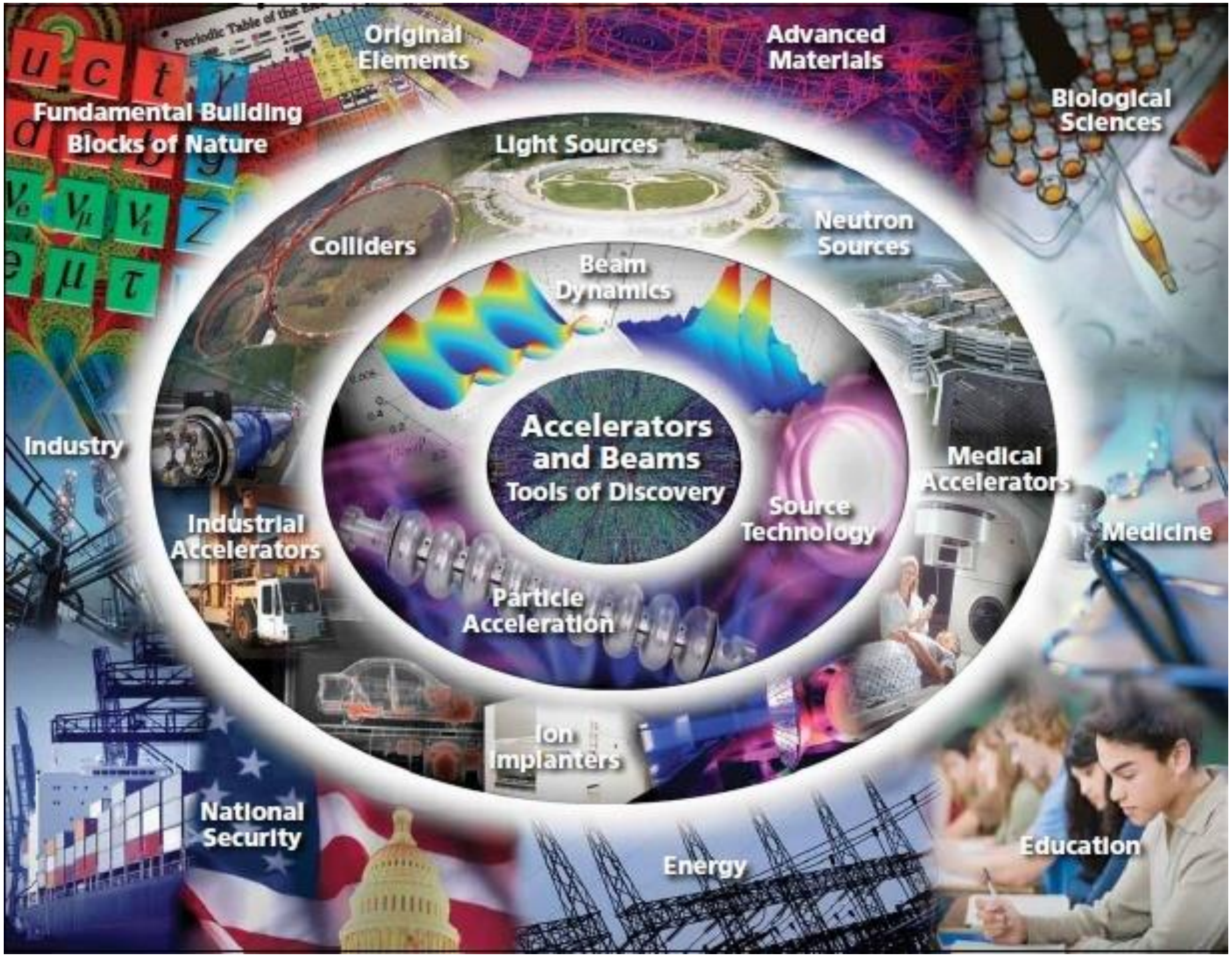
Introduction to Particle Accelerators

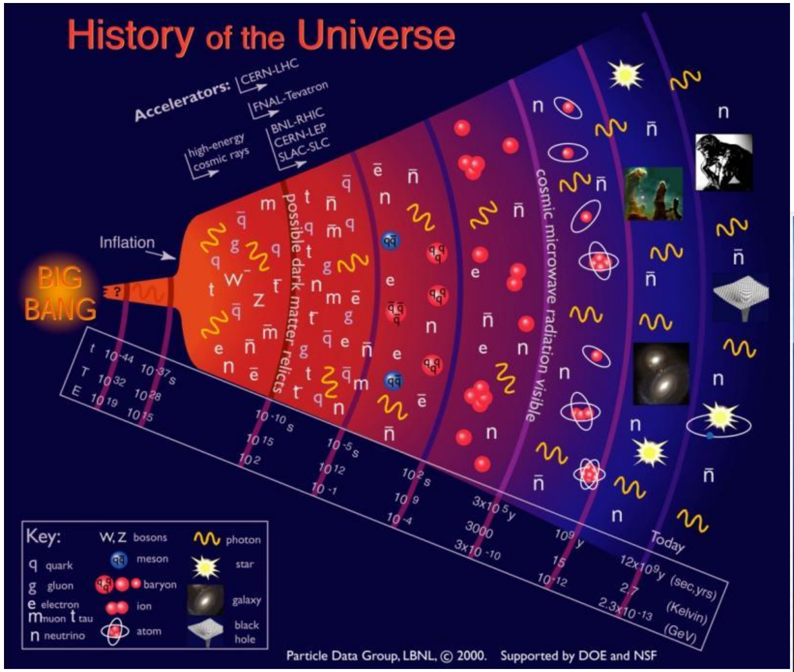
Professor Emmanuel Tsesmelis
CERN & University of Oxford

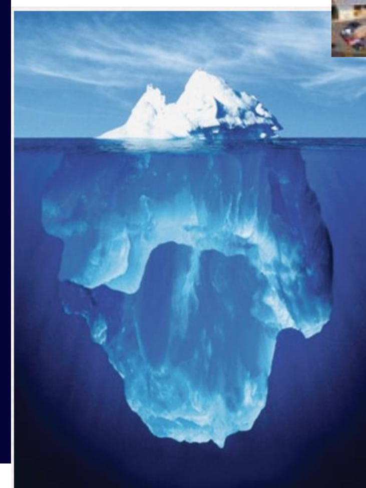
APPEAL-9
University of Oxford
30 June 2018

