Introduction to Synchrotron Radiation and its applications

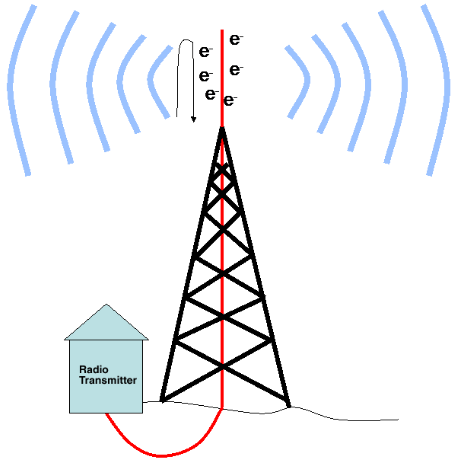
Caterina Biscari

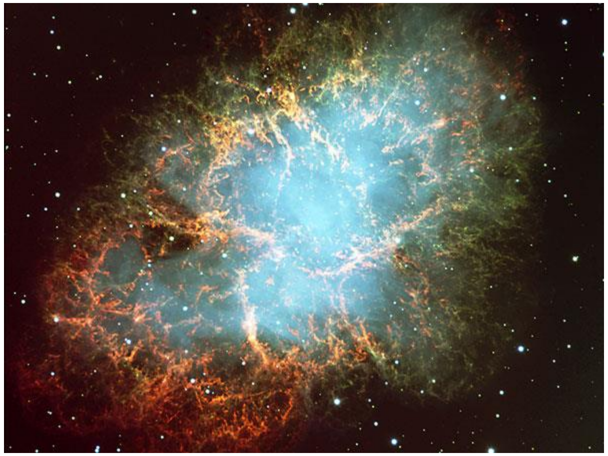
ALBA Synchrotron

Crab Nebula,(www.en.wikipedia.org/wiki/Pulsar)

What is synchrotron radiation

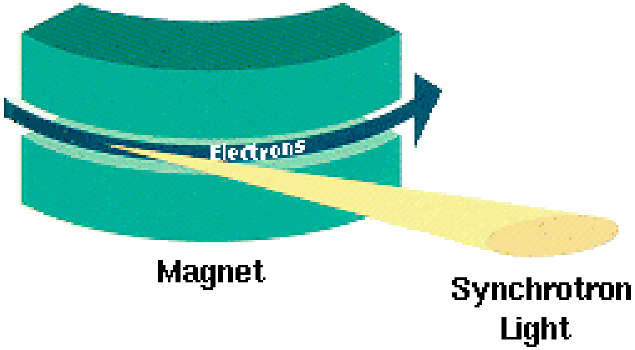
Electromagnetic radiation is emitted by charged particles when accelerated

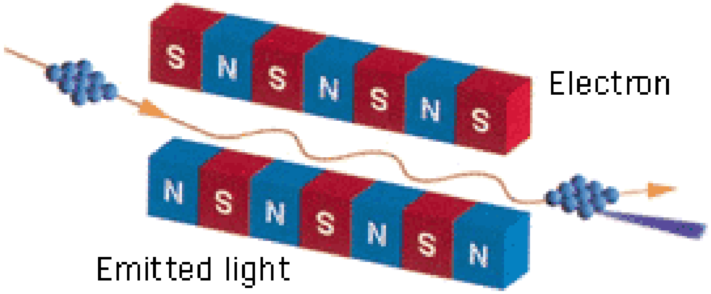




The electromagnetic radiation emitted when the charged particles are accelerated radially (v ⊥ a) is called synchrotron radiation

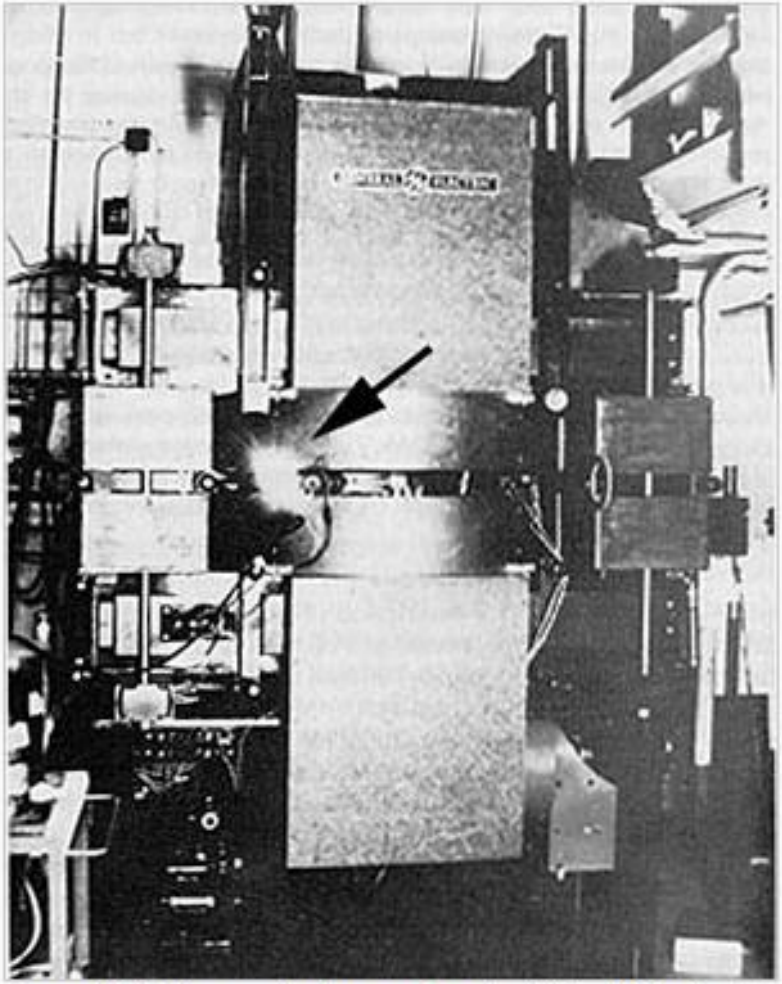
It is produced in the storage rings using bending magnets, undulators, and wigglers





Discovery of synchrotron radiation (1946)

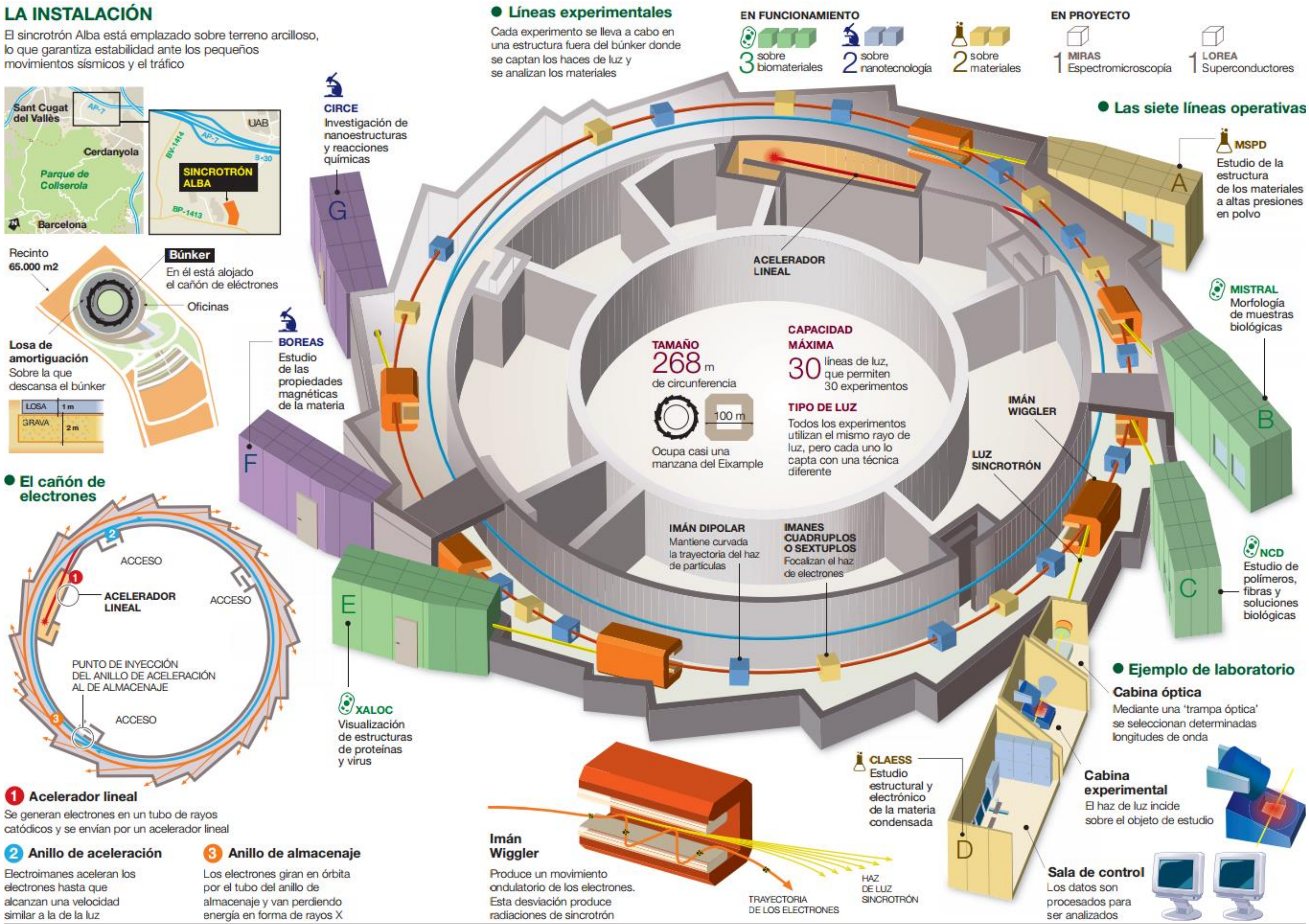
General Electric
synchrotron accelerator - 300 MeV
2nd synchrotron ever built
Visible light through the glass vacuum chamber
SR had been predicted, but its frequency was not known



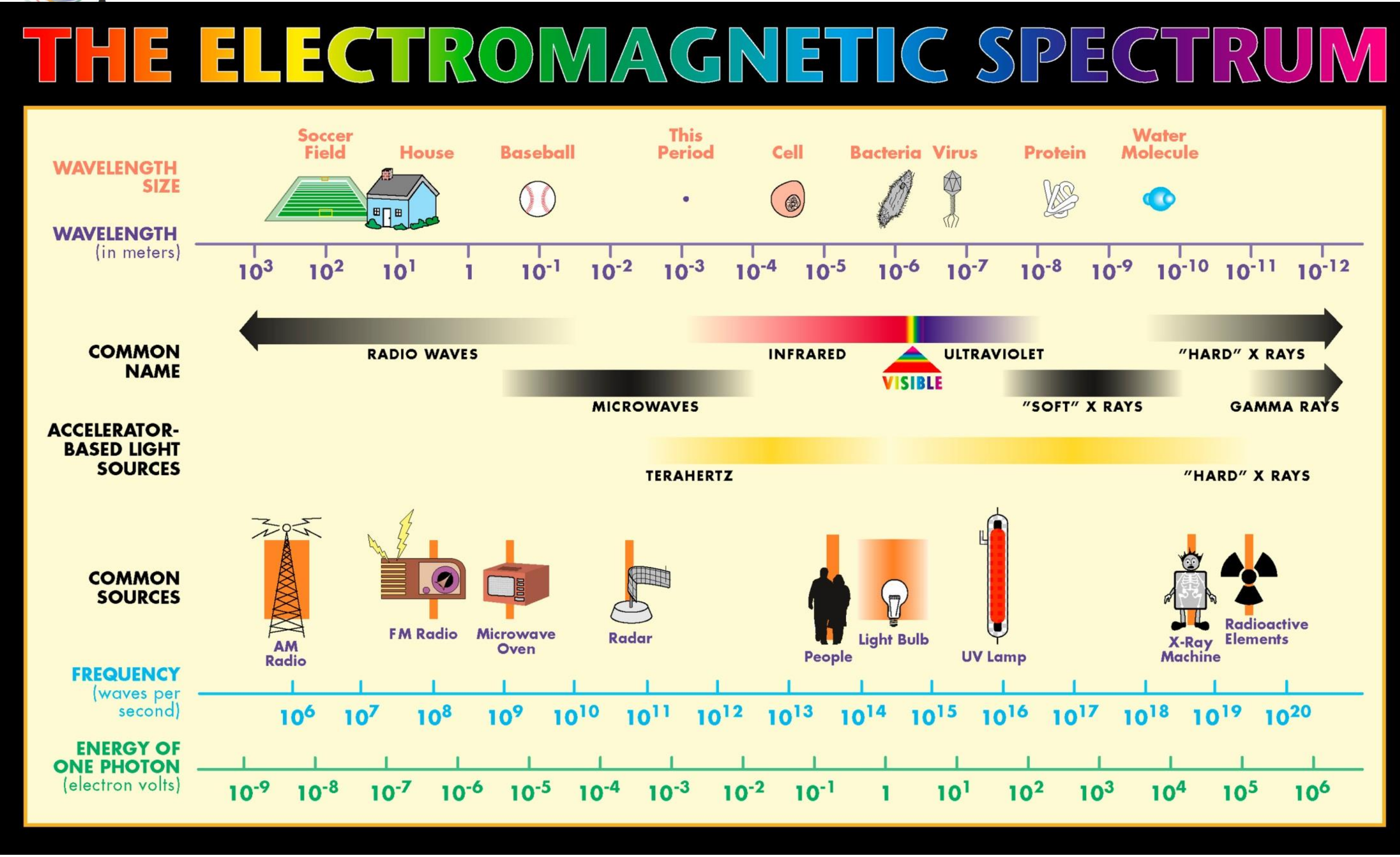
General Electric synchrotron accelerator built in 1946, the origin of the discovery of synchrotron radiation. The arrow indicates the evidence of radiation.

SL

● IN OPERATION ○ *IN CONSTRUCTION*



LA INSTALACIÓN
El sincrotrón Alba está emplazado sobre terreno arcilloso, lo que garantiza estabilidad ante los pequeños movimientos sísmicos y el tráfico
Sant Cugat del Vallès
Cerdanyola
Parque de Collserola
Barcelona
AP-7
UAB
BV-1414
B-30
SINCROTRÓN ALBA
BP-1413
Recinto 65.000 m2
Búnker
En él está alojado el cañón de eléctrones
Oficinas
Losa de amortiguación
Sobre la que descansa el búnker
LOSA
1 m
GRAVA
2 m
El cañón de electrones
ACCESO
ACELERADOR LINEAL
ACCESO
PUNTO DE INYECCIÓN DEL ANILLO DE ACELERACIÓN AL DE ALMACENAJE
ACCESO
1 Acelerador lineal
Se generan electrones en un tubo de rayos catódicos y se envían por un acelerador lineal
2 Anillo de aceleración
Electroimanes aceleran los electrones hasta que alcanzan una velocidad similar a la de la luz
3 Anillo de almacenaje
Los electrones giran en órbita por el tubo del anillo de almacenaje y van perdiendo energía en forma de rayos X
Líneas experimentales
Cada experimento se lleva a cabo en una estructura fuera del búnker donde se captan los haces de luz y se analizan los materiales
EN FUNCIONAMIENTO
3 sobre biomateriales
2 sobre nanotecnología
2 sobre materiales
EN PROYECTO
1 MIRAS Espectromicroscopía
1 LOREA Superconductores
Las siete líneas operativas
CIRCE
Investigación de nanoestructuras y reacciones químicas
G
BOREAS
Estudio de las propiedades magnéticas de la materia
F
E
XALOC
Visualización de estructuras de proteínas y virus
MSPD
Estudio de la estructura de los materiales a altas presiones en polvo
A
MISTRAL
Morfología de muestras biológicas
B
NCD
Estudio de polímeros, fibras y soluciones biológicas
C
CLAESS
Estudio estructural y electrónico de la materia condensada
D
ACELERADOR LINEAL
TAMAÑO
268 m
de circunferencia
100 m
Ocupa casi una manzana del Eixample
CAPACIDAD MÁXIMA
30 líneas de luz, que permiten 30 experimentos
TIPO DE LUZ
Todos los experimentos utilizan el mismo rayo de luz, pero cada uno lo capta con una técnica diferente
IMÁN WIGGLER
LUZ SINCROTRÓN
IMÁN DIPOLAR
Mantiene curvada la trayectoria del haz de partículas
IMANES CUADRUPLOS O SEXTUPLOS
Focalizan el haz de electrones
Imán Wiggler
Produce un movimiento ondulatorio de los electrones. Esta desviación produce radiaciones de sincrotrón
TRAYECTORIA DE LOS ELECTRONES
HAZ DE LUZ SINCROTRÓN
Ejemplo de laboratorio
Cabina óptica
Mediante una 'trampa óptica' se seleccionan determinadas longitudes de onda
Cabina experimental
El haz de luz incide sobre el objeto de estudio
Sala de control
Los datos son procesados para ser analizados



