Accelerators and Society

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Special thanks to Prof. F. Gianotti, Dr. B. Holzer, Dr. G. Iadarola

Outline

- How do accelerators work
- CERN: Large Hadron Collider
- Health, medicine and other accelerator applications

How do accelerators work

Accelerator: a device that increases the kinetic energy of the particles using electromagnetic fields $\vec{F}=q(\vec{E}+\vec{v}\times\vec{B})$ $\vec{F}=m\vec{a}$

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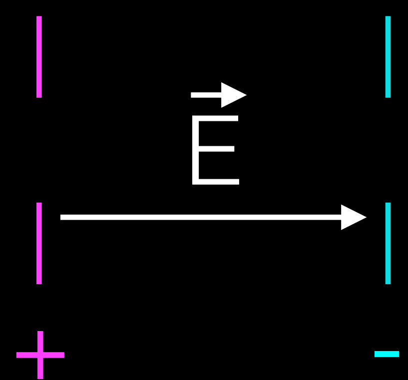

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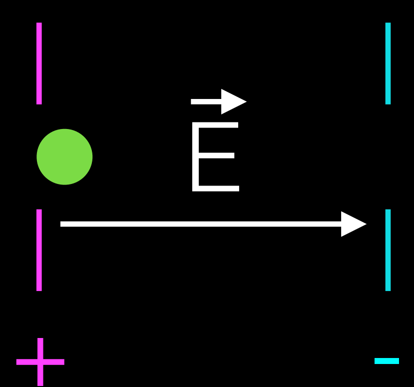

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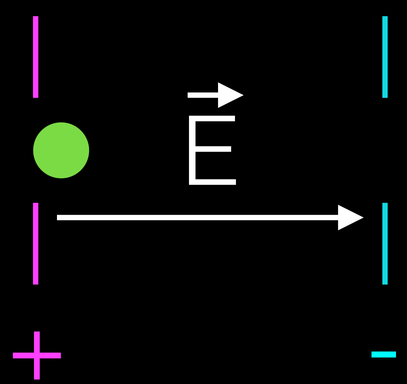

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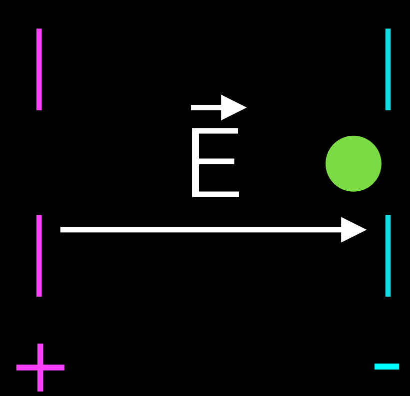

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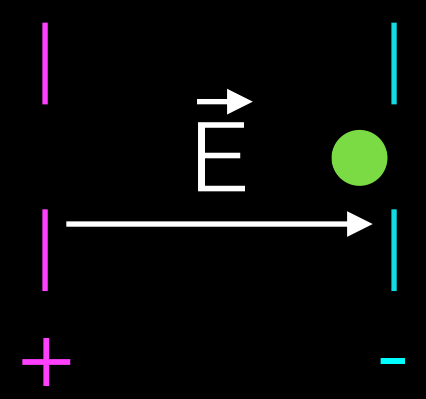

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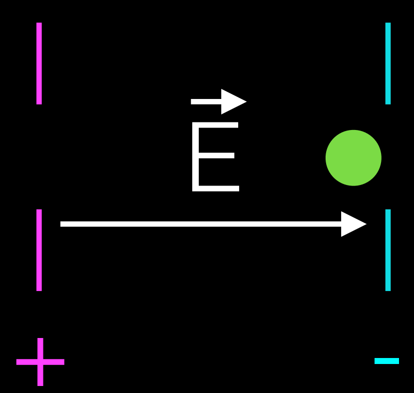

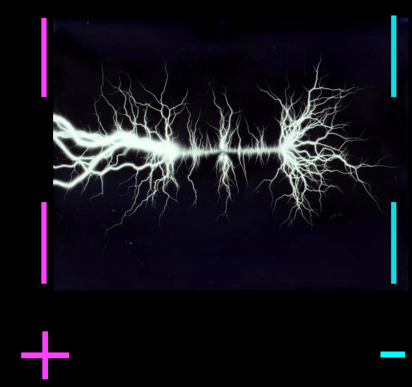

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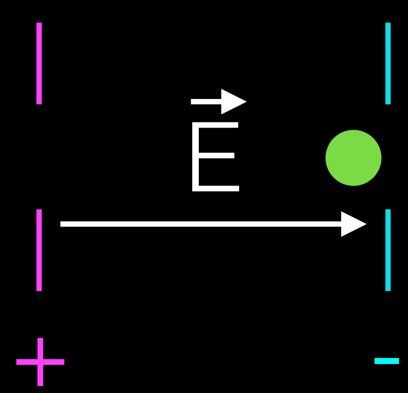

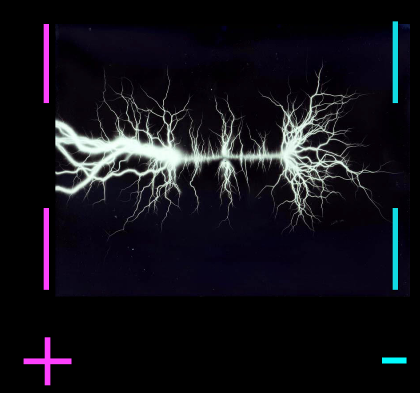

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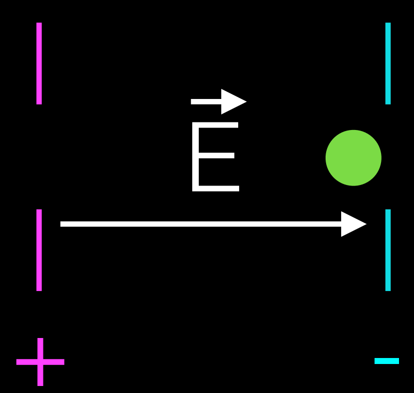

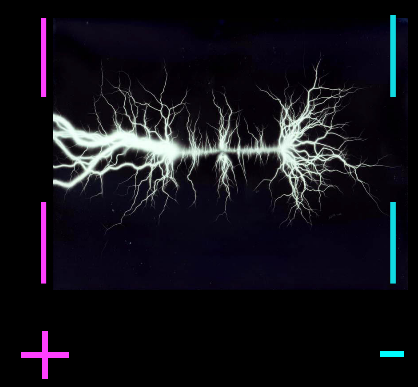

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Limitation of maximum achievable energy to a few MeV (Cockroft-Walton, Van de Graaff, etc)

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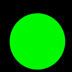

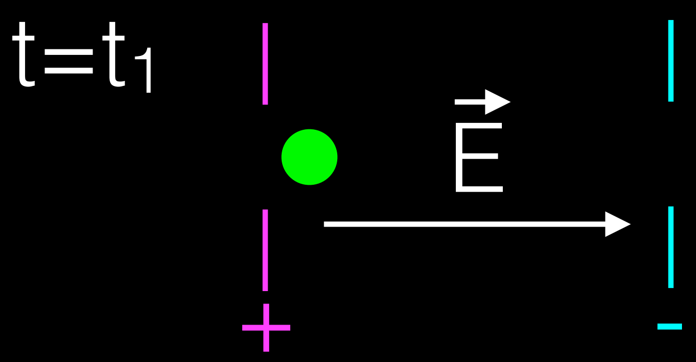

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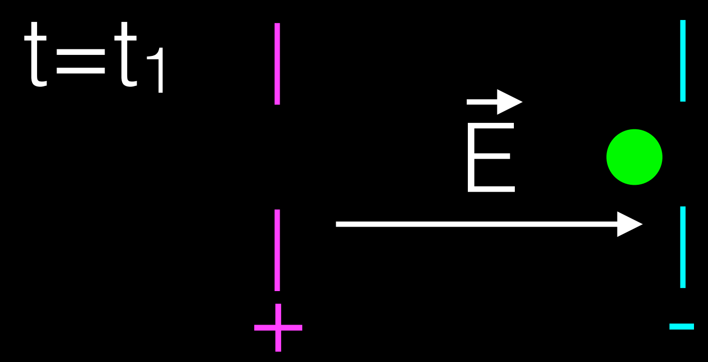

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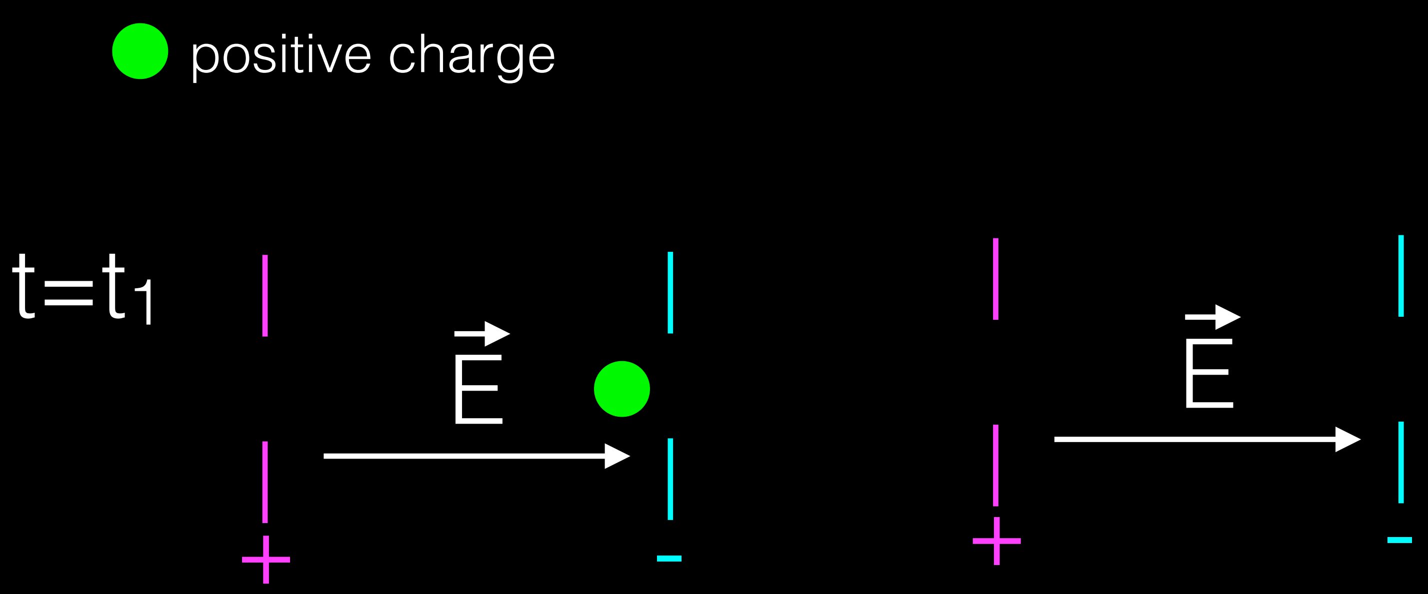

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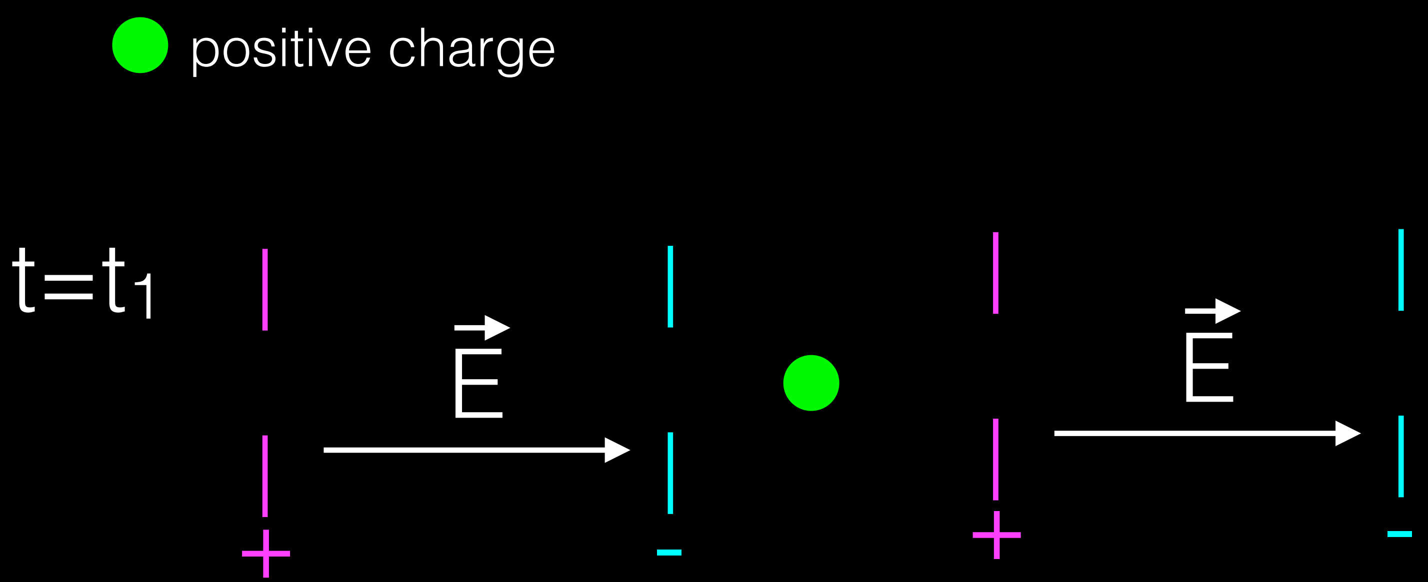

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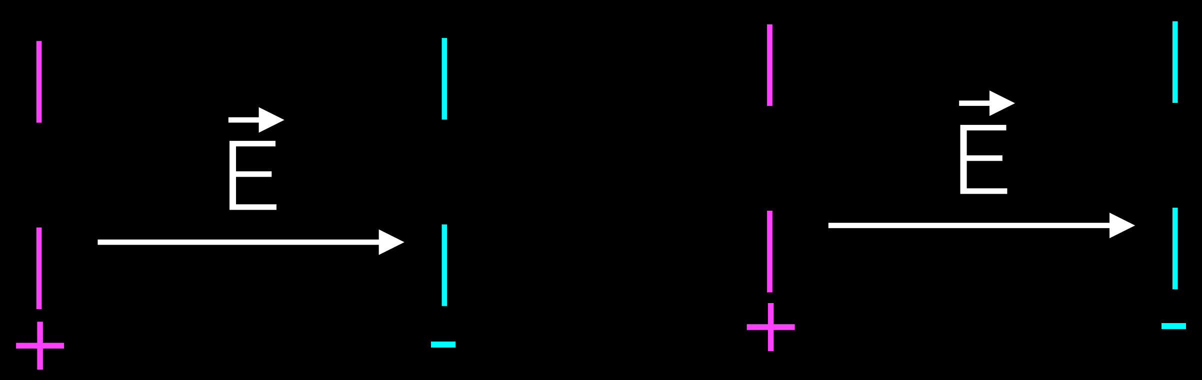

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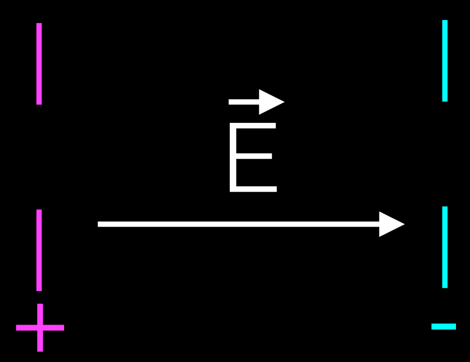

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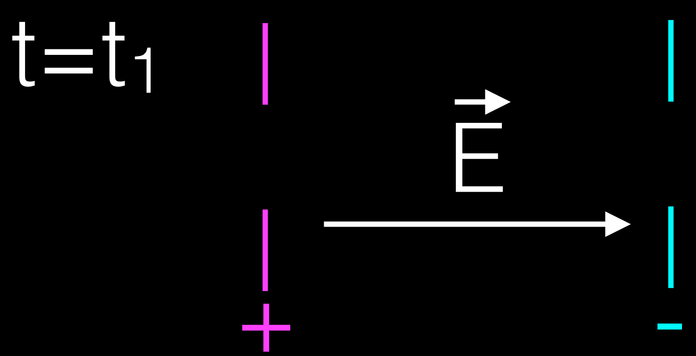

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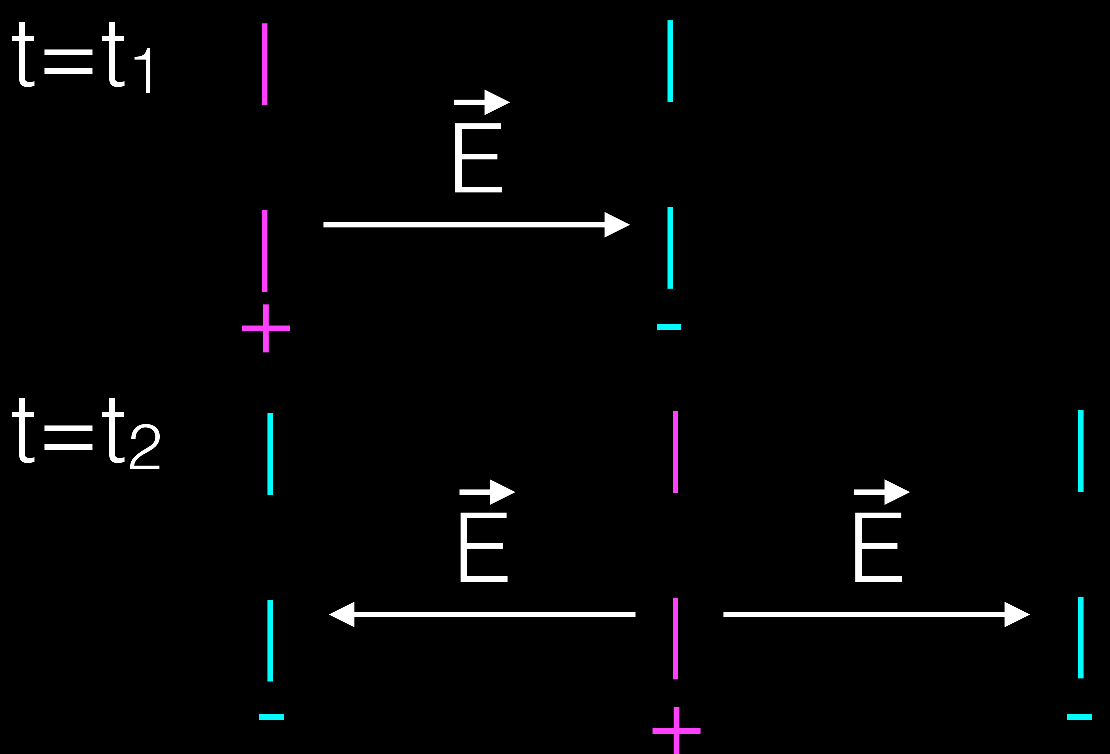

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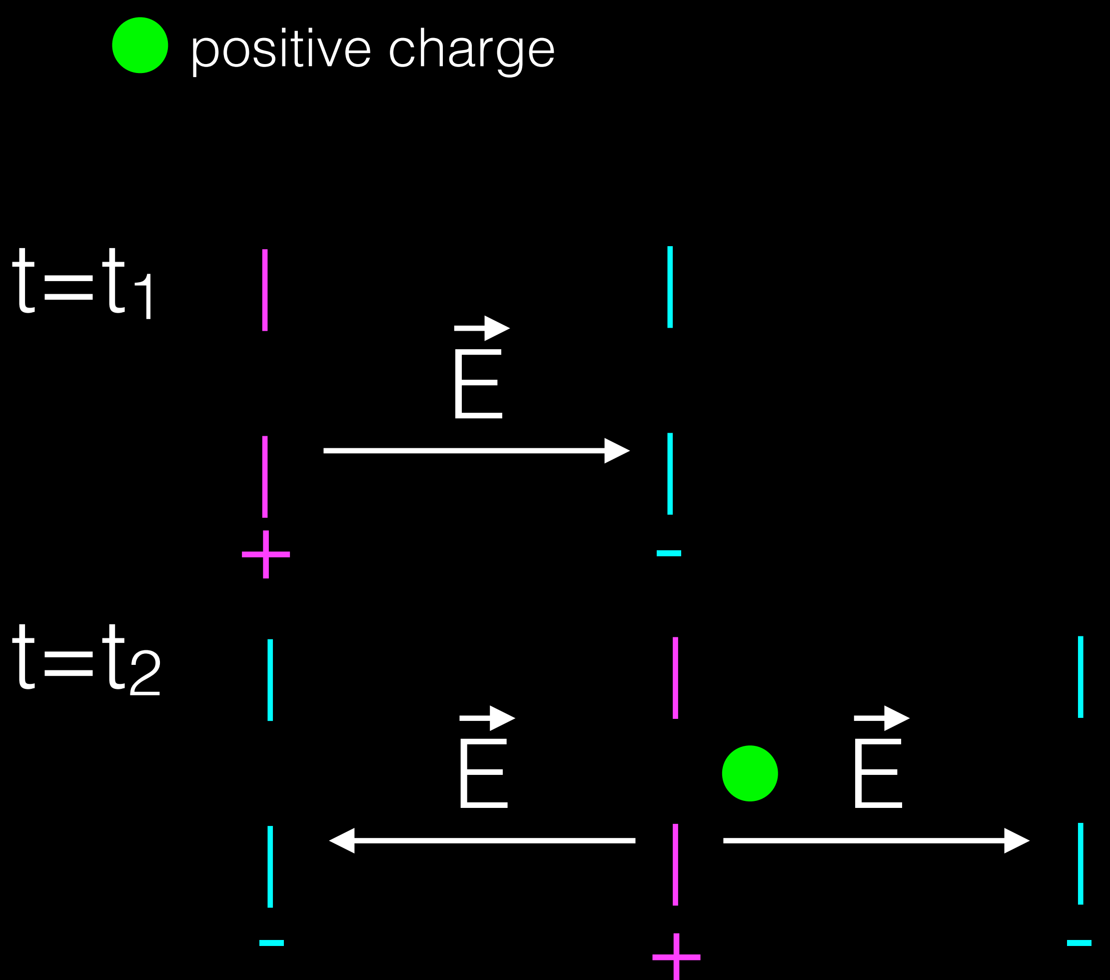

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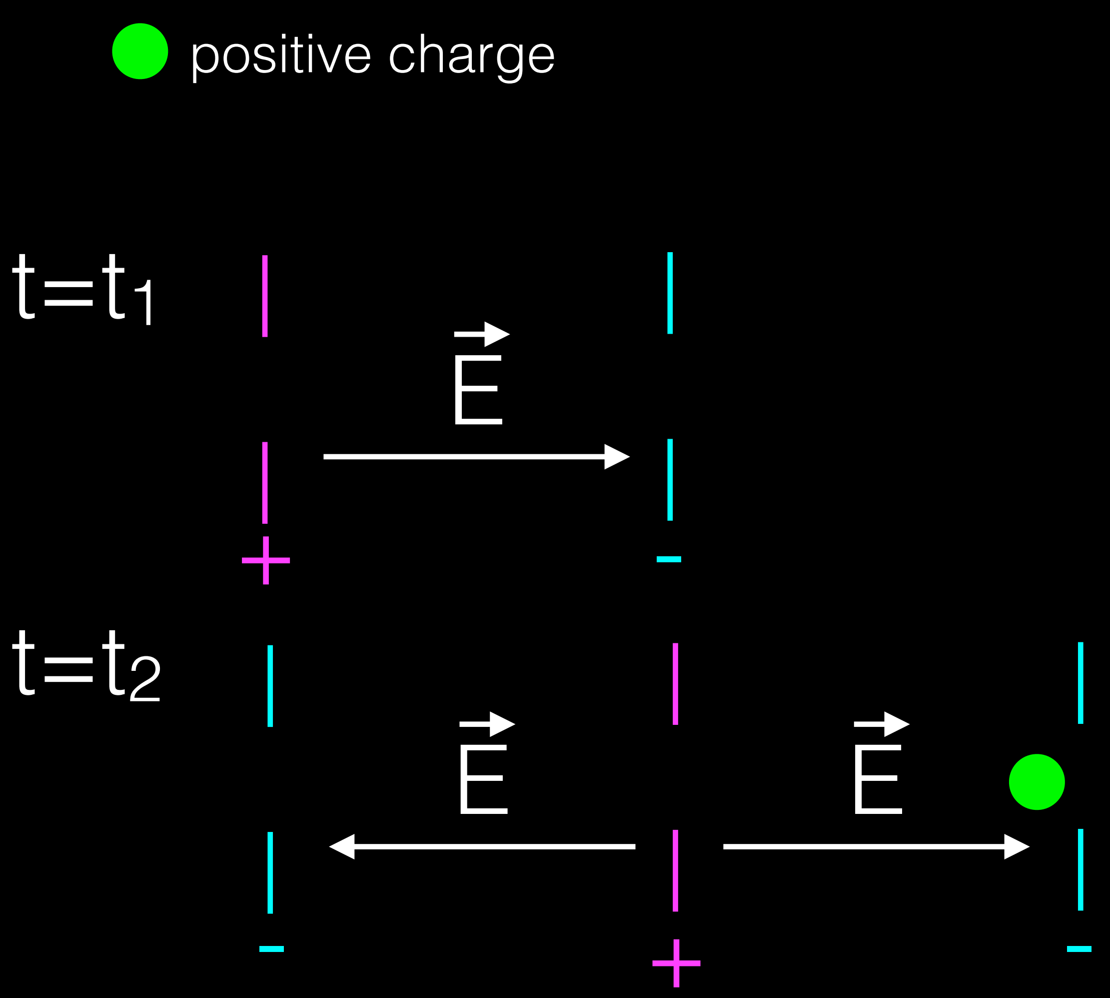

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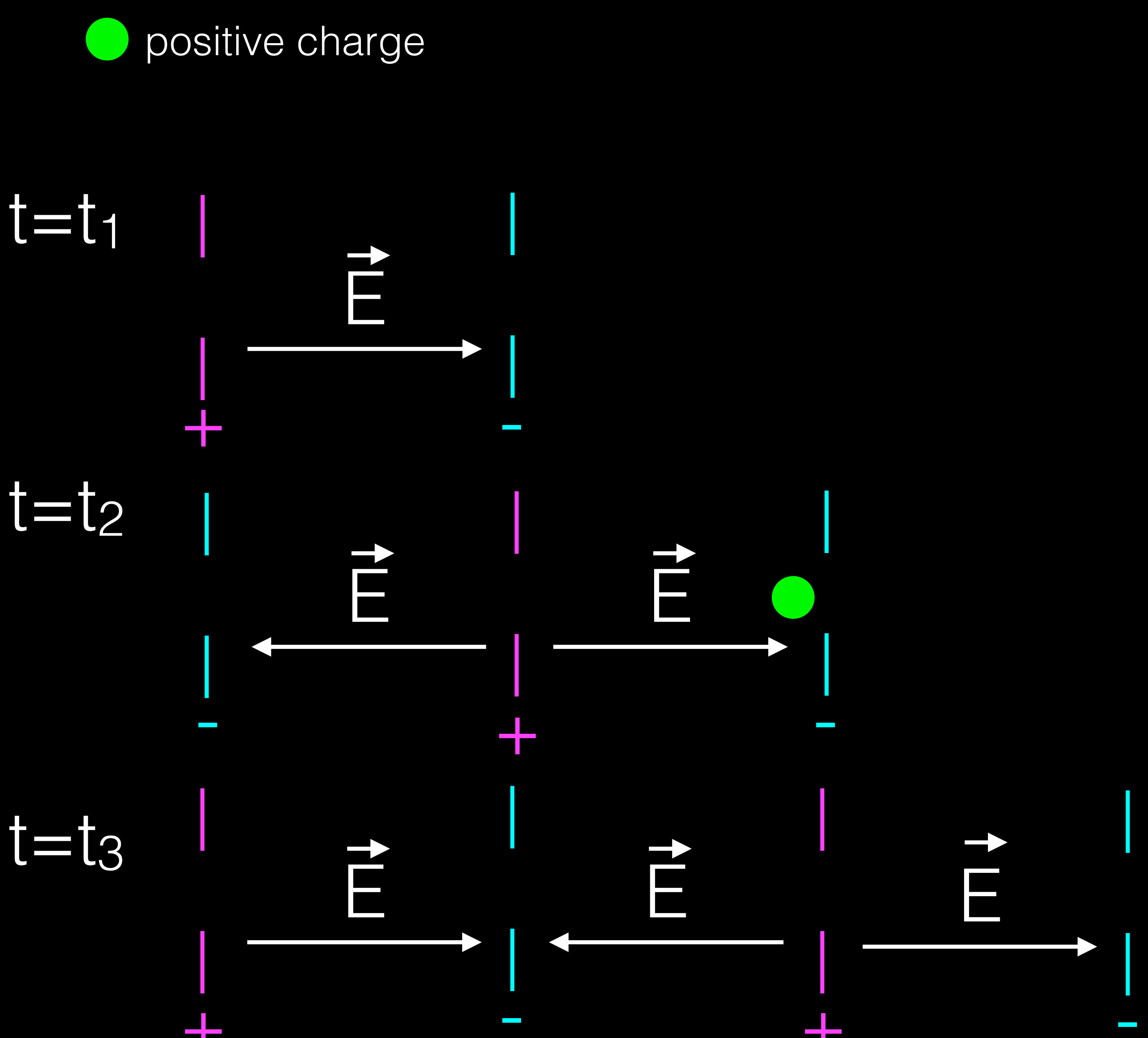

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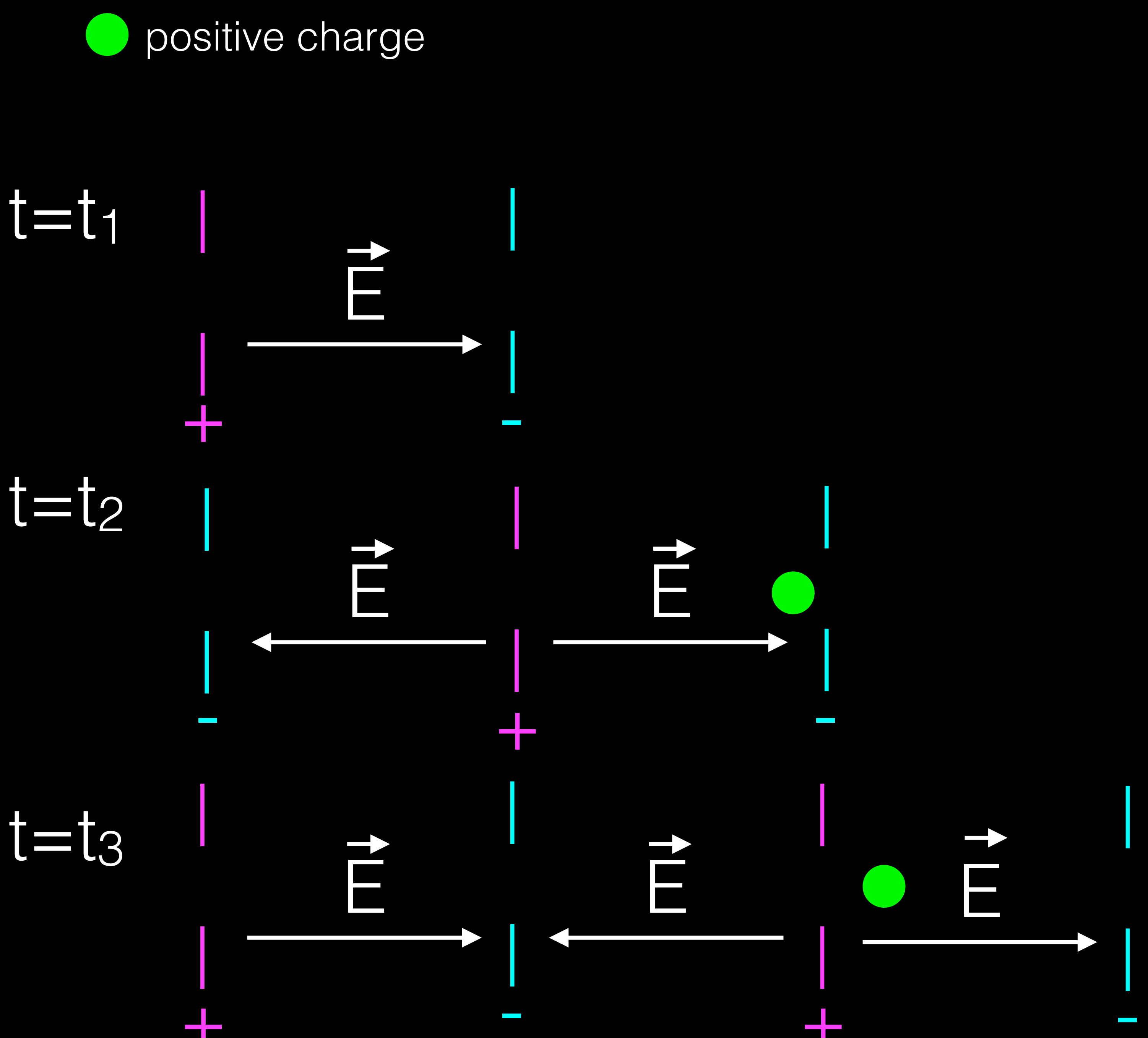

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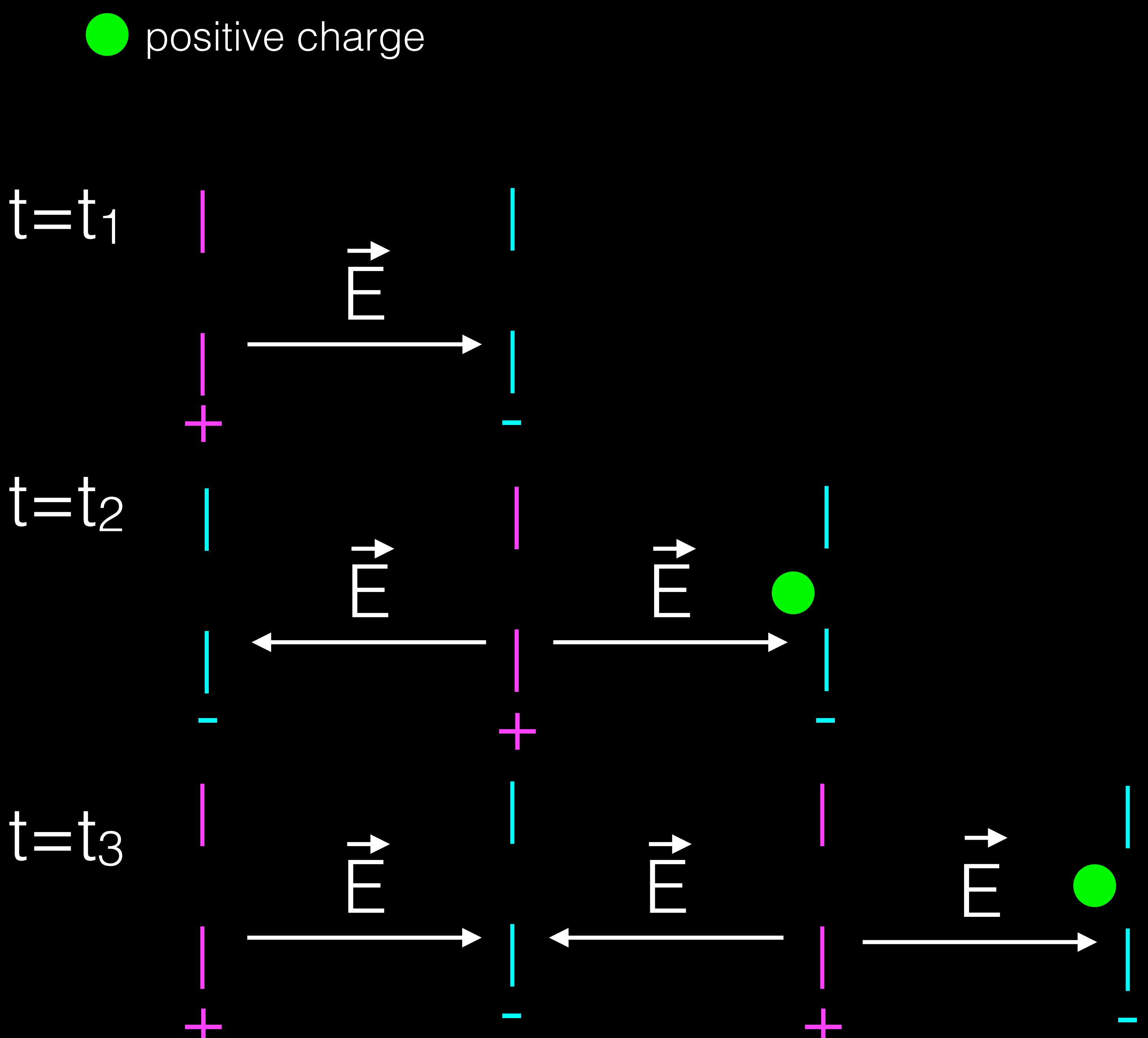

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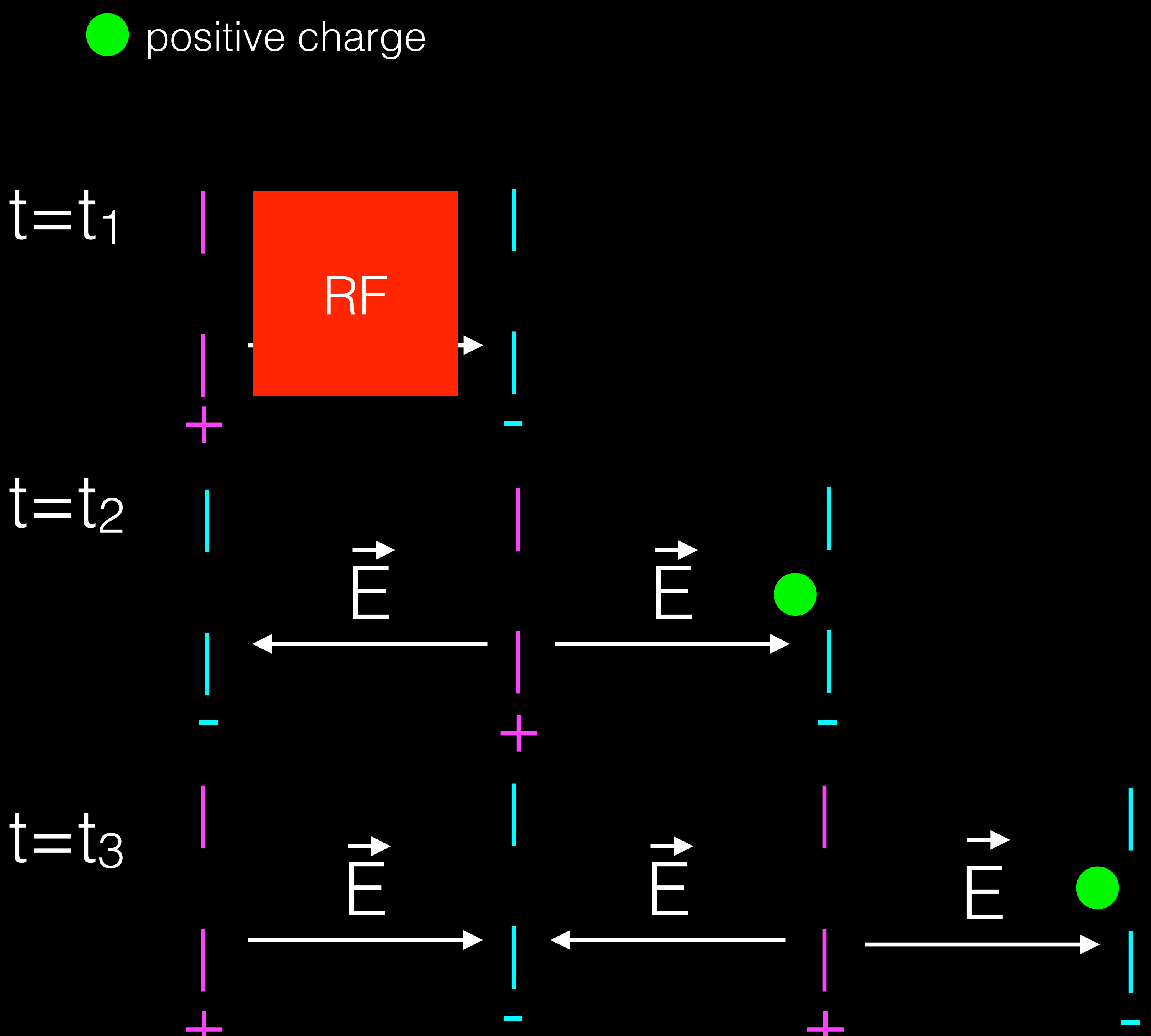

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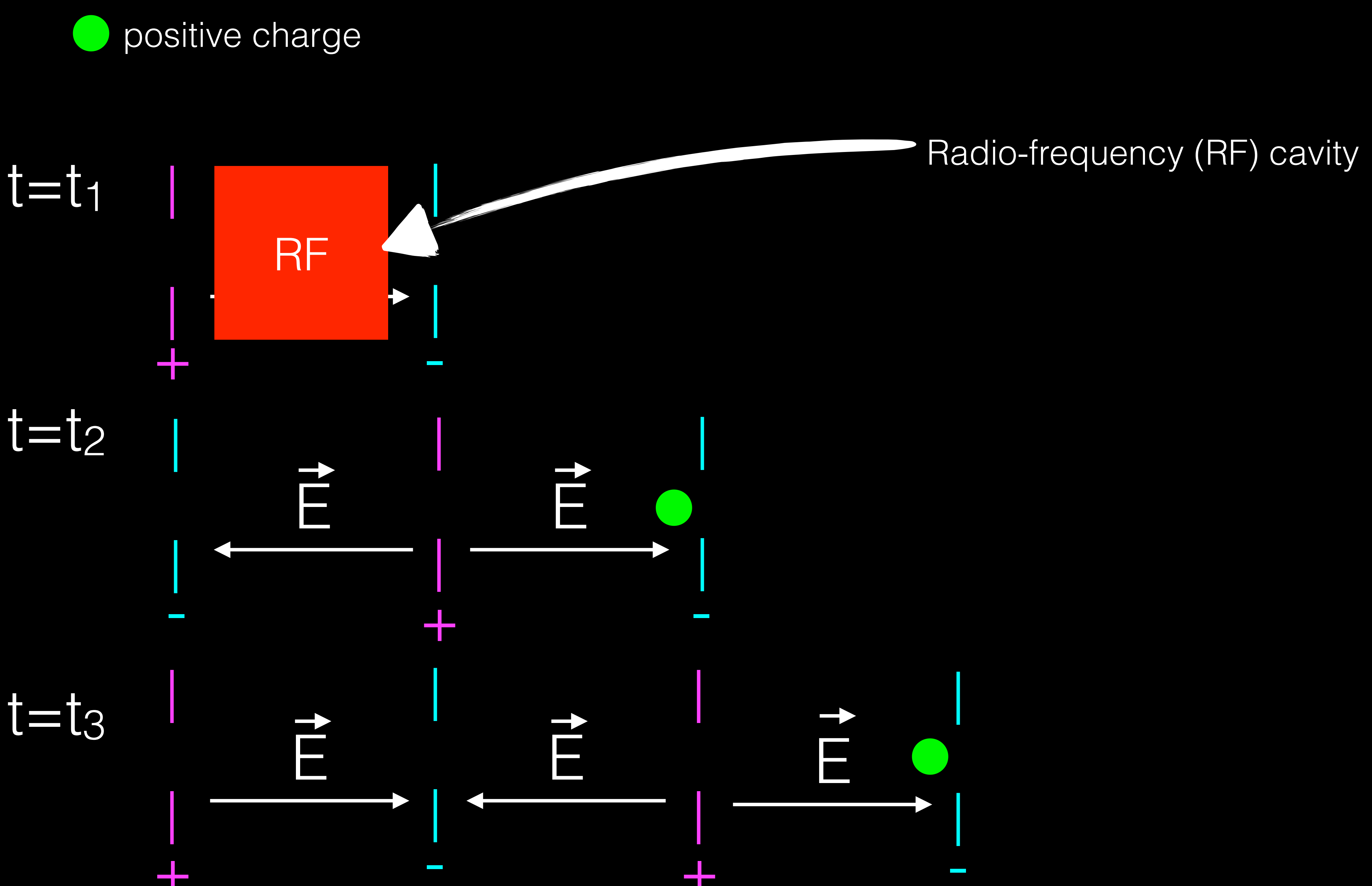

