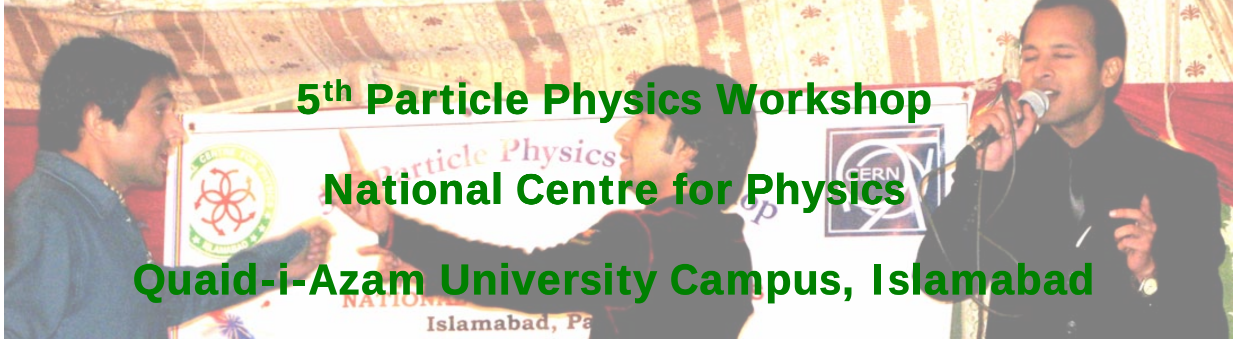


PARTICLE BEAMS,
TOOLS FOR MODERN SCIENCE AND MEDICINE

Hans-H. Braun, CERN

2nd Lecture

Examples of Modern Applications and their Technological Challenges

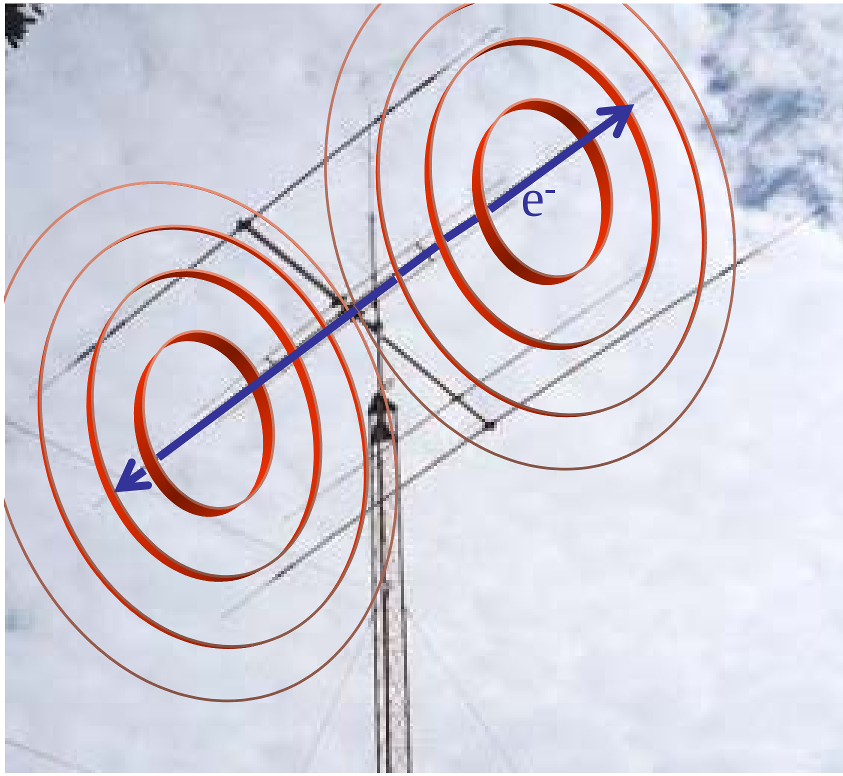
o Synchrotron Radiation,
from Nuisance to Bright Light

o Beams for Medicine

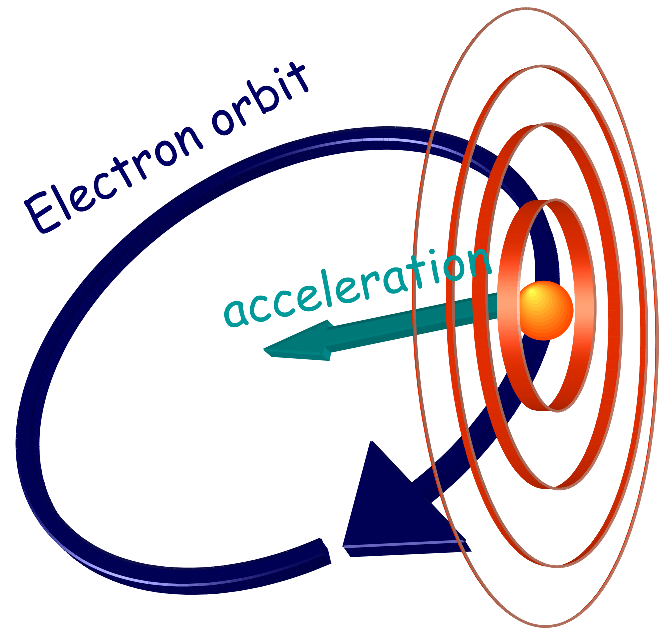
o Particle Accelerators for Particle Physics

Synchrotron Radiation

Antenna



Synchrotron

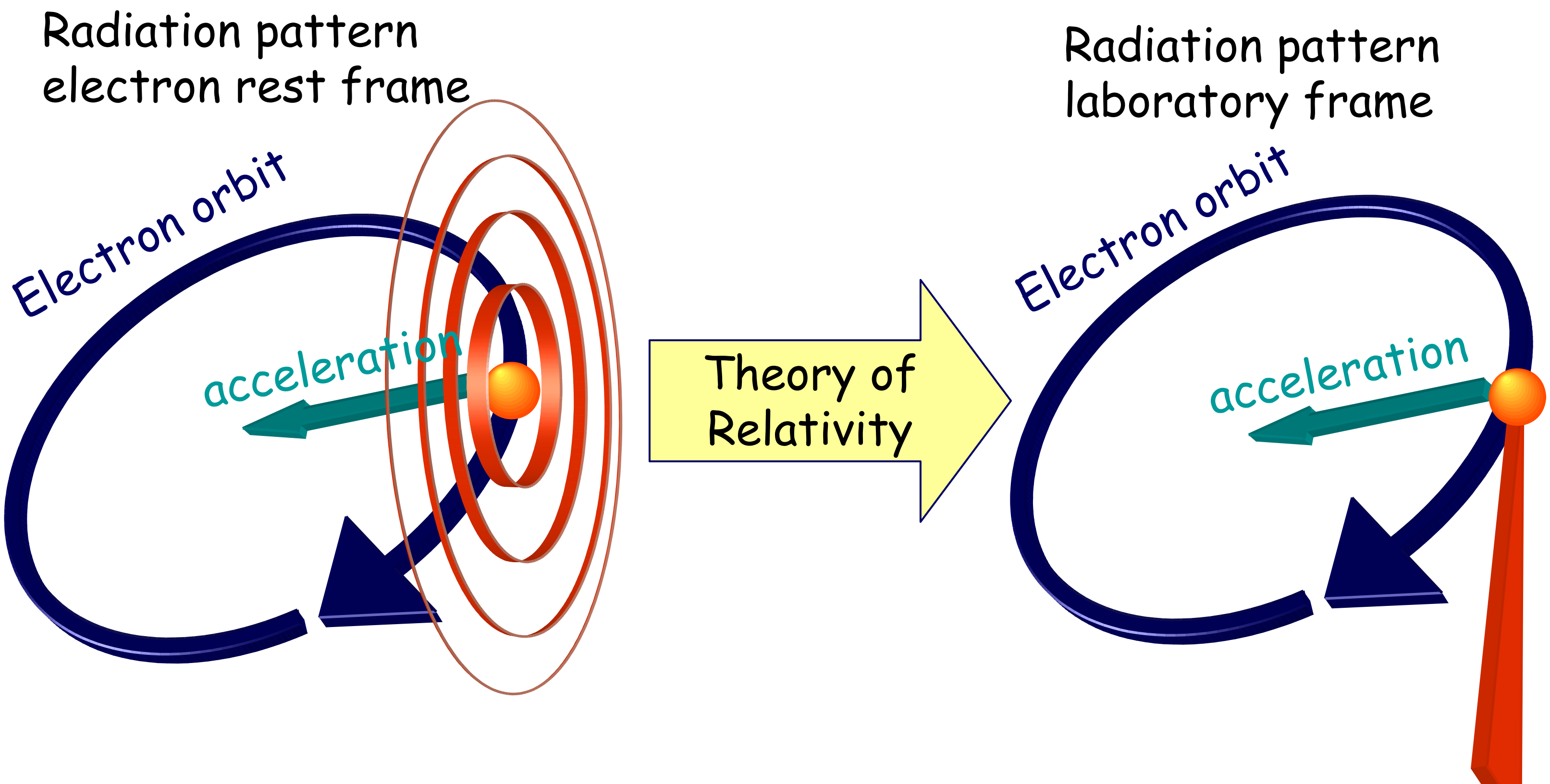


Maxwell Equations:

Varying electric currents $\Rightarrow$ electromagnetic radiation.

Microscopic scale:

Varying electric currents $\Leftrightarrow$ Acceleration/Deceleration of electrons



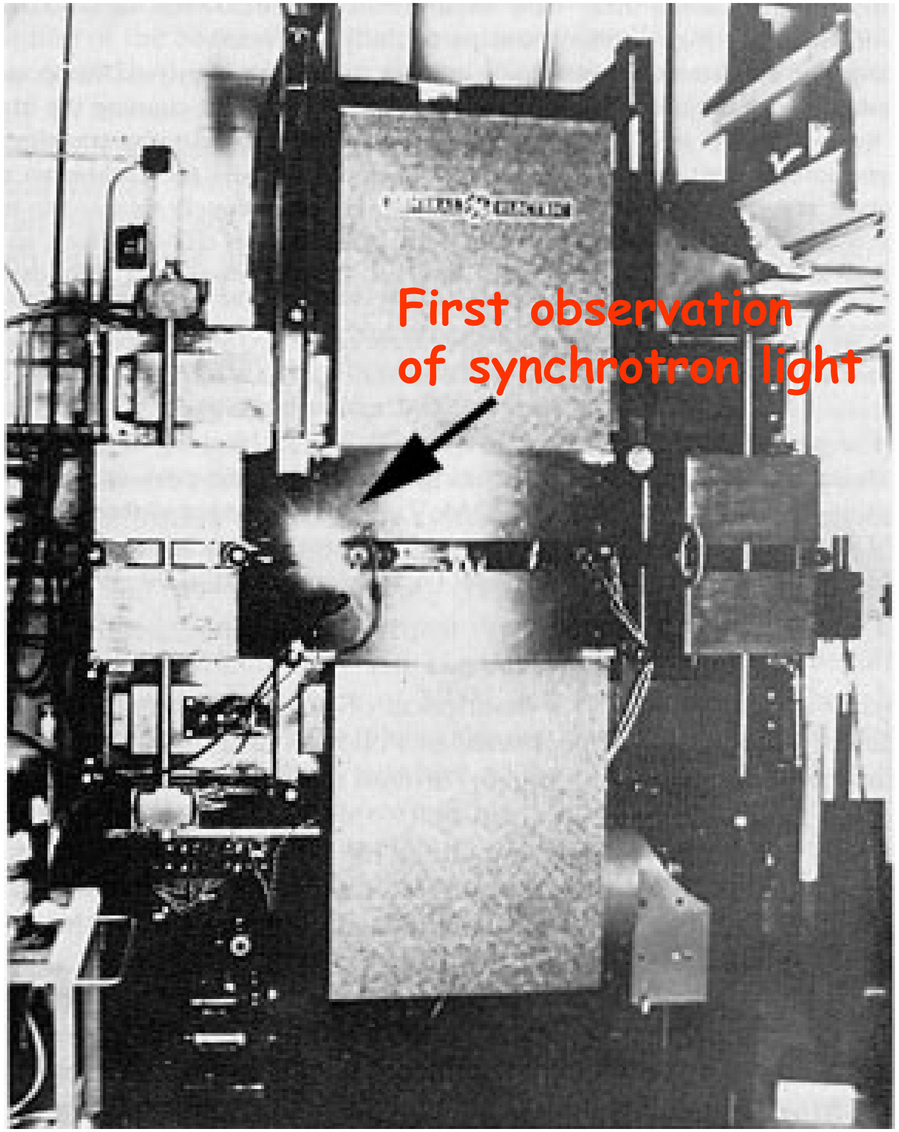
Radiation from charges with velocity close to light velocity gets “Lorentz boost”

$\Rightarrow$ Radiation is concentrated in a forward cone with opening angle

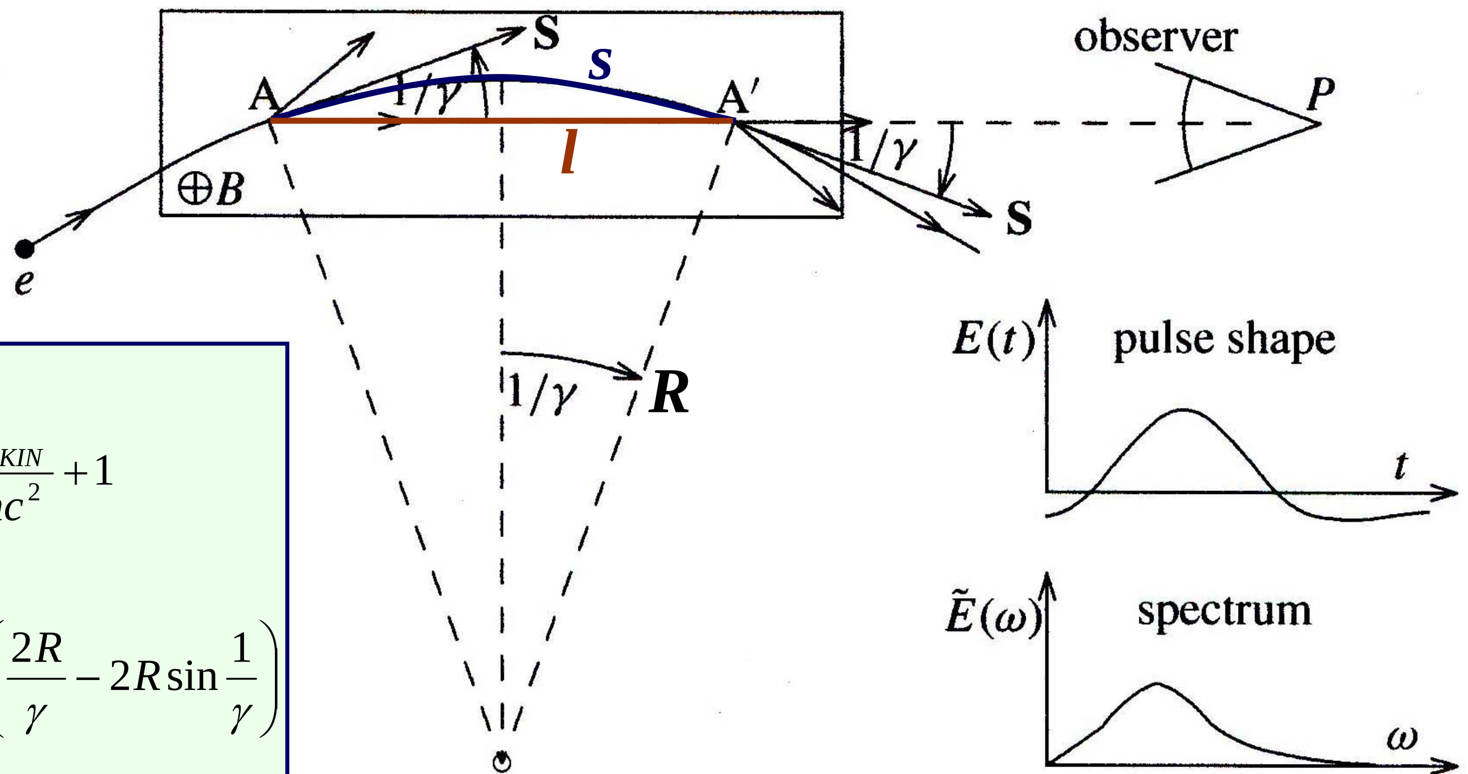
$$\phi = \sqrt{1-\frac{v^2}{c^2}} = \frac{1}{\gamma}$$