Sources on earth

Outstanding characteristic of synchrotron radiation

High brilliance and flux (combined with high collimation)

Wavelength tunability (depending of source & optics)

Beam size tunability (depending of source & optics)

(Partially) coherent radiation

Polarization (linear, elliptical or circular)

Time structure

Generations of Light Sources

1970s : 1st Generation – HEP rings used parasitically for X-ray production

1980s : 2nd Generation – Dedicated X-ray sources

1990s: 3rd Generation – Radiation facilities with wigglers, undulators, high brilliance

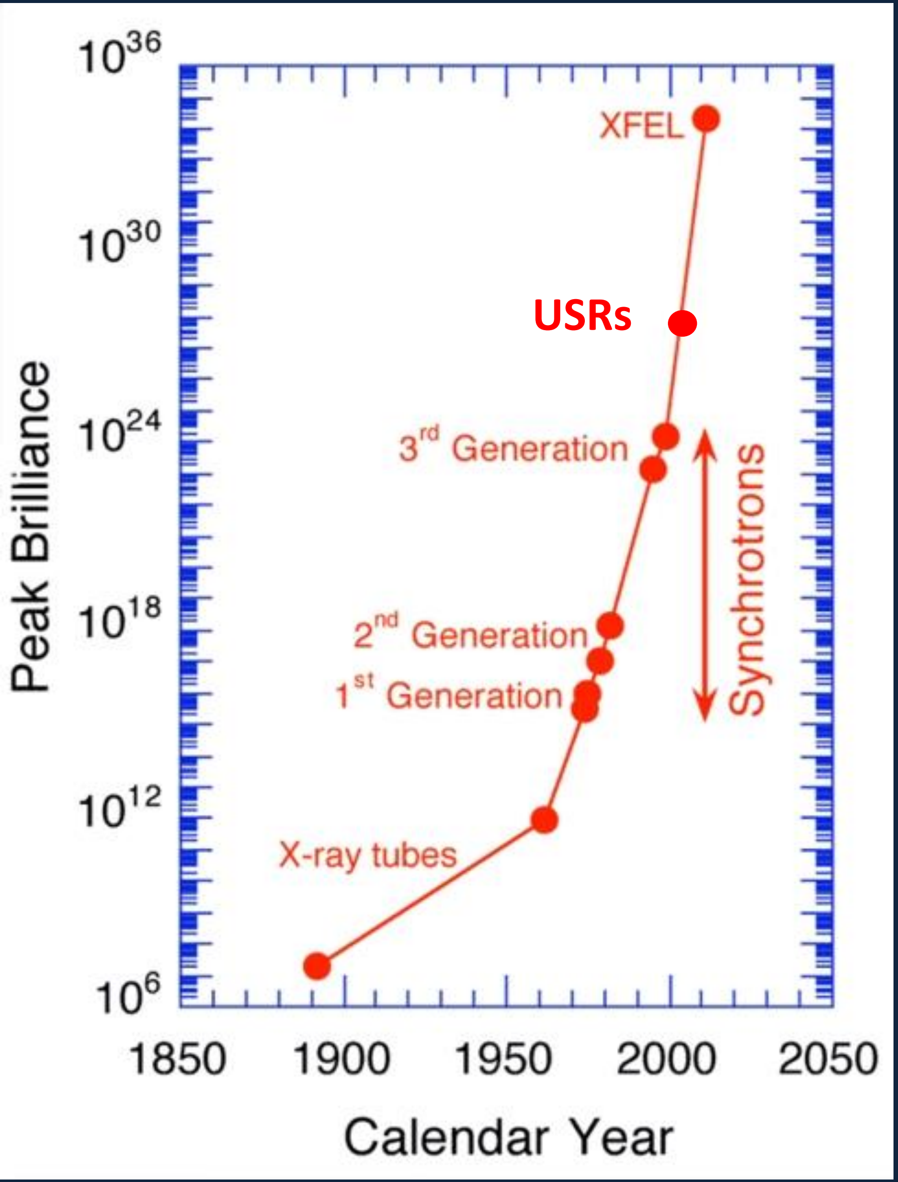
2010s: Ultimate Storage Rings (USR) – Diffraction limited

2000s: 4th Generation – Free Electron Lasers driven by Linacs

Light source brilliance

photons/s/mm²/mr²/0.1%BW

photons per time, space, energy definition



From 3rd generation of beginning of century to USR

ALBA
2011 1st beam
3 GeV
C = 269 m
ε = 4.6 nm

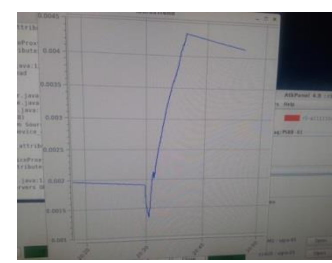
Increase C
Lower ε

NSLS II
2014 1st beam
3 GeV
C = 620 m
ε = 1.5 nm

MAX IV
2015 1st beam
3 GeV
C = 528 m
ε = 0.3 nm

MBA*
Lower ε

In commissioning



8 October '15

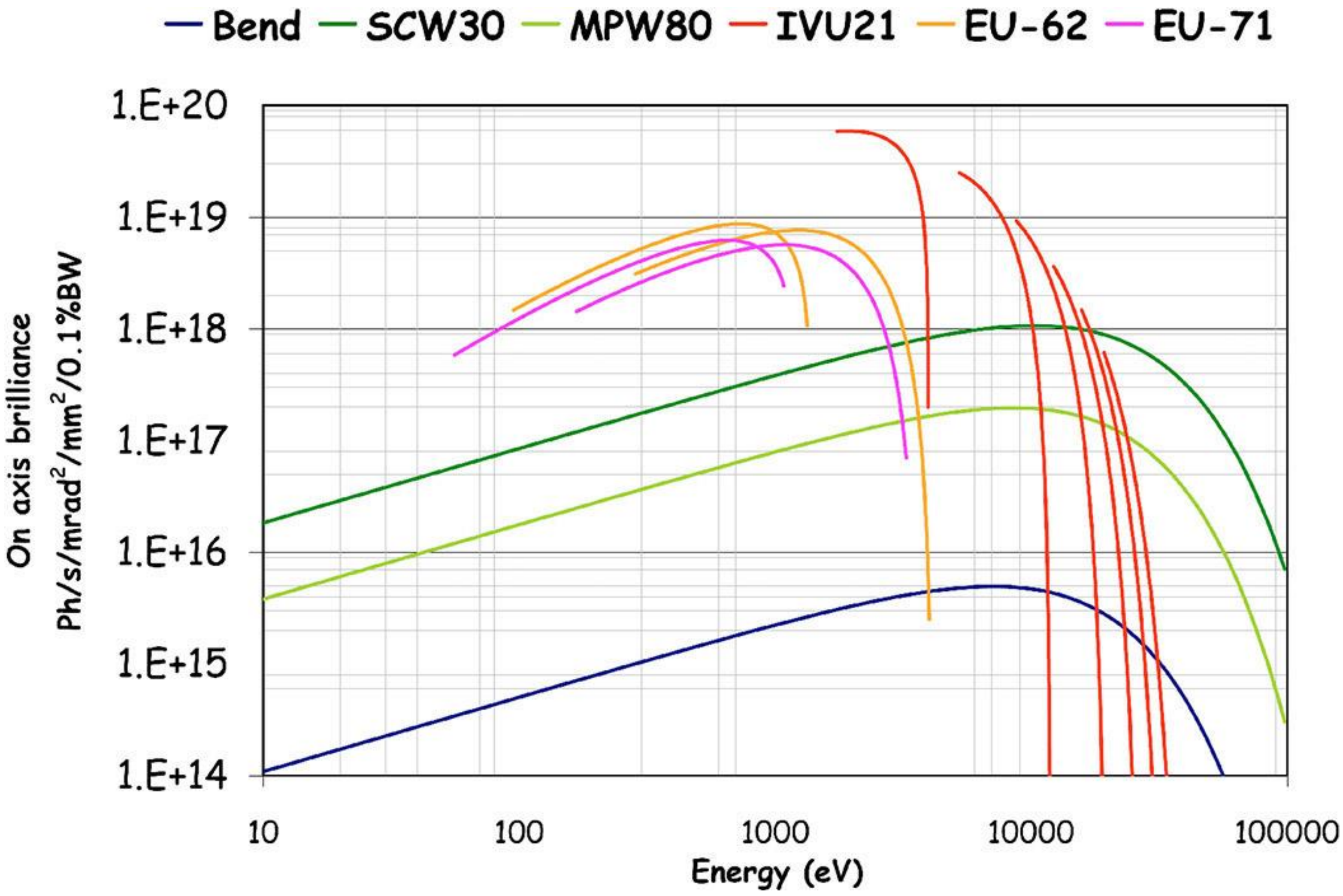
*MBA: Multi Bend Achromats

(Photos approximately in scale)

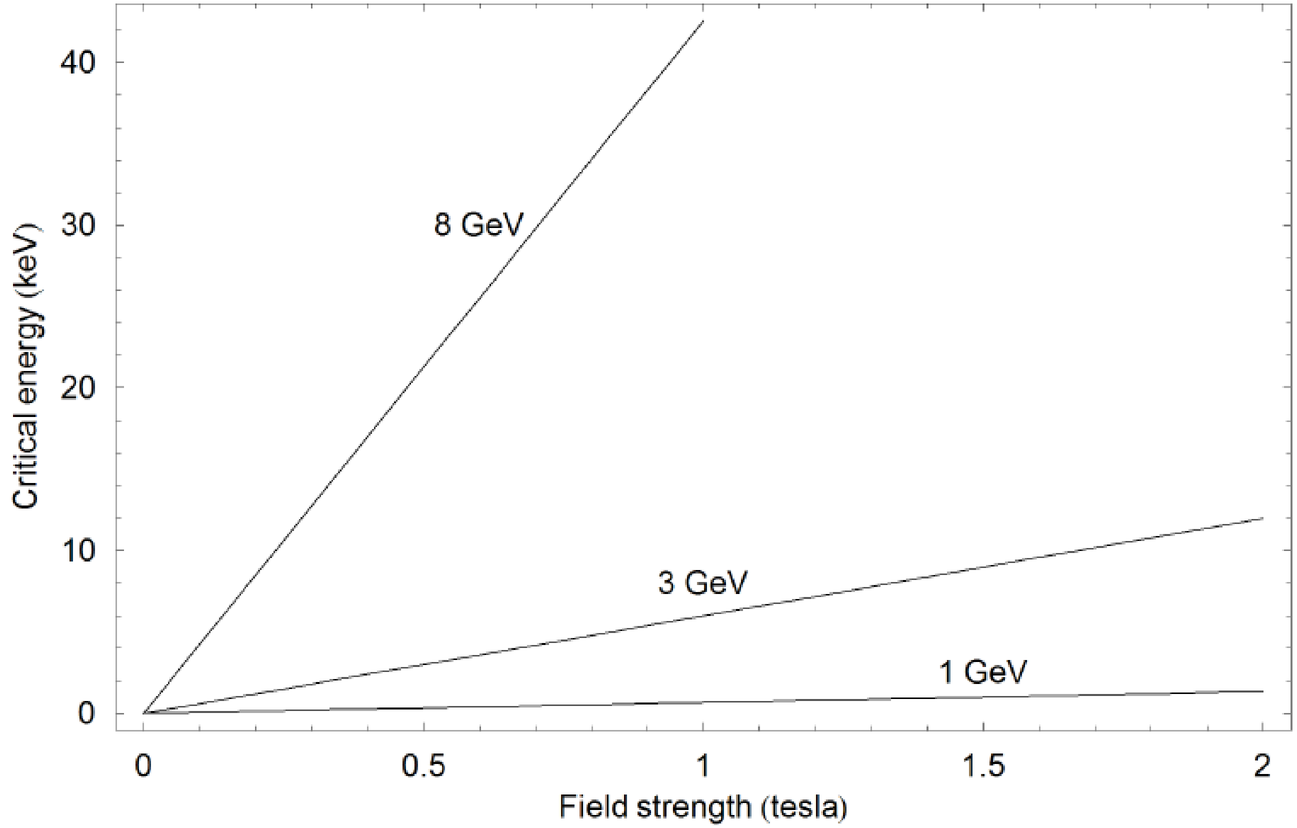
Synchrotron Light Sources key parameters

Photon beam property	Accelerator property
Photon energy range	Energy, magnetic field, insertion device parameters
Photon flux	Energy, current
Brightness	Energy, current, emittance
Polarization	Magnetic field orientation
Time structure	Rf frequency
Stability	Feedback, beam lifetime, injection system
Beamline capacity	Dipoles, insertion devices

ALBA photon spectra



Critical energy and magnetic field



$$E_c = \frac{3}{2}\frac{\hbar c}{\rho}\gamma^3$$

$$E_c[eV] = 665.0255\ B[T].E[GeV]^2 = \frac{1239.842}{\lambda_c[nm]}$$

Choice of Beam Energy

- Higher e- energy
- Harder X-rays
- Better beam lifetime
- More stable beams

- Lower e-energy
- Lower magnetic fields
- Lower emittance for the same lattice
- Less rf power
- Lower operating costs

Radiation damping

↓

Emittance going versus zero

Quantum nature of radiation

↓

Quantum excitation

Emittance equilibrium distribution

Natural bunch length

Natural energy spread

Emittance in an e- storage ring

The emittance is determined by a balance between two competing processes: quantum excitation of betatron oscillations from photon emission and longitudinal re-acceleration within the RF cavities

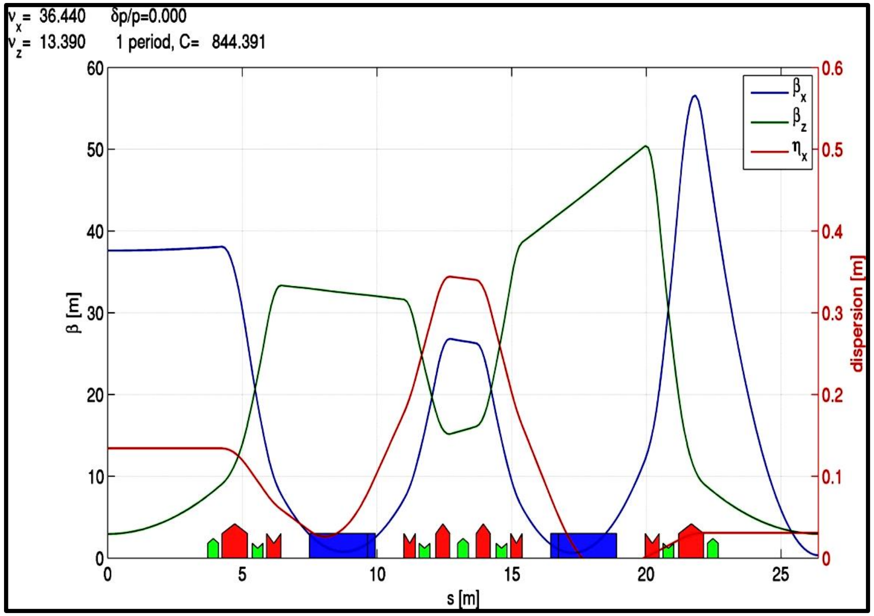
The emittance depends on the dispersion and on the betatron functions in the dipoles, and on the energy

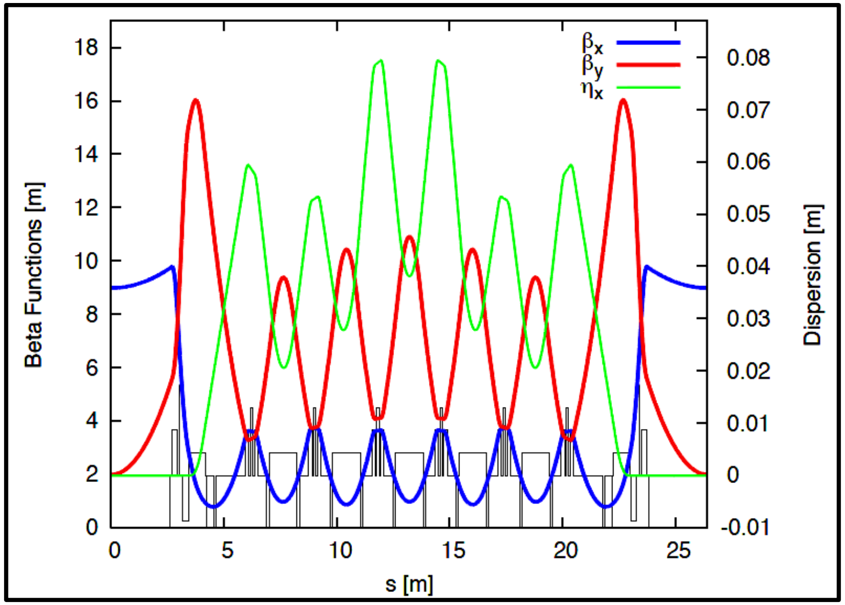
$$\varepsilon_x = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \frac{\gamma^2}{J_x} \frac{\langle H/\rho^3 \rangle}{\langle 1/\rho^2 \rangle}$$

