Hitchhikers Guide to Accelerators

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University of Geneva, 2013-11-31

Physics is not about finding 'truths' ...

…but about discovering how nature works.

Physicists' fundamentals:

What, When, Why, How (exactly)...

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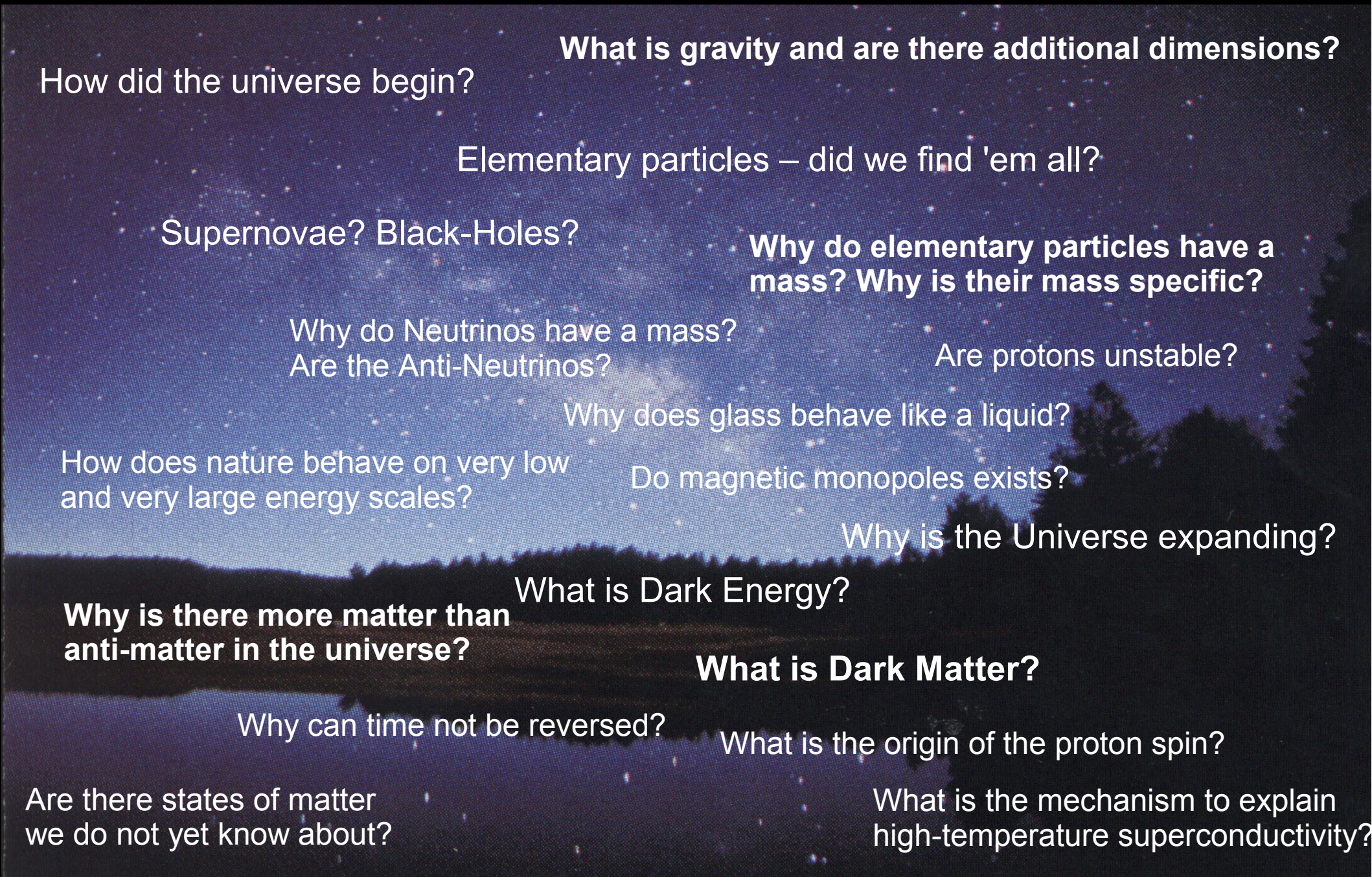
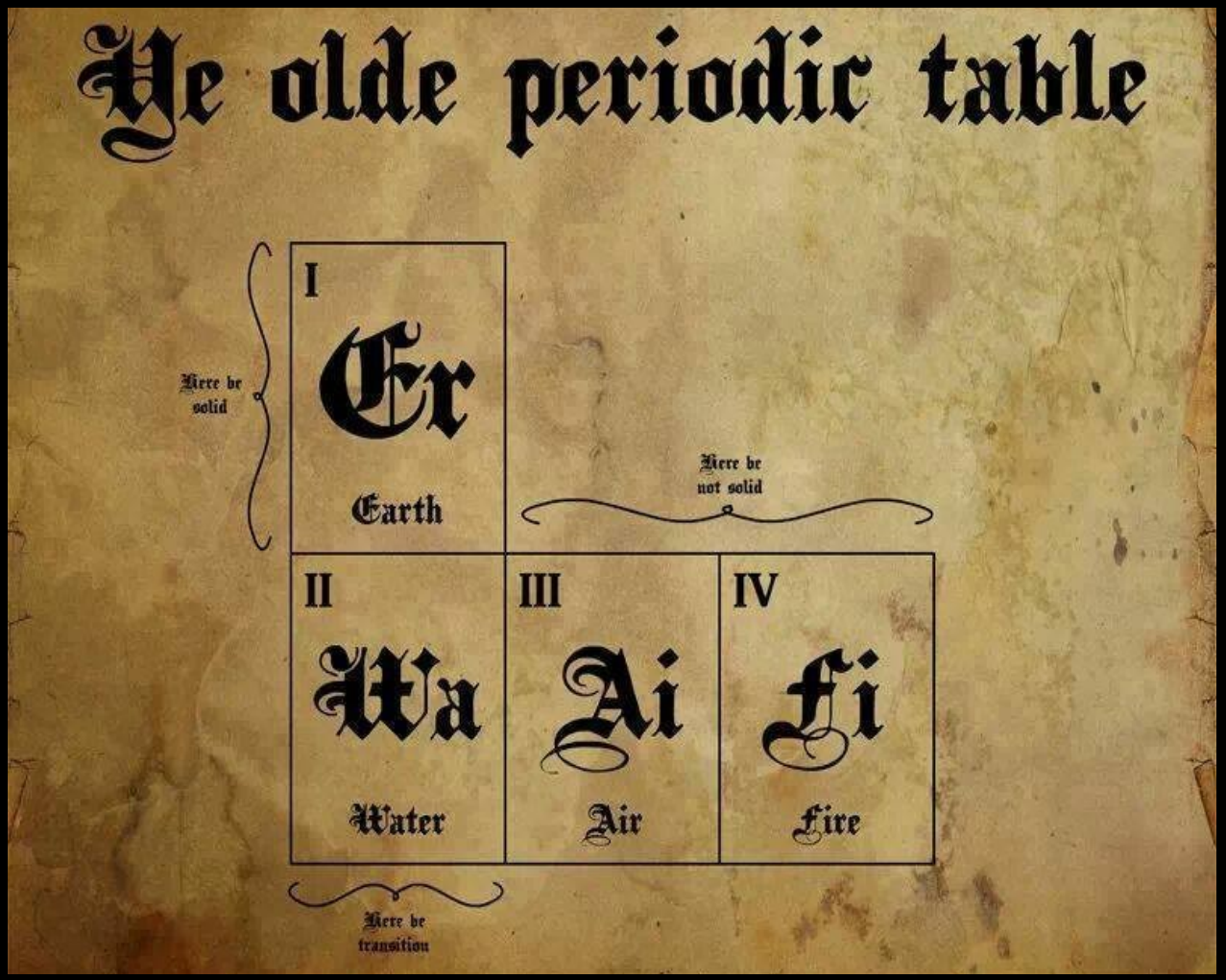
What, When, Why, How (exactly)...



High-Energy-Physics:
Understand the World in its most fundamental Form ...

- Very ancient Greek idea ... world is made out of

Atoms (ἄτομος, "indivisible")



Refined Periodic Table of Elements – 2500 years later

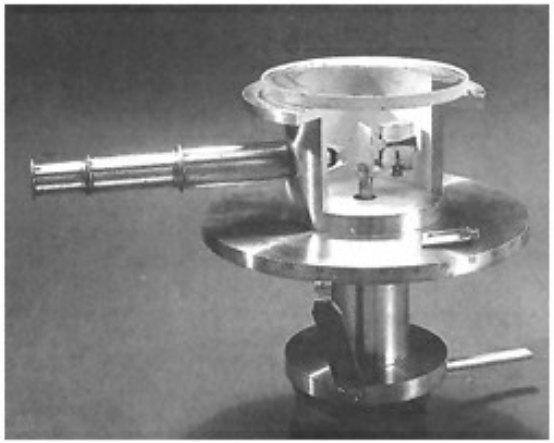
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 –71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 –103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

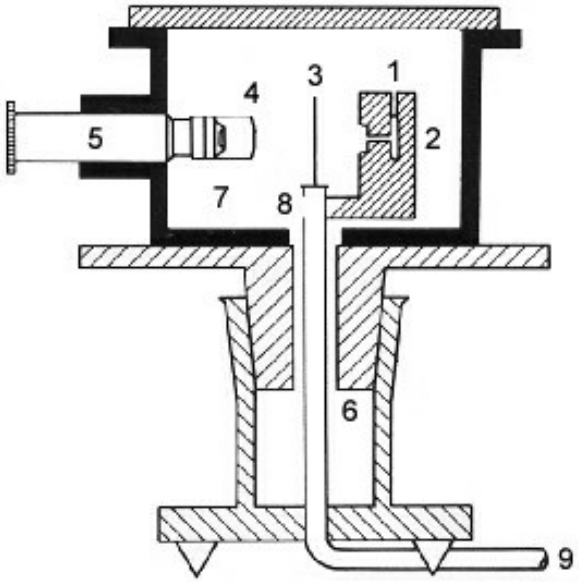
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

