INTERNATIONAL YEAR OF LIGHT 2015

# Synchrotron light: a very bright torch and some uses


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DAΦNE Light
Synchrotron Radiation Facility

*INSPYRE 2015 – INternational School on modern PhYsics and REsearch- LNF – 19 February 2015*

# 2015 - International year of light

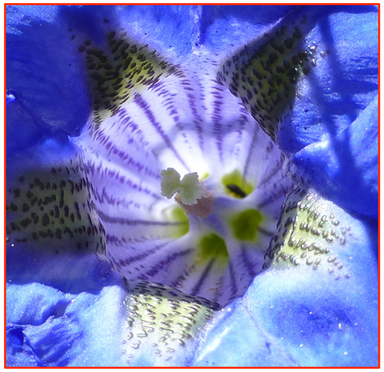
INTERNATIONAL
YEAR OF LIGHT
2015

United Nations designated ***2015 as the International Year of Light and Light-based Technologies.***
***2015 marks many anniversaries***:

- the ***first scientific accounts of optics published*** by the Islamic scholar Ibn al-Haytham in 1015;
- August Fresnel's proposal in 1815 that ***light is a wave***;
- James Clerk Maxwell's 1865 ***electromagnetic theory of light***;
- Albert Einstein's 1915 ***general theory of relativity***;
- 1965 the ***discovery of the cosmic microwave background radiation*** and the ***development of optical fibers*** for communication.

# Light sources

***Fire** is not a very useful light source to see small details because its emitted power is **spread in all directions**!*



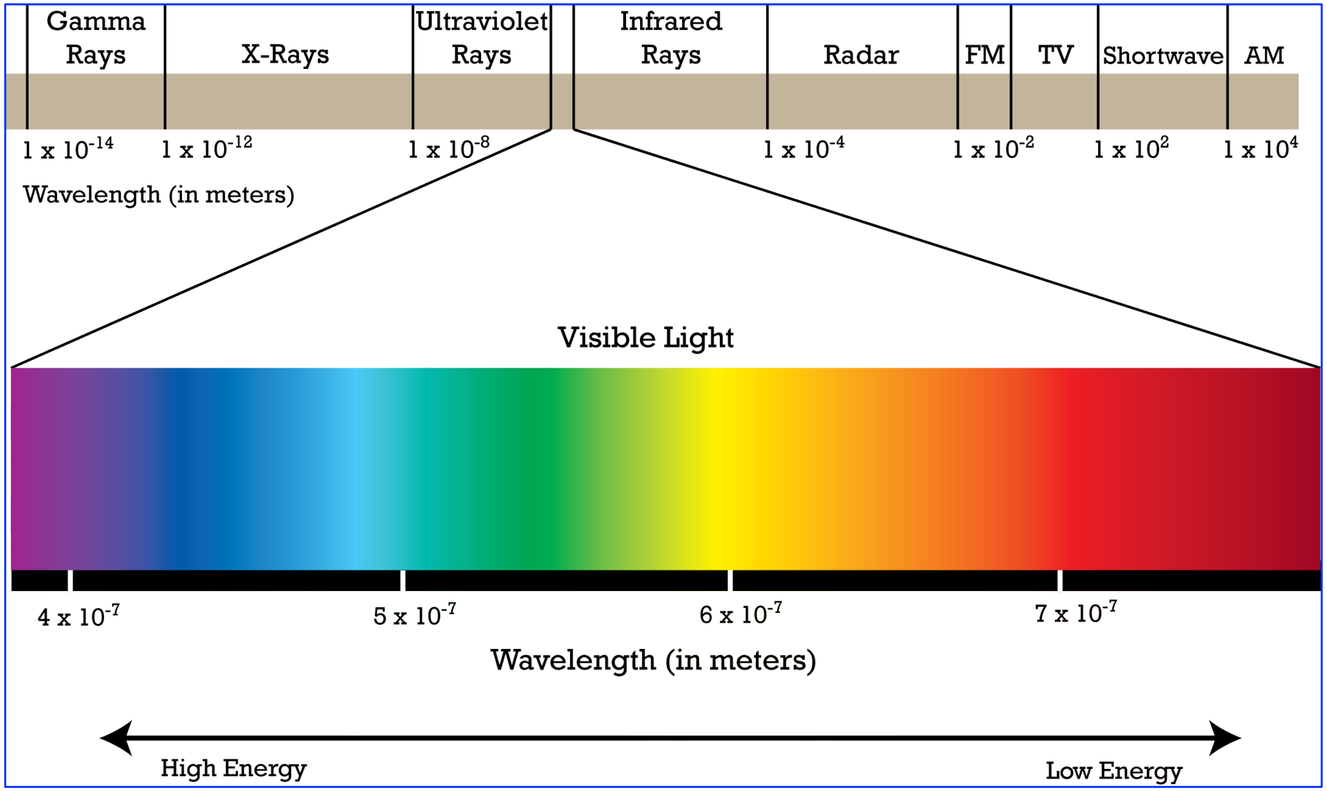
*A torchlight is more adequate because due to its small size the emission is **concentrated within a narrow angular spread: this a "bright" source**!*

***Synchrotron radiation is a very bright light source** that, as will be shown, gives us the chance to **study also things that we cannot "see " with our eyes using not visible light but X-rays**!*

# Visible Light

***Visible light*** is only a ***tiny slice of the electromagnetic spectrum***. The entire electromagnetic spectrum of light is huge, spanning from ***gamma rays on one end to radio waves***.

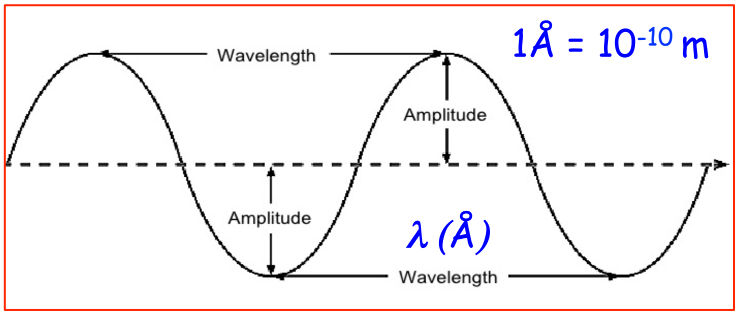
***Visible Light is the light we can see using our eyes***. This tiny human spectrum encompasses a very specific range of wavelengths from about ***380 nm to 780 nm***.

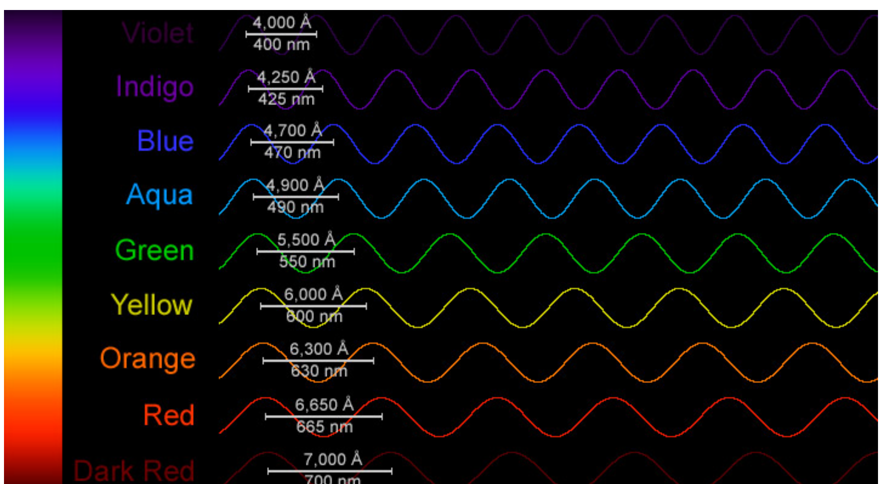


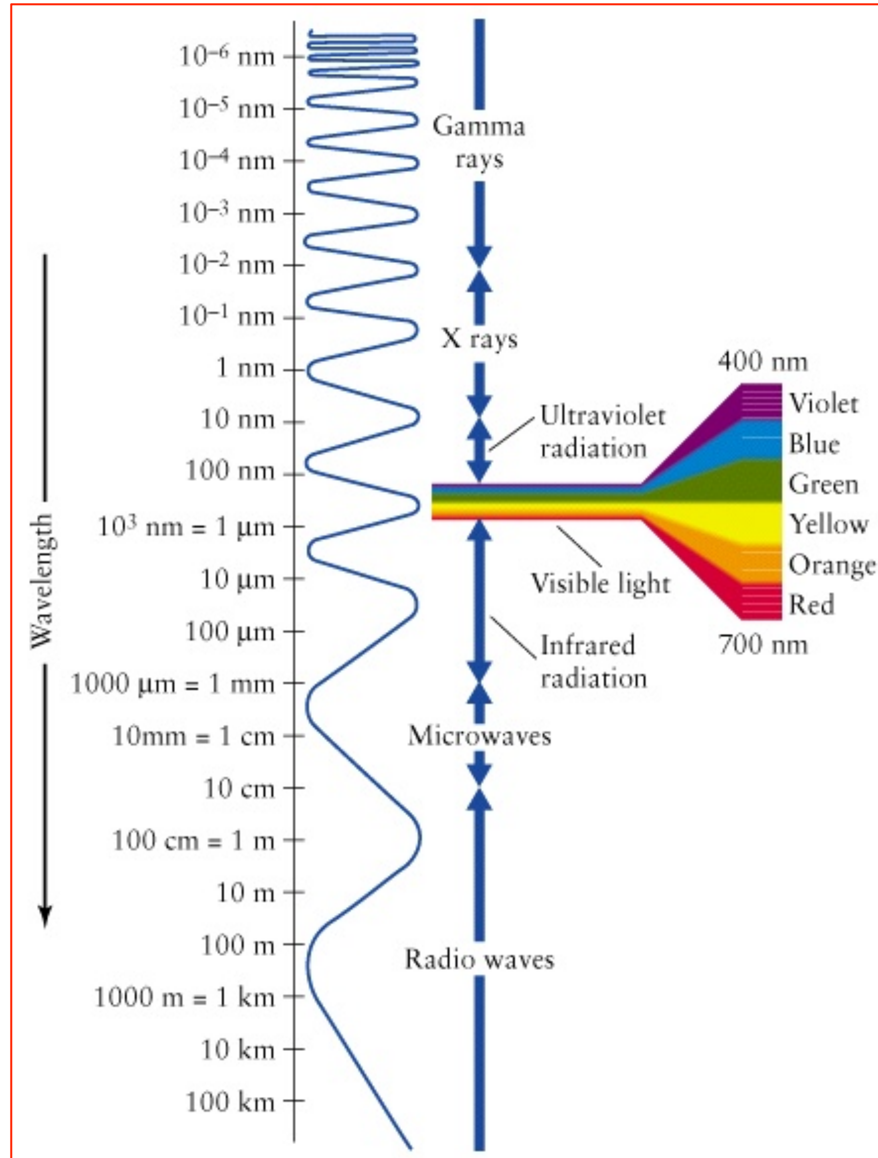

***Physiologically we see these frequencies because the photoreceptors in our retinas are sensitive to them***. When photons of light hit the photoreceptors it creates an electrochemical signal which is the first step in a fascinating process which ultimately results in us seeing colors.

# Light and waves

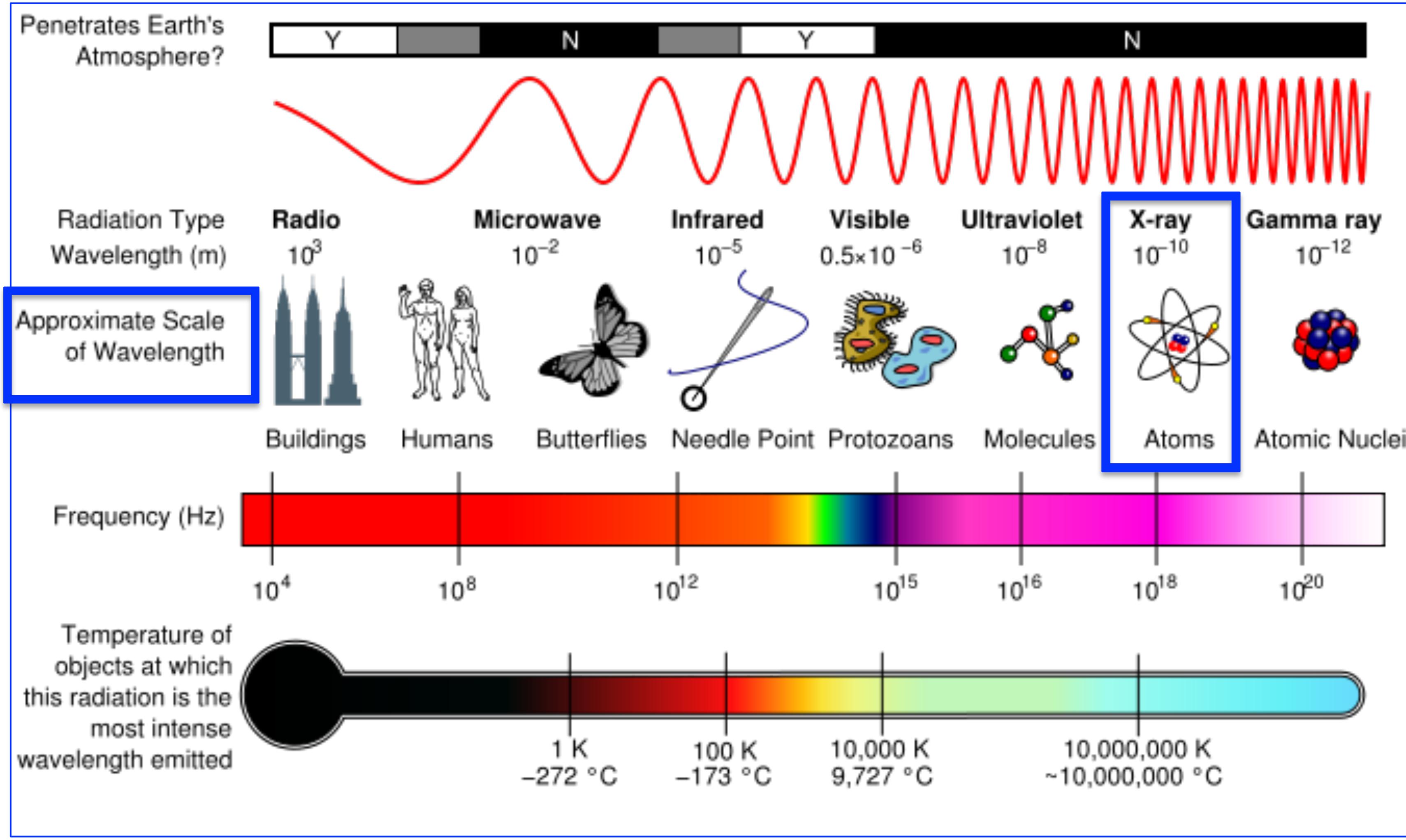
***Light travels as waves*** of energy. Waves of light have different ***wavelengths*** (the distance between the top of one wave and the top of the next). ***Different colors of visible light have different wavelengths***.



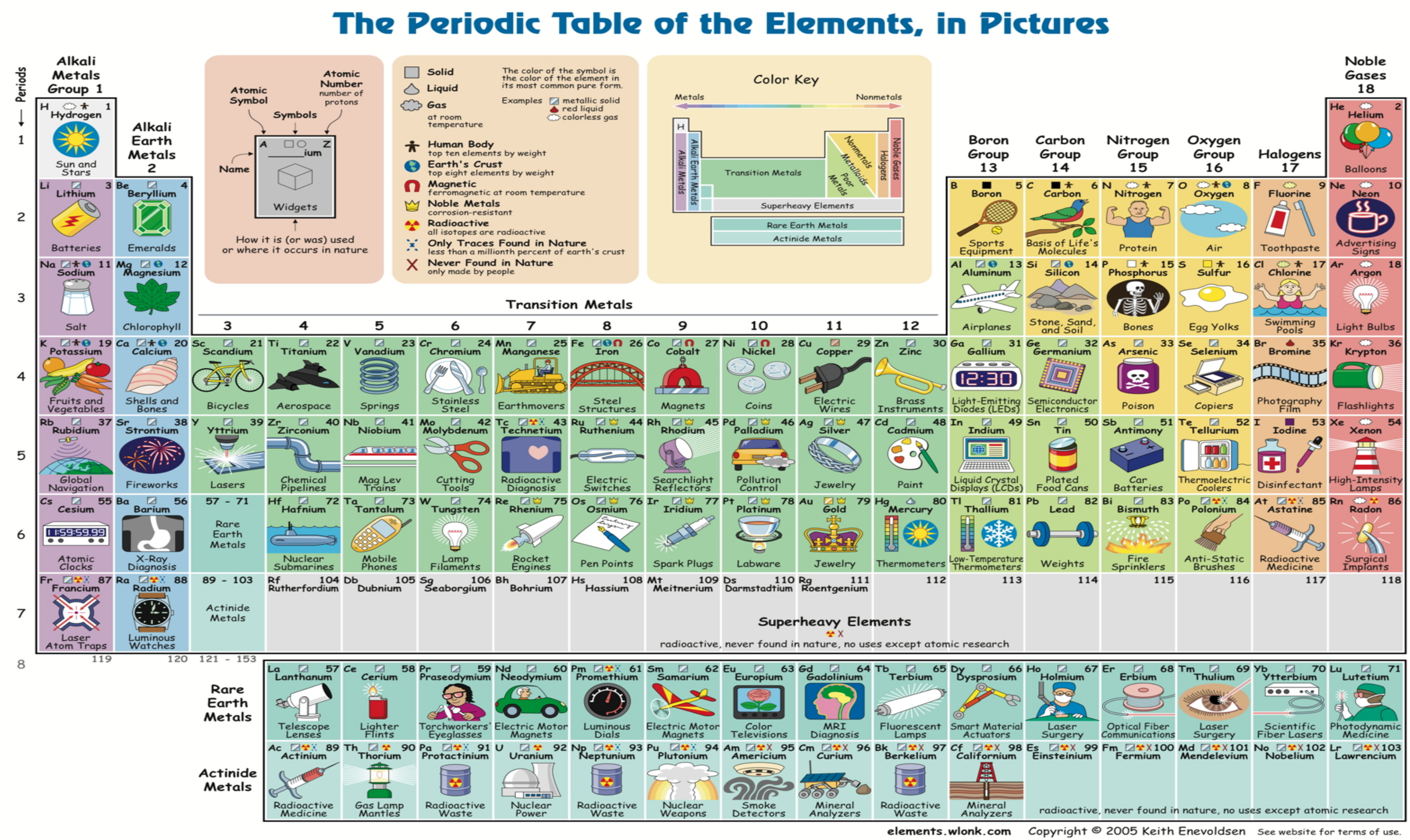
# Electromagnetic Spectrum and X-rays




The ***wavelength*** ($\lambda$) and ***frequency*** ($\nu$) ***of light are strictly related***: the higher the frequency the shorter the wavelength! This is because ***all light waves move through vacuum at the same speed*** (*c* = speed of light) and the equation that relates wavelength and frequency for electromagnetic waves is: $\lambda\nu = c$

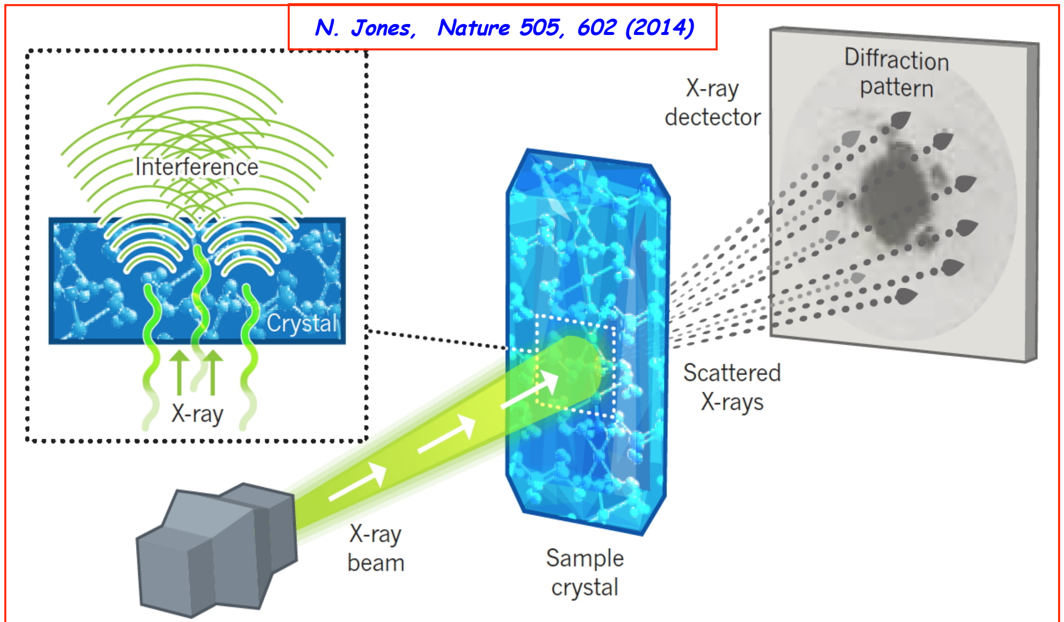
# Atoms

*Matter is everything around us! All matter such as solids, liquids, and gases, is composed of atoms. Therefore, atoms are considered to be the basic building block of matter. From the periodic table, it can be seen that there are only about 100 different kinds of atoms. These same 100 atoms form thousands of different substances ranging from the air we breathe to the metal used to support tall buildings.*



# Atoms and X-rays

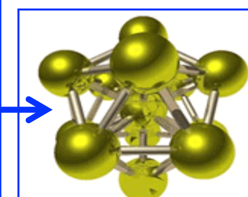
N. Jones, Nature 505, 602 (2014)




*With X-rays we can study atoms because wavelengths are of the order of $10^{-10}$ m or 0.1 nm or 1Å*

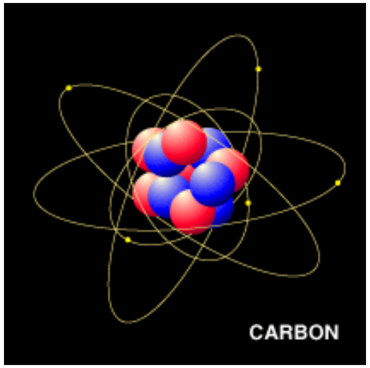
*Matter is composed of atoms!*

*Using X-rays we can study the atomic structure of materials! The atomic structure primarily affects the chemical, physical, thermal, electrical, magnetic, and optical properties.*

*Why is this important?*

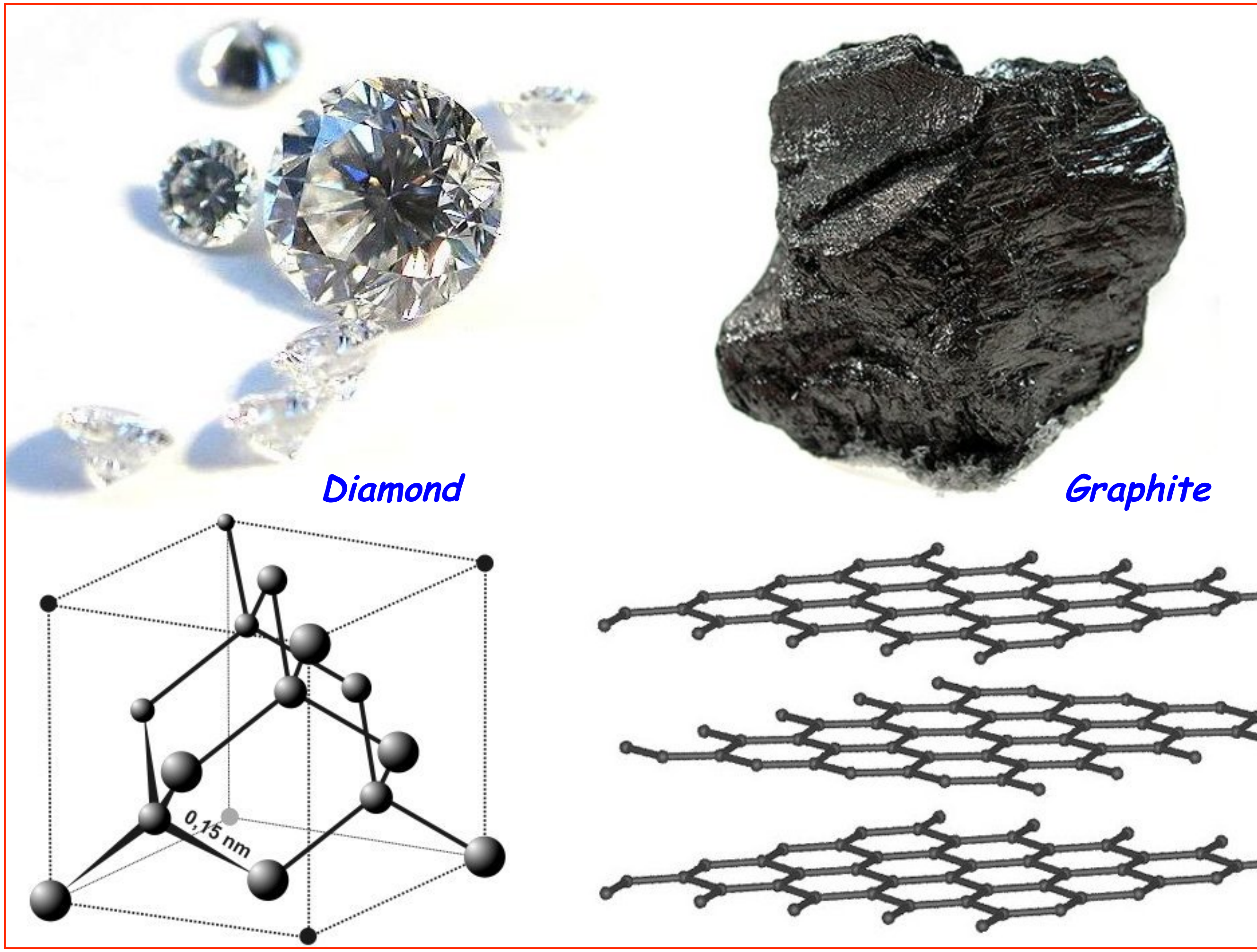
# Atoms and X-rays




Both diamond and graphite are made entirely out of carbon!

The differing properties of graphite and diamond arise from their distinct crystal structures.

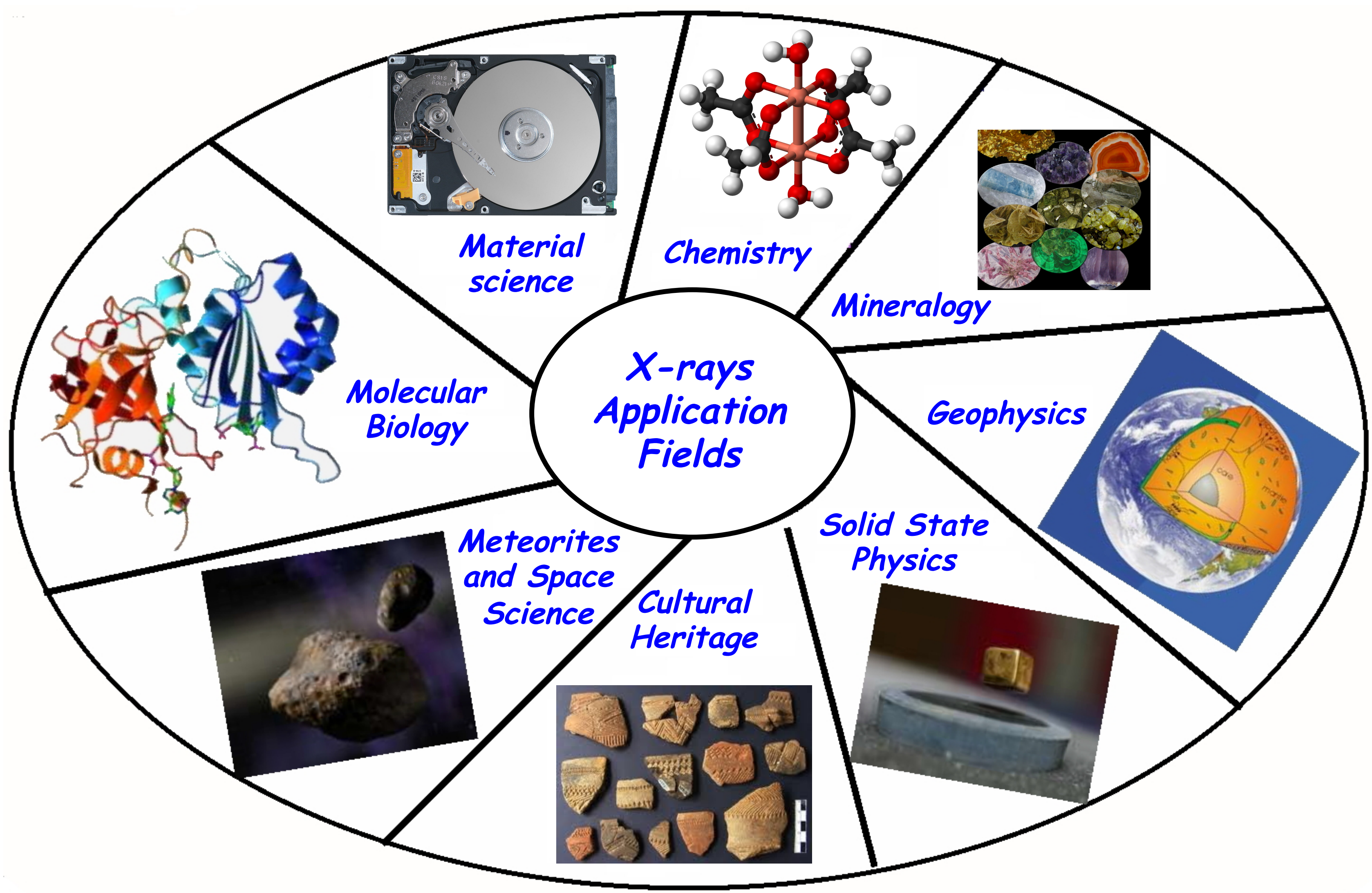
Graphite is opaque and metallic- to earthy-looking, while diamonds are transparent and brilliant.




