Introduction to Particle Accelerators

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APPEAL-4
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organized by
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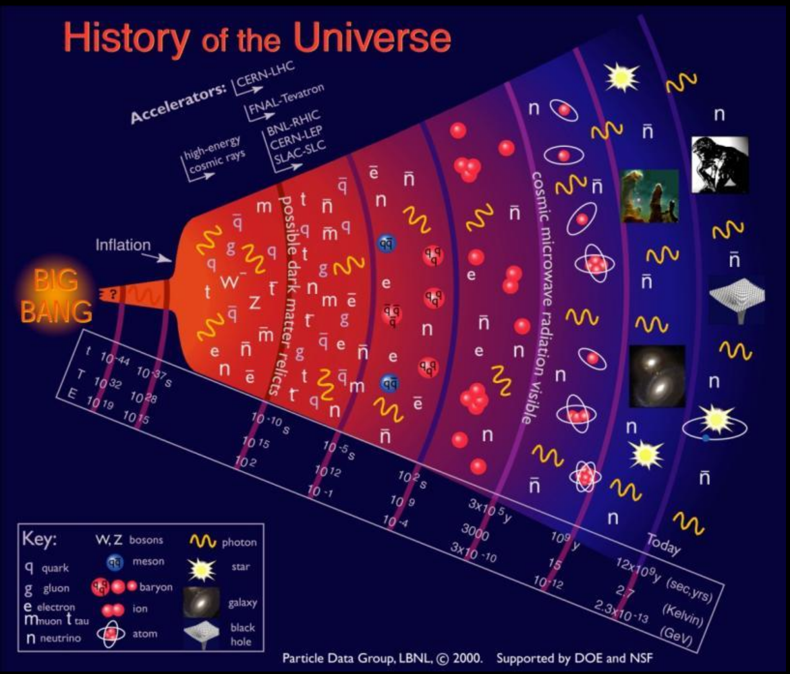
The Discovery of the Higgs Boson – A Step Closer to the Big Bang

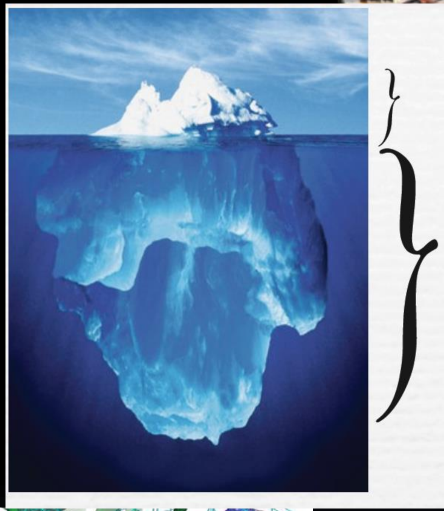
What is JAI

The John Adams Institute for Accelerator Science is a centre of excellence in the UK for advanced and novel accelerator technology, created in 2004 to foster accelerator R&D in the universities

Sir John Adams (24 May 1920 - 3 March 1984) was the 'father' of the giant particle accelerators which have made CERN the leader in the field of high energy physics.
He was an extraordinary accelerator designer, engineer, scientist and administrator.
He worked during WWII in the Radar Laboratories of the Ministry of Aircraft Production.
Thereafter he worked at the Atomic Energy Research establishment at Harwell on design & construction of a 180 MeV synchro-cyclotron.
He came to CERN in 1953 & was appointed director of the PS division in 1954 at the age of 34, becoming the leader for the world's biggest particle accelerator project.
In 1961-66 Adams worked as director of the Culham Fusion Lab. From 1966-71 he was member of the Board of the UK Atomic Energy Authority.
In 1971 he returned to CERN and served until 1975 as Director-General of then called Laboratory II, responsible for the design & construction of the SPS.
From 1976-80 he was executive DG of CERN and instrumental in approval of LEP.

Particle Accelerators – to study macro and micro world

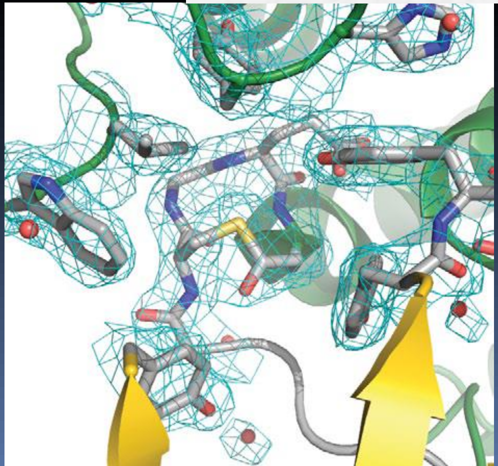


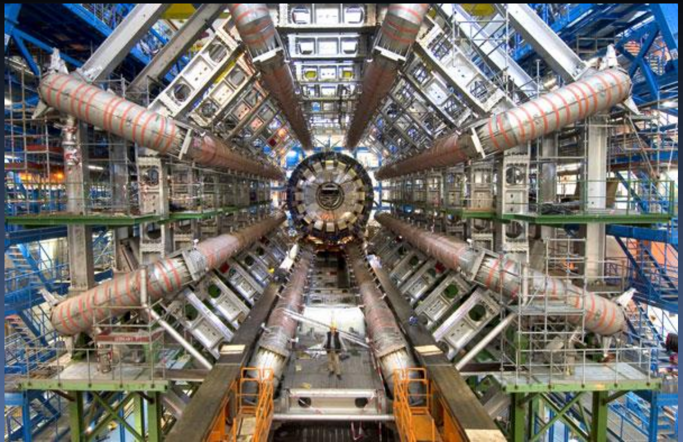


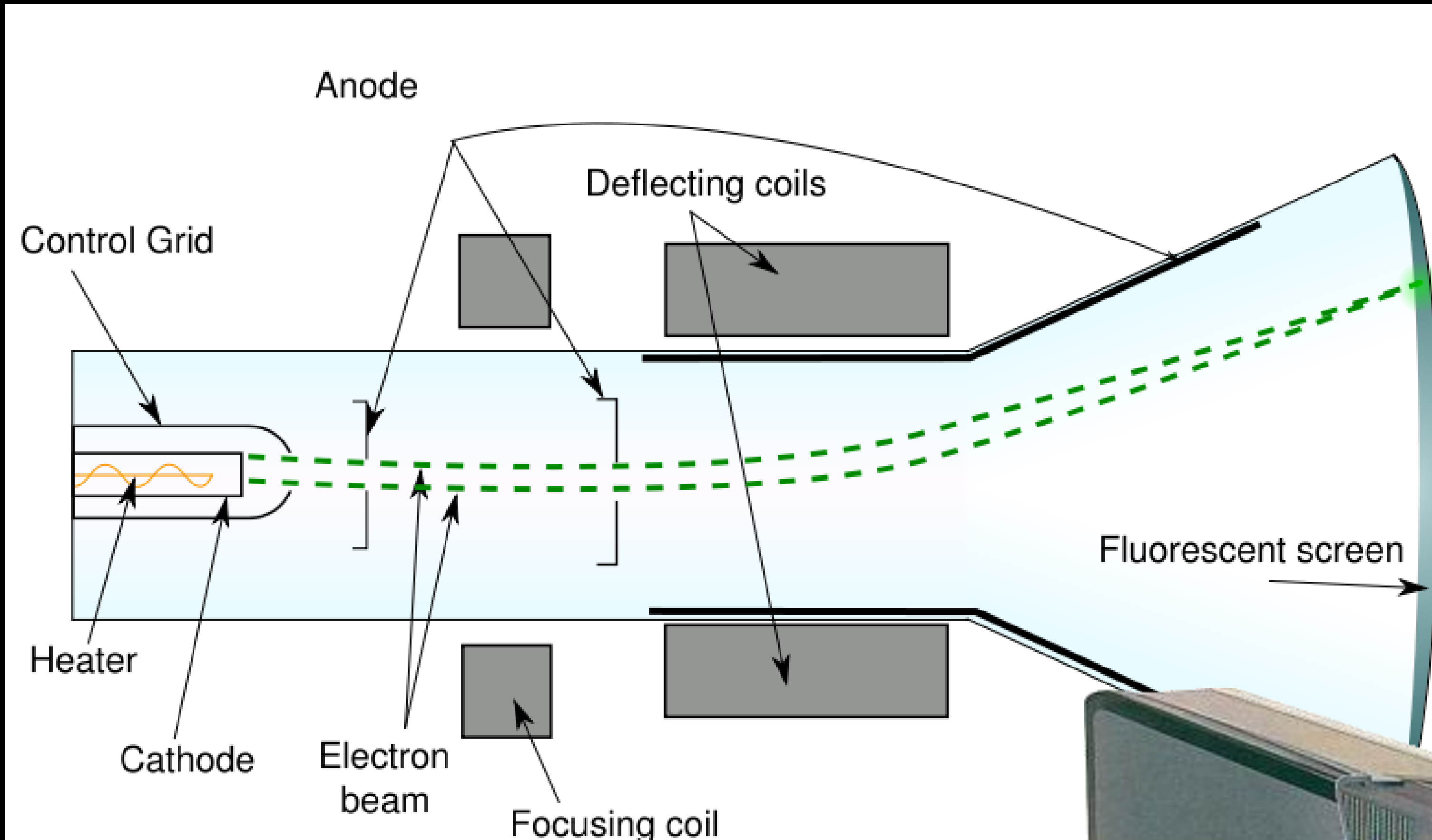
Known Matter

Unknown Matter

DARK MATTER &
DARK ENERGY

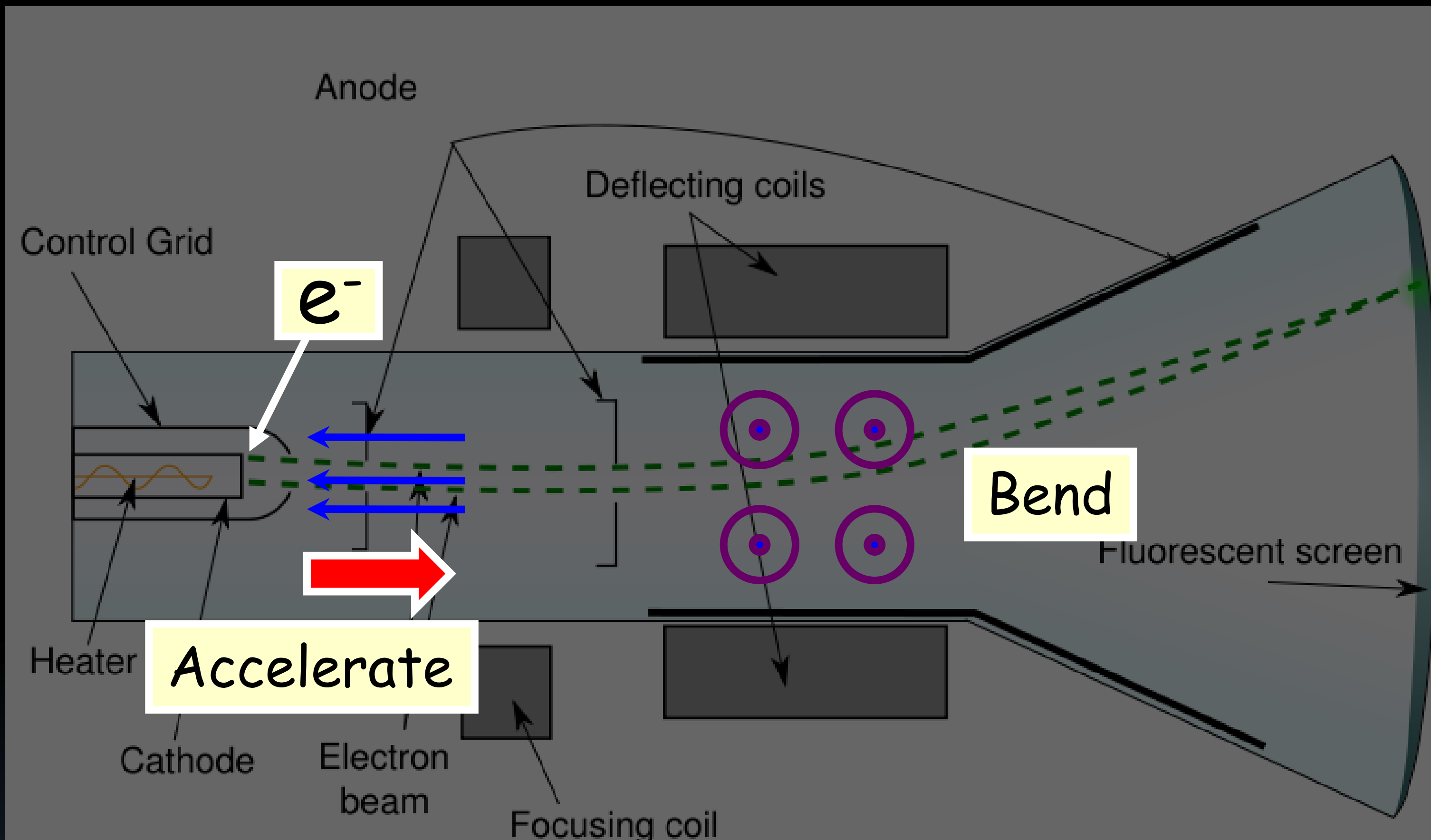




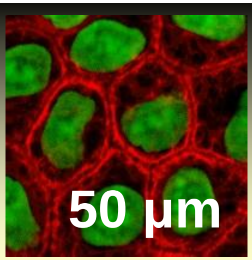


Your (old) TV is an accelerator

TV is an accelerator



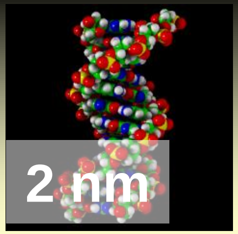
The structure of matter…



Extra magnification?

CELLS
Twenty
per mm

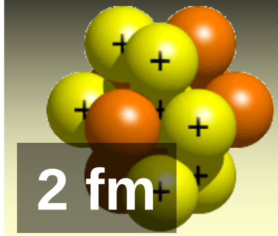
Microscope



x 25 thousand

DNA
Five hundred
thousand
per mm

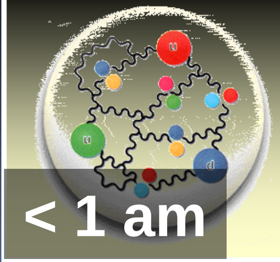
Electron microscope



x 1 million

Nucleus
Five hundred
billion
per mm

Particle Accelerators



x 2 thousand

Quarks
More than one
million billion
per mm

Key Equation

$$\lambda = h/p$$

De Broglie wavelength

Planck Constant

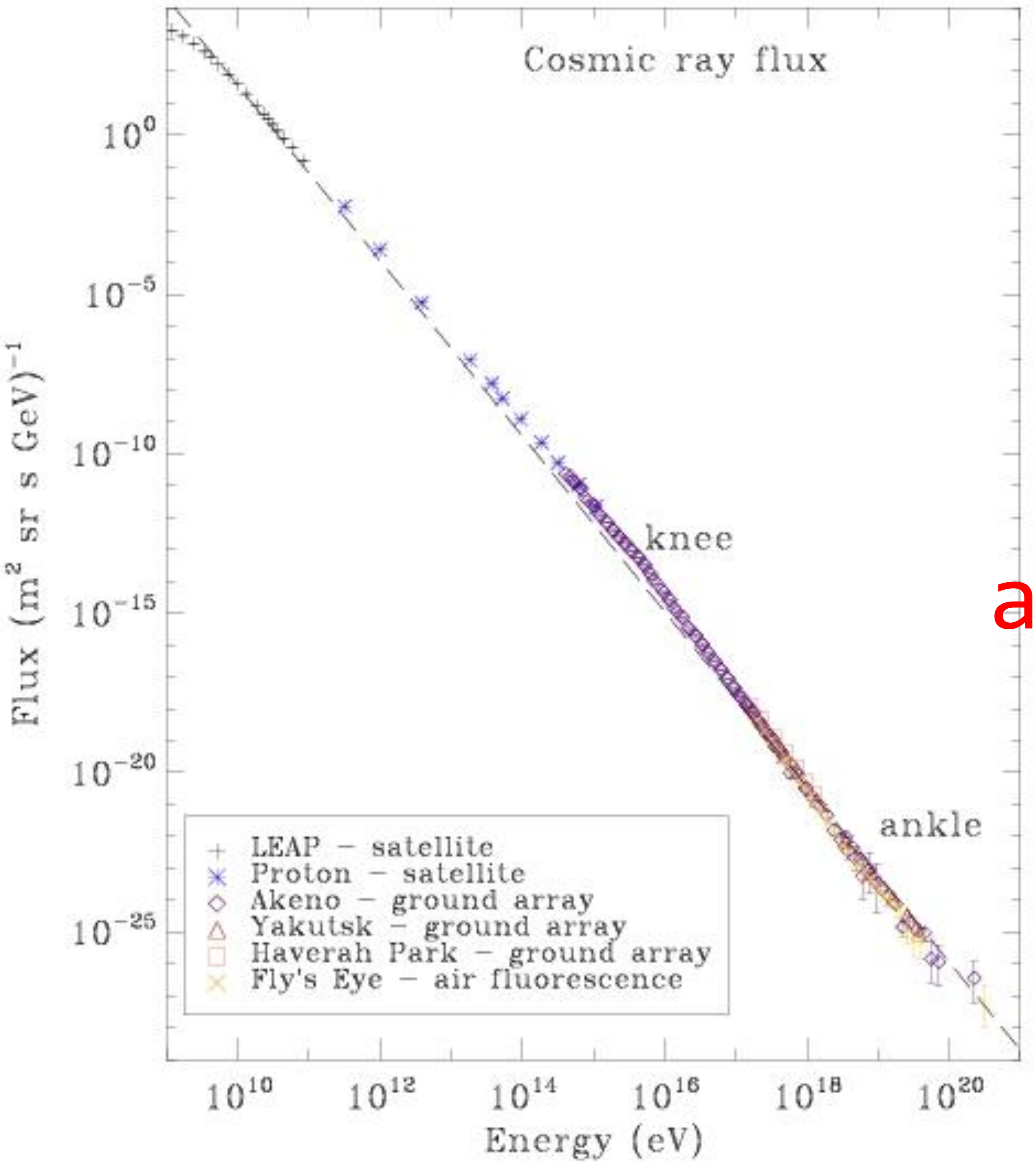
Momentum

See small? Large momentum

Natural accelerators?

Lightning: > MV/m over many tens of meters to initiate it

Cosmic rays



Natural accelerators?

Slide: Dr. Klara Schure (Oxford)

Image Credits: X-ray: NASA/CXC/KIPAC/N. Werner et al Radio: NSF/NRAO/AUI/W.

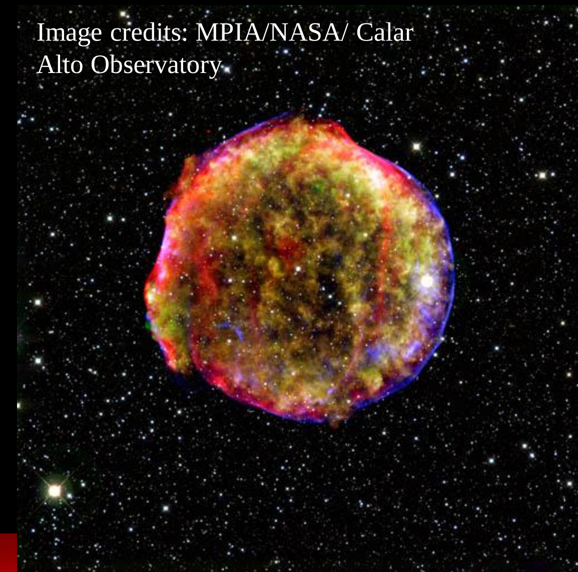


Image credits: MPIA/NASA/ Calar Alto Observatory

credits: X-ray: NASA/CXC/CfA/R.Kraft et al Ra
VLA/Univ. of Hertfordshire/M.Hardcastle et al.

