
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Elias Métral

Elias.Metral@cern.ch
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http://emetral.web.cern.ch/emetral/

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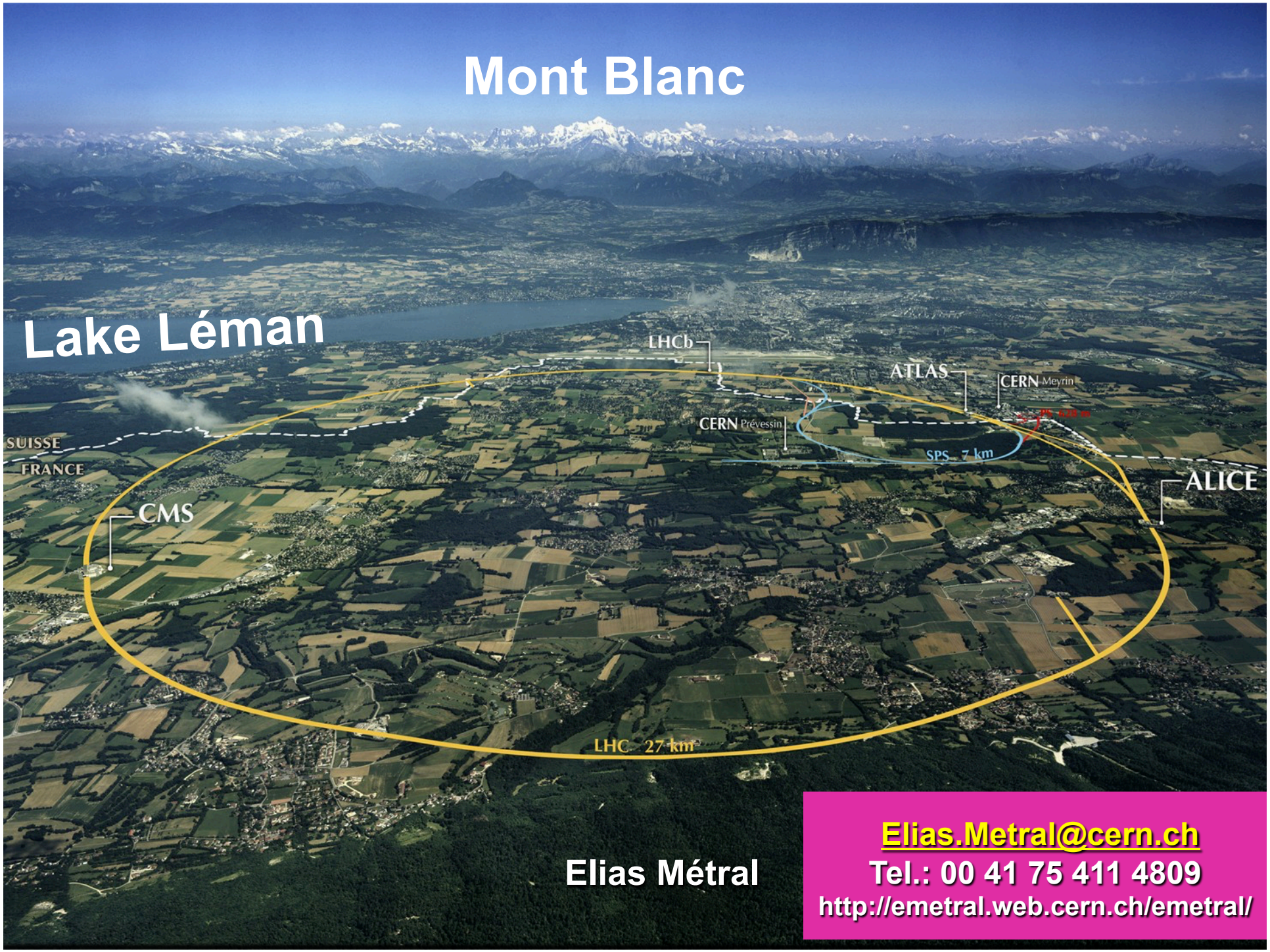

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Au delà du Boson de Higgs

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CERN (créé en 1954):

Conseil Européen pour la Recherche Nucléaire = Laboratoire européen pour la physique des particules

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THE CERN LHC:
LARGE HADRON COLLIDER

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Google
10/09/2008: LHC startup
WHY?
WHAT?
HOW?
LHCb
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CERN Meyrin
CERN Prévessin
SPS 7 km
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WHY?

A historical day : 4th July 2012

Peter Higgs

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=> Announcement of the discovery of a new particle ("Higgs-like" boson)

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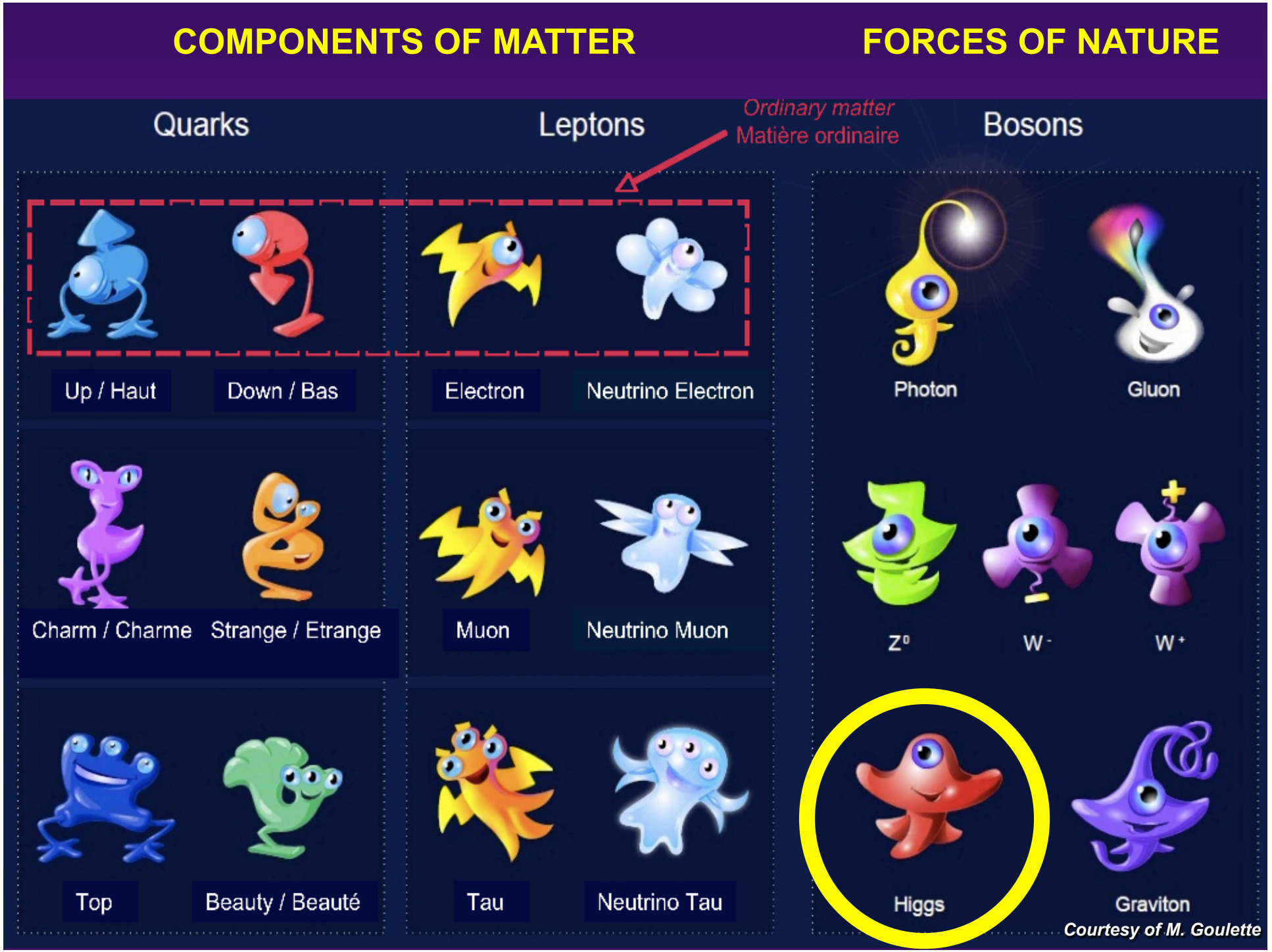
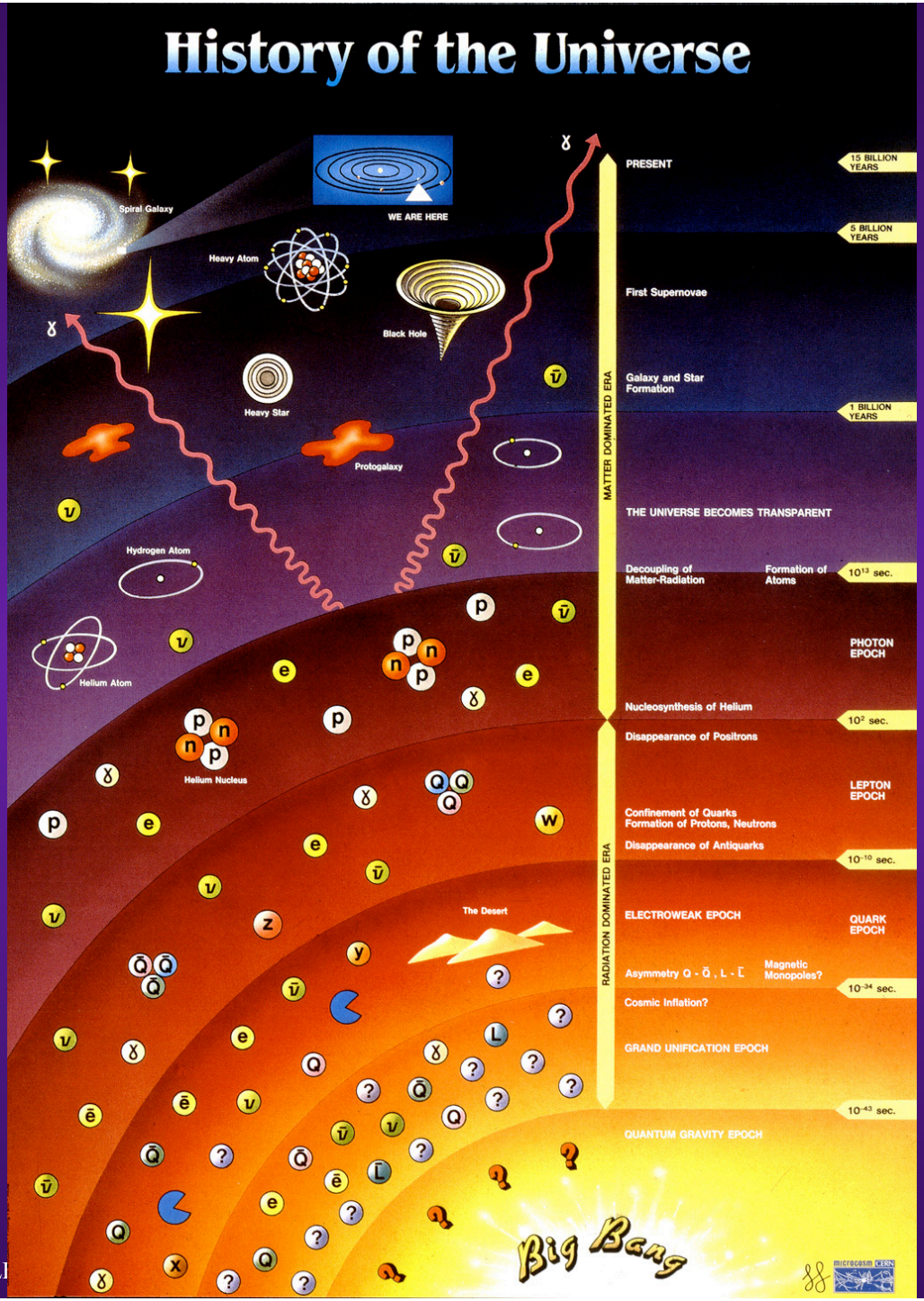
2013 Nobel prize in physics awarded to F. Englert and P. Higgs for their theoretical work on Higgs boson (1964)

Peter Higgs

Verify the Standard Model


COMPONENTS OF MATTER
FORCES OF NATURE
Quarks
Leptons
Ordinary matter
Matière ordinaire
Bosons
Up / Haut
Down / Bas
Electron
Neutrino Electron
Photon
Gluon
Charm / Charme
Strange / Etrange
Muon
Neutrino Muon
Z⁰
W⁻
W⁺
Top
Beauty / Beauté
Tau
Neutrino Tau
Higgs
Graviton
Courtesy of M. Goulette


History of the Universe
Spiral Galaxy
WE ARE HERE
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
PRESENT
15 BILLION YEARS
5 BILLION YEARS
First Supernovae
Galaxy and Star Formation
1 BILLION YEARS
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
10^13 sec.
PHOTON EPOCH
Nucleosynthesis of Helium
10^2 sec.
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks
Formation of Protons, Neutrons
Disappearance of Antiquarks
10^-10 sec.
ELECTROWEAK EPOCH
QUARK EPOCH
Asymmetry Q - Q̄ , L - L̄
Magnetic Monopoles?
10^-34 sec.
Cosmic Inflation?
GRAND UNIFICATION EPOCH
10^-43 sec.
QUANTUM GRAVITY EPOCH
MATTER DOMINATED ERA
RADIATION DOMINATED ERA
Big Bang

Search for physics beyond the Standard Model

=> Unsolved mysteries

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  => Dark energy?