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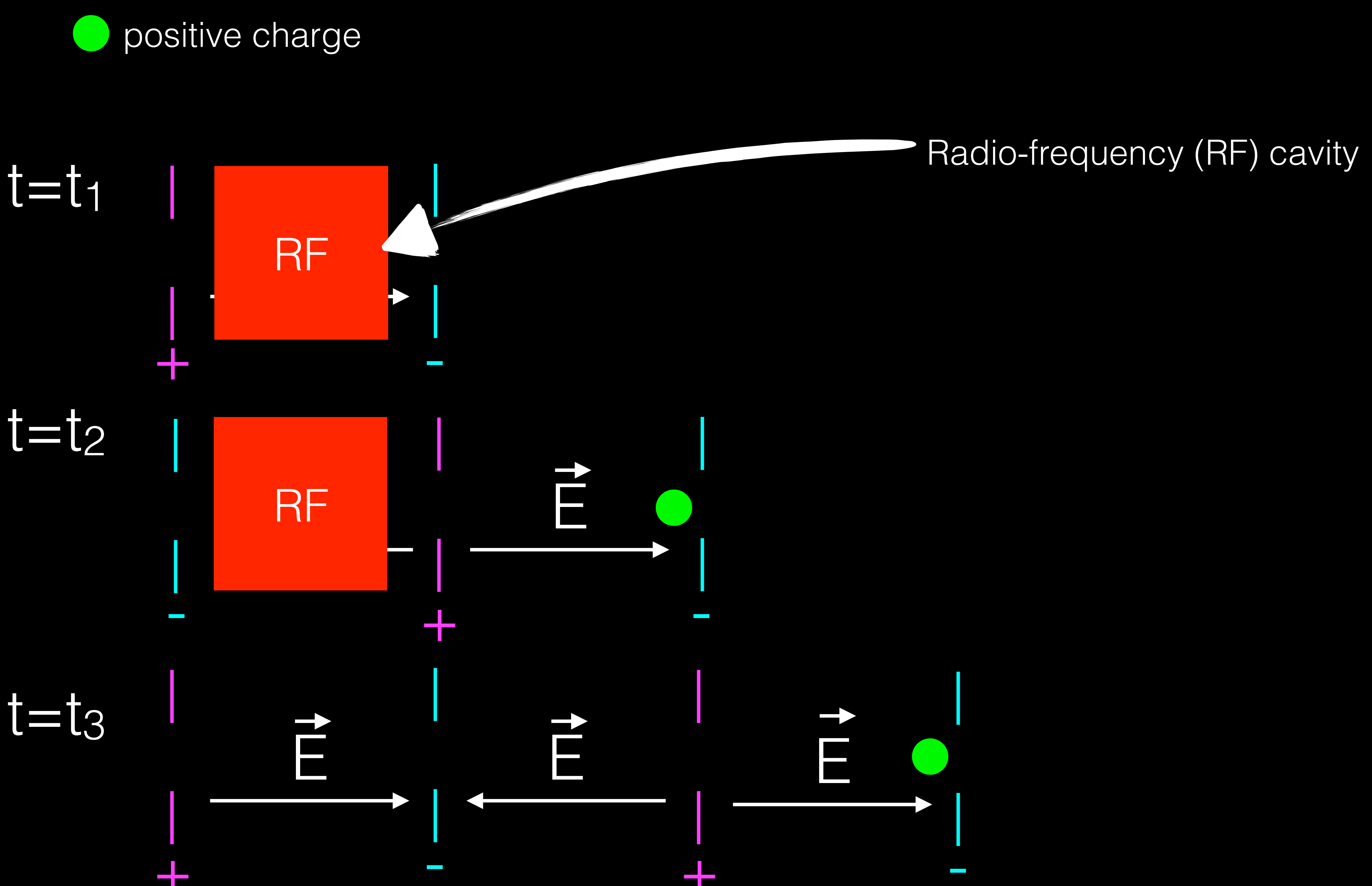

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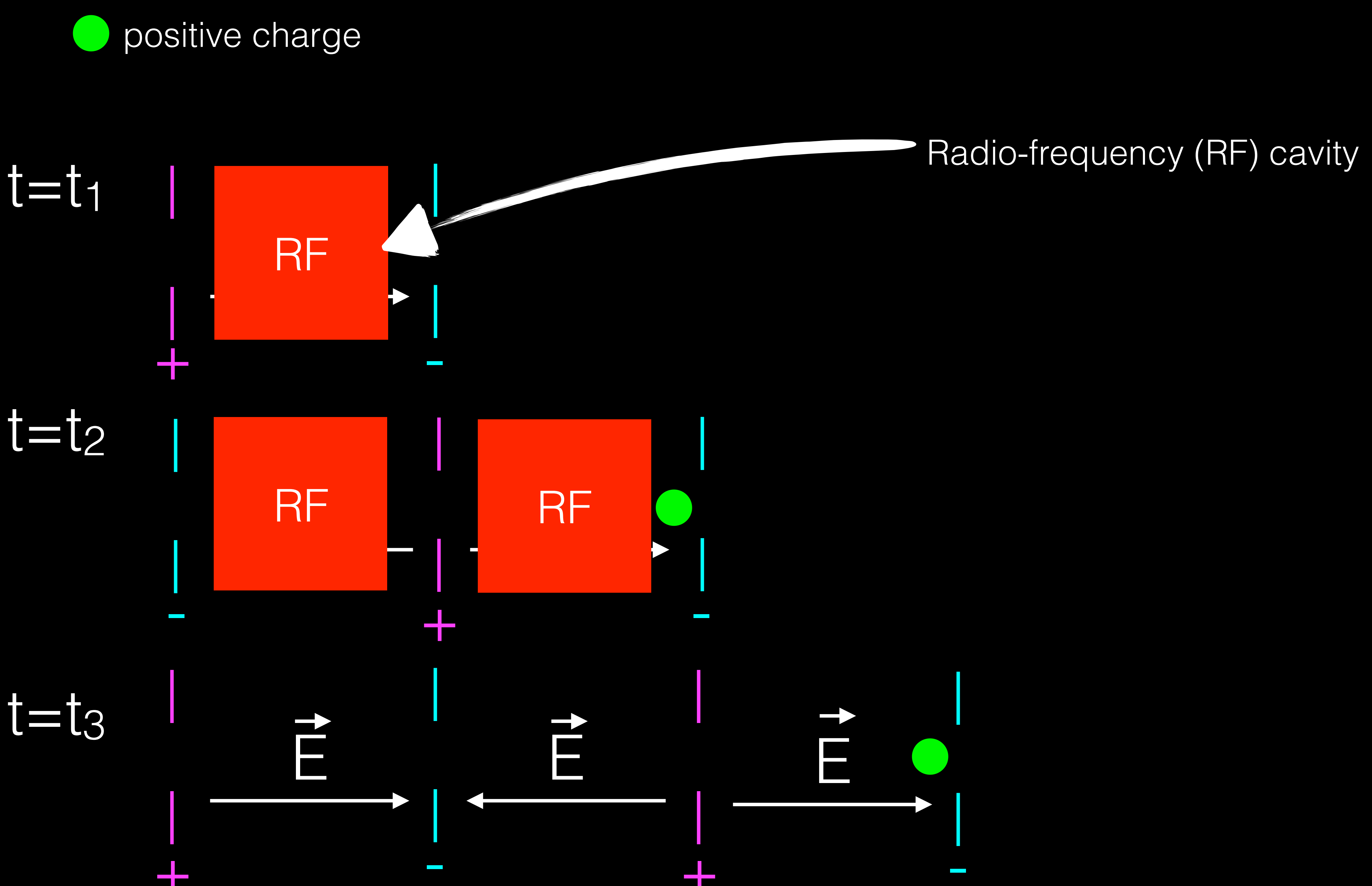

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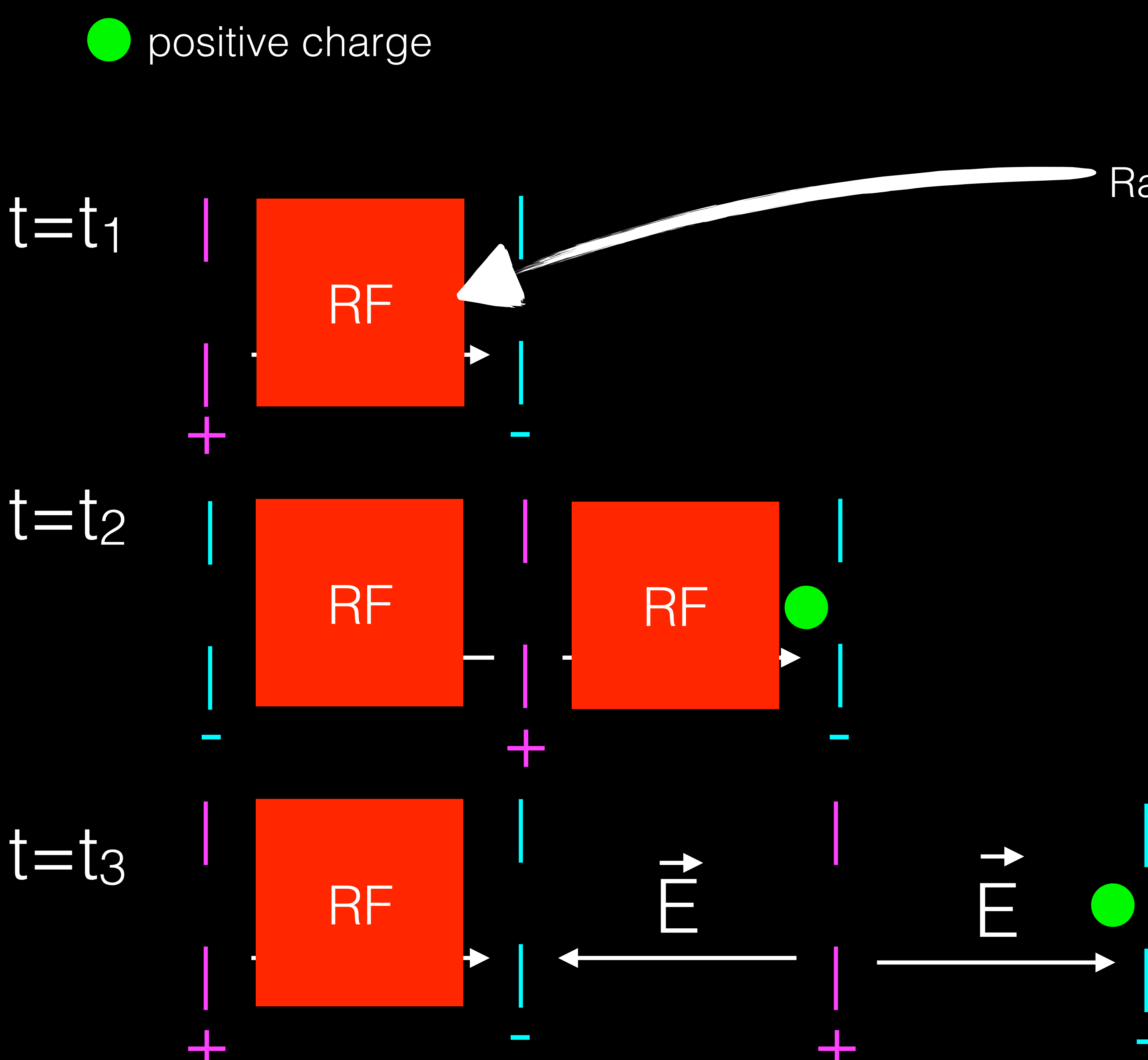

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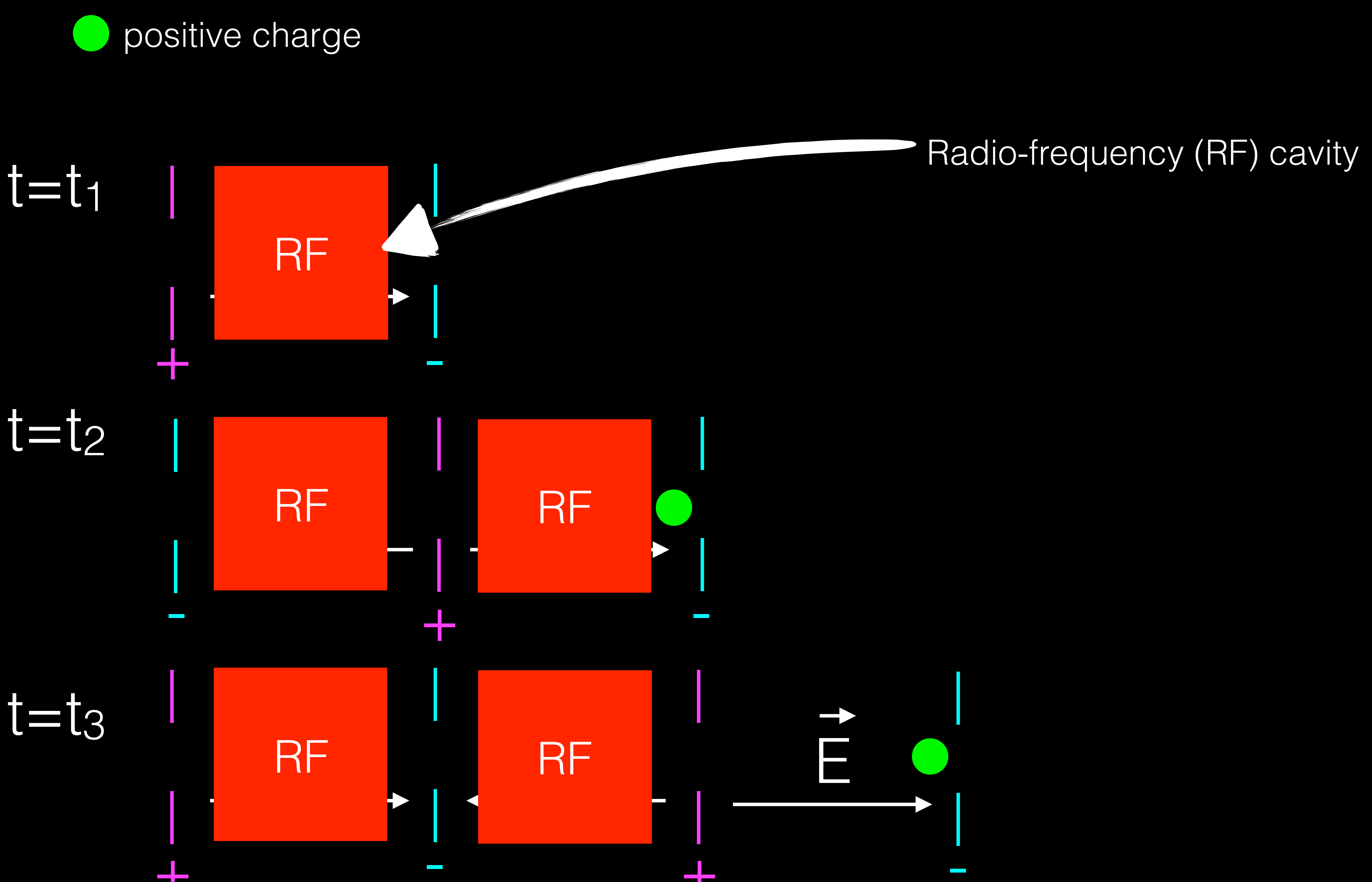

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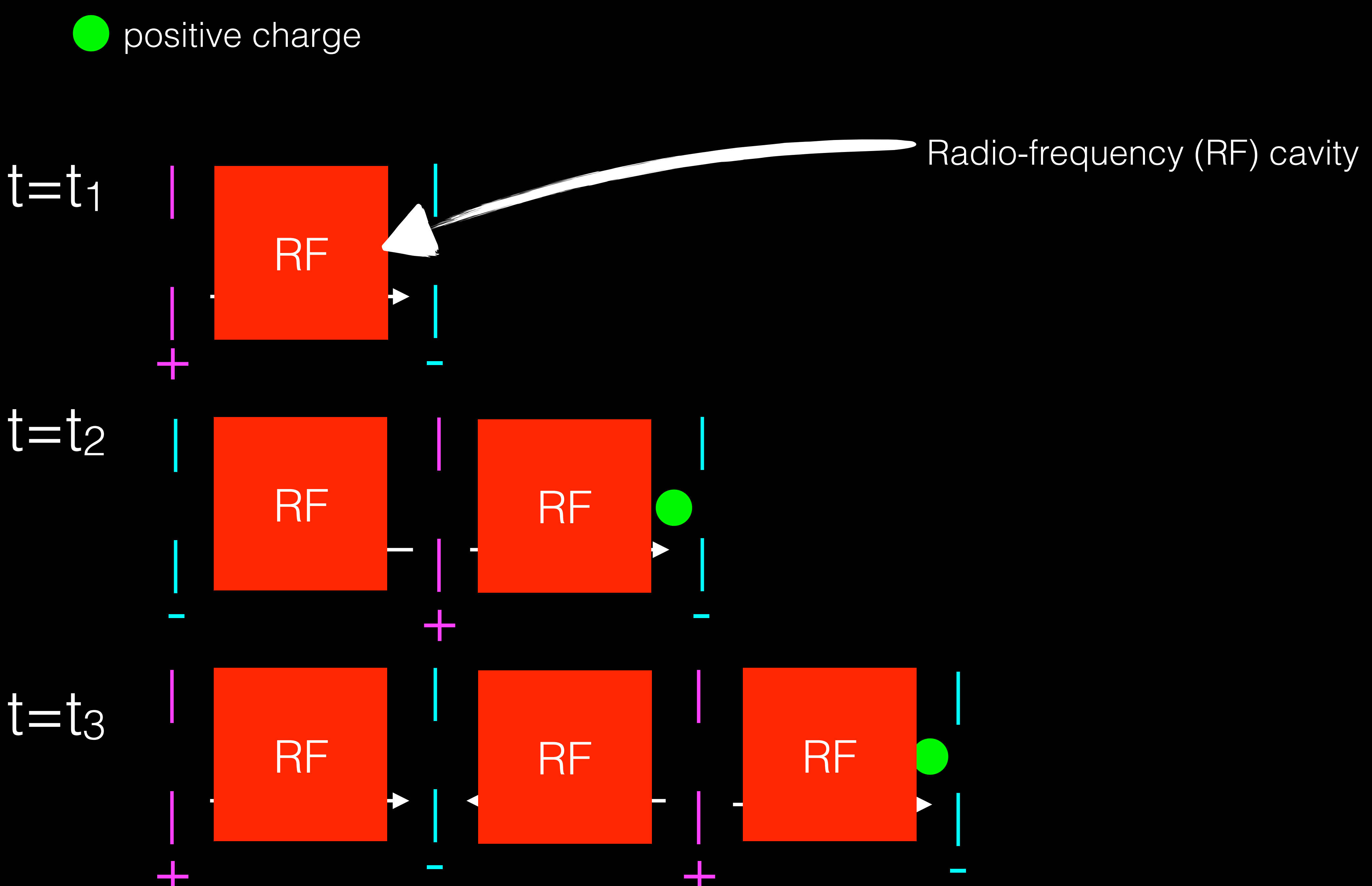

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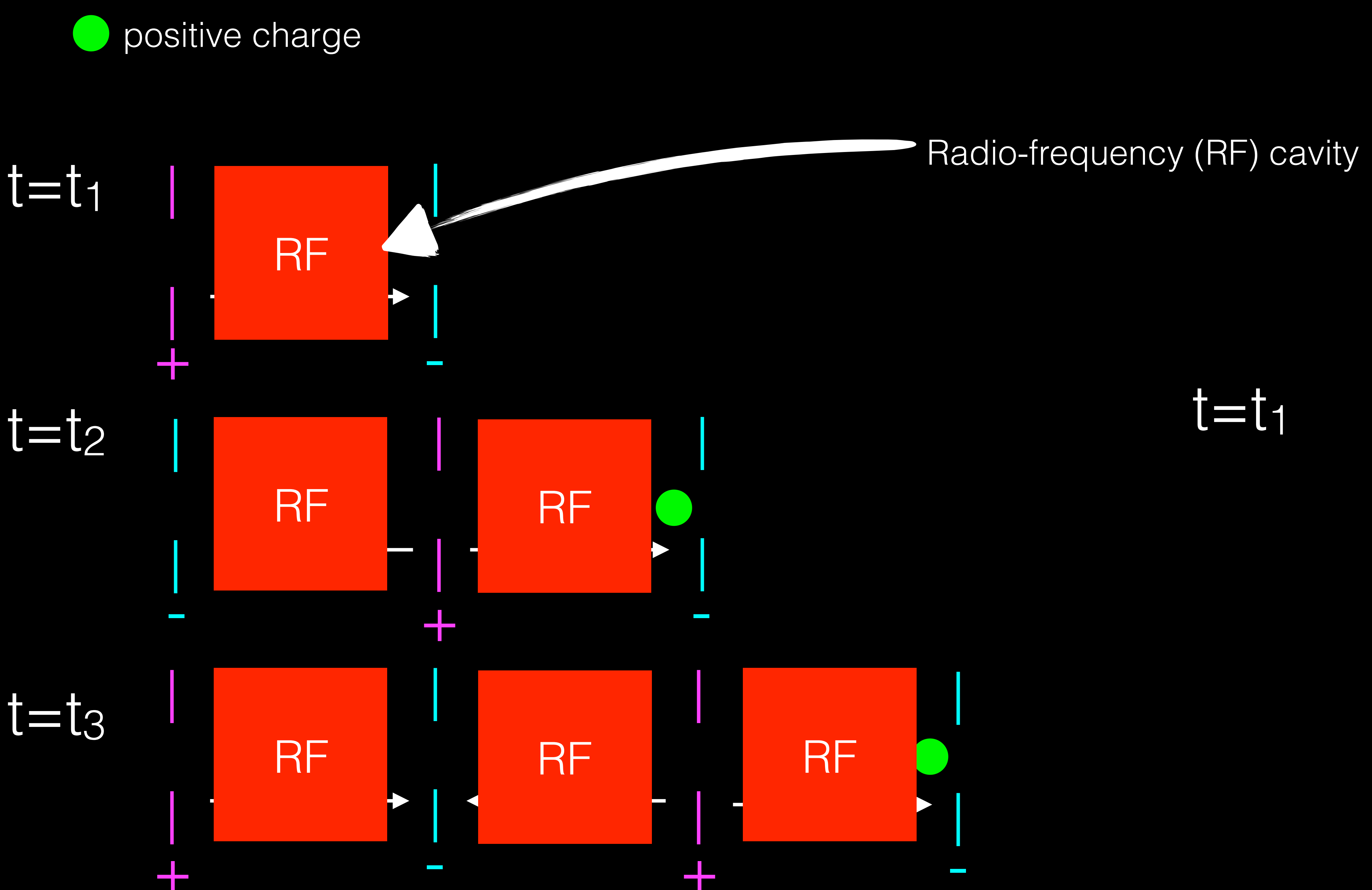

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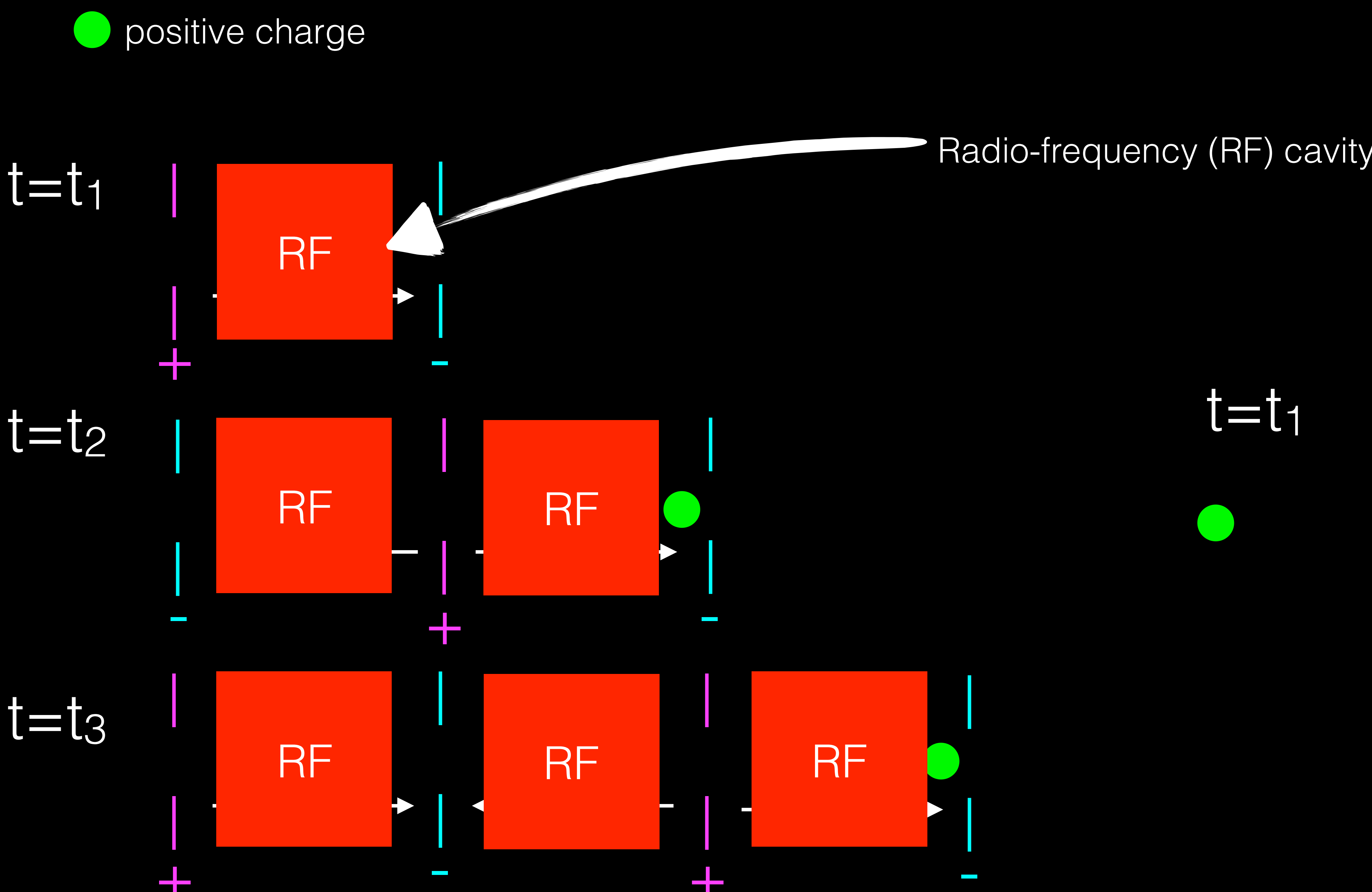

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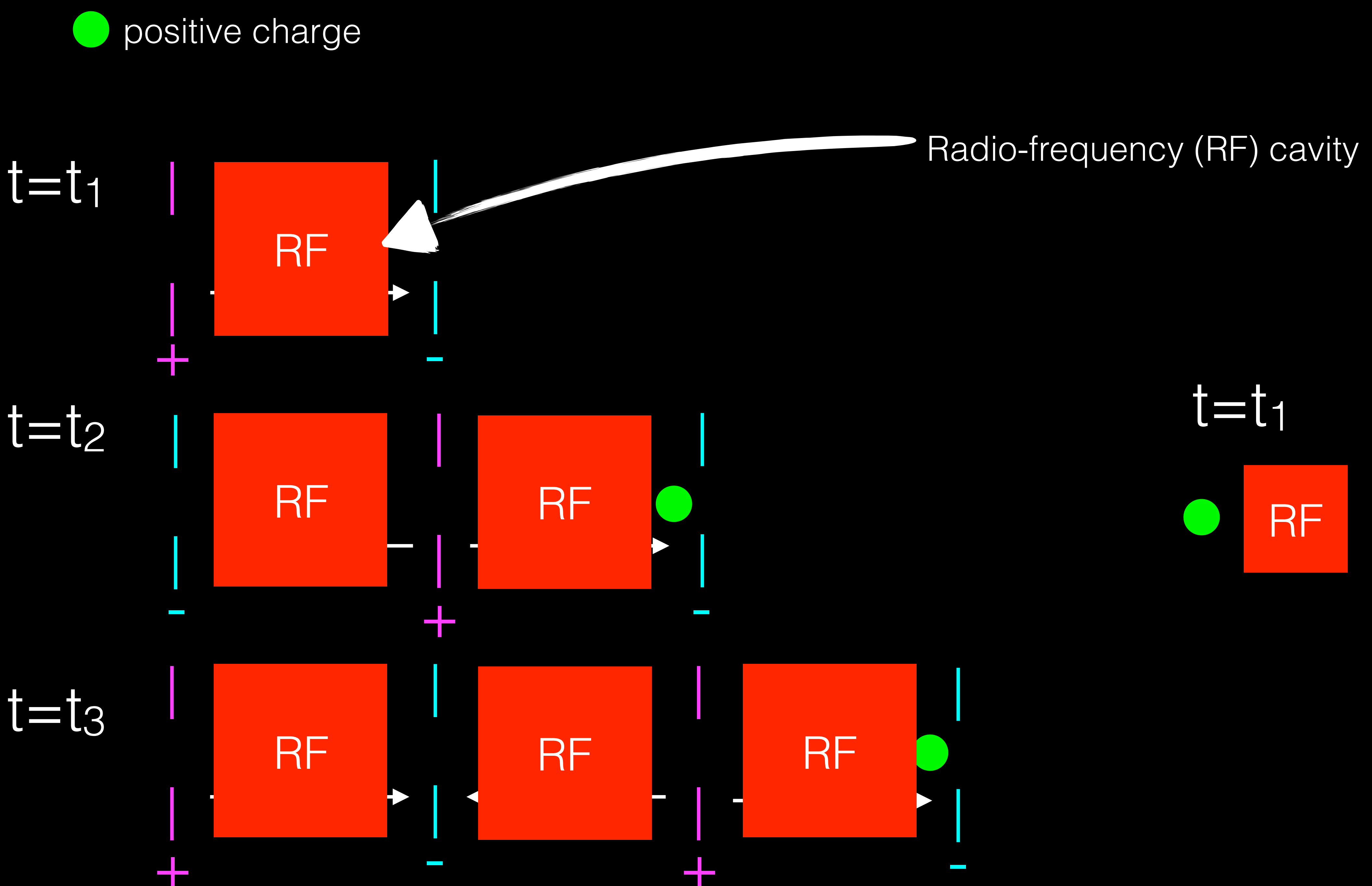

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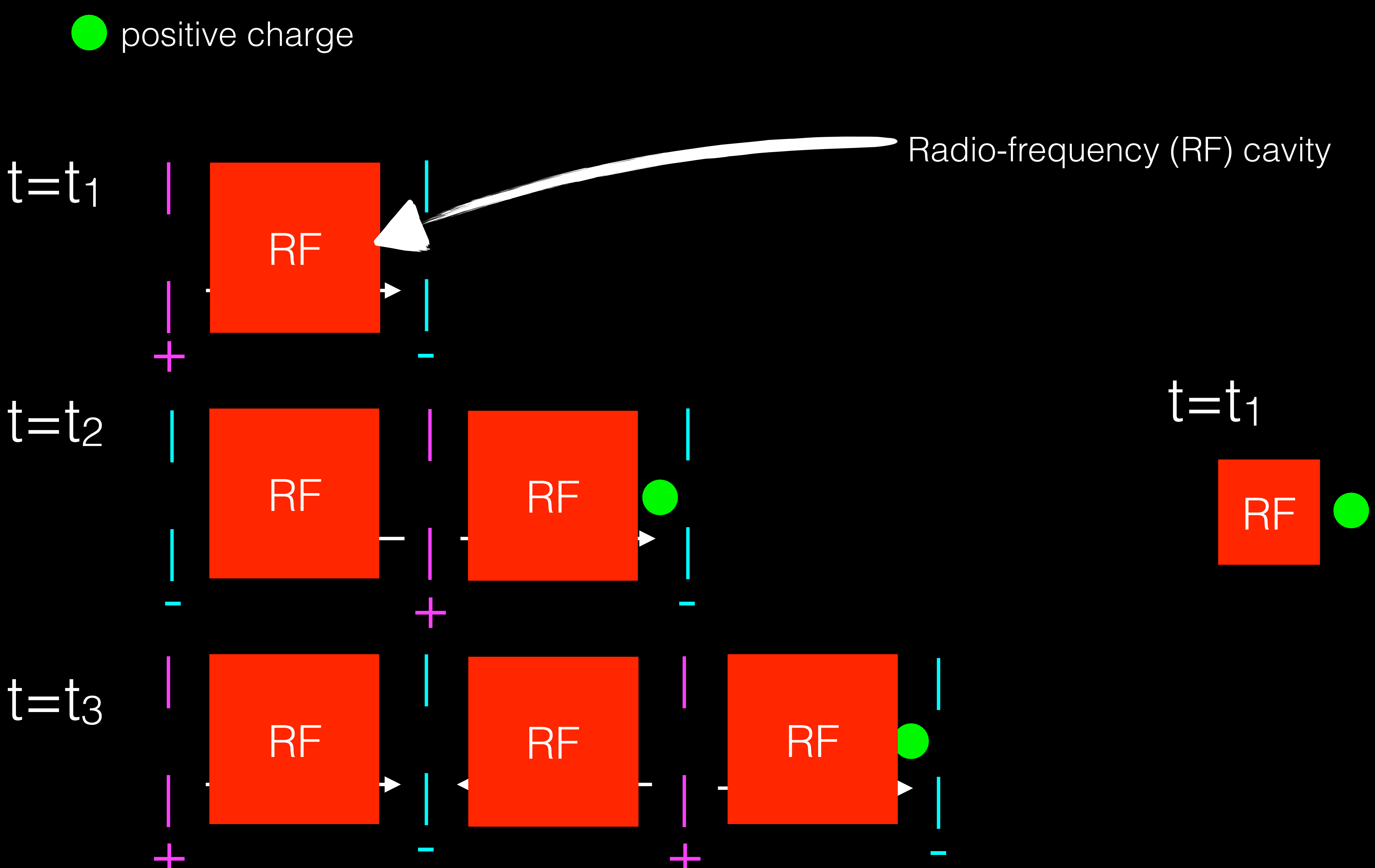

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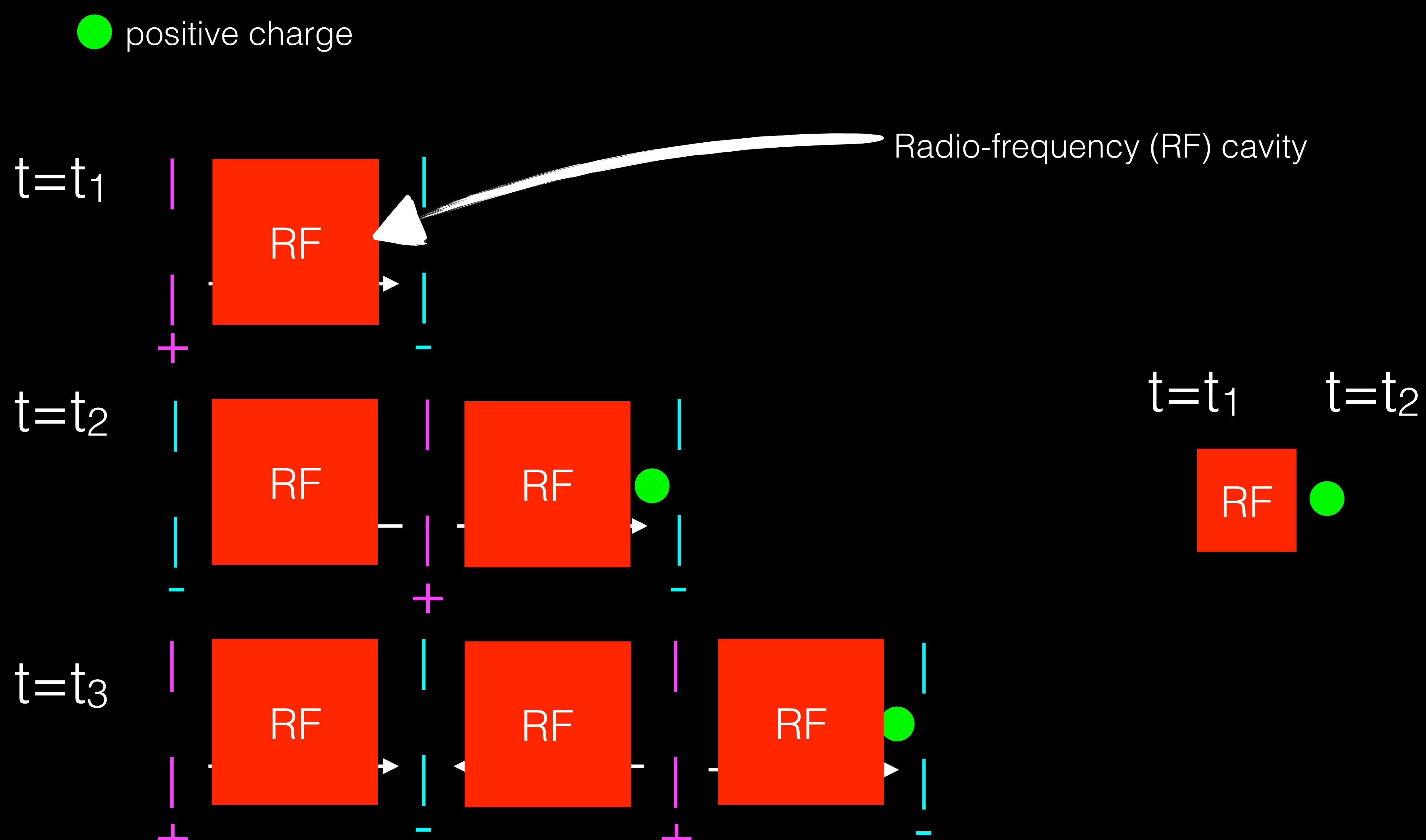

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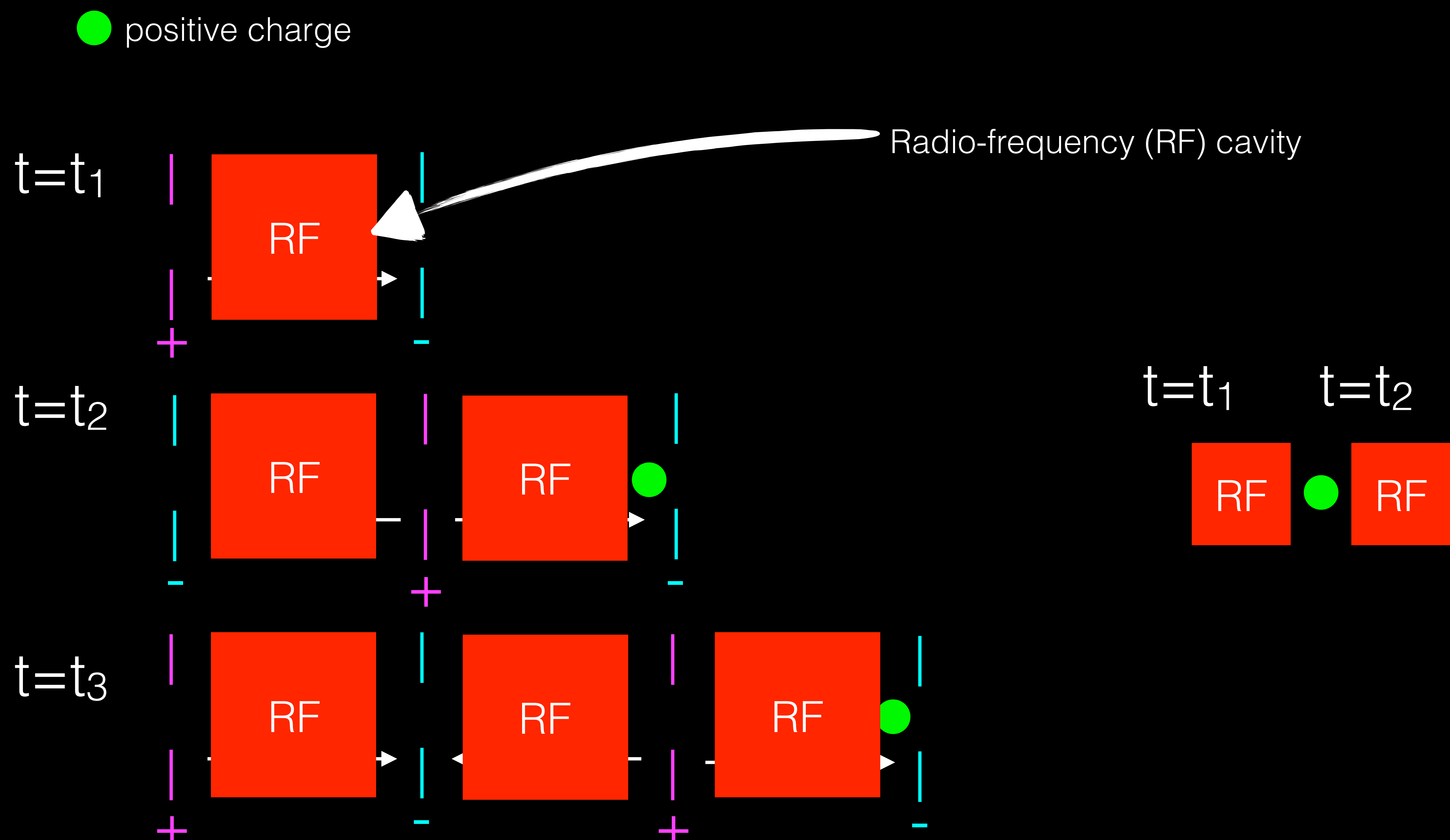

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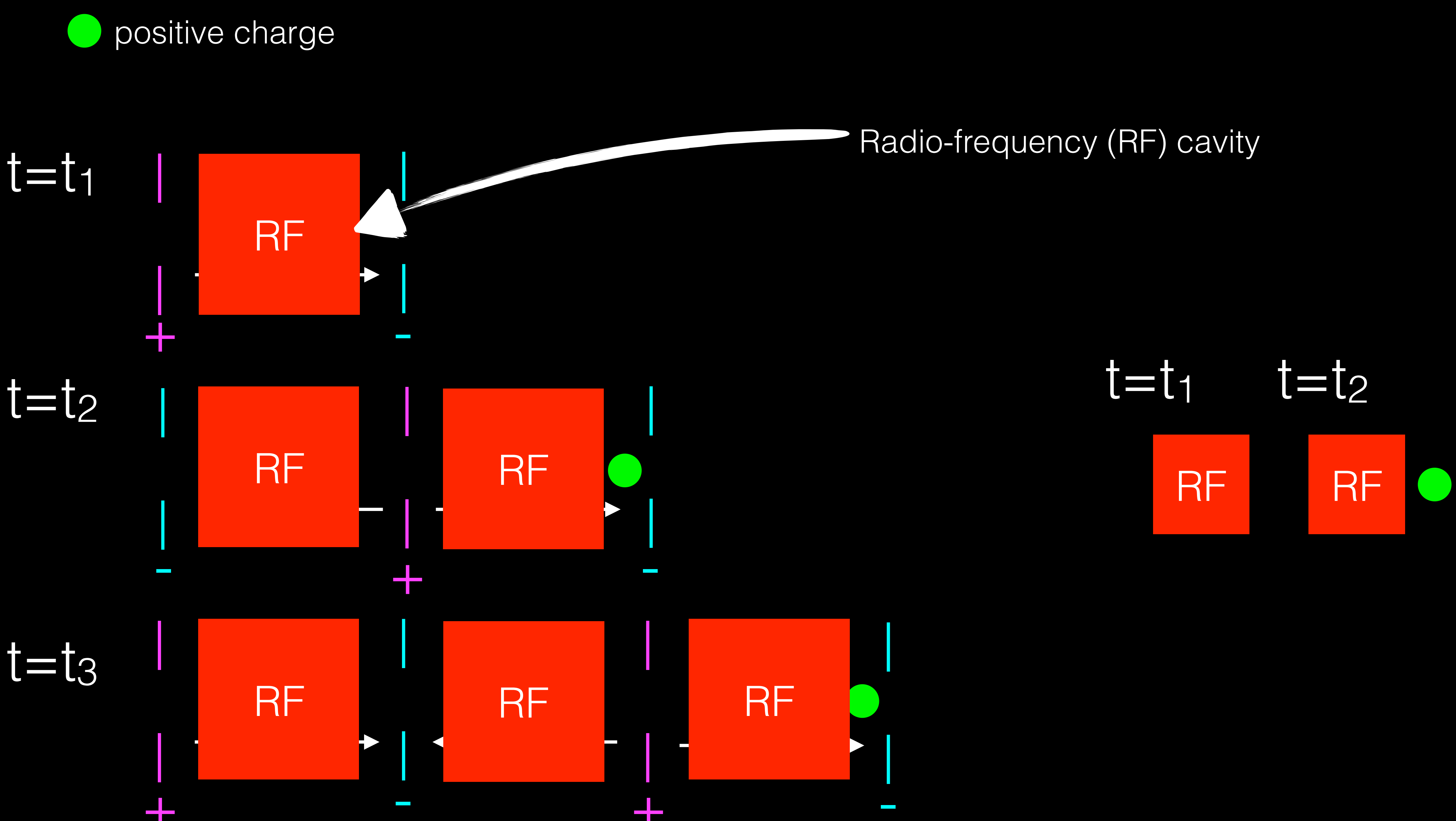