Introduction



Particle Accelerators – to study macro and micro world

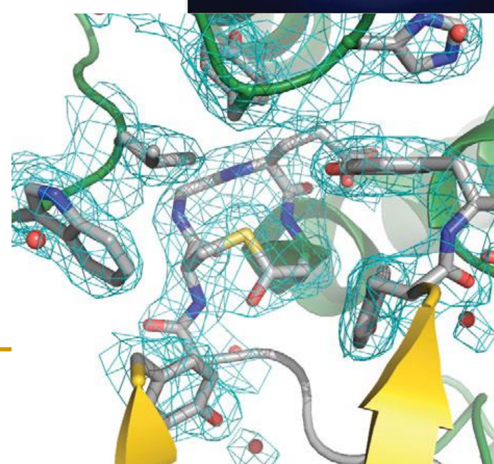


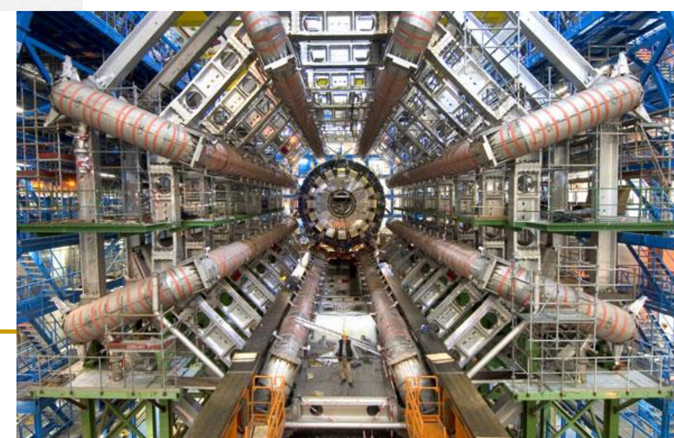


Known Matter

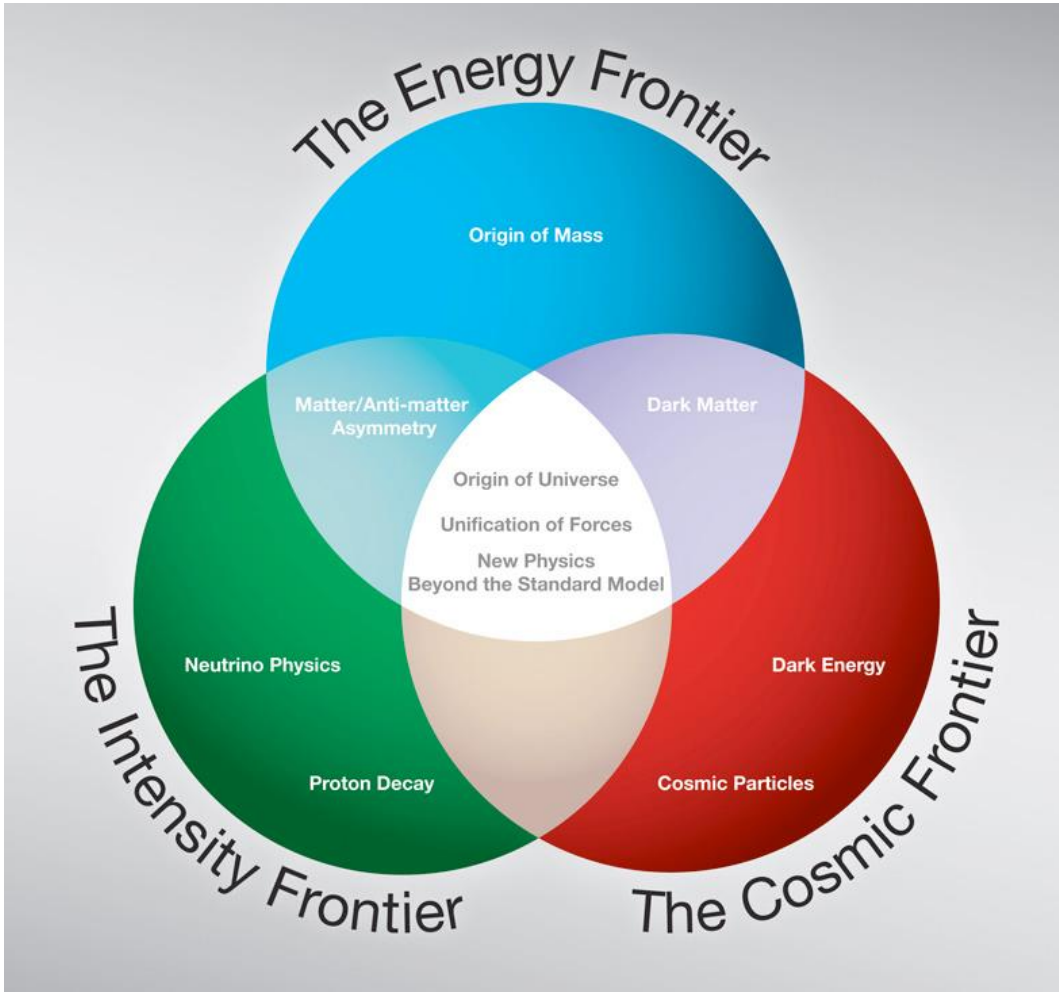
Unknown Matter

DARK MATTER &
DARK ENERGY



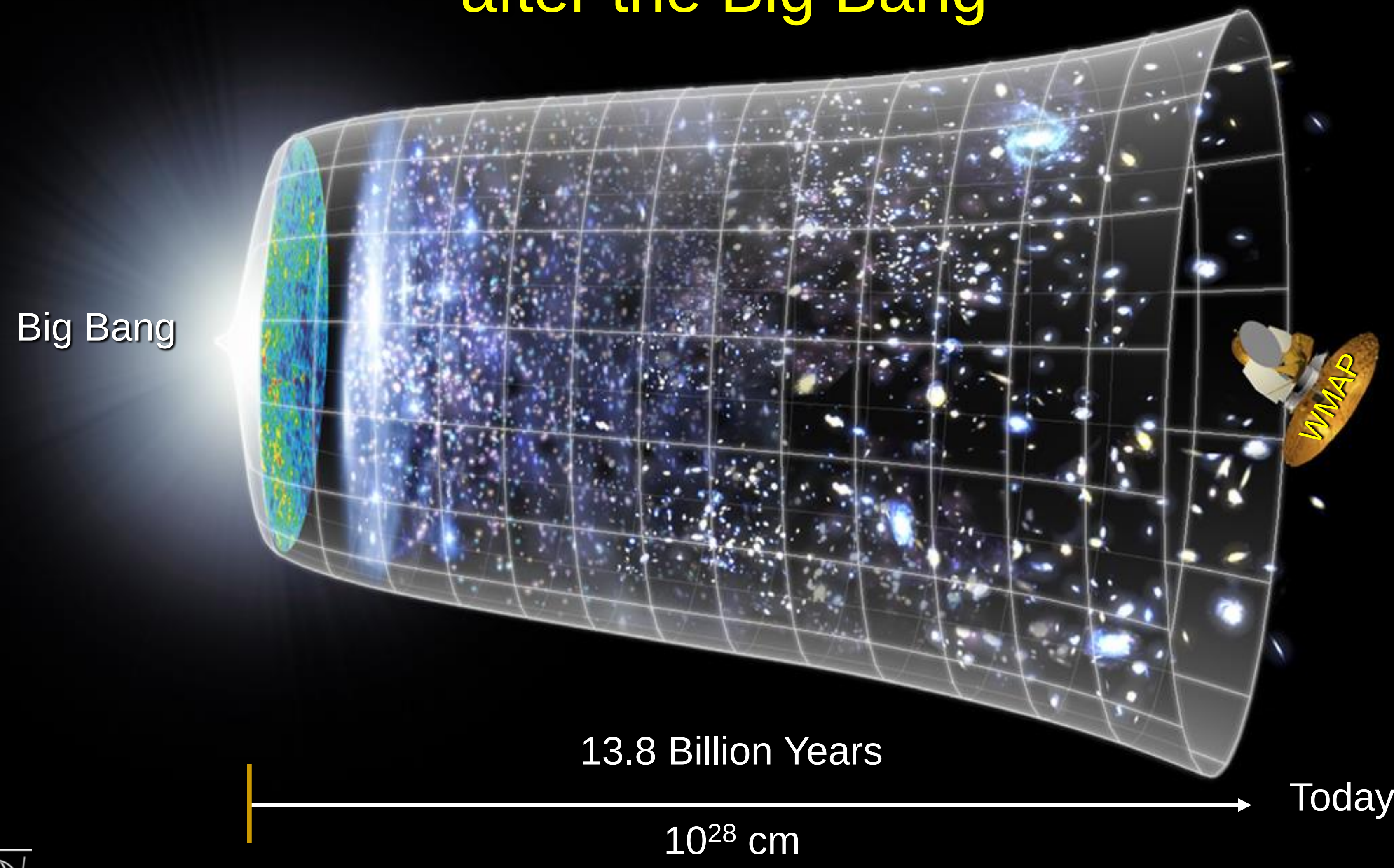


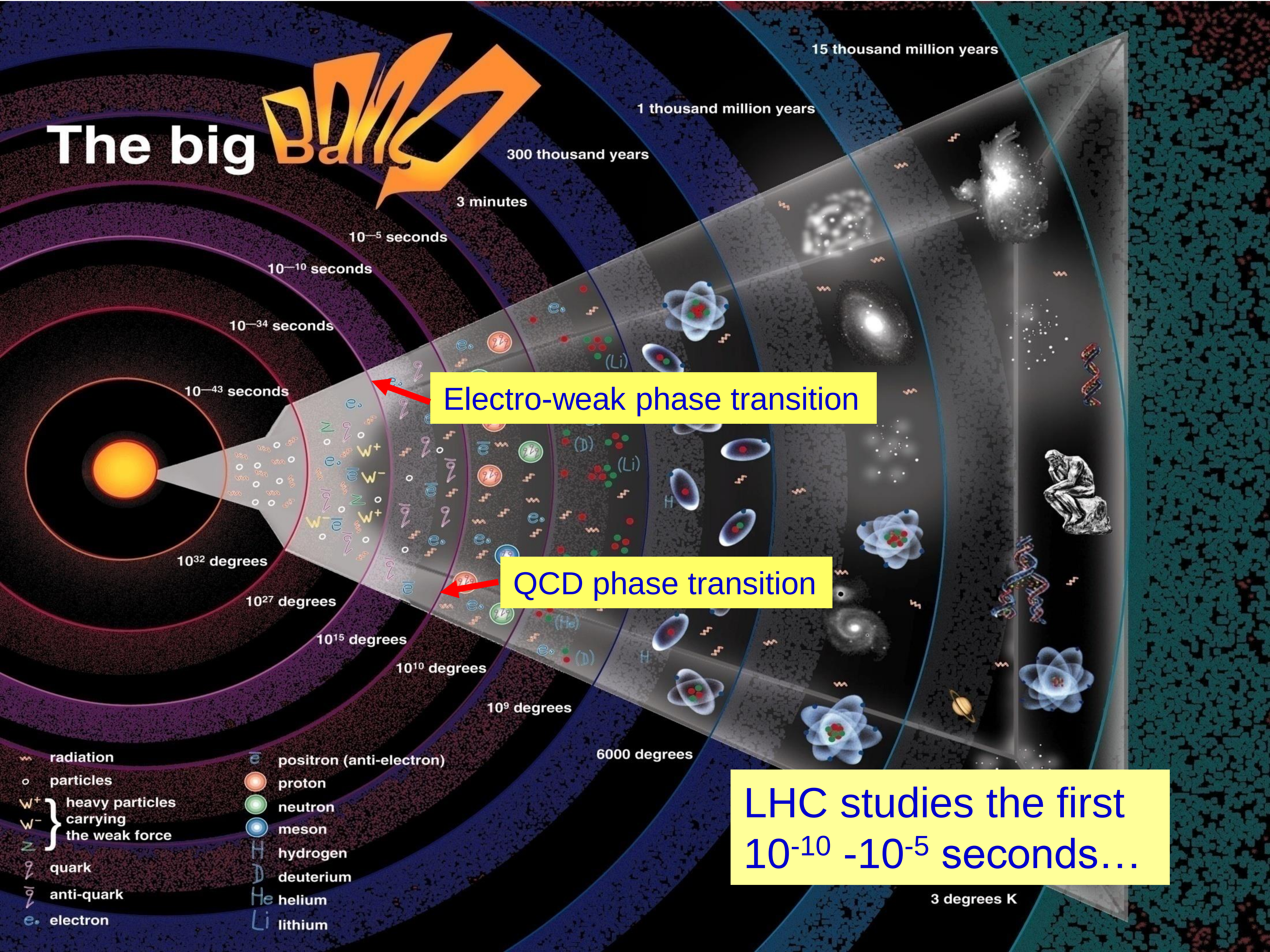
The Three Frontiers



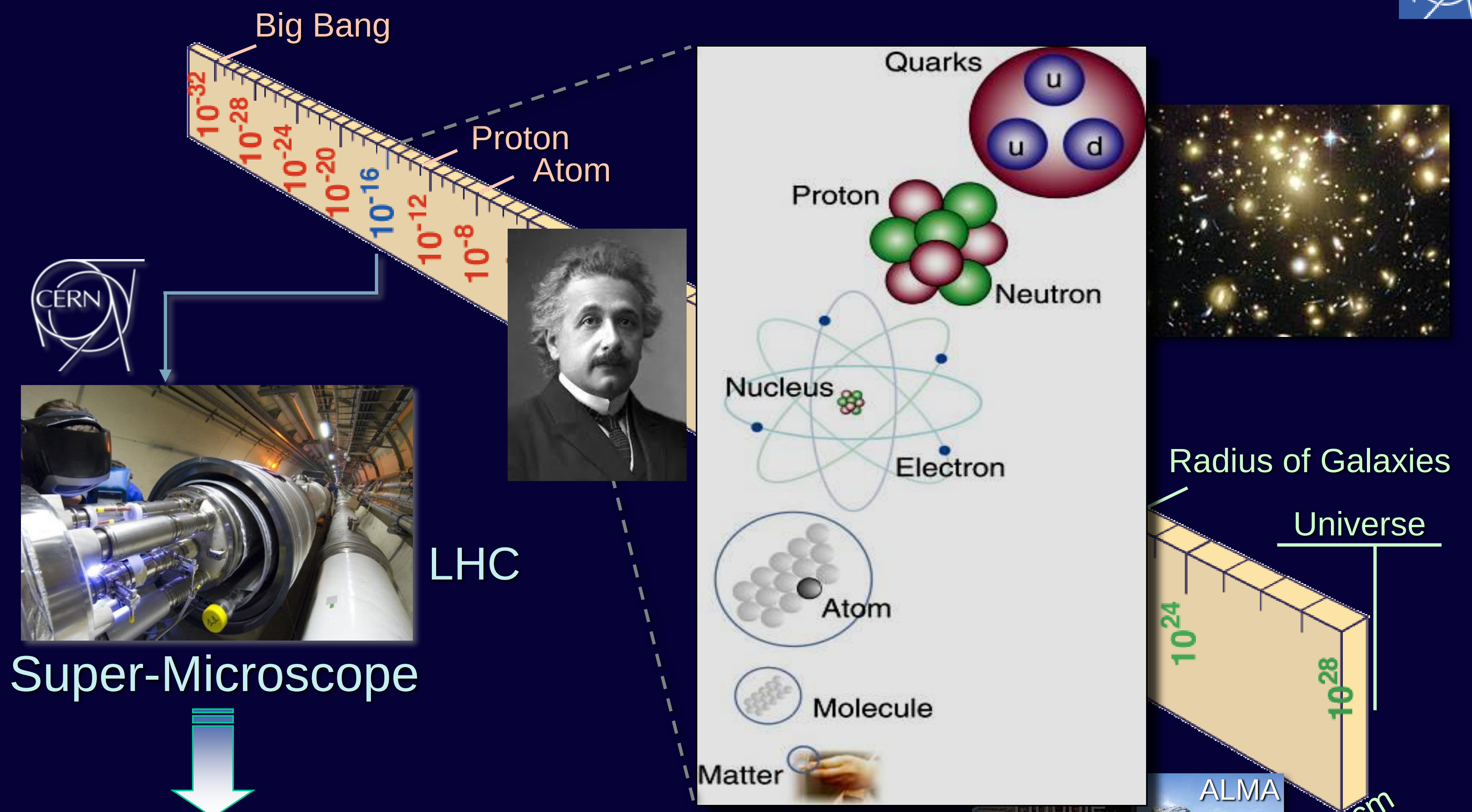
Our Scientific Challenge:

to understand the very first moments of our Universe after the Big Bang



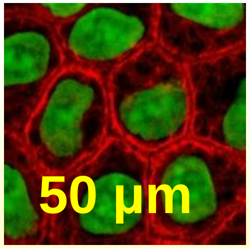


LHC studies the first 10^{-10} - 10^{-5} seconds…



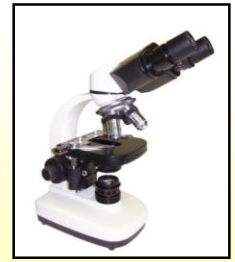
Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

The structure of matter…

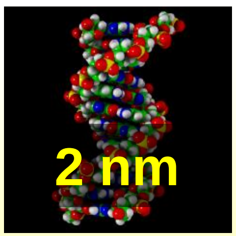


Extra magnification?

CELLS
Twenty per mm



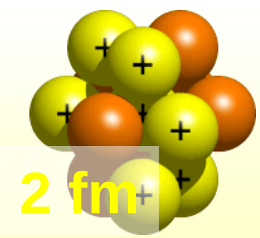
Microscope



x 25 thousand

DNA
Five hundred thousand per mm

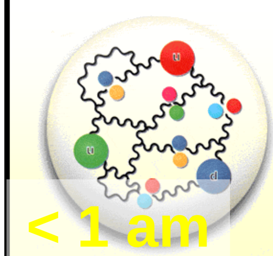
Electron microscope



x 1 million

Nucleus
Five hundred billion per mm

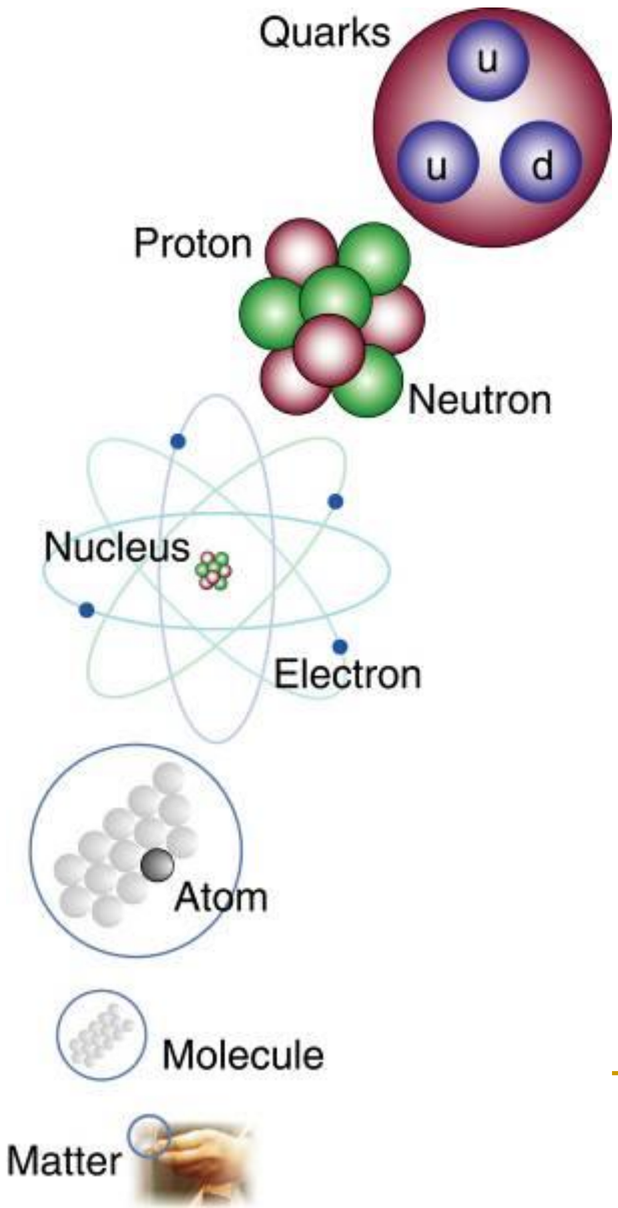
Particle Accelerators

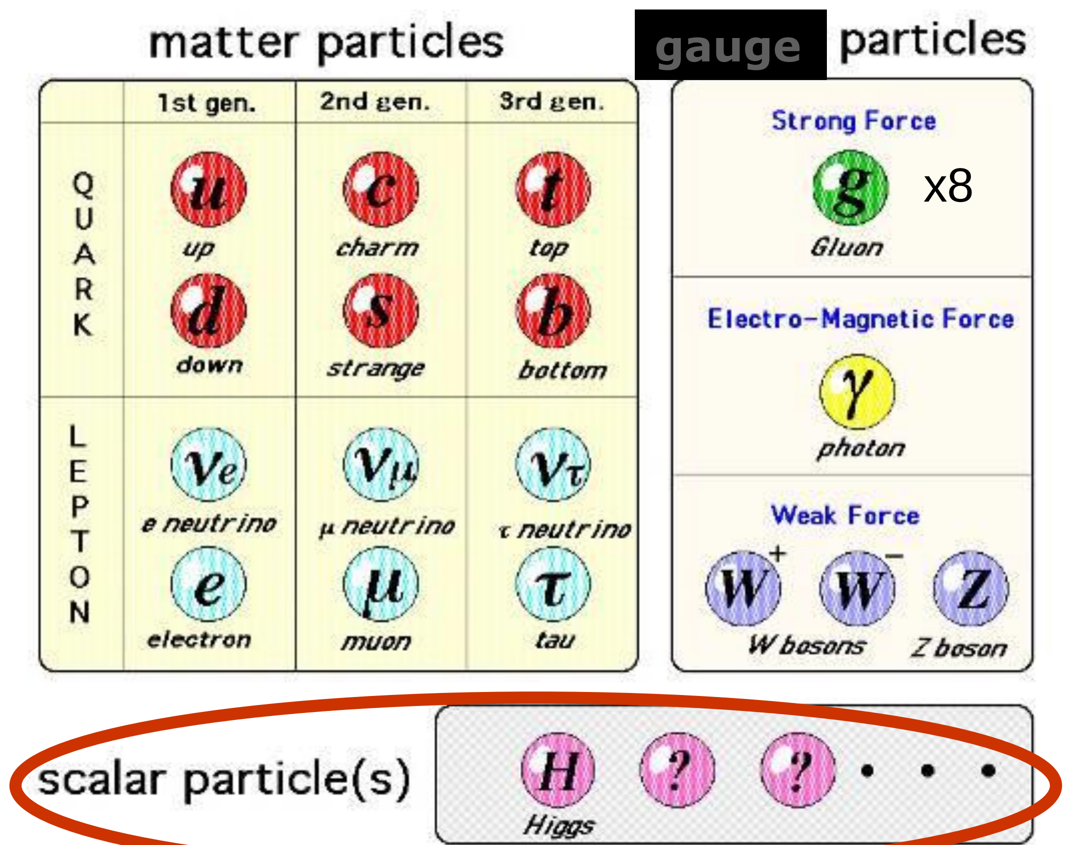


x 2 thousand

Quarks
More than one million billion per mm

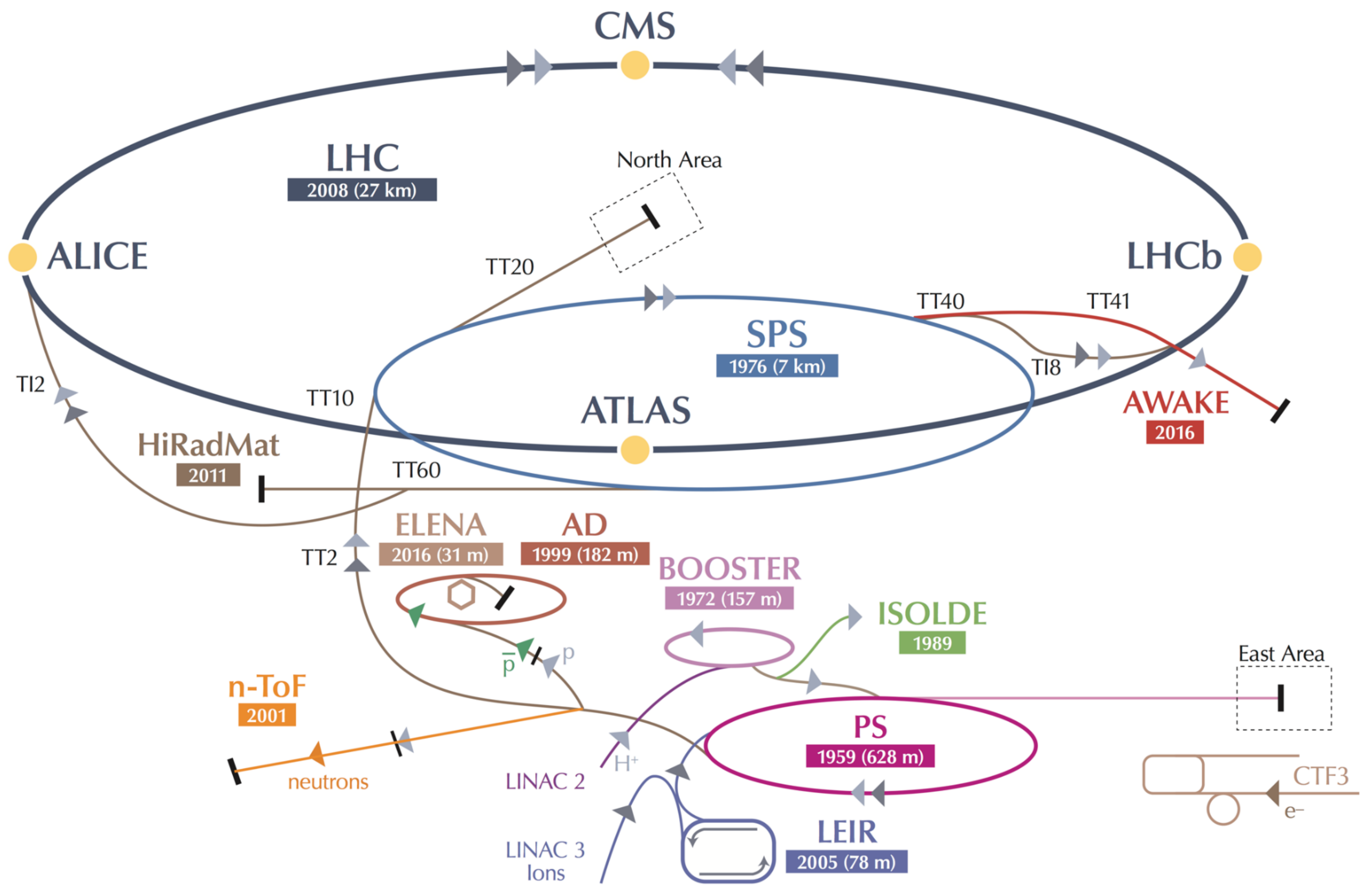
The Study of Elementary Particles & Fields & Their Interactions