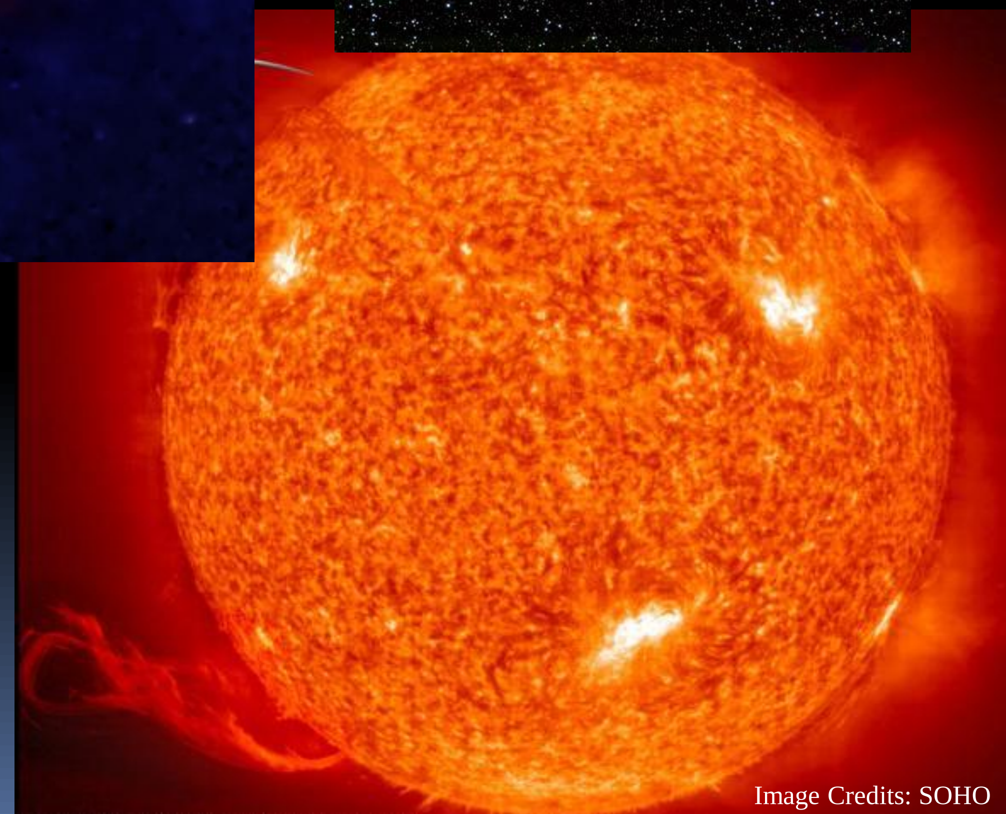
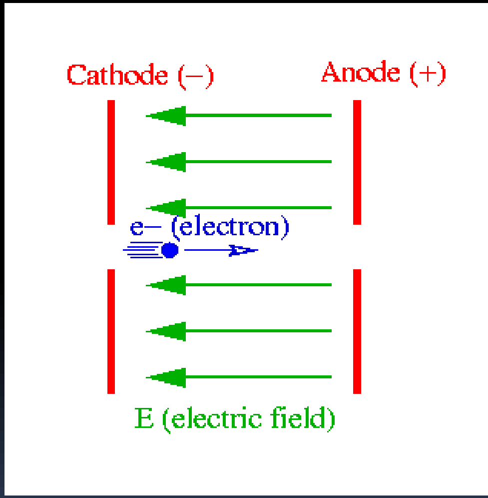


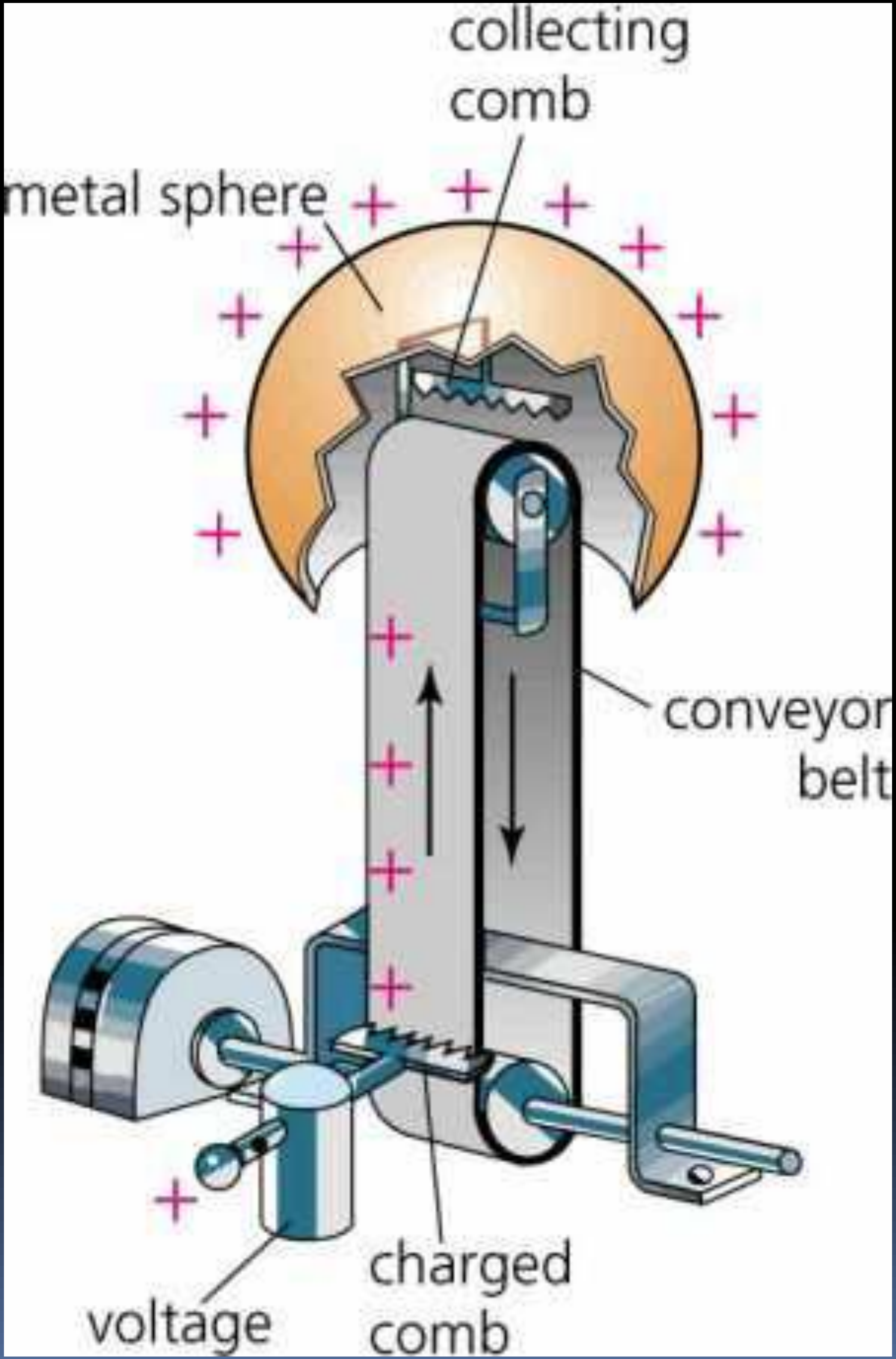
Image Credits: SOHO

Slide: Dr. Klara Schure (Oxford)

Electrostatic accelerators

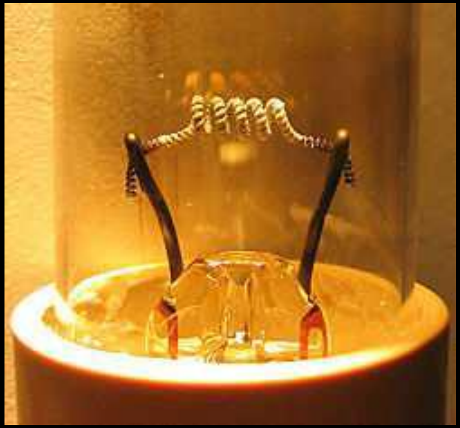
- Example of electrostatic accelerators - “Van de Graaff”

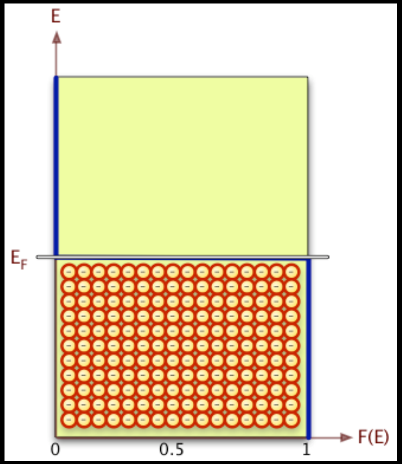


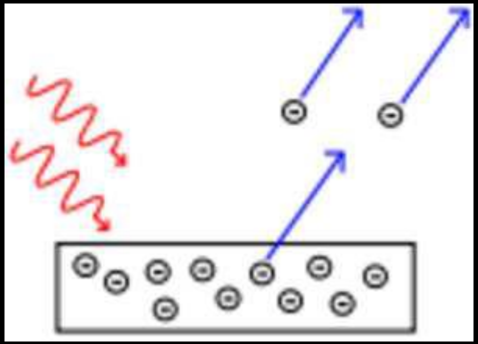


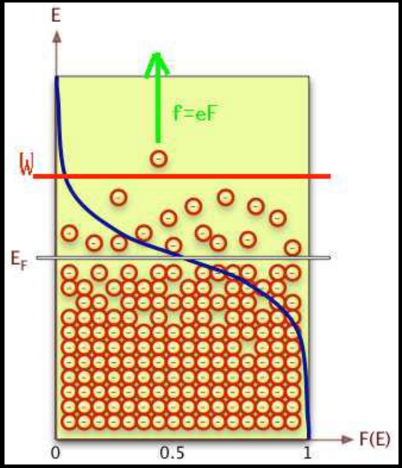
Accelerator start from a source of particles

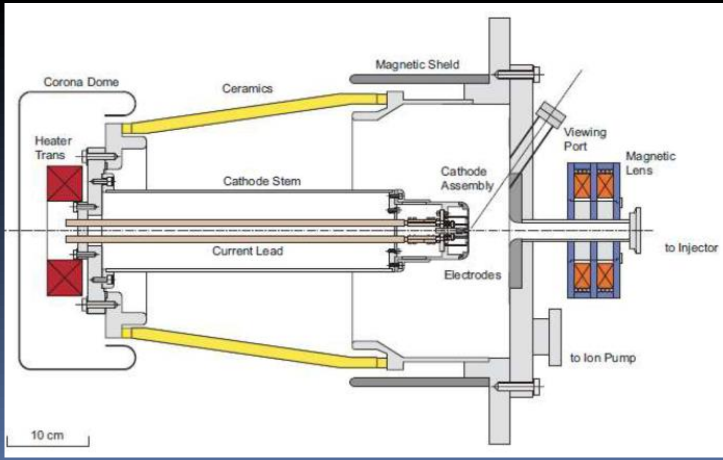
- Electron gun
  - Heated cathode
  - Thermionic emission
  - Electrons extracted by electric field
- Photo electron gun
  - Laser kicks electrons out

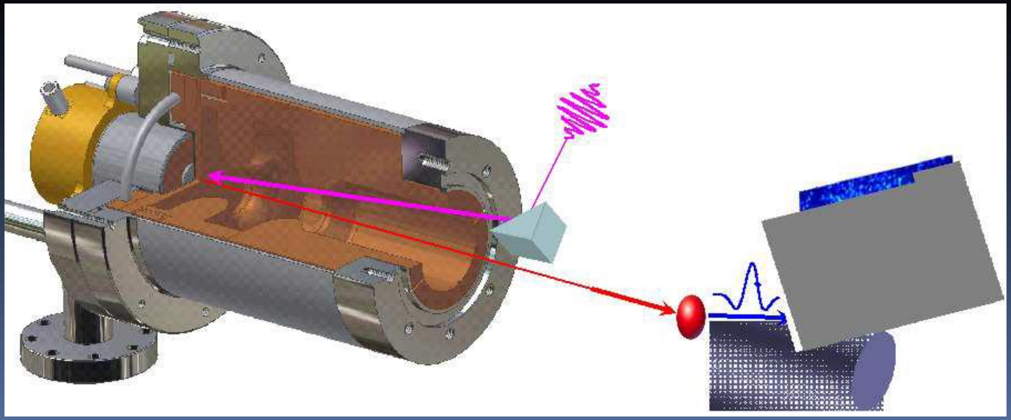






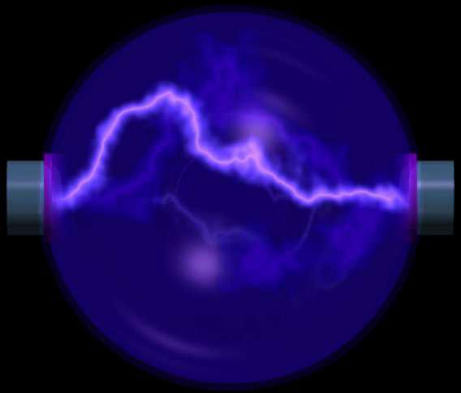


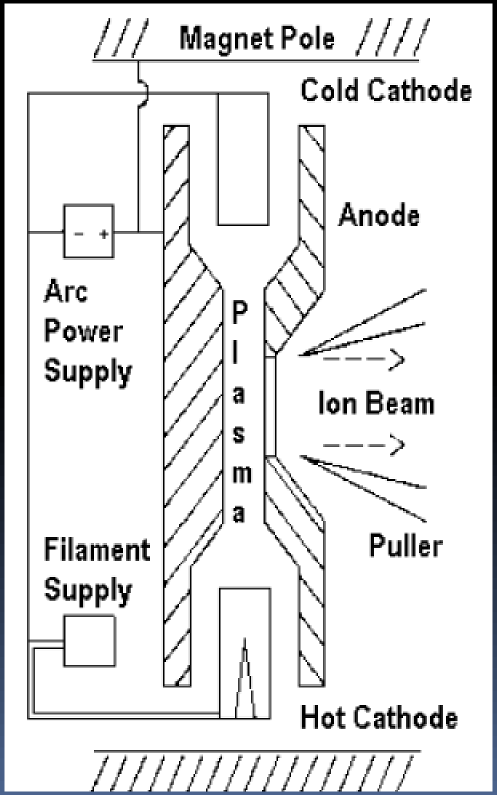




Ion sources

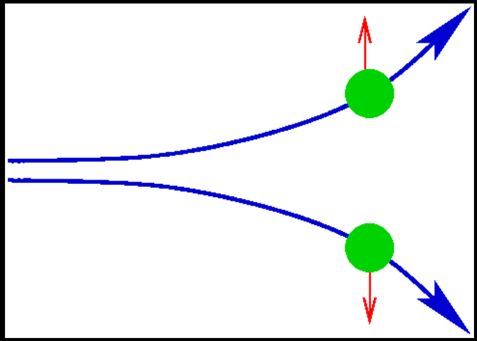
- A source of positive or negative ions can be arranged using electric discharge in gas
- Atoms are stripped from their electron, and the ions are then extracted

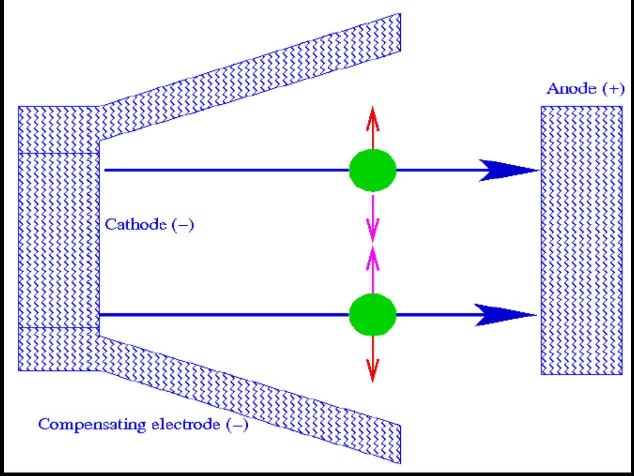


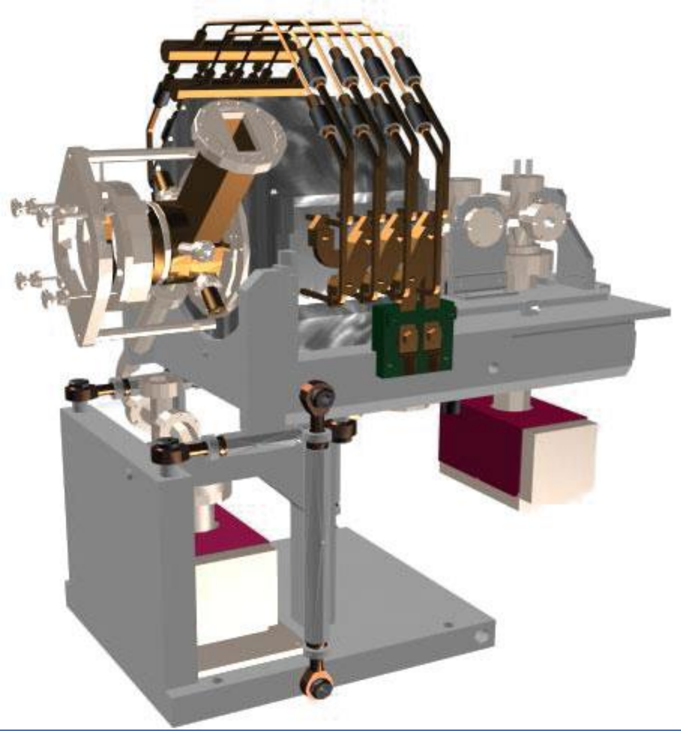


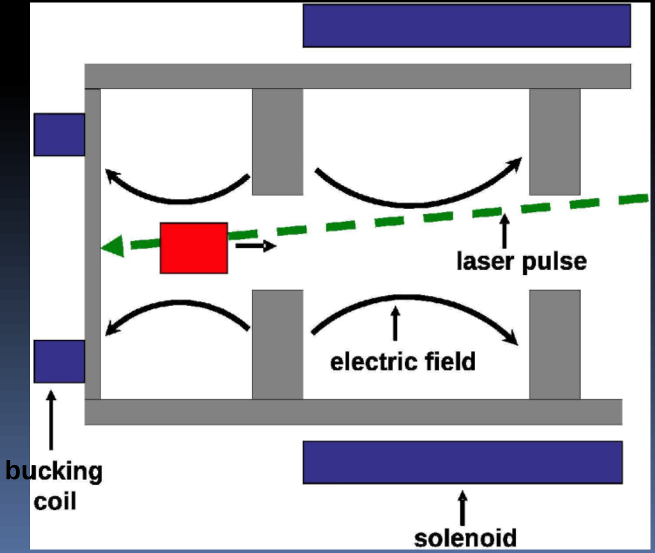
Space charge effects

- Coulomb forces are especially important at low energy - "space-charge" effects
- Compensated by adjusting electrodes shapes and use of solenoids

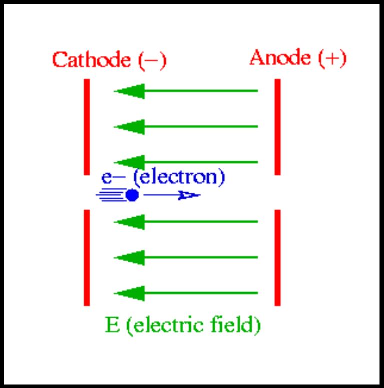


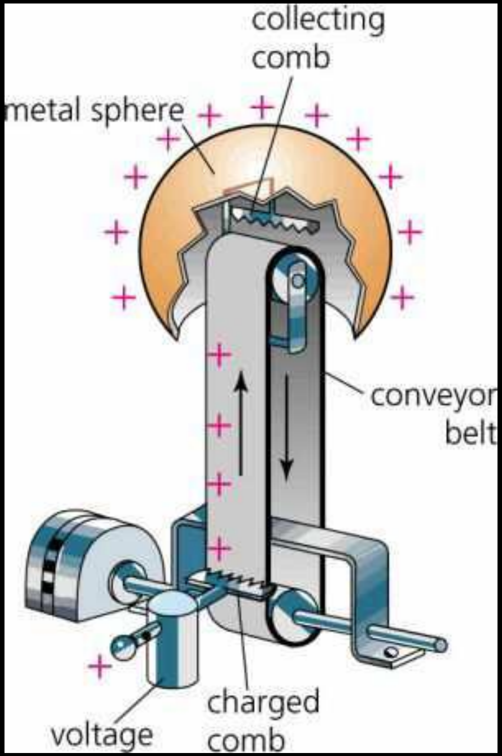




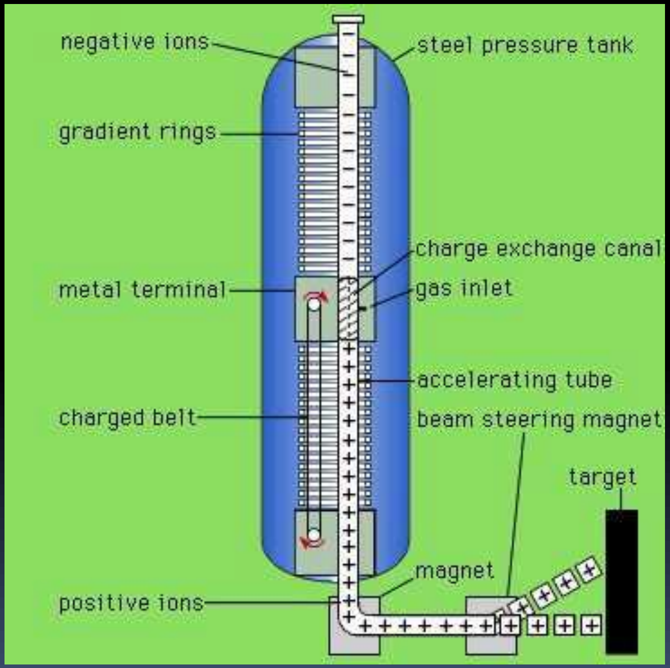


Electrostatic accelerators





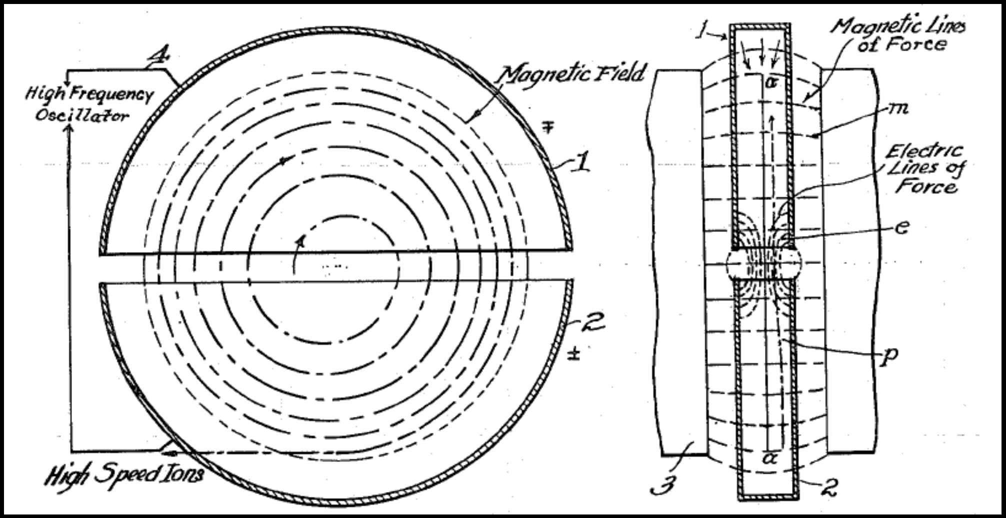
- Example of electrostatic accelerators - “Van de Graaff”
- Tandem is a version with charge exchange in the middle