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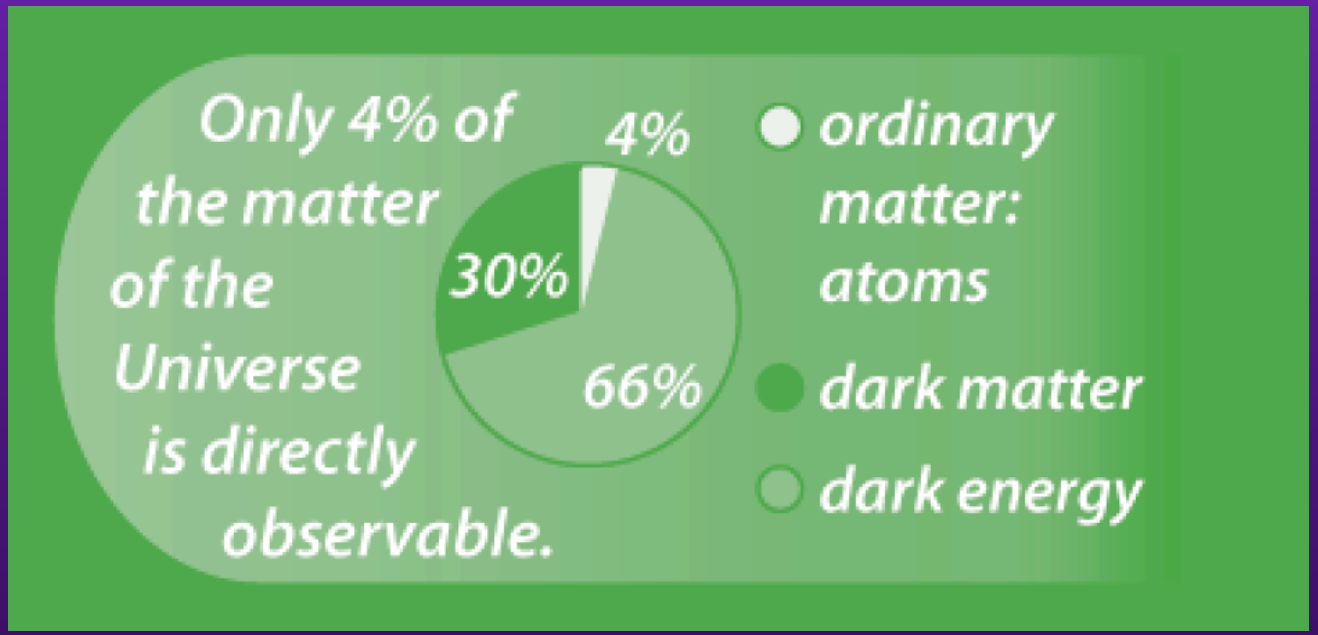
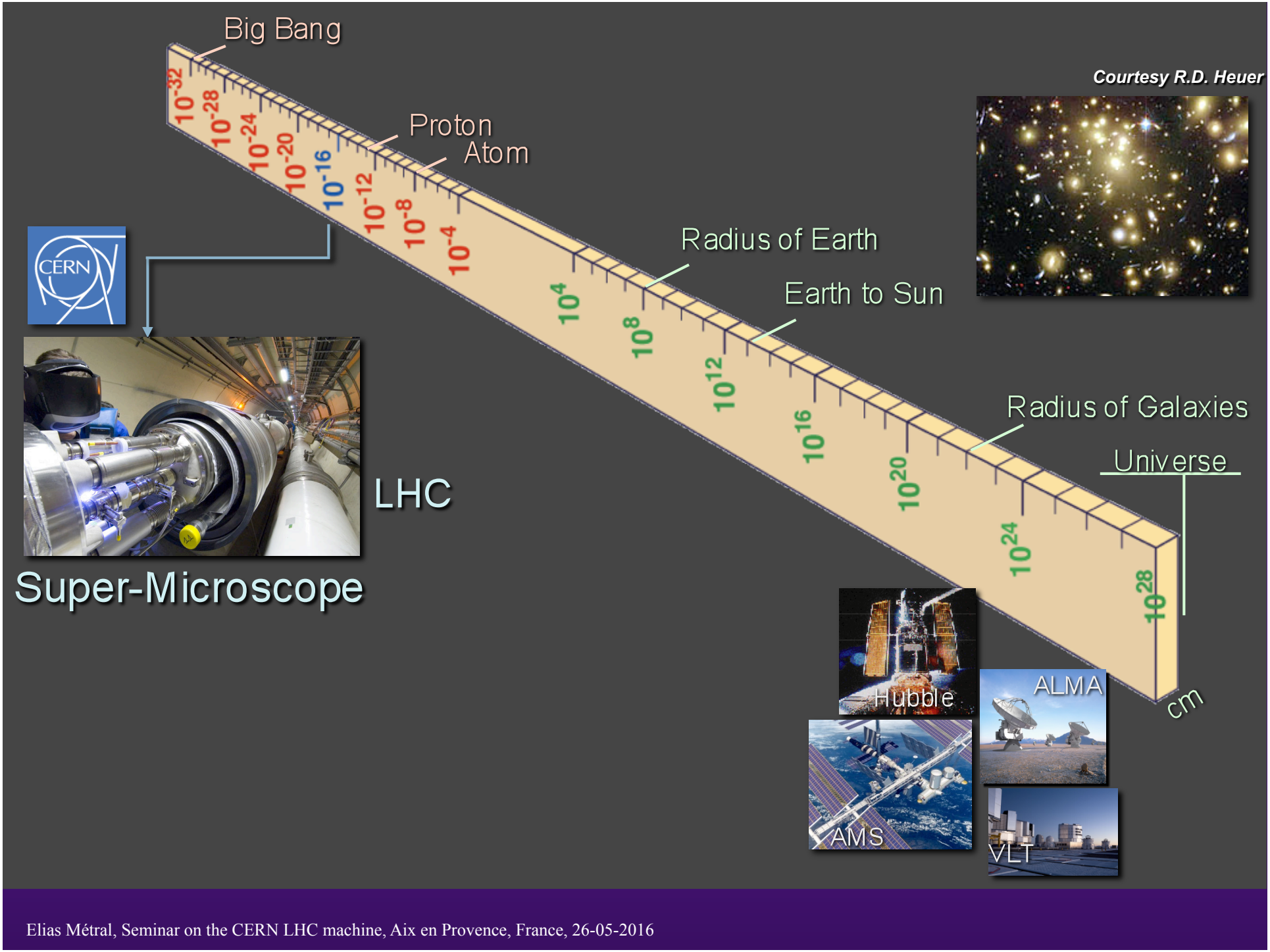
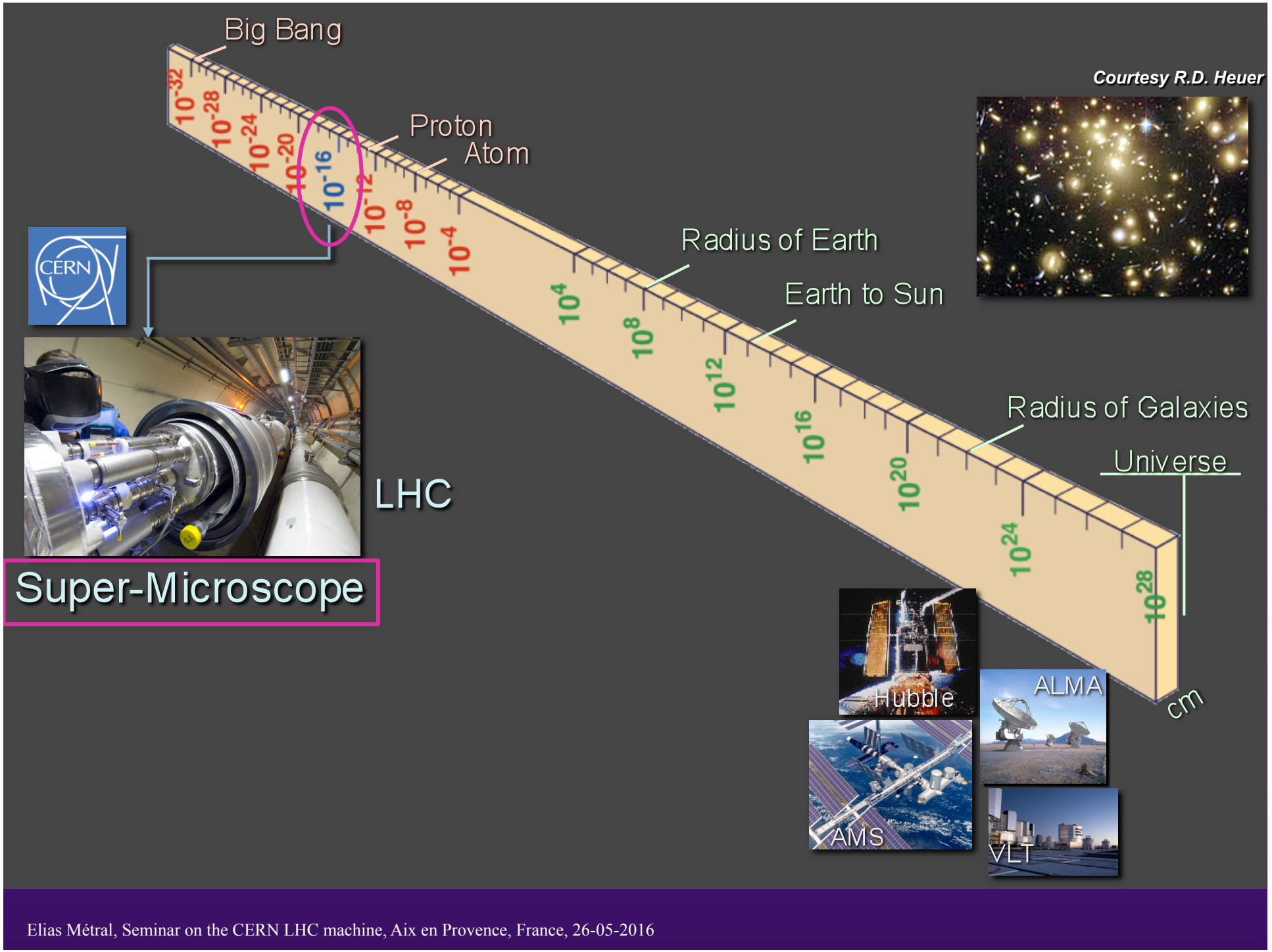
- Etc.



WHAT?


Big Bang
Proton
Atom
Radius of Earth
Earth to Sun
Radius of Galaxies
Universe
cm
Courtesy R.D. Heuer
CERN
LHC
Super-Microscope
Hubble
ALMA
AMS
VLT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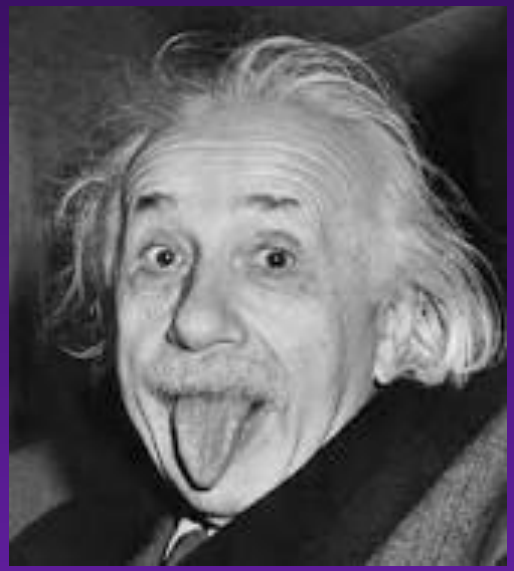
- With a collider, we do the opposite as in Nuclear Plants => We create matter (new particles) starting from energy, while in Nuclear Plants we create energy starting from matter (Uranium, etc.)

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



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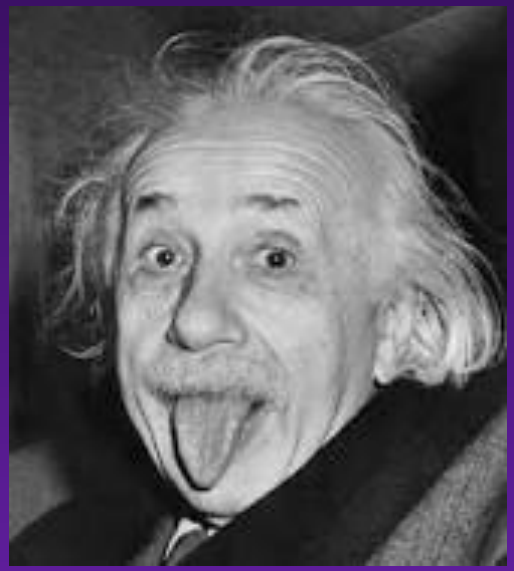

$$\lambda \propto \frac{1}{E}$$

Wavelength => Should be < object to be resolved

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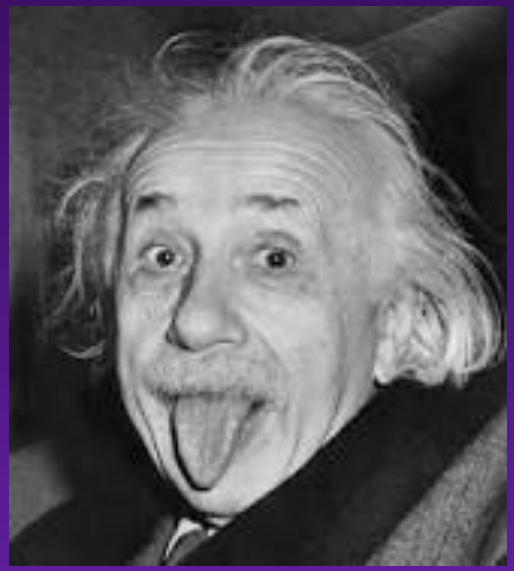

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Object	Size [m]	Energy needed [GeV]
Atom	10^{-10}	~ 10^{-5}
Nucleus	10^{-14}	~ 0.1
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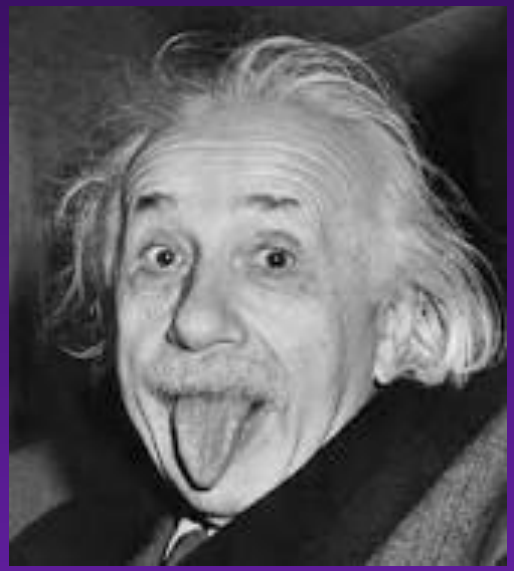

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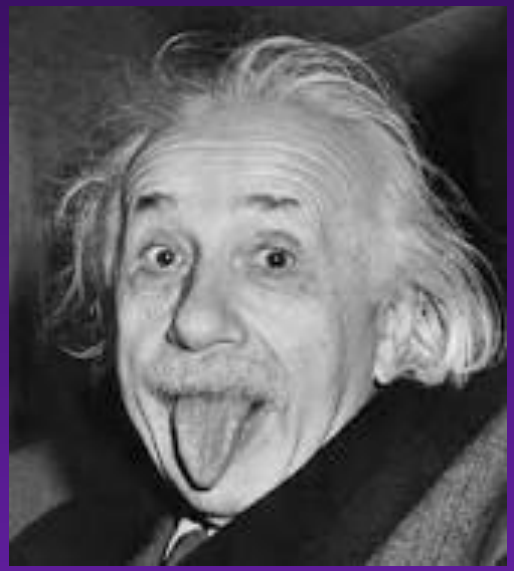