Example: $E_{Electron} = 100\,\text{MeV}\,, \quad mc^2 = 0.511\,\text{MeV}, \quad v = 0.999987 \cdot c = 299788544\ \text{m/s}$

$$\Rightarrow \quad \phi = 0.3^0$$



General Electric Synchrotron
1947



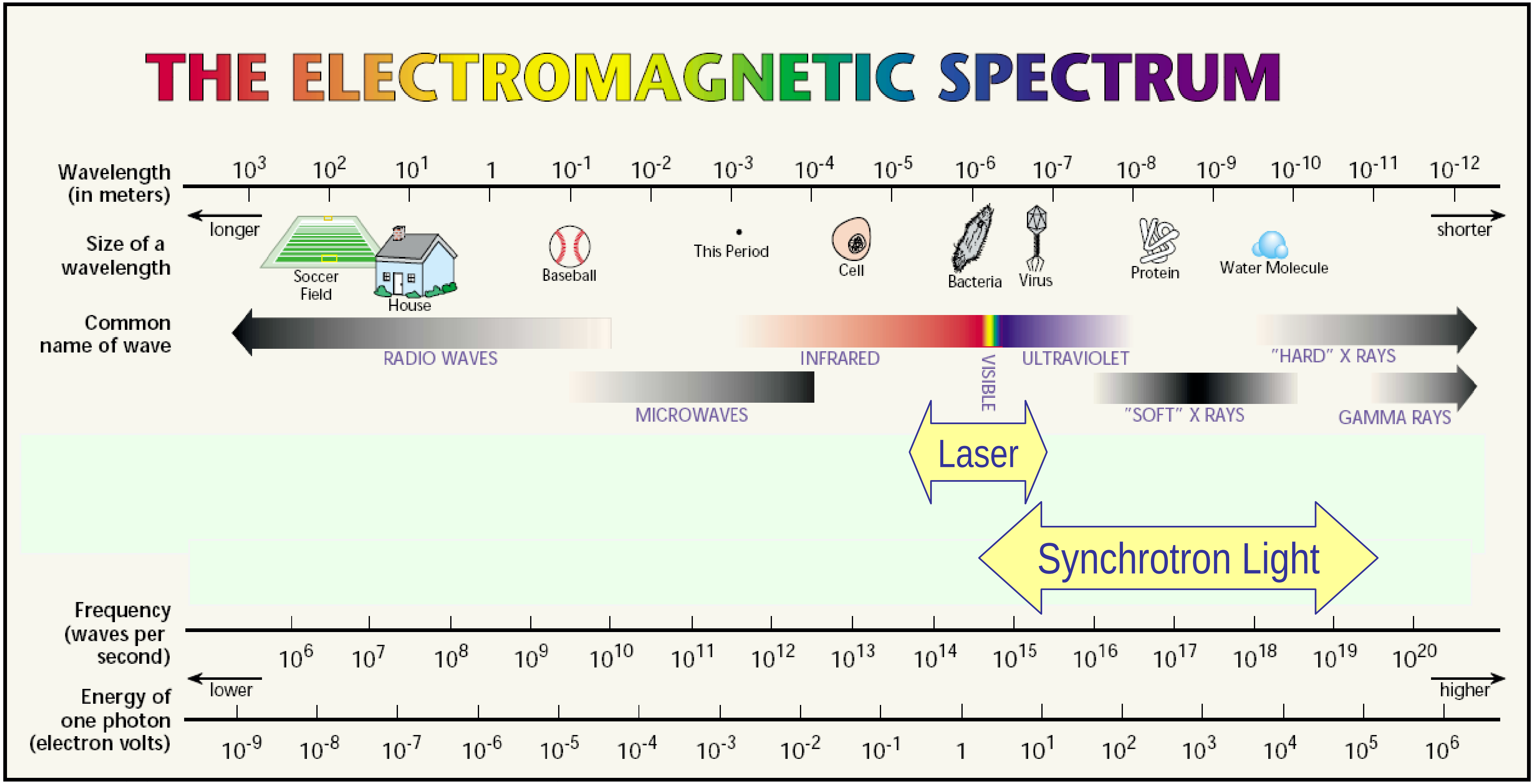
$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{E_{KIN}}{mc^2} + 1$$

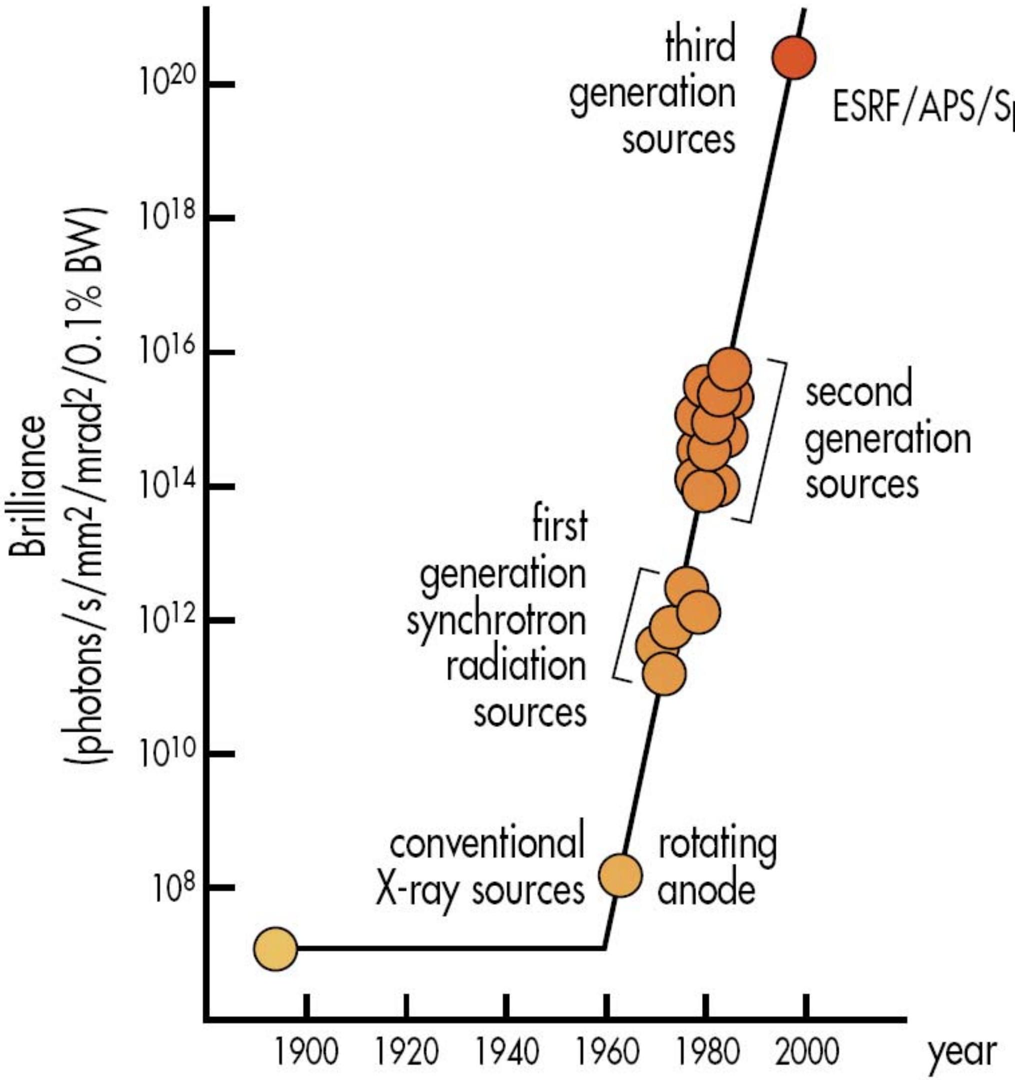
$$\tau = \frac{1}{v}(s-l) = \frac{1}{v}\left(\frac{2R}{\gamma} - 2R\sin\frac{1}{\gamma}\right)$$

$$\approx \frac{1}{3}\frac{R}{c\gamma^3}$$

$$\nu_{SR} \approx \frac{3c\gamma^3}{R}$$

The typical frequency of the synchrotron-radiation spectrum.

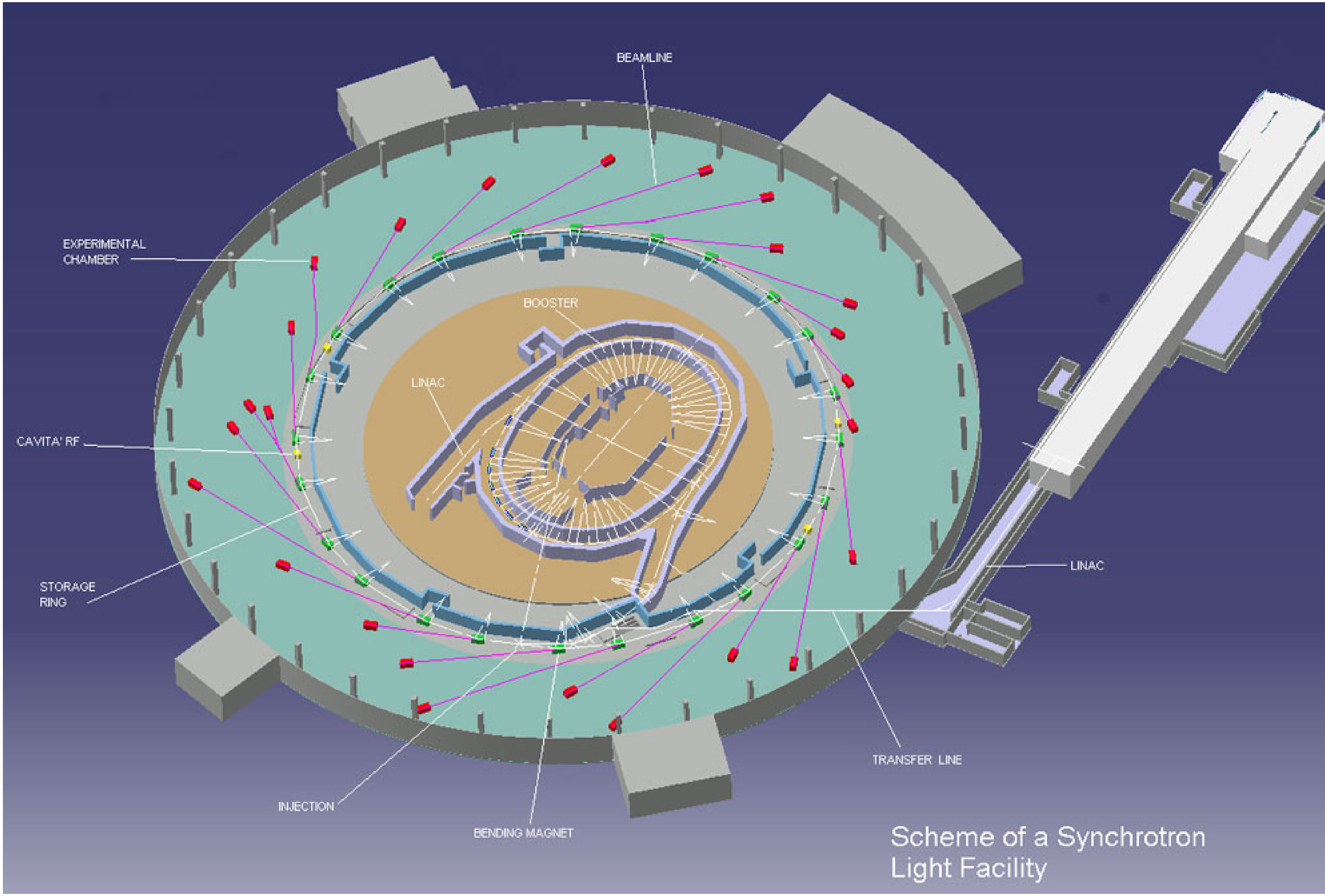

THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Laser
Synchrotron Light
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6



Increase in the brilliance of X-rays since the beginning of the century.

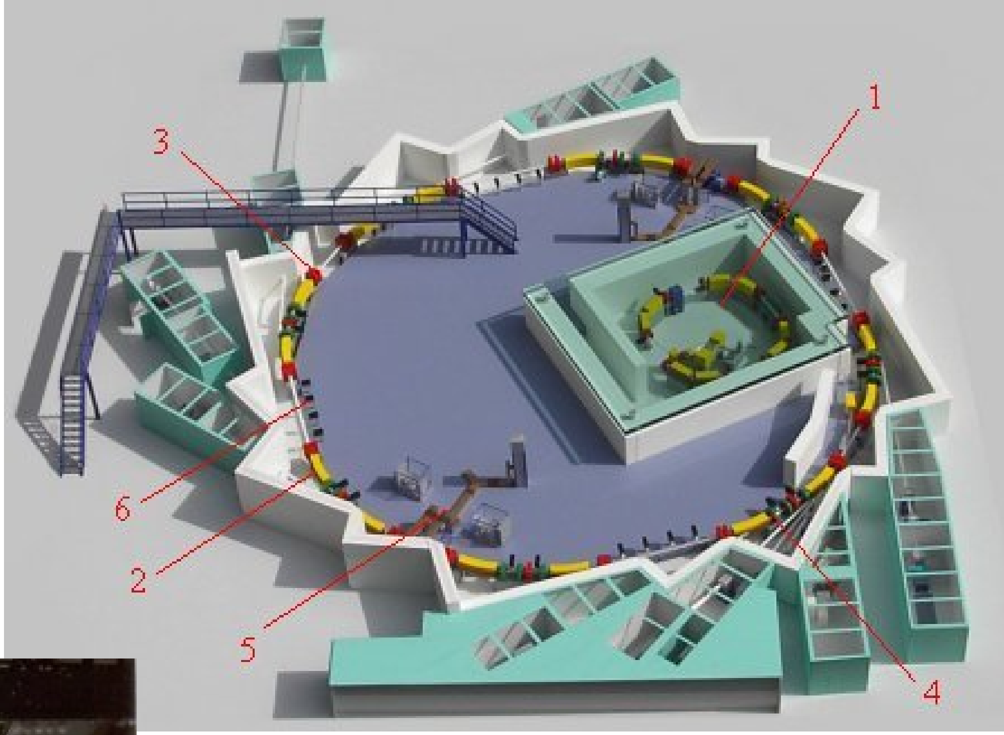
High brilliance allows selection of small wavelength range and source size with high light intensity.

Key feature for spectrocopy
And diffraction experiments !


BEAMLINE
EXPERIMENTAL CHAMBER
BOOSTER
LINAC
CAVITA' RF
STORAGE RING
LINAC
INJECTION
BENDING MAGNET
TRANSFER LINE
Scheme of a Synchrotron Light Facility

The ANKA 2500 MeV electron storage ring

Karlsruhe/Germany



1. The injector produces electrons and pre-accelerates them.
2. The bending magnets (yellow) are the actual source of synchrotron radiation.
3. Quadrupol (red) and
4. sextupol magnets (green) are used to correct the orbit of the electrons.
5. The loss of energy through radiation is compensed in the so-called RF cavities of the accelerators.
6. Of special importance is the high vacuum system with a multitude of pumps.

Synchrotron Radiation Facilities around the World

Each red dot corresponds to an investment of typically a few 100.000.000 €
Beam energies range from 500 MeV to 8000 MeV

Short primer on X-rays

X-rays have weak absorption in matter
$\Rightarrow$ resolve interior of objects

X-rays are scattered/absorbed mainly by the core electrons of atoms and not the valence electrons. The core electron energy levels are little affected by chemical bonds

$\Rightarrow$ Scattering pattern of X-rays unravel atom position in crystal lattice, i.e. crystal structure.

$\Rightarrow$ The absorption properties of monochromatic x-rays are very sensitive to the elements in the specimen with a wavelength dependence of absorption edges following a simple function of atomic number Z (Moseley law). This allows the detection of small traces of impurities and contaminations in a specimen.

Experimental Techniques
in SR beamlines
(from ESRF brochure)

DIFFRACTION/SCATTERING
X-rays are deviated in specific directions depending on the relative positions of atoms. The X-ray patterns enable the structure of crystals and the molecular packing in materials to be determined.

SMALL-ANGLE X-RAY SCATTERING
Inhomogeneities in materials (precipitates, clusters, phase separation..) cause very small deviations in X-ray beams. The technique is invaluable for studying alloys, polymers, viruses, ceramics, colloids...

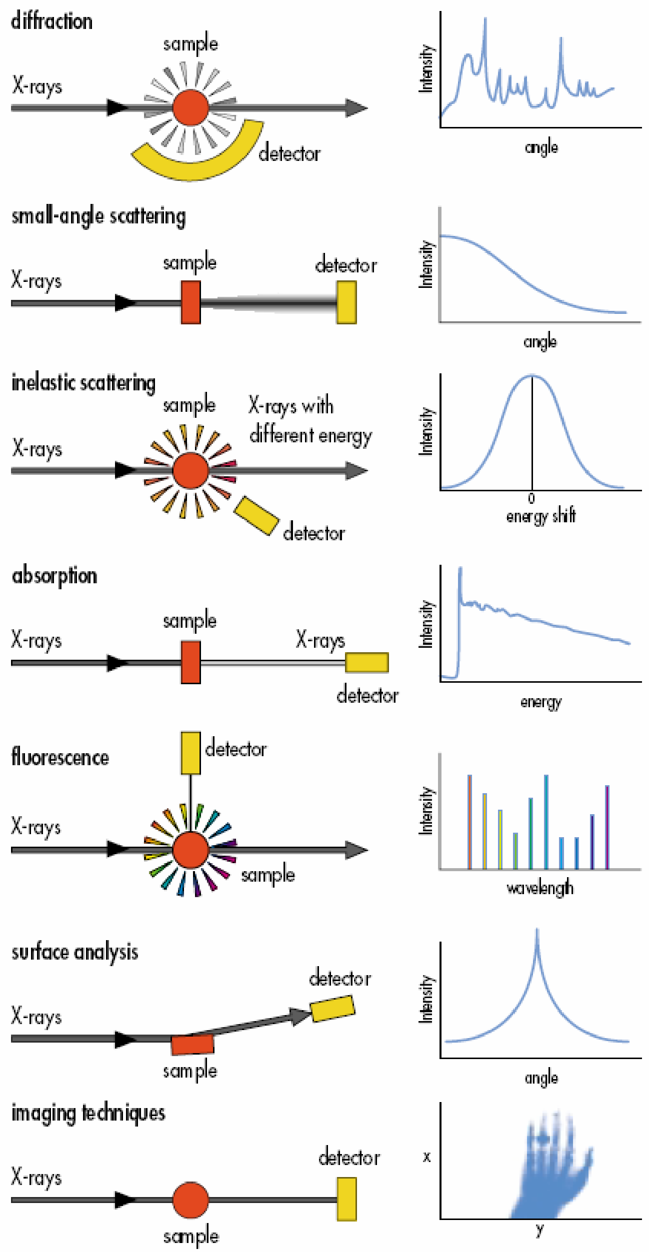
INELASTIC SCATTERING
X-rays passing through a substance can lose or gain energy due to internal collective motion. The technique is used to study dynamics in materials.

