Lecture 17
Applications of Accelerators

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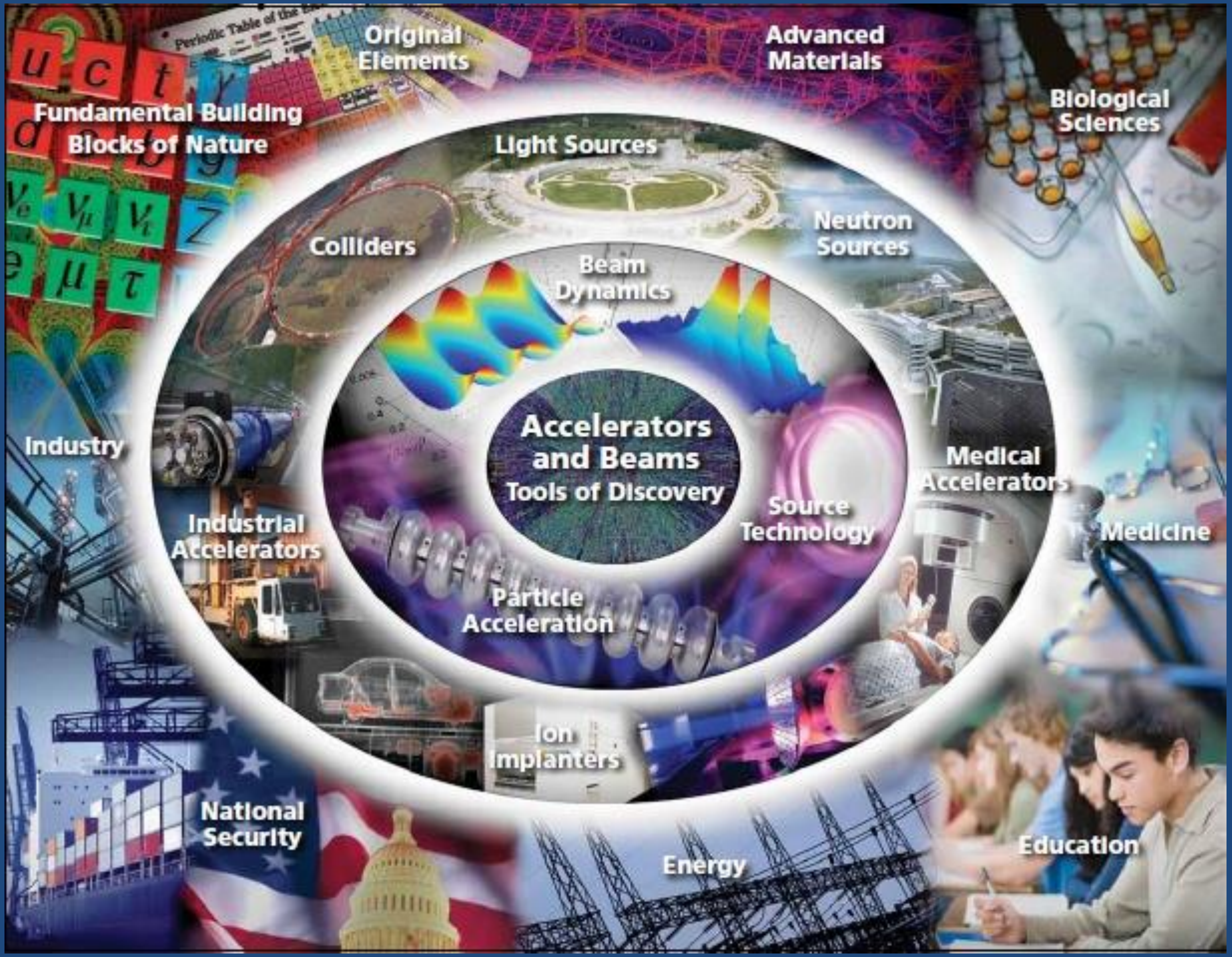
JAI Accelerator Physics Course
11 March 2015

Introduction



24 Nobel Prizes in Physics with contribution from Accelerators
plus Higgs boson discovery award in 2013

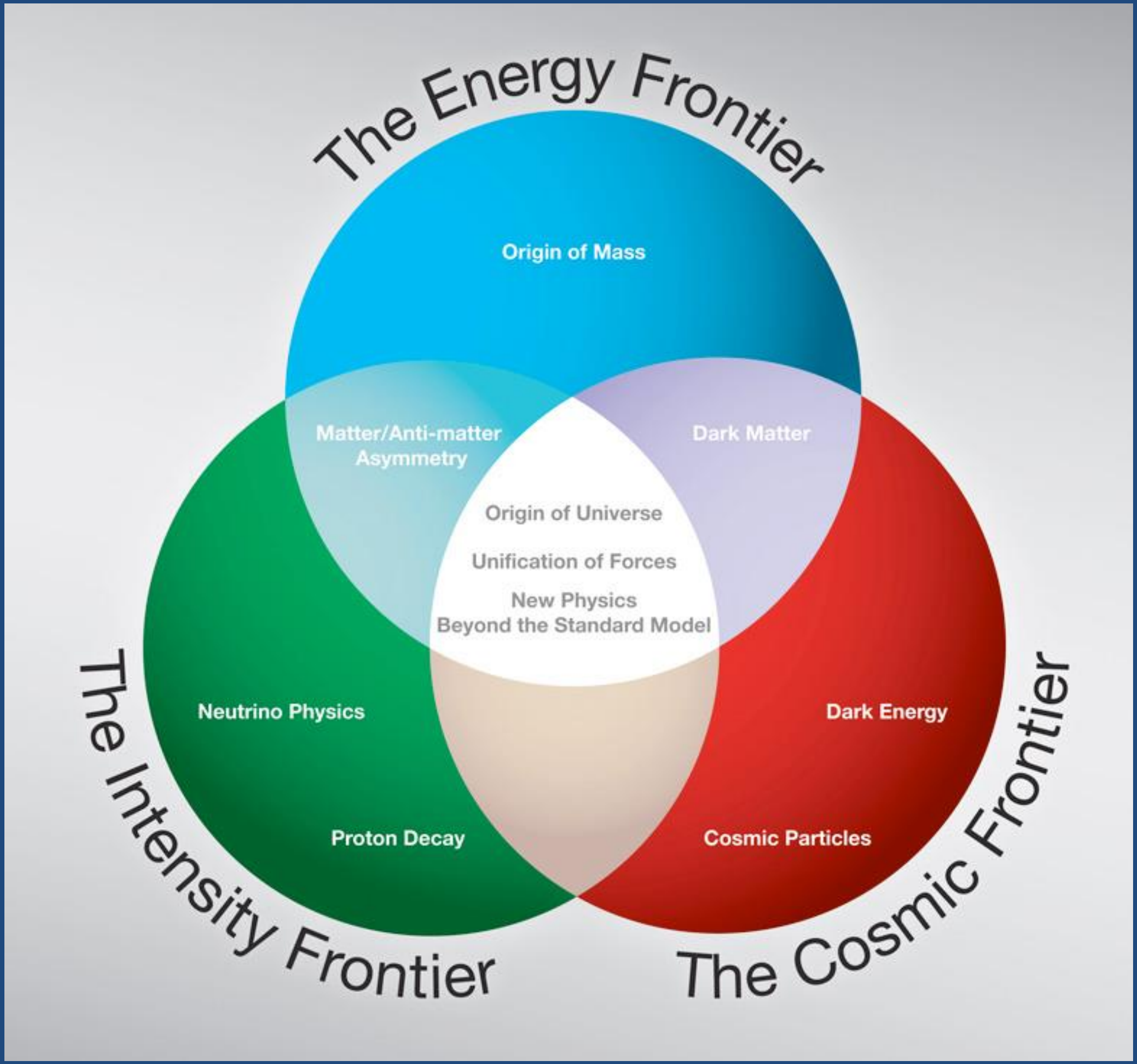
Fraction of Nobel Prizes in Physics directly connected to accelerators is ~30%

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

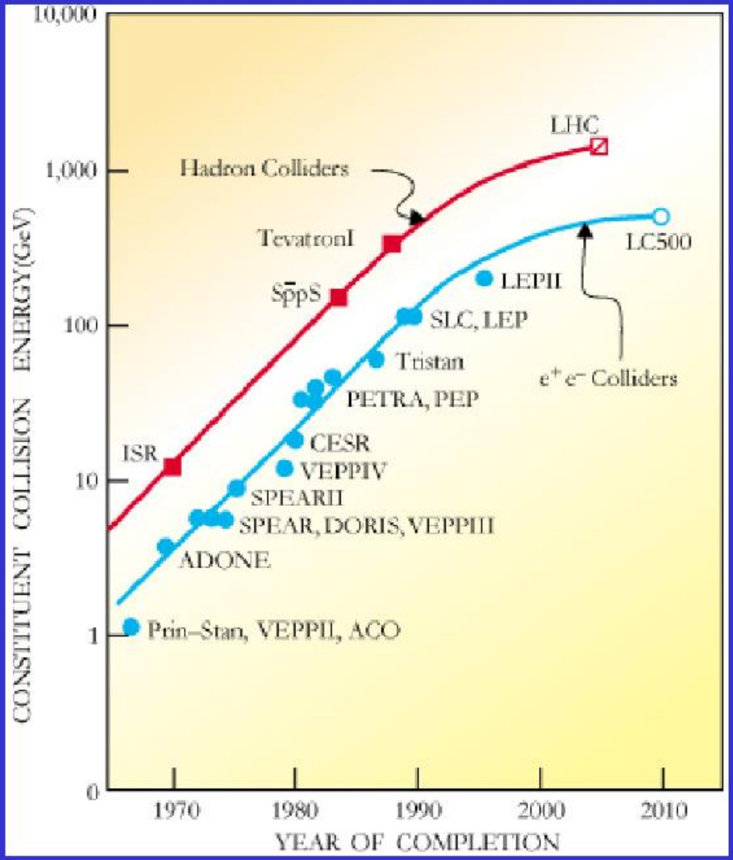
A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & submitted to the Physics in Perspective Journal, Dec 2010.

ACCELERATORS FOR DISCOVERY SCIENCE

The Three Frontiers



Colliders – Energy vs. Time



M. Tigner: "Does Accelerator-Based Particle Physics have a Future?" Physics Today, Jan 2001 Vol 54, Nb 1

The Livingston plot shows a saturation effect!

Practical limit for accelerators at the energy frontier:

Project cost increases as the energy must increase!

Cost per GeV C.M. proton has decreased by factor 10 over last 40 years (not corrected for inflation)!

Not enough: Project cost increased by factor 200!