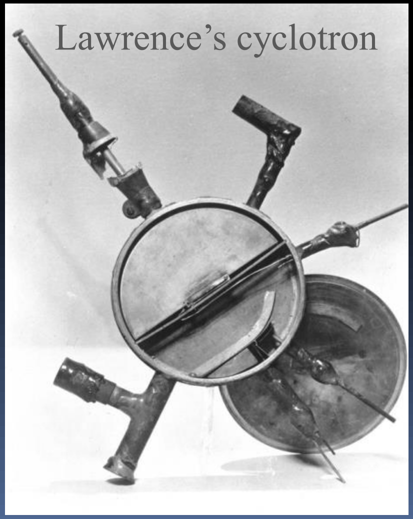


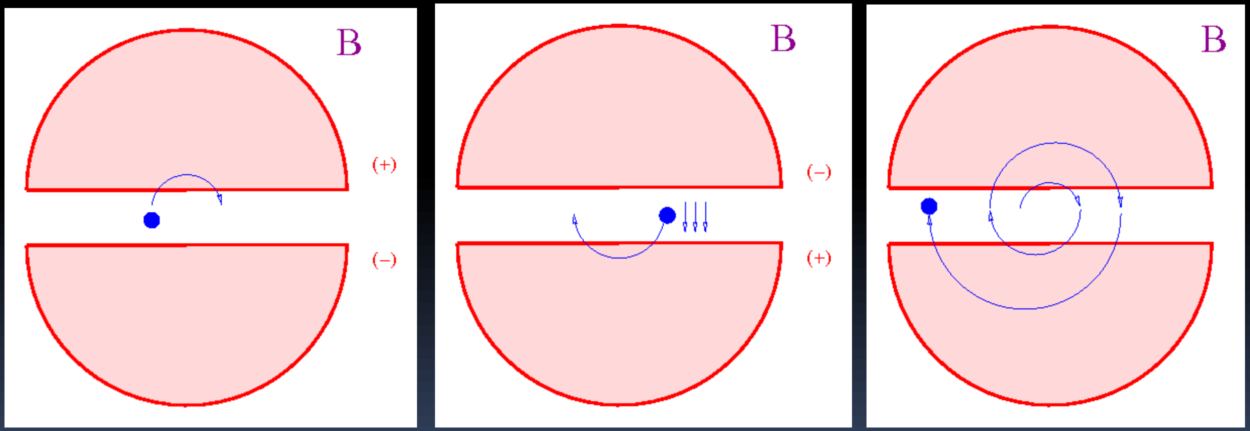
- With any electrostatic accelerators it is difficult to achieve energy higher than ~20MeV (e.g. due to practical limitations of the size of the vessels)

Cyclic accelerators

- In 1931 Lawrence designed a “cyclotron”, a circular device made of two electrodes placed in a magnetic field
- Cyclotrons can accelerate (e.g.) protons up to hundreds of MeV



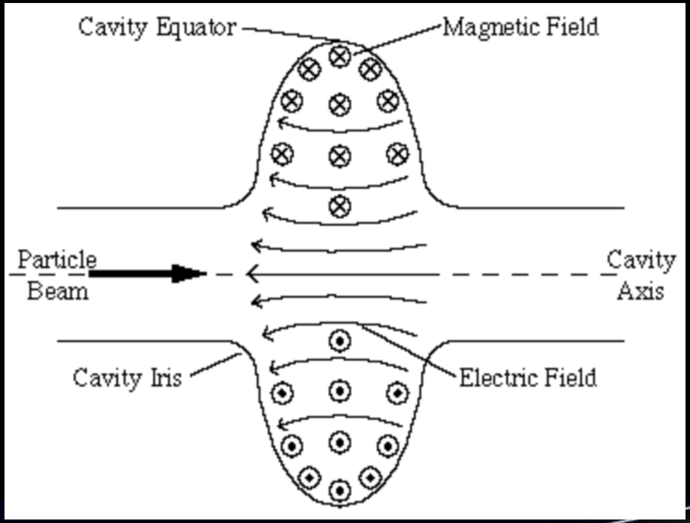


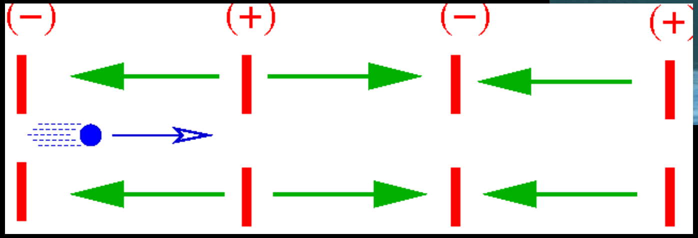


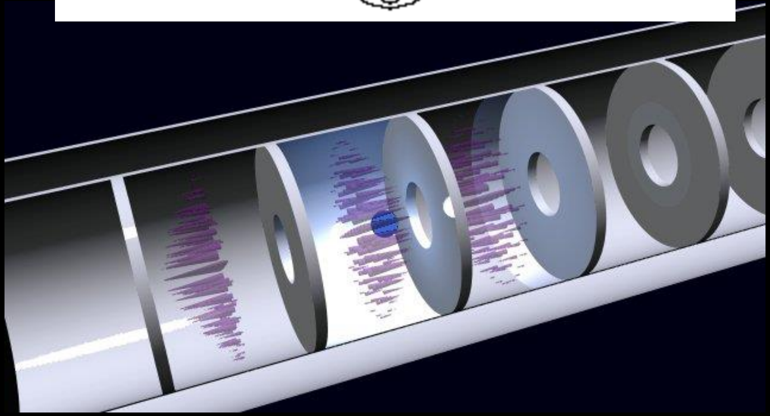
Cyclotrons cannot accelerate to high energies due to relativistic effects

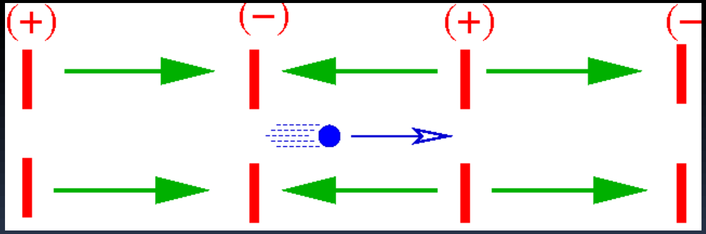
RF cavities

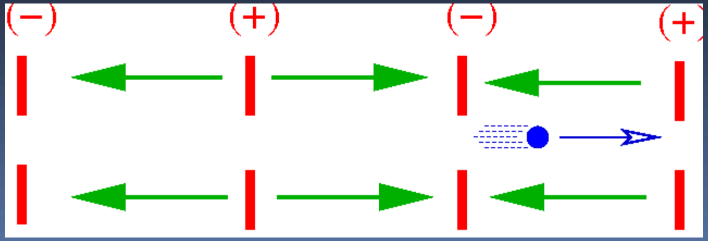
- …are used in almost all modern accelerators…
- In RF cavity the particles "surf" on an electromagnetic wave that travels in the cavity

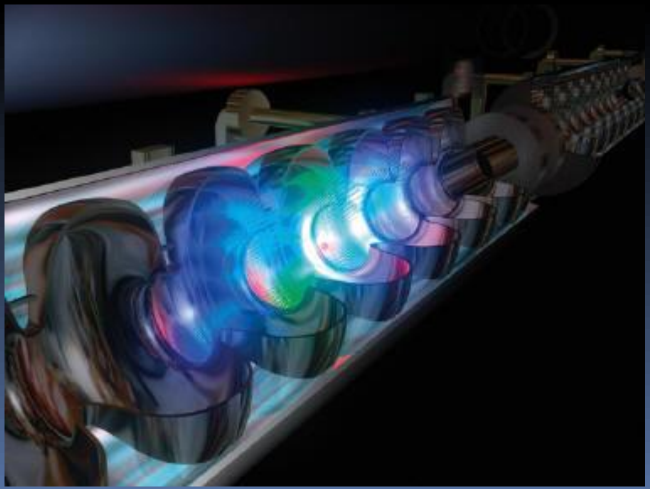






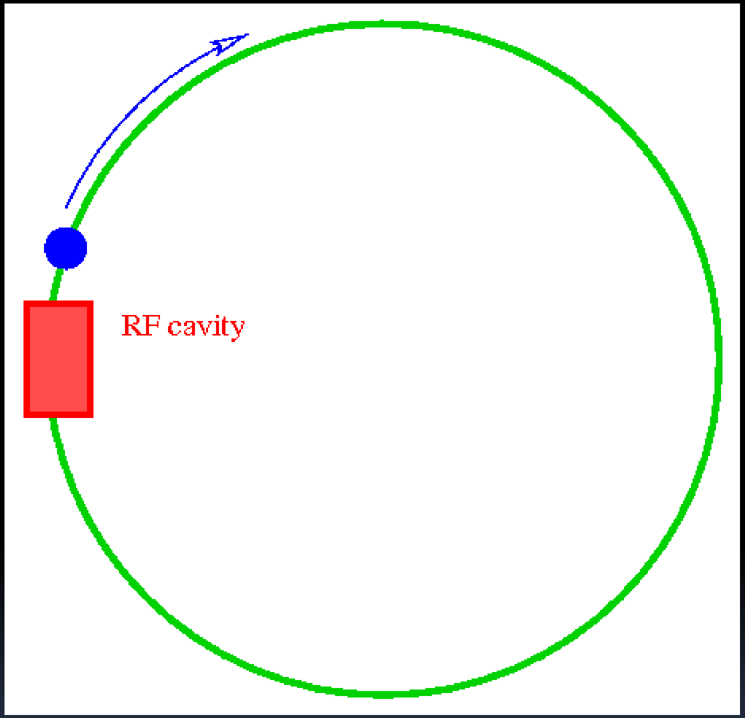






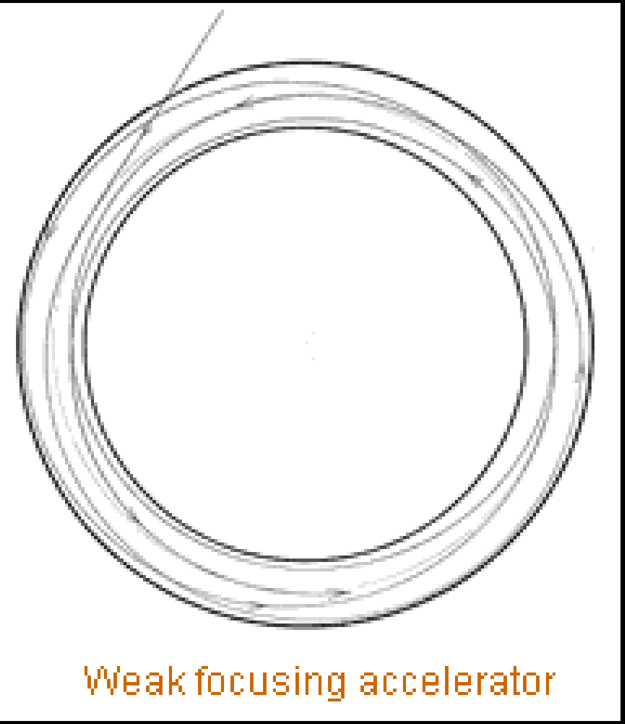
Synchrotrons

- Synchrotrons can accelerate to very high energy
- E.g., LHC is synchrotron
- Limitation of synchrotrons (especially for electrons) is due to "synchrotron radiation"



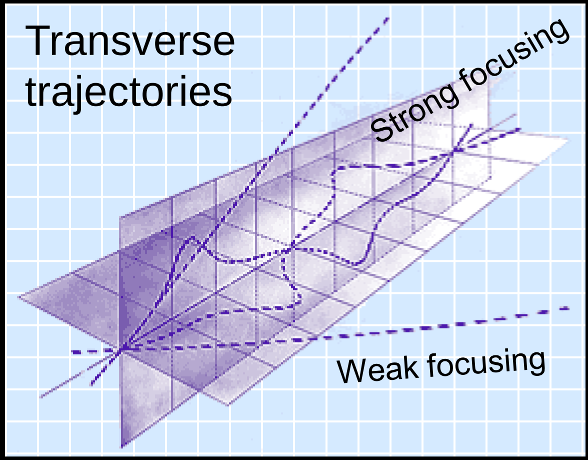
Focusing

- Focusing is needed to confine the orbits
- First accelerators had “weak focusing” – when focusing period was larger than the perimeter

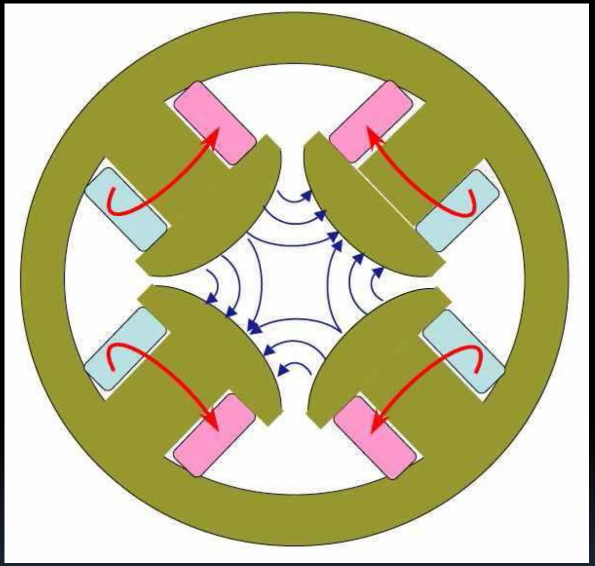


10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful for his time. Its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world

- “Strong focusing” alternates focusing-defocusing forces (provided by quadrupoles) to give overall focusing in both X & Y planes



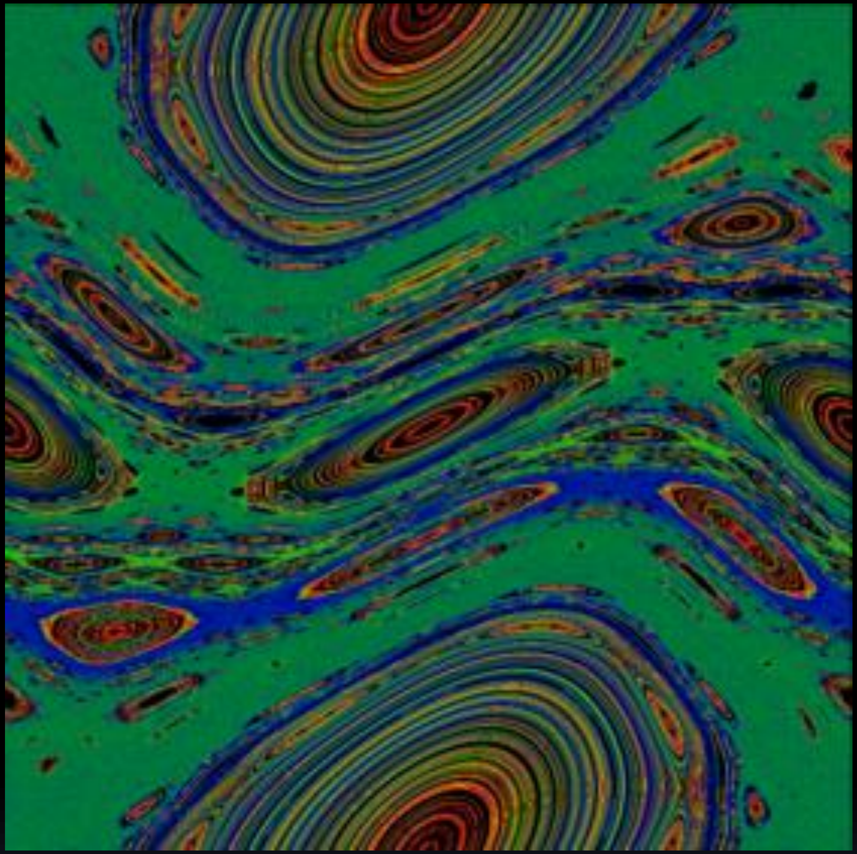
Strong focusing allow use of more compact magnets, thus achieving many times larger energy with the same cost



CERN's Proton Synchrotron, the first operating strong-focusing accelerator

200-m diameter ring, weight of magnets 3,800 tons

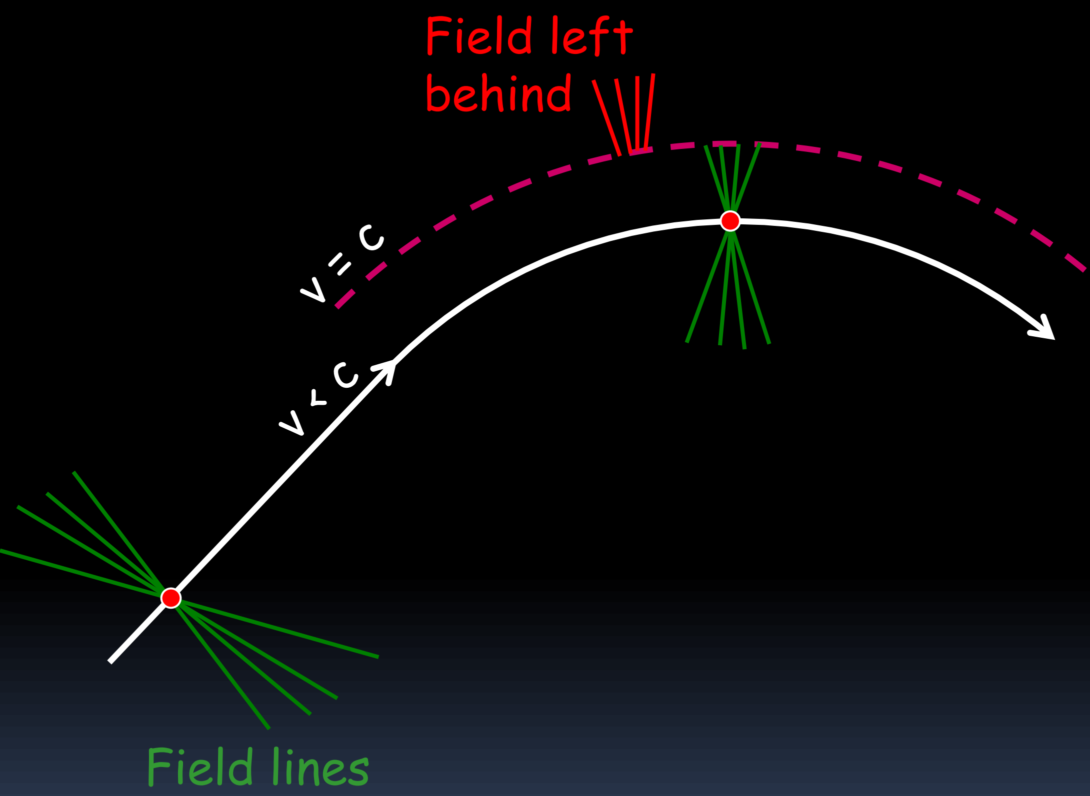
Chaos Seen in Movement of Ring-Herding Moons of Saturn October 11, 2002