ABSORPTION
The absorption curve of a material shows sharp details which are characteristic of the electronic structure of the atoms. The fine structure of this curve provides information on the local order of the atoms.

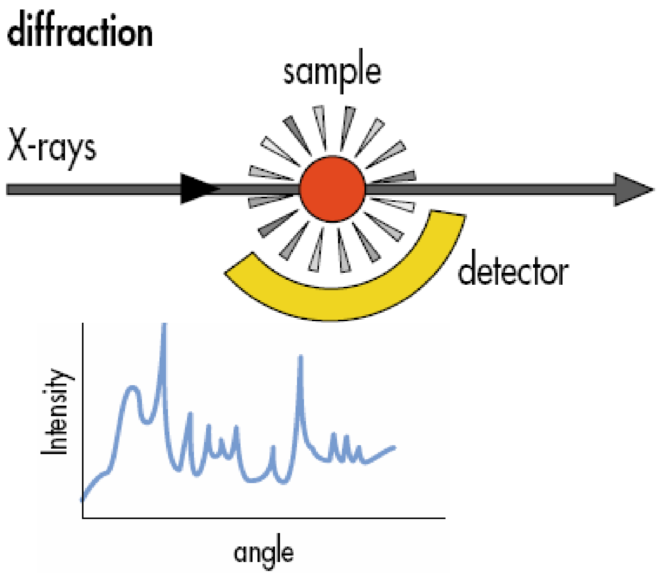
FLUORESCENCE
X-ray photons excite electrons in a probe element. These electrons immediately relax, emitting X-rays characteristic of that element. This is a powerful method for measuring trace element concentrations.

SURFACE ANALYSIS
Analysis of the surface of materials can be made by scattering, absorption and fluorescence at grazing angles. These techniques show how the surface layers are quite different from the bulk material.

IMAGING TECHNIQUES
Here, X-rays are used to provide a direct image of an object from a few cm in size down to a few hundred angströms. Applications range from medical imaging to microelectronics. Due to their coherence, third generation synchrotron beams give new life to radiography. In addition, scanning mode imaging at micrometer resolution can be combined with the techniques described above.

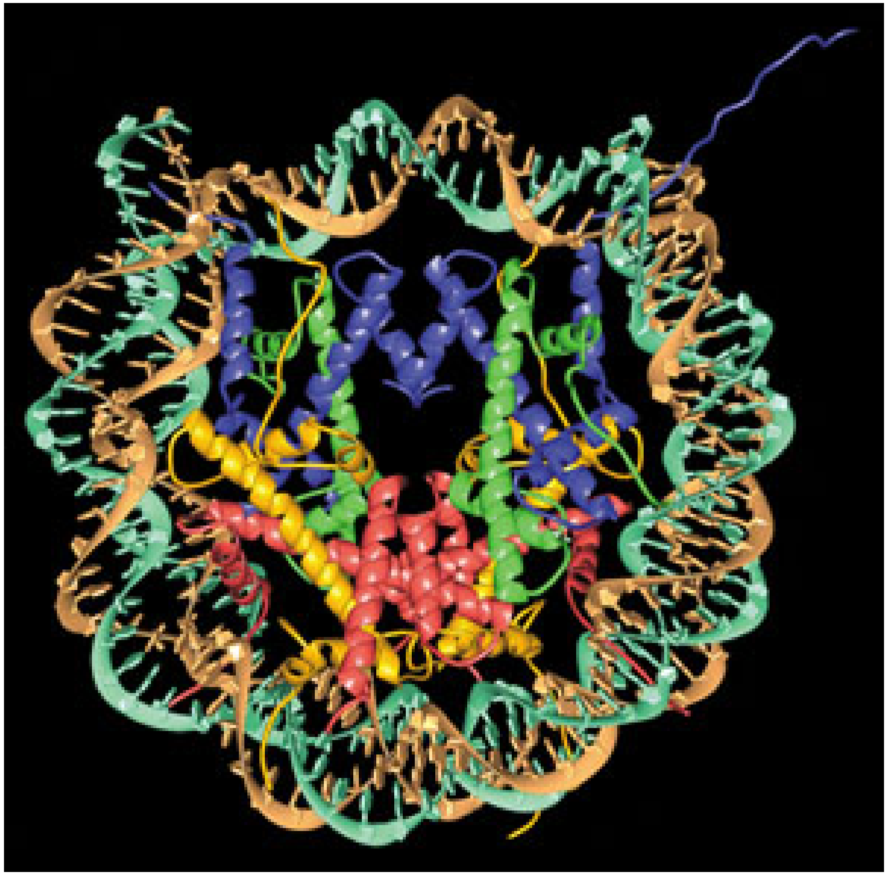


Applications of Synchrotron Radiation
Example 1: Protein crystallography (x-ray scattering)



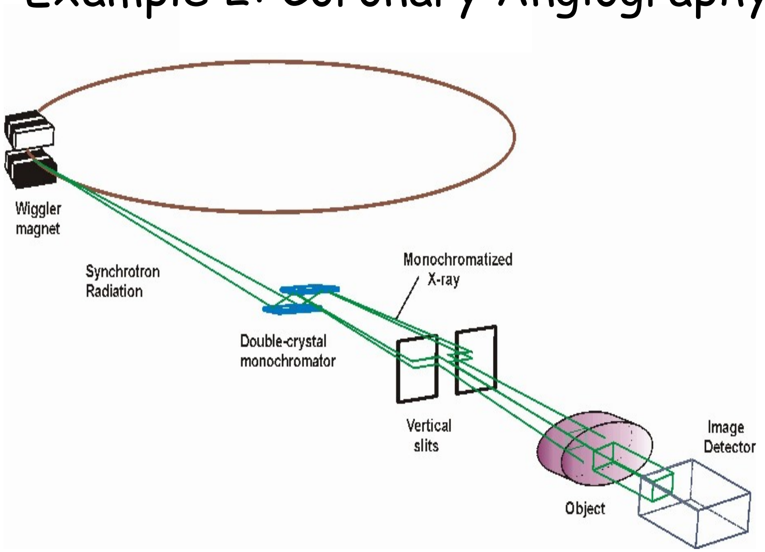
DIFFRACTION/SCATTERING

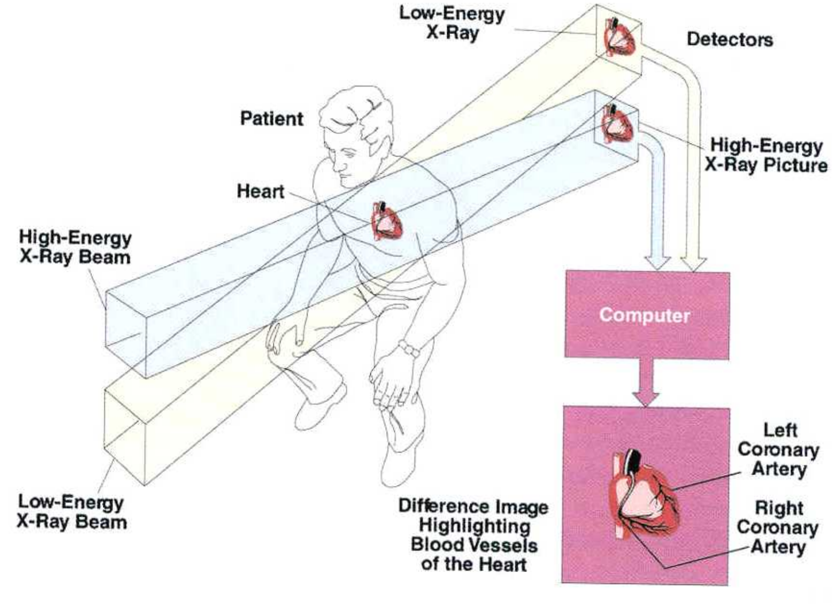
X-rays are deviated in specific directions depending on the relative positions of atoms. The X-ray patterns enable the structure of crystals and the molecular packing in materials to be determined.



The structure of the nucleosome core, with the DNA wound round proteins called histones. (T J Richmond, Zürich.)

Applications of Synchrotron Radiation
Example 2: Coronary Angiography





Intravenous coronary angiography with synchrotron radiation 501

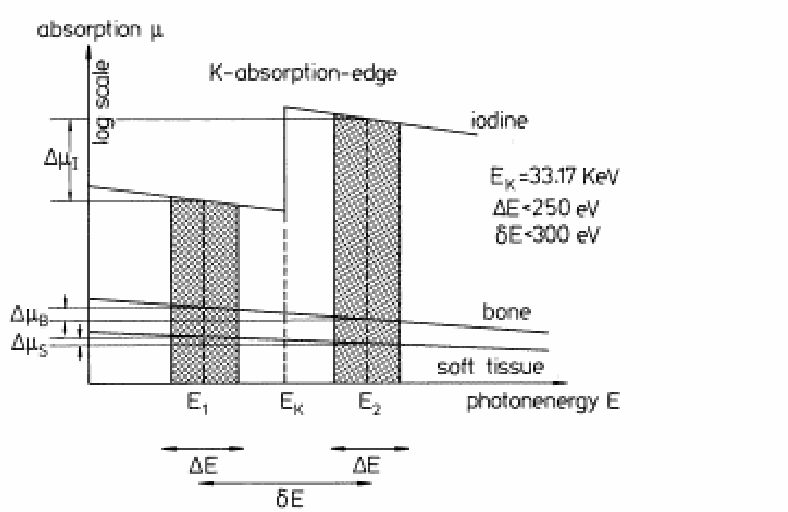
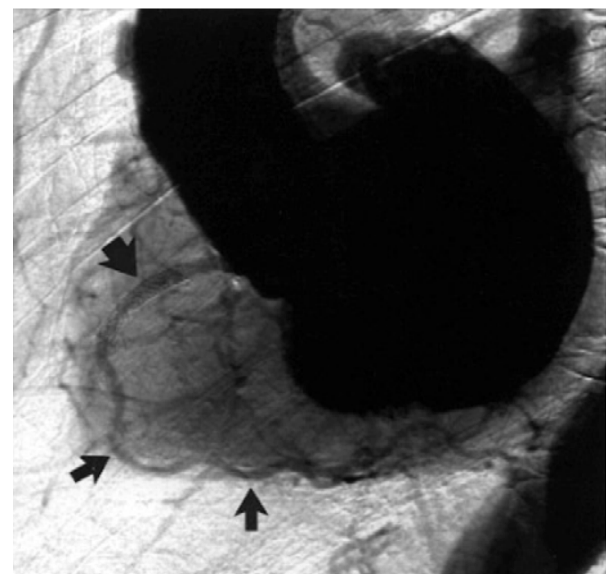
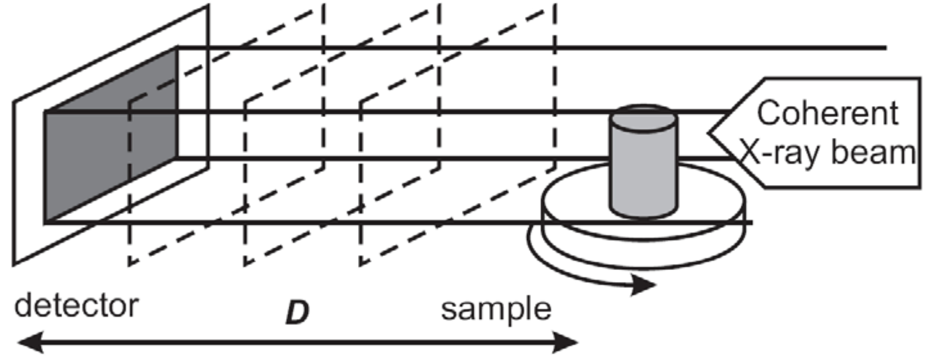


Figure 1. The difference in absorption at the K-edge is used to enhance the contrast of iodine by logarithmic subtraction.

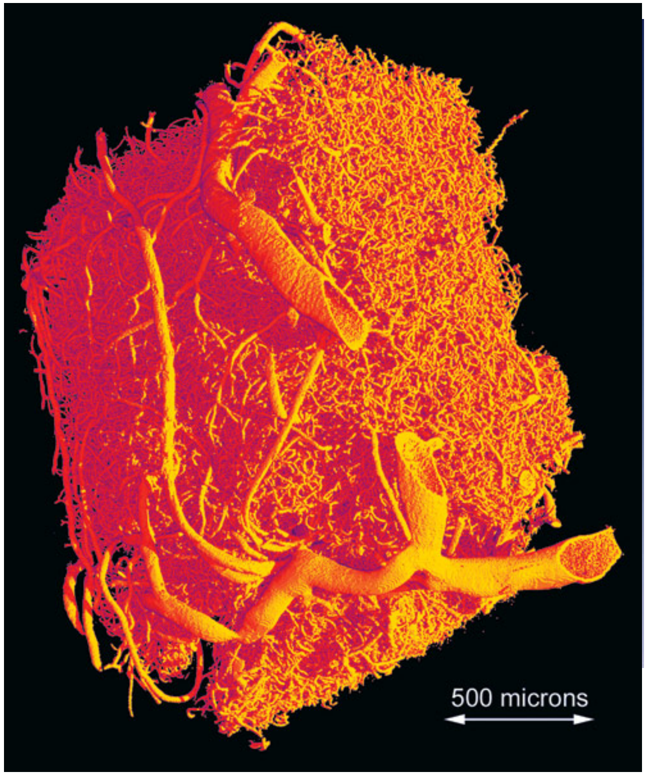


Intravenous angiogram of a 72 year old male. The right coronary artery (arrows) with a stent in the proximal part (broad arrow) is visible.

Applications of Synchrotron Radiation
Example 3a: Micro Tomography of biological samples



Earwig (ESRF)



3D reconstruction of the brain of a transgenic mouse, study of Alzheimer's disease, Krucker et al., (SCRIPPS, UZh, ETHZ, PSI).

Applications of Synchrotron Radiation

Example 3b: Micro Tomography of cracks in metal

measured at ESRF

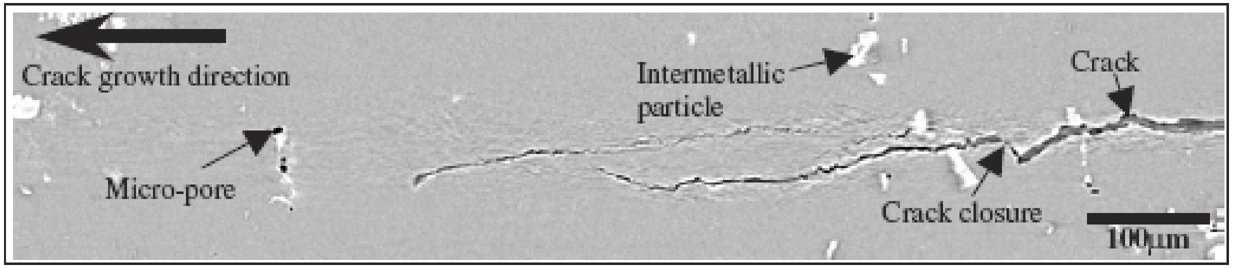


Figure 1. A 2D slice of a reconstructed volume illustrating the crack morphology and microstructural features along the crack growth direction.

