ESRF
The European Synchrotron

Ricerca con la luce di sincrotrone

Francesco Sette

DIPARTIMENTO DI FISICA
SAPIENZA
UNIVERSITÀ DI ROMA

Raggi X – l'incontro del 4-12-2017, di oggi e del 22-01-2018

- Scienza con i raggi X: lo sviluppo della luce di sincrotrone e del Free Electron Laser come sorgenti di raggi X, la ricerca con i raggi X e le loro applicazioni

Cattedra Fermi
Ricerca con la luce di sincrotrone

Francesco Sette

Programma Ciclo I; Dicembre 2017 – Aprile 2018

Dicembre 2017	
04/12	Raggi X – Storia, sorgenti e applicazioni I
18/12	Raggi X – Storia, sorgenti e applicazioni II
Gennaio 2018	
22/01	Raggi X – Storia, sorgenti e applicazioni III
Febbraio 2018	
12/02	Interazione Materia – Raggi X
Marzo 2018	
12/03	Raggi X da sorgenti di luce di sincrotrone e laser ad elettroni liberi I
26/03	Raggi X da sorgenti di luce di sincrotrone e laser ad elettroni liberi II
Aprile 2018	
09/04	Ottica e strumenti per l'osservazione dei Raggi X
30/04	Applicazioni ed opportunità di ricerca attuali e future

Programma Ciclo II; Settembre 2018 – Dicembre 2018

Settembre 2018	
03/09	Scienza dei materiali I
17/09	Scienza dei materiali II
Ottobre 2018	
01/10	Studio della materia in condizioni estreme (pressione, temperatura, etc.)
29/10	Biologia e medicina I
Novembre 2018	
12/11	Biologia e medicina II
Dicembre 2018	
10/12	Studio di artefatti e tesori naturali
17/12	Future opportunità nella ricerca su materiali e materia vivente con i raggi X prodotti in grandi infrastrutture di ricerca

Prime tre presentazioni

4 Dicembre 2017 – I raggi X, il loro uso, e interazione radiazione-materia

- **Esempi d'utilizzazione dei raggi X**
- **La scienza dei materiali e della materia vivente, ed il legame con il progresso tecnologico della società umana**
- **I raggi X e il loro uso nella caratterizzazione dei materiali e della materia vivente**
- **L'interazione radiazione materia: principi generali e le grandi scoperte che ci hanno permesso di capire la struttura degli atomi, le proprietà della luce e l'interazione radiazione materia.**

18 Dicembre 2017 – Ricerca con i Raggi X , sorgenti di luce di sincrotrone ed il sincrotrone europeo di Grenoble

- Ricerca e osservazioni con i raggi X
- Gli acceleratori di elettroni come sorgente di luce di sincrotrone
- Il sincrotrone europeo ESRF di Grenoble

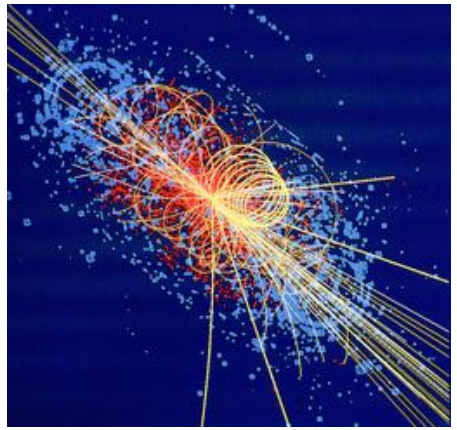
22 Gennaio 2018 – Ricerca con la luce di sincrotrone

- Esempi di ricerca con la luce di sincrotrone

Curiosità e tecnologia alla base del progresso della società umana

Stone Age

…… Quantum Age



Iron Age

Bronze Age

La comprensione di proprietà e funzioni dei materiali e della materia vivente *continua* a stimolare il progresso dell' umanità

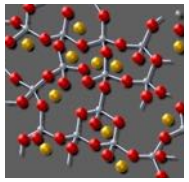
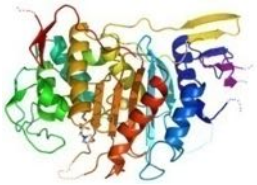
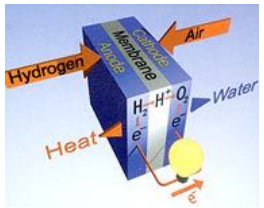
- Dall'ECONOMIA DI OGGI a una nuova ECONOMIA SOSTENIBILE
- Confrontarsi con CRITICHE SFIDE GLOBALI PER UN MOND PACIFICO E SOSTENIBILE per le generazioni future
- **SALUTE, ENERGIA, AMBIENTE, DISPONIBILITA' D'ACQUA E DI GENERI ALIMENTARI, ACCESSO E UTILIZZAZIONE DI NUOVI PRODOTTI INTELLIGENTI E FUNZIONALI, PACE E SICUREZZA NELLA VITA DI TUTTI I GIORNI, ETC.**

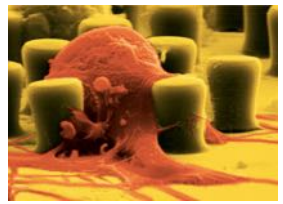
La scienza dei materiali identifica la crescita della nostra società: I materiali del futuro?

La nuova avventura umana: le risorse a nostra disposizione non sono infinite!

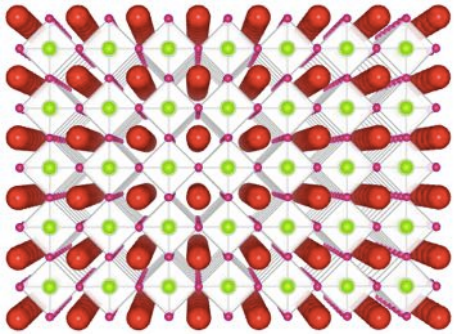
- Gestione
- Sostenibilità
- Impatto sull'ambiente: acqua – aria – terra

Comprendere, disegnare, immaginare, funzionalizzare, caratterizzare nuovi materiali



La scienza dei materiali identifica la crescita della nostra società: I materiali del futuro?



Structure

Characterization

Properties

Processing

Performance

Comprendere, disegnare, immaginare, funzionalizzare, caratterizzare nuovi materiali

Non solo i raggi X, ma anche fasci di elettroni, positroni neutroni, protoni, muoni, etc. hanno importanti applicazioni nello studio dei materiali

I raggi X per capire dove sono gli atomi e come la loro disposizione nello spazio sia legata alle proprietà e le funzioni del materiale in questione

SCIENCE WITH X-RAYS AT THE ESRF IN GRENOBLE, FRANCE

GRENOBLE ~ 100 YEARS AGO

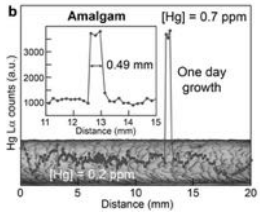
Grenoble
~1910

BIOLOGY AND MATERIAL SCIENCE IN EVERYDAY LIFE

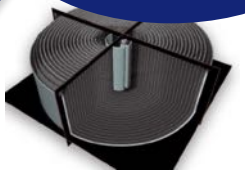
Materials for energy distribution and storage

Cleaner fuel injectors

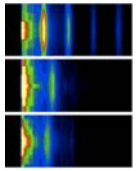
Pollution (heavy metals in the environment, food, products, etc.)



Li-ion batteries



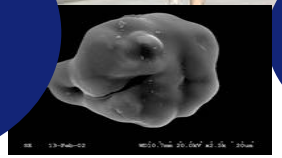
Prevention of Cardiac diseases



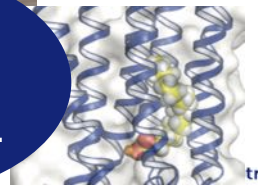
Mobile phones Components

Artificial hips, Dental implants, Biocompatible materials

Cosmetic products



New Drugs: diabetes, cancers, etc.

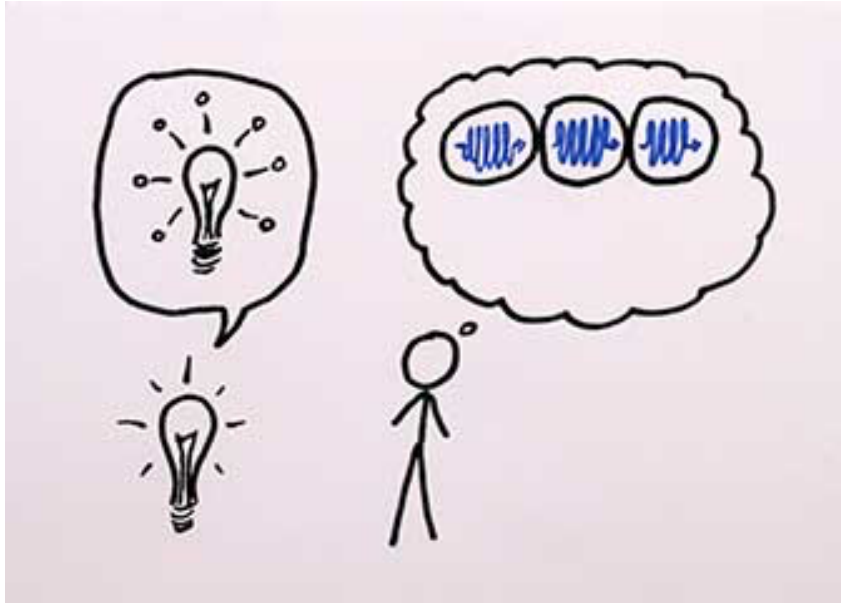


ESRF AT WORK

Quantum theory
Special Relativity theory
Generalized Relativity theory

Equivalence Energy-Mass
(Einstein Relation):

$$E=mc^2$$



Equivalence Energy-Light Quanta Frequency
(Einstein-Planck Relation):

$$E=hf$$

LA REGOLA D'ORO DI FERMI-DIRAC

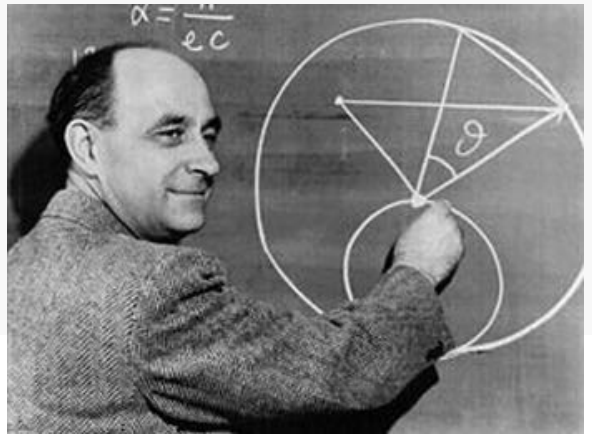
a) La descrizione di un fenomeno naturale implica necessariamente il concetto di interazione fra differenti entitá

b) La meccanica quantistica con il suo complesso meccanismo formale, sviluppa il concetto di funzioni d'onda per decrivere lo stato nello spazio e nel tempo di un Sistema di oggetti che interagiscono fra loro. Formalmente, esistono condizioni che possono rendere questi stati stazionari, vale a dire tali da non variare nel tempo e capaci di conservare la propria energia. Il quadrato di una funzione d'onda corrisponde alla probabilitá di trovare ciascuno degli oggetti in un certo luogo dello spazio.

c) Introdotta una perturbazione di un Sistema in uno stato stazionario, questa puó provocare una transizione del Sistema ad un altro stato, descrivibile a sua volta in modo generale come una sovrapposizione di stati stazionari.

d) La REGOLA D'ORO DI FERMI permette di CALCOLARE in termini molto generali la probabilitá nel tempo $W_{i->n}$ per la transizione del Sistema dal suo stato iniziale $<i|$ ad uno possibile stato finale $|n>$ come consequenza della perturbazione P, con h la costante di Planck:

$$W_{i->n}=2\pi/h\ |<i|P|n>|^2$$



E. Fermi, Nuclear Physics, University of Chicago Press, 1950

P.A.M. Dirac, The Quantum Theory of Emission and Absorption of Radiation, in Proc. Roy. Soc. (London) A, vol. 114, nº 767, 1° marzo 1927, pp. 243–265

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- **Il sincrotrone europeo ESRF di Grenoble**

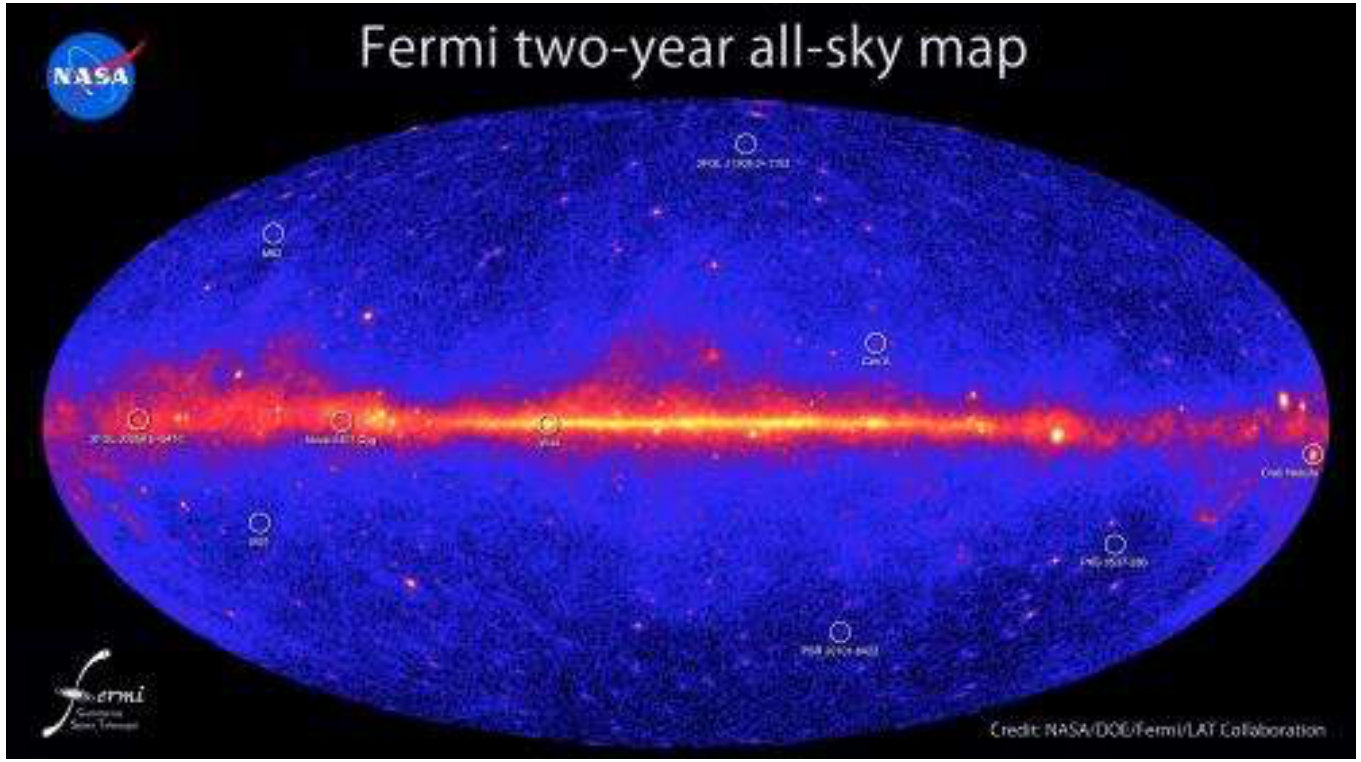
22 Gennaio 2018 – Ricerca con la luce di sincrotrone

- Esempi di ricerca con la luce di sincrotrone

Lo sviluppo della ricerca con I raggi X

600 mysteries in the night sky

October 19, 2011 by Dauna Coulter



An all-sky map of gamma-ray emissions made by the Fermi Space Telescope.
Hundreds of the sources in the map are complete mysteries.