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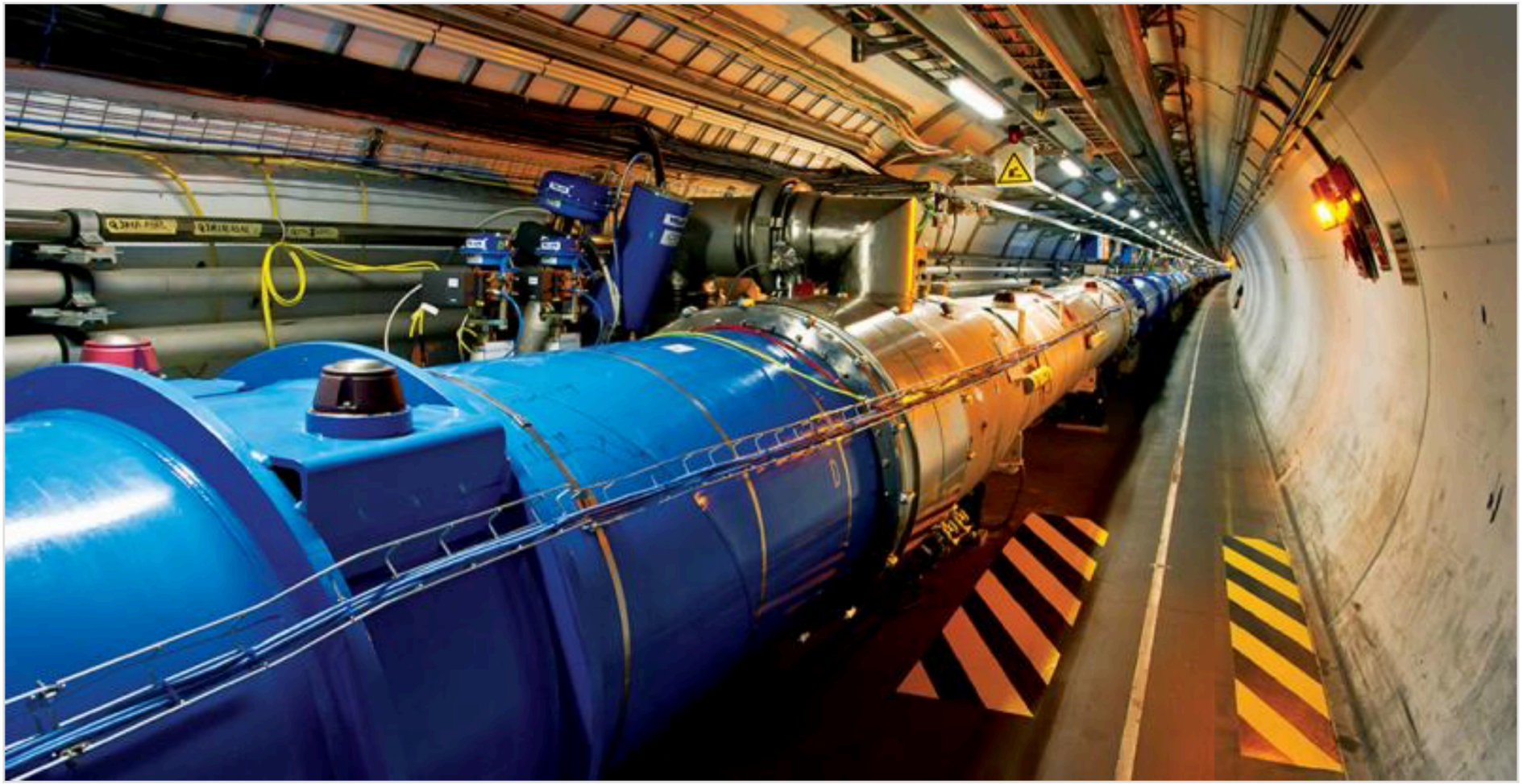
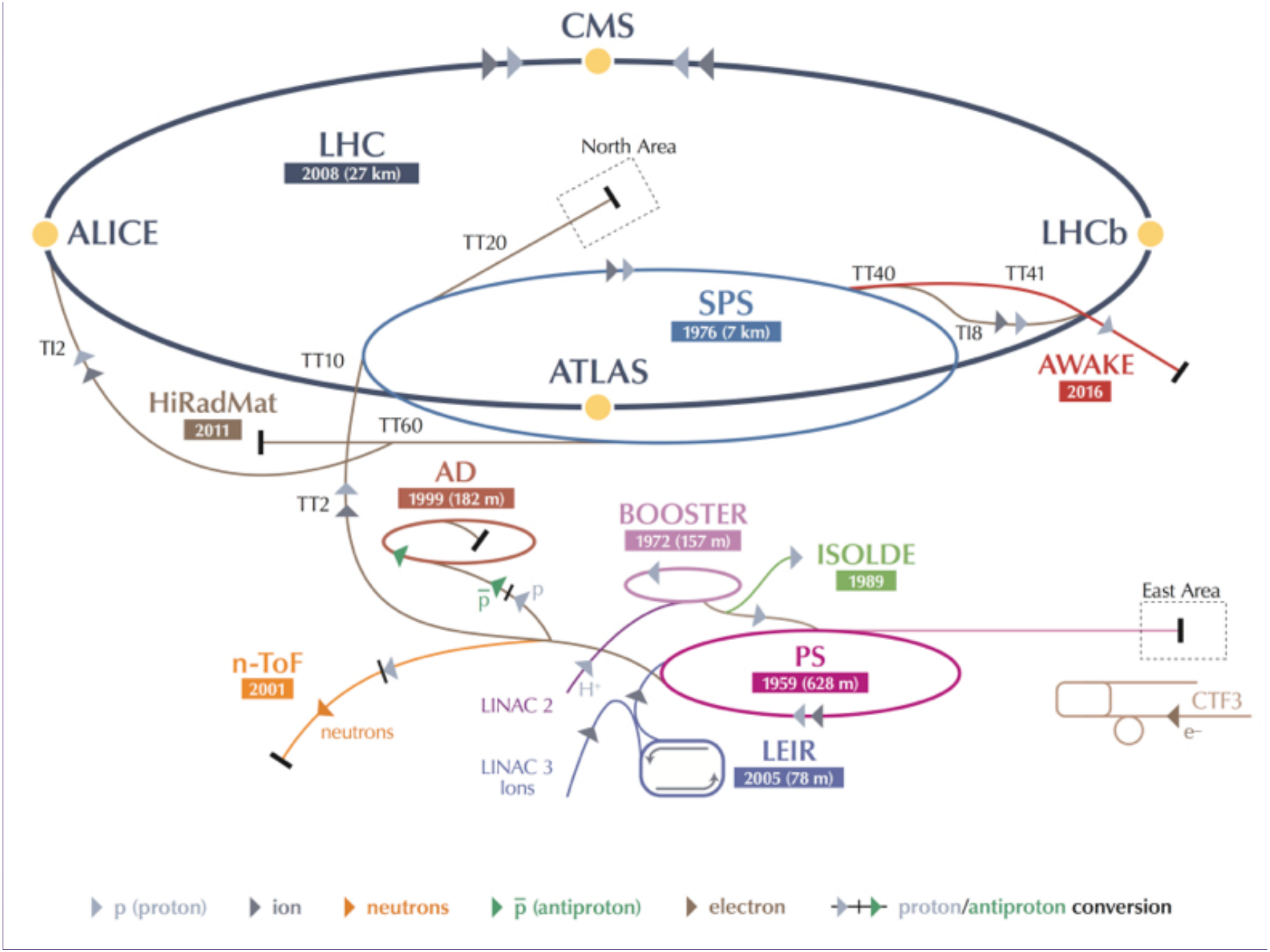
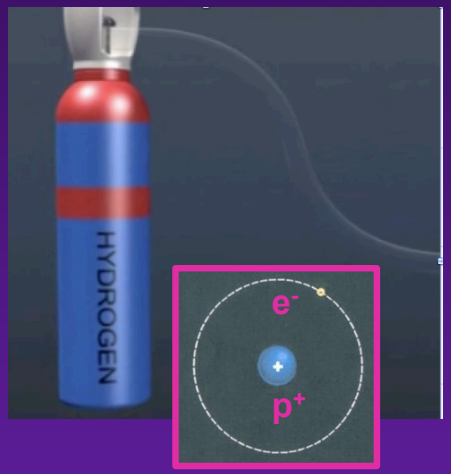
3) "Vacuum" (where the particles circulate) should be good enough for the particles not to be perturbed

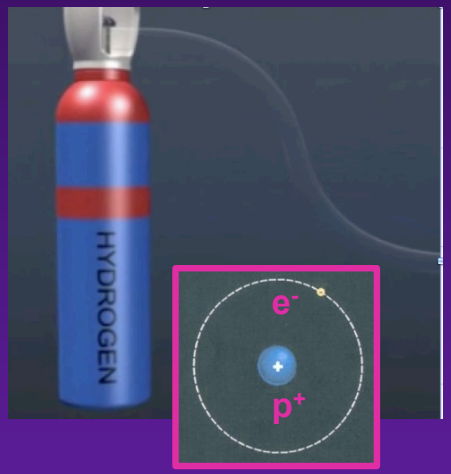


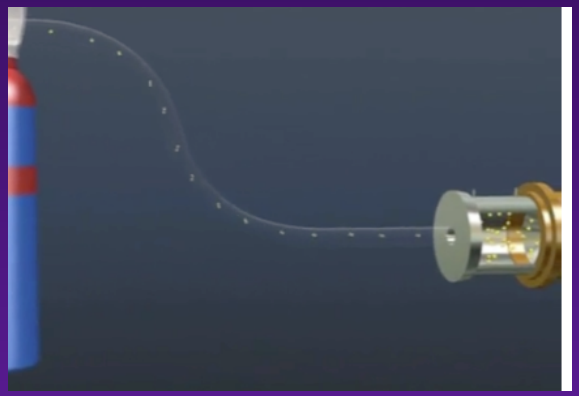
Le Grand collisionneur de hadrons (LHC) est le plus grand et le plus puissant accélérateur de particules du monde. (Image: CERN)


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
p̄
p
n-ToF
2001
PS
1959 (628 m)
H⁻
CTF3
e⁻
LINAC 2
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
electron
proton/antiproton conversion

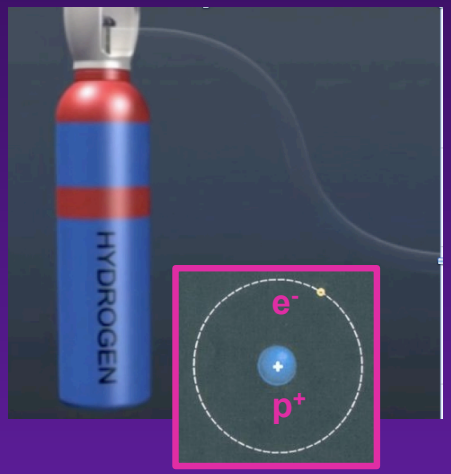
HOW?

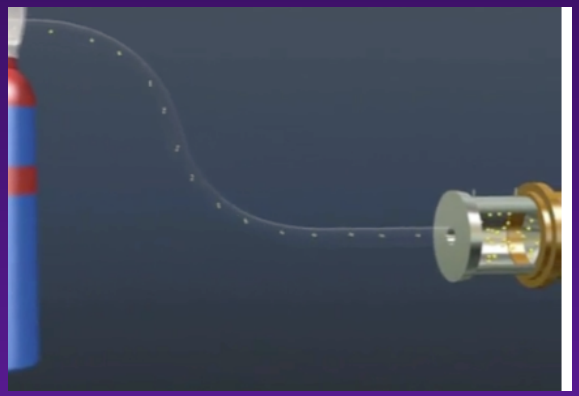

HYDROGEN
e-
p+

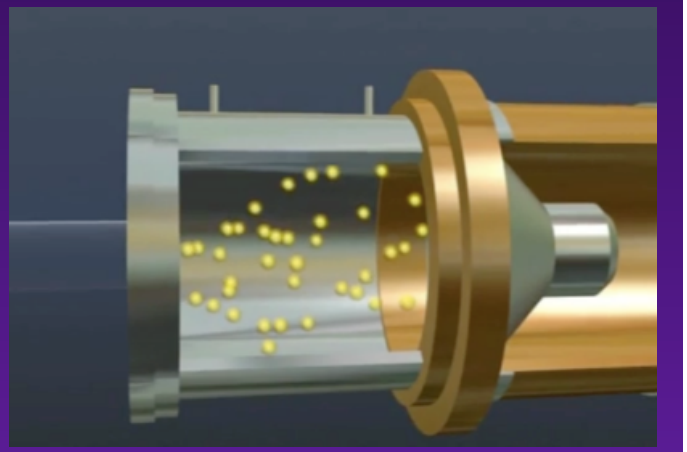




H atoms are taken from a bottle







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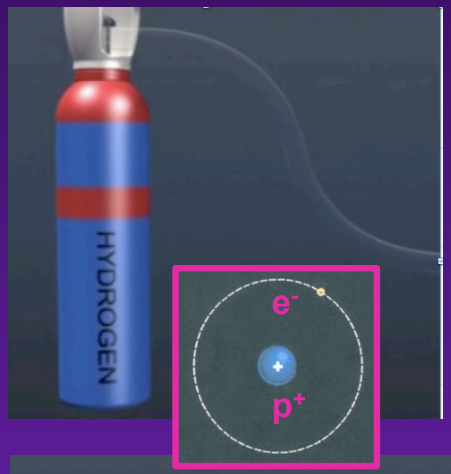