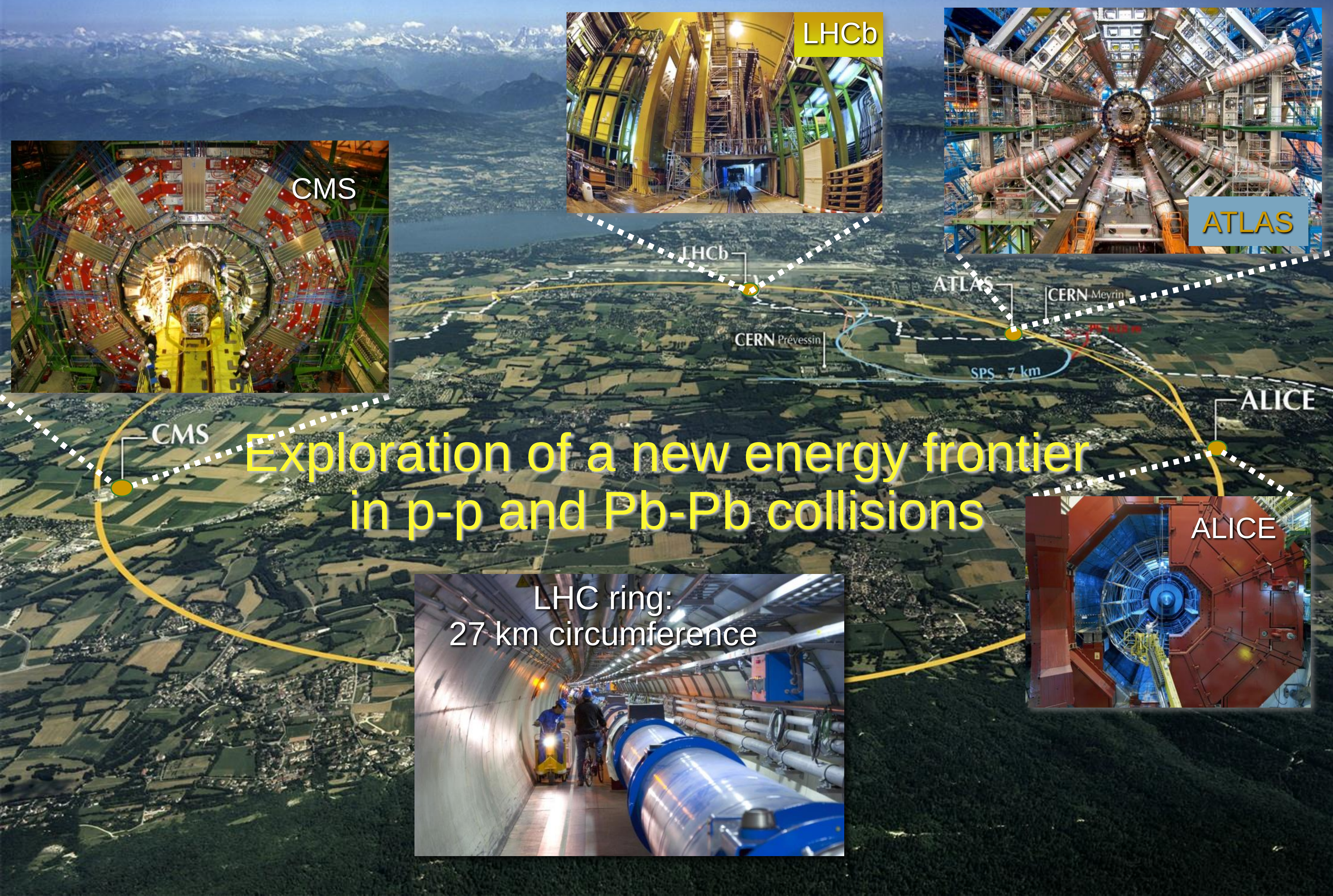


Elements of the Standard Model

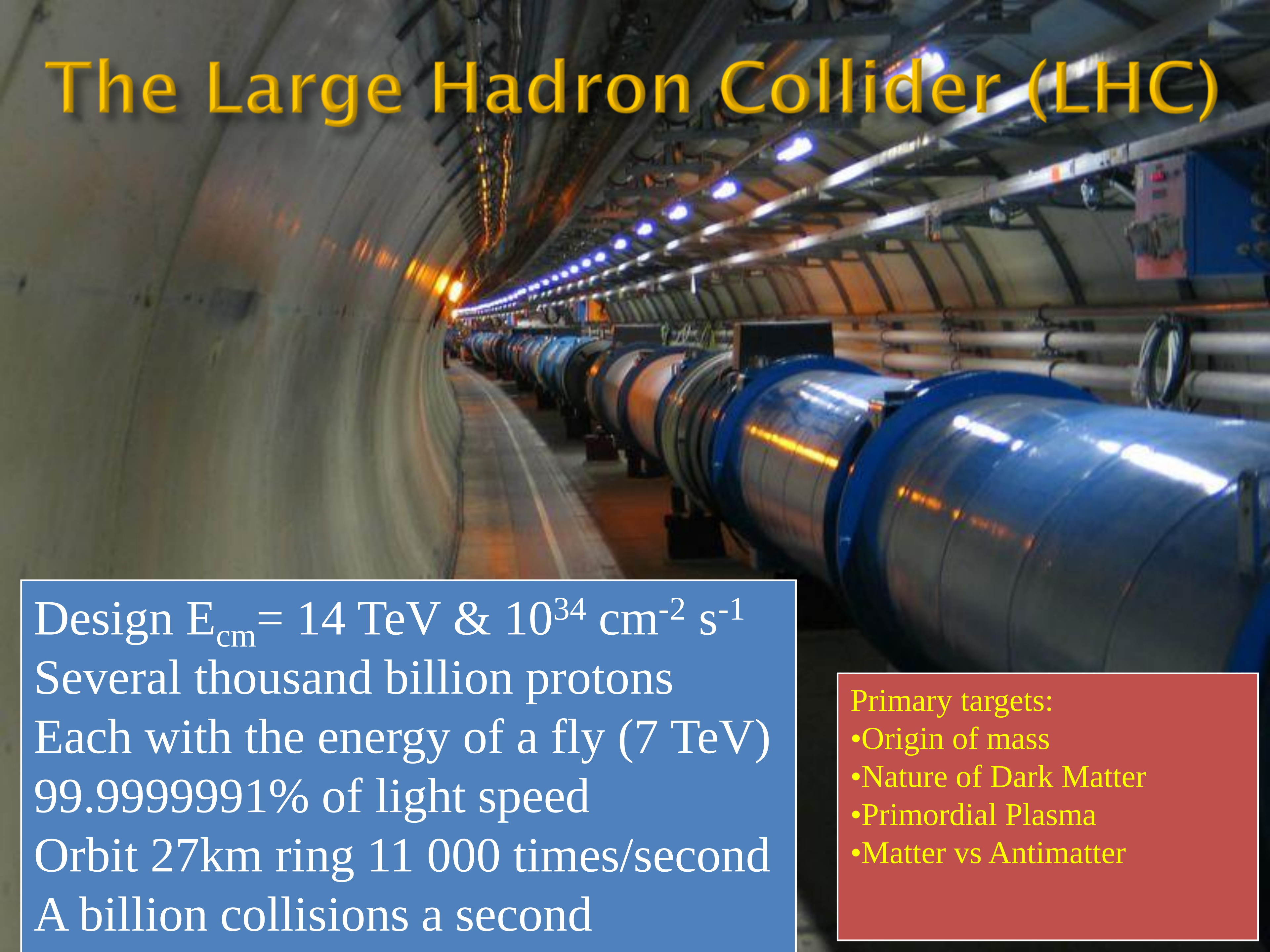
CERN Accelerator Complex



A New Era in Fundamental Science



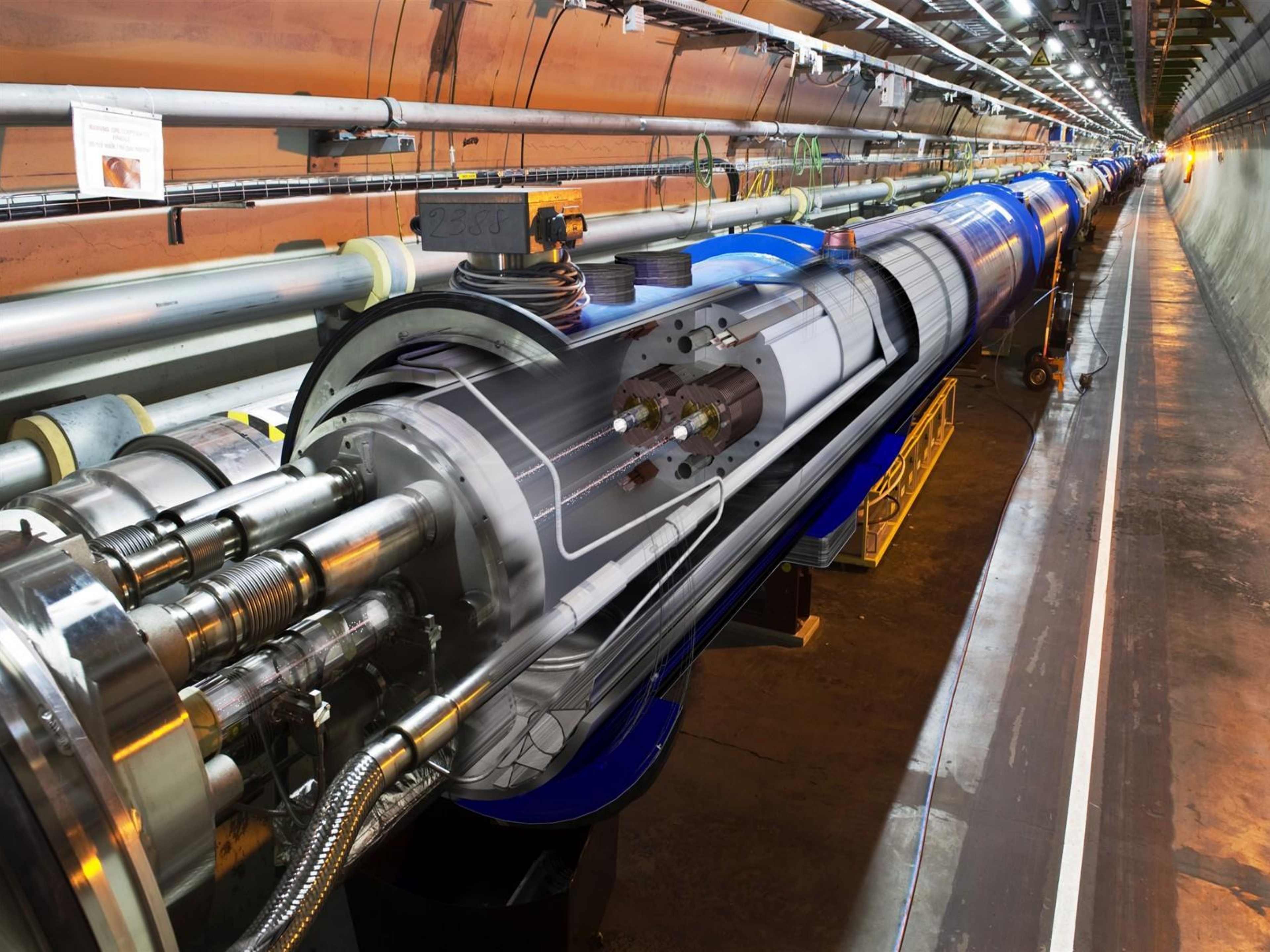
The Large Hadron Collider (LHC)



Design E_{cm}= 14 TeV & 10^{34} cm^{-2} s^{-1}
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

The LHC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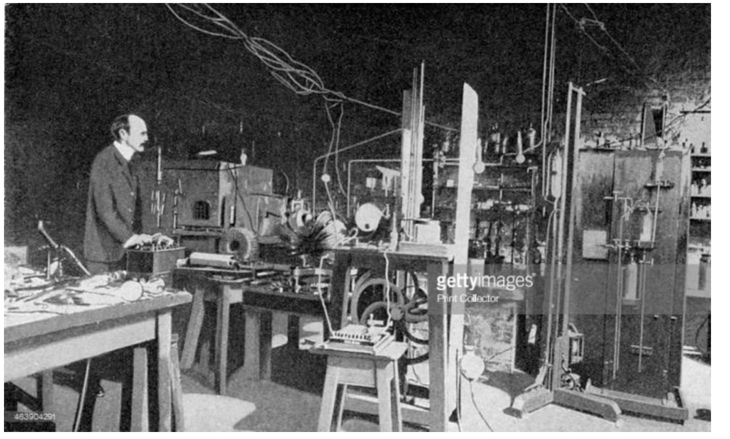
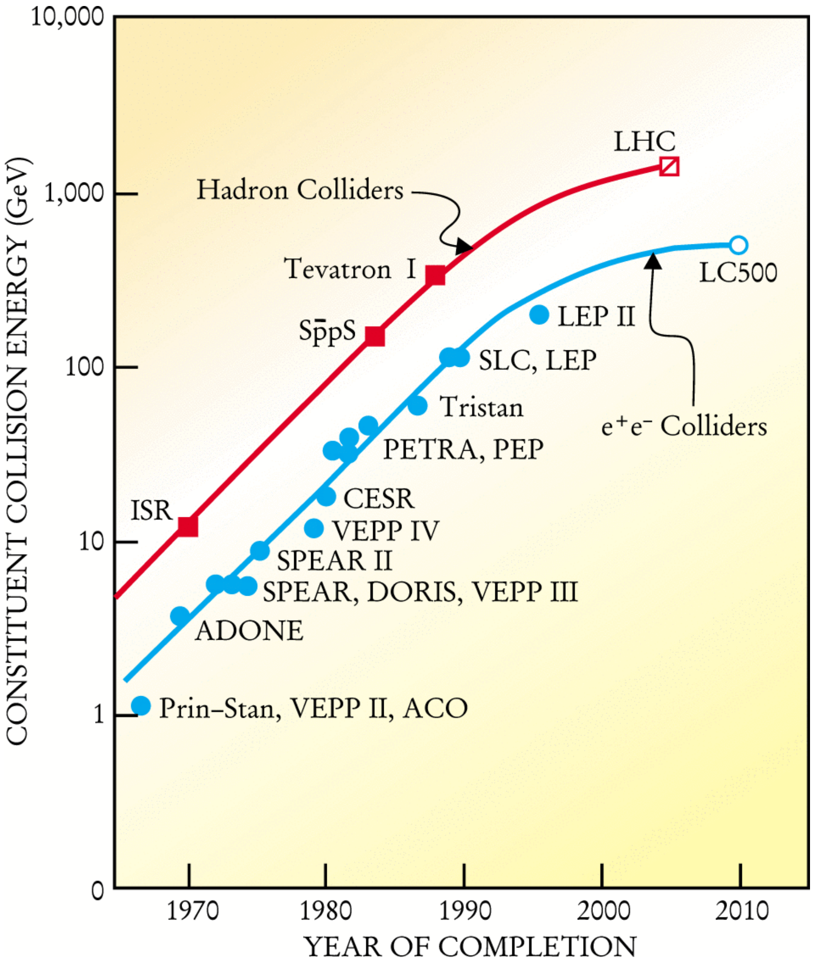
Accelerator Development

- Characterised by rapid progress for over a century.
  - From cathode-ray tubes to the LHC.
  - From the discovery of the electron to the discovery of the Higgs boson.
- Advances in accelerators require corresponding advances in accelerator technologies
  - Magnets, vacuum systems, RF systems, diagnostics,...
- But timelines becoming long, requiring:
  - Long-term planning.
  - Long-term resources.
  - Global collaboration.



Livingston Plot

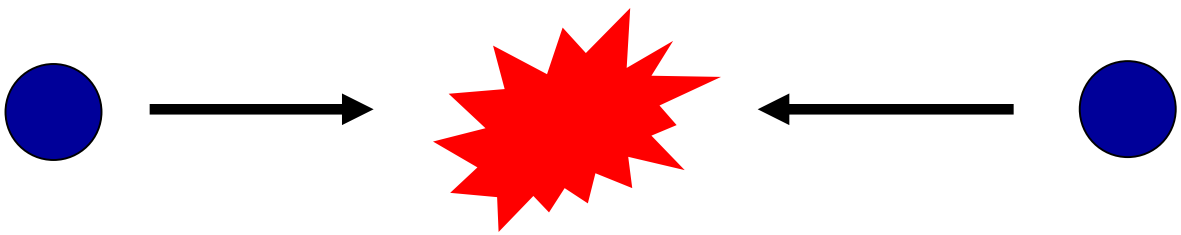


- Around 1950, Livingston made following observation:
  - Plotting energy of accelerator as a function of year of commissioning, on semi-log scale, the energy gain has linear dependence.
- Observations today:
  - Exhibition of saturation effect:
    - New technologies needed.
  - Overall project cost increased
    - Project cost increased by factor of 200 over last 40 years.
  - Cost per proton-proton E_{CM} energy decreased by factor of 10 over last 40 years.

Accelerator Parameters (I)

Particle colliders designed to deliver two basic parameters to HEP user.

I. Centre-of-Mass Energy E_{CM}



$$E = mc^2 = \gamma m_0 c^2$$

Higher energy produces more massive particles.

When particles approach speed of light, they become more massive but not faster.

Why Colliders?

