

Accelerators for Science + Society

making Higgs Bosons and much more!

Philip Burrows

John Adams Institute, Oxford University

Large Hadron Collider (LHC)

**Largest,
highest-energy
particle
collider**

**CERN,
Geneva**



In case you missed it ...

The Boston Globe

All eyes on collider as it comes to life

The Daily Telegraph

Will atom smasher signal end of the world?

[Le LHC, un succès européen à célébrer](#)

**Large Hadron Collider e International
Linear Collider a caccia del bosone di Higgs**

Frankfurter Allgemeine
FAZ.NET

Wir stoßen die Tür zum dunklen Universum auf

WILL THE WORLD END AT 6.30PM TONIGHT?



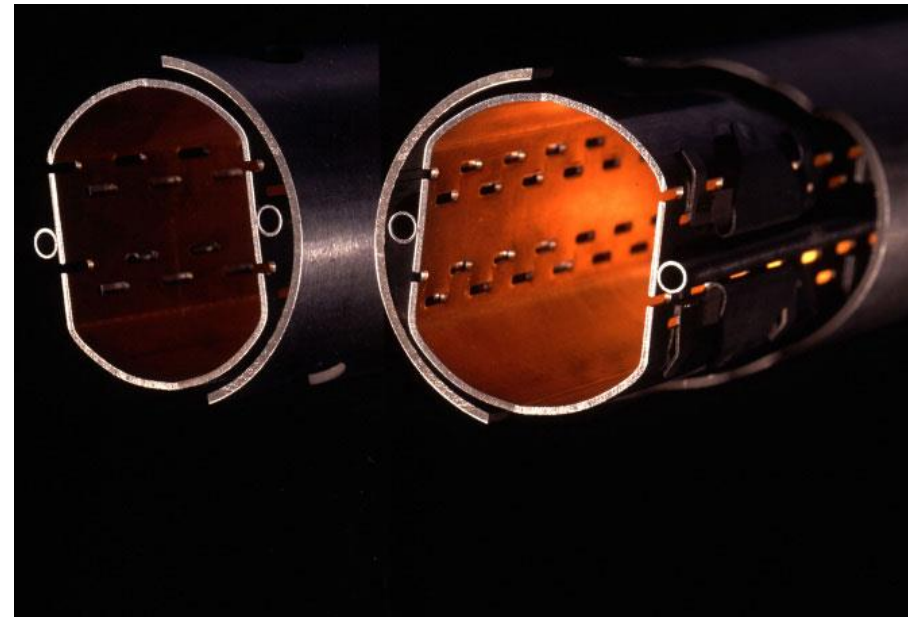
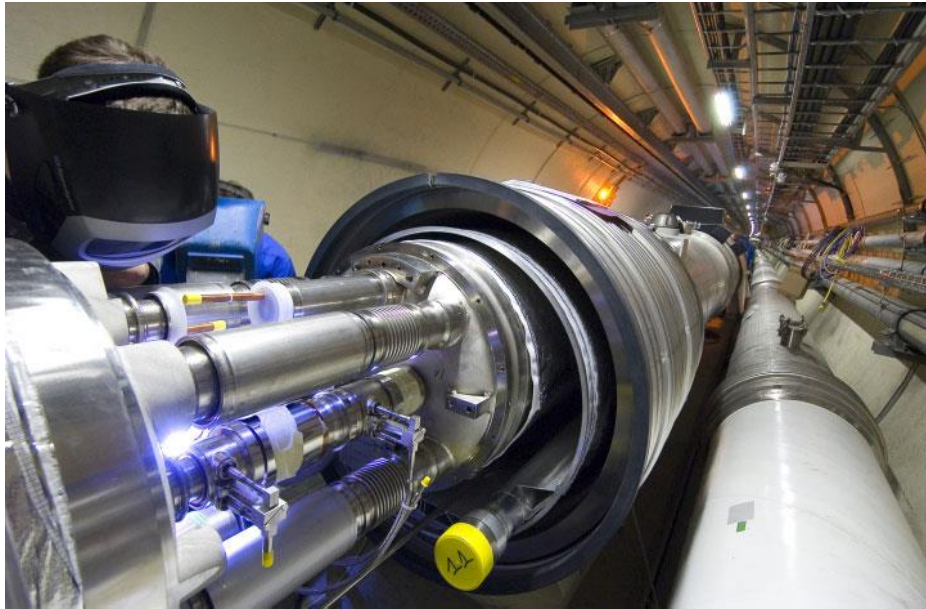
**LET'S GET
SMASHED**

The fastest racetrack on the planet

The protons will reach **99.99999991%** speed of light, and go round the 27km ring 11,000 times per second



The emptiest vacuum in the solar system



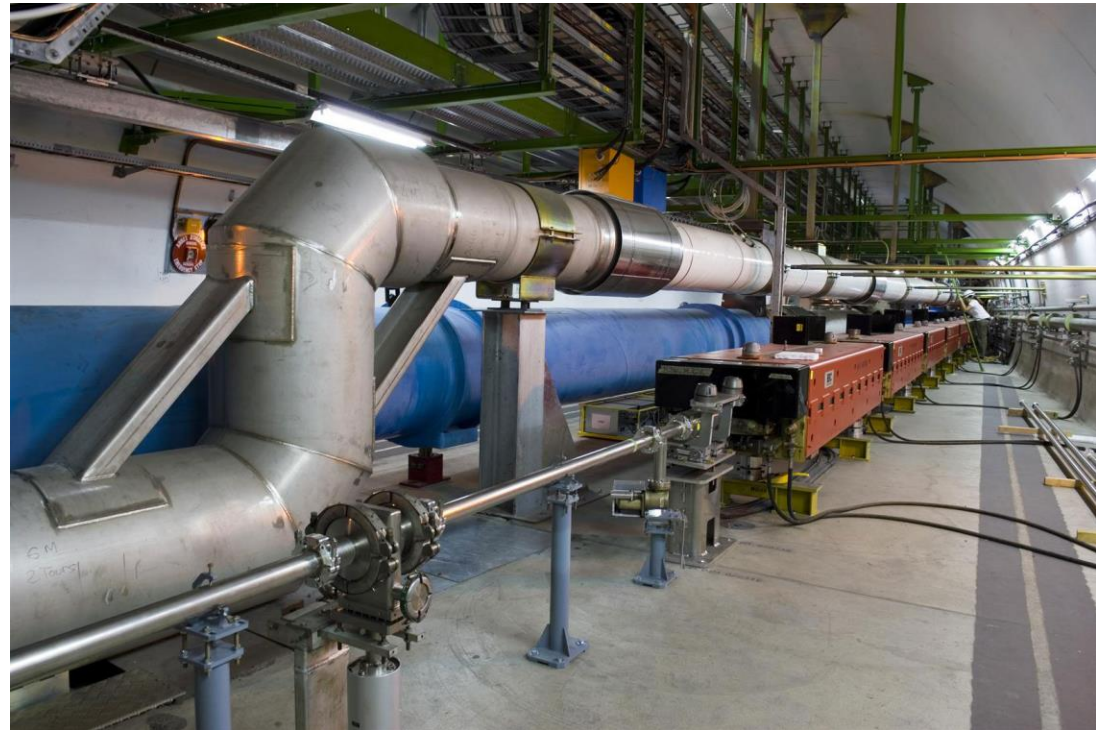
**Ten times more atmosphere on the Moon
than inside LHC beam pipes**

The coldest places in the galaxy

The LHC operates at -271 C (1.9K),

colder than outer space.

A total of 36,800 tonnes are cooled to this temperature.



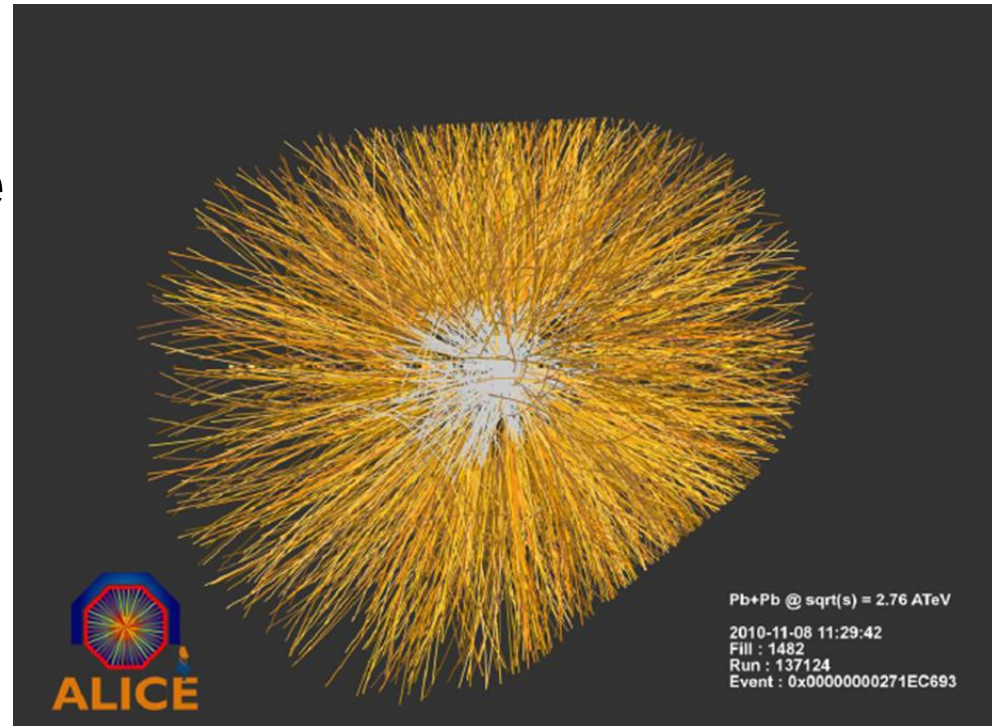
The largest refrigerator ever

The hottest spots in the galaxy

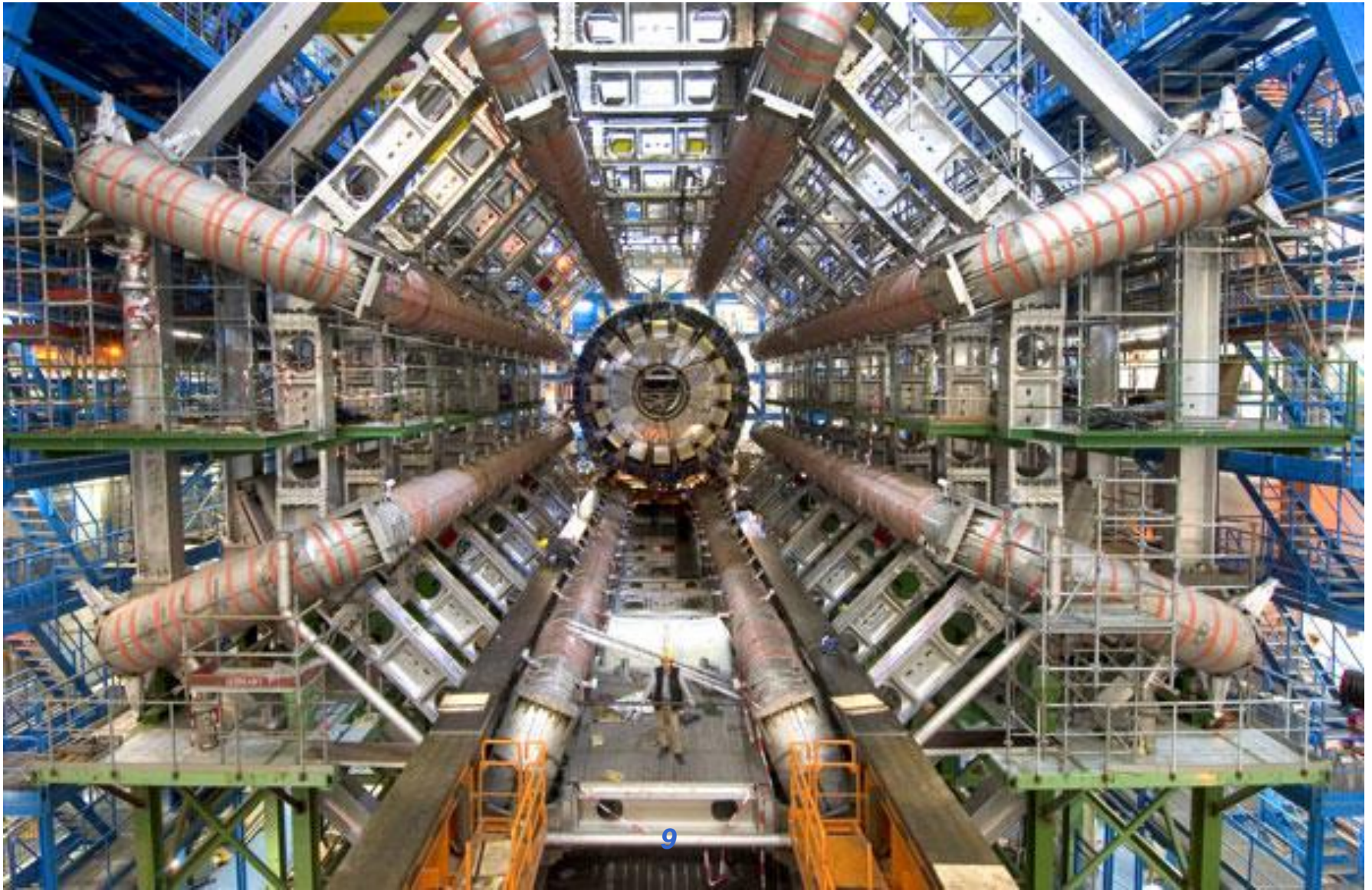
When the two beams collide, they will generate temperatures

1000 million times hotter than the heart of the sun,

but in a minuscule space



The biggest detectors ever built



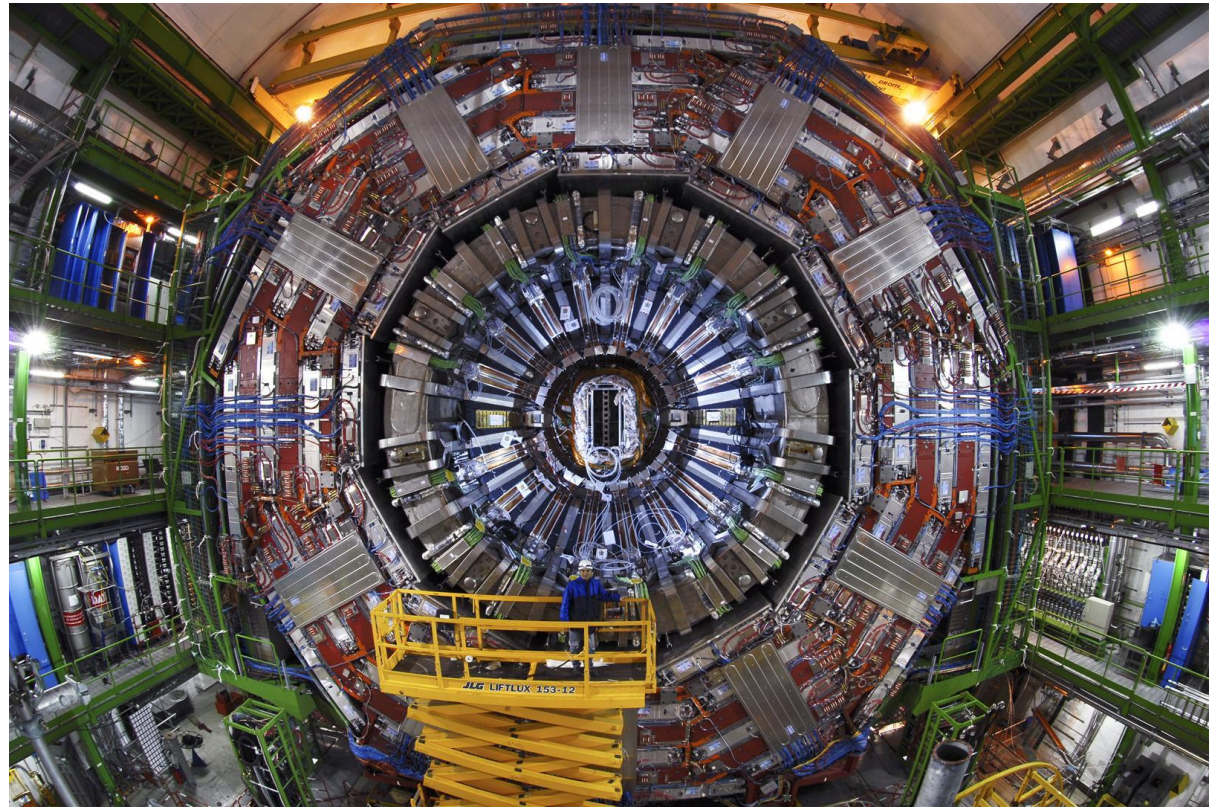
The biggest detectors ever built

To sample and record the debris from up to

**600 million
proton
collisions per
second,**

we are building
gargantuan devices

to measure particles
with micron precision.



Data rate

> 10 Petabytes of data per experiment per year

Data rate

> 10 Petabytes of data per experiment per year



The most extensive computer system

To analyse the data

**hundreds of
thousands of
computers**

around the world are
being harnessed in
the Grid



Amount of Stored Energy in LHC

~ 10 GJoules

Same amount of Kinetic Energy

~ 10 GJoules



Sometimes things go wrong ...