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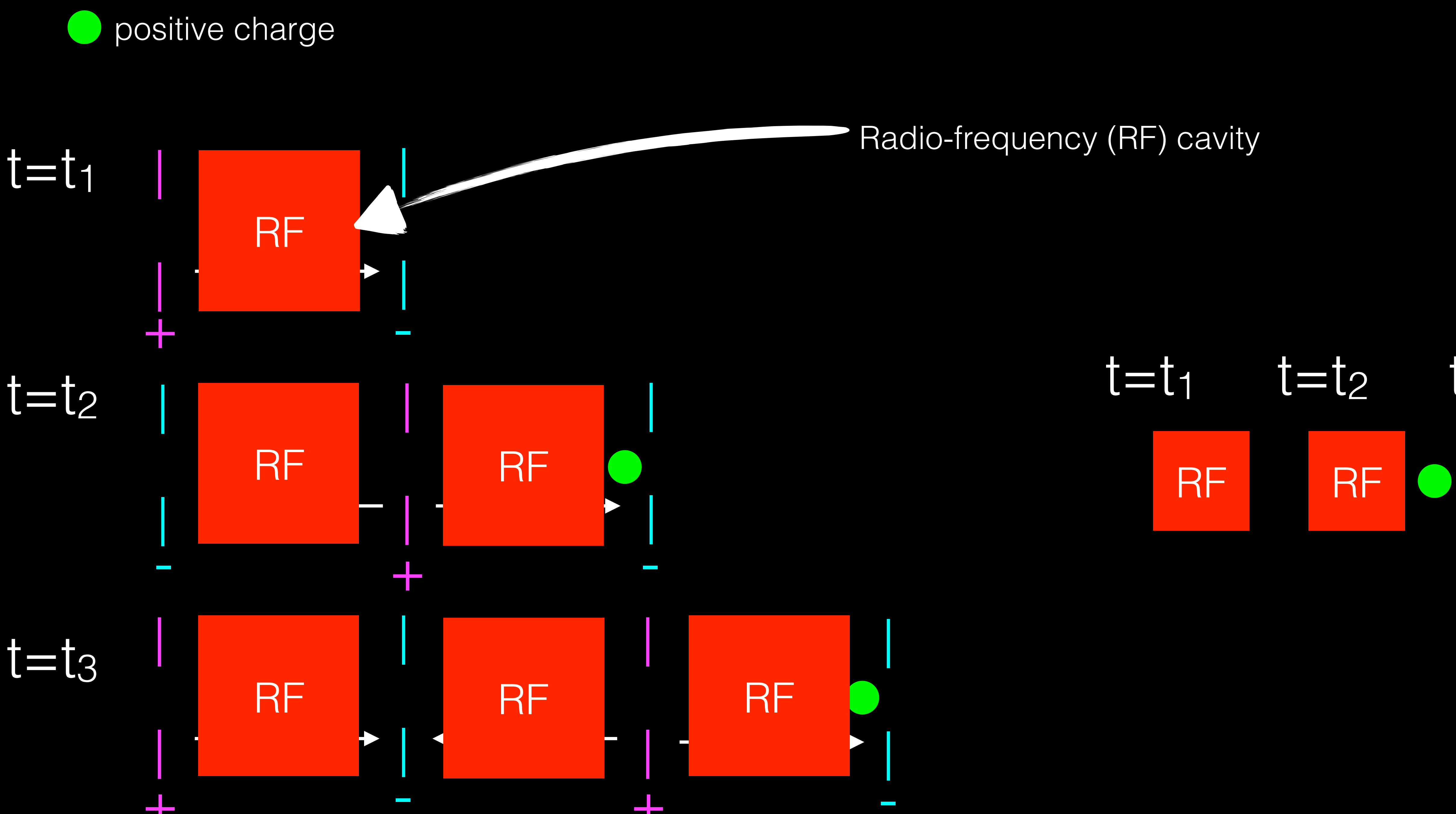

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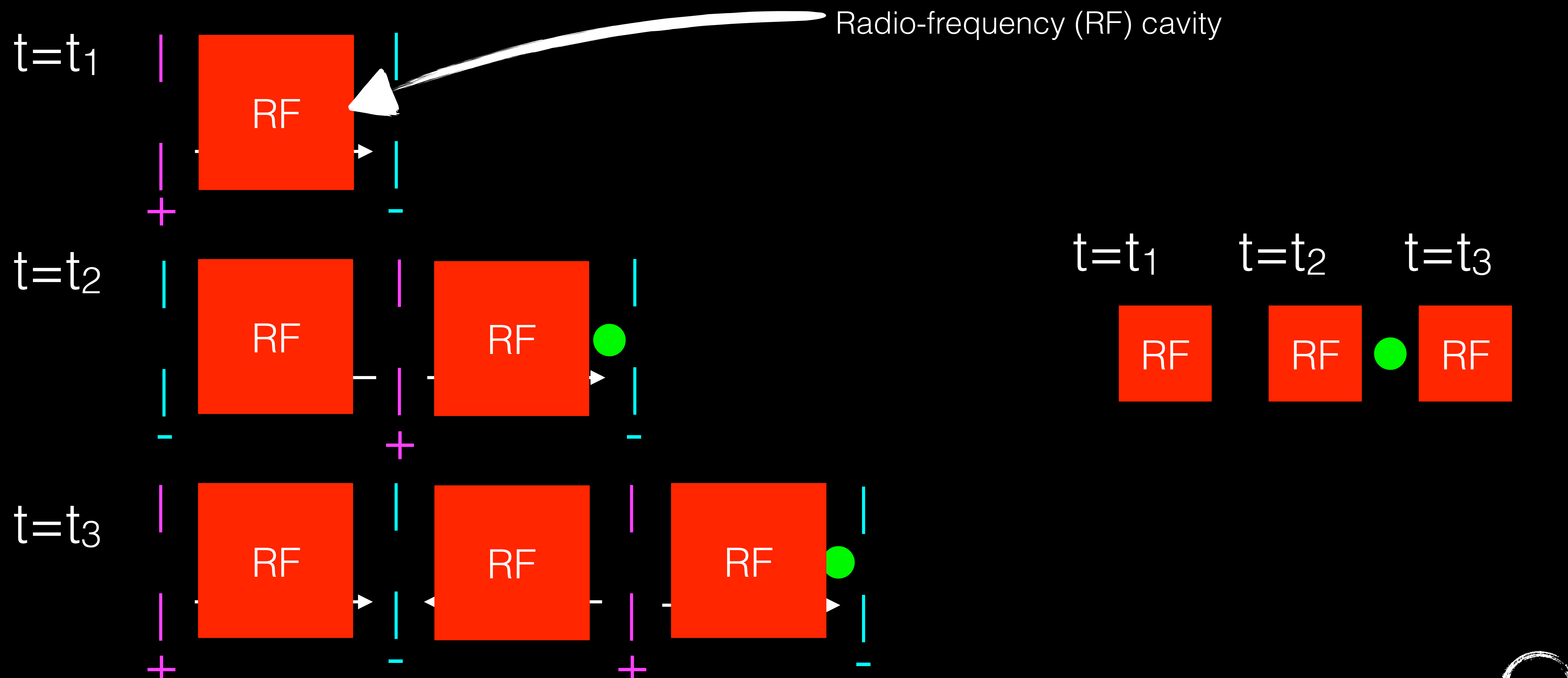

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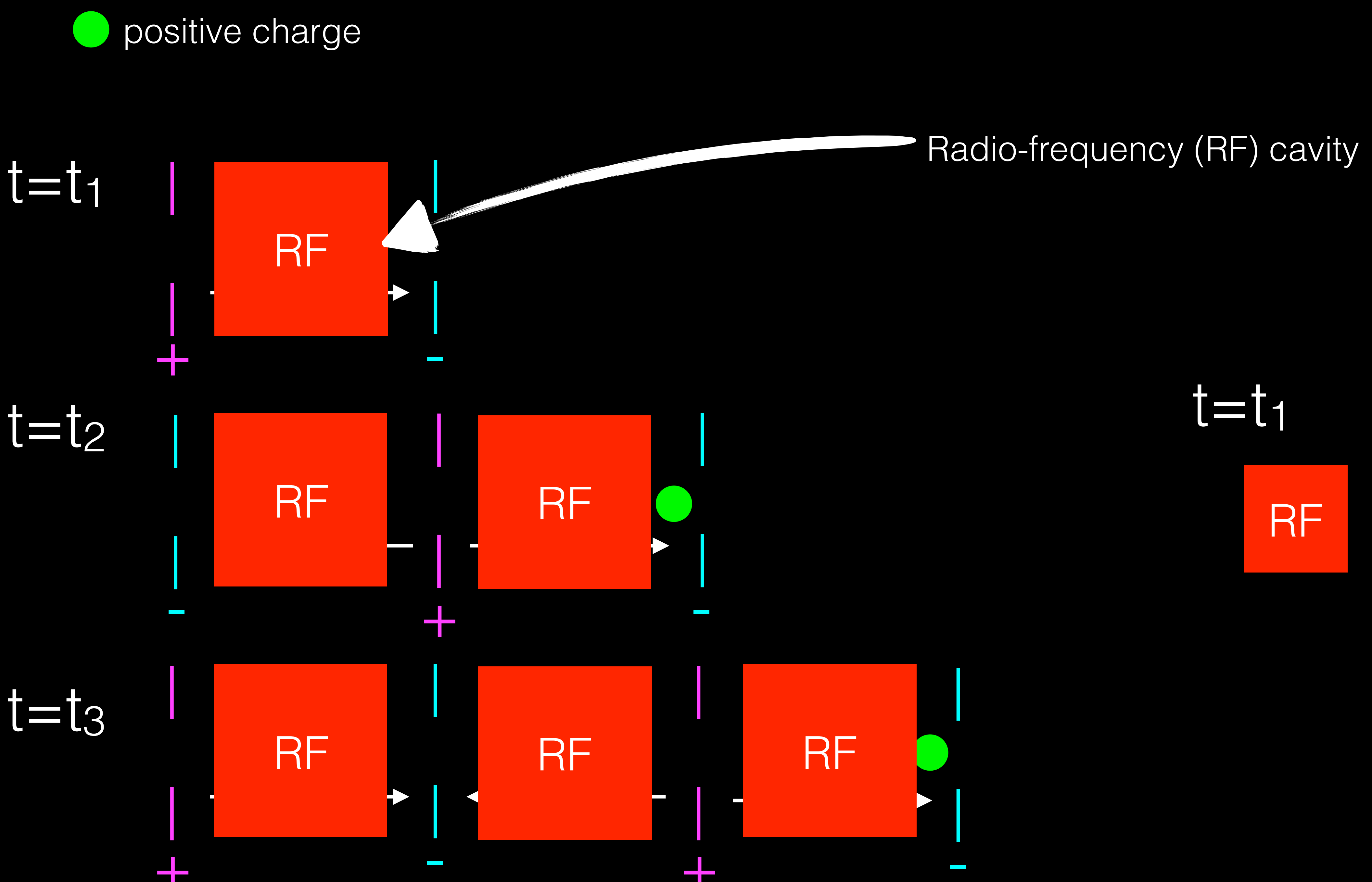
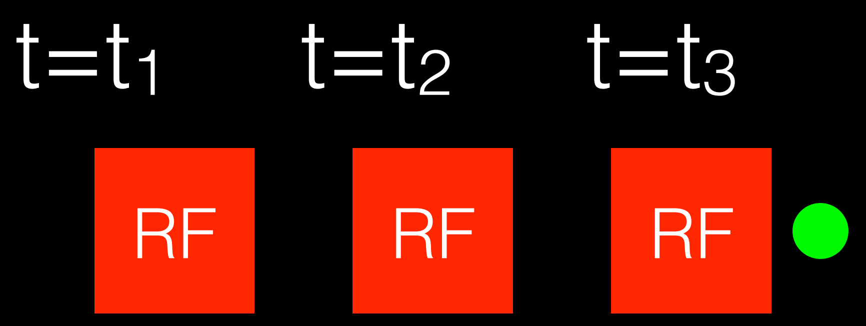
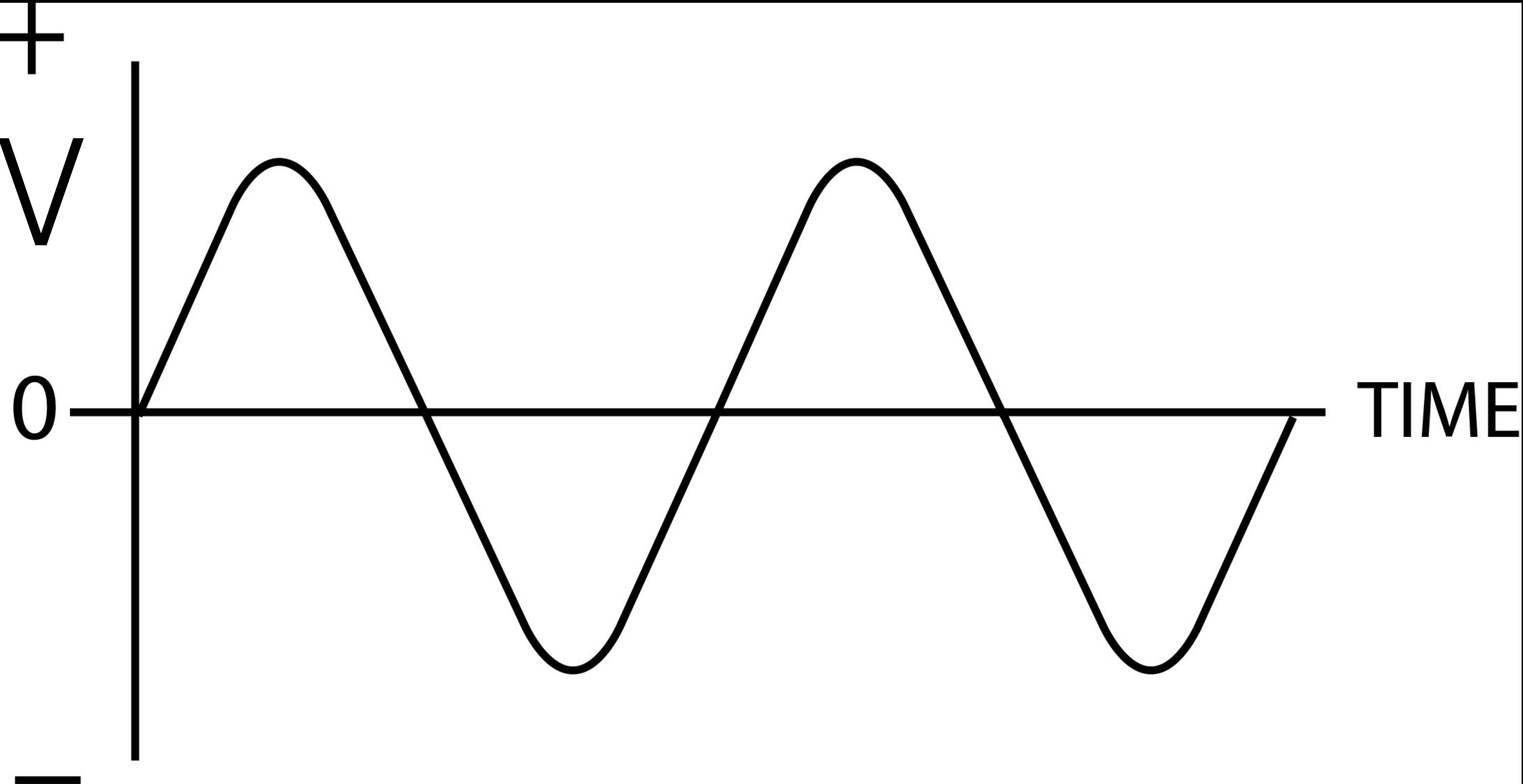




Inside an RF cavity



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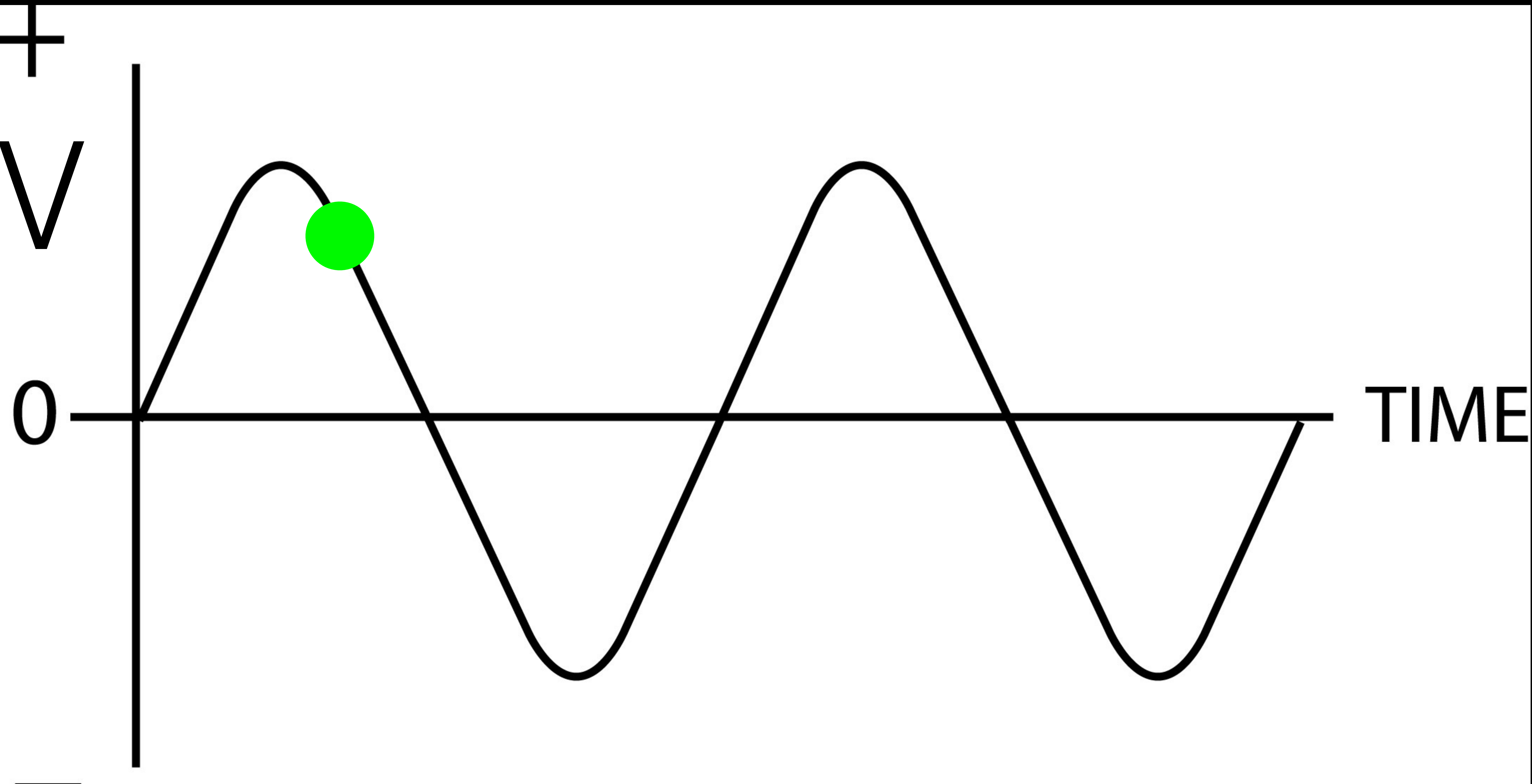

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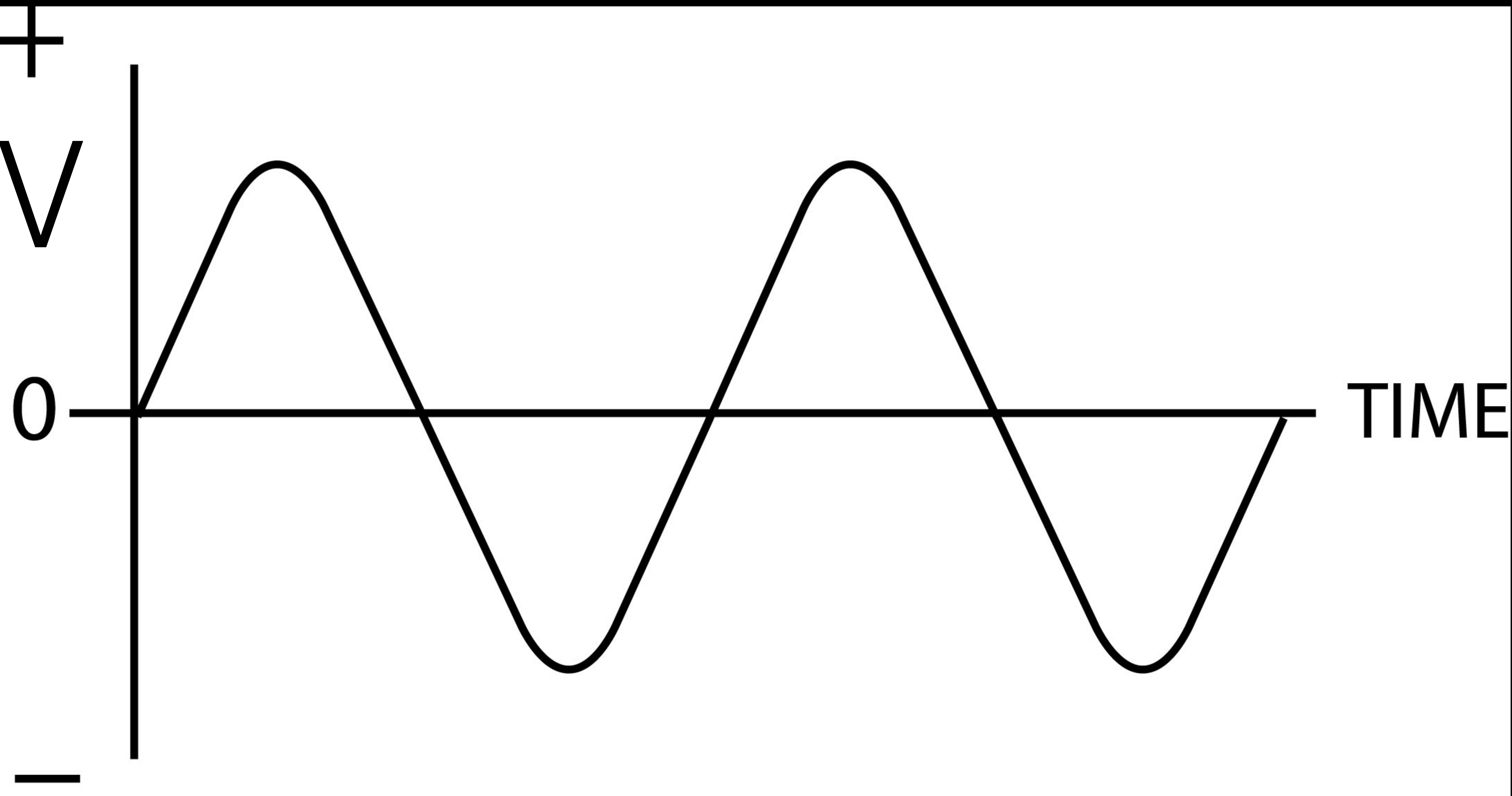

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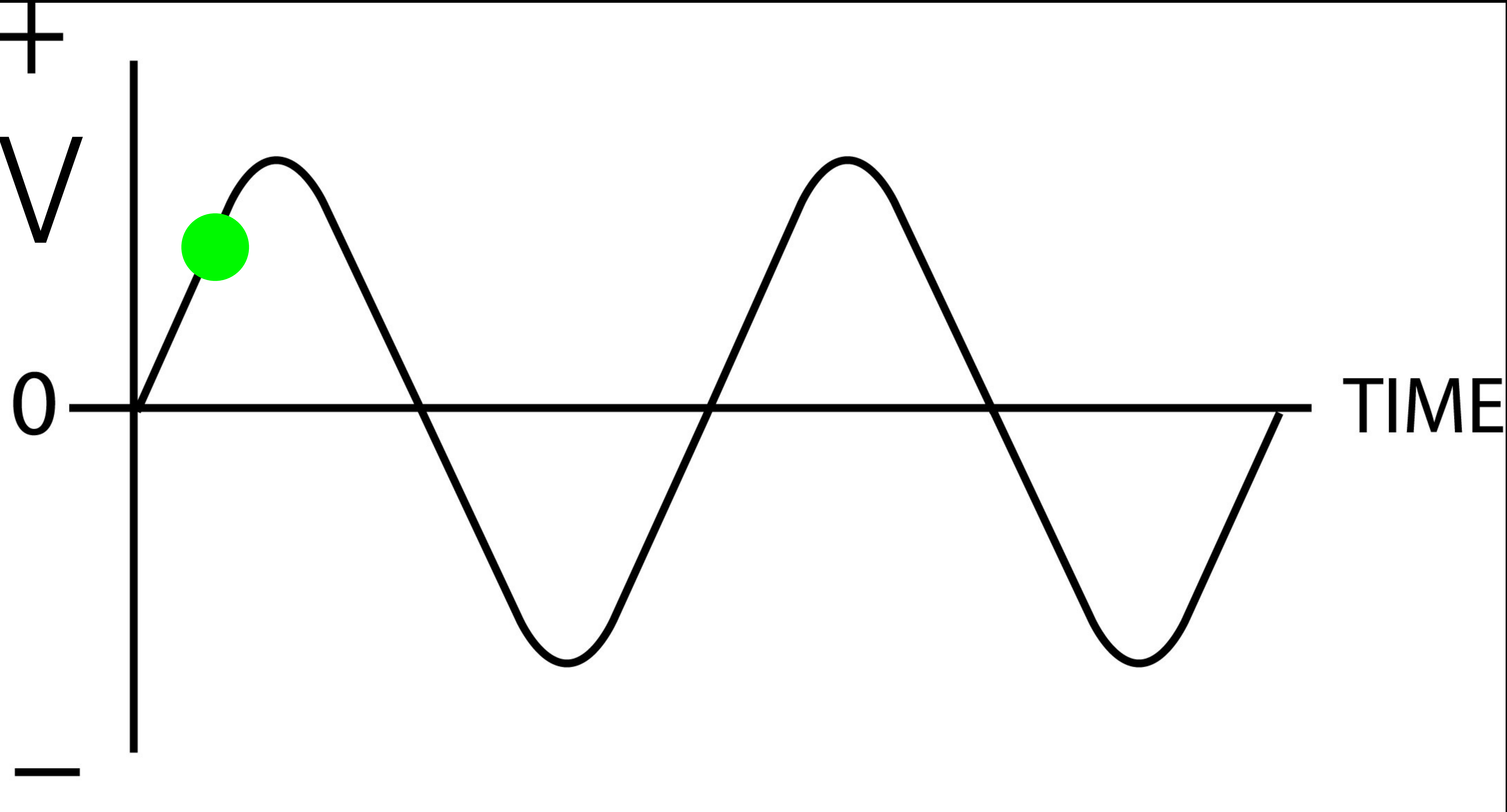

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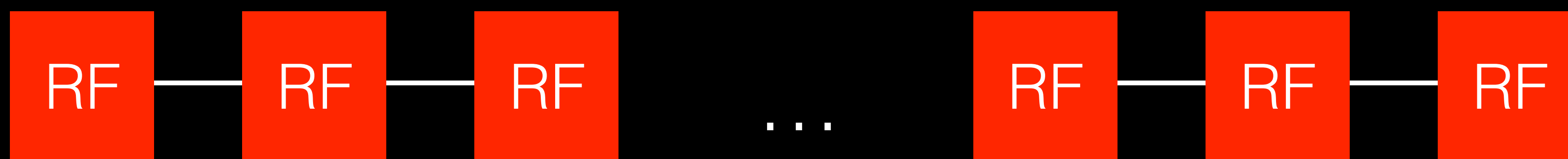

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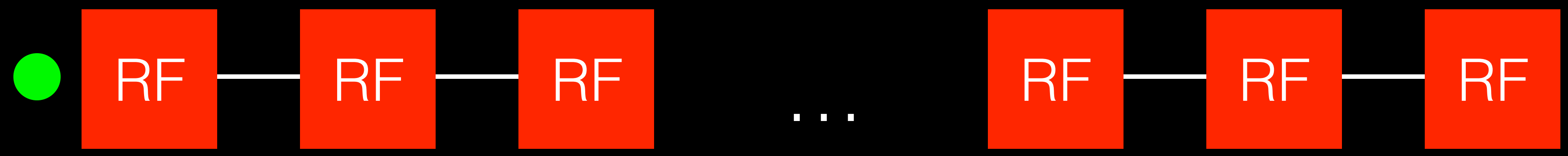

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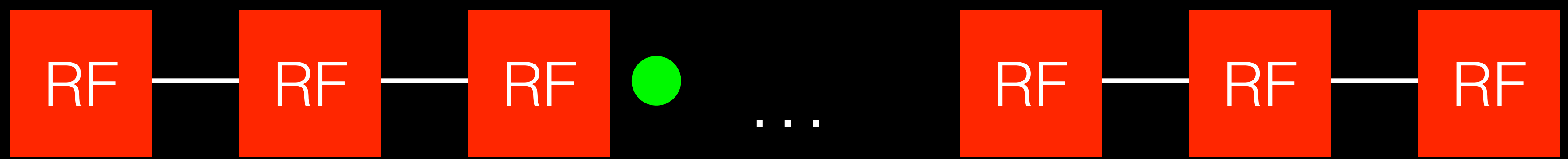

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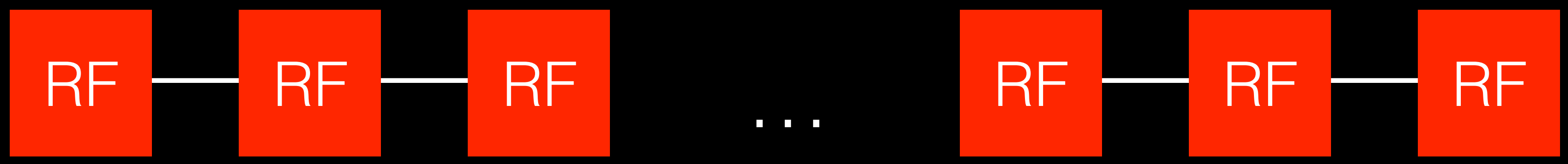

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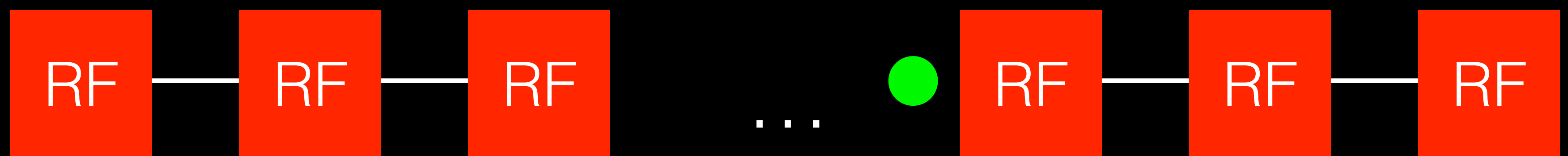

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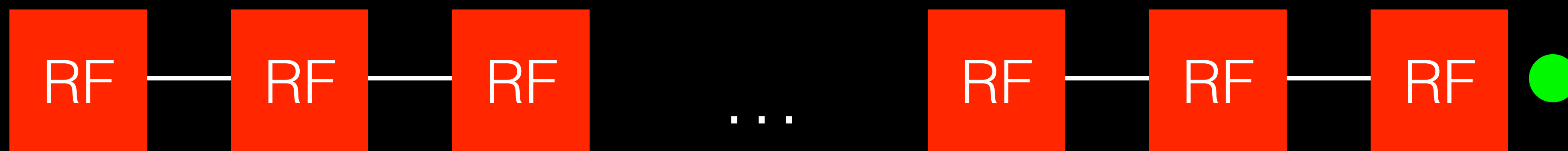

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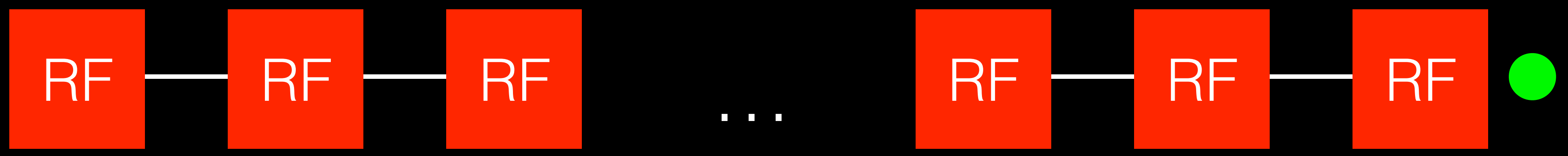

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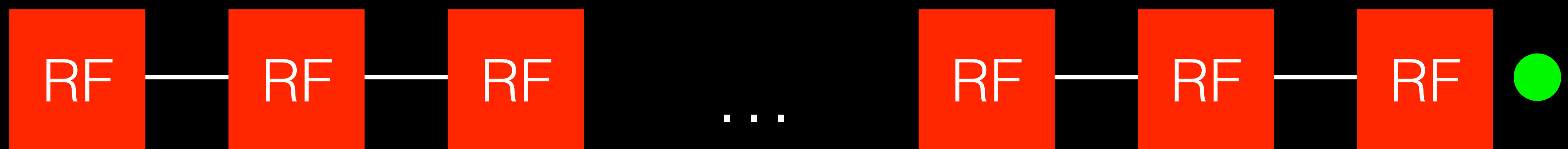

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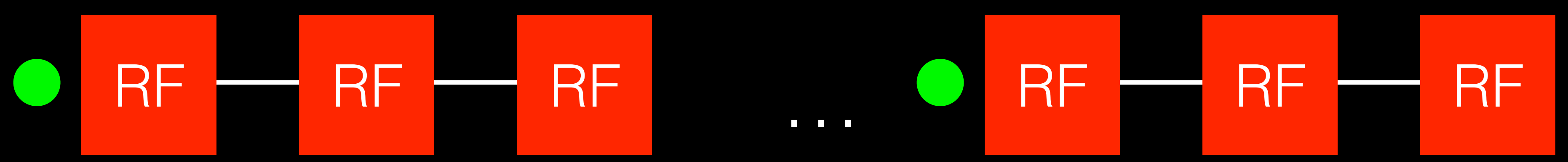

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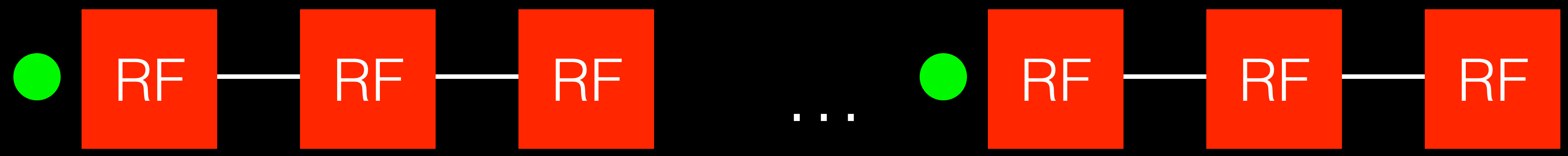

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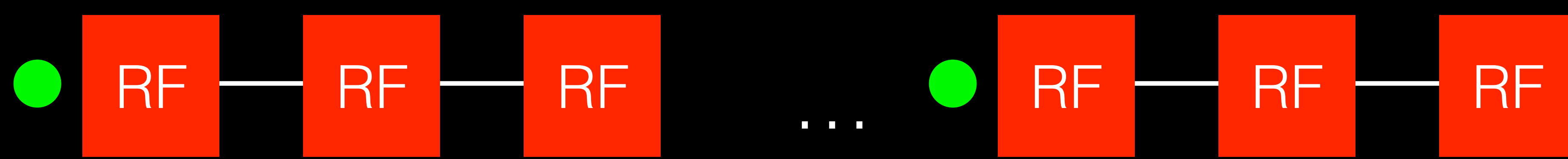

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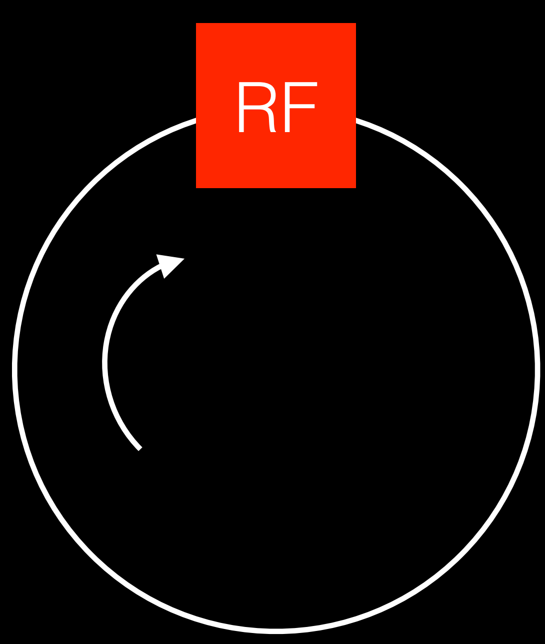

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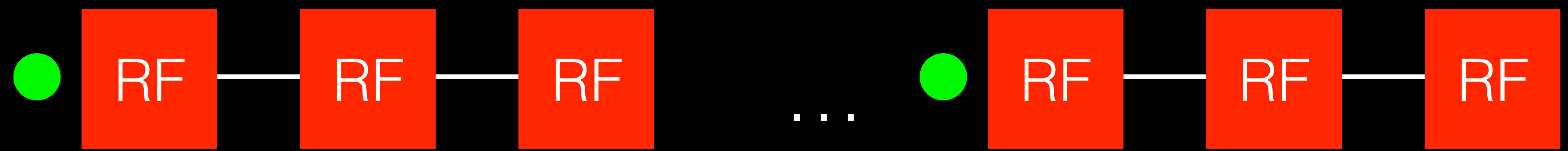

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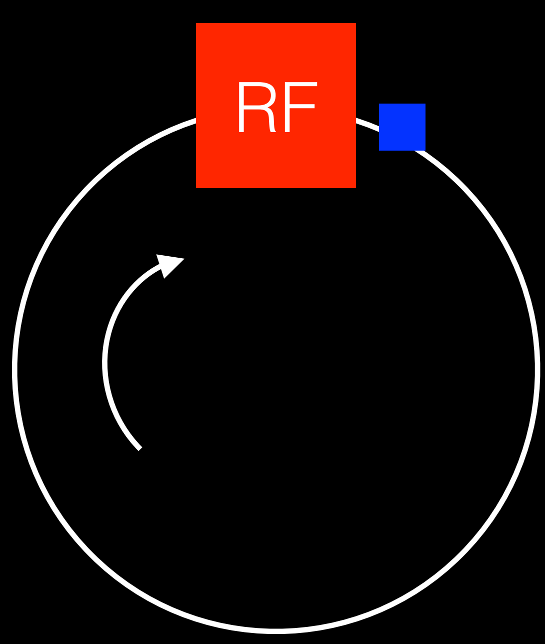

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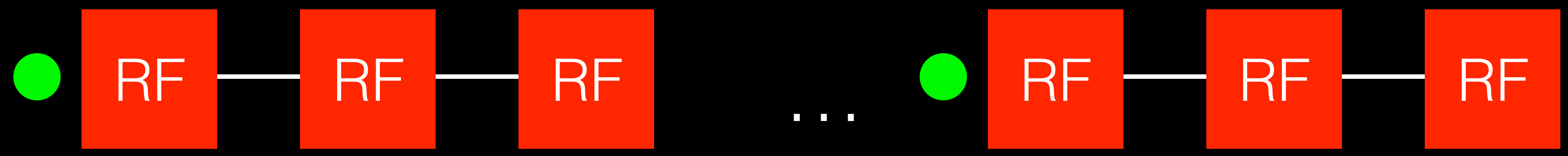

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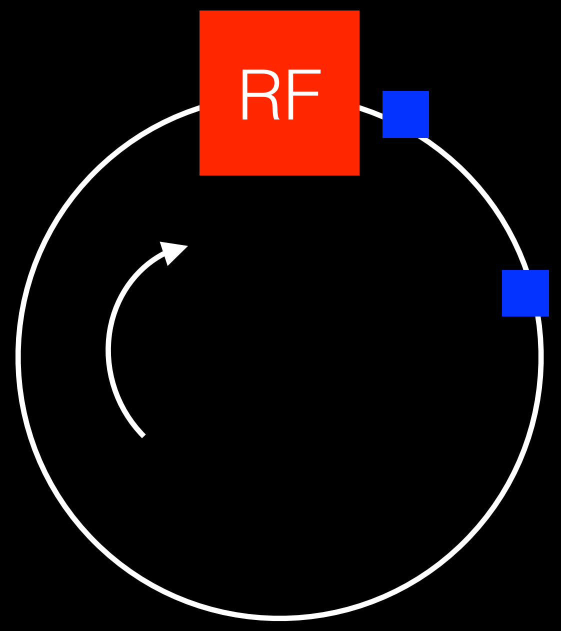

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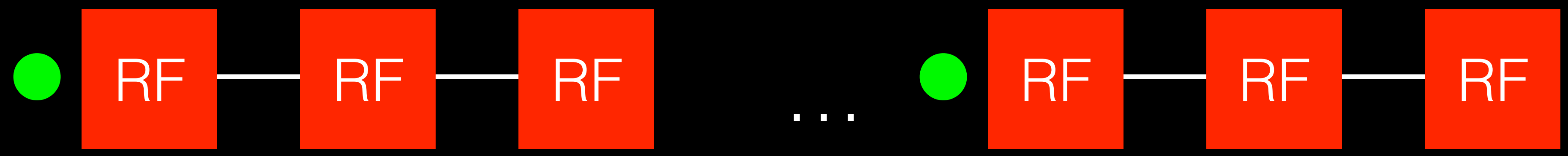

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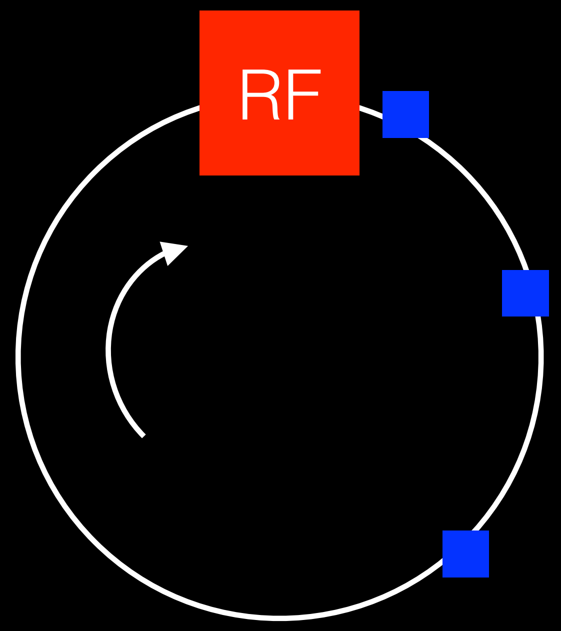

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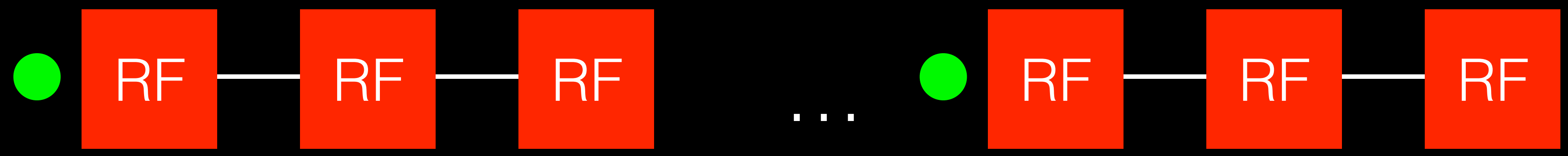

