likewise, the electron bunch length H must also be very small, corresponding to a small photon pulse duration $H/v \approx H/c$, in the femtosecond range or less

The spatial coherence of x-FEL's is high (close to the diffraction limit)

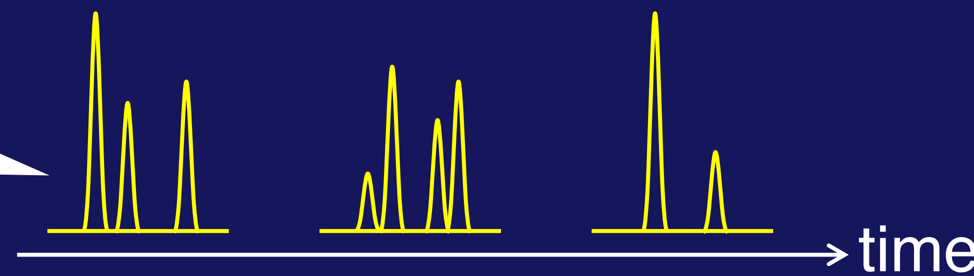


The diffraction by two pinholes of 32.5 nm pulses from the FERMI FEL (Trieste) demonstrates 96% spatial coherence

On the contrary, a serious problem affects the x-FEL time (longitudinal) coherence:

SASE amplifies waves that are stochastically emitted when the electron bunch enters the wiggler

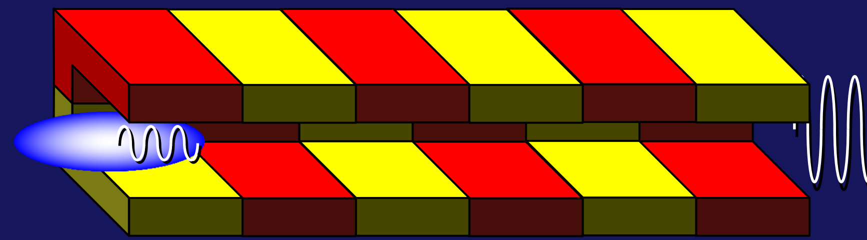
The time structure changes from pulse to pulse, broadening the wavelength spectrum and limiting the time coherence



Possible solution: "seeding", i.e., amplifying a wave with high time coherence, produced by an external source and injected into the x-FEL

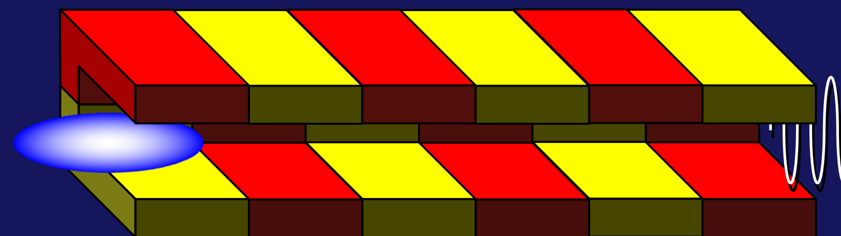
A complicated technology, but now a reality

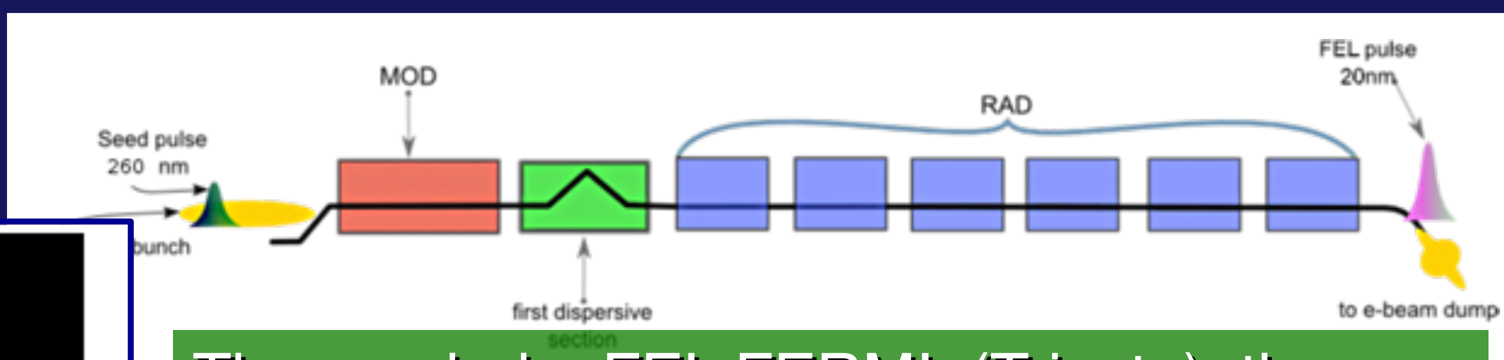
SASE vs. seeding:

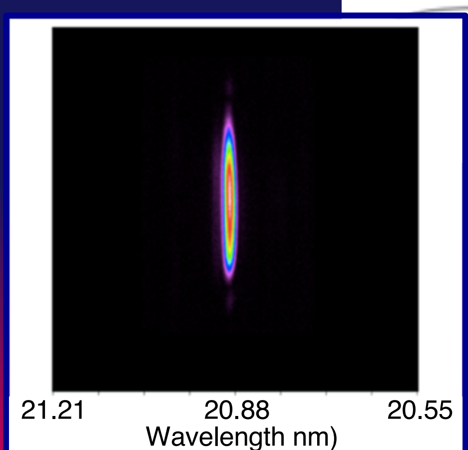


SASE amplifies waves spontaneously (randomly) emitted by electrons as the bunch enters the wiggler

Seeding amplifies waves injected by an external source







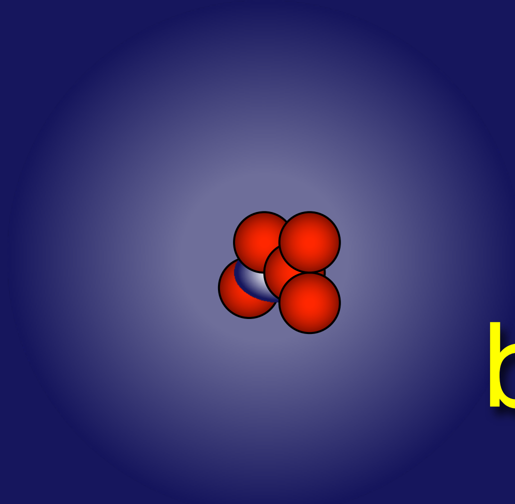
The seeded x-FEL FERMI (Trieste): the narrow wavelength bandwidth demonstrates high time coherence (E. Allaria et al., Nature Photonics **6**, 699 (2012) and **7**, 913 (2013)

The FERMI FEL in Trieste

X-ray FEL's are now a reality:
what can we do with them?

x-FEL's emit femtosecond pulses of tens of gigawatts: <u>how</u> can we handle all this power, and how can we use it?

…sent into a molecule or a nanoparticle, it causes an explosion:



boom!

…but, as the pulse is ultrashort, we can try to extrapolate from diffraction data the structure <u>before</u> the explosion

What happens at the femtosecond scale typical of x-FEL pulses?

Fast chemical reactions

In 100 femtoseconds shock and sound waves travel in solids over atomic distances

A water molecule dissociates in 10 femtoseconds

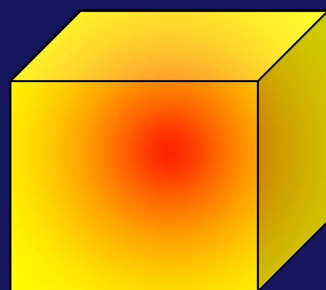
Photons propagate over hundreds of nanometers

Typical periods of molecular vibrations: 10-100 femtoseconds

Laser surgery without collateral damage

Novel micromachining techniques, etc…

The high power and energy density of an x-FEL can create extreme short-lived conditions for materials



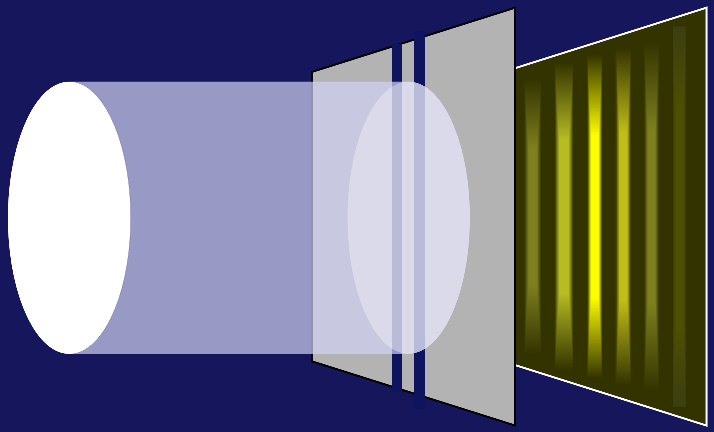
HED (High Energy Density) regime:

- Extreme pressure
- Extreme temperature
- Extreme density, etc…

The experiments are important for:

- Nuclear fusion research
- Laboratory astrophysics
- Technology of high-power sources, and other fields

FELs go to the roots of quantum physics:



What causes interference and diffraction for photons?

First-order Quantum Electrodynamics (QED):
(1) Interference and diffraction are wave-like interactions of each photon only with itself
(2) Multiple-photon effects are negligible

BUT: with "seeded" x-FELs, (2) can change and lead to new techniques!

Joachim Stöhr, Synchrotron Radiation News 32 (2019)

Ending our journey, I would like to thank:

- Primoz Rebernik for his contributions to our FEL theory
- Maya Kiskinova and Yeukuang Hwu for disclosing their experimental results
- The school organizers for their kind invitation

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