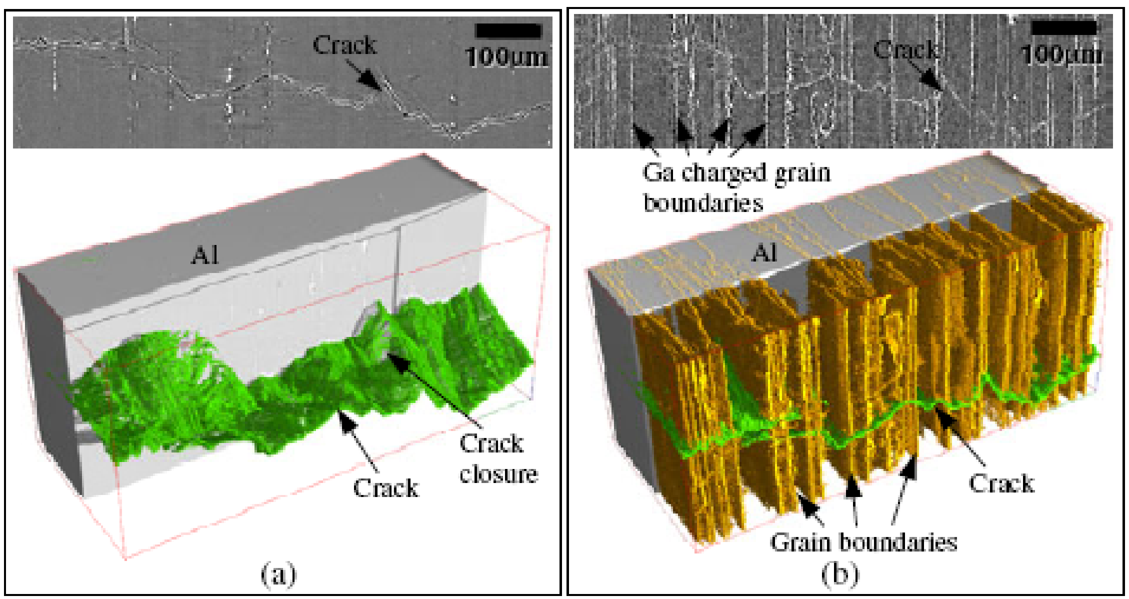
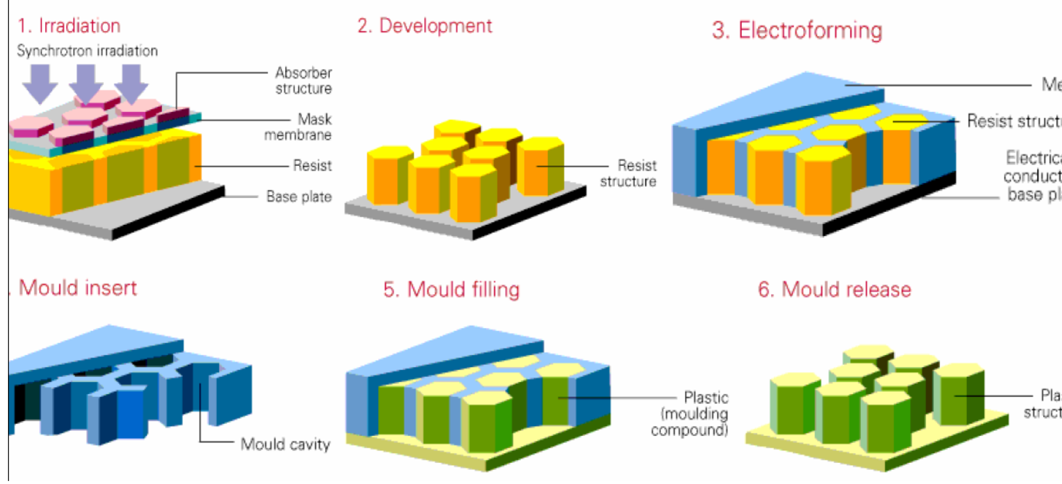


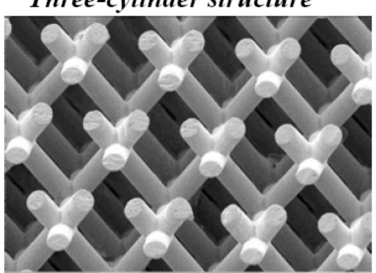
Figure 2. A 2D cross-sectional slice and 3D rendered perspective view of a crack in a tomographic volume (a) without and (b) with application of Ga.

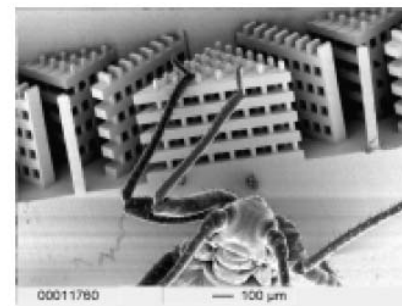
Applications of Synchrotron Radiation
Example 4: LIGA

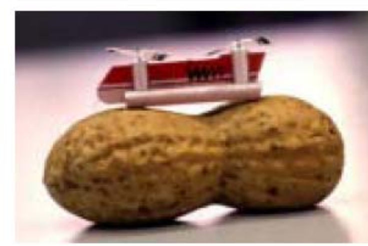
LIGA Process

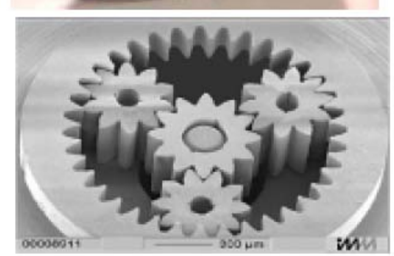


Three-cylinder structure

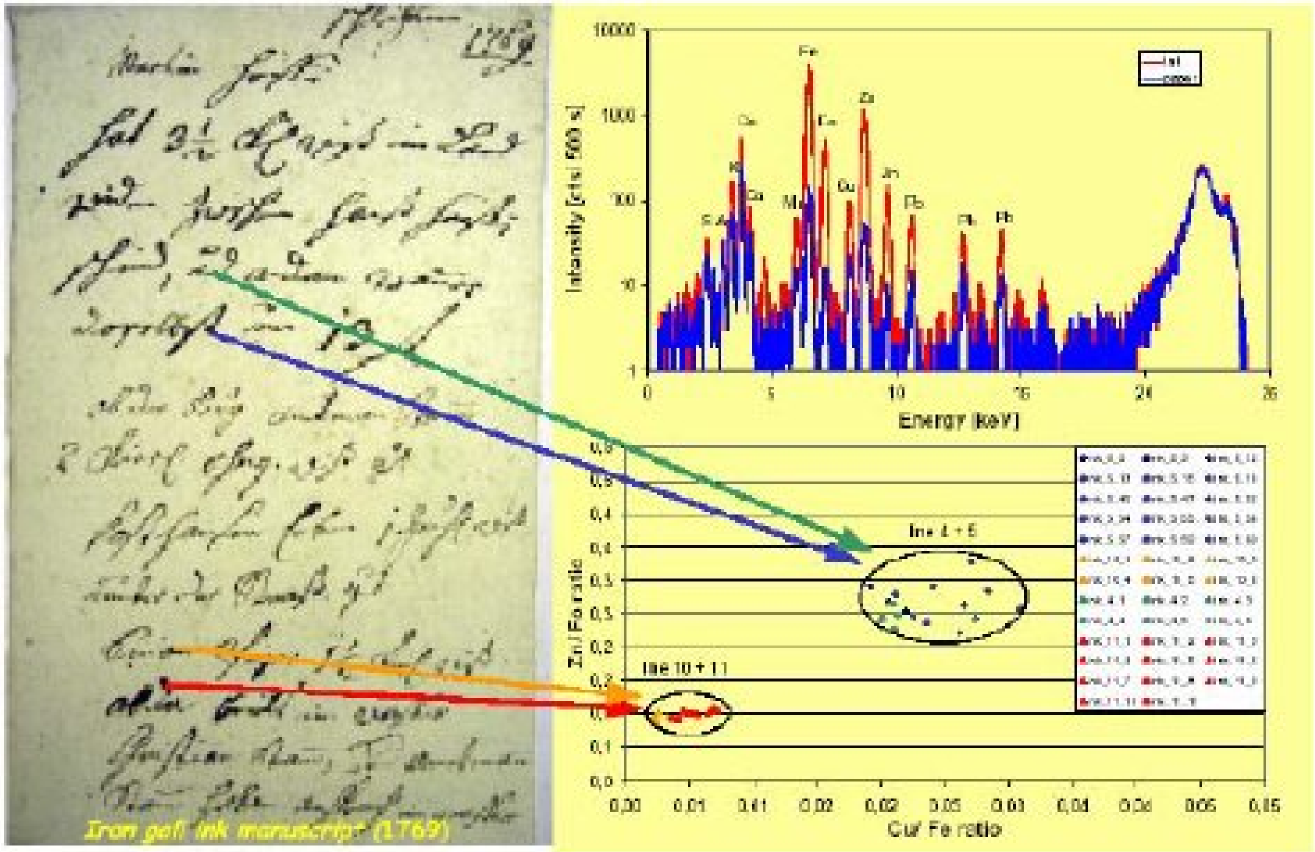








Applications of Synchrotron Radiation
Example 5: Conservation of Historic Manuscripts



Original iron gall ink manuscript on legal land description of the year 1769; left: photo of the manuscript; right top: representative µSXRF spectra of the iron gall ink and paper; right bottom: zinc to copper ratio of iron gall ink in different lines of the manuscript (ANKA Karlsruhe)

Accelerators in medicine

Two types of applications.

I. Proton zyklotrons for production of short-lived radioactive isotopes. These isotopes are used for various diagnostic techniques. For example positron emission tomography (PETS).

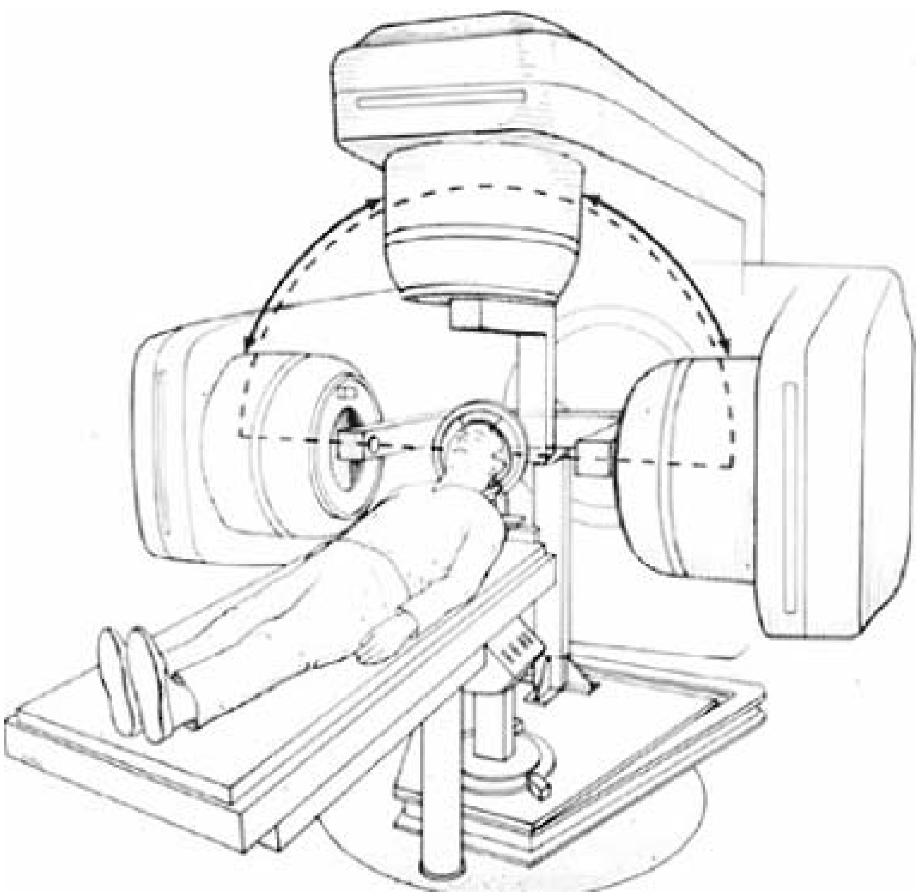
II. Tumor treatment by ionizing radiation.
Ionizing radiation can be

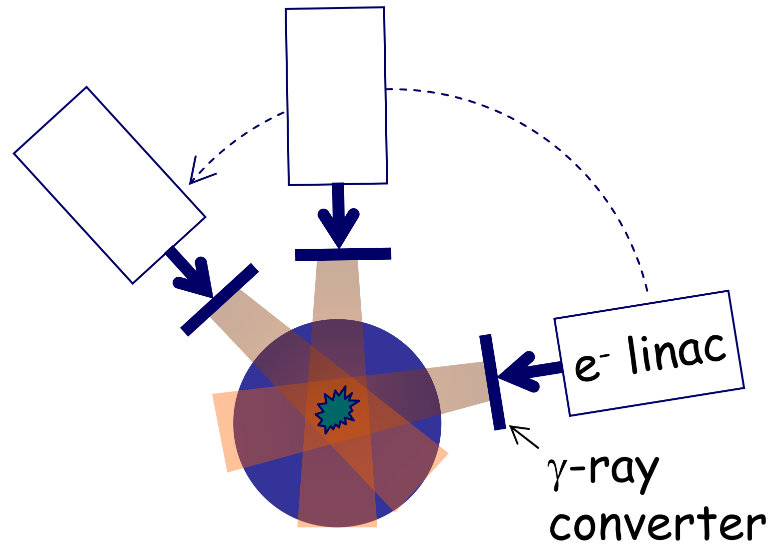
- x-rays beams
- γ–ray beams
- electron beams
- proton beams
- ion beams (usually Carbon ions)

The basic mechanism is always the same: the beam knocks electrons out from molecules, breaking chemical bonds in the DNA of the cancer cells.
The problem is to affect the tumor with minimum damage of healthy surrounding tissue.

More than 6000 medical accelerators world wide !

Gantry for cancer treatment with electron accelerator

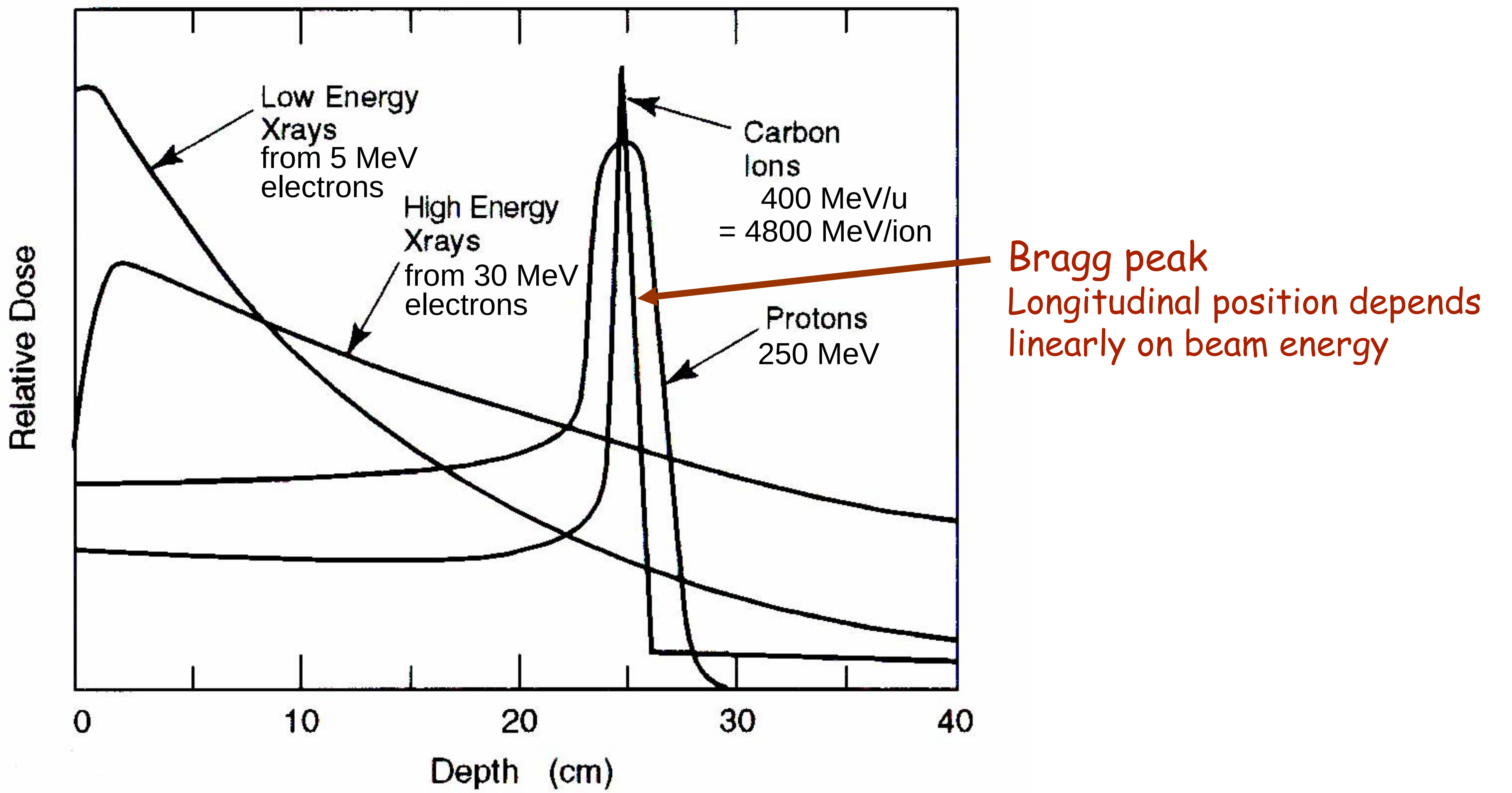




X-ray or NMR Computer Tomography to localize tumor in 3D.