J_x is the Robinson partition number evaluated for the horizontal plane
The emission of photons is done in bendings, where there is dispersion. The electron amplitude oscillation afterwards is given by the dispersion, the original amplitude oscillation and energy loss

The smaller the dispersion the smaller the final equilibrium emittance: **increasing the n. of dipoles in a ring the dispersion decreases and so does the emittance**

The evolution to Multi-Bend Lattice





Double-Bend Achromat (DBA)

- Many 3rd gen. SR sources
- Local dispersion bump (originally closed) for chromaticity correction

Multi-Bend Achromat (MBA)

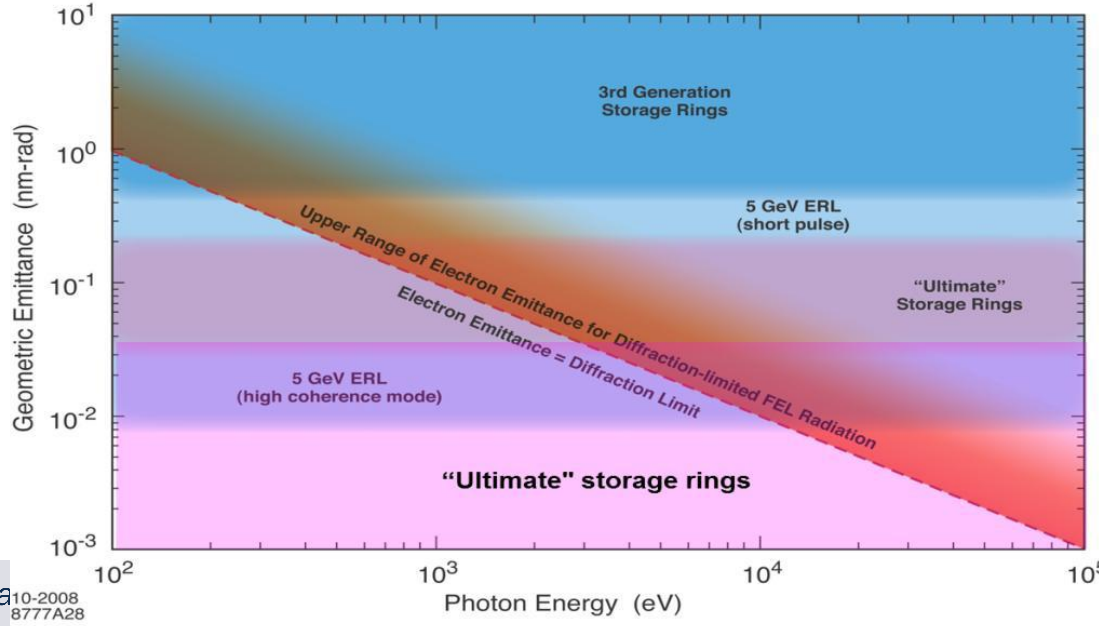
- MAX IV and other USRs
- No dispersion bump, its value is a trade-off between emittance and sextupoles (DA)

The evolution to DLSR or USR (Diffraction Limited or Ultimate Storage Rings)

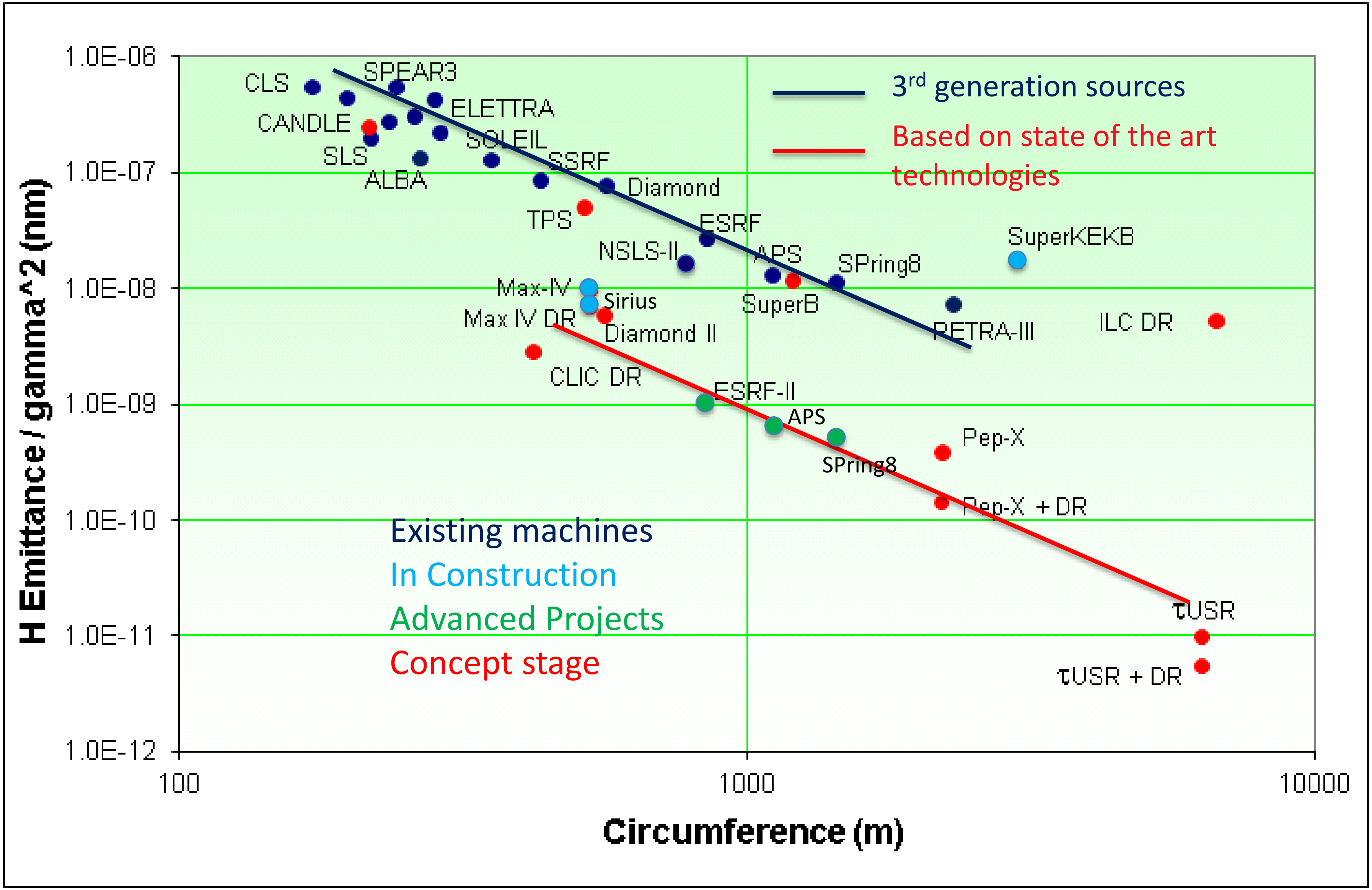
The brilliance of a synchrotron light source can be increased by reducing the emittance of the beam, up to the limit where the natural diffraction prevents any further reduction of the photon beam size and divergence.
Even in the limit of zero beam emittance the phase space of the radiation emission from an undulator is itself finite due to diffraction effects at the source. For single-mode photon emission, the corresponding diffraction-limited ‘emittance’ of the photon beam is given by

$$\varepsilon(photon) \le \frac{\lambda}{4\pi} = 0.159\lambda = 98.66[pm\,rad]/E_\gamma[keV]$$

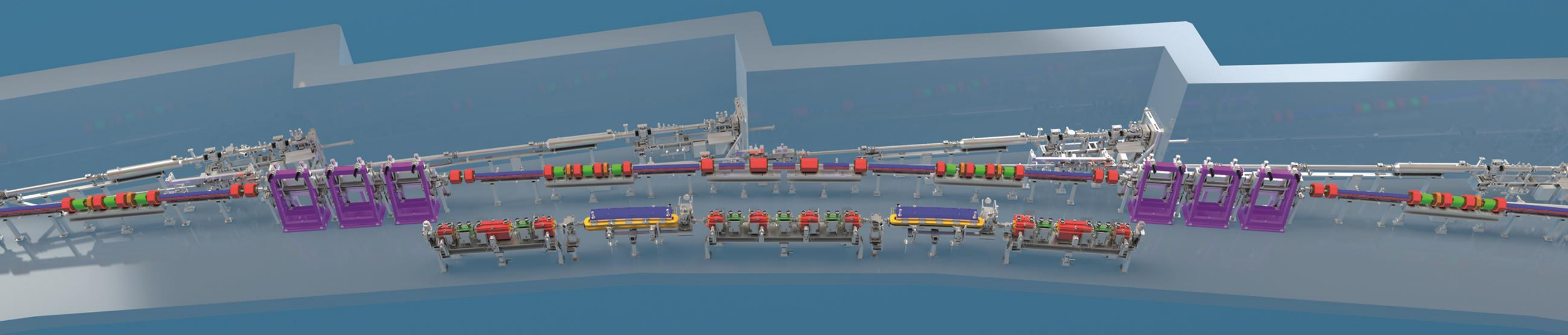
A light source is referred as ‘diffraction limited’ when the e- beam emittance is less than that of the radiated photon beam at the desired X-ray wavelength



Low Emittance Rings Trend



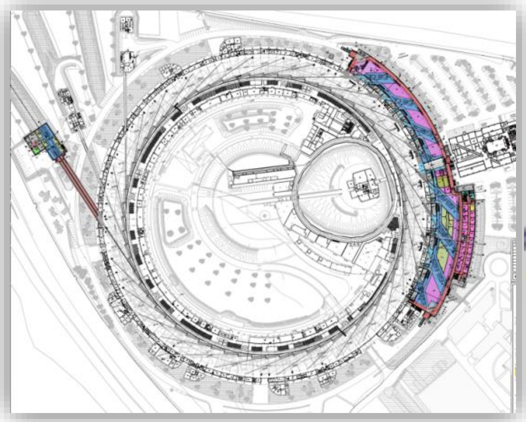
Storage rings going brighter by Making very low emittances:



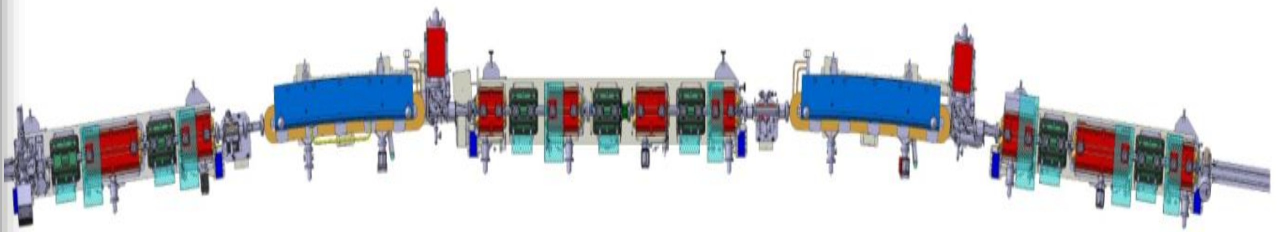
ESRF: brighter beams by 2020

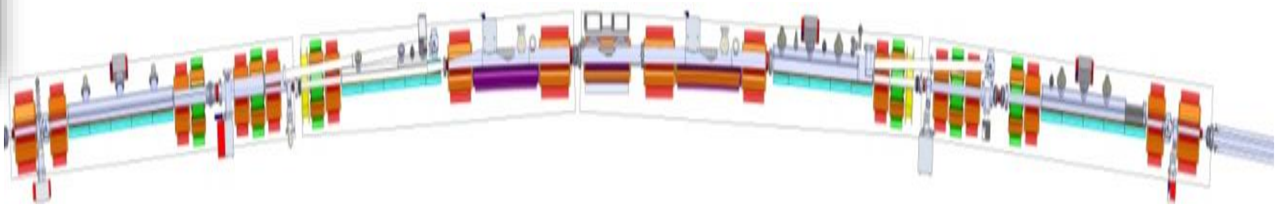
Other facilities planning upgrades

ESRF Phase II Upgrade



Present ESRF Arc Layout: Ex=4nm





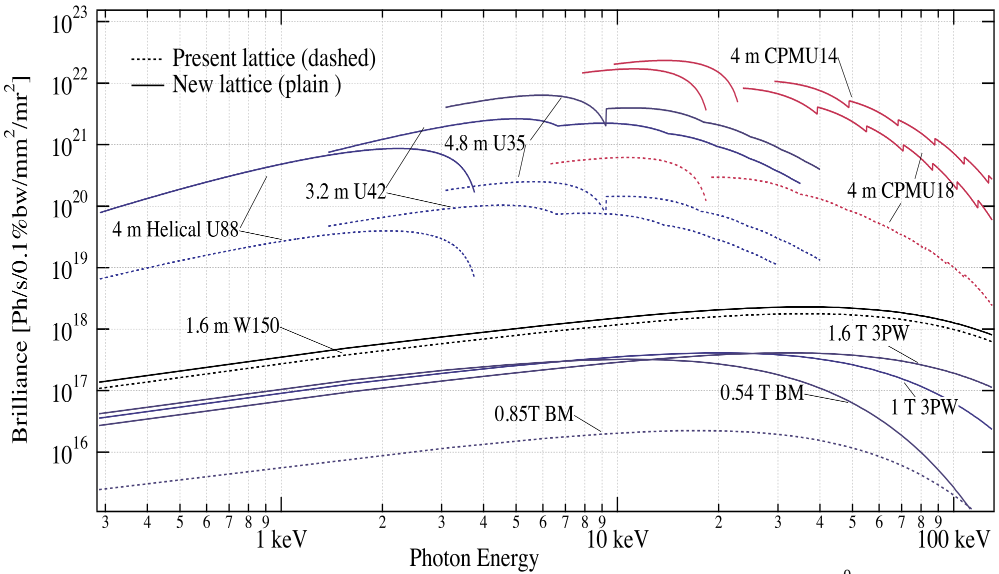
New Low Emittance Layout: Ex=0.135nm

The 844m Accelerator ring consists of 32 identical Arcs.

Each Arc is composed by a well defined sequence of Magnets, Vacuum Components (vacuum vessel, vacuum piumps etc), sensors (diagnostic) etc.

All the Arcs will be replaced with a completely new Layout

BRILLIANCE AND COHERENCE INCREASE

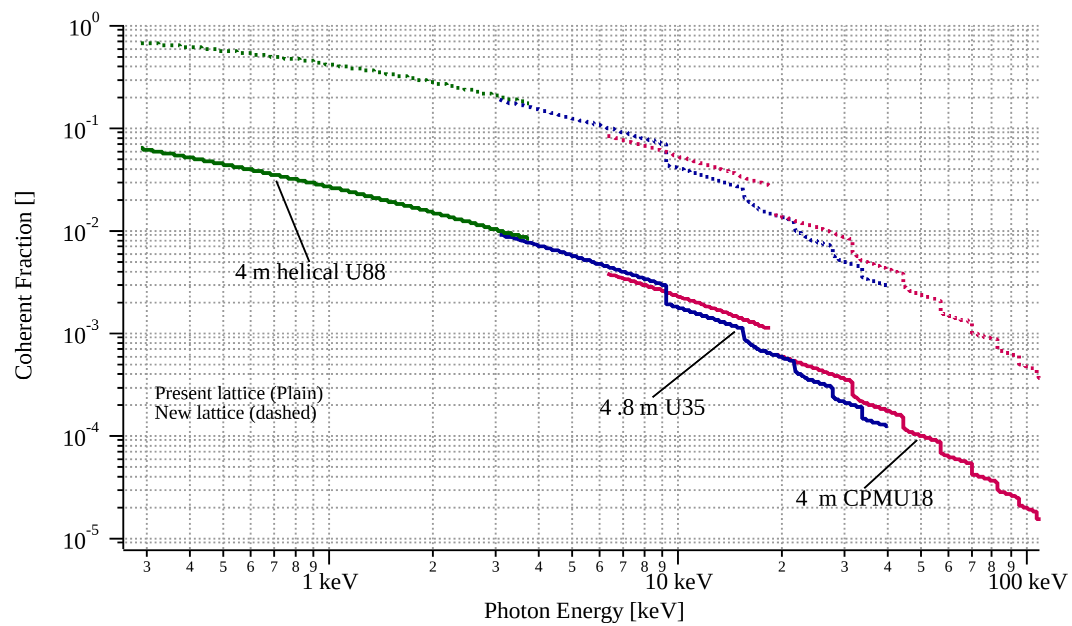


Brilliance

Source performances will improve by a factor 50 to100

Hor. Emittance [nm]	**4**	**0.15**
Vert. Emittance [pm]	**3**	**2**
Energy spread [%]	**0.1**	**0.09**
β_x[m]/β_z [m]	**37/3**	**4.3/2.6**

Coherence



Photon sources: dipole fields

Dipoles determine:

- Property of SR from dipoles
- Natural energy spread and bunch length of beam
- Rf parameters
- Main energy loss per turn