- Fermi sees **gamma rays** coming from directions in the sky where there are no obvious objects likely to produce gamma rays,"
- Gamma rays are by their very nature heralds of great energy and violence. They are a super-energetic form of light produced by sources such as **black holes** and massive **exploding stars**.
- "Some of the mystery sources could be clouds of dark matter – something that's never been seen before,"
- About 85% of the gravitational mass of the universe is dark matter. The stuff we see makes up the rest. Dark matter is something that pulls on things with the force of its gravity but can't be detected in any other way. It doesn't shine – doesn't emit or scatter light – hence the adjective "dark."
- Astronomers cannot detect dark matter directly using electromagnetic radiation telescopes. But dark matter just might shine in gamma rays.

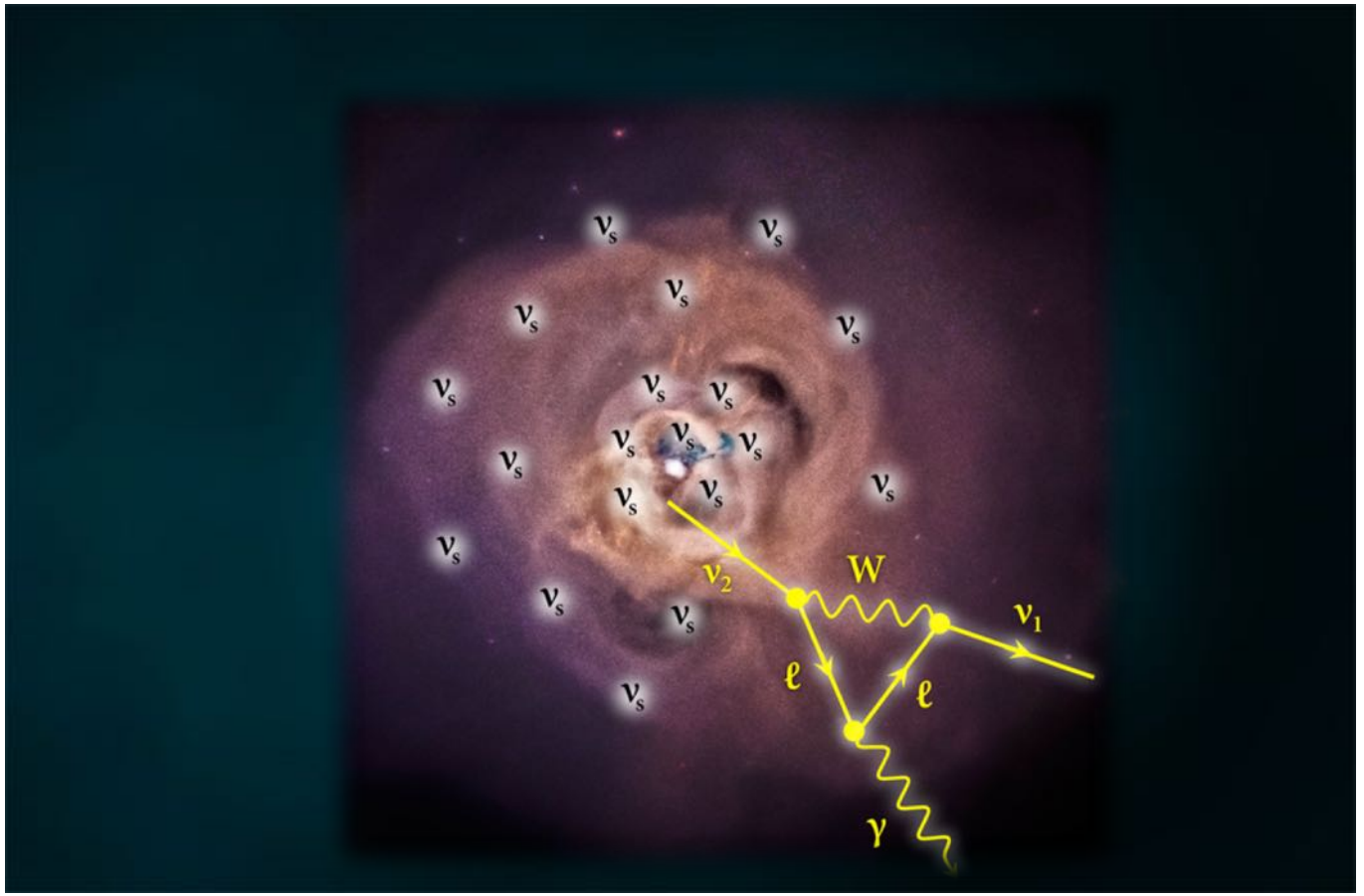
Mysterious X-Ray Signal Could Reveal Dark Matter

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse

Phys. Rev. Lett. 113, 251301 (2014)

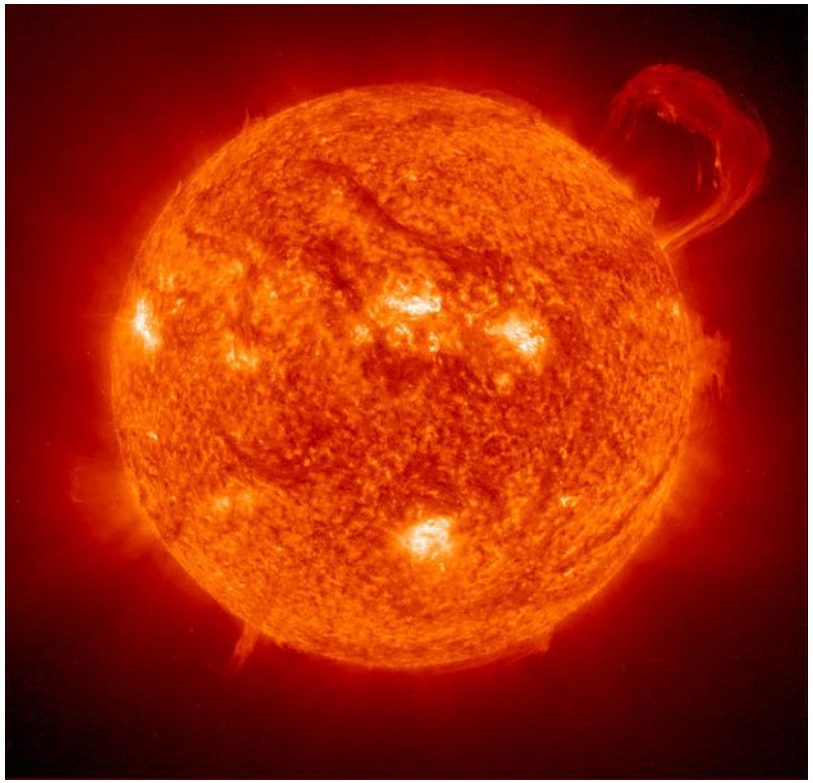
We report a weak line at 3.52±0.02 keV in **X-ray** spectra of the Andromeda galaxy and the Perseus galaxy cluster observed by the metal-oxide-silicon (MOS) and p-n (PN) CCD cameras of the XMM-Newton telescope. This line is not known as an atomic line in the spectra of galaxies or clusters. It becomes stronger towards the centers of the objects; is stronger for Perseus than for M31; is absent in the spectrum of a deep "blank sky" data set. Although for each object it is hard to exclude that the feature is due to an instrumental effect or an atomic line, it is consistent with the behavior of a dark matter decay line. Future (non-)detections of this line in multiple objects may help to reveal its nature.

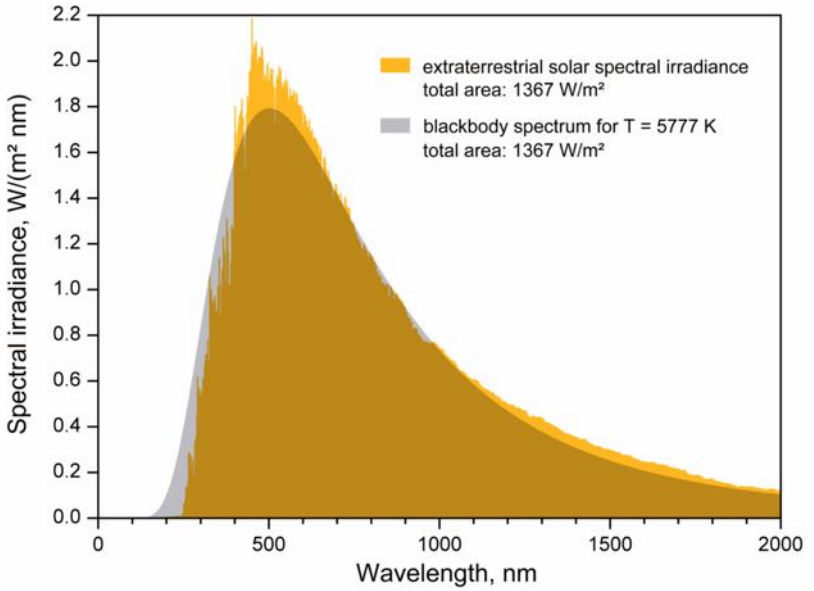


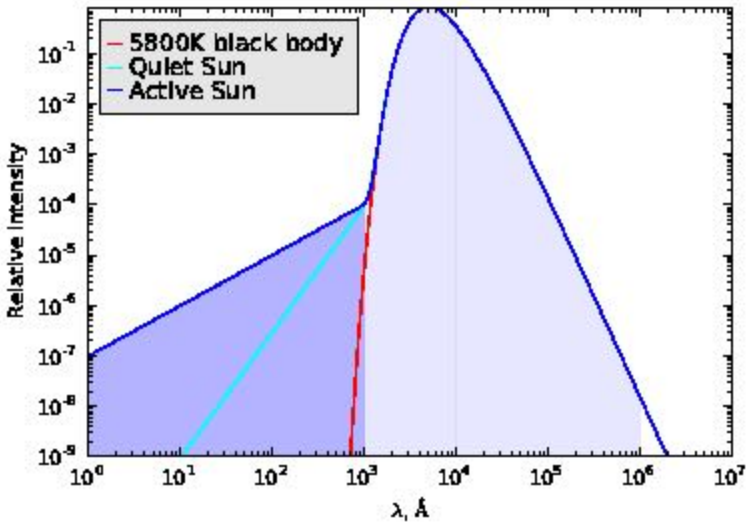
An X-ray image of the hot gas in the central region of the Perseus Cluster of galaxies, taken by the Chandra X-ray Observatory

http://arxiv.org/pdf/1402.4119v1.pdf

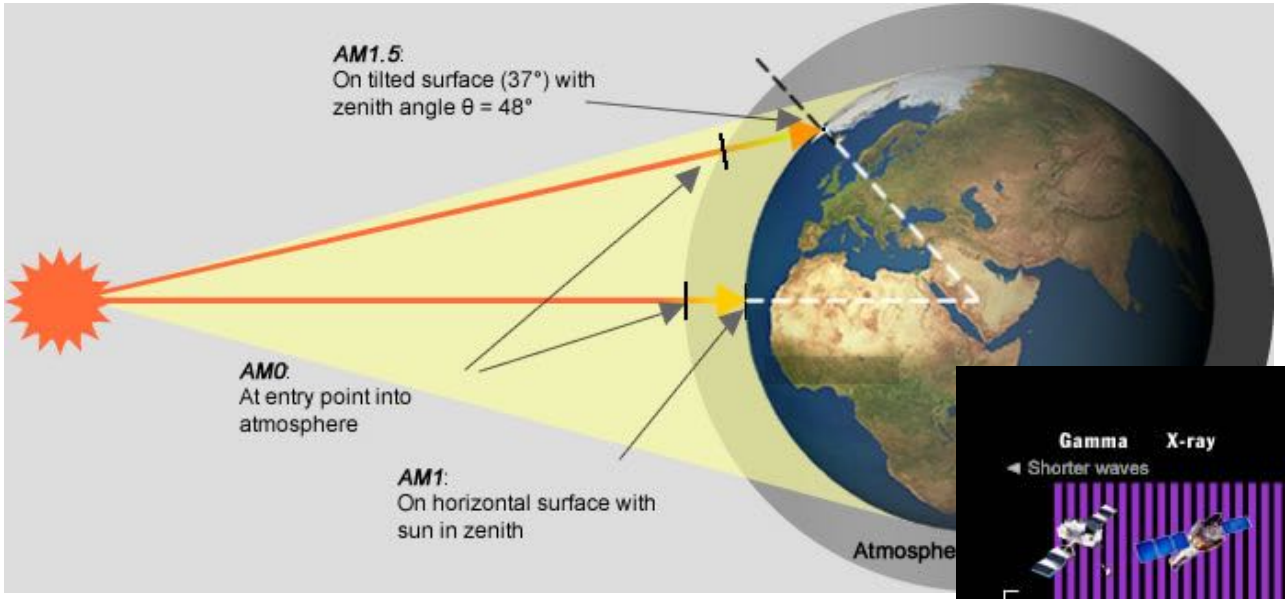
THE SUN

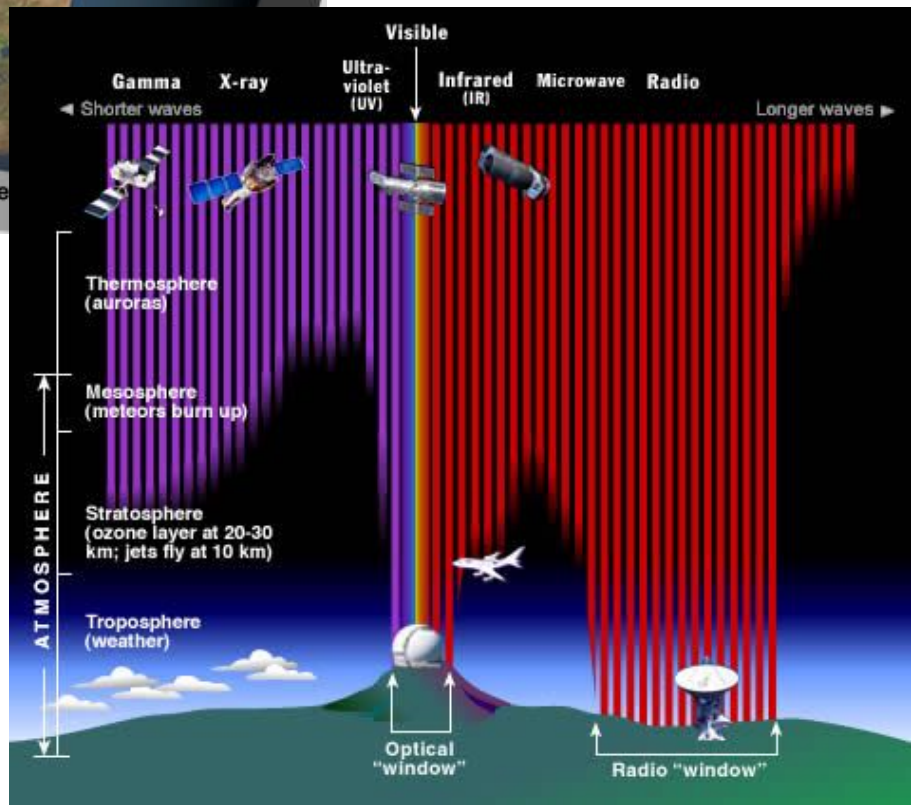



extraterrestrial solar spectral irradiance
total area: 1367 W/m²
blackbody spectrum for T = 5777 K
total area: 1367 W/m²
Spectral irradiance, W/(m² nm)
Wavelength, nm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
0
500
1000
1500
2000