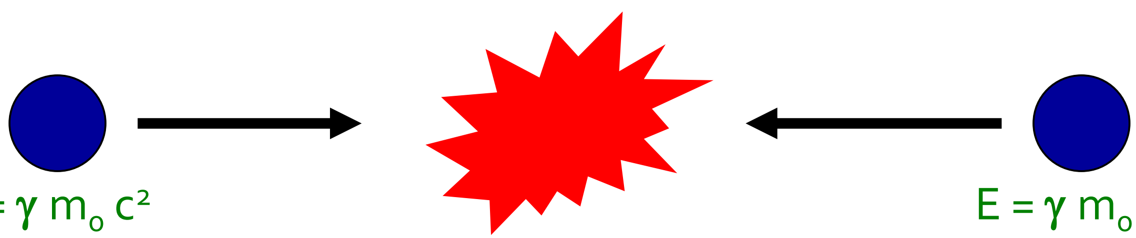
Fixed-target

$E = \gamma\, m_o\, c^2$

$P = \gamma\, m_o\, v$

Only a tiny fraction of energy converted into mass of new particles
(due to energy and <u>momentum</u> conservation)

Colliders



$E = \gamma\, m_o\, c^2$ $E = \gamma\, m_o\, c^2$

Entire energy converted into the mass of new particles

De Broglie Wavelength

Momentum

$$\lambda = h / p \; (1.2\ \mathrm{fm} / \mathrm{p}\,[\mathrm{GeV/c}]\,)$$

De Broglie wavelength

Planck Constant

De Broglie Wavelength
Wave-particle duality
for higher E, probe shorter distances inside matter.

Accelerator Parameters (II)

Particle colliders designed to deliver two basic parameters to HEP user.

II. Luminosity

- Measure of collision rate per unit area.
- Event rate for given event probability ("cross-section"):

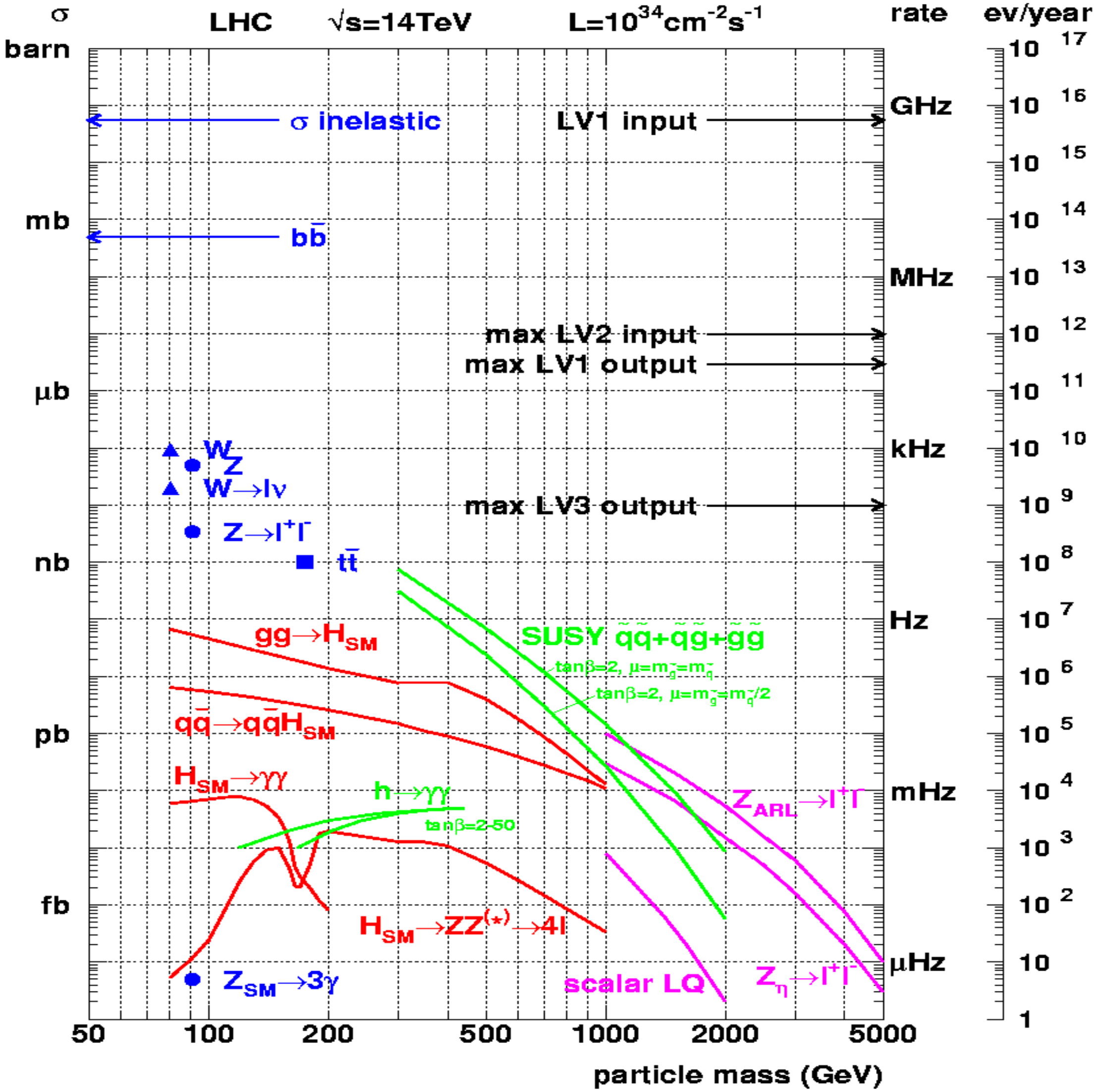
$$\boxed{R = \mathscr{L}\,\sigma}$$

For a Collider, instantaneous luminosity L is given by

$$\boxed{\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}}$$

- → Require intense beams, high bunch frequency and small beam sizes at IP.

Cross-sections at the LHC



"Well known" processes. Don't need to keep all of them …

New Physics!!
We want to keep!!

Collider Types

- Hadron Colliders
  - Desire high energy
    - Only ~10% of beam energy available for hard collisions producing new particles
      - Need *O*(10 TeV) Collider to probe 1 TeV mass scale.
      - High-energy beam requires strong magnets to store and focus beam in reasonable-sized ring.
  - Desire high luminosity
    - Use proton-proton collisions.
      - High bunch population and high bunch frequency.
    - Anti-protons difficult to produce if beam is lost
      - *c.f.* SPS Collider and Tevatron

Collider Types

- Lepton Colliders (e+e-)
  - Synchrotron radiation is the most serious challenge
    - Energy loss of a particle per turn

$$U_0 = \frac{4\pi}{3} \frac{r_e \gamma^4}{R} \mathrm{mc}^2$$

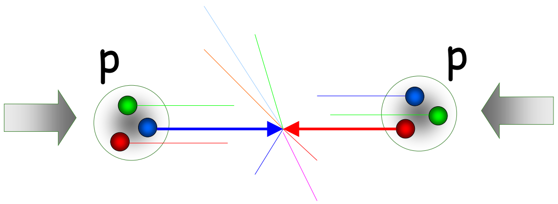
    - Emitted power in circular machine is

$$P_{SR}[\mathrm{kW}] = \frac{88.5\, E^4[\mathrm{GeV}]\, I[\mathrm{A}]}{\rho[\mathrm{m}]}$$

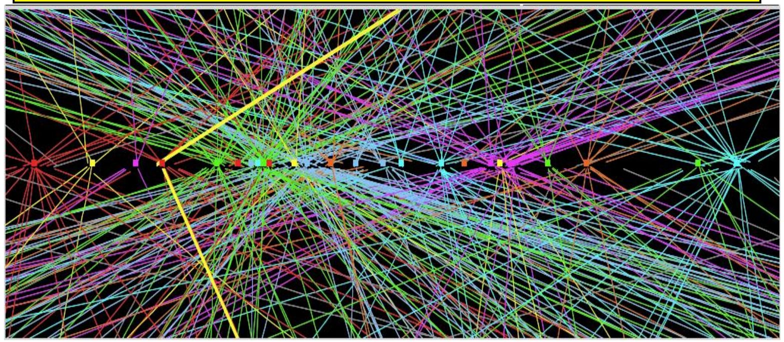
      - For collider with E_{CM} = 1 TeV in the LHC tunnel with a 1 mA beam, radiated power would be 2 GW
        - Would need to replenish radiated power with RF
        - Remove it from vacuum chamber
  - Approach for high energies is Linear Collider.

Collider Characteristics

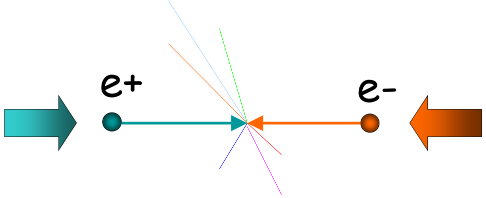
- Hadron collider at the frontier of physics
  - Huge QCD background
  - Not all nucleon energy available in collision

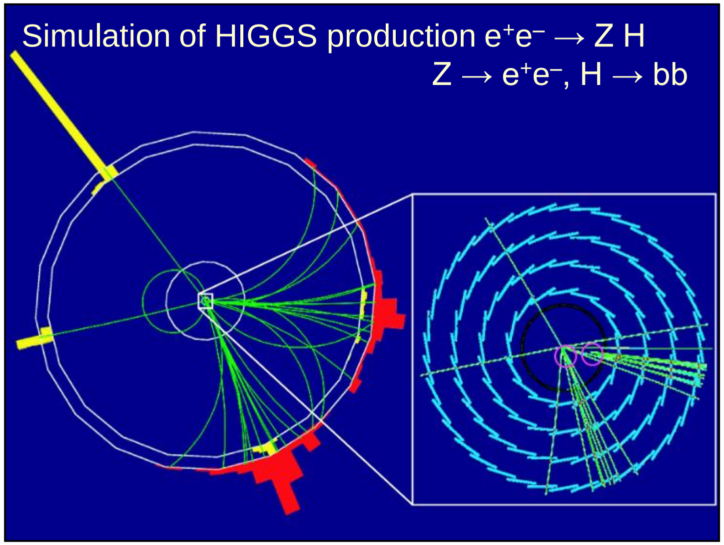


ATLAS Z → μμ event from 2012 data with 25 reconstructed vertices

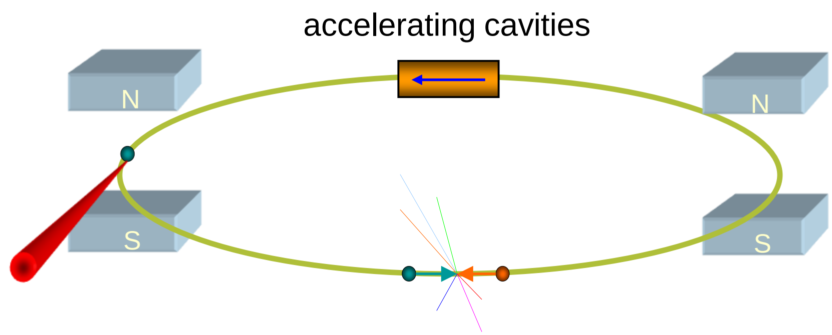


- Lepton collider for precision physics
  - Well defined initial energy for reaction
  - Colliding point like particles





Circular versus Linear Collider

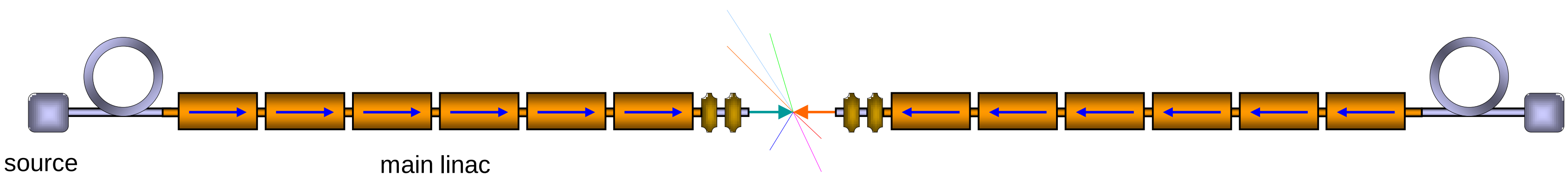


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)



Linear Collider

few magnets, many cavities, single pass beam

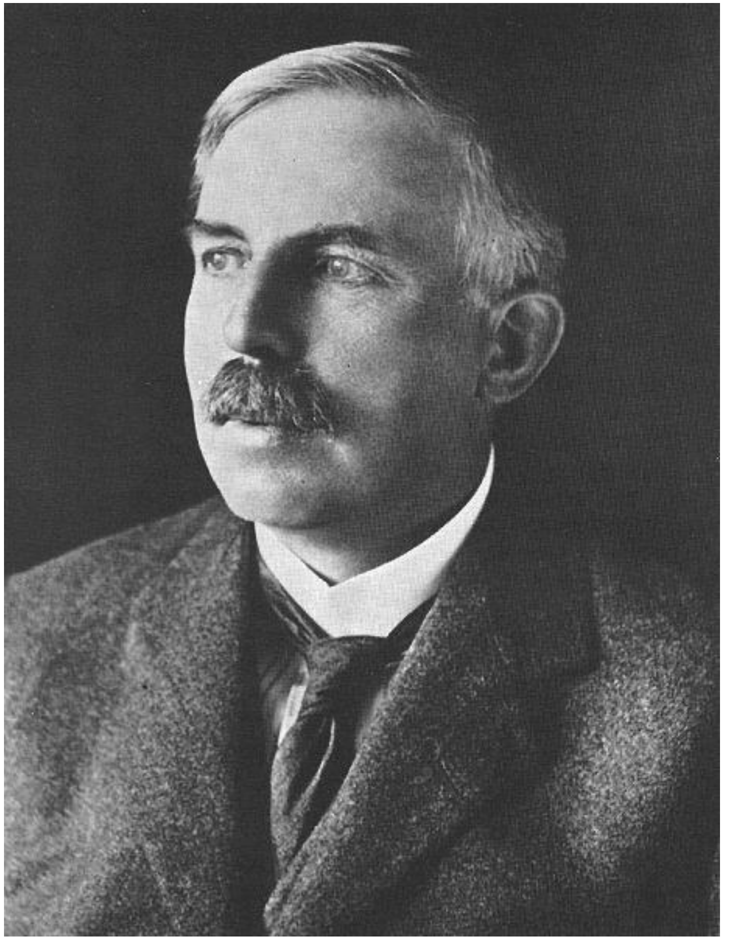
higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

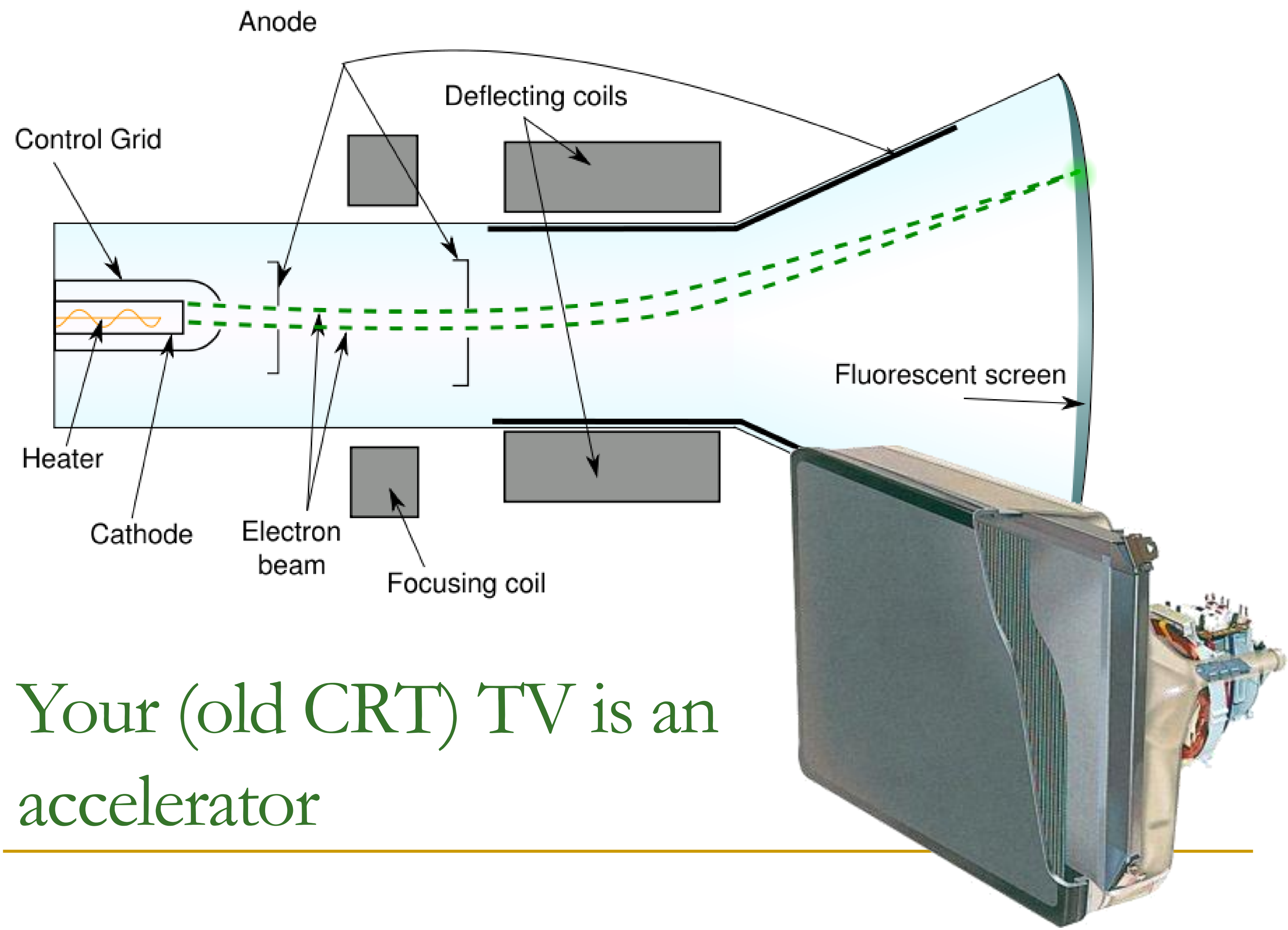
Rutherford fired the starting pistol

At the Royal Society in 1928 he said:

"I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances".