Orbits in accelerator, dynamical system, often exhibit chaotic dependence

Saturn's F ring and Prometheus

Synchrotron radiation

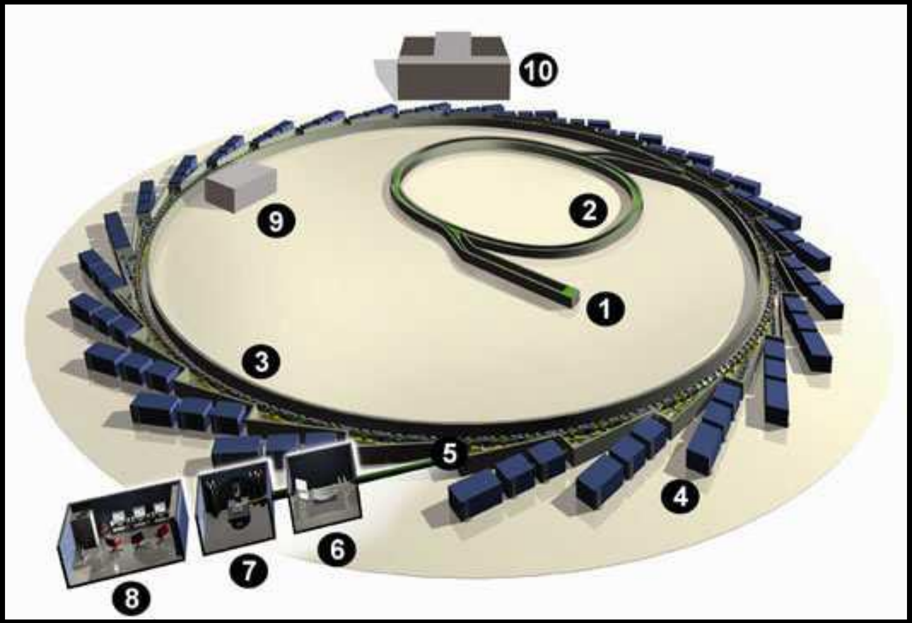


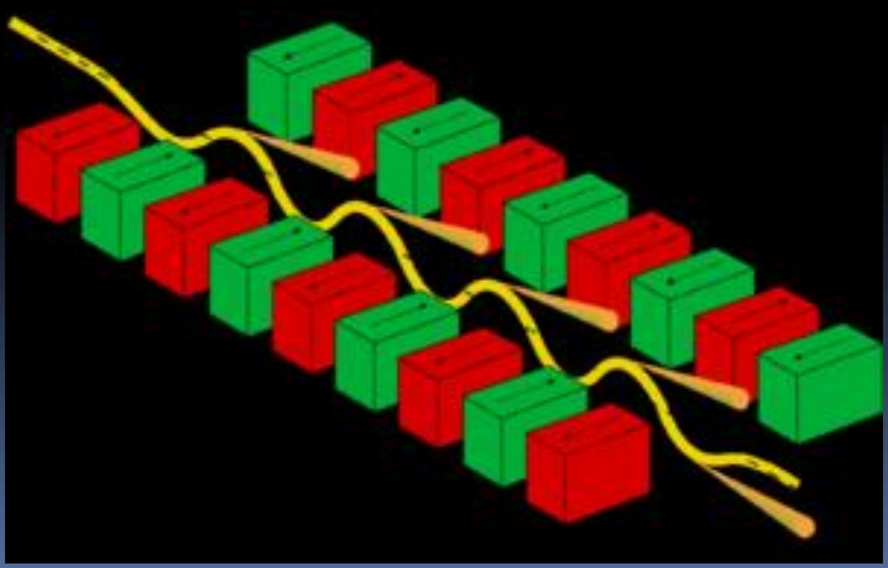
- Caused by field "left behind" during motion on a curved trajectory
- Energy loss per meter is proportional to γ^4 and to $1/R^2$
- Can be both harmful and useful

E.g. at LEP the electron would loose few % of its energy every turn

Good use of synchrotron radiation

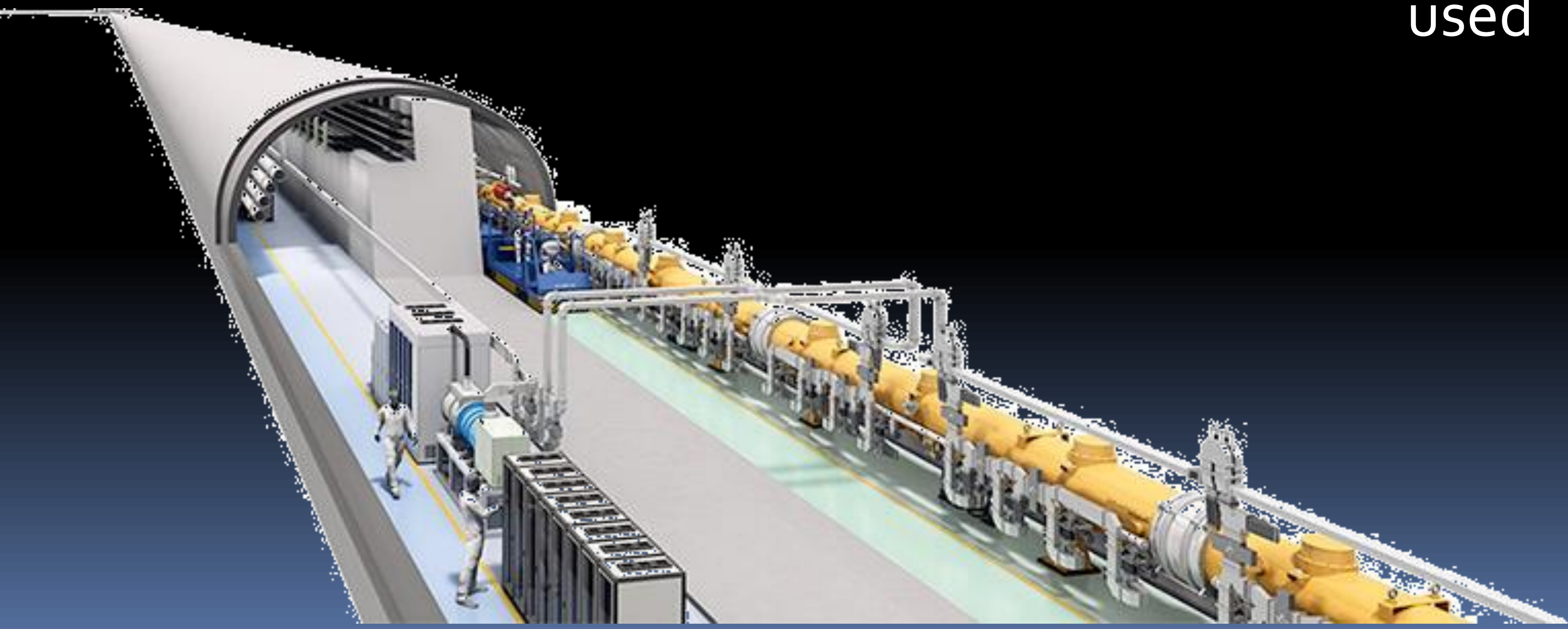
- Synchrotron radiation light sources exploit this feature to create scientific instruments
- Example – Diamond light source
- Special magnets (undulators) are inserted to further enhance the synchrotron radiation





Linear accelerator

- Synchrotron radiation for e- or e+ for energies > 100GeV / beam practically preclude use of circular accelerators
  - For such energies, linear accelerators have to be used

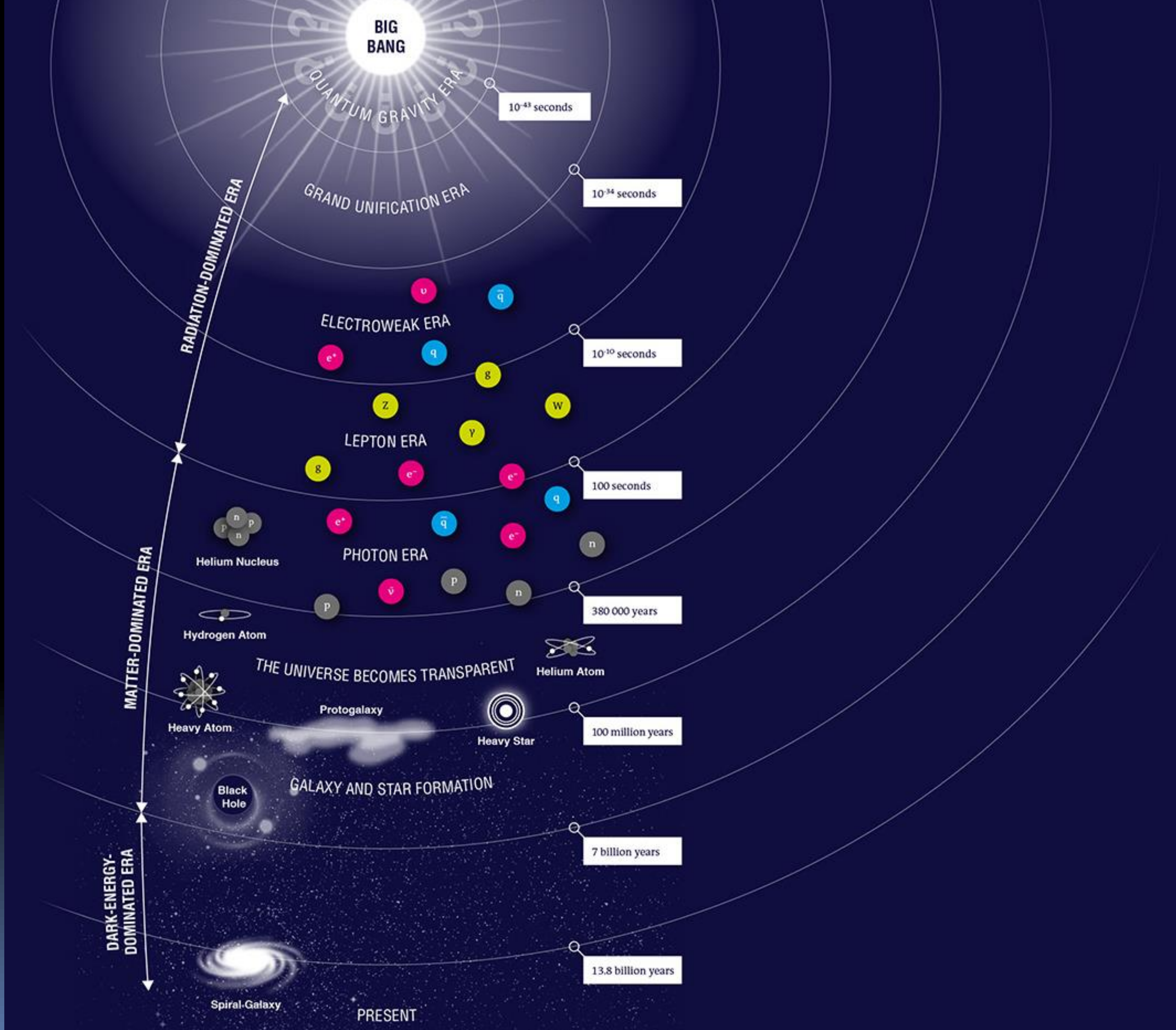


Why build colliders?

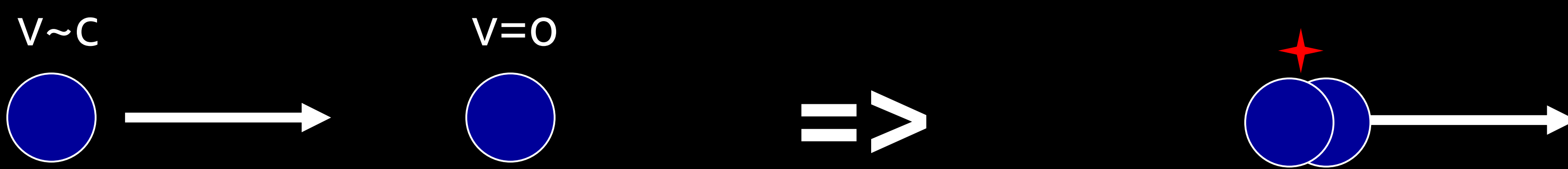
- Want to see what matter is made of

- Smash matter apart and look for the building blocks

- Take small pieces of matter:
  - accelerate them to very high energy
  - crash them into one another


BIG BANG
QUANTUM GRAVITY ERA
10^-43 seconds
GRAND UNIFICATION ERA
10^-34 seconds
RADIATION-DOMINATED ERA
ELECTROWEAK ERA
10^-10 seconds
LEPTON ERA
100 seconds
Helium Nucleus
PHOTON ERA
380 000 years
MATTER-DOMINATED ERA
Hydrogen Atom
THE UNIVERSE BECOMES TRANSPARENT
Helium Atom
Heavy Atom
Protogalaxy
Heavy Star
100 million years
Black Hole
GALAXY AND STAR FORMATION
7 billion years
DARK-ENERGY-DOMINATED ERA
13.8 billion years
Spiral Galaxy
PRESENT

Why colliders?



$E = \gamma m c^2$

$P = \gamma m v$

Only a tiny fraction of energy converted into mass of new particles

(due to energy and <u>momentum</u> conservation)

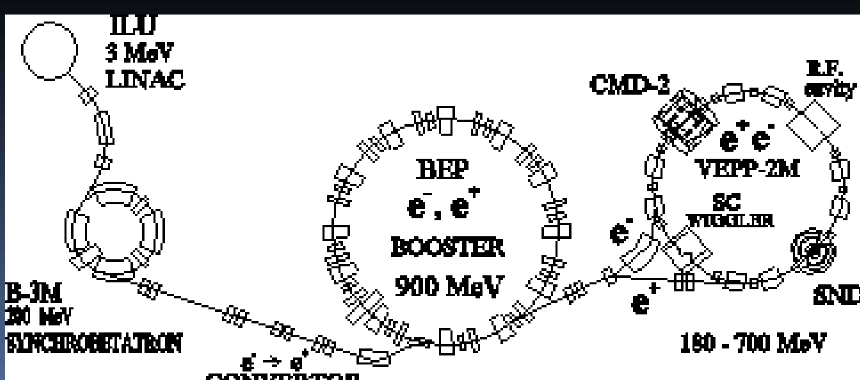
$E = \gamma m c^2$ $E = \gamma m c^2$

Entire energy converted into the mass of new particles

LEP Collider, CERN

SLAC Linear Collider

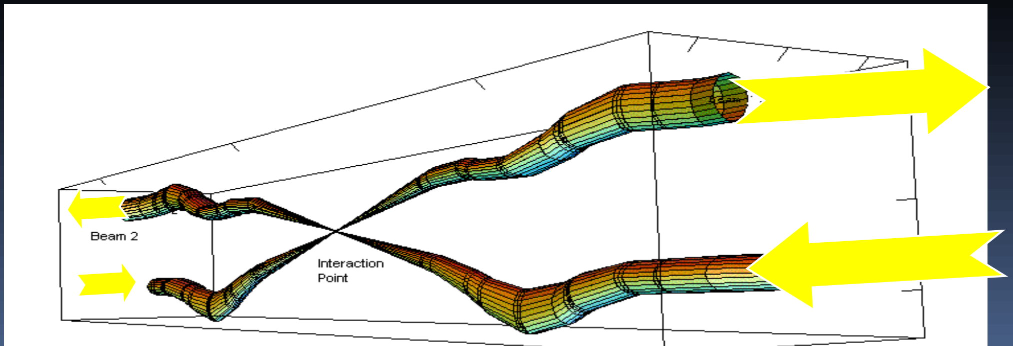
VEP Colliders
BINP, Novosibirsk



Tevatron collider,
Fermilab

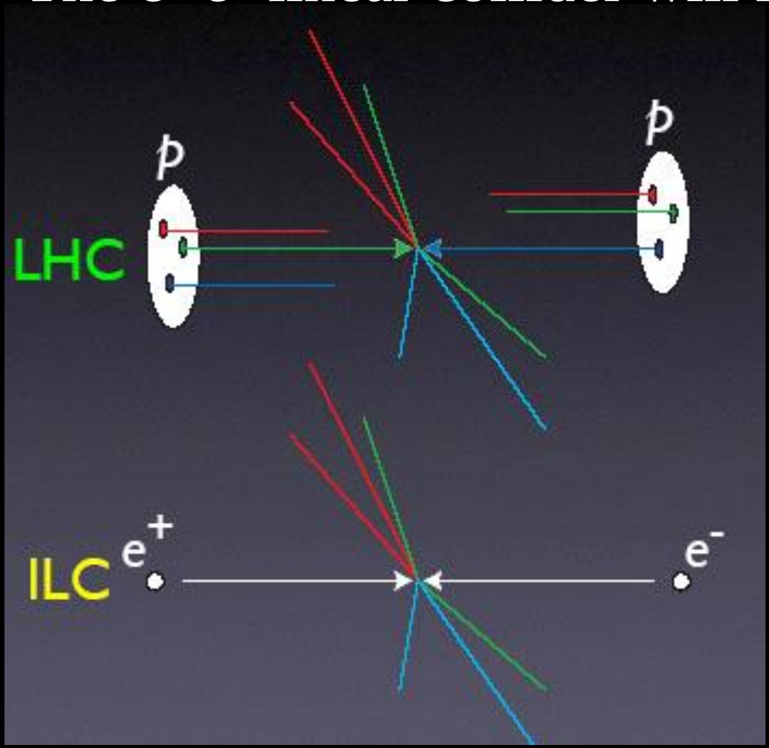
LHC collision points

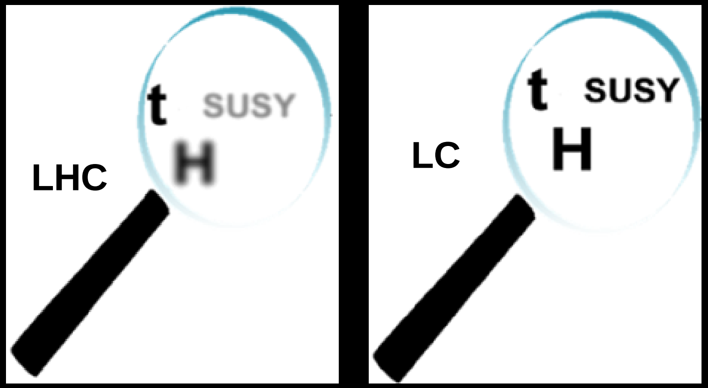
At four places the beams intersect

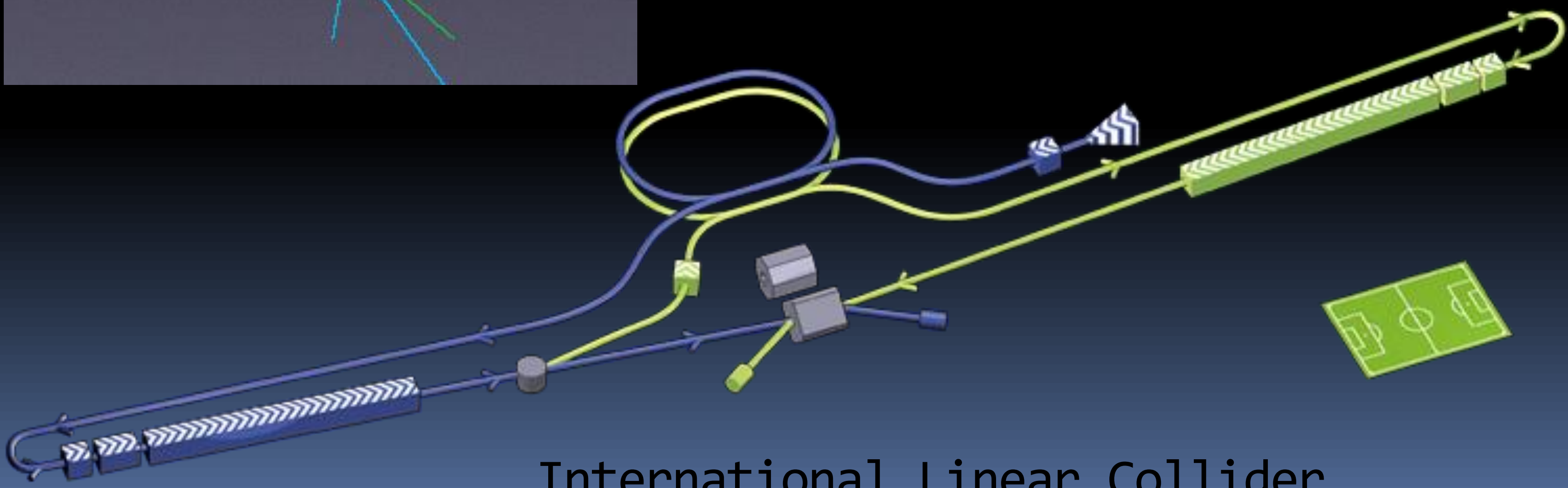


Relative beam sizes around IP1 (Atlas) in collision

LHC will open the curtain of a theatre of new physics
The e+e- linear collider will illuminate the stage