New technology needed…

Colliders - 2006

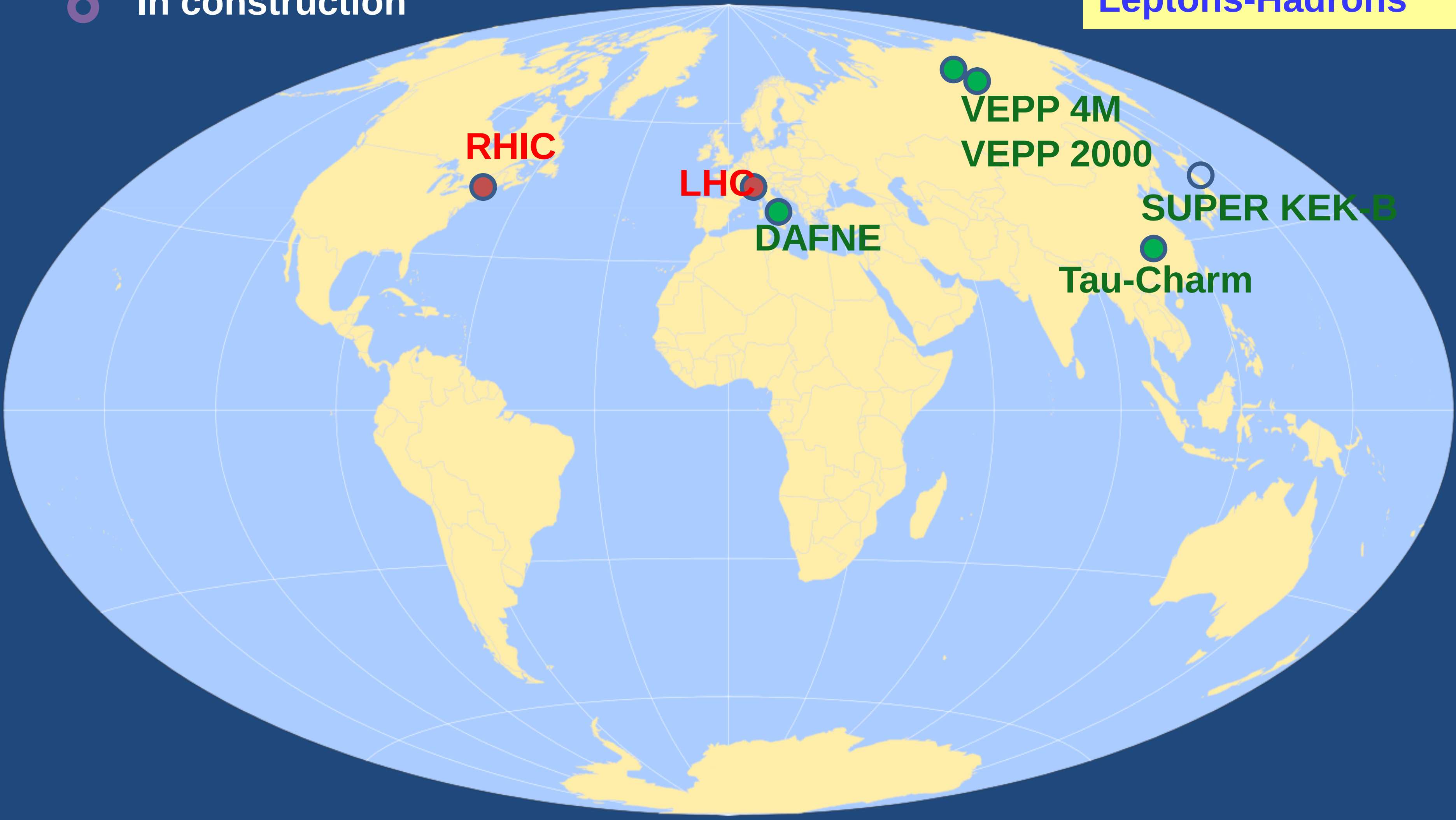
- In operation
- In construction

Hadrons
Leptons
Leptons-Hadrons

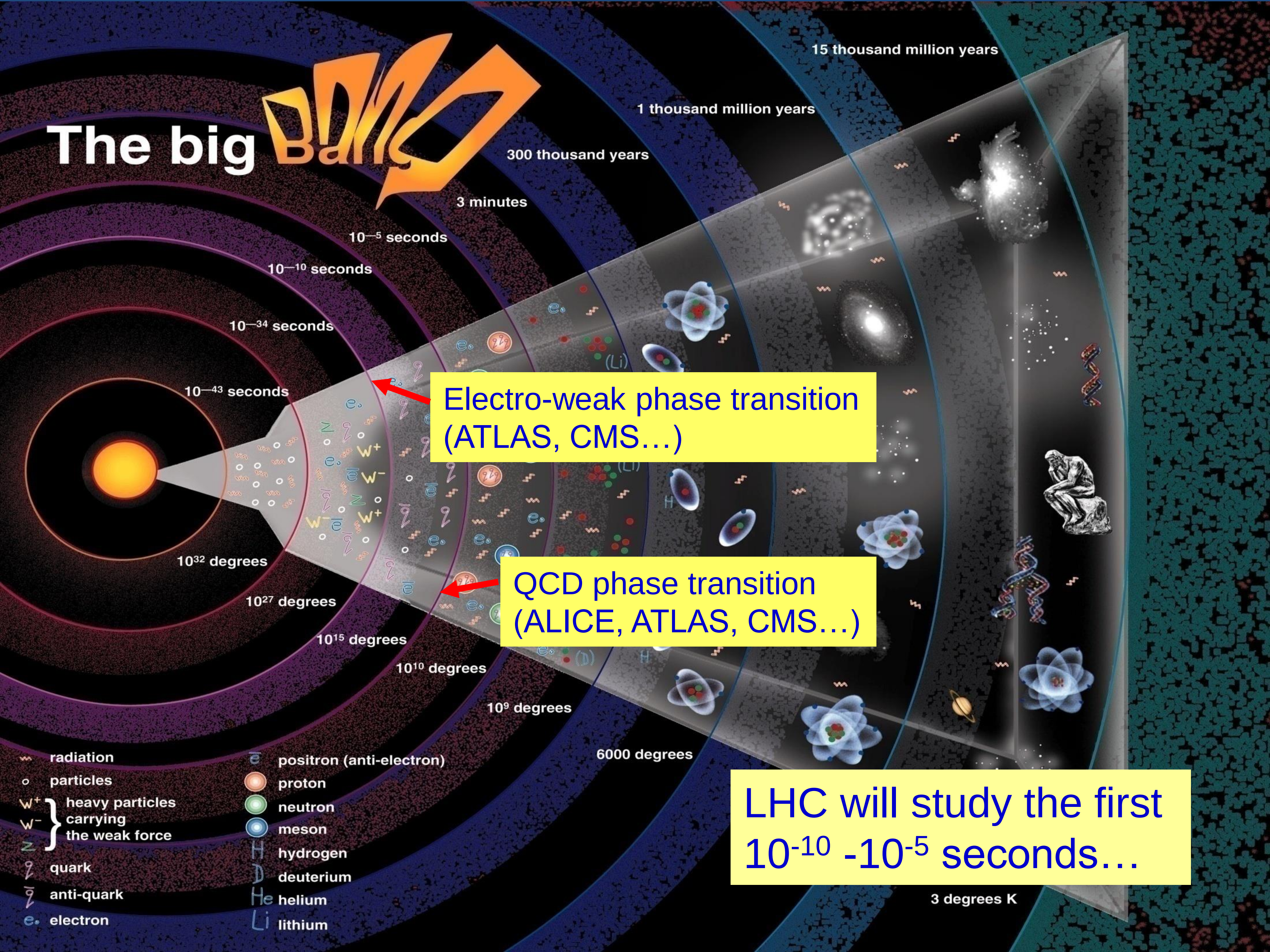
Colliders - 2012

- In operation
- In construction

Hadrons
Leptons
Leptons-Hadrons



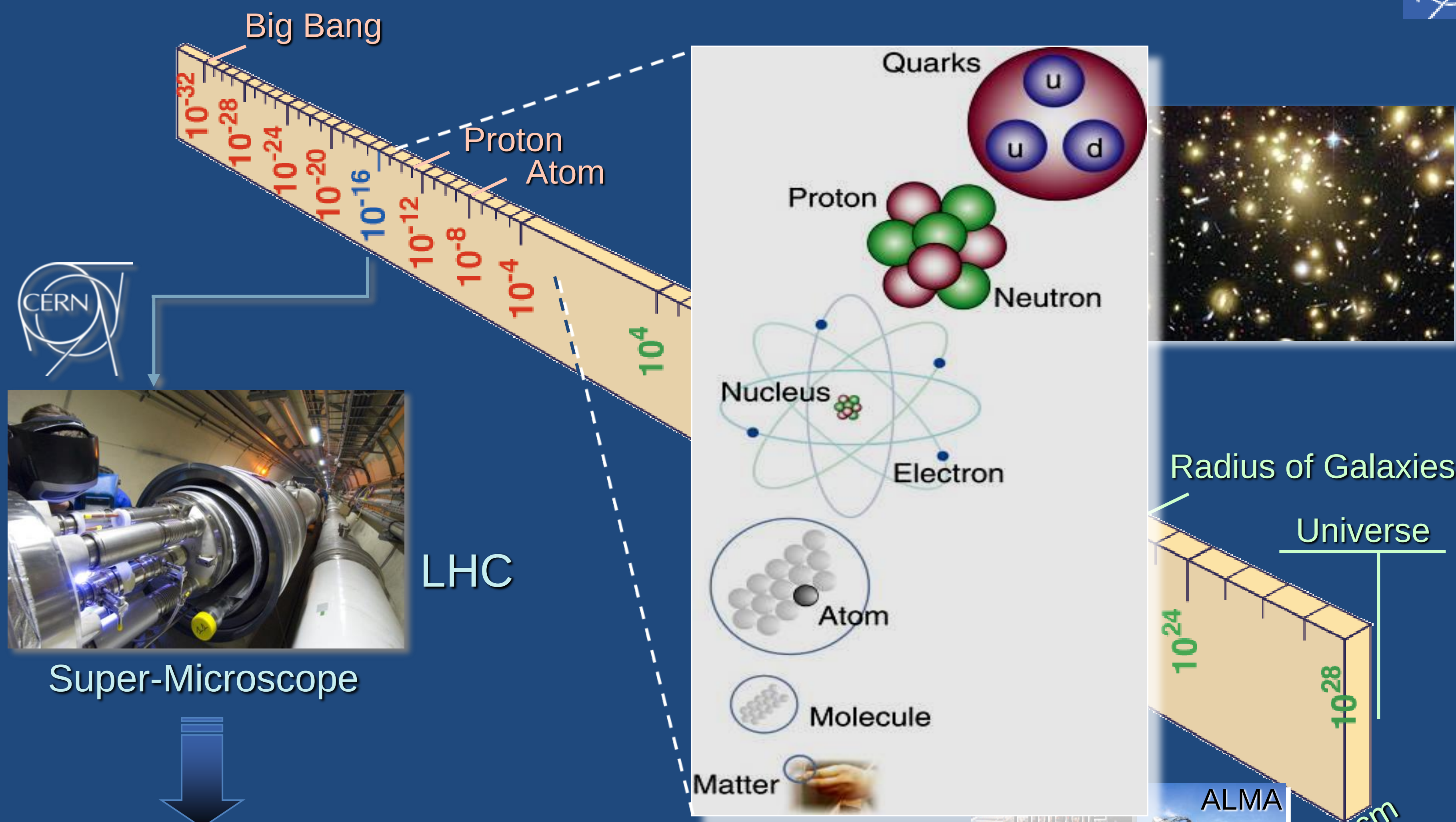
THE
LARGE HADRON COLLIDER



Electro-weak phase transition (ATLAS, CMS…)

QCD phase transition (ALICE, ATLAS, CMS…)

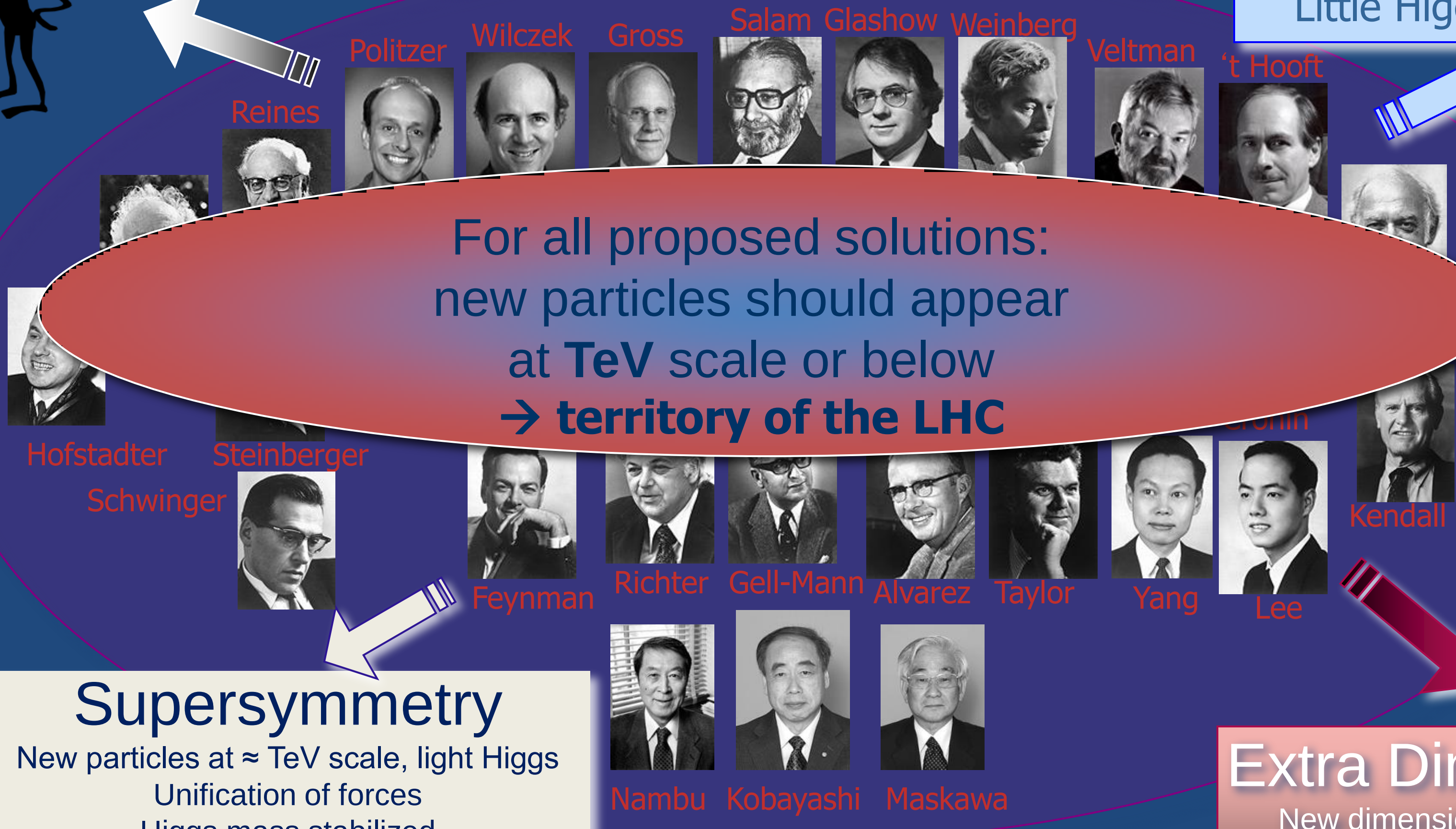
LHC will study the first 10^{-10} -10^{-5} seconds…



Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

Solutions?

Standard Model



For all proposed solutions:
new particles should appear
at **TeV** scale or below
→ territory of the LHC

Technicolor
New (strong) interactions produce EWSB

Extensions of the SM gauge group :
Little Higgs / GUTs / ...

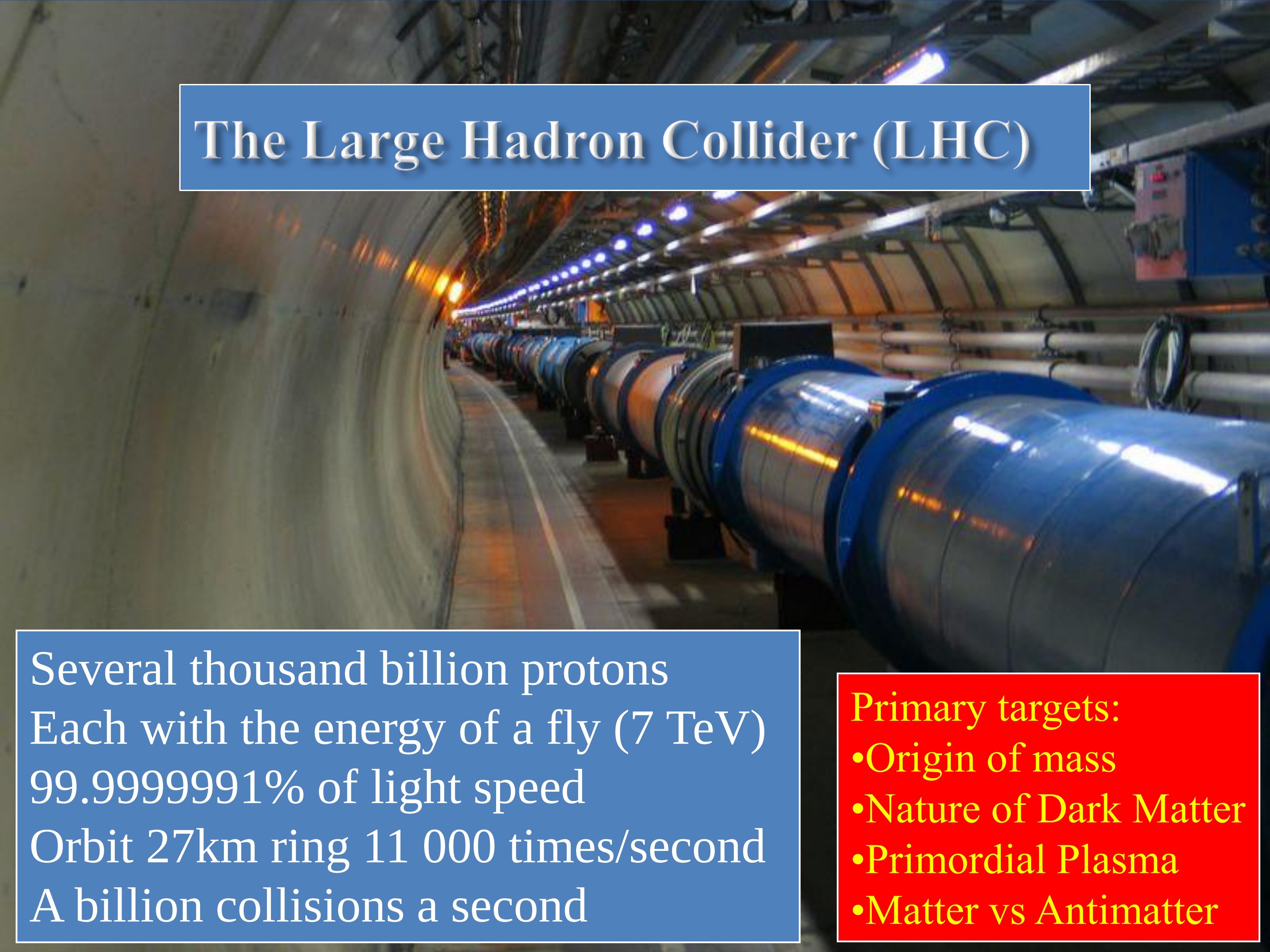
Selected NP
since 1957
Except P. Higgs

Supersymmetry
New particles at ≈ TeV scale, light Higgs
Unification of forces
Higgs mass stabilized
No new interactions

Extra Dimensions
New dimensions introduced
$m_{Gravity} \approx m_{elw}$ ➲ Hierarchy problem solved
New particles at ≈ TeV scale

Successful for ever ??

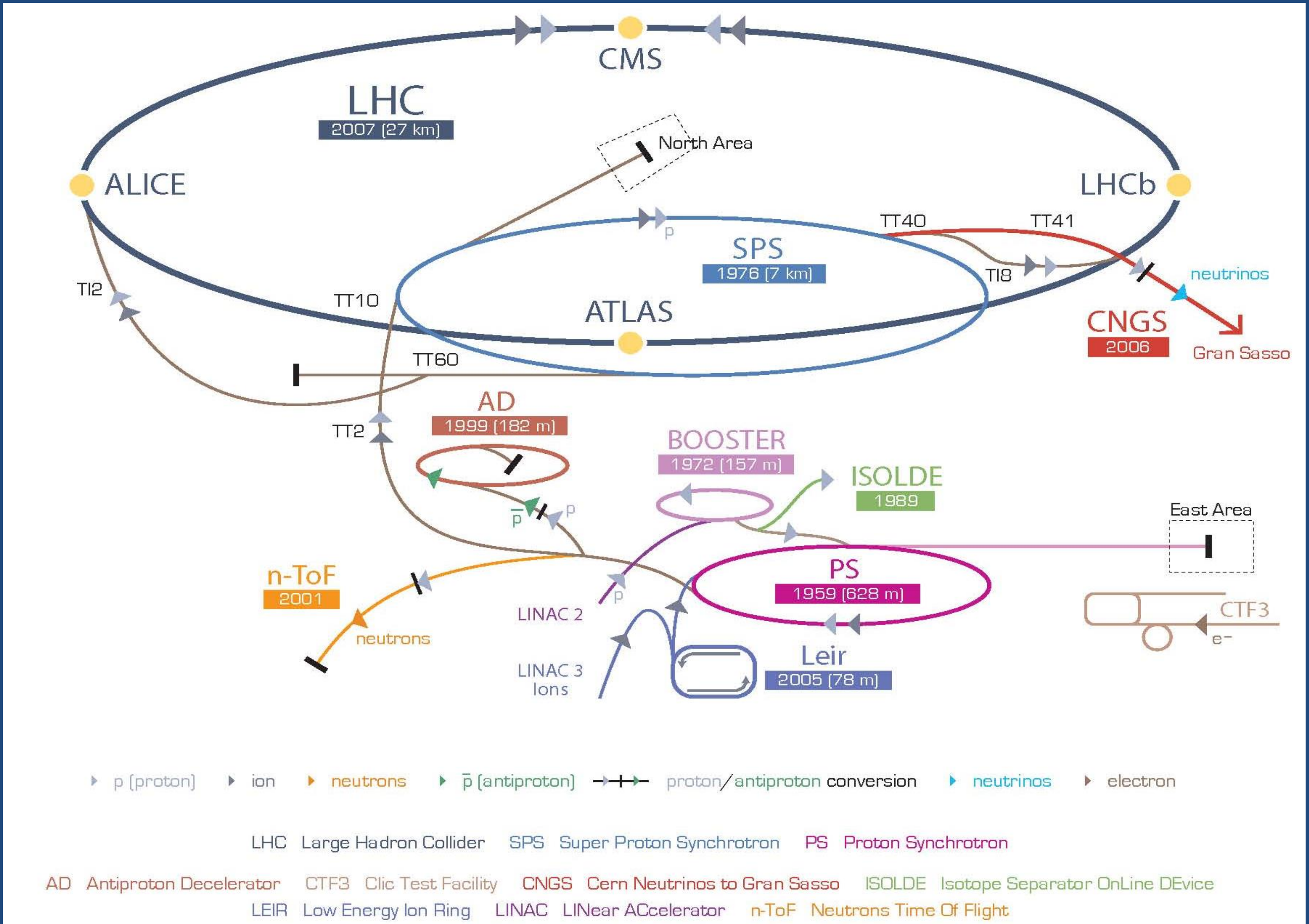
The Large Hadron Collider (LHC)