LHC dipole magnets (before)



Some of magnets (after)



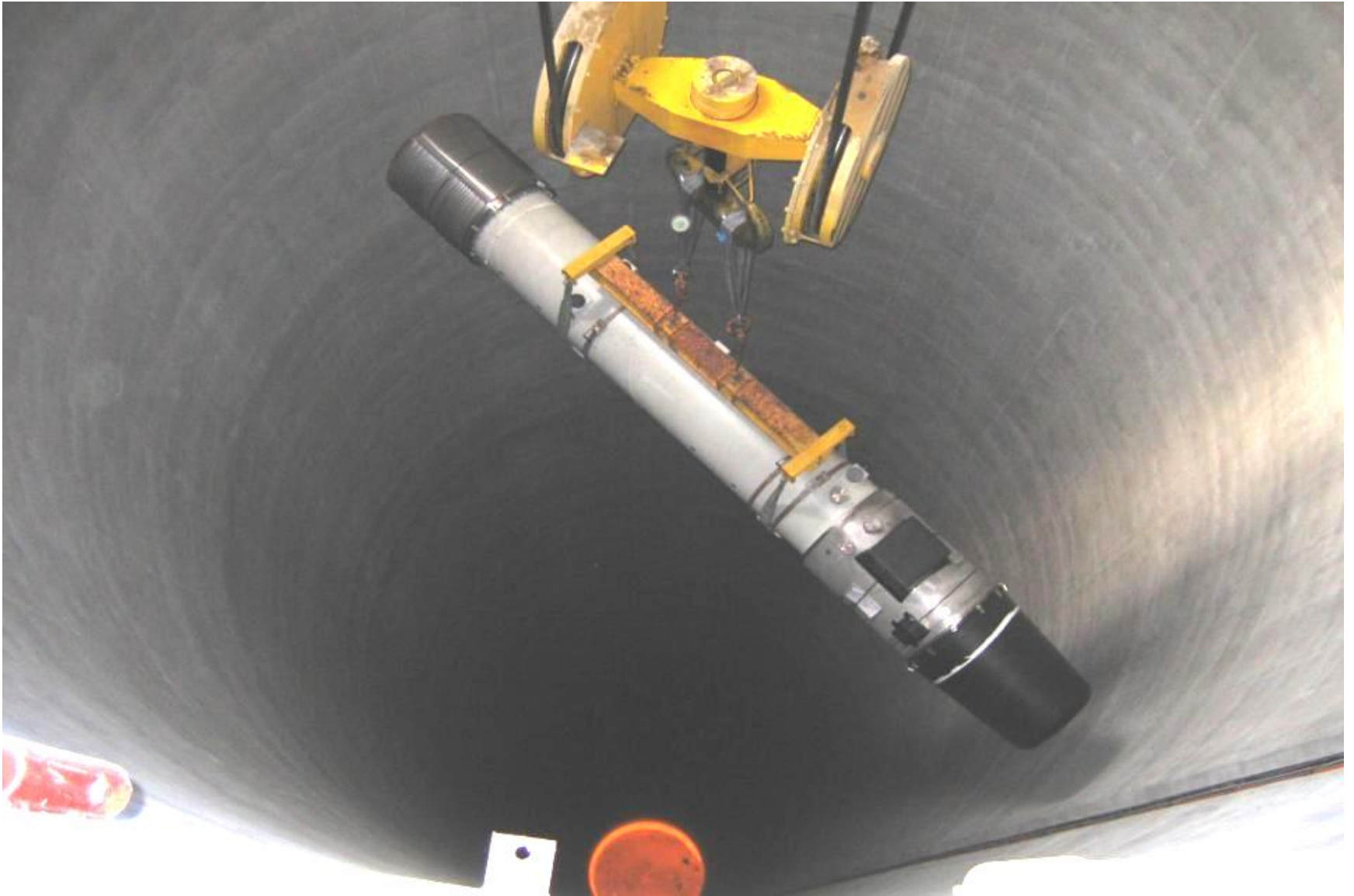
Magnet removal from tunnel



Magnet repair on surface



Last repaired magnet descending



Large Hadron Collider (LHC)

**Largest,
highest-energy
particle
collider**

**CERN,
Geneva**

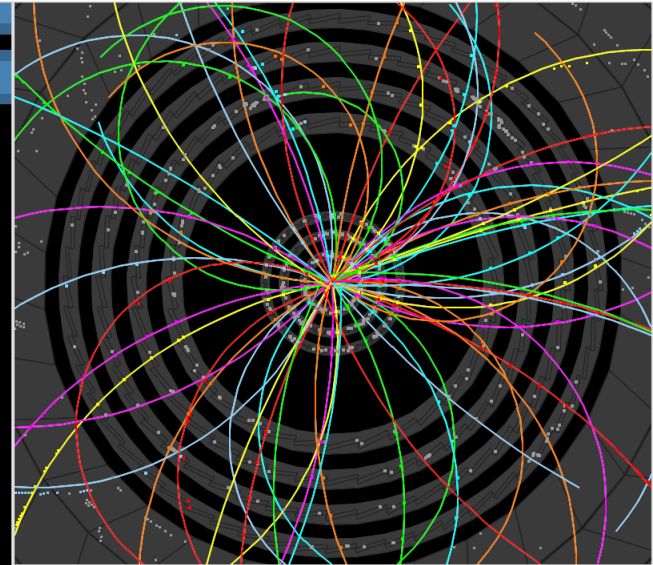
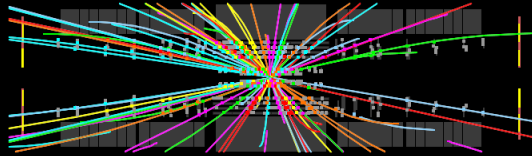


At last!



Highest energy subatomic collisions

<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>



ATLAS
EXPERIMENT

Run Number: 152166, Event Number: 451982

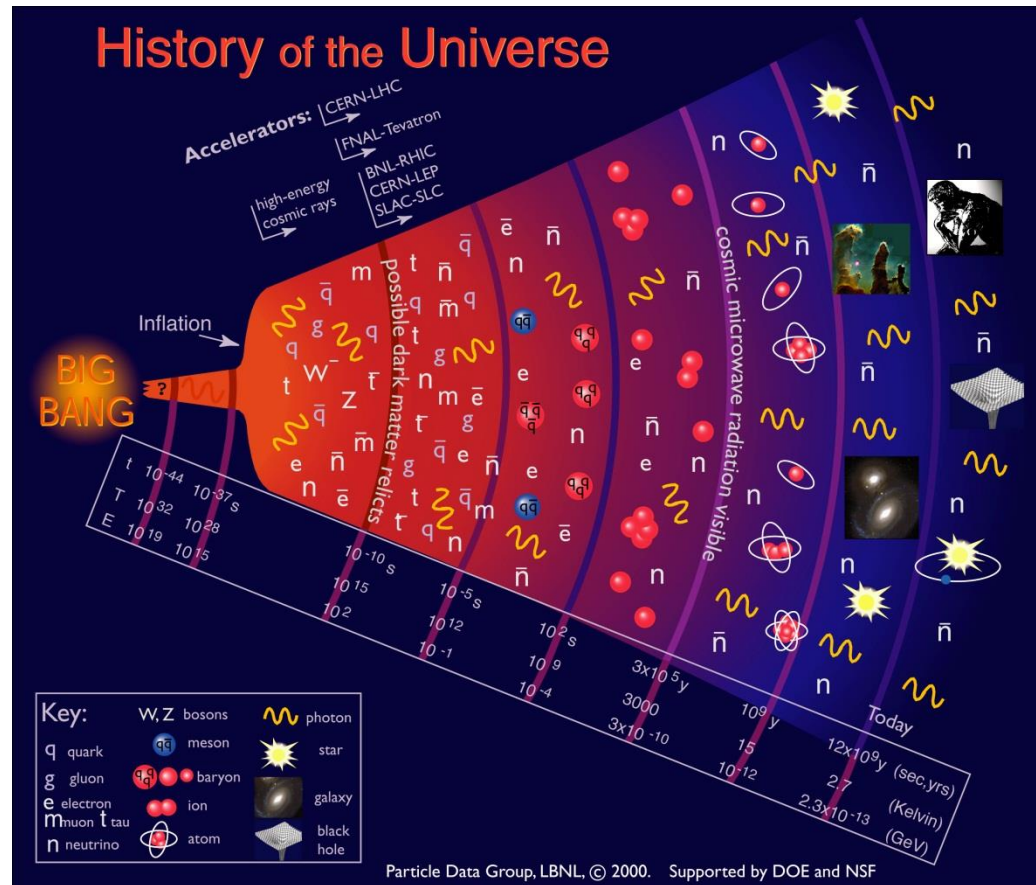
Date: 2010-03-30 13:28:15 CEST

Why build accelerators?

Handwritten mathematical notes on a grid background:

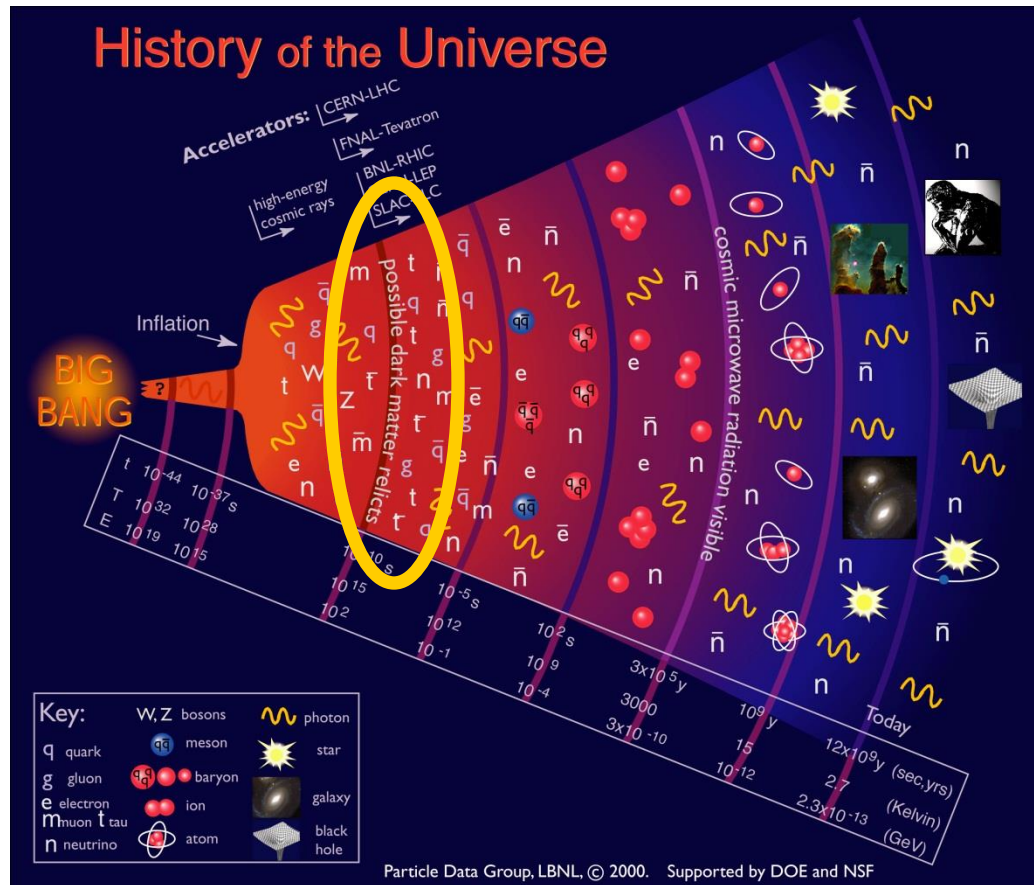
- $\frac{Gm_1m_2}{d^2}$
- $\frac{d}{dx} \int_a^b f(x) dx = \lim_{n \rightarrow \infty} \sum_{i=0}^{n-1} f(x_i) \Delta x$
- $F = \frac{Gm_1m_2}{d^2}$
- $\int_a^b F(u, u', x) dx = \min_{u} \lim_{n \rightarrow \infty} \sum_{i=0}^{n-1} F(u_i, u'_i, x_i) \Delta x$
- $Ax = \lambda x$
- $F = \frac{Gm_1m_2}{d^2}$
- $Ax = \lambda x$
- $\int_a^b F(u, u', x) dx$
- $F = \frac{Gm_1m_2}{d^2}$
- $\int_a^b F(u, u', x) dx$
- $\pi = \frac{c}{d}$
- $Z_{n+1} = 2$
- $\left(1 + \frac{1}{n}\right)^n$
- $Ax = \lambda x$
- $\frac{Gm_1m_2}{d^2}$
- $Ax = \lambda x$
- 2^{15}

Uncovering the origin of the universe



Older larger ... colderless energetic

Telescopes to the early universe



Older larger ... colderless energetic

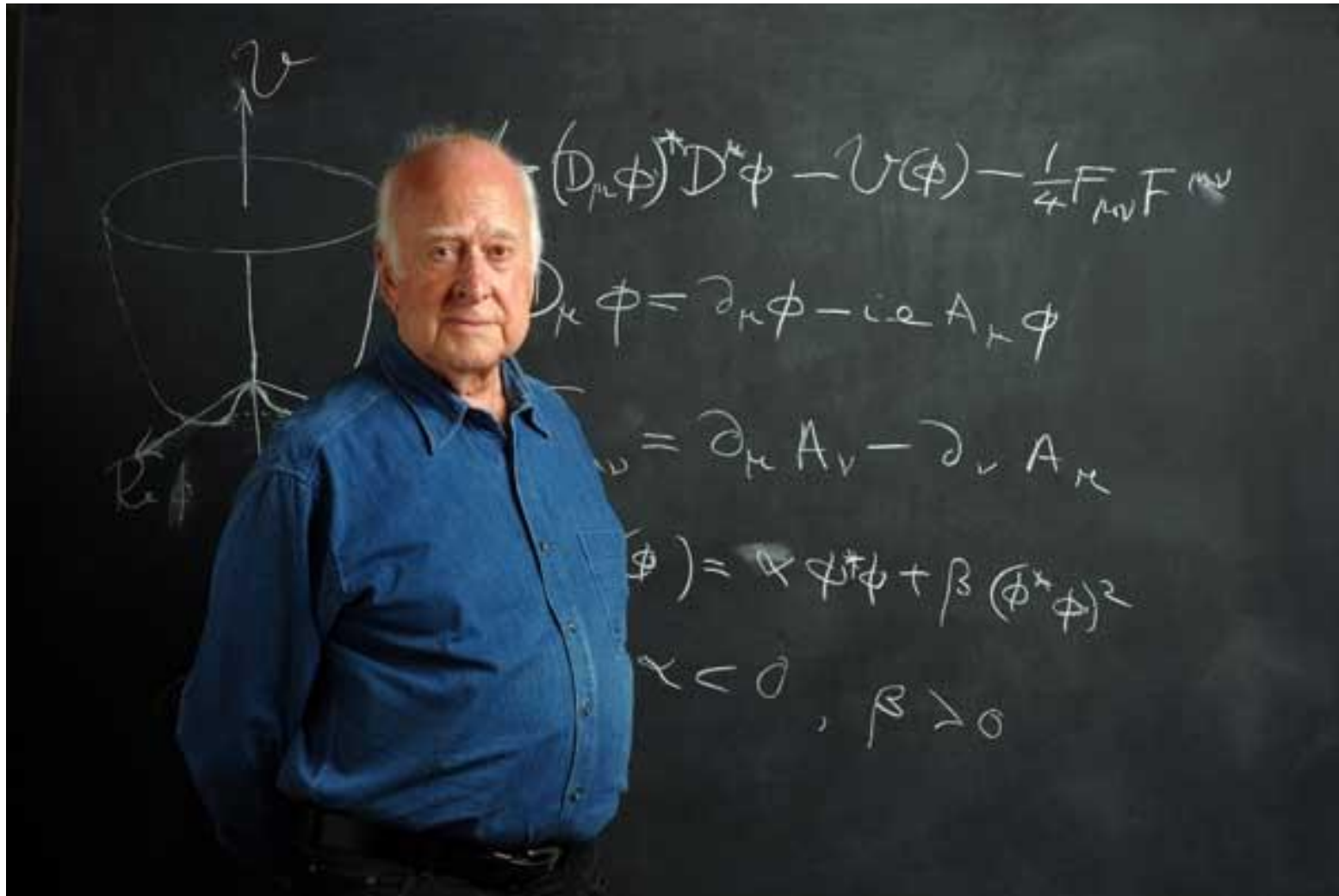
Composition of the universe



Particle Physics Periodic Table

Quarks	u up	c charm	t top	Force Carriers
	d down	s strange	b bottom	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
	e electron	μ muon	τ tau	W W boson

The Standard Model and Higgs



Composition of the universe



Dark Matter



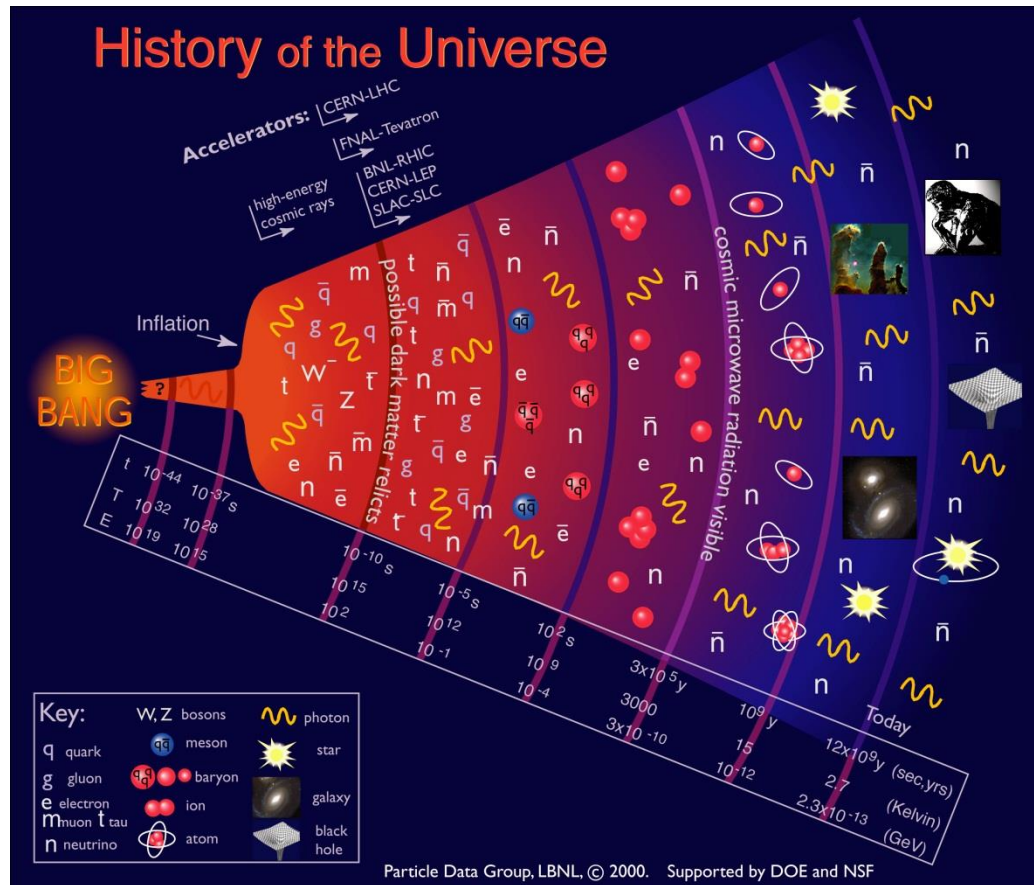
Composition of the universe



Dark Energy



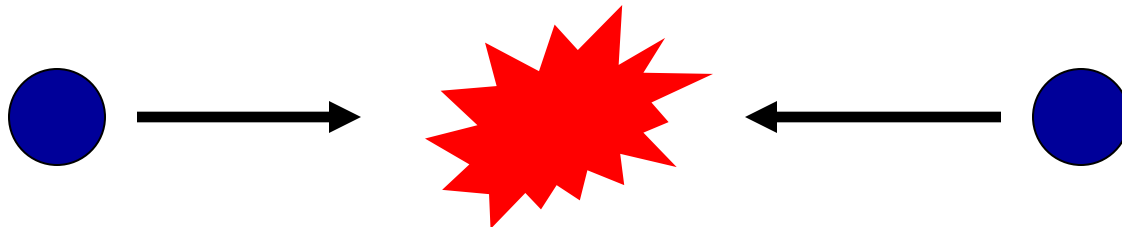
Why build accelerators?



Older larger ... colderless energetic

Why build accelerators?

- **Want to see what matter is made of**
- **Smash matter apart and look for the building blocks**
- **Take small pieces of matter:
accelerate them to very high energy
crash them into one another**



- **LHC: protons crashing into protons head-on**

High energy is critical

Size of structure we can probe with a collider like LHC

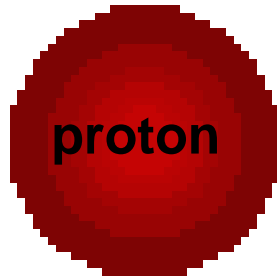
$$= h / p \quad (\text{de Broglie, 1924})$$

h = Planck's constant = 6.63×10^{-34} Js

p = momentum of protons

The larger the momentum (energy), the smaller the size

How to accelerate protons to high energies?



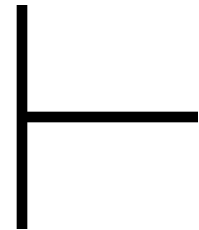
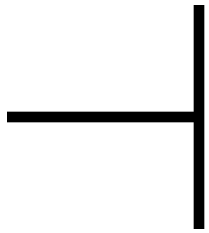
protons carry electric CHARGE → feel electric force

Accelerating protons

Apply an electric field → accelerate!