In ***graphite,*** the ***individual carbon atoms link up to form sheets of carbon atoms***. Within each sheet every carbon atom is bonded to three adjacent carbon atoms (***covalent bonds***) producing hexagonal rings of carbon atoms. ***Weak bonding forces called van der Waals forces hold the sheets together***. Because these ***forces are weak, the sheets can easily slide past each other***. The sliding of these ***sheets gives graphite its softness for writing and its lubricating properties***.

***In diamonds***, ***each carbon atom is strongly bonded to four adjacent carbon atoms located at the apices of a tetrahedron*** (a three-sided pyramid). The four valence electrons of each carbon atom participate in the formation of ***very strong covalent bonds***. These bonds have the same strength in all directions. ***This gives diamonds their great hardness.***

# X-rays application fields



# Bright X-ray source?

HE Particle accelerators

↓

Synchrotron light

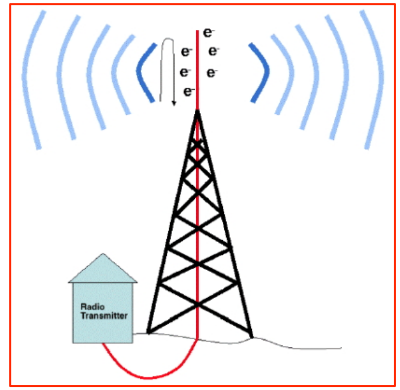
# Answers to be given!

- What is synchrotron light?
- How is it produced?
- History?
- Properties?
- Sources?
- How and why is it used?
- Applications?

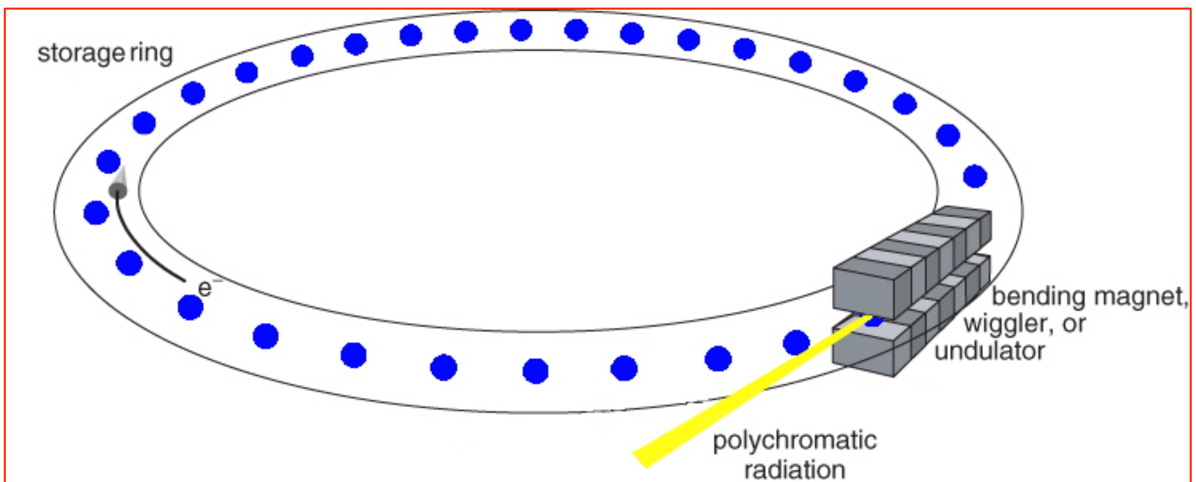
# Synchrotron radiation

***Accelerated charged particle, like $e^+$, $e^-$ and ions, emit electromagnetic radiation.***

$v \ll c$ or $\beta = v/c \ll 1$

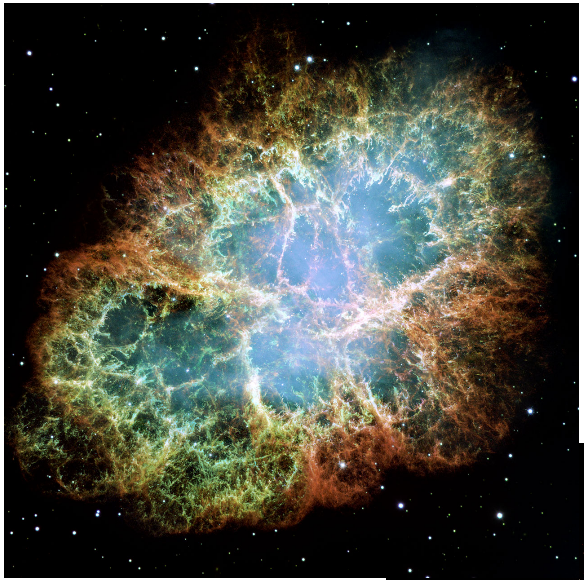



*When charged particles, **moving at relativistic speeds** ($v \approx c$), are forced to **change the direction of their motion (acceleration)**, under the effect of magnetic fields, **in circular particle accelerators, like synchrotrons**, the radiation produced is called **synchrotron radiation**.*

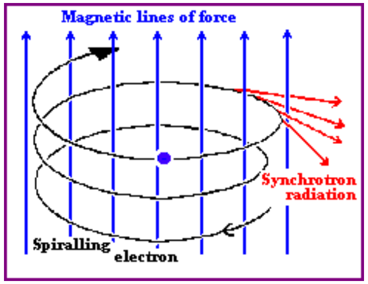


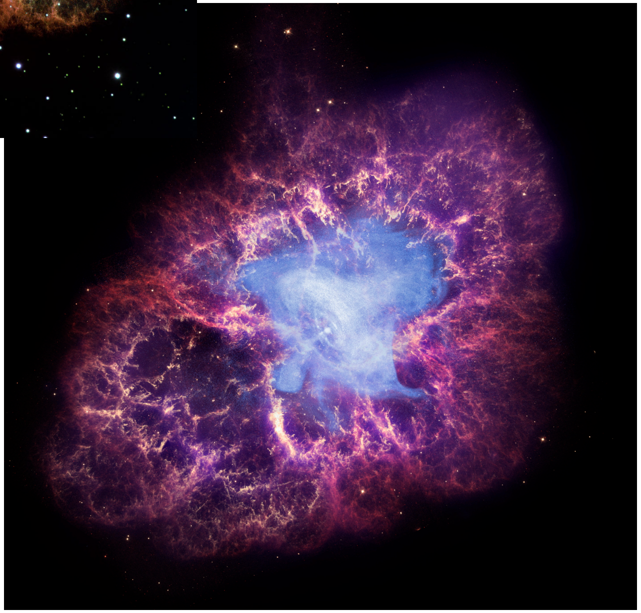

$v \approx c$ or $\beta = v/c \approx 1$

# Synchrotron light is present in nature!



NASA Hubble Space Telescope image of the Crab Nebula (NASA, ESA and Allison Loll/Jeff Hester (Arizona State University)).



NASA's Great Observatories' View of the Crab Nebula X-Ray-blue: NASA/CXC/J.Hester (ASU); Optical-red and yelllow: NASA/ESA/J.Hester & A.Loll (ASU); Infrared-perple: NASA/JPL-Caltech/R.Gehrz (Univ. Minn.)

*Synchrotron radiation is a very important emission process in astrophysics!*

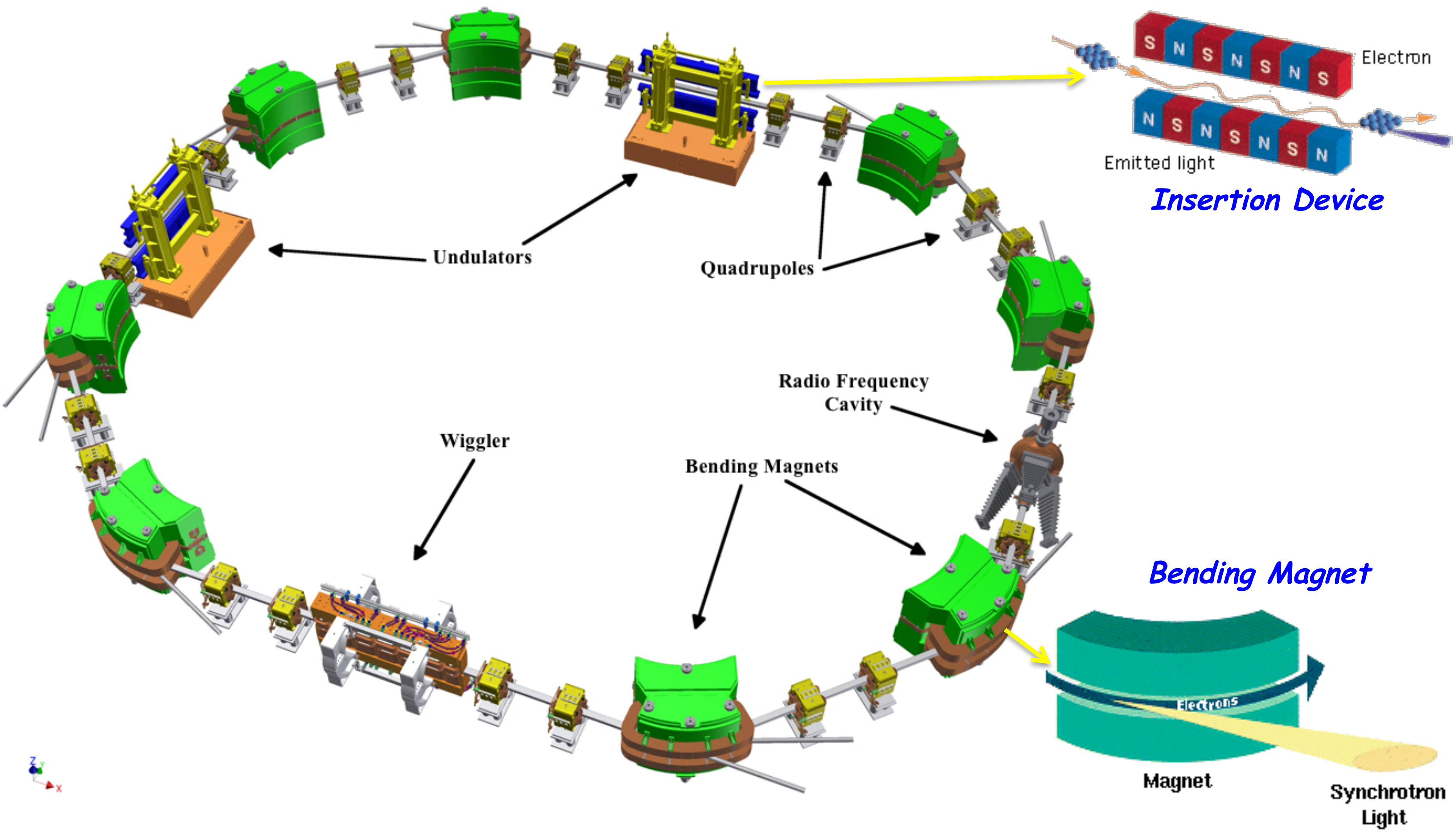
*Crab Nebula: remnant of a supernova explosion seen on earth by Chinese astronomers in 1054, at about 6500 light years from Earth in the constellation Taurus !*

***The heart of the nebula is a rapidly-spinning neutron star, a pulsar, that powers the strongly polarised bluish 'synchrotron' nebula.***

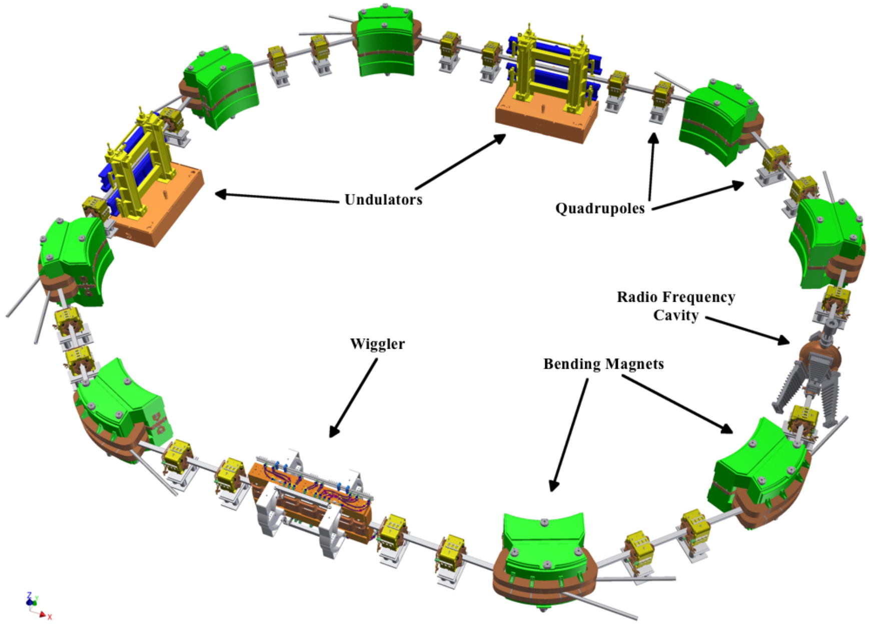
The ***Crab pulsar*** is ***slowing at the rate of about $10^{-8}$ sec per day***, and the ***corresponding energy loss agrees well with the energy needed to keep the nebula luminous***. Some of this luminosity takes the form of ***synchrotron radiation, requiring a source of energy for accelerating charged particles***.

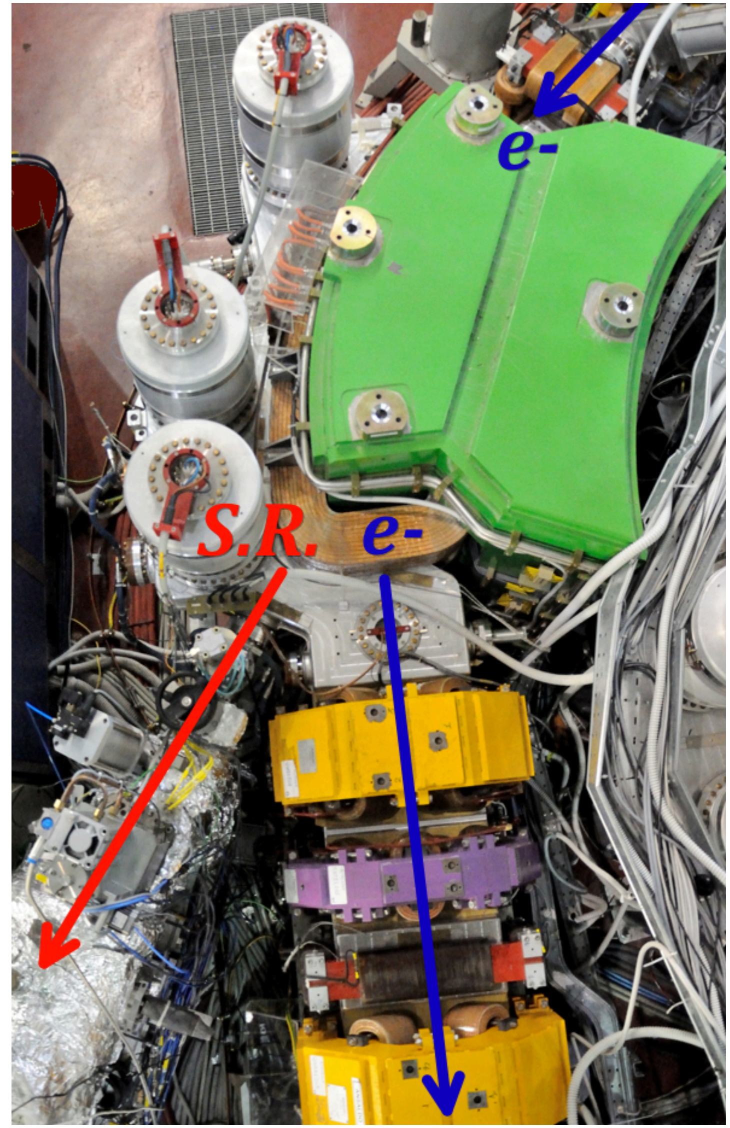
*Composite image data from* ***three of NASA's Great Observatories****. The* ***Chandra X-ray Observatory image*** *is shown in blue, the* ***Hubble Space Telescope optical image*** *is in red and yellow, and the* ***Spitzer Space Telescope's infrared*** *image is in purple. The X-ray image is smaller than the others because extremely energetic electrons emitting X-rays radiate away their energy more quickly than the lower-energy electrons emitting optical and infrared light.* ***The Crab Nebula is one of the most studied objects in the sky, truly making it a cosmic icon.***

# Synchrotron light artificially produced by circular particle accelerators

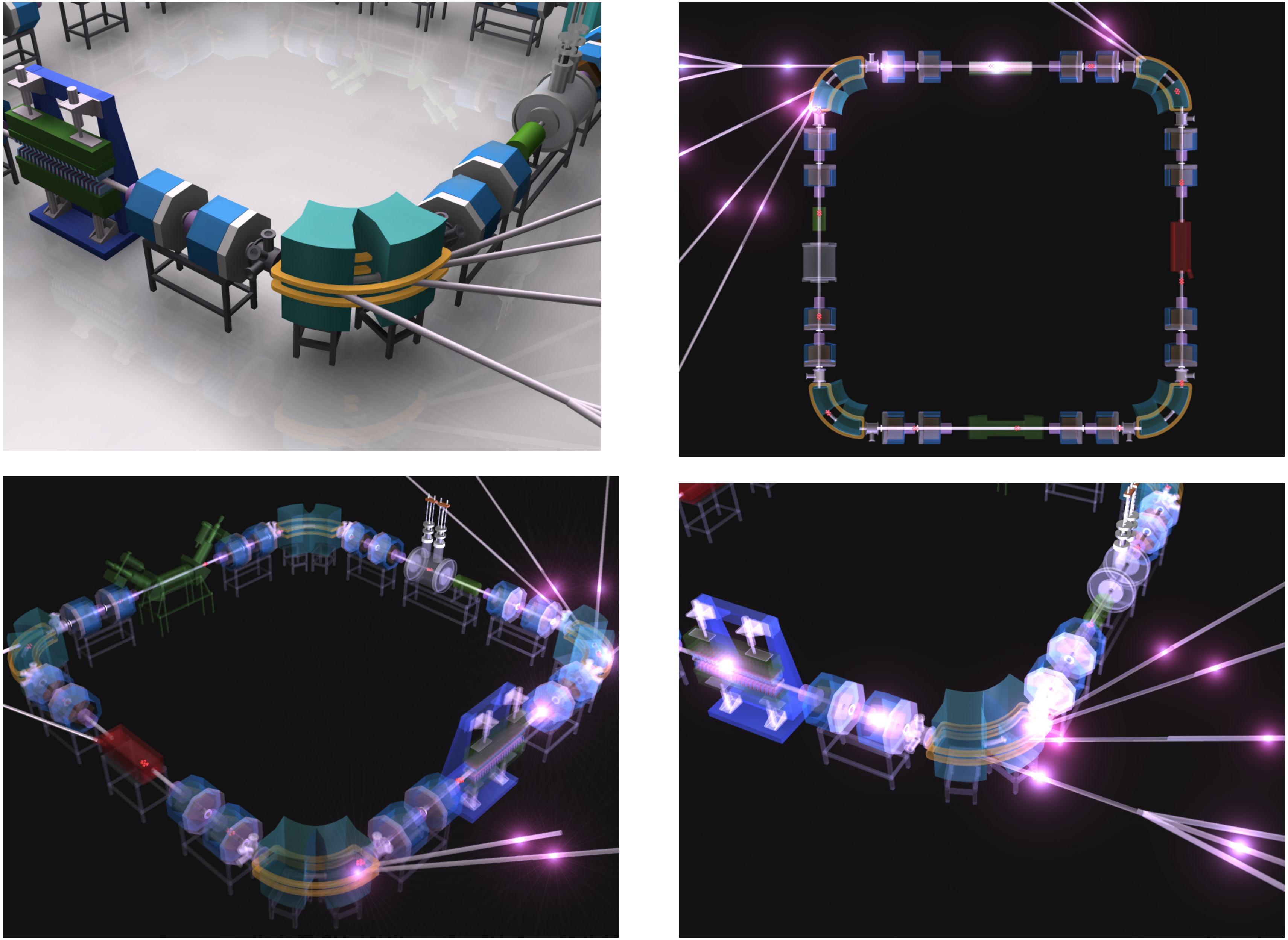


# Bending magnets



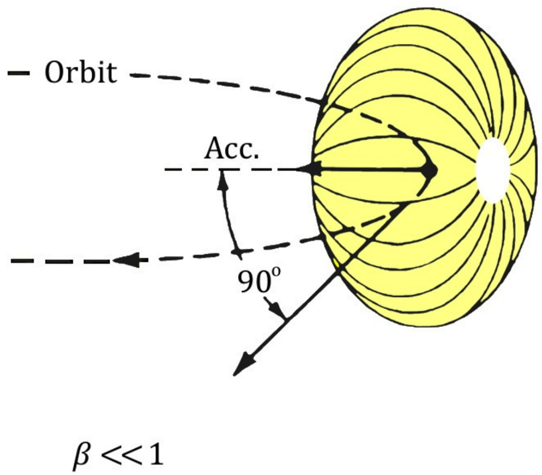

DAΦNE bending magnet

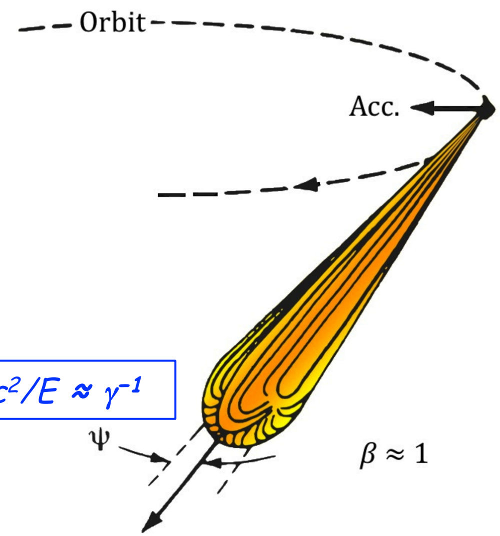


ASTRID (Aarhus - Denmark) http://www.isa.au.dk/animations/pictures/pic-index.asp

http://www.isa.au.dk/animations/Finalmovie/astrid_total_v2.mov

# Synchrotron radiation: physics




$\psi \approx mc^2/E \approx \gamma^{-1}$

v << c or $\beta$ = v/c << 1

$$P = 2\, e^2 a^2/(3c^3) \quad [W]$$

*P* = total emitted power, *a* = acceleration

At low electron velocity (non-relativistic) the radiation is emitted in a ***non-directional pattern***.

***1897 Lamor***: calculates power radiated by an accelerated charged particle
***1898 Liénard***: extends the theory to relativistic particles in a circular path

v ≈ c or $\beta$ = v/c ≈ 1

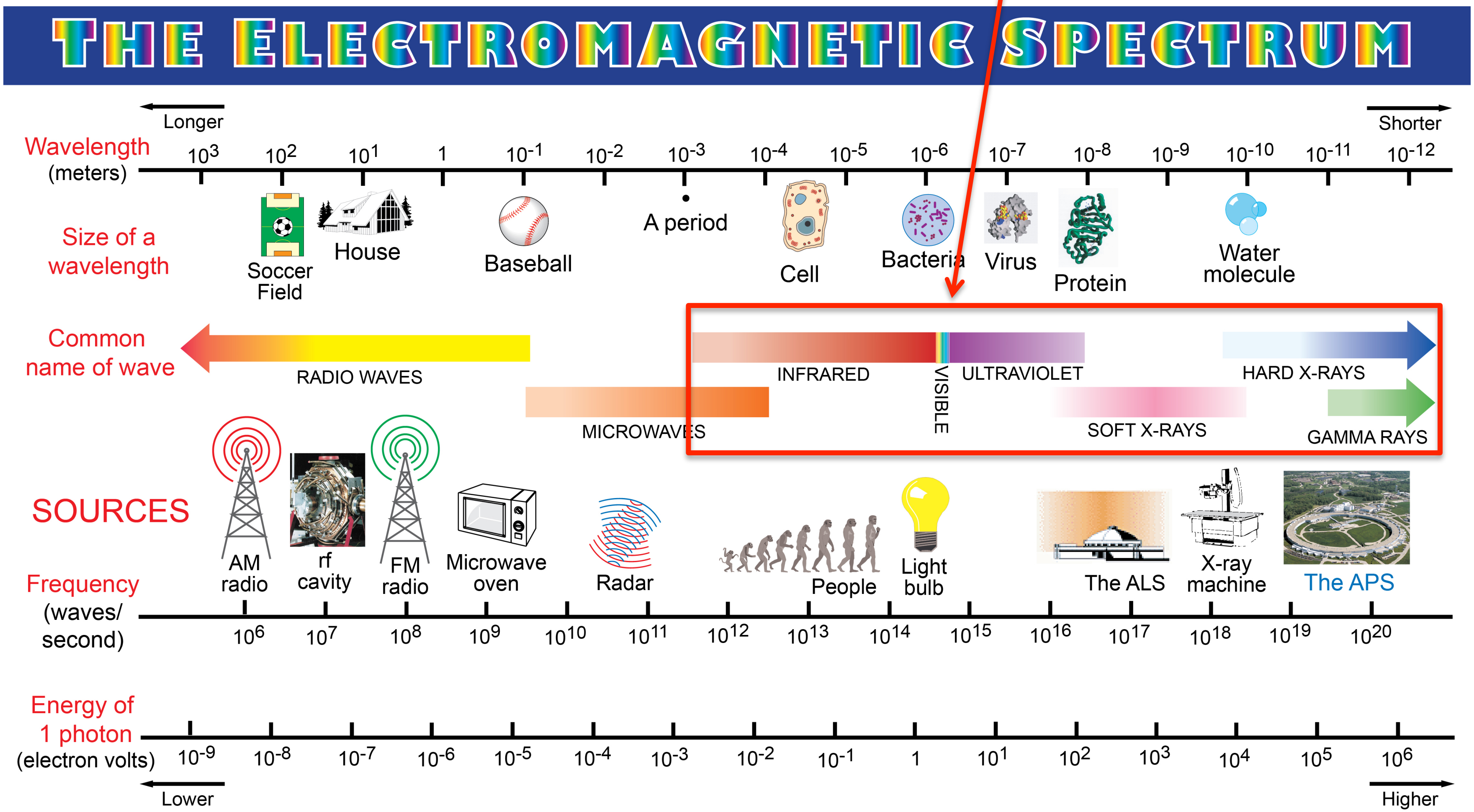
For a relativistic effect, when the speed of the emitting electrons increases to relativistic values (v ≈ c ) the radiation pattern is compressed into a ***narrow cone in the direction of motion, resulting into an emission tangential to the particle orbit***.