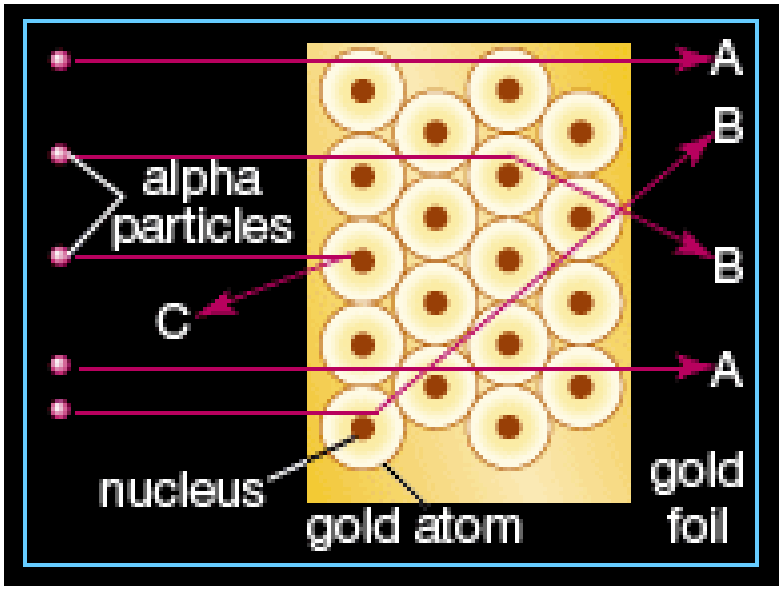
- Known in antiquity
- also known when (akw) Lavoisier published his list of elements (1789)
- akw Mendeleev published his periodic table (1869)
- akw Deming published his periodic table (1923)
- akw Seaborg published his periodic table (1945)
- also known (ak) up to 2000
- ak to 2012

First Particle Physics Experiment: 'Atoms' are not fundamental Particles

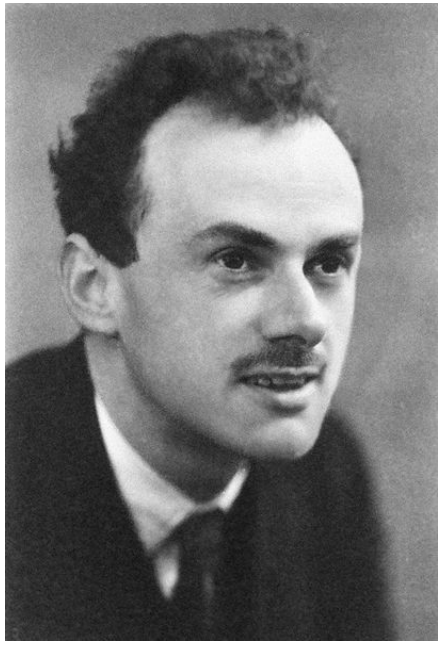
1911
Rutherford-Geiger–Marsden experiment: found nuclei in the atom by firing alpha particles at gold and observing them to bounce back







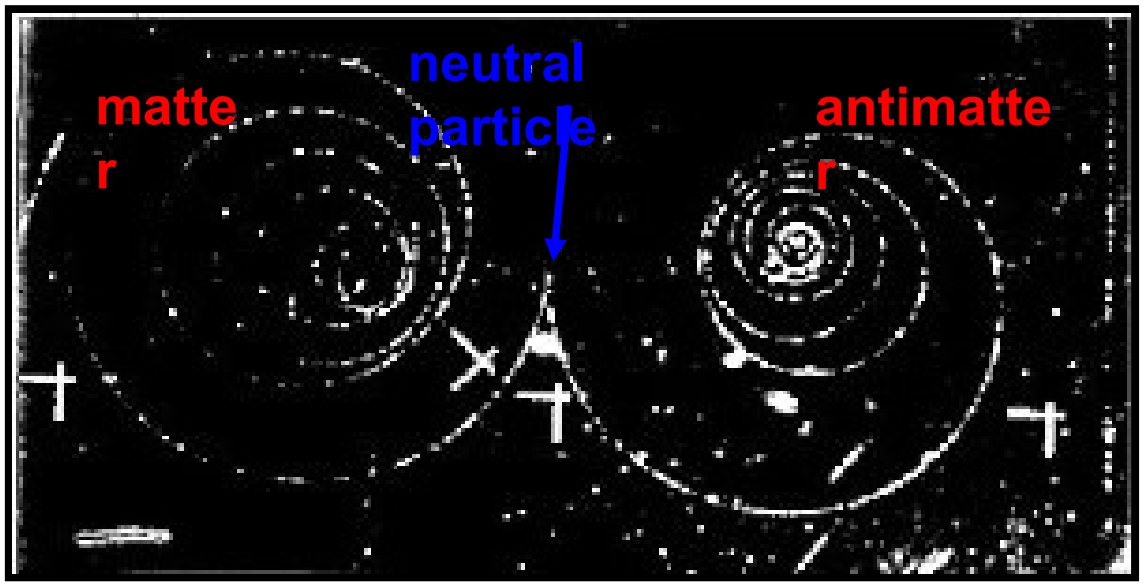
First Particle Physics Experiment: 'Atoms'



1933 Nobel Prize:
Paul Dirac & Erwin Schrödinger
"for the discovery of new productive forms of atomic theory"
– combined general relativity with quantum mechanics

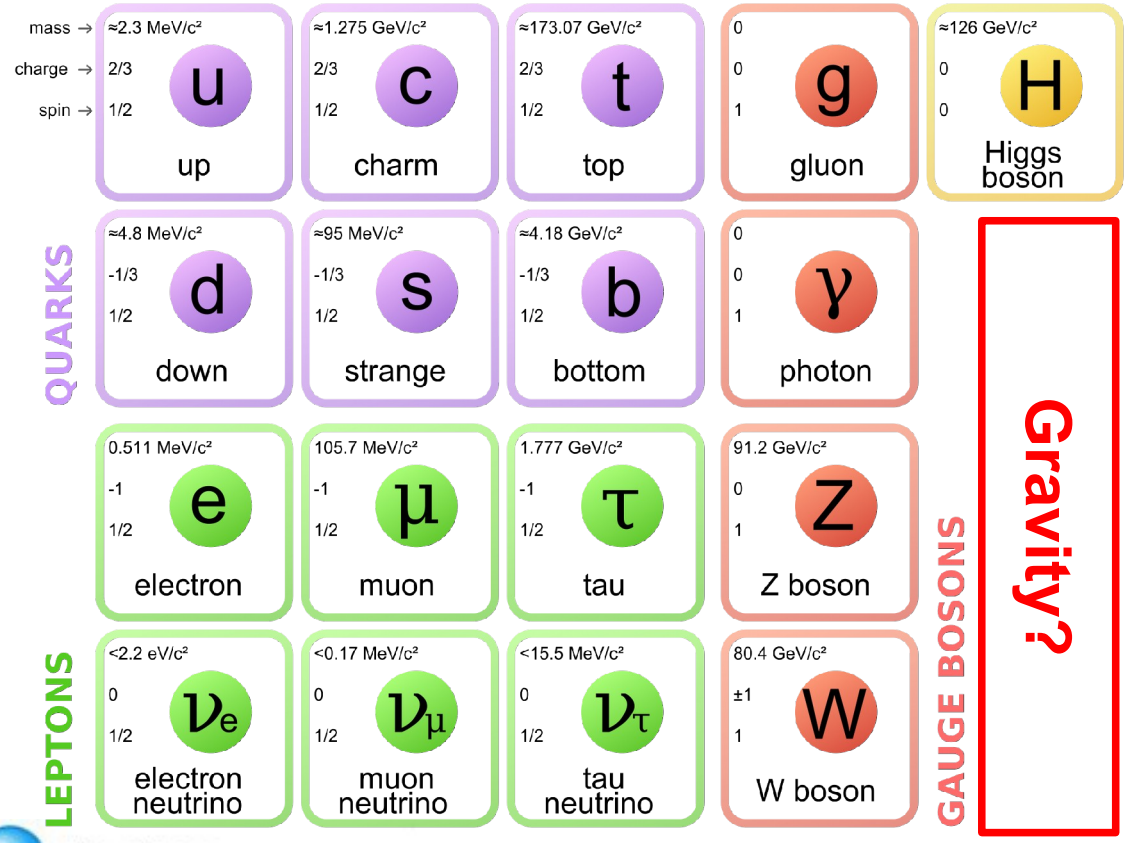
– predicted existence of anti-matter

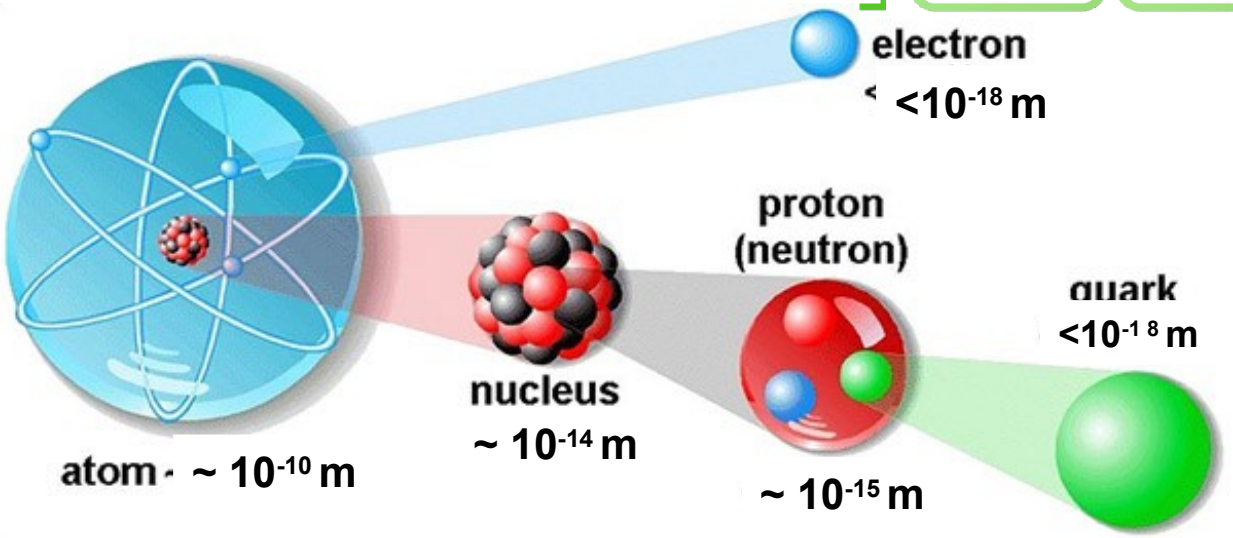
$E=mc^2$



Leading to an Avalanche of New Discoveries and Scientific and Technological Advances

- What are the true 'Atoms'?