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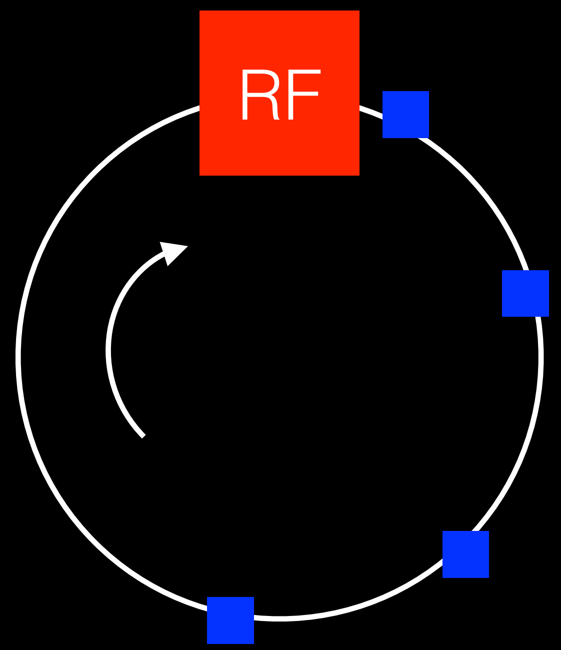

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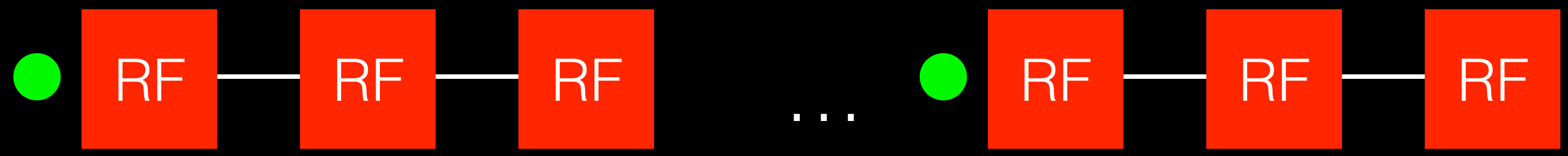

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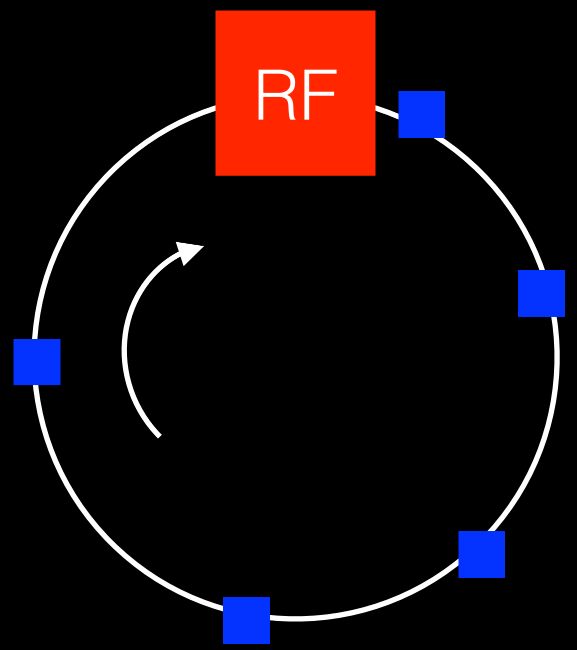

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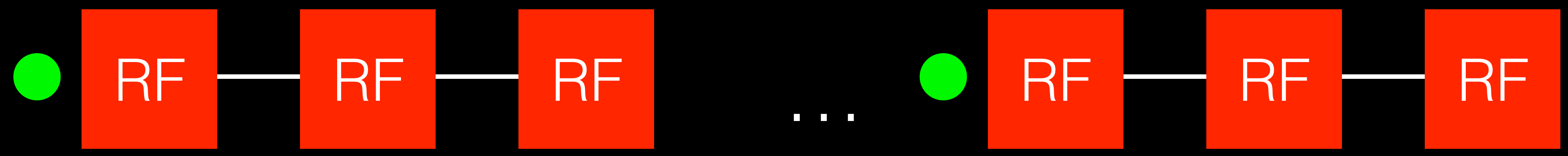

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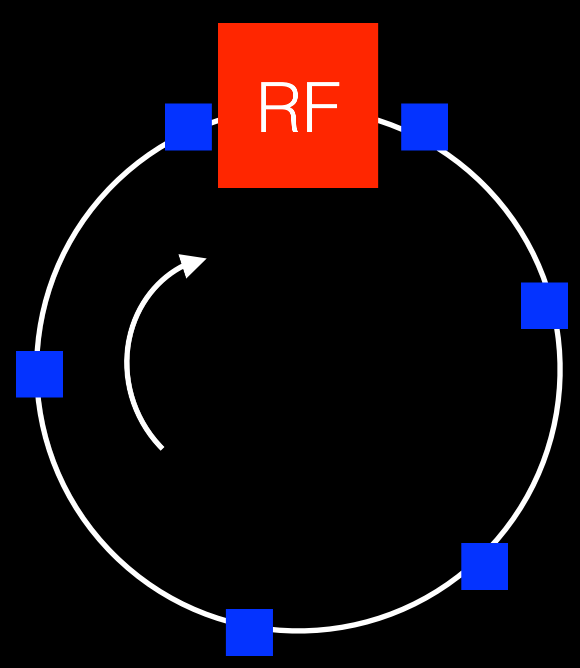

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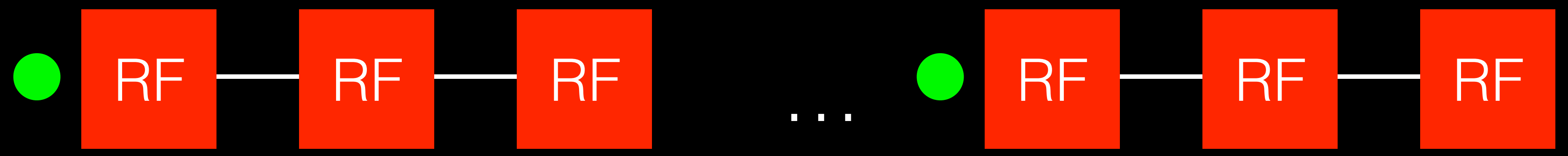

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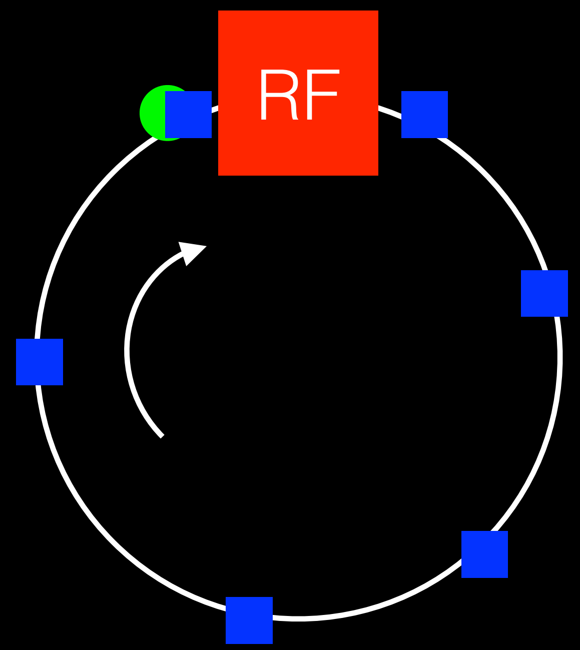

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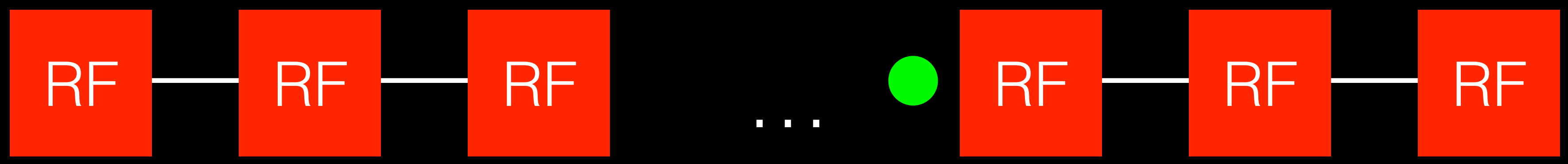

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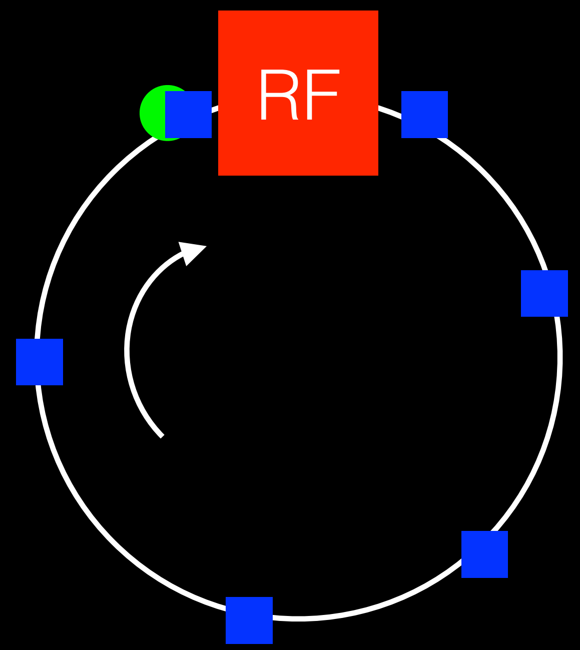

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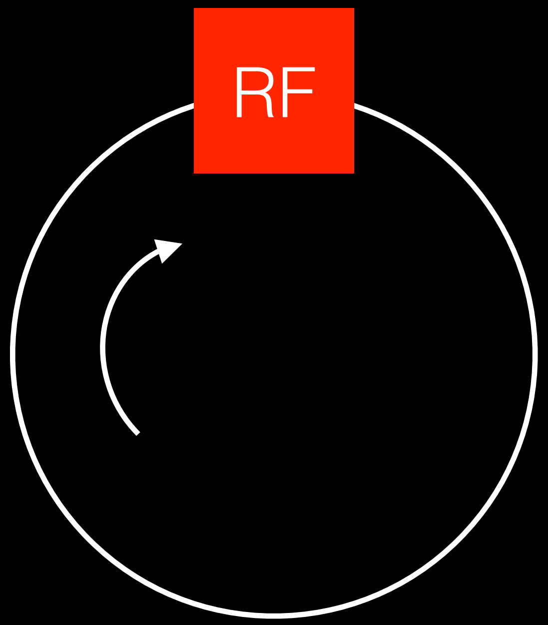

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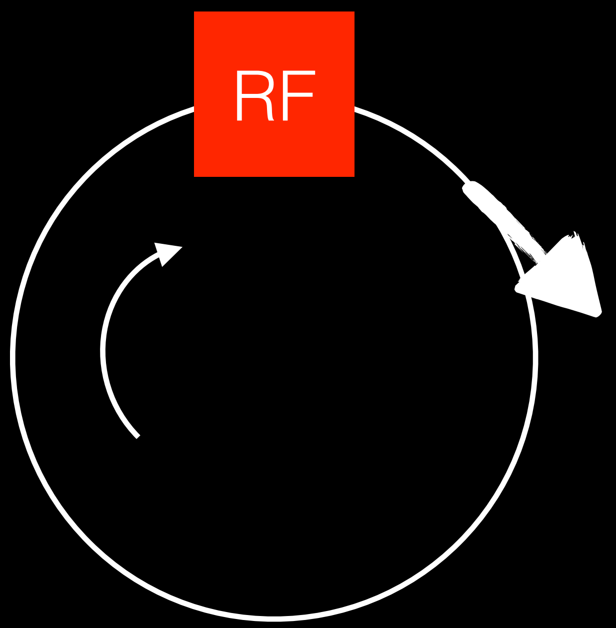

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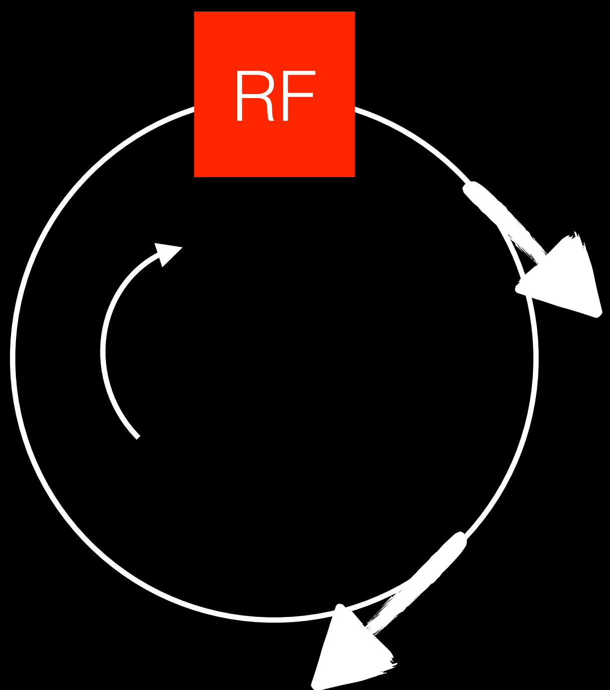

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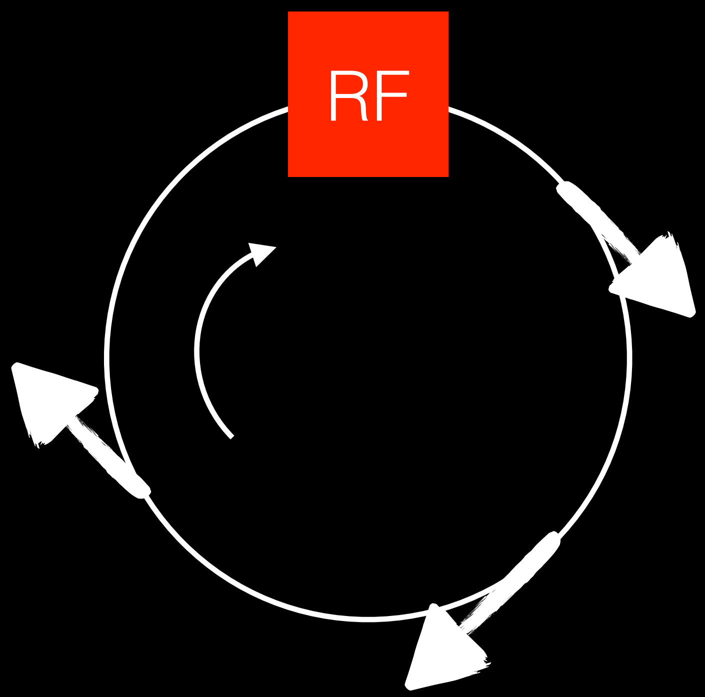

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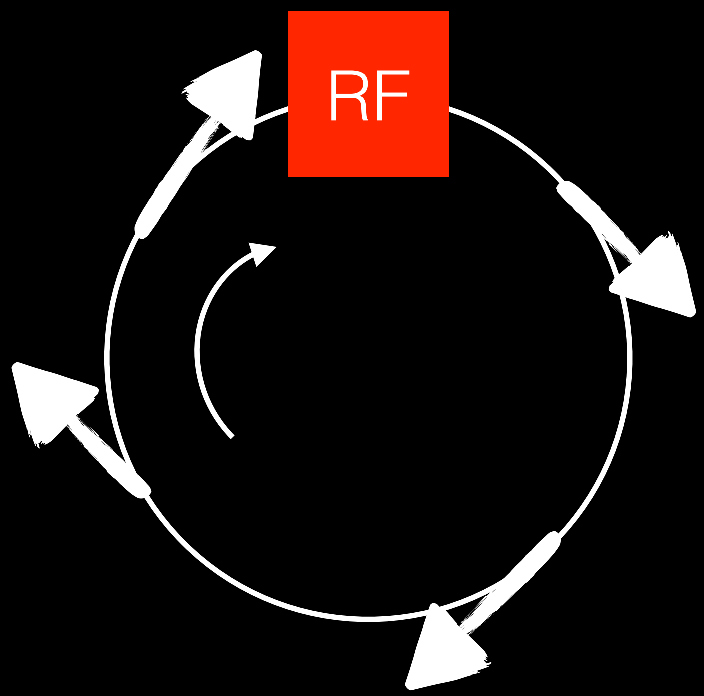

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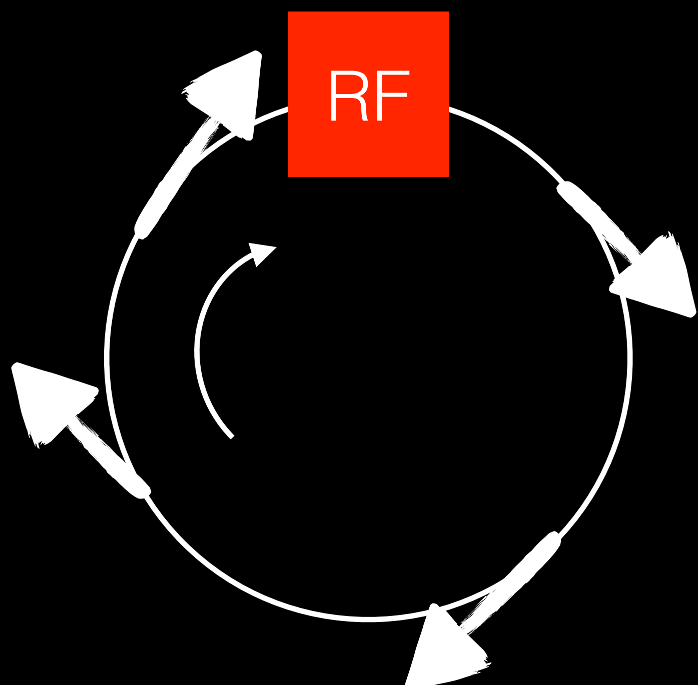

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- Lighter particles emit more light in circular accelerators (radiation~$(1/m^4)$)

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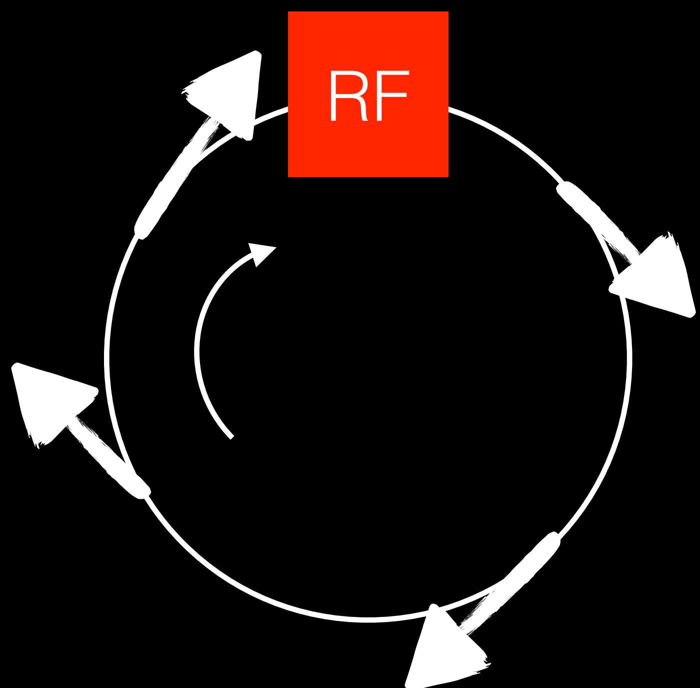

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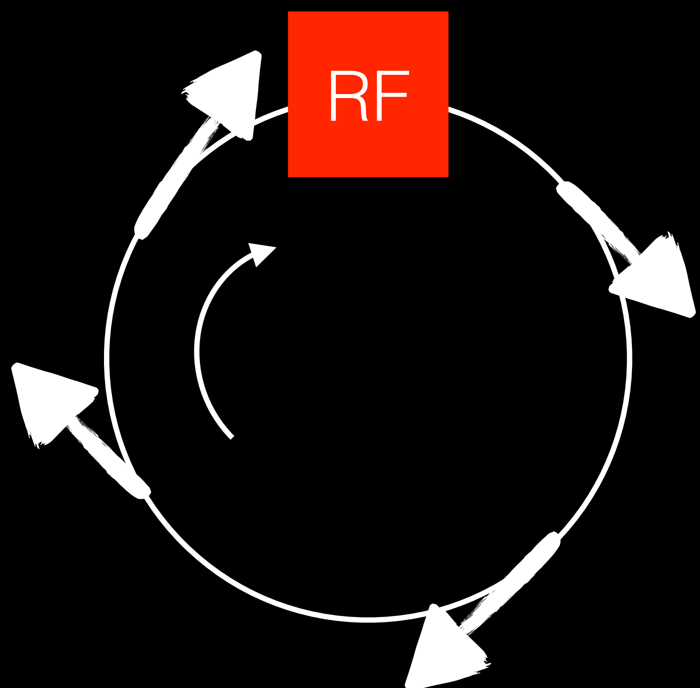

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- Emitted light can be useful! So many circular machines accelerate light particles in order to produce light

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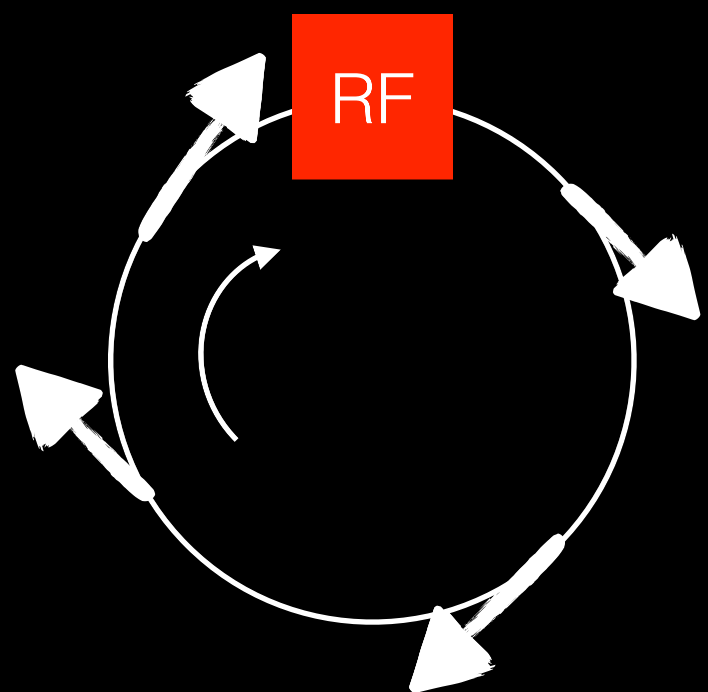

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Light-sources; more about that later!

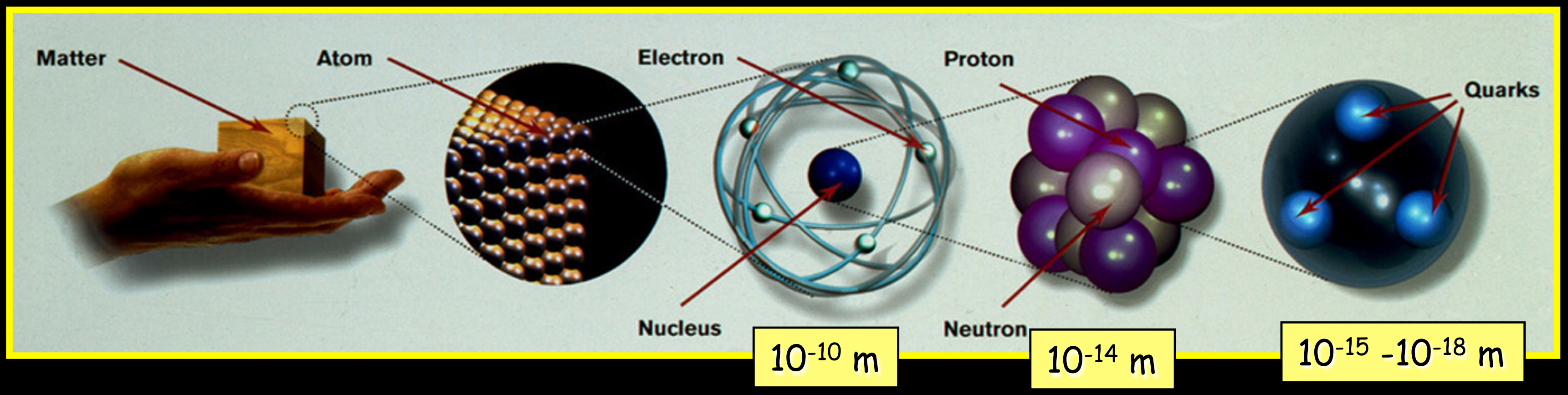
Where are accelerators used

- Research & Development

[1]

Fundamental physics

Study the elementary particles (e.g. the building blocks of matter: electrons and quarks) and the forces that control their behaviour at the most fundamental level



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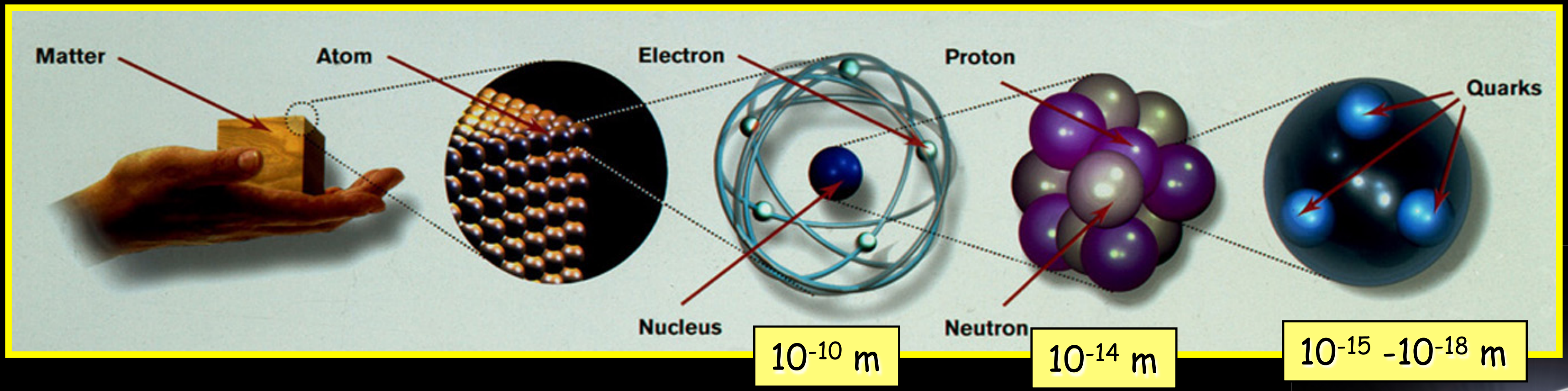
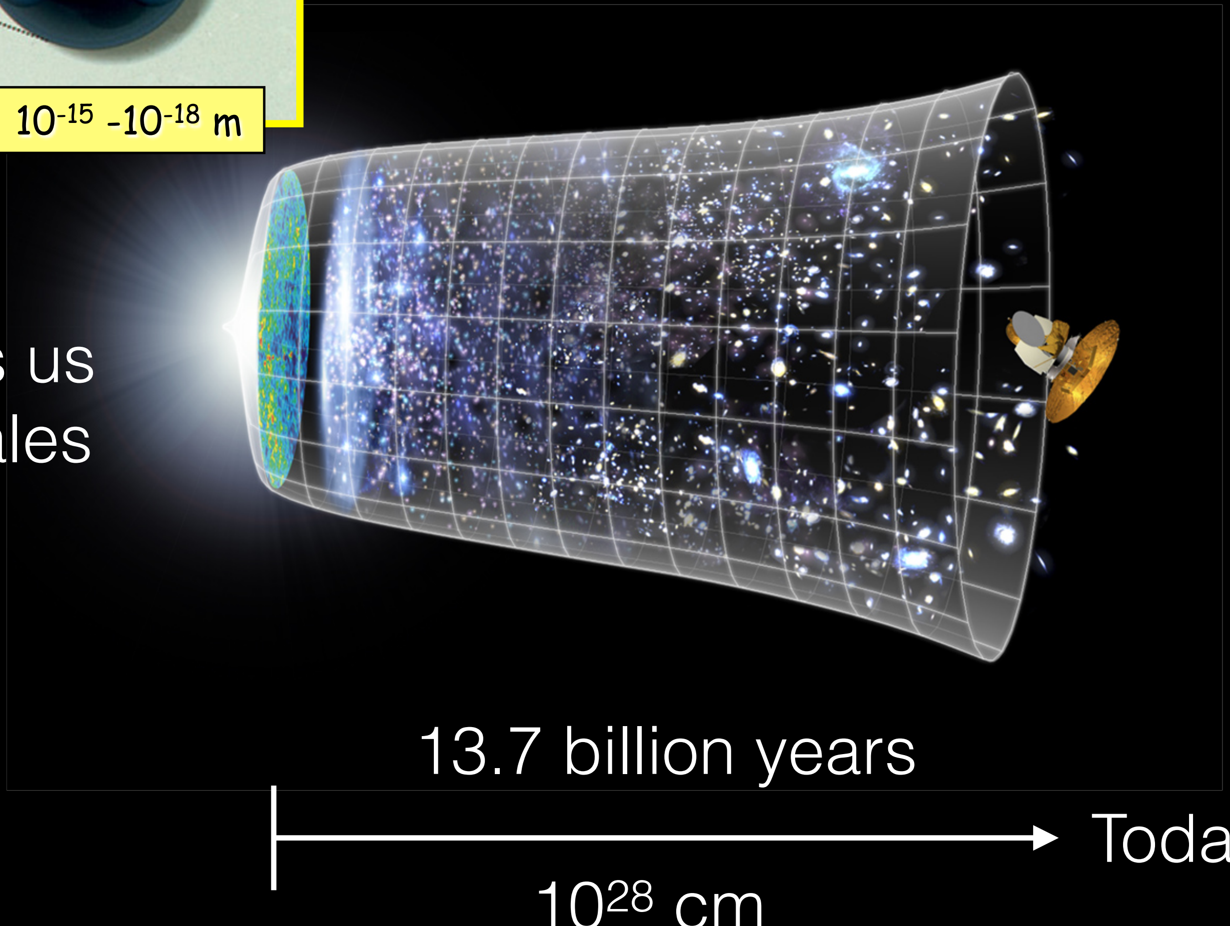


Particle physics at modern accelerators allows us to study the fundamental laws of nature on scales down to 10^{-18} m

- insight into the structure and evolution of the Universe
- from the very small to the very big



The Standard Model

The Standard Model

- The elementary particles and their interactions are described by a very successful theory: the Standard Model (SM)

- Before the LHC, all particles (but one, the Higgs boson) foreseen by the SM had been observed, and the SM predictions had been verified with extremely high precision by experiments at CERN and other labs all over the world (over 50 years)

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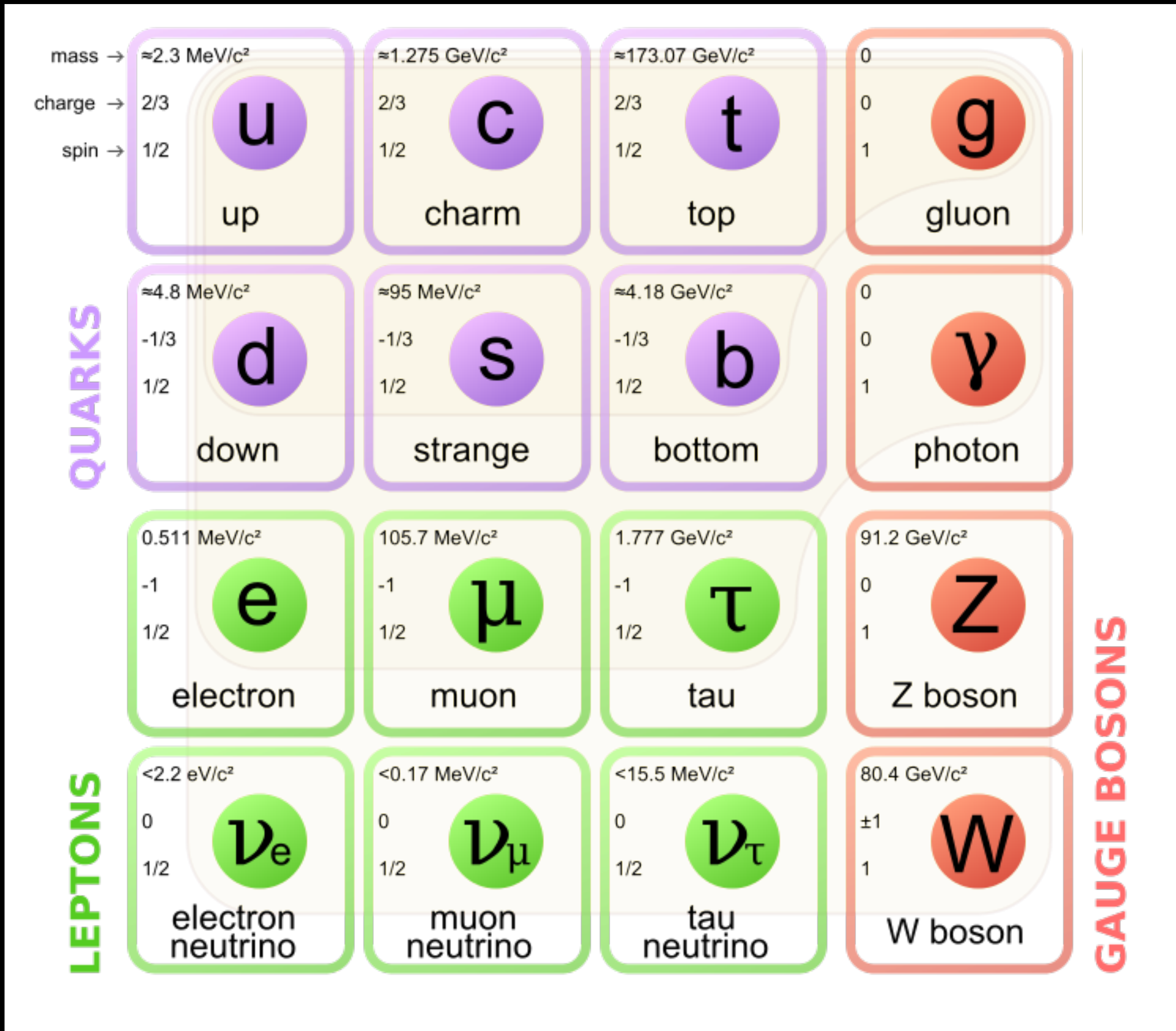

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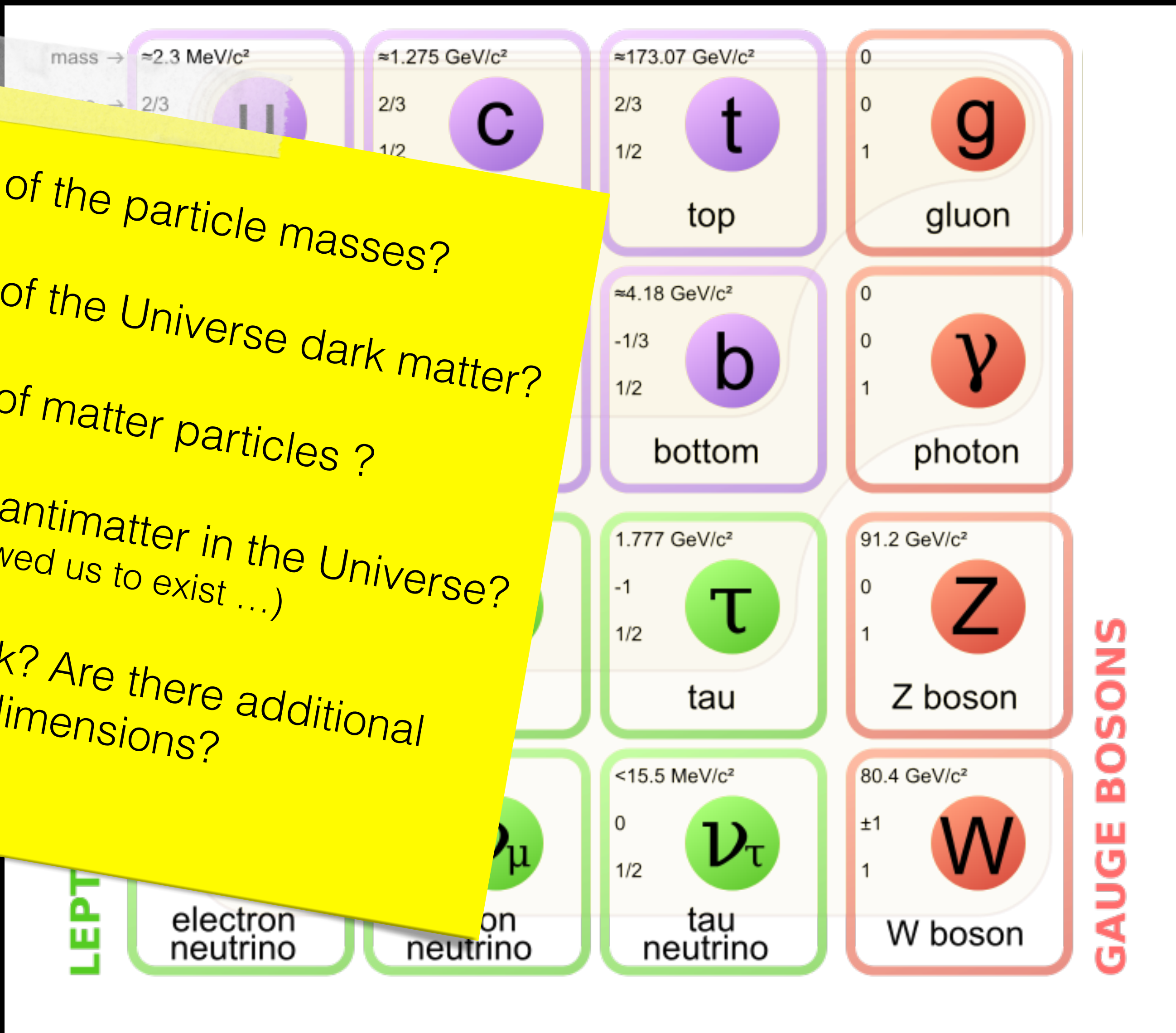

What is the origin of the particle masses?

What is the nature of the Universe dark matter?

Why 3 generations of matter particles ?

Why is there so little antimatter in the Universe?
(Nature's favouritism allowed us to exist …)

Why is gravity so weak? Are there additional (microscopic) space dimensions?

…..