$$P_{rad} = \frac{2}{3}\frac{Q^2 c}{R^2}\left[\frac{E}{mc^2}\right]^4$$

*E* = particle energy, *m* = mass, *R* = radius of curvature

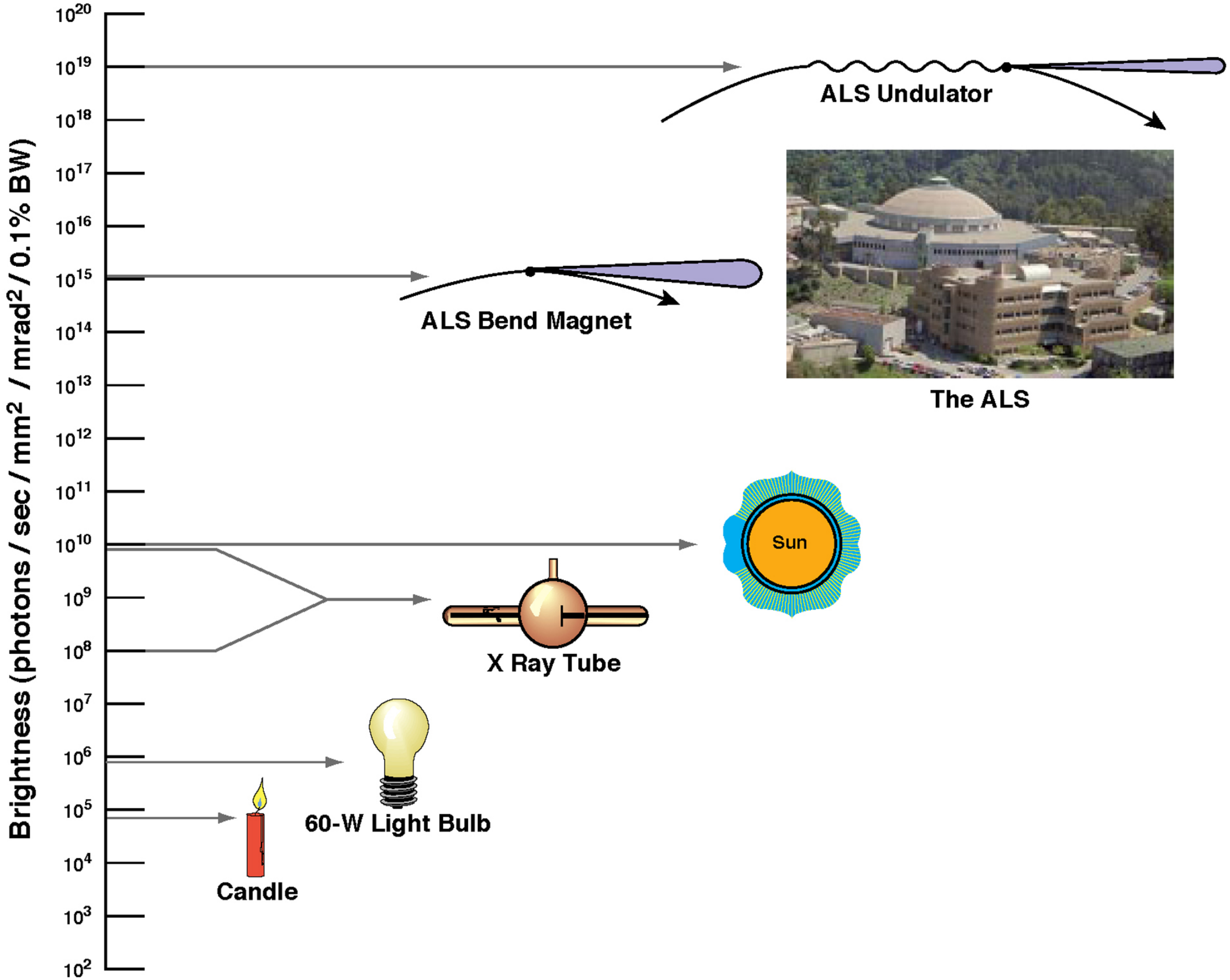
*1945* Schwinger: classical theory of radiation from accelerated relativistic electrons

**Spectral range covered by Synchrotron Radiation!**



# How Bright Is the Advanced Light Source?

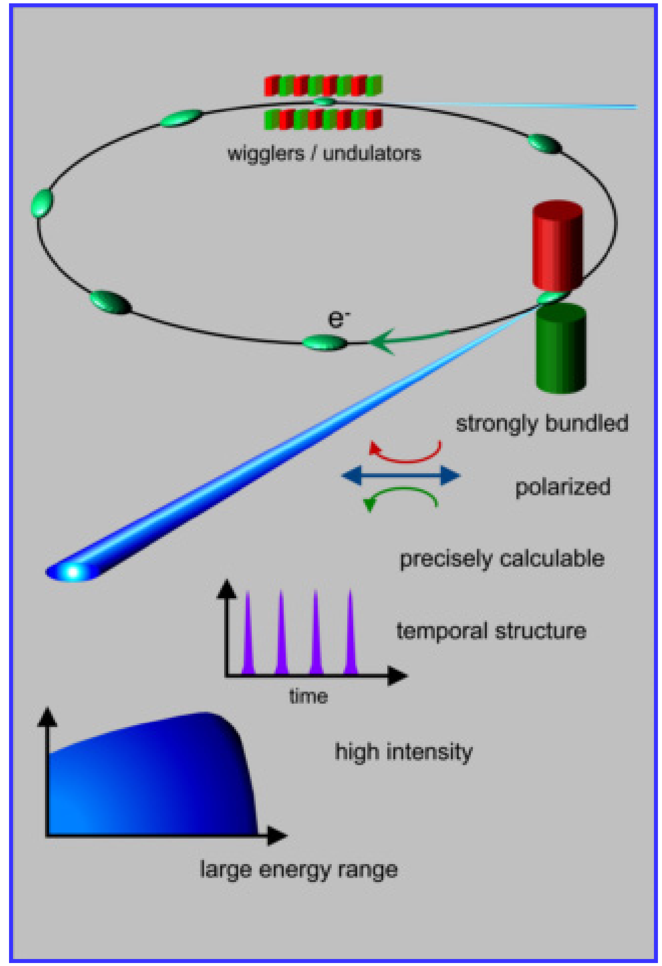
ALS



# Synchrotron Radiation Properties

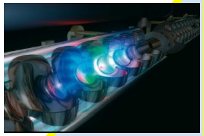
***What makes synchrotron radiation interesting, powerful and unique?***

- *Very high flux and brightness* ***(with undulators)*** highly collimated photon beam generated by a small divergence and small size source (partial coherence)
- *Broad spectral range* ***(tunability)*** which covers from microwaves to hard X-rays: the user can select the wavelength required for experiment- *continuous (Bending Magnet/Wiggler) - quasi-monochromatic (Undulator)*
- *Small source size*
- *Collimated beams*
- *High stability* (**submicron source stability**)
- *Pulsed time structure* - pulsed length down to tens of picoseconds allows the resolution of processes on the same time scale
- *Polarization (linear, circular, elliptical with Insertion Devices)*
- *High vacuum environment*



# *Short history*

# Synchrotron Light Short History and Name

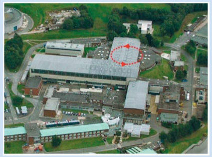


4th gen. - LINAC based accelerators
FELs

3rd* gen. ultimate storage rings like MAX IV
(Sweden) near future

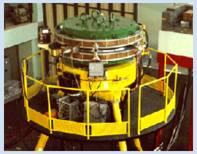
3rd gen. dedicated storage ring ESRF (France)
1994

Brightness increase



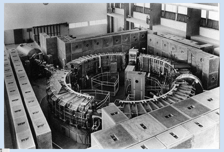
2nd gen. dedicated storage ring SRS (UK)
1981

1st gen. dedicated ring Tantalus I (USA)
1968

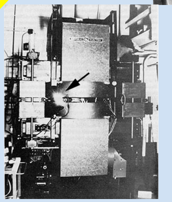


Storage rings development
1960s

ADA - B. Touschek - LNF

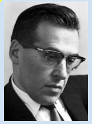


Parasitic use of electro-synchrotrons
1961



First observation of synchrotron radiation
1947

General Electric Res. Lab. - 70 MeV Electro-Synchrotron ( N.Y. USA)

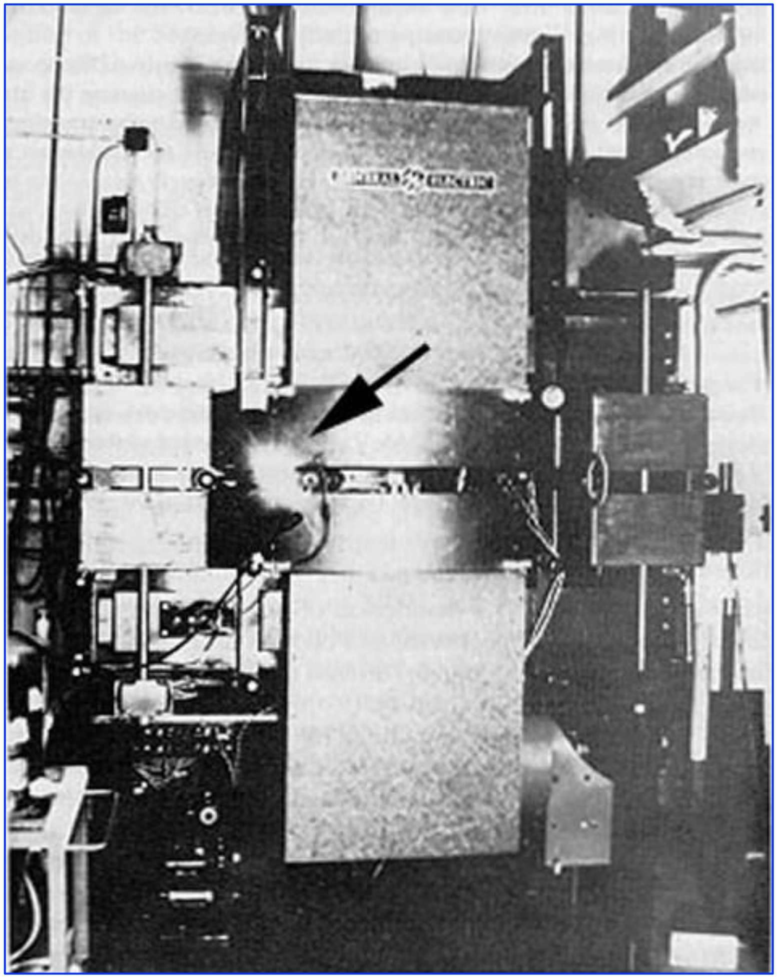


J. Schwinger Nobel Prize 1965 Classical Relativistic quantum field theory

Proof of concepts, tests of theories
1897-1946

# Synchrotron radiation: history

## First generation: parasitic operation and storage rings



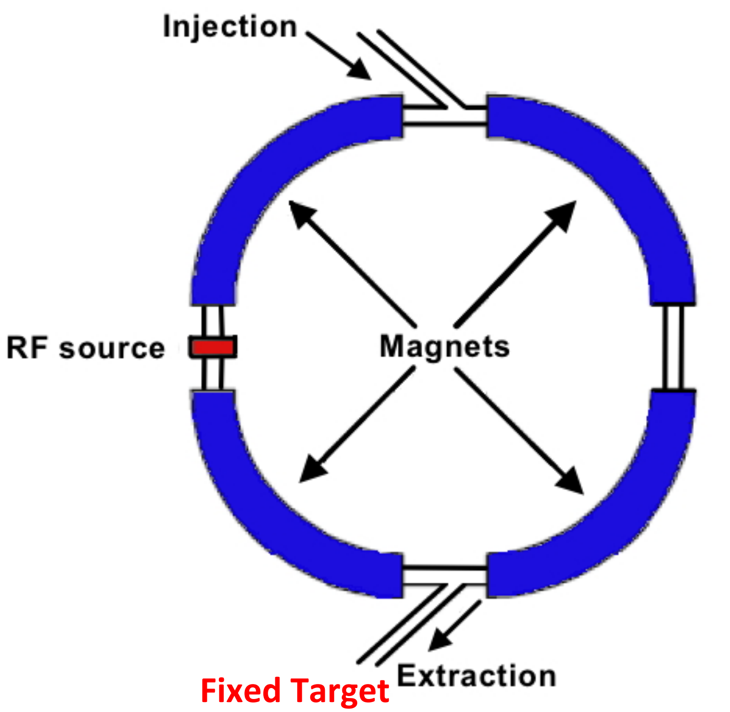
**1947 *General Electric Res. Lab.* - 70 MeV Electron Synchrotron – N.Y. USA**

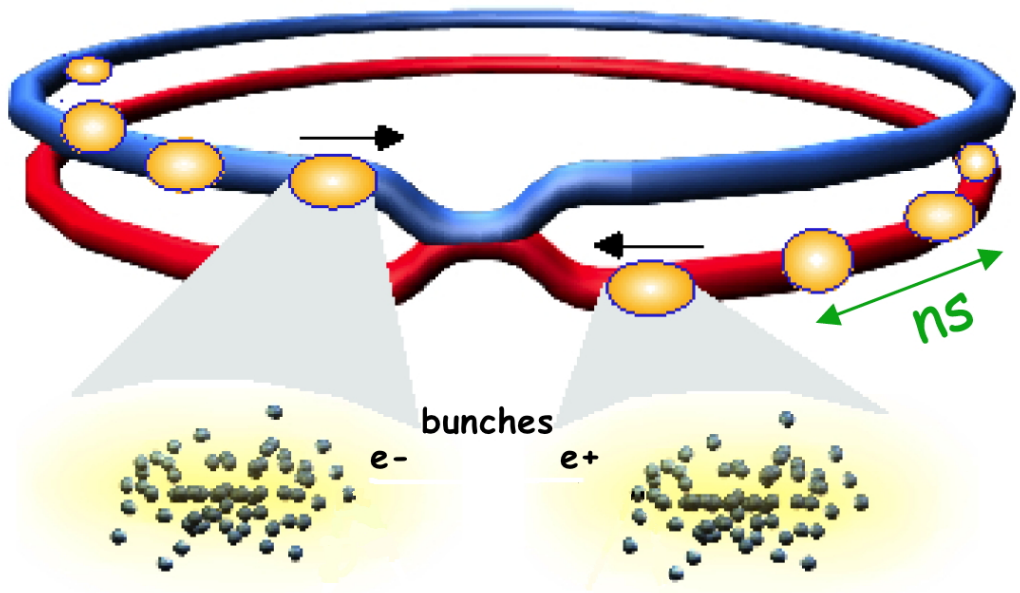
***Starting point: Proof of concepts, tests of theories!***

- In the 50s and 60s machines built for High Energy Physics: synchrotrons (***1947 First 'visual observation of synchrotron radiation***).
- Synchrotron radiation was considered a ***nuisance by particle physicists***: ***unwanted but unavoidable loss of energy***!
- 1961 US National Bureau of Standards (now NIST) modified their electron synchrotron : ***access to the synchrotron radiation users***.
- Synchrotron radiation scientists became ***parasites*** of nuclear physics experiments. (***1961 Frascati – CNEN Electrosynchrotron – ( 0.4-1.1) GeV***)
- 1968 ***First storage ring dedicated*** to synchrotron radiation research: ***Tantalus*** (University of Wisconsin) only ***bending magnets***.


*F.R. Elder, A.M. Gurewitsch, R.V. Langmuir, and H.C. Pollock*, ***Radiation from Electrons in a Synchrotron***, *Phys. Rev.* ***71***, *829* (*1947*)
*G. C. Baldwin and D.W. Kerst*, ***Origin of Synchrotron Radiation***, Physics Today, **28**, 9 (*1975*)

# Synchrotrons and Storage Rings




*Synchrotron*

| |
|---|
| Particle beam on fixed target<br><br>$E_{CM} = (mE)^{1/2}$ |

*Storage rings*

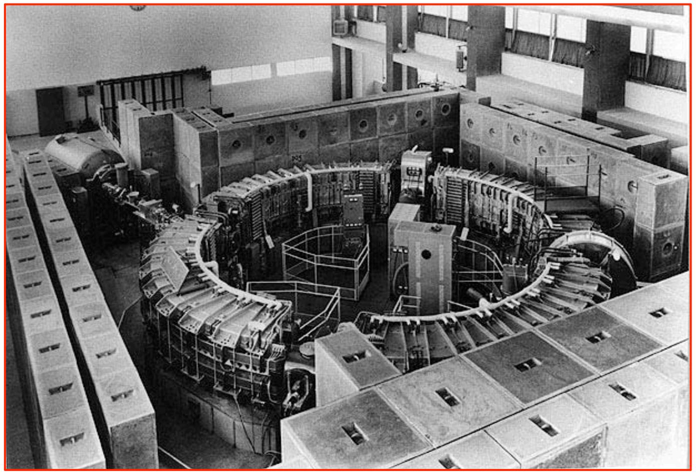
| |
|---|
| Colliding particle beams<br><br>$E_{CM} = 2E$ |

**Colliding beams more efficient**

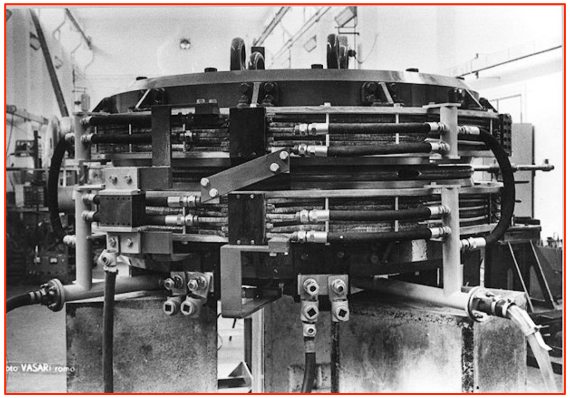
*E= particle energy >> $mc^2$; $E_{CM}$= centre-of-mass energy*

# Synchrotron radiation: short history

## Frascati: ElettroSynchrotron, ADA and ADONE



Frascati - CNEN (Comitato Nazionale Energia Nucleare) Laboratory ElettroSincrotrone – (0.4-1.1) GeV, C= 28 m (1959-1975)



LNF ADA (Anello Di Accumulazione) – first electron-positron storage ring (proposed by B. Touschek) 0.25 GeV, C= 5 m (1961-1964)

LNF ADONE (big ADA) electron-positron storage ring 1.5 GeV per beam, C = 105 m (1969-1993)

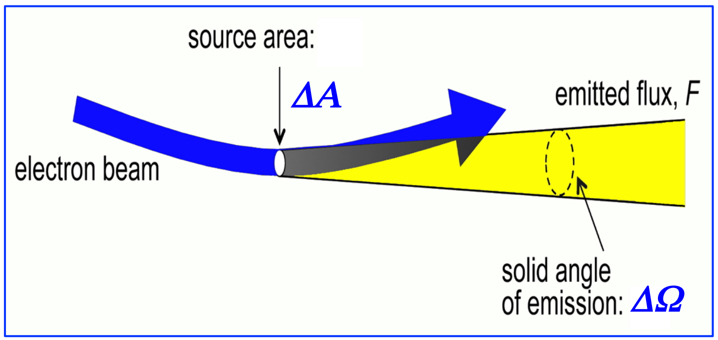
1976-1993 LNF ADONE 1.5 GeV parasitic/dedicated use for SR experiments after its use for HE experiments.

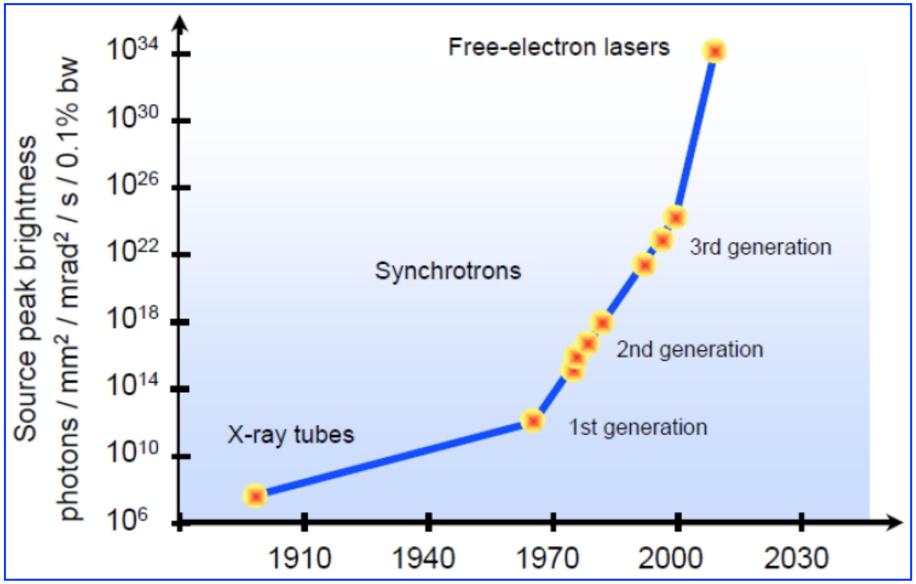
# Increasing brightness

***Brightness*** (flux density in phase space) is an invariant and depends on the ***size of the source*** ***($\Delta A$)*** (electron beam) and on ***the angular divergence of the radiation ($\Delta\Omega$)***, given by the convolution of the angular distribution of synchrotron radiation with the angular divergence of the electron beam.

***Brightness more important than flux*** (photons/s).

***Brightness = photon flux/ [($\Delta A$) ($\Delta\Omega$)]***




In a storage ring the ***product of the electron beam transverse size*** and ***angular divergence*** is a constant along the ring and is called ***emittance*** ***(vertical*** and ***horizontal emittance).***

***Increase of a factor 1000 every 10 years!!!***

***Brightness is the main figure of merit of synchrotron radiation sources and its huge increase, was obtained designing low emittance machines, minimizing the source size and the beam divergence.***

$$\textit{Spectral Brightness} = \frac{photons}{second \cdot mrad^2 \cdot mm^2 \cdot 0.1\%BW}$$

# Synchrotron radiation: short history

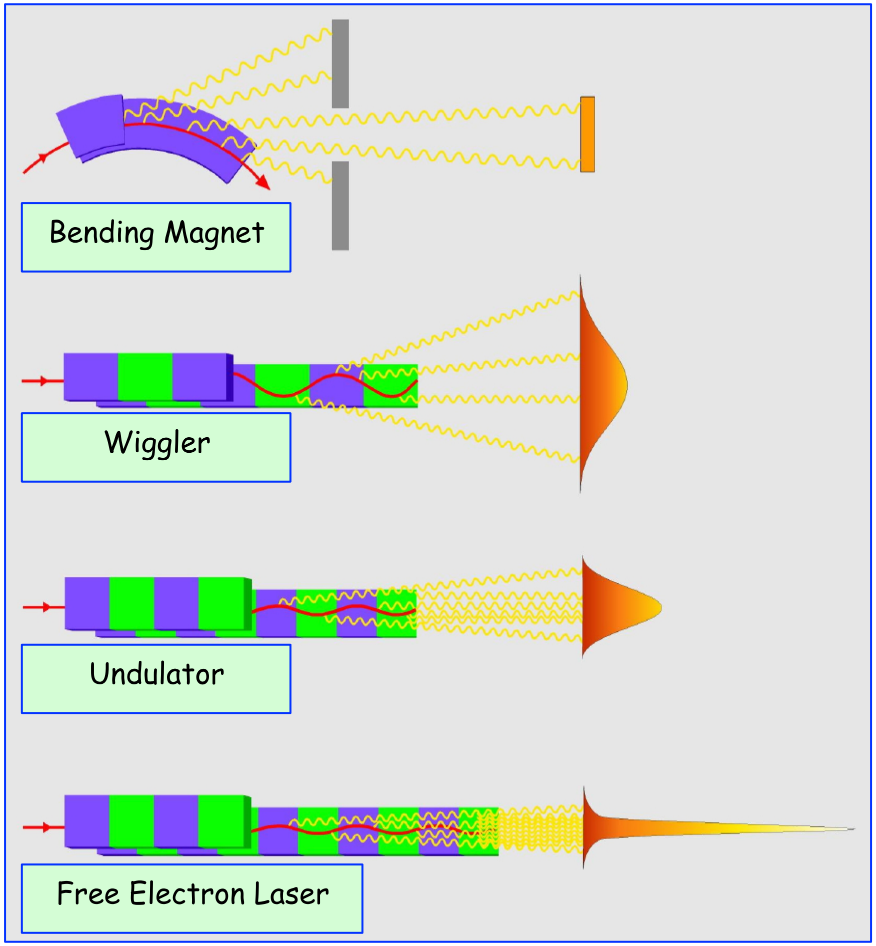
## Third generation: optimized sources

*Synchrotron light is now a unique tool for science!*

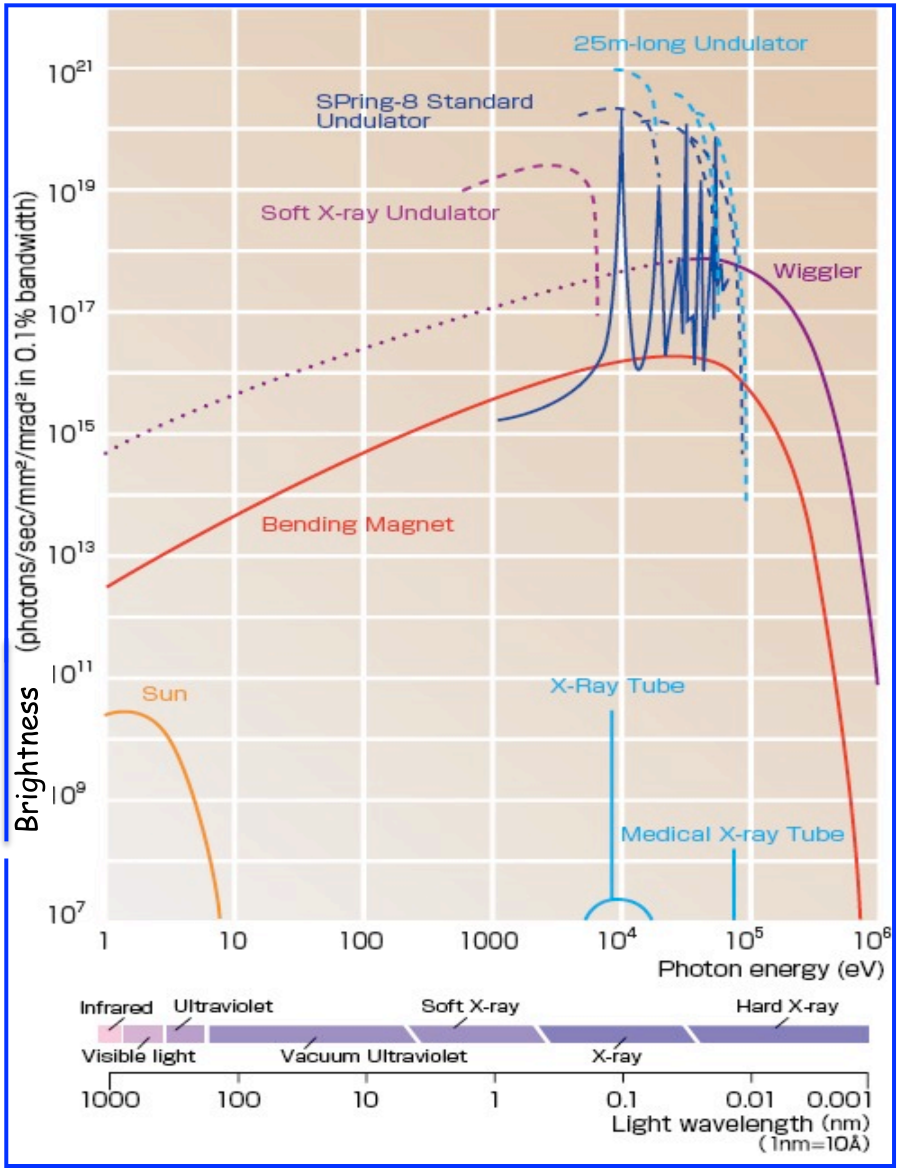
*ESRF, Grenoble - France 6 GeV, C = 844 m opened to users in 1994*

- *Sources designed specifically for high brightness or low emittance.*
- *Emphasis on research with insertion devices like undulators!*
- *High-energy machines able to generate hard x-rays*
- *Larger facilities to support rapidly growing user community, many beamlines high number of users.*