Several thousand billion protons
Each with the energy of a fly (7 TeV)
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

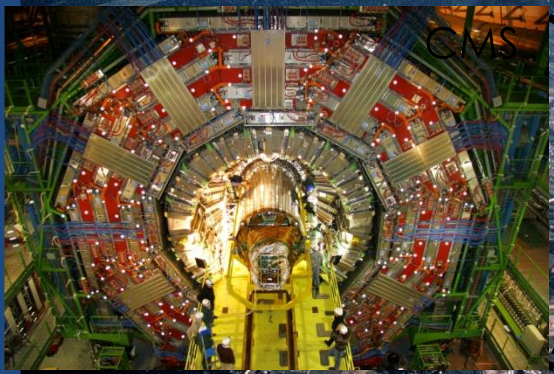
Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

CERN Accelerator Complex

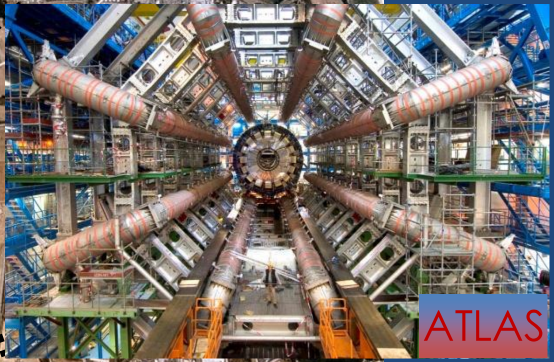


Entered a New Era in Fundamental Science

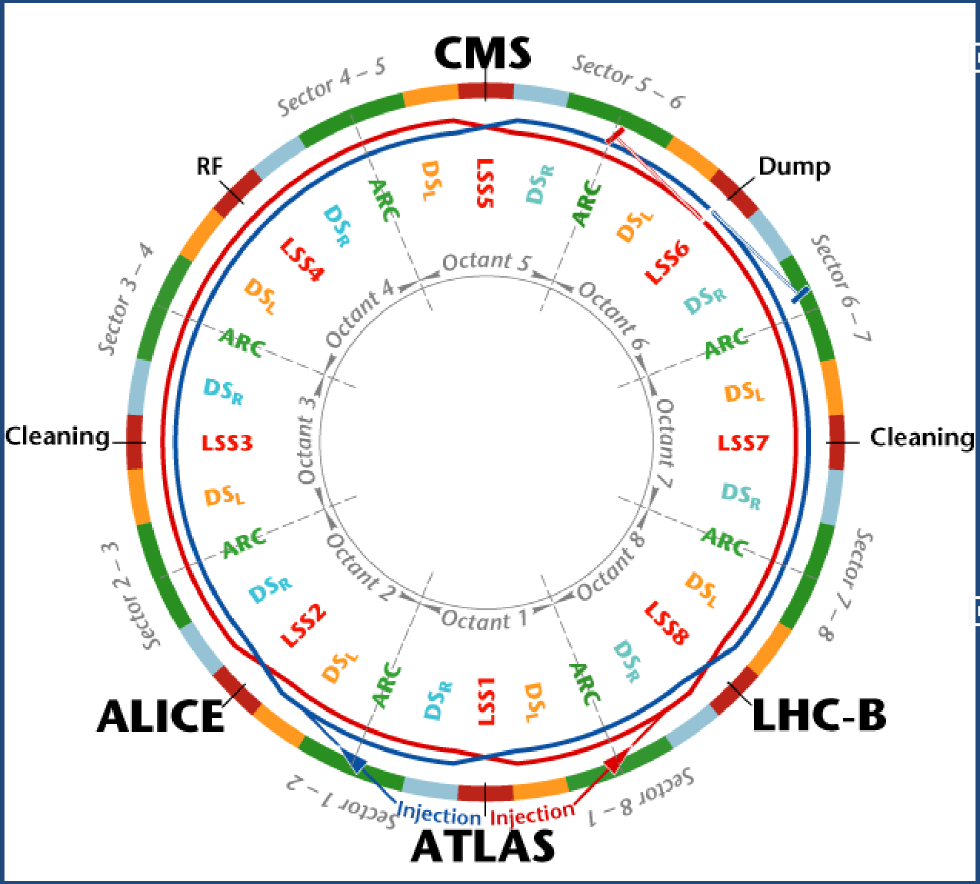
Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.



Exploration of a new energy frontier
Proton-proton collisions at E_{CM} = 14 TeV

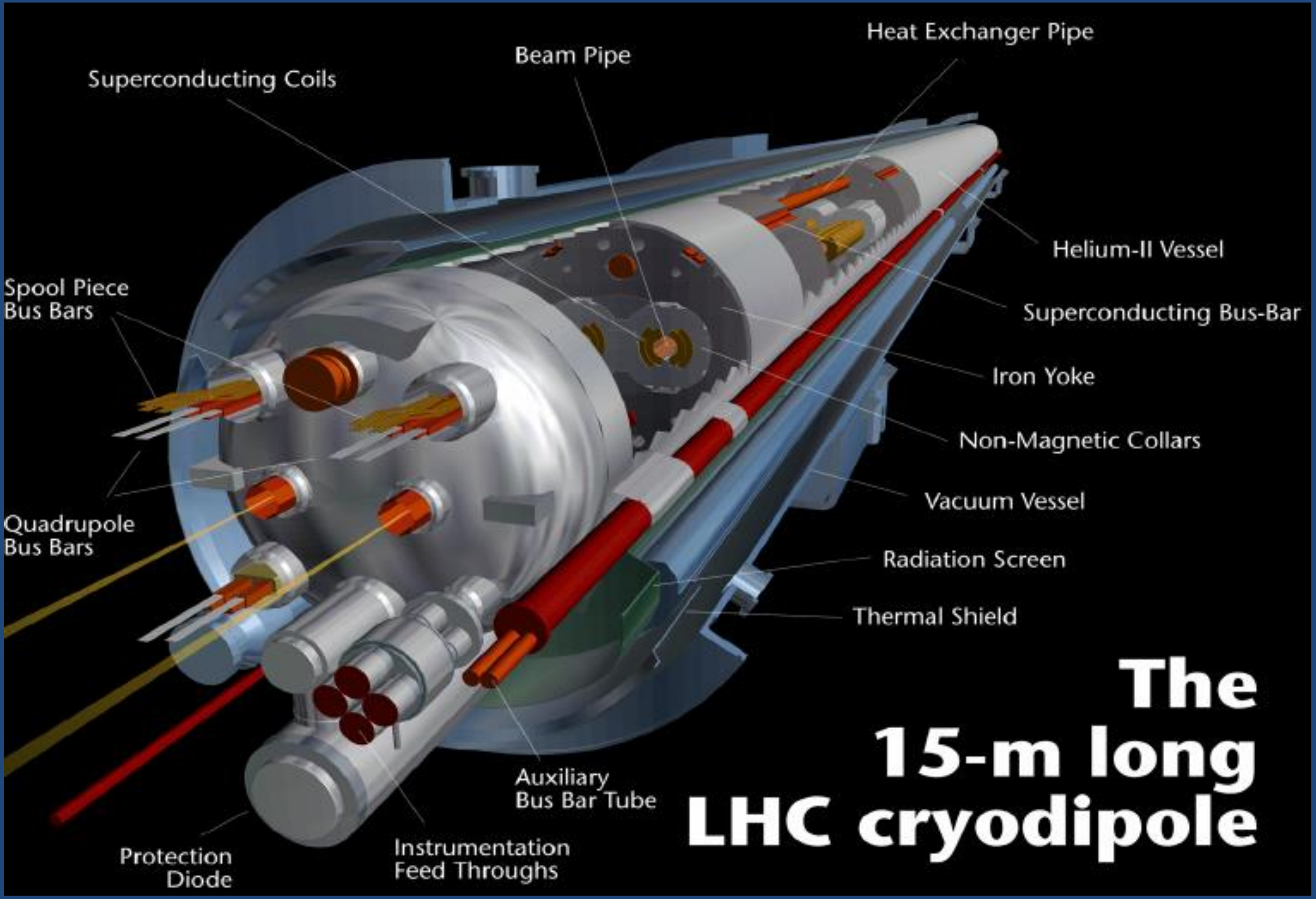


LHC Lay-out



- The LHC is a two-ring superconducting proton-proton collider made of eight 3.3 km long arcs separated by 528 m Long Straight Sections.
- While the arcs are nearly identical, the straight sections are very different.

LHC Main Bending Cryodipole

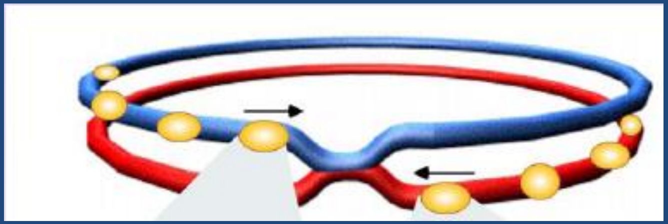


8.5 T
nominal field

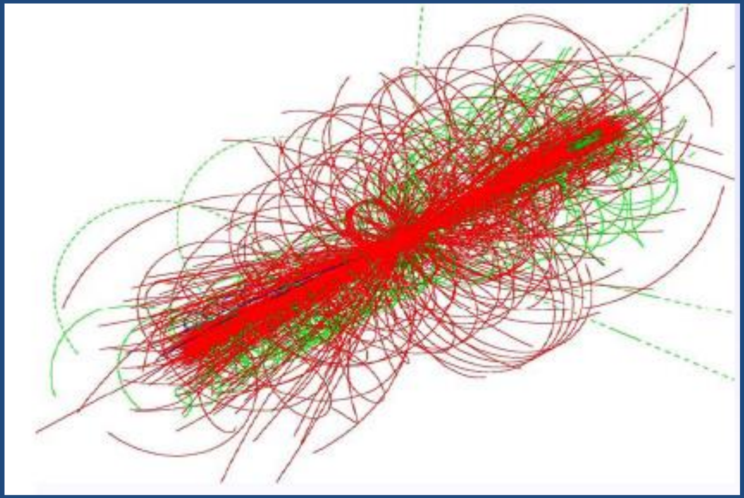
12 kA
nominal current

The LHC Arcs

Proton-Proton Collisions at the LHC



Design Energy:
7 + 7 = 14 TeV



- 2808 + 2808 proton bunches
  separated by 7.5 m
  → collisions every 25 ns
  = 40 MHz crossing rate

- 10^{11} protons per bunch

- at 10^{34}/cm^2/s
  ≈ 35 pp interactions per crossing
  pile-up

→ ≈ 10^9 pp interactions per second !!!

- in each collision
  ≈ 1600 charged particles produced

enormous challenge for the detectors
and for data collection/storage/analysis

Why do Things Weigh?

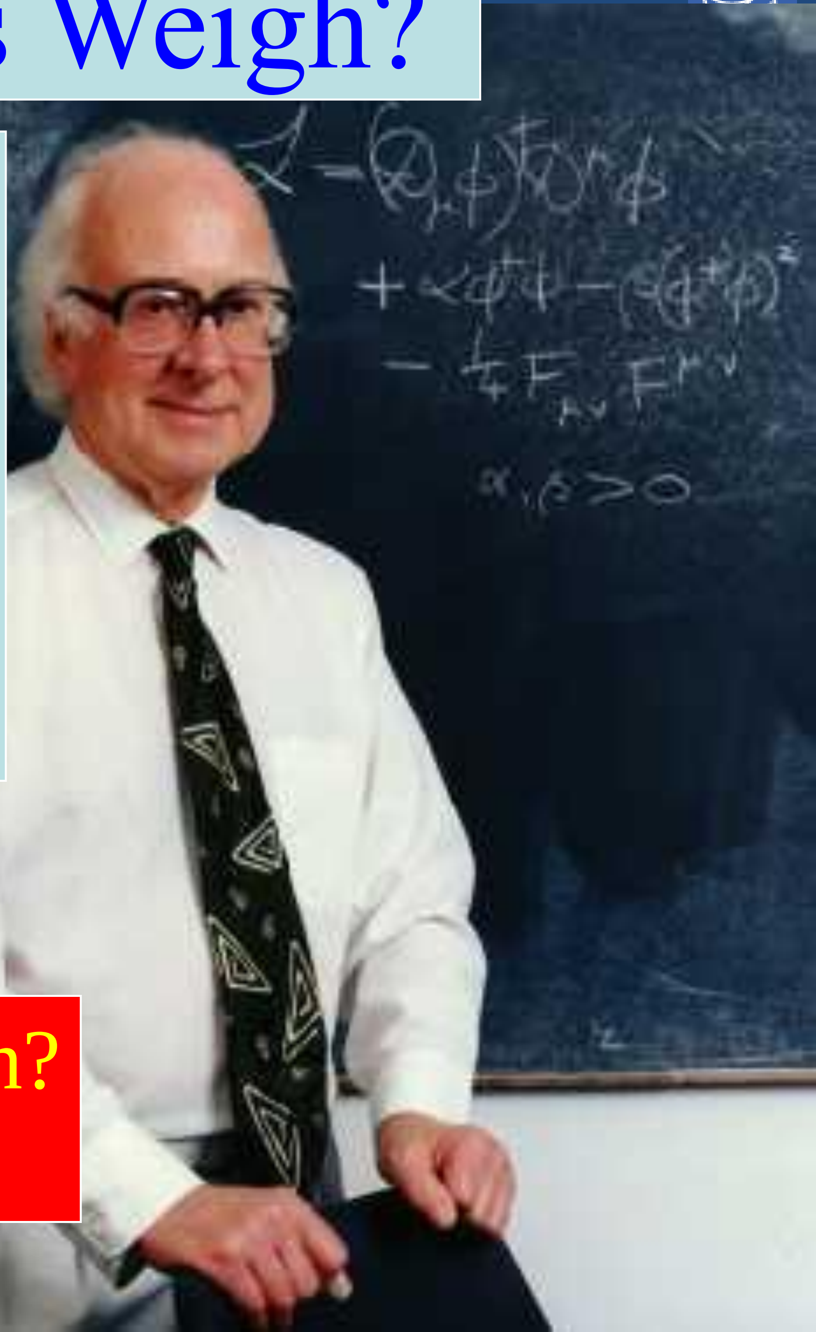
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



Where do the masses come from?

Are masses due to Higgs boson?
(the physicists' Holy Grail)

Higgs Boson

All particles generated at the Big Bang without mass.

Interacting with the Higgs field, particles acquire mass.

Greater the interaction, the greater the mass.

Higgs field fills the whole universe.

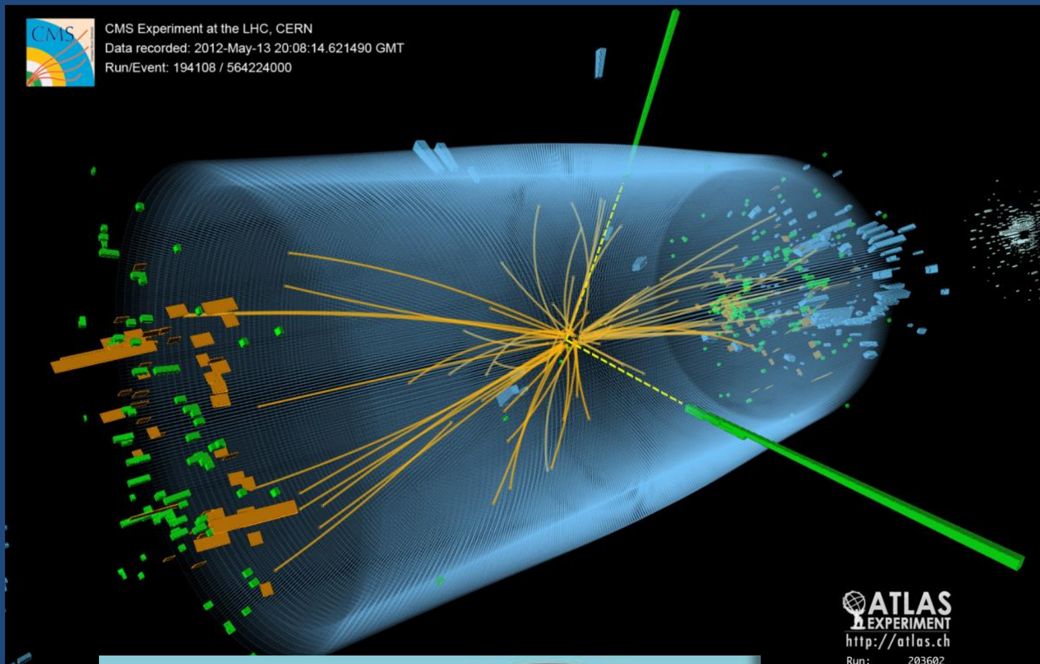
British physicist Peter Higgs proposed (1964) the so-called Higgs Boson particle associated with eponymous mechanism & field.