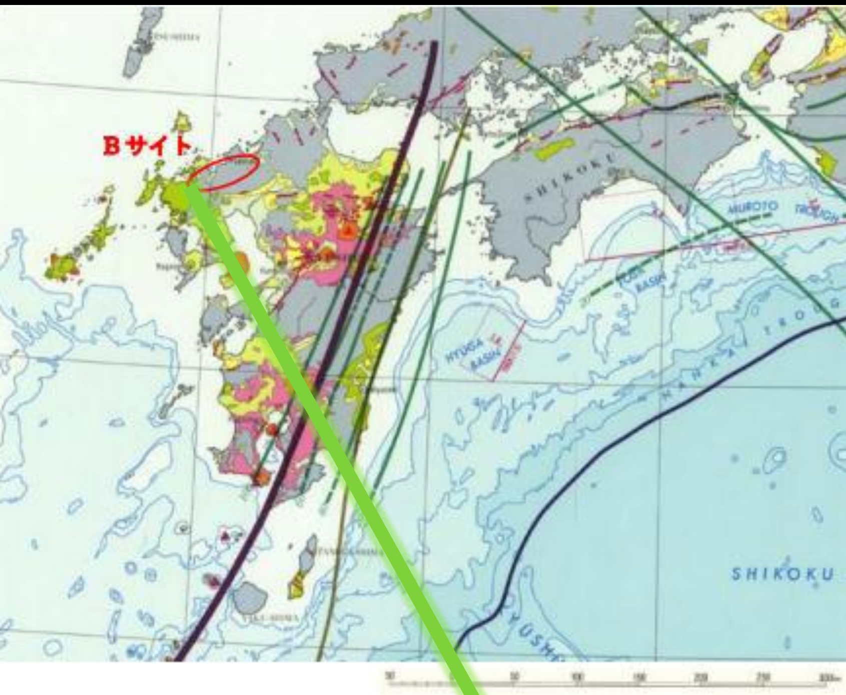




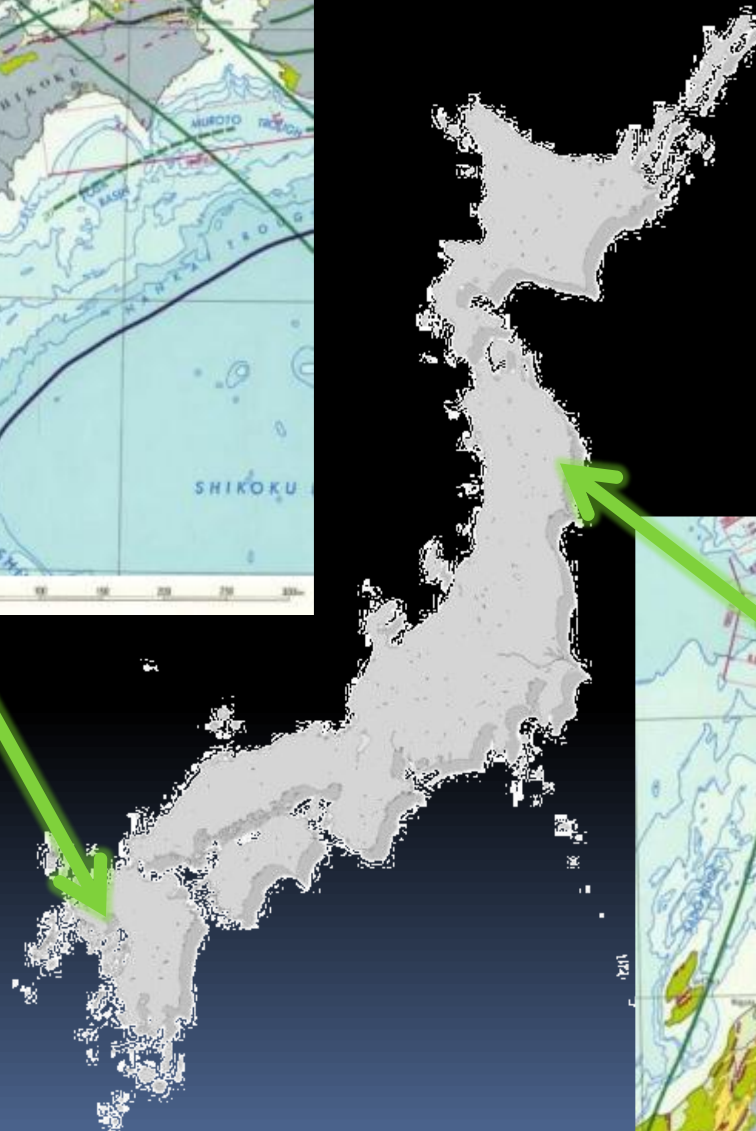


International Linear Collider

Japan ILC initiative

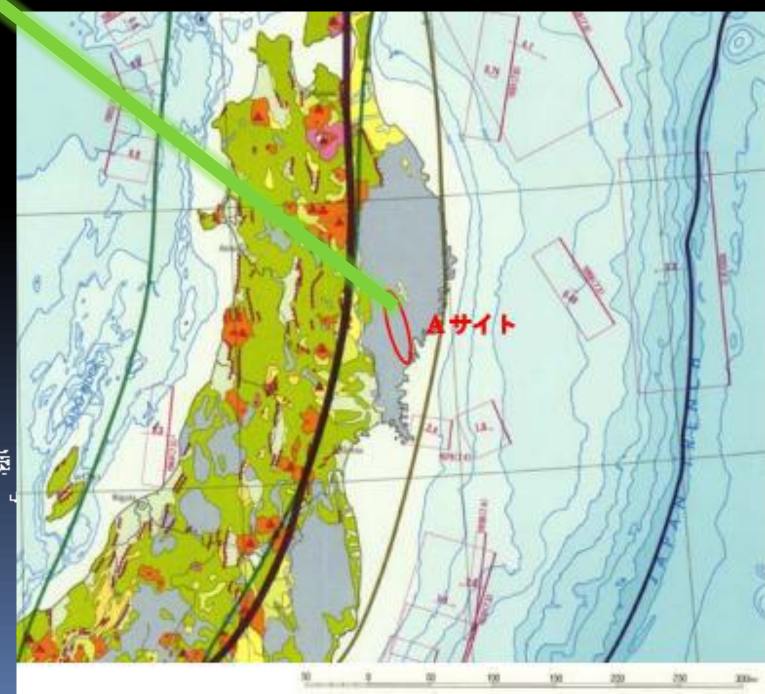


Creation of Global Science City with ILC as the Core



KITAKAMI-Site

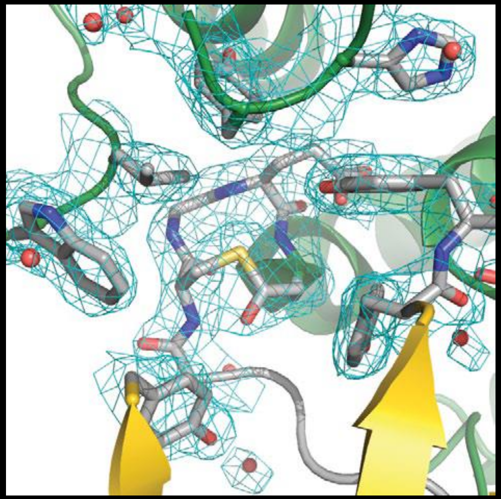
SEFURI-Site



Japan ILC initiative

Accelerators & discovery science

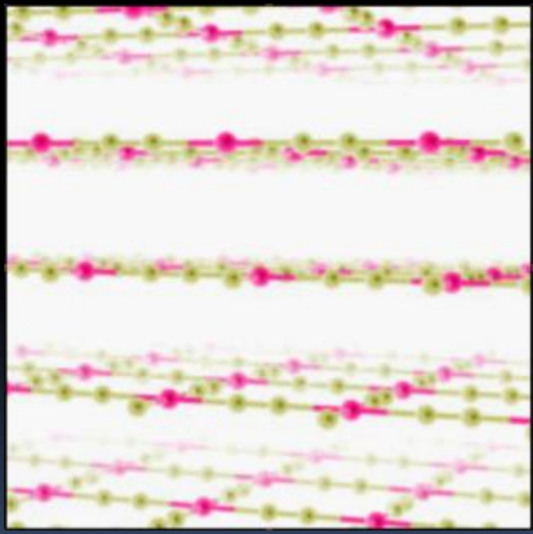
Protein structure revealed with help of light sources



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)



Accelerators enabled many discoveries
The fraction of the Nobel prizes in Physics directly connected to accelerators is about 30%

diamond

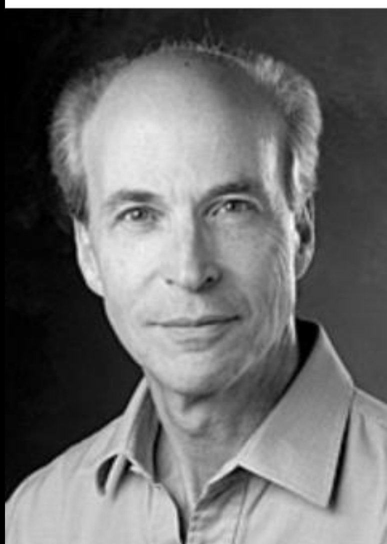
Science & Technology Facilities Council

24 Nobel Prizes in Physics that had direct contribution from accelerators

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].

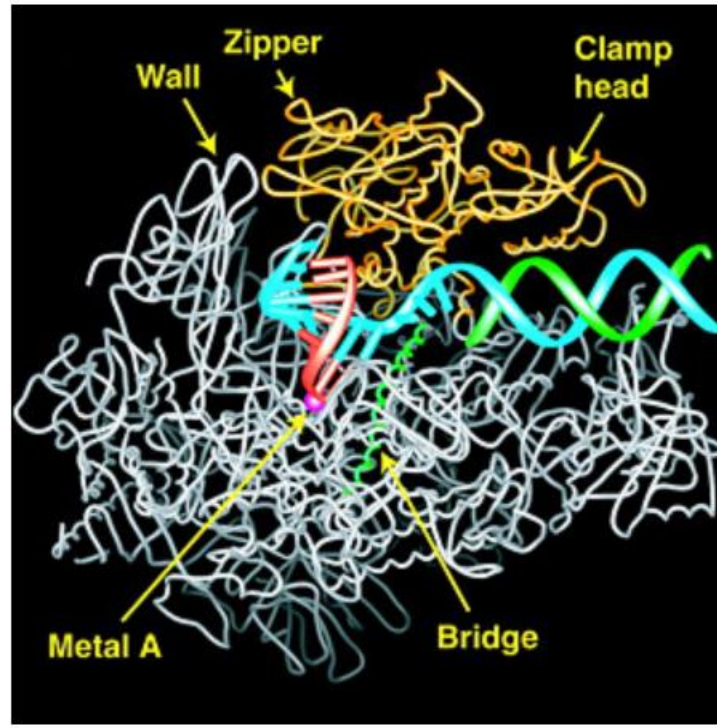
A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & submitted to the Physics in Perspective Journal, Dec 2010.

The Nobel Prize in Chemistry 2006
Roger D. Kornberg



Roger Kornberg’s Nobel Prize-winning determination of the structure of RNA polymerase has been described as a “technical tour de force.” The key to the visualization of this fundamental biological molecule in action was synchrotron radiation, supplied by the powerful X-ray crystallography instruments at the Stanford Synchrotron Radiation Laboratory.

Science

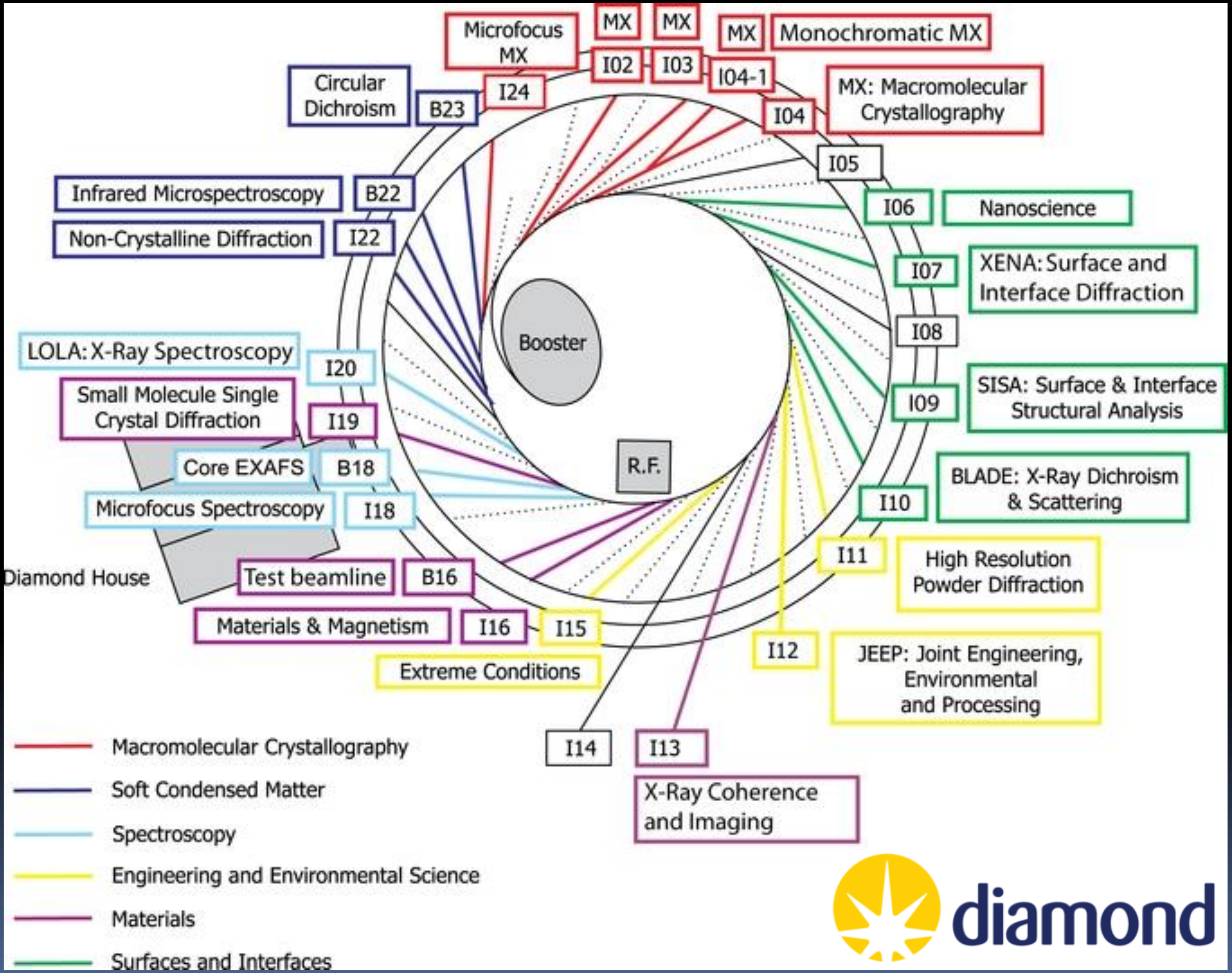


The transcription process visualized by Roger Kornberg and his colleagues in his X-ray crystallography studies published online April 19, 2001, in *Science*. The protein chain shown in grey is RNA polymerase, with the portion that clamps on the DNA shaded in yellow. The DNA helix being unwound and transcribed by RNA polymerase is shown in green and blue, and the growing RNA stand is shown in red.

Diamond: synchrotron source of X-rays

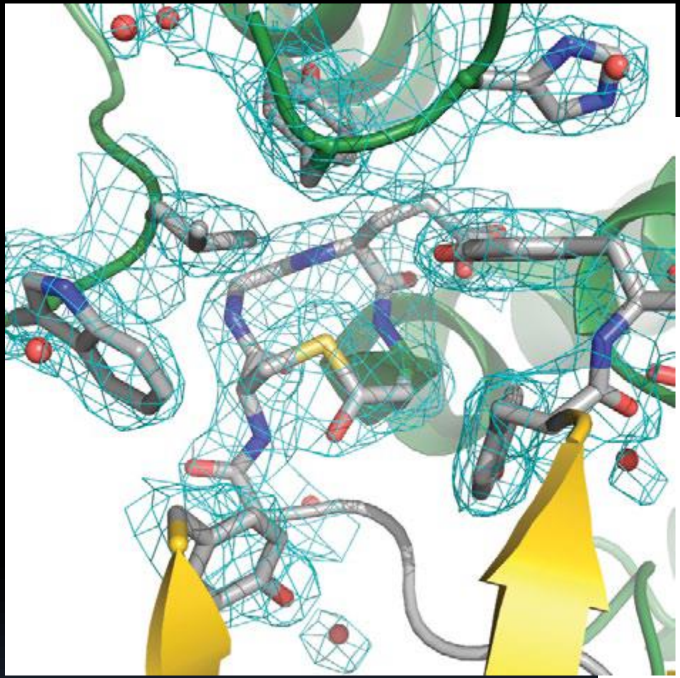
Diamond Light Source, Harwell Science and Innovation Campus, UK