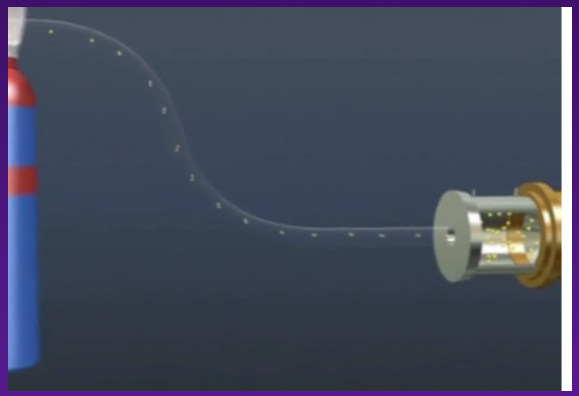

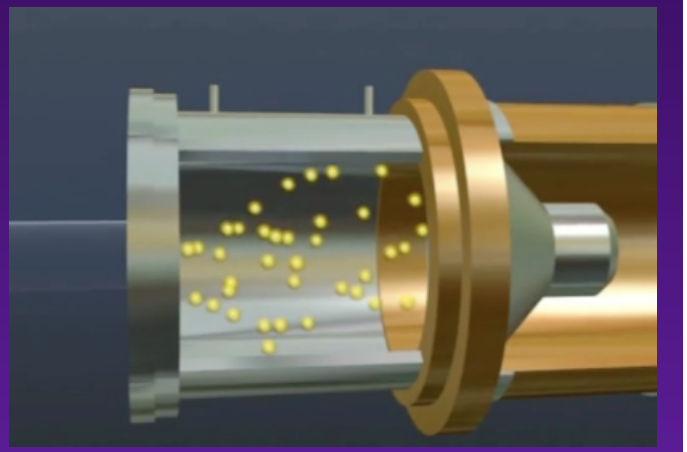

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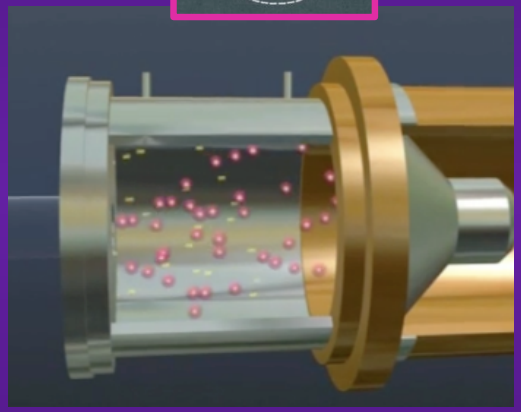
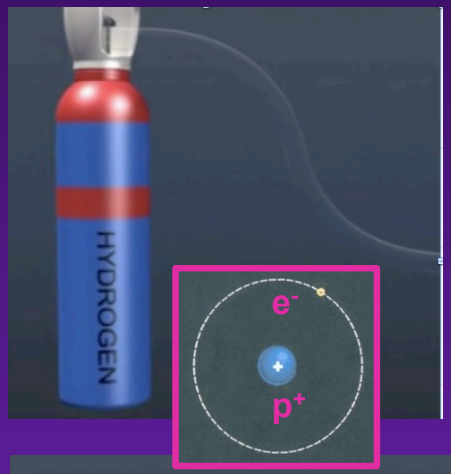
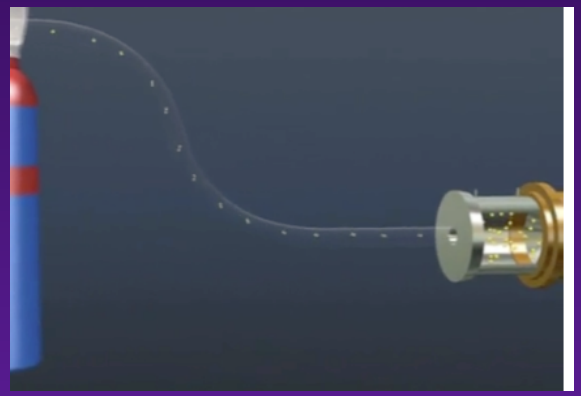
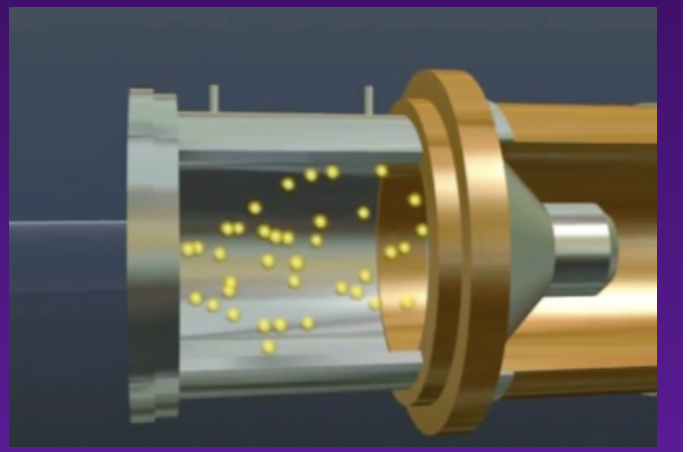


p^+ created by stripping orbiting e^- from H atoms







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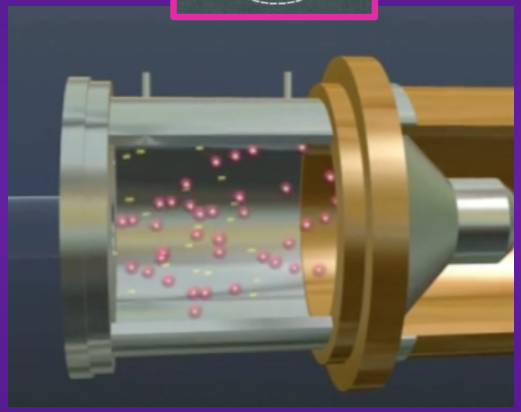

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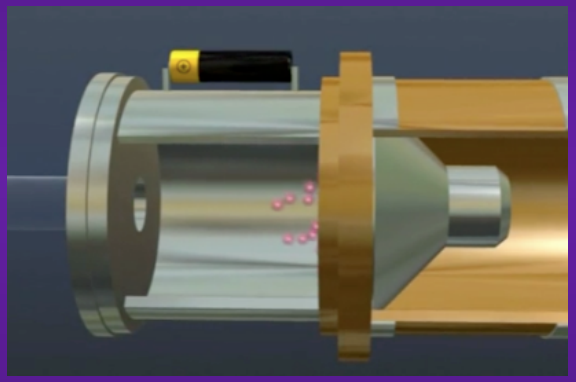
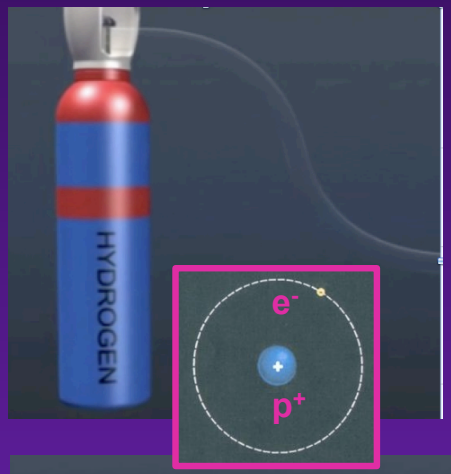
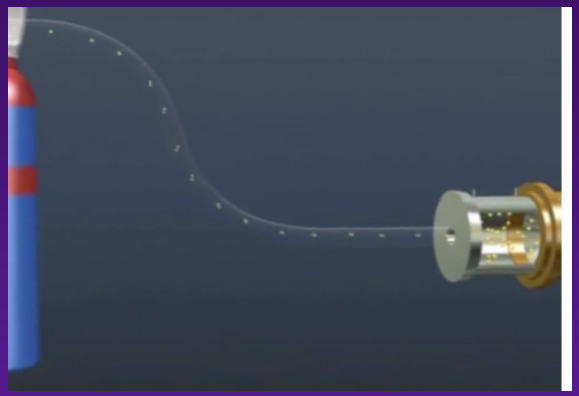


Acceleration by electric fields (voltage differences)





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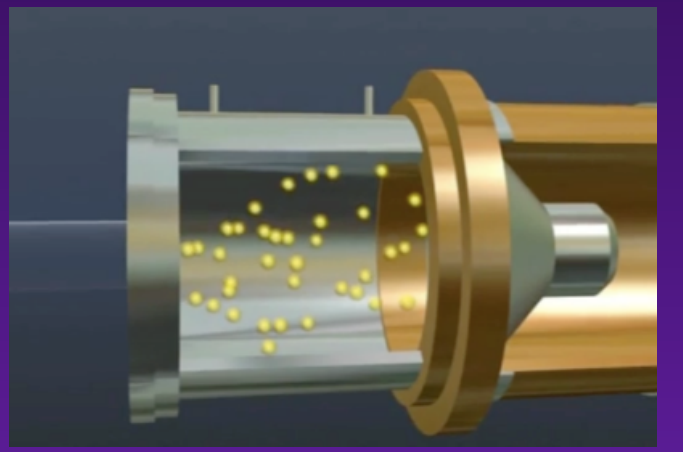

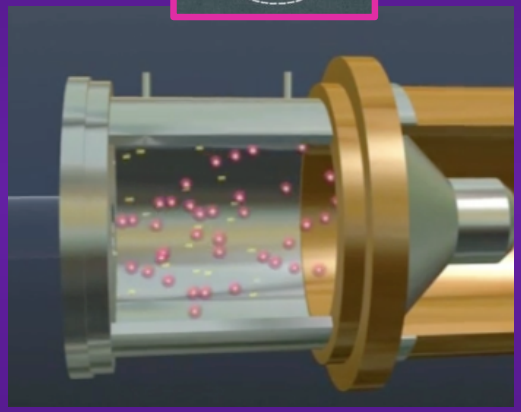

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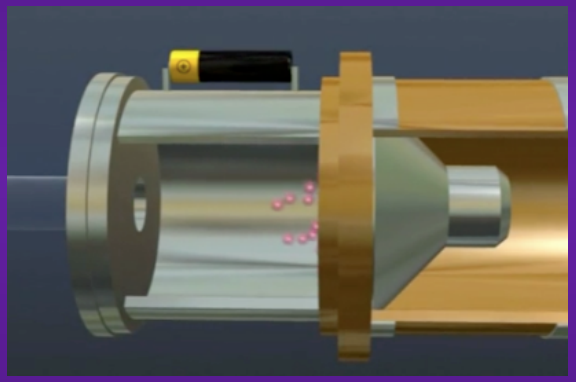

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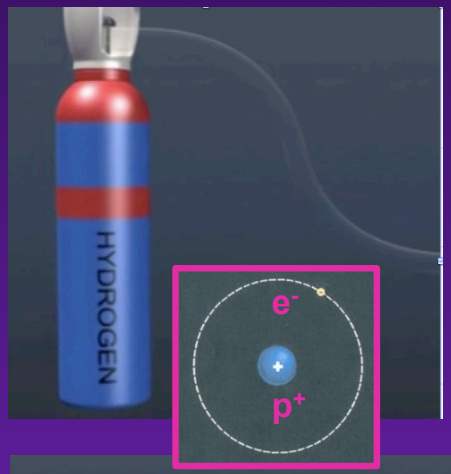

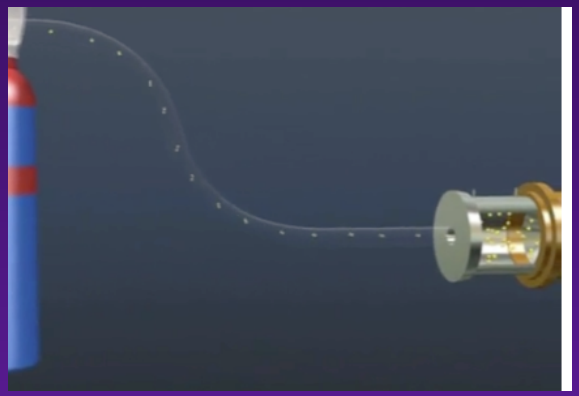

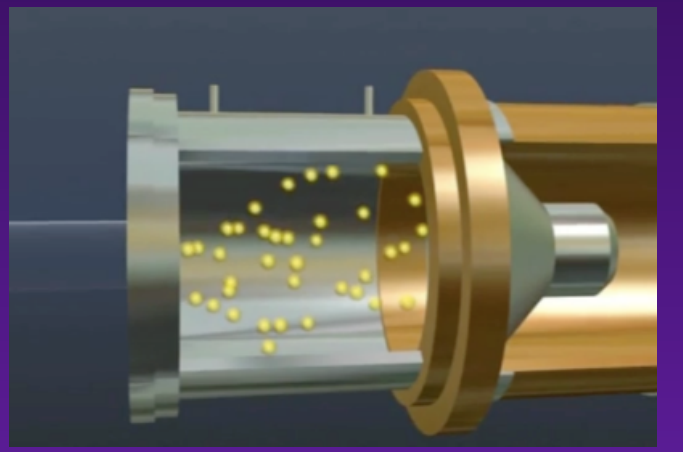

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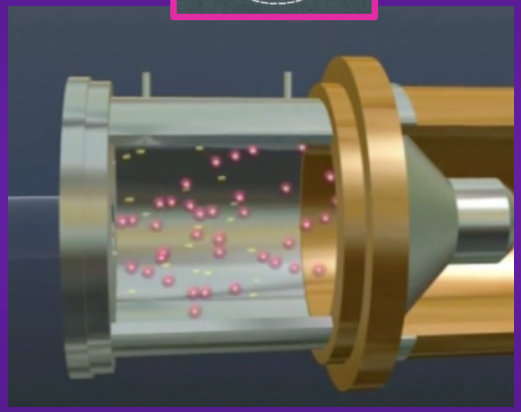

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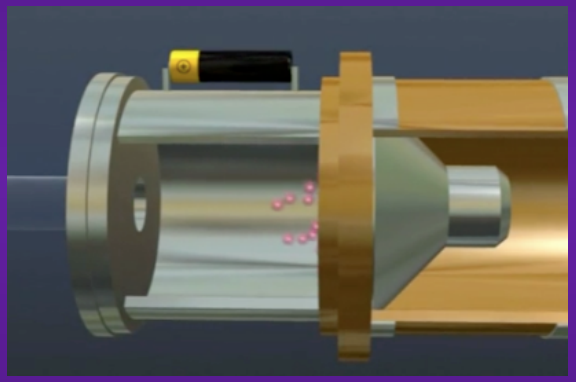

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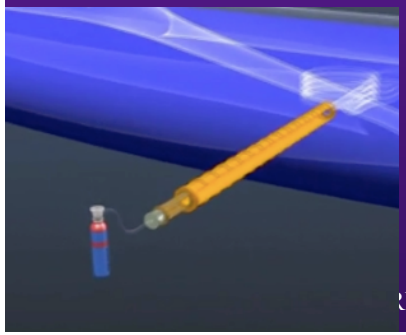
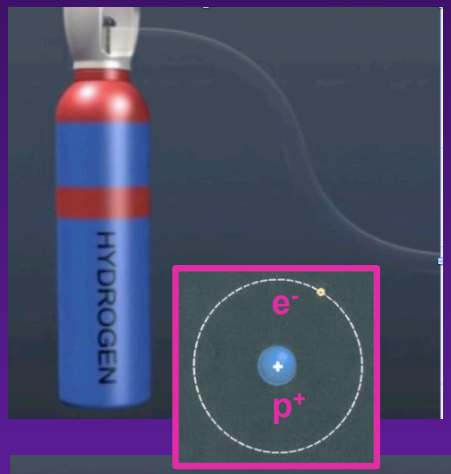
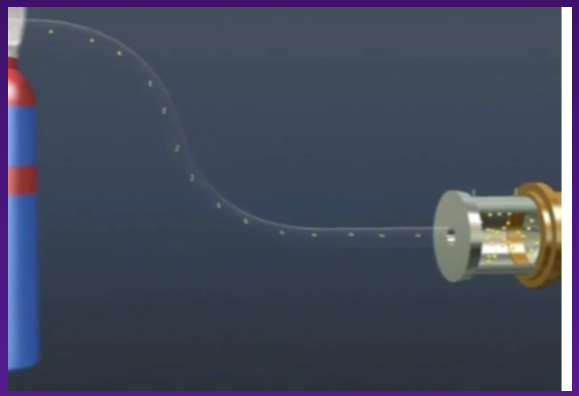
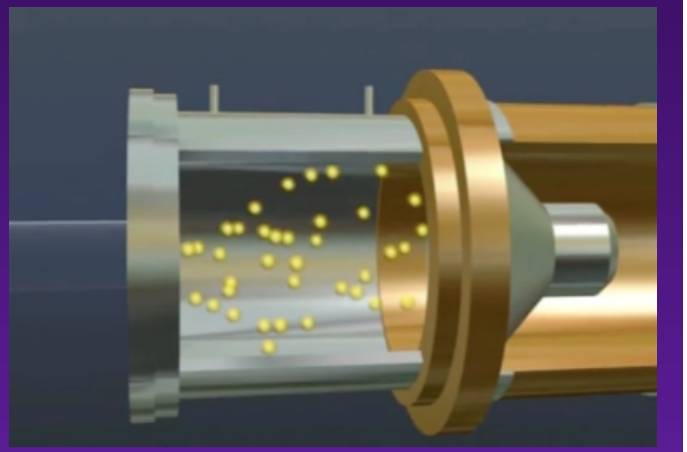
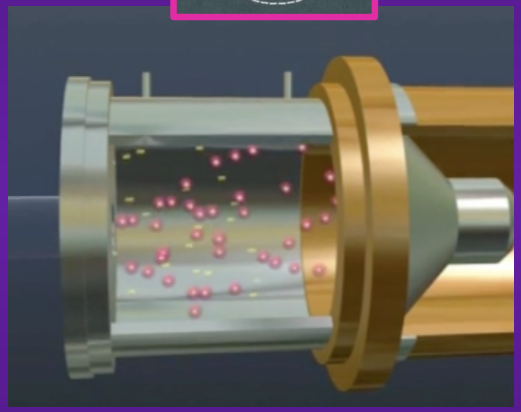