The big elephant in the room

Time-Scales: Idea → Experimental Verification

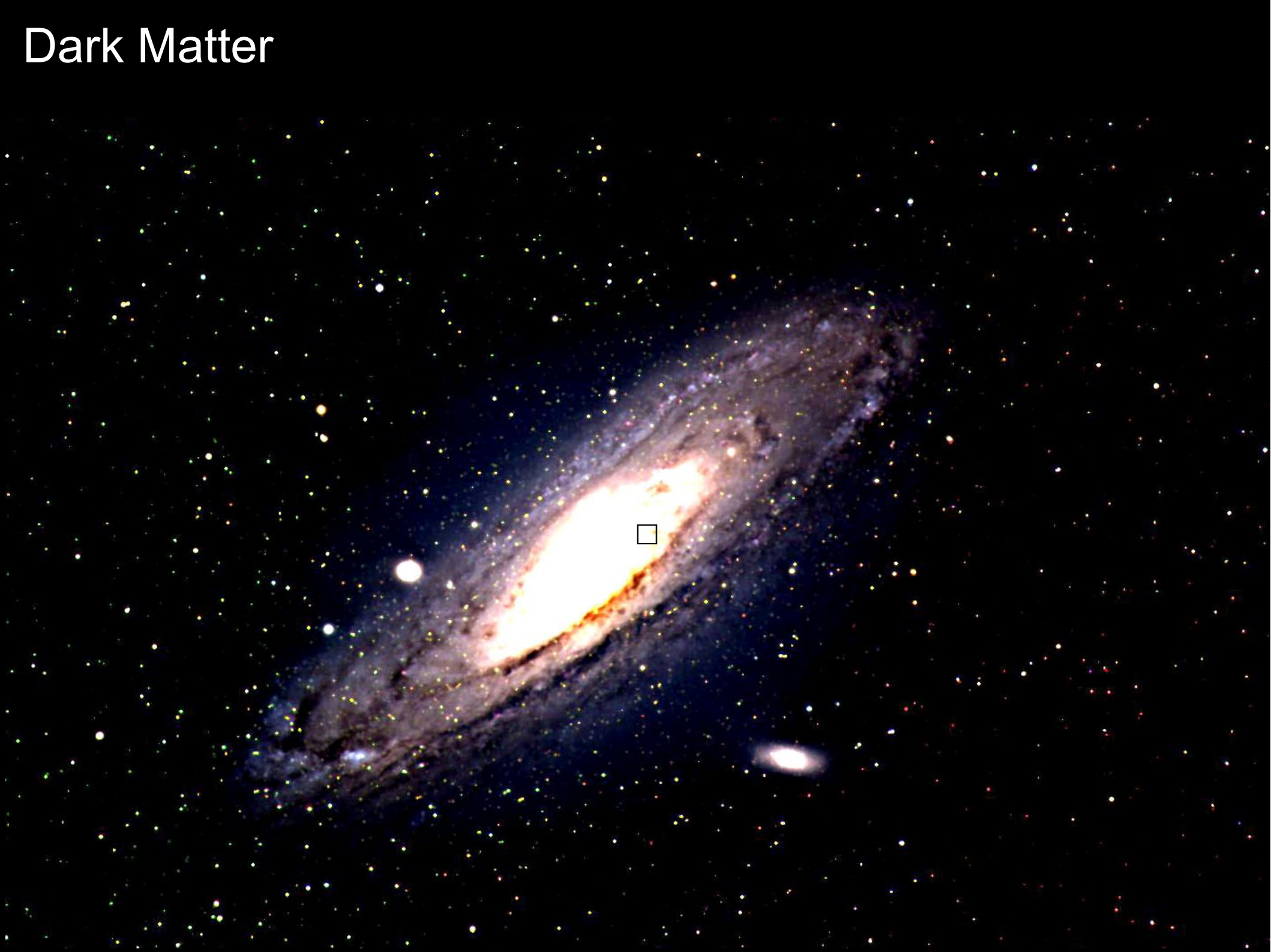
François Englert & Peter Higgs
1964 Theory → 4th July 2003 discovery → 2013 Nobel Prize

Why do elementary particles have a mass?

… what's behind the 'Higgs©' particle?

Dark Matter, the Age of the Universe, ...
… and why there was a “Big Bang”