Usually normal conducting dipoles are used

B_{max} = 1.8 T

B_{usual} = 1.5 T

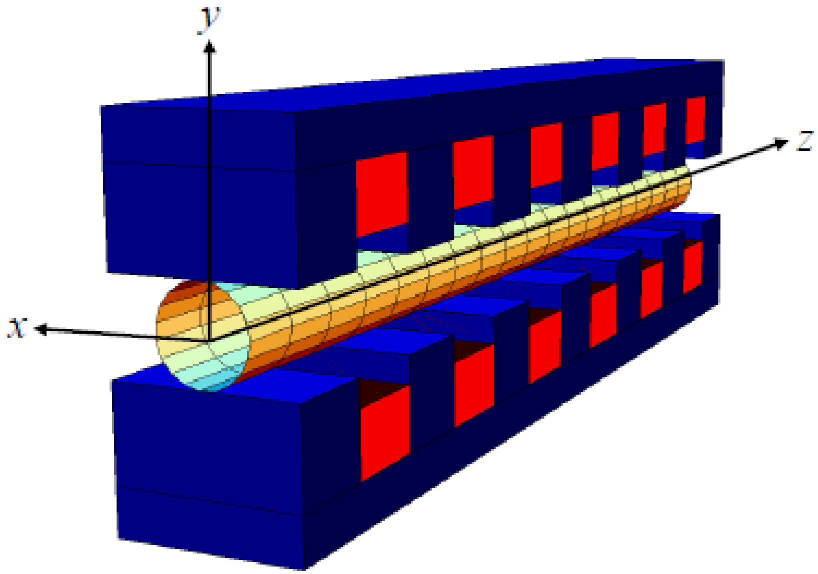
E = 3 GeV

$B\rho$ ~ 10 Tm => ρ = 6-7 m

Critical energy:

$$E_{cr} = \frac{3}{2}\hbar c \frac{\gamma^3}{\rho} \approx 9 - 10\ keV$$

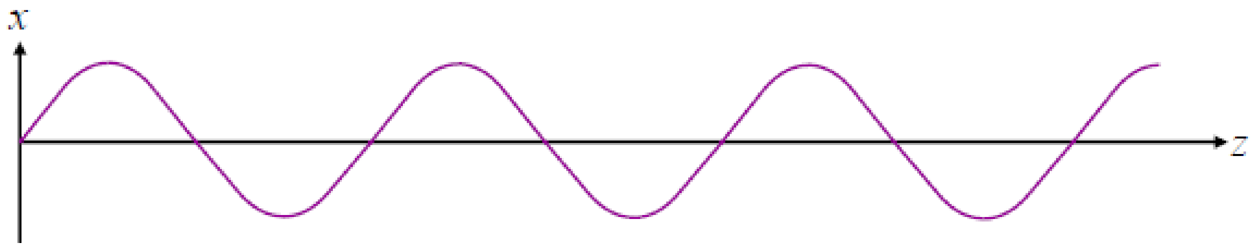
Insertion devices



$$B_y = B_w \sin(k_z z)$$

Peak field = B_w

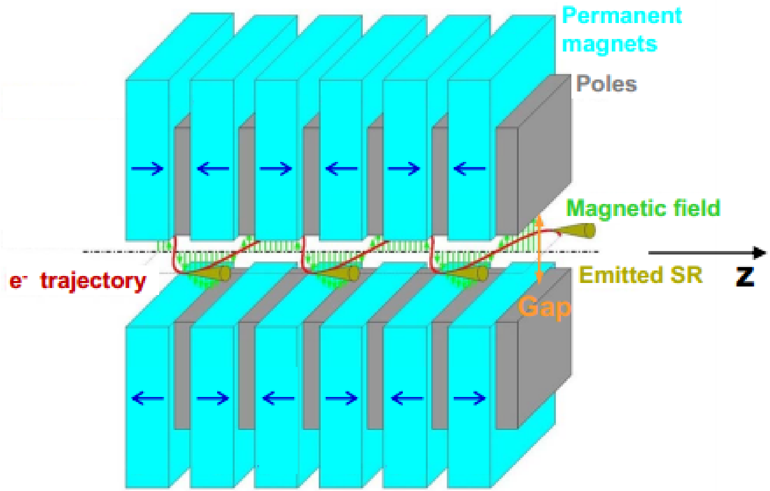
Period = $\lambda_w = \dfrac{2\pi}{k_z}$



Deflection parameter K:

$$K = \frac{e}{2\pi m_o c} B_W \lambda_w = 0.934\ B_W[T]\ \lambda_w[cm]$$

Wigglers



- Alternating **magnetic field**

$$B(z) = B_0 \sin\left(\frac{2\pi}{\lambda_U} z\right)$$

Period length λ_U (typ. 10-30cm)
Peak field B_0 (typ. >1.5T)
Number of periods $N=L/\lambda_U$ (typ. 5-100)

- ***K*-parameter: *K* >> 1, typ. *K* > 10**

Opening angle of the emitted SR $\delta = \pm K/\gamma$

→ spatial power distribution (typ. ~mrad)

Intensities of all poles add up (incoherently)

$Flux_{Wiggler} = 2 \cdot N \cdot Flux_{Dipole}$ (for equal E_c)

→High intensities
→High photon energies

Critical energy:

E_c [keV] = $0.665 \cdot E_e^2$[GeV] $\cdot B_0$[T]

Emitted total power of a wiggler or undulator with length $L=N \cdot \lambda_U$: (typ.: 50kW)

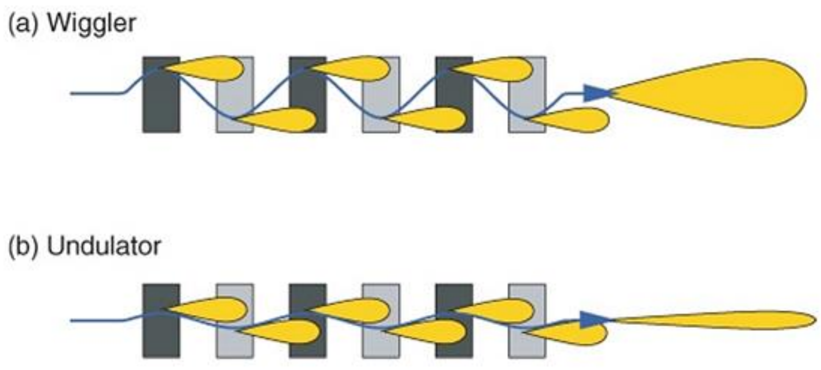
$P_{tot} = 0.633 \cdot B_0^2$ [T] $\cdot L$ [m] $\cdot E_e^2$ [GeV] $\cdot I_e$ [A]

Polarisation of wiggler radiation:
linearly polarised in the orbit plane ψ=0,
unpolarised out of plane

M. Tischer | Insertion Devices | CAS Chios Sep. 2011 | Page 10

Undulators

Insertion devices with short periods, such that K<1



wiggler - incoherent superposition K > 1
Max. angle of trajectory > $1/\gamma$

undulator - coherent interference K < 1
Max. angle of trajectory < $1/\gamma$

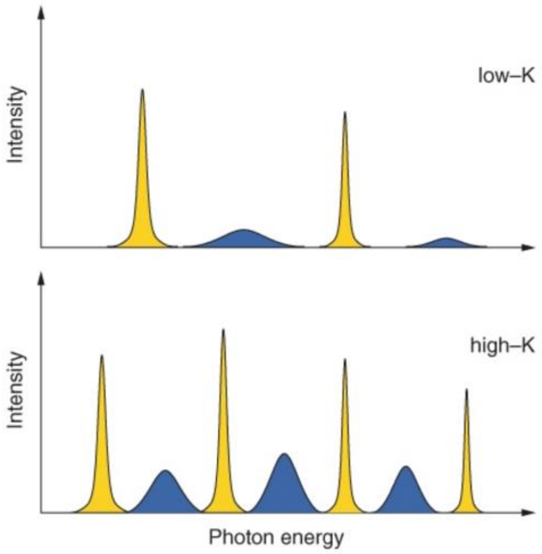
$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1+\frac{K^2}{2}\right) \approx \frac{\lambda_u}{n\gamma^2}$$

n = *harmonic*

$$\varepsilon_n(eV) = 9.496\frac{nE[GeV]^2}{\lambda_u[m]\left(1+\frac{K^2}{2}\right)}$$

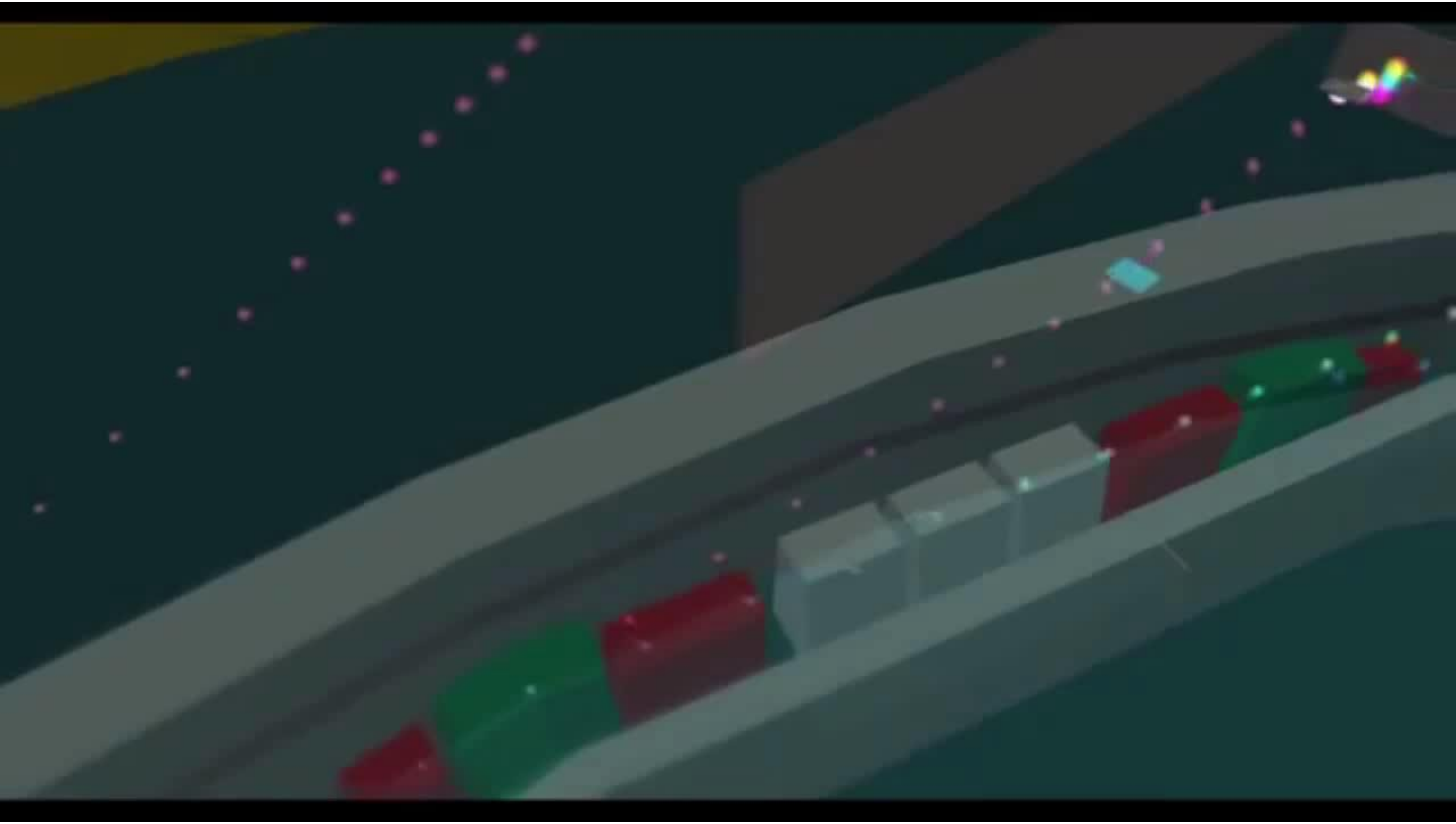
On axis

Bandwidth $\frac{\Delta\omega}{\omega} = \frac{1}{2N_u}$



Quasi-monochromatic spectrum with peaks at lower energy than a wiggler


ANNEAU
DE STOCKAGE
SOLEIL



Elettra

Interaction between the light and the matter

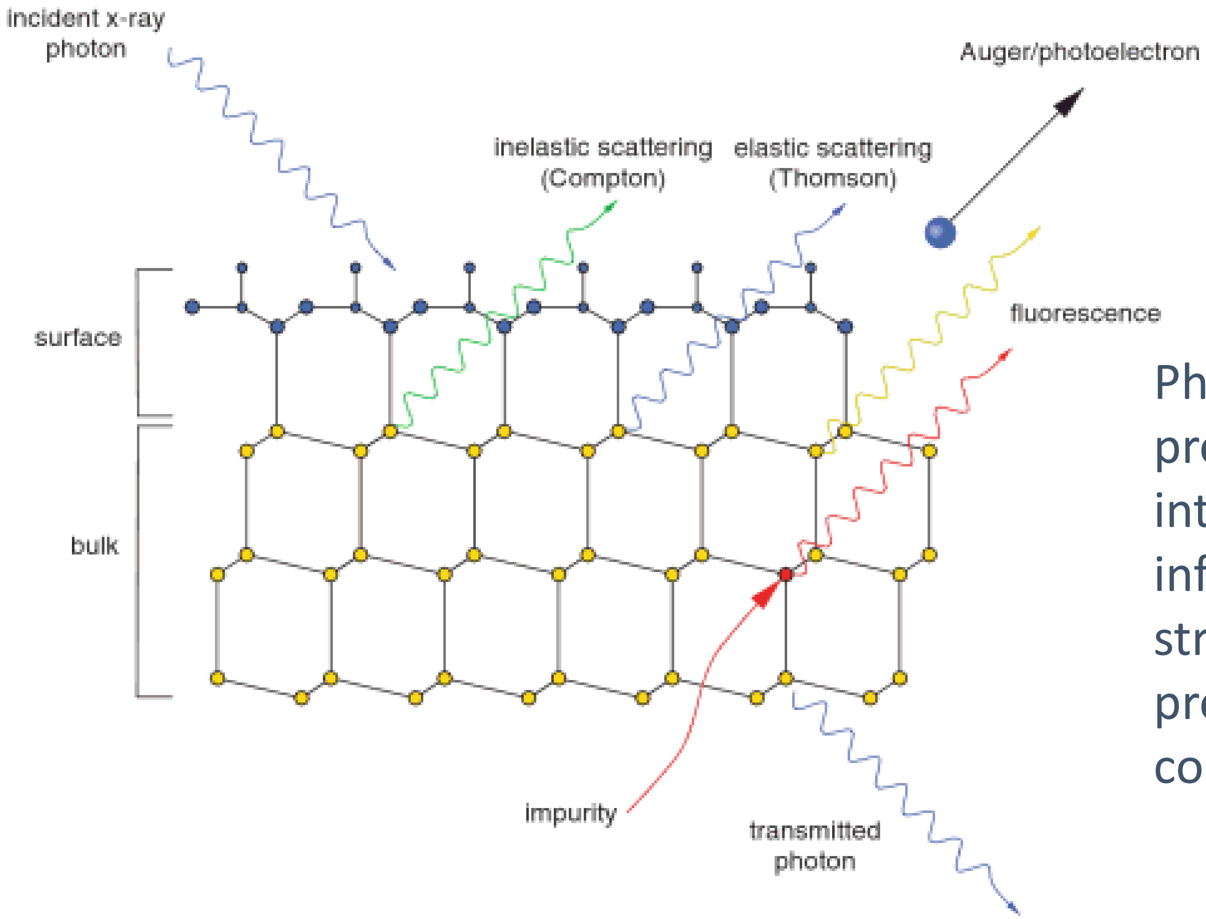
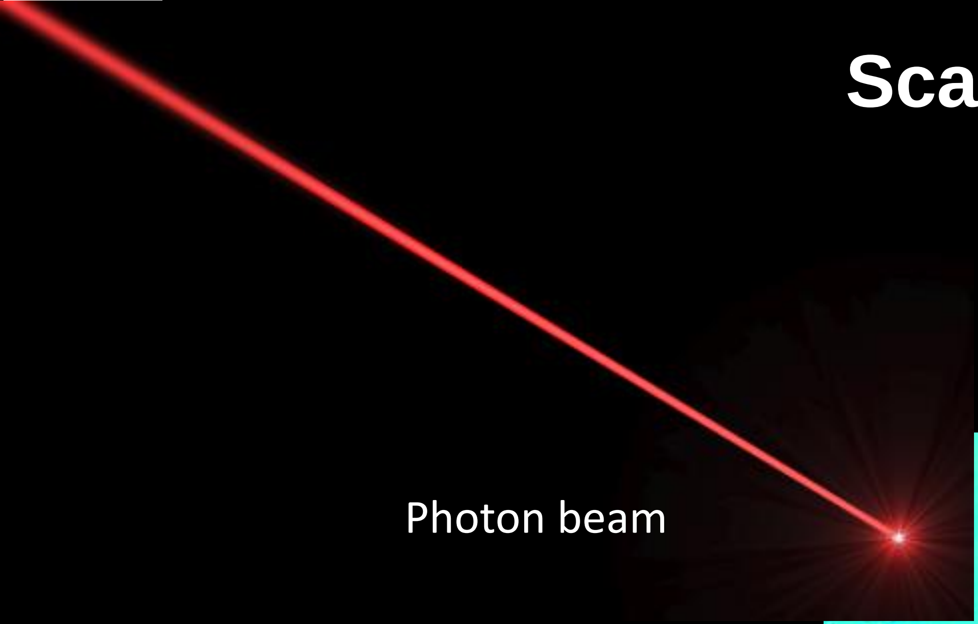