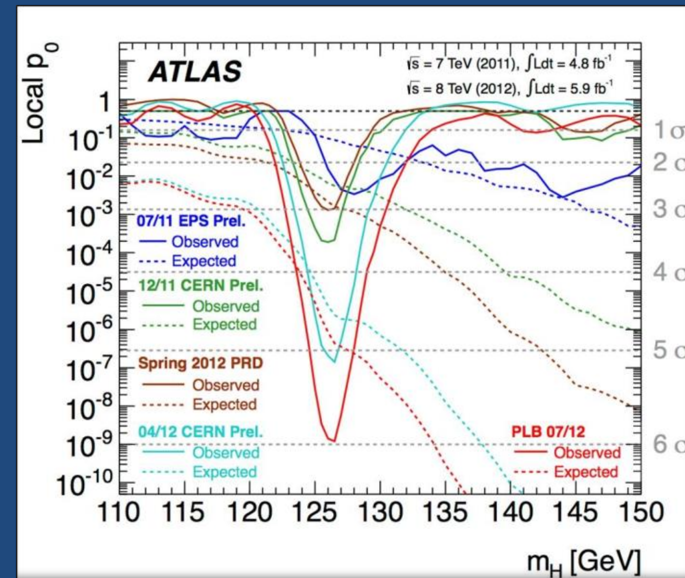
Interaction with the Higgs field

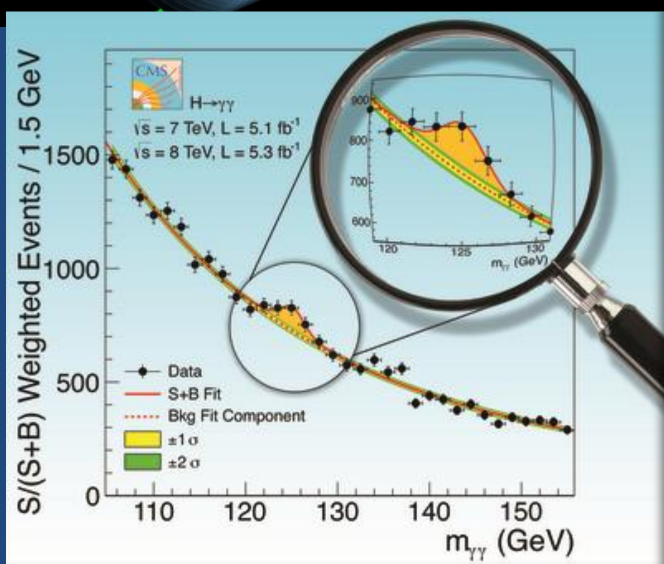
≡

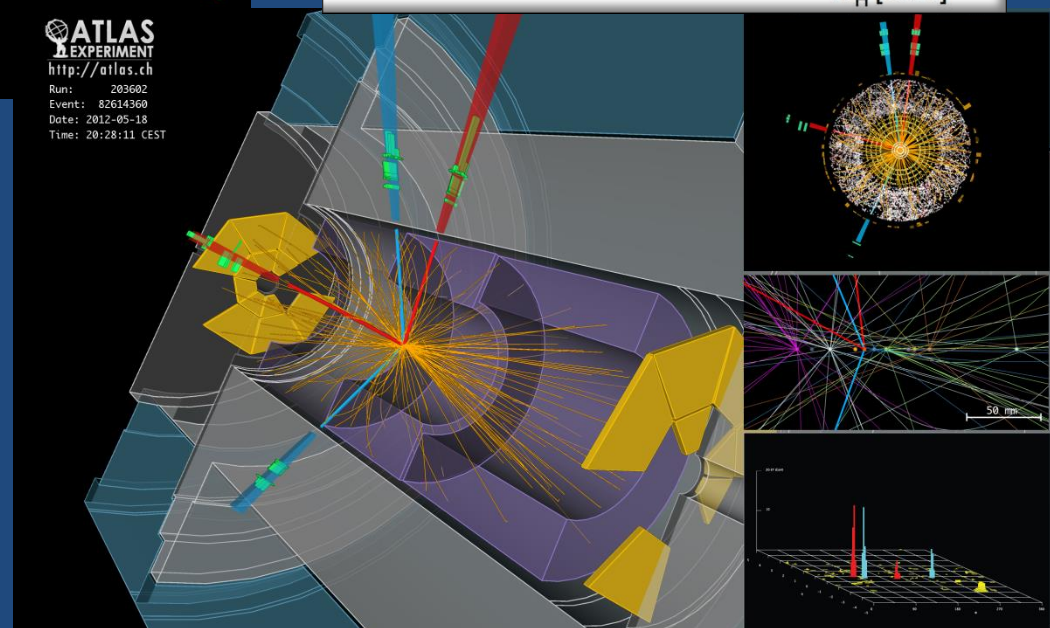
Friction with viscous liquid

4 July 2012
“CERN experiments observe particle consistent with long-sought Higgs boson”









An impressive history…

Acknowledgements

- A very wide range of measurements have shown that SM predictions for known physics have been ~spot on.
  - A tribute to a large amount of work done by our theory colleagues along with the results from the other collider experiments at LEP, Tevatron, HERA, b-factories etc.
- And the Higgs cross section WG and all those theorists who prepared the way for today!

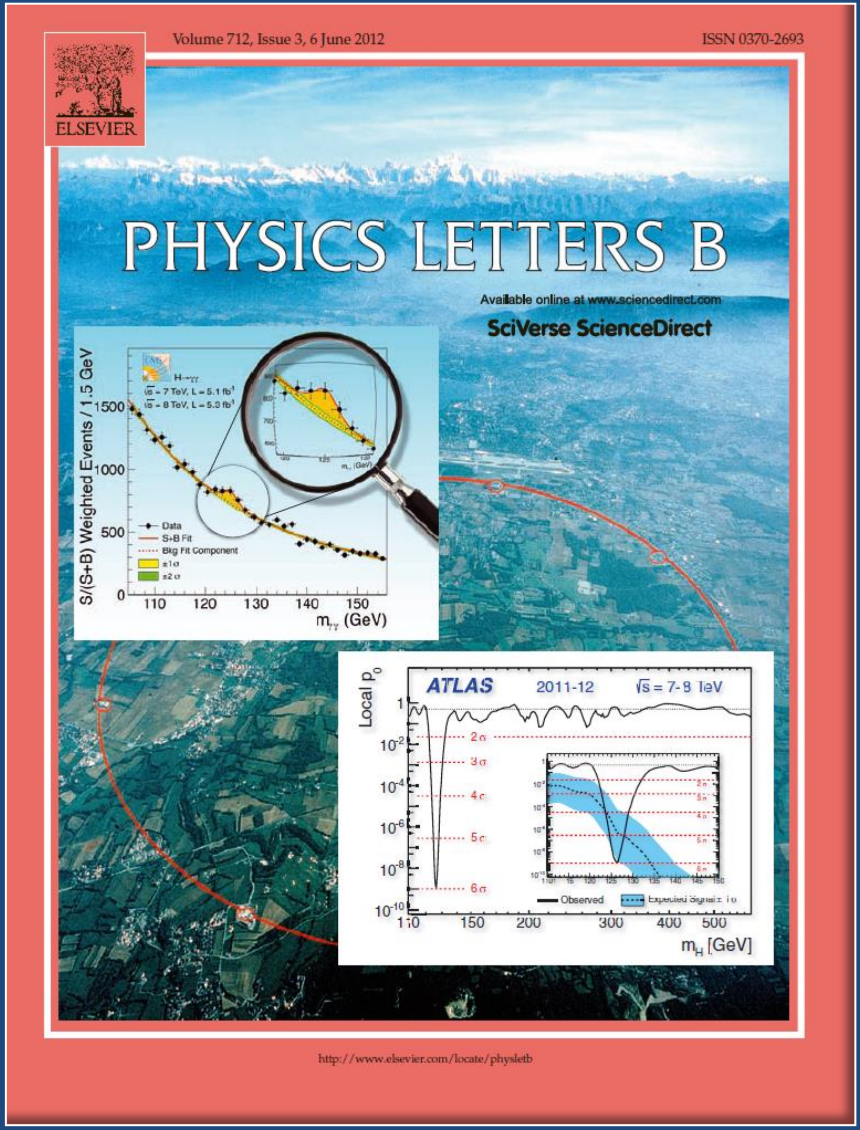
Electroweak Theory

[1] S. Glashow, Nucl. Phys. 22 (1961) 579, doi:10.1016/0029-5582(61)90469-2.
[2] S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264, doi:10.1103/PhysRevLett.19.1264.
[3] A. Salam, Weak and electromagnetic interactions, in: N. Svartholm (Ed.), Elementary Particle Physics: Relativistic Groups and Analyticity, Proceedings of the Eighth Nobel Symposium, Almquvist and Wiskell, 1968, p. 367.

Electroweak Symmetry Breaking

[4] F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964) 321, doi:10.1103/PhysRevLett.13.321.
[5] P.W. Higgs, Phys. Lett. 12 (1964) 132, doi:10.1016/0031-9163(64)91136-9.
[6] P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508, doi:10.1103/PhysRevLett.13.508.
[7] G. Guralnik, C. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585, doi:10.1103/PhysRevLett.13.585.
[8] P.W. Higgs, Phys. Rev. 145 (1966) 1156, doi:10.1103/PhysRev.145.1156.
[9] T.W.B. Kibble, Phys. Rev. 155 (1967) 1554, doi:10.1103/PhysRev.155.1554.

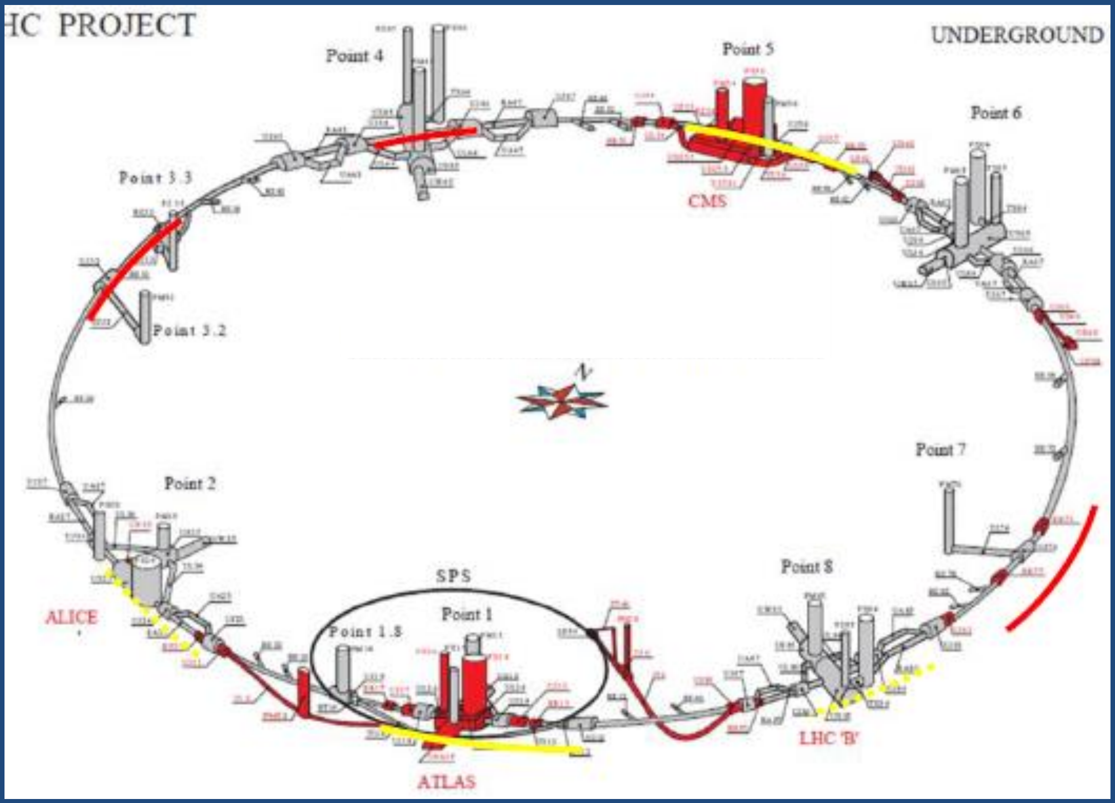
The Highlight of a Remarkable Year 2012



Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "*for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider*".

The HL-LHC Project



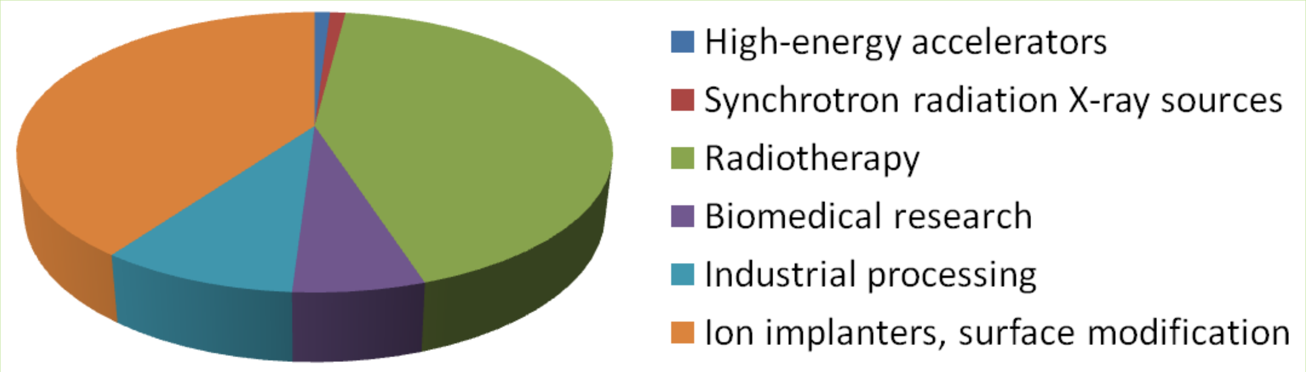
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection…

Major intervention on more than 1.2 km of the LHC

ACCELERATOR TECHNOLOGY TRANSFER

Accelerators Worldwide

The number of accelerators worldwide exceed 20000



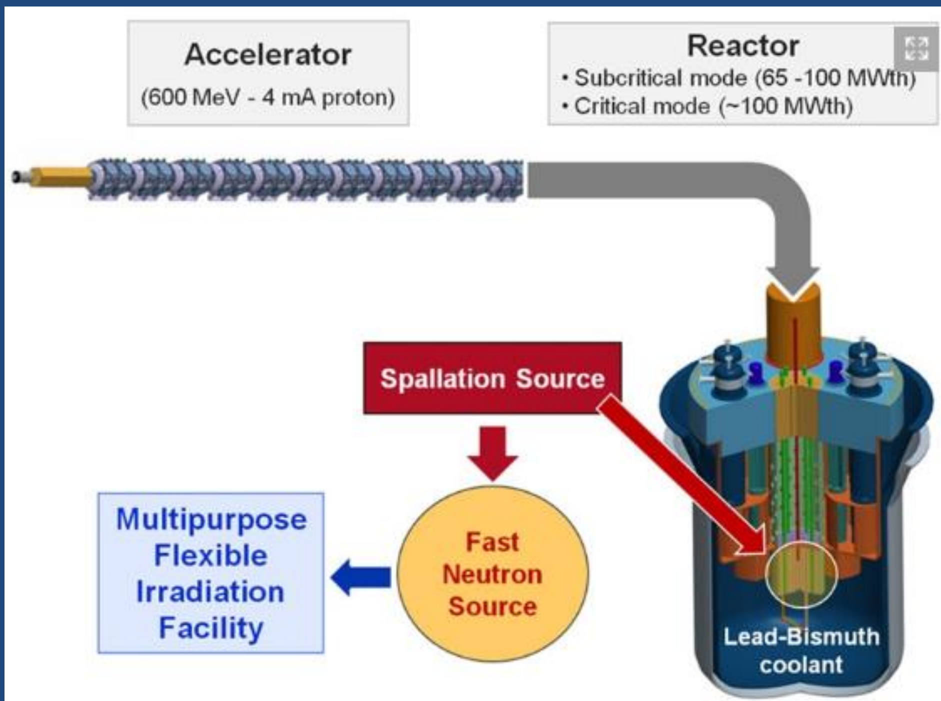
- Market for **medical and industrial** accelerators exceeds **$3.5 billion**. All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500 billion [1]