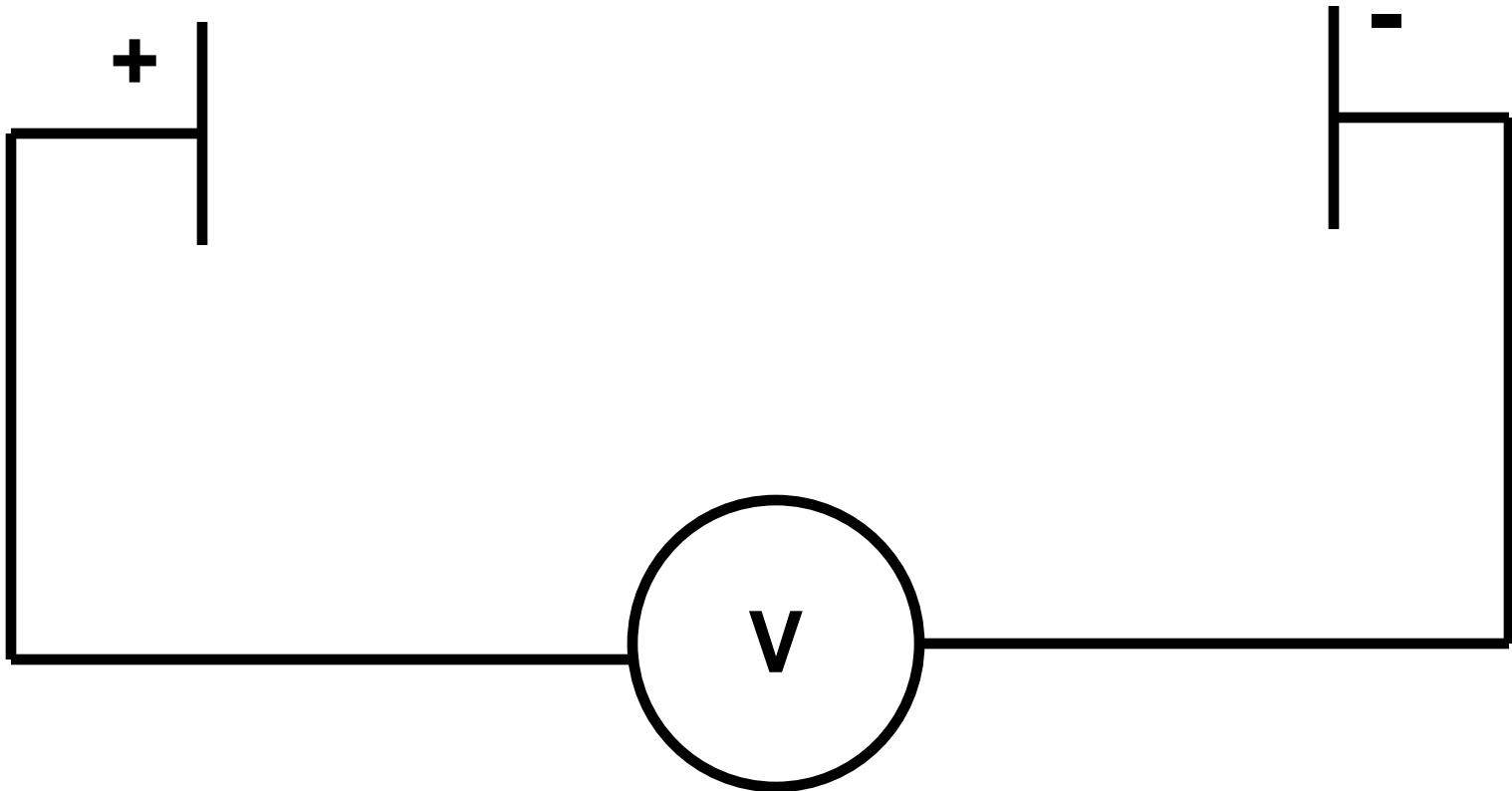
Accelerating protons

Apply an electric field \rightarrow accelerate!



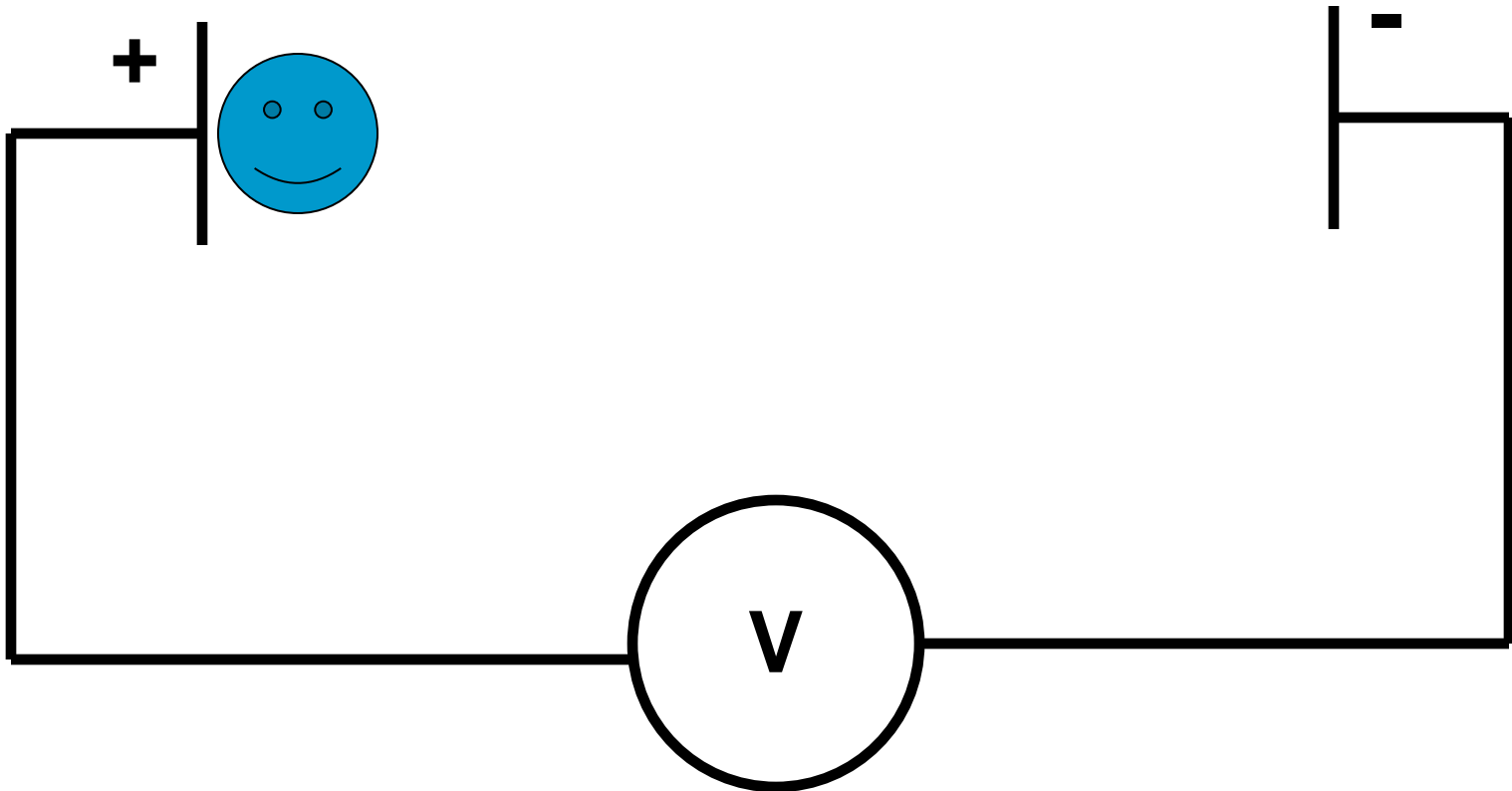
Accelerating protons

Apply an electric field \rightarrow accelerate!



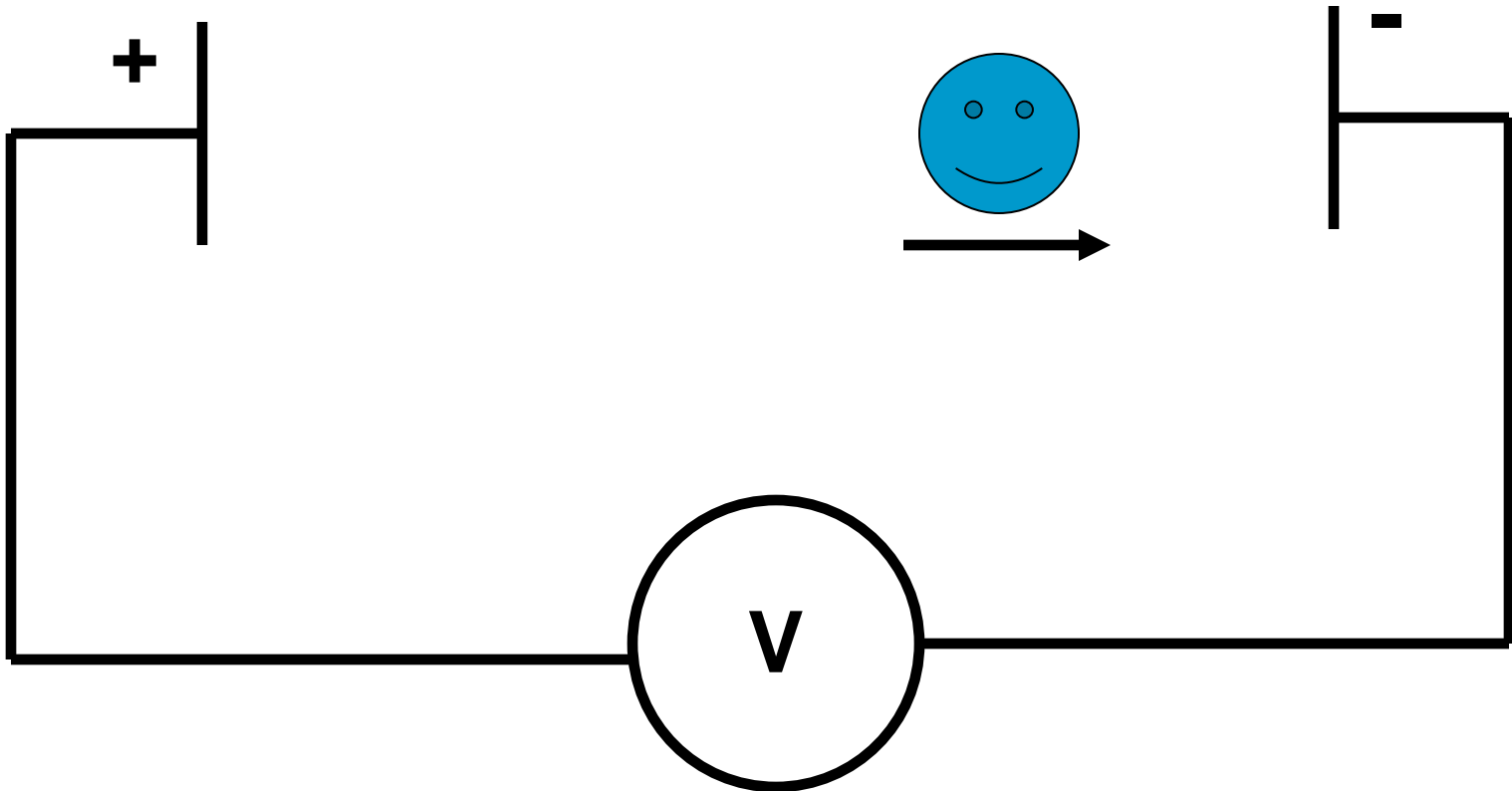
Accelerating protons

Apply an electric field \rightarrow accelerate!

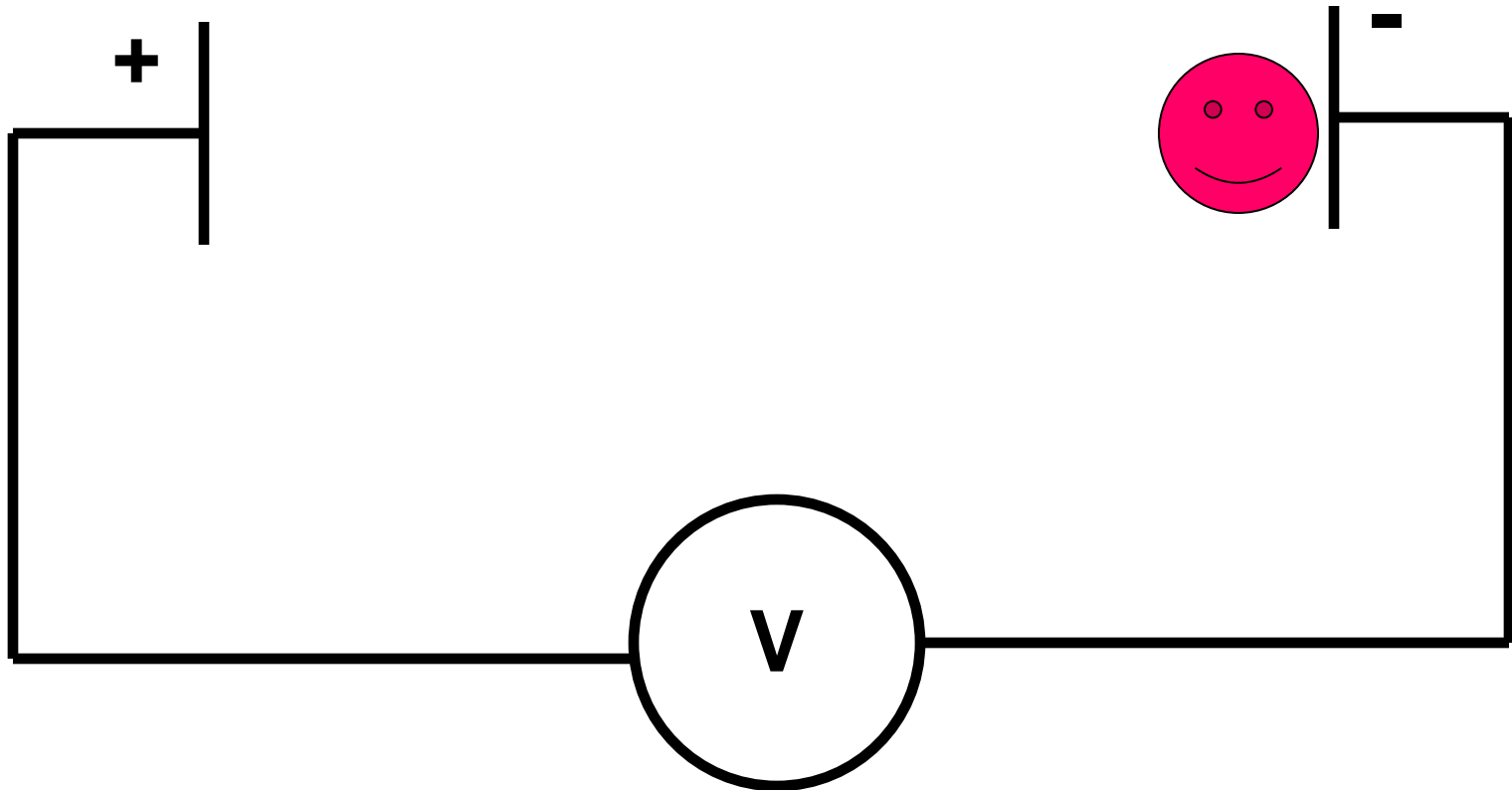


Accelerating protons

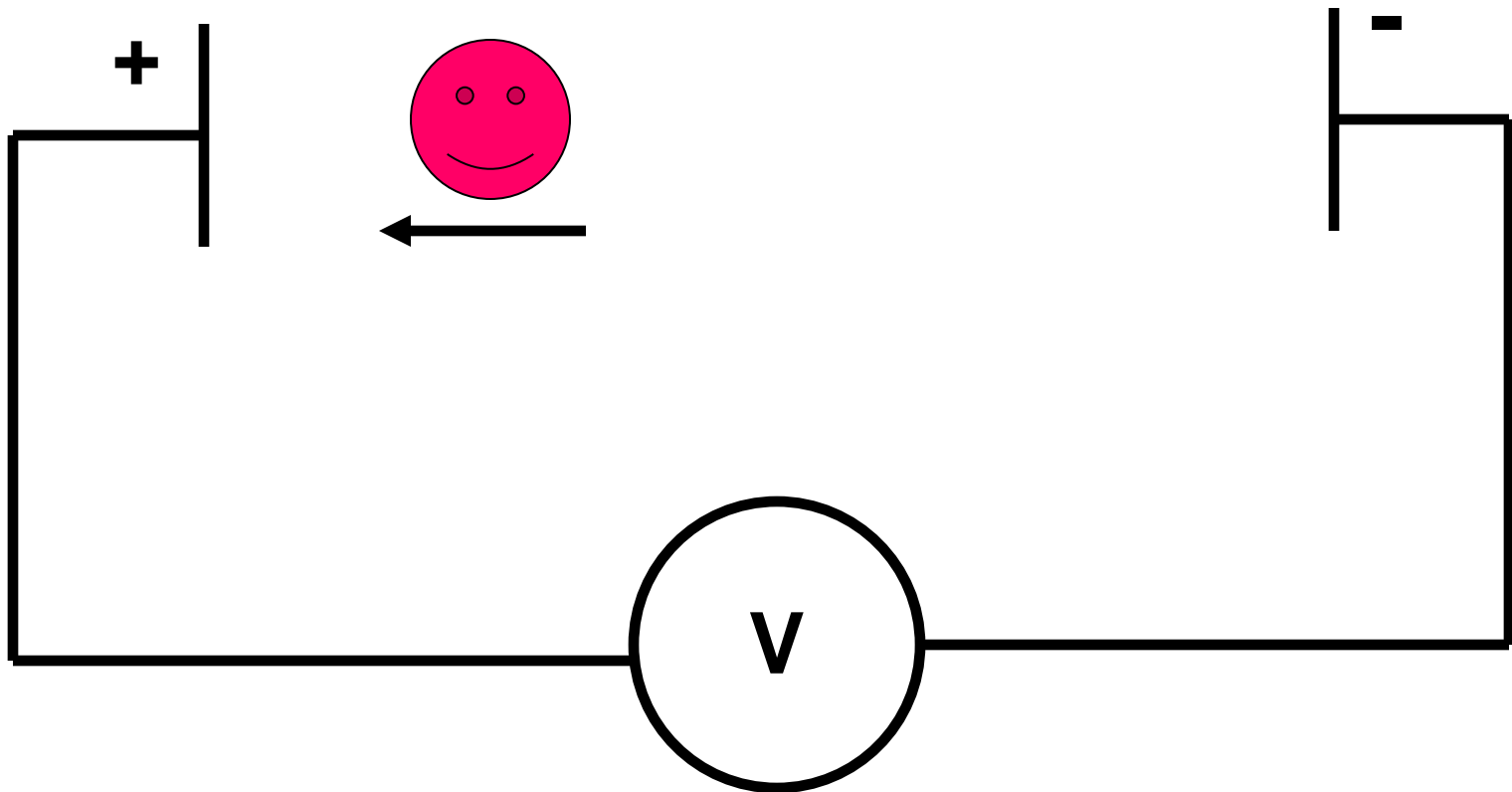
Apply an electric field \rightarrow accelerate!