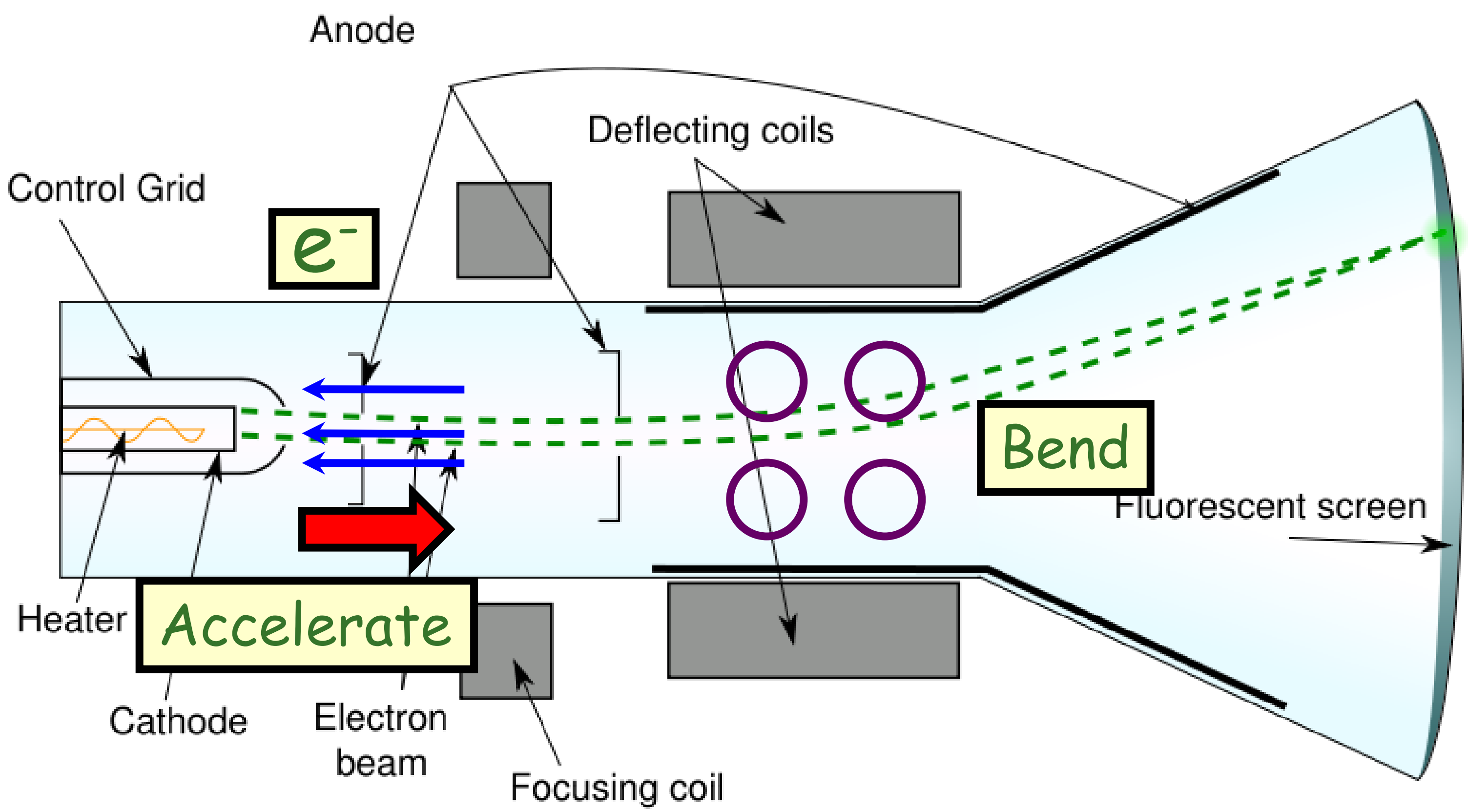


Lightning: requires > MV/m over many tens of meters to initiate it



Your (old CRT) TV is an accelerator

A TV as an Accelerator

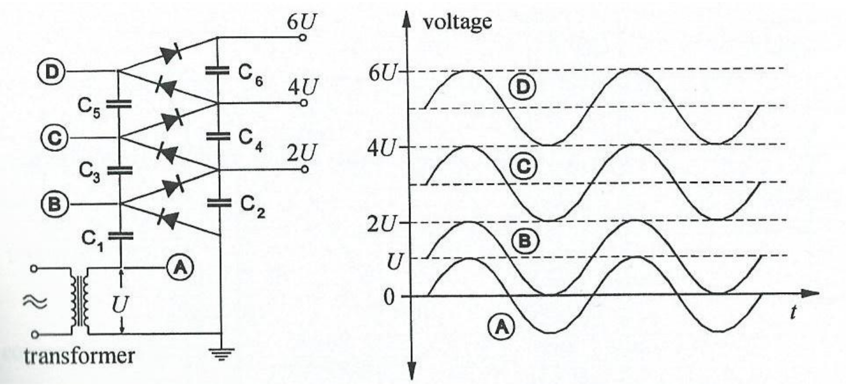


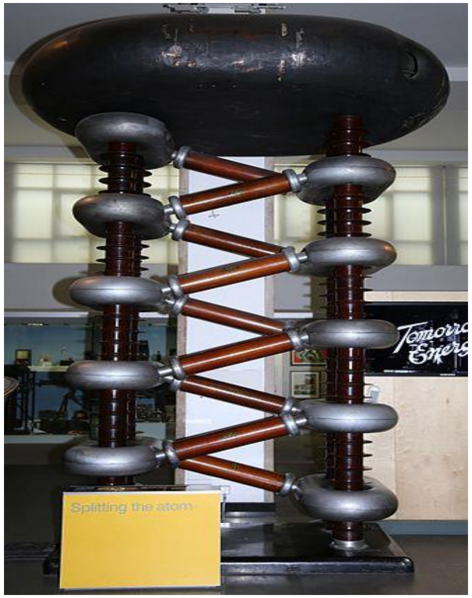
Electrostatic Accelerators
The Cockcroft-Walton

- Based on system of multiple rectifiers.
- Voltage generated by cascade circuit

$$U_{\rm tot} = 2Un - \frac{2\pi I}{\omega C}\left(\frac{2}{3}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n\right)$$

- Modern CWs
  - Voltages up to ~4 MV.
  - Beam currents of several hundred mA with pulsed particle beams of few μs pulse length.

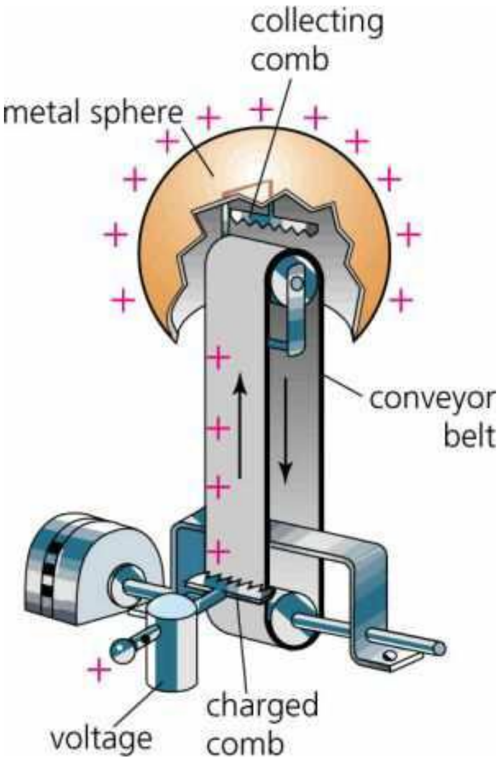


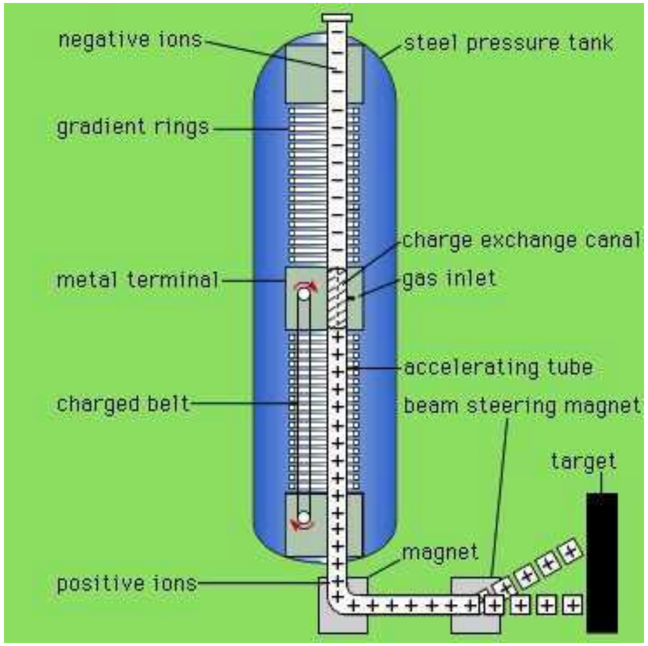


Electrostatic Accelerators – van de Graaff

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

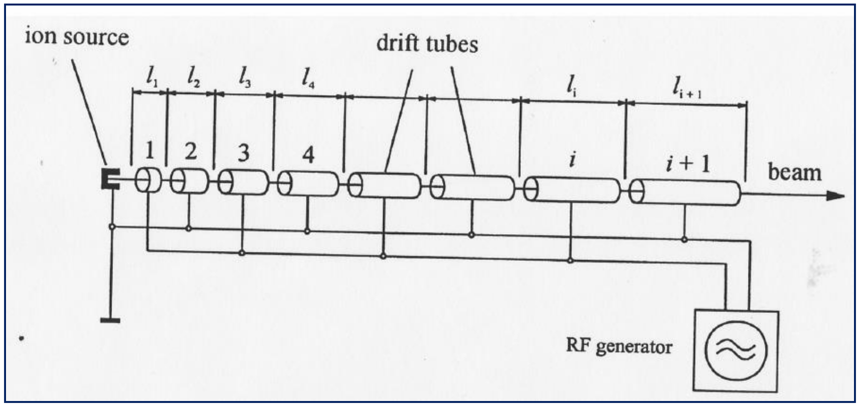
- Tandem is a version with charge exchange in the middle
 (~1000 MeV).



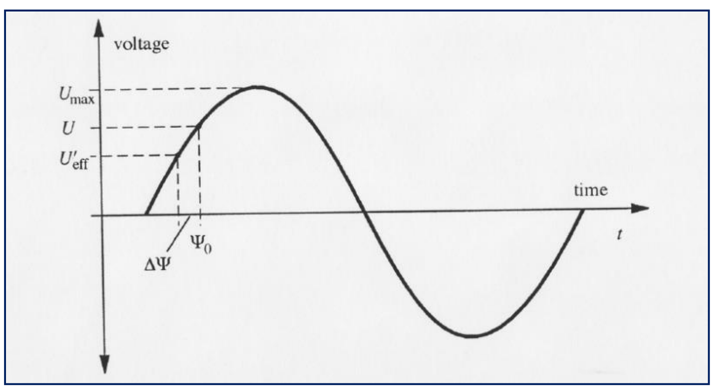


Linear Accelerators

Wideröe linear accelerator

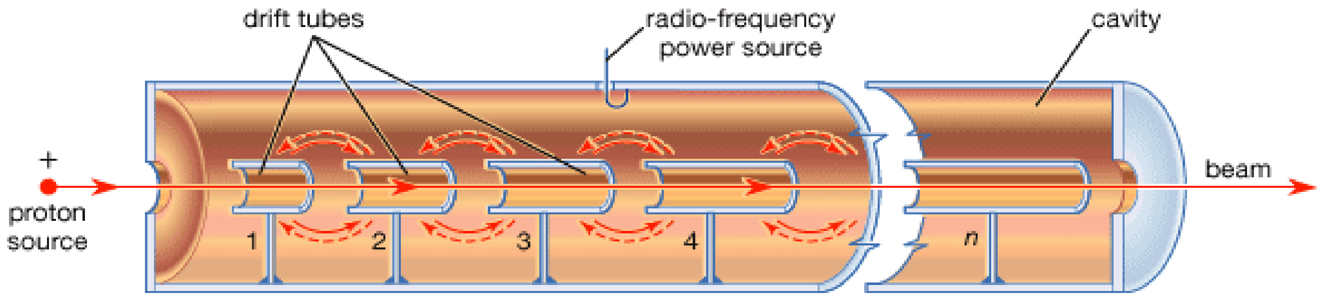


Phase focusing in linacs



- Principle
  - Use rapidly-changing high frequency voltages instead of direct voltages (Ising)
  - Energy is proportional to number of stages *i* traversed by particle.
  - The largest voltage in entire system is never greater than V_{max}
    - Arbitrary high energies without voltage discharge.

Drift Tube Linac: Higher Integrated Field



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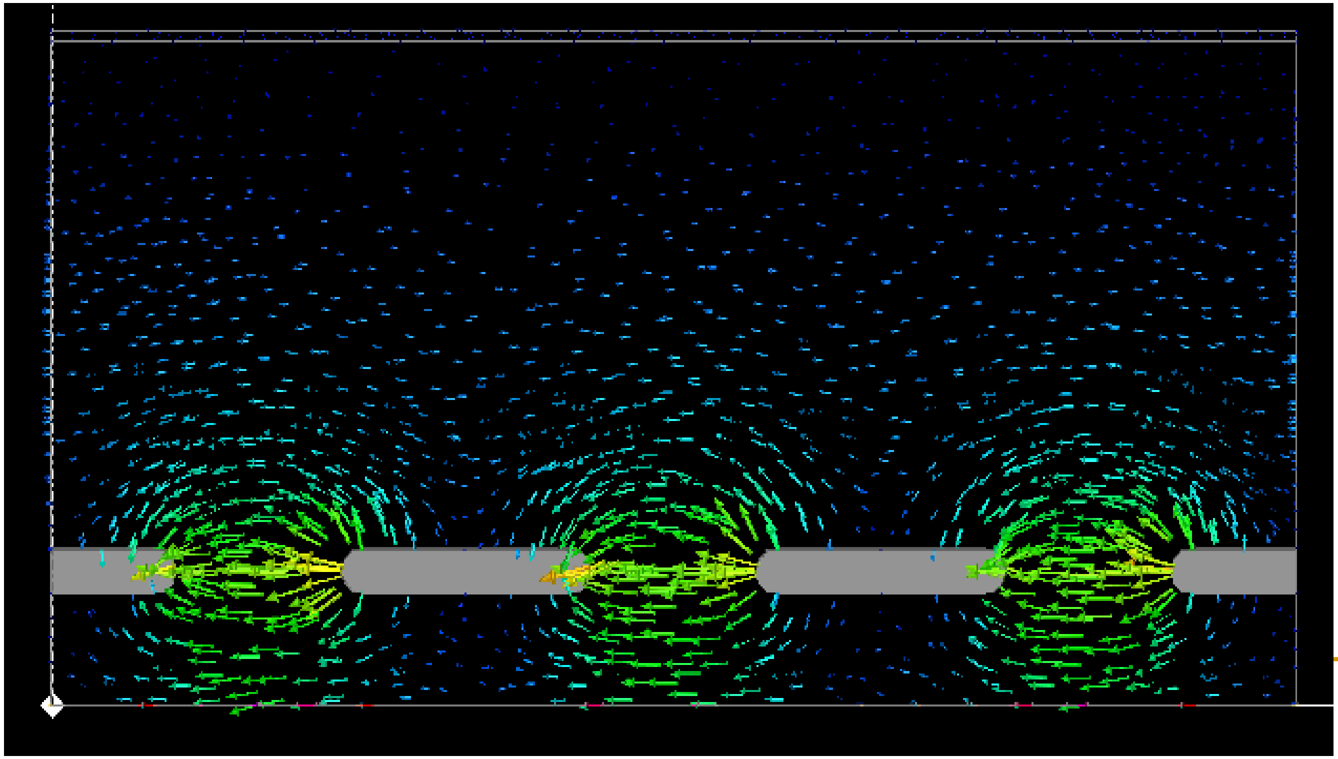
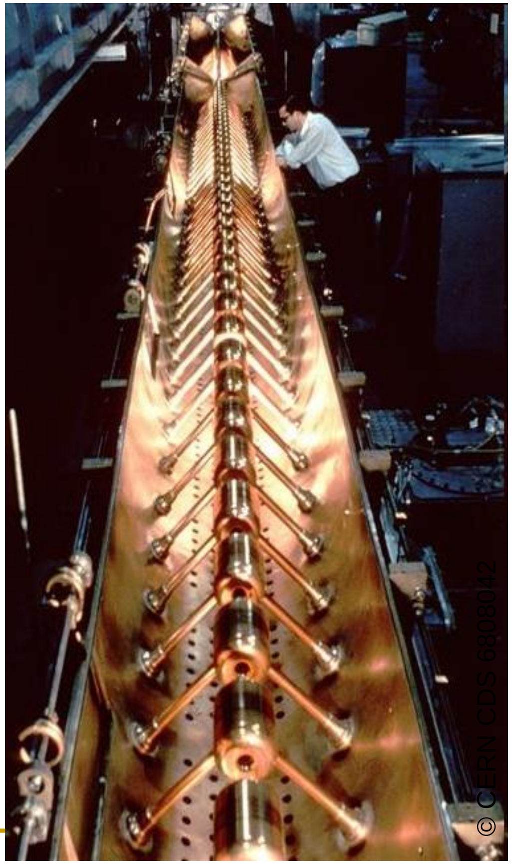
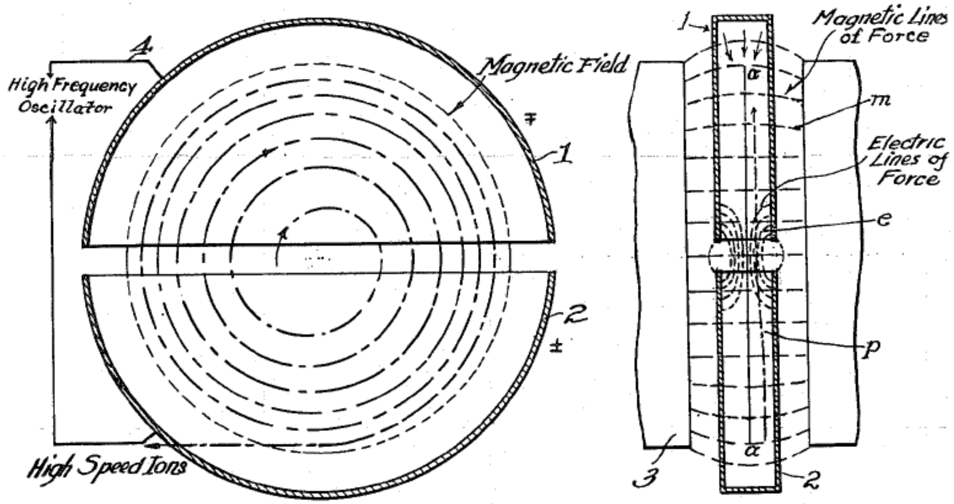