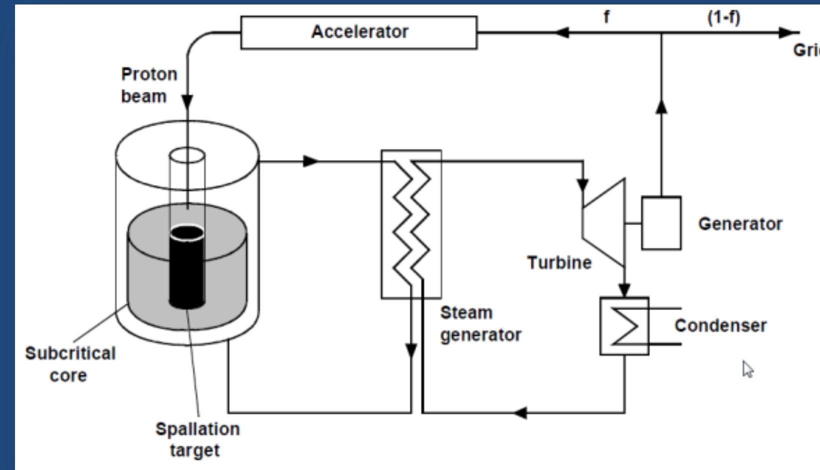
[1] http://www.acceleratorsamerica.org/

Accelerators are not only for high-energy physics

Accelerators for Energy

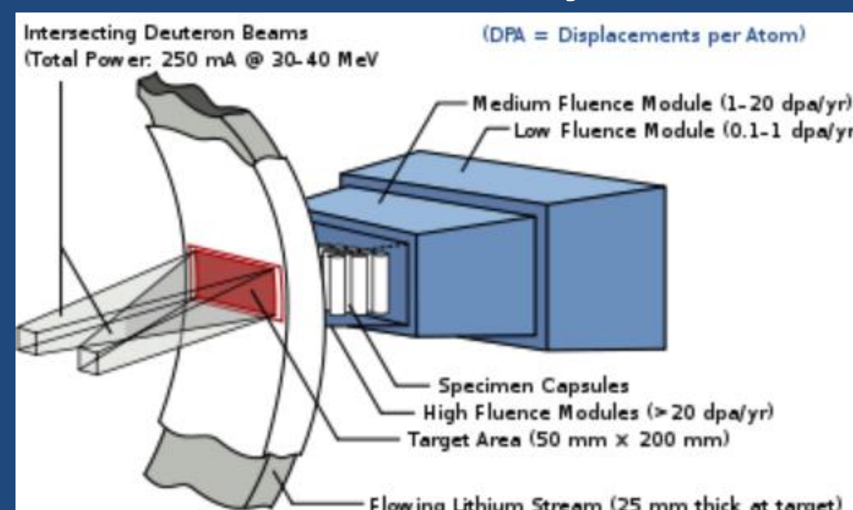
Accelerators can drive next-generation reactors (ADSR) that burn non-fissile fuel, such as thorium





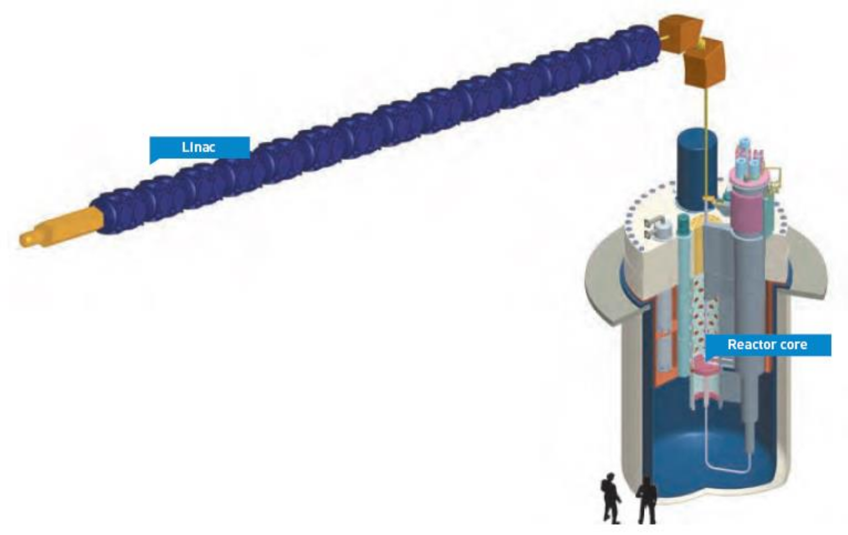
MYRRHA: Multi-purpose hybrid research reactor for high-tech applications, conceived as an accelerator driven system

International Fusion Material Irradiation Facility (IFMIF)



Accelerators for Energy

- Accelerator-Driven Subcritical System (ADS)
  - External source of neutrons to drive sub-critical reactor loaded with non-fissile fuel such as ^{232}Th.
  - Neutrons produced by high-power proton beam through spallation, breeding ^{233}U causing it to fission.
  - Cannot support self-sustaining chain reaction.
  - ^{232}Th is widely-available natural resource.
  - Released thermal power is 100 times that of beam energy.
  - Turning off the accelerator stops the fission reaction.



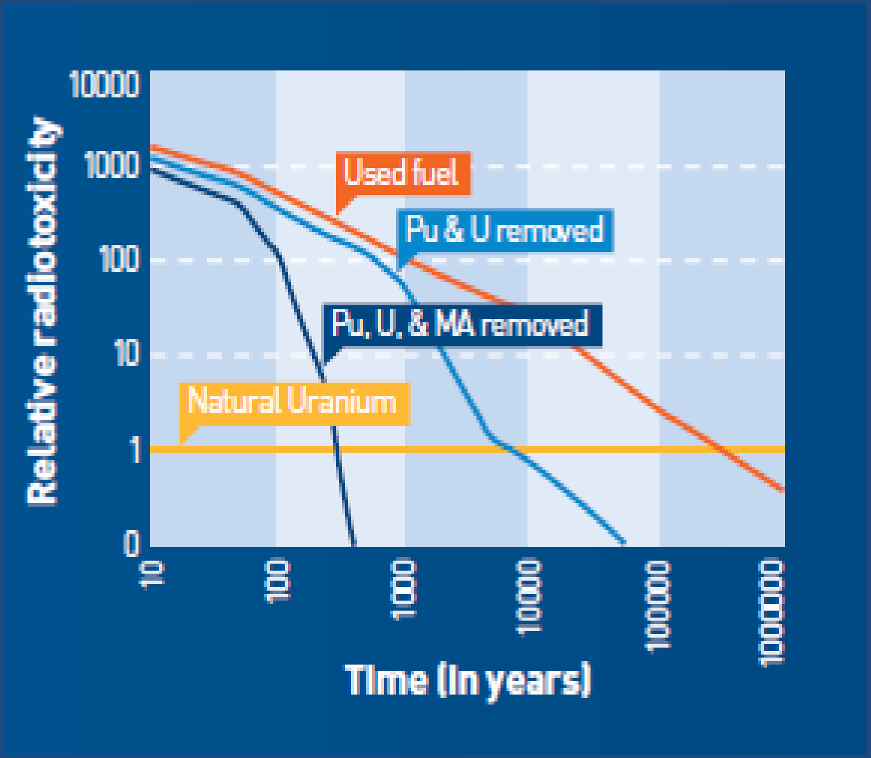
Use of Th instead of U produces less actinides.

Th cycle produces much less long-lived radioactive waste (e.g. Pu).

Enough Th is available to sustain such systems for 10 centuries.

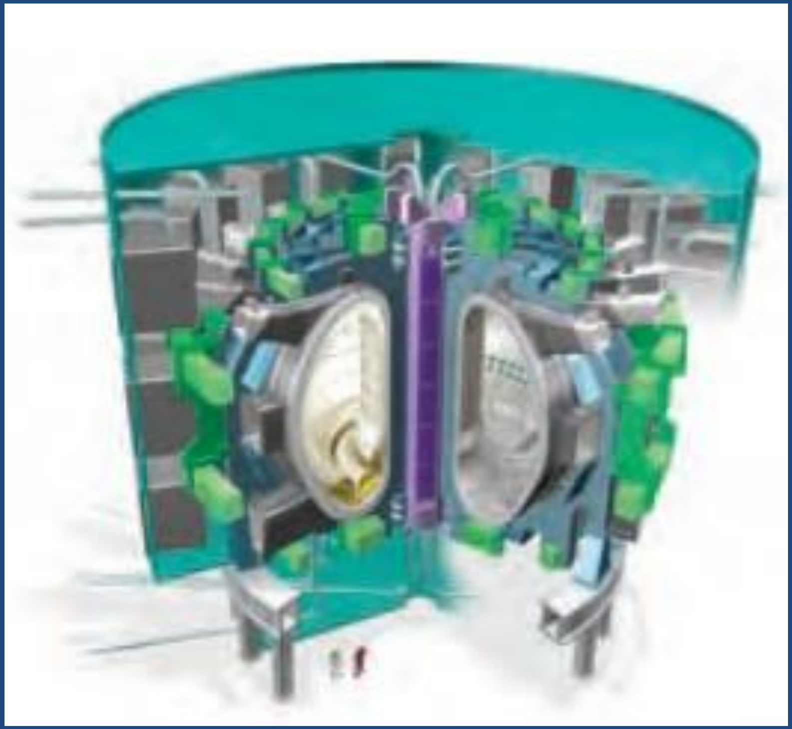
Accelerators for Energy

- ADS & Radioactive Waste Transmutation
  - ADS neutrons interact with surrounding fuel material containing separated long-lived isotopes.
    - Transmute these isotopes into shorter-lived products.



Accelerators for Energy

- International Thermonuclear Experimental Reactor (ITER)
  - Ion beams to be part of plasma heating techniques for fusion
    - Provide high current drive efficiency required magnetic confinement fusion facilities.
    - Required tens of A of ion current at 1 MeV kinetic energy.

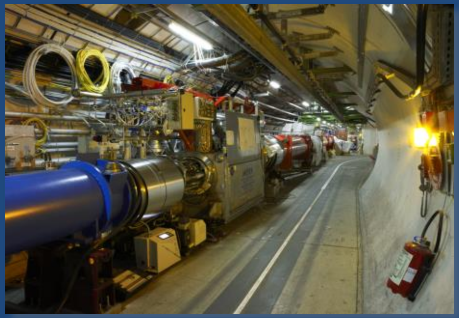


Accelerators for the Environment

- CLOUD experiment at the CERN PS
  - Experiment using cloud chamber to study possible link between cosmic- rays and cloud formation.
    - Studies suggest that cosmic-rays may have an influence on the amount of cloud cover through the formation of new aerosols (tiny particles suspended in the air that seed cloud droplets).
  - Understanding the underlying microphysics in controlled laboratory conditions is a key to unraveling the connection between cosmic-rays, clouds and climate.
  - First time high-energy physics accelerator used to study atmospheric and climate science.

Medical Application as an Example of Particle Physics Spin-off

Combining Physics, ICT, Biology and Medicine to fight cancer

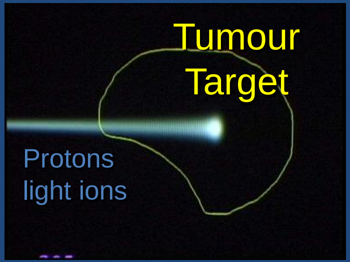


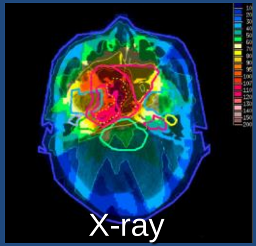
Accelerating particle beams

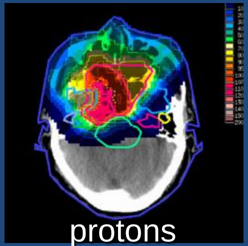
~30’000 accelerators worldwide

~17’000 used for medicine

Hadron Therapy



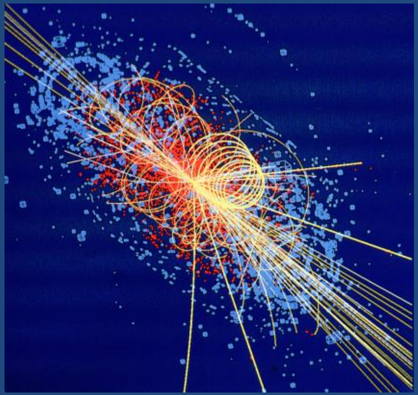




Leadership in Ion Beam Therapy now in Europe and Japan

>100’000 patients treated worldwide (45 facilities)

>50’000 patients treated in Europe (14 facilities)

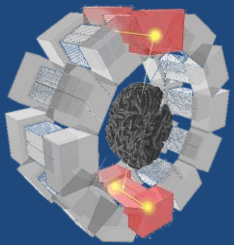


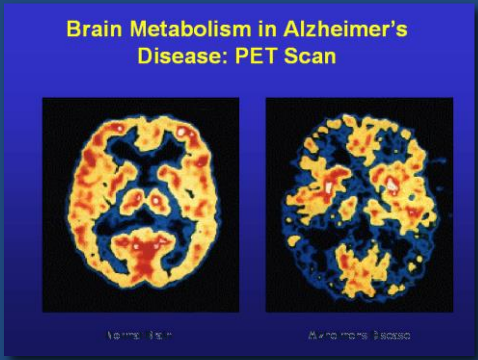
Detecting particles

Imaging

Clinical trial in Portugal, France and Italy for new breast imaging system (ClearPEM)

PET Scanner





Accelerators for Medical Use

- **Production of radionuclides with (low-energy) cyclotrons**
  - **Imaging**
  - Therapy
- **Electron linacs for conventional radiation therapy.**
- **Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u 12C-ions).**

Accelerators for Medicine

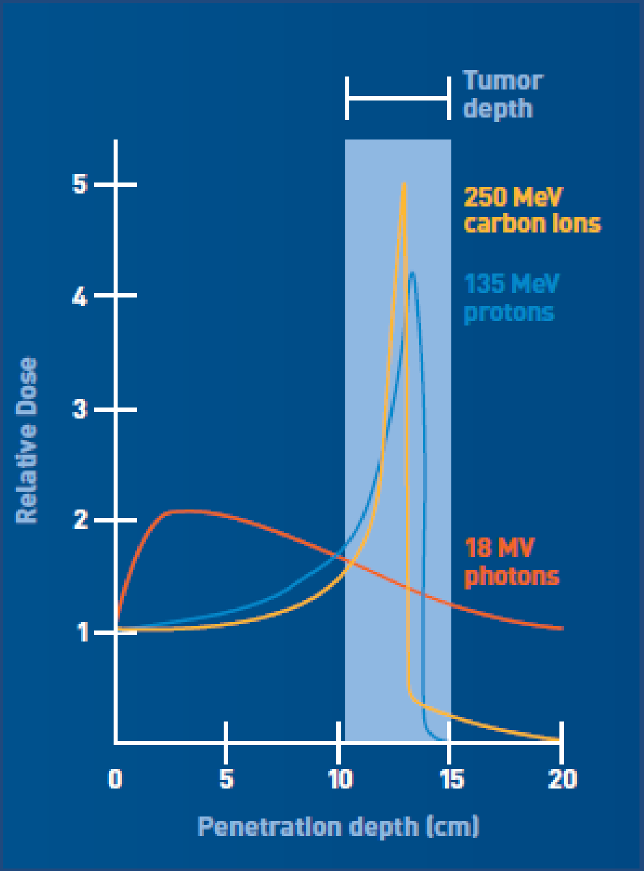
- Medical Therapy
  - X-rays have been used for decades to destroy tumours.
  - For deep-seated tumours and/or minimizing dose in surrounding healthy tissue use hadrons (protons, light ions).
  - Accelerator-based hadrontherapy facilities.