Accelerating electrons

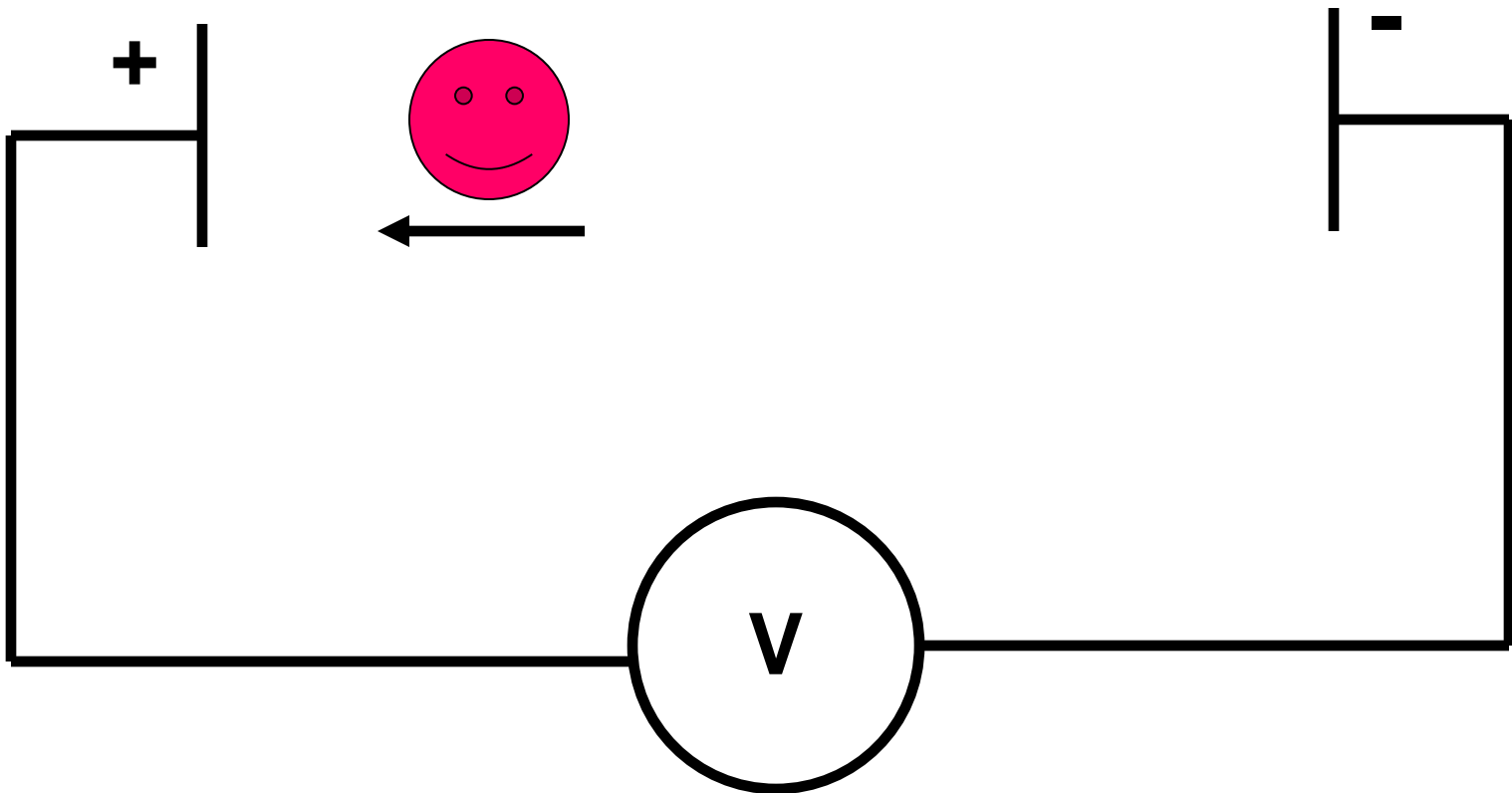


Accelerating electrons

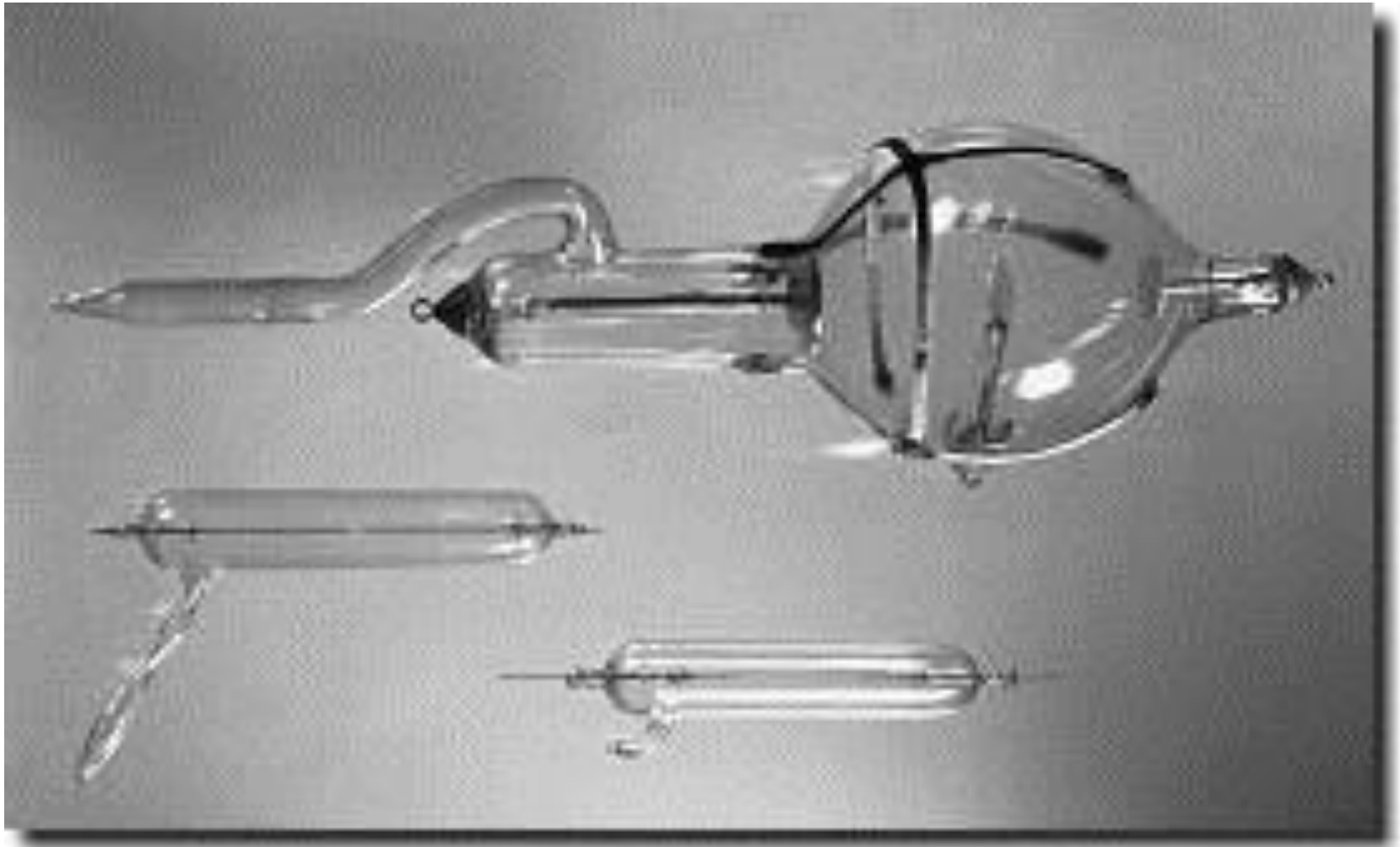


Accelerating electrons

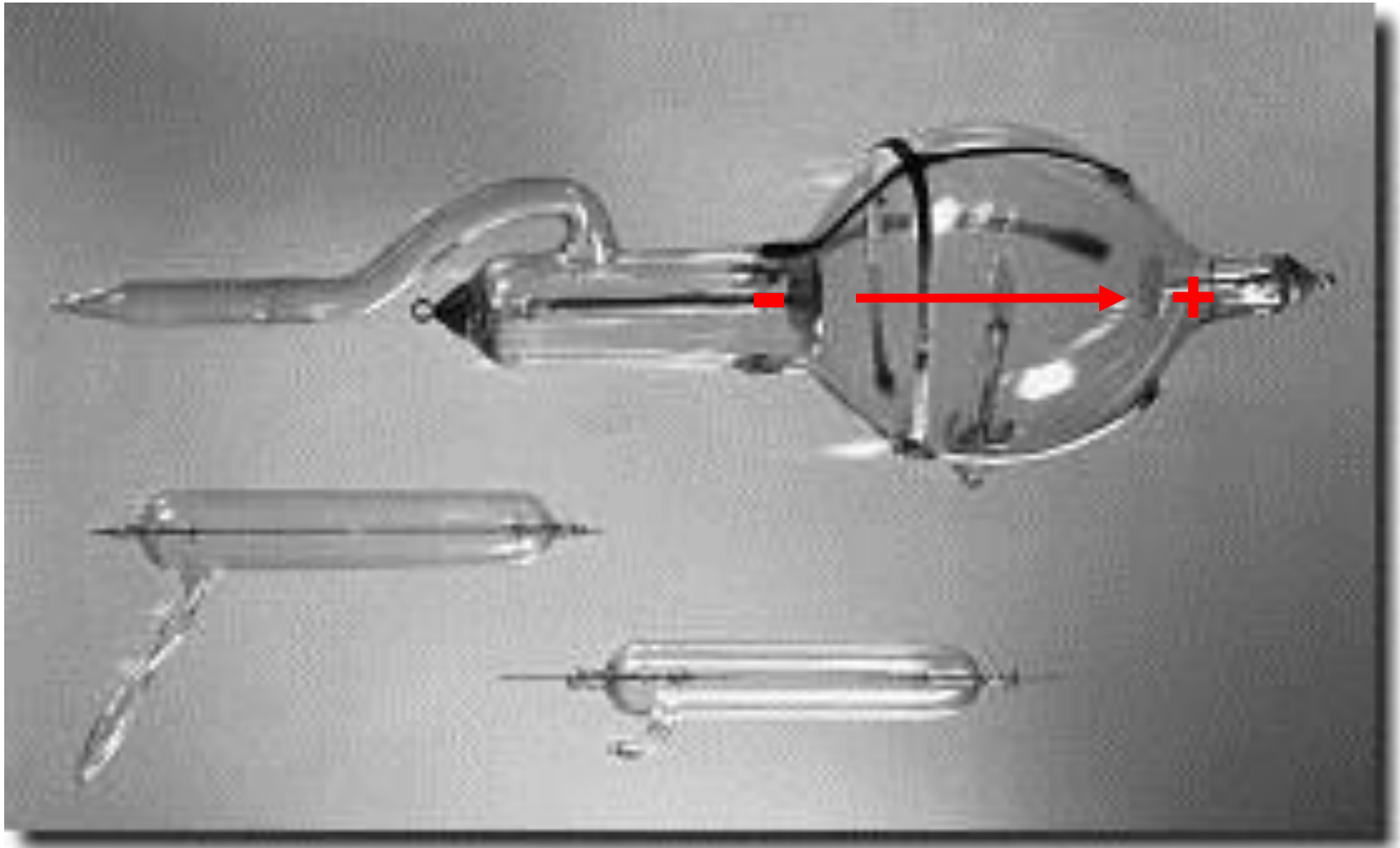
Energy ~ voltage



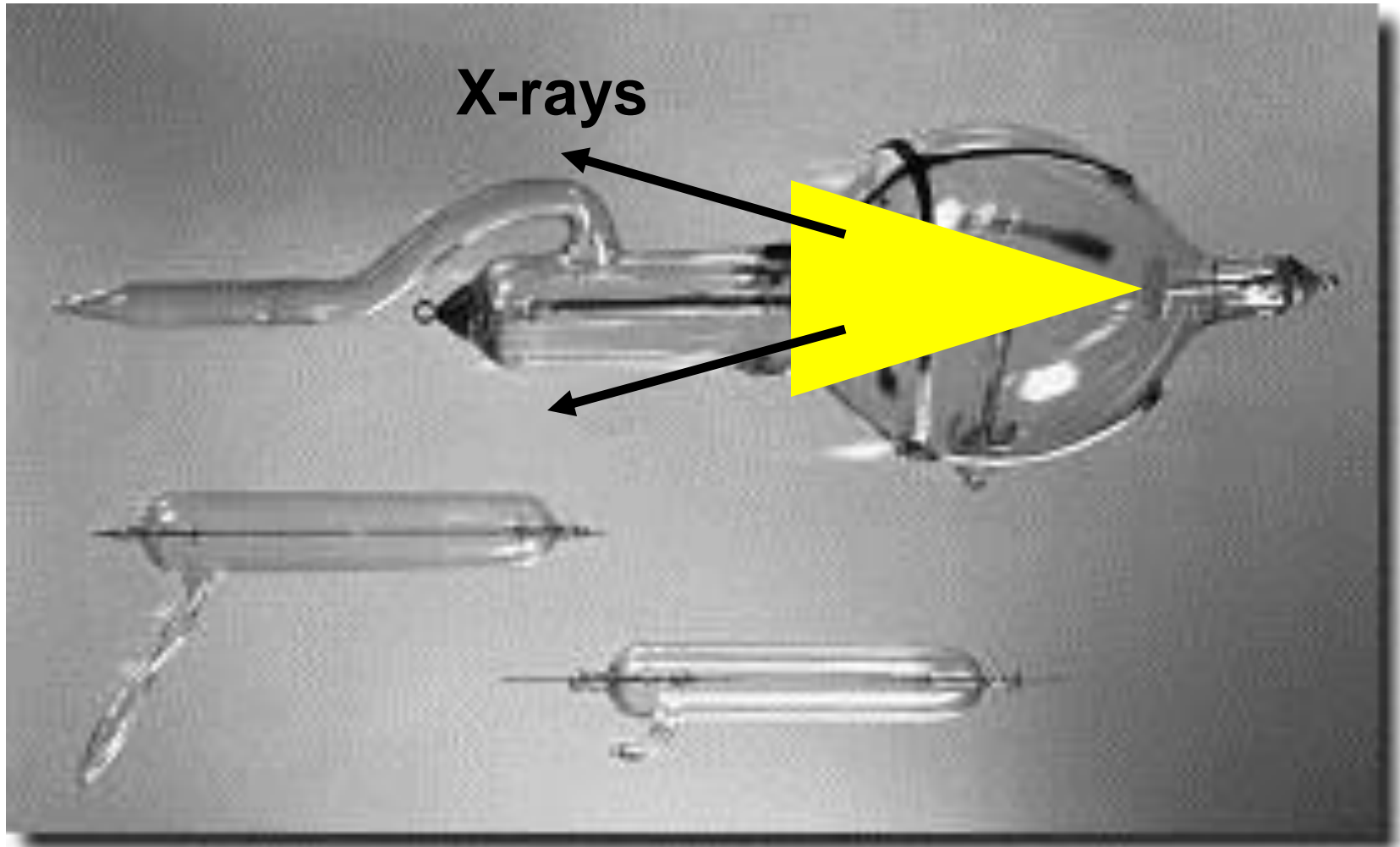
The early days



The early days



The early days

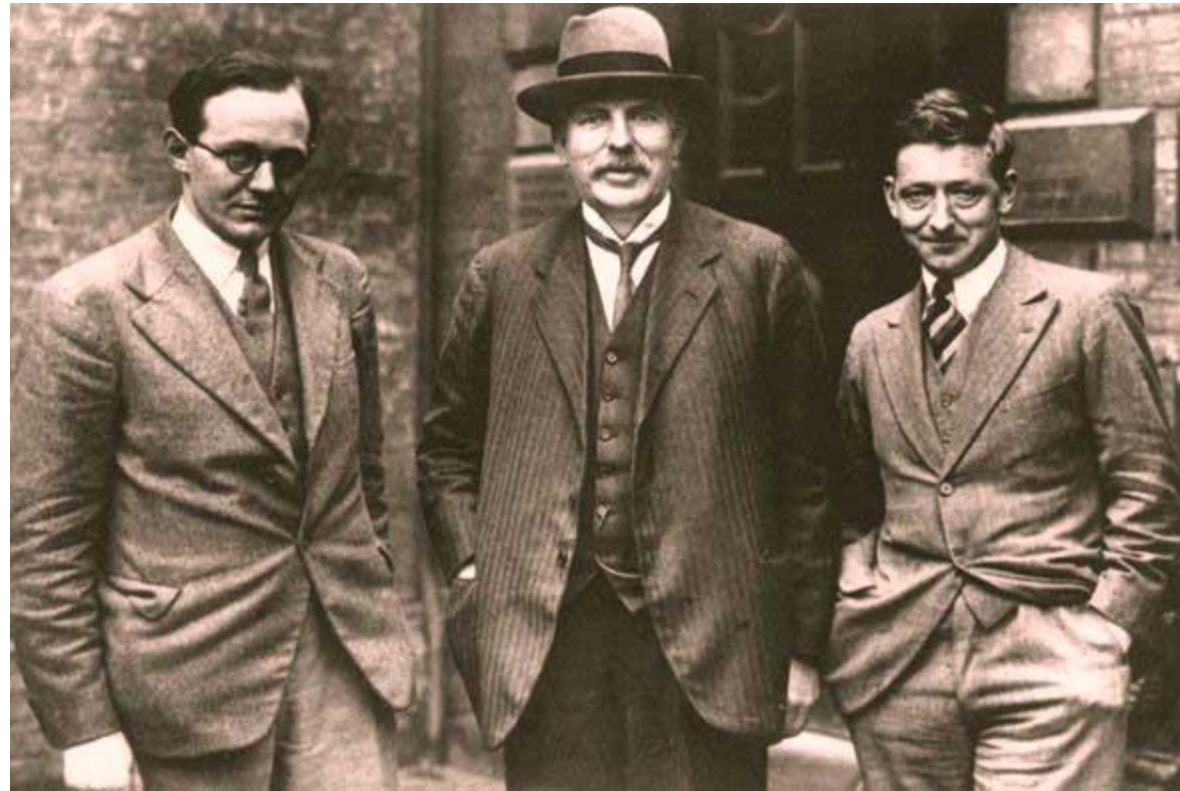
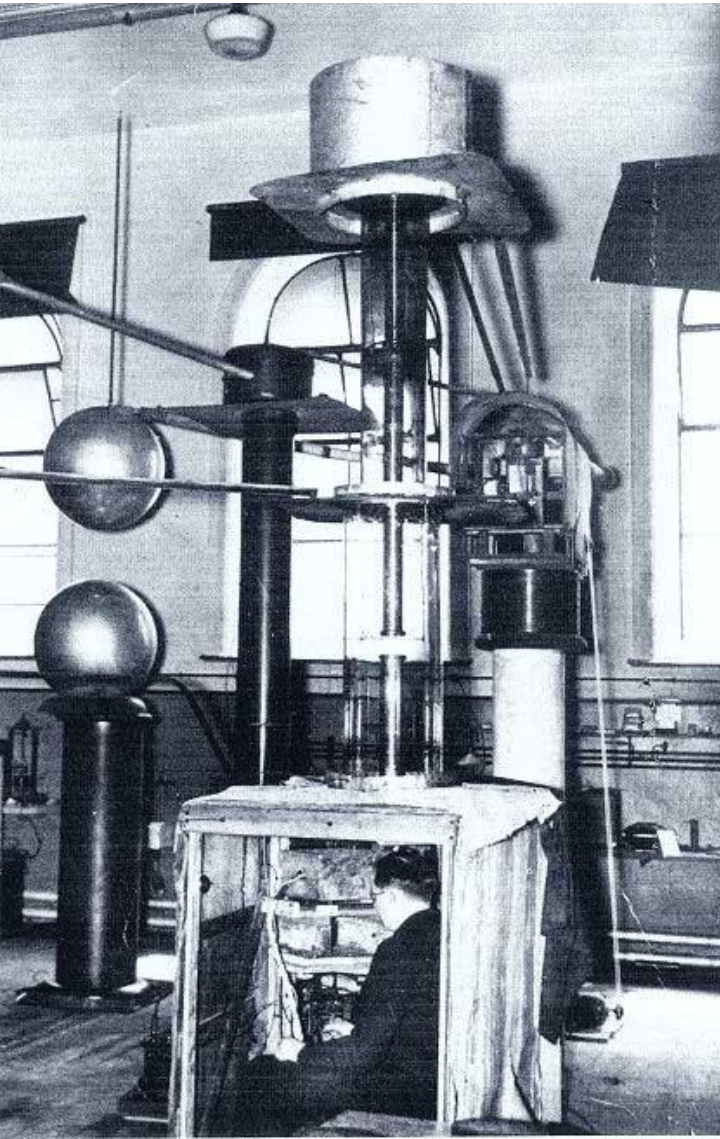


First use of an accelerator in medicine!