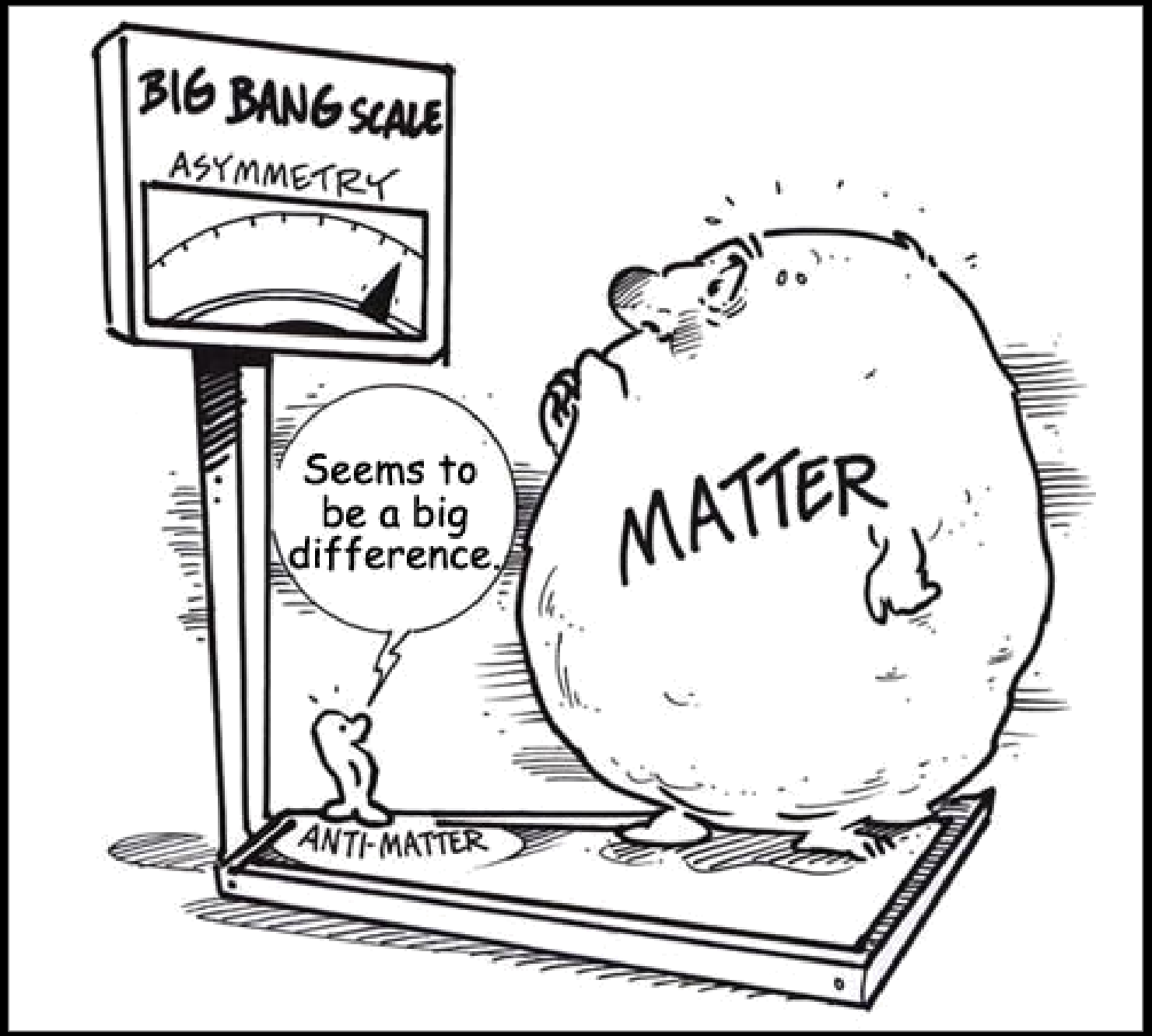
Dark Matter



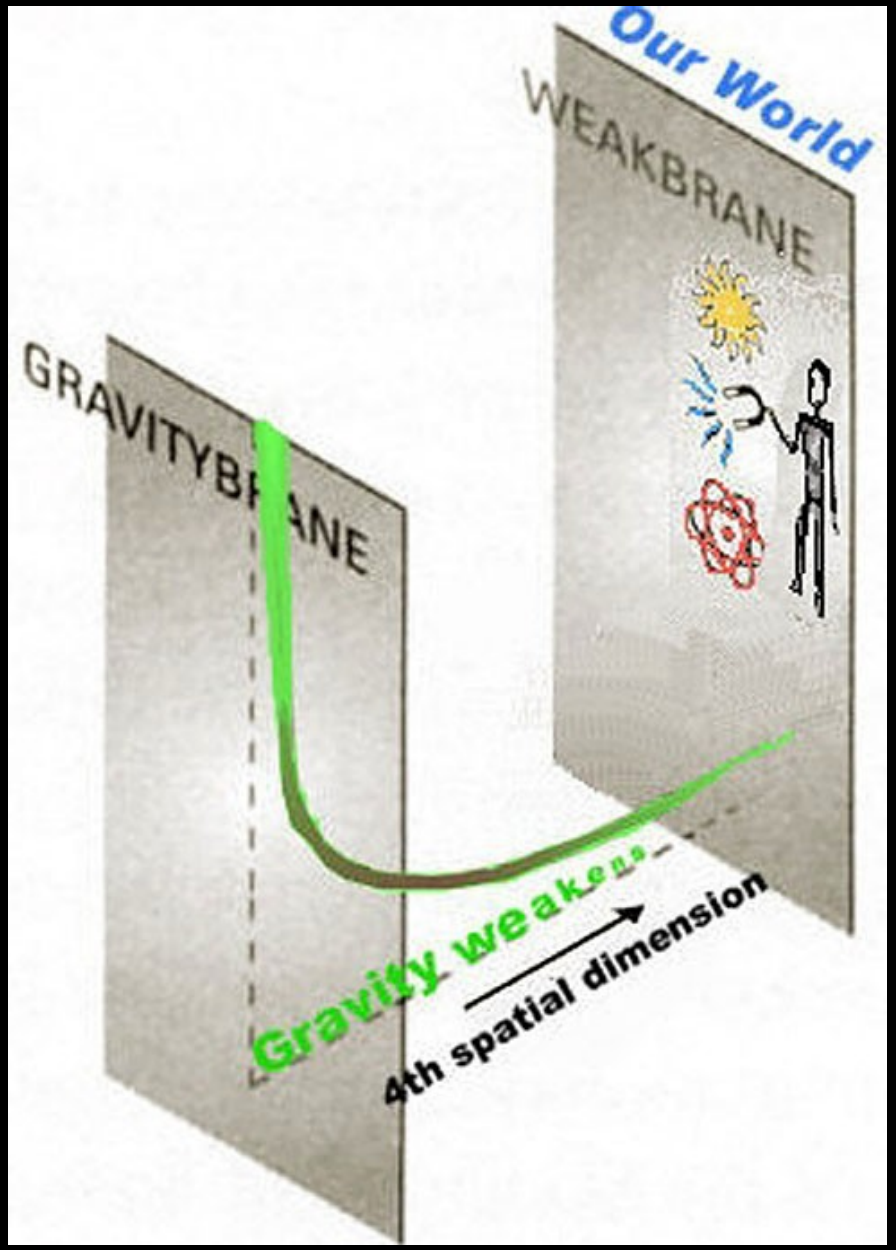
Anti-Matter does exist …

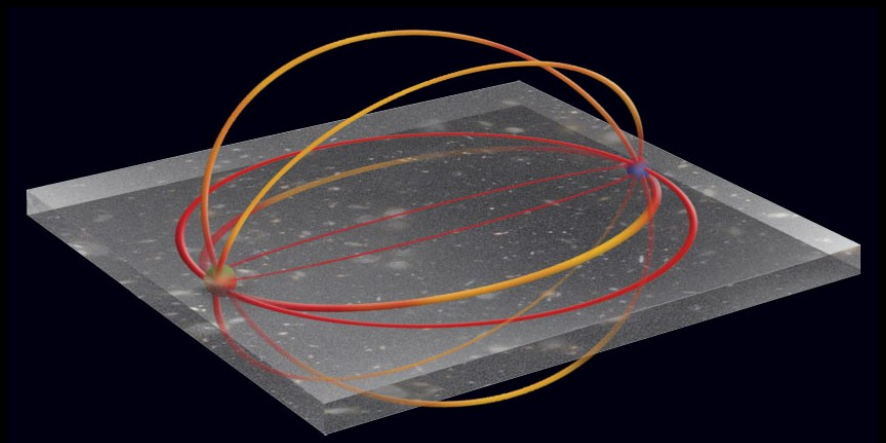
Anti-Matter does exist …

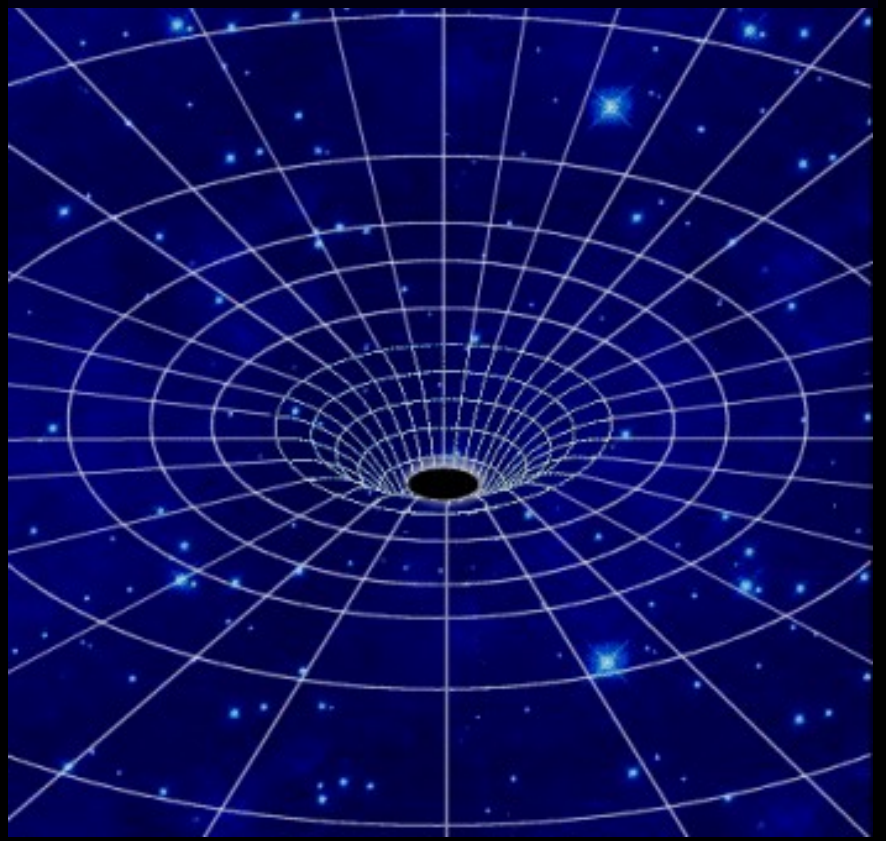
… but why is it so rare in the Universe?



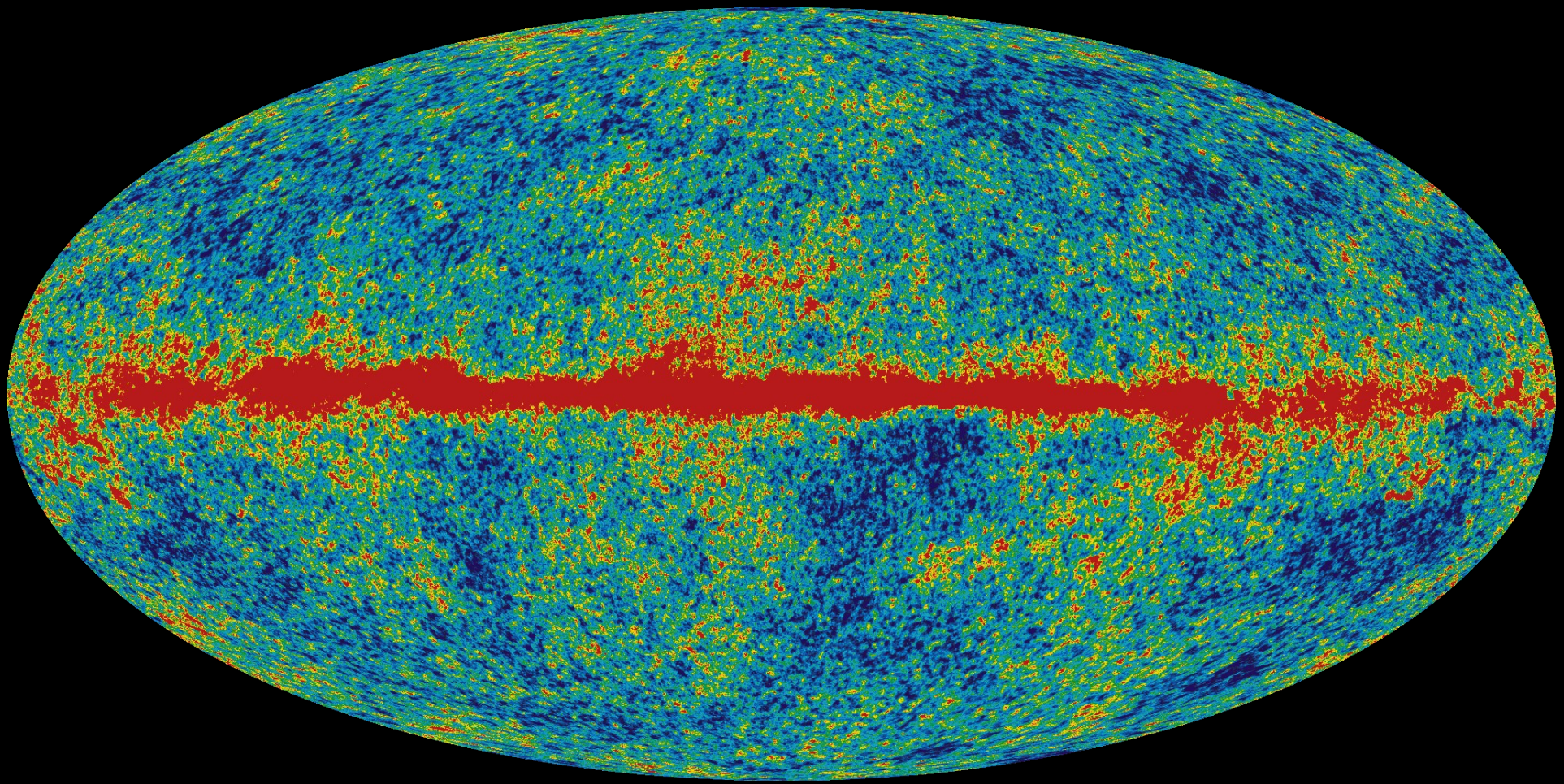
Does our world have more than 3+1 dimensions?
How does gravity work? Or:
What the … are “micro-black-holes” and why we are excited about (even worse) unstable ones?



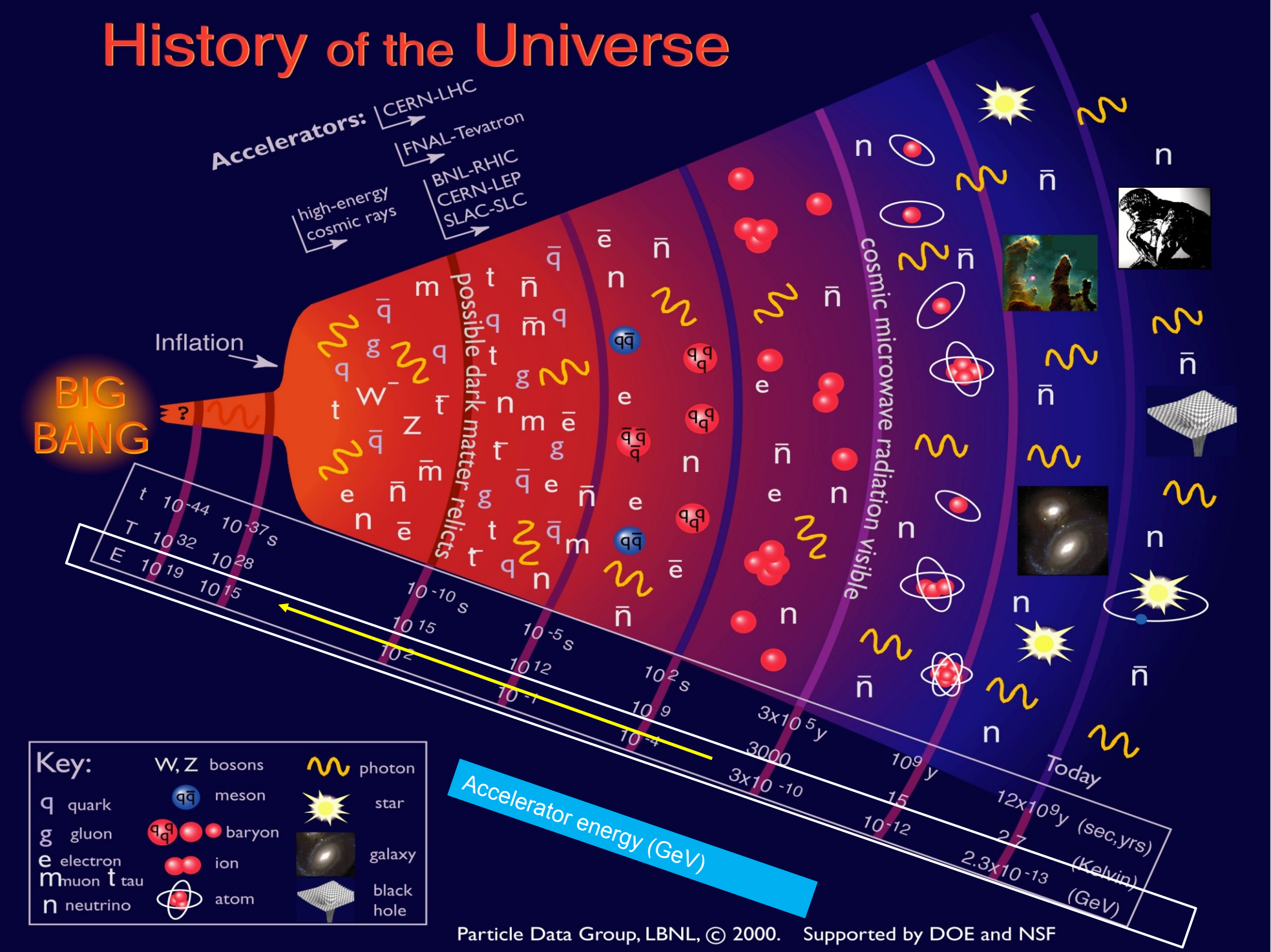




Dark Matter, the Age of the Universe, ...
… and why there was a “Big Bang”