Accelerator cancer therapy

Loma Linda Proton Treatment Centre
Constructed at FNAL

Accelerators for Medicine

Photons, Protons and Light Ions

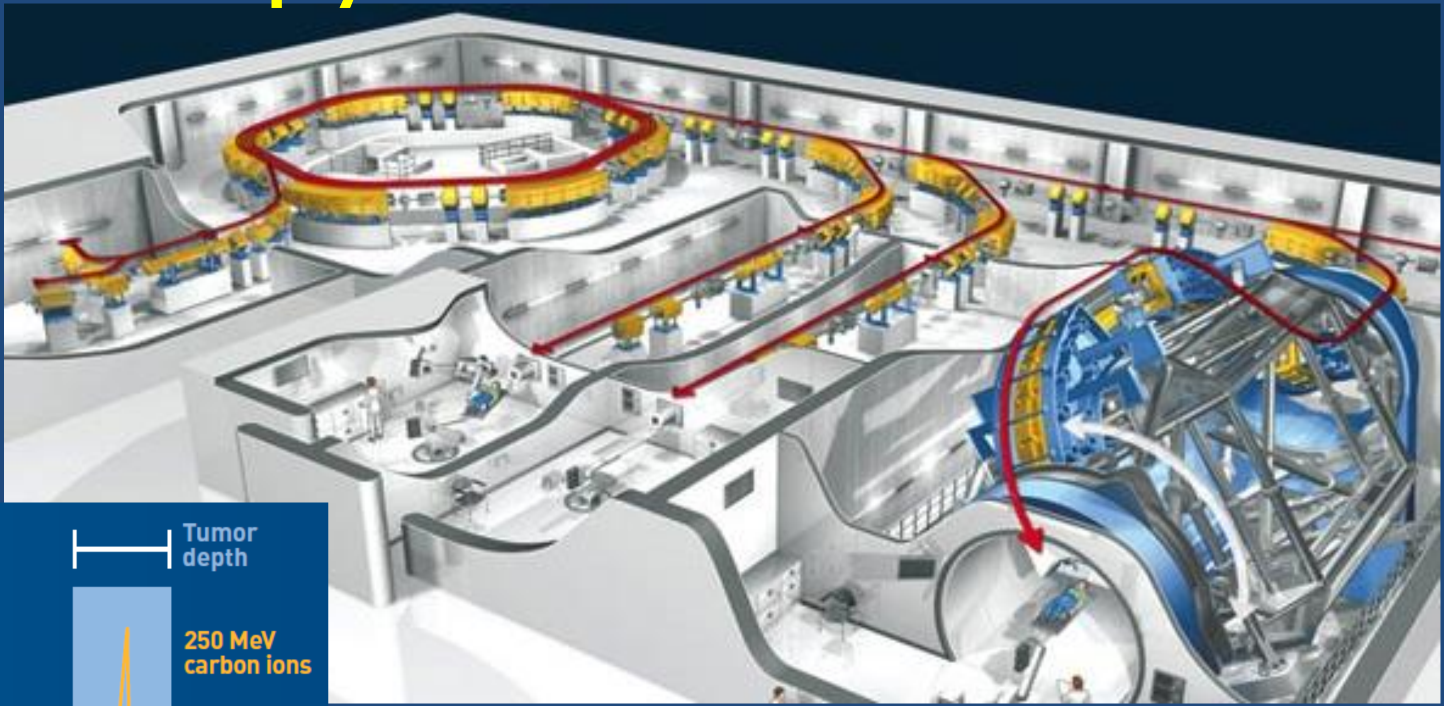


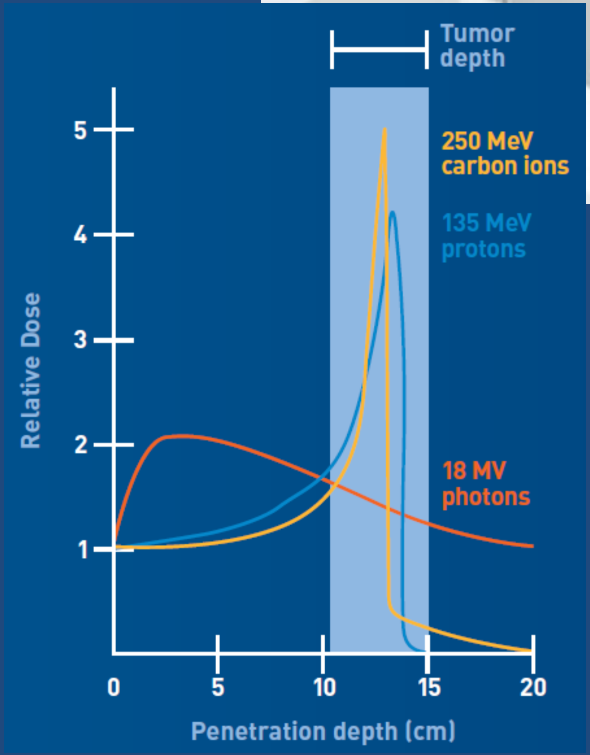
The Clatterbridge Centre for Oncology

Established 1989 – 60 MeV protons

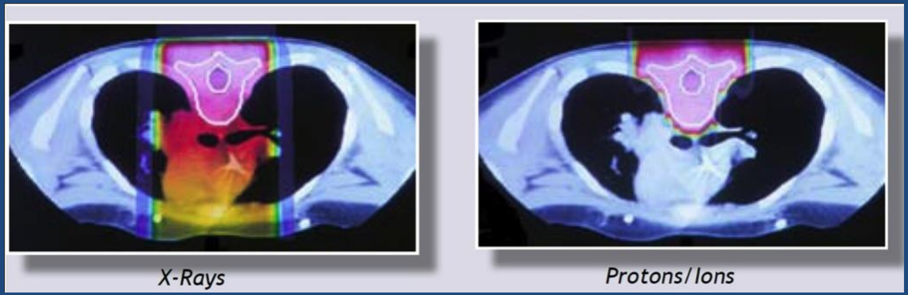
First hospital-based proton therapy – more than 1400 patients with ocular melanoma

Radiotherapy with Ions



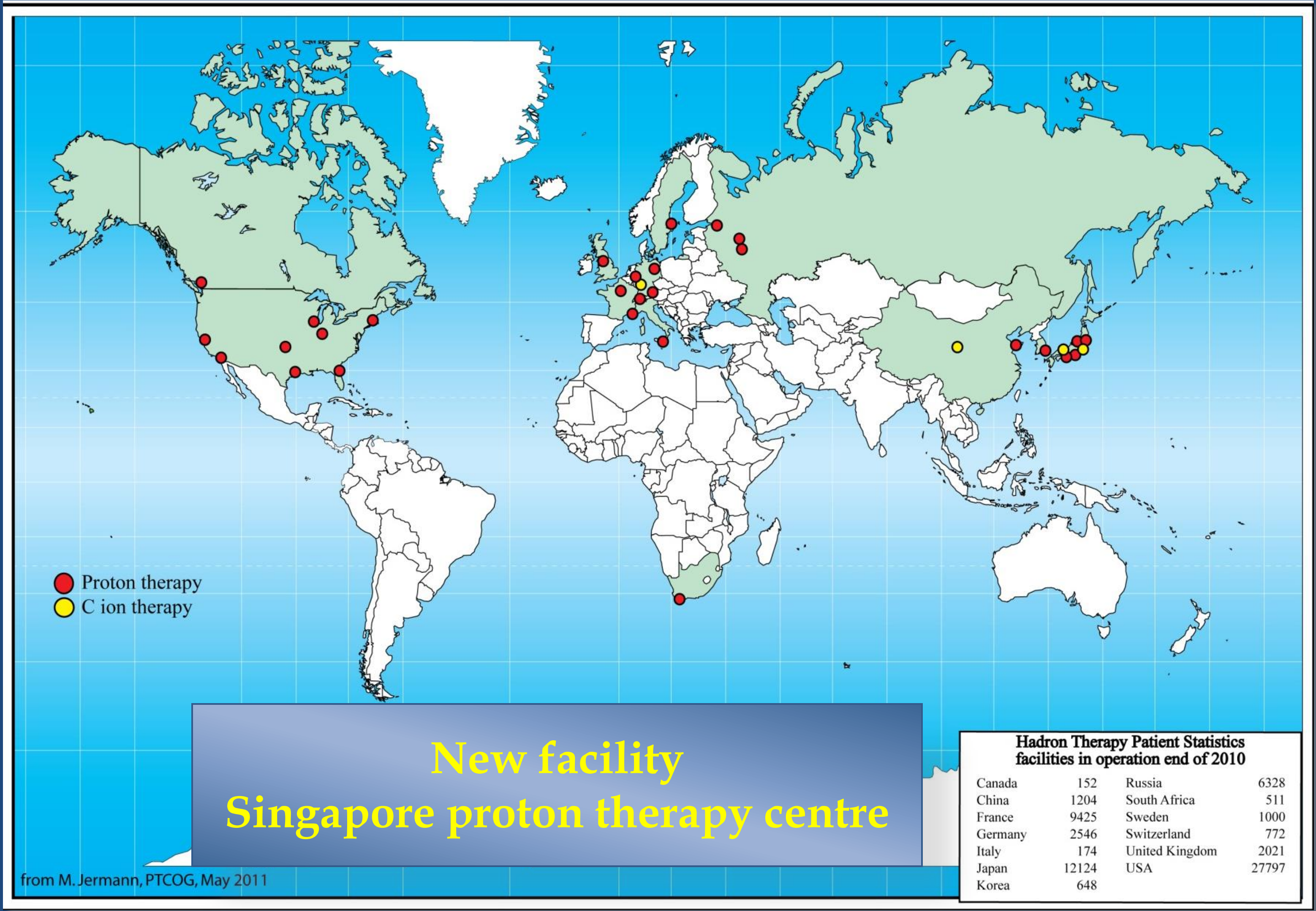


Heidelberg Ion Therapy Facility (protons & carbon)



Cancer therapy with x-rays and protons or heavier ions

Centers for HADRON Therapy
in operation end of 2010



Hadron Therapy Patient Statistics facilities in operation end of 2010

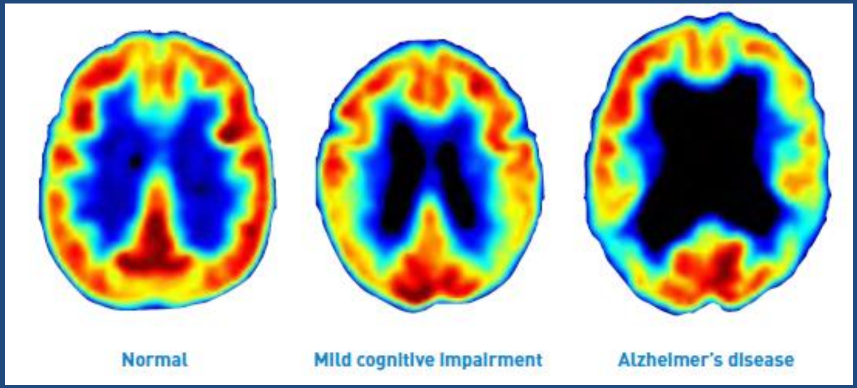
Canada	152	Russia	6328
China	1204	South Africa	511
France	9425	Sweden	1000
Germany	2546	Switzerland	772
Italy	174	United Kingdom	2021
Japan	12124	USA	27797
Korea	648		

Worldwide: 30 centres (4 have C-ions): ~ 65’000 patients
Europe: 9 centres (with C-ions at GSI and Heidelberg): ~ 16’000 patients

Accelerators for Medicine

- Medical Imaging
  - Radioisotopes have become vital components in medicine.
    - Produced at reactors or accelerators.
  - Positron Emission Tomography (PET)
    - Requires positron emitter ^{18}F
  - ^{99}Mo / ^{99m}Tc
    - 100 kW of 200 MeV protons impinging on depleted U target produce neutrons.
    - Neutrons targeted on low-enriched U thus producing ^{99}Mo.

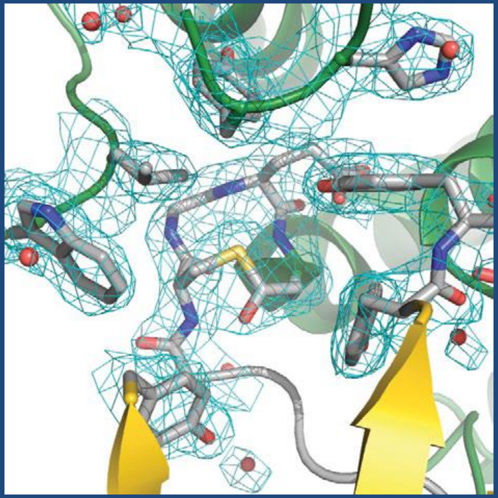
Bone scans indicating increased ^{99m}Tc intake due to cancer growth



PET Scan

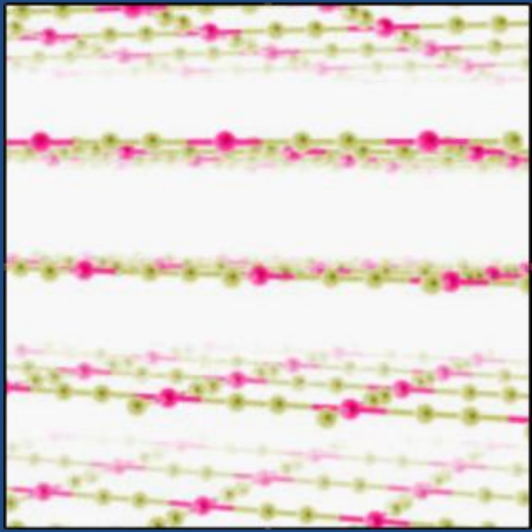
Neutrons & X-rays

Protein structure revealed with help of light sources



ISIS and Diamond neutron and X-ray sources
Harwell, UK

Neutron and X-ray imaging essential for studies of proteins and advanced materials.

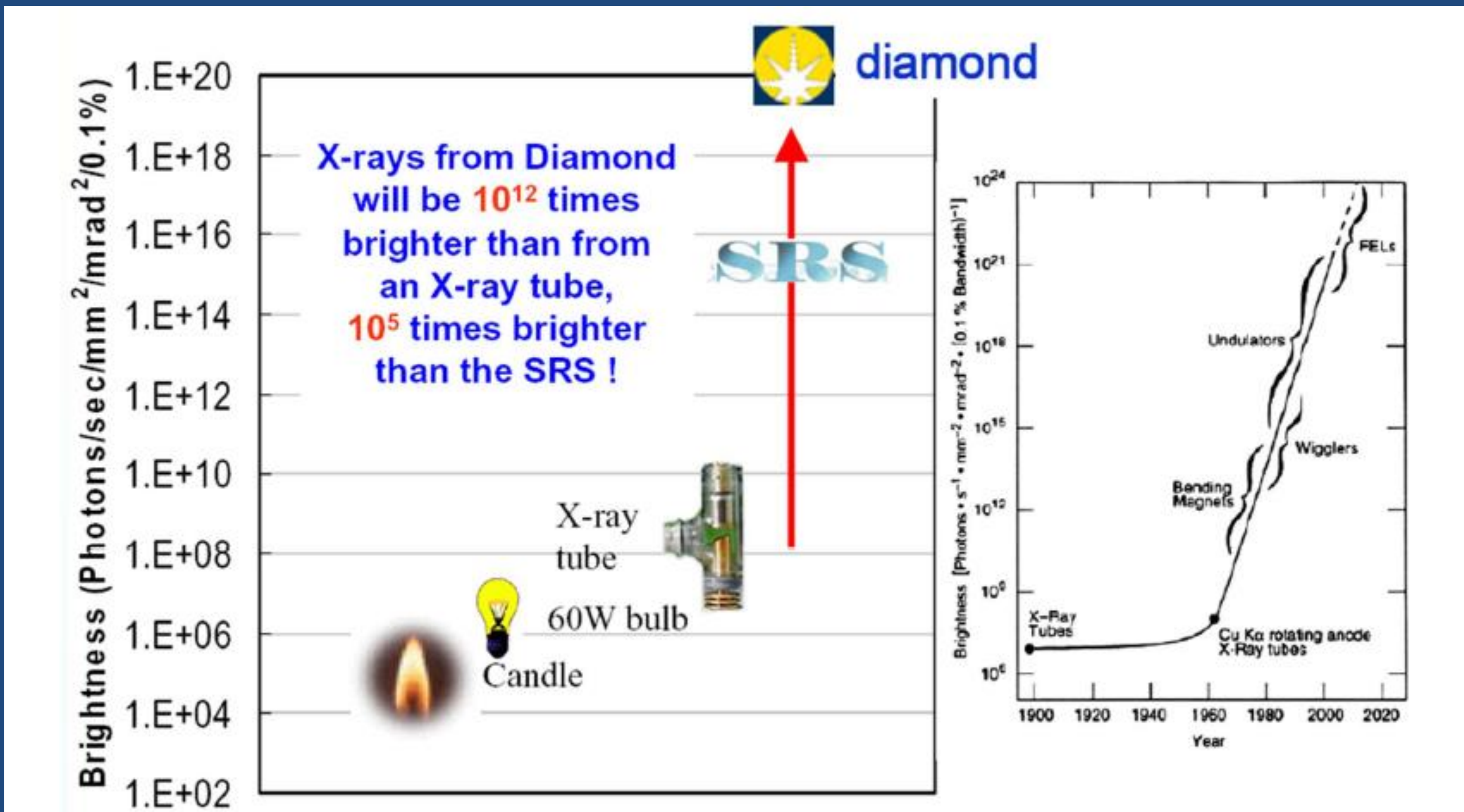


2-d material (graphene)