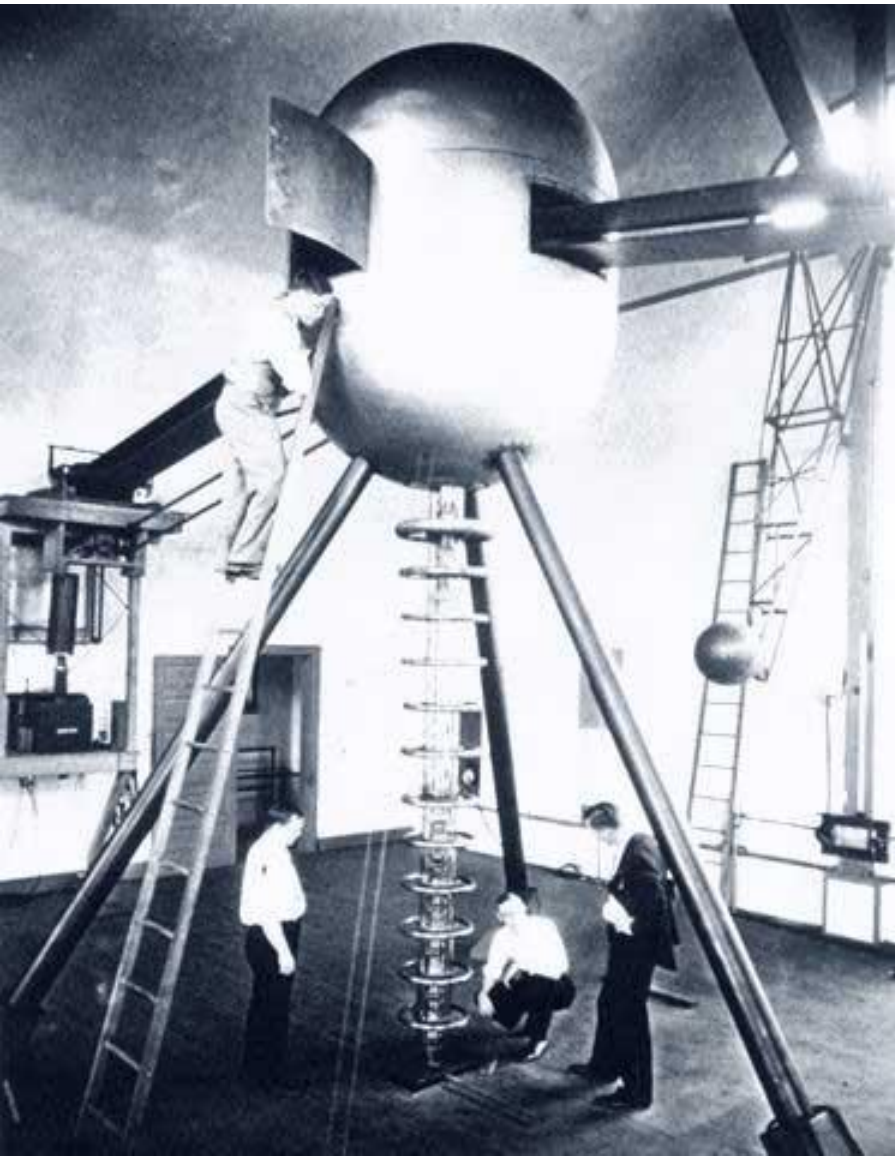
**Mrs. Roentgen's
hand**

Cockcroft – Walton Accelerator



800,000 Volts

Van de Graaff Accelerator

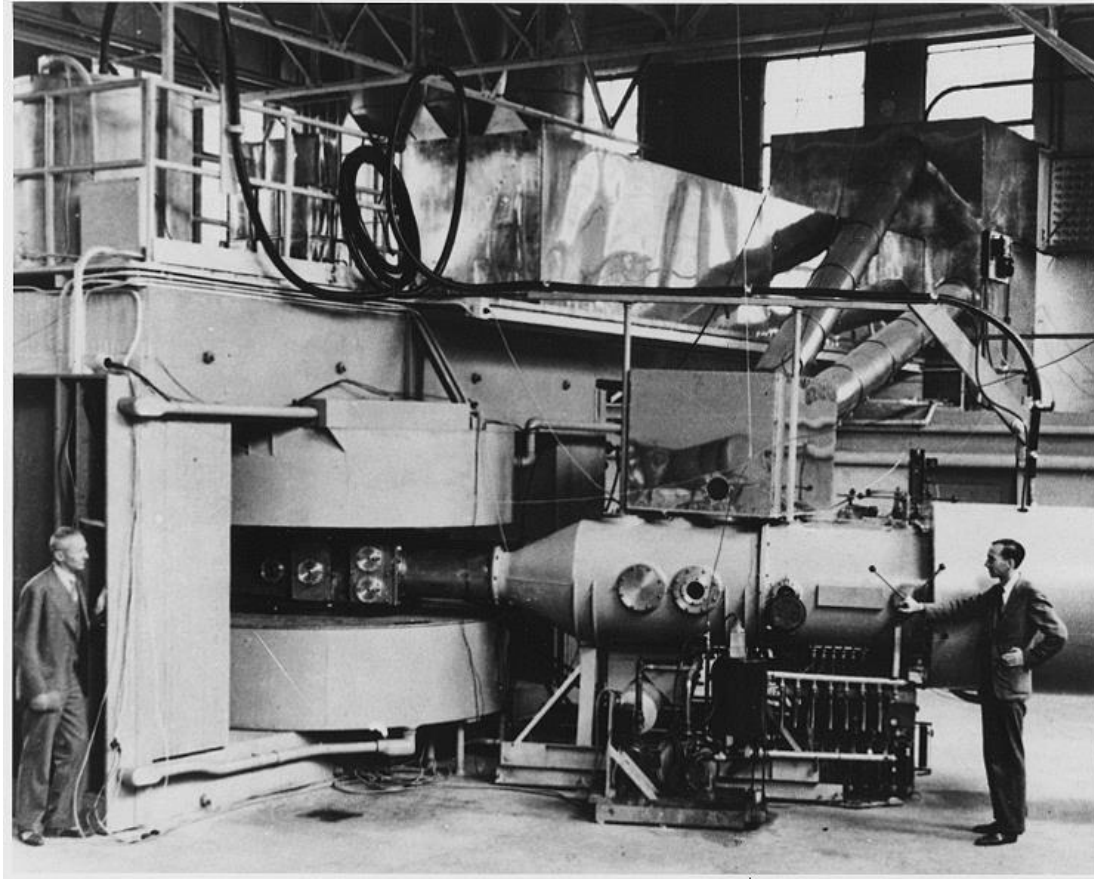


1500,000 Volts

Lawrence Cyclotron



80,000 Volts



25,000,000 Volts

How many Volts???

Voltage [Volts]

Size probed [metres]

How many Volts???

Voltage [Volts]

1000,000 (Mega)

Size probed [metres]

0.000 000 000 000 1

How many Volts???

Voltage [Volts]

1000,000 (Mega)

1000,000,000 (Giga)

Size probed [metres]

0.000 000 000 000 1

0.000 000 000 000 000 1

How many Volts???

Voltage [Volts]

1000,000 (Mega)

1000,000,000 (Giga)

1000,000,000,000 (Tera)

Size probed [metres]

0.000 000 000 000 1

0.000 000 000 000 000 1

0.000 000 000 000 000 000 1

How many Volts???

Voltage [Volts]

1000,000 (Mega)

1000,000,000 (Giga)

1000,000,000,000 (Tera)

Size probed [metres]

0.000 000 000 000 1

0.000 000 000 000 000 1

0.000 000 000 000 000 000 1

LHC:

7000,000,000,000

7 trillion Volts

0.000 000 000 000 000 000 000 01

10-20 metres**

How to reach LHC energies?

- We need 7000,000,000,000 Volts /proton beam
How to do this??

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How to do this??



- Would need 10,000,000,000,000 AA batteries

How to reach LHC energies?

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How to do this??



- Would need 10,000,000,000,000 AA batteries
- 500 M km = 3 x Earth's orbit radius around Sun

How to reach LHC energies?

- We need 7000,000,000,000 Volts /proton beam
How to do this??



- Would need 10,000,000,000,000 AA batteries
- 500 M km = 3 x Earth's orbit radius around Sun
- £10,000,000,000,000 – discount for bulk buy?!

Accelerating Technology

- **Batteries have too low voltage per metre:
1.5 Volts per 5 cm = 30 Volts / m ('gradient')**

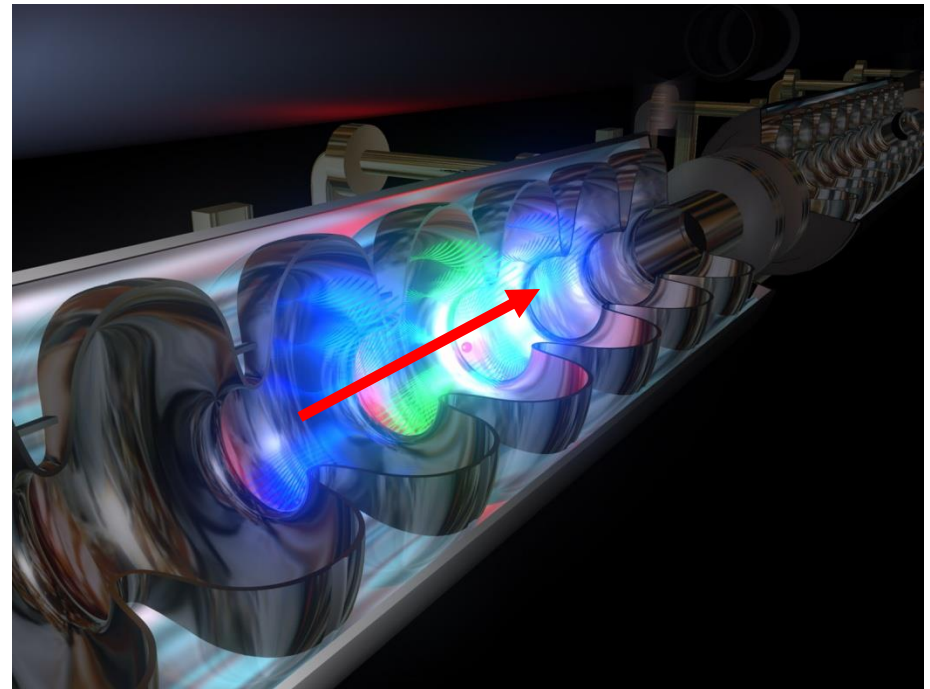
Accelerating Technology

- **Batteries have too low voltage per metre:**
1.5 Volts per 5 cm = 30 Volts / m ('gradient')
- **Forefront accelerating gradients ~ 30 MILLION Volts / m**
- **Hence largest accelerator (LHC) is ****ONLY**** 27 km long!**

Accelerating Technology

- **Batteries have too low voltage per metre:**
1.5 Volts per 5 cm = 30 Volts / m ('gradient')
- **Forefront accelerating gradients ~ 30 MILLION Volts / m**
- **Hence largest accelerator (LHC) is ****ONLY**** 27 km long!**
- **Accelerate using radio-frequency EM waves launched into metal cavities ...**
- **Protons gain energy by 'surfing' the waves**

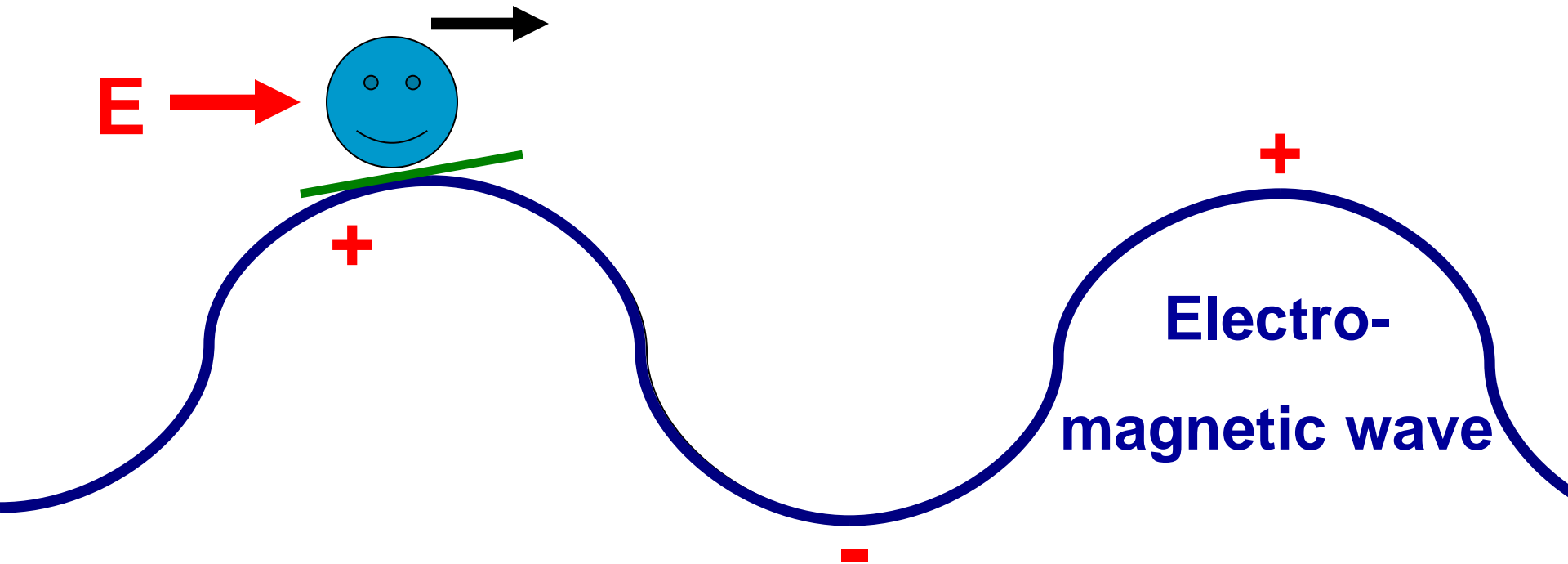
Niobium Accelerating Structures



Human surfer



Subatomic surfer



Large Hadron Collider (LHC)



How many accelerators?