5800K black body
Quiet Sun
Active Sun
Relative Intensity
λ, Å

FILTERING SUN LIGHT





X-RAYS: DISCOVERY IN 1895

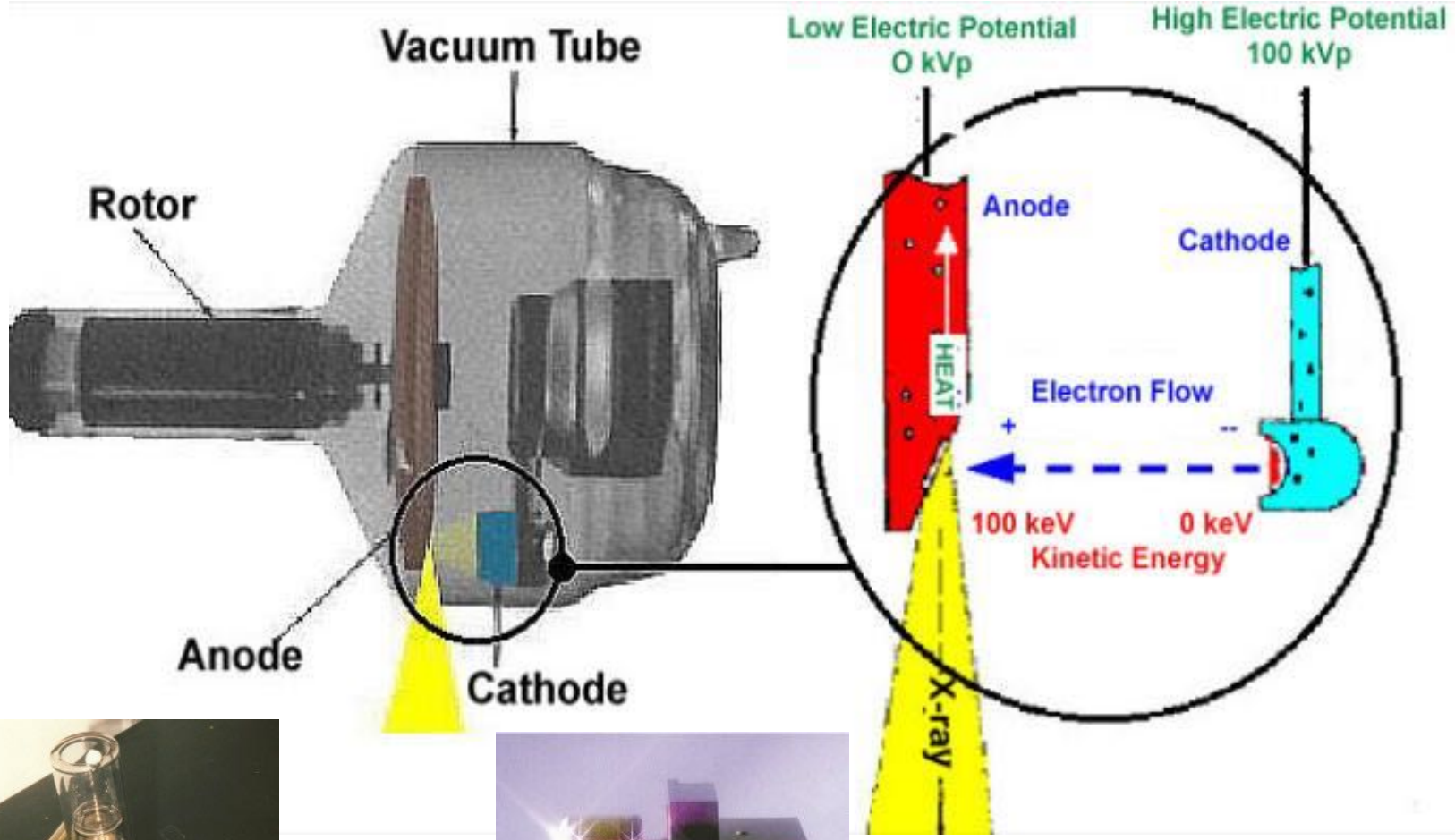
X-rays ... some kind of unknown particles without mass and charge!

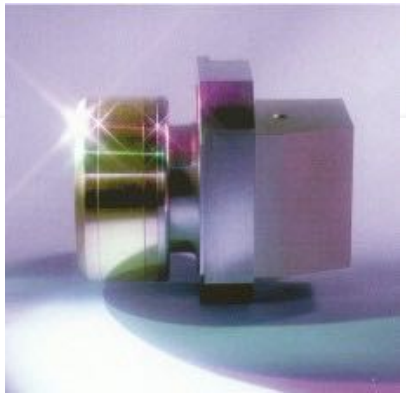
Wilhelm Conrad Röntgen (1845-1923)
First Nobel Prize for Physics, 1901

The first "röntgenogram"
8 November 1895

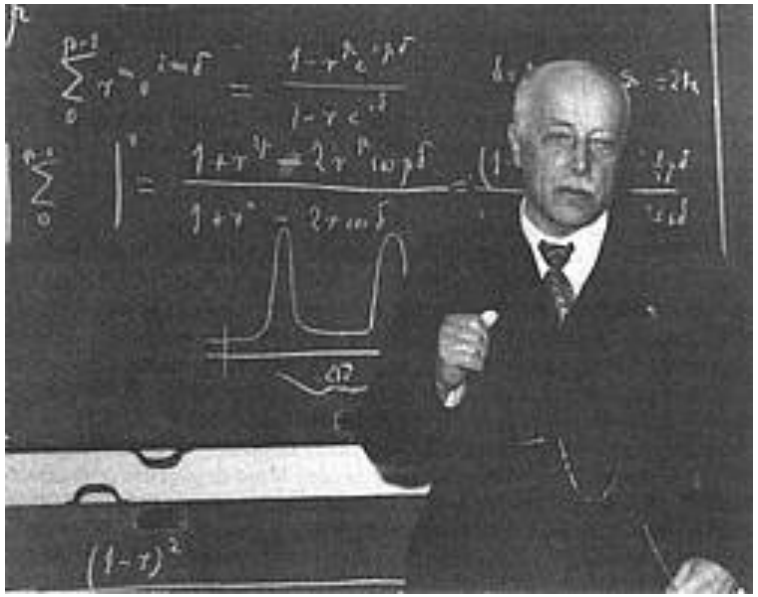
X-RAYS: DISCOVERY IN 1985 AND THE FIRST STEPS

X-RAYS

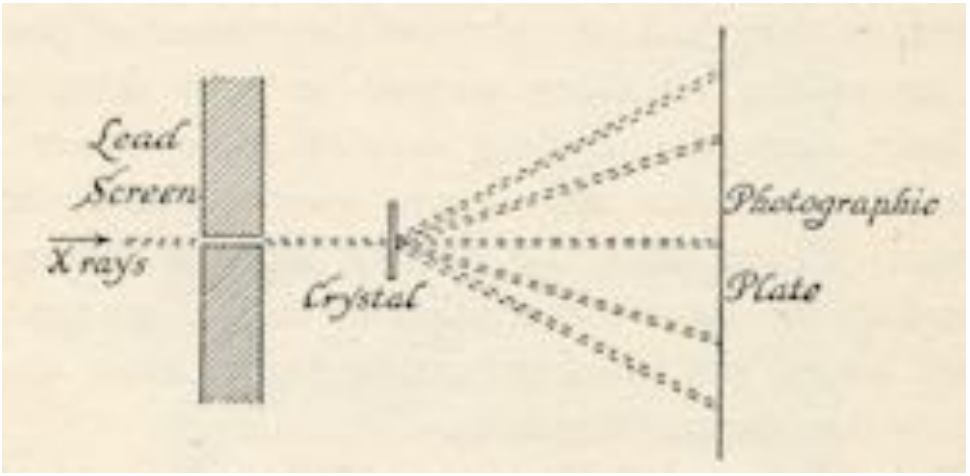

Vacuum Tube
Rotor
Anode
Cathode
Low Electric Potential
O kVp
High Electric Potential
100 kVp
Anode
Cathode
HEAT
Electron Flow
+
--
100 keV
0 keV
Kinetic Energy
X-ray

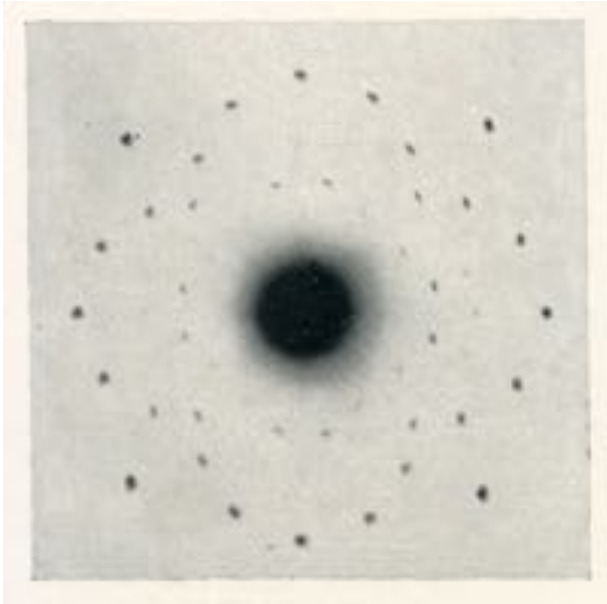


X-rays ... some kind of waves

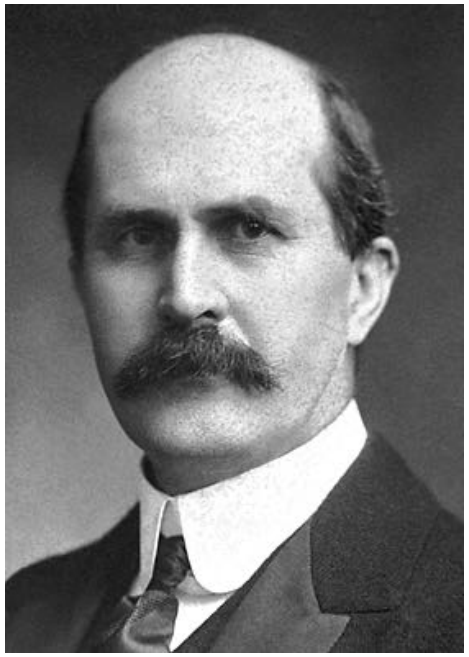


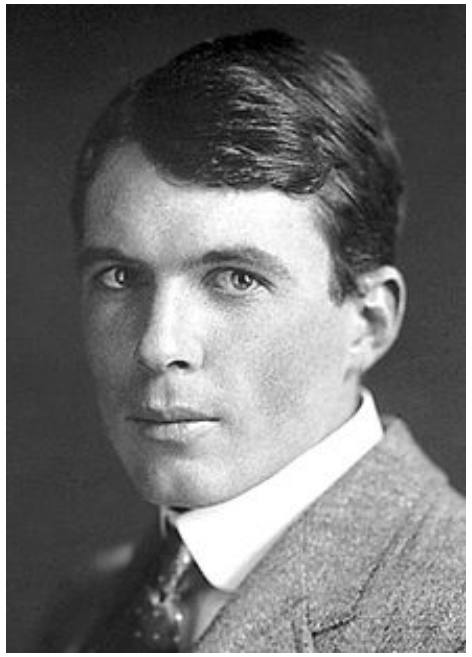
Max Von Laue (1879-1960)
Nobel Prize for Physics, 1914

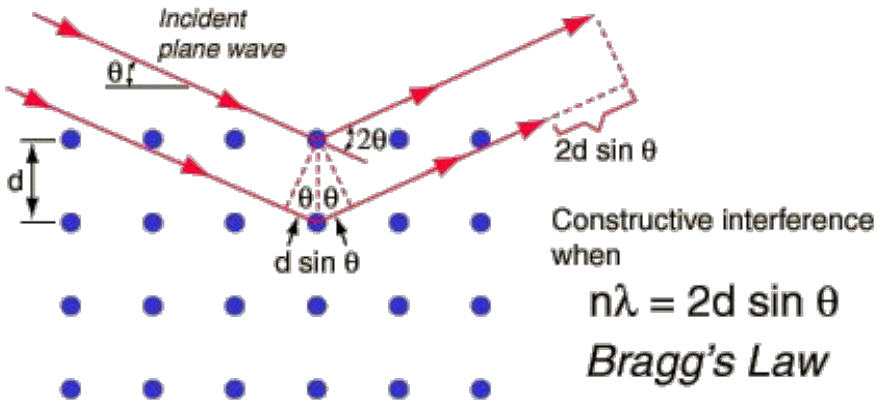




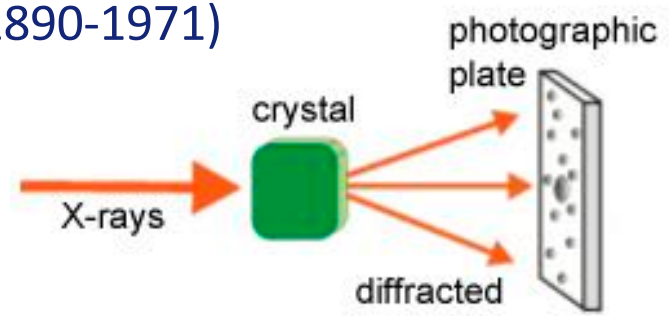
X-rays ... some kind of waves with "atomic resolution"

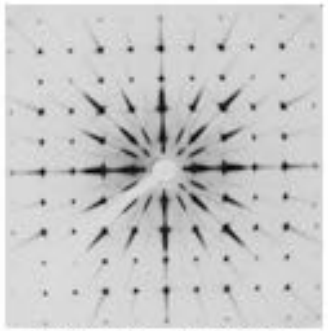




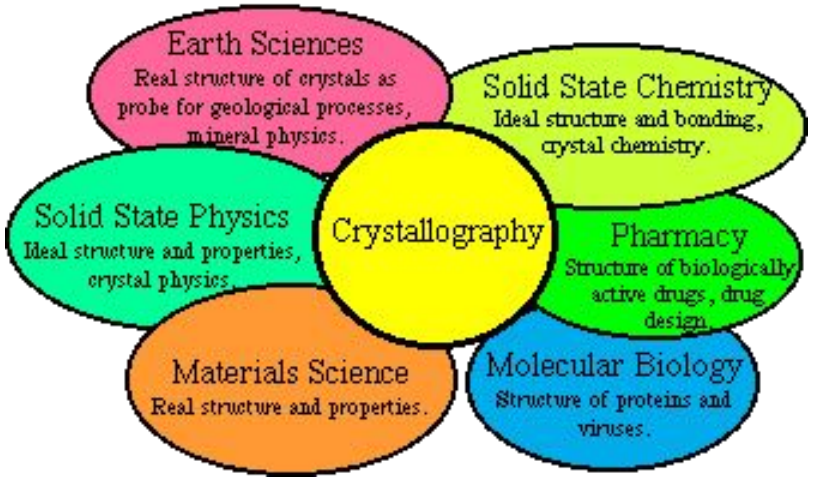


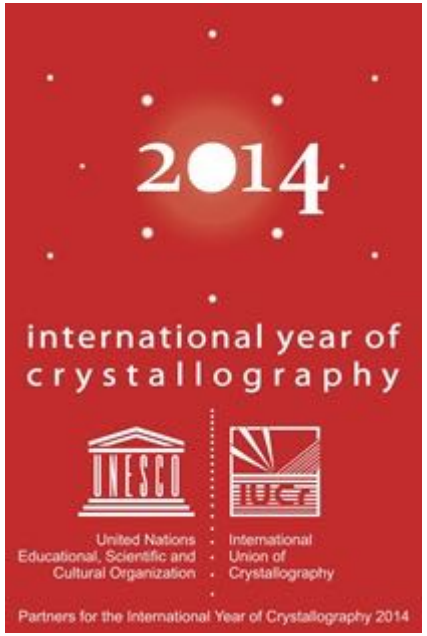
W.H. (1862-1942) and W.L. Bragg(1890-1971)
Nobel Prize for Physics, 1915