Diamond beamlines

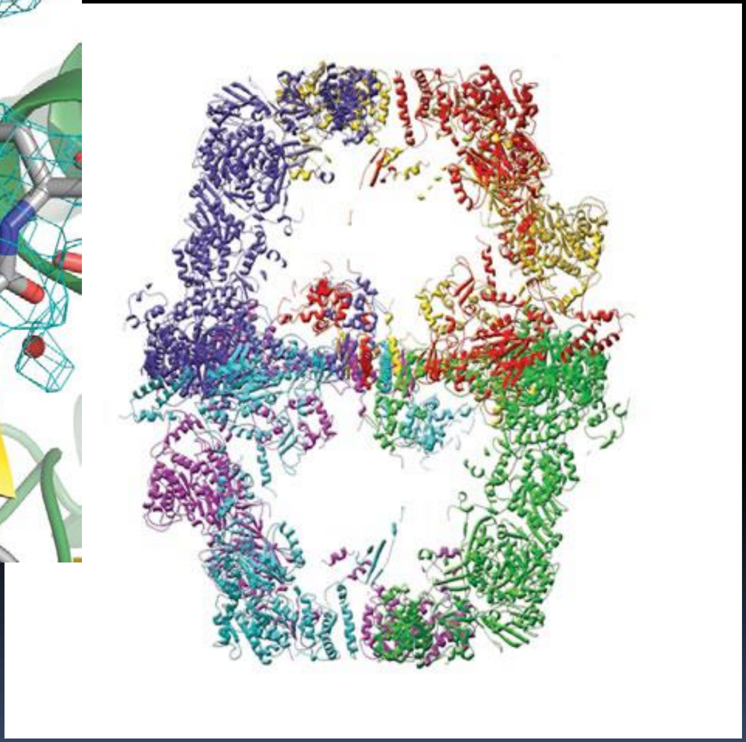


Protein structure revealed by light sources

HIV glycoprotein

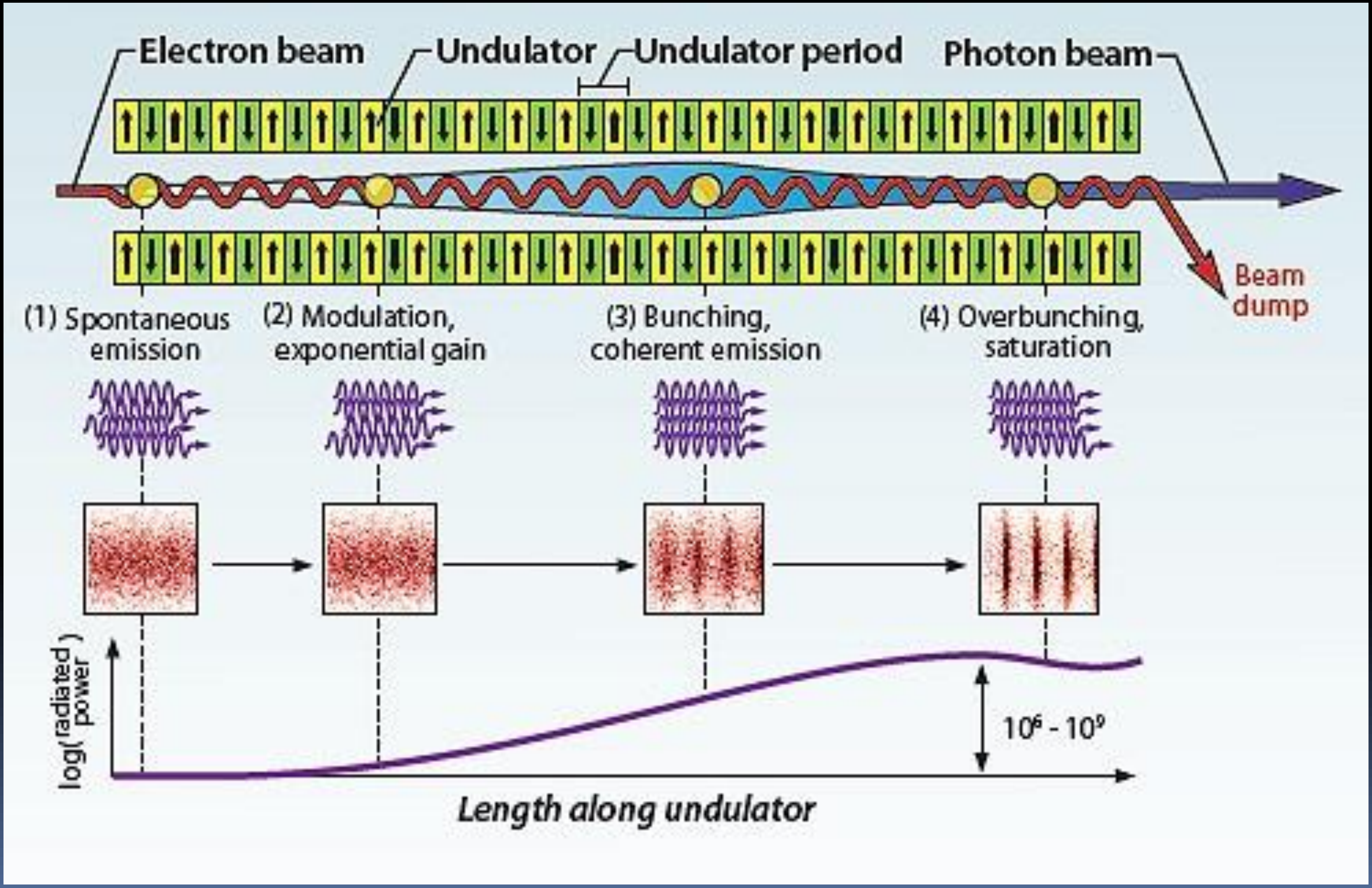


mosquito
immune system



yeast enzyme

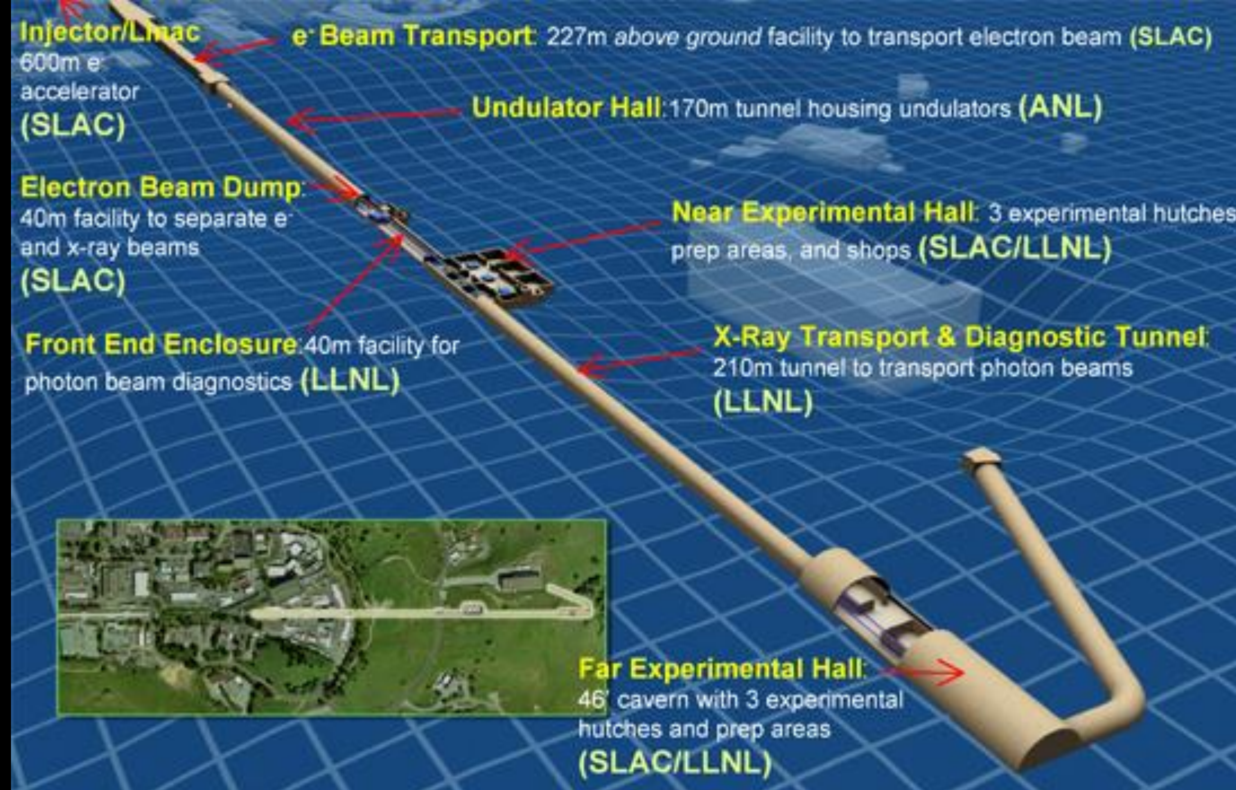
4^{th} generation light source – Free Electron Laser

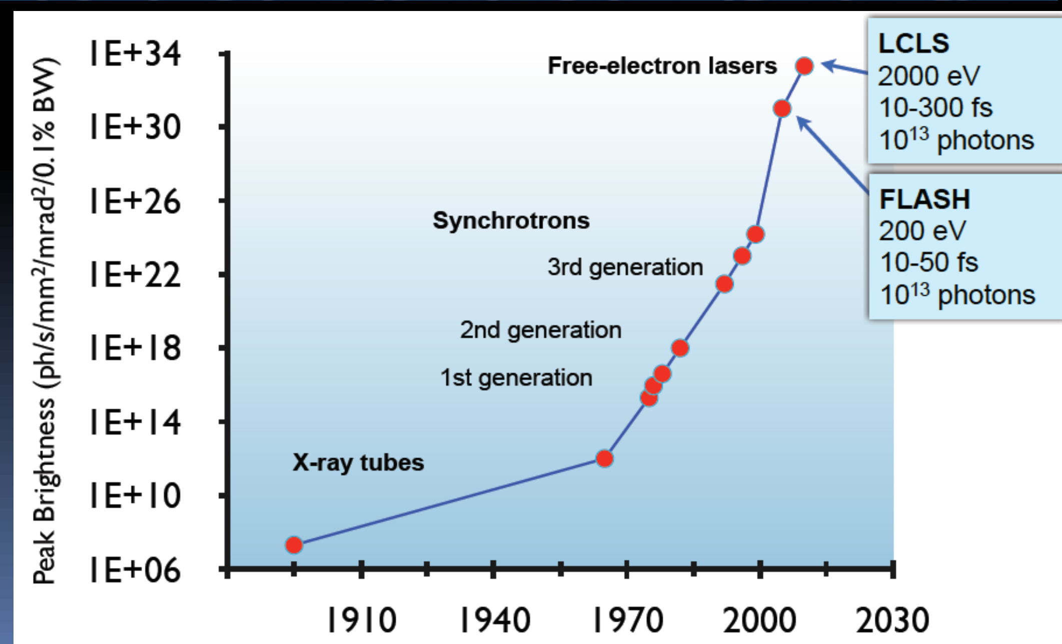


4th generation light source –

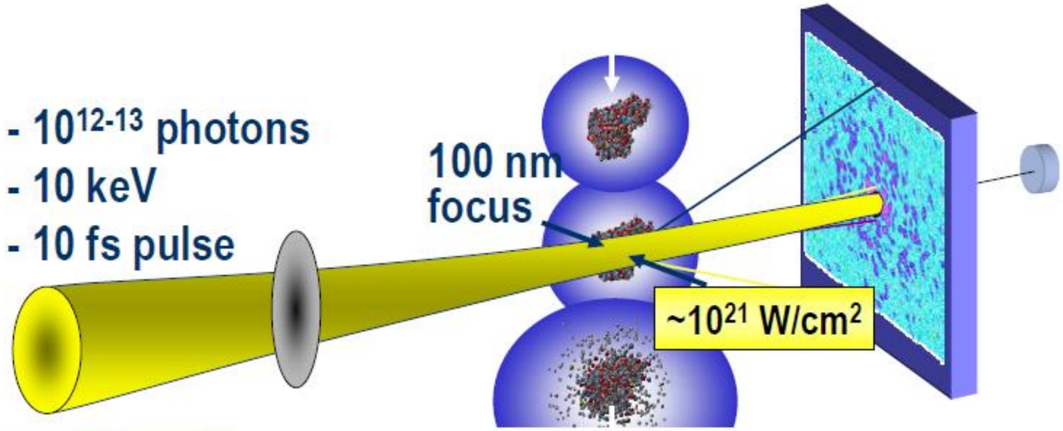
X-ray FEL-

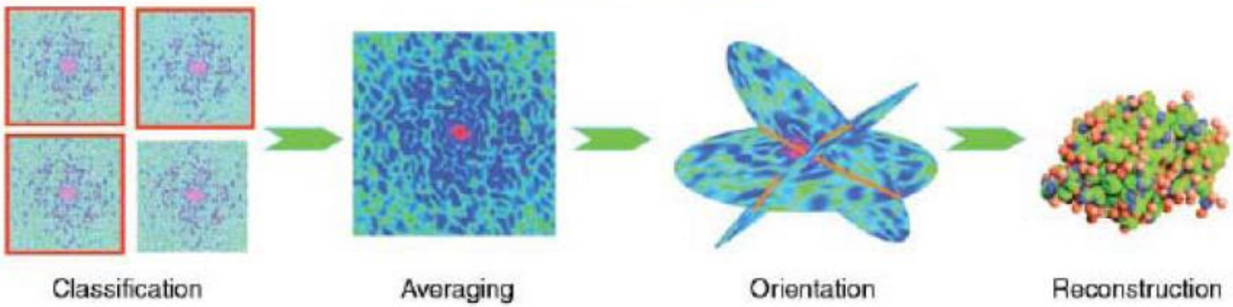
LCLS at SLAC



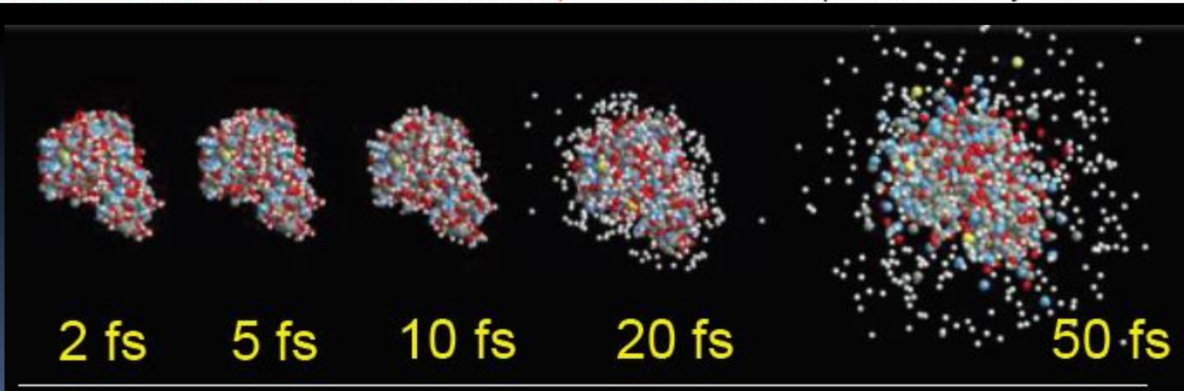


Coherent diffractive imaging of single particles





Calculations. in vacuum Neutze et al., Nature 2000 Chapman, Gaffney Science 2007

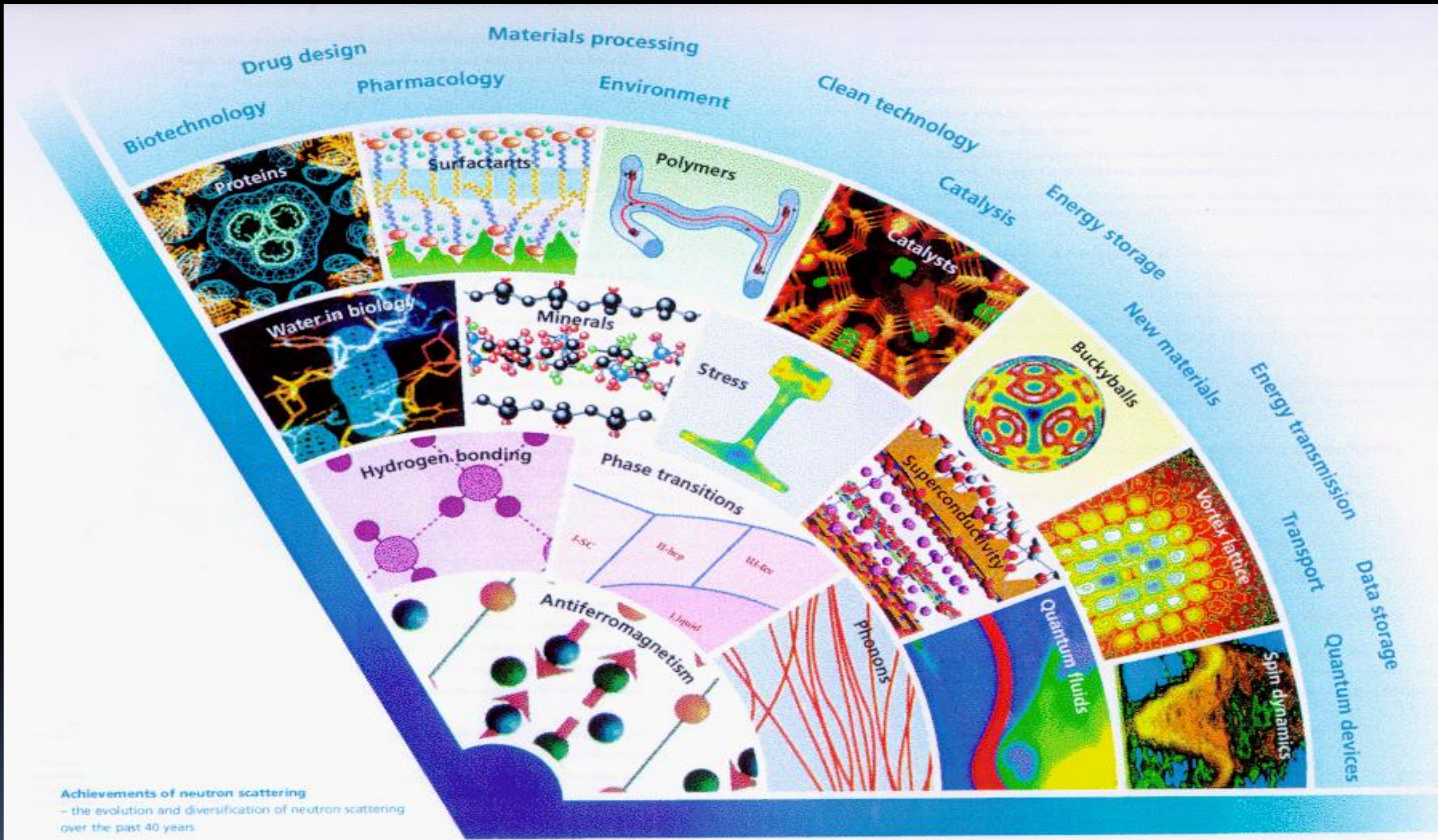


ISIS: neutron and muon source

ISIS pulsed neutron and muon source at the Rutherford Appleton Laboratory, UK

Science & Technology Facilities Council ISIS

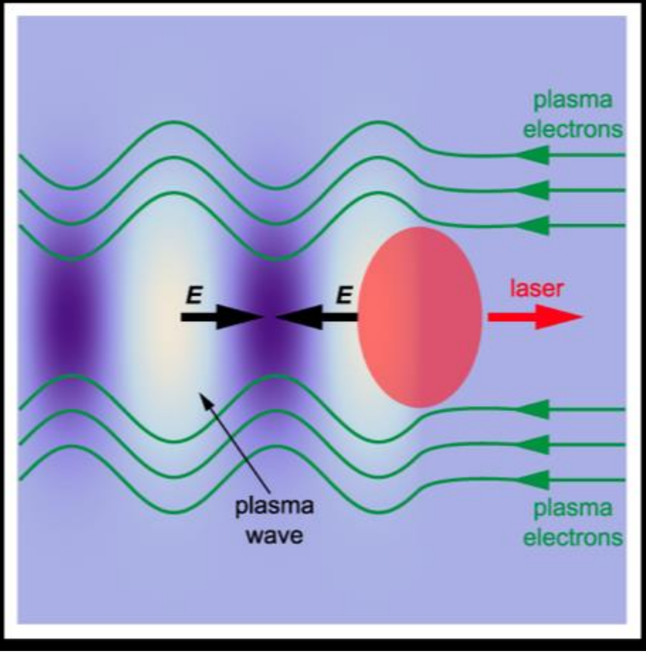
ISIS: neutron and muon source

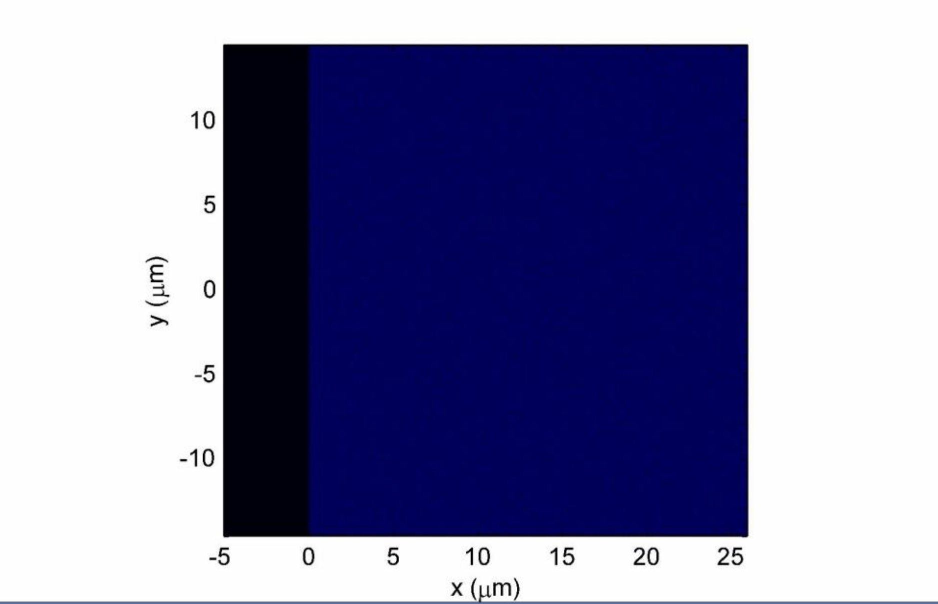


Achievements of neutron scattering
– the evolution and diversification of neutron scattering over the past 40 years

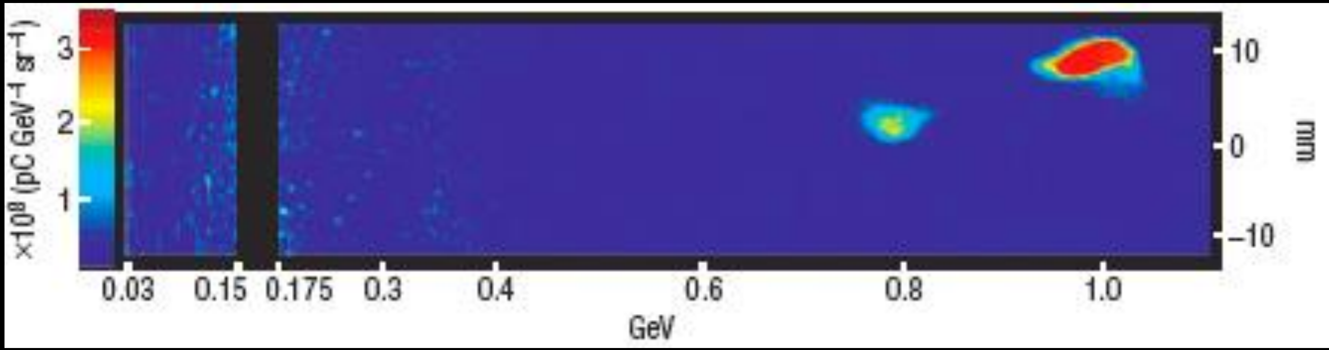
Laser-Driven Plasma Accelerators

- Ponderomotive force of short (50fs), intense (10^{18} W cm^{-2}) laser pulse expels plasma electrons
- This sets up plasma wave which trails laser pulse
- Electric fields within plasma wave of order 100 GV/m formed
- 3 to 4 <u>orders of magnitude</u> bigger than in conventional accelerator!