# Comparing the achievable brightness




Courtesy DESY

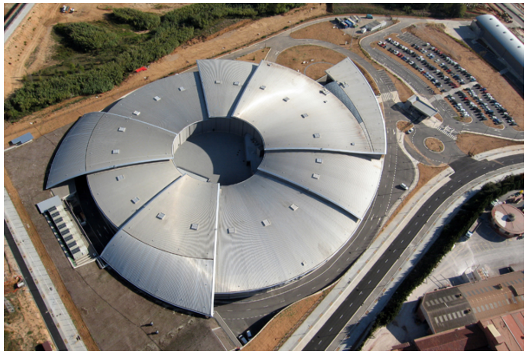



Courtesy SPring-8

# 3rd Generation Light Sources

ESRF - France

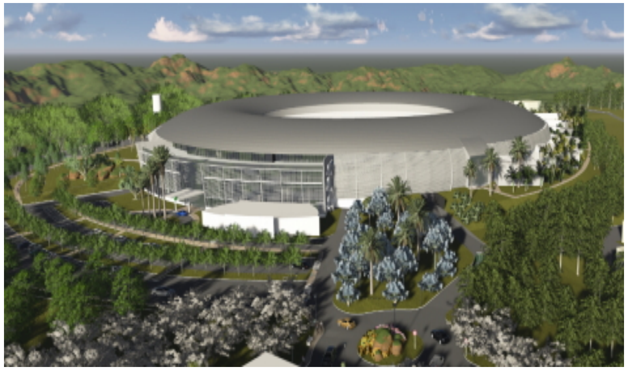
DIAMOND - UK



ALBA - Spain

## Under construction – Ultimate SR facilities


Lund - Sweden

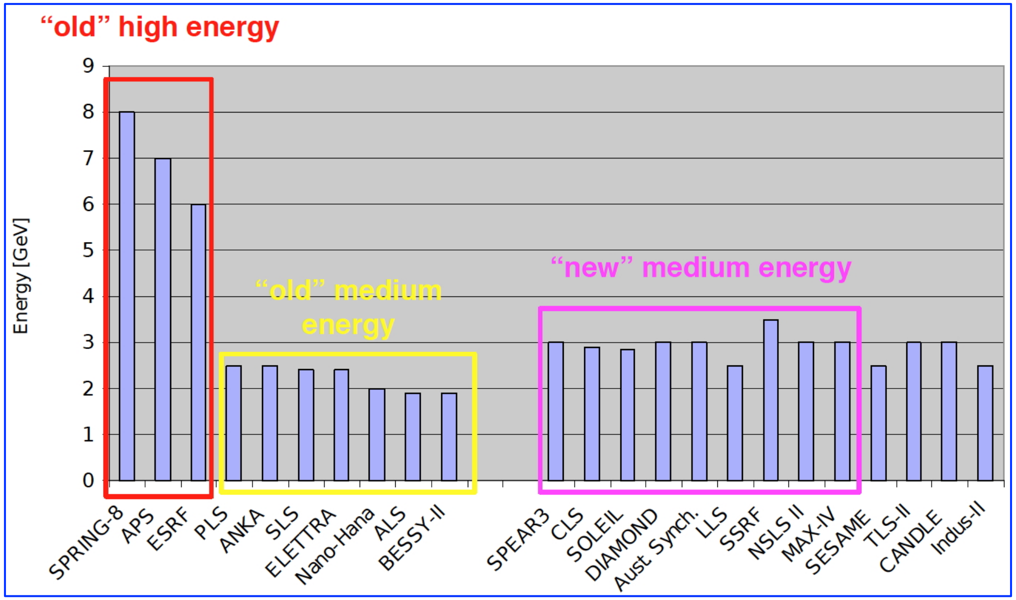


Sirius - Brazil


Shanghai -China

# Synchrotron radiation facilities

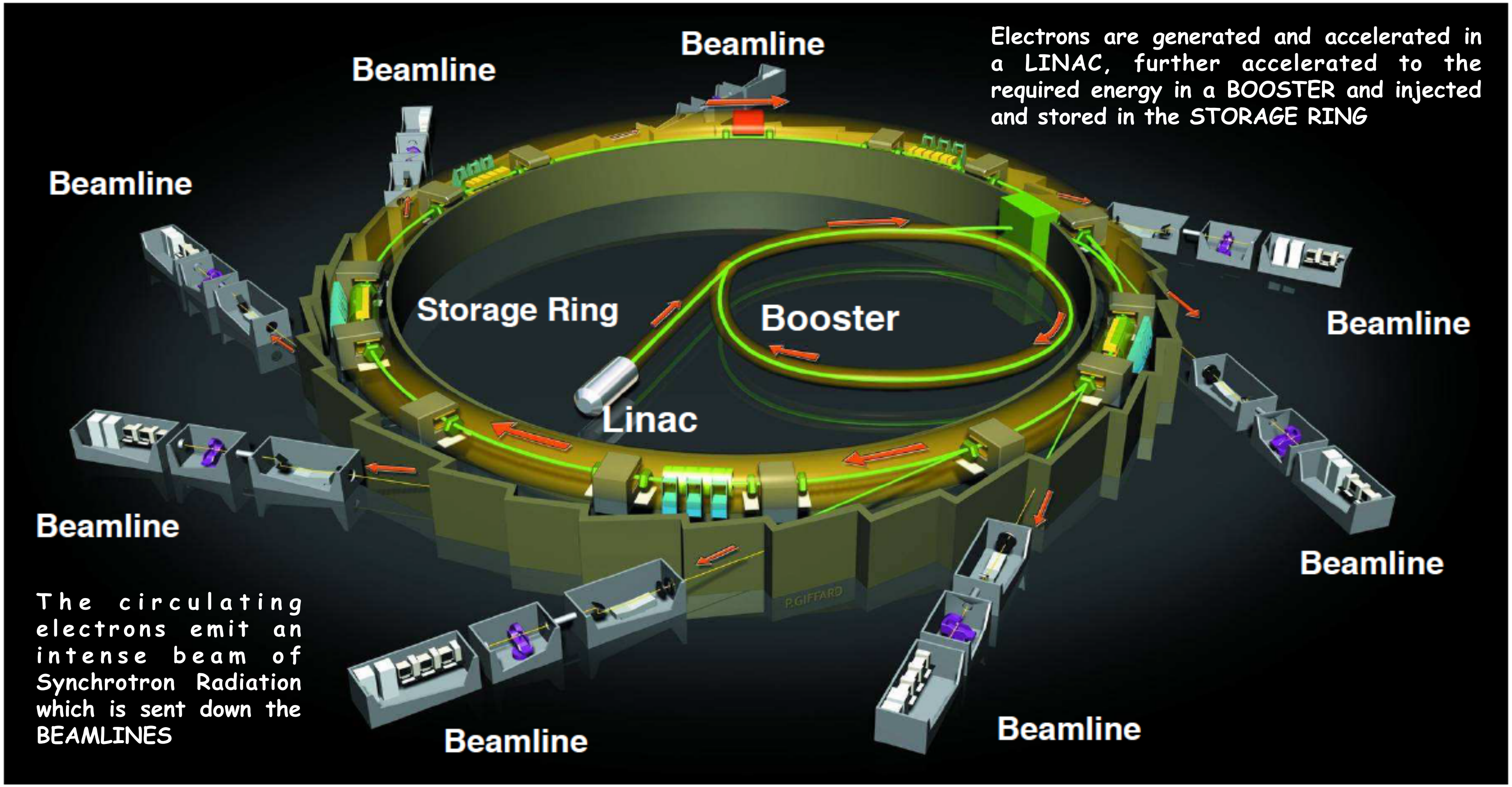
**18 in America**
**25 in Asia**
**25 in Europe**
**1 in Oceania**
*including facilities under design and FELS*





*Info on European Synchrotron Radiation Facilities: www.wayforlight.eu*
*About 67 operational Synchrotron Radiation Facilities Around the World information on: [www.lightsources.org](www.lightsources.org)*

# Schematic view of a Synchrotron Radiation facility




As a function of the energy range to be used each beamline must be optimized for a particular field of research.

Beamline schematic composition:

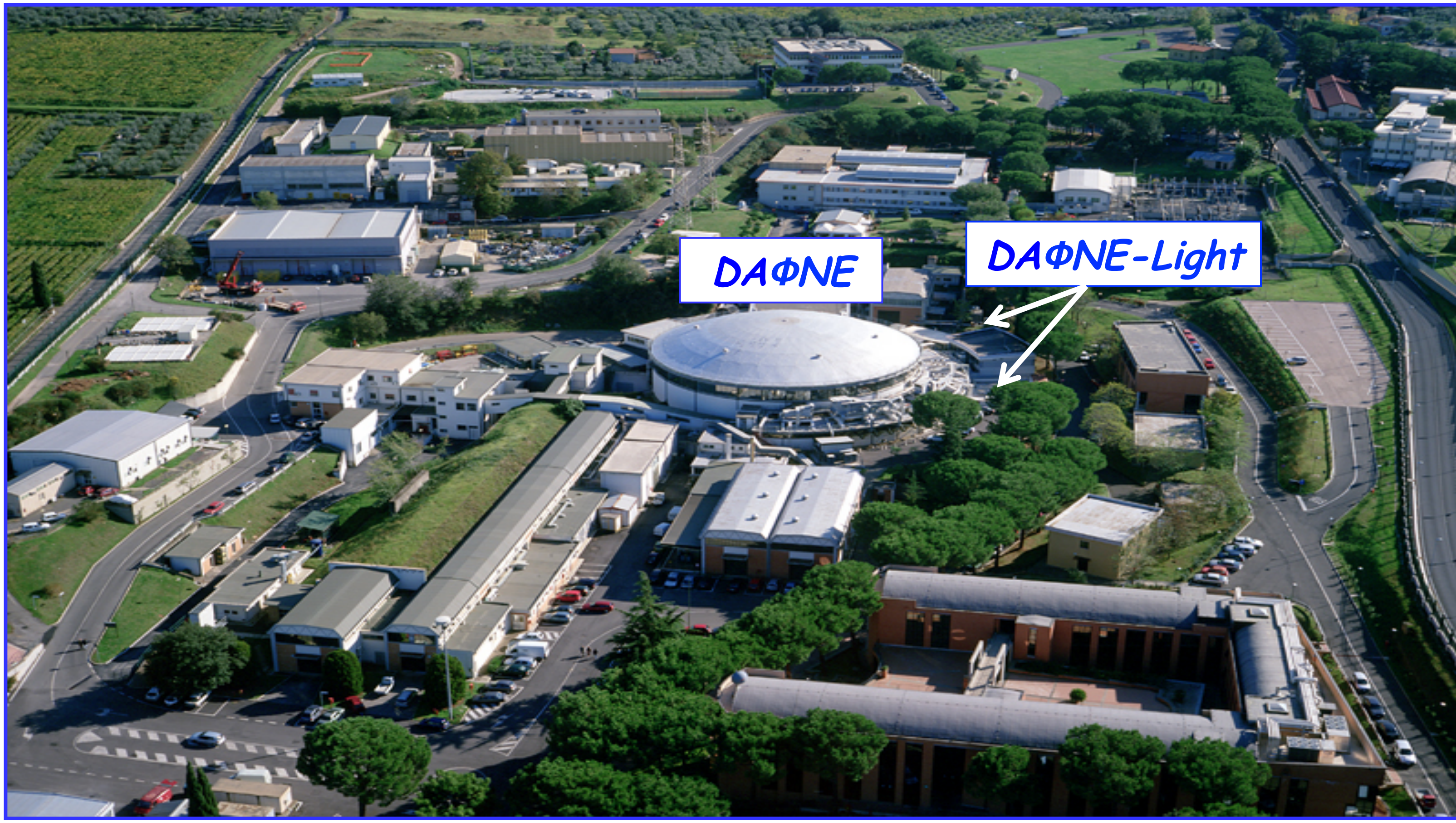
- ***Front end***
- ***Optical hutch***
- ***Experimental hutch***
- ***Control and computing***

The ***front end*** isolates the beamline vacuum from the storage ring vacuum; **defines the angular acceptance of the synchrotron radiation** via an aperture; blocks(beam shutter) when required, the x-ray and Bremsstrahlung radiation during access to the other hutches.

# Synchrotron radiation @ INFN-Frascati National Laboratory

# DAΦNE-Light

## INFN-LNF Synchrotron Radiation Facility



# Beamlines @ DAΦNE

1) SINBAD - IR beamline (1.24 meV - 1.24 eV)

2) DXR1- Soft x-ray beamline (900-3000 eV)

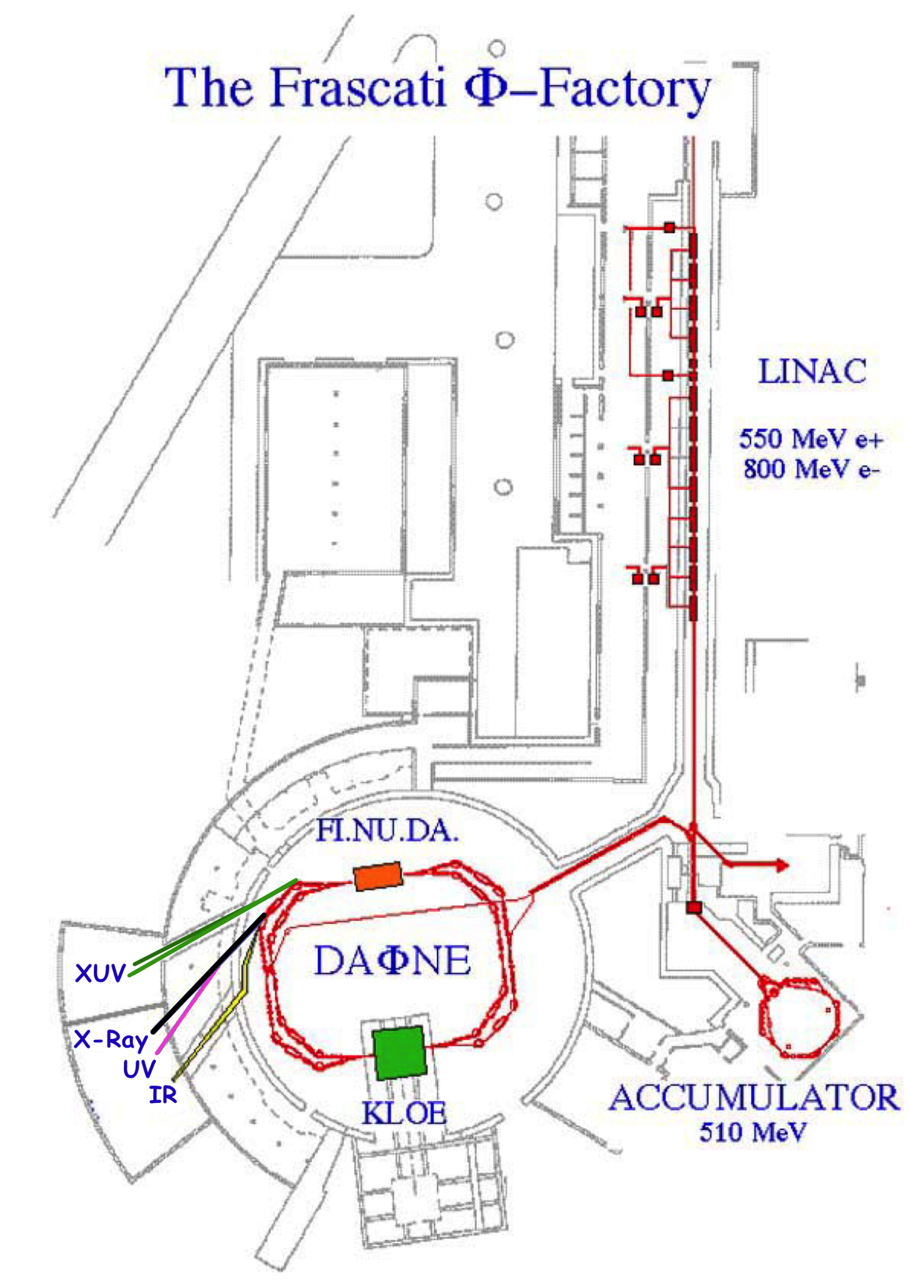
Open to Italian and EU users

3) DXR2 – UV-VIS beamline (2-10eV) new setup.

XUV beamlines

4) Low Energy Beamline (35-200 eV) ready for commissioning;

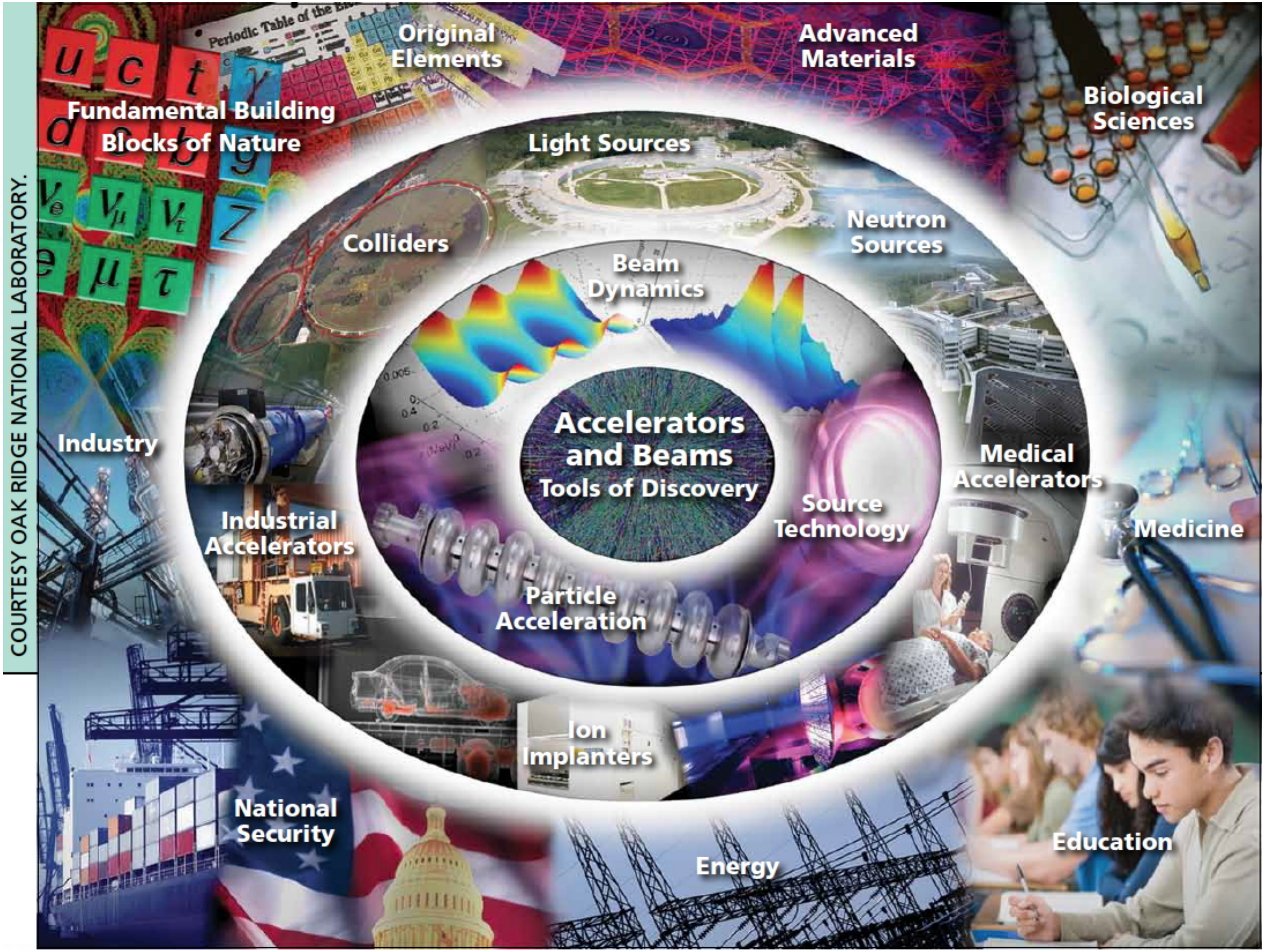
5) High Energy Beamline (60-1000eV) ready for commissioning.



# Available techniques

- FTIR spectroscopy, IR microscopy and IR imaging
- UV-Vis absorption spectroscopy
- Photochemistry: UV irradiation and FTIR micro-spectroscopy and imaging.
- Soft x-ray spectroscopy: XANES (X-ray Absorption Near Edge Structure) light elements from Na to S
- SEY (secondary electron yield) and XPS (X-ray photoelectron spectroscopy) – by electron and photon bombardment

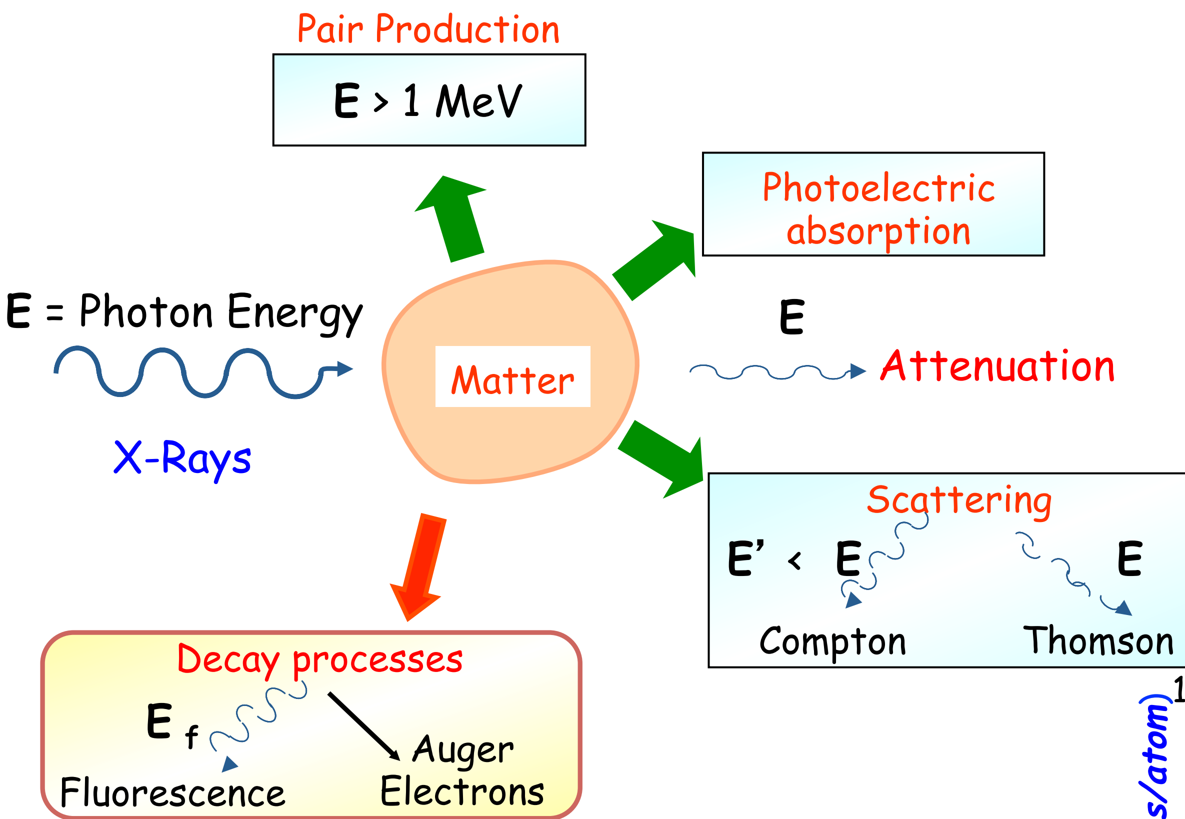
# From accelerators to applications

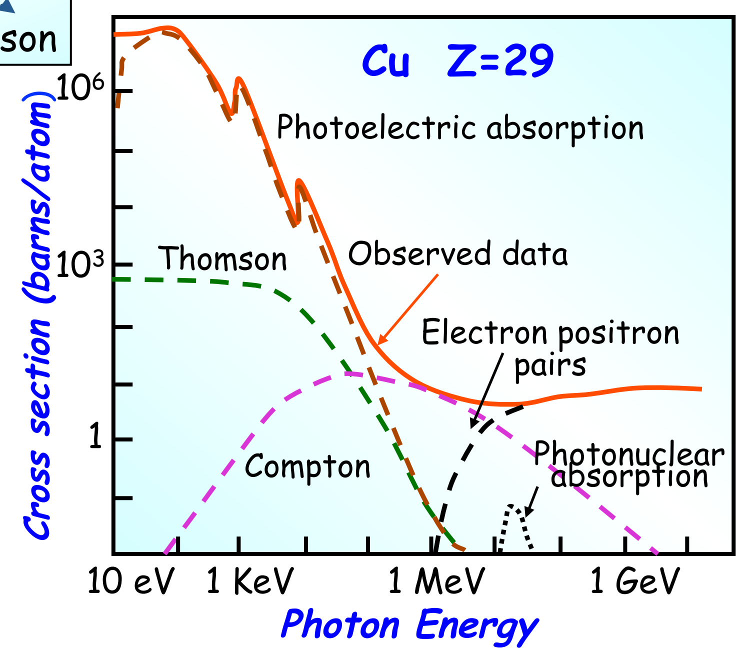



***E. Malamud*** *Ed.*, ***Accelerators and Beams tools of discovery and innovation*** (http://www.aps.org/units/dpb/news/edition4th.cfm) ***2013***

# X-Ray Interaction with Matter:
## Absorption and Scattering

# Interaction of X-rays with matter

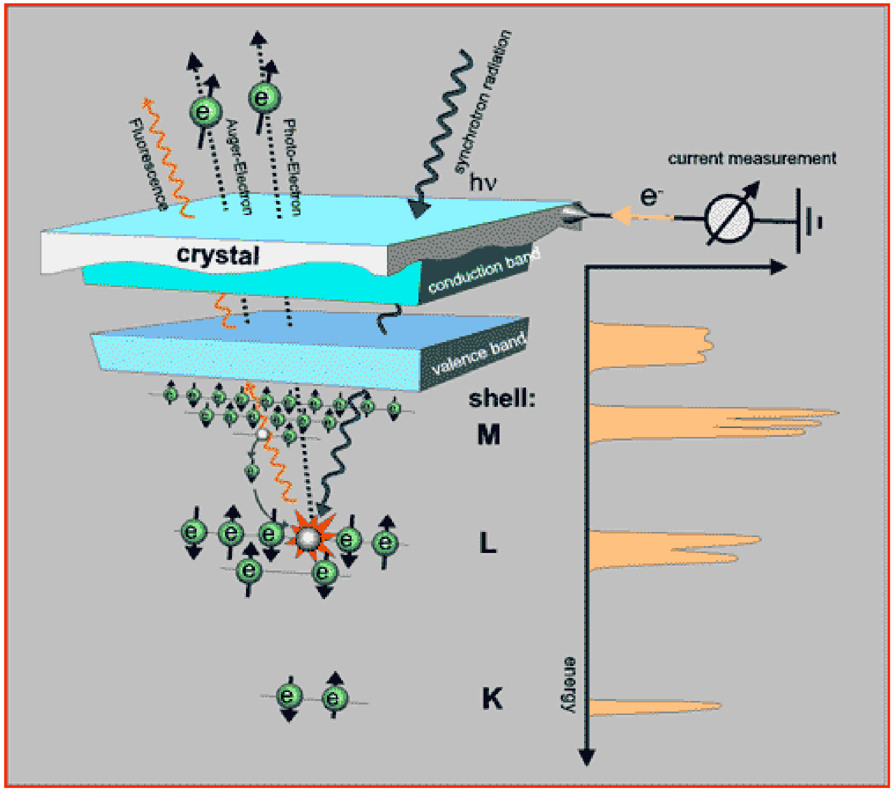


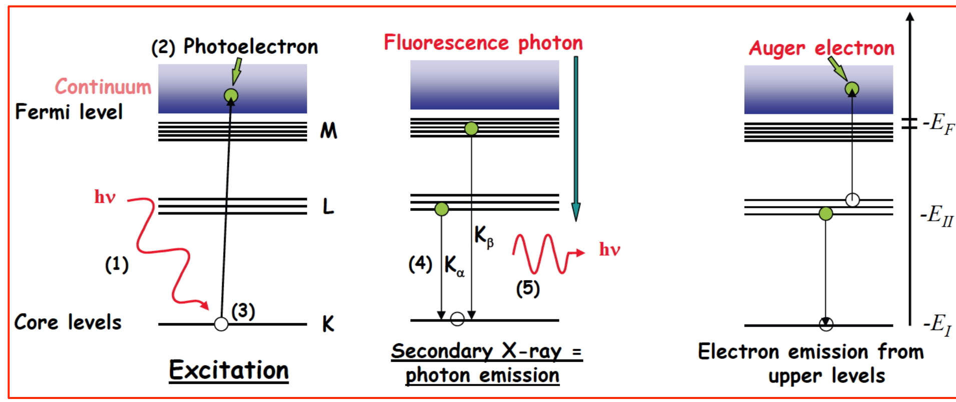




There are different types of interaction of X-rays with matter but taking into account the energy range of interest the ones that will be taken into account are ***absorption*** and ***elastic*** or ***Thomson scattering***.

# Photoelectric absorption

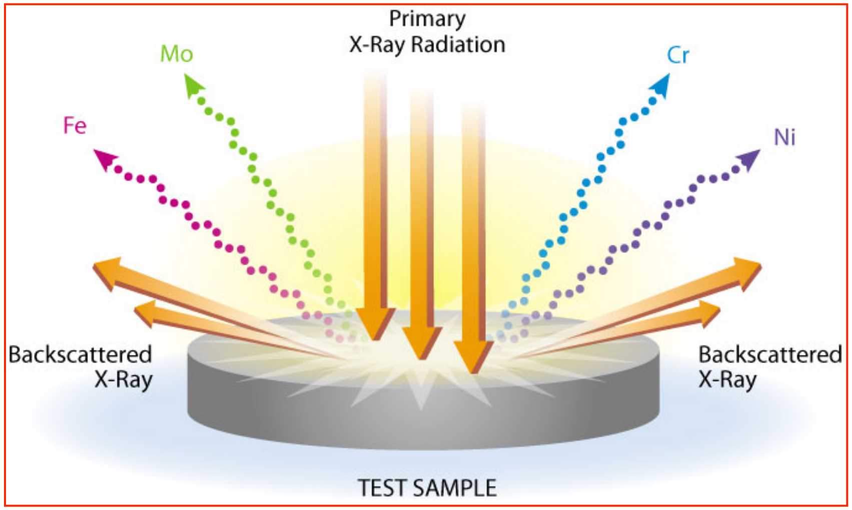
The probability of a photoelectric interaction is a function of the photon energy and the atomic number of the target atom.
A photoelectric interaction cannot occur unless the incident x-ray has energy equal to or greater than the electron binding energy.