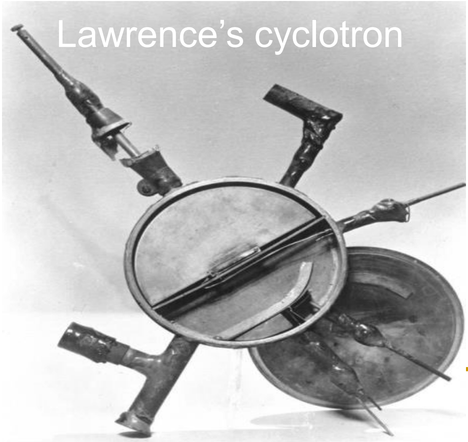
CERN LINAC1

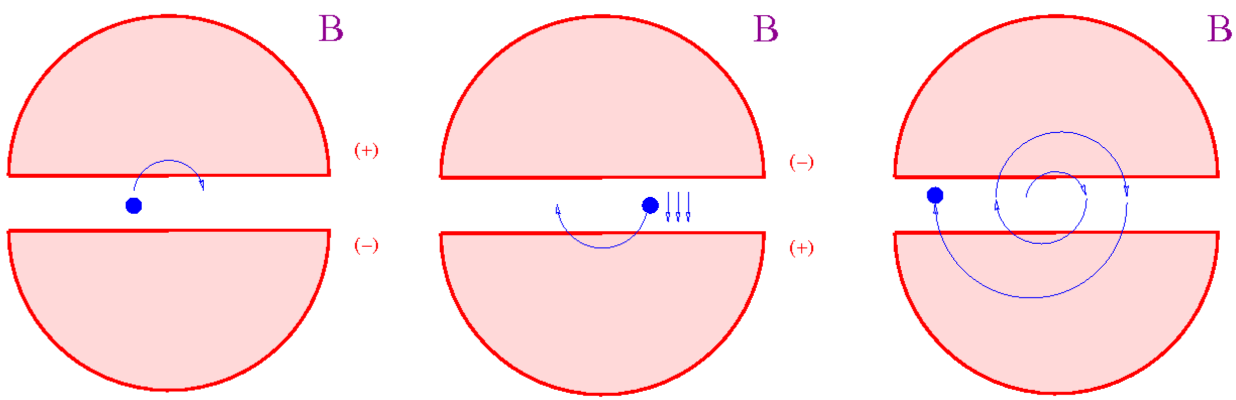


Cyclic Accelerators

- 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.




Lawrence’s cyclotron

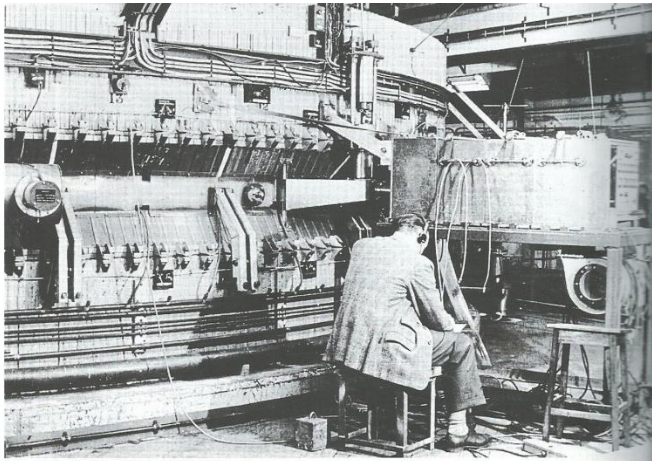


Mark Oliphant & the Synchrotron

"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field...which would be varied in such a way that the radius of curvature remains constant as the particle gains energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."

Mark Oliphant, Oak Ridge, 1943

With Ernest Rutherford in 1932



1 GeV machine at Birmingham University

Synchrotrons

- From

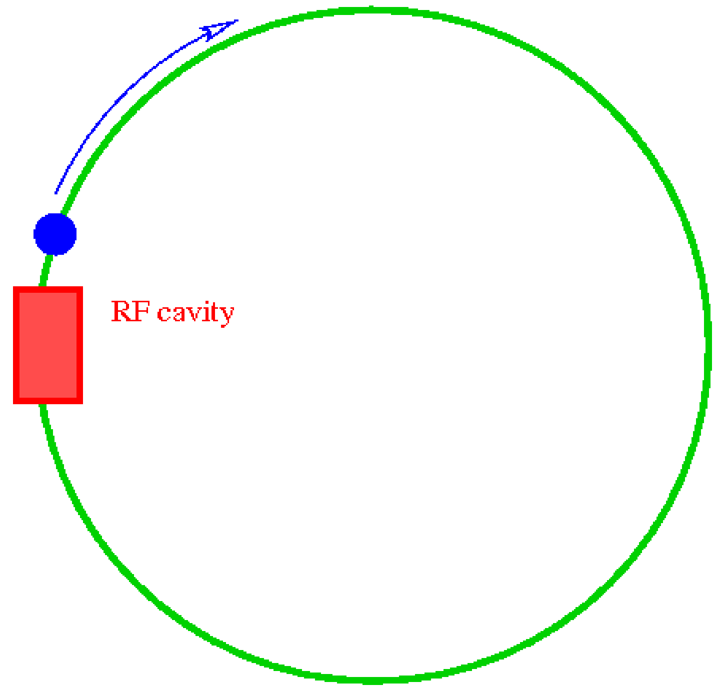
  $R = E / (ecB)$

  E/B kept constant since R is fixed.

  B increases synchronously with rising E

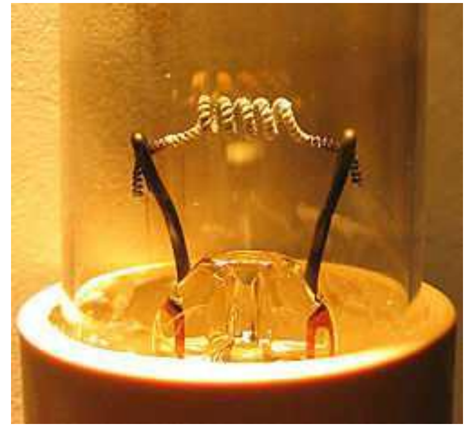
- Synchrotrons can accelerate to much higher energies.
  - e.g., LHC is synchrotron

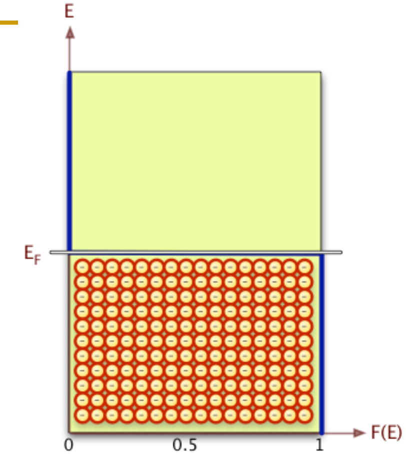
- Limitation of synchrotrons (especially for electrons) is due to “synchrotron radiation”.

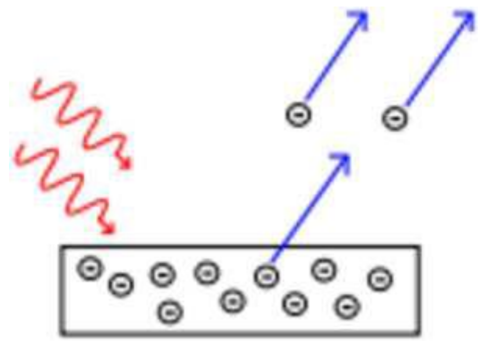


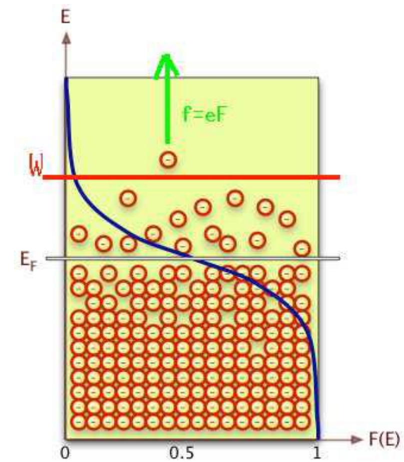
Accelerator complexes start from a source of particles

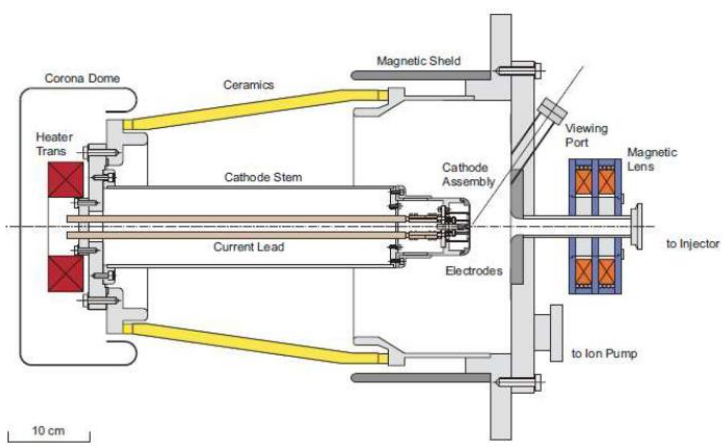
- Electron gun
  - Heated cathode
  - Thermionic emission
  - Electrons extracted by electric field
- Photo electron gun
  - Laser kicks electrons out

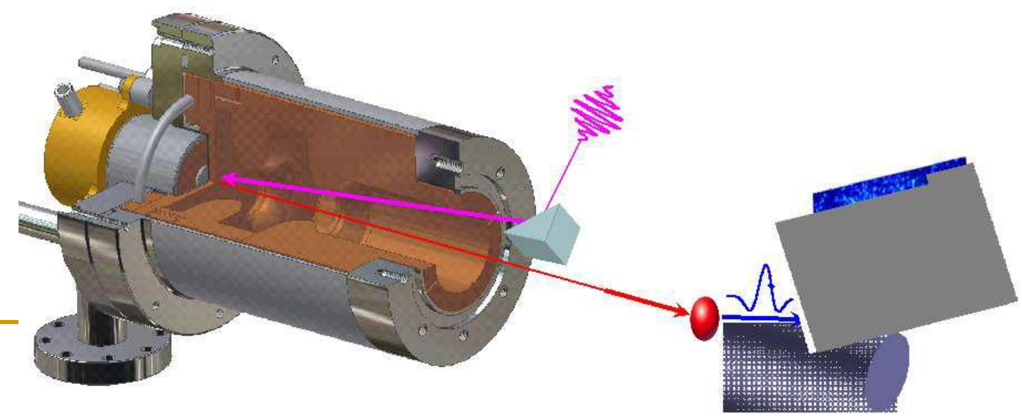




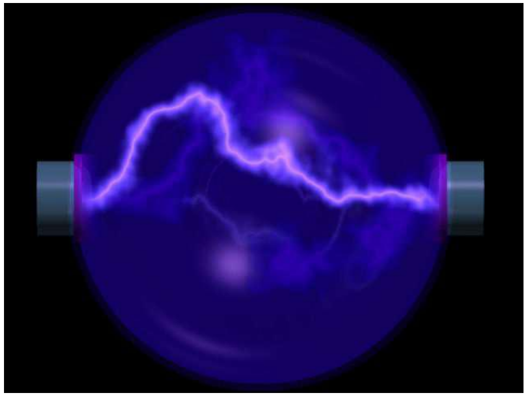




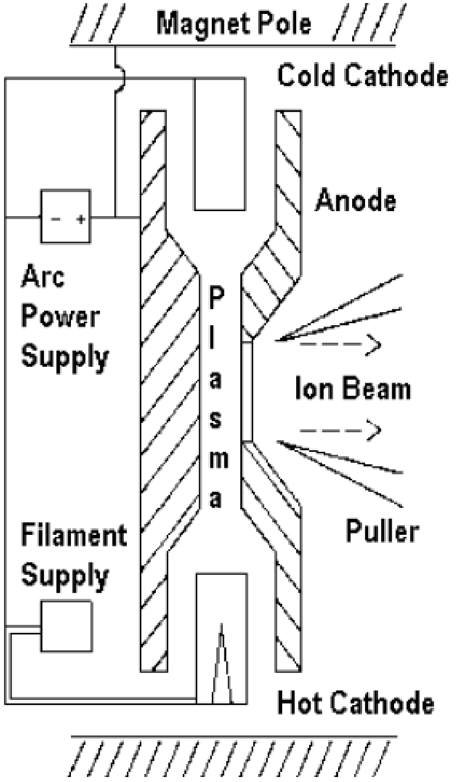




Ion Sources

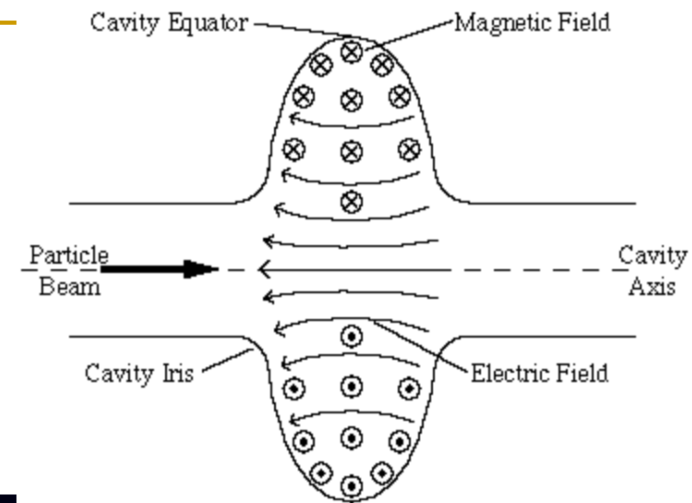


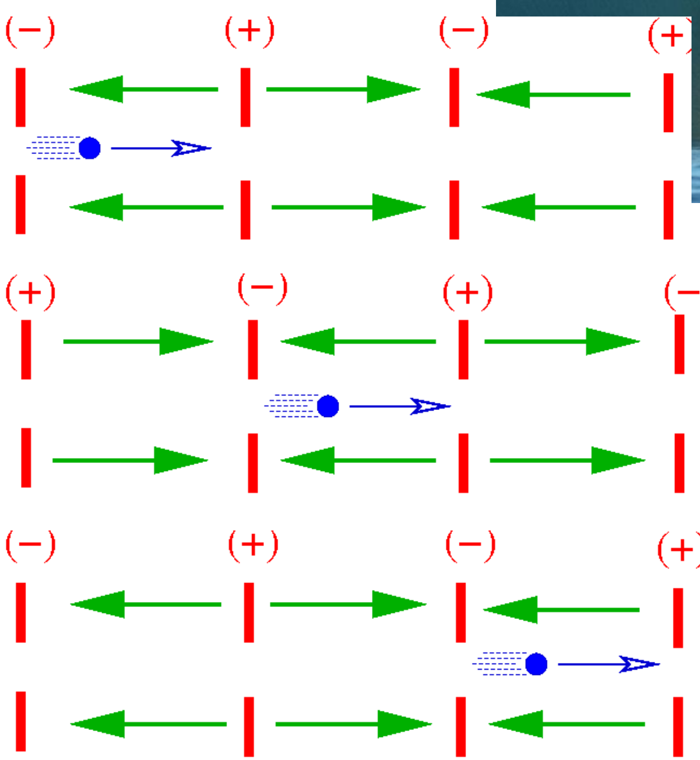
- A source of positive or negative ions can be produced using electric discharge in gas.
- Atoms are stripped of their electron(s) and the ions are then extracted.