The Standard Model

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The LHC at CERN is built to address these and other fundamental questions

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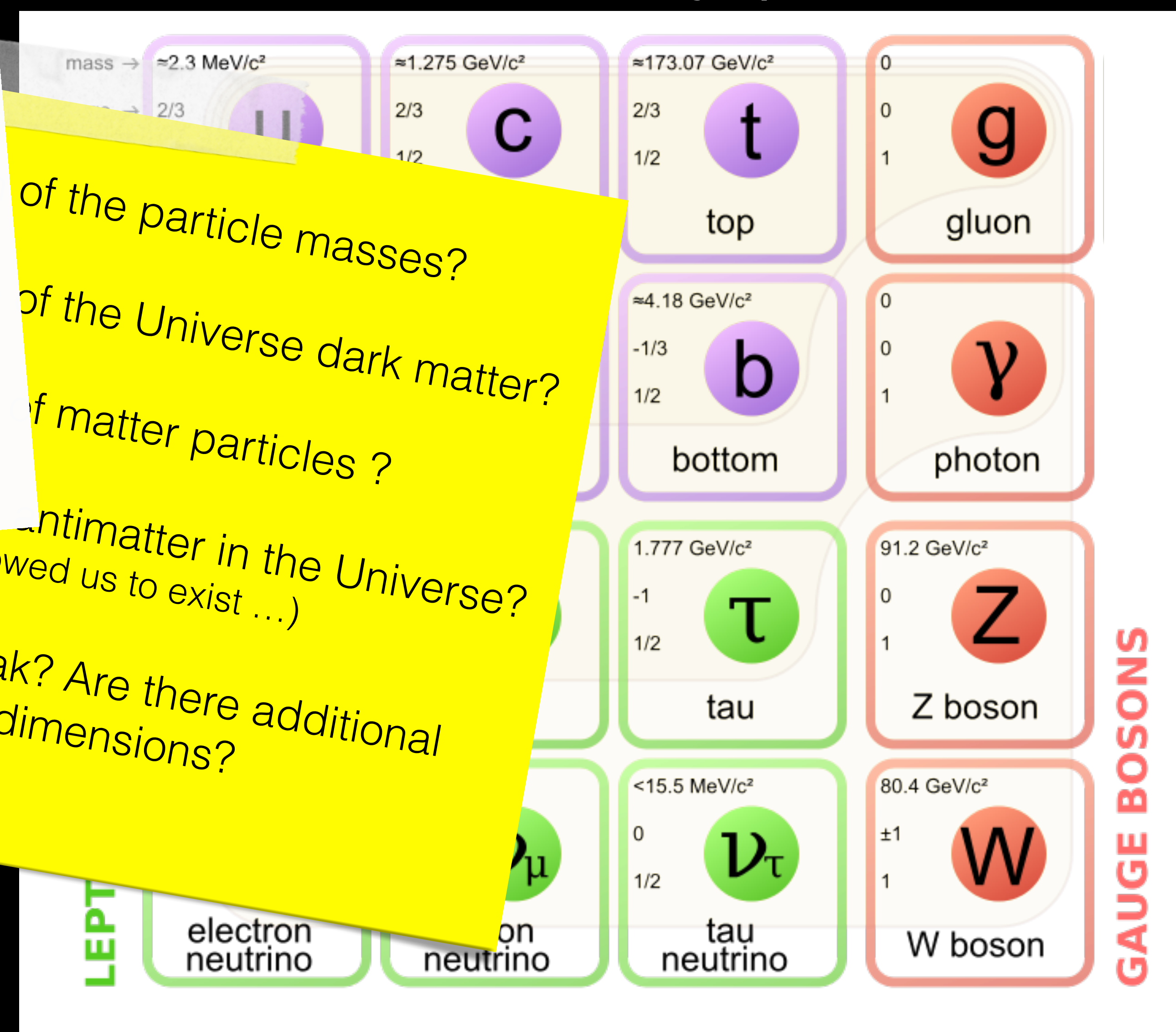
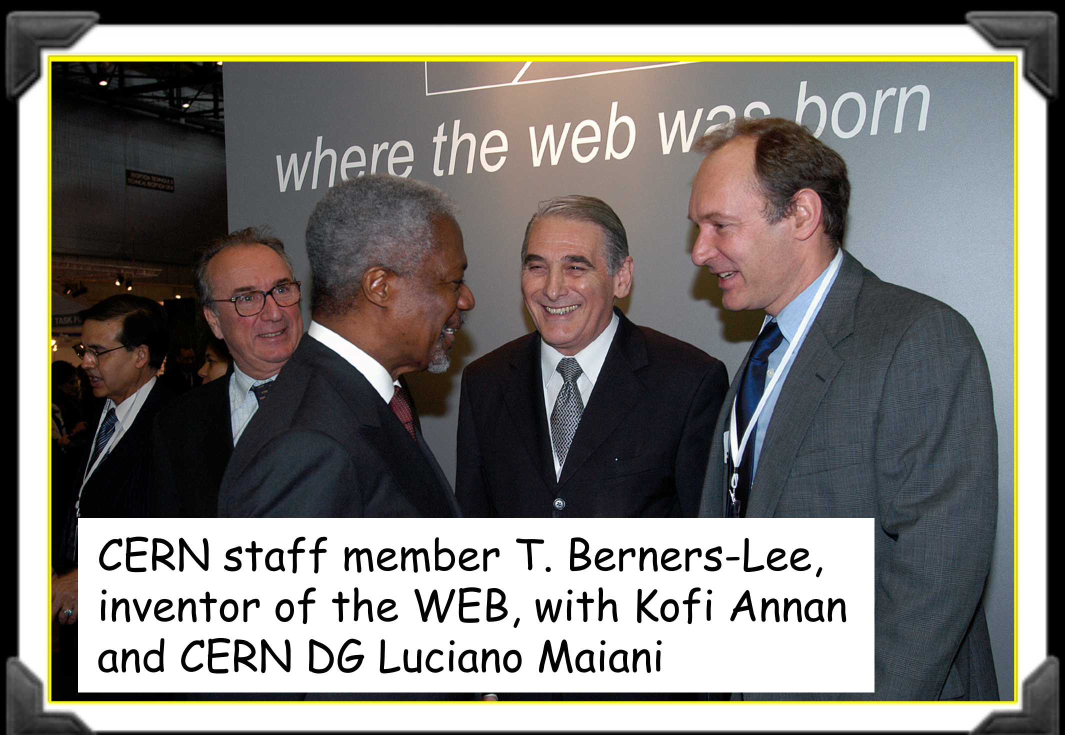


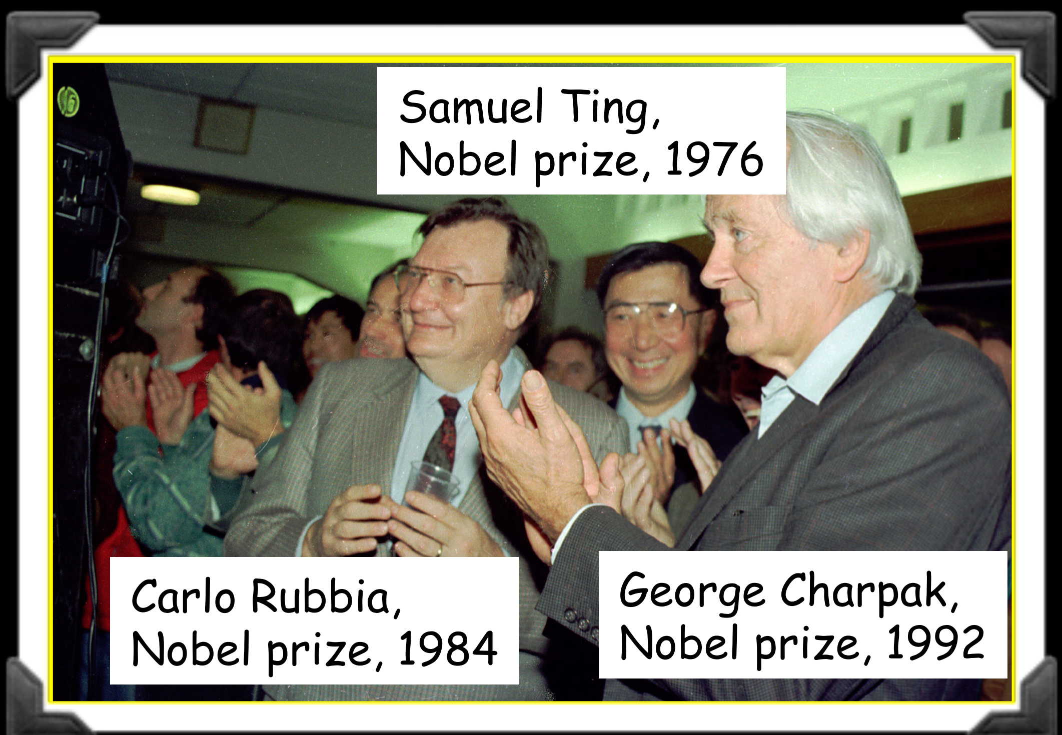
CERN: European Organisation for Nuclear Research

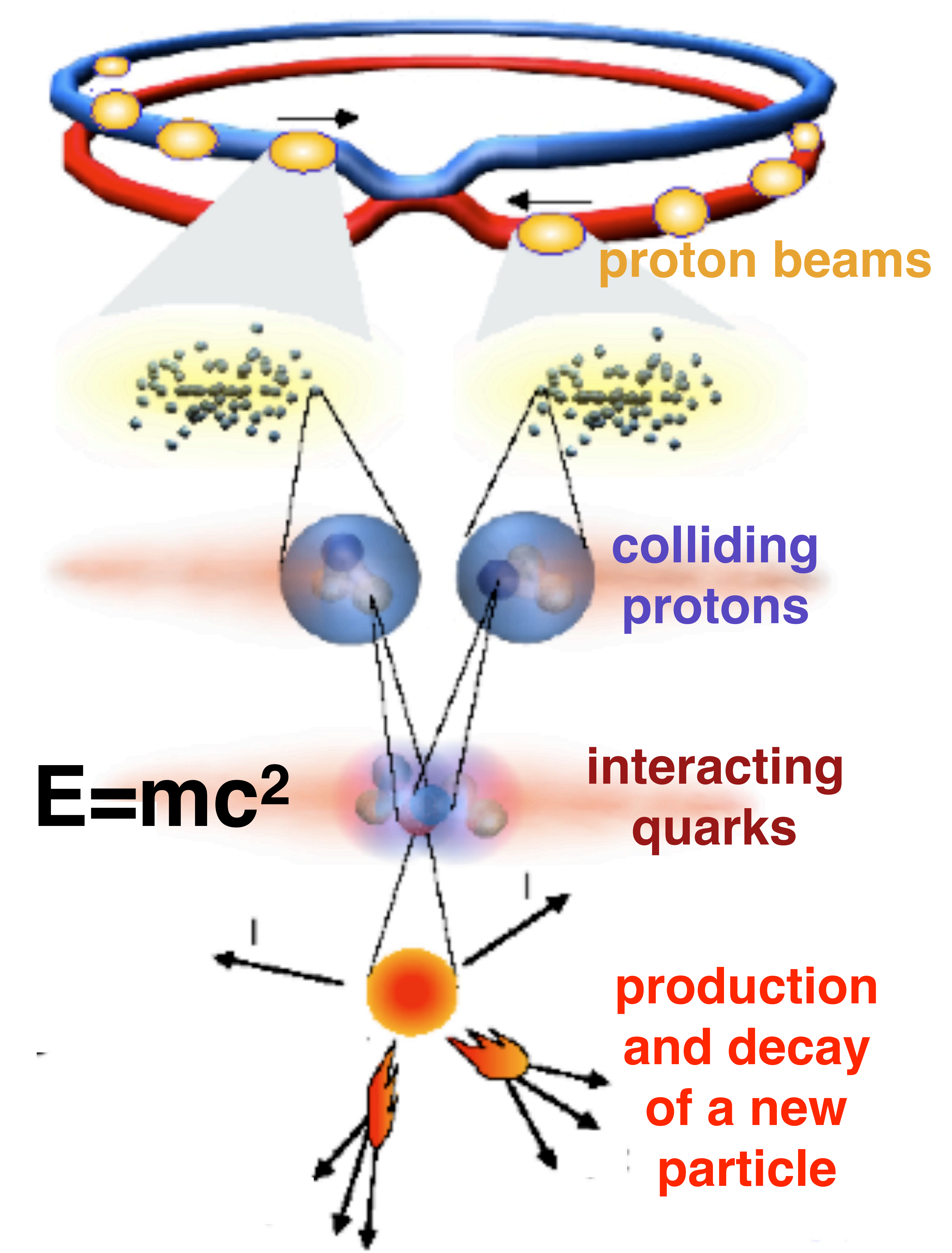
The world's largest particle physics laboratory
Recently celebrated 60 years of:

- fundamental research and discoveries (and Nobel prizes)
- technological innovation and technology transfer to society (e.g. WWW)
- training and education (young scientists, school students and teachers)
- bringing the world together (10,000 scientists from >100 nationalities)



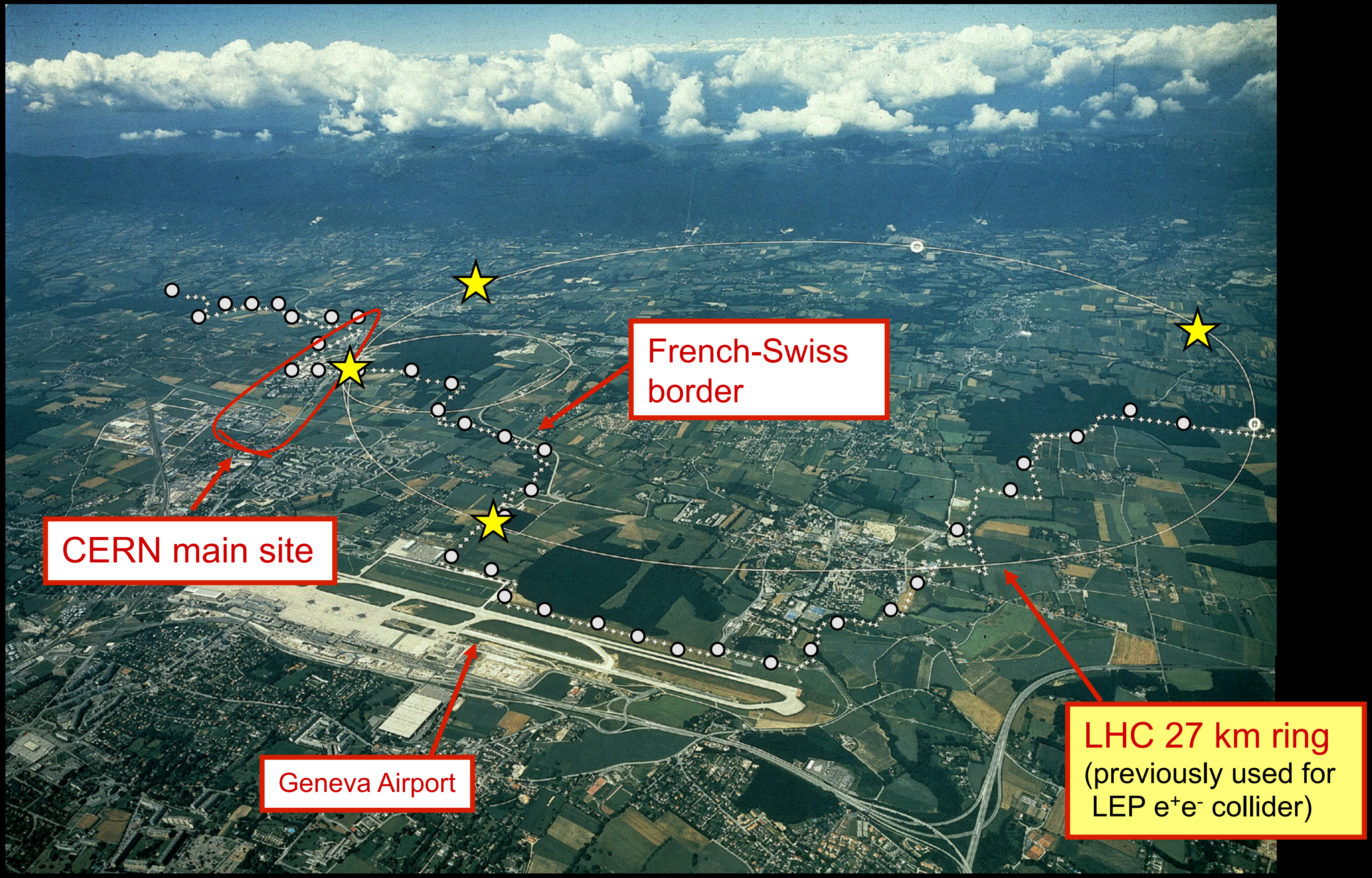
CERN staff member T. Berners-Lee, inventor of the WEB, with Kofi Annan and CERN DG Luciano Maiani


Samuel Ting, Nobel prize, 1976
Carlo Rubbia, Nobel prize, 1984
George Charpak, Nobel prize, 1992


proton beams
colliding
protons
interacting
quarks
$E=mc^2$
production
and decay
of a new
particle

LHC: the Large Hadron Collider

- 27 km ring, 50-175 m underground, across France/Switzerland
- 2 high-energy proton beams circulating in opposite directions and colliding at 4 points, where 4 big experiments have been installed
- Unprecedented collision energy: 8 TeV —> 13 TeV



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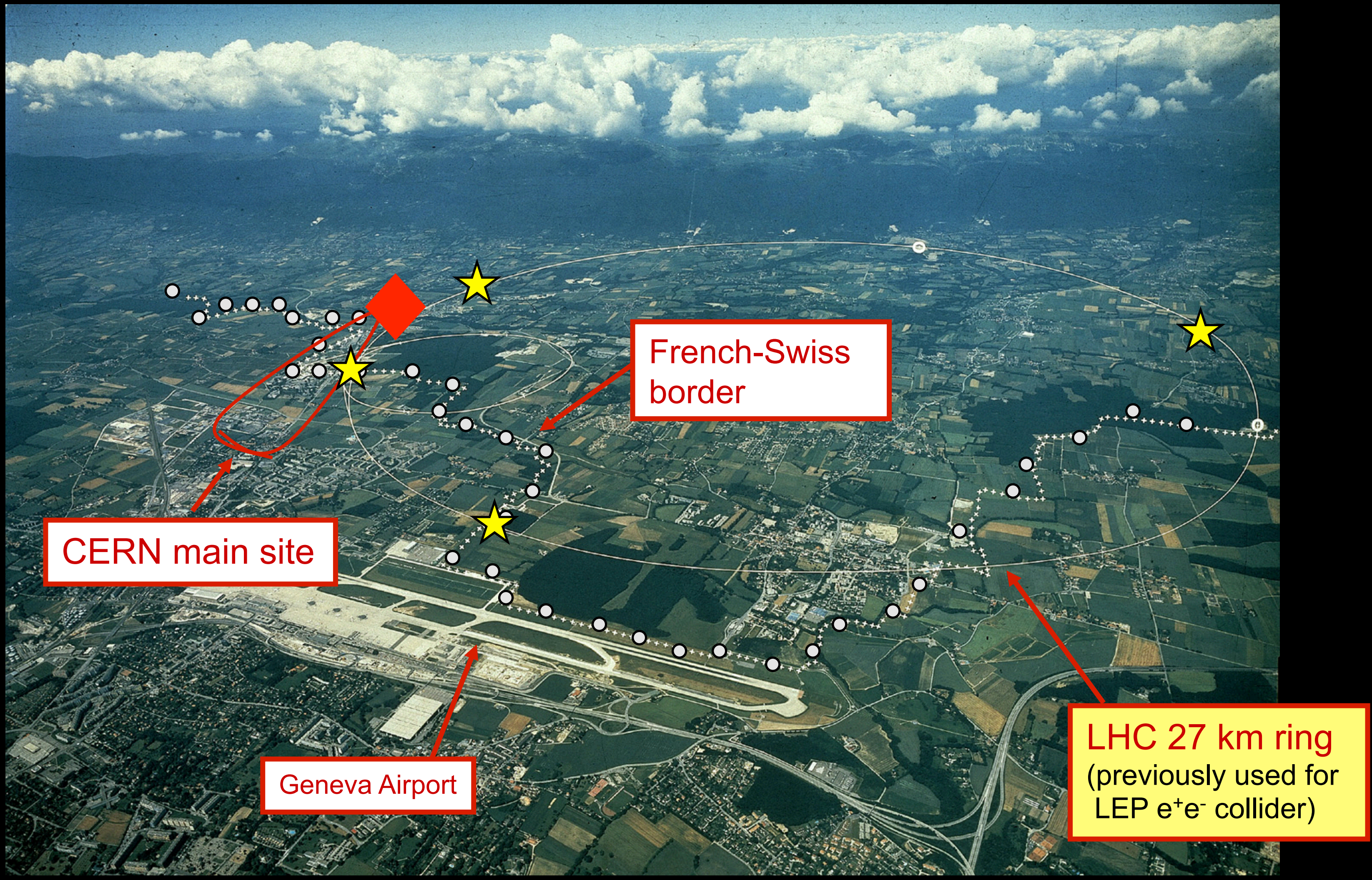

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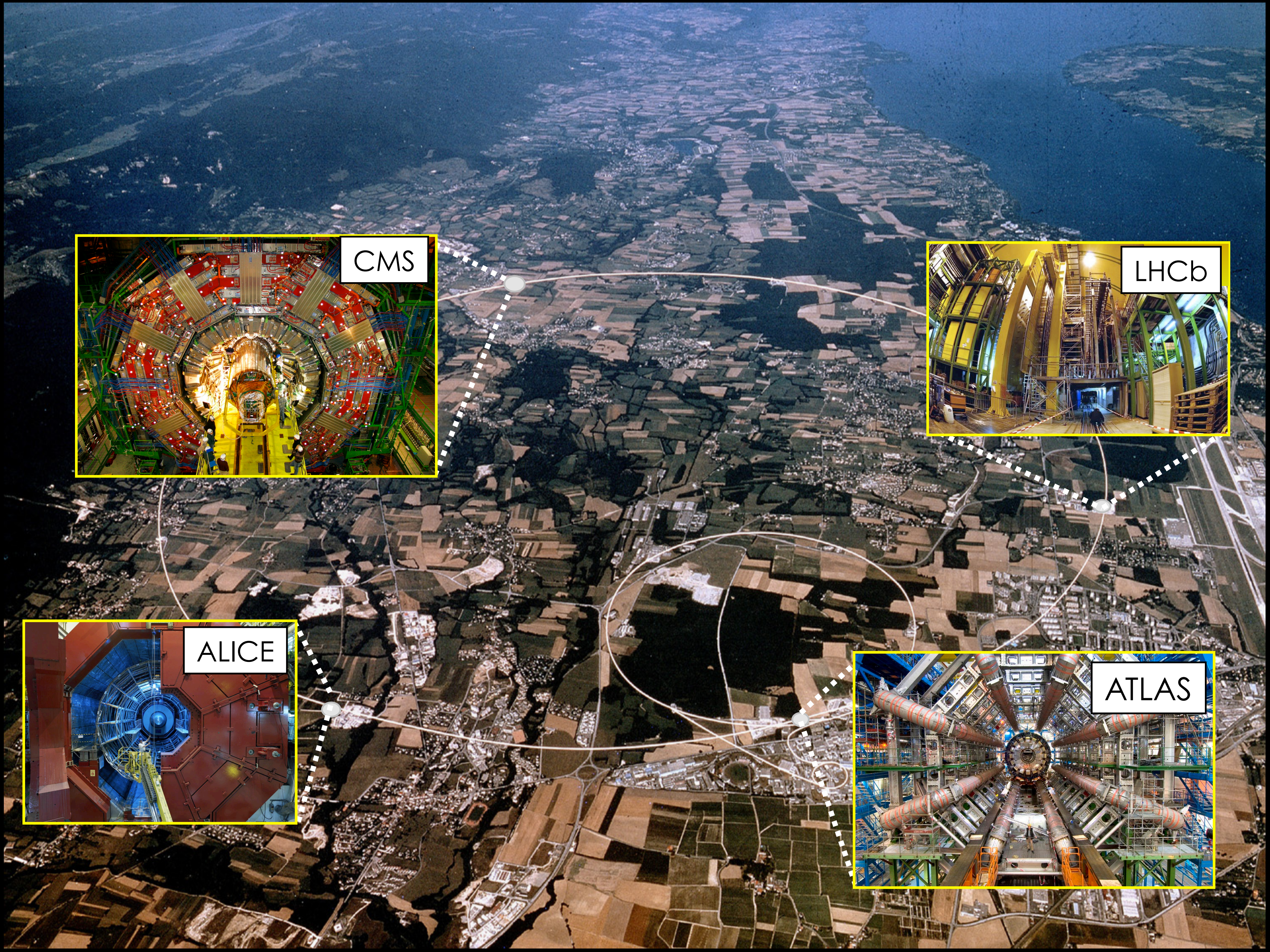

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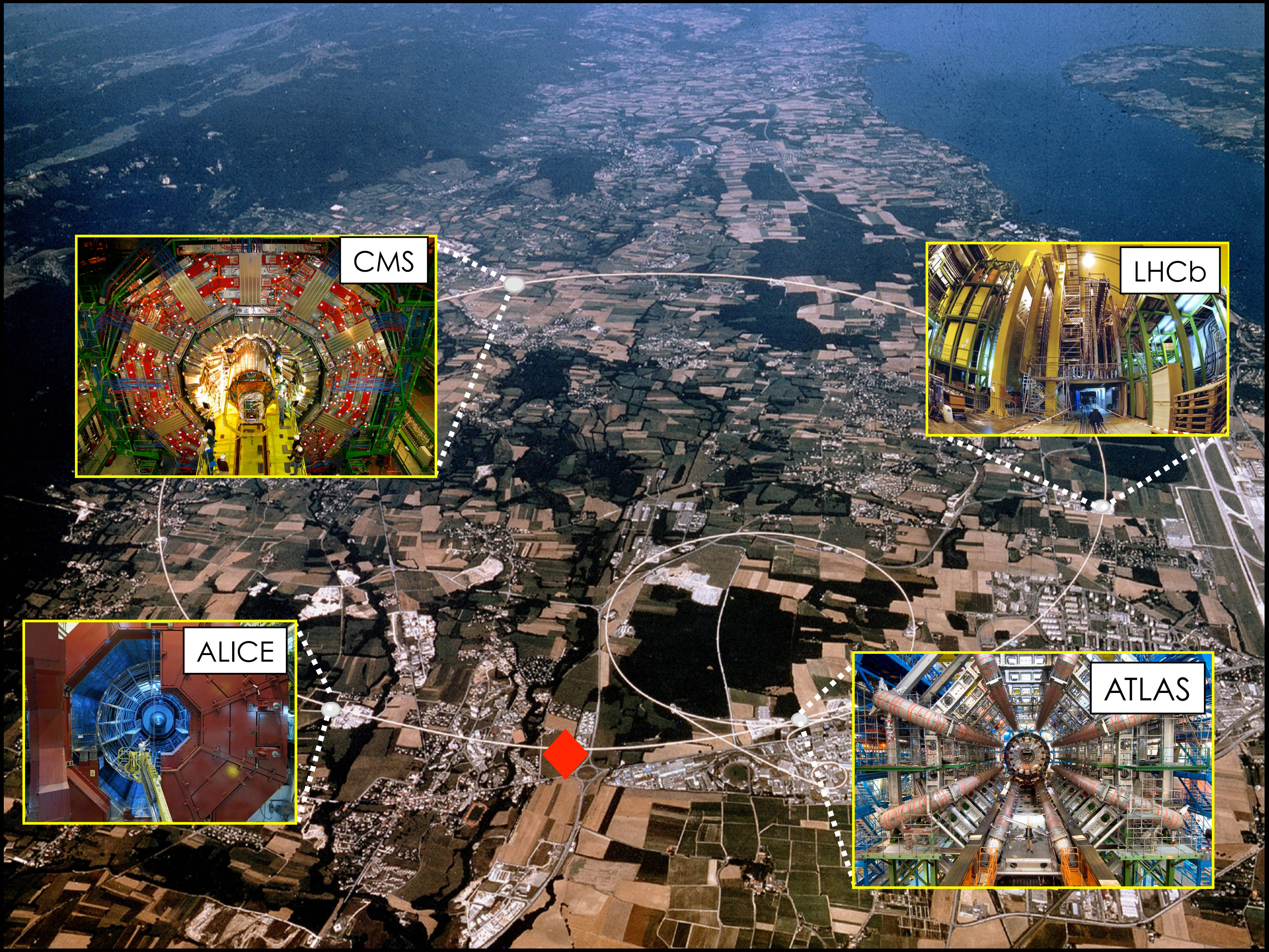
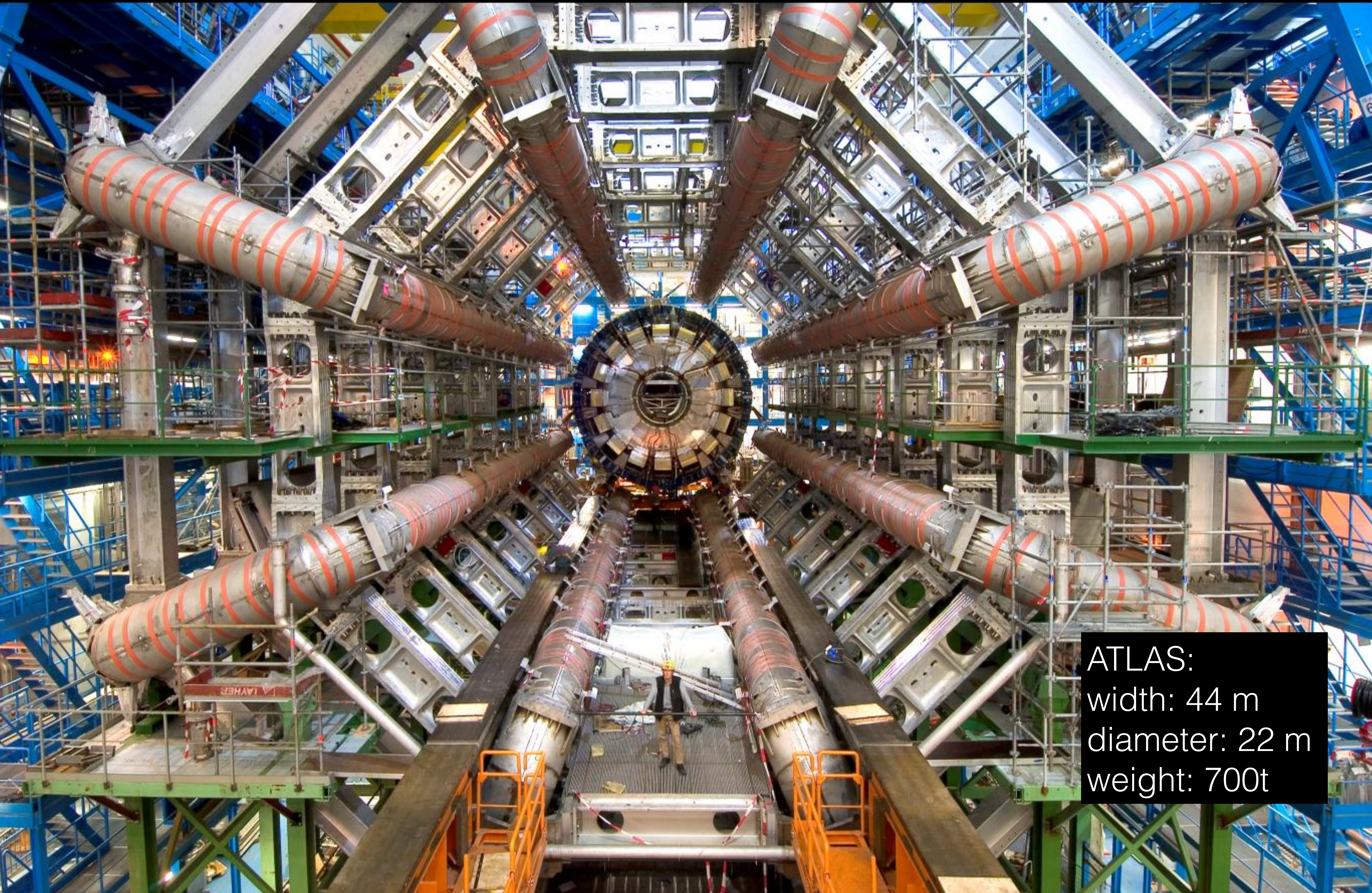


ATLAS Detector



LHC: the Large Hadron Collider

- The highest energy and most powerful accelerator in the world

- The most high-tech and complex detectors
- The most advanced computing infrastructure
- The most innovative concepts and technologies (cryogenics, new materials, electronics, data transfer and storage,…)
- The widest international collaborations

EVER achieved in accelerator-based particle physics

One of the most ambitious projects in science in general

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20Nov2009
Operation starts
(>20 yrs from concept to start of operation)

Feb2013
End of 1st
data-taking period
E@collision: 8 TeV

Mar2015
Start of 2nd
data-taking period
E@collision: 13 TeV

The highest energy ever achieved by a particle accelerator

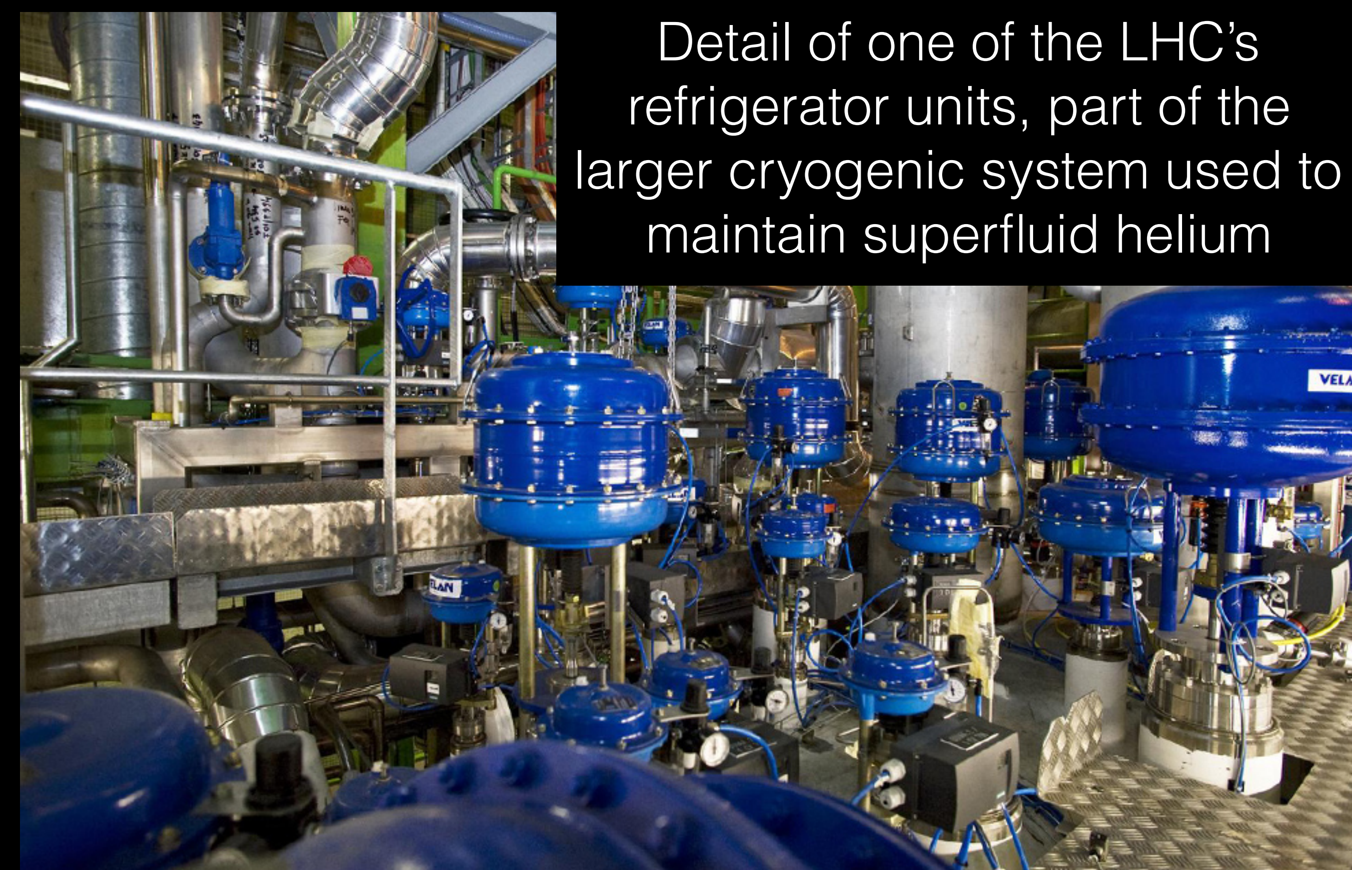
- Unprecedented energy: 6.5 TeV per beam particle; collision energy: 13 TeV in 2015 (1 TeV= 10^{-7} Joule)

Note: huge amount of energy concentrated in the collision point (13 TeV corresponds to 10^{14} times the temperature in this room); however, small energy on macroscopic scale (1 J just enough to swat a mosquito)

Cooler than outer space

Most challenging component of the LHC:

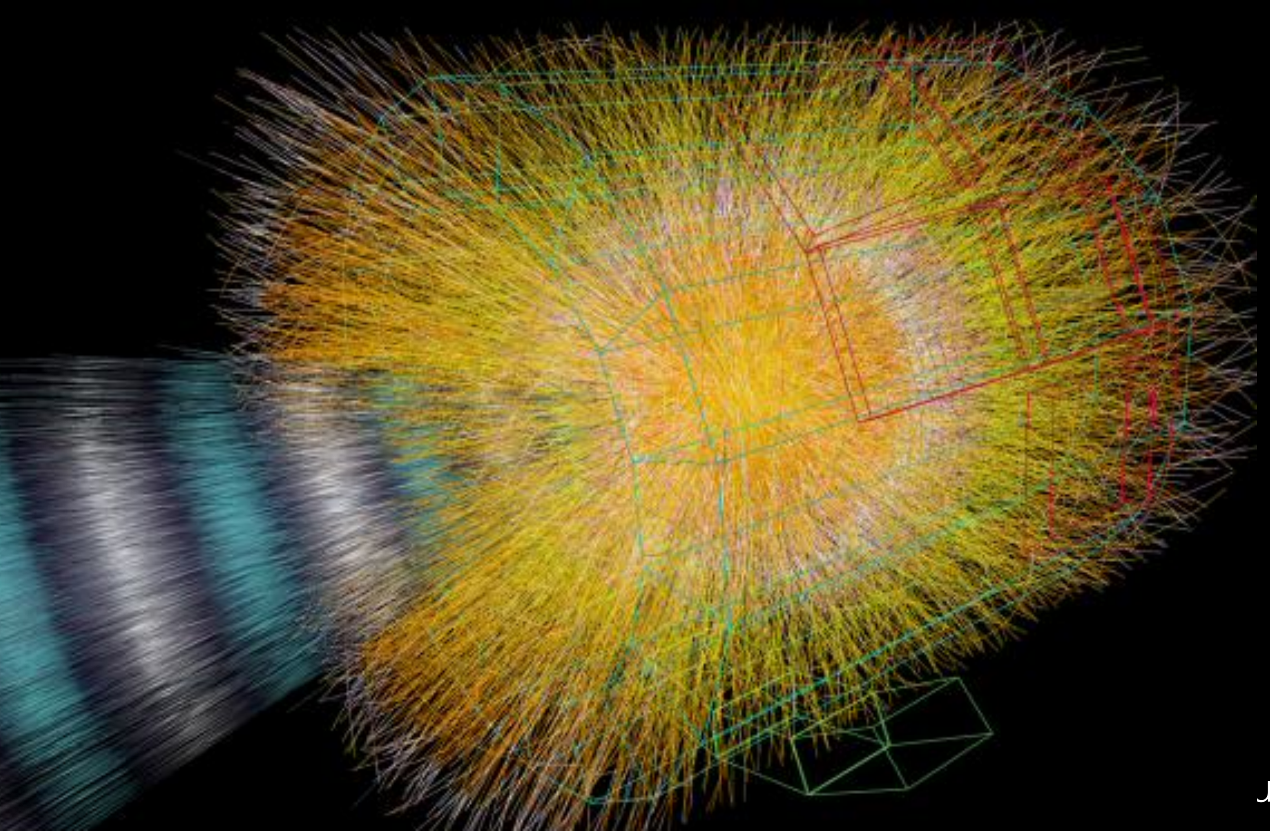
- 1,232 high-tech superconducting magnets
- provide 8.3 T (needed to bend 7 TeV beams inside a 27 km ring)
- 7,600 km of NbTi superconducting cable work at 1.9K (-271 C; outer space: 2.7 K=-270 C)

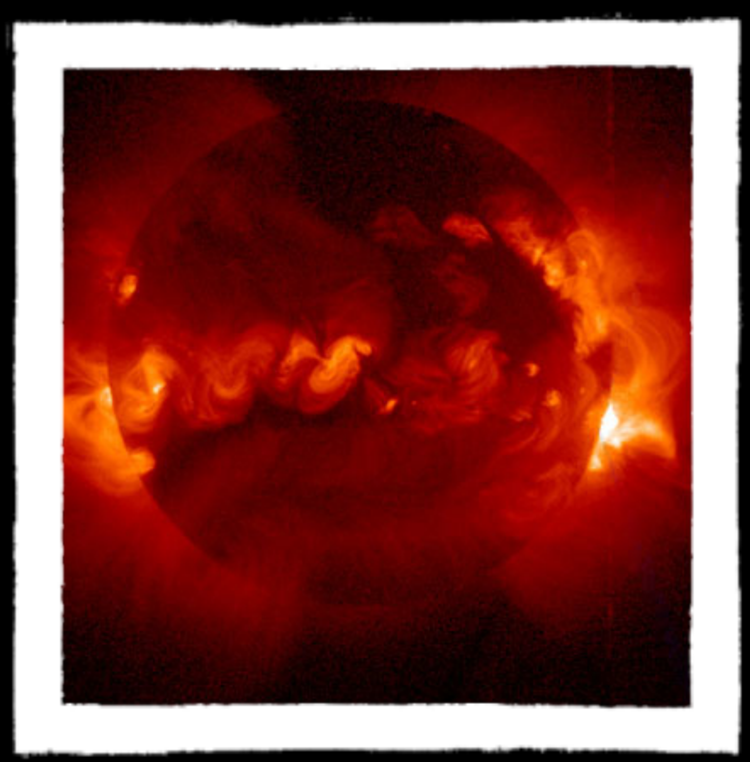


Detail of one of the LHC's refrigerator units, part of the larger cryogenic system used to maintain superfluid helium

Hottest place in the Galaxy

- 2.5×10^{14} protons circulate in each direction
- Energy stored in the beams (design operation): ~350 MJ (like a British aircraft carrier at 12 knots)
- Beam cross section at collision points: 16 μm (~4x smaller than that of a typical a human hair)
- Particle collisions create (within a tiny volume) temperatures of >1.6 trillion C (100,000 times higher than in the centre of the sun)





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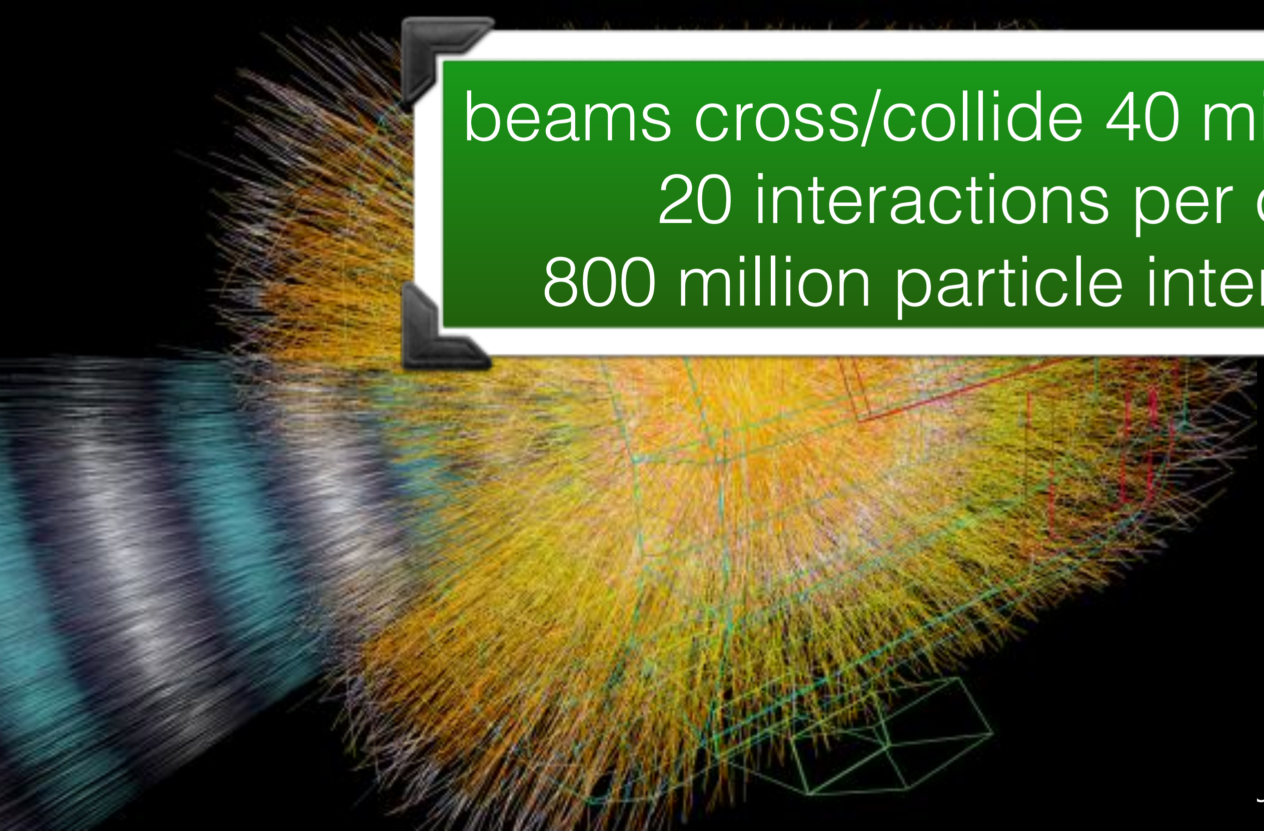
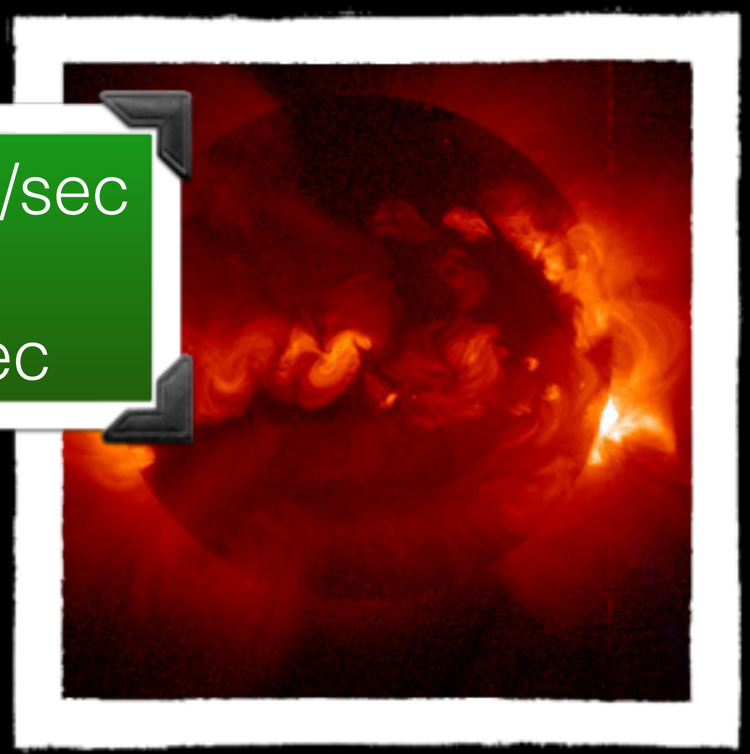
- 2.5×10^{14} protons circulate in each direction
- Energy stored in the beams (design operation): ~350 MJ (like a British aircraft carrier at 12 knots)
- Beam cross section at collision points: 16 μm (~4x smaller than that of a typical a human hair)
- Particle collisions create (within a tiny volume) temperatures of >1.6 trillion C (100,000 times higher than in the centre of the sun)



beams cross/collide 40 million times/sec
20 interactions per crossing
800 million particle interactions/sec



The Higgs mechanism

The Higgs mechanism

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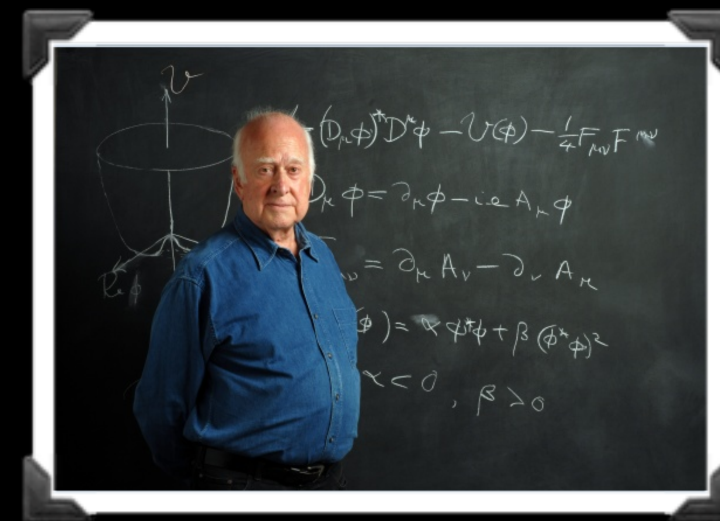
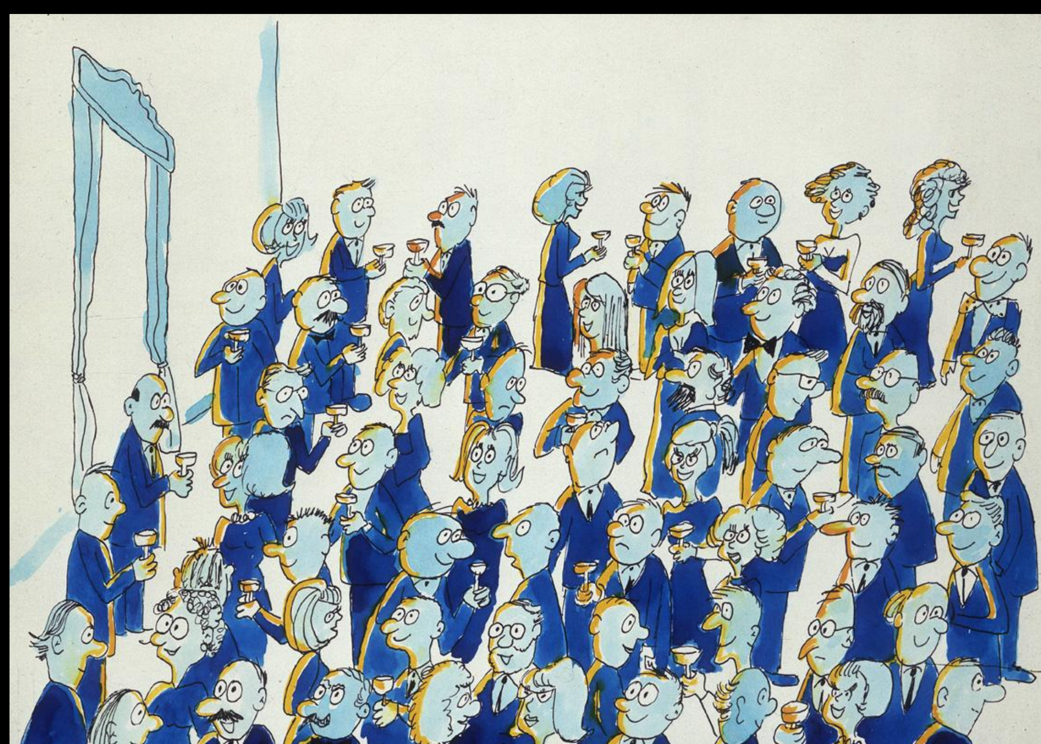
Note: a world without "Higgs" would be a very strange one!