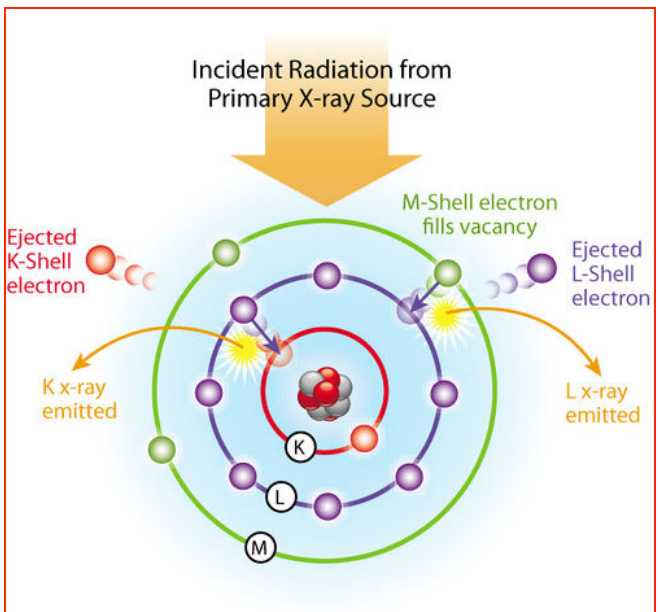




**Absorption and decay effects XRF (X Ray Fluorescence) and AES (Auger Electron).**

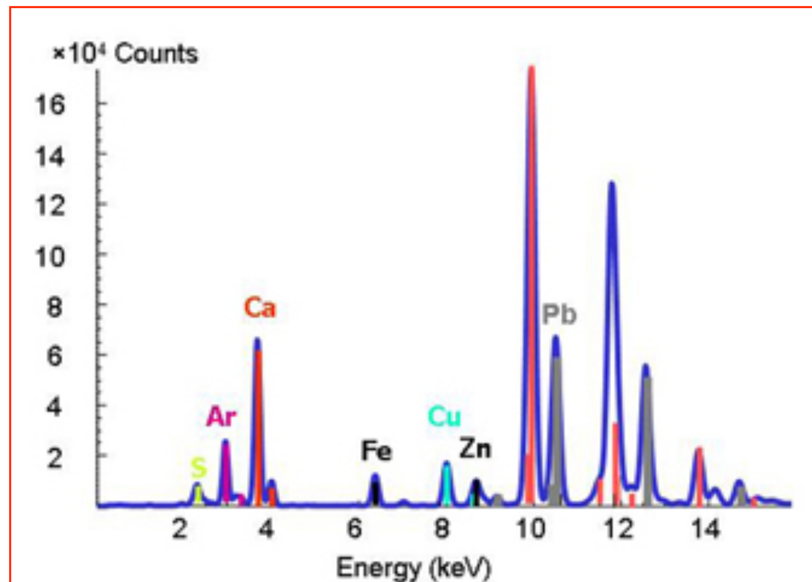
# Decay Process: X-ray Fluorescence



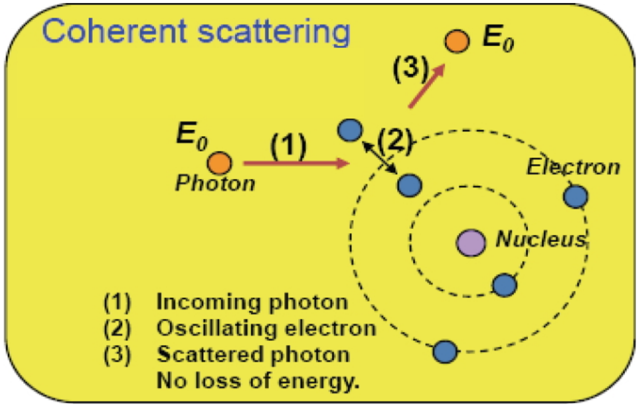

***X-ray fluorescence spectrometry*** (***XRF***) can be used to accurately ***measure the atomic composition of a material***. In an atom, the electrons orbit around the nucleus in characteristic patterns referred to as "shells." ***X-rays have enough energy to knock electrons out of a shell***. If an electron is extracted from an inner shell, an electron from an outer shell will move to replace it. When the electron moves from the outer shell to the inner shell, it ***releases energy in the form of a photon (light)***. The energy of the ***"fluorescent" photon*** released is distinct for each atomic element creating a measurable "fingerprint" for that element. XRF produces ***a non-destructive chemical analyses of any kind of sample***. XRF is detected using energy resolved detectors like solid state HP Ge or SDD (Siicon Drift Detectors) detectors.




**Mosely's Law : *E ≈ $Z^2$***



# Thomson Elastic scattering

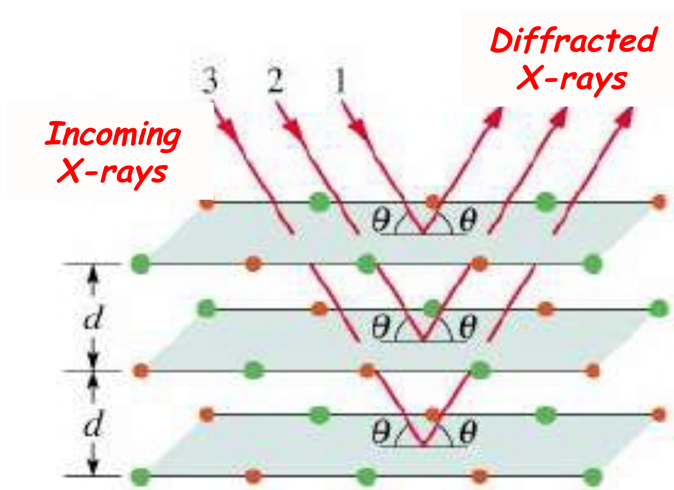



***X-rays incident upon samples will either be transmitted***, in which case they will continue along their original direction, or ***will be scattered by the electrons of the atoms in the material***. All the atoms in the path of the X-ray beam scatter X-rays.

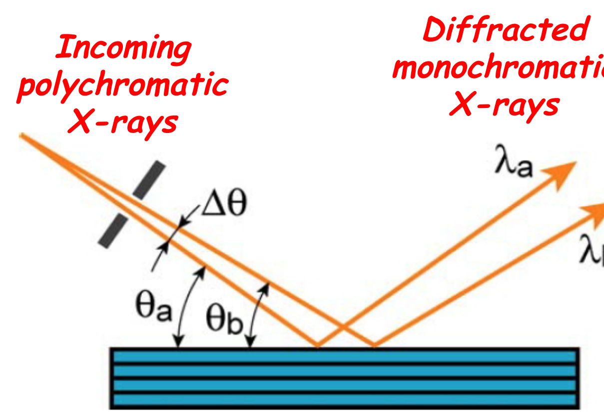
***Elastic or coherent scattering*** :
Thomson diffusion (elastic) if $E < E_{binding}$

***X-ray diffraction is based on elastic scattering*** and results from the coherent sum of all EM waves that are ***diffused from each atom of a periodic structure constituting the matter*** (the same that occurs with visible light interaction with a grating). The ***scattering of x-rays by crystal atoms***, produces ***diffraction patterns*** (*peaks are formed when scattered X-rays constructively interfere*) that yields ***information about the structure of the crystal but also to monochomatize X-ray white beams*** .

With ***visible light we can use a prism and light refraction to separate different wavelengths*** with ***X-ray we use crystals and diffraction***.



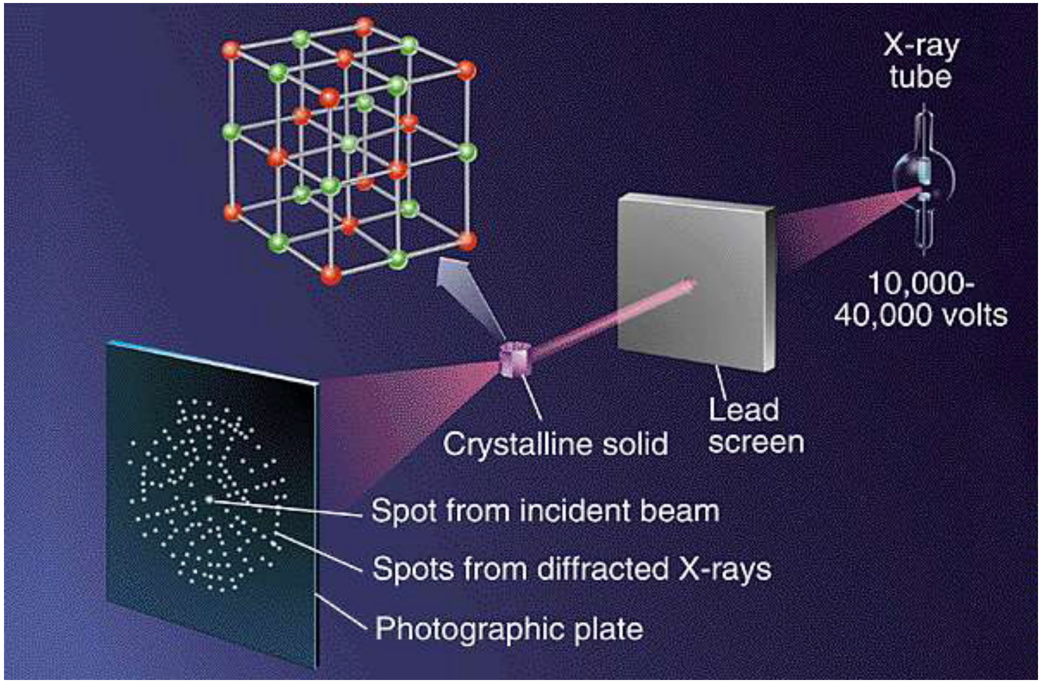

$$n\lambda = 2d\sin\theta$$ *Bragg's Law*

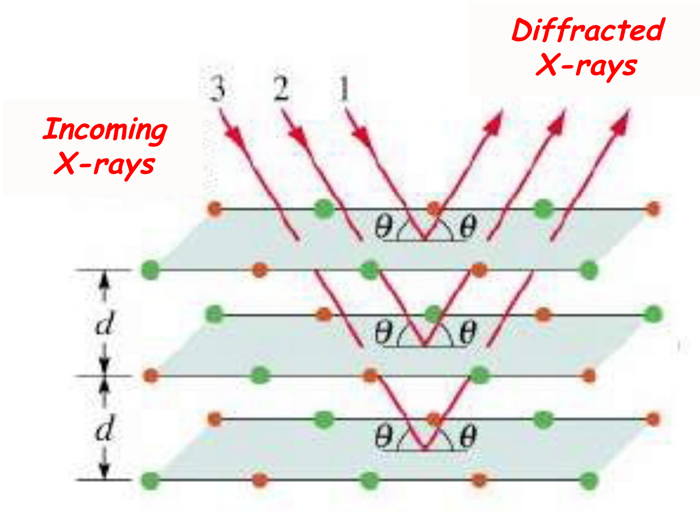


# Elastic scattering and diffraction

***X-ray diffraction is an important tool*** used to identify ***phases by comparison with data from known structures***, ***quantify changes in the cell parameters***, ***orientation***, ***crystallite size and other structural parameters***. It is also used to determine the (crystallographic) structure (i.e. cell parameters, space group and atomic coordinates) of novel or unknown crystalline materials.

The ***interference pattern of X-rays scattered by crystals*** (XRD or X Ray Diffraction pattern) can be ***used study the atomic structure of interest***. ***Bragg's law explains the relation between***: ***d***, the ***distance between atomic layers*** in a crystal, $\lambda$ is ***the wavelength of the incident X-ray beam*** and $\theta$ ***the angle of incidence*** at which the faces of ***crystals appear to reflect X-ray beams.***




**Bragg's Law:** $n\lambda = 2d \sin\theta$

# Imaging: Scattering and Absorption

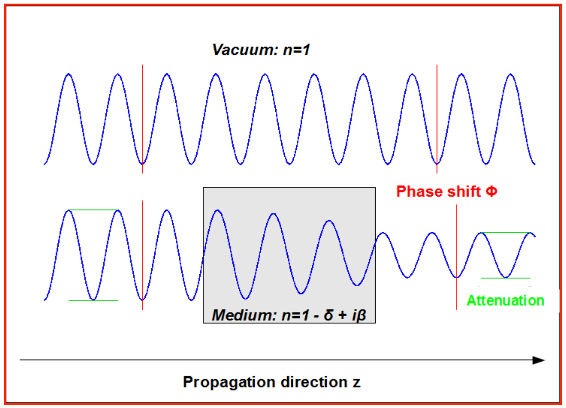
***Radiology is a branch of medicine that uses imaging technology to diagnose and treat disease.***
***Conventional radiology relies on X-ray absorption*** as the unique source of contrast and is based exclusively on the detection of amplitude variation of the transmitted X-rays.
***Main limitation poor contrast for samples with low-Z composition.***

***Phase sensitive imaging techniques are based on the observation of the phase shifts*** produced by the object on the incoming wave.

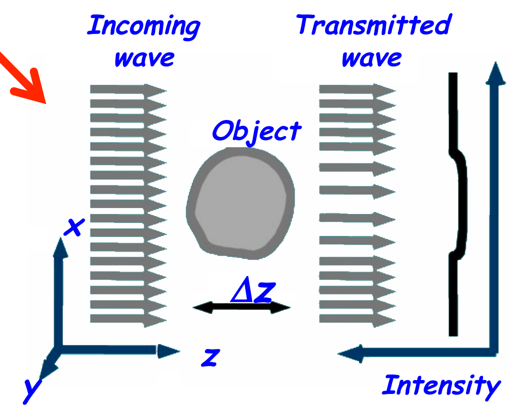
***Refractive index***

$$n = 1 - \delta + i\beta$$

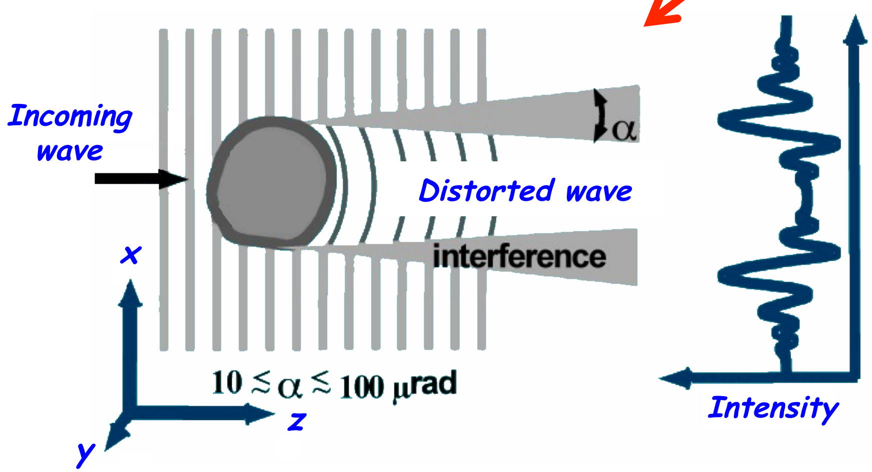
$\beta$ = *absorption term*
$\delta$ = *phase shift term*

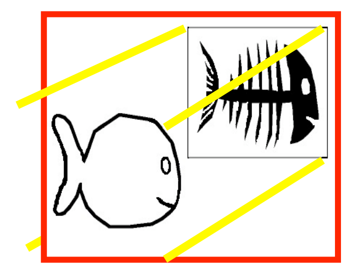



***Conventional radiology relies on X ray absorption***

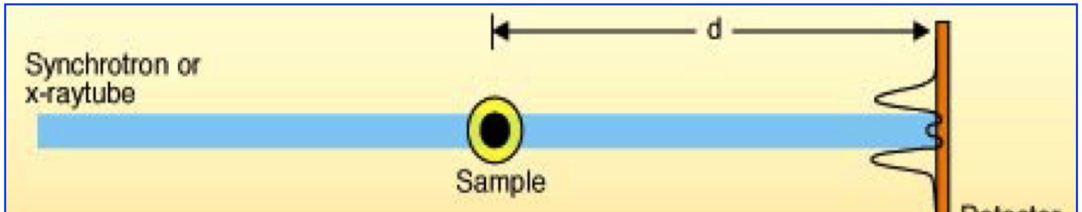



***Phase sensitive radiology relies on phase shifts***



# Phase contrast imaging




*R.Fitzgerard, Physics Today, July 2000*

The technique exploits the ***high spatial coherence of the X-ray source***.

- For ***d = 0 -> absorption image***

- For ***d > 0*** -> ***interference between diffracted and un-diffracted wave produces edge and contrast enhancement***: variations of $\delta$ are detected

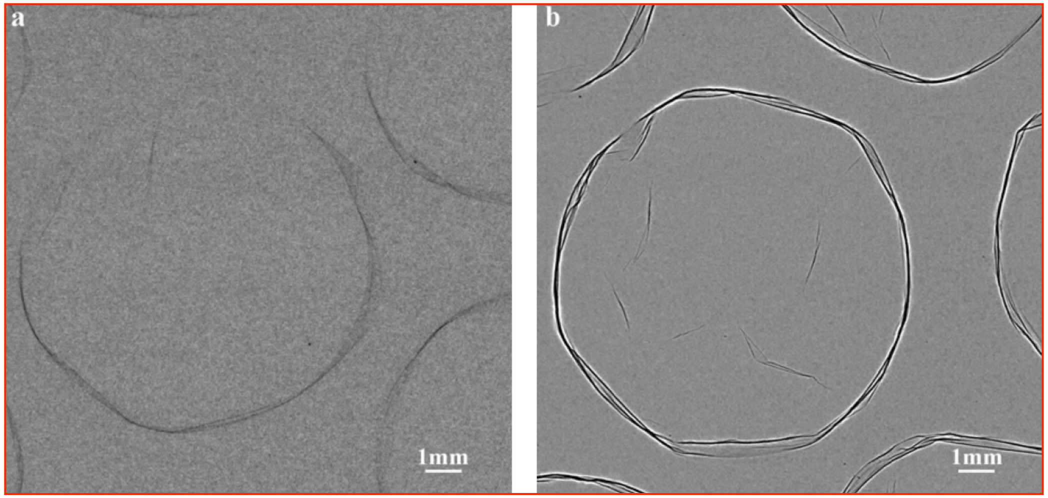
***Refractive index $n = 1 - \delta + i\beta$***

*For biological samples in the energy range: 15 -25 KeV*

***$\delta \sim 10^{-6}$; $\beta \sim 10^{-10}$***

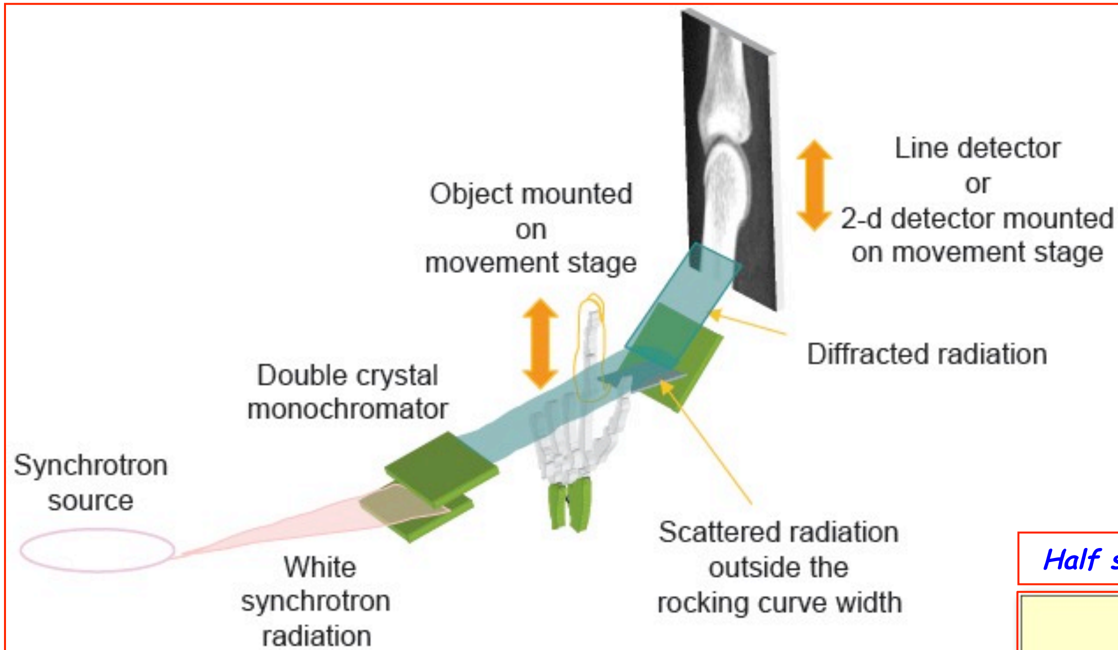
***Phase effects >> absorption effects***

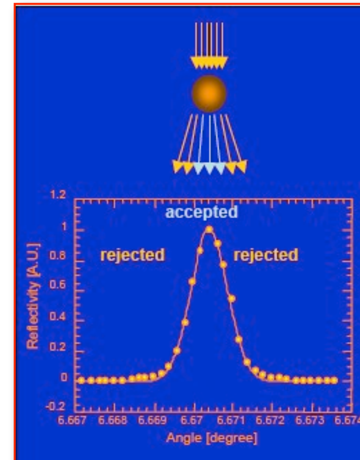
***Images of a nylon air bubble wrap in***: a) ***conventional (absorption) X-ray imaging*** and b) ***phase contrast imaging***, edge detection regime. The edge-enhancement in b) allows the visualization of details not visible in a).

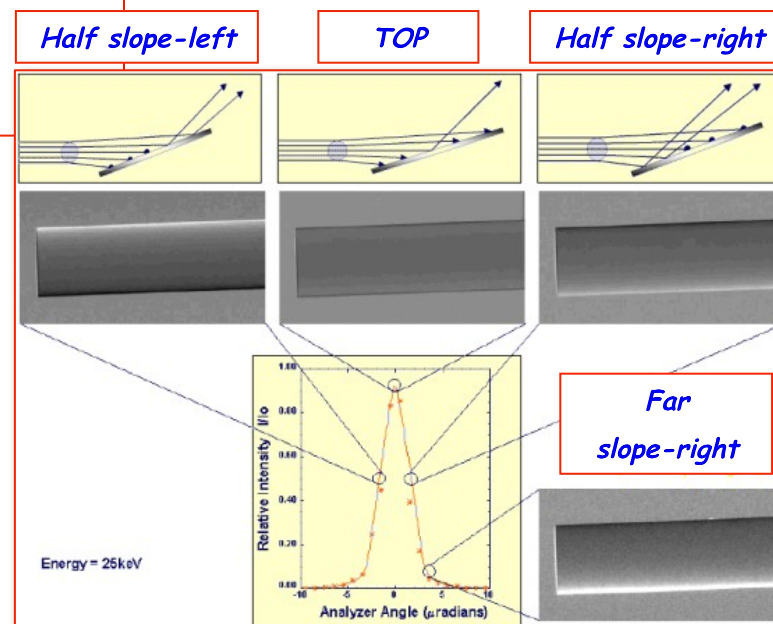



**B. Kaulich et al.**, *Trieste - Melbourne cooperation in advanced imaging with synchrotron radiation*, **2006**

# Imaging: Scattering and Diffraction



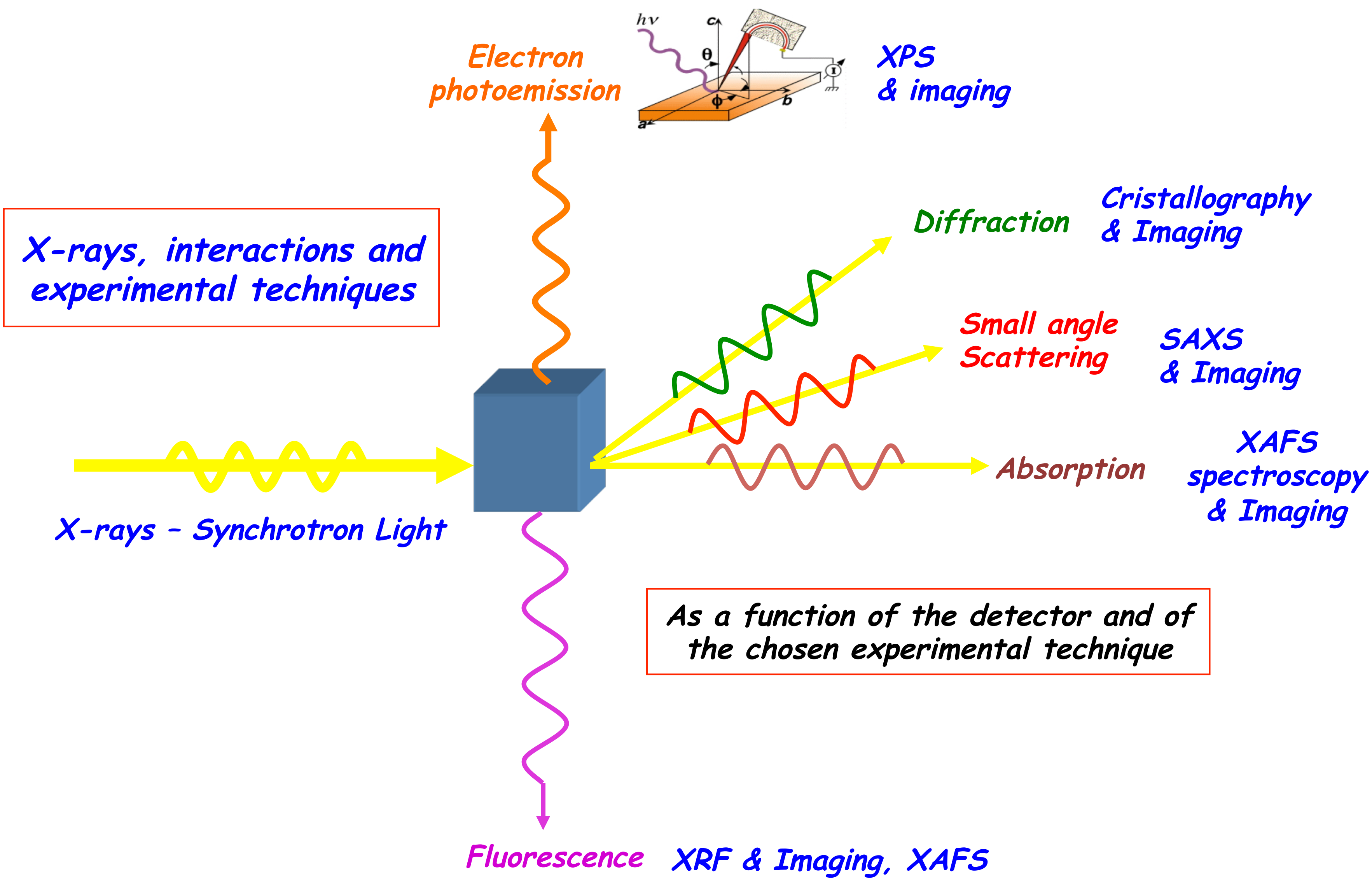




***Diffraction Enhanced Imaging*** (DEI) or **Analyzer-Based Phase-Contrast Imaging** (ABI-PCI) is based on the use of ***a perfect crystal analyzer crystal placed between the sample and the imaging detector***.