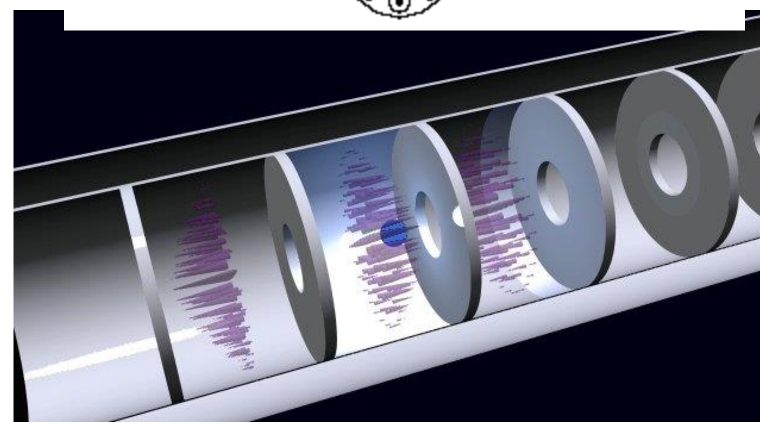


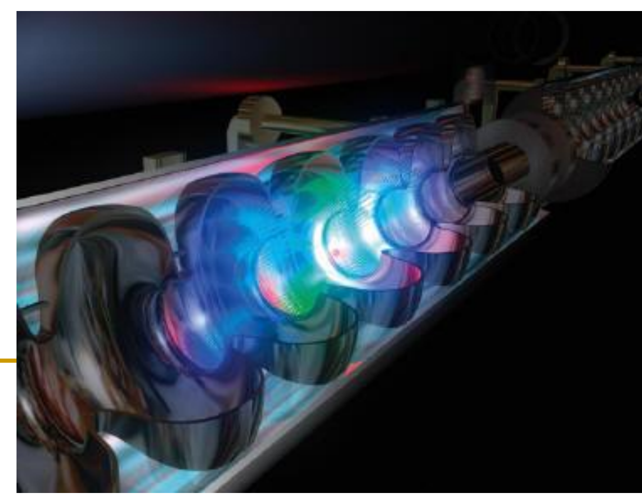
RF Cavities

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



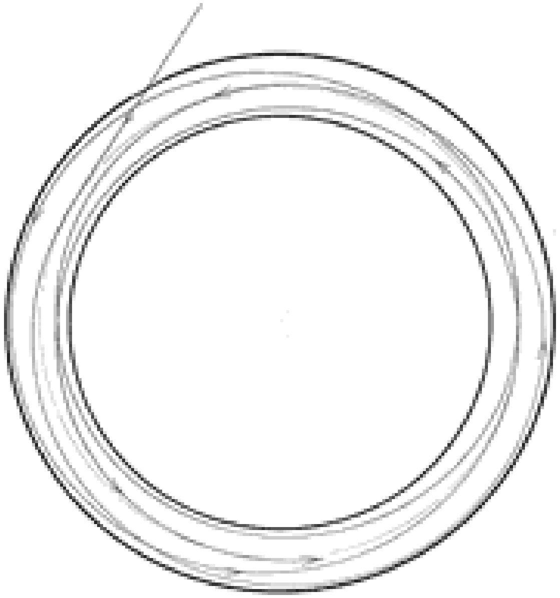






Focusing

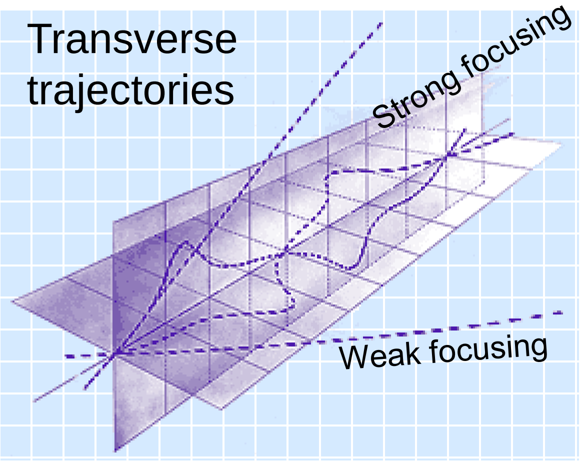
- Focusing is needed to confine the orbits.
- First accelerators had “weak focusing” – focusing period is larger than the perimeter.



Weak focusing accelerator

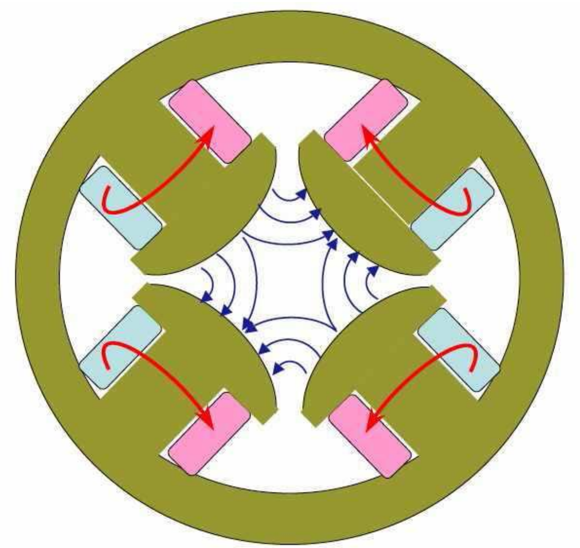
10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful of its time. Its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world.

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



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

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



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

Steering the Particle Beams

- A magnetic field can be used to deflect the particles.
- Lorentz force: $f = q(E + v \times B)$
- The LHC uses very strong magnets to keep its particles in a circular orbit.

LHC Dipole

http://lhc-machine-outreach.web.cern.ch

High-field Accelerator Magnets

- Magnetic rigidity $B\rho$ used to describe motion of relativistic particle of charge e and momentum p in magnetic field of strength B and bending radius ρ

$$B\,\rho = p\,/\,e \text{ (in SI units)}$$

$$B\,\rho\,[\text{T.m}] \sim 3.3356\,p\,[\text{GeV/c}]$$

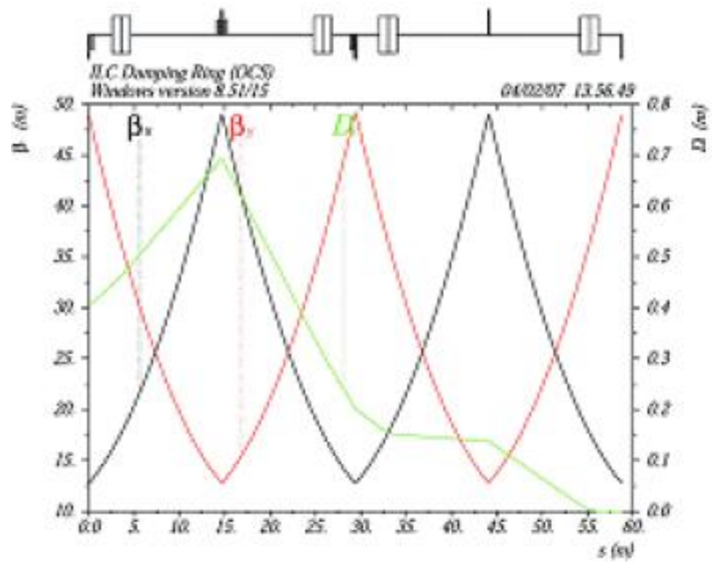
  - Two approaches for raising collision energy:
    - Increase magnetic field of bending magnets.
    - Increase ring circumference and hence radius ρ.
- Final focus Quadrupoles

$$B\,L_q \approx 1\,/\,\sigma^*$$

    - Design quadrupoles for largest integrated field $B\,L_q$ to obtain smallest beam size σ^* at IP.

F0D0 Lattice

- Quadrupole focuses in one plane and defocuses in the other.
- To keep beam within envelope, quadrupoles arranged to focus alternately in each plane.
- Called \`F0D0' (Focusing-Defocusing) lattice.
- At Collider, lattice slightly more complex as space needs to be created for experiments/utilities.

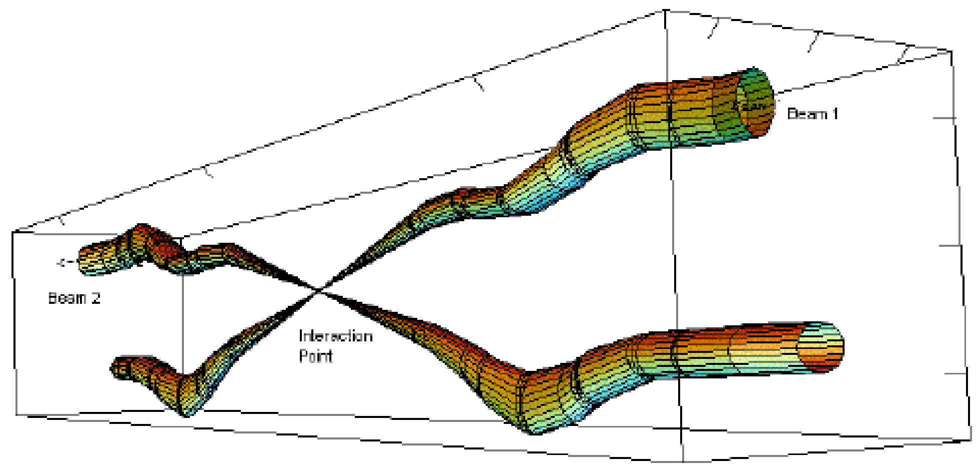


Magnet layout

http://ilc-china.ihep.ac.cn

Beam Size

- The beam size varies along the accelerator.
- At ISIS the beam can be as wide as 100mm.
- In Diamond it is only a few hundred micrometers wide.
- In the LHC near the interaction points the beam is only 64 micrometres wide (the size of a human hair).



Relative beam sizes around IP1 (Atlas) in collision

Beam size in the LHC

http://lhc-machine-outreach.web.cern.ch/

Charge and Current

- The charge of one electron (or one proton) is 1.6×10^{-19} Coulombs.
- The LHC can store up to 3×10^{14} protons.
- This corresponds to a total charge of 4.8×10^{-5} C, that is 48 micro-Coulombs.
- As it takes 90 microseconds for the particles to travel around the ring this corresponds to a current of 0.54 Amps!
  Current = Charge/duration

The LHC tunnel
http://cds.cern.ch

Stored Beam Energy

- 1 electron-volt is 1.6×10^{-19} Joules.
- 3.5 TeV= 560 nJ.
- Hence the full beam of 3×10^{14} protons contains 1.7×10^{8} J, that is 170 Megajoule.
- This energy is comparable to that of an Airbus 380 at 100km/h!
- This will double when the beam will reach 7 TeV!
- An energy of 170 MJ over 90 microseconds corresponds to a power of 2 Petawatt! Power=Energy/time

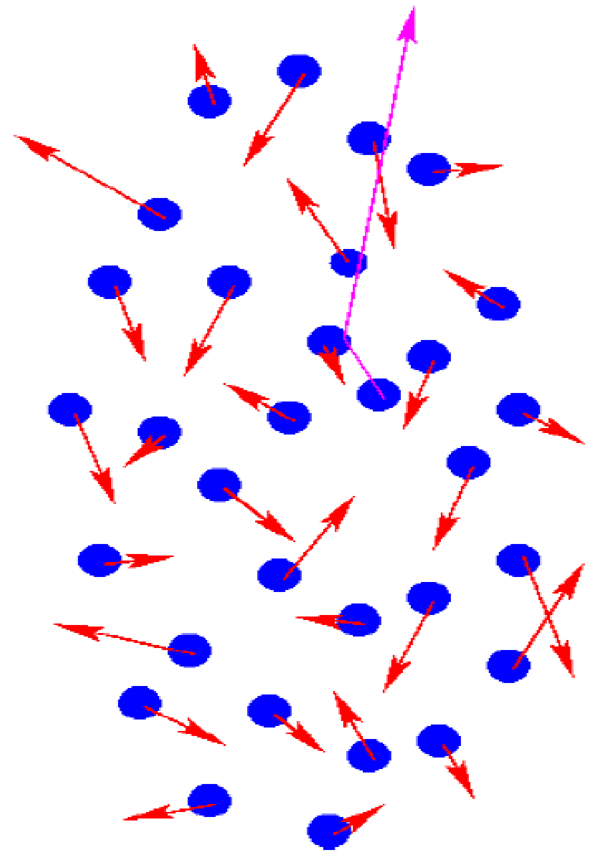
Airbus A380

wikipedia

Beam Lifetime

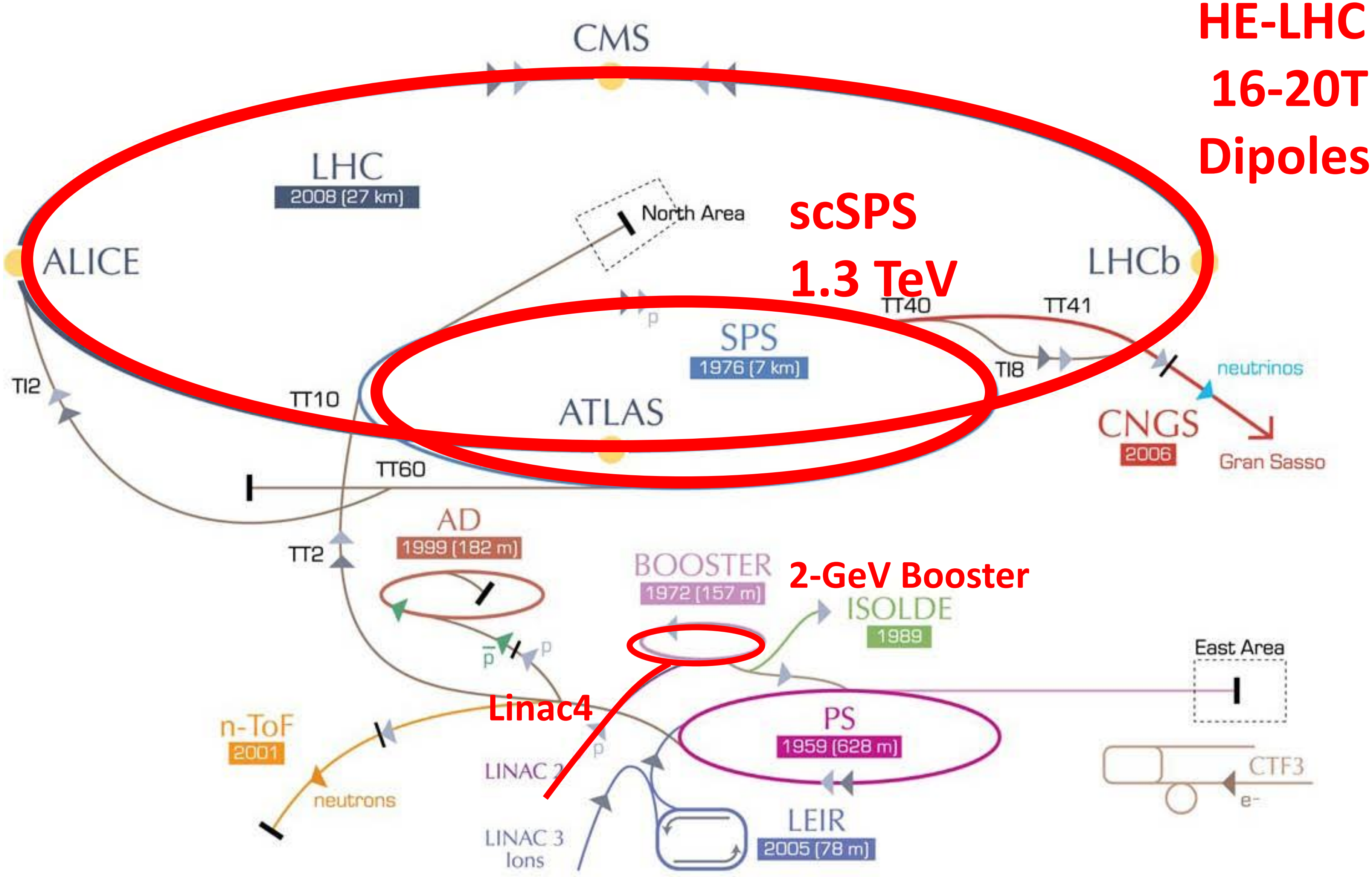
Lifetime

- The beam does not stay for ever in a ring.
- Some particles will scatter on each other and be ejected from the beam.
- Some particles “hit” the walls of the beampipe.
- In some rings the beam lifetime can be only a few minutes.
- In rings where stability is important (such as the LHC or Diamond) the beam lifetime will be several days.