- a) 1-10
- b) 10-100
- c) 100-1,000
- d) 1,000-10,000
- e) > 10,000

Accelerators Worldwide

**> 25,000
accelerators
in use**

Accelerators Worldwide



44%

Radio-
therapy

Radiotherapy with X-rays

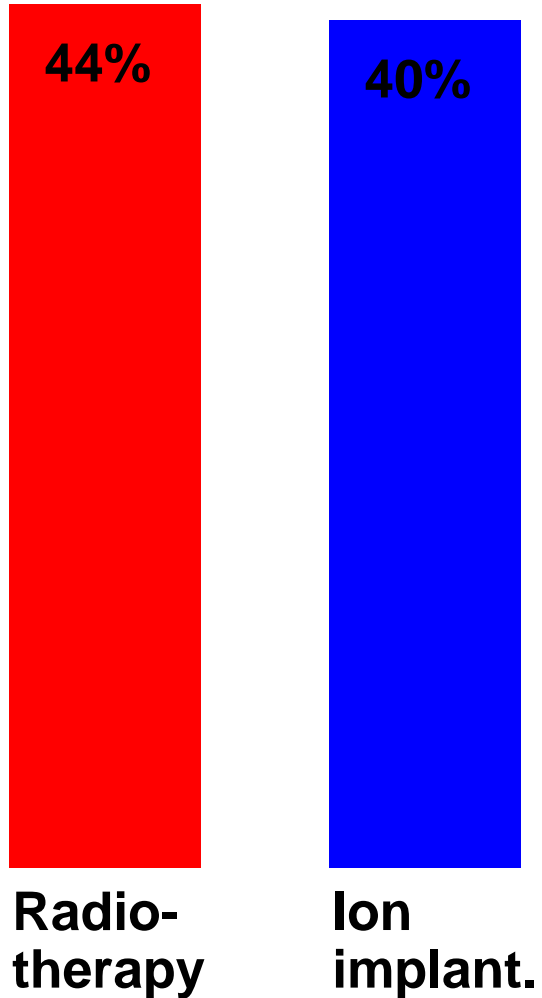


**100,000 patients treated
per day in US alone**

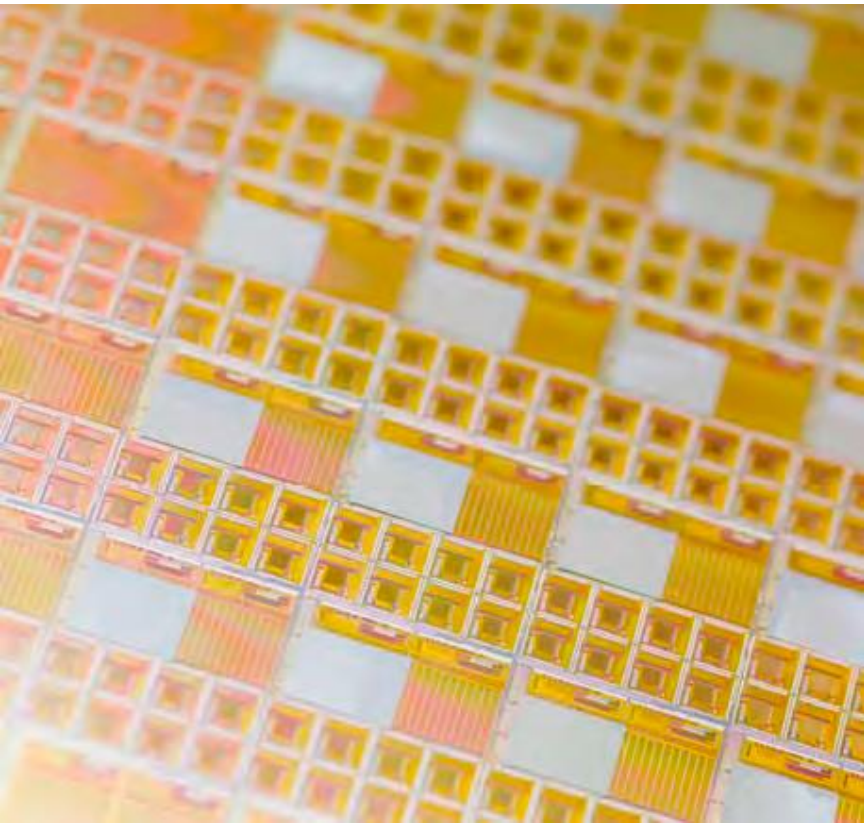
Cancer therapy with protons



Accelerators Worldwide



Semiconductor doping



Ion beam applications

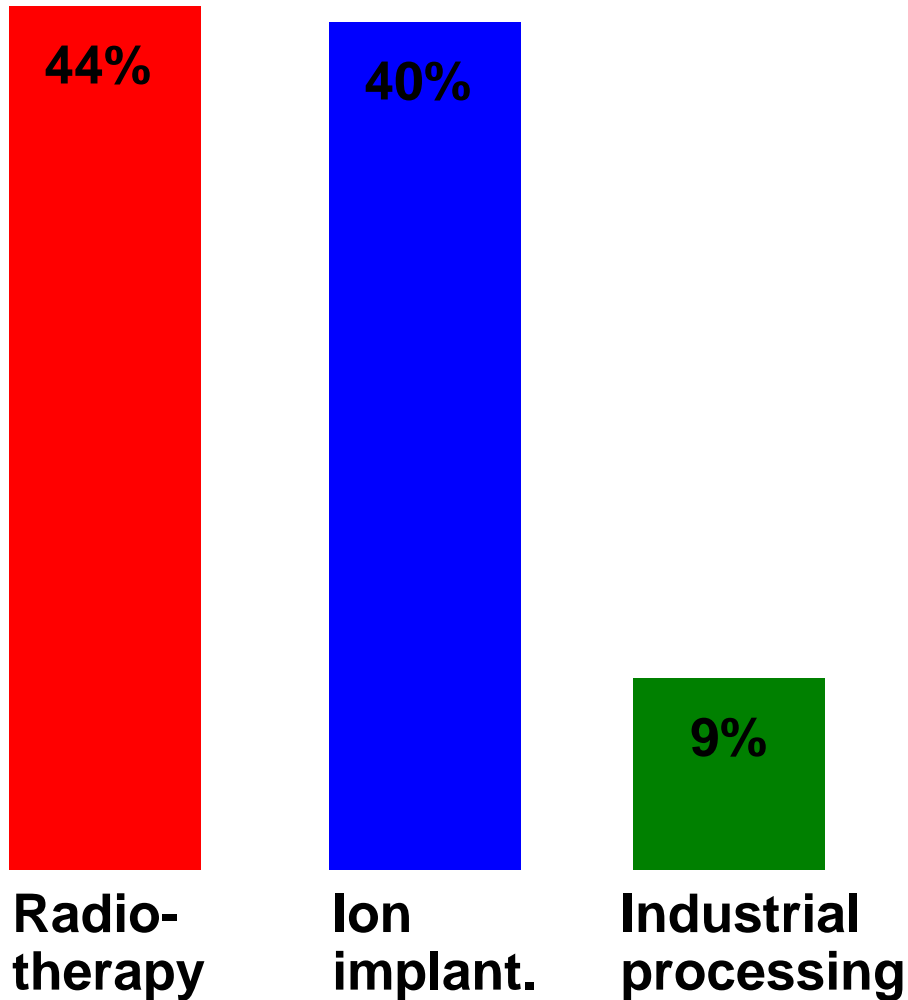


Artificial joints

**Art
analysis**



Accelerators Worldwide

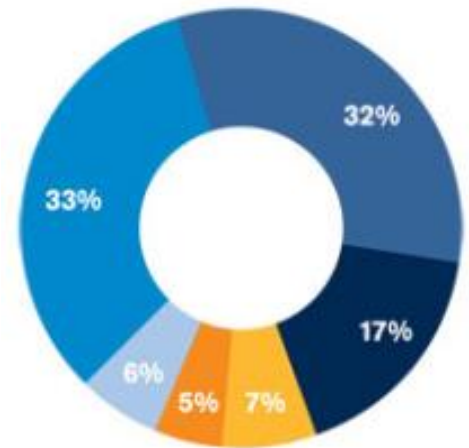


Electron beams in industry



Markets for industrial electron beams total \$50 billion per year.

Image source: IAEA Working Material on Industrial Electron Beam Processing



- Wire cable tubing
- Ink curing
- Shrink film
- Service
- Tires
- Other

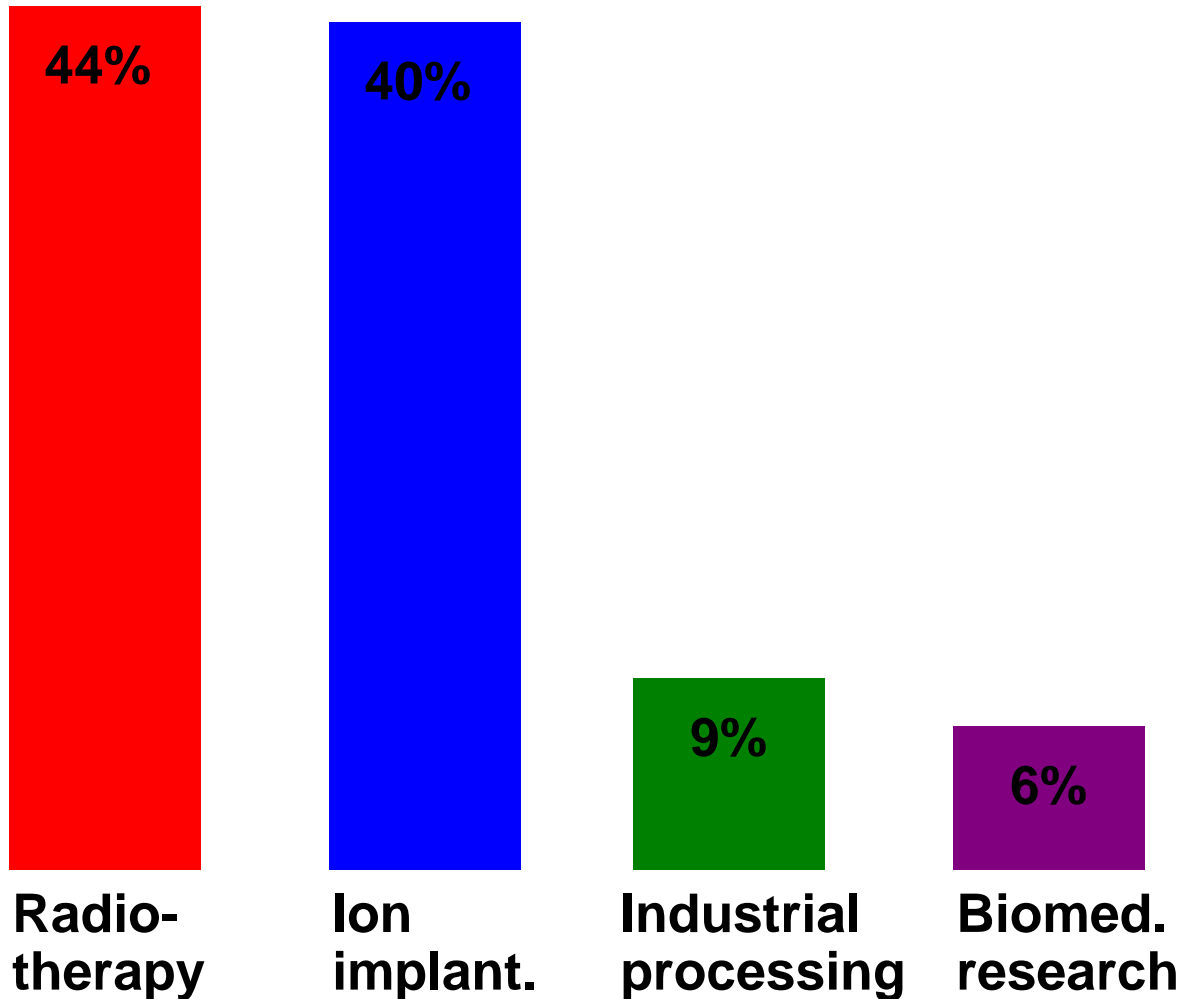


Accelerator Market

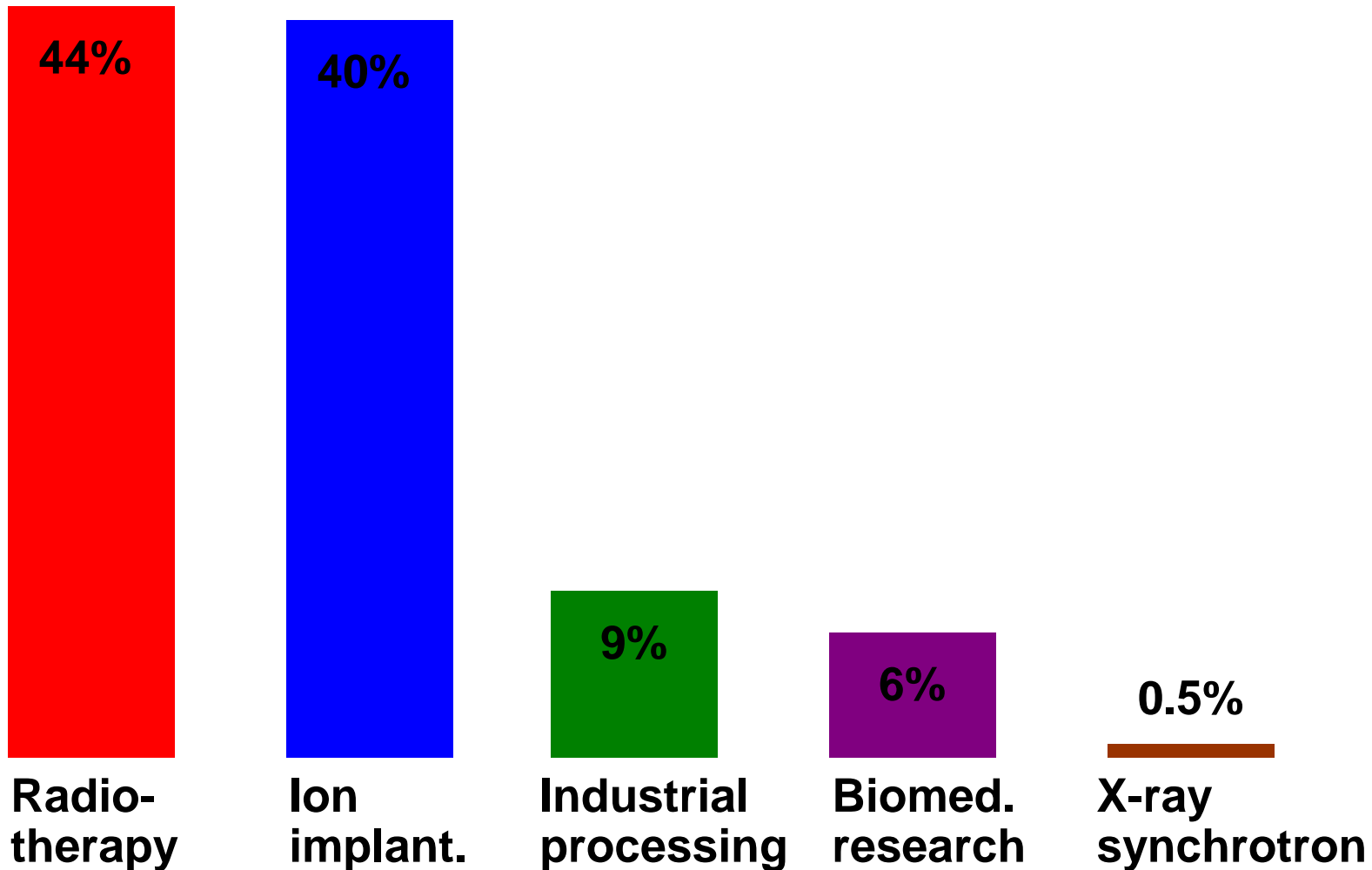
- **Medical + industrial:** **\$3.5B / year**
growing at 10% / year
- **Ion implantation:** **\$1.5B / year**
- **Value of products processed, treated or inspected by particle beams:** **\$500B / year**



Accelerators Worldwide



Accelerators Worldwide



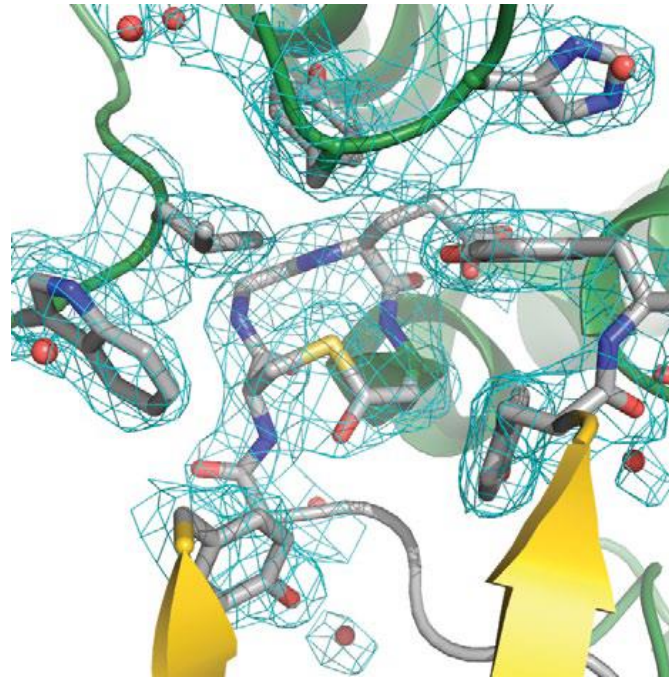
Diamond: synchrotron source of X-rays



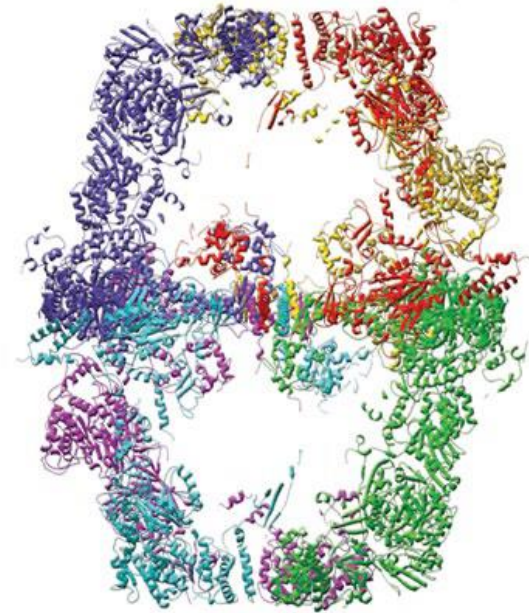
Protein structure



HIV glycoprotein



**mosquito
immune system**

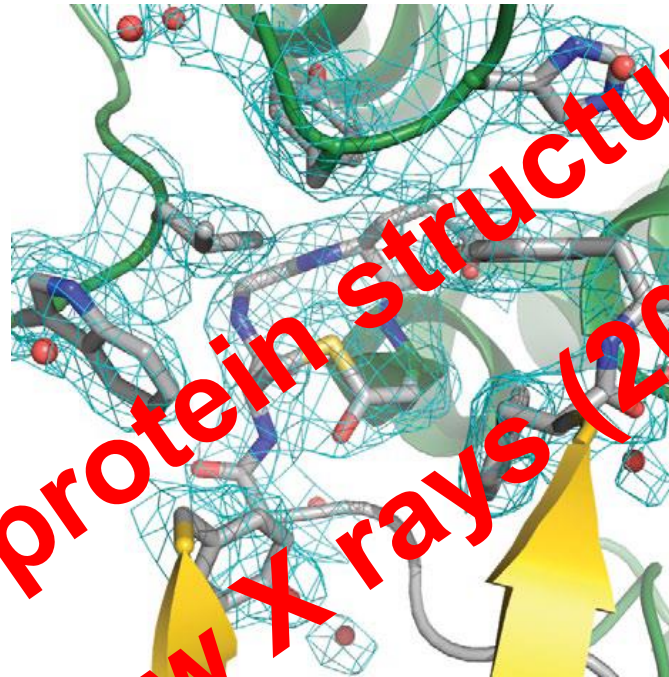


yeast enzyme

Protein structure

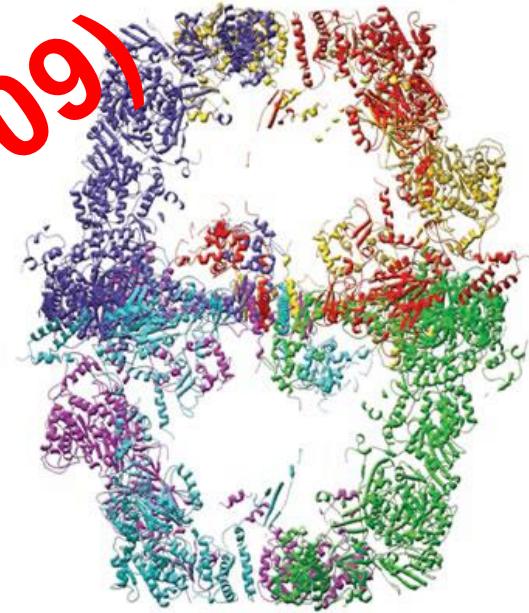


HIV glycoprotein



mosquito

immune system



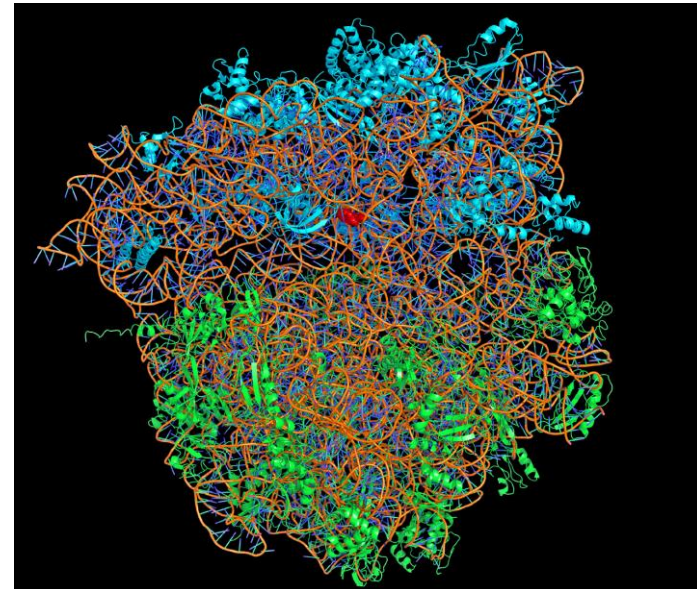
yeast enzyme

> 50,000 protein structures solved w X rays (2009)