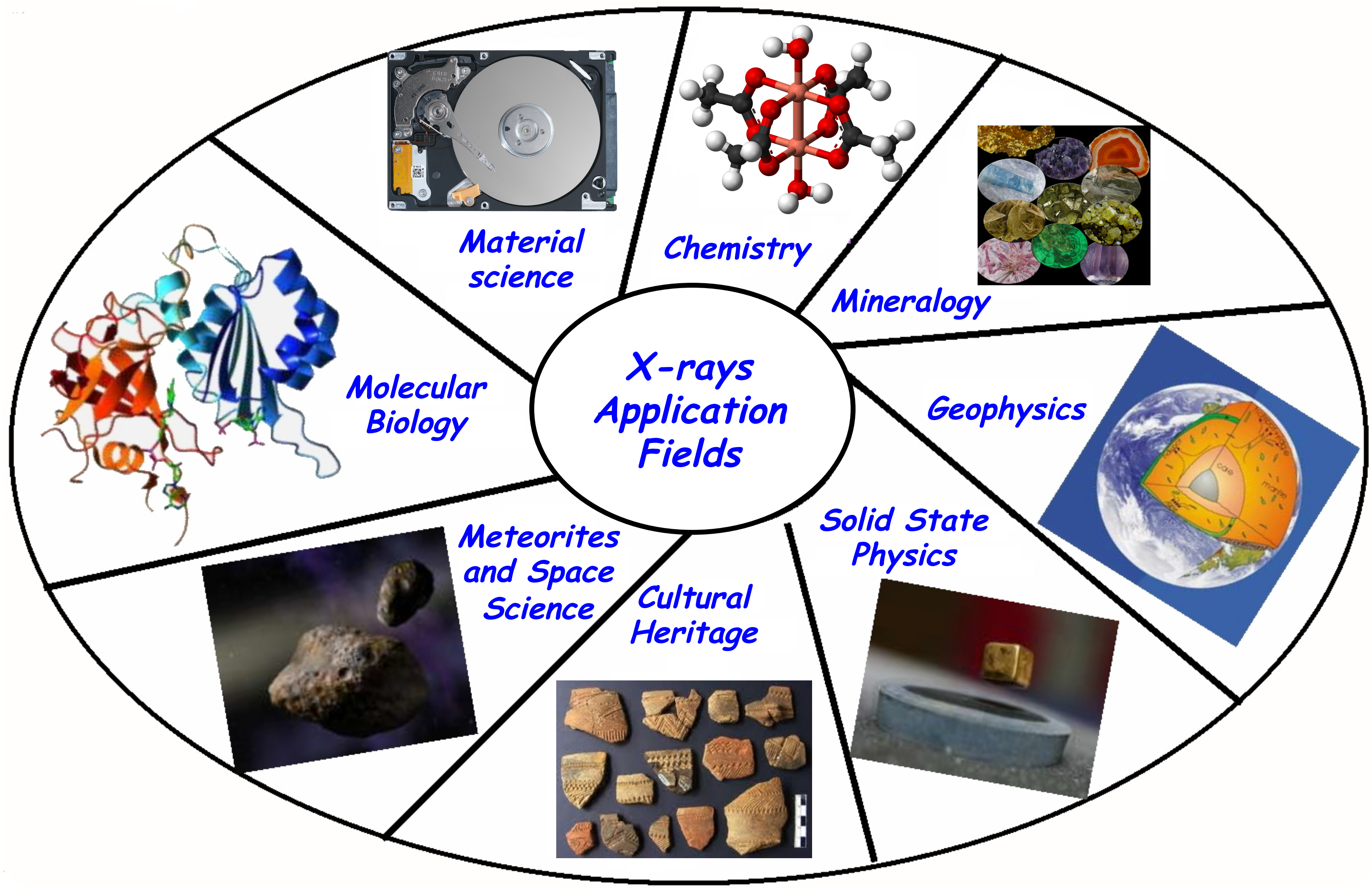
The ***analyzer acts as an angular filter,*** selectively ***accepting or rejecting the photons deviated in the sample at very small angles*** like a perfect and extremely narrow slit: the ***filtering function is the rocking curve*** (FWHM 1-20 μrad) . The images are recorded at different angular positions along the rocking curve that is centered at the Bragg angle for the Si (111) reflection at 25 keV ( $\Delta\theta = 0$). Photons deviated outside the rocking curve width are not detected

***A. Bravin*** – ID17 Biomedical Beamline - ***ESRF*** and ***G. Tromba*** – Sincrotrone Trieste -***ELETTRA***

# X-rays interactions with matter and experimental techniques



# Synchrotron radiation applications using X-rays



# Some applications using X-rays (synchrotron light)

Cultural heritage

Imaging and radiology

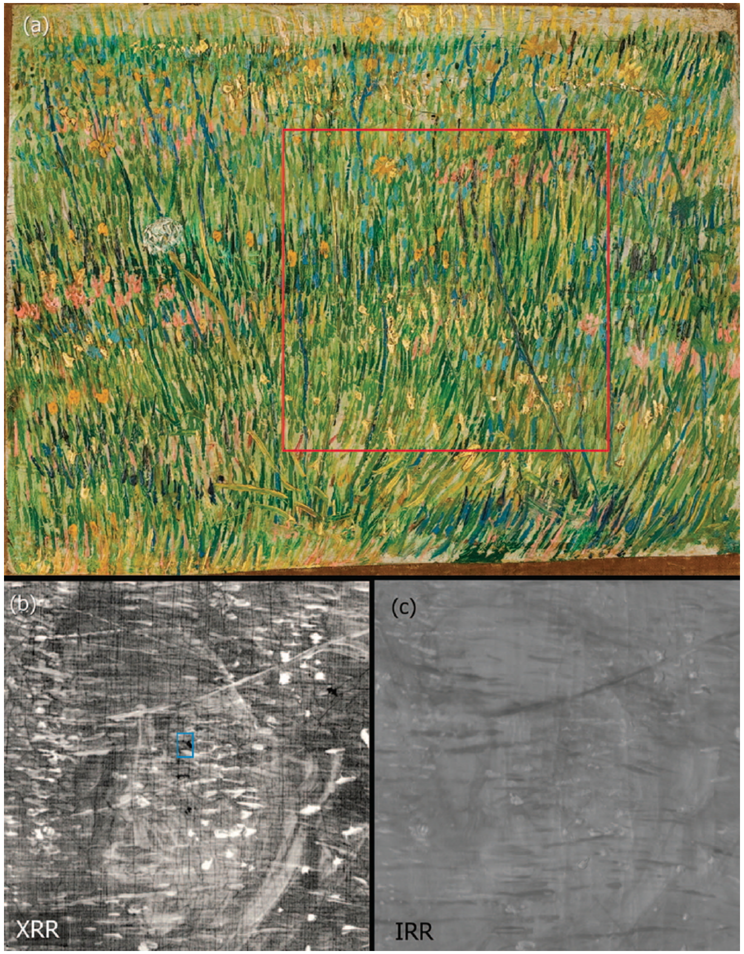
Imaging and paleontology

Bio-crystallography

# Applications in the field of cultural heritage

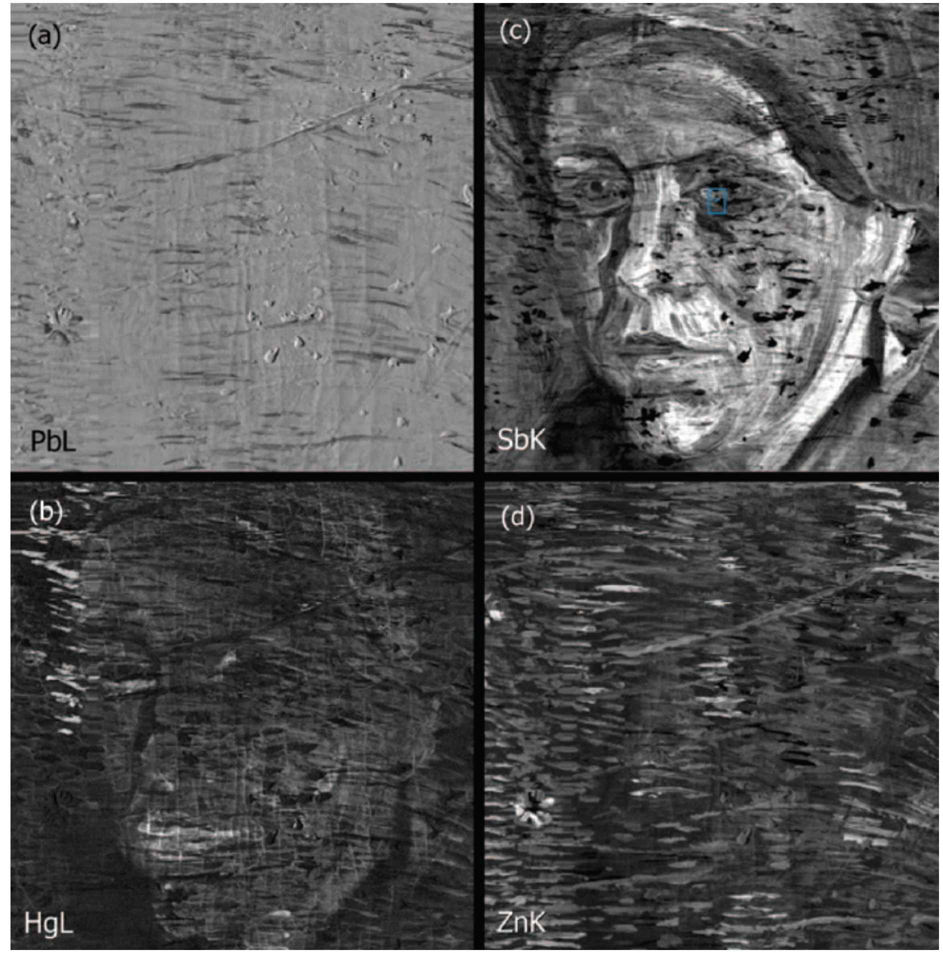
# Visualization of a Lost Painting of van Gogh using XRF

***Vincent van Gogh*, Patch of Grass**, Paris 1887, Kroller-Muller Museum, Otterlo, The Netherlands, (KM 105.264; F583/JH1263).




*Conventional X-Ray Radiation (XRR)transmission radiography*

*Infrared reflectography (IRR)*




***Synchrotron Radiation – XRF*** (black, low intensity and white, high intensity). Hg L shows the distribution of vermillion, Sb K of Naples yellow and Zn K of zinc white.

**J. Dik et al.**, *Visualization of a Lost Painting by Vincent van Gogh Using Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping*, **Anal. Chem. 2008**, **80**, 6436

# Visualization of a Lost Painting of van Gogh


a) ***Tritonal color reconstruction*** of Sb (yellowish white) and Hg (red) (b) **Detail from Vincent van Gogh, Head of a Woman**, Nuenen 1884-85,Kro ller-Muller Museum, Otterlo (KM 105.591;F154/JH608). (c) **Detail from Vincent van Gogh, Head of a Woman**, Nuenen 1884-85, Van Gogh Museum, Amsterdam (F156/ JH569).

**Vincent van Gogh (1853-1890), is best known for his vivid colors and his short but highly productive career. His productivity is even higher than generally realized, as many of his known paintings cover a previous composition. Van Gogh would often reuse the canvas of an abandoned painting and paint a new or modified composition on top. These hidden paintings offer a unique and intimate insight into the genesis of his works.**

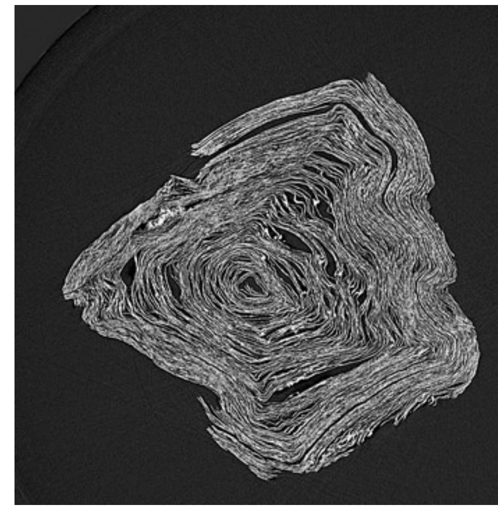
**J. Dik et al.**, *Visualization of a Lost Painting by Vincent van Gogh Using Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping*, **Anal. Chem. 2008**, **80**, 6436

# Revealing letters in rolled Herculaneum papyri using X-ray phase-contrast tomography

Close up photography of ***Herculaneum Papyrus*** scroll PHerc.Paris.4. The photographied zone is 5cm. (*Credit: E. Brun*)

Hundreds of papyrus rolls, buried by the eruption of Mount Vesuvius in 79 AD and belonging to the only library passed on from Antiquity, were discovered 260 years ago at Herculaneum.

These carbonized papyri are extremely fragile and are inevitably damaged or destroyed in the process of trying to open them to read their contents.



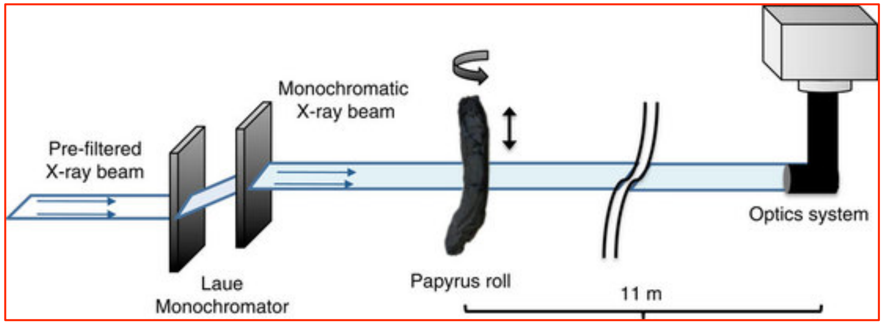
***A section of papyrus***. Letter sequences are found in a fragment of a hidden layer. (*Credit: CNRS-IRHT UPR 841 / **ESRF** / CNR-IMM Unité de Naples*)

***V. Mocella*** *et al.*, **Nature Communications** - DOI: 10.1038/ncomms6895- ***January 2015***

**https://www.youtube.com/watch?v=d3aWBgNYOCU**

# Revealing letters in rolled Herculaneum papyri.

In recent years, new imaging techniques have been developed to read the texts without unwrapping the rolls. ***Until now, specialists have been unable to view the carbon-based ink of these papyri***, even when they could penetrate the different layers of their spiral structure.
For the first time ***X-ray phase-contrast tomography*** (*beamline ID17 of the ESRF, Grenoble, France*) can ***reveal various letters hidden inside the precious papyri without unrolling them***.
This attempt opens up new opportunities to read many Herculaneum papyri, which are still rolled up, thus enhancing our knowledge of ancient Greek literature and philosophy.





The ***papyrus alphabet from PHerc.Paris.4. as revealed by the XPCT experiment***, primarily from the ***innermost region of the papyrus***, where the individual coils are more distinguishable, are reported on lines 1 and 2; on ***line 3 the infrared images of the same letters from the unrolled (opened) papyrus PHerc. 1471***, which was used as a reference for the writing style of the scroll PHerc.Paris. 4.

***V. Mocella** et al.*, **Nature Communications** - DOI: 10.1038/ncomms6895- ***January 2015***

# Blackening of Pompeian Cinnabar paintings studied by X-ray micro-XRF imaging

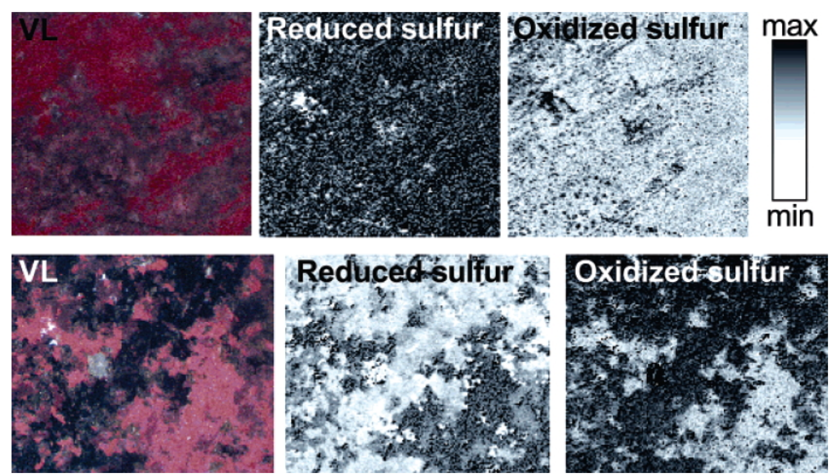
## Painting alterations

*A wall painted red in the remains of Pompei: turning black*

Scientists have ***wondered for many years why the red in Pompeii's walls***, a dye that is made from cinnabar (HgS), **turns black**.

The ESRF scientists found that the ***chemical composition in the affected samples*** was different from that of cinnabar, which indicated that **some important chemical reactions had taken place.**

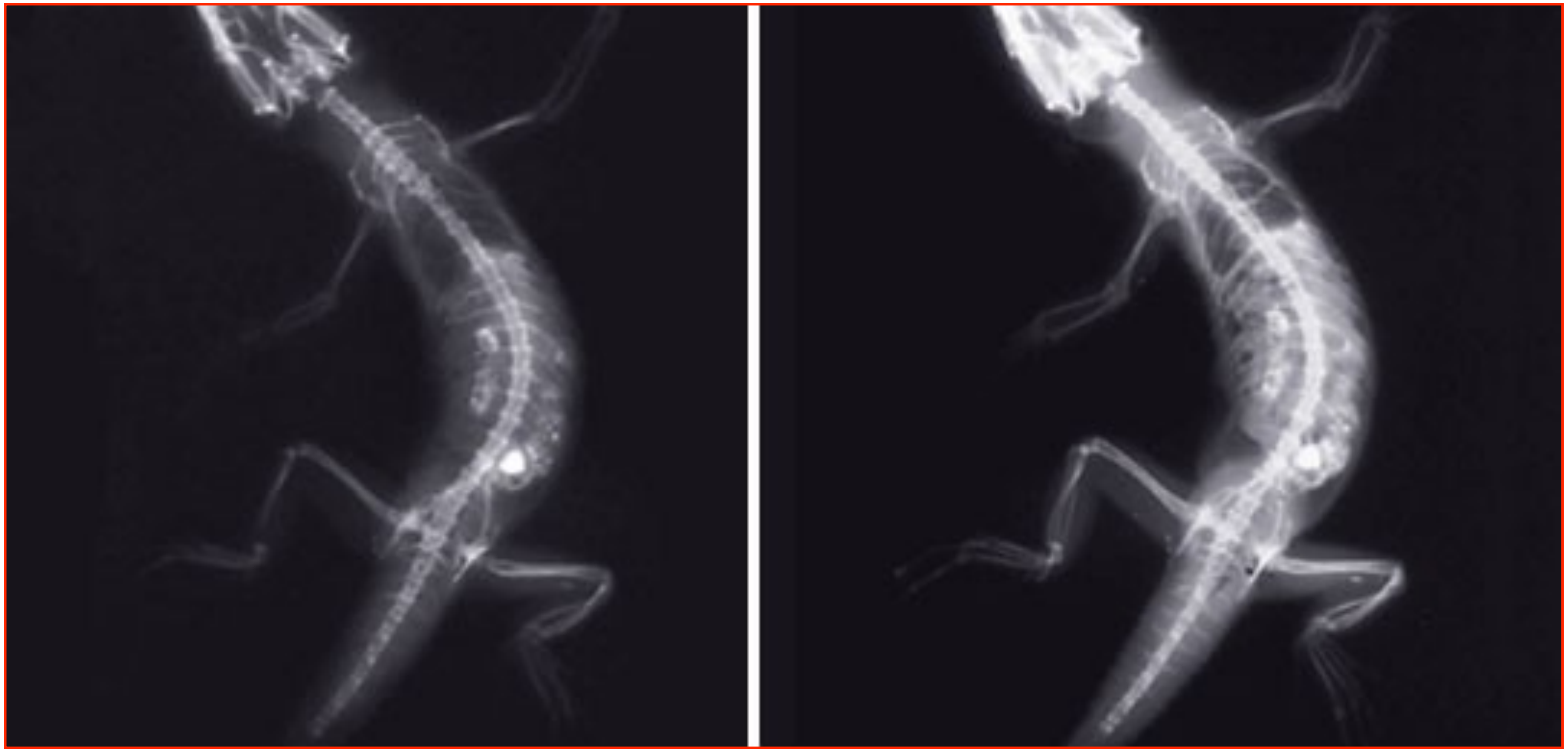
On the one hand, ***cinnabar had reacted with chlorine***, which led to the formation of grey chlorine mercury compounds. The chlorine came from the sea and possibly punic wax (the wax that was used in the frescoes).
***Reduced and oxidized sulfur distributions reveal that the sulfated black coating consists of a 5-μm-thick layer covering intact cinnabar.***




***M. Cotte, et al.*, *Anal. Chem.***, 78, 7484-7492 (2006).

# *Imaging and Radiology*

# Imaging and history



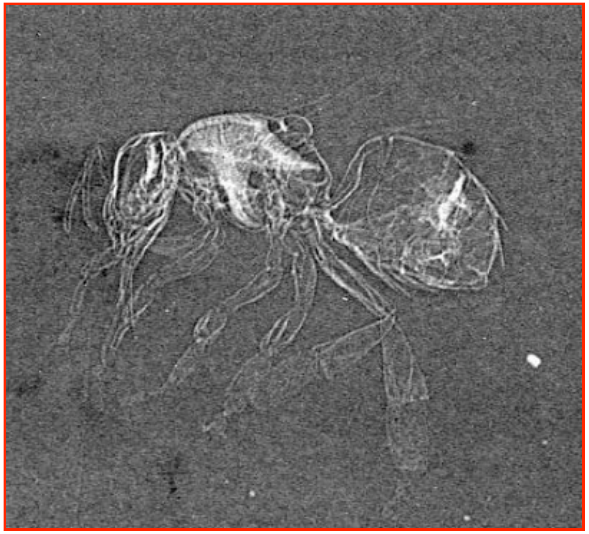
Early '90 – First radiography achieved using the synchrotron radiation 17 keV X-rays produced by ADONE (LNF)

E. Burattini, INFN - Asimmetrie 6 2008

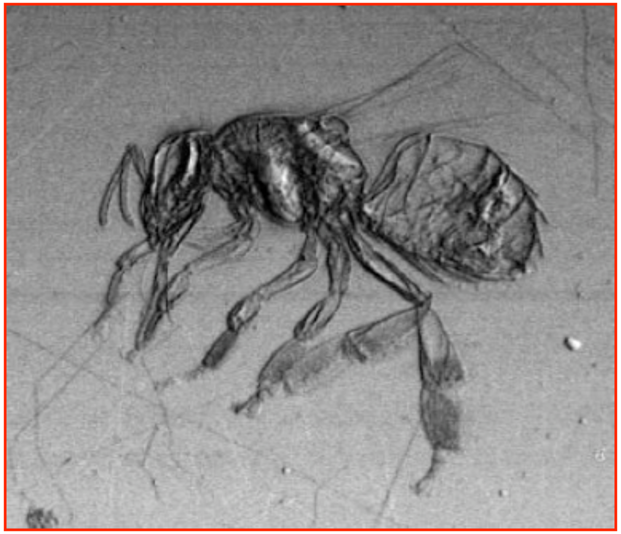
# X-rays, Synchrotron radiation and Imaging

A century after the beginning of absorption radiography, a form of phase radiography and tomography thus appeared. It is based on simple propagation, makes it possible to visualize internal structures in optically non transparent materials, with a resolution and sensitivity far superior to conventional X-ray imaging based on absorption.

Conventional absorption image



Phase contrast image



Diffraction enhanced Phase contrast image

G. Tromba - ELETTRA- Sincrotrone Trieste

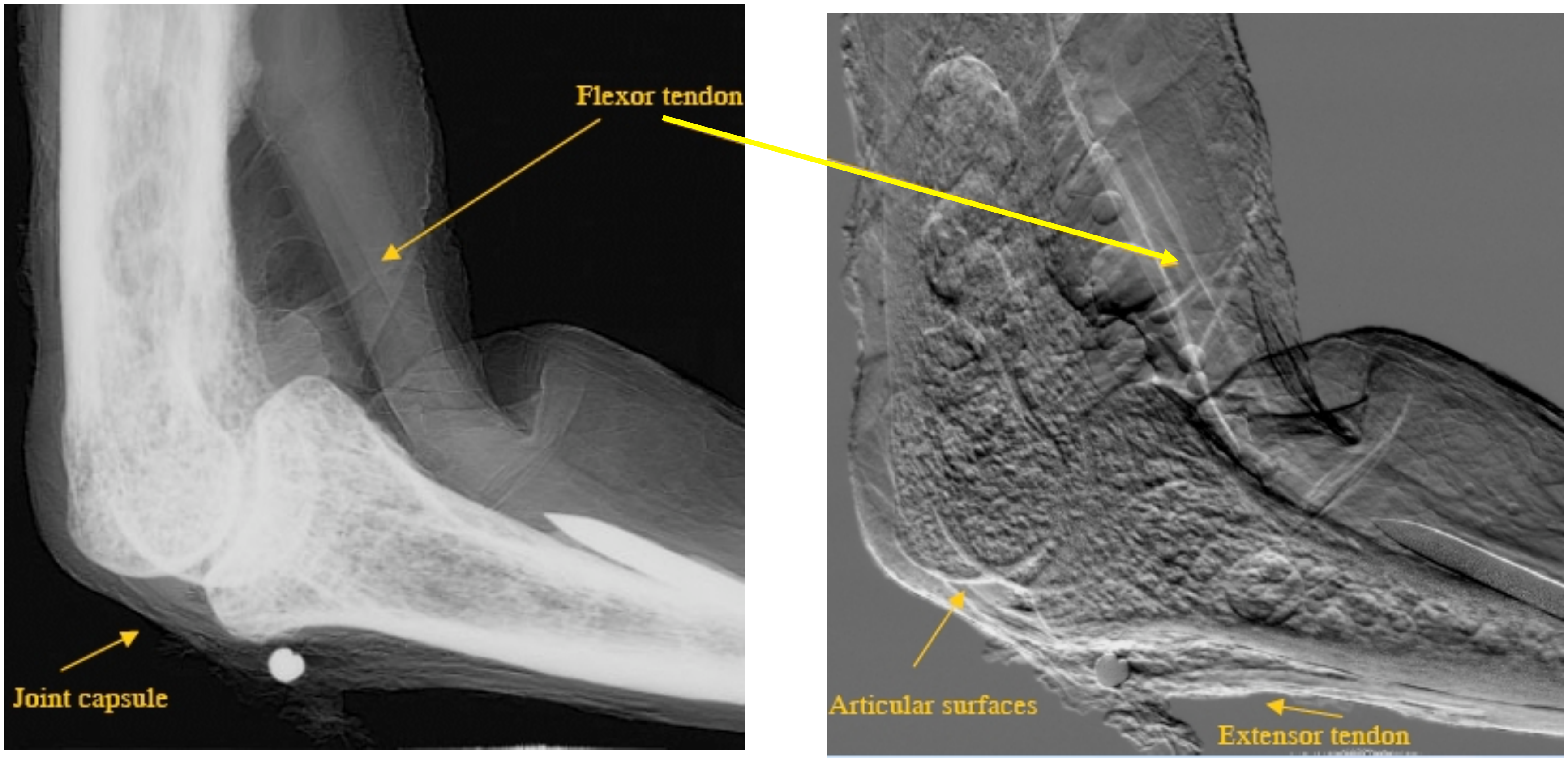
# Analyser Based Imaging (ABI) images at two positions of the rocking curve



*R. Fitzgerald, Physics Today 53, 23 (2000)*

# Diffraction Enhanced Imaging

Index finger proximal interphalangeal joint

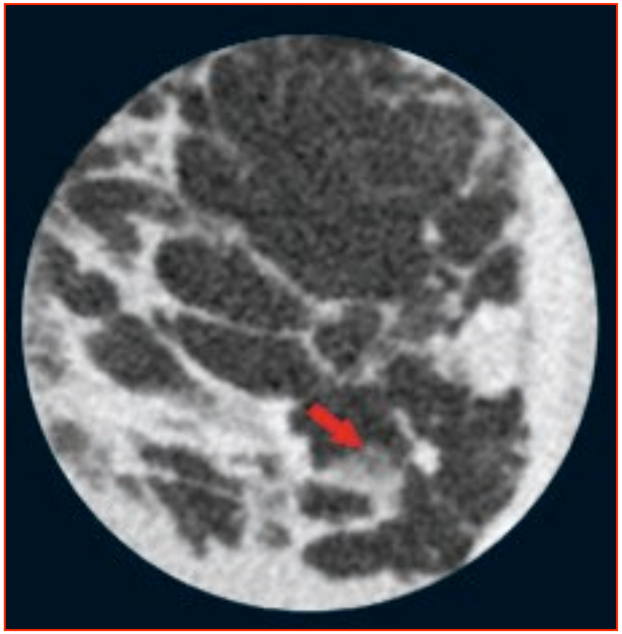



Apparent absorption Image

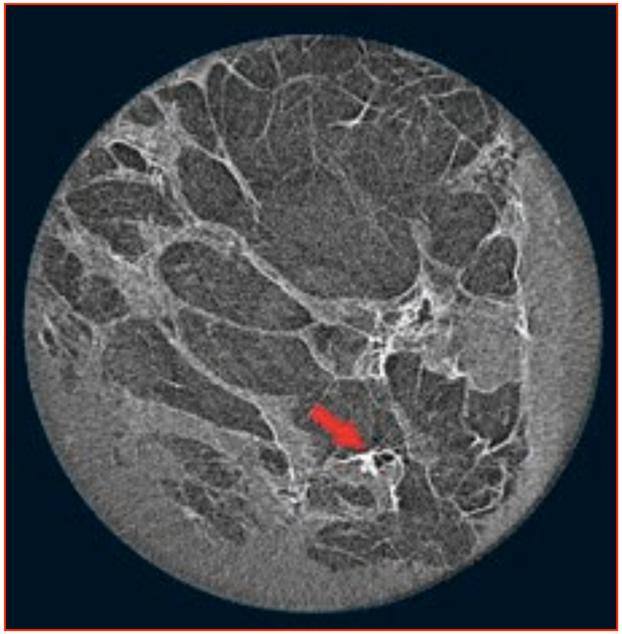
Refraction Image

Daresbury, Elettra, University of Trieste Collaboration within PHASY project: R. Lewis et al.