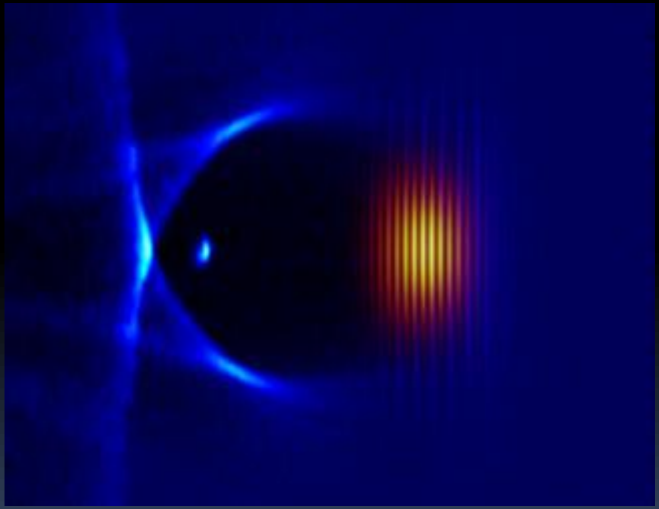


Laser-Plasma Acceleration



1GeV acceleration in just 3cm of plasma

W. Leemans, B. Nagler, A. Gonsalves, C. Toth, K. Nakamura, C. Geddes, E. Esarey, C. B.Schroeder, & S. Hooker, ***Nature Physics*** 2006



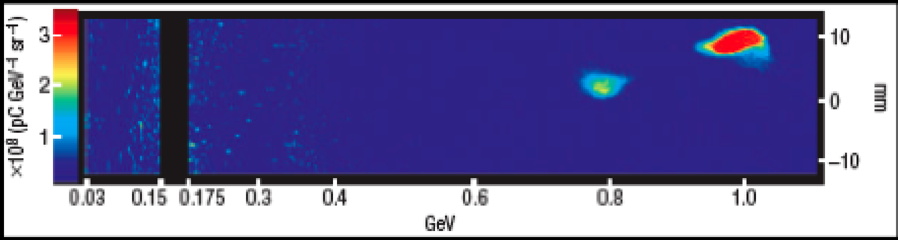
← **Simulation of laser-plasma acceleration**

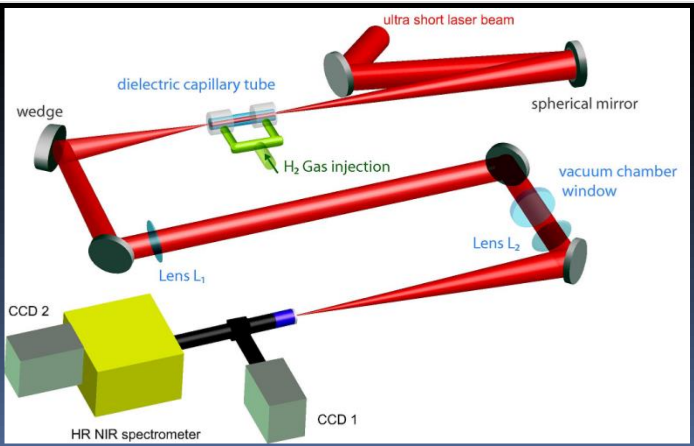
Rapid progress in beam energy achieved with laser-plasma acceleration shows that the synergy of accelerators, laser and plasma is revolutionizing the field of accelerator science

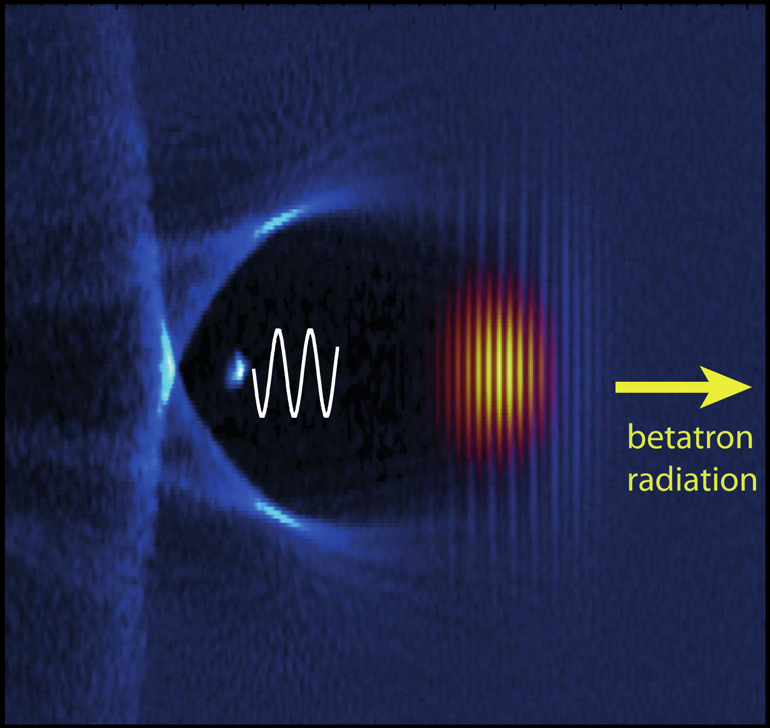
Rapid progress is being made …

- 2004: First quasi-monoenergetic beams generated (IC, LBNL, LOA)
- 2006 First GeV beams generated (Oxford & LBNL)
- 2008 Generation of visible radiation in undulator (Strathclyde & Jena)
- 2009 Measurement of $E_z L$ ~ 1 GeV in weakly nonlinear regime (LPGP, Strathclyde, Lund, JIHT)
- 2009: Generation of extreme UV radiation in undulator (MPQ & Oxford)
- 2011: Biological imaging with betatron radiation (IC, Michigan & MPQ)

The Economist



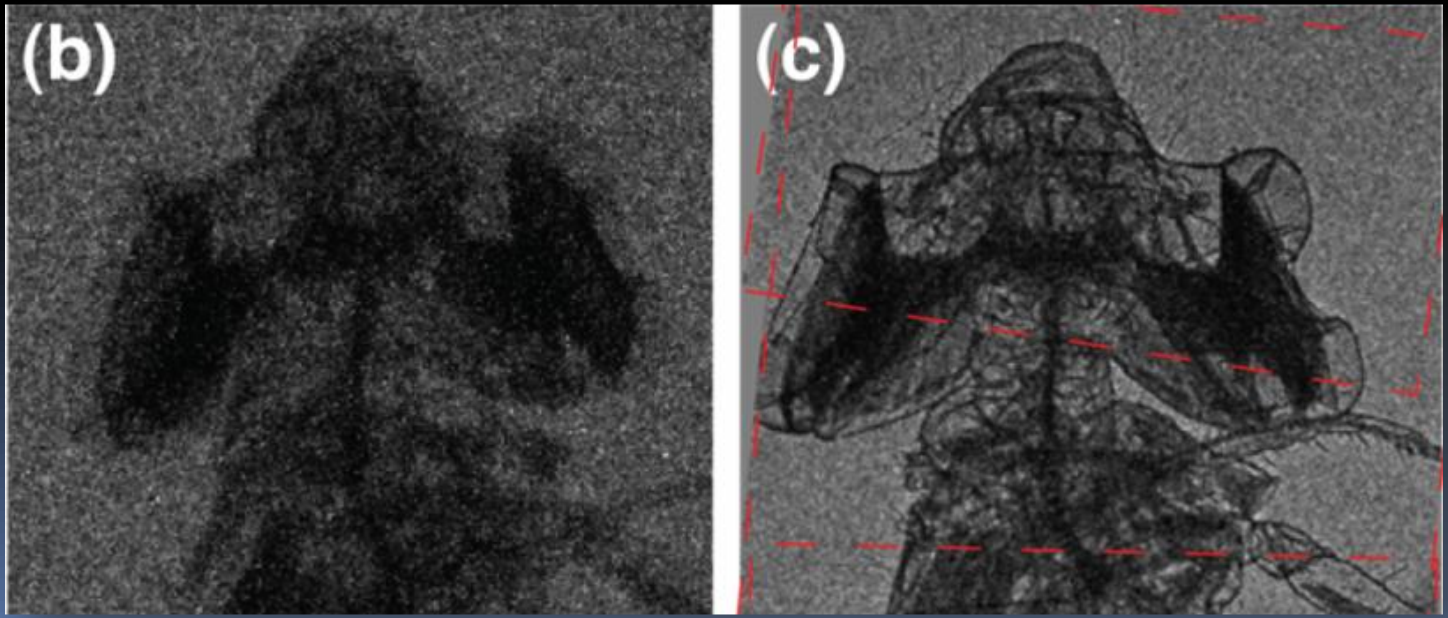


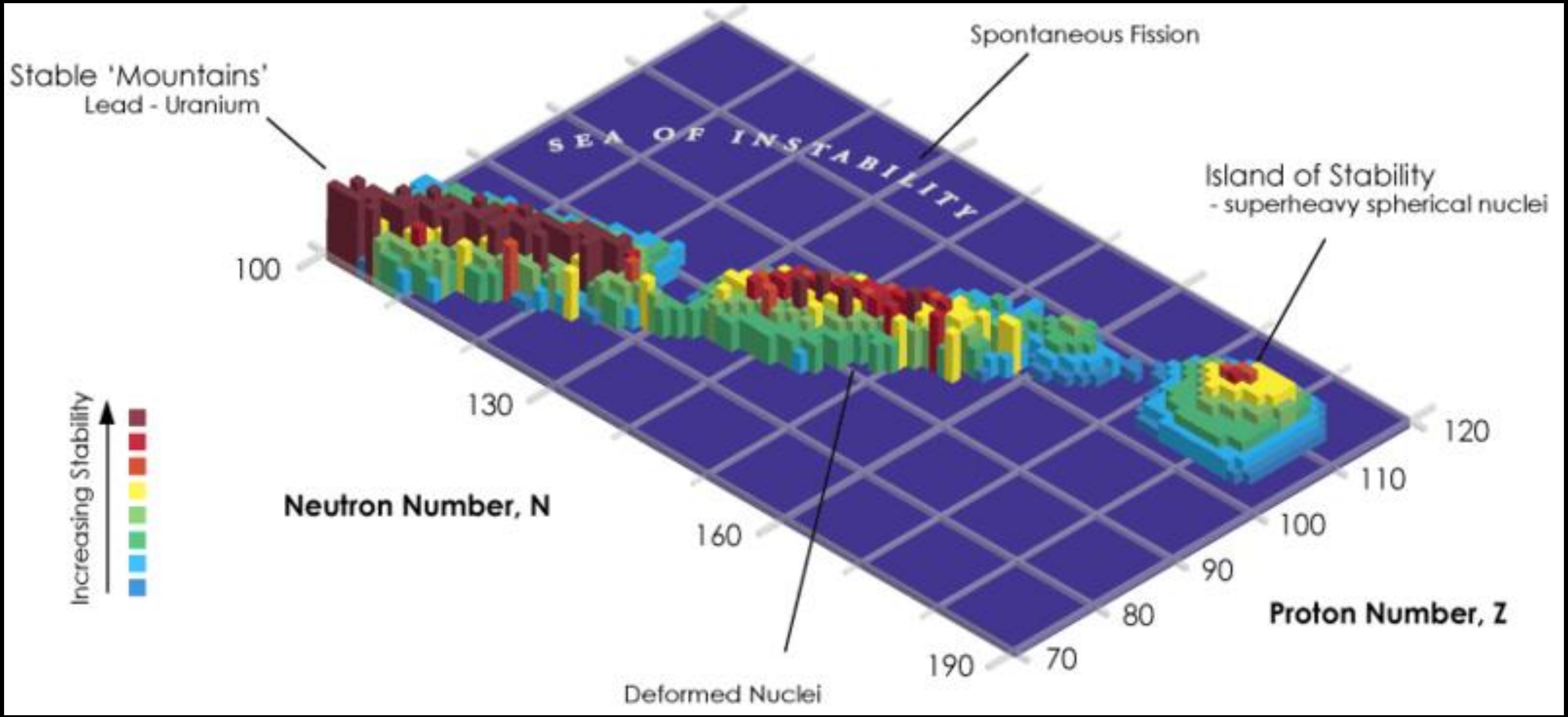


Betatron radiation sources

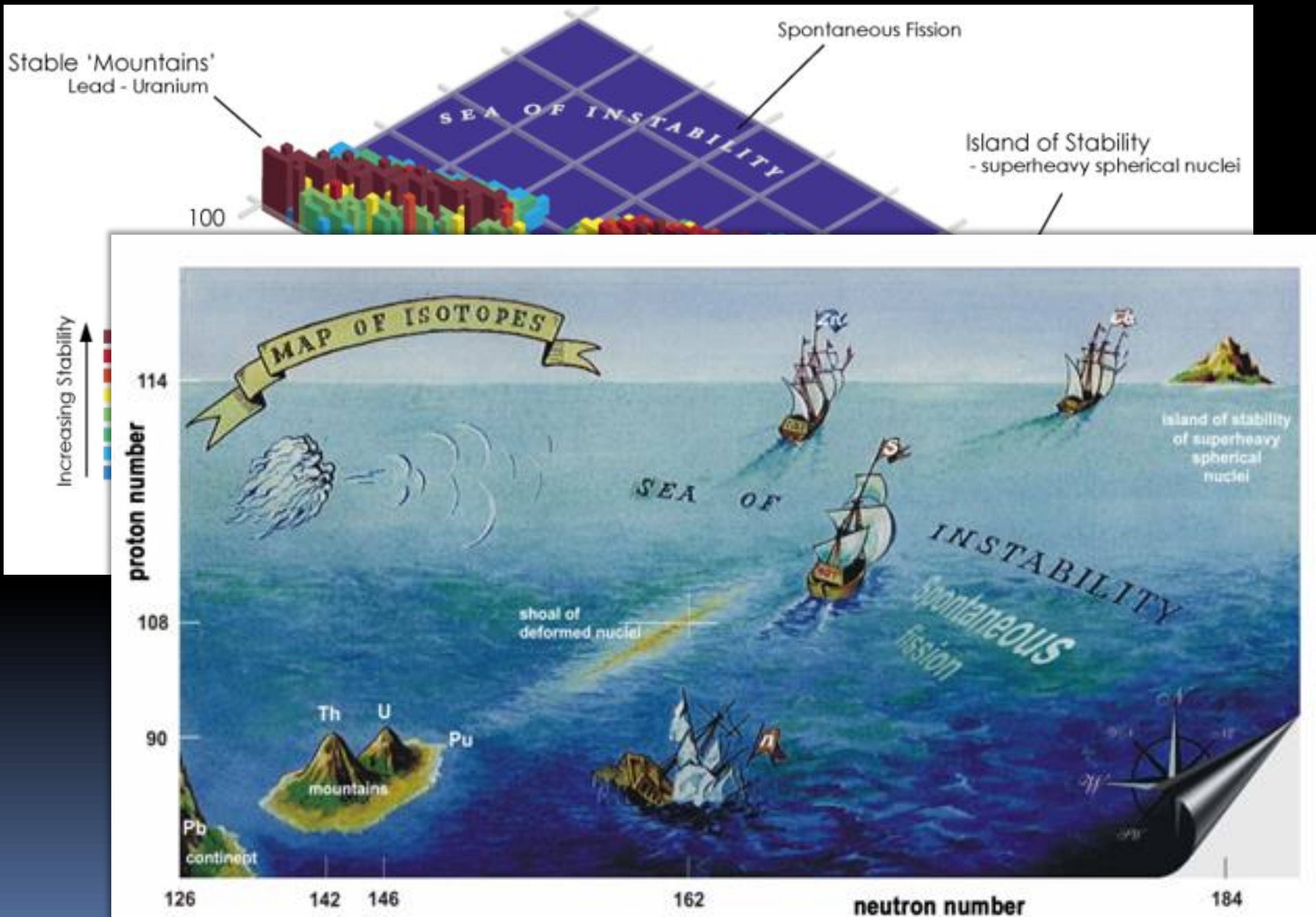
- Strong radial electric field within plasma wave cause transverse oscillation of electron bunch
- Generates very bright betatron radiation in 1- 100 keV range

S. Kneip et al., Appl. Phys. Lett. **99, 093701 (2011)**

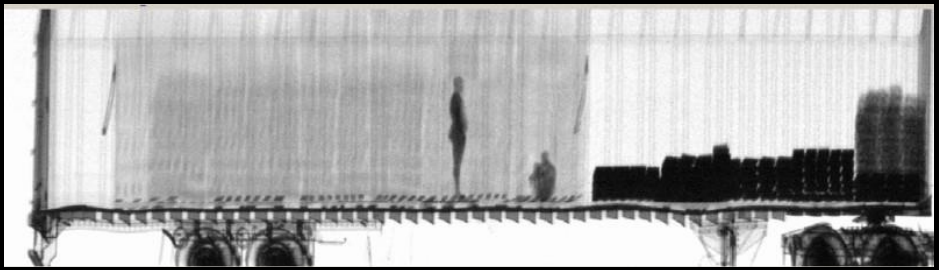




Accelerators for synthesis of transuranium elements

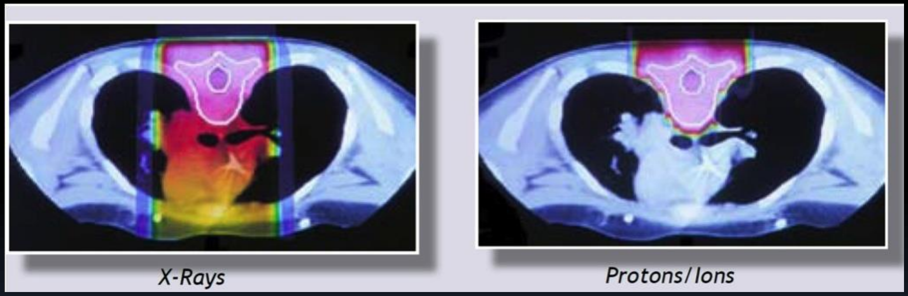

Spontaneous Fission
Stable 'Mountains'
Lead - Uranium
SEA OF INSTABILITY
Island of Stability
- superheavy spherical nuclei
100
Increasing Stability
MAP OF ISOTOPES
proton number
114
108
90
SEA OF INSTABILITY
island of stability of superheavy spherical nuclei
shoal of deformed nuclei
Spontaneous fission
Th
U
Pu
mountains
Pb
continent
126
142
146
162
184
neutron number

Accelerators are not only for high energy physics and discovery science



Security

Gamma-ray image of a truck [VACIS]



Healthcare

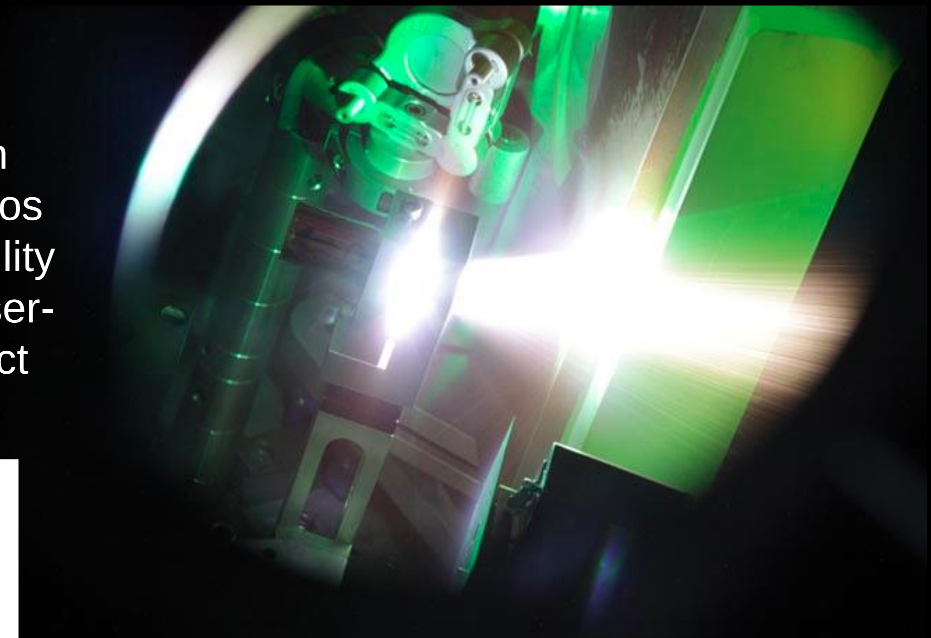
Cancer therapy with x-rays and protons or heavier ions

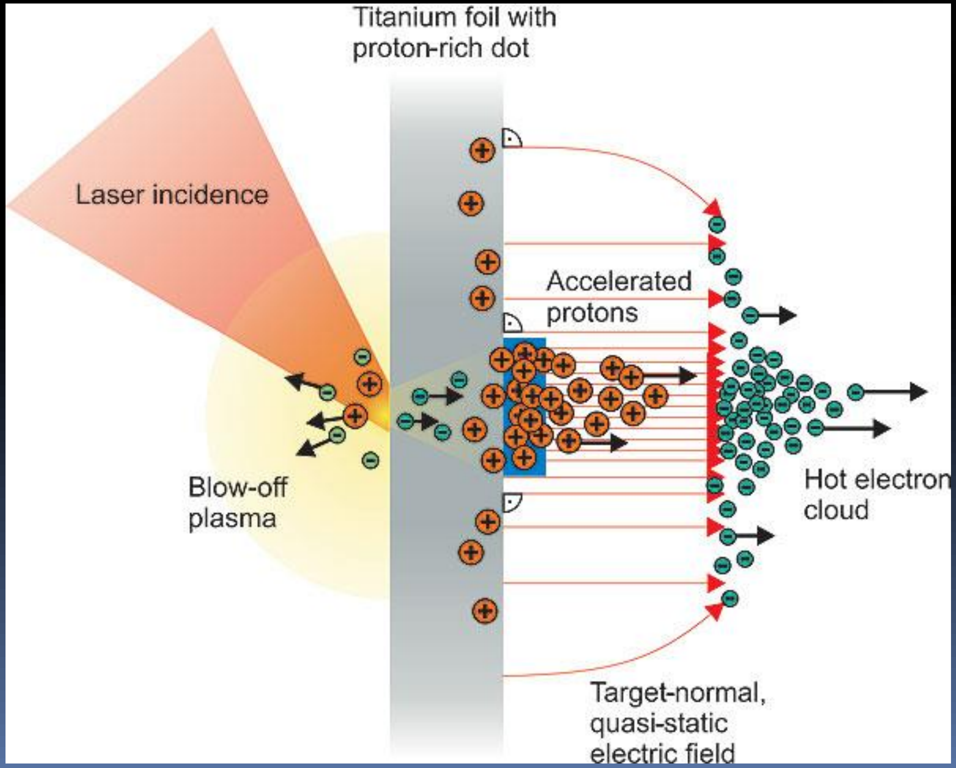
Energy…

Using laser-driven neutrons to stop nuclear smugglers

Researchers have successfully demonstrated for the first time that laser-generated neutrons can be enlisted as a useful tool in the War on Terror.

A burst of laser energy 50 times greater than the worldwide output of electrical power slams into an extremely thin foil target to produce neutrons at Los Alamos National Laboratory's TRIDENT laser facility during a recent experiment, which proved that laser-driven neutrons can be used to detect and interdict smuggled nuclear materials.