2009 Chemistry Nobel Prize

Ramakrishnan, Steitz, Yonath

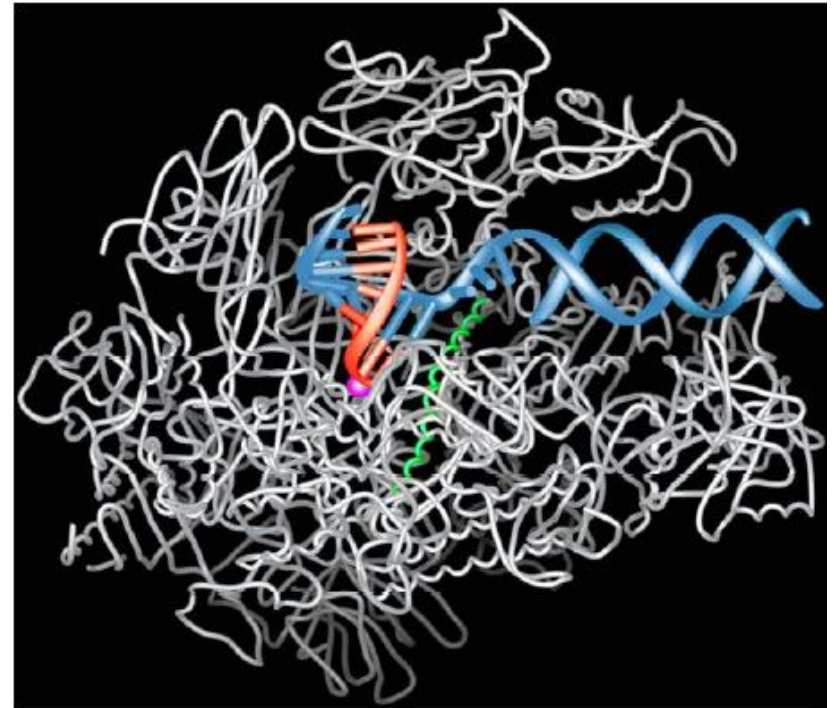
‘studies of the structure and function of the ribosome’



2006 Chemistry Nobel Prize

Roger Kornberg

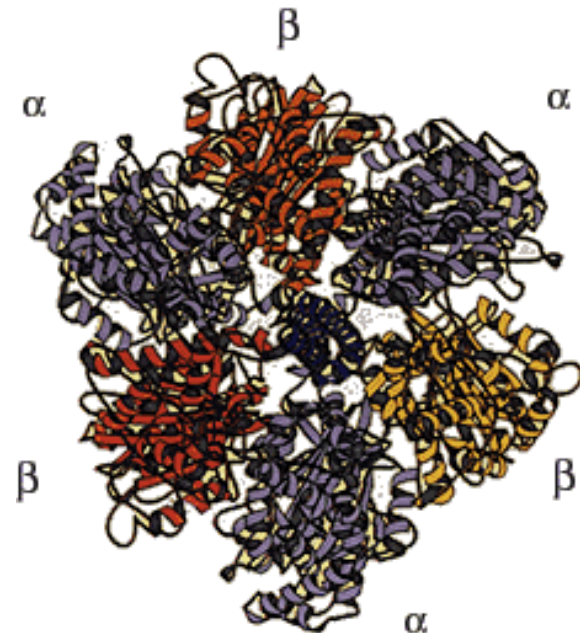
‘studies of the molecular basis of eukaryotic transcription’



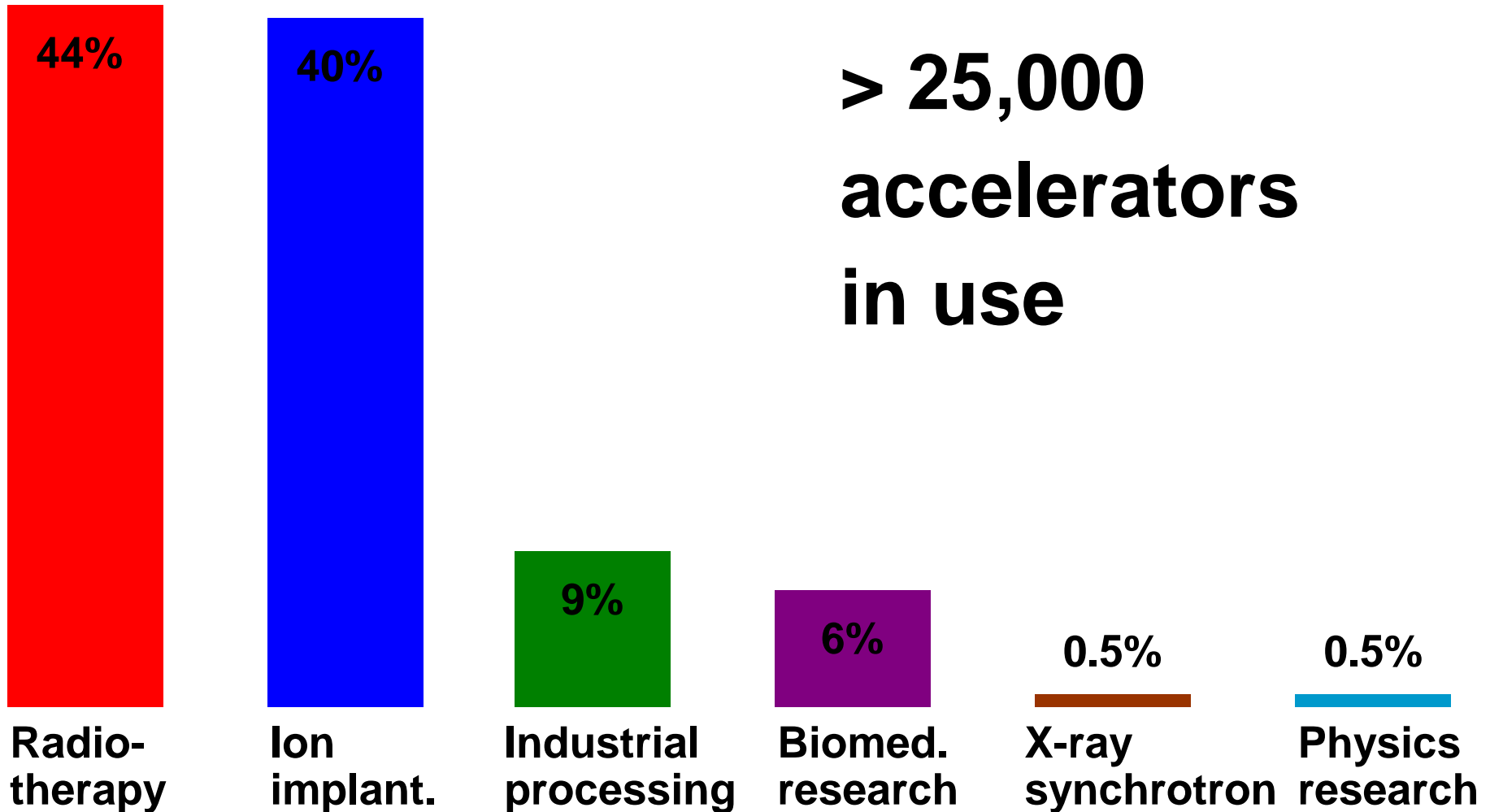
1997 Chemistry Nobel Prize

Boyer + Walker

‘for elucidation of the enzymatic mechanism underlying the synthesis of adenosine triphosphate (ATP)’



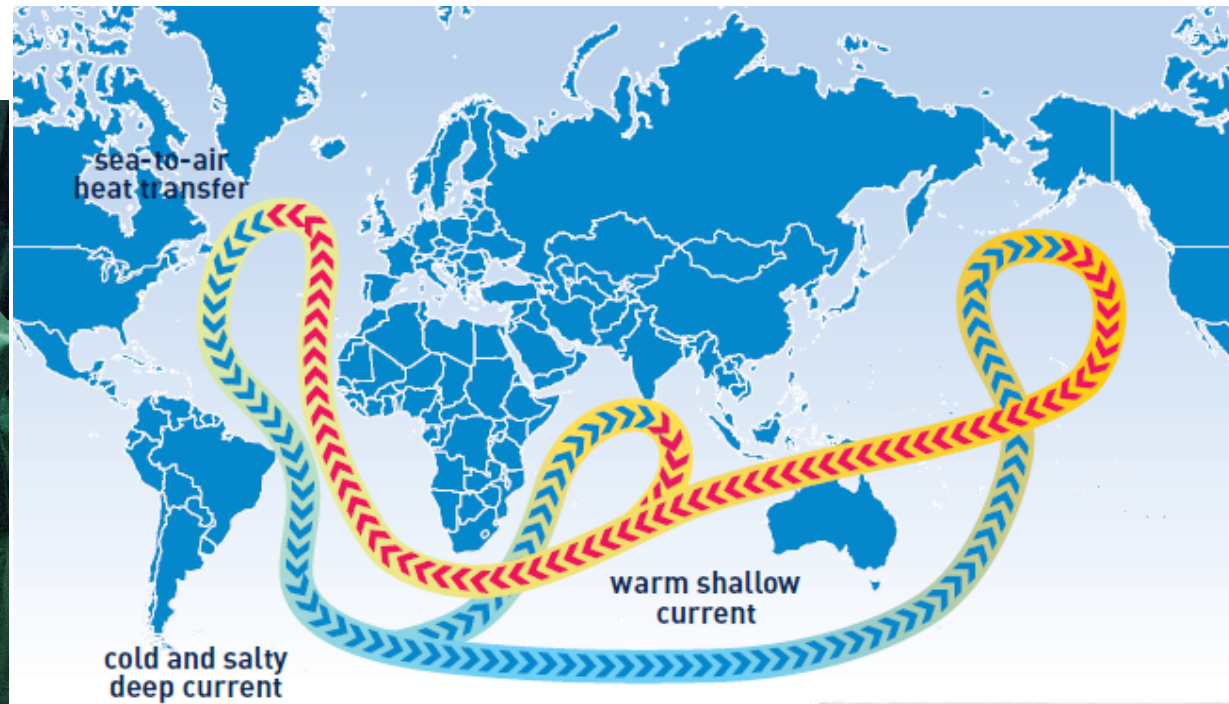
Accelerators Worldwide



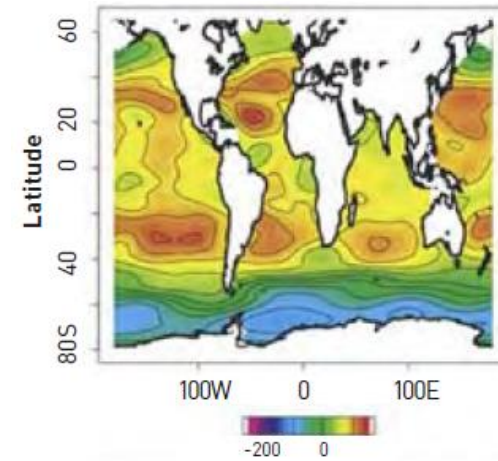
Accelerator-based mass spectrometry



Ice man dating



**C_{14} absorption
vs. depth**



Scientific importance of accelerators

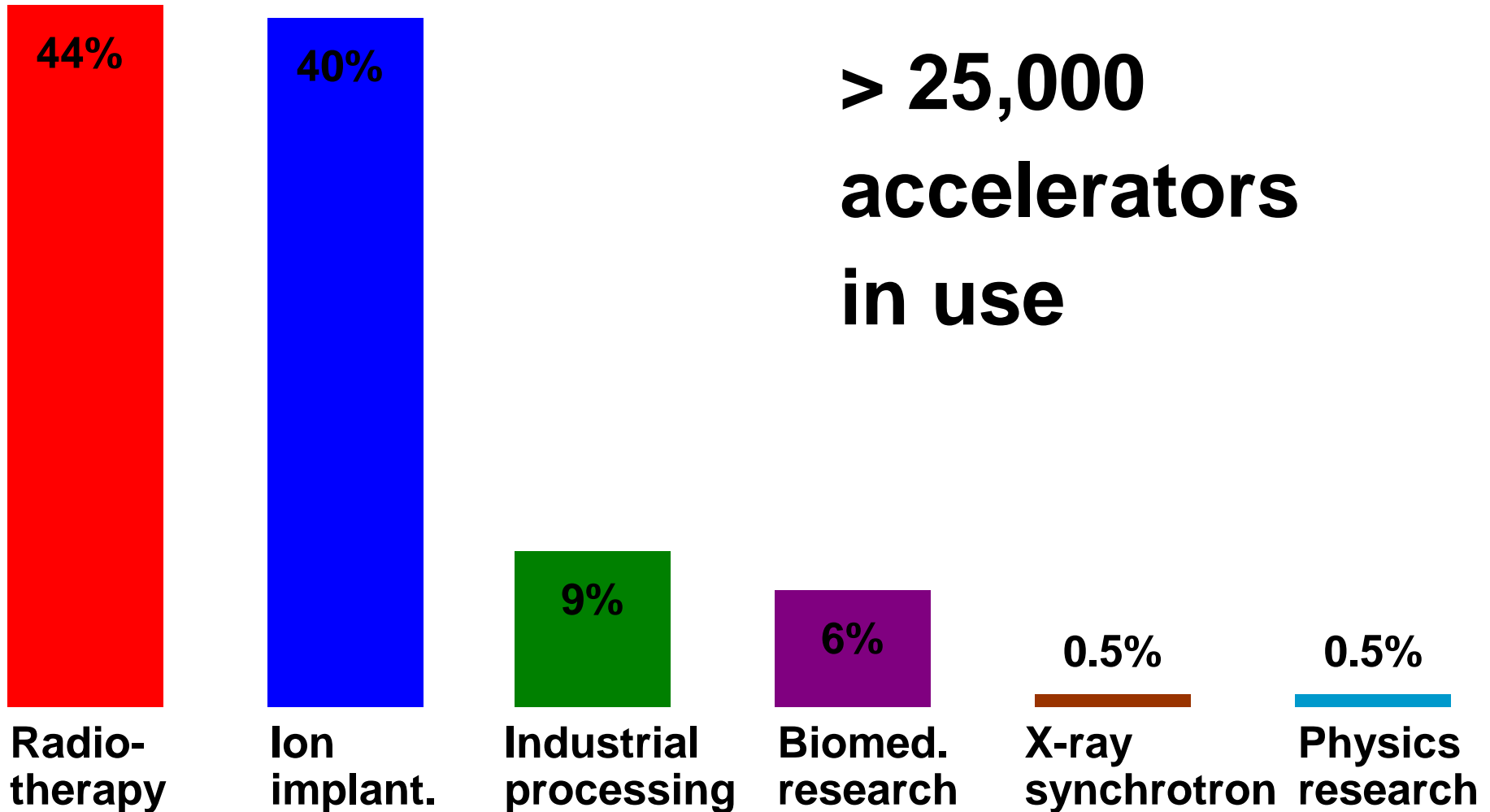
- **30% of physics Nobel Prizes awarded for work based on accelerators**



- **Recent chemistry Nobel Prizes awarded for work reliant on accelerators!**



Accelerators Worldwide



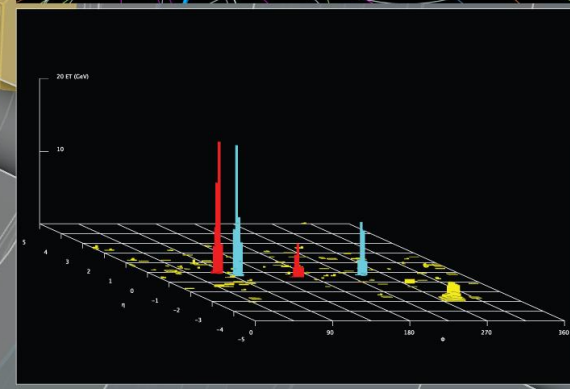
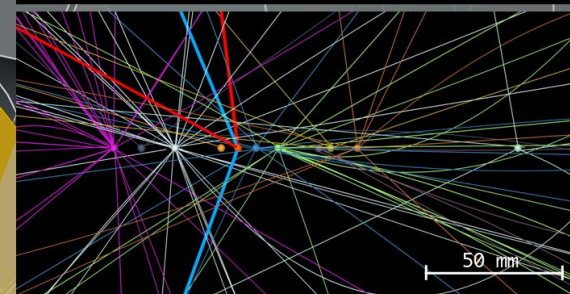
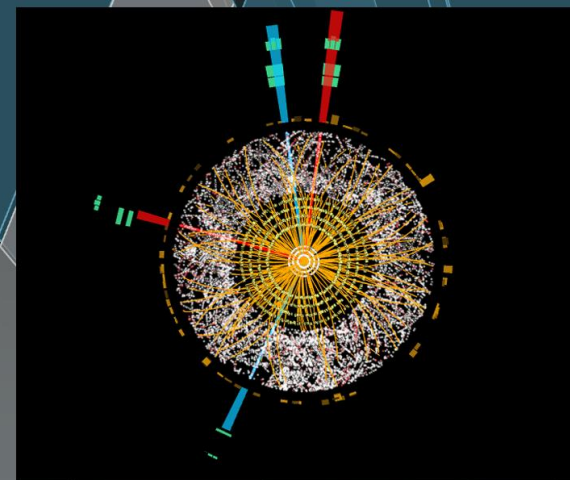
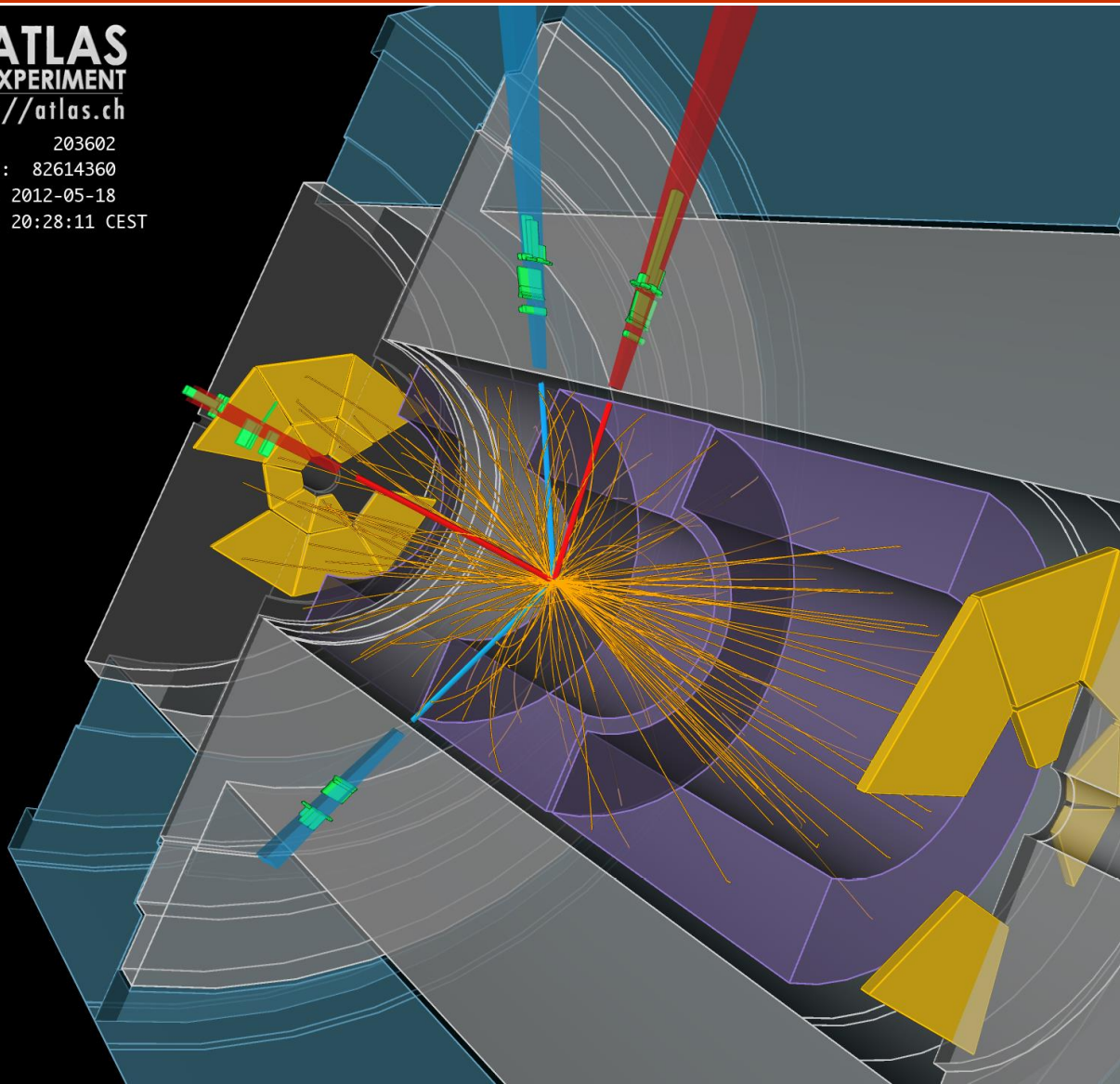
Large Hadron Collider (LHC)