The Higgs boson

The Higgs Mechanism as exemplified by Prof. David Miller, UCL





Imagine a room full of people quietly chattering. This is like space filled only with the Higgs field

[2]

The Higgs boson

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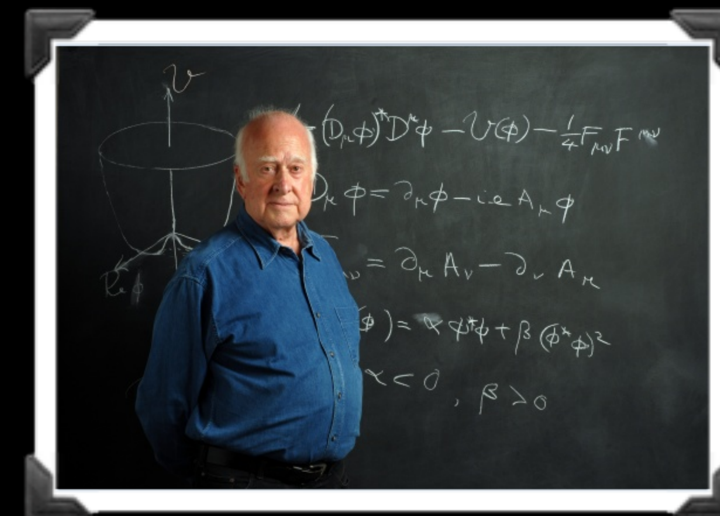

A well known politician walks in, creating a disturbance as she moves across the room, and attracting a cluster of admirers with each step. The politician is like a particle traversing the Higgs field

[2]

The Higgs boson

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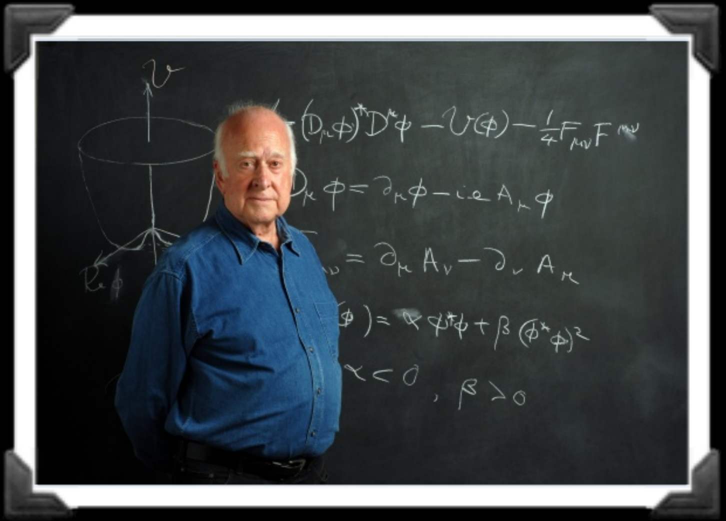
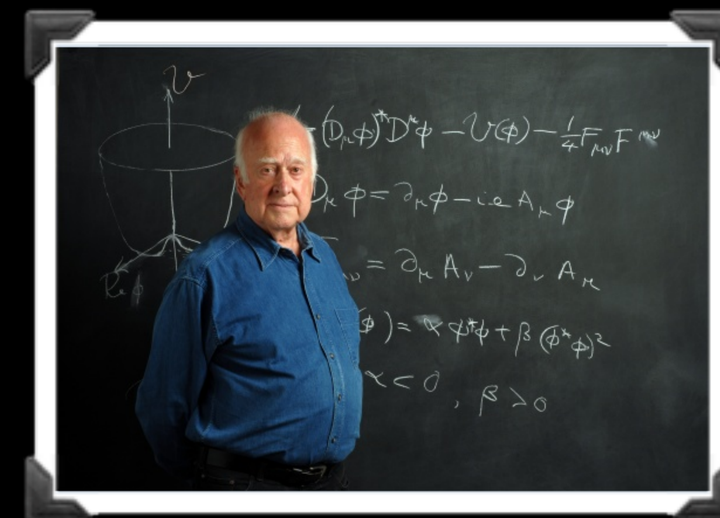


This increases her resistance to movement, i.e. she acquires mass, just like a particle moving through the Higgs field

[2]

The Higgs boson



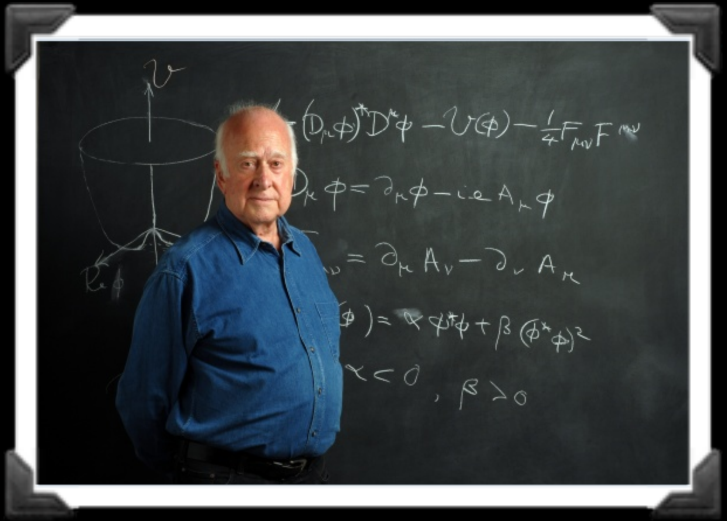
The Higgs Mechanism as exemplified by Prof. David Miller, UCL

A rumour crosses the room….

[2]

The Higgs boson

The Higgs Mechanism as exemplified by Prof. David Miller, UCL



It creates the same kind of clustering, but this time among the people in the room. In this analogy, these clusters are the Higgs particle

[2]

The Higgs boson

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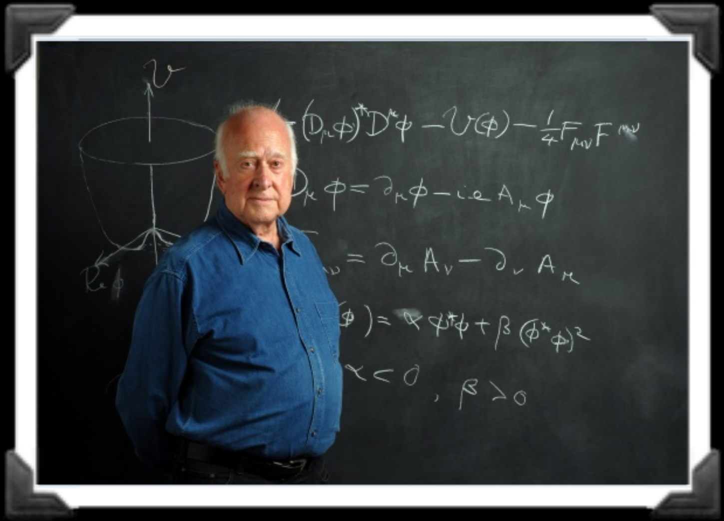

July 2012: discovery by ATLAS and CMS of a new Higgs-like particle with mass ~125 GeV (~130x proton-mass)

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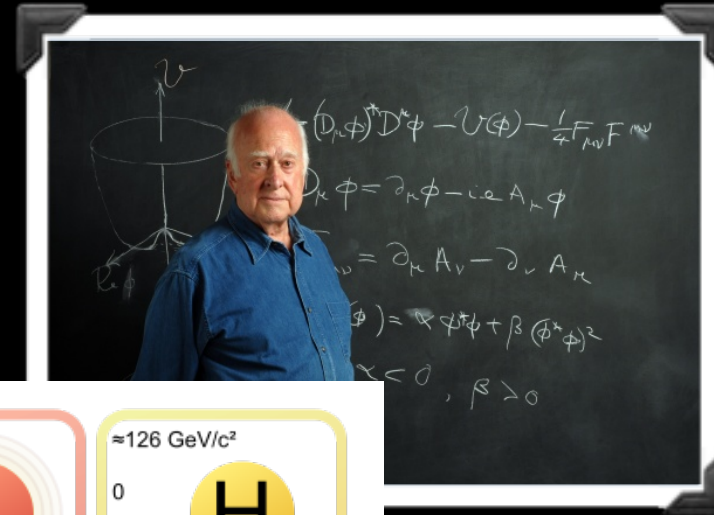

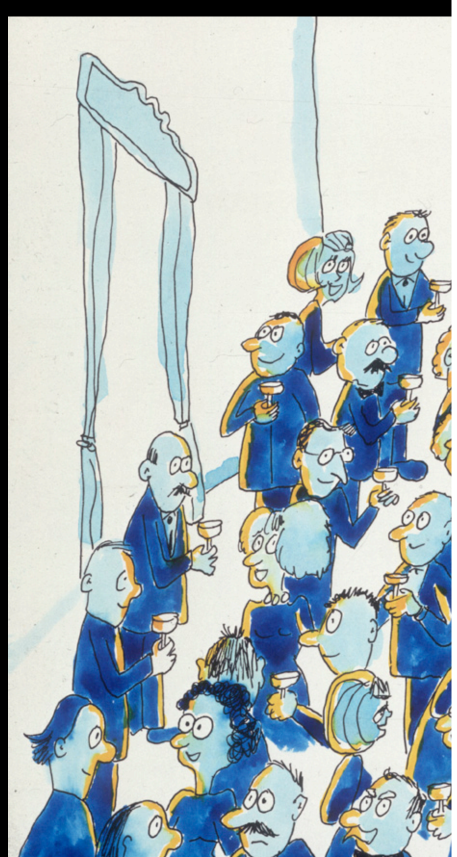

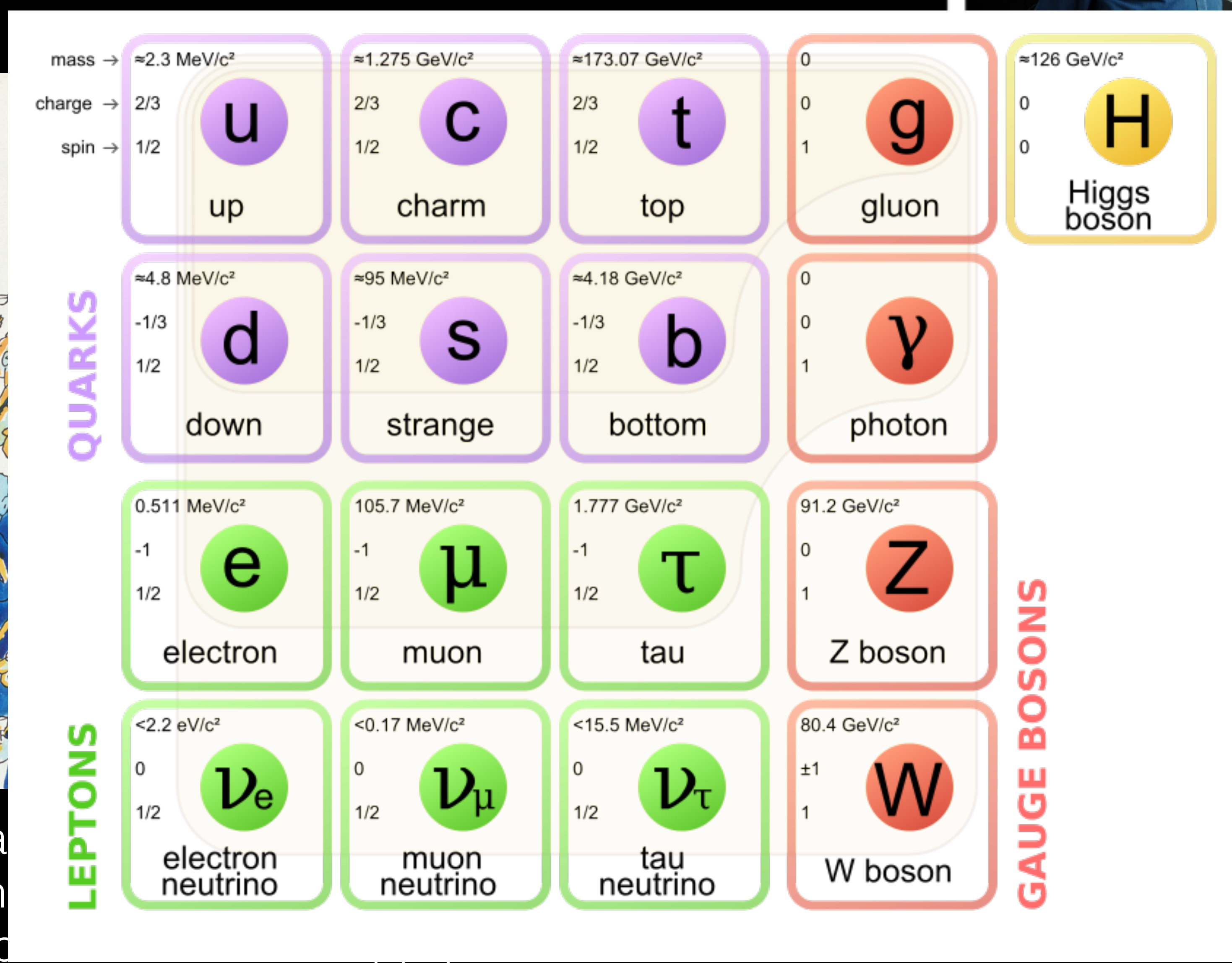

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It creates the sa
time among th
analogy, these c

[2]

Future of High Energy Physics

More powerful accelerators will be needed in the future to address the unanswered questions, requiring new ideas, ingenuity, new developments in order to provide higher energy at affordable costs

Future of High Energy Physics

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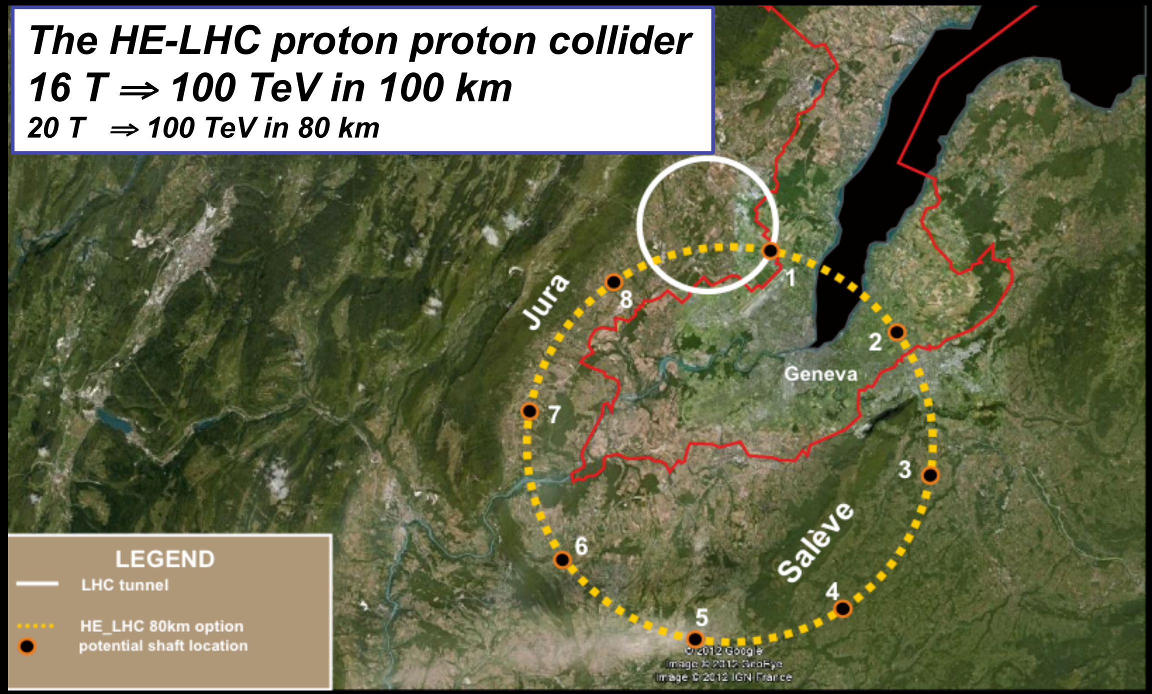
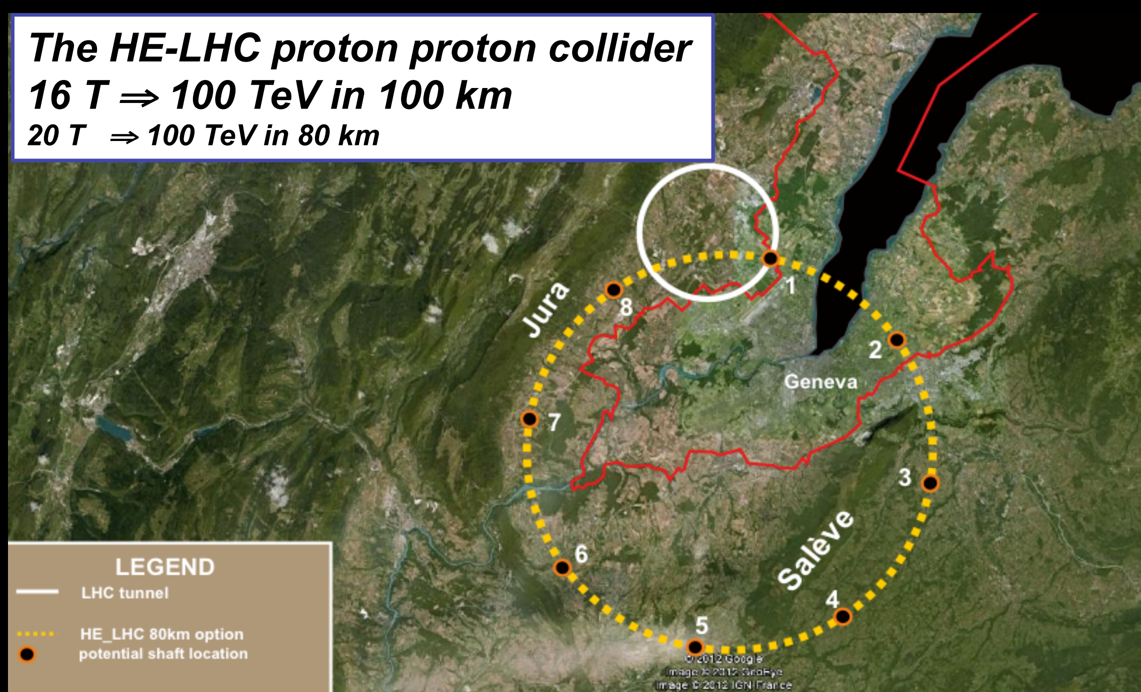
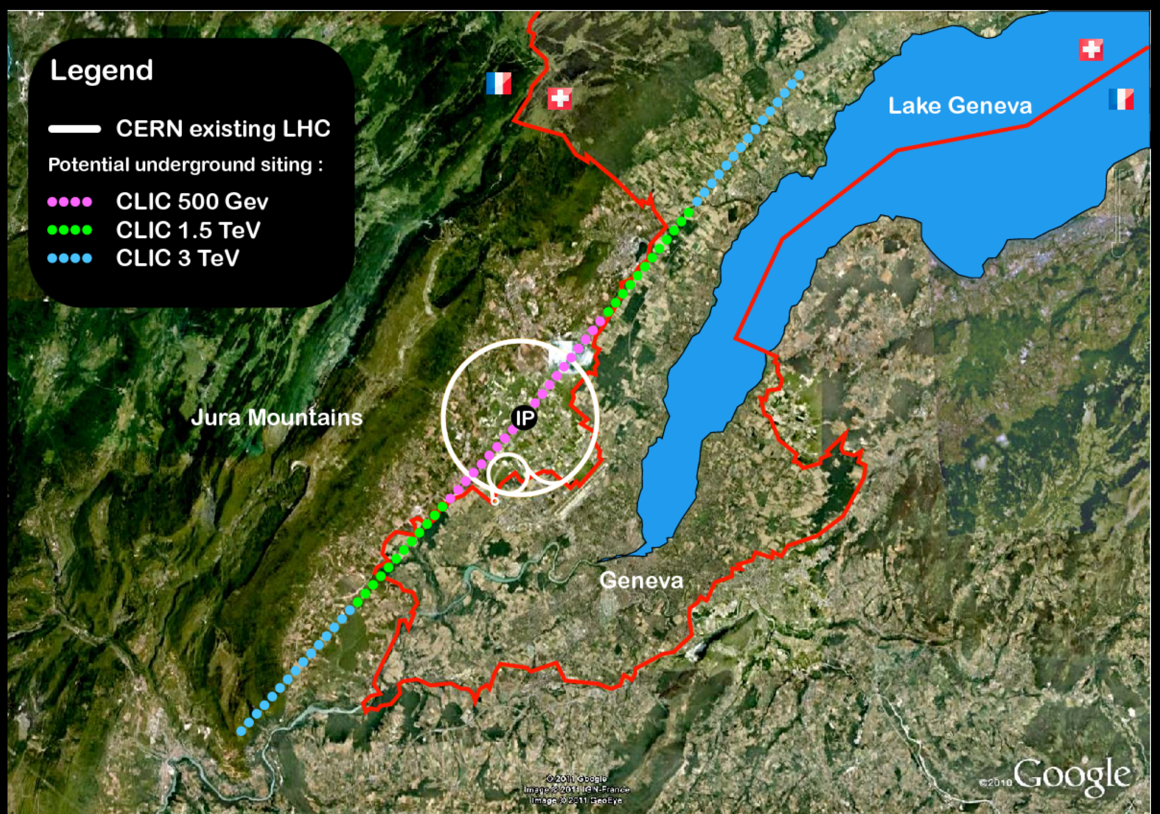


Future Circular Collider (FCC):

- High energy collider studies for pp /e^+e^- in a 80-100 km tunnel

Future of High Energy Physics





Future Circular Collider (FCC):

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Compact Linear Collider (CLIC):

- High-energy and high-luminosity collider carried out by a world-wide collaboration
- Will accelerate and collide electrons and positrons at a nominal energy of 3 TeV (energy scale never reached by any existing lepton collider), 42km

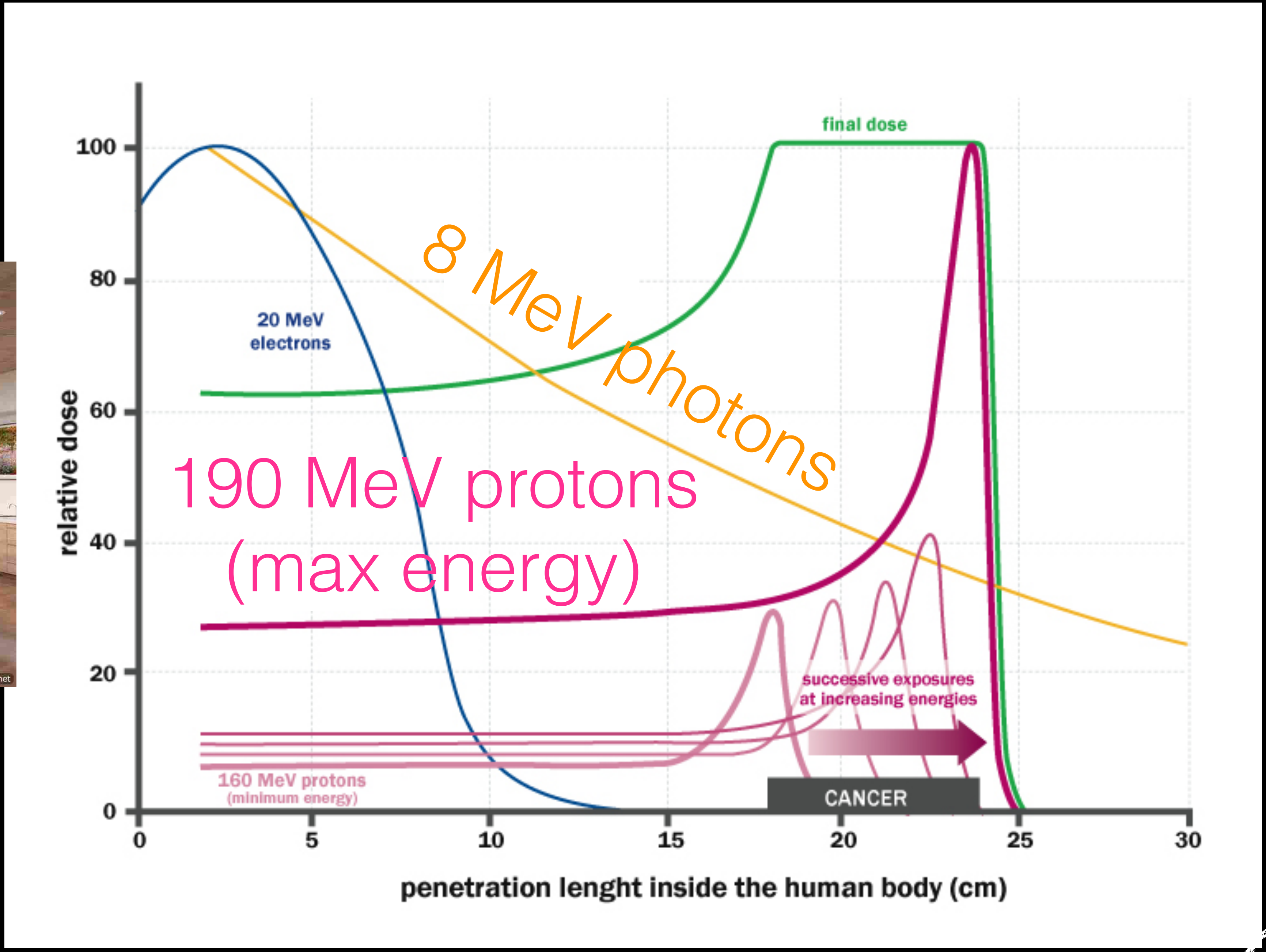
Where are accelerators used

- Health & Medicine

Health and Medicine

Treating cancer—radiotherapy—the most common treatment for cancer:

- beam of radiation is fired into the body by particle accelerator
- dose deposition and biological consequences depend on beam particle type used and its energy



Health and Medicine

Medical imaging (X-ray image, MRI scan, PET etc)

Positron Emission Tomography (PET): medical imaging technique; produces detailed 3D image

- radioactive isotope introduced to the body; results in photons emitted and detected; image production
- physics behind this technique first understood by particle physicists who played a role in the development of the technique
- detectors of PET scanners first developed for particle physics experiments
- accelerators are used for the synthesis of radioisotopes

PET scan

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PET scan

My MRI scan :)

MRI: Magnetic Resonance Imaging (MRI)
Development in the 1970's

- ability to image soft tissue within the body
- basic physical principles first discovered by particle physicists in the 1930's
- accelerator physics: developed powerful superconducting magnets required for the technique to work

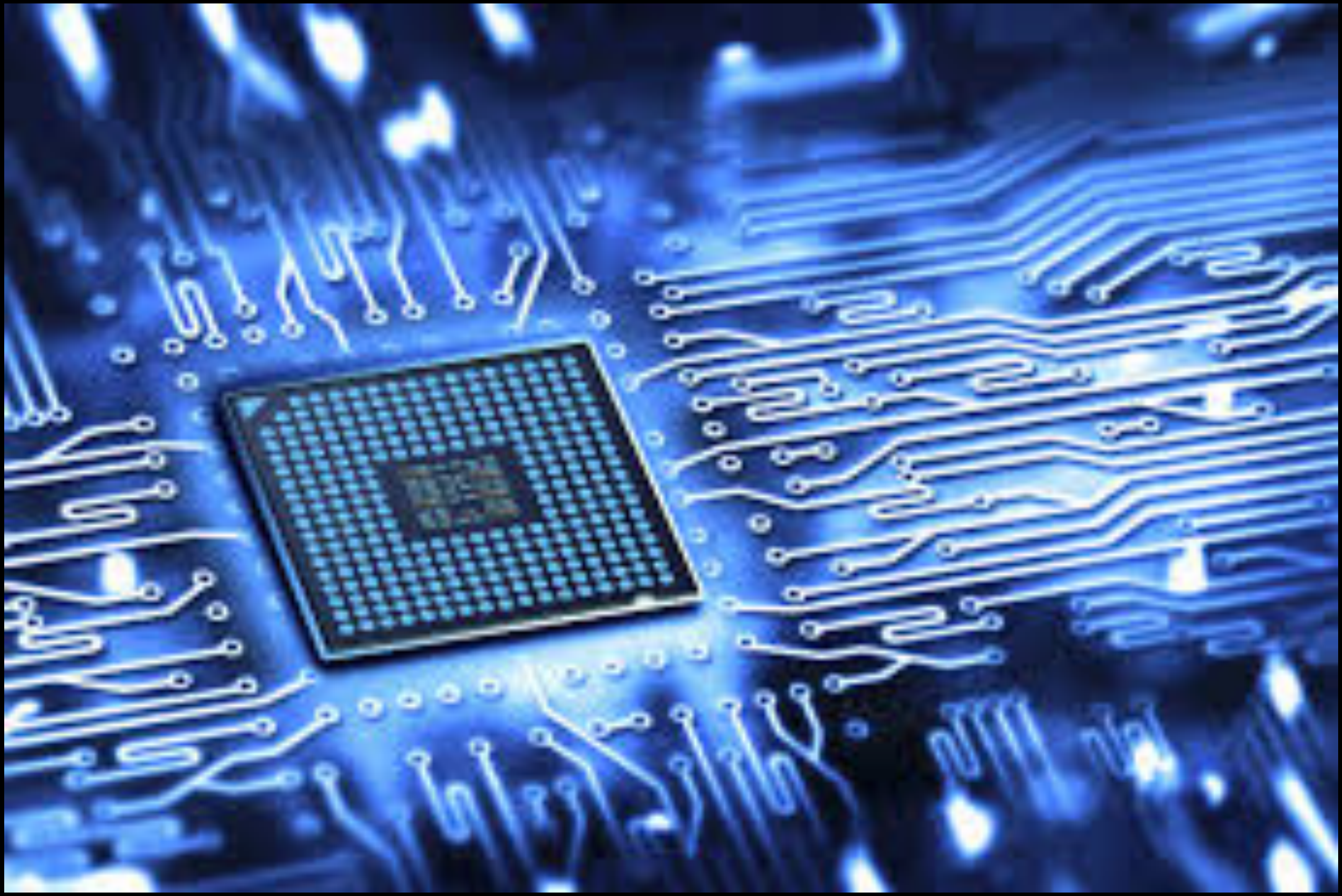
Where are accelerators used

- Energy & Environment
  - Oil and gas exploration
  - Biofuel production

Where are accelerators used

- Industry

- Ion implantation for electronics
- Hardening surfaces
- Hardening materials
- Welding and cutting
- Treating waste and medical material



Where are accelerators used

- Prospects

- Cleaner and safer nuclear power
- Fusion energy
- Replacing ageing research reactors

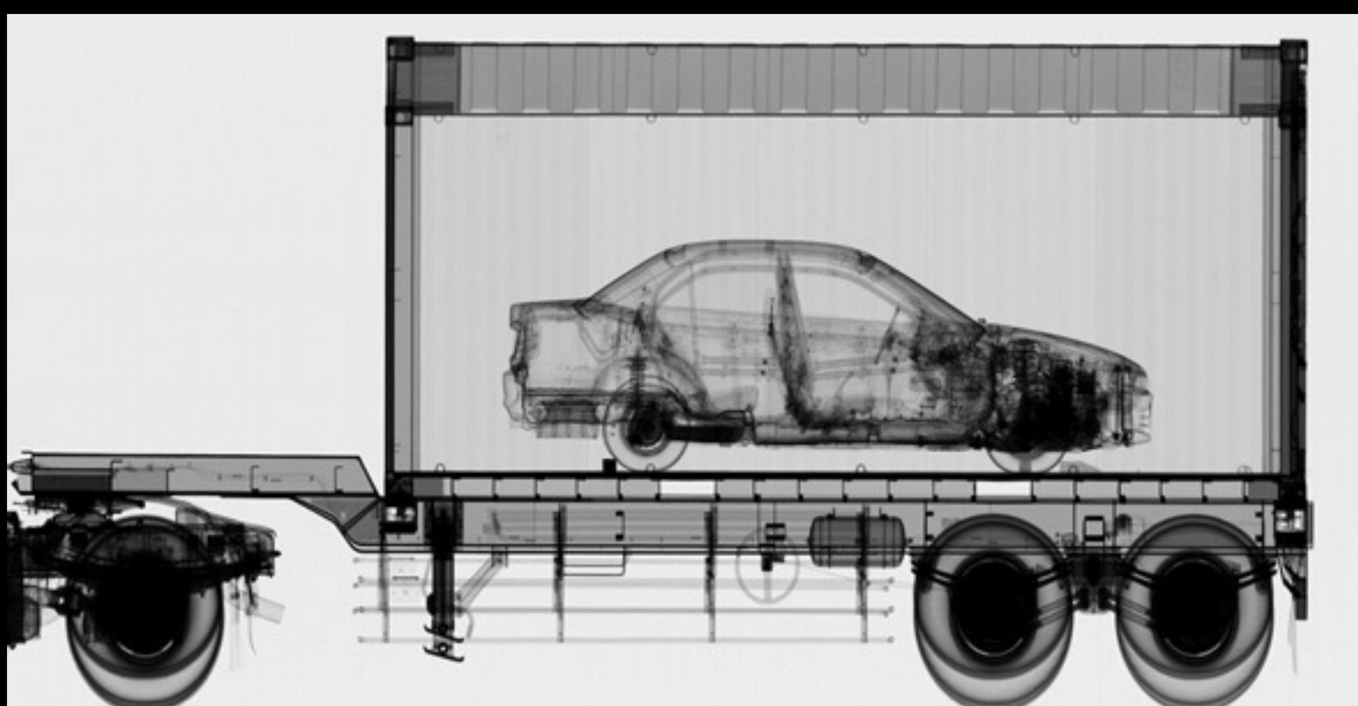
Where are accelerators used

•Material characterisation

- Cultural heritage
- Cargo scanning

THE ARTEMIDORUS PAPYRUS: SOLVING AN ANCIENT PUZZLE WITH RADIOCARBON AND ION BEAM ANALYSIS MEASUREMENTS

M E Fedi[1,2] • L Carraresi[1,3] • N Grassi[1] • A Migliori[1,3] • F Taccetti[1] • F Terrasi[4] • P A Mandò[1,3]



“Particle beams are used for non-destructive analysis of works of art and ancient relics.” [2]

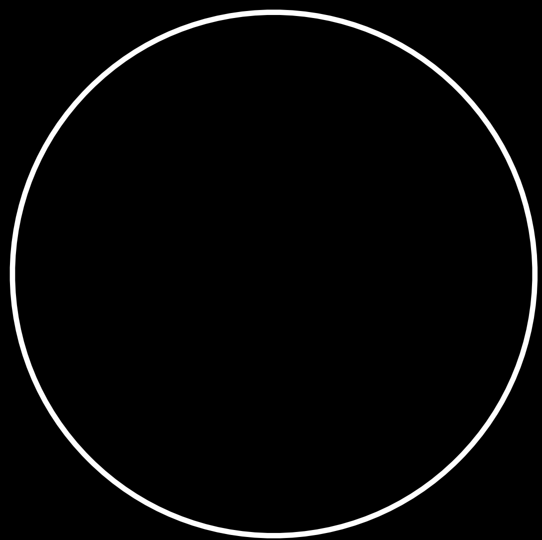
“On average, it takes 30 seconds to scan a shipping container. When all 5000 containers on a ship need to be unloaded in a matter of hours, every minute counts” [3]

Light Sources

Light Sources

- High energy electrons can emit extremely bright and coherent beams of high energy photons via synchrotron radiation; powerful microscopes: the higher the energy the better the resolution ($E=h/\lambda$)

Light Sources



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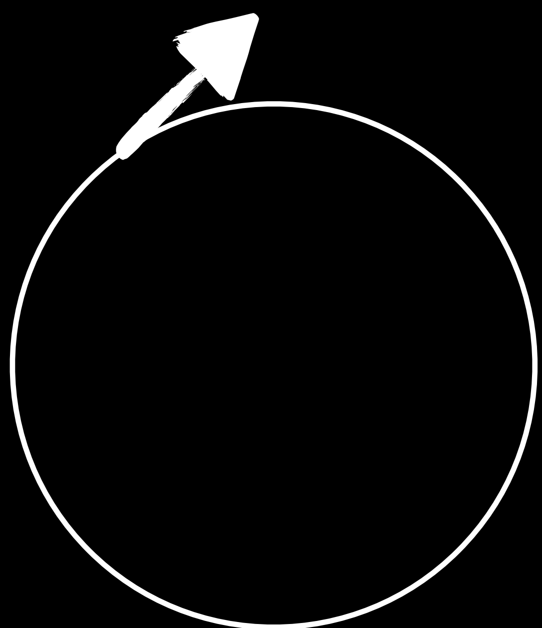

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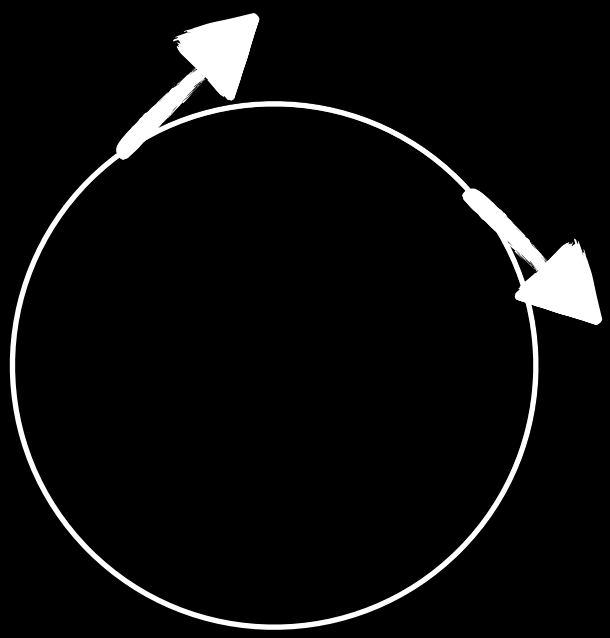

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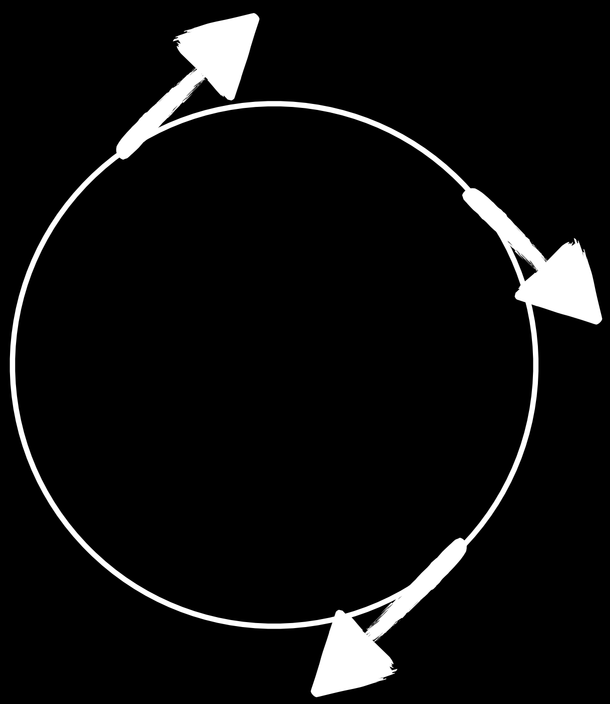

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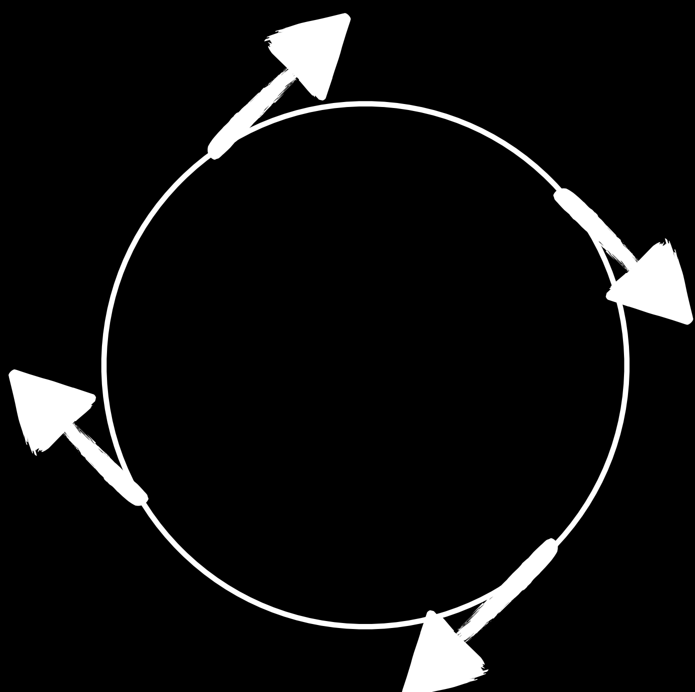

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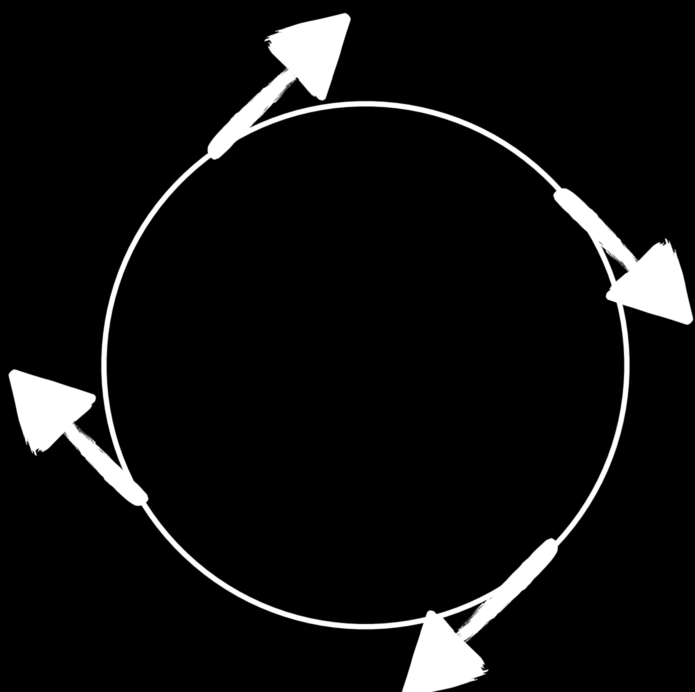