X-ray crystallography: understanding materials and living matter





X-RAY SCIENCE : 14 NOBEL PRIZES IN PHYSICS, 12 IN CHEMISTRY AND 1 IN PHYSIOLOGY AND MEDICINE

X-ray Science: Imaging, Scattering, Diffraction, Spectroscopy

PHYSICS

2002 - Riccardo Giacconi
"for pioneering contributions to astrophy

1981 - Kai M. Siegbahn
"for his contribution to the development

1961 - Rudolf Ludwig Mössbauer
"for his researches concerning the reson

1958 - Pavel Alekseyevich Cherenkov, I
"for the discovery and the interpretation

1936 - Victor Franz Hess
"for his discovery of cosmic radiation"

1927 - Arthur Holly Compton
"for his discovery of the effect n

1924 - Karl Manne Georg Sieg
"for his discoveries and research

1921 - Albert Einstein
"for his services to Theoretical Physics, a

1918 - Max Karl Ernst Ludwig Planck
"in recognition of the services he rende

1917 - Charles Glover Barkla
"for his discovery of the characteristic R

1915 - Sir William Henry Bragg and Wi
"for their services in the analysis of cryst

1914 - Max von Laue
"for his discovery of the diffraction of X-r

1905 - Philipp Eduard Anton von Lenar
"for his work on cathode rays"

1901 - Wilhelm Conrad Röntgen
"in recognition of the extraordinary servi

CHEMISTRY

2012 - Robert J. Lefkowitz and Brian K. Kobilka
"for studies of G-protein-coupled receptors"

2011 - Dan Shechtman
"for the discovery of quasicrystals"

2009 - Venkatraman Ramakrishnan, Thomas A. Steitz and Ada E. Yonath
"for studies of the structure and function of the ribosome"

2007 - Roger D. Kornberg
"for his studies of the molecular basis of eukaryotic transcription"

1976 - William N. Lipscomb
"for his studies on the structure of boranes illuminating problems of chemical bonding"

1972 - Christian B. Anfinsen
"for his work on ribonuclease, especially concerning the connection between the amino acid sequence and the biologically active conformation"

1972 - Stanford Moore and William H. Stein
"for their contribution to the understanding of the connection between chemical structure and catalytic activity of the active centre of the ribonuclease molecule"

1964 - Dorothy Crowfoot Hodgkin
"for her determinations by X-ray techniques of the structures of important biochemical substances"

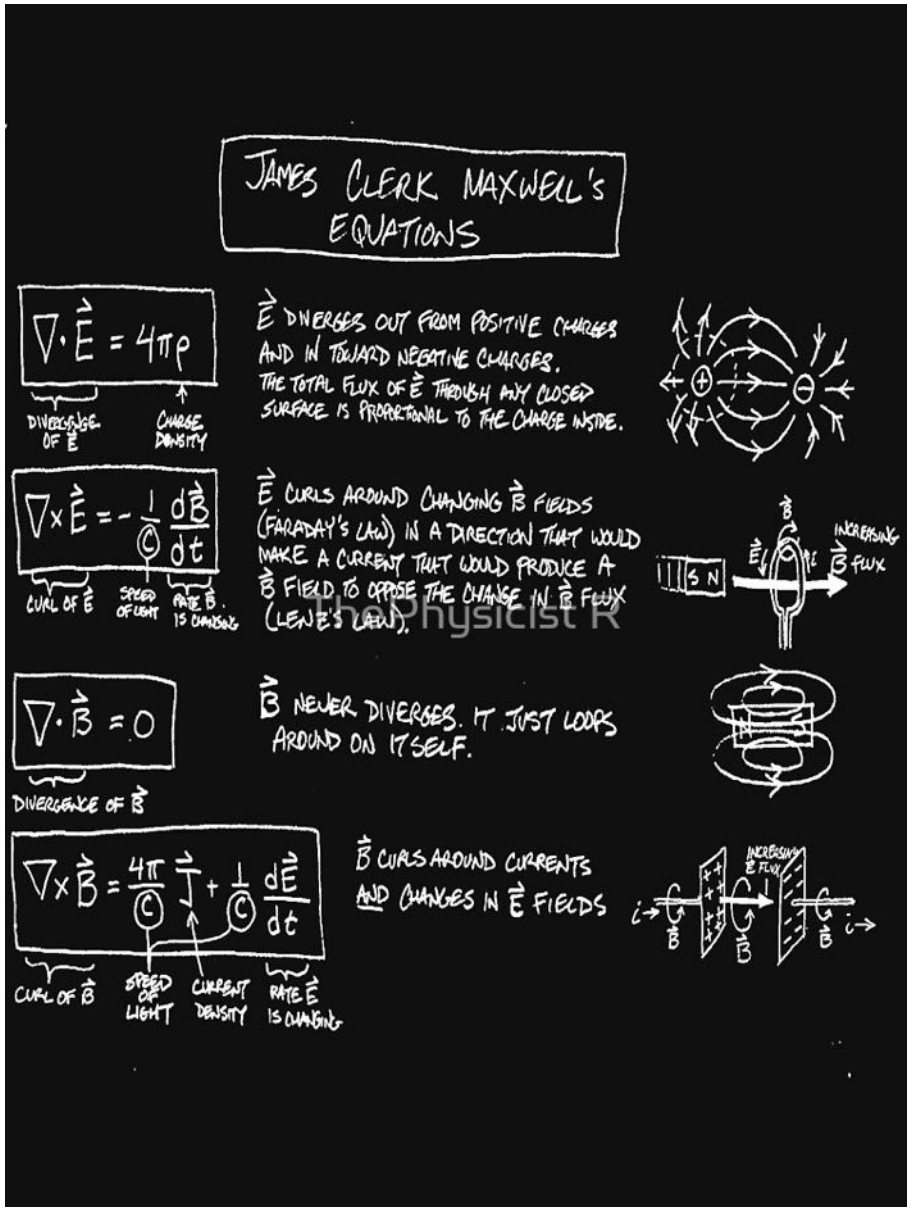
1962 - Max Ferdinand Perutz and John Cowdery Kendrew
"for their studies of the structures of globular proteins"

1936 - Petrus (Peter) Josephus Wilhelmus Debye
"for his contributions to our knowledge of molecular structure through his investigations on dipole moments and on the diffraction of X-rays and electrons in gases"

Physiology and Medicine

1962 - Francis Harry Compton Crick, James Dewey Watson and **Maurice Hugh Frederick Wilkins**
"for their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material"

UN'ATRO METODO PER LA PRODUZIONE DI RAGGI X: LA NASCITA DEGLI ACCELERATORI RELATIVISTICI DI ELETTRONI E LA PRODUZIONE DI LUCE DI SINCROTRONE



The electrodynamic theory of synchrotron radiation is entirely based on Maxwell's equations

- The foundations were laid by:
  - A. Liénard (1898)
  - G. A. Schott (1907)
  - J. Schwinger (1945)
- The theory was far in advance of the development of particle accelerators

Alfred-Marie LIENARD (1869-1958)

Dieu Electricité

Alfred-Marie LIENARD (1869-1958)

"Champ électrique et magnétique produit par une charge électrique concentrée en un point et animée d'un mouvement quelconque" L'Éclairage Électrique, 16(27), pp. 5-14 (1898)

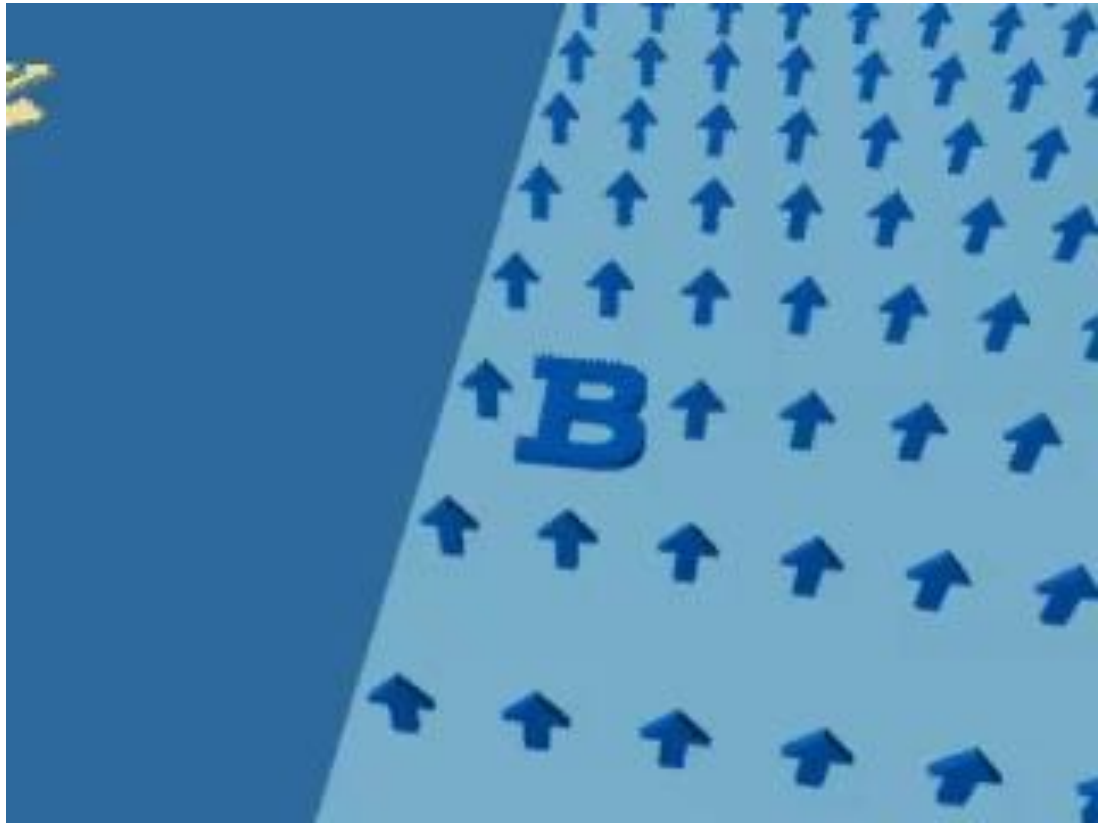
$$W = \frac{2}{3}\frac{e^2 c}{R^2}\beta^4\gamma^4$$

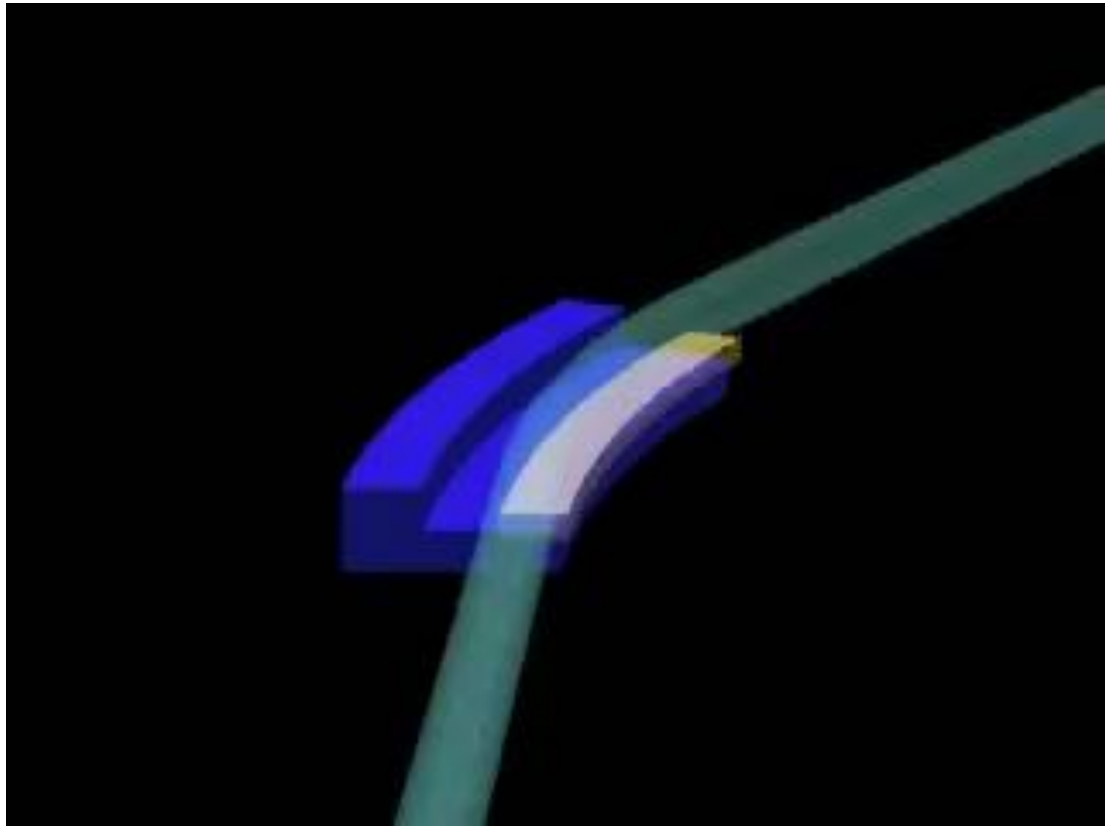
W: **la potenza (energia per unità di tempo) emessa dall'elettrone;**
c, v: **rispettivamente le velocità della luce e dell'elettrone;**
e: **la carica dell'elettrone;**
R: **il raggio di curvatura della traiettoria dell'elettrone;**

$$\vec{\beta} = \frac{\vec{v}}{c} \qquad \gamma = \frac{E}{mc^2}$$

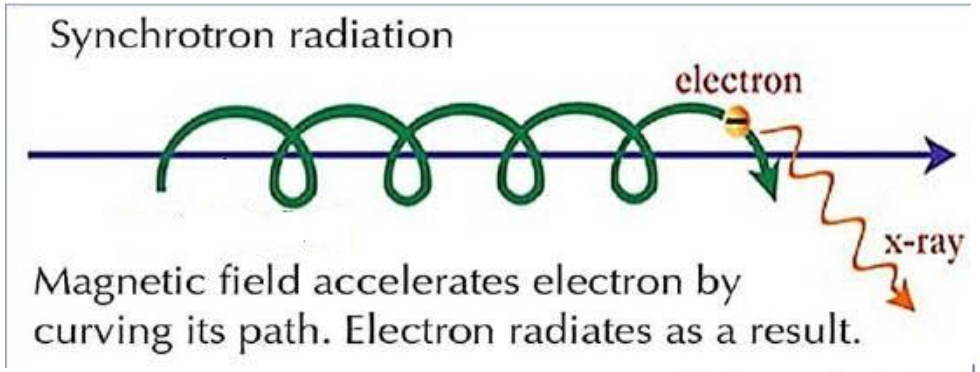
Un elettrone sottomesso ad una forza - cambiando traiettoria - perde una parte rilevante della sua energia cinetica tramite emissione di radiazione elettromagnetica (luce)

RELATIVISTIC ELECTRONS





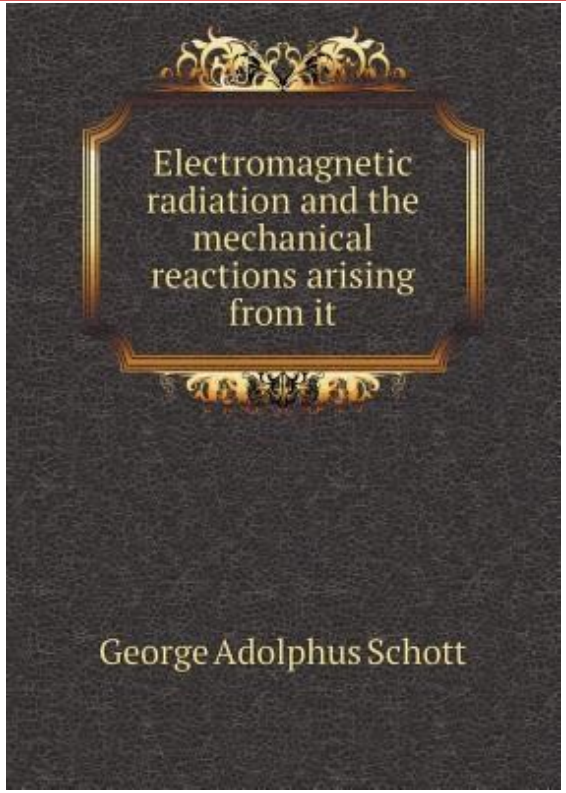
An electron submitted to a force can loose a considerable fraction of its kinetic energy by emission of light



GEORGE ADOLPHUS SCHOTT

$$I(\omega)=\frac{\sqrt{3}}{2\pi}\frac{\omega_0 e^2}{c}\left(\frac{E}{mc^2}\right)F\left(\frac{\omega}{\omega_c}\right)$$

$$F(\xi)=\xi\int_{\xi}^{\infty}K_{5/3}(\eta)\,d\eta$$



Where $\omega_c=\frac{3}{2}\omega_0\left(\frac{E}{mc^2}\right)^3$ is a critical harmonic frequency, E is the particle energy, m is the particle mass, $K_{5/3}(\eta)$ is a modified Bessel function. Plot of the function $F(\xi)$ is shown in Fig. 1. The function reaches a maximum value at 0.29 (approximately one third of the critical frequency). Approximate formulas [2] for small and large values of ξ are:

for $\xi \ll 1$

$$F(\xi)\approx 2^{2/3}\Gamma\left(\frac{2}{3}\right)\xi^{1/3}\approx 2.15\xi^{1/3} \tag{4}$$

for $\xi \gg 1$

$$F(\xi)\approx\sqrt{\frac{\pi}{2}}\xi^{1/2}\exp(-\xi)\left[1+\frac{55}{72}\frac{1}{\xi}\right] \tag{5}$$

These approximate functions are also shown in Fig. 1.