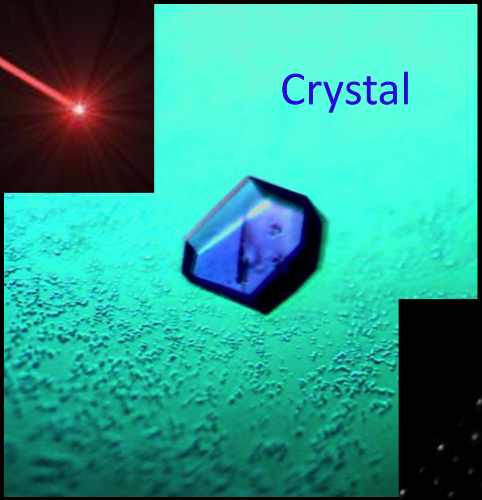
Figure 2.1 *The interaction of x-rays with matter. Surface (and interface) regions of a solid or liquid material are characterized by physical properties and structures that may differ significantly from those of the bulk structure. The x-rays may be elastically or inelastically scattered, or absorbed, in which case electrons or lower-energy photons can be emitted. If none of the above occur, the photon is transmitted through the sample.*

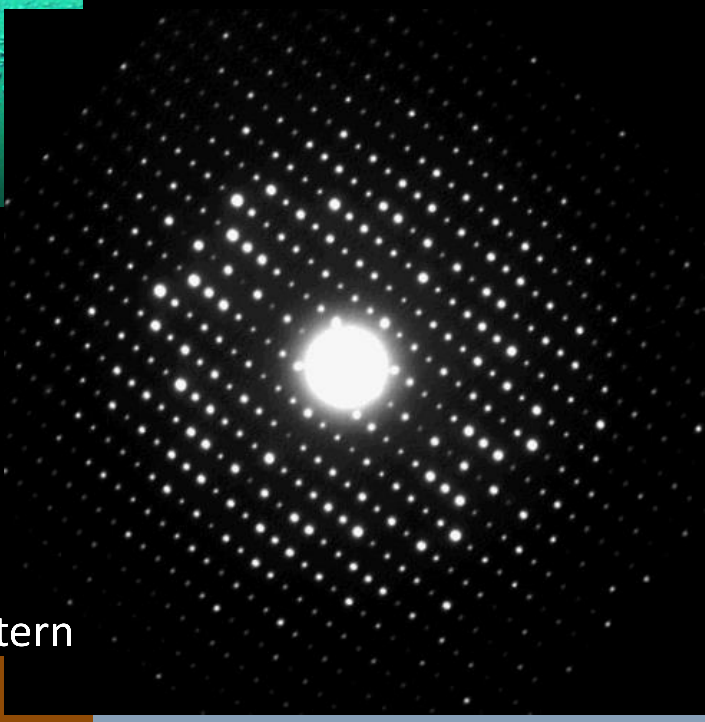
Photons and electrons produced during the interaction contain information on the structure of matter, its properties and composition

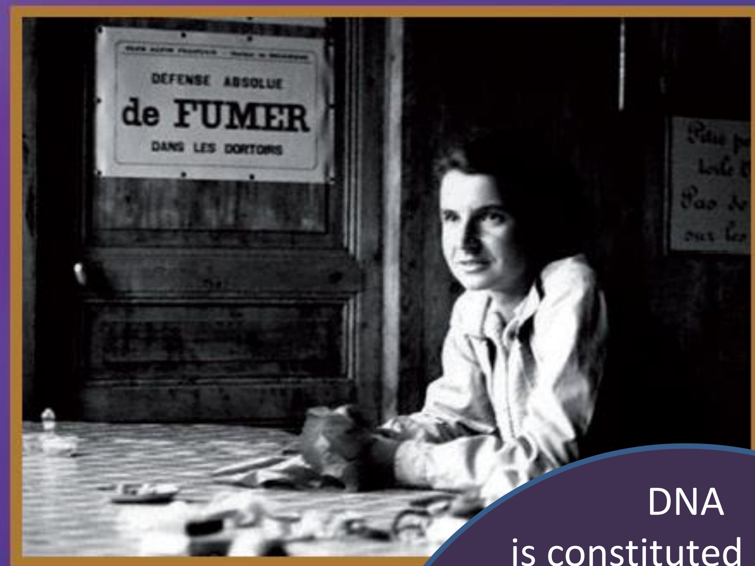
From 'An Introduction to Synchrotron Radiation' Philip Willmott

Scattering - Diffraction

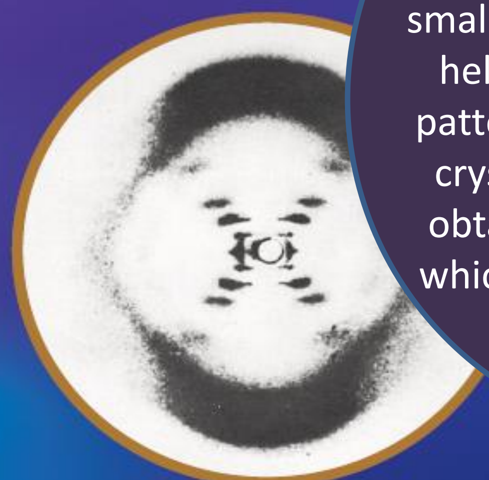








DNA and X Rays

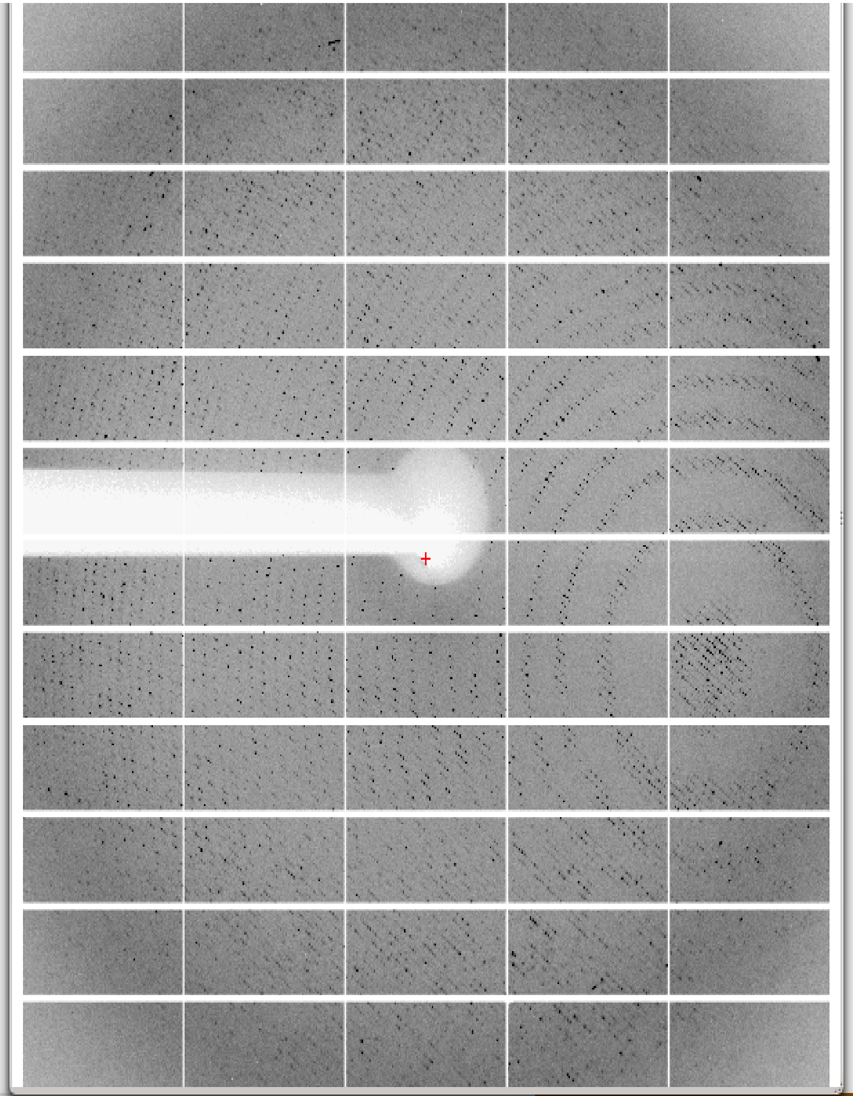


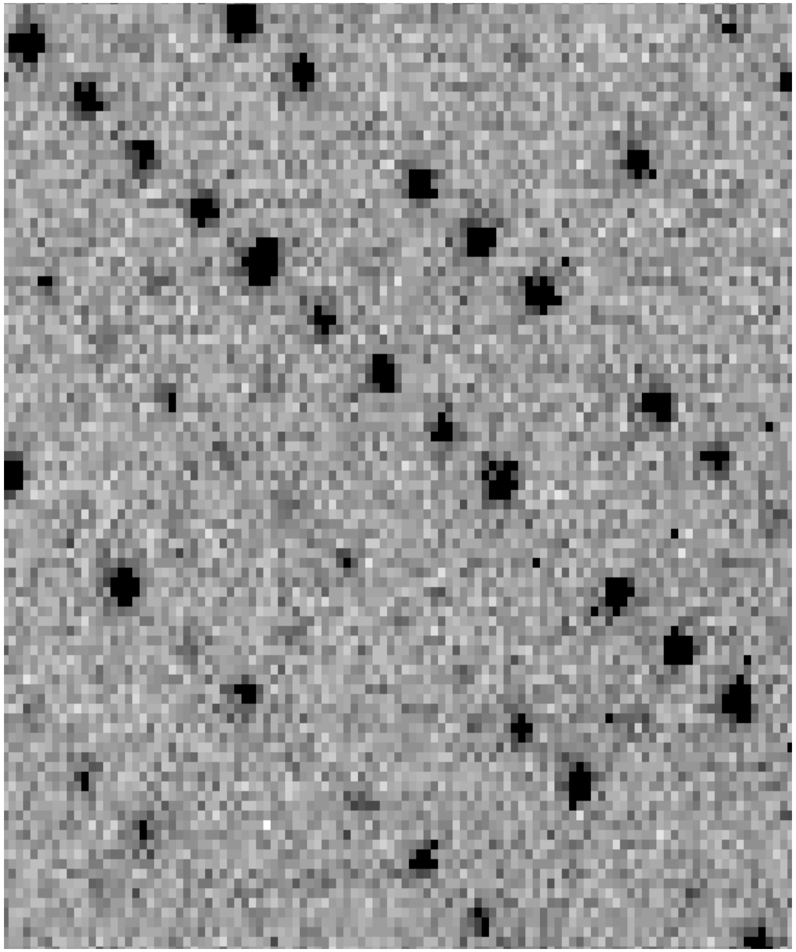
1952
Photo 51:
first image by X-ray diffraction

DNA
is constituted by two complementary filaments formed by regular sequences of small molecules, forming double helixes. It was the diffraction pattern of X rays from a pseudo crystal formed by DNA fibers, obtained by Rosalind Franklin, which allowed determining the form of this molecules.

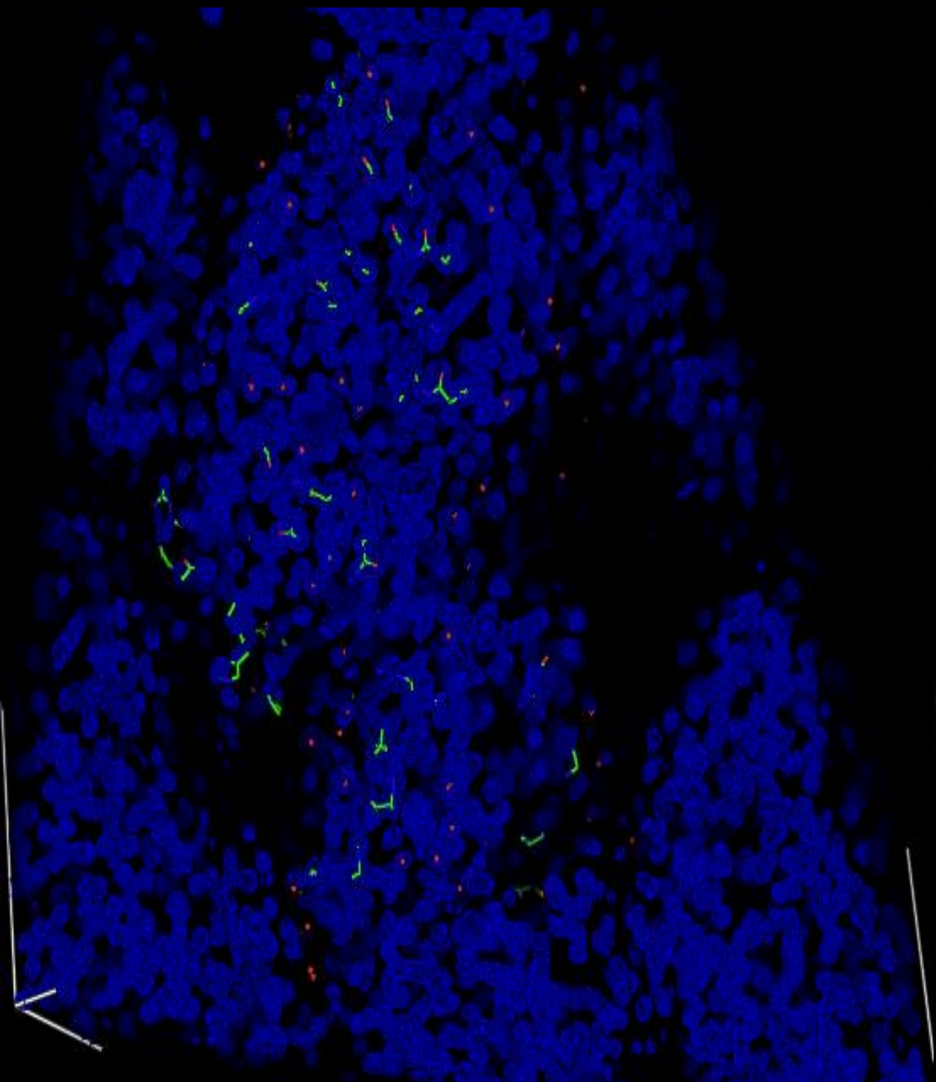
Diffraction pattern of a protein crystal.