Particle scattering inside a bunch

High-Energy LHC (HE-LHC)



Future Circular Collider (FCC) Study

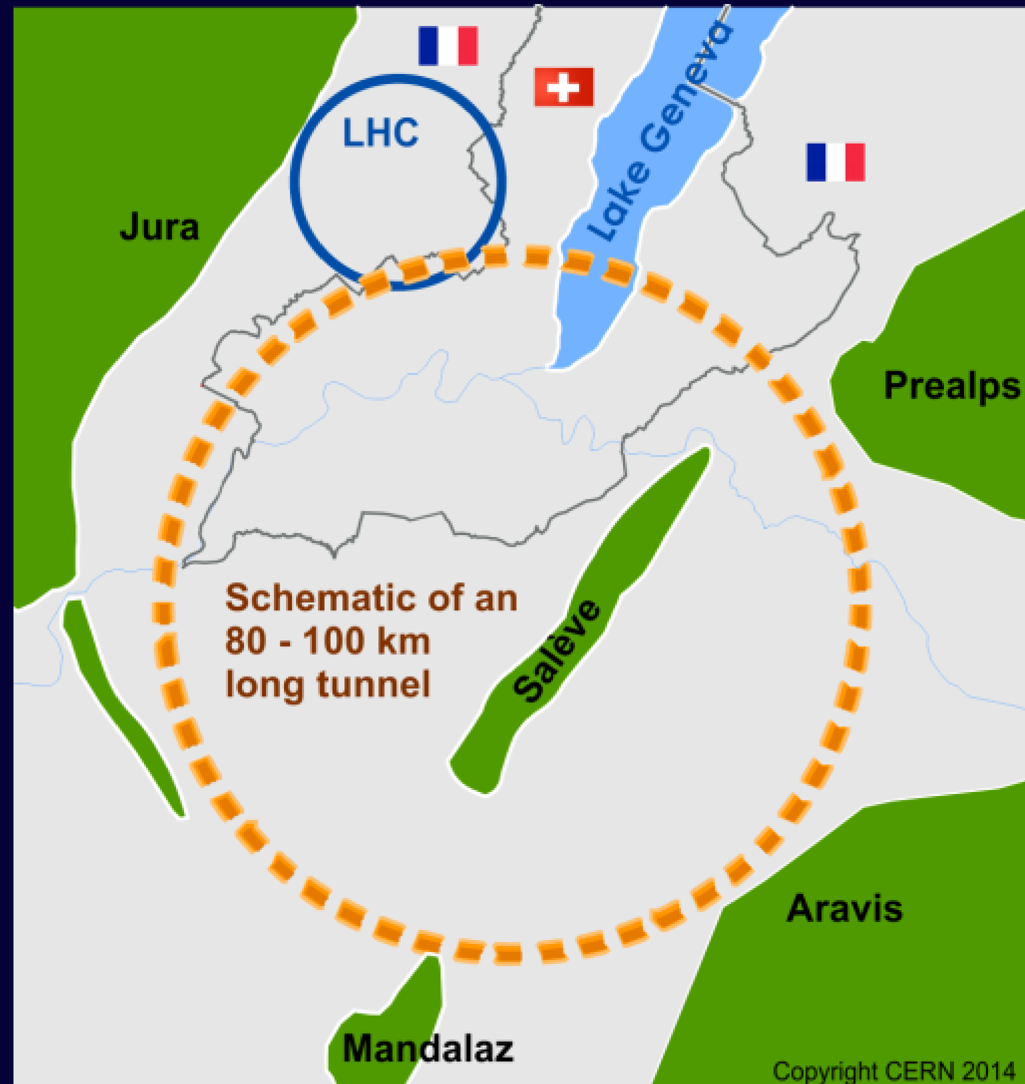
Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

potential intermediate step

- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



HE-LHC in the present LHC tunnel with FCC-hh technology

CEPC/SppC in China

- CEPC
  - Circular Electron Positron Collider
  - 50 -70 km ring, up to 100 km?
  - 90-250 GeV
  - Z and Higgs factory
- SppC
  - Super proton proton Collider with CM energies > 100 TeV
  - In the same ring as CEPC

Site Candidates

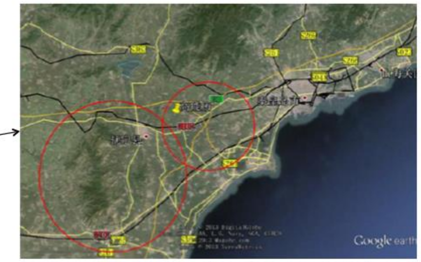
Bejing

Baoding
(xiong an)

Tianjin

4

1



2

3

1) Qin huang dao，Heihe （Completed in 2014）

2) Huanging，Shanxi（Completed in 2017)

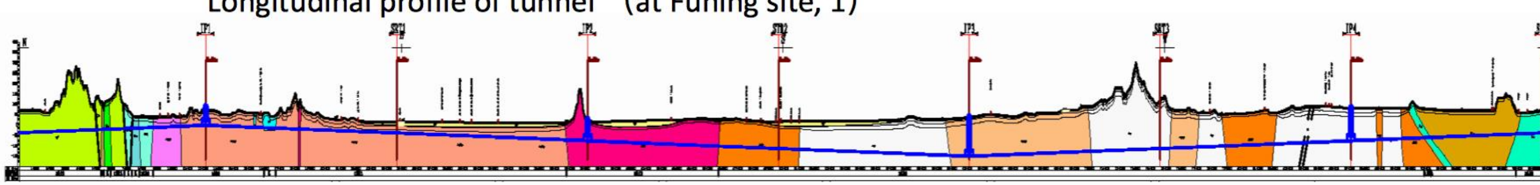
3)Shen shan，Guangdong (Completed in 2016)

4) Baoding (Xiong an), Hebei (Started in August 2017, near Beijing

5) Zhejiang (under contact)

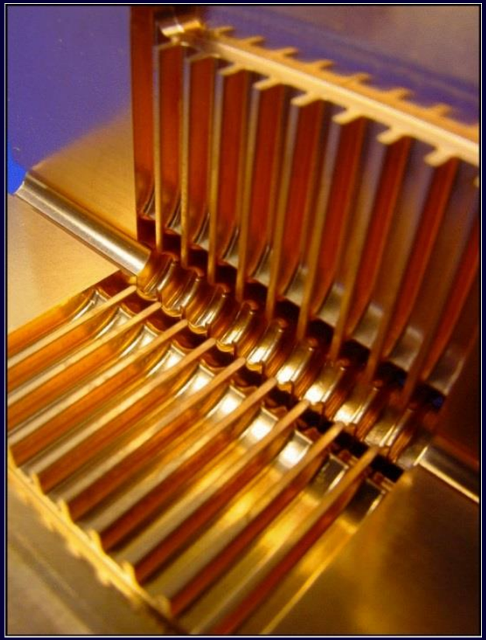
6) Jiangsu (under contact)

Longitudinal profile of tunnel （at Funing site, 1）



ILC and CLIC

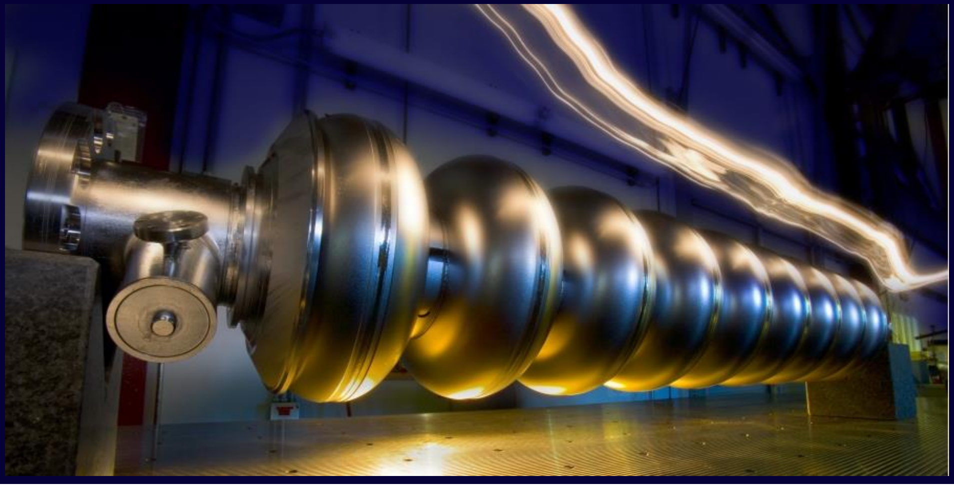
CLIC
(Compact Linear Collider)



2-beam acceleration scheme at room temperature.
Gradient 100 MV/m.
$\sqrt{s}$ up to 3 TeV.
Physics + Detector studies
for 350 GeV - 3 TeV.

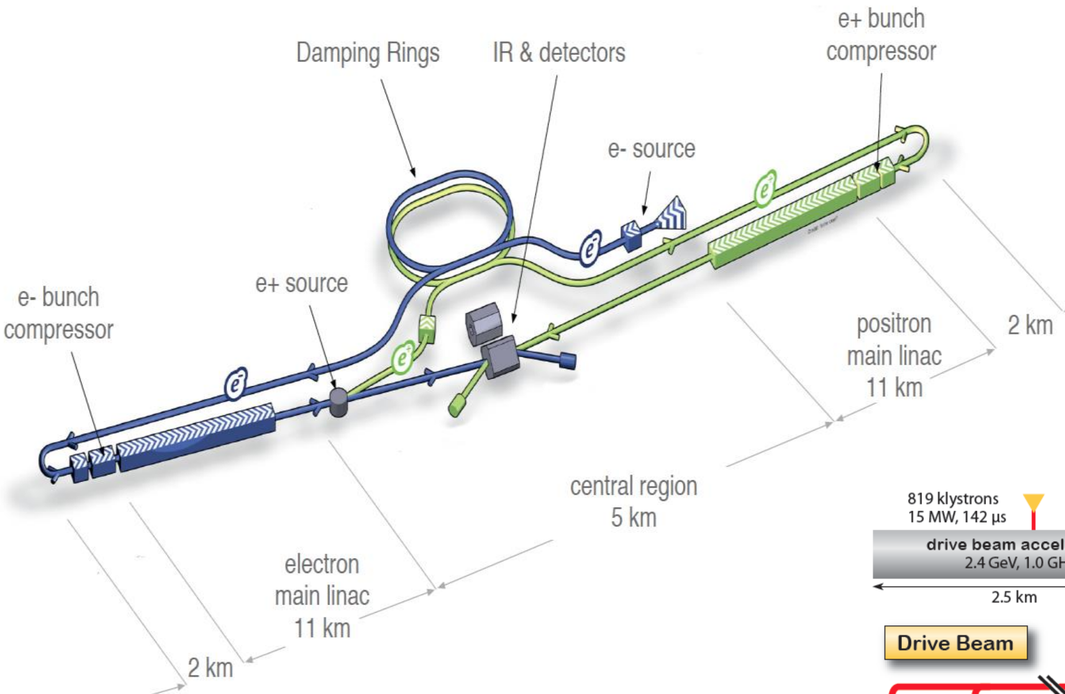
Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

ILC (International Linear Collider

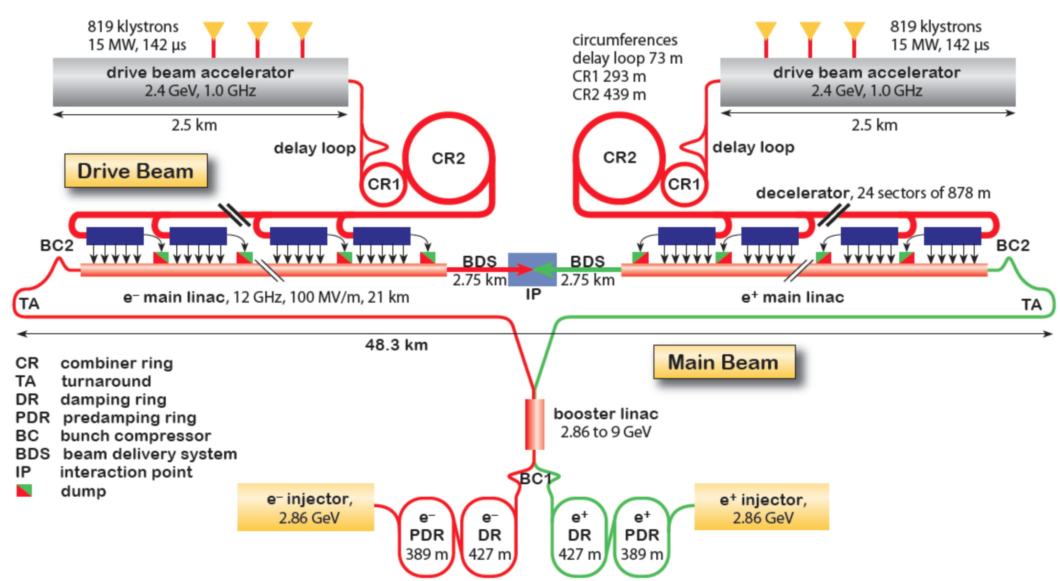


- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

CLIC and ILC

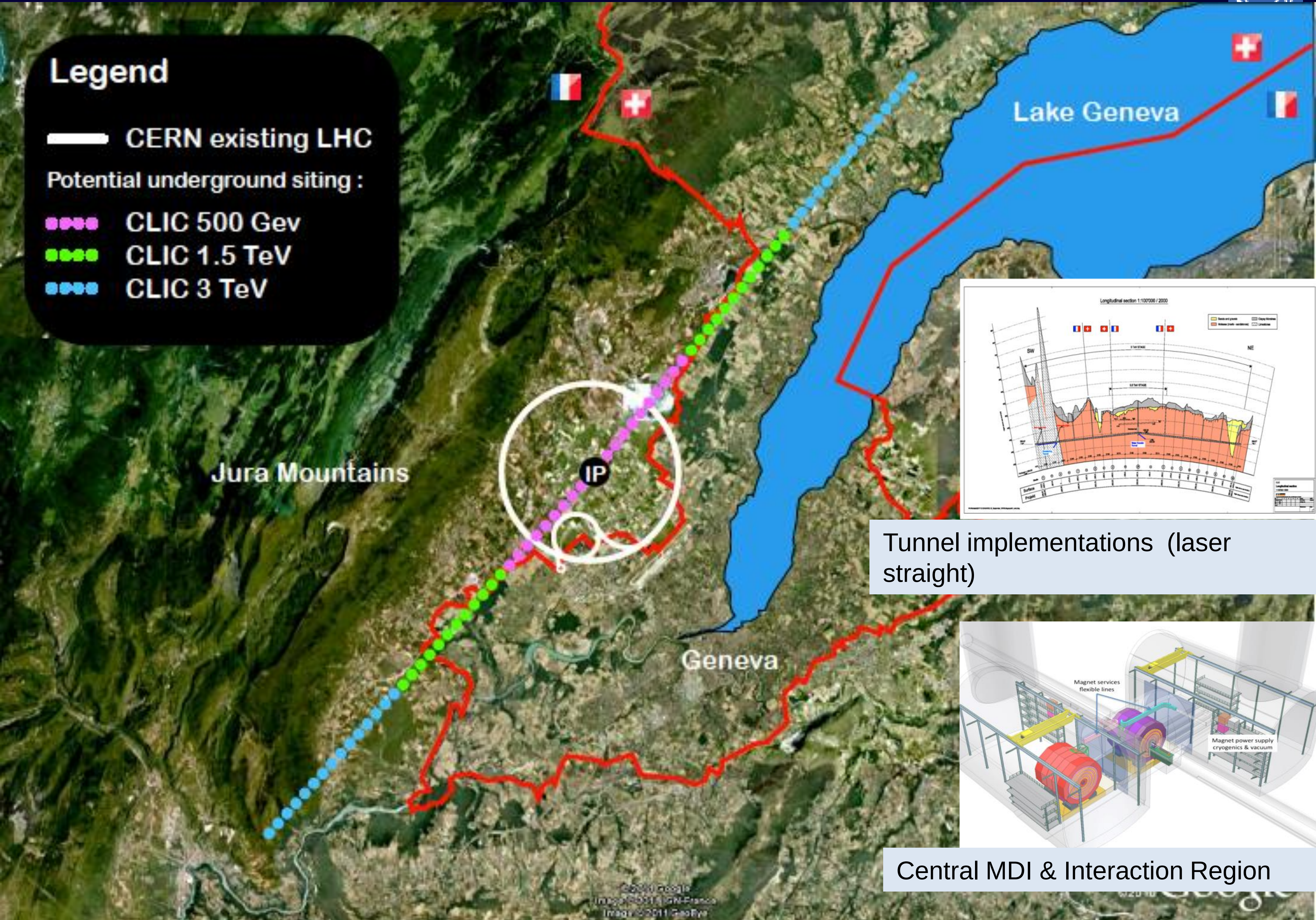


ILC
0.5 TeV CM, upgreadable to 1 TeV
SC RF industrialized
mature design (TDR in 2012)
Possibility of hosting is evaluated by Japanese government



CLIC
Two-beam scheme, 1-3 TeV CM
Option for 380 GeV explored (klystrons)
CTF3 facility – key R&D done
Ready for demonstrator project

CLIC near CERN



Tunnel implementations (laser straight)

Central MDI & Interaction Region

24 (+1) 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.

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".*

Thank You!

Accelerating Science and Innovation