June 2013 Los Alamos press release

http://www.lanl.gov/newsroom/news-releases/2013/June/06.04-laser-driven-neutrons.php

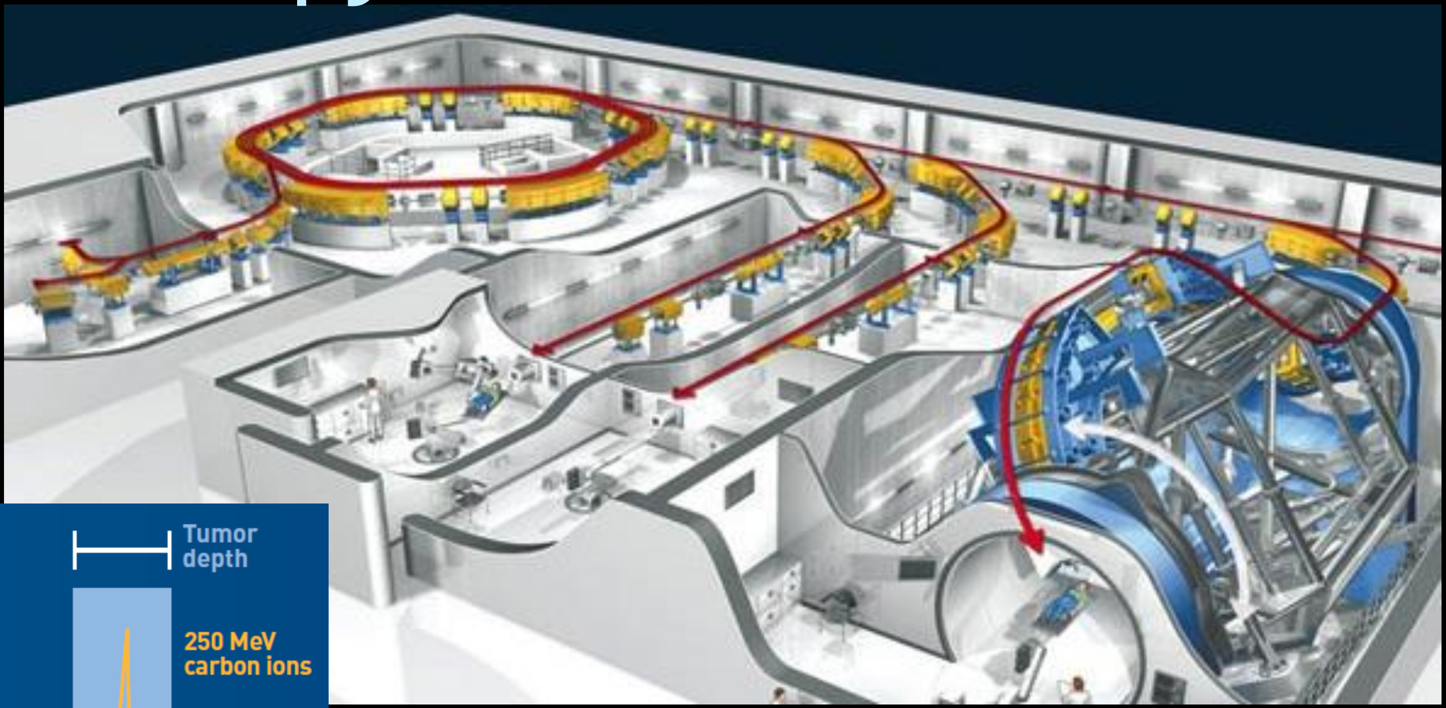
Accelerators for medical use

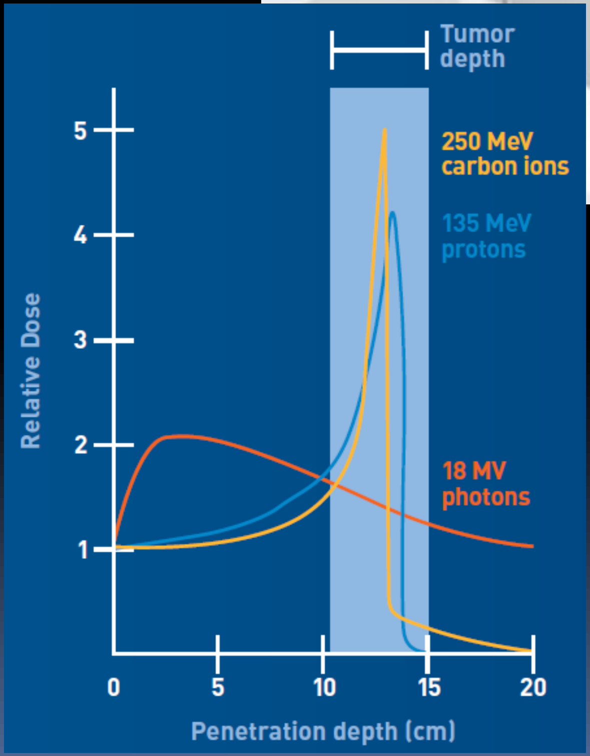
- **Production of radionuclides with (low-energy) cyclotrons**
  - **Imaging**
  - Therapy
- **Electron linacs for conventional radiation therapy**
- **Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u 12C-ions)**

Medical Particle accelerators in UK

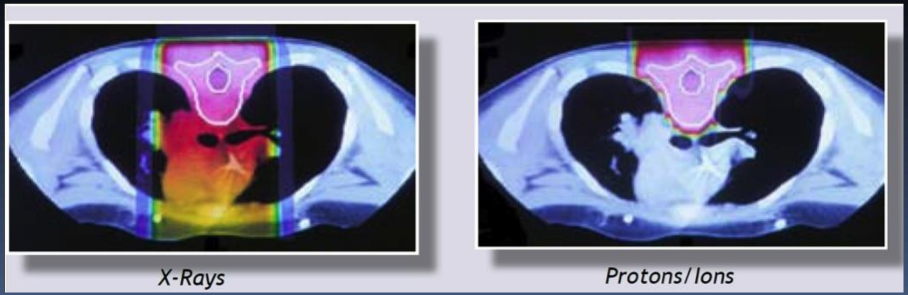
- Exposure to high doses of X-rays and gamma-rays can kill cells.
- Radiotherapy is a well established technique in which a small particle accelerator is used to produce X-rays. These X-rays are focussed on a cancer cell and kill it.
- Every major hospital in the UK has several accelerators used for radiotherapy.
- The accelerators needed for such therapy are compact (a few meters long) and they are built on an industrial scale.

Radiotherapy with ions





Heidelberg Ion Therapy Facility (protons & carbon)

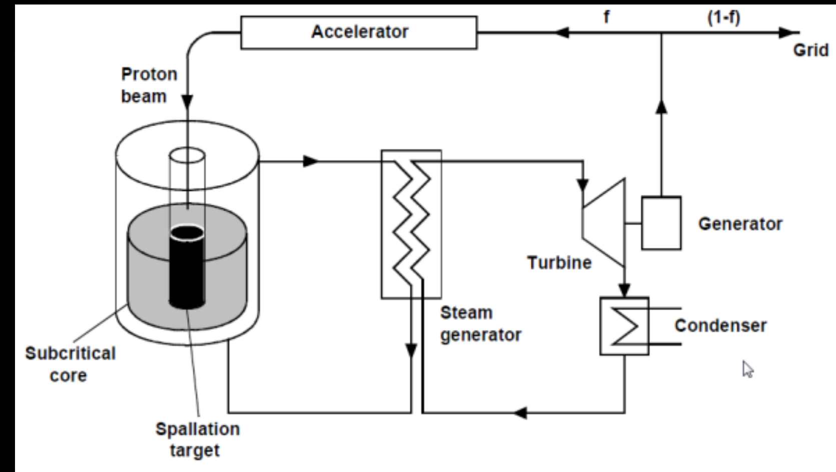


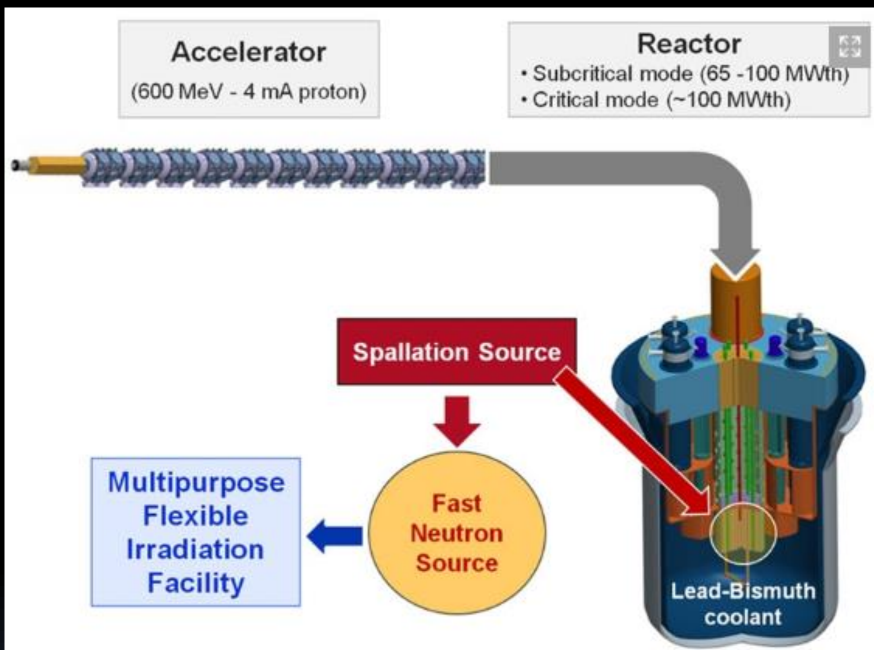
Cancer therapy with x-rays and protons or heavier ions

Clatterbridge: cancer treatment w protons

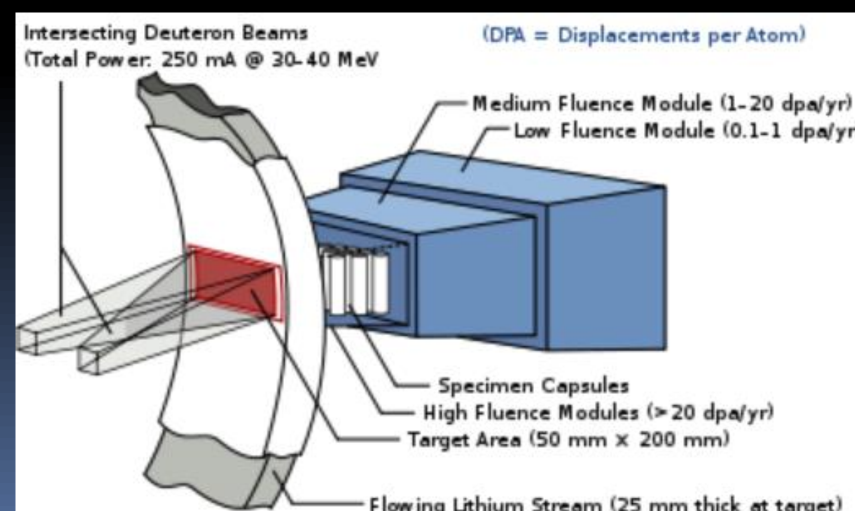
Energy

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





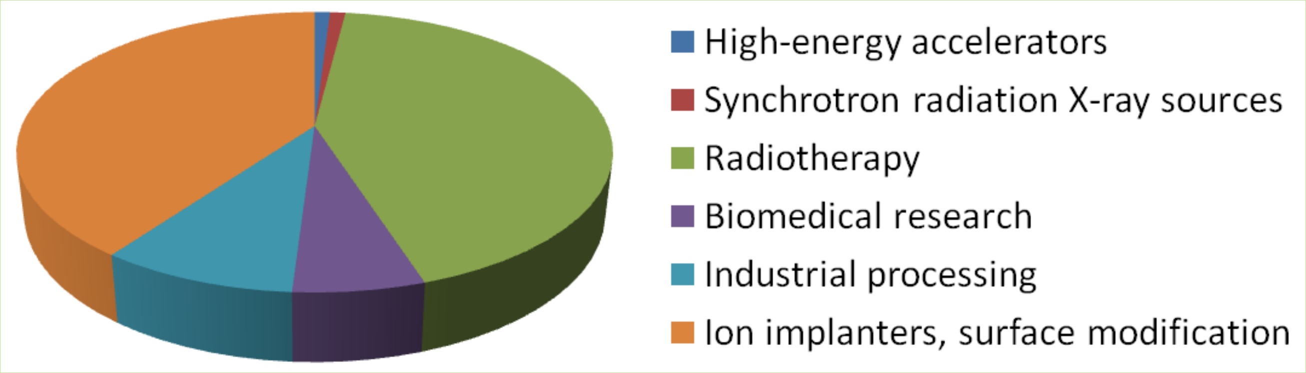
MYRRHA: Multi-purpose hybrid research reactor for high-tech applications, conceived as an accelerator driven system



International Fusion Material Irradiation Facility (IFMIF)

Accelerators Worldwide

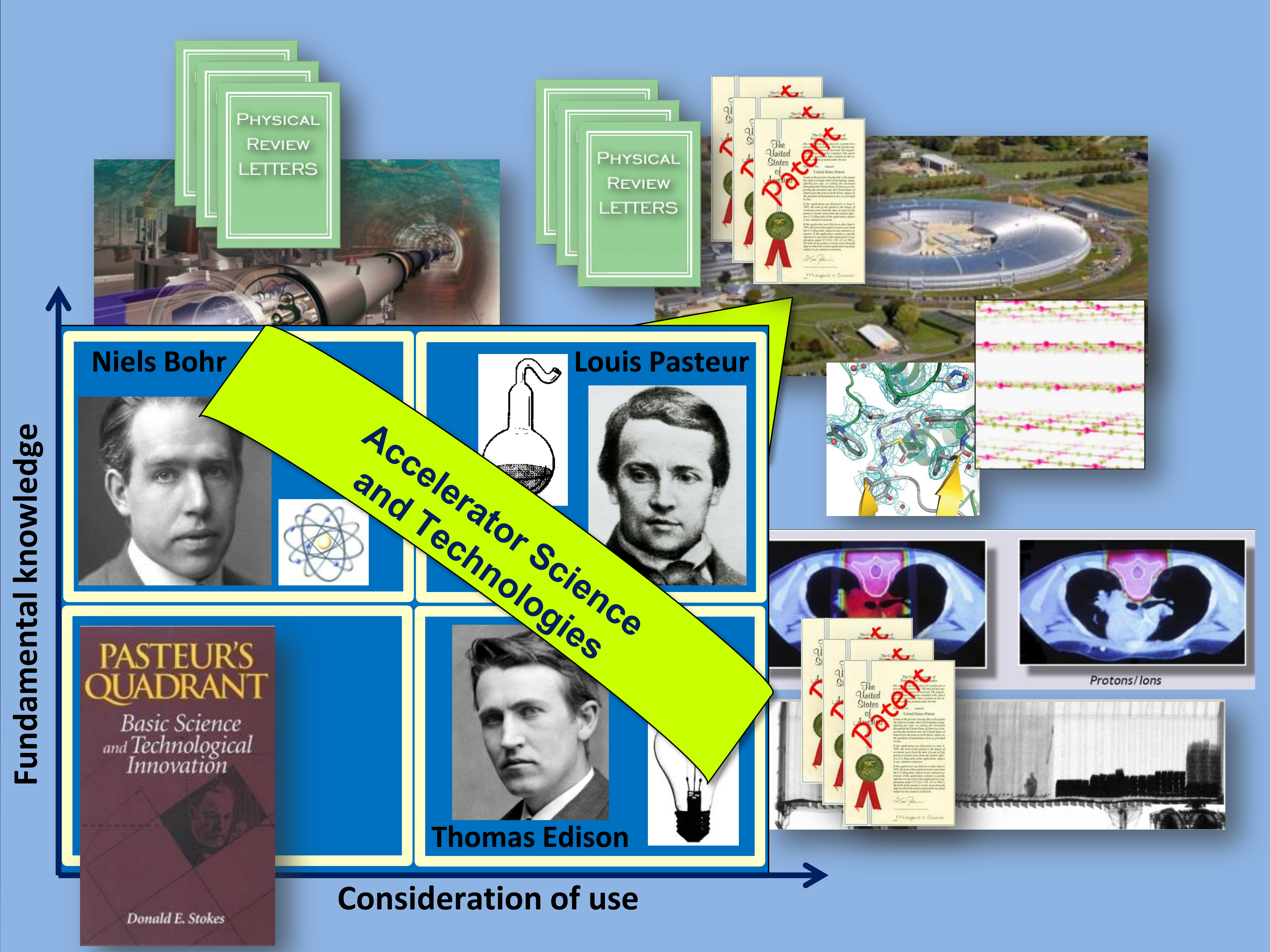
The number of accelerators worldwide exceed 20000

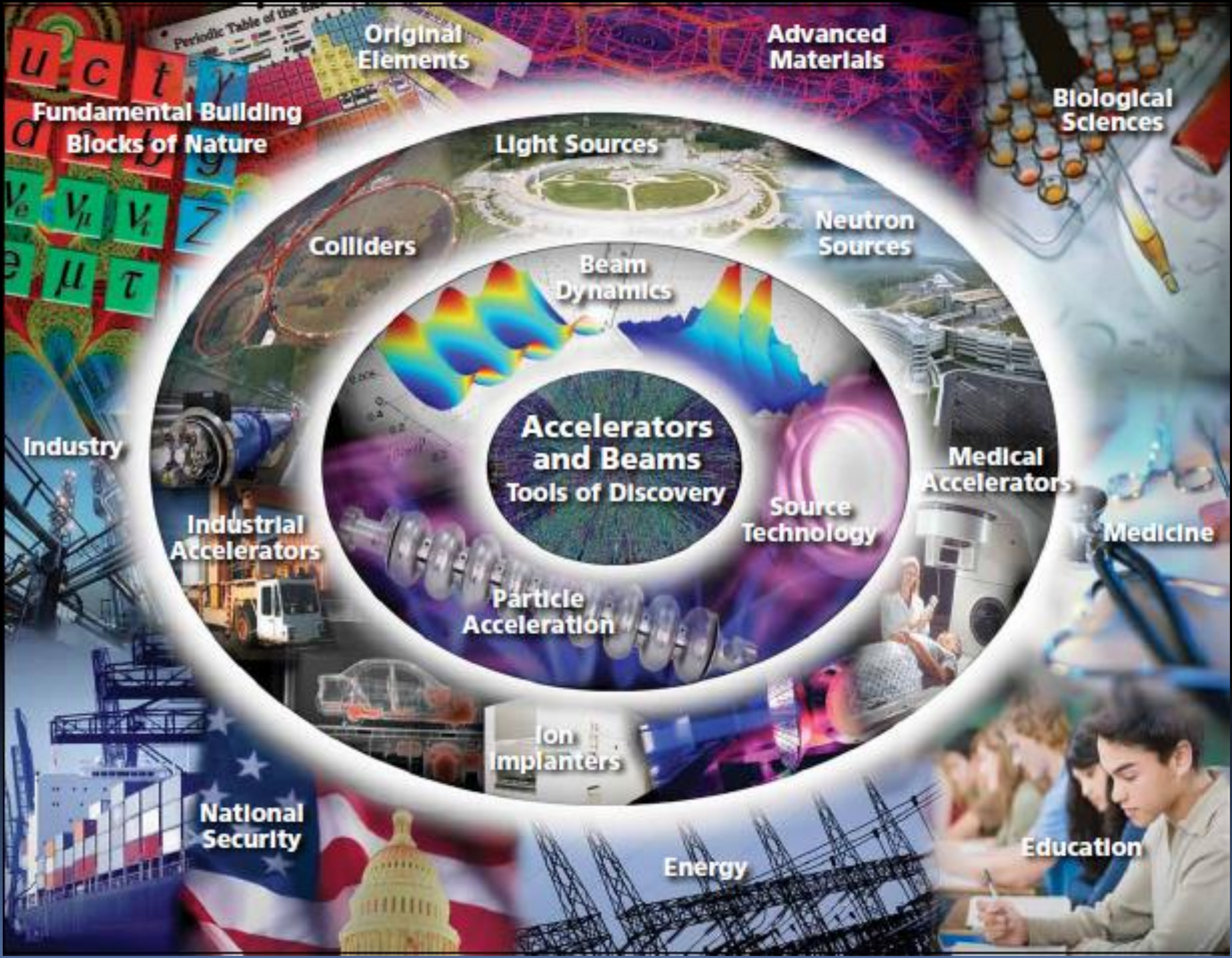


- Market for **medical and industrial** accelerators exceeds **$3.5 billion**. All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500 billion [1]

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

Accelerators are not only for high energy physics


PHYSICAL REVIEW LETTERS
PHYSICAL REVIEW LETTERS
Patent
Patent
Niels Bohr
Louis Pasteur
Accelerator Science and Technologies
Thomas Edison
PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Protons/Ions
Fundamental knowledge
Consideration of use


Original Elements
Advanced Materials
Fundamental Building Blocks of Nature
Biological Sciences
Light Sources
Colliders
Neutron Sources
Beam Dynamics
Industry
Accelerators and Beams
Tools of Discovery
Medical Accelerators
Source Technology
Industrial Accelerators
Medicine
Particle Acceleration
Ion Implanters
National Security
Energy
Education