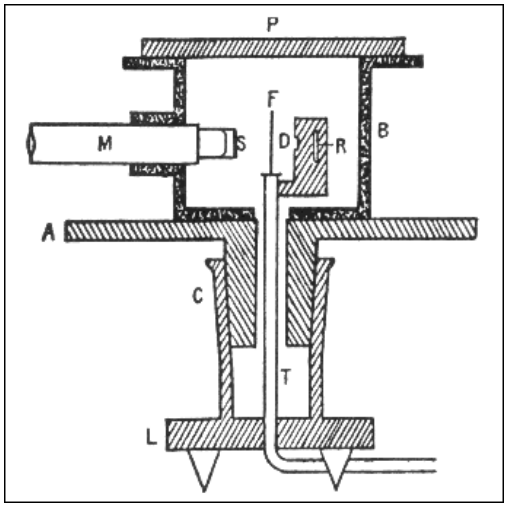


History of the Universe



It all looks so easy...

Main Outcome of Rutherford's experiment (my personal view)



- 'Atoms' are not Atoms → 'Elementary Particles'
- Need to use particles that are smaller than the structure to be investigated
- Need a microscope, patience and persistence
  (… and a lot of students)

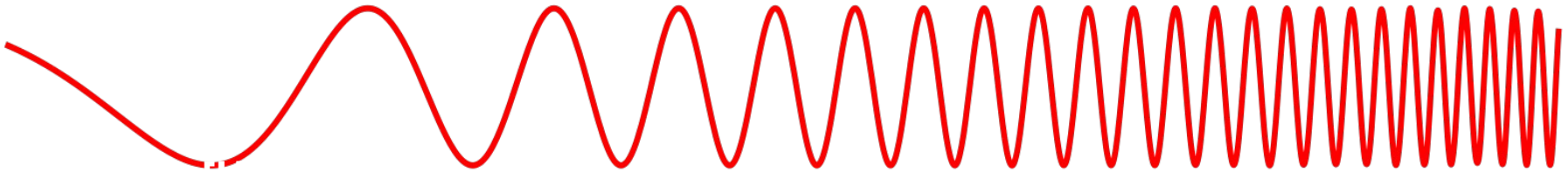
- De Broglie's 'Particle – Wave' dualism (1924):

$$\lambda = \frac{h}{p}$$

h: Planck's constant
p: momentum of particle
λ: wavelength/visible detail

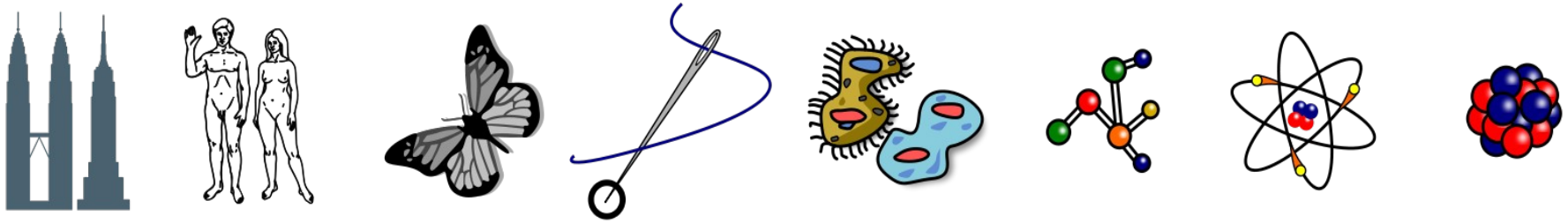
… So high momentum/energy gives us short wavelengths so we can make out small details or create new particles or High-Energy-Physicists credo: we want to see smallest particles, thus need the highest energy particle sources → accelerators

De Broglie: Wavelength and Scales

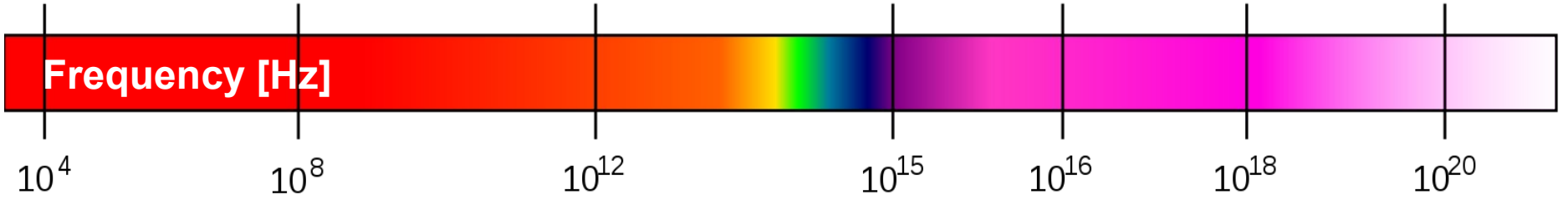


Wavelength [m]

Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
10^{3}	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}



Buildings	Humans	Butterflies	Needle Point	Protozoans	Molecules	Atoms	Atomic Nuclei



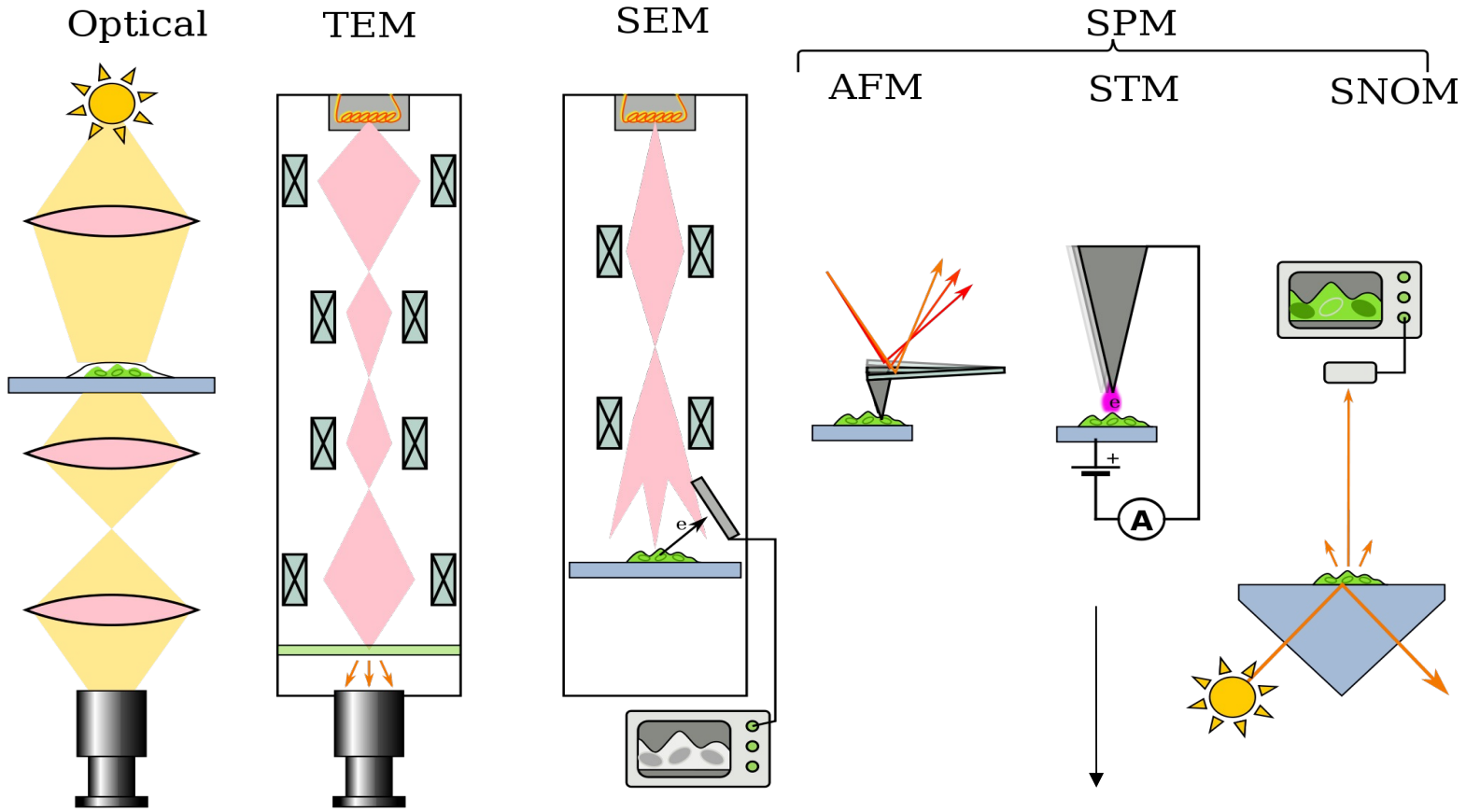
Energy/Momentum Electron Volt [eV]

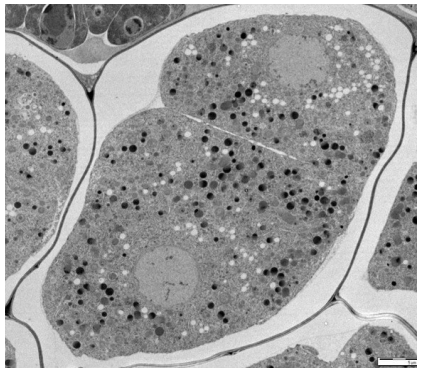
~1 μeV **~1 eV** **~1 MeV**

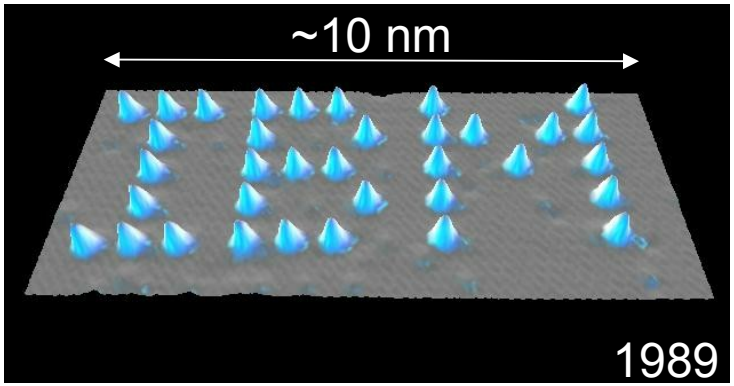
LHC (Higgs)
few hundred GeV/7 TeV

How to resolve Small Structures I
Cells, Molecules, Semiconductors ...