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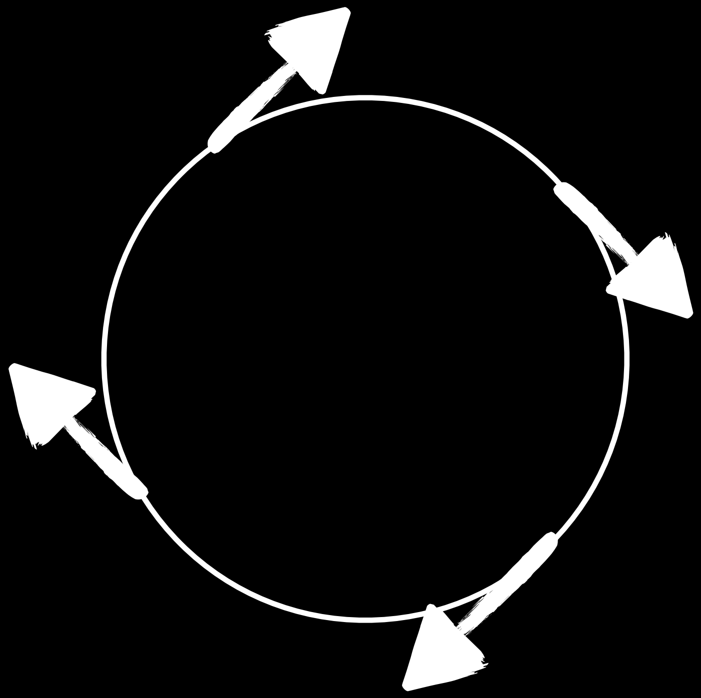

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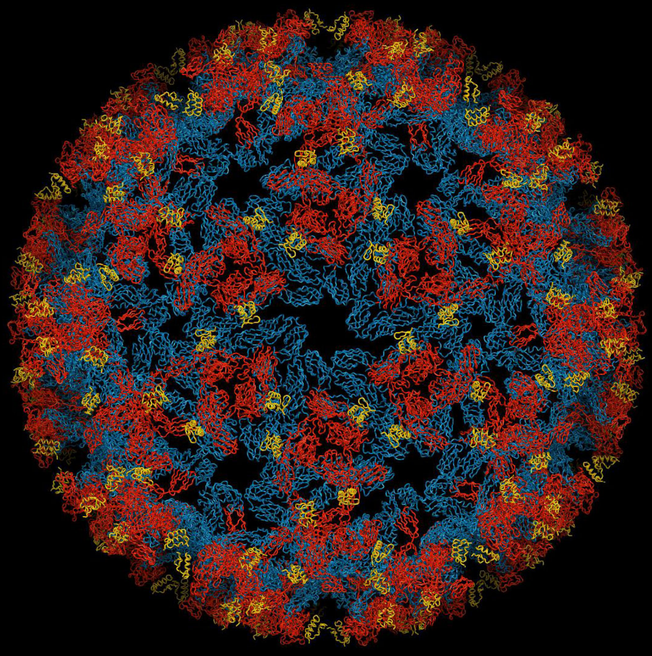
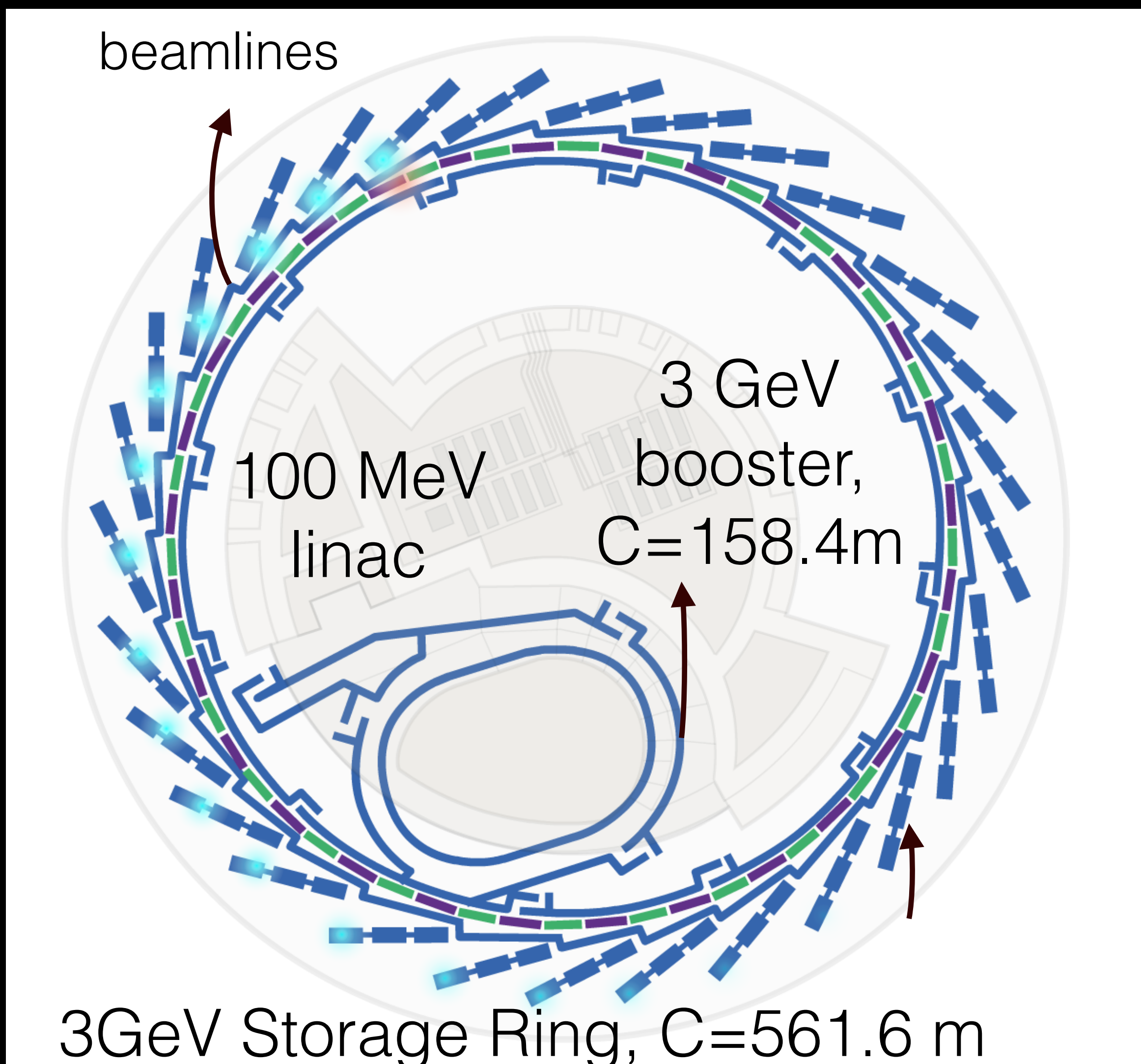
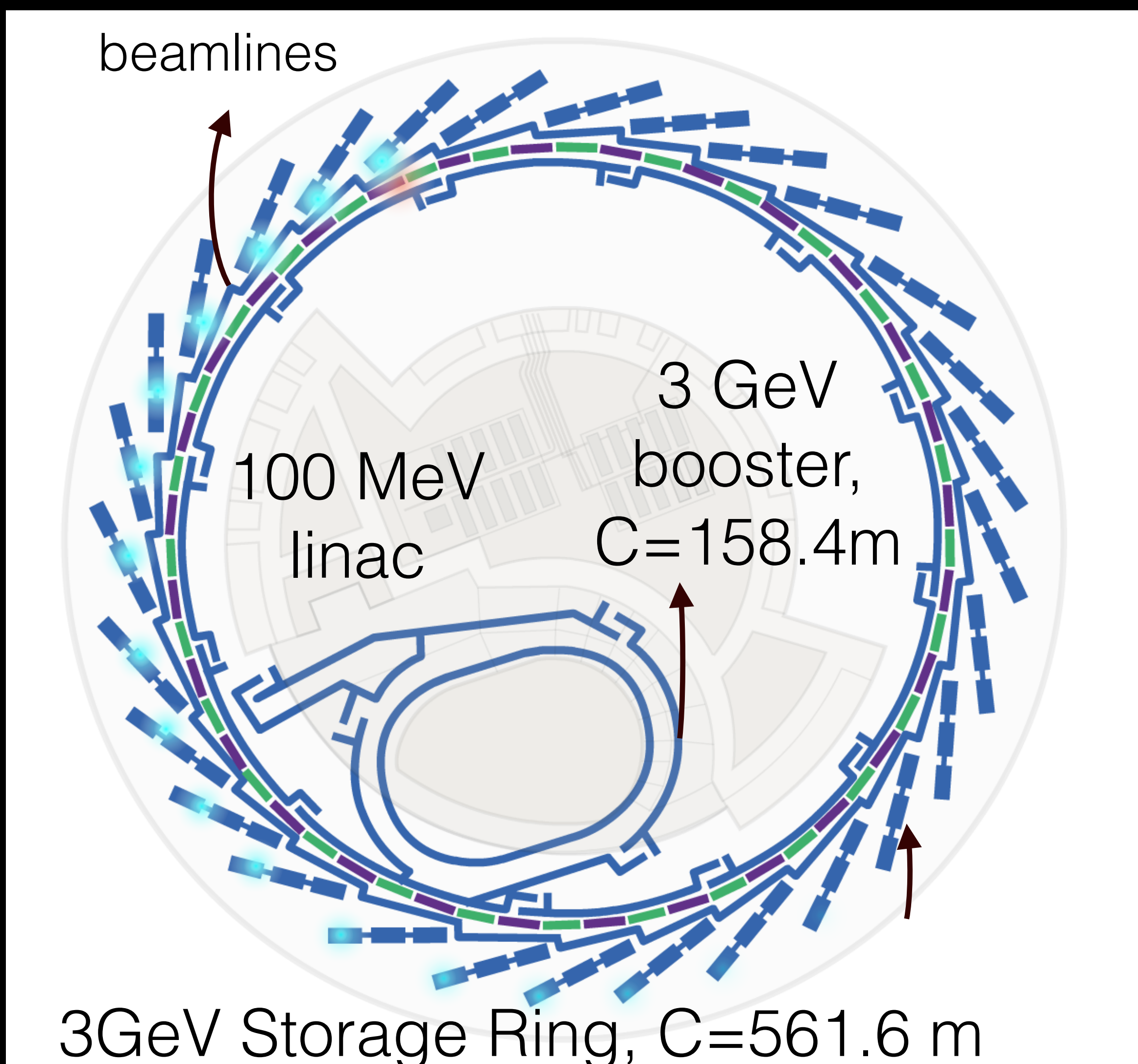


Protein modelling: Synchrotron light allows scientists to solve 3D structure of proteins e.g. the Chikungunya virus. Image credit: Voss et al., Nature (2010) 468, 709 (via Synchrotron Soleil, France)

Diamond Light Source



Diamond Light Source



Recent work published in the journal Nature explains how scientists from Imperial College London used Diamond's X-rays to help solve the structure of a key enzyme found in retroviruses like HIV, a puzzle that scientists have been trying to solve for 20 years. This new discovery could potentially lead to better treatments for the virus. Lead author on the paper, Dr Peter Cherepanov, says, "Regular access to the

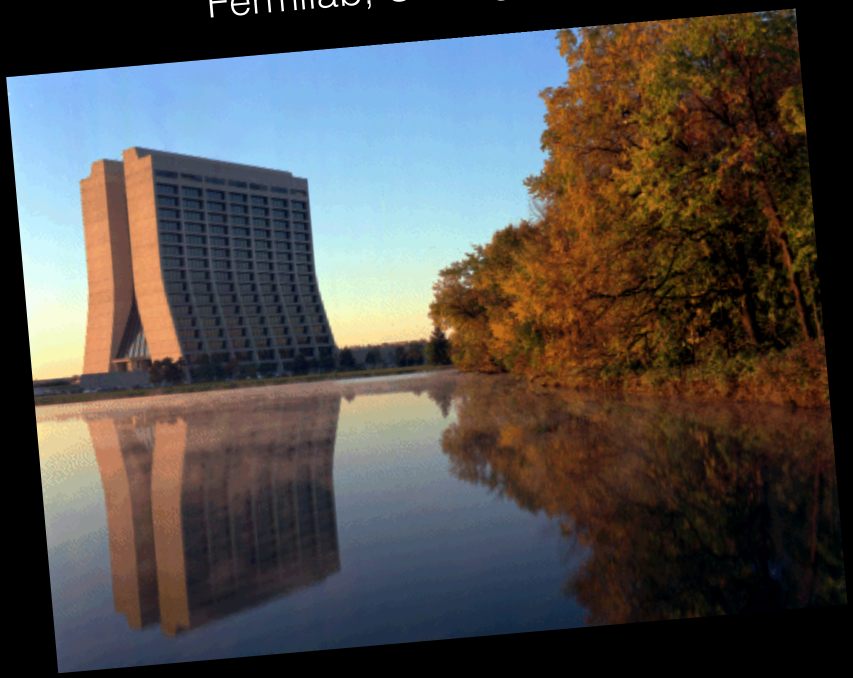
There are currently more than 30,000 accelerators in operation around the world!

Accelerator physics:
field with
international collaborations!

Seeing the world!

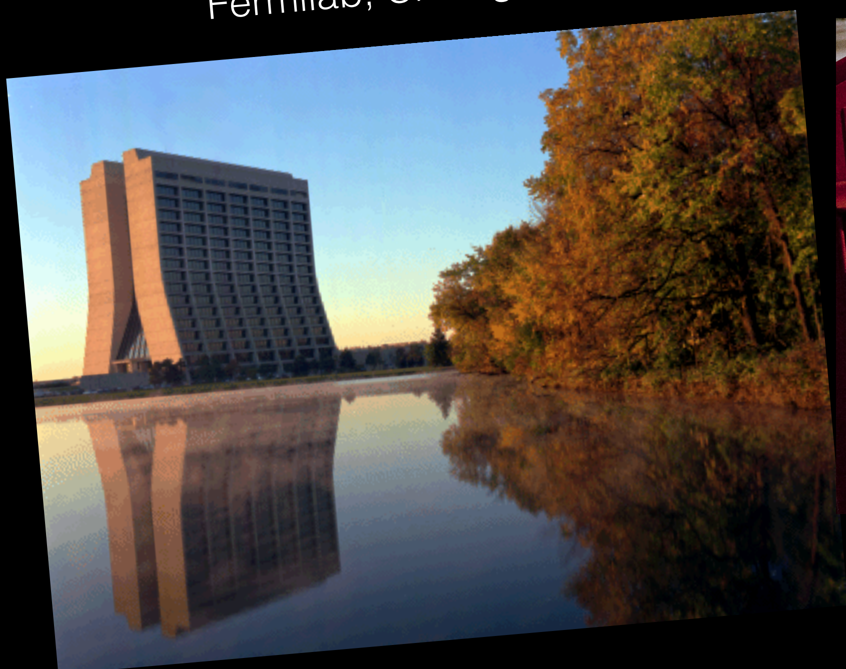
Seeing the world!

Fermilab, Chicago



Seeing the world!

Fermilab, Chicago



London

Seeing the world!

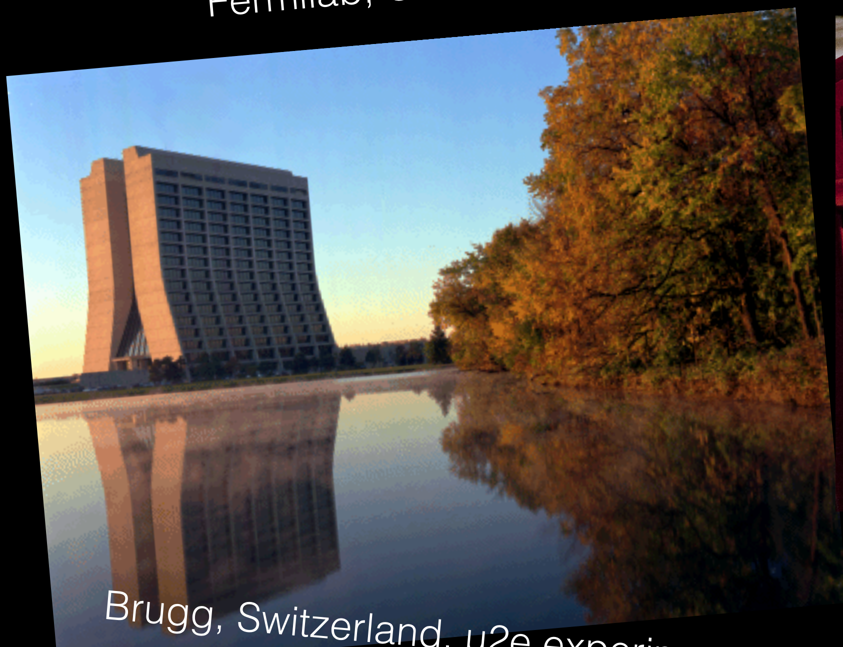
Fermilab, Chicago

London

Brugg, Switzerland, μ2e experiment

Seeing the world!

Fermilab, Chicago



London

Brugg, Switzerland, μ2e experiment

Oxfordshire

Seeing the world!

Fermilab, Chicago

London

Geneva

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Oxfordshire

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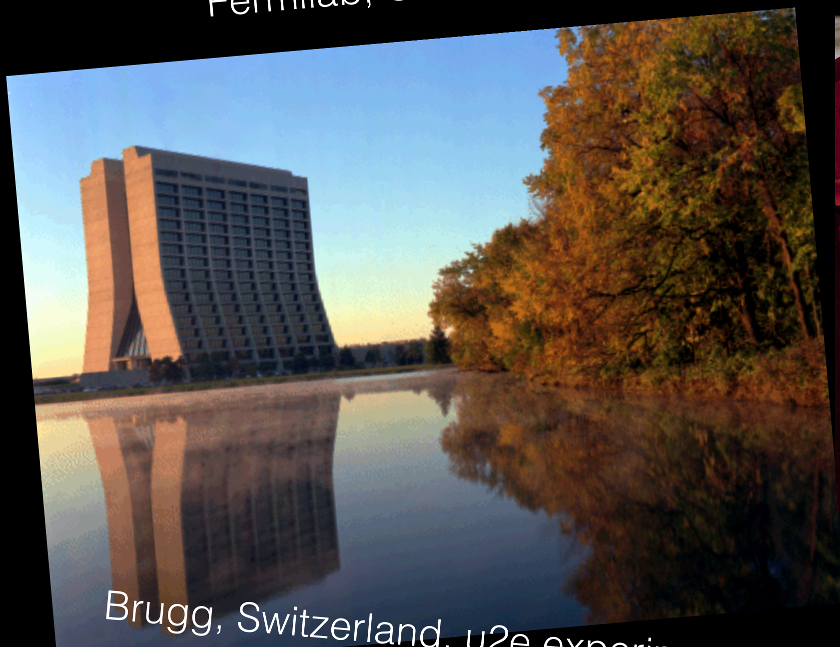
Fermilab, Chicago



London

Geneva

Oxford

Brugg, Switzerland, μ2e experiment

Oxfordshire

New York

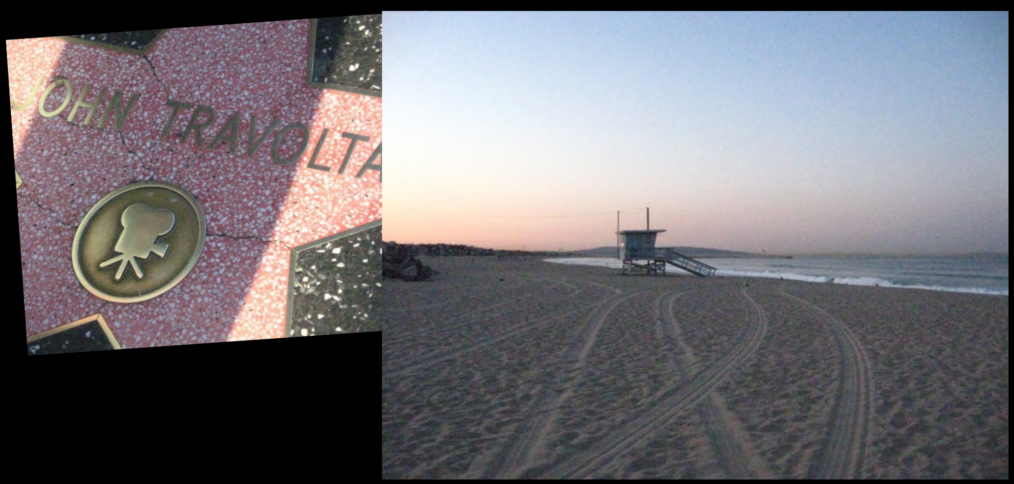
Kyoto, Japan

New York

Kyoto, Japan

New York

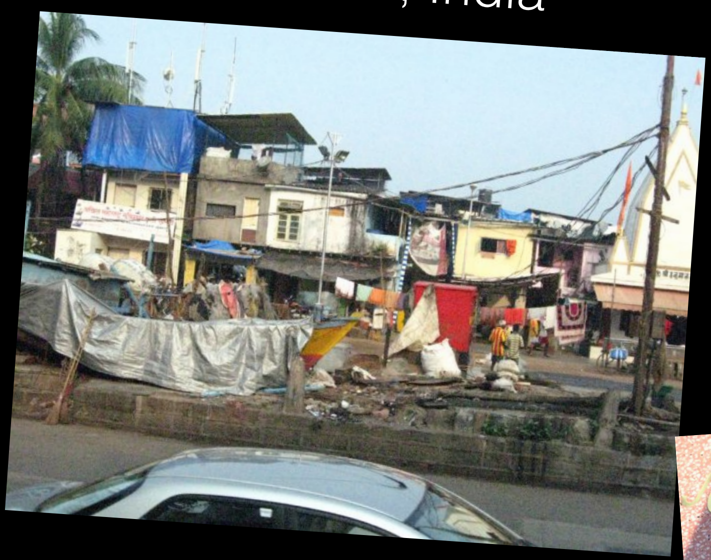
California



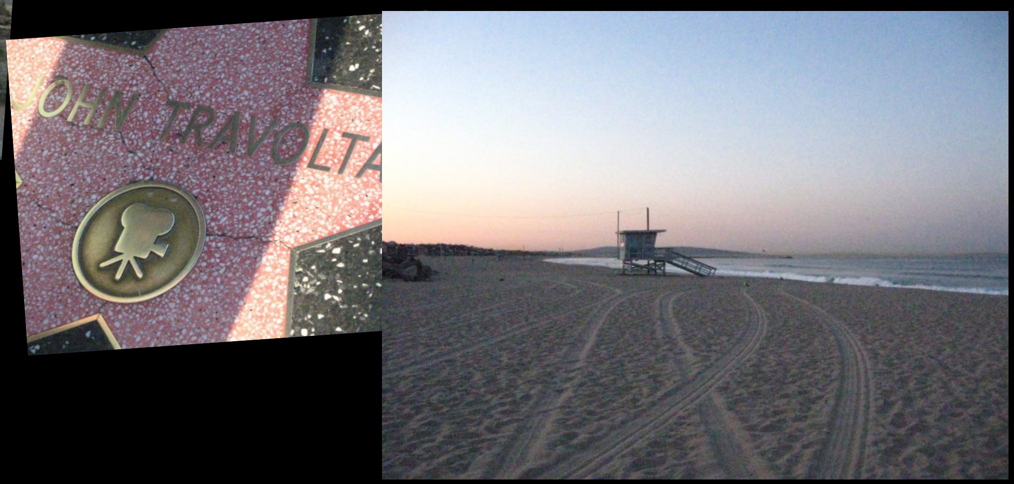
Kyoto, Japan

New York

Mumbai, India



California



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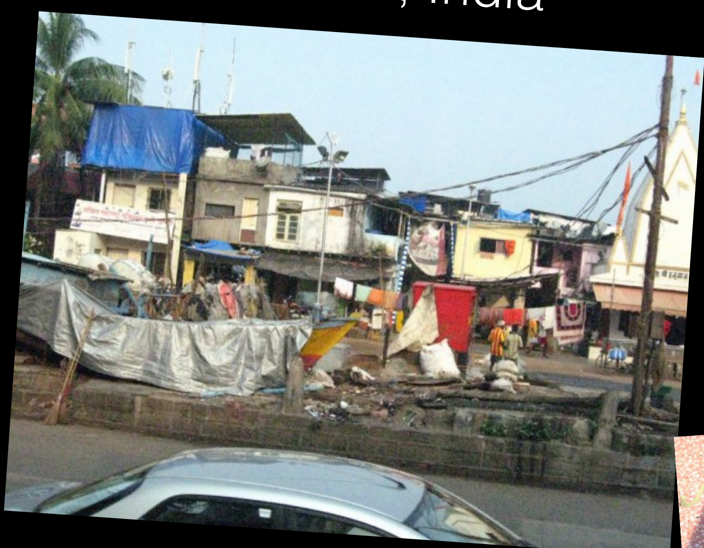
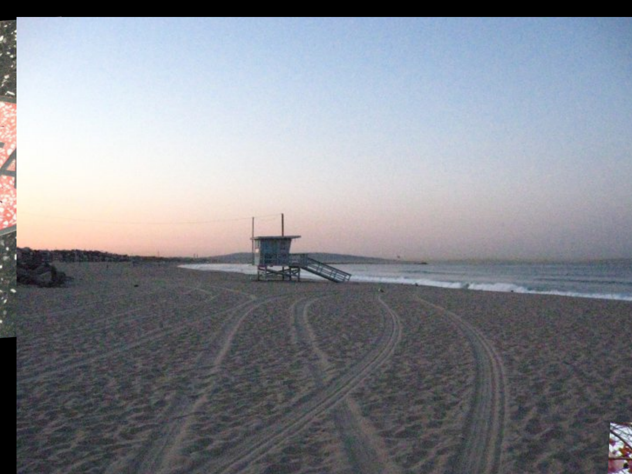


California



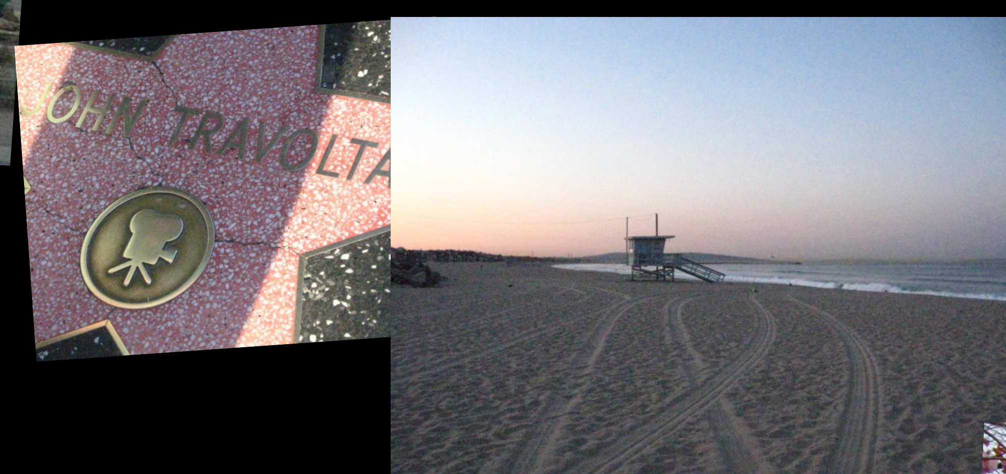
Glasgow, Scotland

Kyoto, Japan

New York

Mumbai, India

California



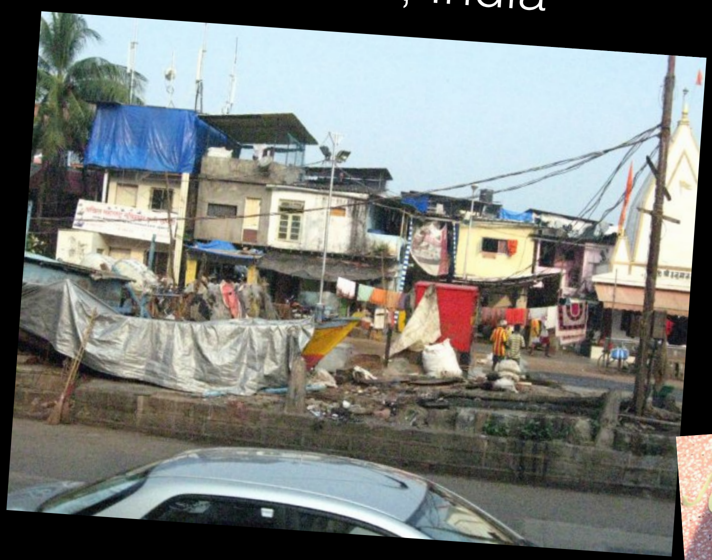
Trondheim, Norway

Glasgow, Scotland

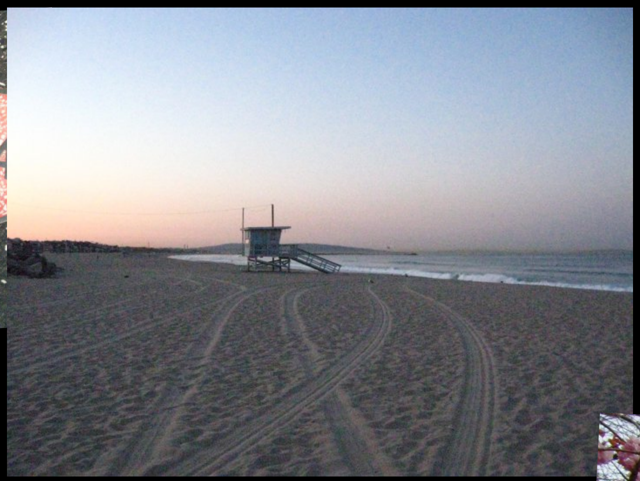
Kyoto, Japan

New York

Mumbai, India



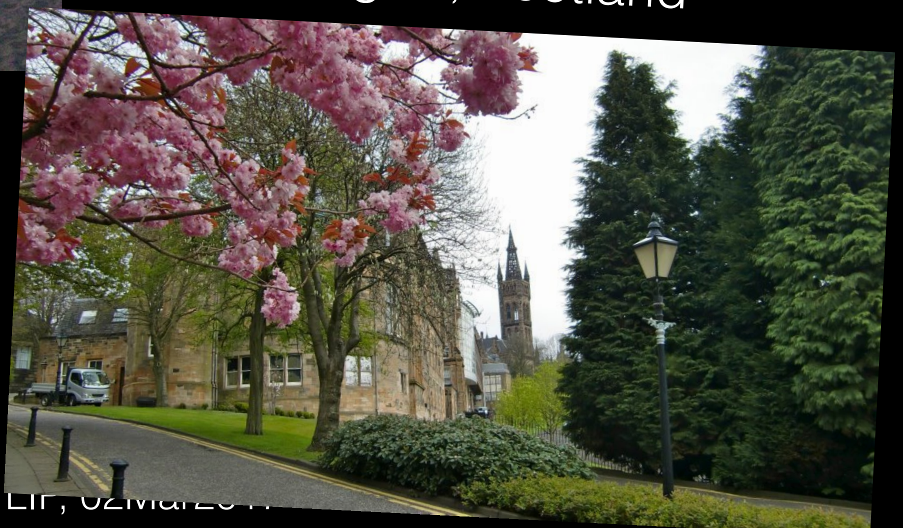
California



Trondheim, Norway

Paris

Glasgow, Scotland

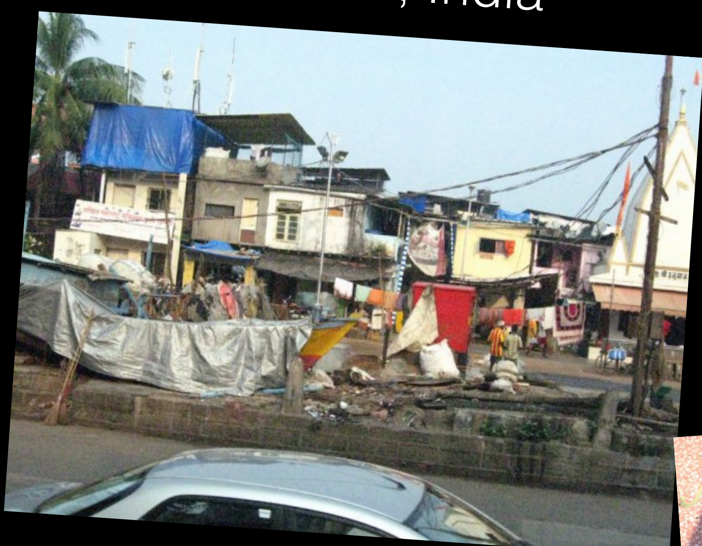


Kyoto, Japan

New York

South Korea

Mumbai, India



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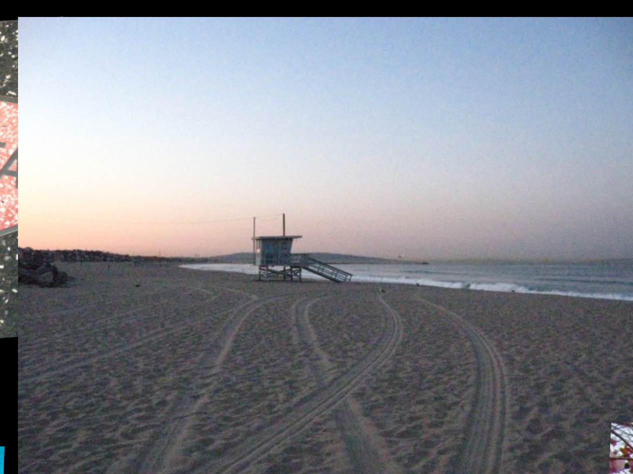

Trondheim, Norway

Paris

Glasgow, Scotland

Would you like to come at CERN?

- Free underground tours: https://visit.cern/tours/guided-tours-individuals
- Summer student programs: https://jobs.web.cern.ch/join-us/summer-student-programme-member-states

Summer students programs outside CERN

- Fermilab: http://eddata.fnal.gov/lasso/summerstudents/view.lasso
- DESY: https://summerstudents.desy.de/
- PSI (Paul Scherrer Institut)
- … and many more

References

1) Accelerators for society
2) A quasi-political Explanation of the Higgs Boson; for Mr Waldegrave, UK Science Minister 1993
3) Accelerator apps: Cargo scanning

Very nice video-talks:
The 60th anniversary celebrations on film
60 Years of CERN and Guinness World Records
A conversation with Fabiola Gianotti
CERN's super-collider-Brian Cox
The significance of the Higgs Boson discovery - Dr. John Ellis - BOLDtalks 2013
CERN Document Server
Prof. David Miller and his analogy for the Higgs Mechanism

Obrigada! :)

Any questions?

Back-up slides

Where are accelerators used

- Research & Development
  - Fundamental physics
  - Material science
  - Solid state and condensed matter physics
  - Biological and chemical science
- Health & Medicine
  - Treating cancer
  - Medical imaging
- Material characterisation
  - Cultural heritage
  - Cargo scanning
- Energy & Environment
  - Cleaning flue gases of thermal power plants
  - Oil and gas exploration
  - Biofuel production
- Industry
  - Ion implantation for electronics
  - Hardening surfaces
  - Hardening materials
  - Welding and cutting
  - Treating waste and medical material
- Prospects
  - Cleaner and safer nuclear power
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Accelerator physics: field with international collaborations!

Where are accelerators used

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[1]

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- Energy & Environment
  - Cleaning flue gases of thermal power plants
  - Oil and gas exploration
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Budget (2012) ~1000 MCHF (about 1 cappuccino/citizen): each Member State contributes in proportion to its income

Electrical power to run the LHC (from French EDF): ~200 MW

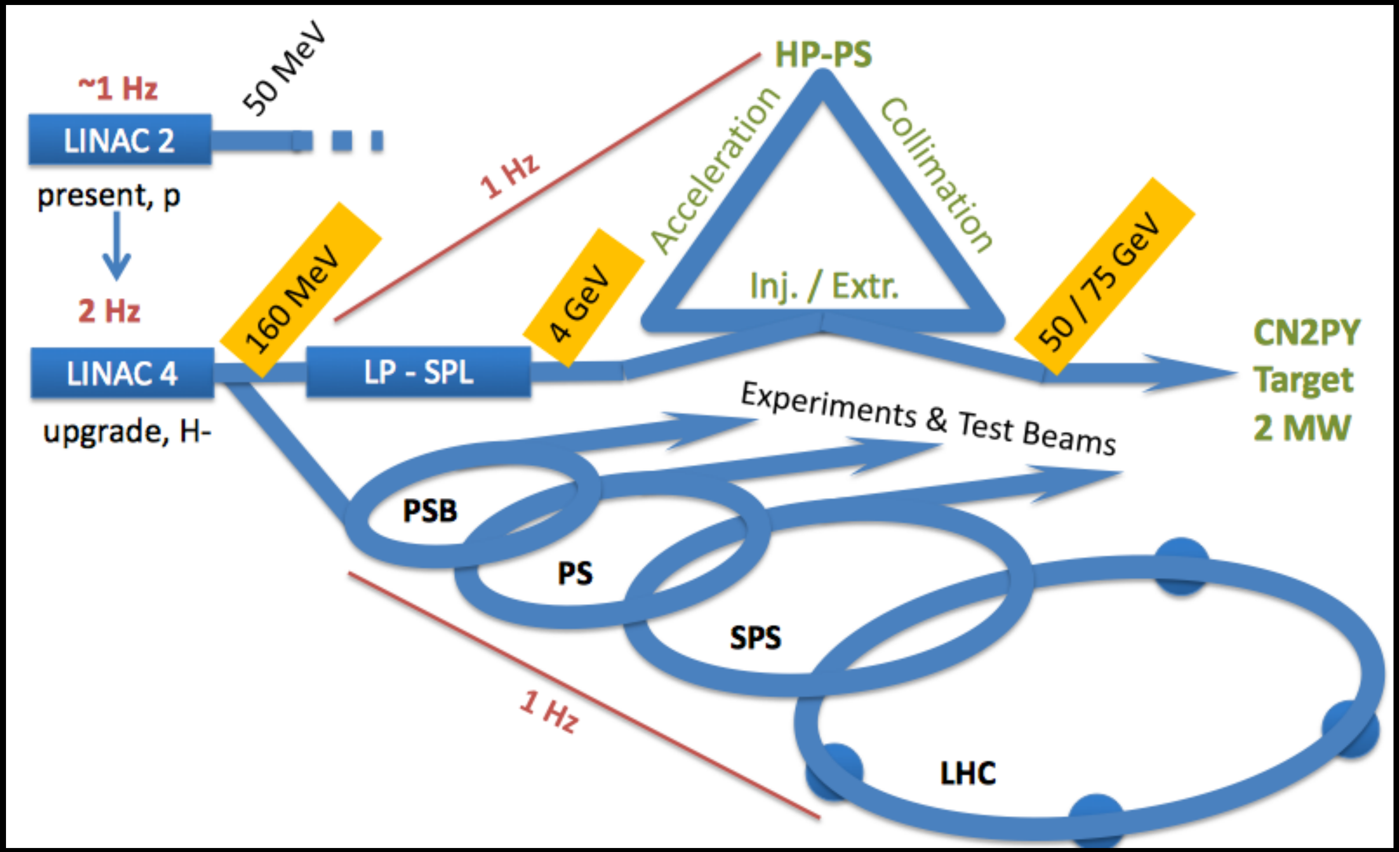
Beam goes around LHC 11,000 times per second

40 MHz crossing rate
~~20 interactions/crossing
800 interactions/sec
for 10-15 hours
2 hours needed to fill LHC (proton fill+beam setup+energy ramp)

2800 bunches/beam, 100 billion protons/bunch (1.15e11)

—>total intensity of the beam: 2e14
—>bunch intensity: 1.15 e11

HP-PS



The Standard Model

The Standard Model

- The elementary particles and their interactions are described by a very successful theory: the Standard Model (SM)
- Before the LHC, all particles (but one, the Higgs boson) foreseen by the SM had been observed, and the SM predictions had been verified with extremely high precision by experiments at CERN and other labs all over the world (over 50 years)

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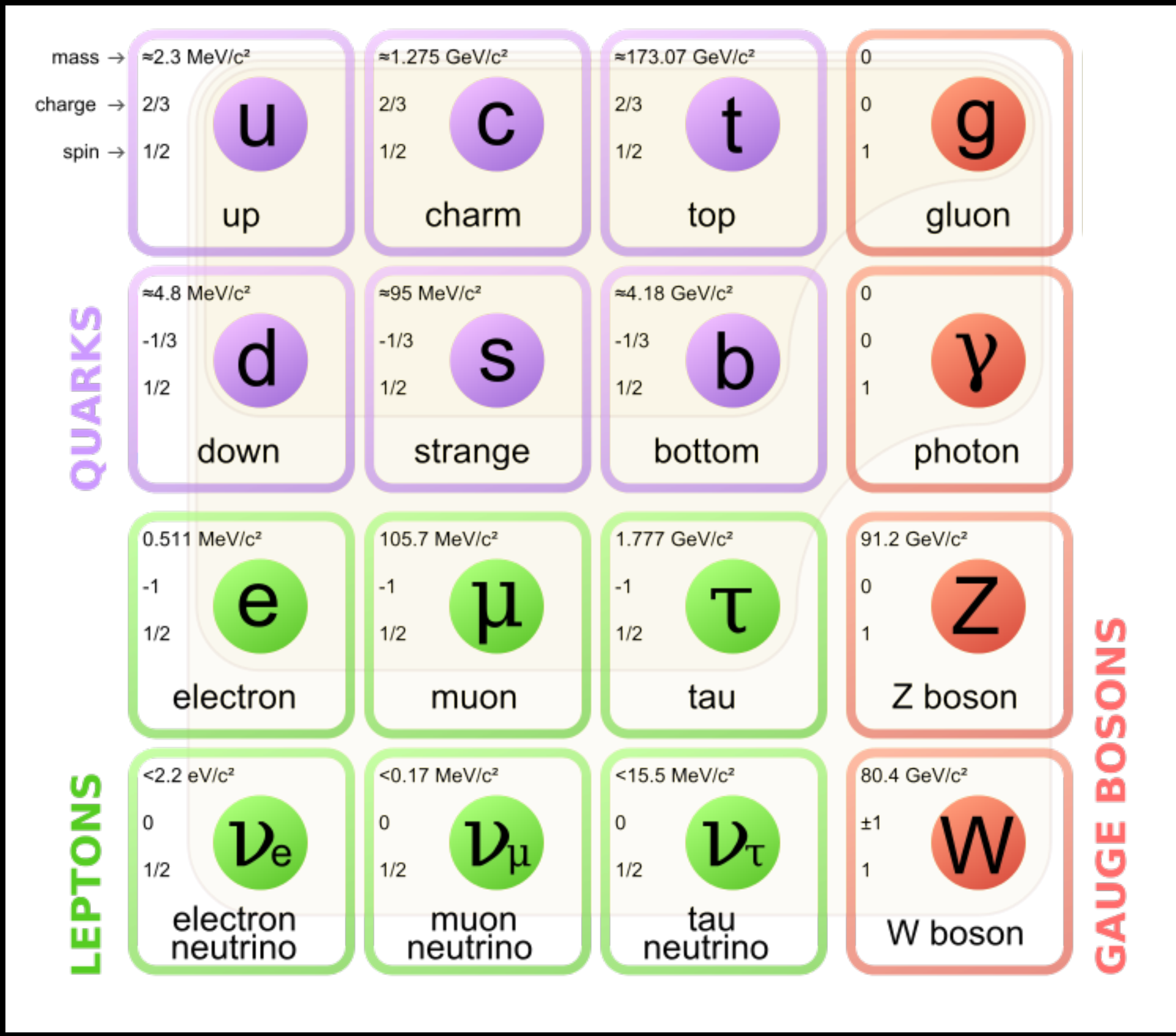
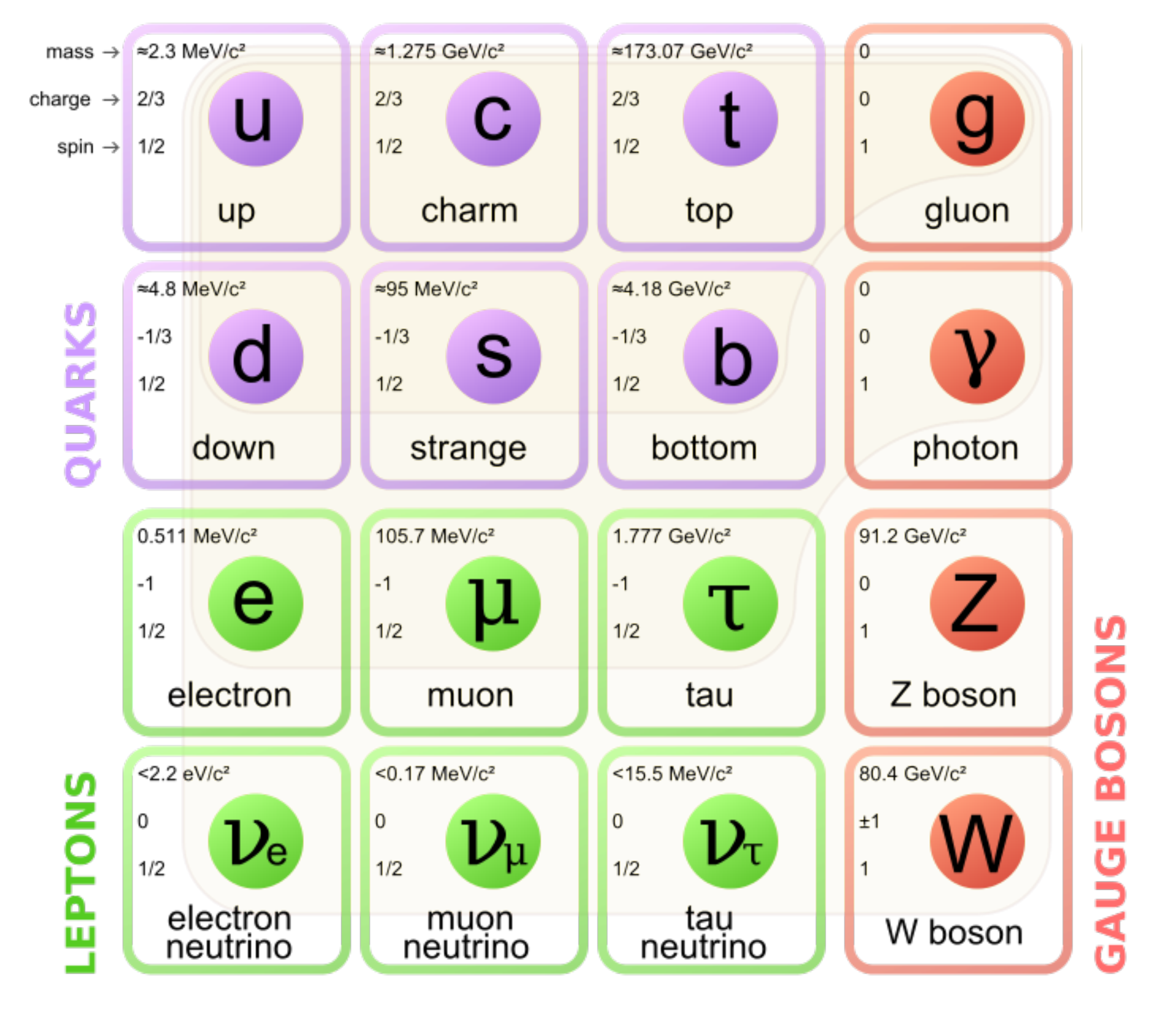
Elementary particles