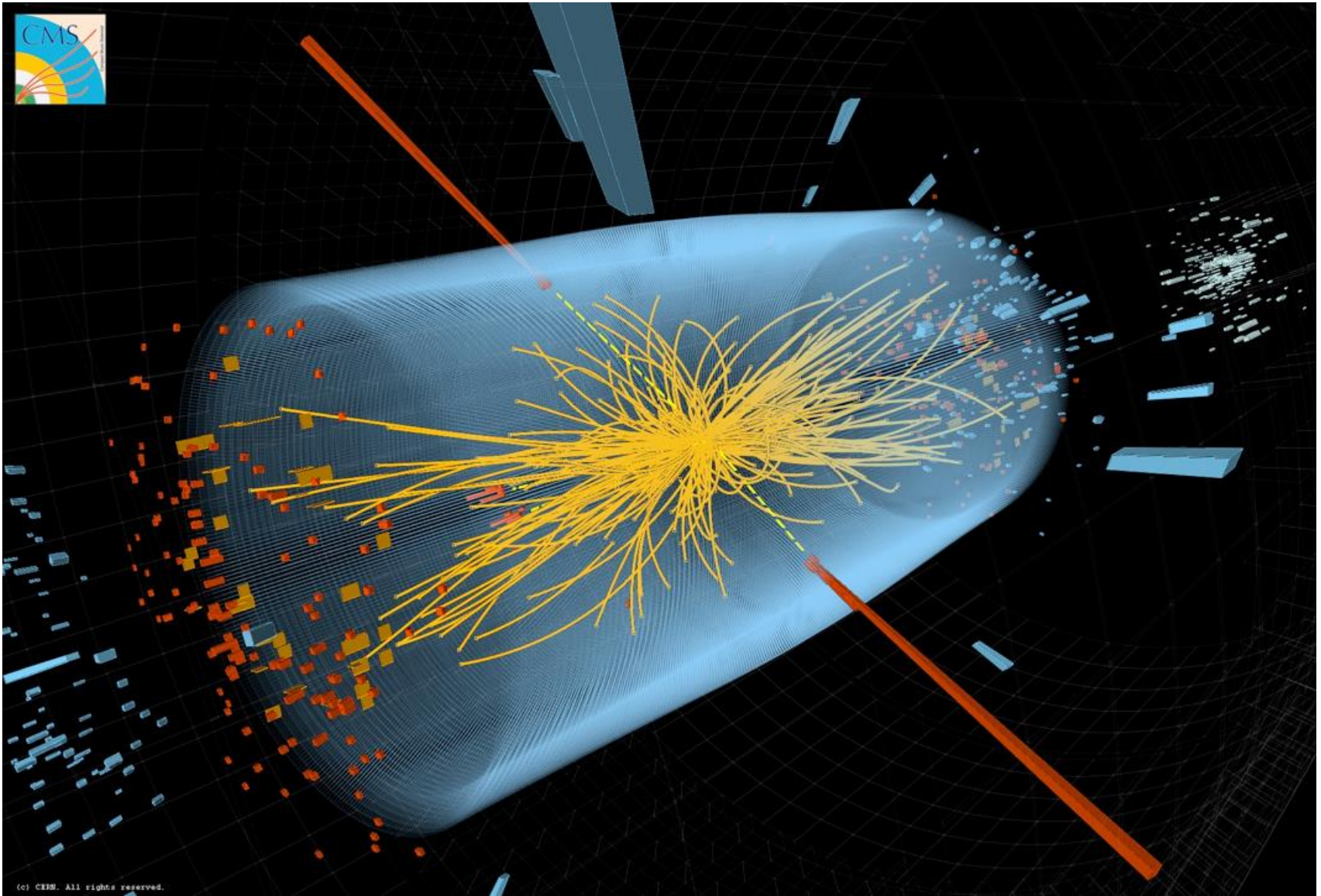
A Higgs boson?

ATLAS
EXPERIMENT
<http://atlas.ch>

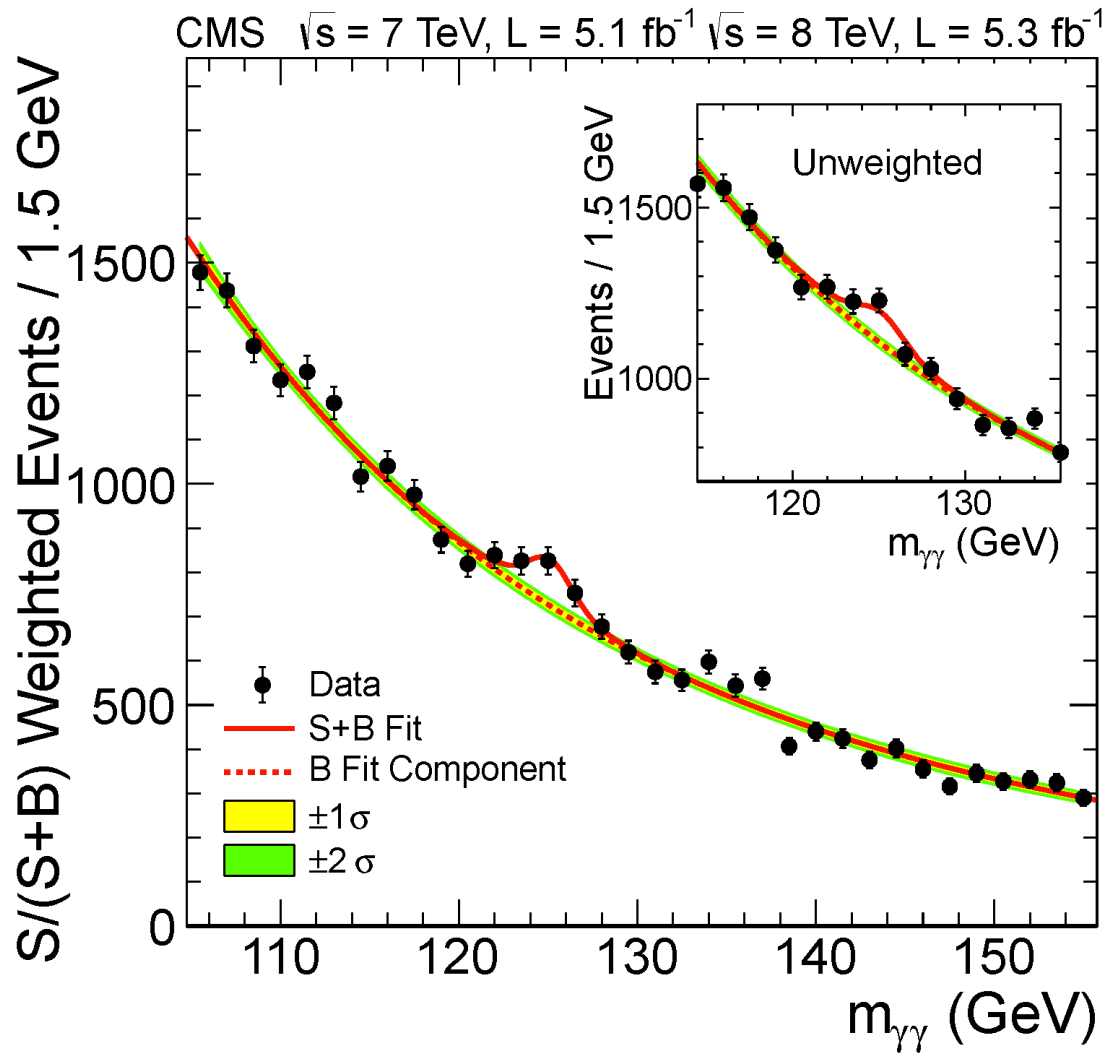
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Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST



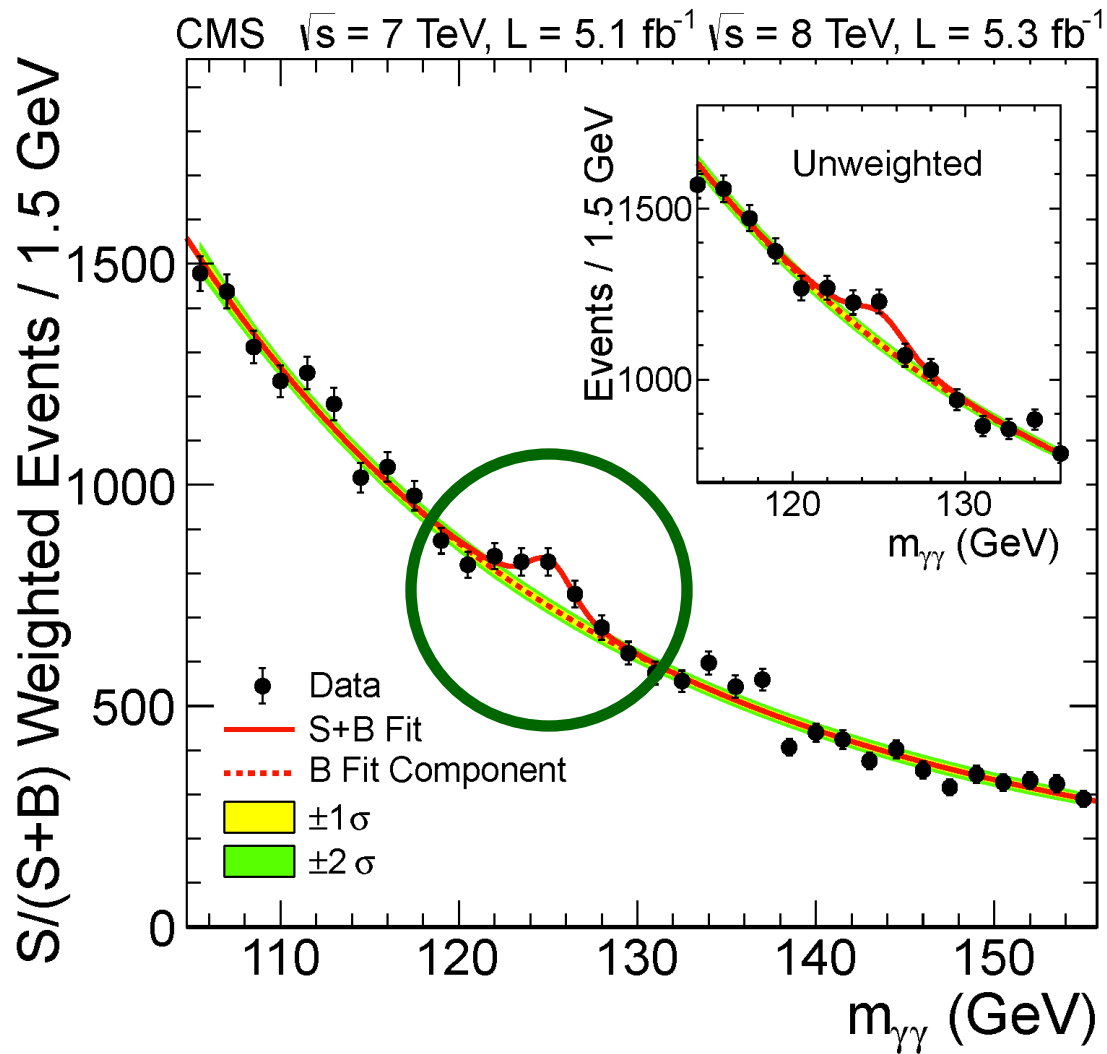
A Higgs boson?



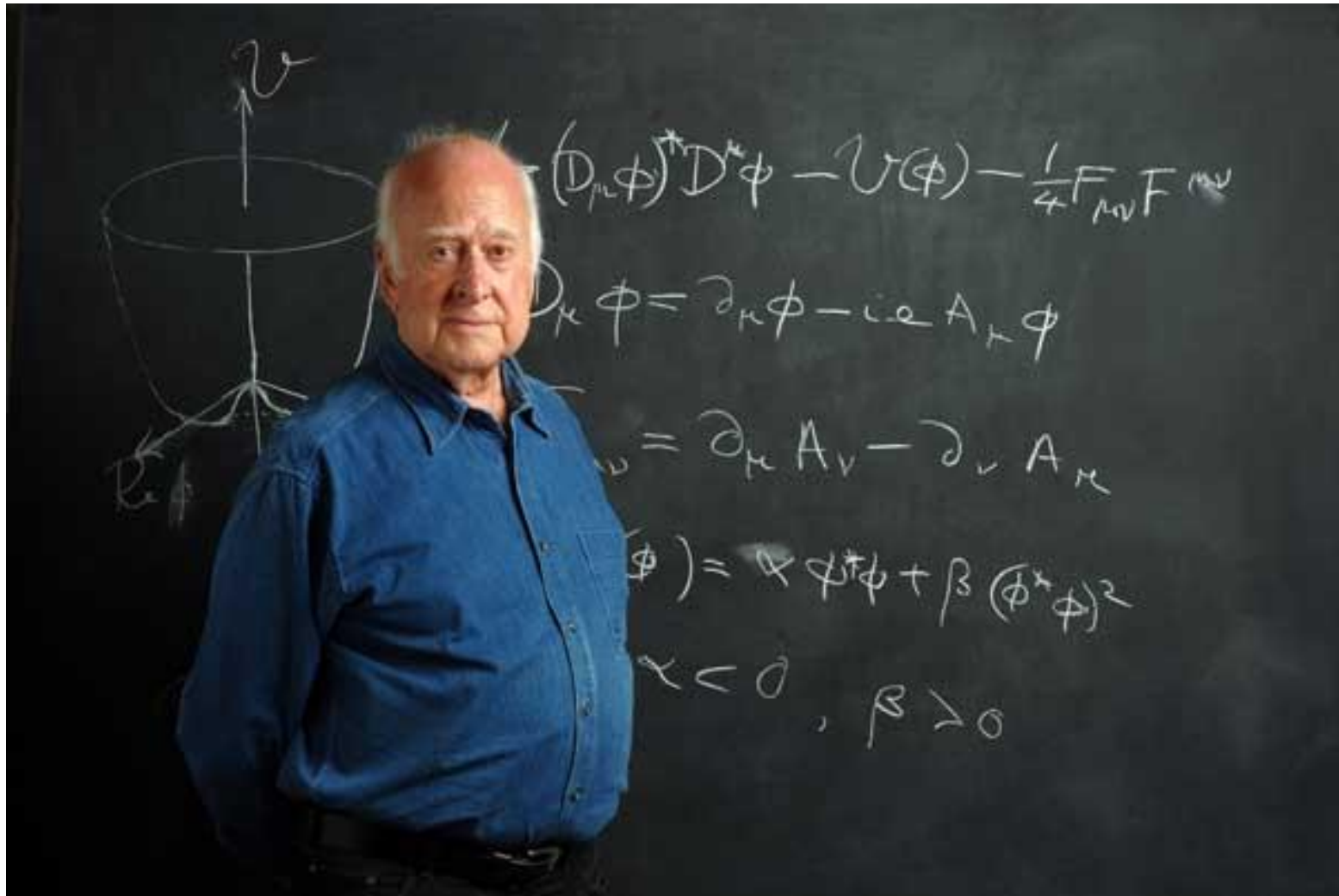
Definitely something there!



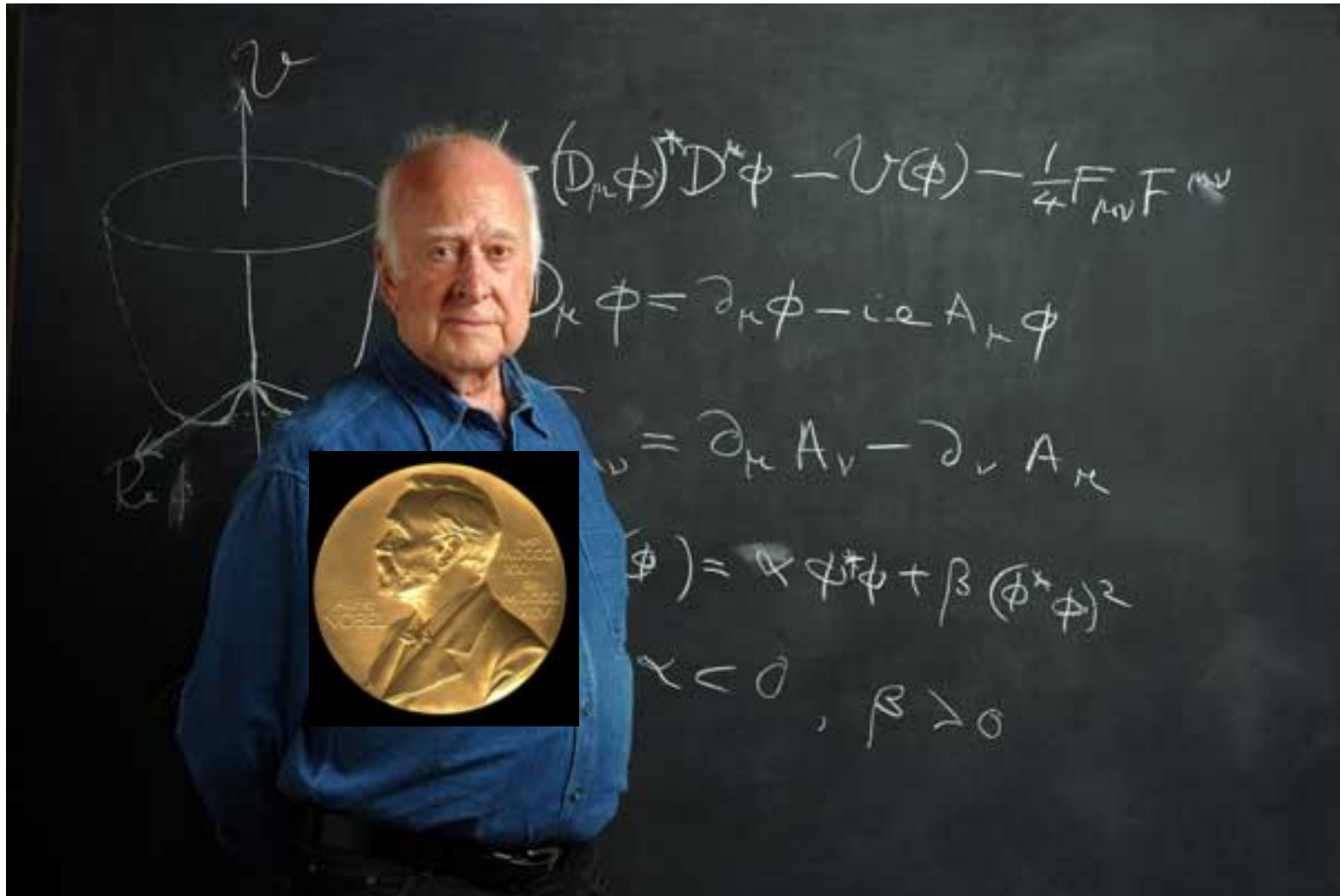
Definitely something there!



It looks like it's probably a Higgs!



It looks like it's probably a Higgs!



Large Hadron Collider (LHC)