# *Improved breast scans offer better diagnoses*



***A conventional CT scan of a breast. The arrow shows the location of the tumour.***



***The new ABI technique shows tissue and tumour seven times clearer than CT scans.***

***Early detection of breast cancer is directly linked to successful treatment***. A radical new screening method is improving the accuracy of scan results. Although ***X-ray mammography is currently the most widely used tool in diagnostic radiology***, it fails to identify about 10–20% of palpable breast cancers. This is because some breasts are more dense than others, especially in young women. In such cases, glandular tissues can mask cancer lesions in mammograms. ***Better results are obtained using X-ray computed tomography (CT) and analyzer-based X-ray imaging (ABI).*** This corresponded to ***a quarter of a dose required for imaging the same sample with a conventional CT scanner***, and the ***spatial resolution of the ABI images was seven times as good***. It is possible to distinguish more micro-calcifications – small deposits of minerals that can indicate the presence of a cancer – and improve the definition of their shapes and margins

***J Keyriläinen et al***. *Radiology* **249**, 321–327 (**2008**) and ***ESRF news***, December 2008

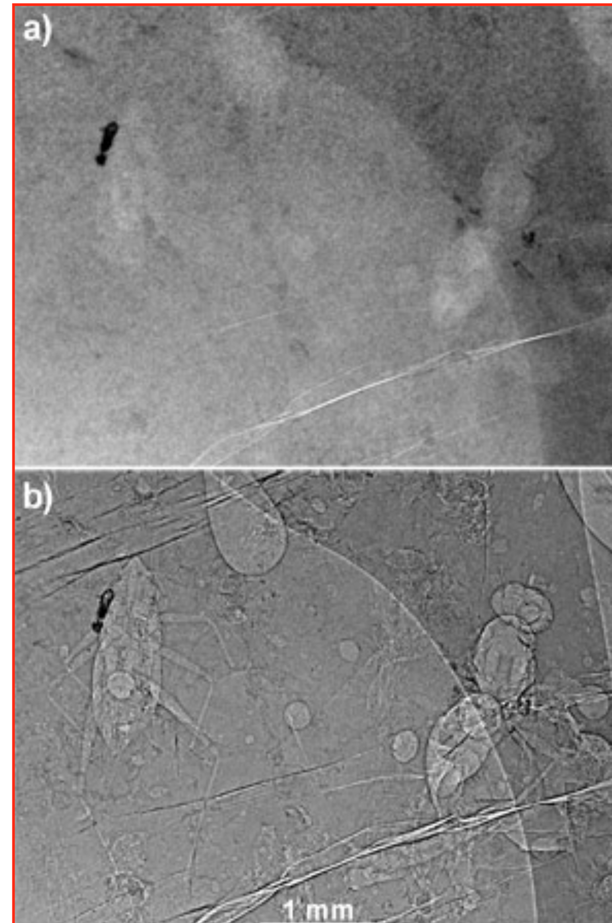
# Imaging and paleontology

# Imaging and paleontology

***Amber has always been a rich source of fossil evidence***. X-rays now make it possible for paleontologists to ***study opaque amber, previously inaccessible using classical microscopy techniques***. Scientists from the University of Rennes (France) and the ESRF found ***356 animal inclusions, dating from 100 million years ago***, in two kilograms of opaque amber from ***mid-Cretaceous*** sites of Charentes (France).


***Pieces of opaque amber-***
***Image credits: V. Girard/D. Néraudeau, UMR CNRS 6118 Rennes***

**Fossil inclusions in opaque amber**




***Radiography of an amber block with inclusions viewed in absorption mode.***

***Propagation phase contrast X-ray synchrotron imaging (990 mm prop. distance)***

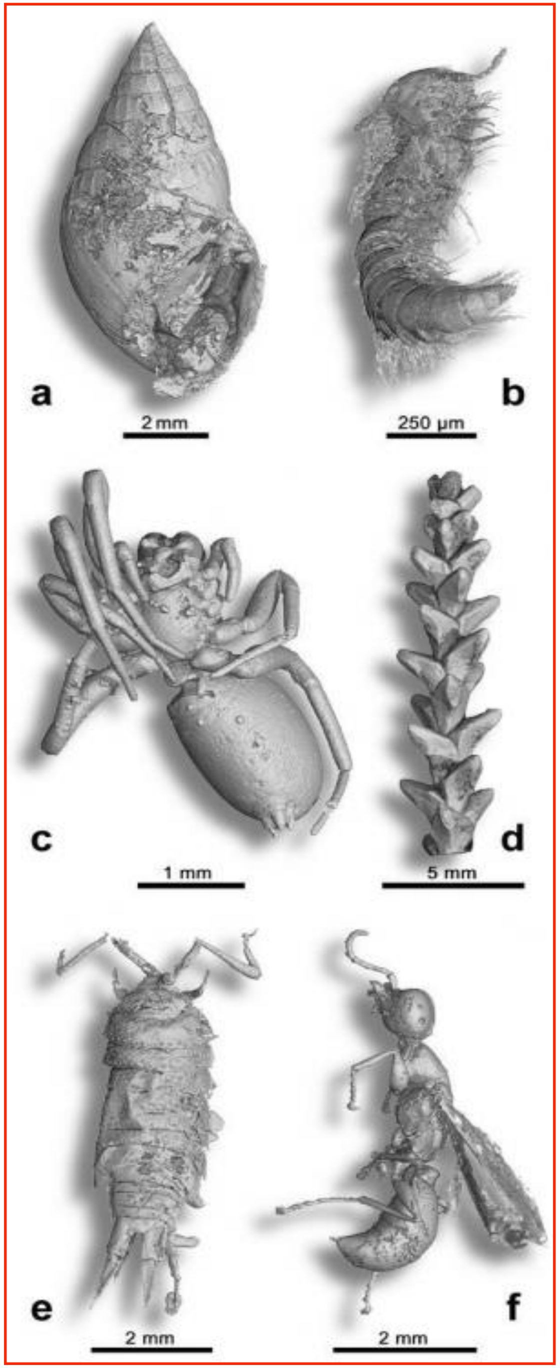
***M. Lak, D. Neraudeau, A. Nel, P. Cloetens, V. Perrichot and P. Tafforeau,*** *Phase Contrast X-ray Synchrotron Imaging: Opening Access to Fossil Inclusions in Opaque Amber*, ***Microscopy and Microanalysis, (2008), 14:251-259***

# Imaging and paleontology

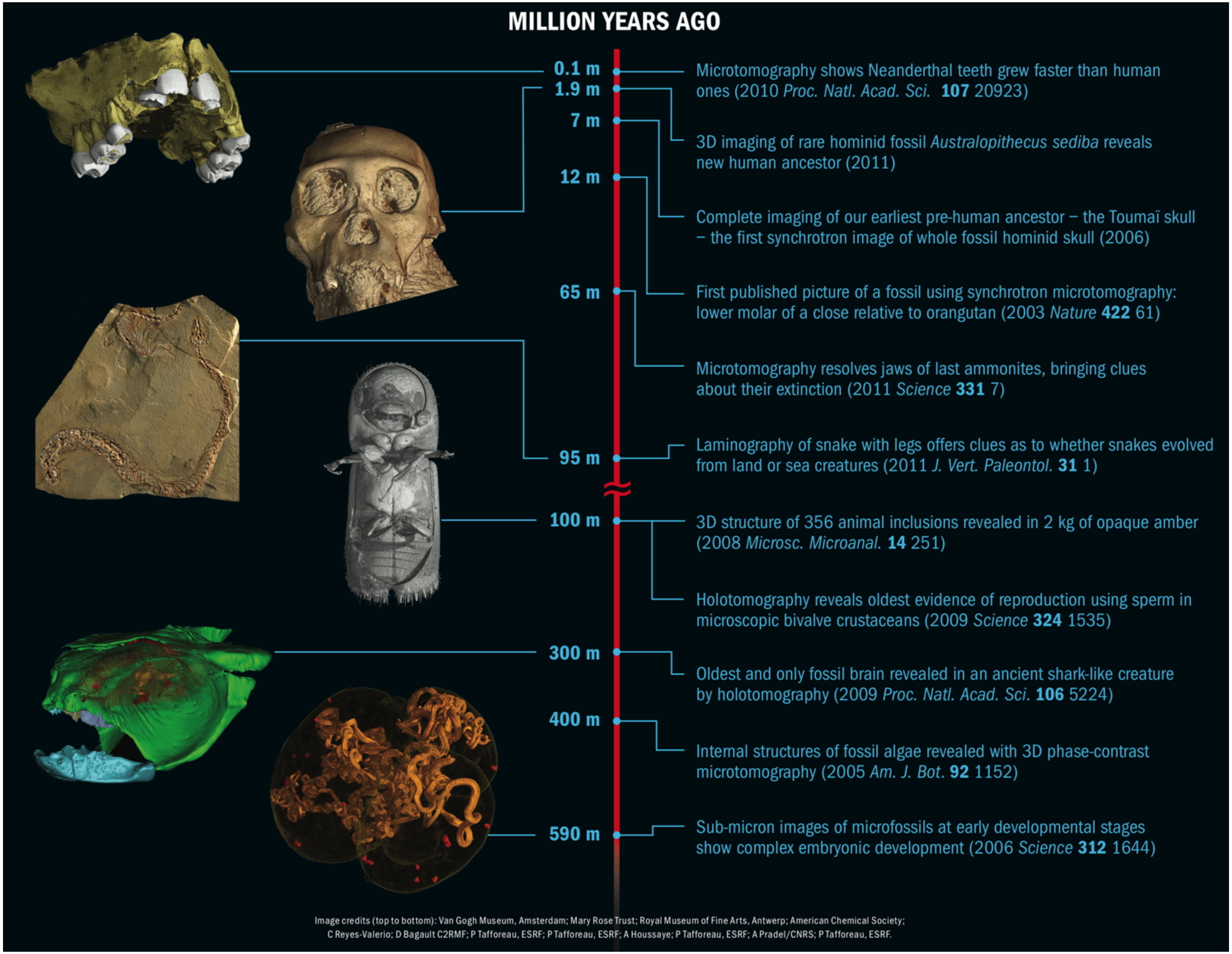
*Synchrotron X-ray microtomography was used to determine the 3D reconstruction and allowed the paleontologists to study the organisms in detail and to describe them.*


*Cretaceous beetle*

*Examples of virtual 3D extraction of organisms embedded in opaque amber: a) Gastropod Ellobiidae; b) Myriapod Polyxenidae; c) Arachnid; d) Conifer branch (Glenrosa); e) Isopod crustacean Ligia; f) Insect hymenopteran Falciformicidae.*



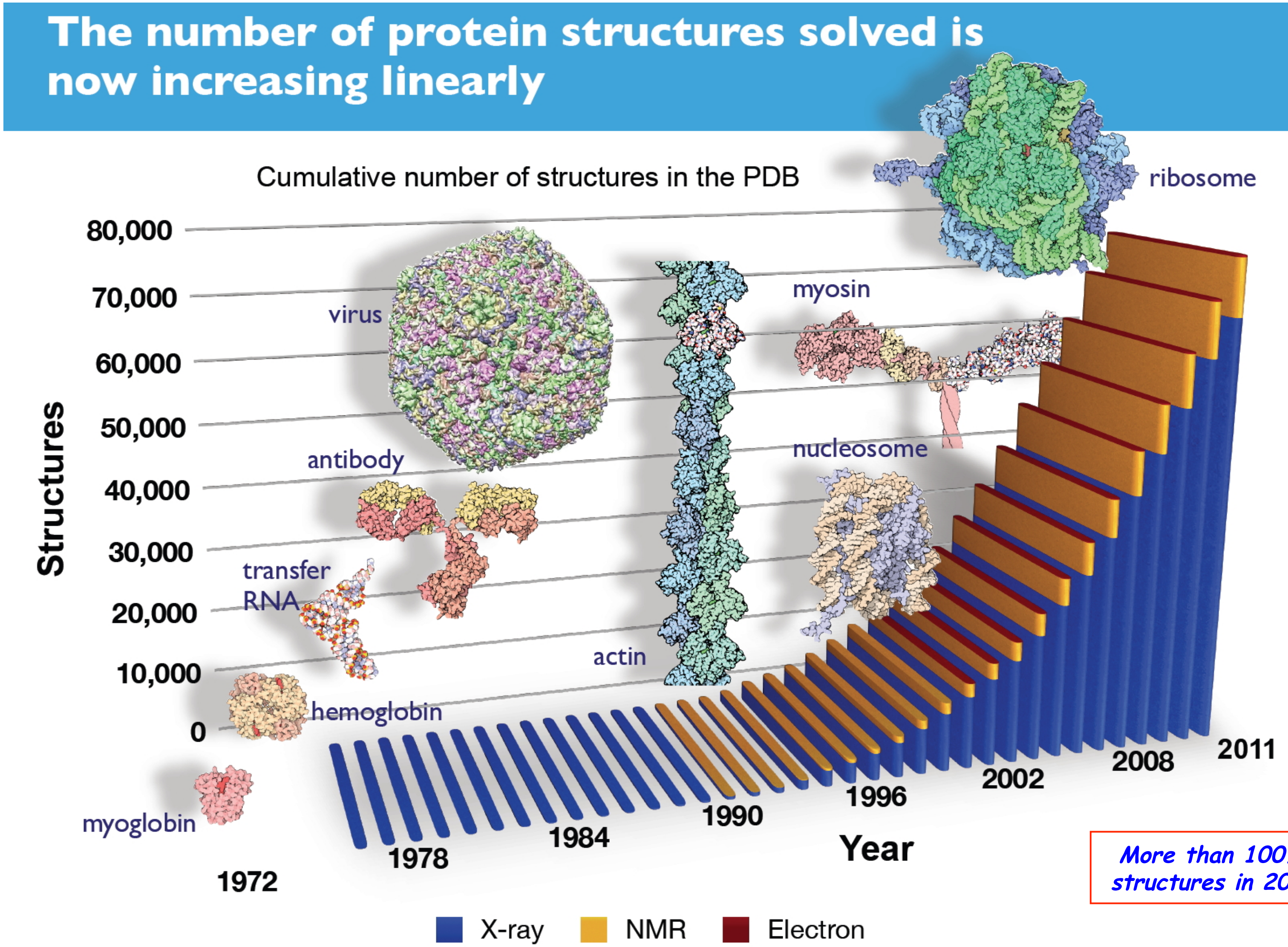

*M. Lak, D. Neraudeau, A. Nel, P. Cloetens, V. Perrichot and P. Tafforeau, Phase Contrast X-ray Synchrotron Imaging: Opening Access to Fossil Inclusions in Opaque Amber, Microscopy and Microanalysis, (2008)*




***Marine Cotte*** - *Synchrotron culture : Focus on: paleontology and cultural heritage* – ***ESRF News –June 2011***

# Biocrystallography

# Biocrystallography



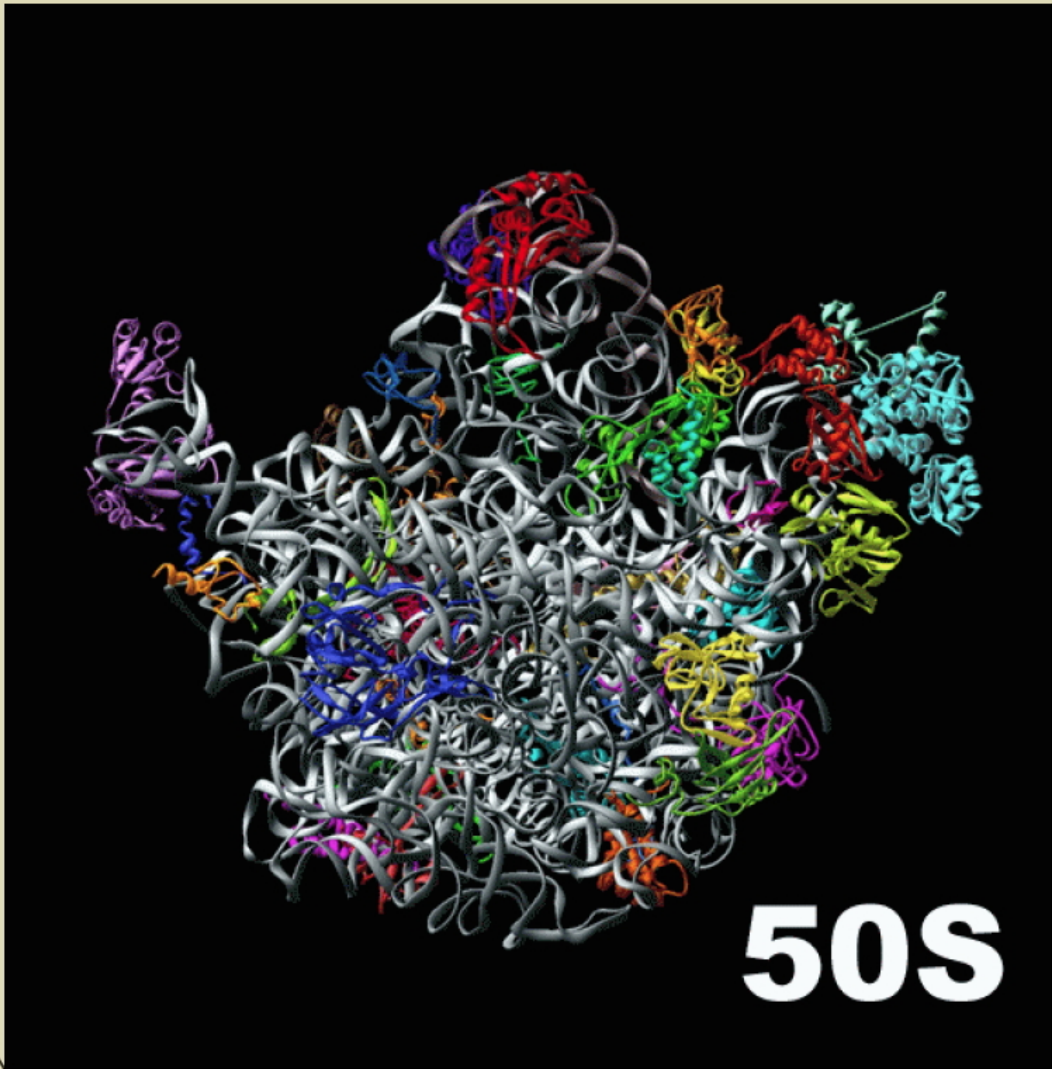

*More than 100.000 structures in 2014 !!!*

*H. Chapman – Lecture on Imaging Molecules with X-ray Free-Electron Lasers - 2012*

Myoglobin
16 kDa

50 YEARS

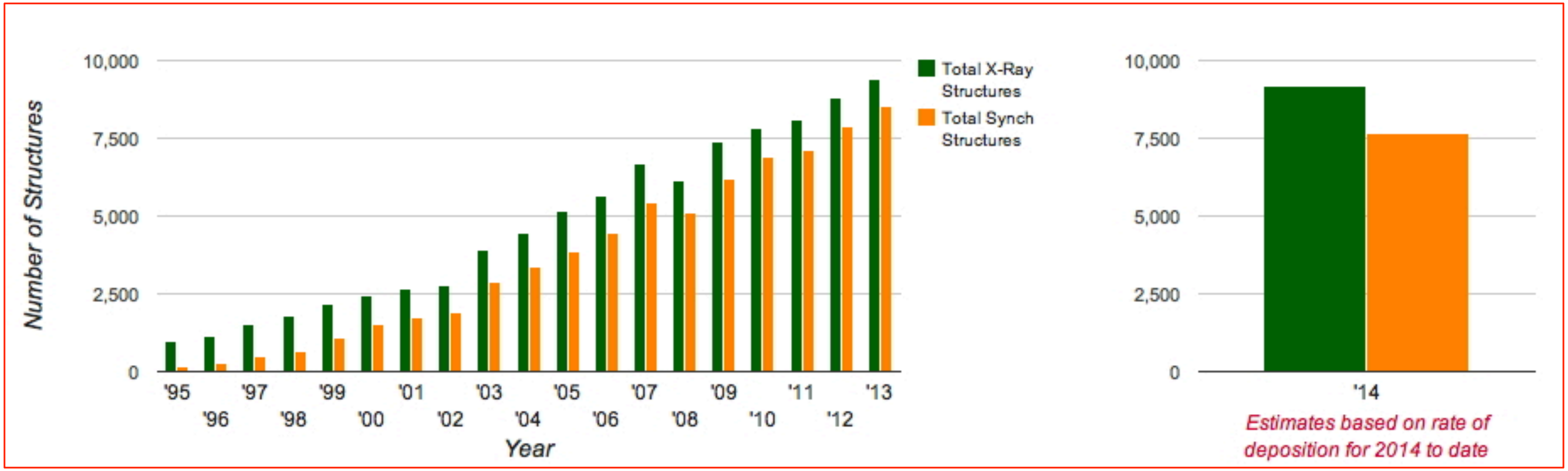
*Peso molecolare:*
*1kDa = 1000 g mol$^{-1}$*




Ribosome 2.5 MDa

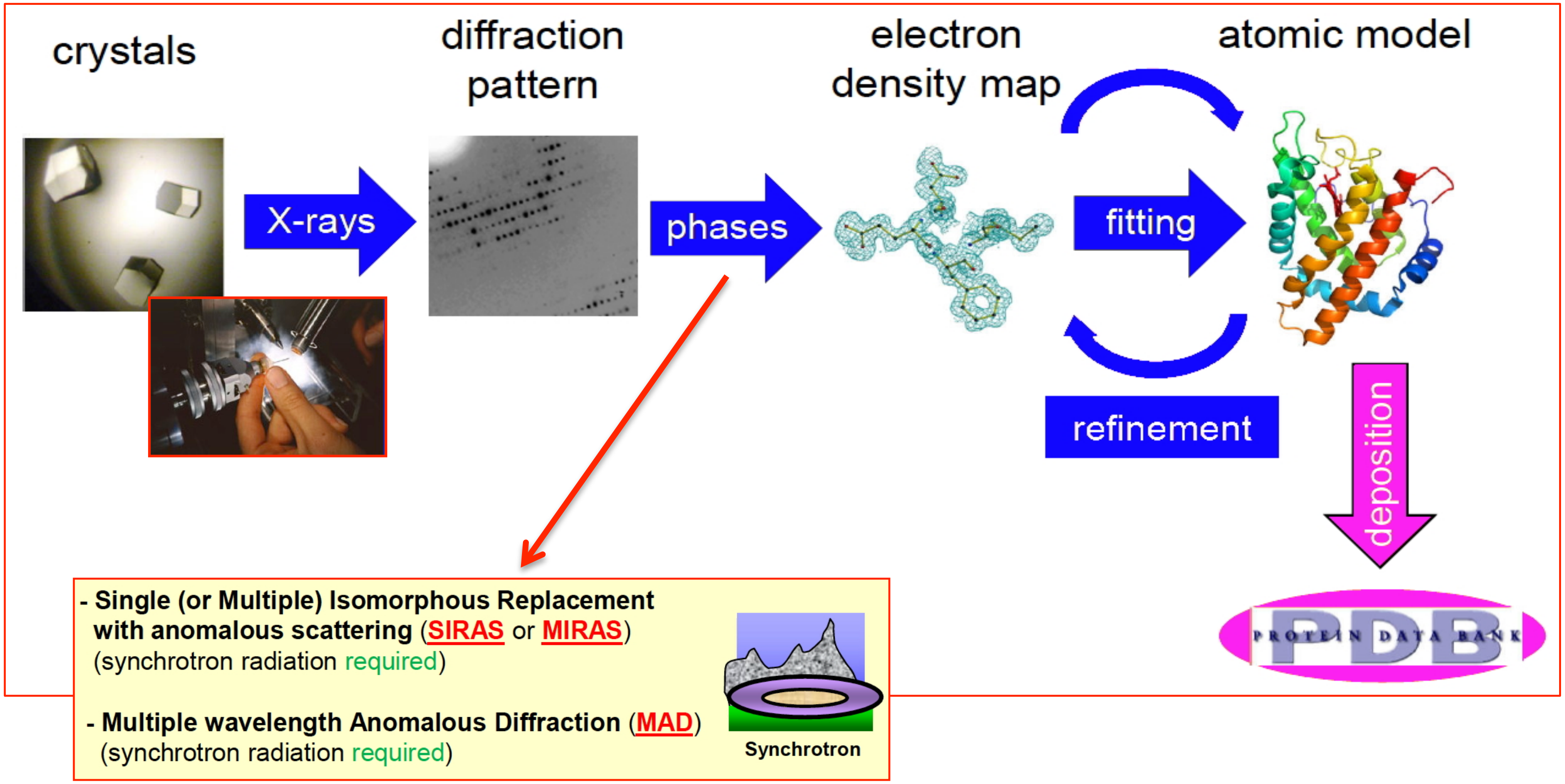
*M. Bolognesi, Univ. Milano, Biologia strutturale, Conf. Luci di sincrotrone, CNR, 2014*

# X-ray biocrystallography and synchrotron radiation




22 July 2014 http://biosync.sbkb.org/index.jsp

# Crystallographic experiment



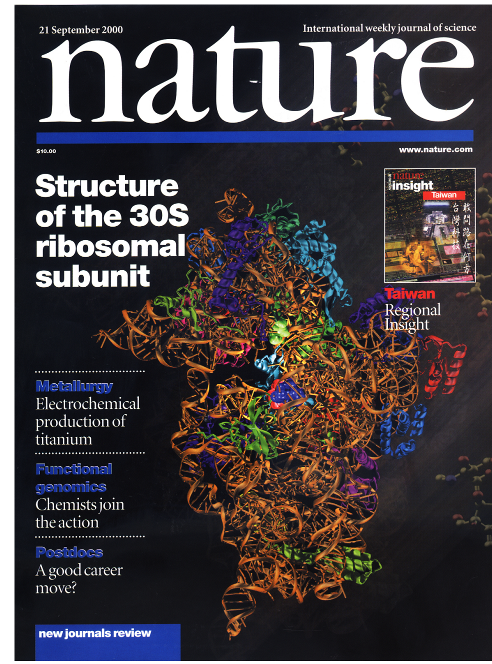

**MAD with Se-methionine substituted protein**: prerequisites enough Met must be present (one Se-Met can phase about 15 kD of protein)

*M. Nardini, Univ. Milano, Lecture on: Synchrotron Radiation and Biocrystallography, 2013*

# Very recent Noble Prizes in Chemistry

2009 "for studies of the structure and function of the ribosome"

Biocrystallography vs. Structural Biology


Using Synchrotron radiation Research

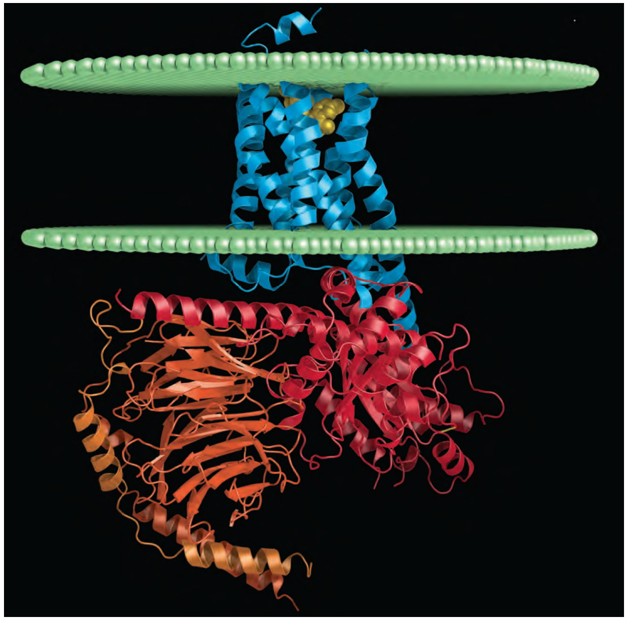
**An understanding of the ribosome's innermost workings is important for a scientific understanding of life.** This knowledge can be put to a practical and immediate use; **many of todays antibiotics cure various diseases by blocking the function of bacterial ribosomes**. Without functional ribosomes, bacteria cannot survive. This is why **ribosomes are such an important target for new and more efficient antibiotics**.