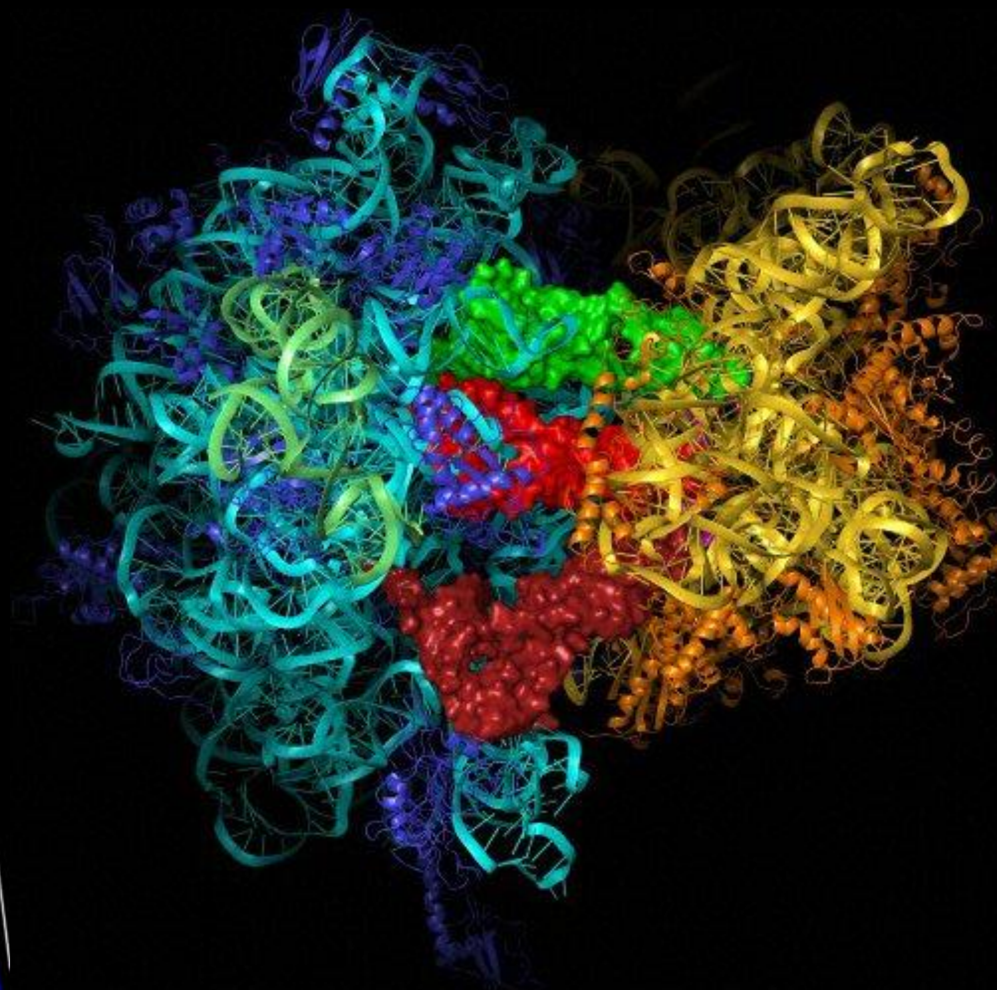
From position and intensity of the spots the protein structure can be defined





Electronic density from which the 3D representation of the protein can be obtained

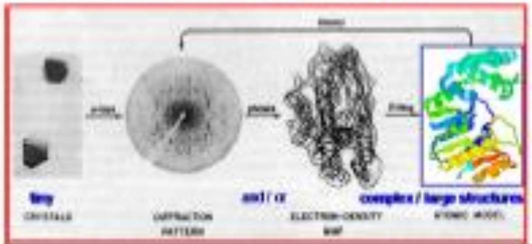




High brilliance and flux

The Nobel Prize in Chemistry **2012** is awarded to Brian K. Kobilka and Robert J. Lefkowitz for studies of G-protein–coupled receptors

G-protein–coupled receptors (GPCRs) form a remarkable modular system that allows transmission of a wide variety of signals over the cell membrane, between cells and over long distances in the body



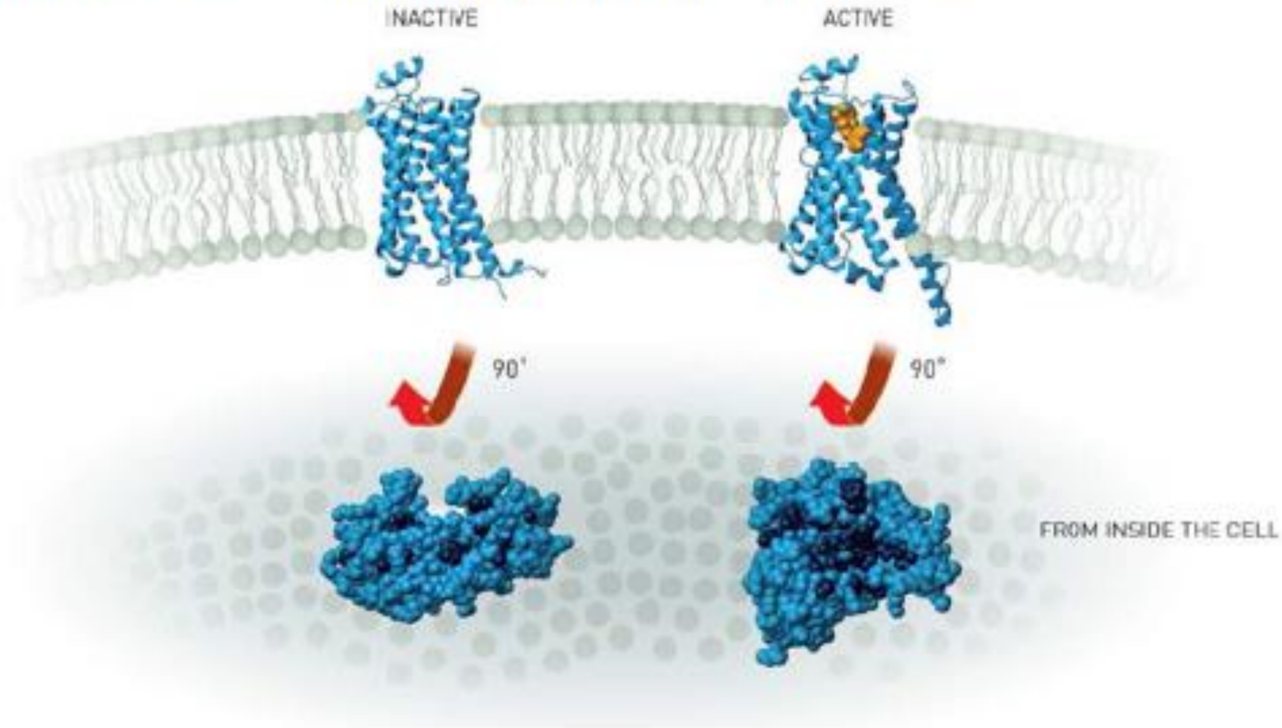


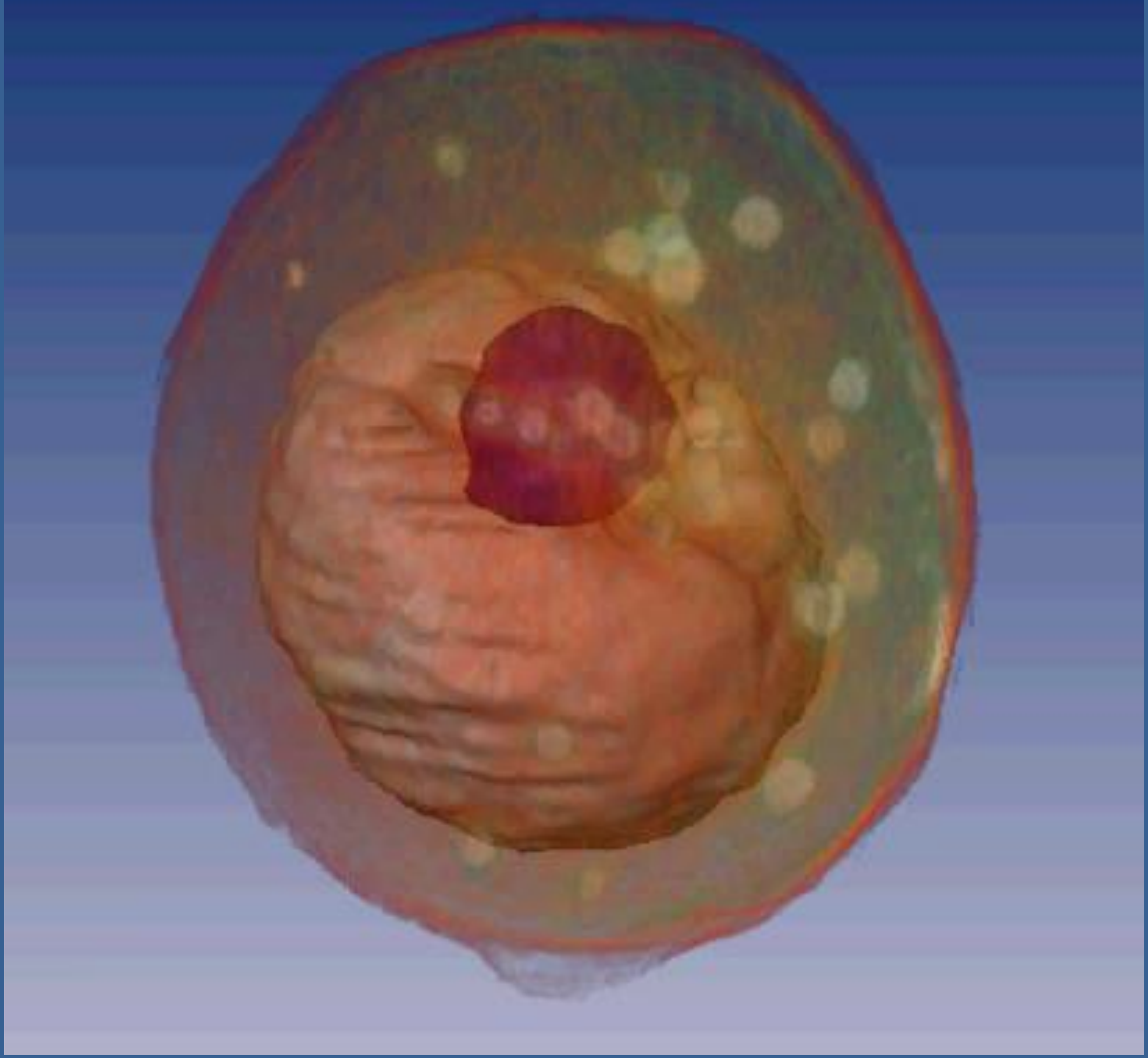
Figure 4. Structural basis of the GPCR signalling mechanism. Non-activated βAR (2bar.pdb) is shown to the left, and activated βAR bound to ligand and G-protein (3sn6.pdb) to the right. At the top, the receptor in the membrane is drawn with blue ribbon that traces the backbone. The bottom view is from the inside of the cell membrane, with the receptor shown using a space-filling model with hydrophobic side chains in dark blue.

Rasmussen SG; et al. (**2011**) Crystal structure of the human beta2 adrenergic receptor-Gs protein complex. *Nature* **477**, 549-555

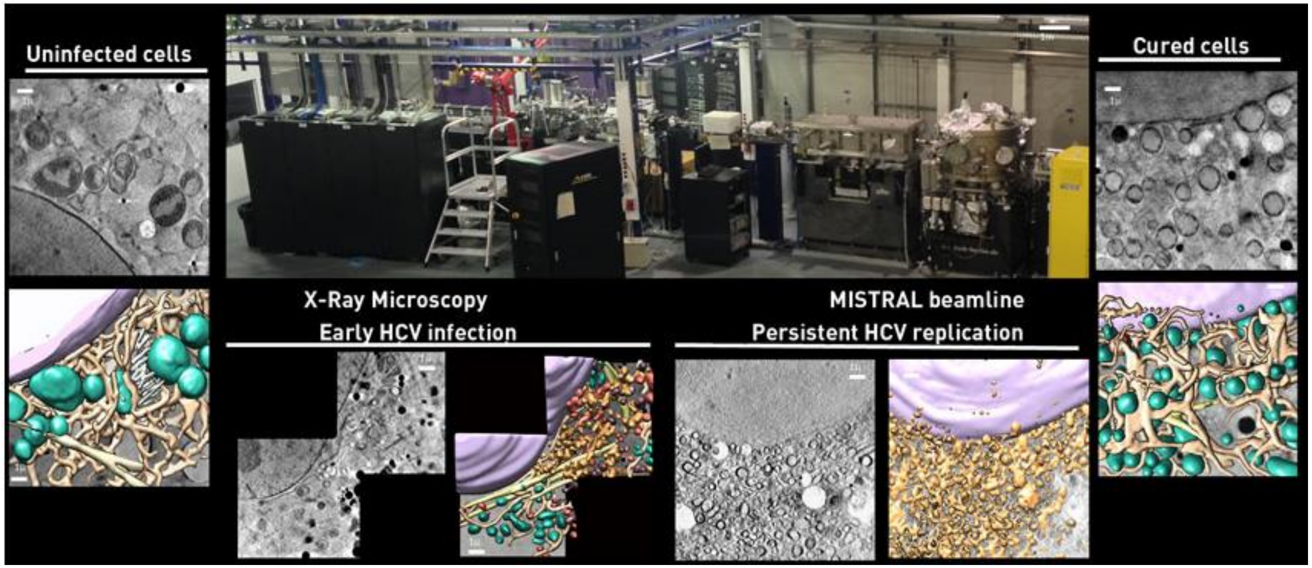
IMAGING

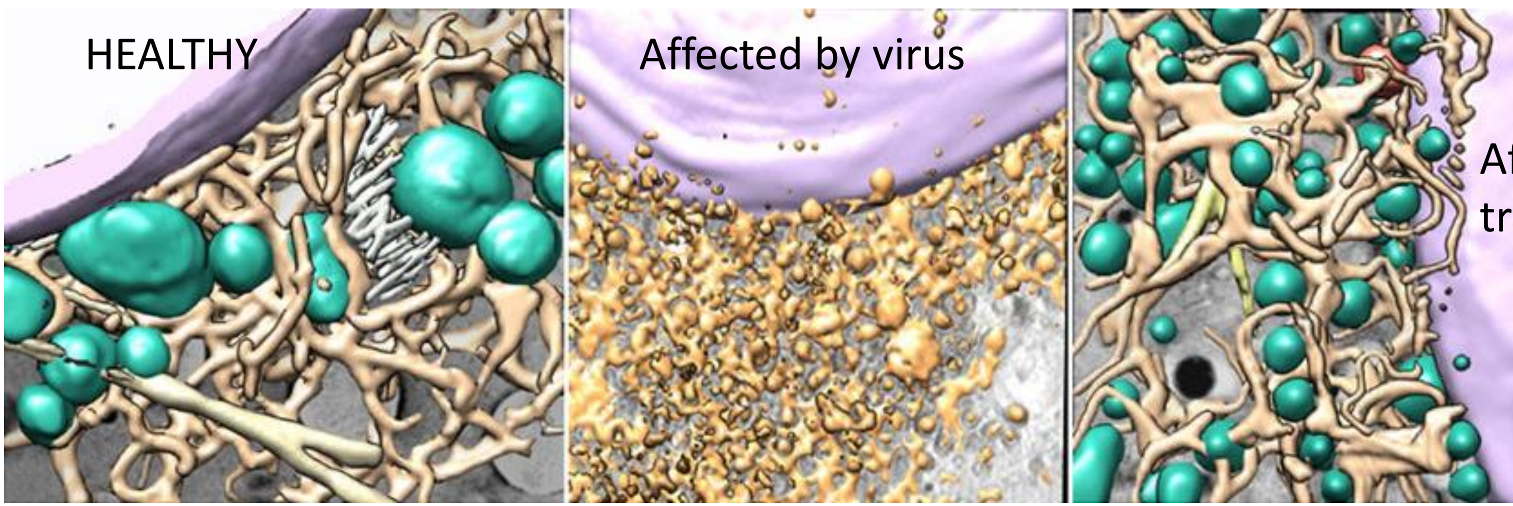
From the image of Roentgen's wife hand in 1985

To the image of a cell in 3D (MISTRAL BL @ALBA)



Hepatitis C Virus effect on a cell





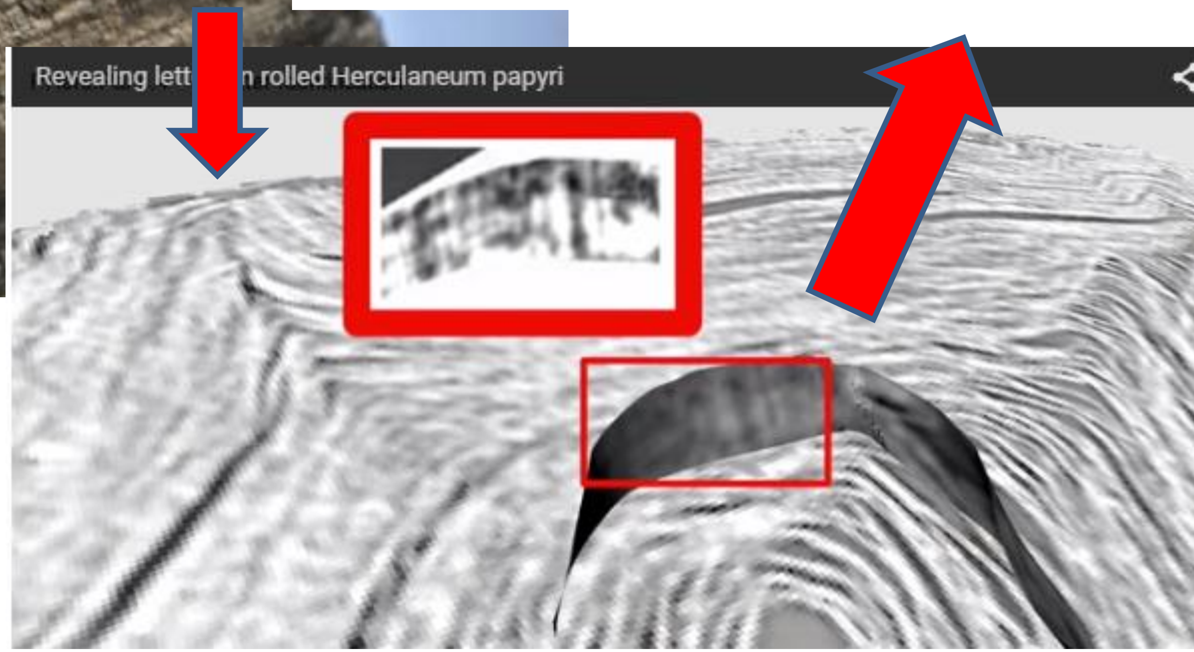
After treatment

Violet: cell nucleus, green: healthy mitochondria, beige: healthy endoplasmic reticulum, yellow: altered endoplasmic reticulum