H atoms are taken from a bottle





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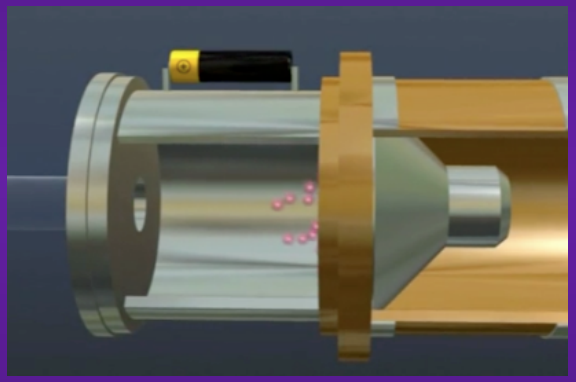
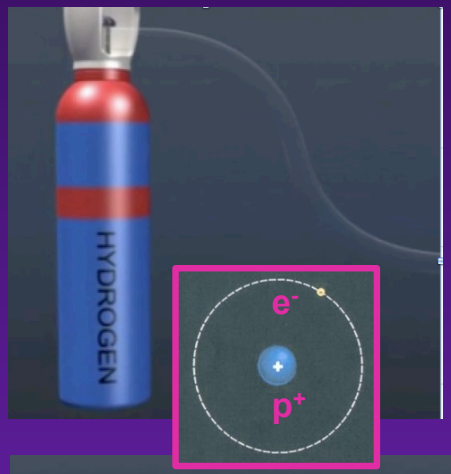
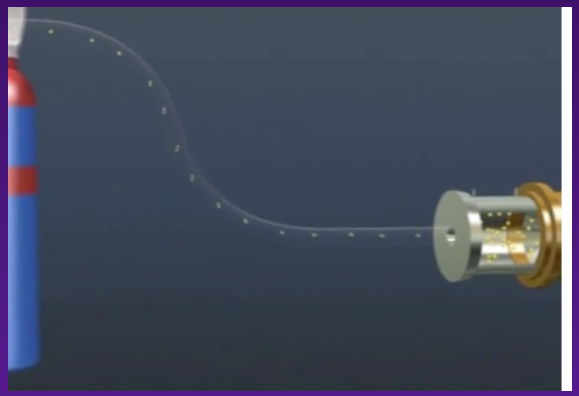


Acceleration by electric fields (voltage differences)

Bunch of p^+

Guidance and focalization by magnetic fields





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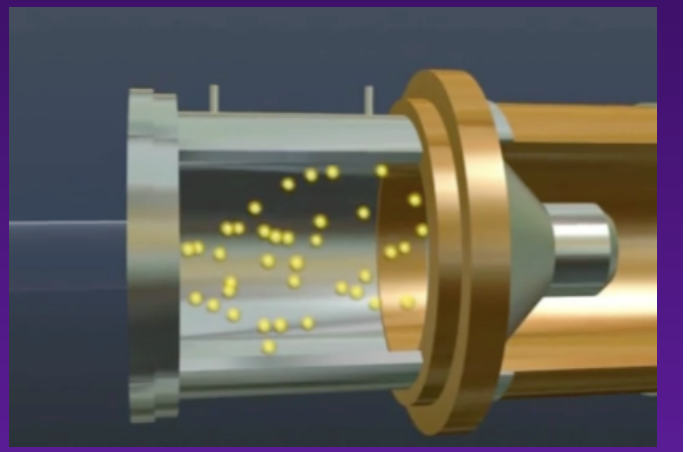

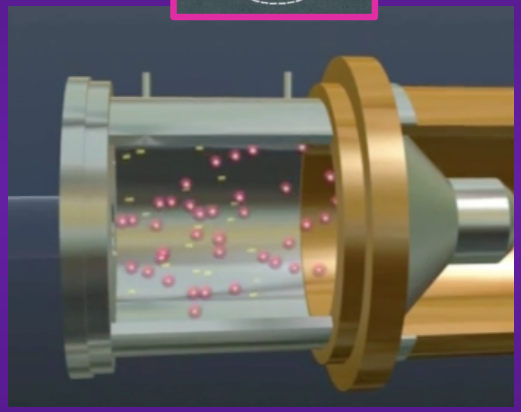

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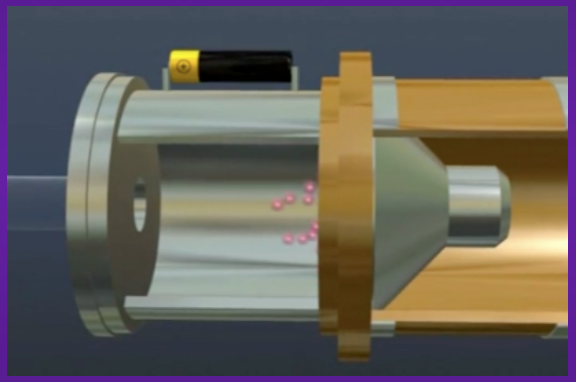

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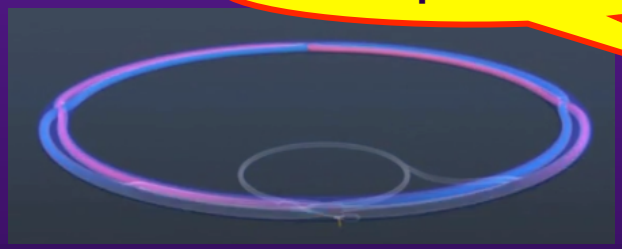
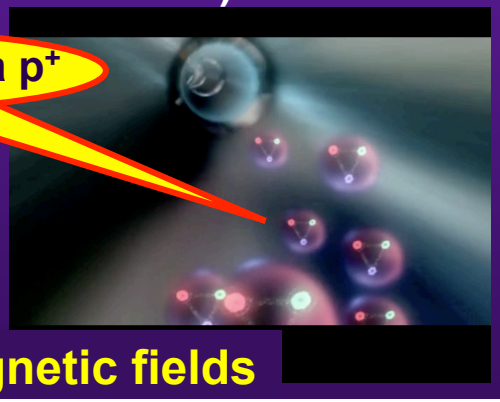
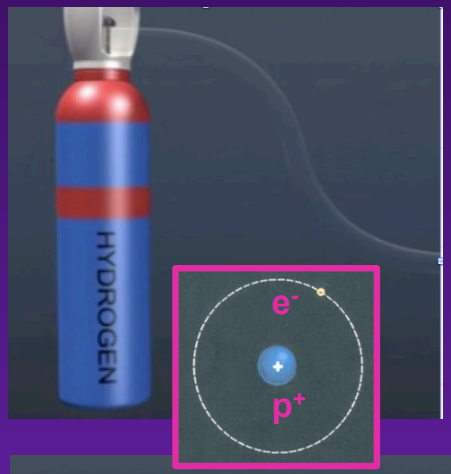
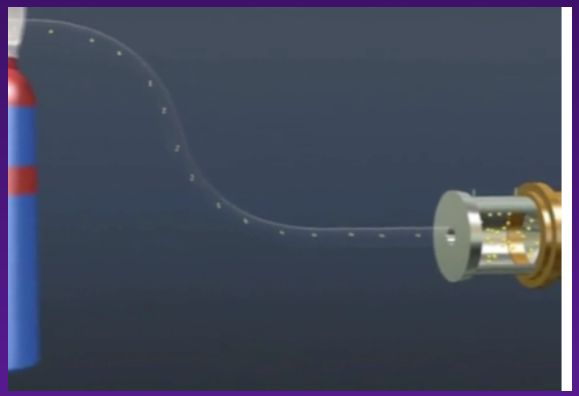


The 3 quarks of a p^+



Guidance and focalization by magnetic fields





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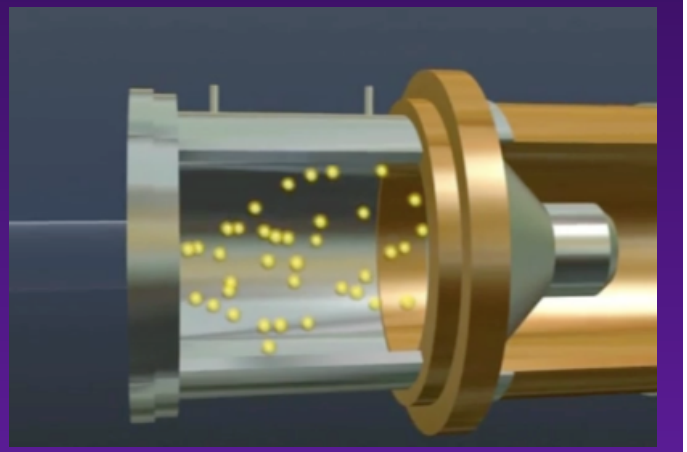

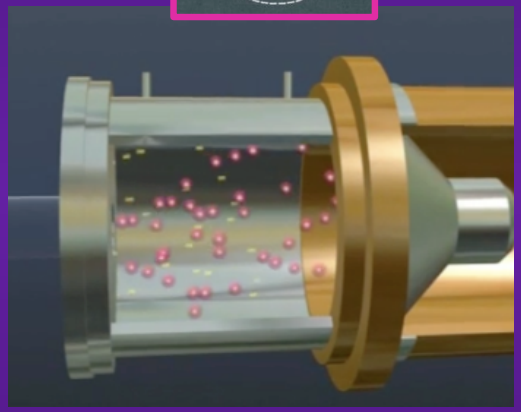

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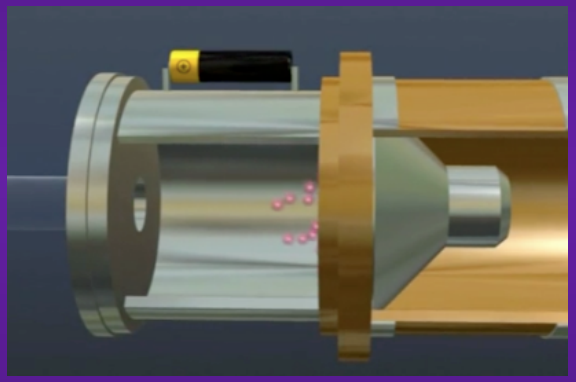

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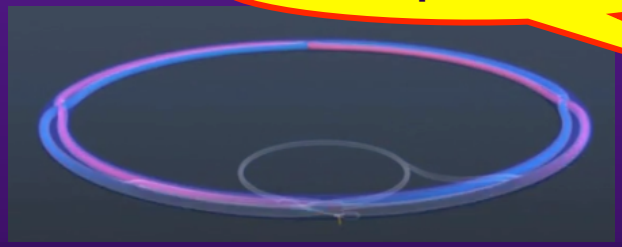

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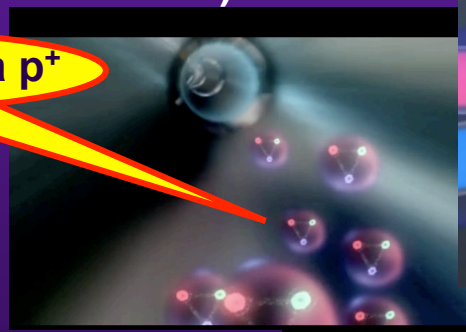
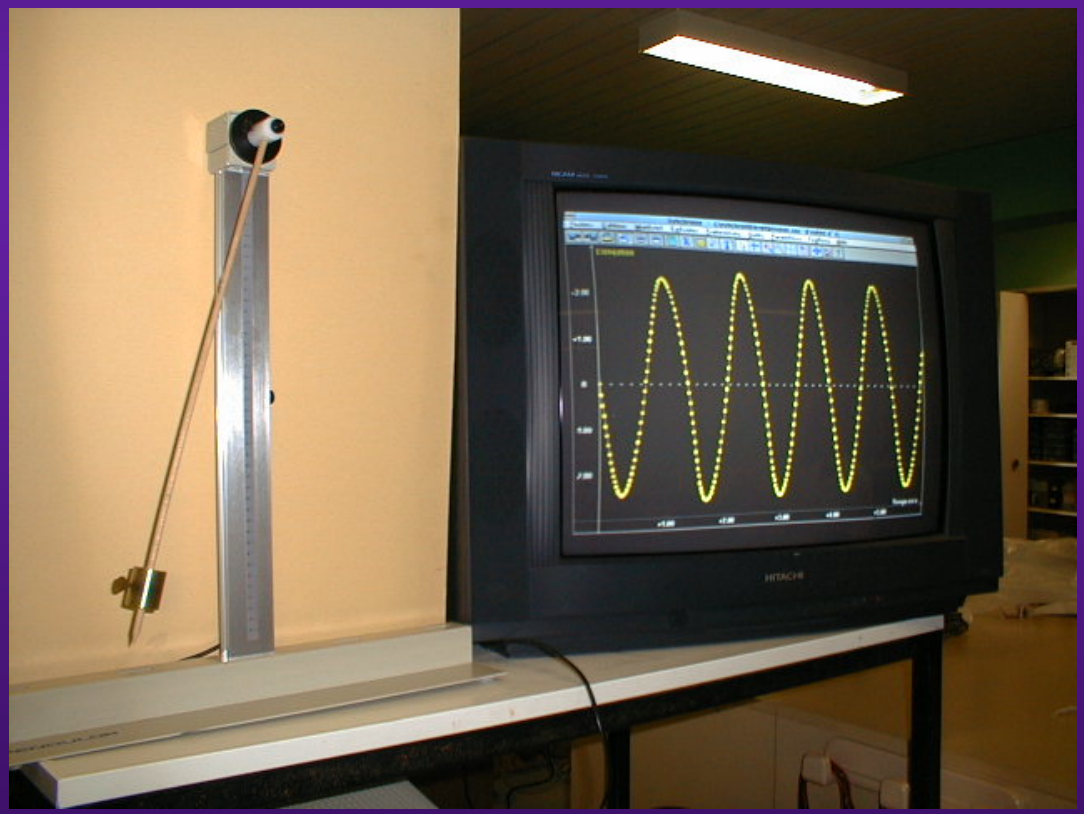
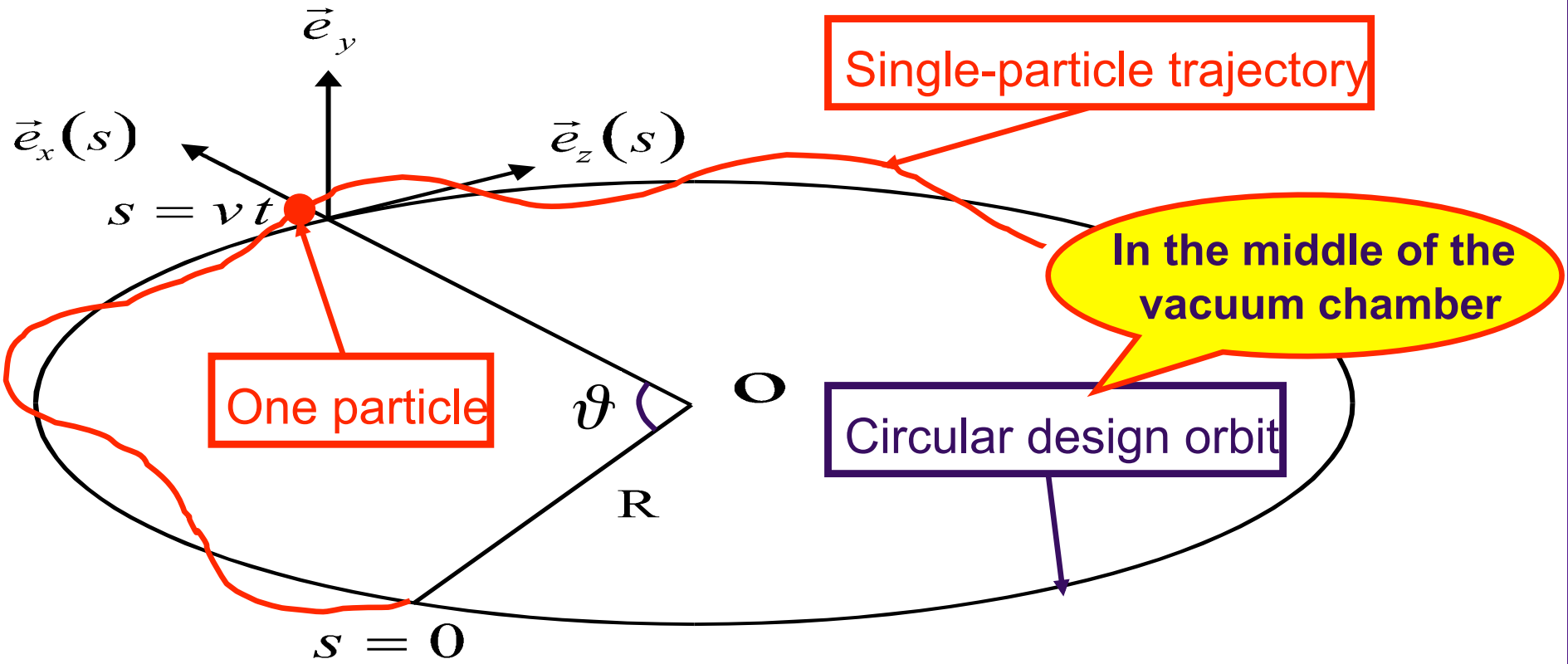