The Standard Model

4 Forces

Elementary particles



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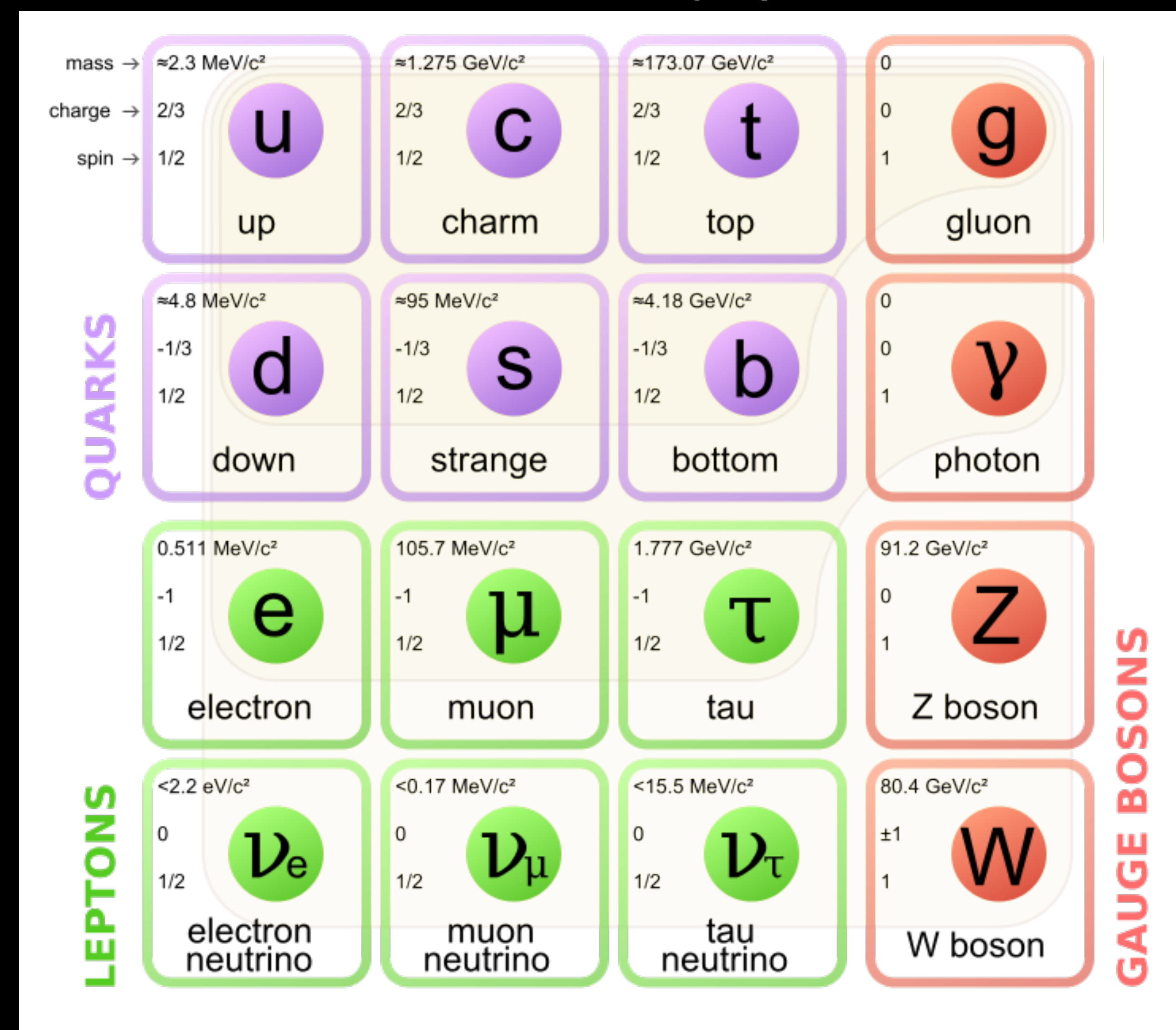

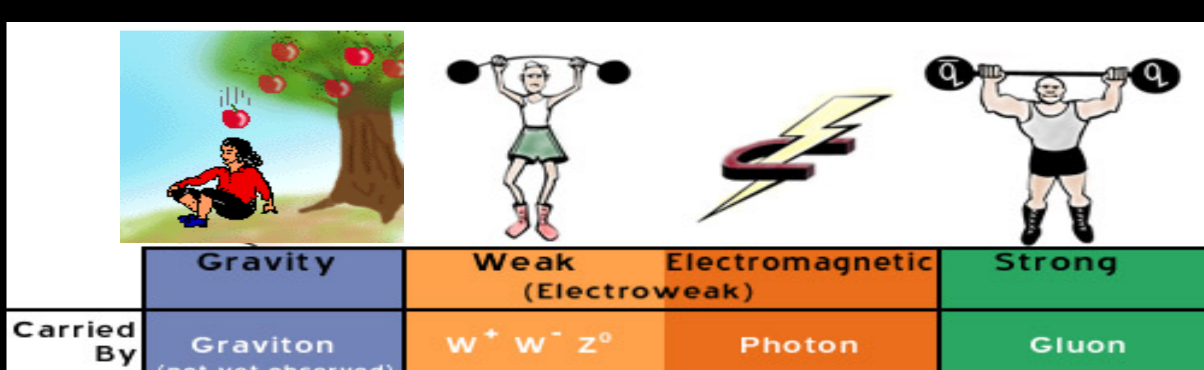

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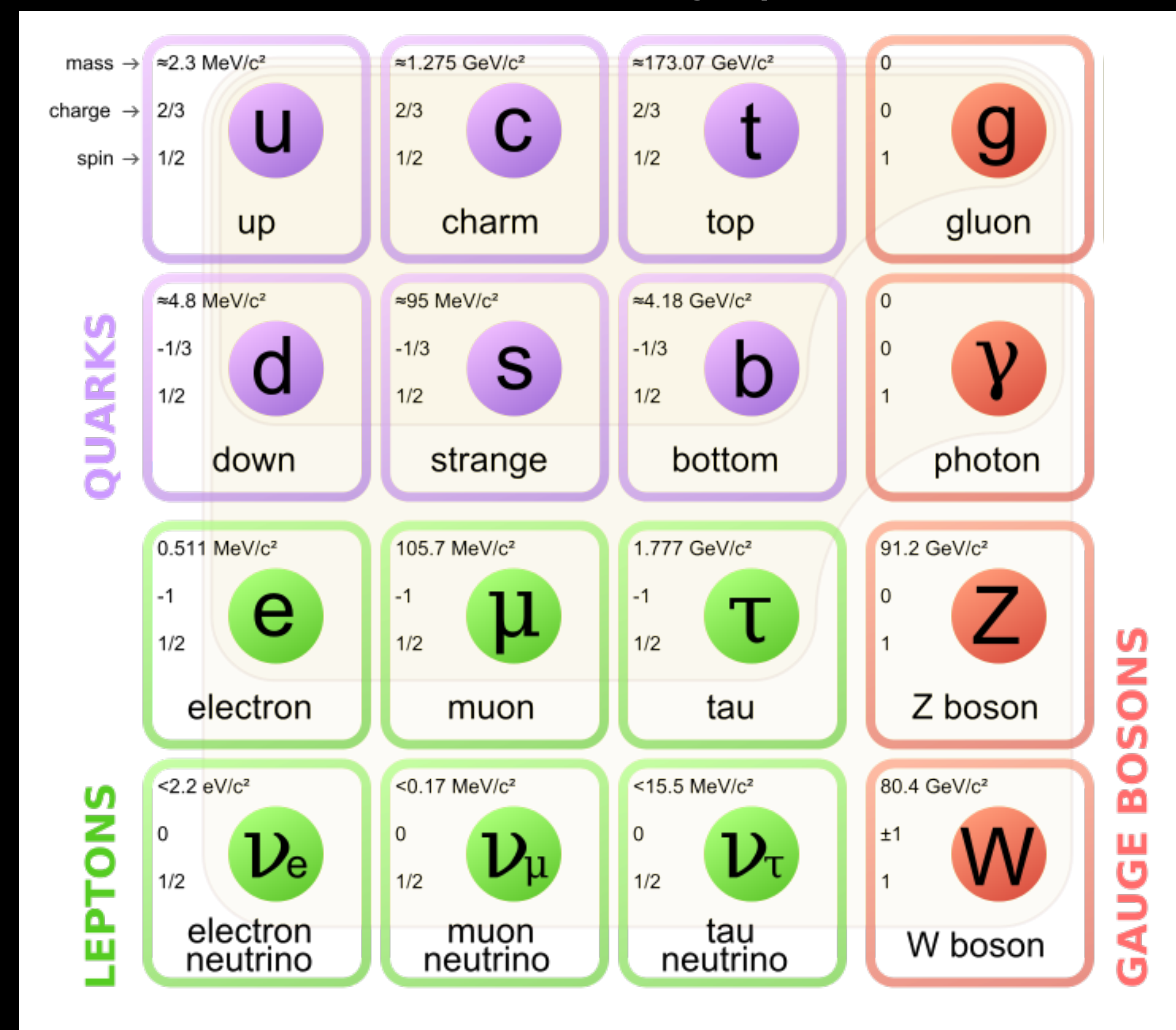
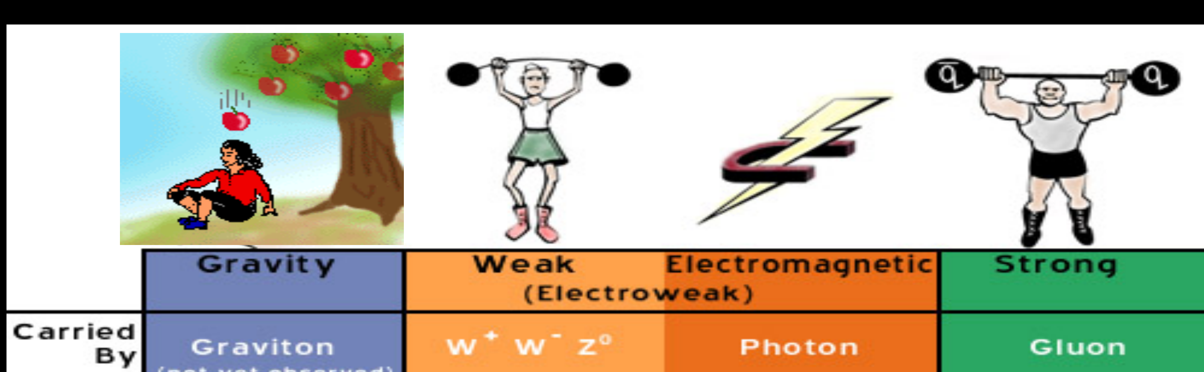
Gravity: attractive force between all matter

Elementary particles





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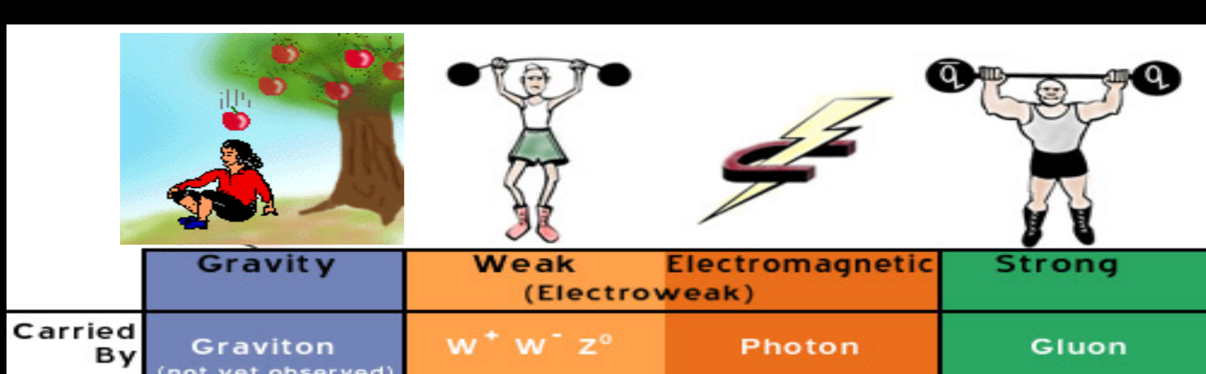
Gravity: attractive force between all matter

The electromagnetic force describes the interaction of charged particles and magnetics



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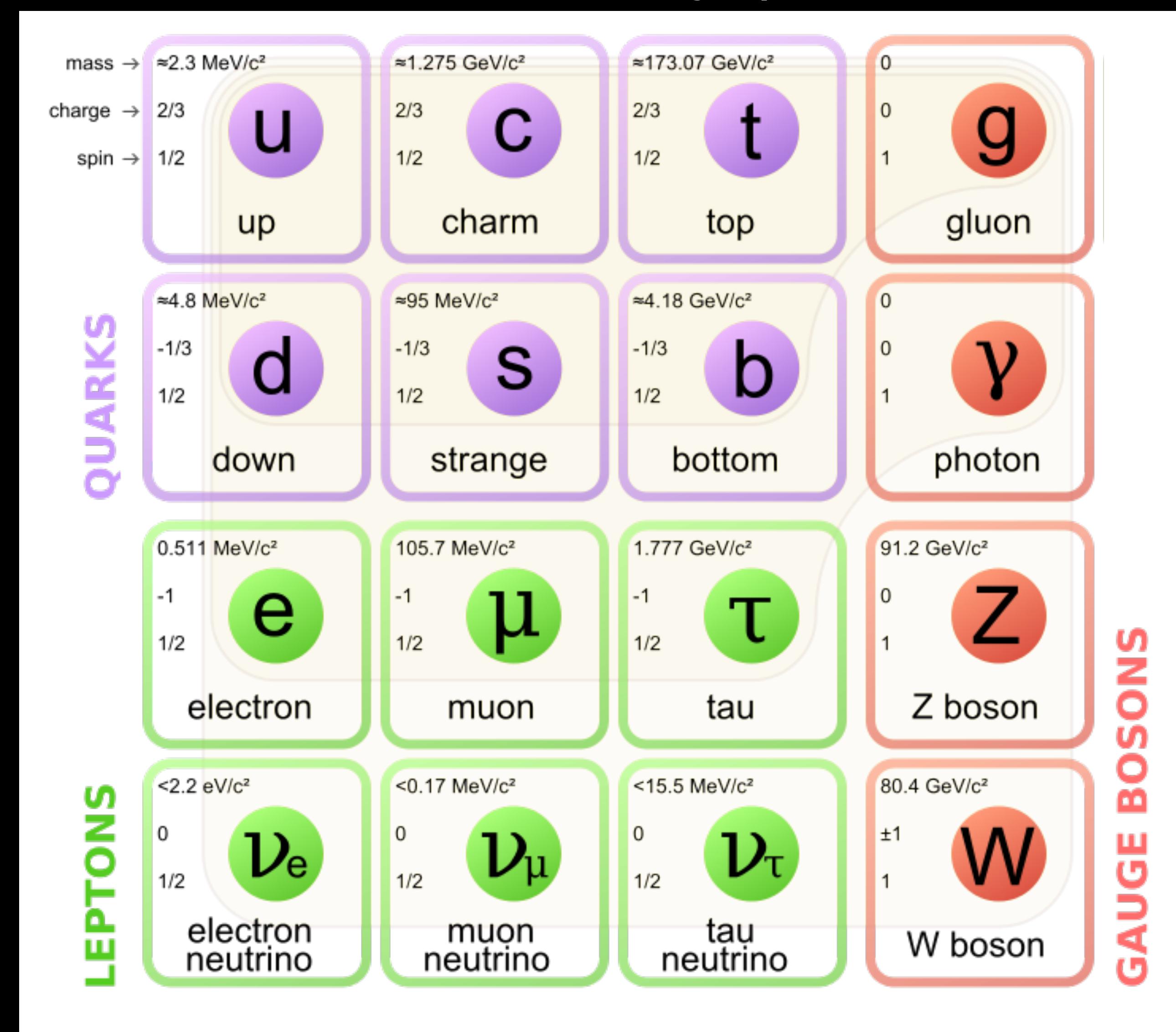

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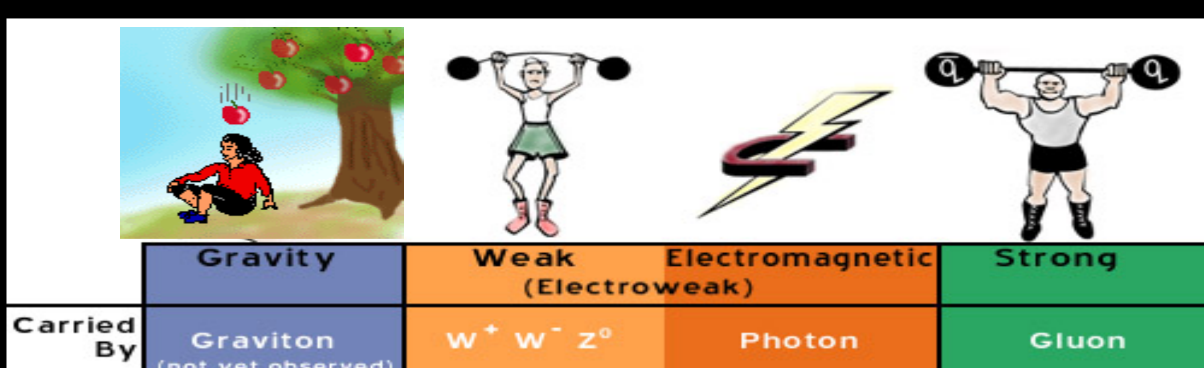
The electromagnetic force describes the interaction of charged particles and magnetics

The strong force binds quarks into protons, neutrons and mesons, and holds the nucleus of the atom together despite the repulsive electromagnetic force between protons



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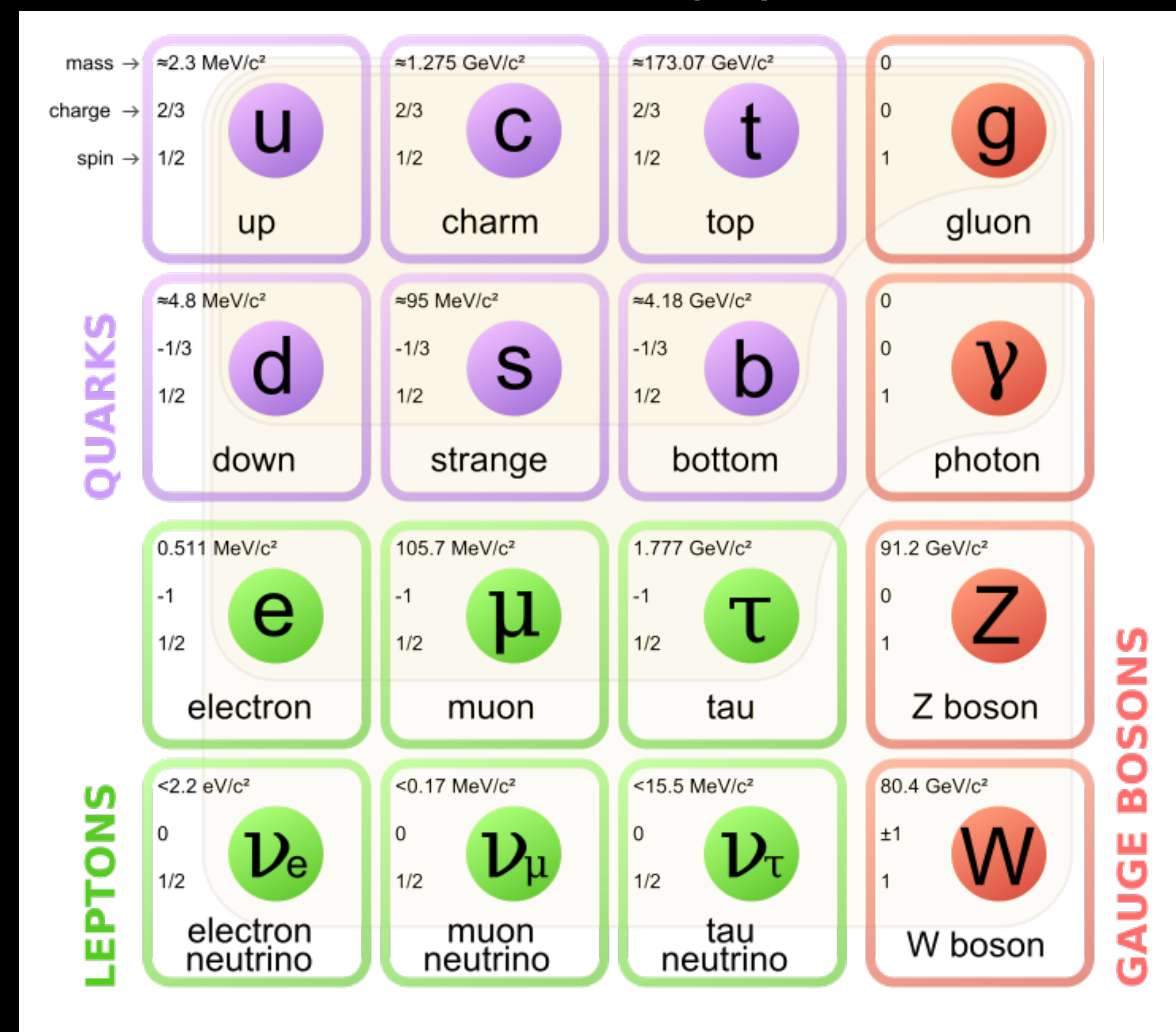

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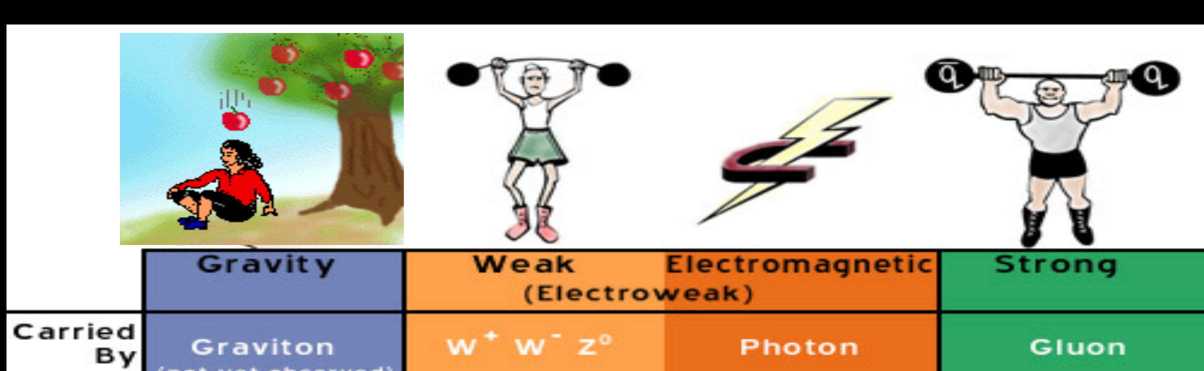
The strong force binds quarks into protons, neutrons and mesons, and holds the nucleus of the atom together despite the repulsive electromagnetic force between protons

The weak force controls the radioactive decay of atomic nuclei and the reactions between leptons (electrons and neutrinos)



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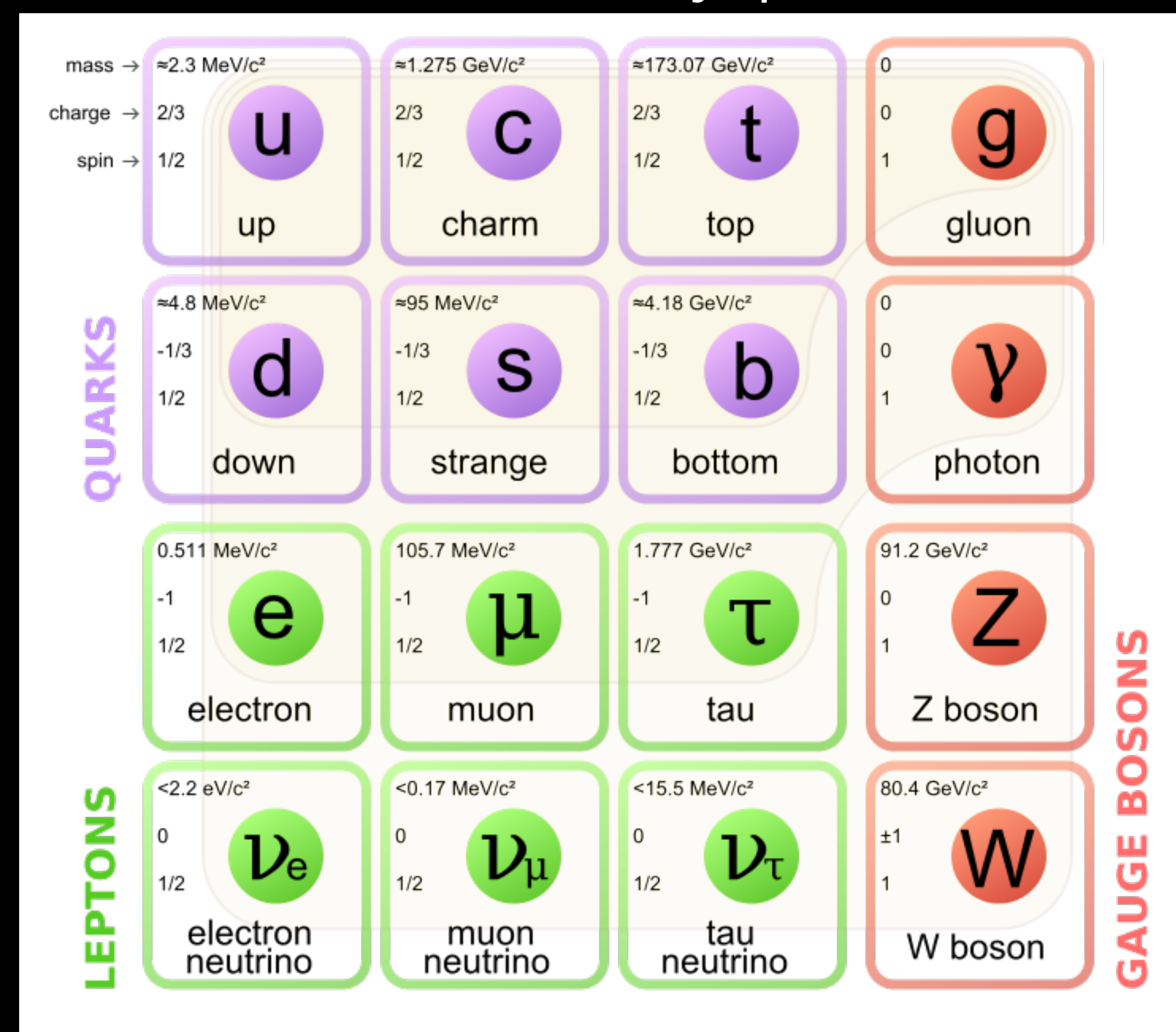

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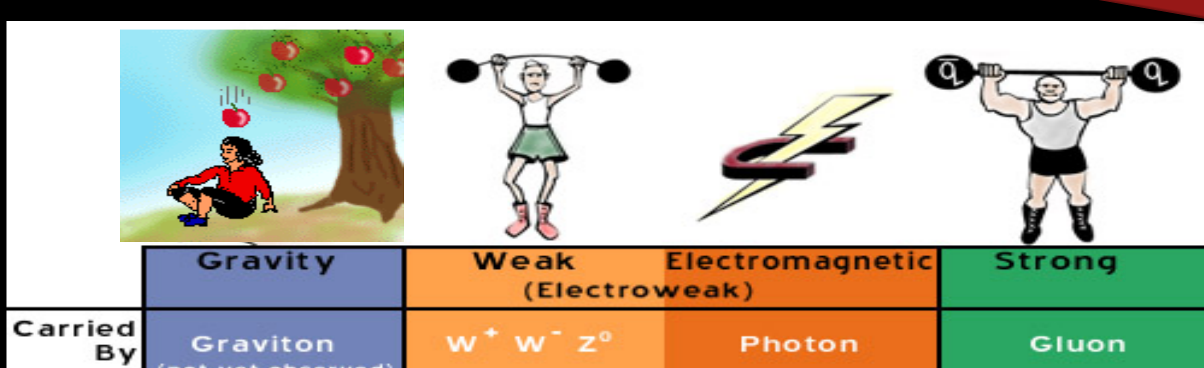


What is the origin of the particle masses?

What is the nature of the Universe dark matter?

Why 3 generations of matter particles ?

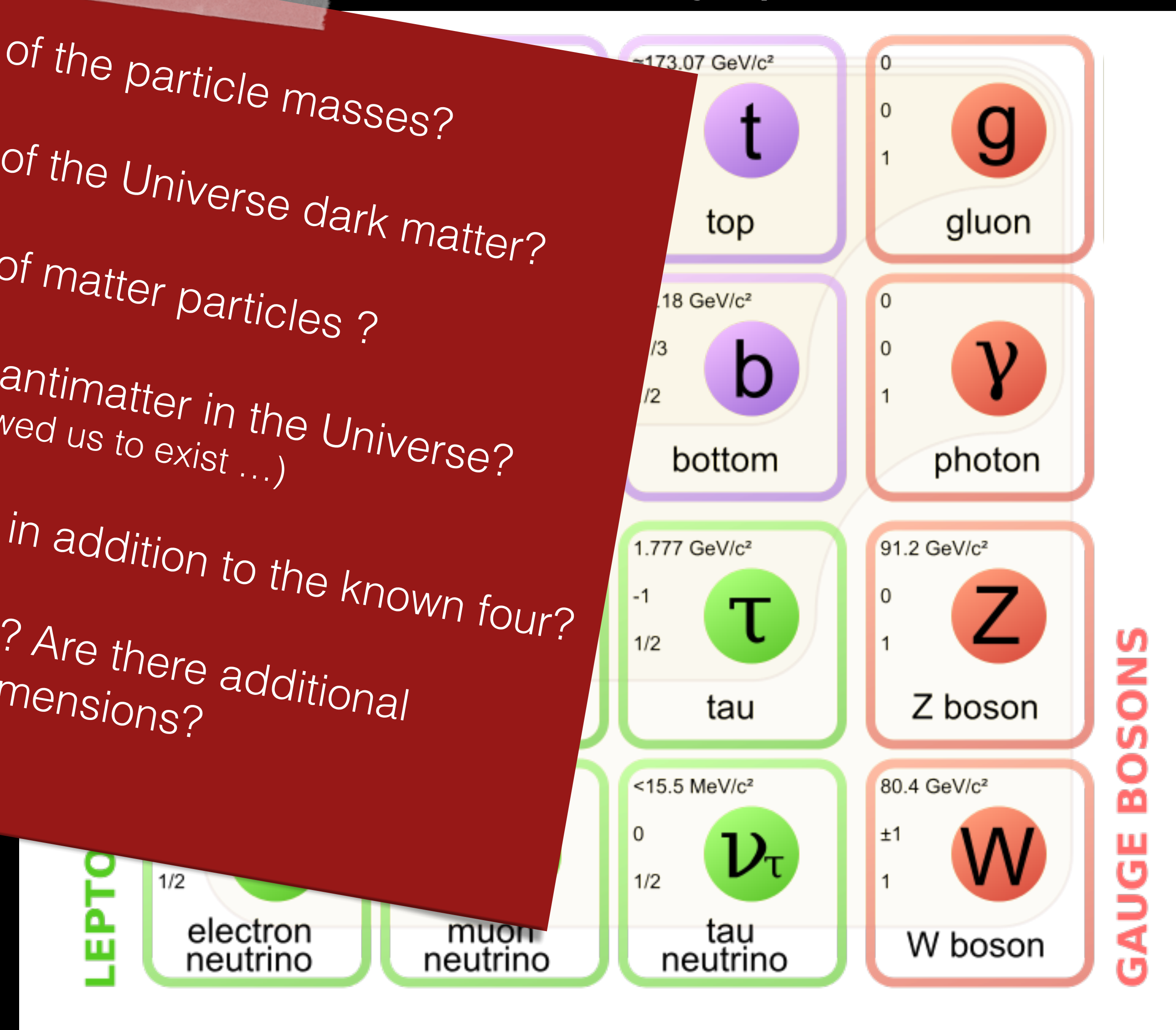
Why is there so little antimatter in the Universe?
(Nature's favouritism allowed us to exist …)

Are there other forces in addition to the known four?

Why is gravity so weak? Are there additional (microscopic) space dimensions?

…..

Elementary particles



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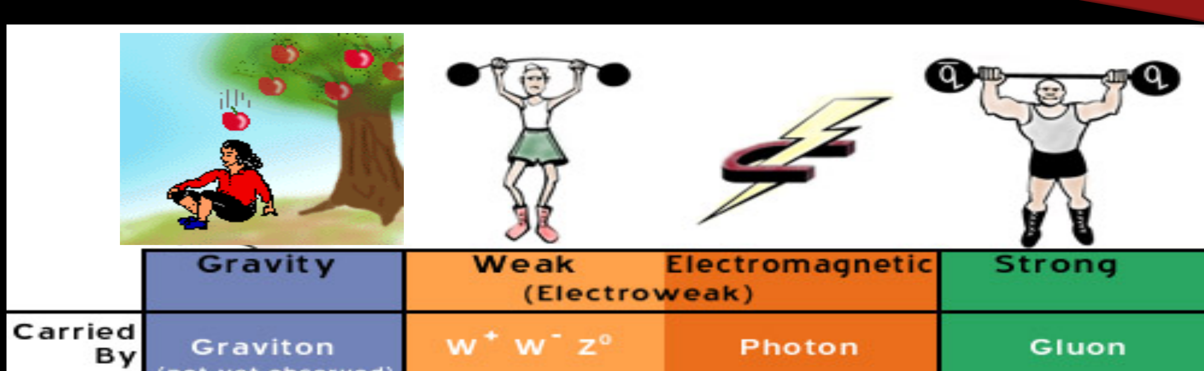

The LHC at CERN is built to address these and other fundamental questions

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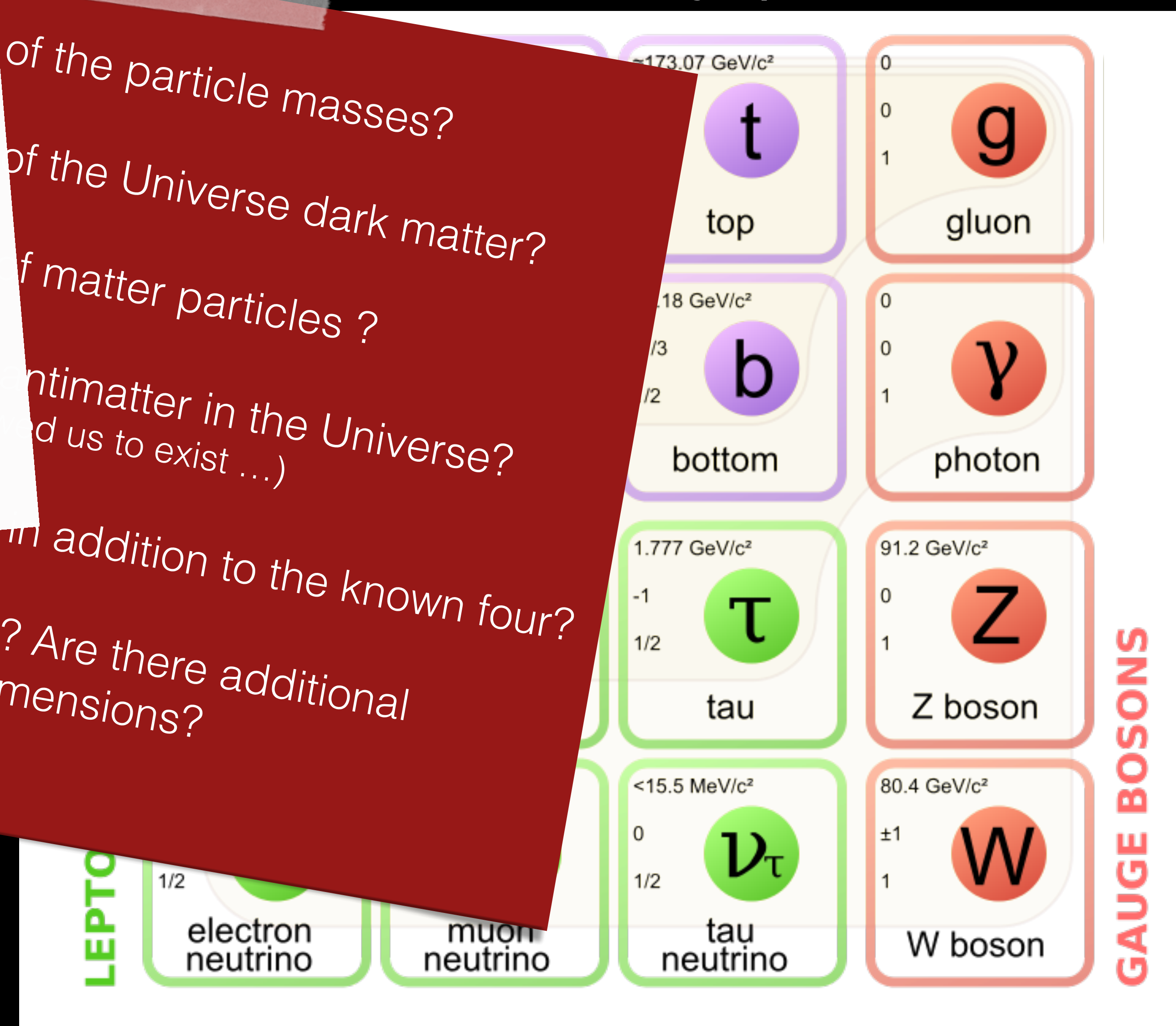


LHC Run 2

13 TeV

Since April 2015 LCH Run 2 has started after 2 year-rebuild

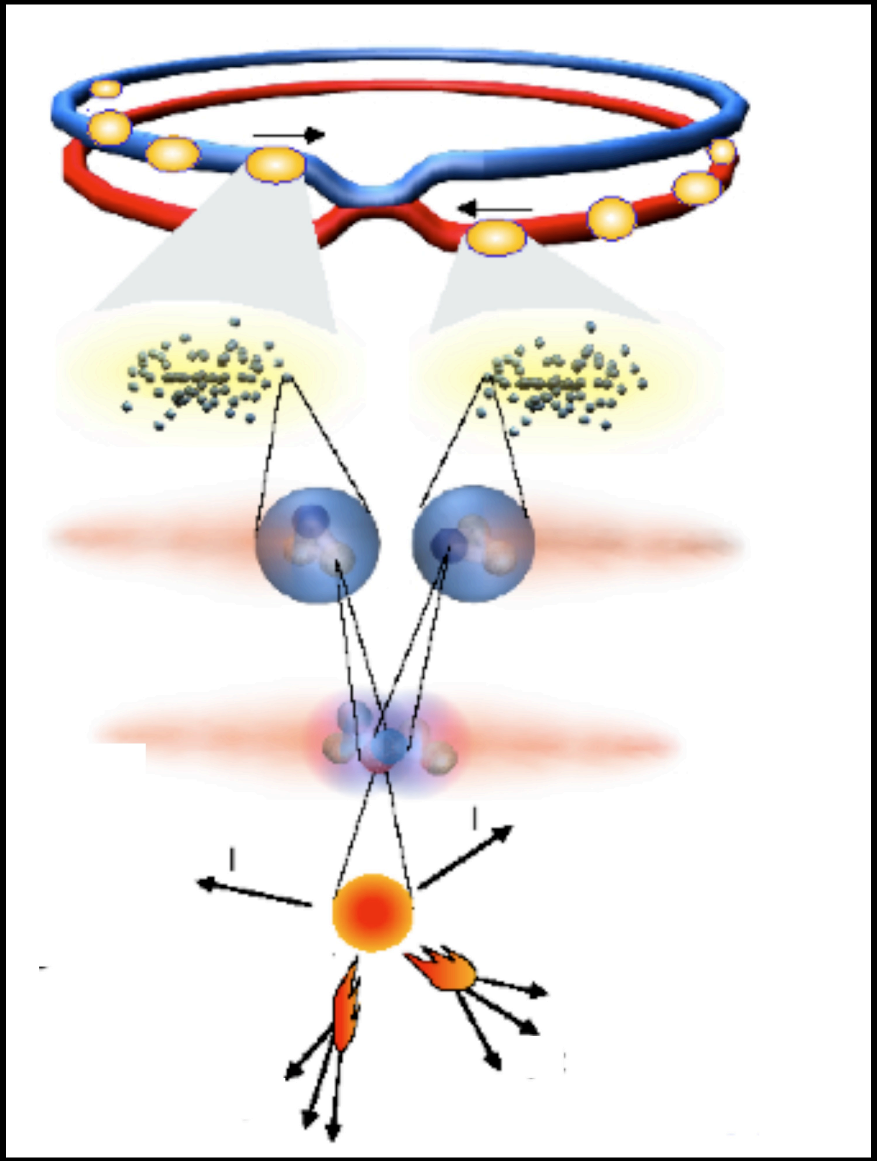
CERN: European Organisation for Nuclear Research

proton beams

colliding protons

interacting quarks

production and decay of a new particle



We accelerate two beams of particles (e.g. protons) close to the speed of light and make them collide

The colliding protons break into their fundamental constituents (e.g. quarks). These constituents interact at high energy:

- study the way fundamental matter behaves
- (new) heavy particles can be produced in the collision ($E=mc^2$). The higher the accelerator energy, the heavier the produced particles can be. These particles then decay into lighter (known) particles: electrons, photons, etc
- reproduce the temperature (~10^{16} K) of the Universe a few instants (10^{-11} s) after the Big Bang

By placing high-tech powerful detectors around the collision point we can detect the collision products and reconstruct what happened in the collision (which phenomena, which particles and forces were involved, etc.)