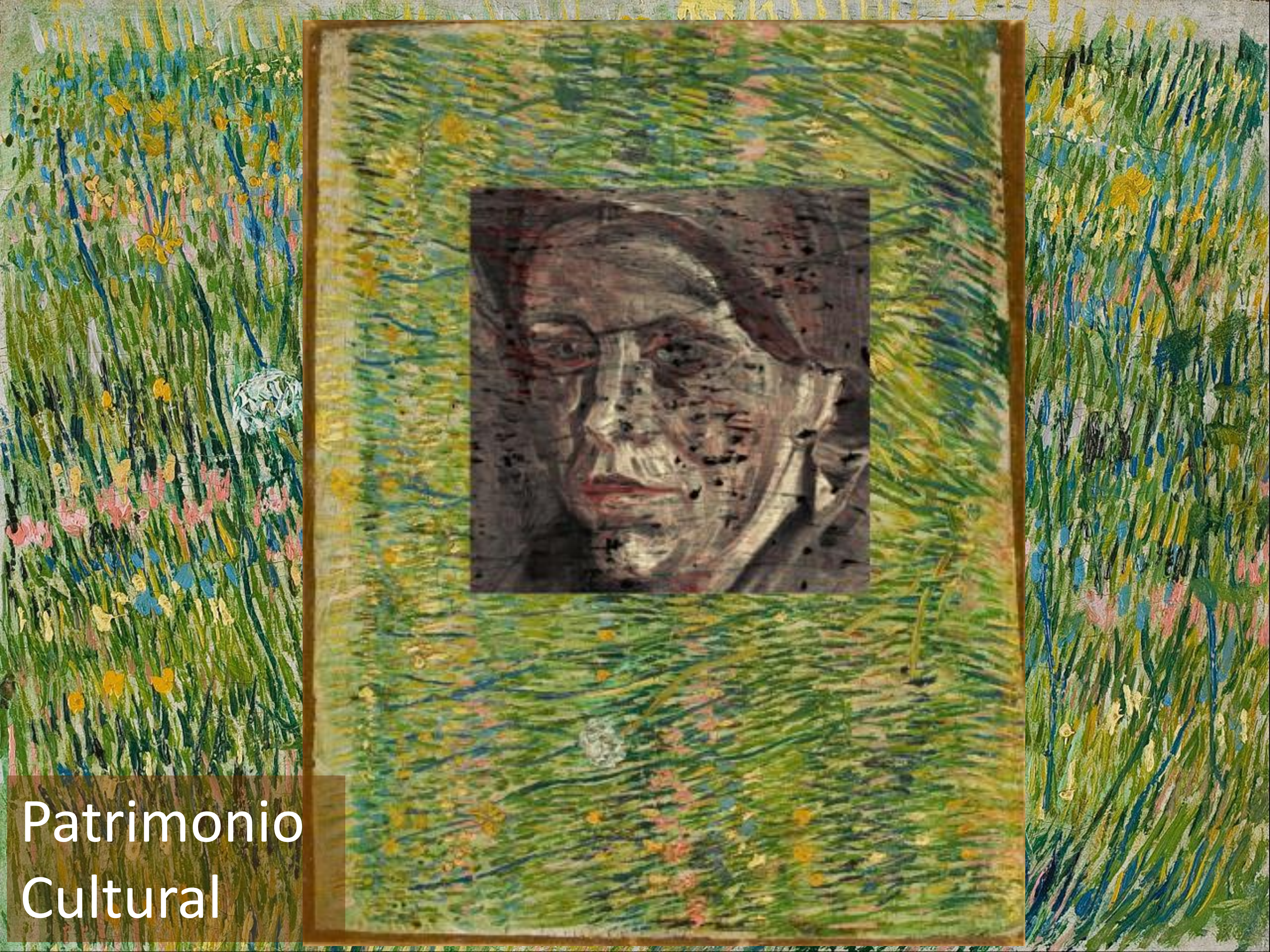
Reference: AJ Pérez-Berná, MJ Rodríguez, FJ Chichón, M Friederike Friesland, A Sorrentino, JL Carrascosa, E Pereiro, and P Gastaminza. Structural Changes In Cells Imaged by Soft X-Ray Cryo-Tomography During Hepatitis C Virus Infection. ACS Nano 2016 DOI: 10.1021/acsnano.6b01374

ESRF: Villa di Ercolano papiri

Transmission microscopy



Works of epicureo Filodemo, teacher of Siron, teacher of Virgilio and Oratium



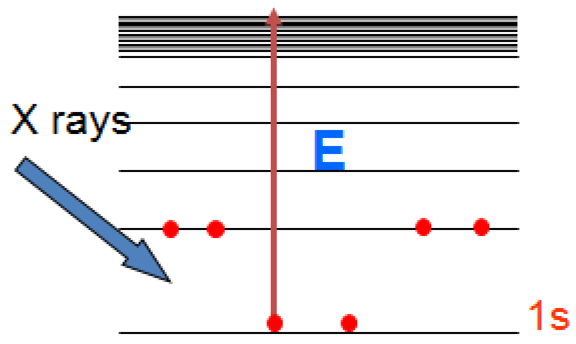
Patrimonio Cultural

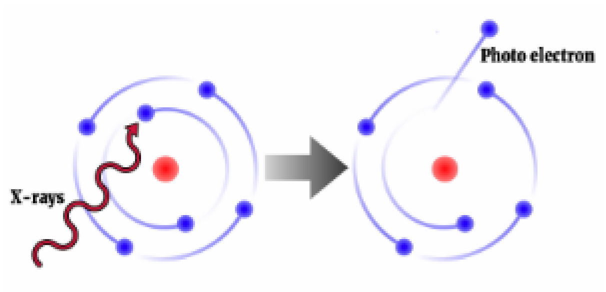
Spectroscopy

Dependence on energy of incident photons of the absorption, emission or fluorescence

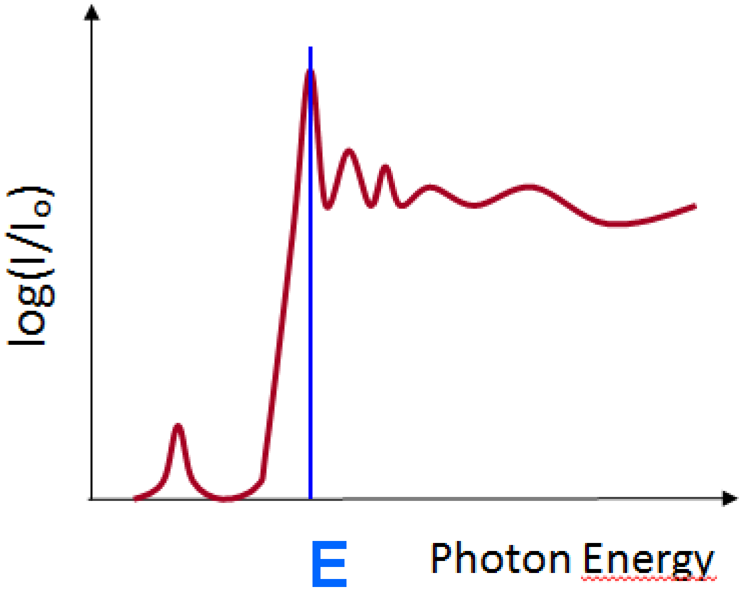
Deduction of composition, status, etc.

The absorption energy and the fine structure of the absorption spectra are sensitive to the valence state of the absorbing atom

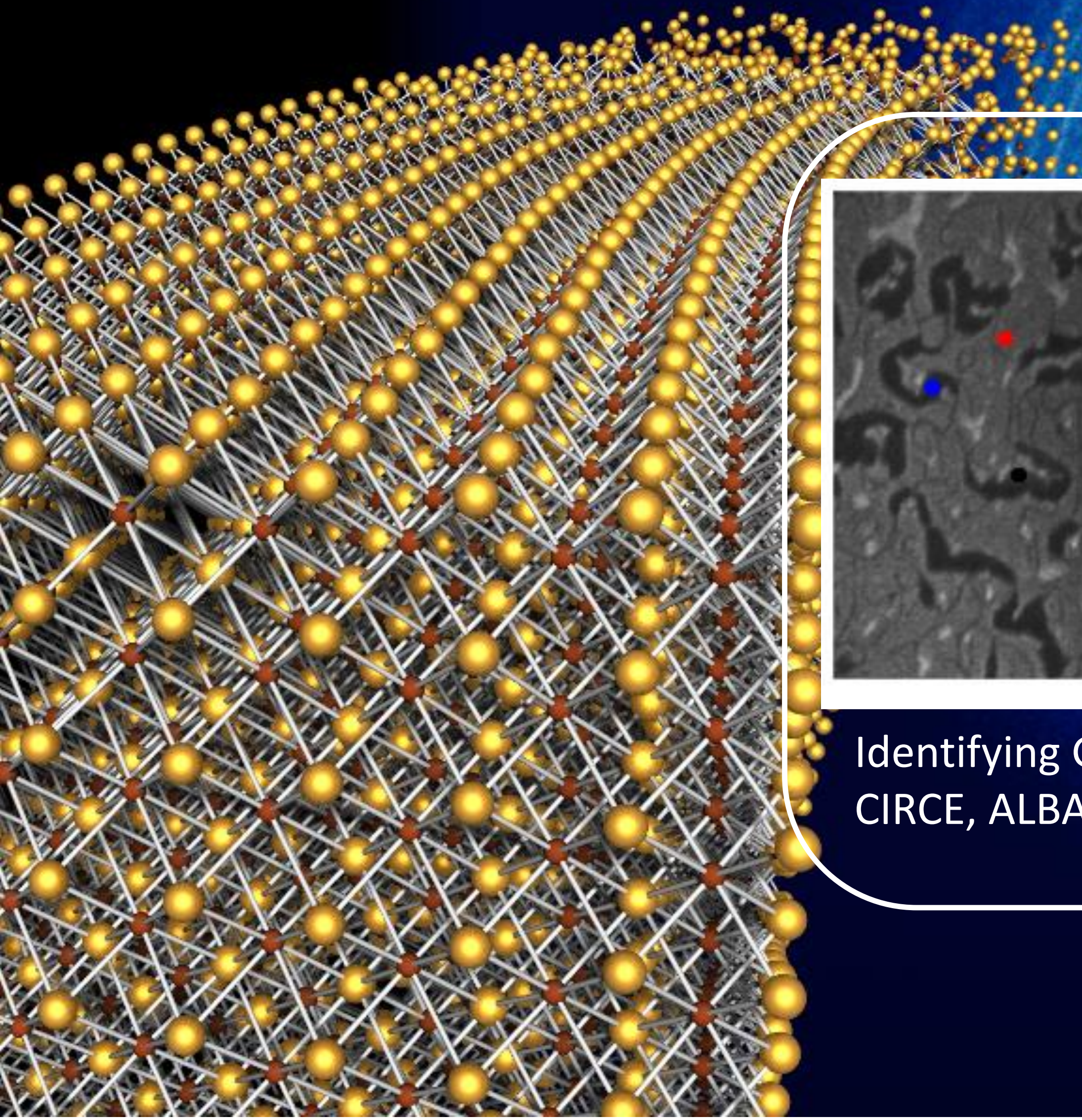


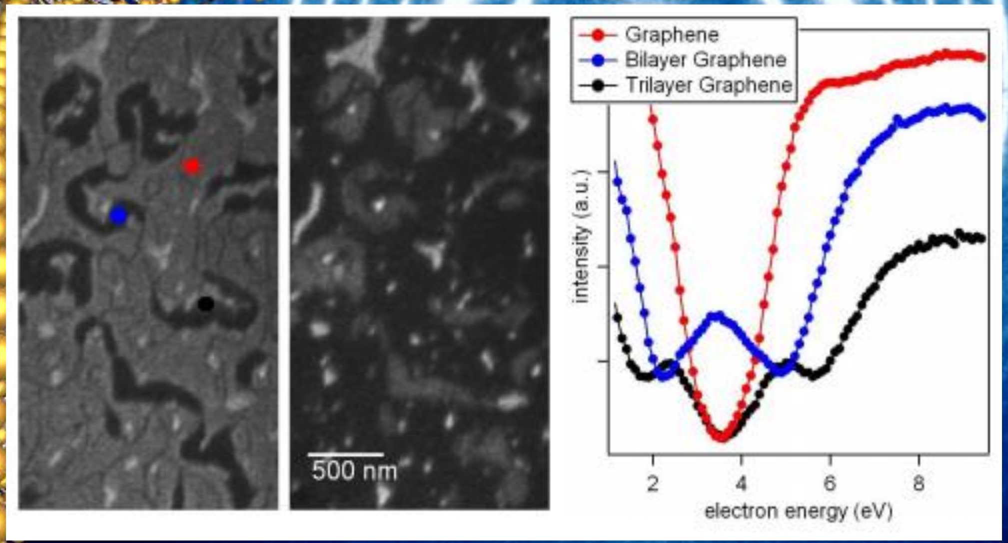


Photoemission



Material science





Identifying Graphene by counting atomic levels at CIRCE, ALBA

CFN, BNL, US

Skyrmions - ALBA – for magnetic memory development

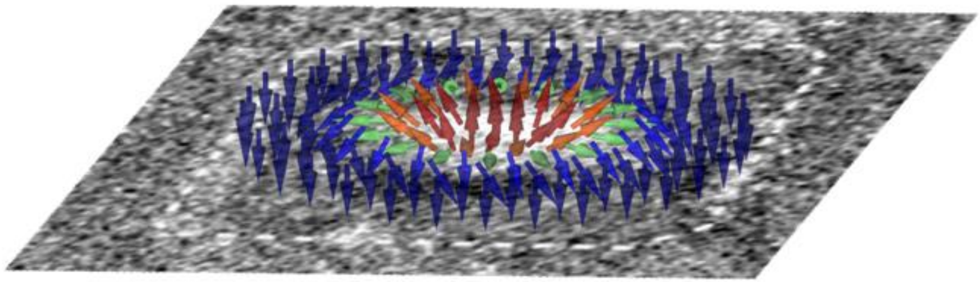
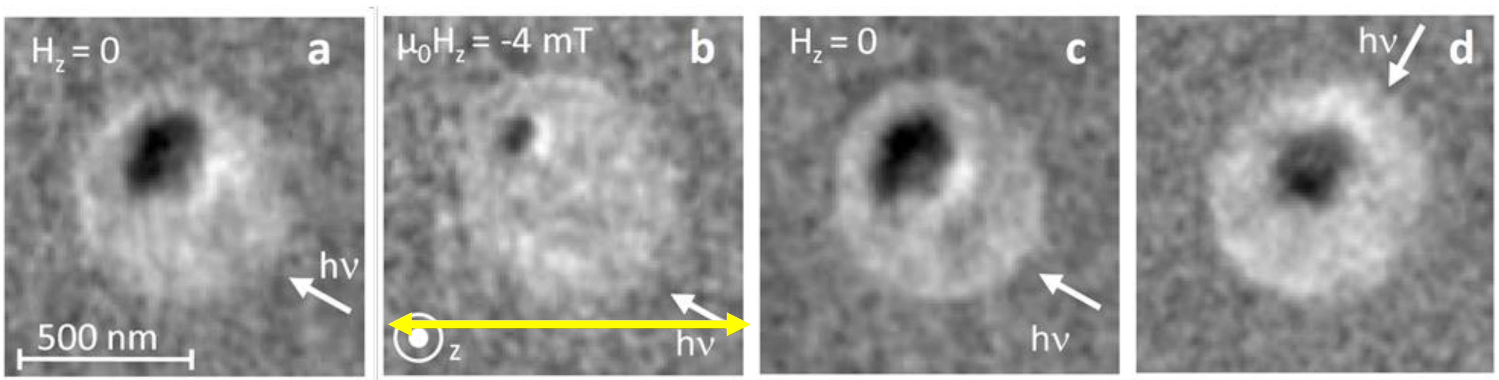


Fig. 1: Sketch of the spin structure of a magnetic skyrmion.

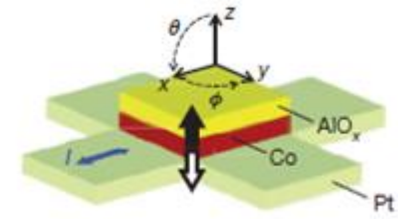


One thousand of mm

Fig. 2: (a) Magnetic microscopy im… Within the white dot (magnetization pointing down), a circular black/white contrast is visible which correspond… he skyrmion center, dark grey, the magnetization points up. The grazing X-ray beam incidence is indicated by the arrow (b). The skyrmion contracts under an applied magnetic field of 4mT and relaxes again when removing it (c). (d) The chiral skyrmion spin structure is confirmed by rotating the contrast direction (beam incidence) by 90°.

Magnetic skyrmions (nanoscale spin textures) observed at room temperature in materials compatible with the microelectronics industry.. These results break an important barrier for the use of skyrmions as nanoscale information carriers in our computers.