Guidance and focalization by magnetic fields

"collision" or "interaction"

- **The TRICK of particle accelerators**
  - **The best way to keep something (here particles) under control (i.e. stable) is to make it oscillate! And this is what we do…**
  - **All the motions are close to the motion of a harmonic oscillator**

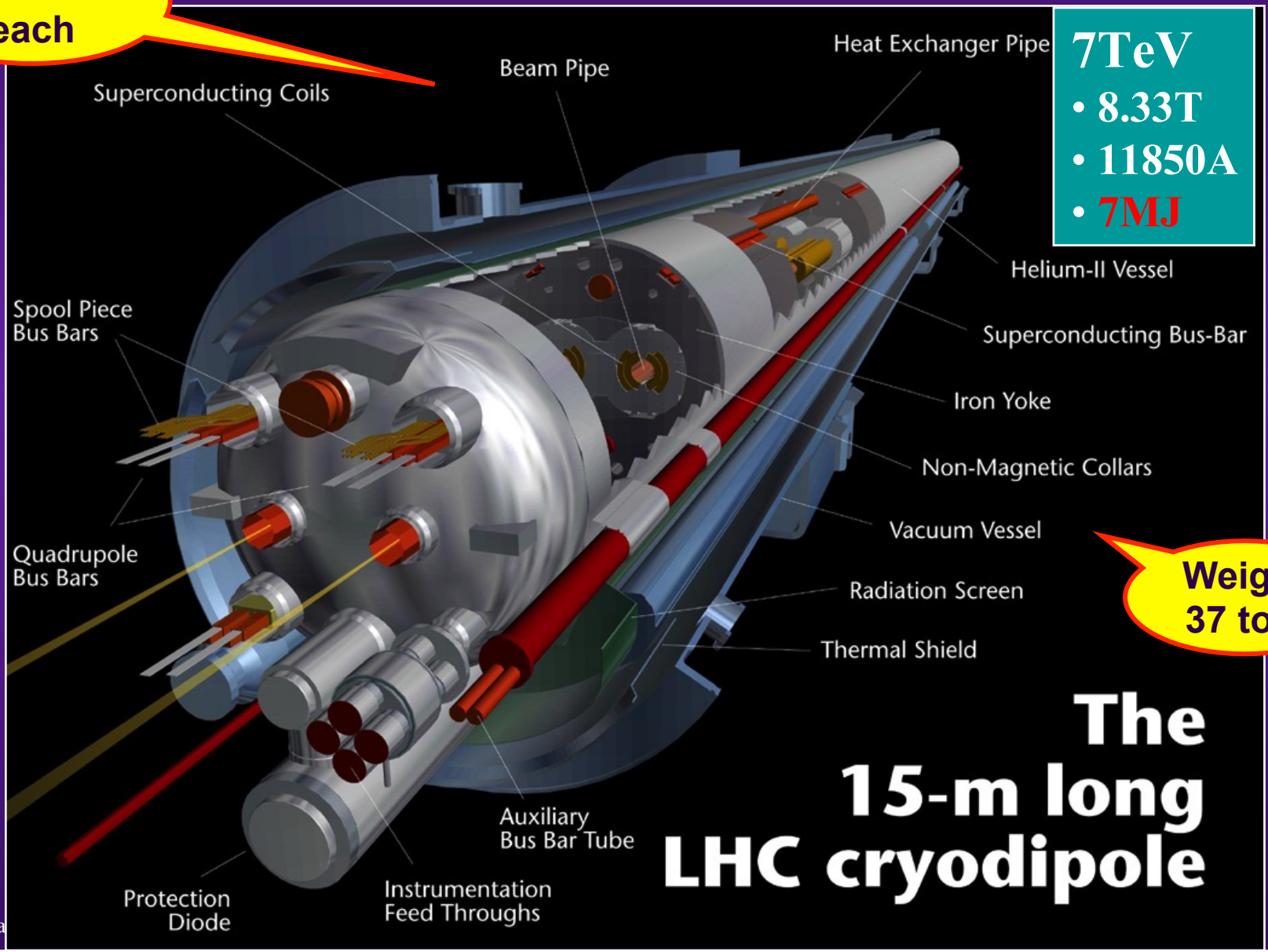


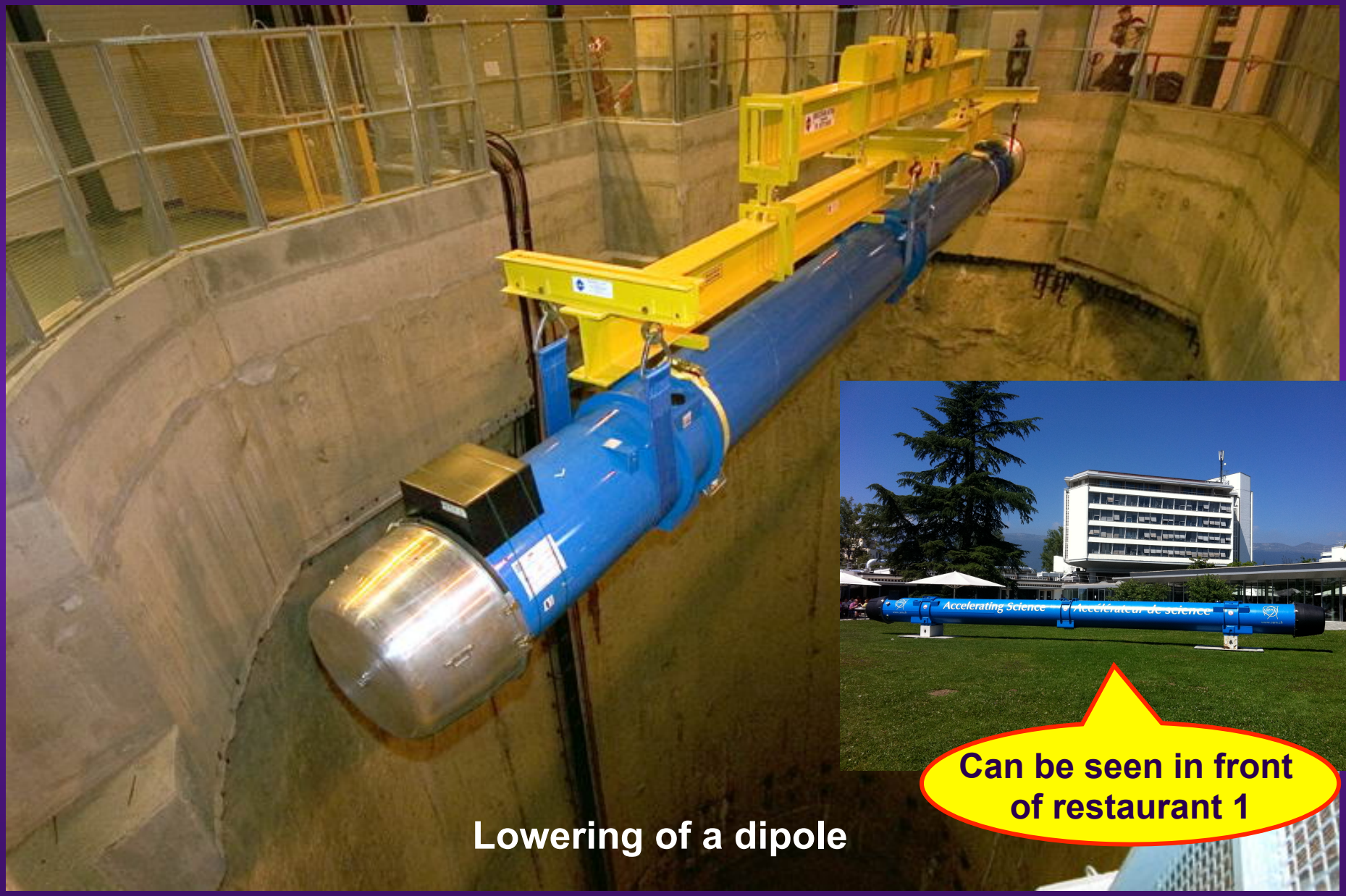

$\vec{e}_y$
$\vec{e}_x(s)$
$\vec{e}_z(s)$
$s = v\,t$
Single-particle trajectory
In the middle of the vacuum chamber
One particle
ϑ
O
R
Circular design orbit
$s = 0$

- **DIPOLES are used to guide the particles along the predefined ideal path, the design orbit, on which – ideally – all particles should move**

⇒ 1232 dipoles, occupying therefore ~ 70% of the LHC

~ 0.5 MCHF each





Can be seen in front of restaurant 1

Installation of the dipoles in the tunnel

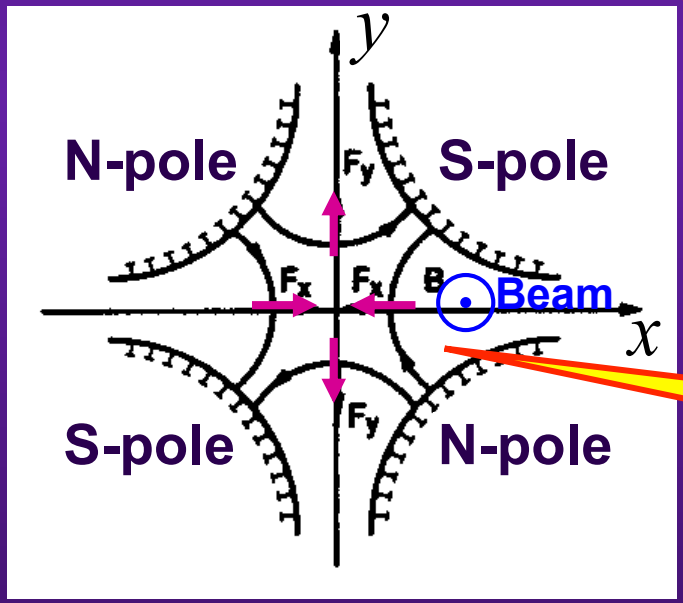
Superconducting interconnection between 2 magnets (2 dipoles here)

- **QUADRUPOLES are used to (focus) confine the particles in the vicinity of the ideal path, from which most particles will unavoidably deviate**

392 in total in the LHC

QUADRUPOLE = Focusing magnet

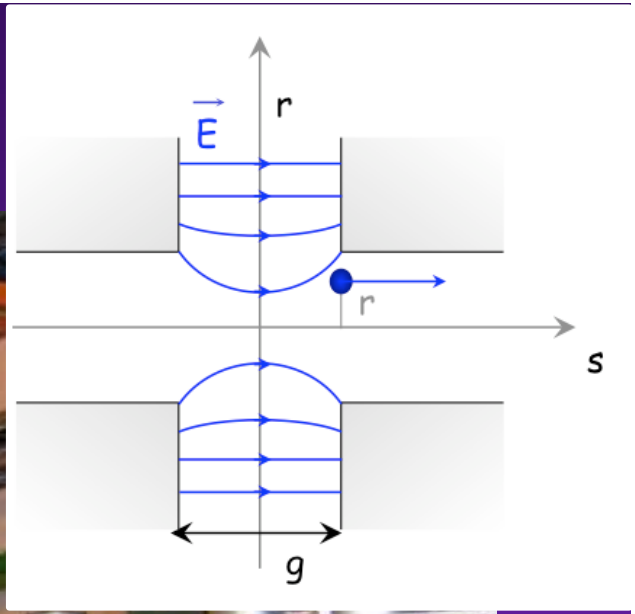
In x (and Defocusing in y) $\Rightarrow$ F-type. Permutating the N- and S- poles gives a D-type