- … use a microscope – only a few electron-volt (eV) needed

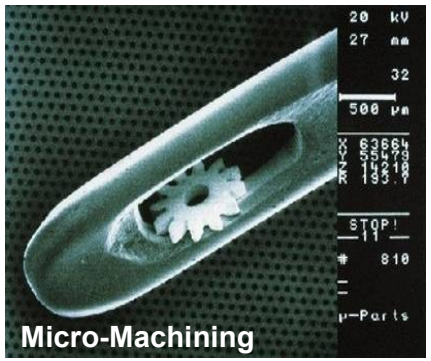


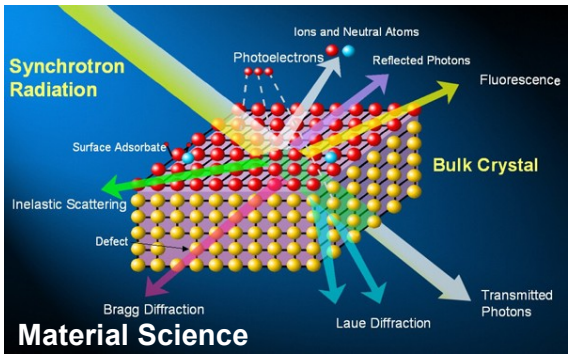


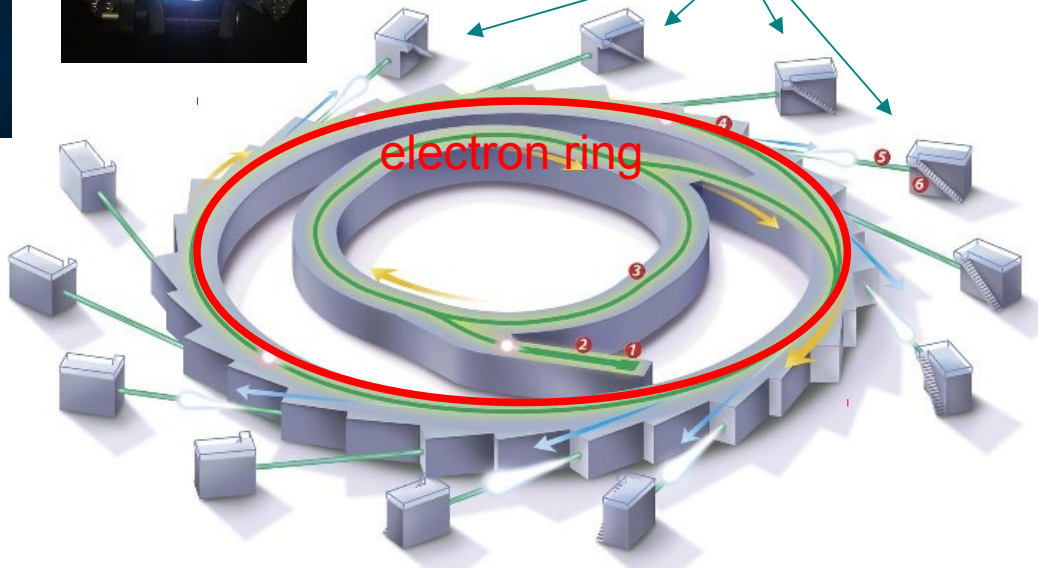


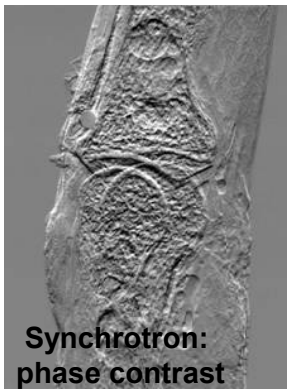
How to resolve Small Structures II
State-of-the Art Biology, Chemistry & Material Science ...

- … a synchrotron light source – few kilo-electron-volt (keV)



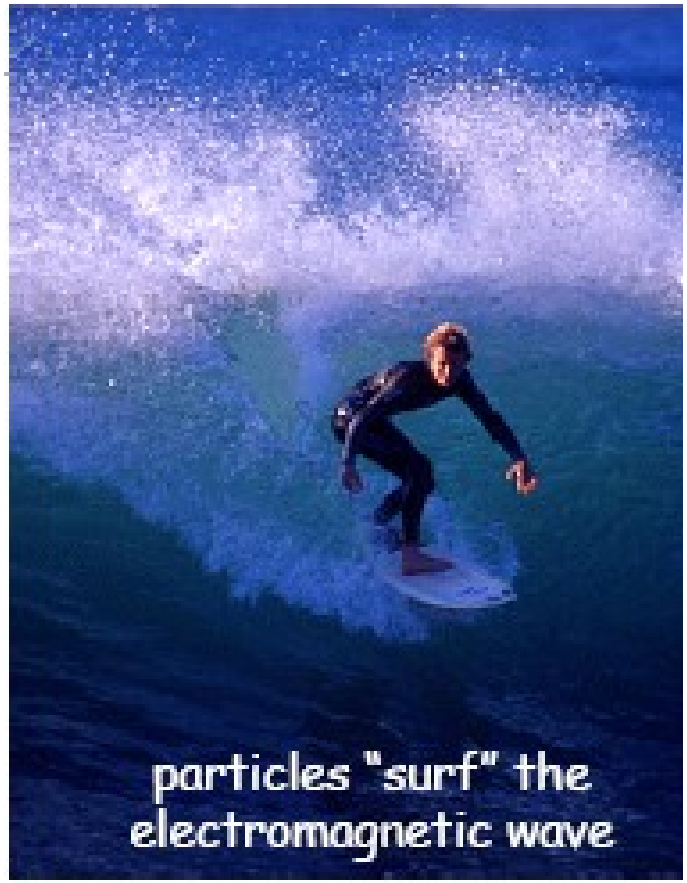


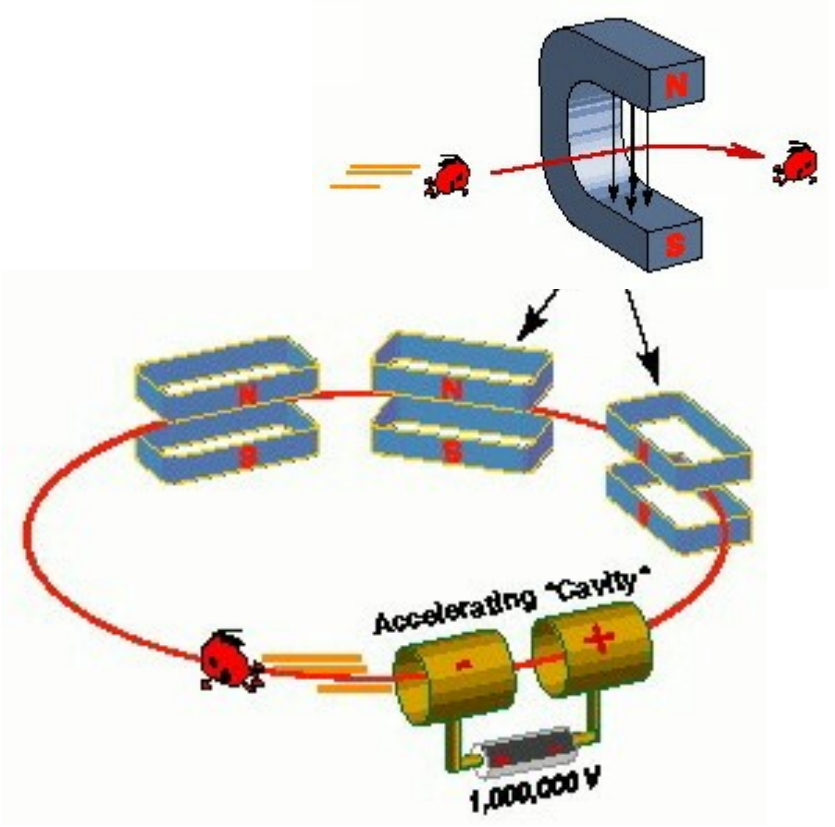




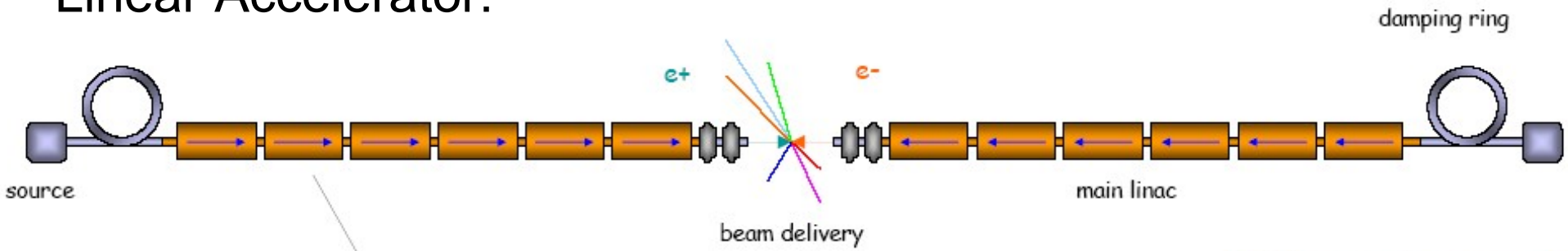
High-Energy Accelerators
To observer and study true 'Atoms'