↓

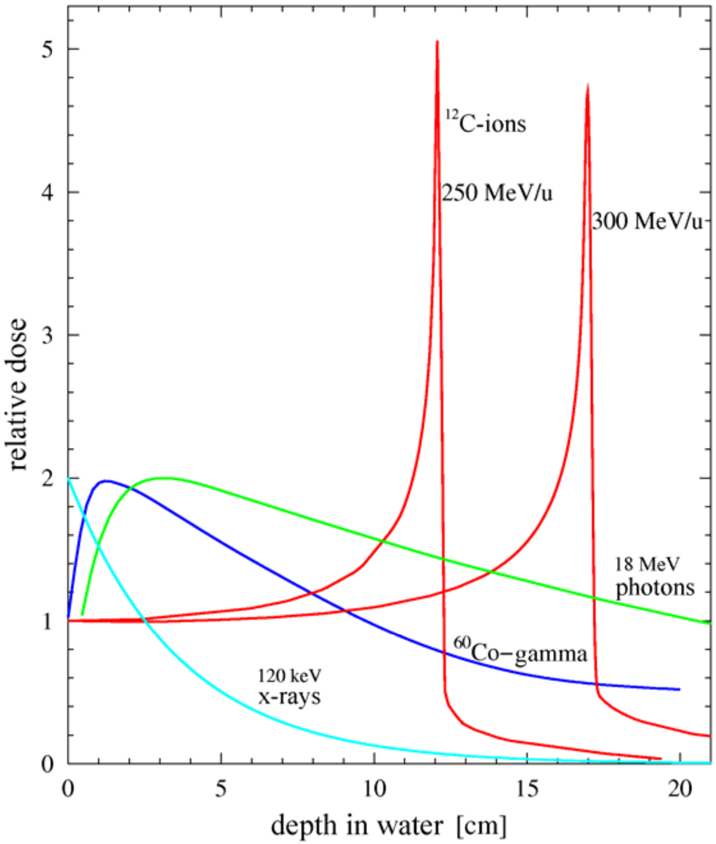
Optimise beam shape and directions to apply required radiation dose to tumor with minimum dose in surrounding tissue

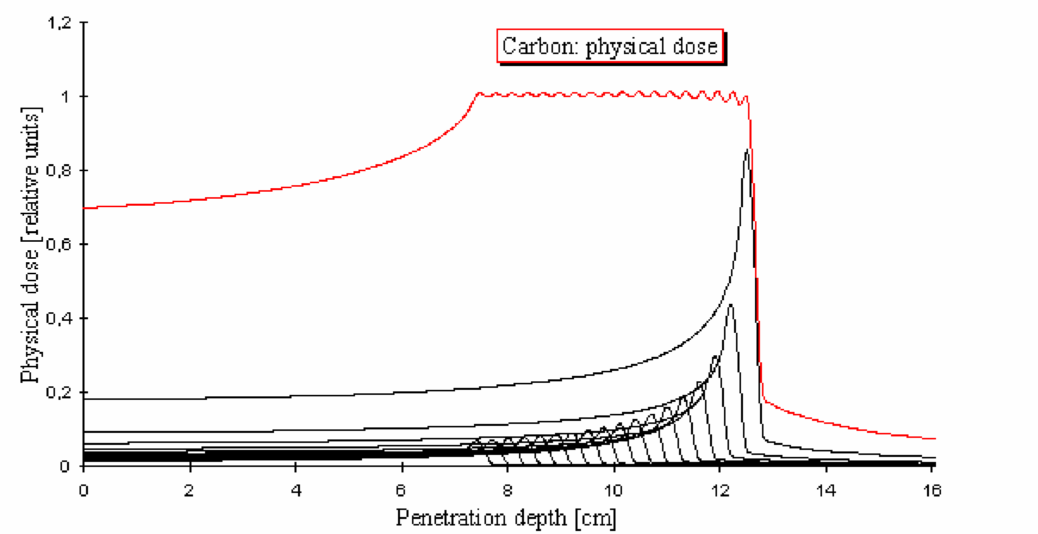


Absorption vs depth for various particles.

Treatment technique: Dose Depth Profiles

Dose depth profile for several kinds of radiation

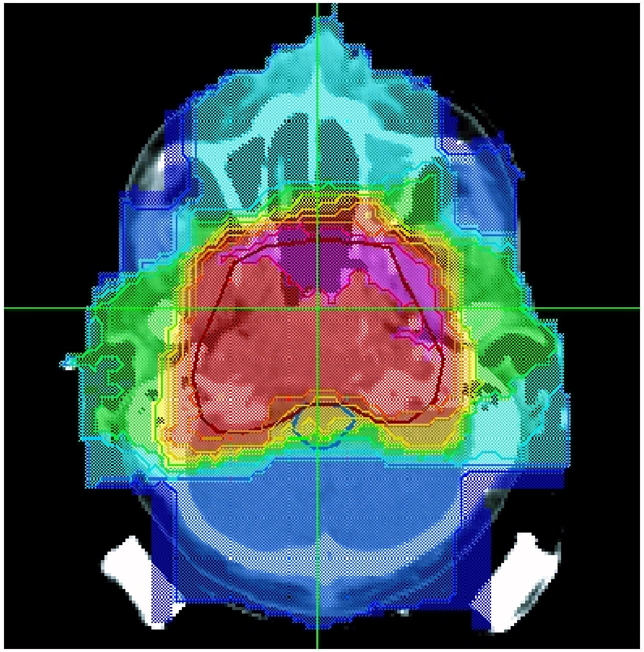


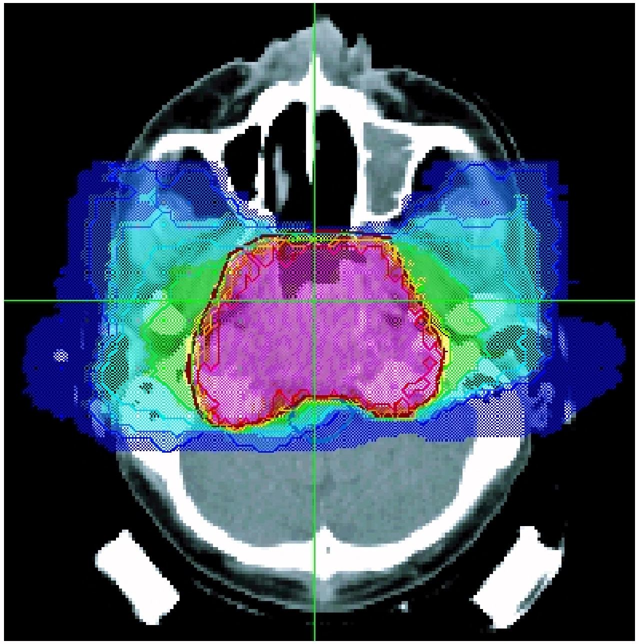


- **Irradiation with different energies => ‘slicing’ of the tumor in isoenergetic planes**
- **Intensity variation per plane to get flat dose distribution**

Treatment Technique: Rasterscan

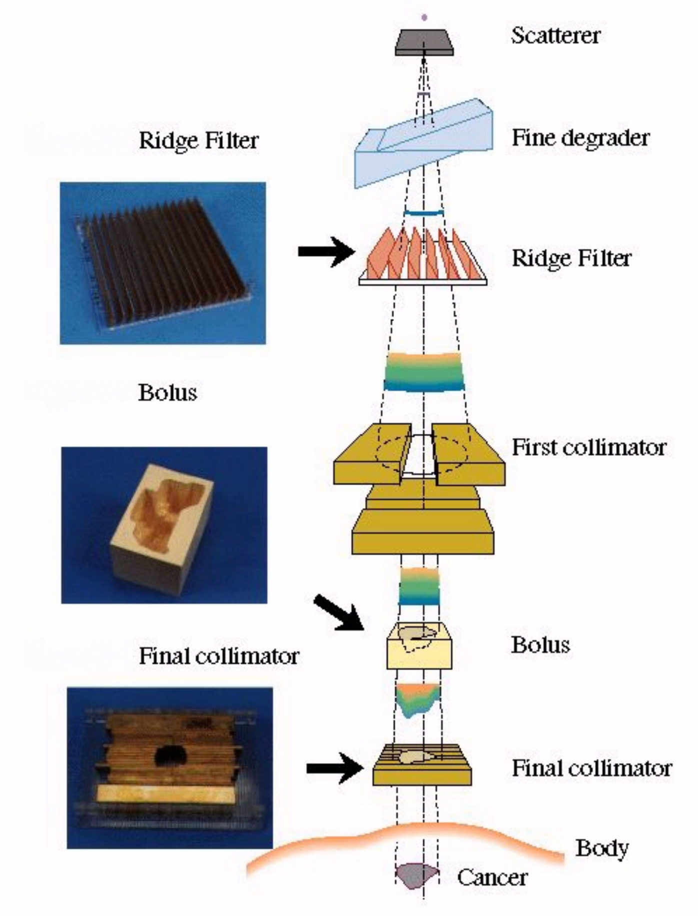
Dose-Distribution (comparison)



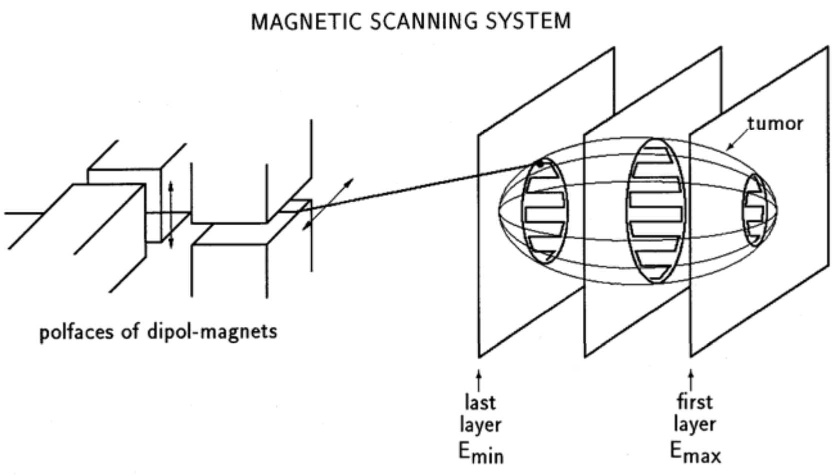


- **Photon-Treatment (4 fields)**
- **Carbon-Treatment (2 fields)**

Treatment Technique: Rasterscan



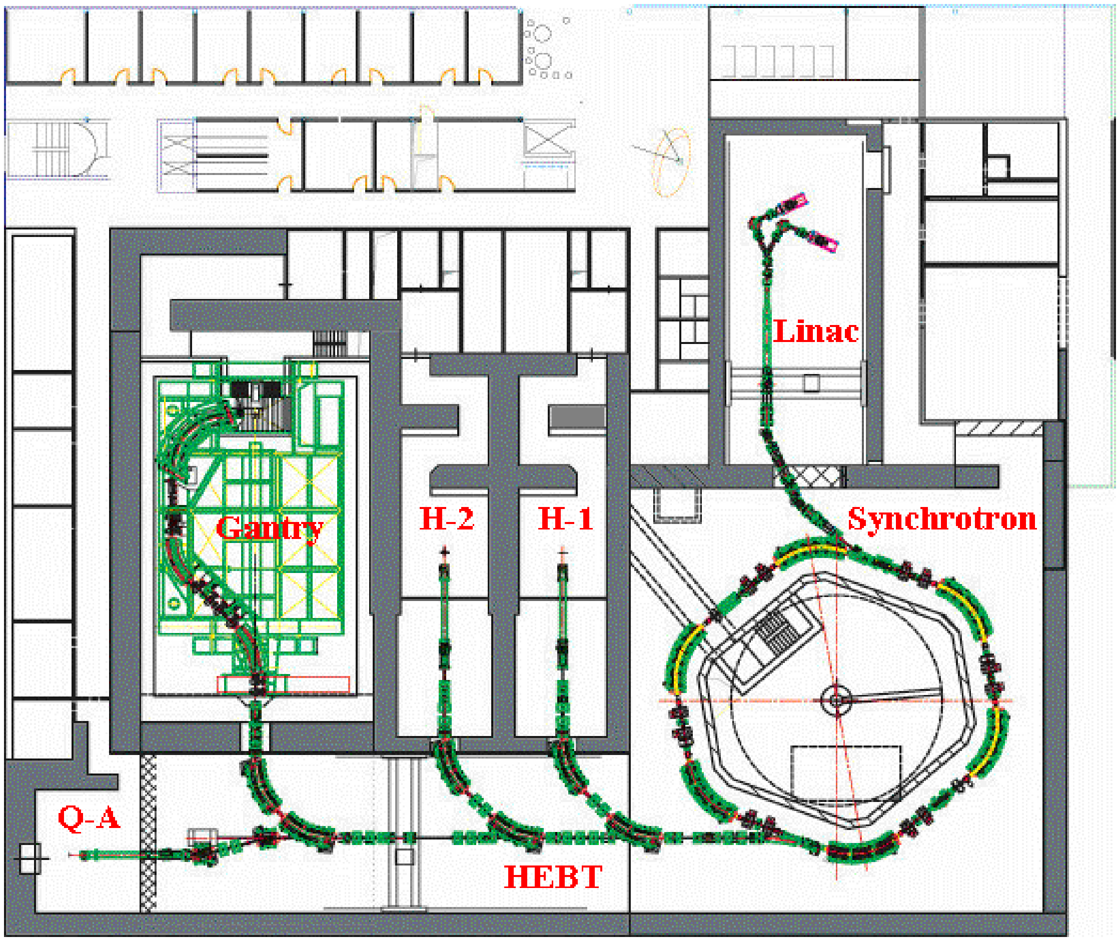
- **Conventional (passive) treatment method**



- **Rasterscan treatment (GSI)**
  - **Active energy, intensity and beam size variation**
  - **Horizontal and vertical scanning of each isoenergetic slice with fast scanner magnets**

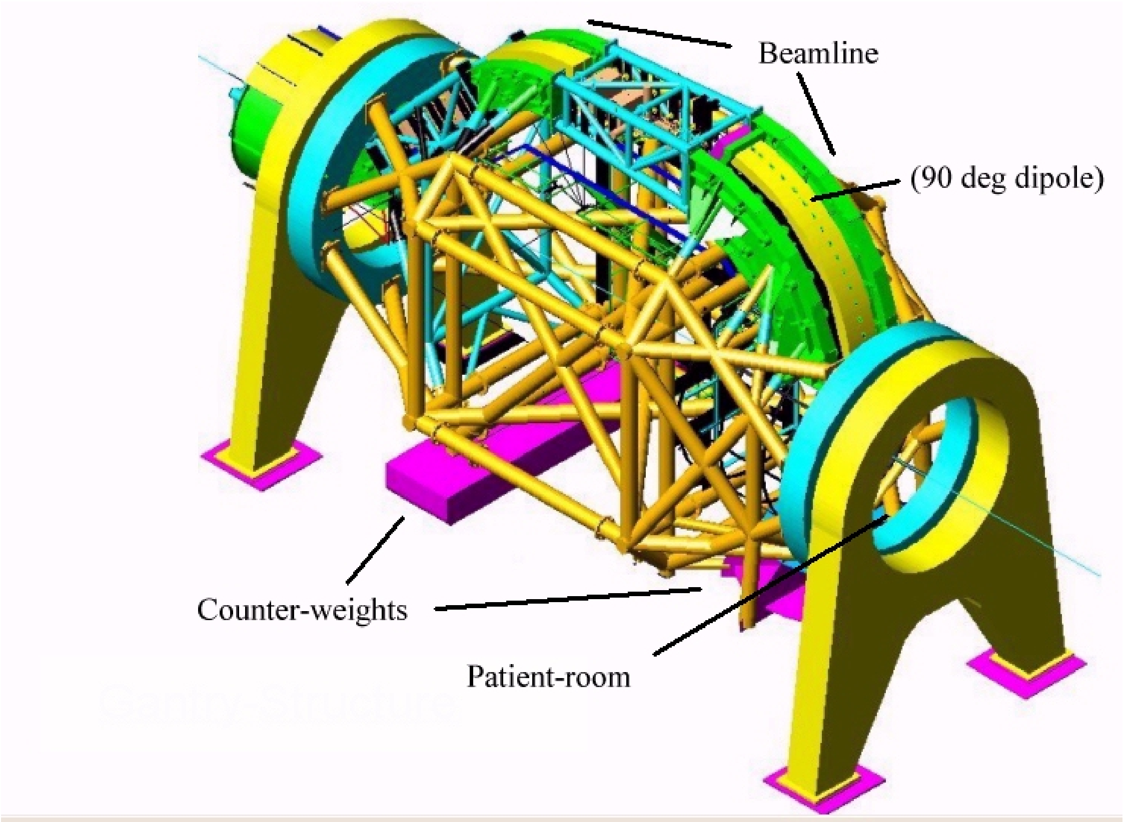
HICAT Layout: System Plan

Dedicated Synchrotron for cancer treatment with carbon ions in Heidelberg/Germany



- Accelerator sections
  - Two ECR sources
  - Injector linac
  - Synchrotron
  - Extraction via RF knock out
  - Two horizontal areas
  - One Gantry
  - One quality assurance place
  - Compact design (area restrictions)