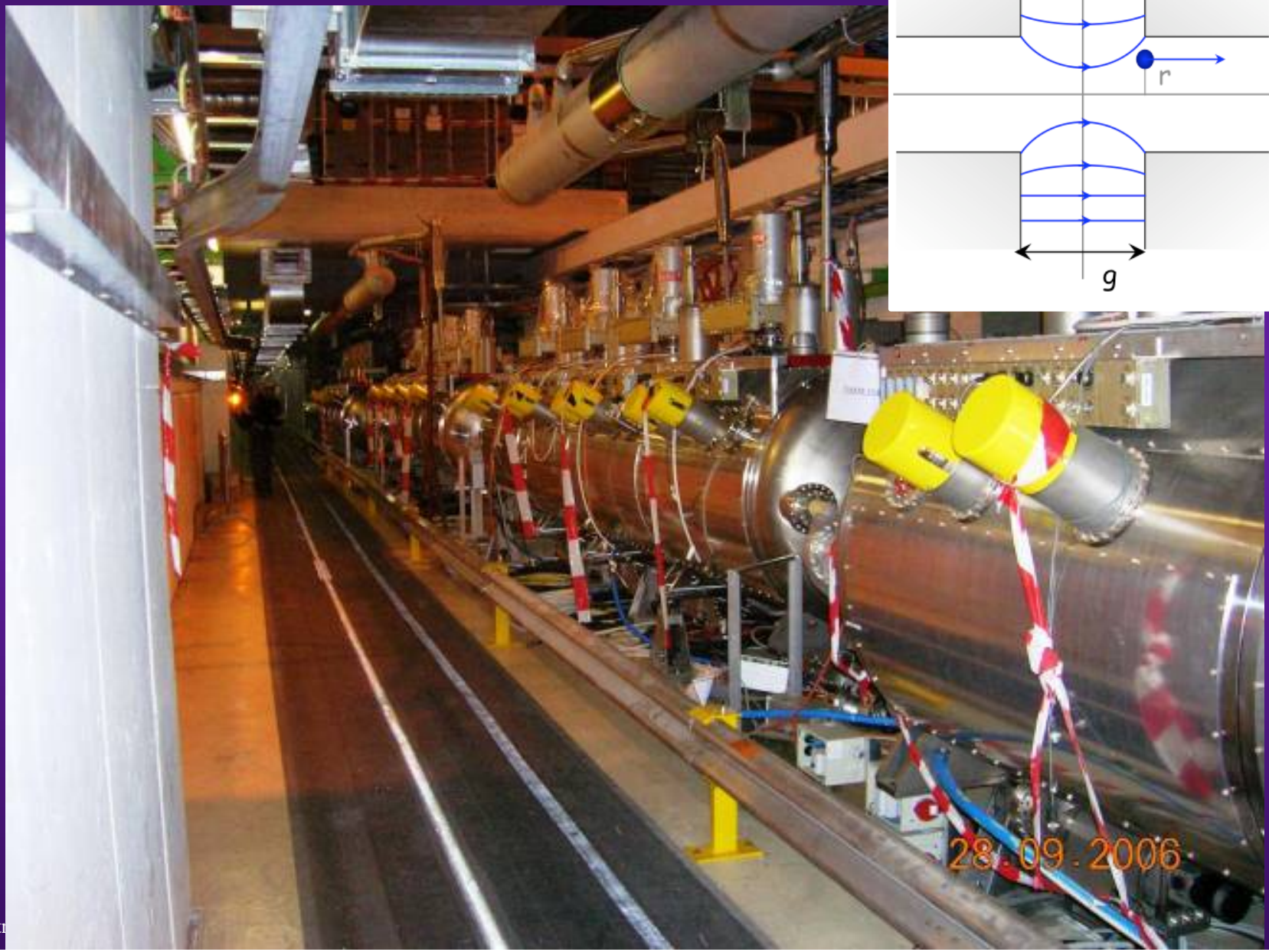


Linear force in x&y

… and SEXTUPOLES (6 poles), OCTUPOLES (8 poles), etc.

- **RF cavities => To “accelerate” the particles**





- **No particle can move with speeds faster than the speed of light in vacuum; however, there is no limit to the energy a particle can attain**

- **And in fact, the LHC should not be called a particle accelerator but a particle MASSIFICATOR as the velocity of the particles is almost not increasing (as it is at the maximum) => Only the mass is increasing**

$$v_{injection} \approx 0.999998\, c$$

$$v_{collision} \approx 0.999999991\, c$$

$$\Rightarrow \quad \frac{v_{collision}}{v_{injection}} \approx 1$$

=> The p^+ in the LHC travel at the speed of light

$$m = \gamma\, m_0 \quad \Rightarrow \quad \frac{m_{collision}}{m_{injection}} \approx 15.6$$

Main figure of merit of a collider

=> Luminosity

=> Luminosity

$$L = \frac{N_{events/\sec ond}}{\sigma_r}$$

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Number of events per second generated in the collisions

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Cross-section of the reaction

=> Luminosity

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Number of events per second generated in the collisions

Cross-section of the reaction

$$L \propto \frac{M\, N_b^2\, f_{rev}}{\sigma_x\, \sigma_y}$$

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Cross-section of the reaction

Number of bunches (= group of particles) per beam

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Revolution frequency

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Number of events per second generated in the collisions

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Number of bunches (= group of particles) per beam

Number of particles per bunch

Revolution frequency

Horizontal beam size of the bunches

=> Luminosity

$$L = \frac{N_{events/\mathrm{sec}\,ond}}{\sigma_r}$$

Number of events per second generated in the collisions

Cross-section of the reaction

$$L \propto \frac{M\, N_b^2\, f_{rev}}{\sigma_x\, \sigma_y}$$

Number of bunches (= group of particles) per beam

Number of particles per bunch

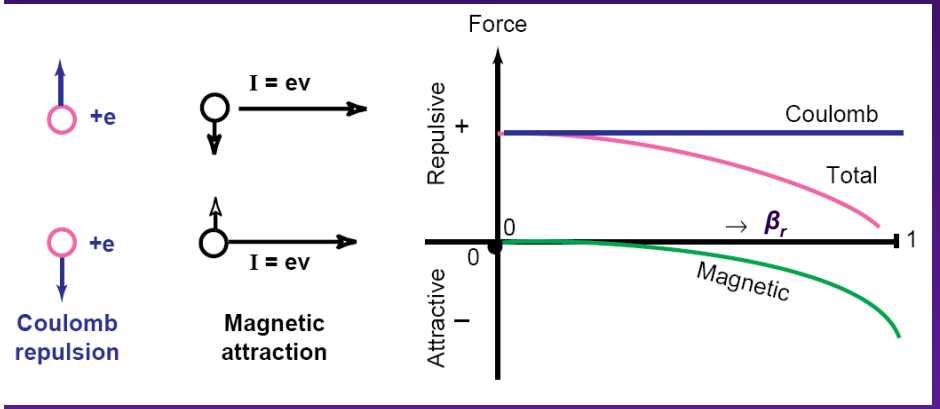
Revolution frequency

Horizontal beam size of the bunches

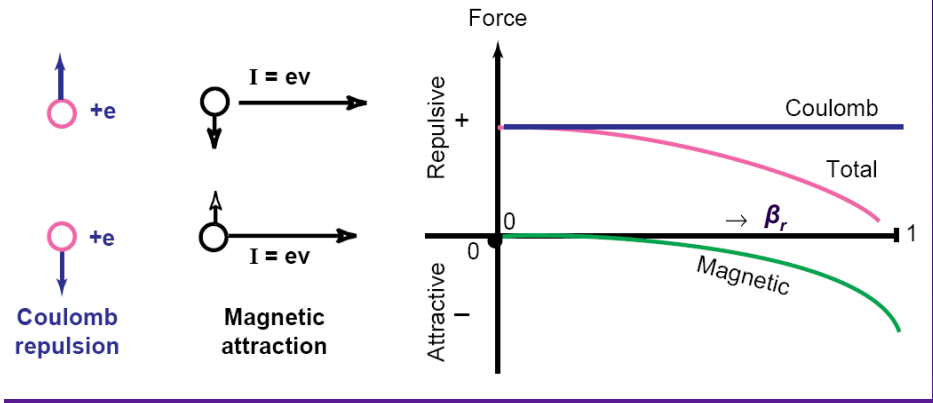
Vertical beam size of the bunches

Challenges

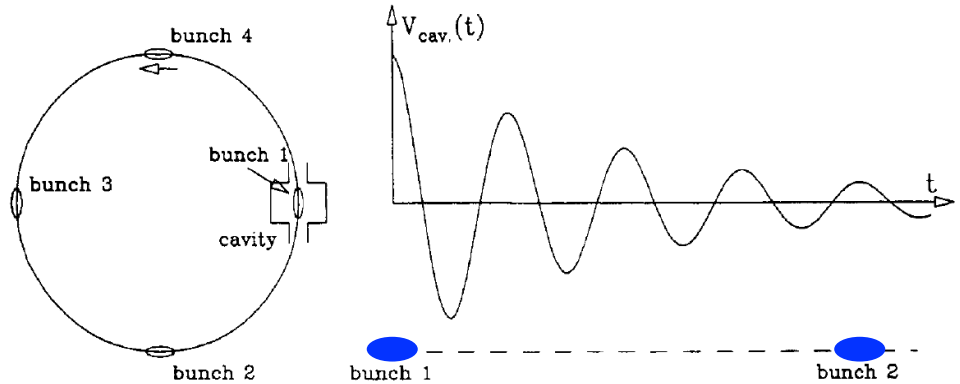
SPACE CHARGE



SPACE CHARGE



WAKE FIELD



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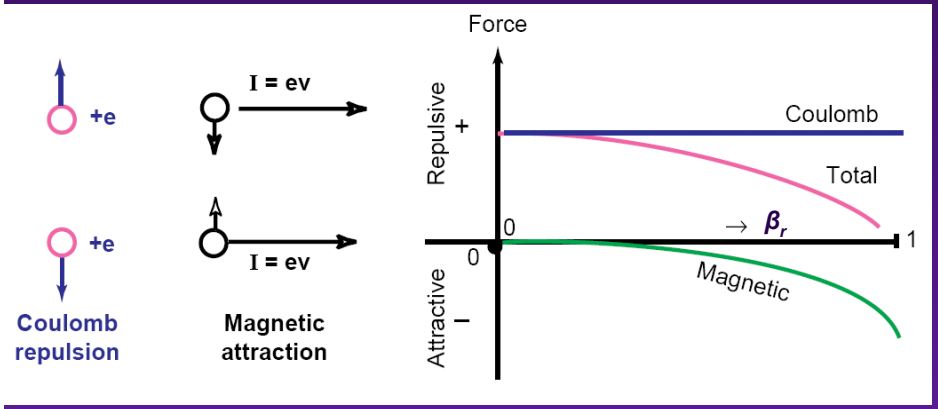

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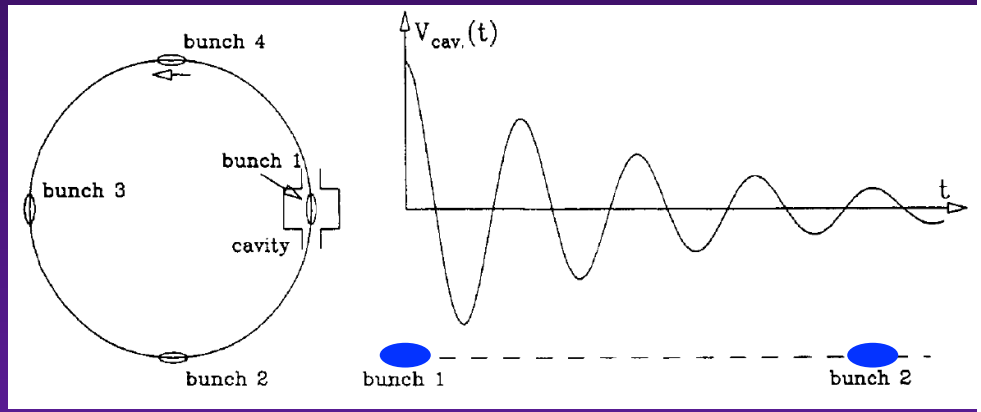
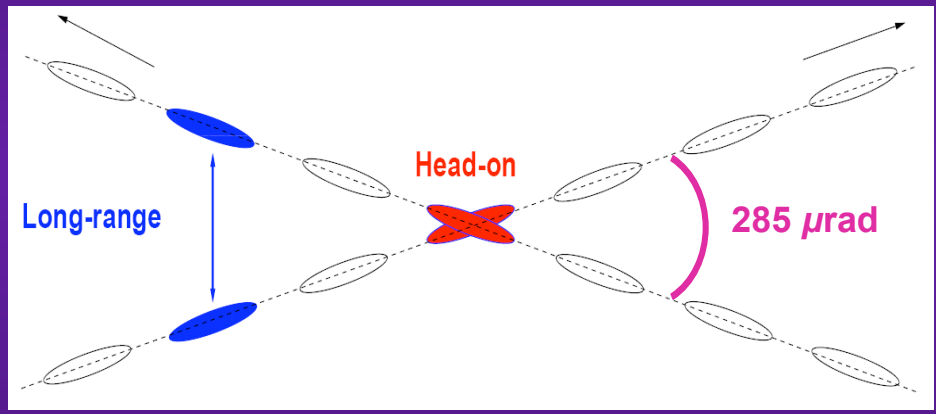


BEAM-BEAM



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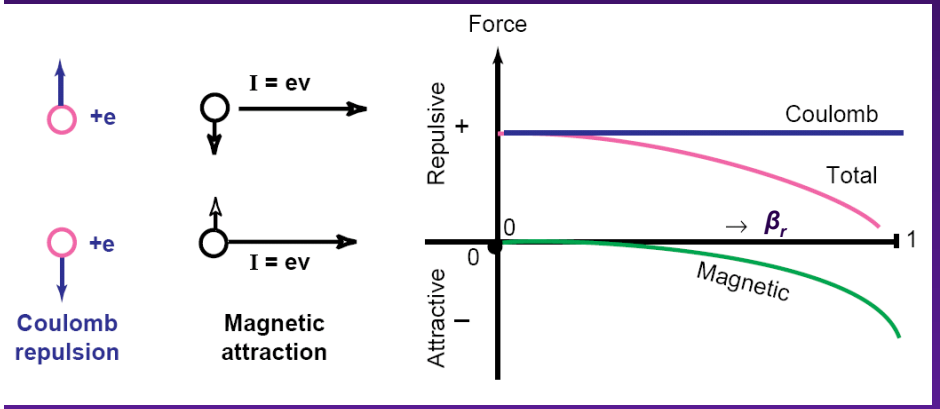