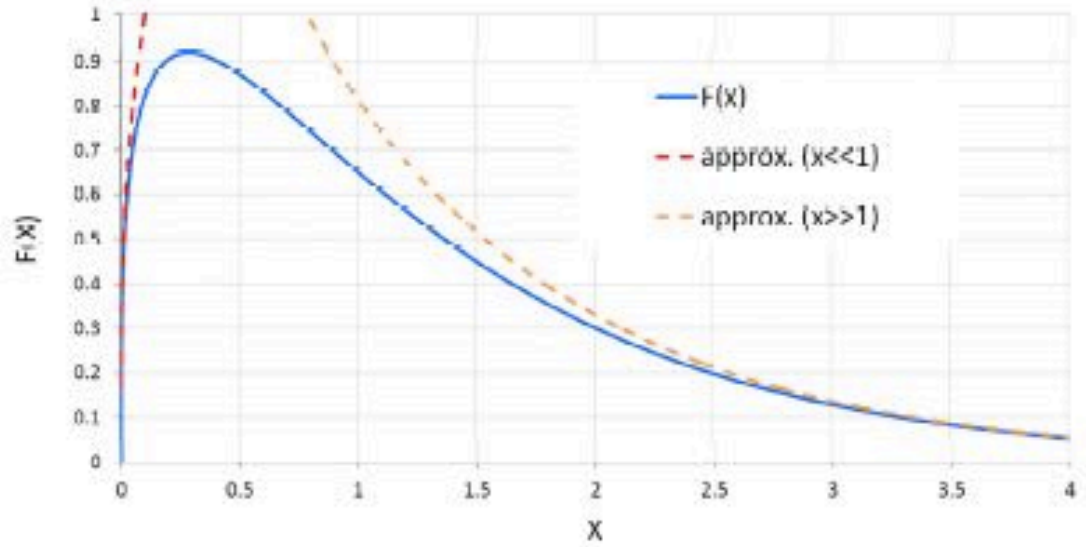
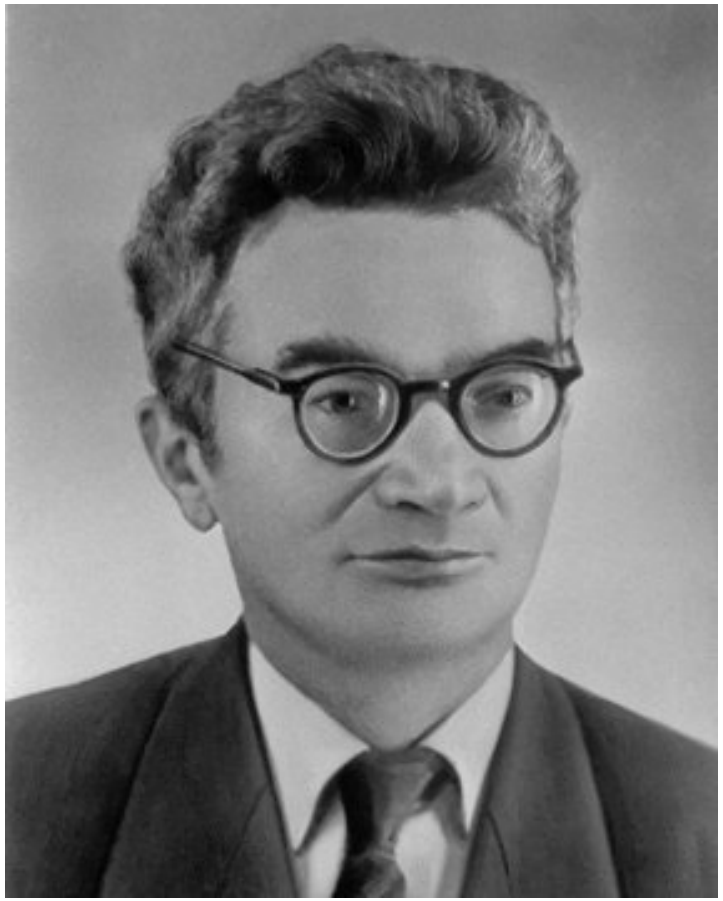


Figure 1: Function F(x) and its approximations

FIRST OBSERVATIONS



In 1943, D. IVANENKO and I. POMERANCHUK predicted the phenomenon of SYNCHROTRON RADIATION given off by relativistic electrons in magnetic fields, and that electron accelerators might be limited by radiation losses

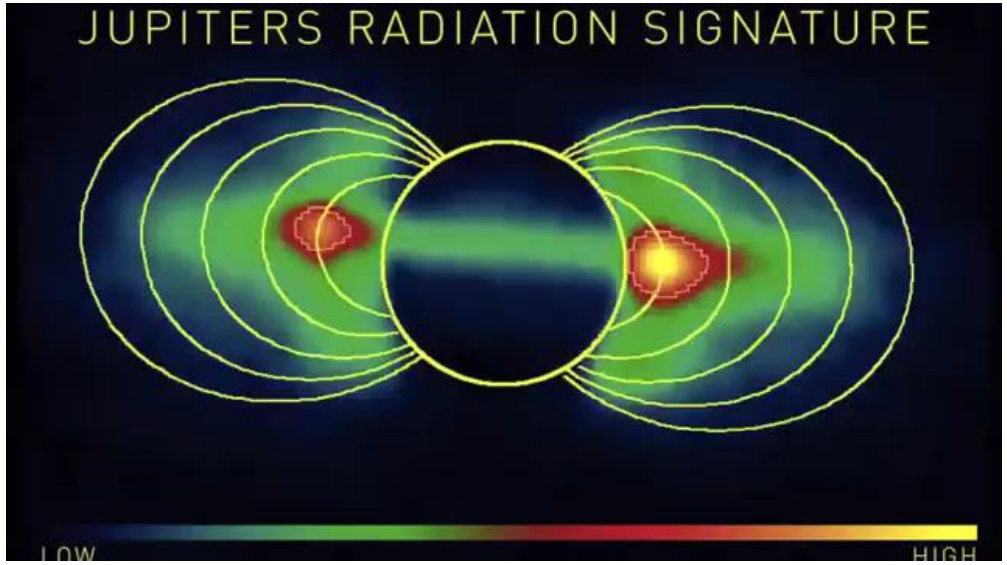
D. Iwanenko and I. Pomeranchuk, Phys. Rev. 65 (1944) 343.

Synchrotron Radiation from the Sky

Crab Nebula

Gas emission (reddish) and synchrotron radiation (bluish) generated by high energy electrons in the magnetic field of a neutron star.

Jupiter's radiation belts



Radiation belts of Jupiter: high energy electrons in the magnetic field of the planet produce synchrotron light, which reproduces the field distribution.

First Observation of Synchrotron Radiation

The General Electric team (Langmuir, Elder, Gurewitsch, Charlton and Pollock) looking at the vacuum chamber of the 70 MeV synchrotron (1947).

FIRST GENERATION; PARASITIC USE OF ACCELERATORS BUILT FOR HIGH ENERGY PHYSICS RESEARCH

Prime attività con la luce di sincrotrone in Italia.

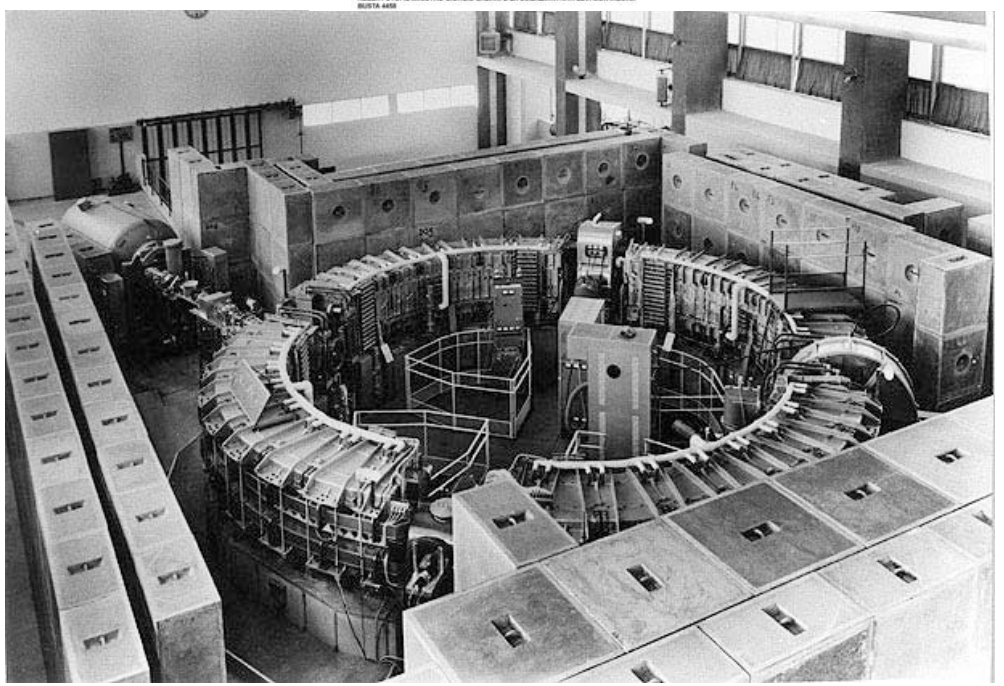
Negli anni '70 nasce il gruppo "Solidi Roma" di giovani scienziati che convergono presso i LNF interessati a sviluppare la nuova spettroscopia X dei solidi.

Il gruppo è formato da Antonio Bianconi, Emilio Burattini, Adalberto Balzarotti, e Mario Piacentini.

Il Prof. Edoardo Amaldi dell'Università di Roma, fondatore e dirigente dell'INFN, sostiene e promuove il progetto.

Giancarlo Chiarotti e Franco Bassani sono i "mentori" del gruppo "Solidi Roma".

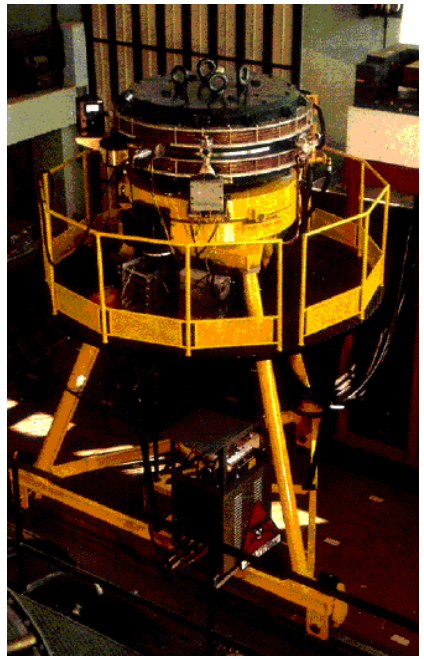
Giorgio Salvini (qui con il premio Nobel 1986 per la Medicina e la Fisiologia, Rita Levi-Montalcini) il "papà dell''elettrosincrotrone idi Frascati, il primo acceleratore circolare costruito in Italia.



Febbraio 1959: L'elettrosincrotroe in funzione; in alto a sinistra l'iniettore

Conventional X-ray Sources and Synchrotron Radiation

Storage Ring, 1961-1964
Key Time for Synchrotron Radiation
First Generation SR Sources



ADA in Frascati (INFN),
the first storage ring for electron and positron beams rotating in opposite Directions.
Proposed by **Bruno Touschek (1921-1978), in 1960**

Anello Di Accumulazione: ADA - 1961

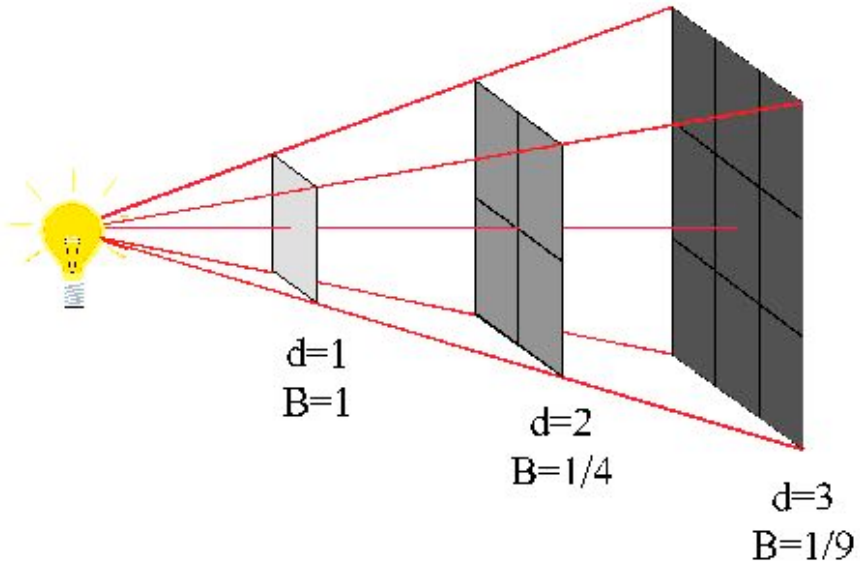
The impact of the ADA Collider has been immense in enabling a new chapter of accelerator physics to be established with the machine being the **first particle-antiparticle collider and the first electron-positron storage ring.**