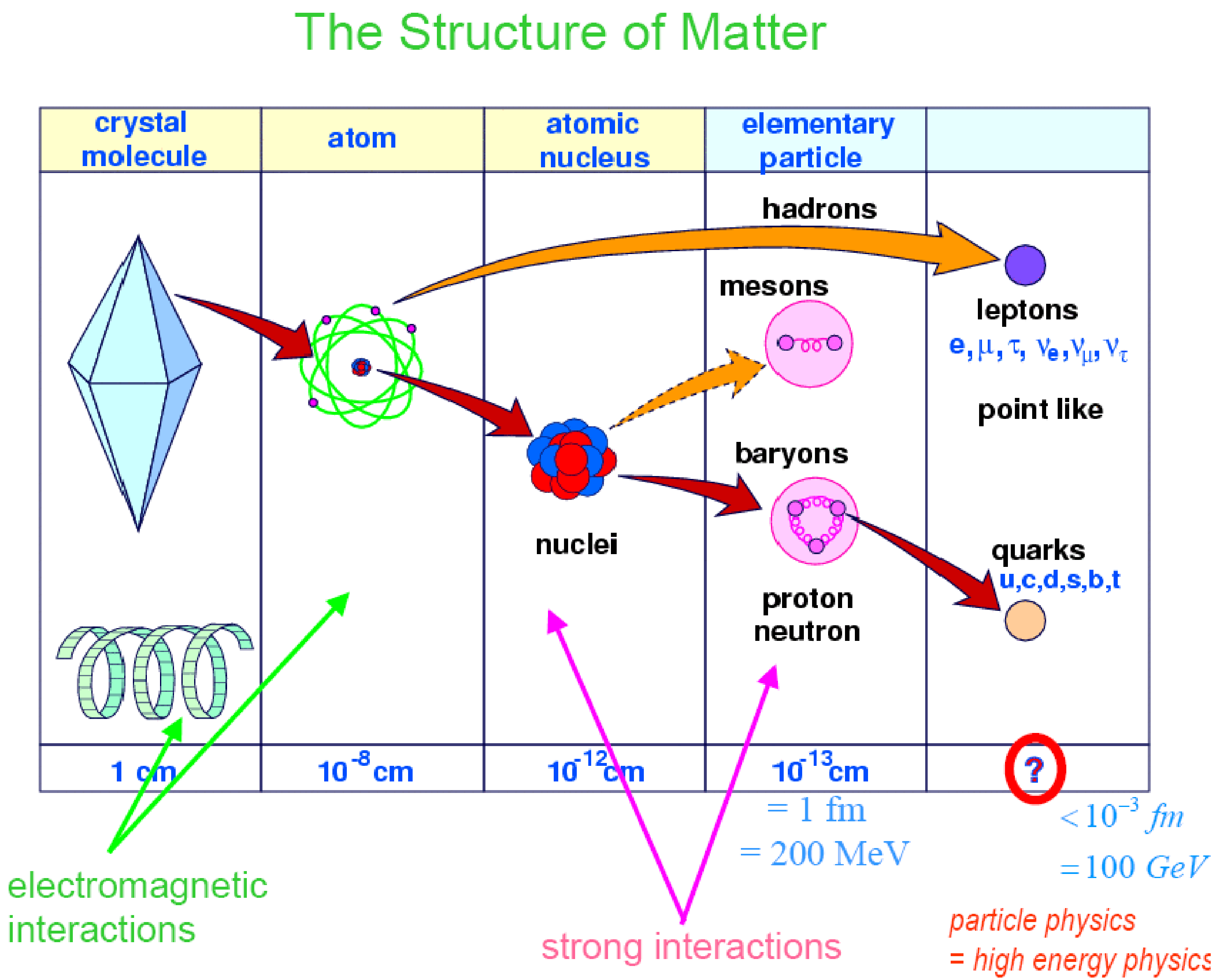
HICAT Layout: Gantry

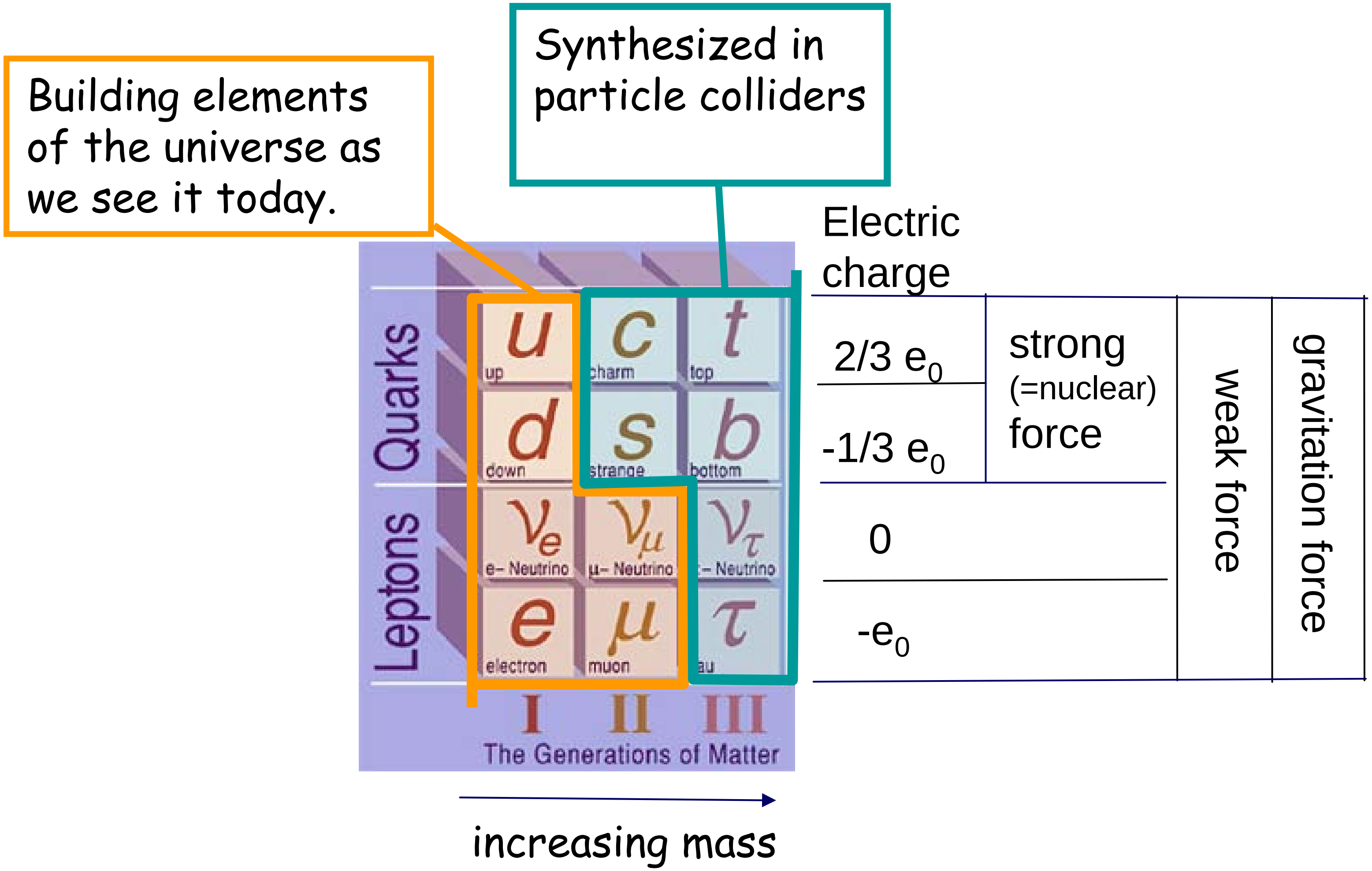


Features

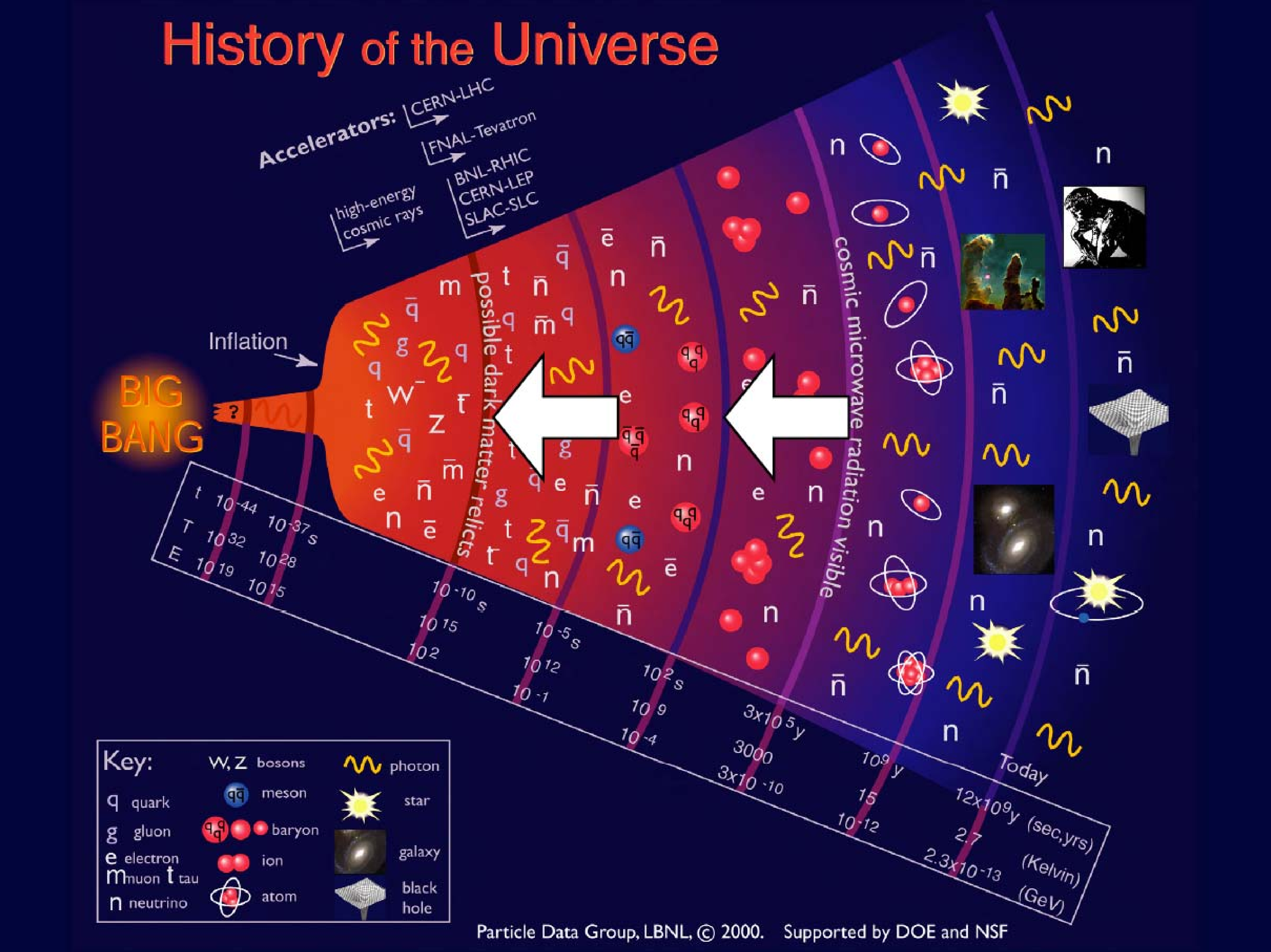
- **First heavy ion gantry**
- **Close to 600 to. weight**
- **13 m diameter**
- **Maximum deformation of 0.5 mm**
- **Integration of rasterscan**

Accelerators for Particle Physics

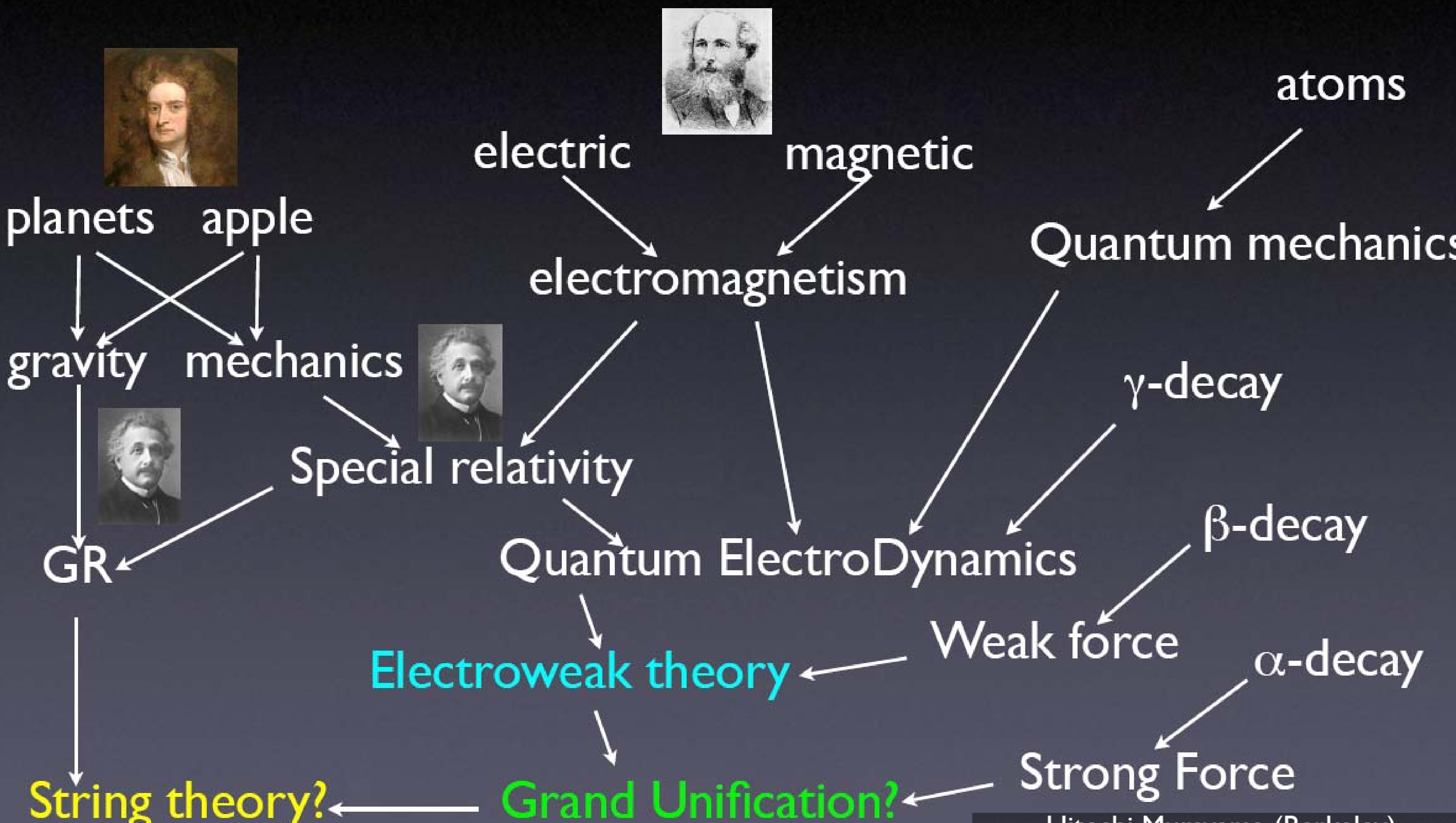




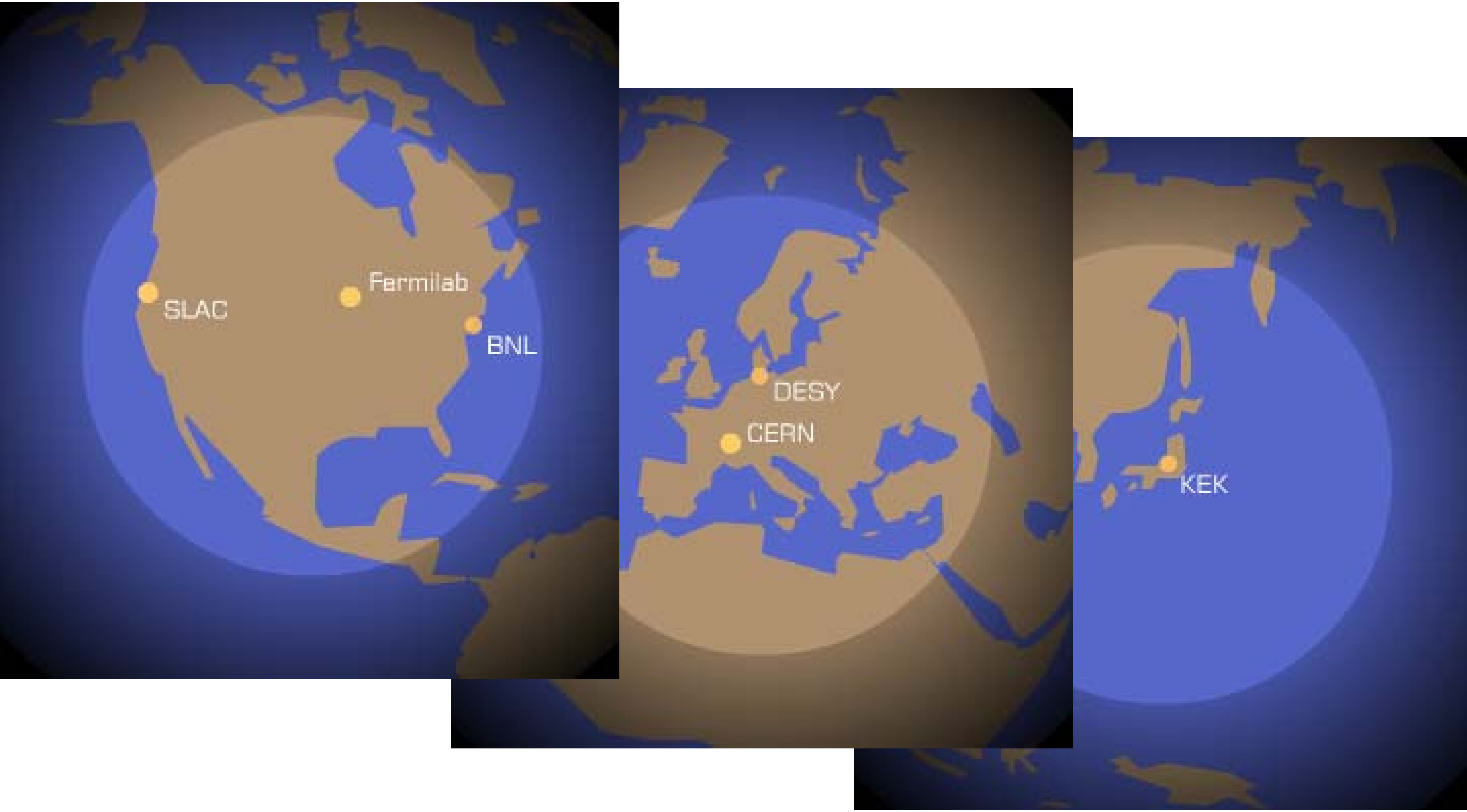
in early universe <u>all</u> quarks and leptons were present in similar numbers.