# Very recent Noble Prizes in Chemistry

*2012 "for studies of G-protein-coupled receptors"*

*Biocrystallography vs. Structural Biology*





*G-Protein Coupled Receptor (blue) sits within lipid bilayer (green) to respond to hormone (yellow)-* **Image by Wayne Decatur** - http://www.hhmi.org/bulletin/winter2013/features/index.html

*Using Synchrotron radiation Research*

G protein coupled receptors (GPCRs) represent ***the largest family of membrane proteins*** (about 800 different proteins) ***controlling body functions***, ***drug transit across membranes*** and representing the richest source of targets for the pharmaceutical industry.

# Conclusions

- Synchrotron radiation has surely revolutionized X-ray applications.
- Most of the SR facilities in the world have beamlines dedicated to different X-ray applications.
- Synchrotron radiation X-ray applications still have a very bright future.

INTERNATIONAL
YEAR OF LIGHT
2015

# *Thank you for your attention*

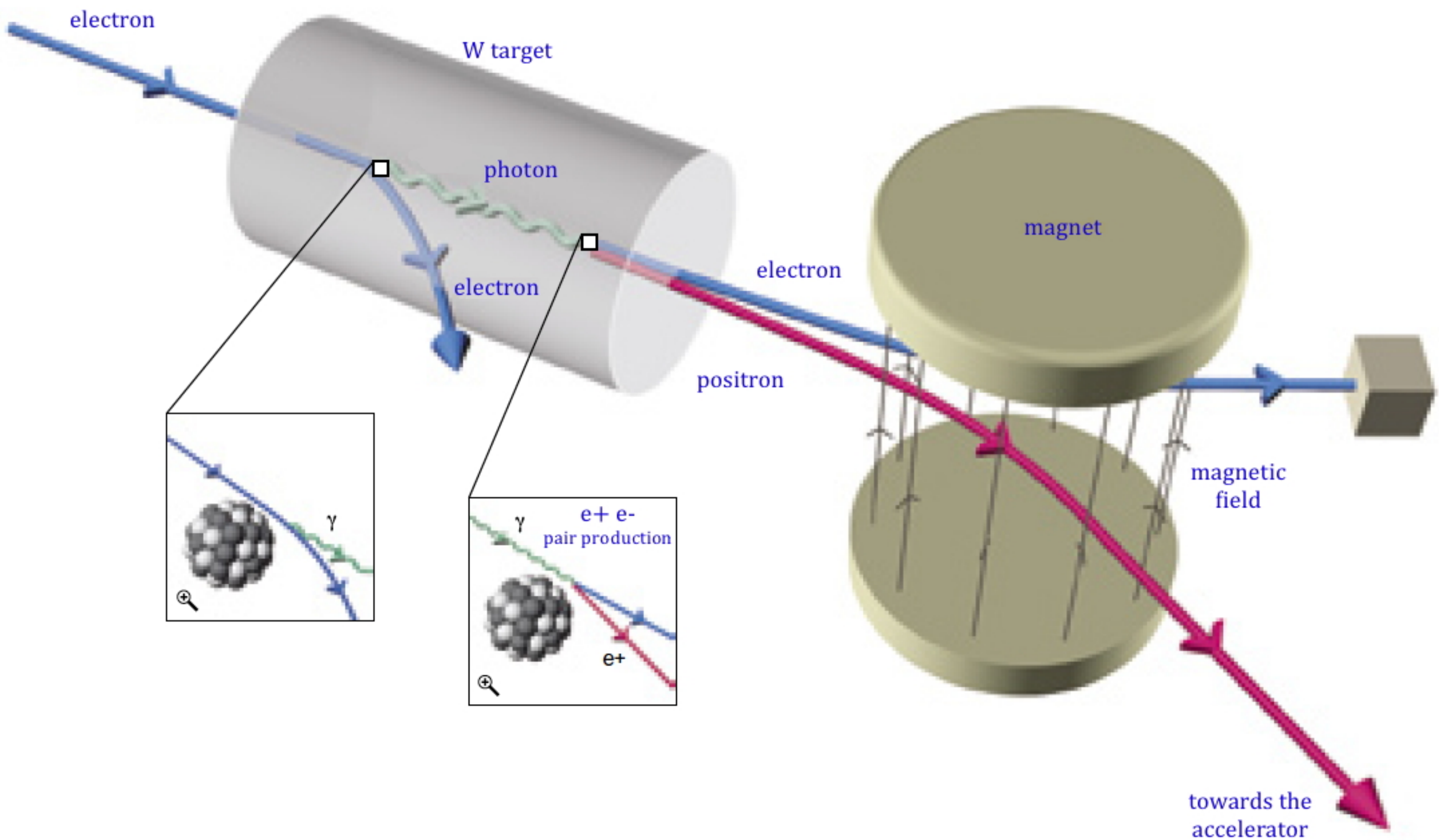
DAΦNE Light
Synchrotron Radiation Facility

***Supplementary material- f.y.k.***

# Reminder

| | | |
|---|---|---|
| • *Speed of light* | | $c = 2.99792458 \times 10^8$ m/s |
| • *Electron charge* | | $e = 1.6021 \times 10^{-19}$ Coulombs |
| • *Electron volts* | | $1\ eV = 1.6021 \times 10^{-19}$ Joule |
| • *Energy and rest mass* | | $1 eV/c^2 = 1.78 \times 10^{-36}$ kg |
| | Electron | $m_0 = 511.0\ keV/c^2 = 9.109 \times 10^{-31}$ kg |
| | Proton | $m_0 = 938.3\ MeV/c^2 = 1.673 \times 10^{-27}$ kg |
| • *Relativistic energy, E* | | $E = mc^2 = m_0\gamma c^2$ |
| • *Lorentz factor, $\gamma$* | | $\gamma = 1/[(1-v^2/c^2)^{1/2}] = 1/[(1-\beta^2)^{1/2}]$<br>$\beta = v/c$ |
| • *Relativistic momentum, p* | | $p = mv = m_0\gamma\beta c$ |
| • *E-p relationship* | | $E^2/c^2 = p^2 + m_0c^2$ |
| | for ultra-relativistic particles | $\beta \approx 1, \quad E = pc$ |
| • *Kinetic energy* | | $T = E - m_0c^2 = m_0c^2\,(\gamma-1)$ |

# Anti-matter positron production




***M. Calvetti***, *Antiparticelle accelerate*, ***Asimmetrie*** 7, 16-21 (***2008***)

# X-rays discovery

EINE NEUE ART
VON
STRAHLEN.

VON

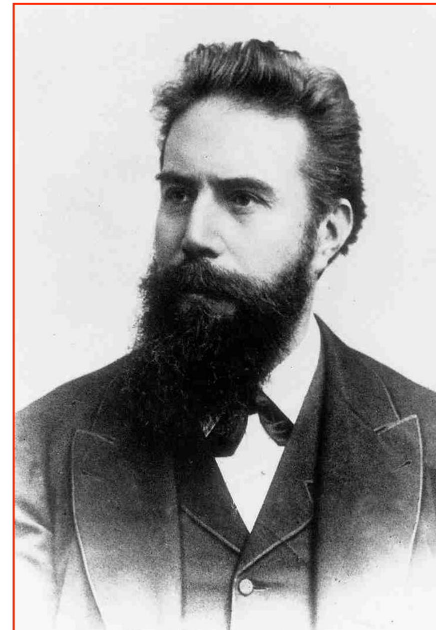
DR. W. RÖNTGEN,
O. Ö. PROFESSOR AN DER K. UNIVERSITÄT WÜRZBURG.

WÜRZBURG.
VERLAG UND DRUCK DER STAHEL'SCHEN K. HOF- UND UNIVERSITÄTS-BUCH- UND KUNSTHANDLUNG.
Ende 1895.

60 ₰.

*On a New Kind of Rays*

While ***Wilhelm Roentgen*** was working on the effects of ***cathode rays*** during ***1895***, he discovered X-rays. His experiments involved the passing of electric current through gases at extremely low pressure. On **November 8, 1895** he observed that certain rays were emitted during the passing of the current through discharge tube. His experiment that involved working in a totally dark room with a well covered discharge tube resulted in the **emission of rays which illuminated a barium platinocyanide screen**. ***The screen became fluorescent even though it was placed two meters away from discharge tube***.



**Wilhelm Conrad Roentgen**

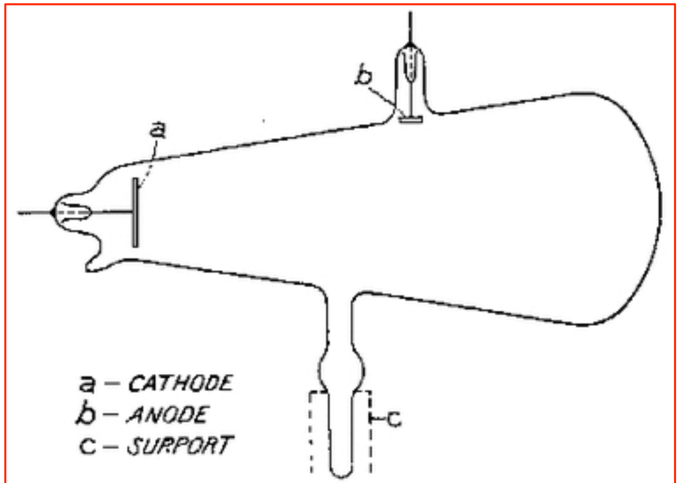



Fig. 1. Earliest type of roentgen tube.

**Gas tube**: electrons are freed from a **cold cathode by positive ion bombardment, thus necessitating a certain gas pressure.**

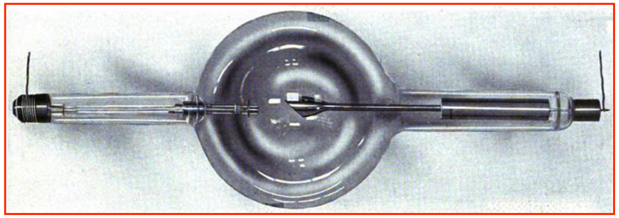
He continued his experiments using **photographic plates** and generated the very ***first "roentgenogram"*** by developing the image of ***his wife's hand*** and analyzed the variable transparency as showed by her bones, flesh and her wedding ring.

# X-ray tubes

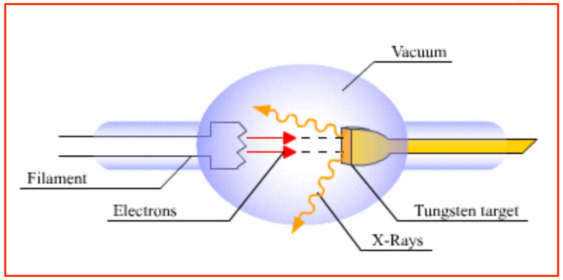
# X-rays: conventional sources

From **gas tubes** (cold cathode) to **high vacuum tubes** (hot cathode)

***Crookes tube***

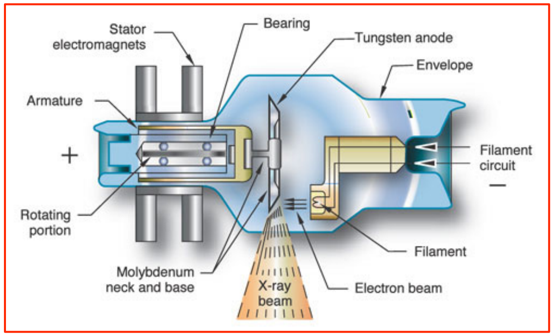


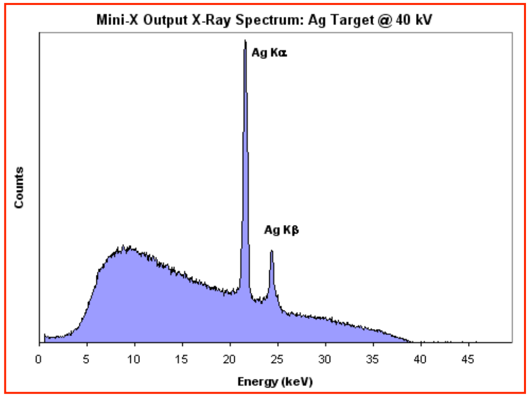
***Coolidge tube***



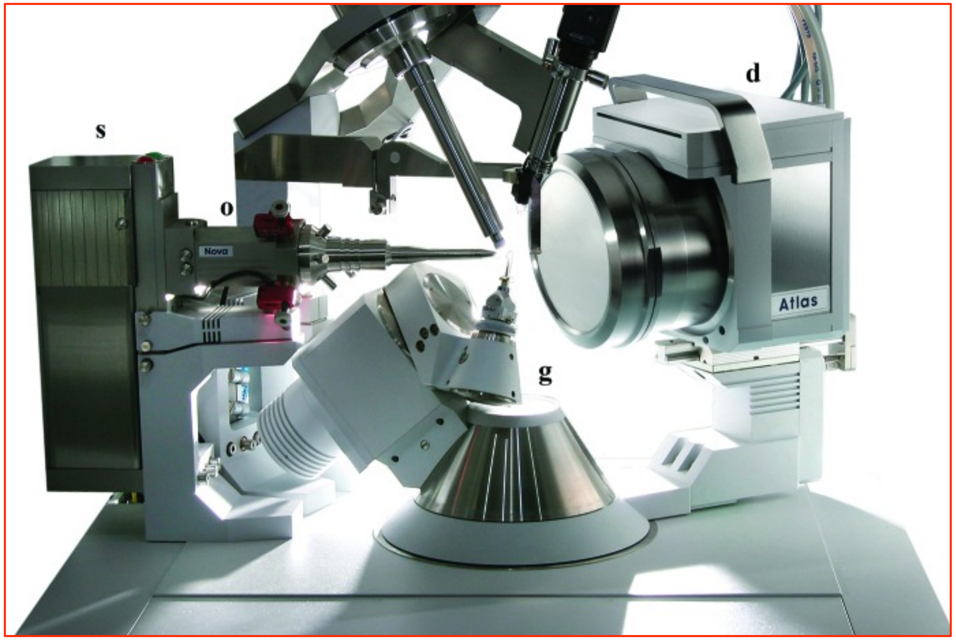

The ***Coolidge tube (1913)***, also called ***hot cathode tube***, is the most widely used. Electrons are produced by thermionic effect from a tungsten filament heated by an electric current. The filament is the cathode of the tube. The high voltage potential is between the cathode and the anode, the electrons are accelerated, and hit the anode.

The ***rotating anode tube is an improvement of the Coolidge tube*** anode surface (water cooled) is always moving, so heat is spread over a much larger surface area giving a 10-fold increase in the operating power.



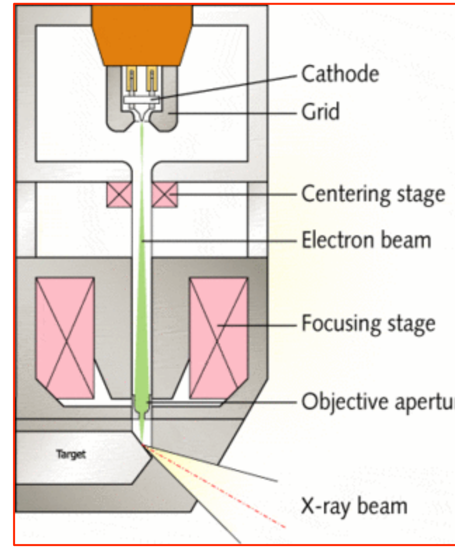
# X-rays: conventional sources




## EVOLUTION

A compact X-ray in-house laboratory system consisting of ***a microfocus sealed-tube source*** (s),focusing multi-layer optics (o), a four-circle goniometer (g) and a CCD detector (d).

Pictures of ***Agilent Technologies.***




**Approximate X-ray beam brilliance for the main types of in-house sources with optics**

| System | Power (W) | Actual spot on anode (μm) | Apparent spot on anode (μm) | Brilliance (photons $s^{-1}$ $mm^{-2}$ $mrad^{-1}$) |
|---|---|---|---|---|
| Standard sealed tube | 2000 | 10000 × 1000 | 1000 × 1000 | $0.1 \times 10^9$ |
| Standard rotating-anode generator | 3000 | 3000 × 300 | 300 × 300 | $0.6 \times 10^9$ |
| Microfocus sealed tube | 50 | 150 × 30 | 30 × 30 | $2.0 \times 10^9$ |
| Microfocus rotating-anode generator | 1200 | 700 × 70 | 70 × 70 | $6.0 \times 10^9$ |
| State-of-the-art microfocus rotating-anode generator | 2500 | 800 × 80 | 80 × 80 | $12 \times 10^9$ |
| Excillum JXS-D1-200 | 200 | 20 × 20 | 20 × 20 | $26 \times 10^9$ |

*T.* ***Skarzynski****, Collecting data in the home laboratory: evolution of X-ray sources, detectors and working practices,* ***Acta Cryst****.* D69 (2013) 1283–1288

# Synchrotron radiation

# Synchrotron radiation: physics

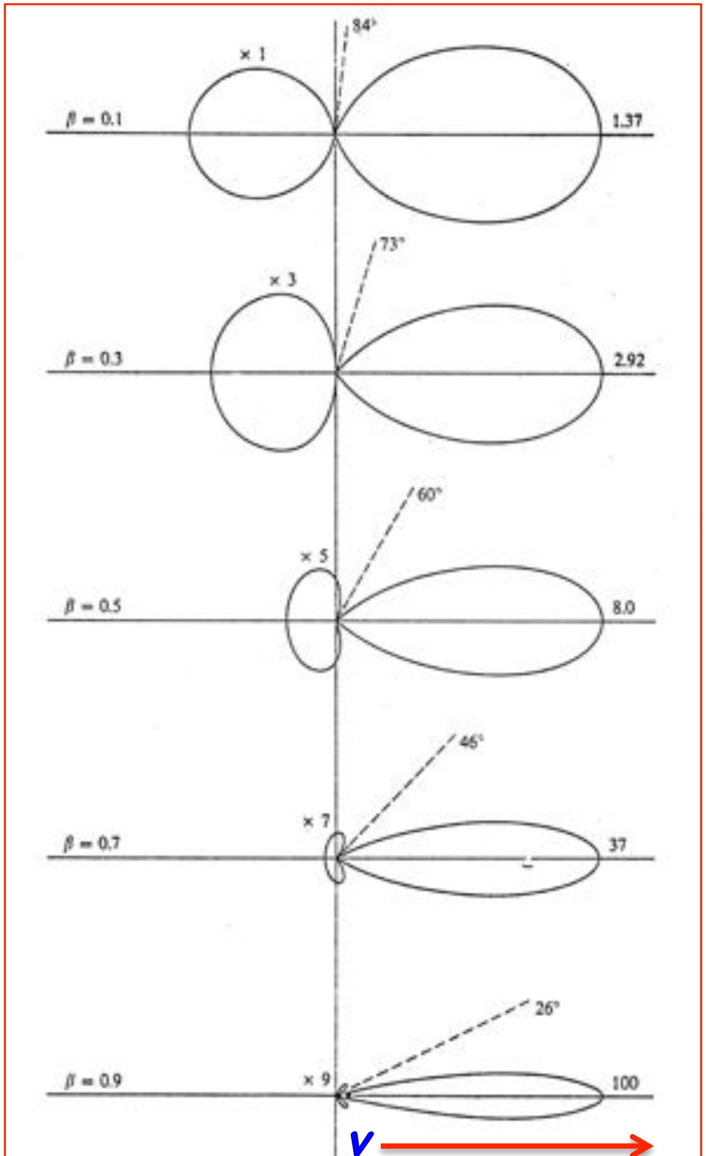


FIG. 7-7

v << c or $\beta = v/c << 1$

As β approaches 1:

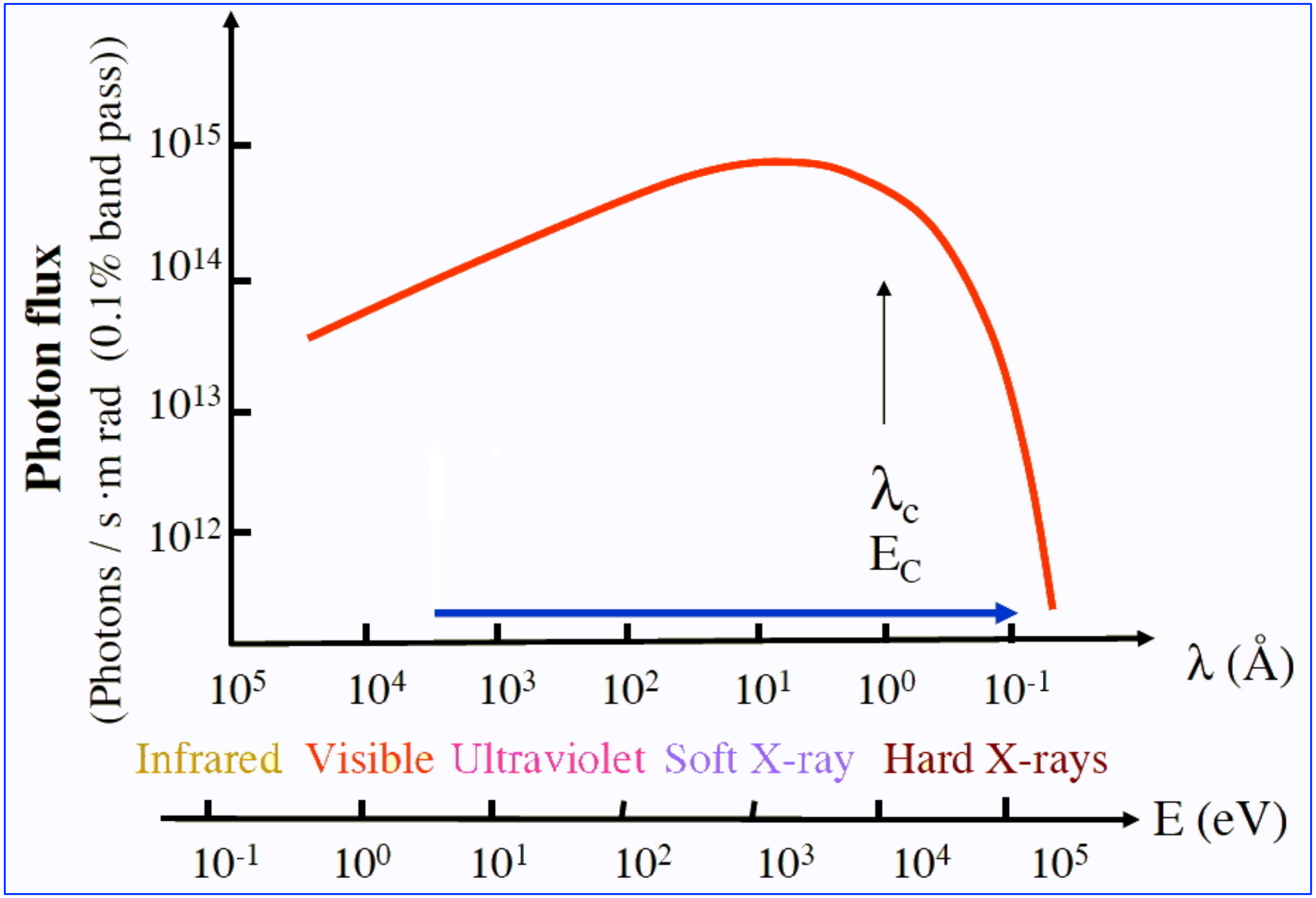
1) The shape of the radiation pattern changes: it is more in the forward direction!
2) the node at θ′ = 90° in the frame of the radiating particle transforms to:

$$\tan\theta_{lab} = \frac{\sin\theta'}{\gamma\left(\cos\theta' + \beta\right)} = \frac{1}{\gamma\beta} \approx \frac{1}{\gamma}$$

$$\gamma^{-1} \approx mc^2/E$$

v ≈ c or $\beta = v/c \approx 1$

# Spectral distribution: universal synchrotron radiation function



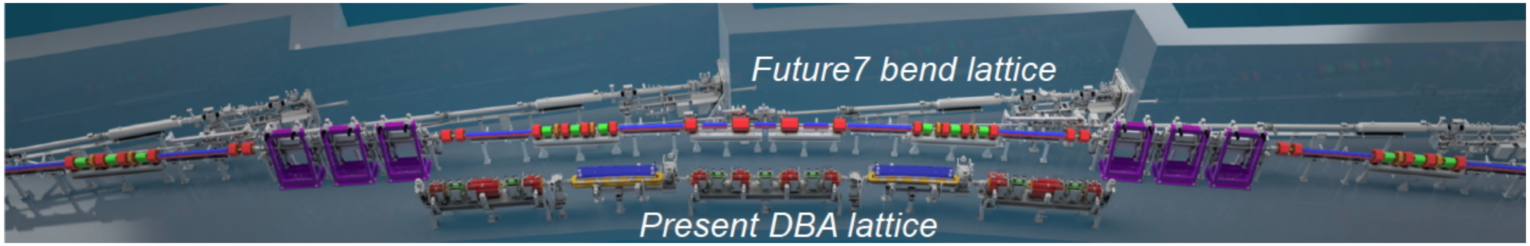

***$E_c$ and $\lambda_c$ respectively critical energy and critical wavelength***

$$E_c[keV] = 2.218\frac{E[GeV]^3}{\rho[m]} = 0.665 \cdot E[GeV]^2 \cdot B[T]$$

# Synchrotron radiation: future

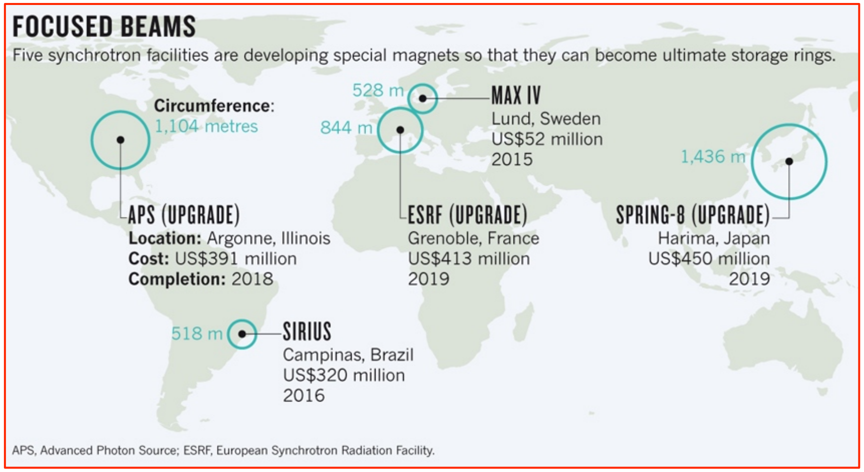
## Ultimate Storage Rings

*Brightness and transverse coherence increase in the X-ray range with implementation of **low emittance lattices** (multi-bend achromat schemes).*

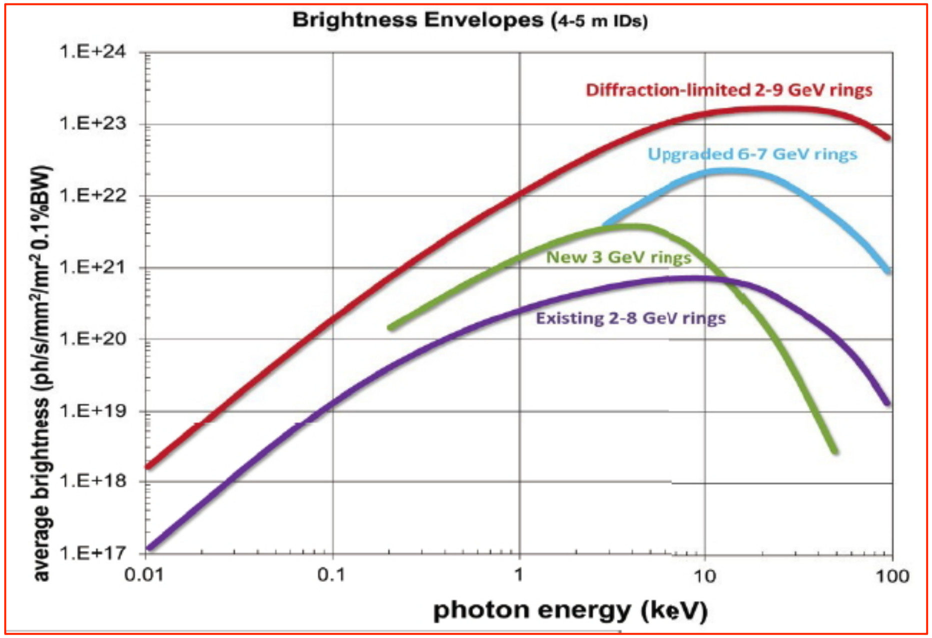



*J.Jacob, Status of the ESRF operation & upgrade, 2013*

***ESRF*** $\varepsilon_x$= 4 nm; $\varepsilon_x$= 5 pm in the future $\varepsilon_x$= 0.16 nm




*E.S. Reich, Ultimate upgrade for US synchrotron, Nature, 2013*




*H. Owen – Univ. of Manchester (UK)*