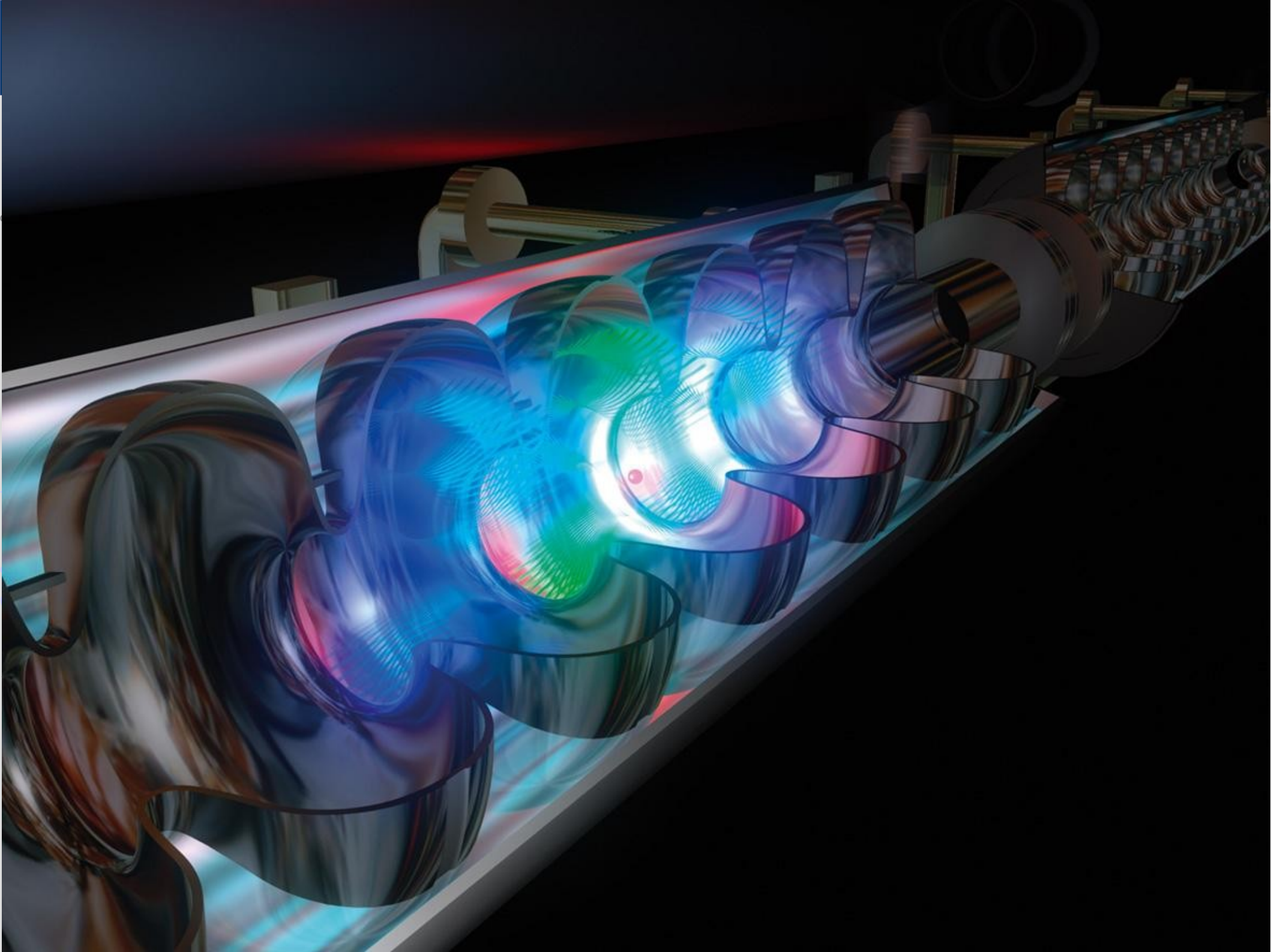
- Circular Accelerator:



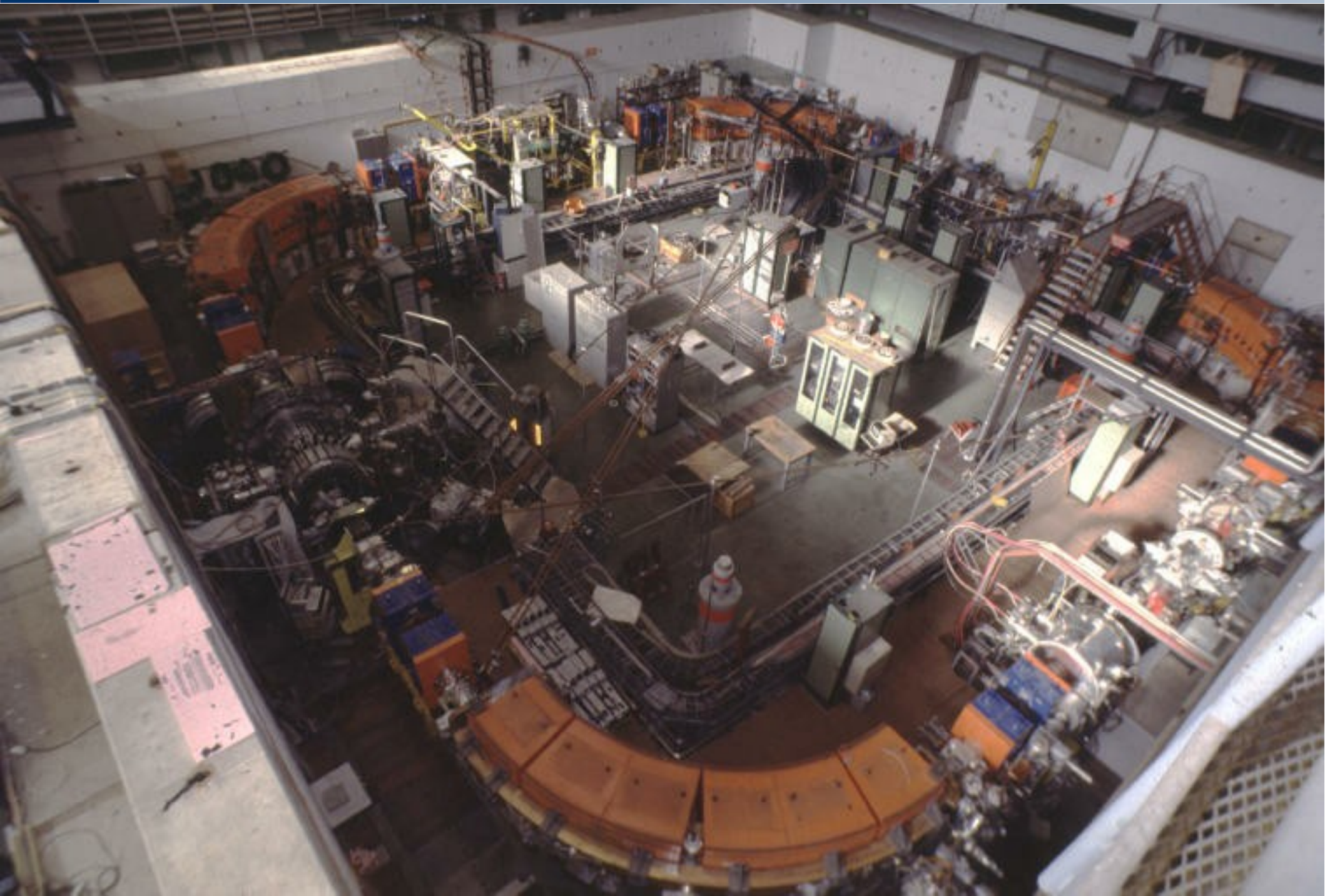


- Linear Accelerator:





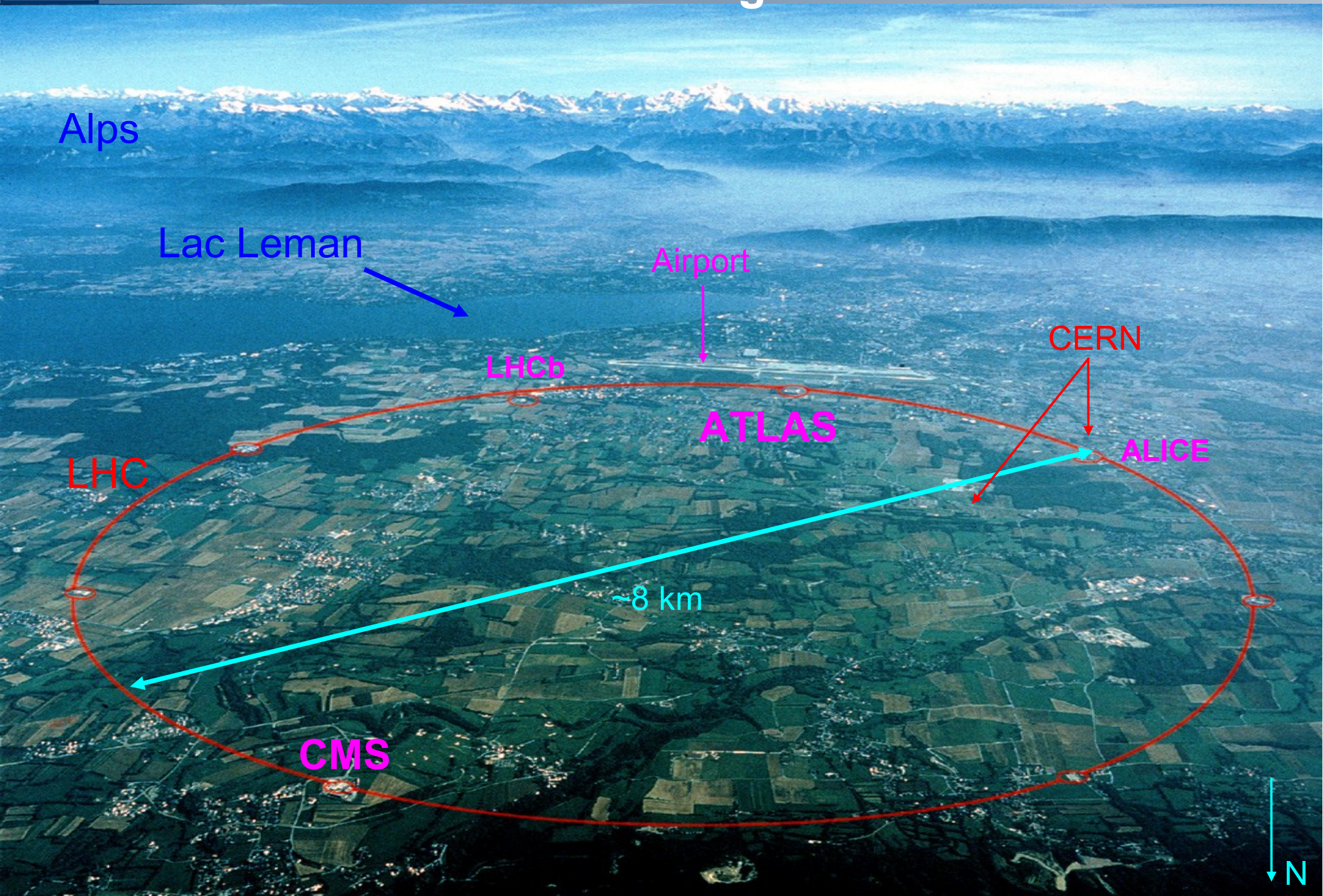
Low Energy Antiproton Ring (LEAR, CERN)