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

History of Unification



High Energy Particle Collider Laboratories around the World



Each yellow dot corresponds to an investment in the order of 1000.000.000 €

CERN 1954-2004

Conseil Européen pour la Recherche Nucléaire

European Center for Particle Physics

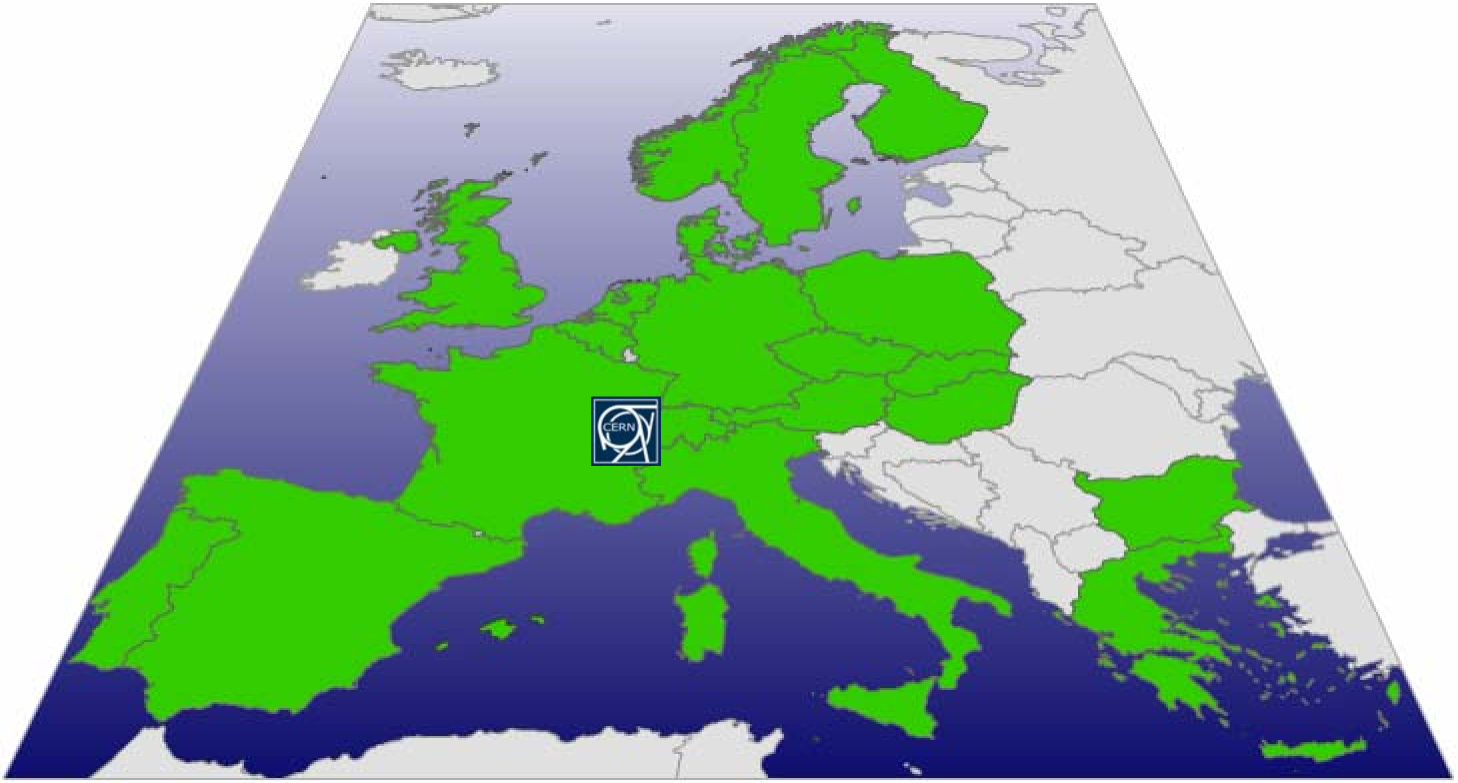
Sur le terrain du futur institut nucléaire

Sous la conduite de M. A. Picot, les membres du Conseil européen pour la recherche nucléaire se sont rendus hier à Meyrin pour reconnaître le terrain où s'élèvera le Centre nucléaire (voir en Dernière heure)

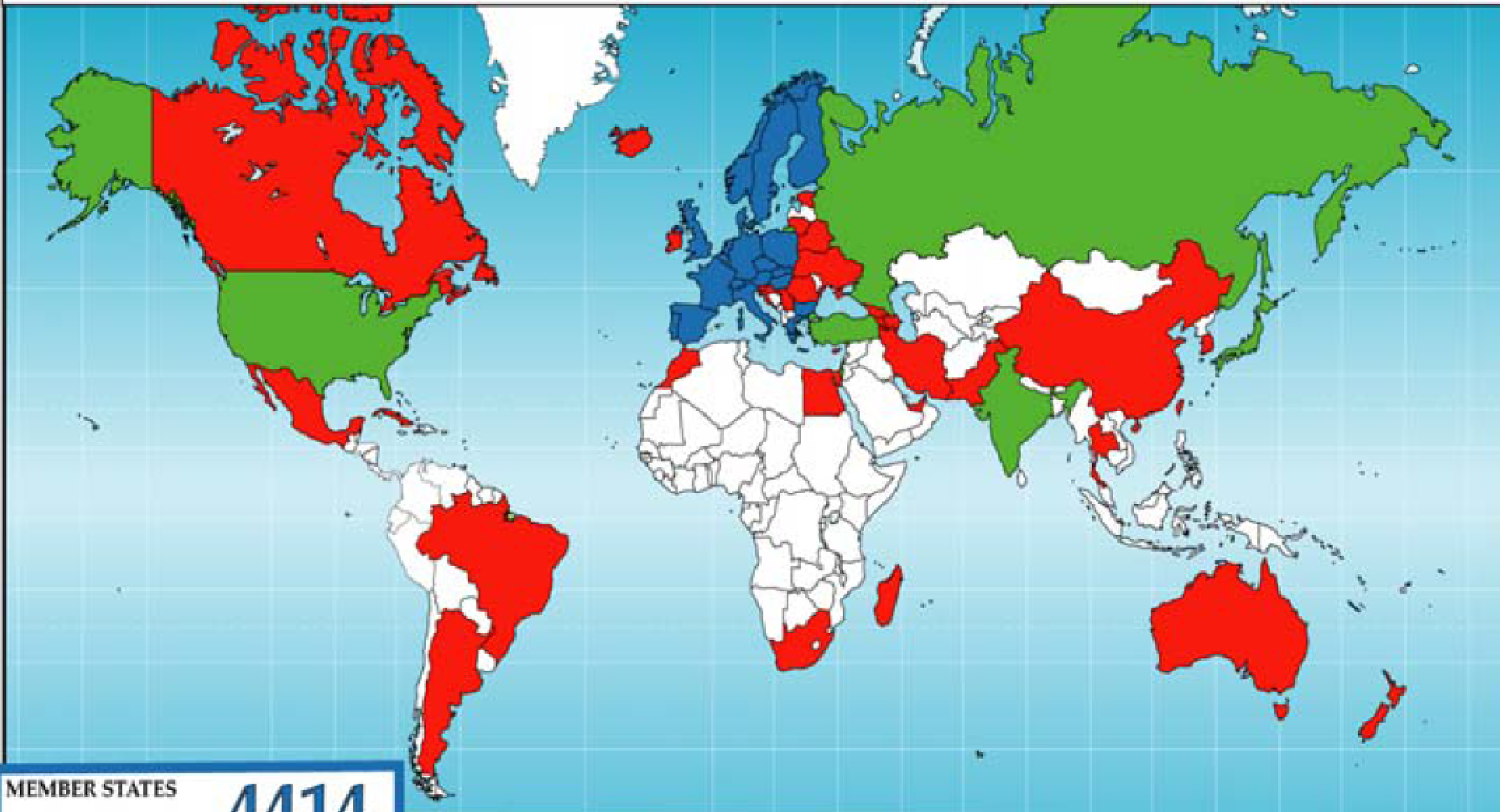
(Photo Freddy Bertrand, Genève)

La Suisse du 30 octobre 1953

The 20 CERN member states



Distribution of All CERN Users by Institute on 14 July 2005



MEMBER STATES 4414

AUSTRIA
BELGIUM
BULGARIA
CZECH REPUBLIC
DENMARK
FINLAND
FRANCE
GERMANY
GREECE
HUNGARY
ITALY
NETHERLANDS
NORWAY
POLAND
PORTUGAL
SLOVAKIA
SPAIN
SWEDEN
SWITZERLAND
UNITED KINGDOM

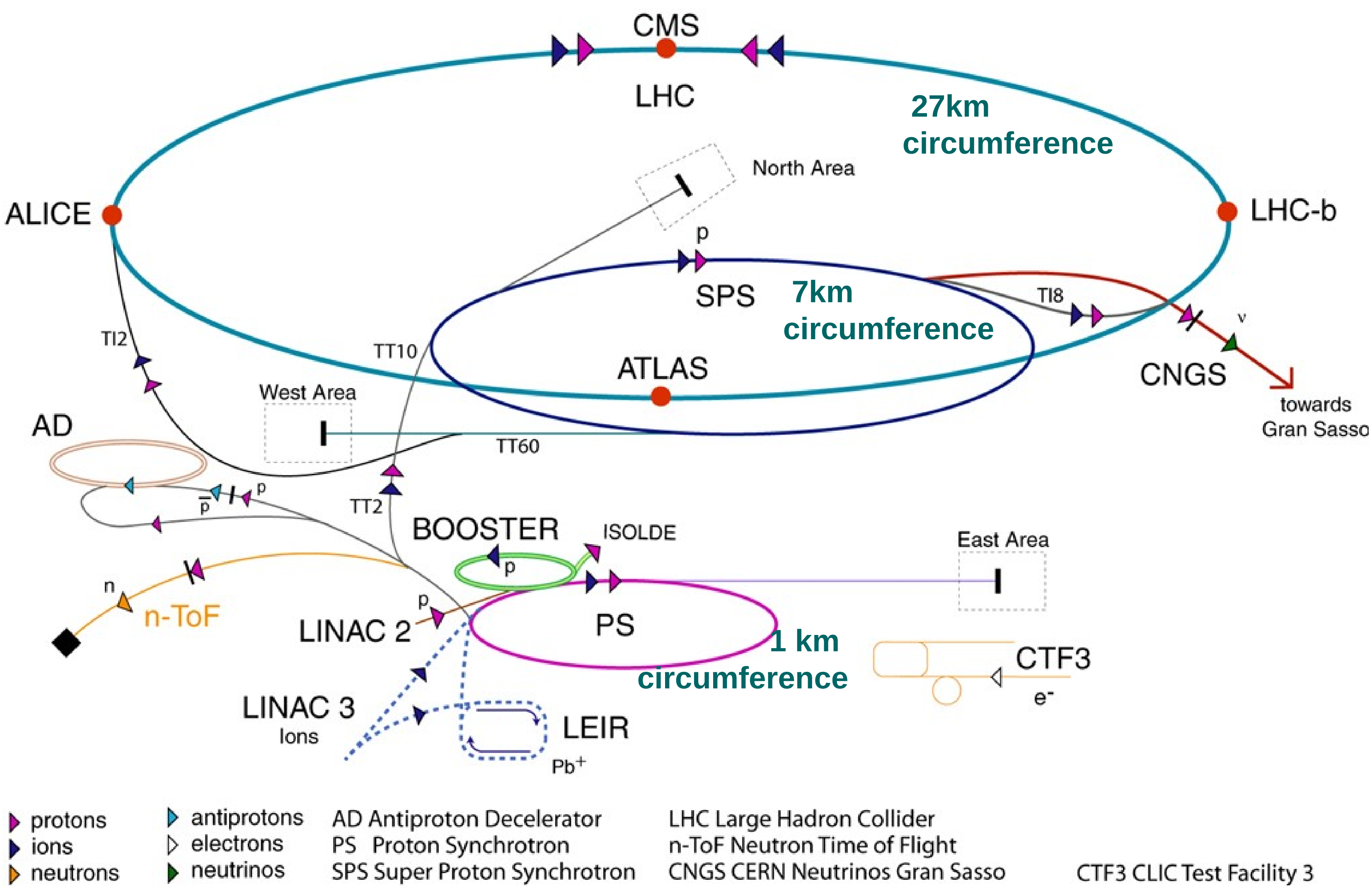
OTHERS STATES 374

ARMENIA	11
ARGENTINA	1
AUSTRALIA	13
AZERBAIJAN	2
BRAZIL	25
BELARUS	16
CANADA	71
CHINA	46
CUBA	2
CYPRUS	7
ESTONIA	9
EGYPT	1
GEORGIA	7
CROATIA	18
IRELAND	7
ICELAND	2
IRAN	5
KOREA	10
LITHUANIA	1
MOROCCO	7
MADAGASCAR	1
MEXICO	13
NEW ZEALAND	2
PAKISTAN	15
ROMANIA	25
SLOVENIA	8
THAILAND	1
TAIWAN	16
UKRAINE	12
SERBIA AND MONTENEGRO	12
SOUTH AFRICA	3
UNITED ARAB EMITATES	4

OBSERVER STATES 1713

INDIA	54
ISRAEL	39
JAPAN	88
RUSSIA	770
TURKEY	25
USA	737

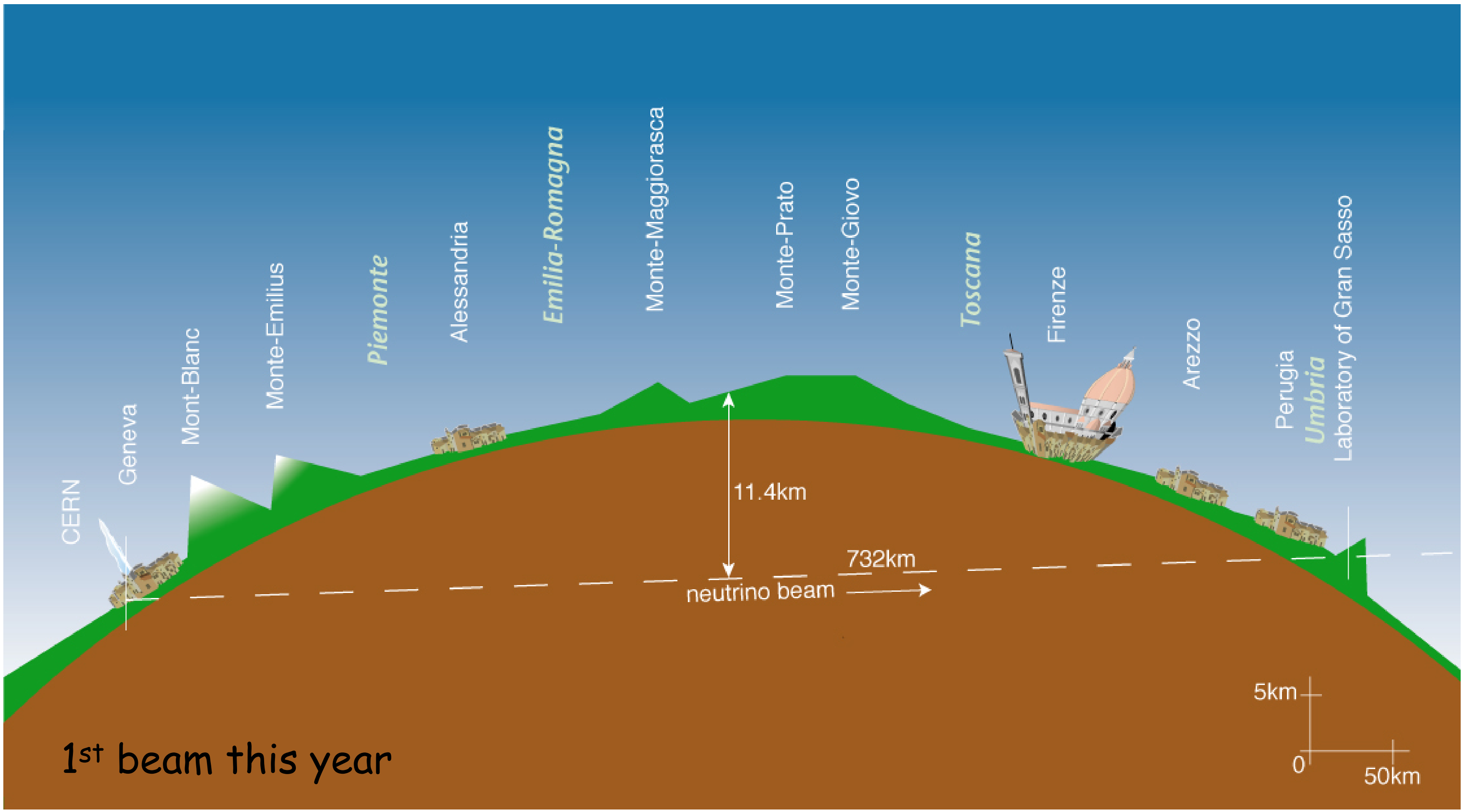
The CERN Accelerator Complex
(not to scale)