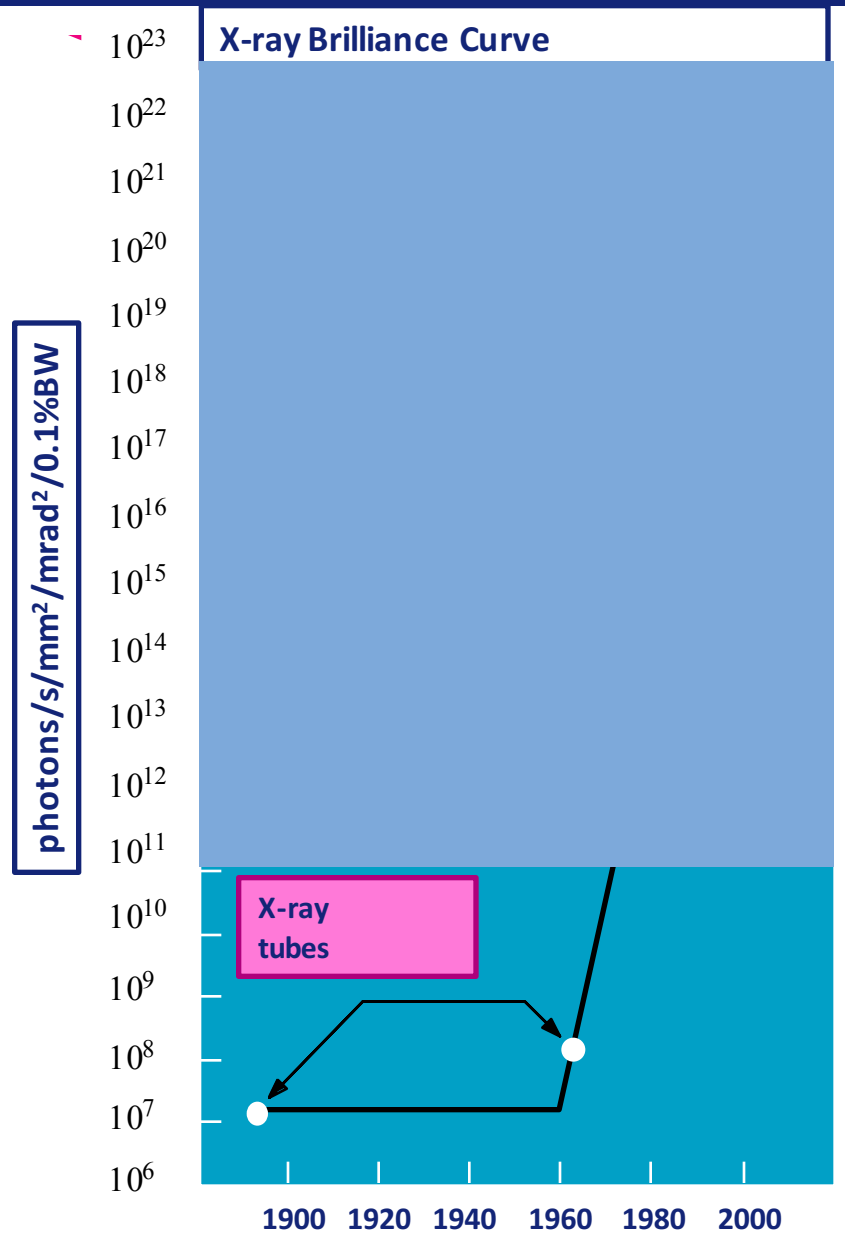
X-RAY SOURCES: TUBES

Conventional X-ray Sources

Source Brilliance:
Number of photons normalized to

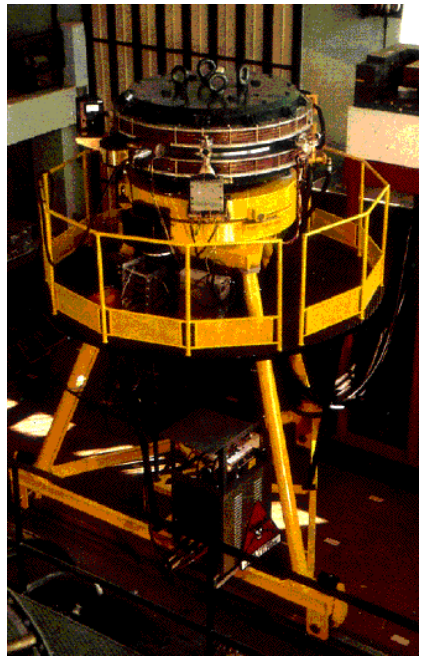
- Unit time
- Transverse source area
- Source emission angle
- Frequency bandwidth





Conventional X-ray Sources and Synchrotron Radiation

Storage Ring, 1961-1964
Key Time for Synchrotron Radiation
First Generation SR Sources



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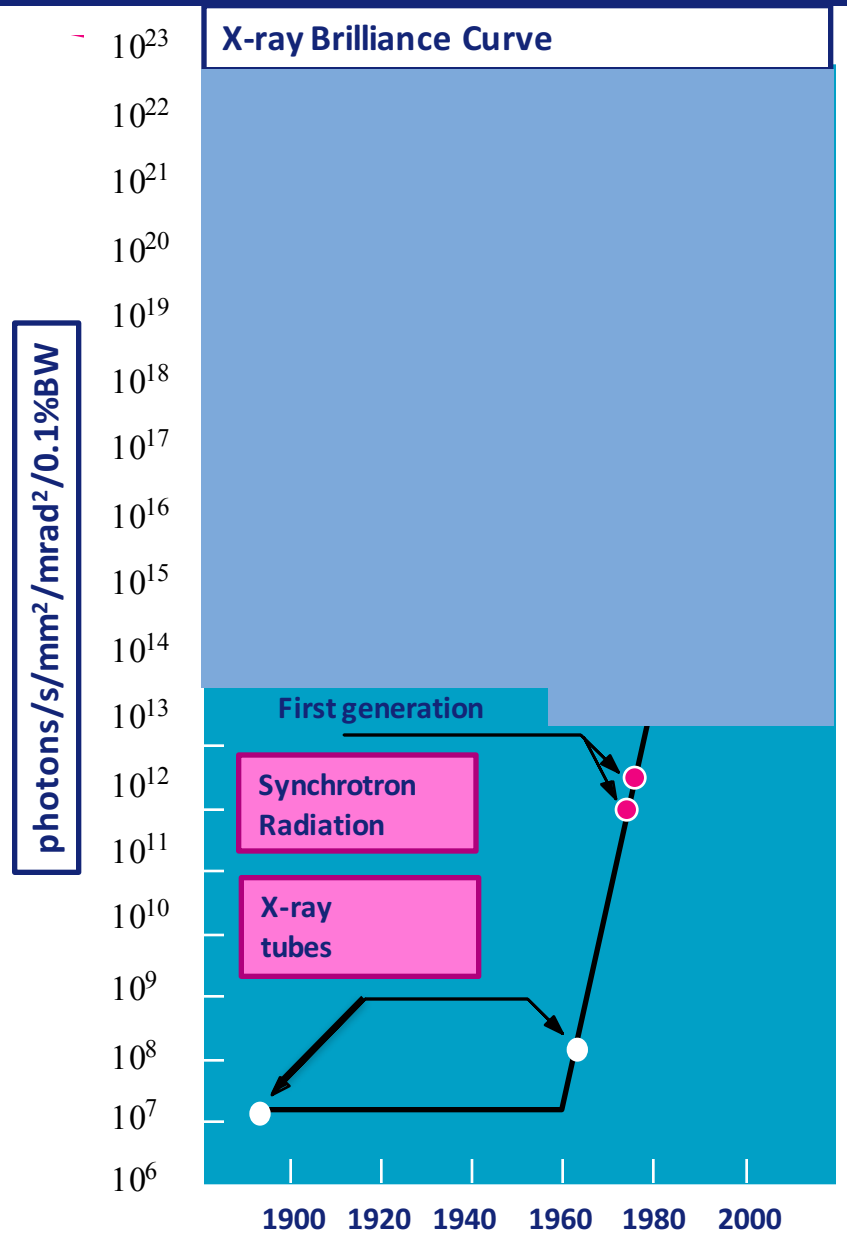
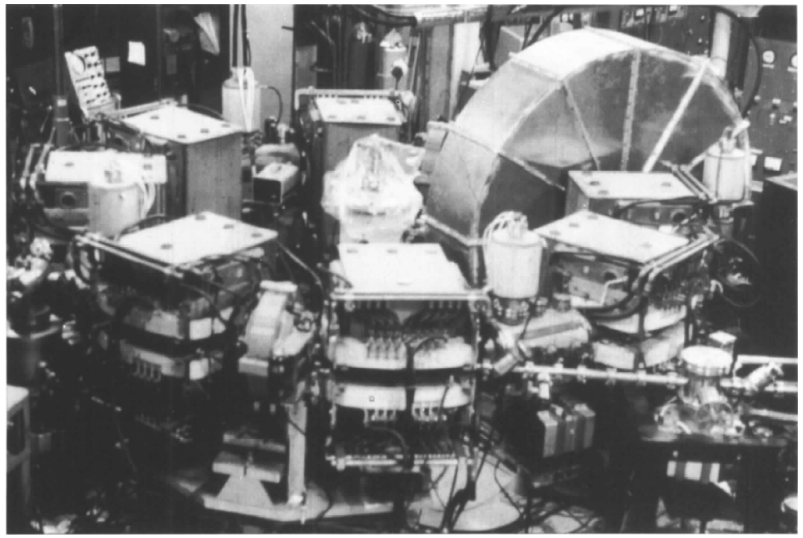
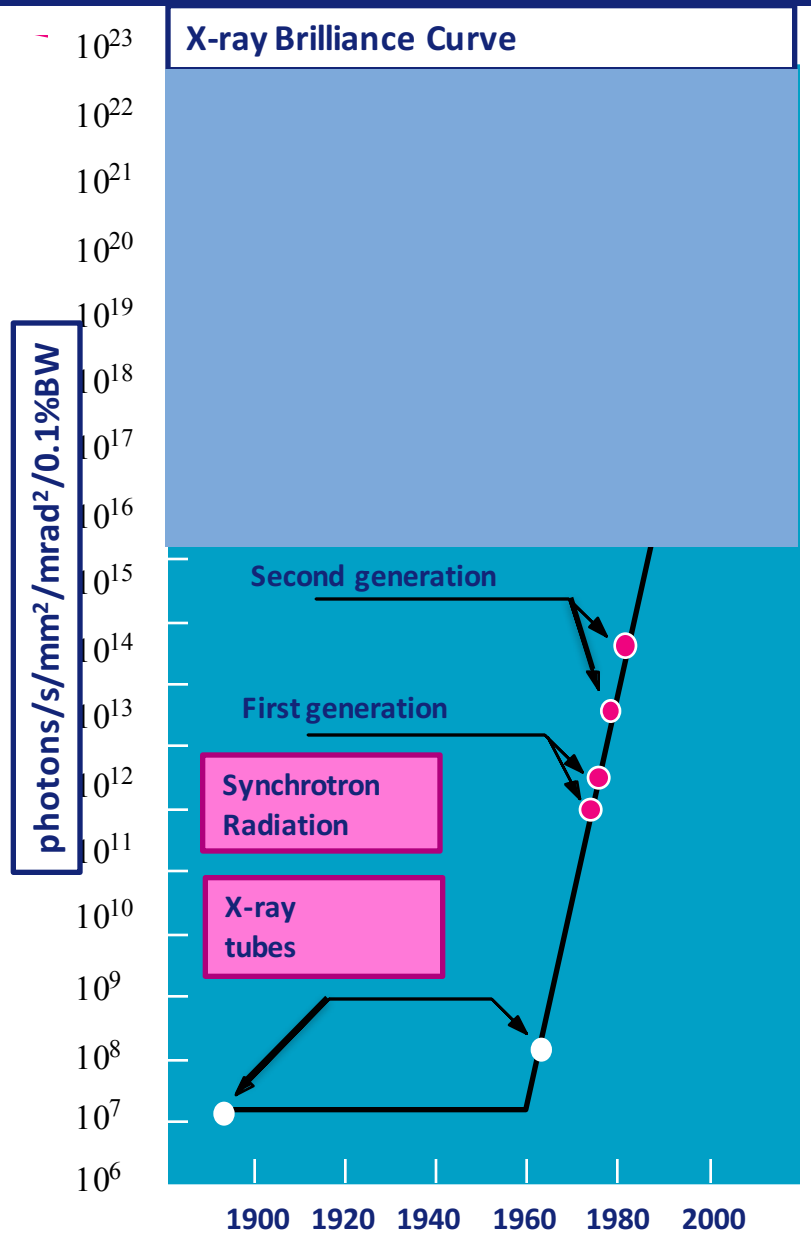


Conventional X-ray Sources and Synchrotron Radiation

Tantalus – University of Wisconsin
The first dedicated source of Synchrotron Radiation, 1968
Second Generation SR Sources



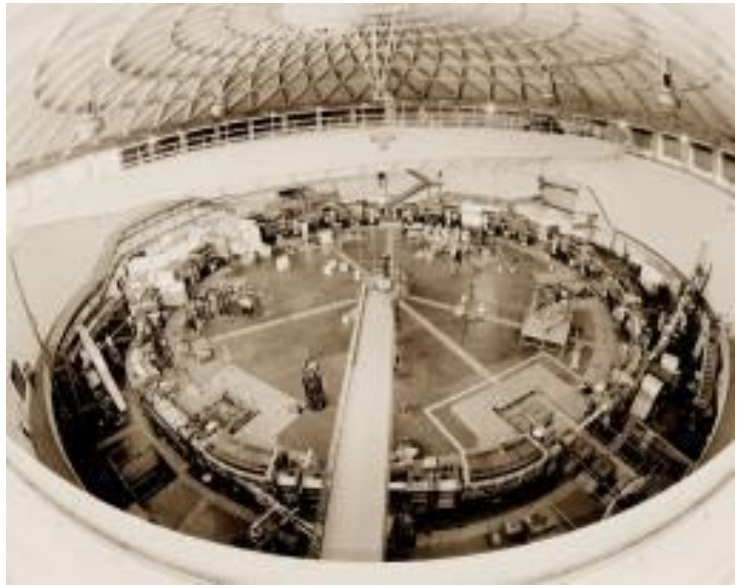


PULS – ADONE

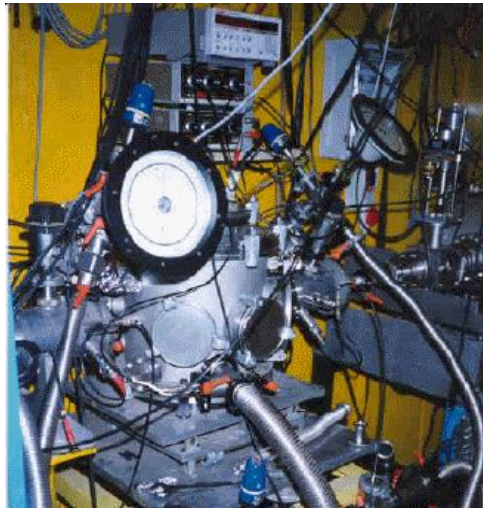
Nel 1974 viene proposto da **A. Balzarotti, A. Bianconi, E. Burattini e M. Piacentini** un progetto nazionale CNR “Progetto per l'Utilizzazione della Luce di Sincrotrone” (PULS) presso Adone e si chiede a **Franco Bassani** di esserne il direttore. **Il progetto è approvato e viene stipulata una convenzione tra il CNR e l’INFN per una “facility” nazionale di radiazione di sincrotrone aperta a tutta la comunità scientifica italiana a Frascati.**

Il progetto PULS del CNR inizia nel 1977

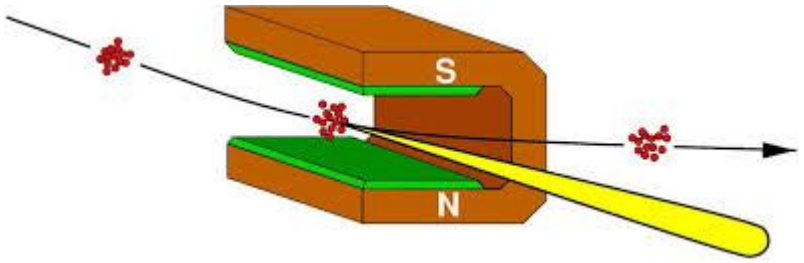
Il collisore elettrone- positrone ADONE di Frascati