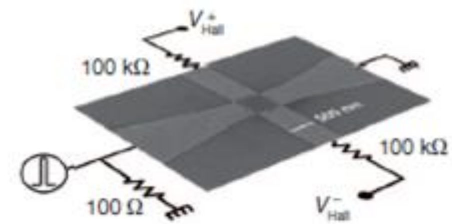
@ BOREAS



Materials for batteries

Spin-orbit fields mechanisms for in-plane current induced magnetization reversal of magnetic tunnel junctions, and their optimization

Fieldlike and antidamping spin-orbit torques in as-grown and annealed Ta/CoFeB/MgO layers



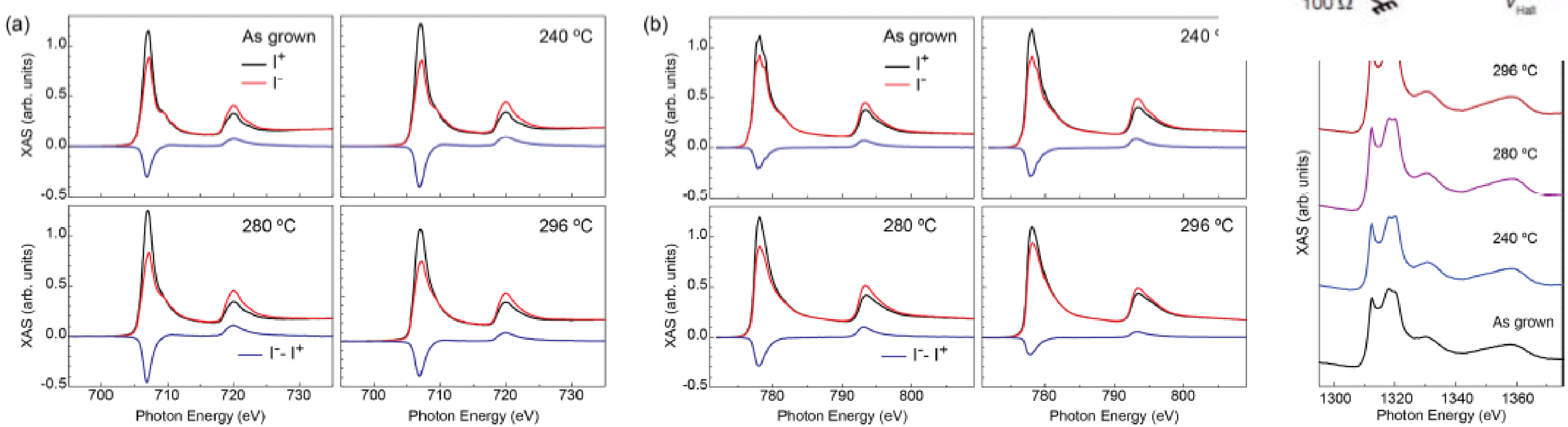


FIG. 4. (Color online) X-ray-absorption and magnetic circular dichroism spectra of as-grown and annealed Ta/CoFeB/MgO trilayers measured at the Fe $L_{2,3}$ edges (a), Co $L_{2,3}$ edges (b), and Mg K edge (c). The spectra were recorded at normal incidence at room temperature in a magnetic field of 1 T.

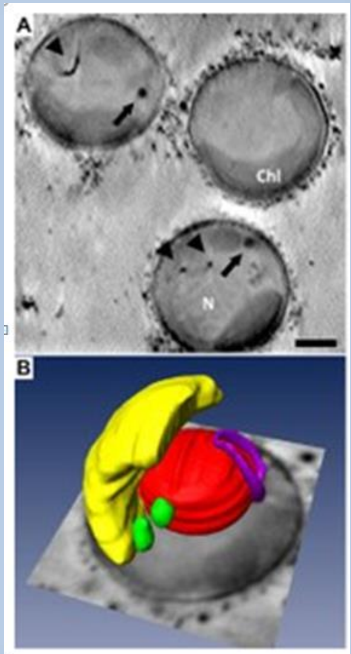
Physical review **B 89** 214419 (2014)

Environmental science – some example from ALBA

Speciation of selenium in wheat to know the Se level in comestibles plants

Analysis of Arsenicum in the soil of an old mine near Madrid for treating and recovering the contaminated soil

Develop better catalists for industrial processes, electric cars, etc



Study the spatial distribution of Calcium in marinae algae to understand effect of climate changes

SL

IN OPERATION *IN CONSTRUCTION*


SYNCHRONISED WITH THE INTERNATIONAL YEAR OF LIGHT
THE AFRICAN LIGHT SOURCE CONFERENCE AND WORKSHOP
16 - 20 NOVEMBER 2015, ESRF GRENOBLE FRANCE
THE AFRICAN LIGHT SOURCE CONFERENCE AND WORKSHOP IS OPEN TO AFRICAN SCIENTISTS, COLLEAGUES, STUDENTS WHO HAVE UTILISED LIGHT SOURCES, AND FRIENDS OF AFRICA WHO SUPPORT THE VISION FOR AN AFRICAN LIGHT SOURCE.
Conference: African Synchrotron Science
The Workshop will review the status of the African User Base at international light sources.
Presentations of African research at Light Sources
Presentations of highlights and status globally
Workshop: Strategy and Policy
Discussions on a Light Source Roadmap for Africa
Visit and insights to an operational international light source
Election of the new, fully mandated Steering Committee for the African Light Source
Dissolution of the Interim Committee
Conference Secretariat
ORGANISING COMMITTEE
MEMBERS
The Interim Steering Committee of the African Light Source
Web Page of the Interim Steering Committee of the African Light Source:

1st AfLS Conference & Workshop
(http://www.saip.org.za/AfLS2015/)

- Venue: ESRF (Grenoble, France)
- Dates: 16-20 November 2015
- First in a series of conferences
- Venue was selected to be on the site of a premier international light source facility.
- Future conferences preferably will be held in Africa.
- Purpose was to develop a Roadmap and replace the Interim AfLS-SC with a fully mandated Steering Committee.

Conference & Workshop Participants

- African researchers and students
- Representatives from international light sources
- European Commission, IUPAP-C13 Commission (Physics for Development), International Union of Crystallography
- Government Policymakers
- Industrial representatives
- Friends of Africa who support the vision for an African Light Source.

Conference & Workshop Agenda

- **First 2 days were a Conference, featuring invited speakers to review the world status of light sources and their achievements, and to assess the state of the African Light Source User Community.**

- **Last 3 days were a Workshop devoted to strategy and policy, informed by invited plenary presentations.**

Several Researcher and Student Participants (Credit ESRF)

Some highlights of the workshop

Industry

Relevance of research at synchrotrons for African Industries

Ingredients	Africa
Sustainable value creation	Inputs & outputs – optimize?
Leverage international footprint	Networks – grow
Developing people	√ - momentum
Enhancing stakeholder relationships	√ - momentum
Technologies requiring research support	Clean water, palaeontology, Ebola
Challenging research questions	Nano-technology for clean water, drug design, drug delivery design
A solid home base	Grow
Prove synchrotron & neutron applications	Celebrate victories
Continuous implementation of synchrotron gained knowledge	Feedback loop
Grow synchrotron knowledge	Partner countries, access, review, synchrotron schools
Advance Intellectual Property	Publications and peer reviewed output
Compose an AFRICAN symphony	YES

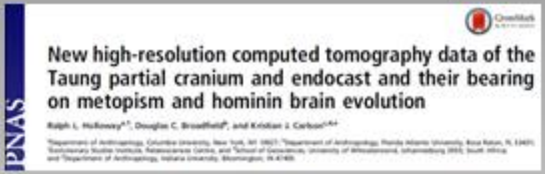
Paleontology

Taung Child

Type specimen

Australopithecus africanus

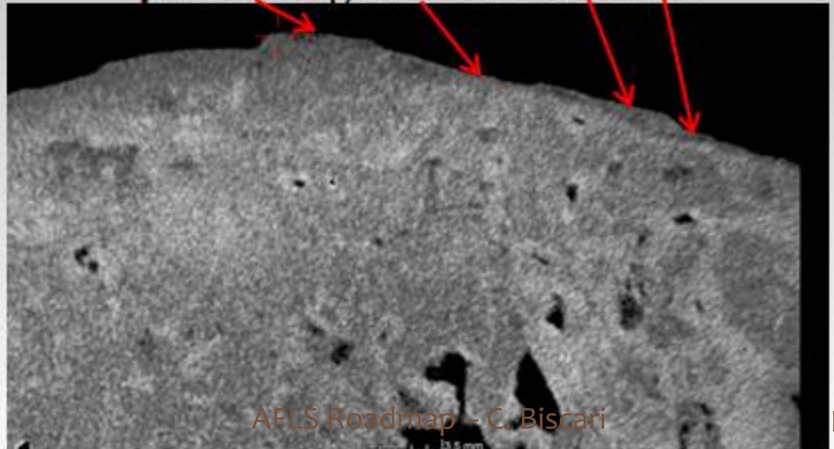
- Refined endocast form (left hemisphere)
- Absolute age-at-death (# of days)

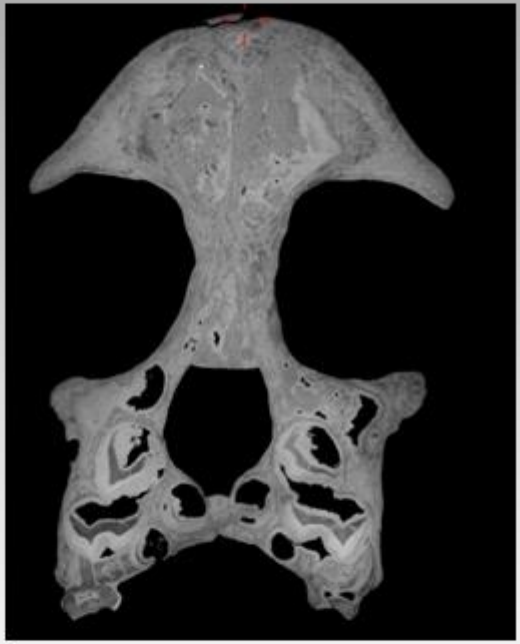

PNAS

New high-resolution computed tomography data of the Taung partial cranium and endocast and their bearing on metopism and hominin brain evolution

Holloway et al. (2014) PNAS 111: 13022-13027

Note thin layer of bone covering the left parietal region of the endocast

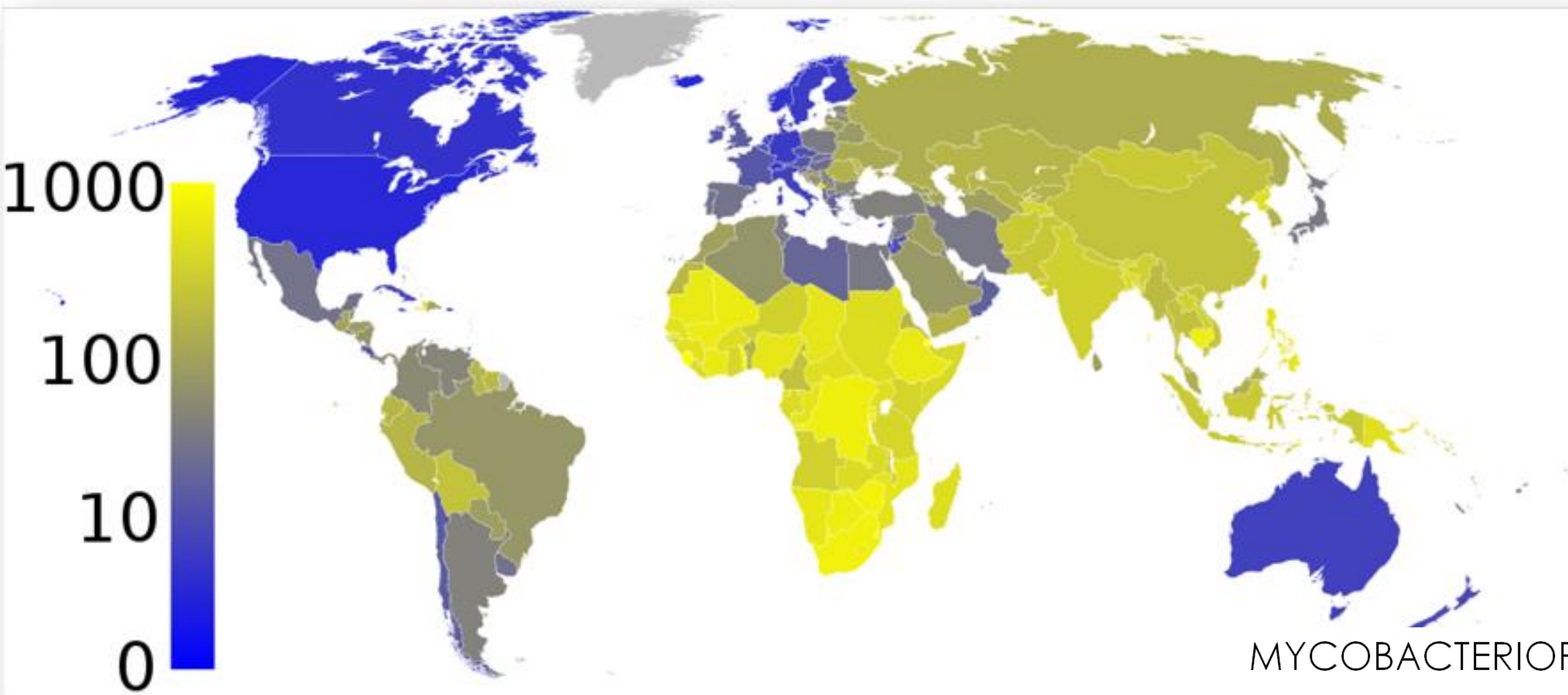




Health

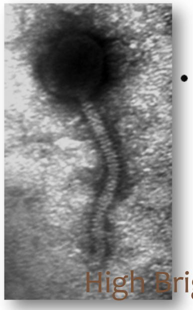
MYCOBACTERIUM TUBERCULOSIS

Prevalence Per 100,000



MYCOBACTERIOPHAGE BUTTERS

Electron Micrograph of Butters



- *Founder: Lena Ma, Lehigh University SEA-PHAGES Program 2011-12*
- Characteristics:
  - N cluster phage
  - Only ~40 kbp linear genome
    - 66 annotated genes (GenBank accession no. NC_021061)
    - Contains several **orphams**

Why is it important?

- Macro and micro challenges facing mankind:
  - Energy security
  - Food security
  - Water security
  - Environmental security
  - Economic security
  - Political and judicial security
  - Basic freedoms to pursue happiness
- Some have technological solutions, all require education, cooperation and the victory of rationality over irrationality

A facility like a synchrotron promotes cooperation, education, technology, and science

The impacts of a synchrotron go way beyond the x-rays it produces

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

BROOKHAVEN NATIONAL LABORATORY

http://thebillingegroup.co

Workshop Outputs

- Grenoble Resolutions that state the reasons for an AfLS
- Roadmap
- Election of a fully mandated African Light Source Steering Committee to drive the Roadmap

Grenoble Resolutions

- **Advanced light sources are the most transformative scientific instruments similar to the invention of conventional lasers and computers.**

- **Advanced light sources are revolutionizing a myriad of fundamental and applied sciences, including agriculture, biology, biomedicine, chemistry, climate and environmental eco-systems science, cultural heritage studies, energy, engineering, geology, materials science, nanotechnology, palaeontology, pharmaceutical discoveries, physics, with an accompanying impact on sustainable industry.**

- The community of researchers around the world are striving collaboratively to construct ever more intense sources of electromagnetic radiation, specifically derived from synchrotron light sources and X-ray free-electron lasers (XFELs), to address the most challenging questions in living and condensed matter sciences.

- The African Light Source is expected to contribute significantly to the African Science Renaissance, the return of the African Science Diaspora, the enhancement of University Education, the training of a new generation of young researchers, the growth of competitive African industries, and the advancement of research that addresses issues, challenges and concerns relevant to Africa.

- For African countries to take control of their destinies and become major players in the international community, it is inevitable that a light source must begin construction somewhere on the African continent in the near future, which will promote peace and collaborations among African nations and the wider global community.

Roadmap Short-term (<3 years)

- Train African researchers and students in the design, operation and utilization of advanced light sources.
- Establish formal partnerships with existing light sources.
- Promote the involvement of industry.
- Establish and enhance Africa's critical feeder infrastructure that empowers light source science.
- Promote outreach and communication to policymakers and public.
- Study the feasibility of constructing African multinational beamlines at existing light sources, with partners .
- Develop a *Strategic Plan* for submission to African Gov'ts.
- Develop an AfLS non-site specific Pre-Conceptual Design Report.

Roadmap Medium-term (<5 years)

- **Conduct a feasibility study, including costs, for an African latest generation light source, with requisite infrastructure.**
- **Develop a detailed Business Plan.**
- **Develop a Governance Model.**

Roadmap Long-term (>5 years)

- Complete the Technical Design Report (TDR) with site selection.
- Establish the AfLS as a legal entity.
- When approved by a sufficient number of African governments, begin the construction of an African latest generation advanced light source, with requisite infrastructure.