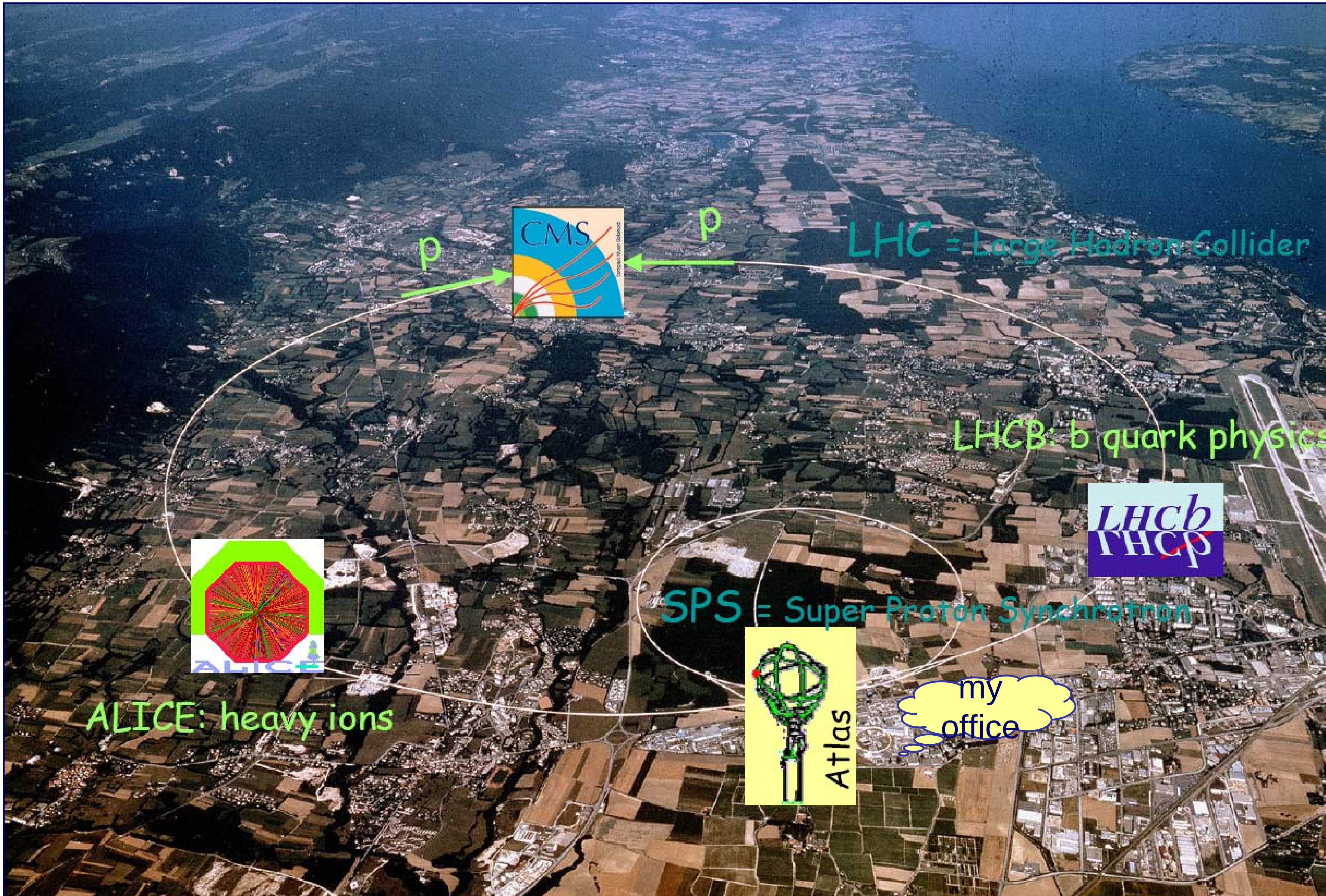
Usually we keep our beams on the CERN site,
but from next year on there will be one exception

CNGS, CERN Neutrinos to Grand Sasso

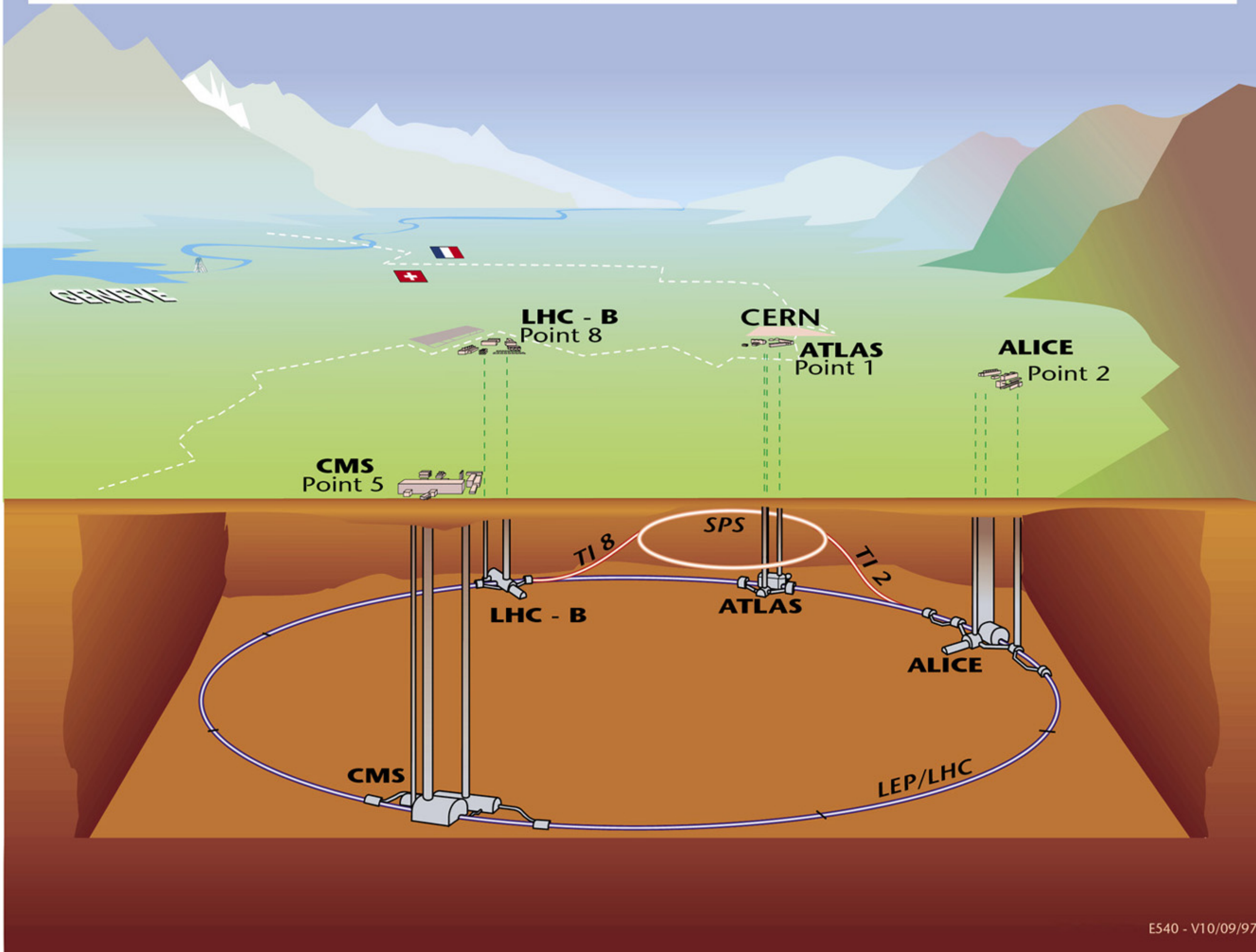
Search for conversion from μ–neutrino to τ-neutrino

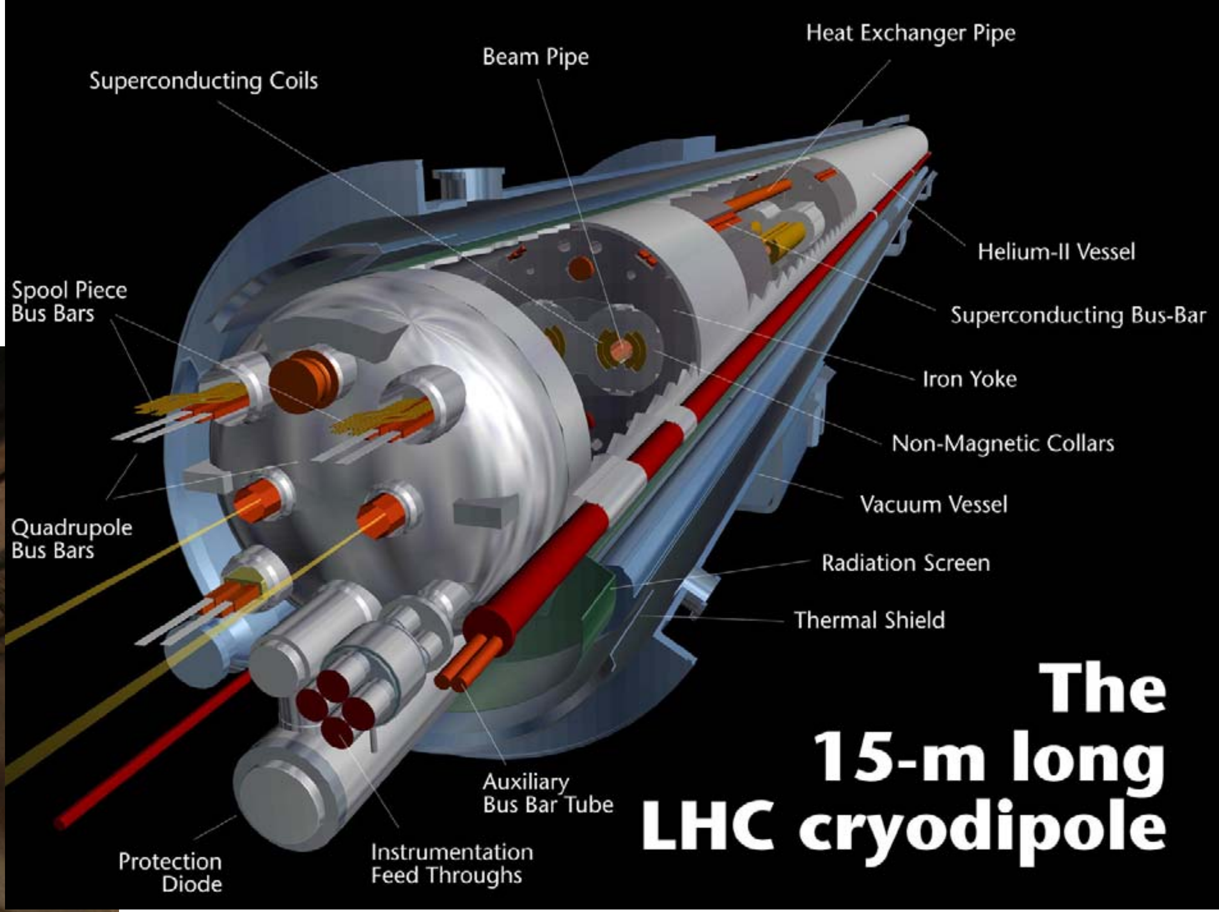


The Large Hadron Collider LHC, 7 TeV proton on proton collisions
the highest energy accelerator ever built



Overall view of the LHC experiments.

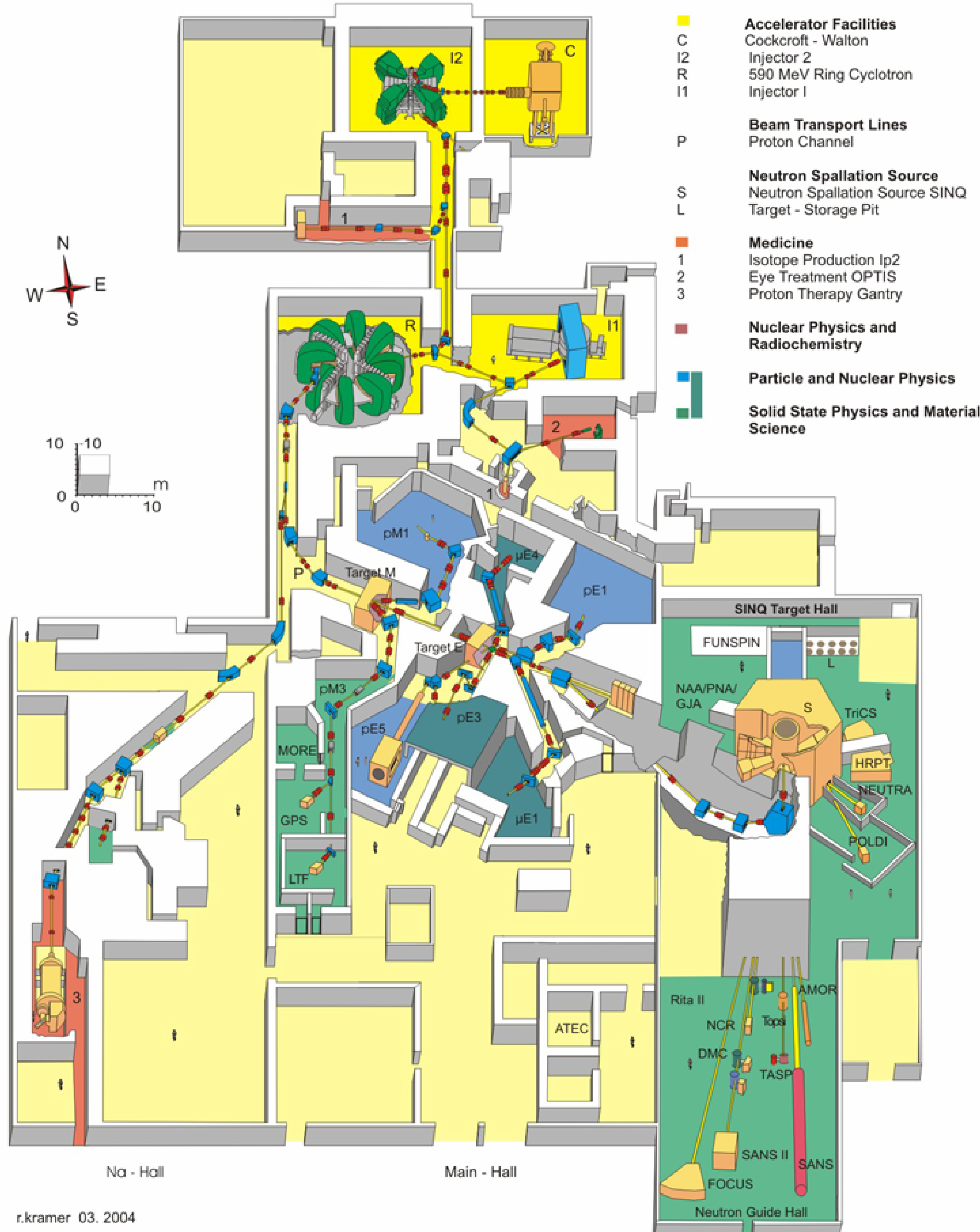




Magnetic field	8.3 T
Operating temperature	-271.1^0 C
Length	14.3 m
Total number	1232

An example how accelerator applications can evolve

PSI (Switzerland)
Experimental areas of
590 MeV , 2 mA proton
ring cyclotron,
an accelerator which was build
in the 1970’ for
nuclear and particle physics
(meson production)



More Info

Synchrotron Radiation

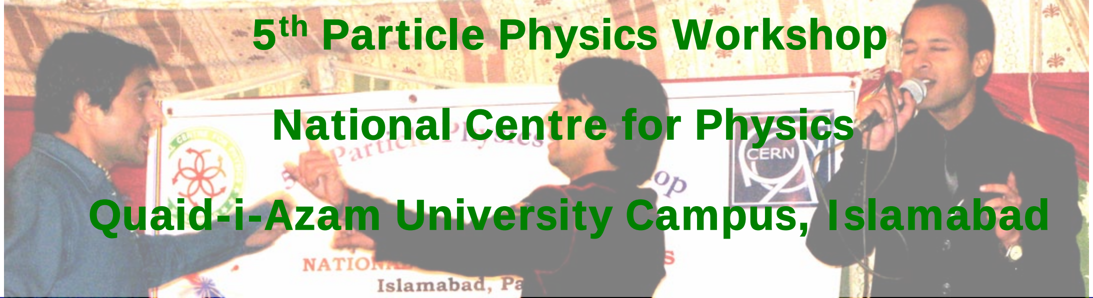
http://www.lightsources.org

**A. Hofmann, "The Physics of Synchrotron Radiation, "
Cambridge University Press, 2004**

**H. Winnick (editor), "Synchrotron Radiation Sources, A Primer,"
World Scientific, 1994**

Particle Physics

http://www.interactions.org



5th Particle Physics Workshop

National Centre for Physics

Quaid-i-Azam University Campus, Islamabad

PARTICLE BEAMS,
TOOLS FOR MODERN SCIENCE AND MEDICINE

Hans-H. Braun, CERN

3rd Lecture

Introduction to Linear e^+/e^- Colliders and CLIC
the Next Generation of Tools for Particle Physics

- o Linear Colliders - Motivation and Concept
- o Technical Challenges for Linear Colliders
- o CLIC