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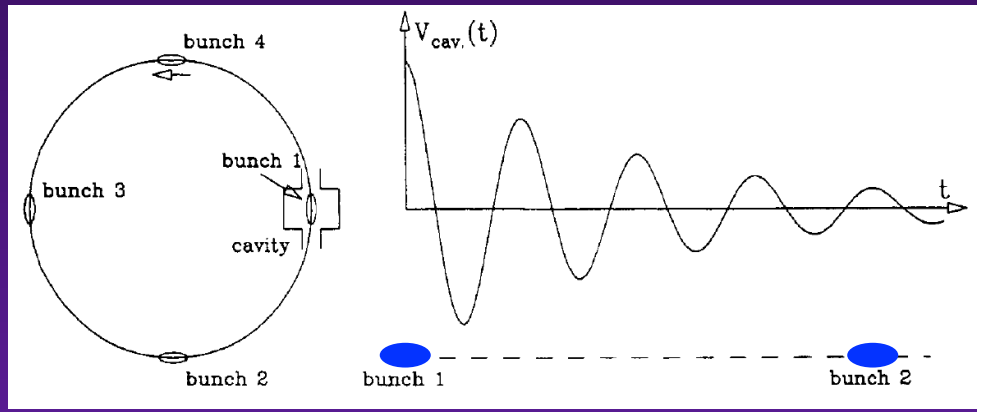
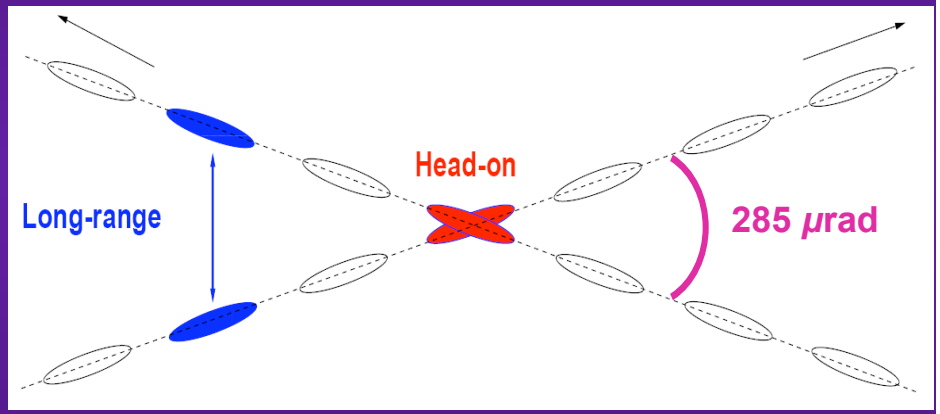
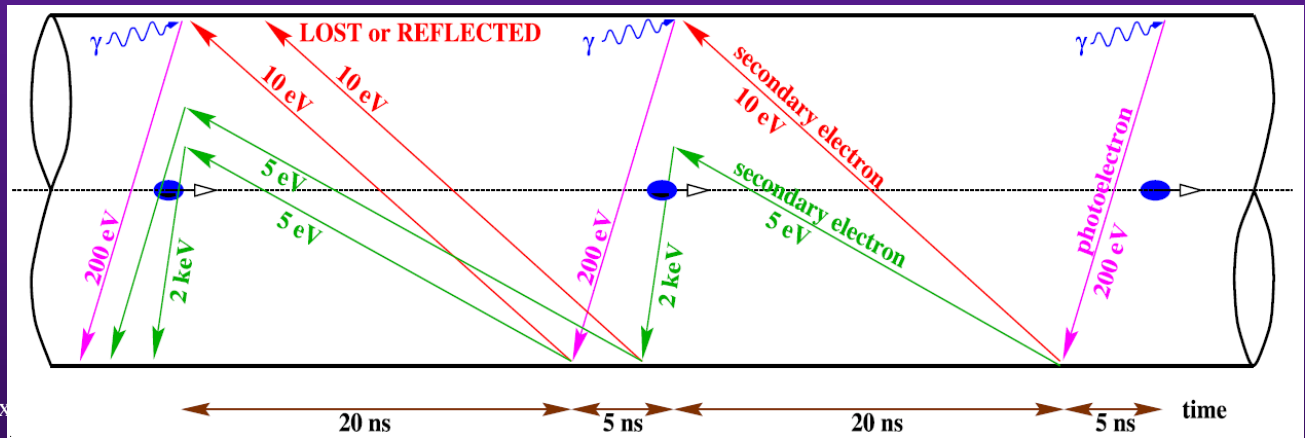


BEAM-BEAM



ELECTRON CLOUD



Future

- **Reach the design luminosity => We are not there yet as we reached for the moment only 77%...**

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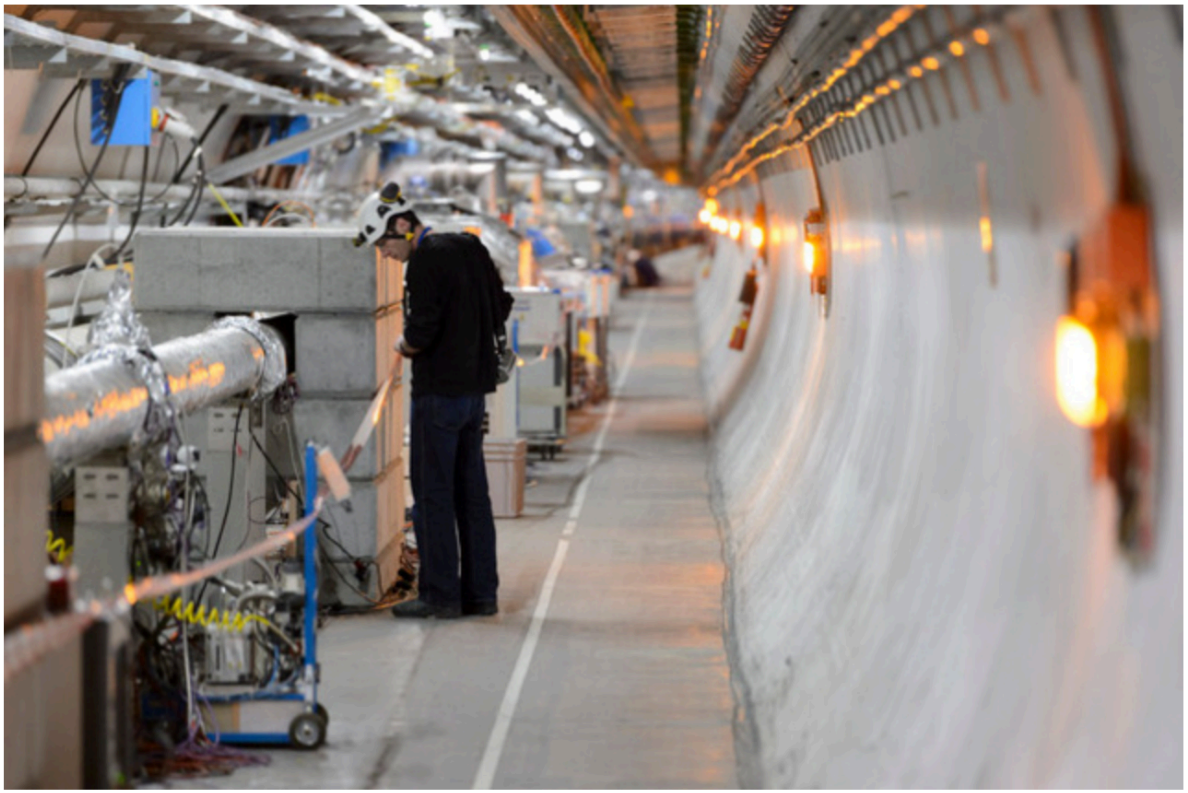
Le LHC du CERN bloqué par une fouine

Genève Une fouine déterminée a perturbé le fonctionnement du plus grand et plus puissant accélérateur de particules du monde.



(Photo d'illustration) Le LHC du CERN s'apprêtait à redémarrer pour une série d'expériences. Il faudra patienter quelques jours afin de réparer les dommages créés par la fouine.

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Le LHC du CERN bloqué par une fouine

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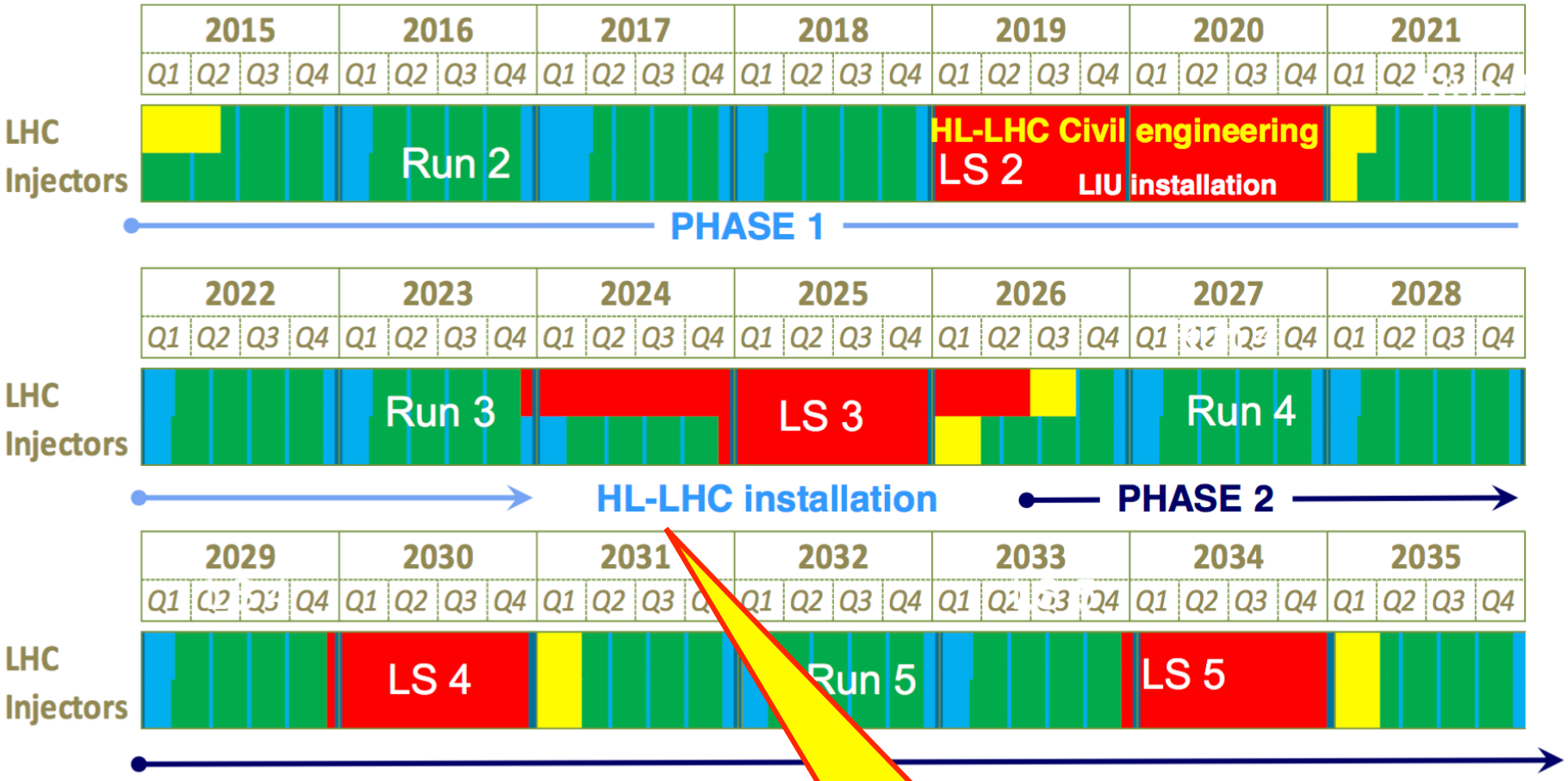
Ce n'est pas la première fois qu'un animal se place entre l'Homme et les secrets de l'Univers: «Nous sommes dans la campagne, et bien entendu il y a des animaux sauvages partout», rappelle le porte parole à NPR. En 2009, un oiseau avait fait tomber un morceau de pain sur des câbles électriques du LHC. Trois ans plus tôt, des ratons laveurs s'étaient quant à eux acharnés sur un accélérateur de particules dans l'Illinois, aux Etats-Unis.

(Photo d'illustration) Le LHC du CERN s'apprêtait à redémarrer pour une série d'expériences. Il faudra patienter quelques jours afin de réparer les dommages créés par la fouine.

LHC roadmap: according to MTP 2016-2020

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



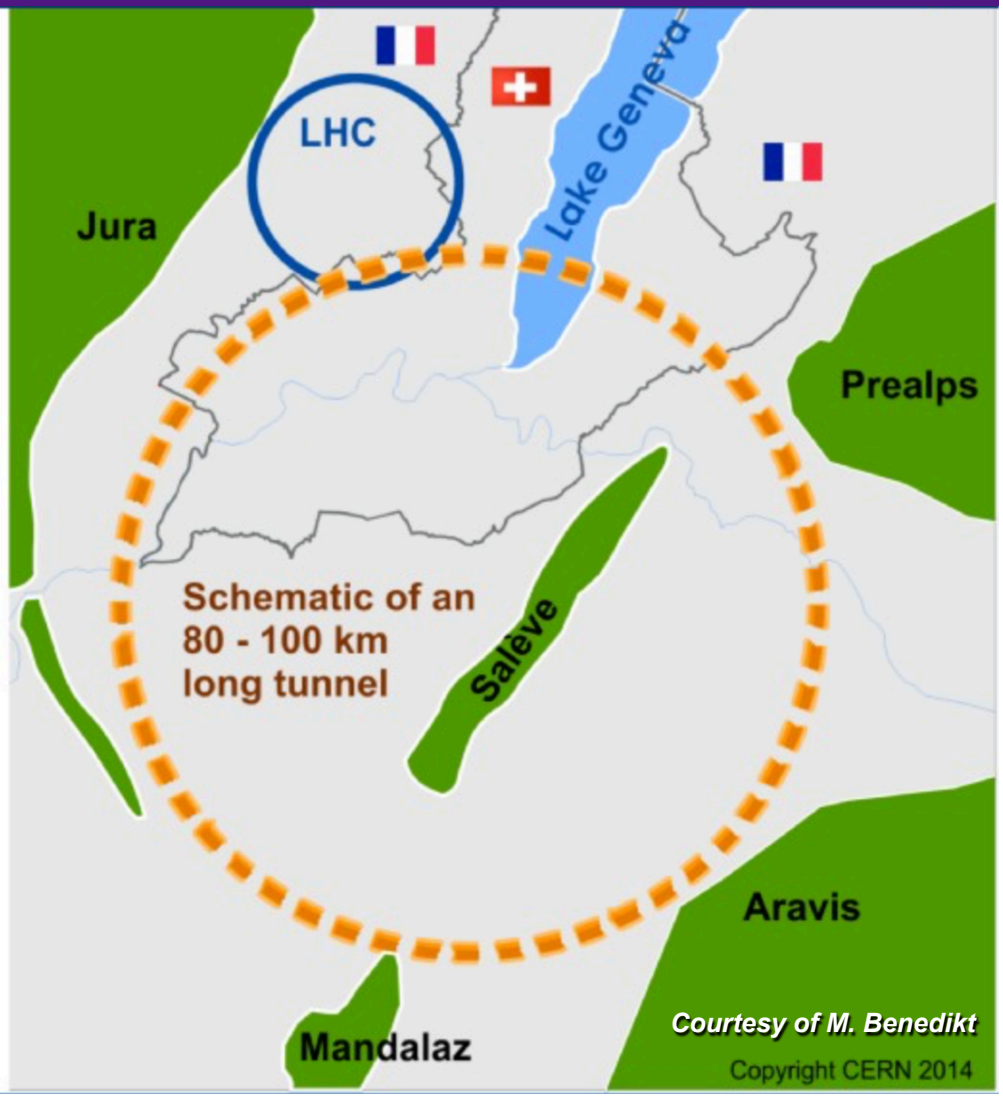
Future Circular Collider

International FCC collaboration (CERN as host lab) to study:

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

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area
- ***e*⁺*e*⁻ collider (*FCC-ee*)** as potential first step
- ***p-e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology



Thank you for your attention!