diamond

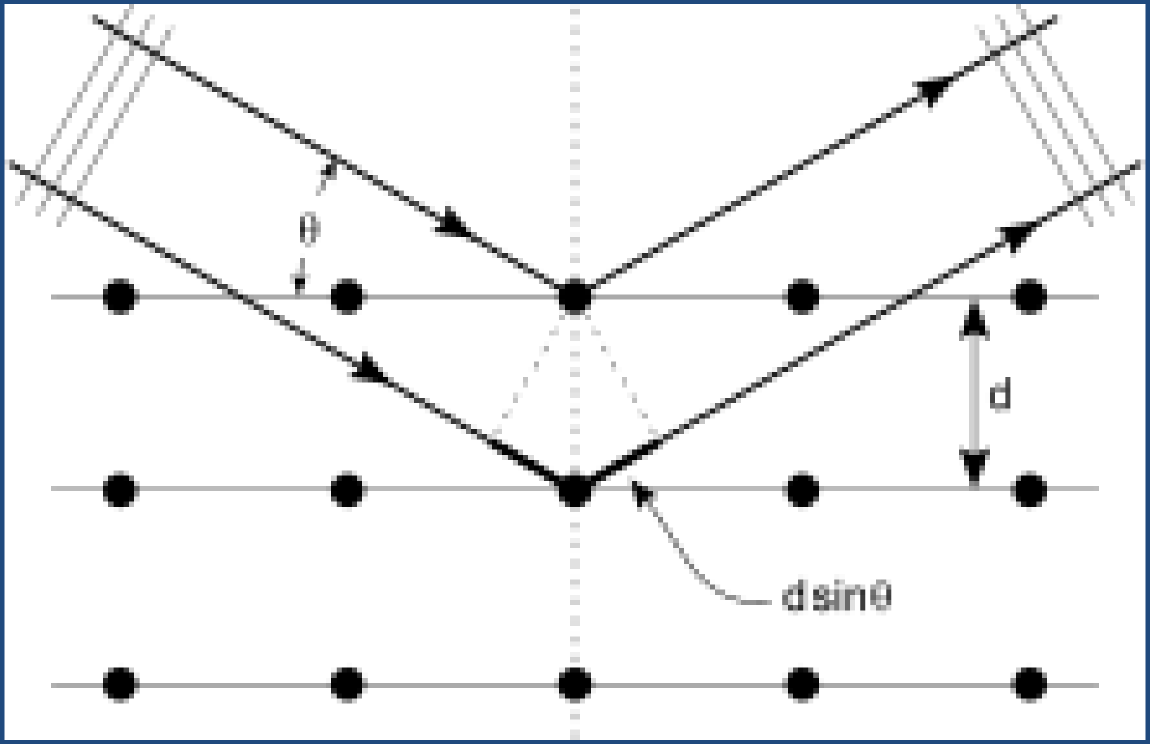
Science & Technology Facilities Council

Accelerators for Synchrotron Light



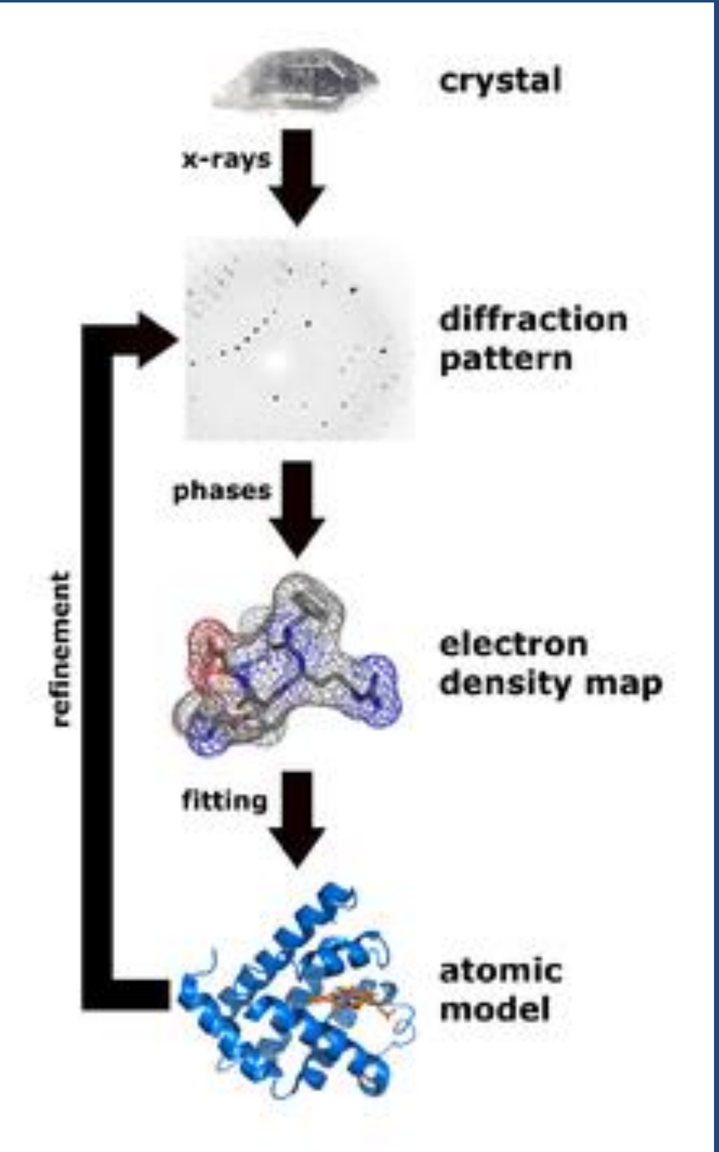
X-ray Diffraction

Max von Laue
1914 Nobel Prize:
'For his discovery of the diffraction of X-rays by crystals'

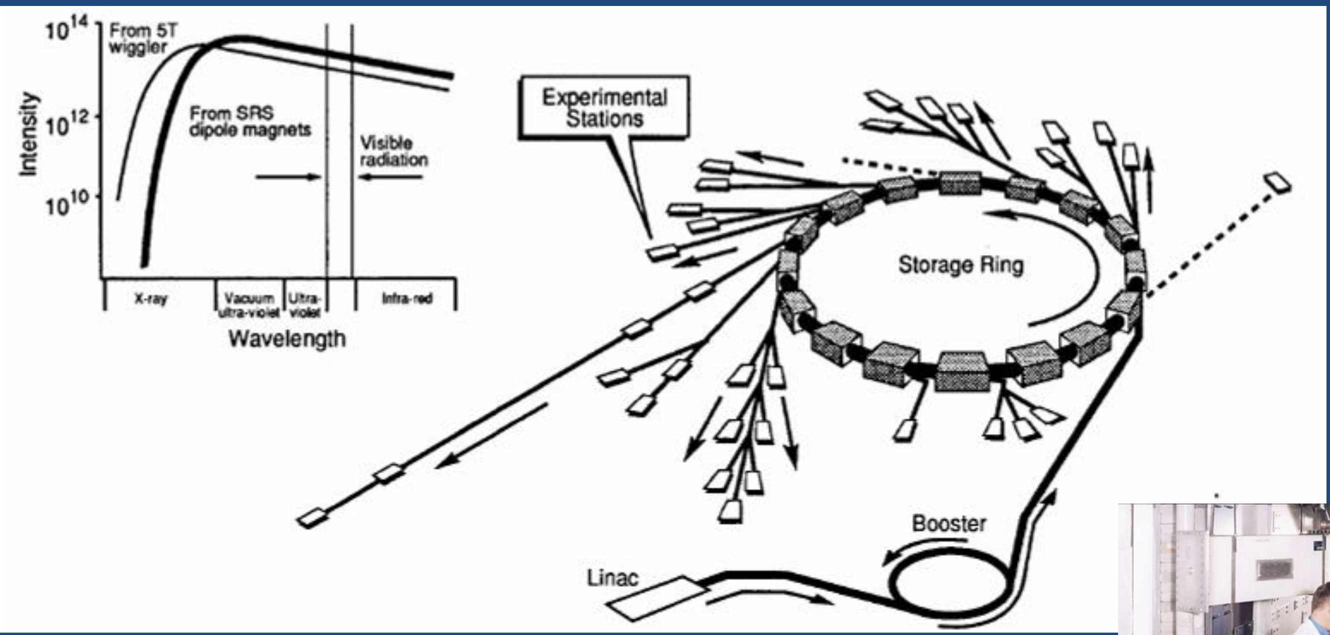


Constructive interference:
$2\, d \sin\theta = n\, \lambda$

X-ray Diffraction Today



Accelerator X-ray Sources

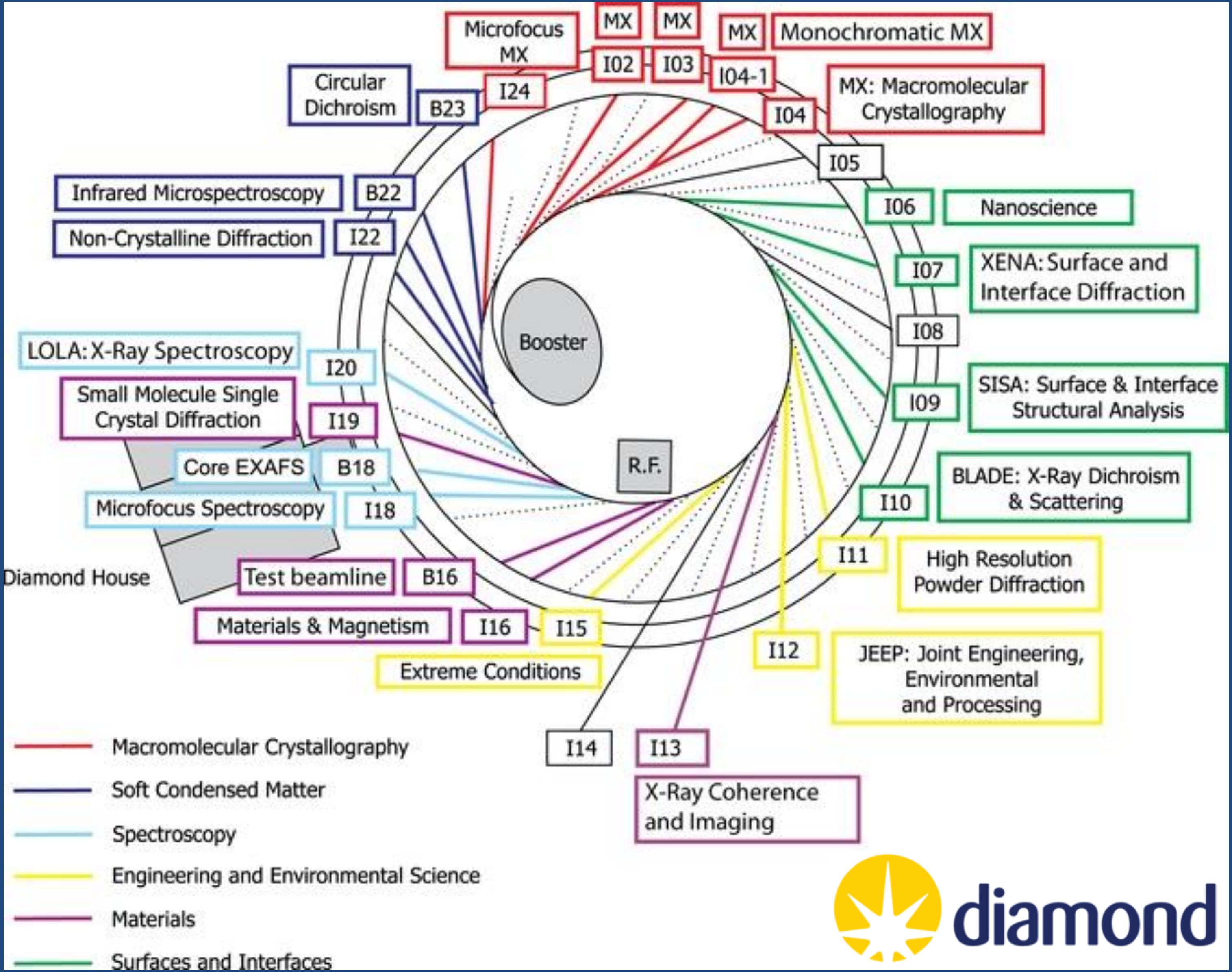


SRS
Daresbury, UK

Synchrotron Source of X-rays

Diamond Light Source, Harwell
Science and Innovation Campus, UK

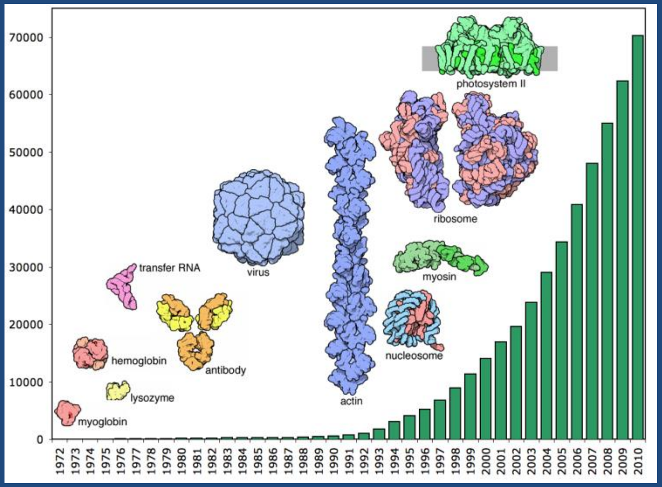
Diamond Beamlines



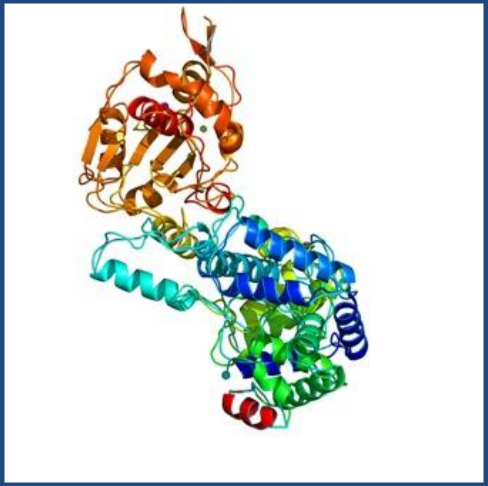
Accelerators for Synchrotron Light

Protein Structures

- Proteins are biological molecules involved in almost every cellular process.
- The protein is produced, crystallised and illuminated by X-rays. The interactions between the X-rays and the crystal form a pattern that can be analysed to deduce the protein structure.
- Over 45,000 structures have been solved by the worldwide synchrotron community.



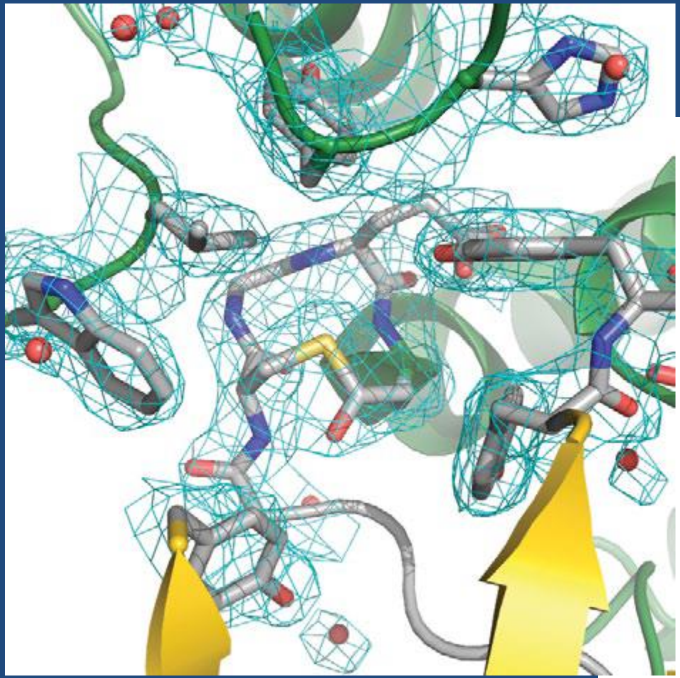
Protein Data Bank



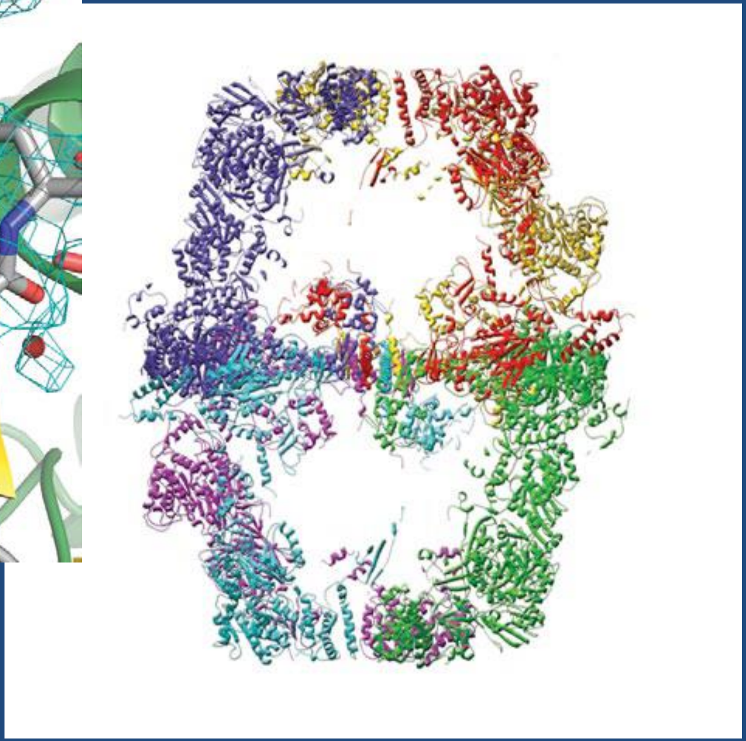
The trimer of the Lassa nucleoprotein, part of the Lassa virus