Apparato XAFS di Spettroscopia X al PULS di Frascati



Second generation synchrotron sources
Bending magnet radiation optimized



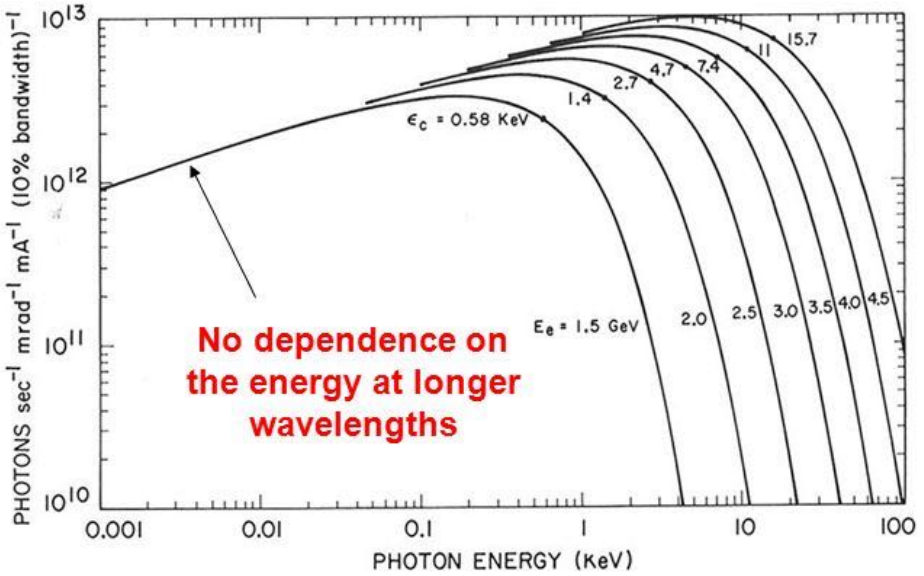
$$W = \frac{2}{3}\frac{e^2 c}{R^2}\beta^4\gamma^4$$

$$\vec{\beta} = \frac{\vec{v}}{c}$$

$$\gamma = \frac{E}{mc^2}$$

Synchrotron radiation emission from a bending magnet

Dependence of the frequency distribution of the energy radiated via synchrotron emission on the electron beam energy



Critical frequency

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

Critical angle

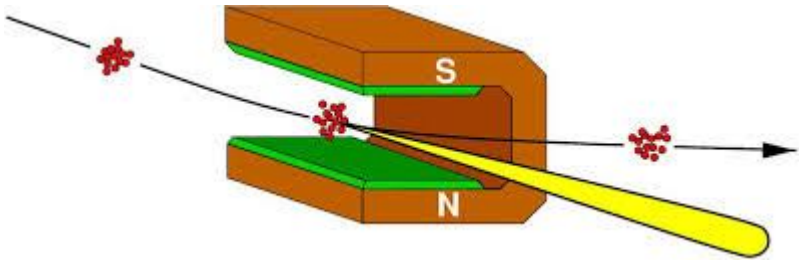
$$\theta_c = \frac{1}{\gamma}\left(\frac{\omega_c}{\omega}\right)^{1/3}$$

Critical energy

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

R. Bartolini, John Adams Institute, 13 November 2014 10/29

Second generation synchrotron sources
Bending magnet radiation optimized



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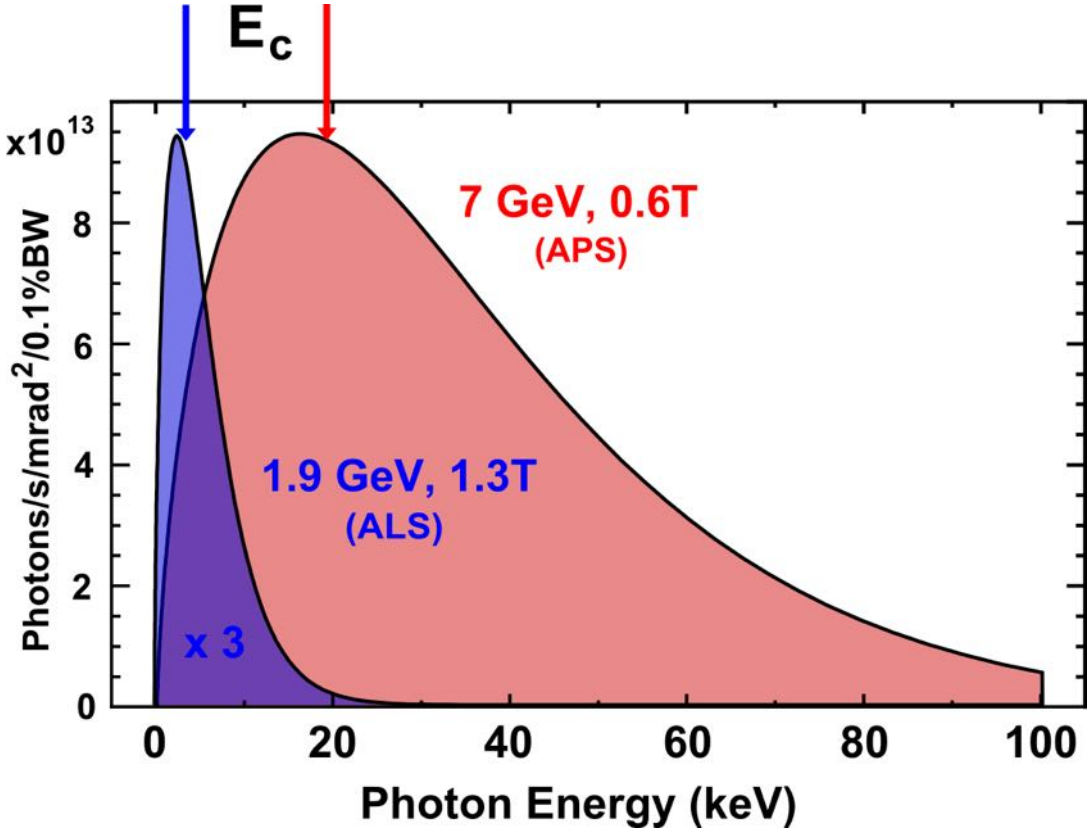
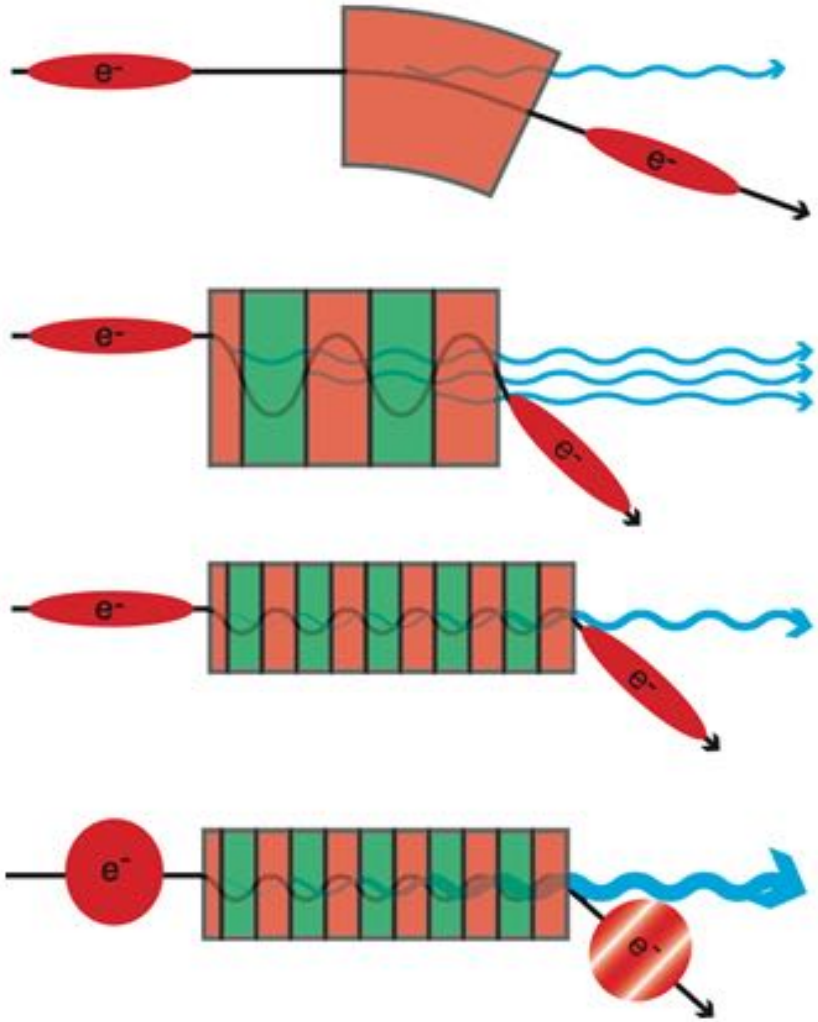


TO THE NEXT GENERATIONS X-RAY SOURCES



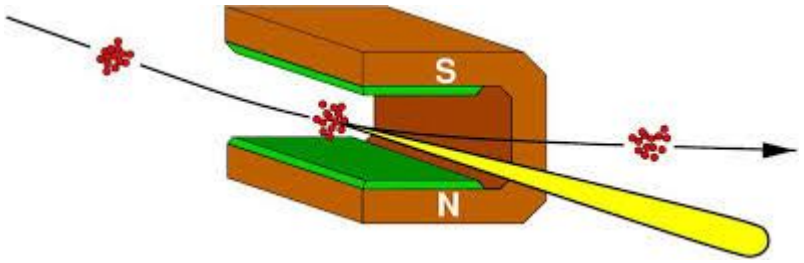
Dipole: I ~ #electrons ← Bending Magnet Radiation

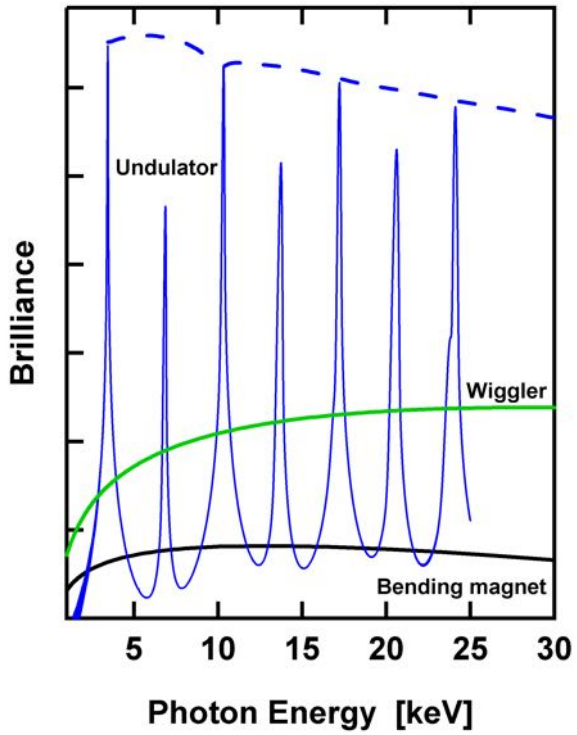
Wiggler: I ~ #poles*#electrons ← Wiggler Radiation

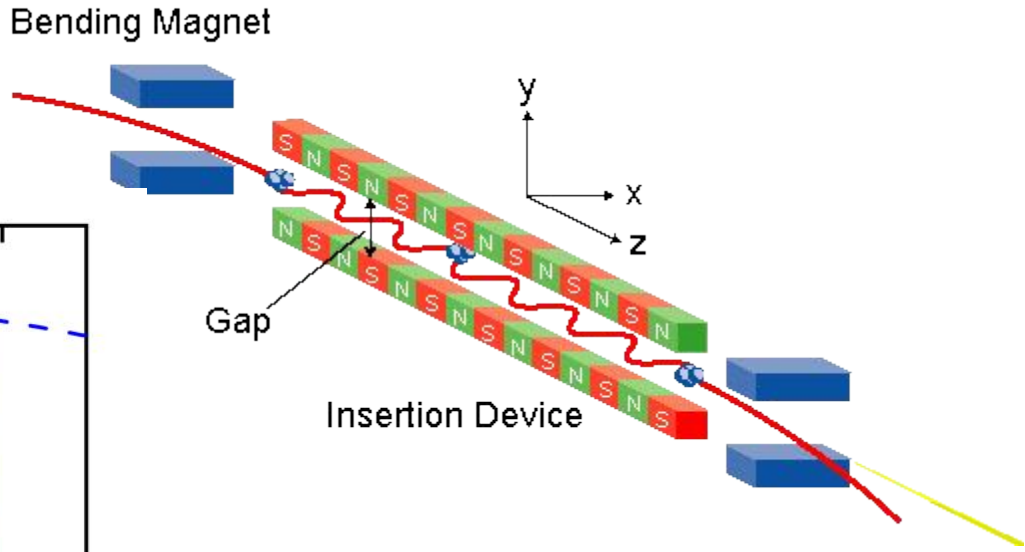
Undulator: I ~ #poles^2*#electrons ← Undulator Radiation

FEL: I ~ #poles^2*#electrons^2 ← SASE FEL Radiation

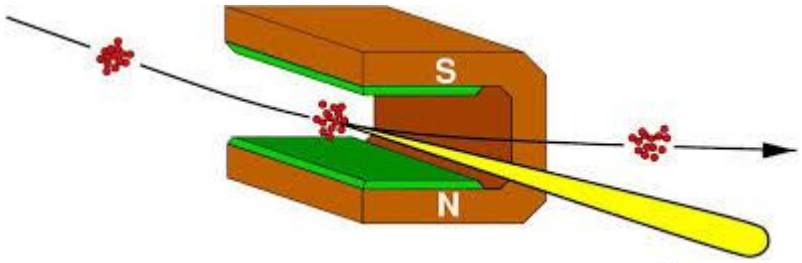
From second to third generation synchrotron sources
From bending magnet to undulator radiation

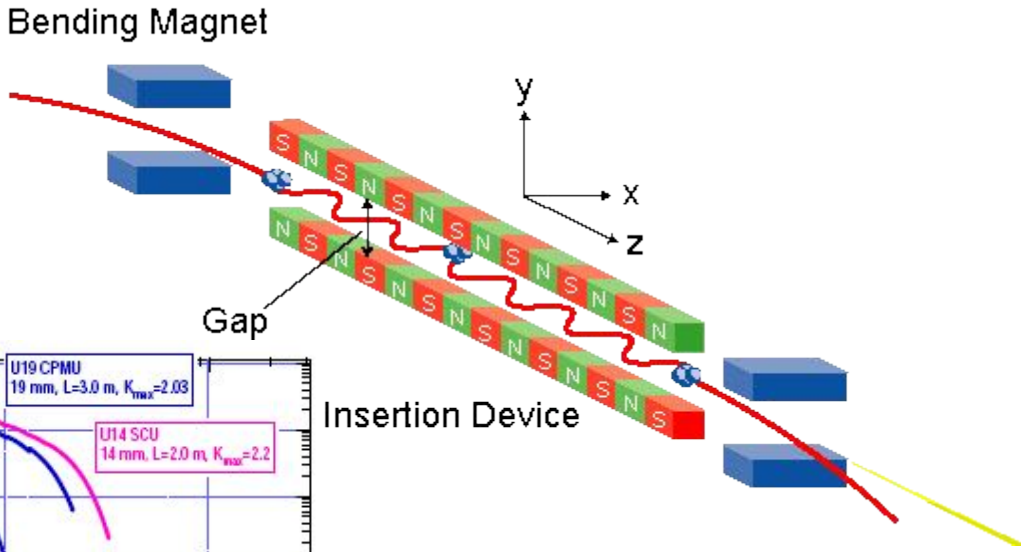






From second to third generation synchrotron sources
From bending magnet to undulator radiation





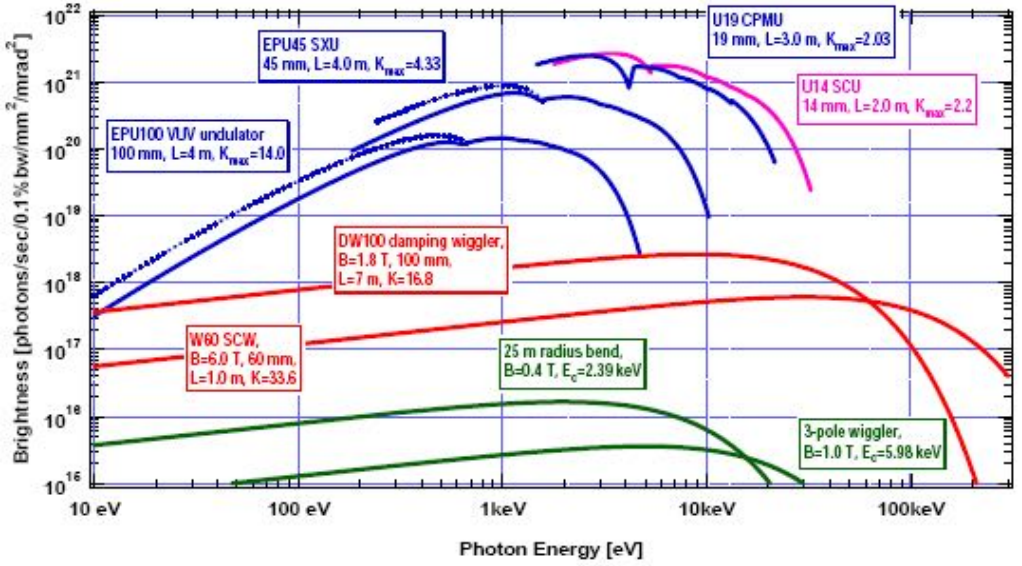
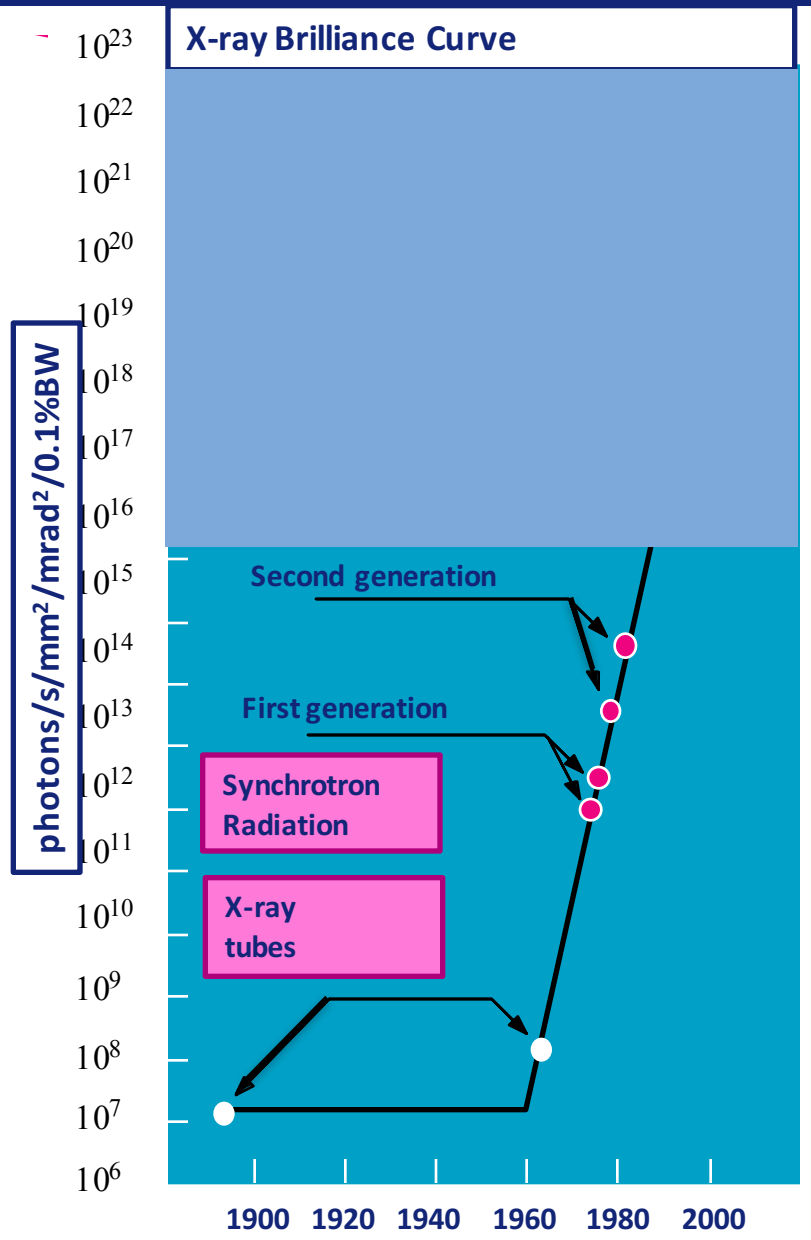


Figure 1. Brightness vs. photon energy for various devices at NSLS-II.

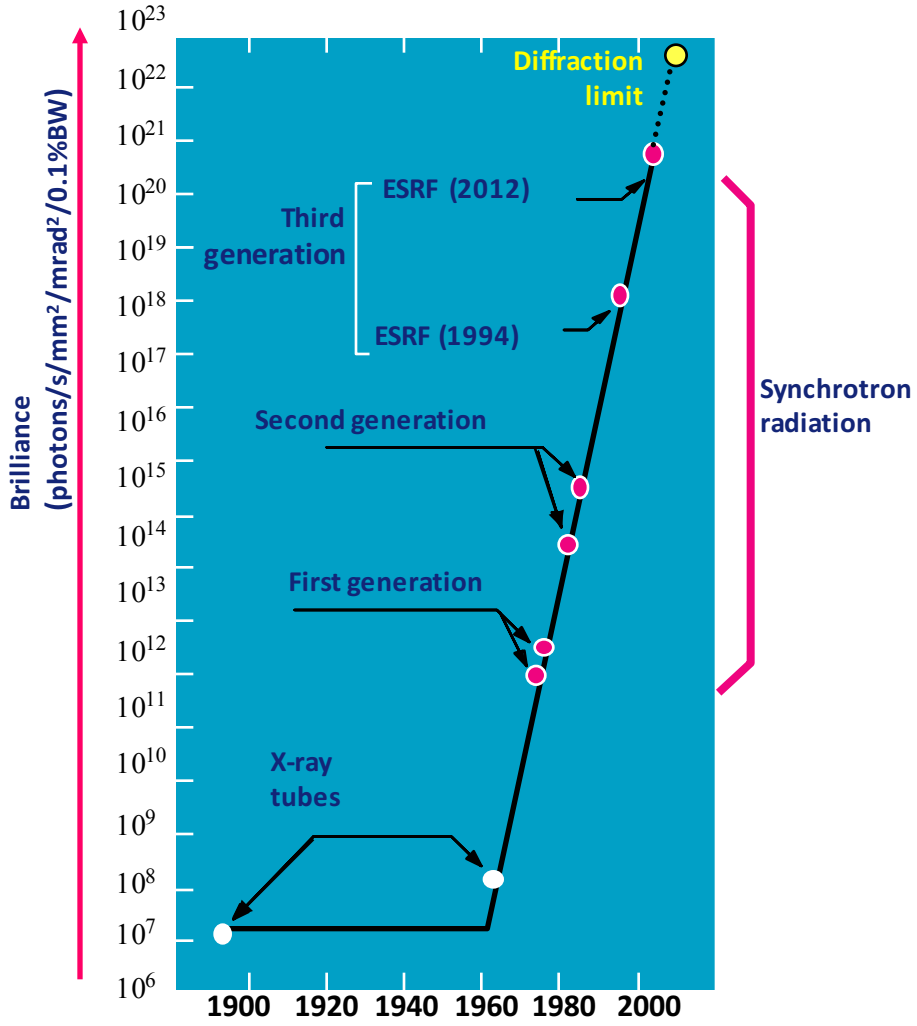
Conventional X-ray Sources and Synchrotron Radiation

Chasman-Green Lattice
Brookhaven, 1975
The way to very low vertical emittance storage rings, and to very high brightness
Third Generation SR Sources
ESRF 1992

Average Brilliance ~100 000 000 000 more than a Laboratory Source



A VERY BRILLIANT LIGHT



Remarkable properties of synchrotron light

- Brilliance
- Coherence
- Pulsed emission
  (duration of a flash: 50 ps)

Moreover:

- Flux
- Polarisation
- Beam stability

Major synchrotrons in the world

2009 – PETRA III – 6 GeV

1996 – Advanced Photon Source - 7 GeV

1994 – European Synchrotron Radiation Facility – 6 GeV

1997 – Super Photon RING 8 GeV

ELETTRA: THE ITALAIN THIRD GENERATION SYNCHROTRON SOURCE

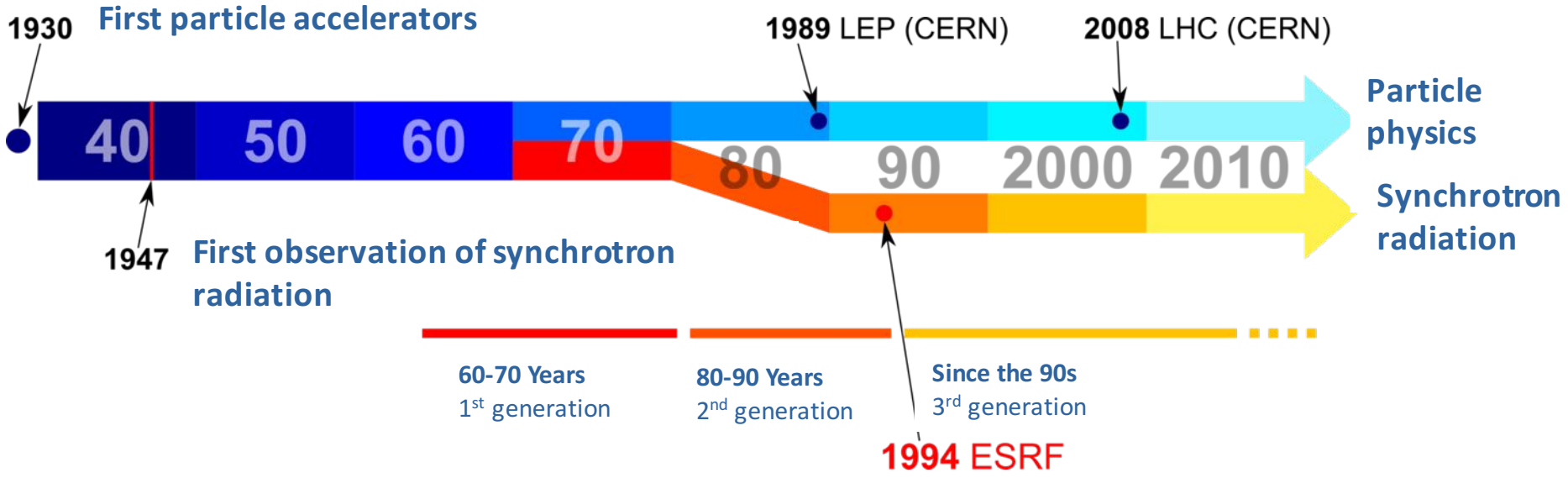
Elettra Sincrotrone Trieste

Elettra - Sincrotrone Trieste - is a multidisciplinary international research center, specialized in generating high quality synchrotron and free-electron laser light and applying it in materials science.

Its mission is to promote cultural, social and economic growth through:

- Basic and applied research;
- Technical and scientific training;
- Transfer of technology and know-how.

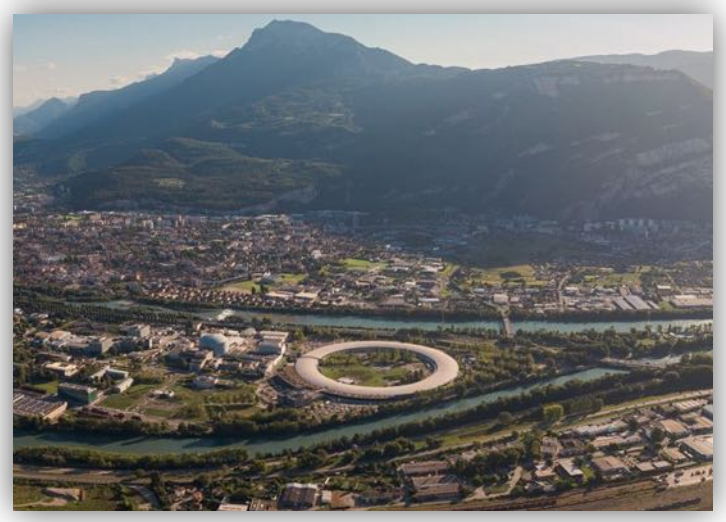
HISTORY OF THE SYNCHROTRON SOURCES



1947: First observation of synchrotron radiation at General Electric (USA).

1994 - *ESRF (France)*

A QUESTION OF SCALE



- **CERN**

The large hadron collider: circumference of 27 km

13 TeV protons on two opposite trajectories

Construction:
~ 13 billion euro

Operation/year cost:
~ 700 million euros

- **ESRF**

The storage ring for synchrotron light: circumference of 844 m

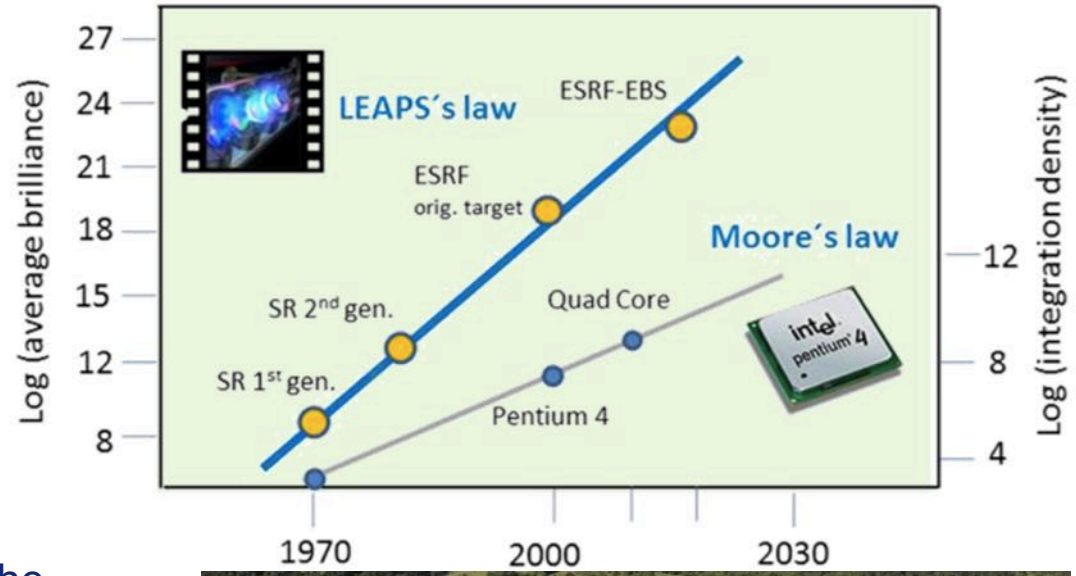
6 GeV electrons

Construction cost:
~ 700 million euro

Operation/year cost:
~ 80 million euros

IMPACT OF SYNCHROTRON LIGHT SOURCES IN EUROPE

- Europe: Pioneer of synchrotron science since the invention of the storage ring (Frascati – 1963)
- 1970s to 90s: Powerful programme at 2nd generation synchrotrons: BESSY – Berlin, HASYLab – Hamburg, LURE – Paris, MAX – Lund; NINA – Daresbury; PULS – Frascati
- **1994: Inauguration of the ESRF, the first third-generation synchrotron, and opening of a new page in X-ray science**
- 1990s to nowadays: the ESRF success and technology drives the construction of eleven very performing synchrotron facilities in Europe, and the building up of a Users Community of 24 000 scientists
- 2013: ESRF-EBS storage ring lattice concept opens a new horizon for future 4th-generation synchrotron sources, which mobilizes the SR world
- 2016: Inauguration of MAX IV, the first fourth generation synchrotron
- **2020: Inauguration of the ESRF-EBS, Extremely Brilliant Source: Opening of a new page for X-ray science**



Elettra Sincrotrone Trieste

ESRF
The European Synchrotron

Grazie dell'attenzione!

Domande?