Protein Structure Revealed by Light Sources

HIV glycoprotein

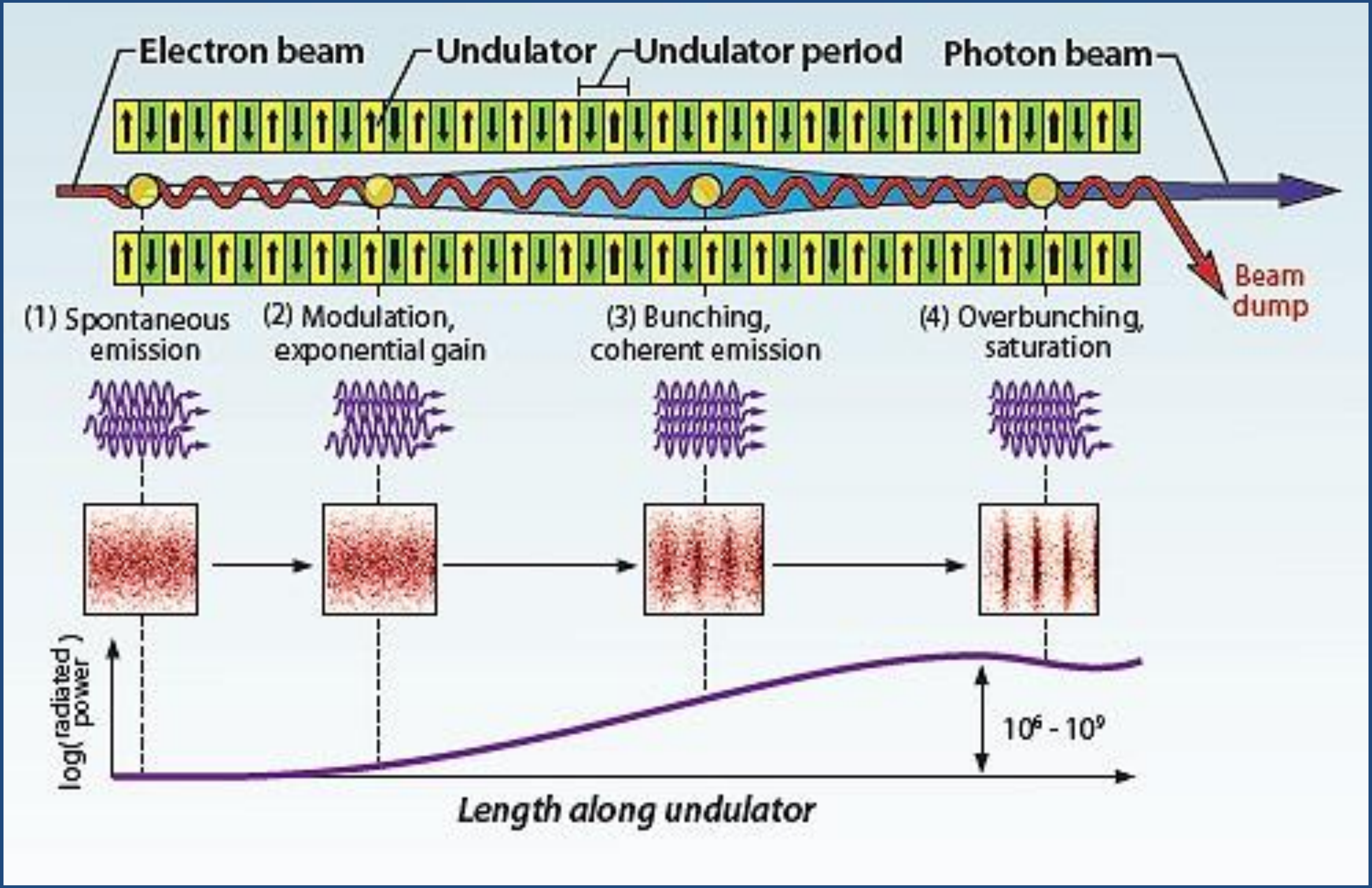


mosquito immune system



yeast enzyme

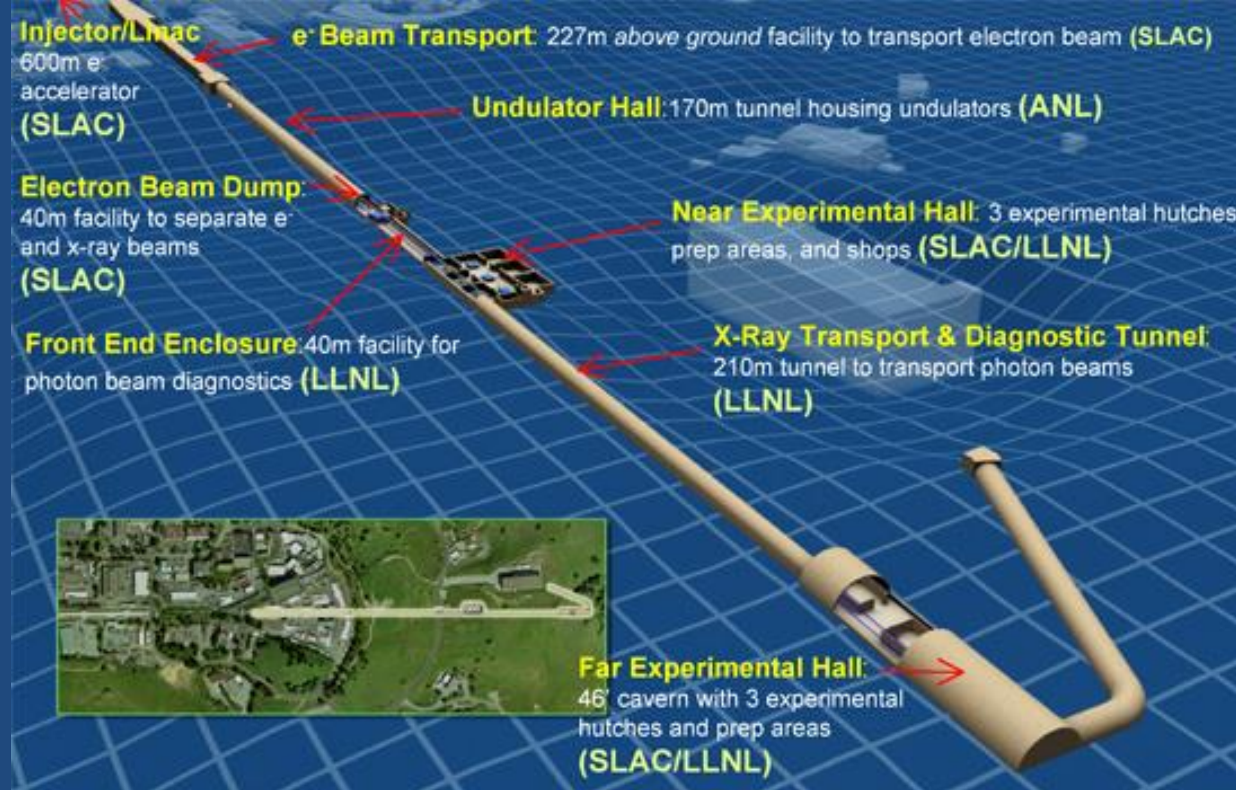
4th Generation Light Source – Free Electron Laser

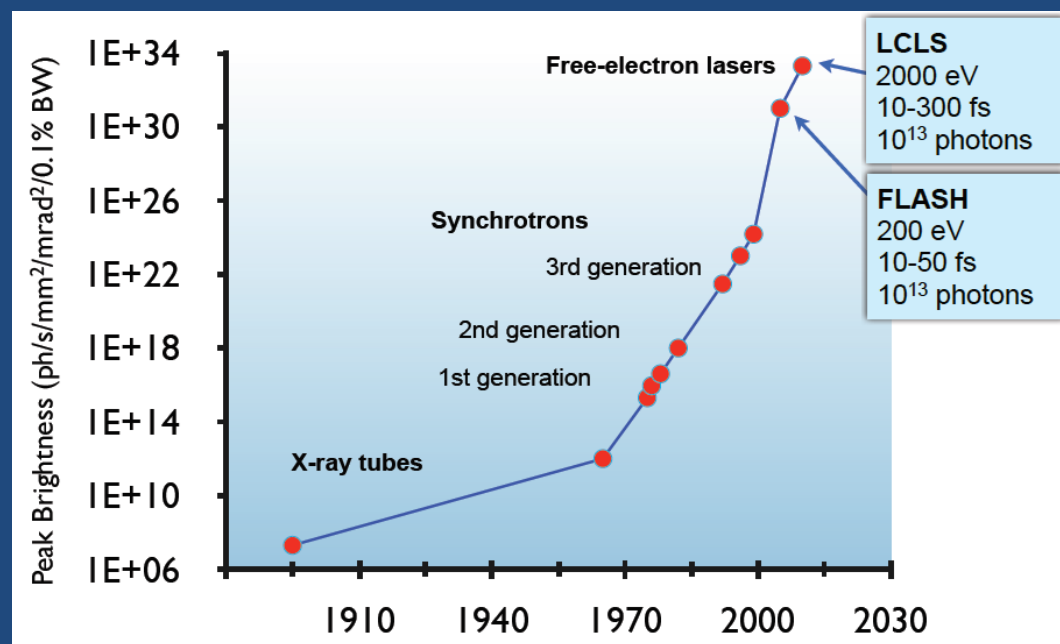


4th Generation Light Source –

X-ray FEL-

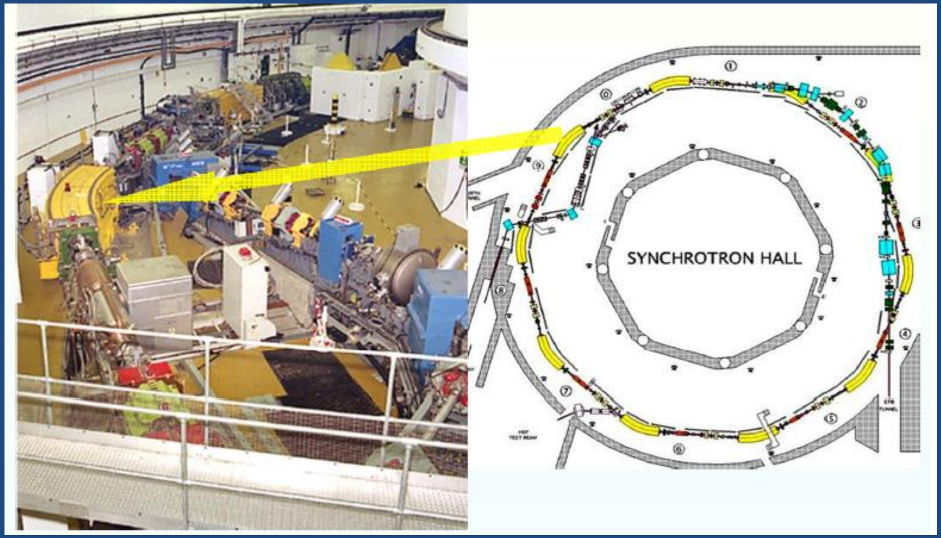
LCLS at SLAC





Accelerators for Neutron Science

- Penetrate deep inside materials since they are deflected only from the nuclei of atoms.
- Statistical observation of deflected neutrons at various positions after the sample can be used to find the structure of a material.
- Loss or gain of energy by neutrons can reveal the dynamic behaviour of parts of a sample, for example dynamic processes of molecules in motion.



ISIS Spallation Facility (800 MeV) at RAL

+ new European Spallation Source (ESS) in Lund

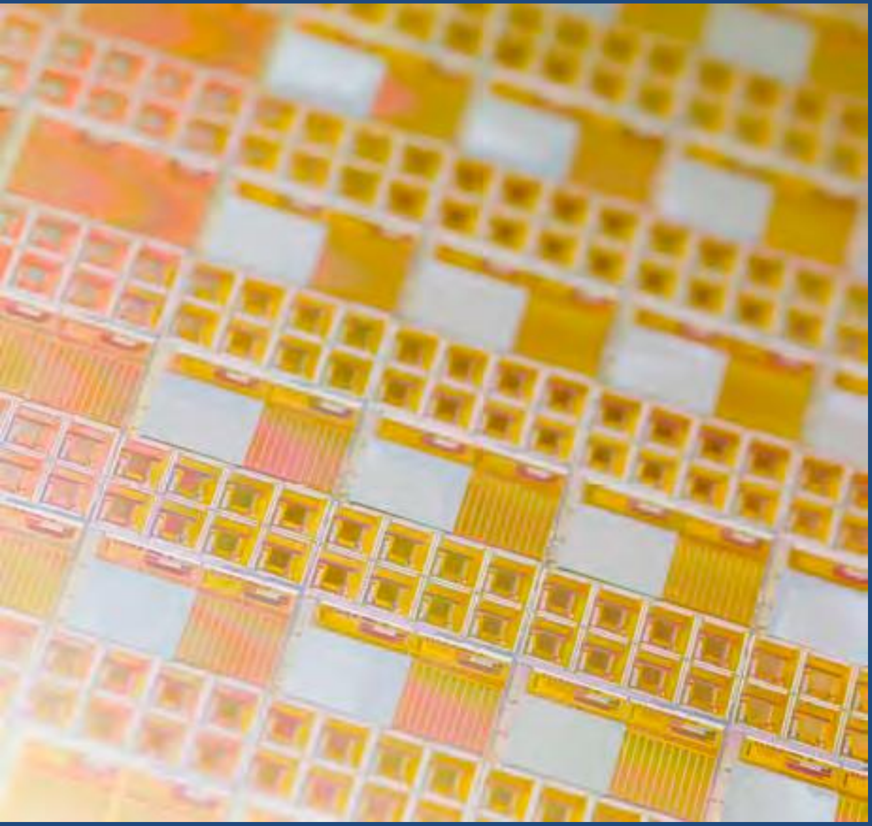
Ion Beam Implantation

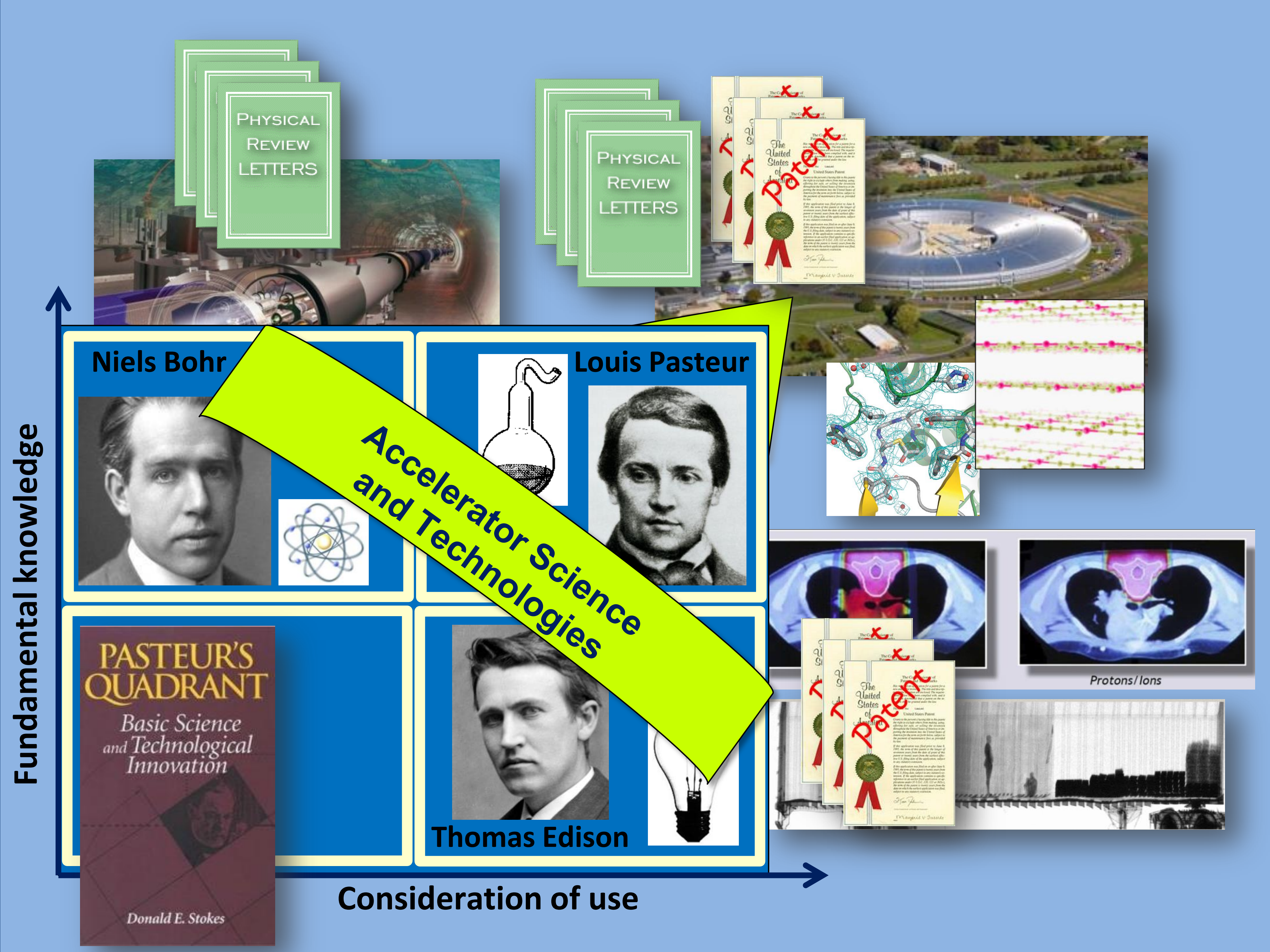
- Ion implantation in semiconductor manufacture
- Typical semiconductor fabrication:

  140 operations, 70 involving ion implantation at specific sites in crystal
- Ions accelerated to modest energies

  Depth of implant controlled by ion beam energy: typically 2 → 600 keV

Ion Beam Implantation Products




Physical Review Letters
Physical Review Letters
Niels Bohr
Louis Pasteur
Accelerator Science and Technologies
Patent
Patent
Protons/Ions
Pasteur's Quadrant
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
Fundamental knowledge
Consideration of use