Super-Proton-Synchrotron (SPS, CERN)

- 7 km circumference, up to 450 GeV Energy
- Discovery of the W & Z Boson (Nobel prizes in 1979 & 1984)

How to resolve Small Structures III
Sub-Atom Structures.... Large Particle Accelerators



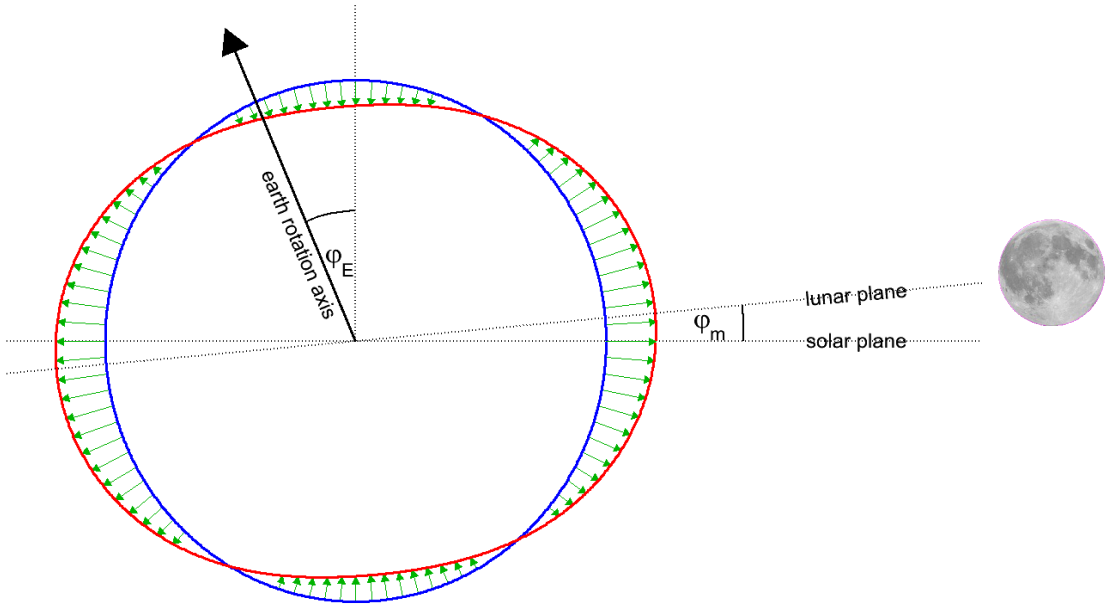
27 km Circumference – 1232 LHC dipole magnets

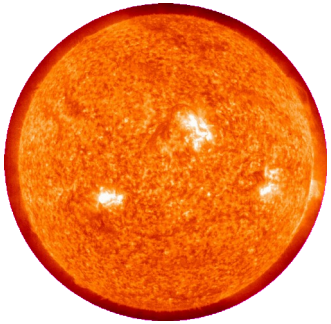
- 7 TeV ↔ B field 8.3 Tesla ↔ **11.8 kA** @ 1.9 K (super-fluid Helium)
- two-in-one magnet design → ~ two accelerators

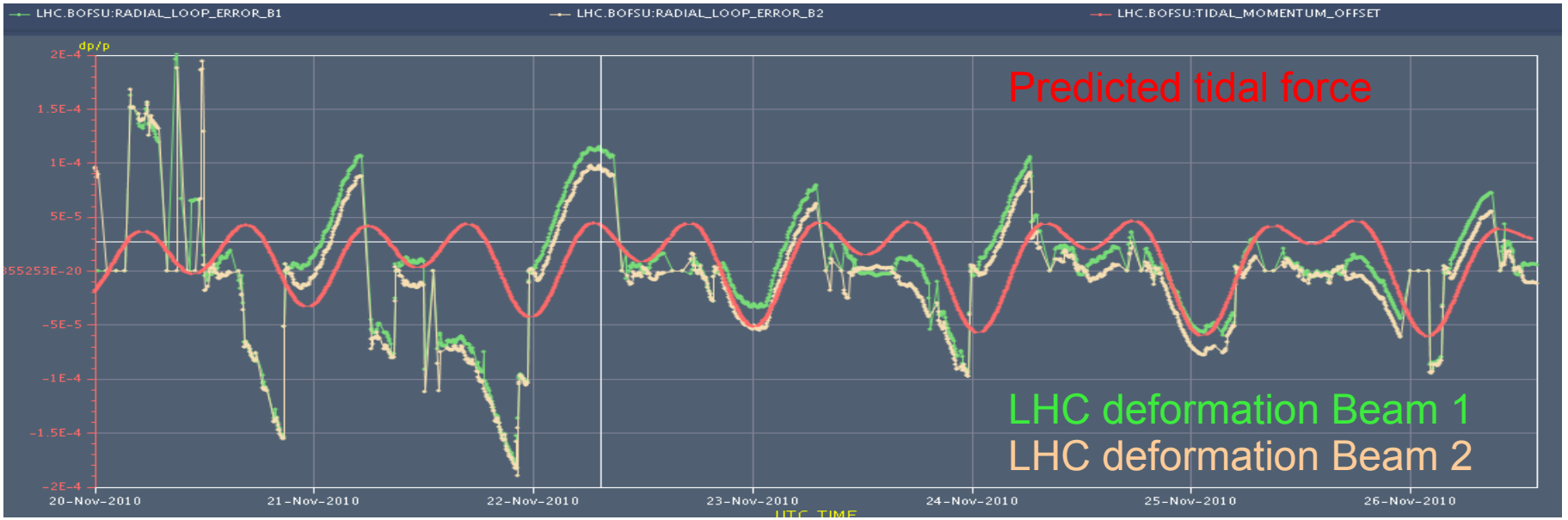
Operating challenges:

- Control of particle stability
- Very low quench levels (~ mJ/cm3) in an environment that stores MJ → GJ

LHC Circumference and Tides ...

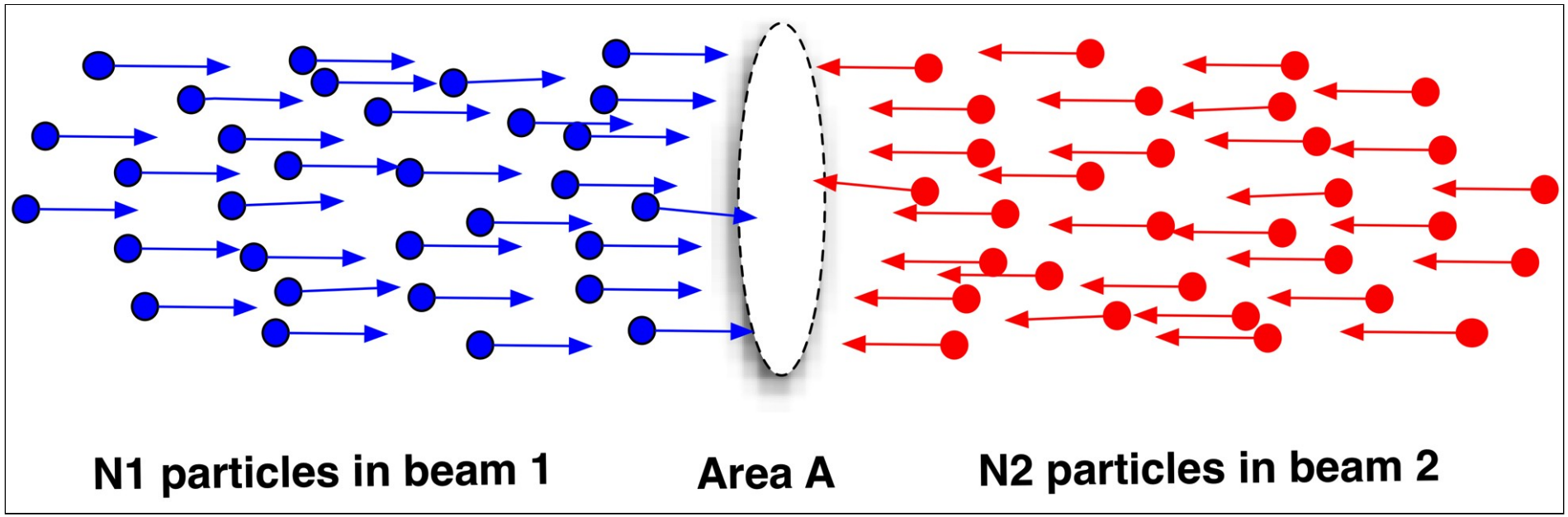






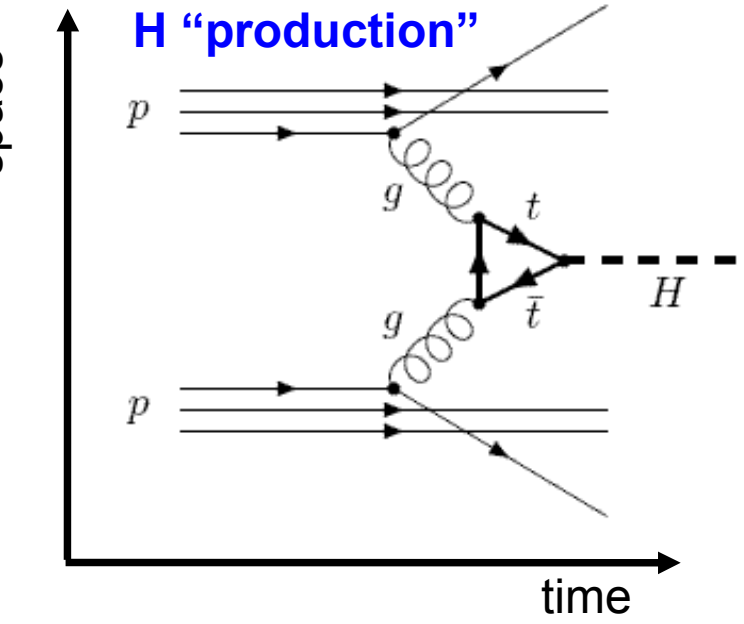
$\Delta x \approx 200$ µm

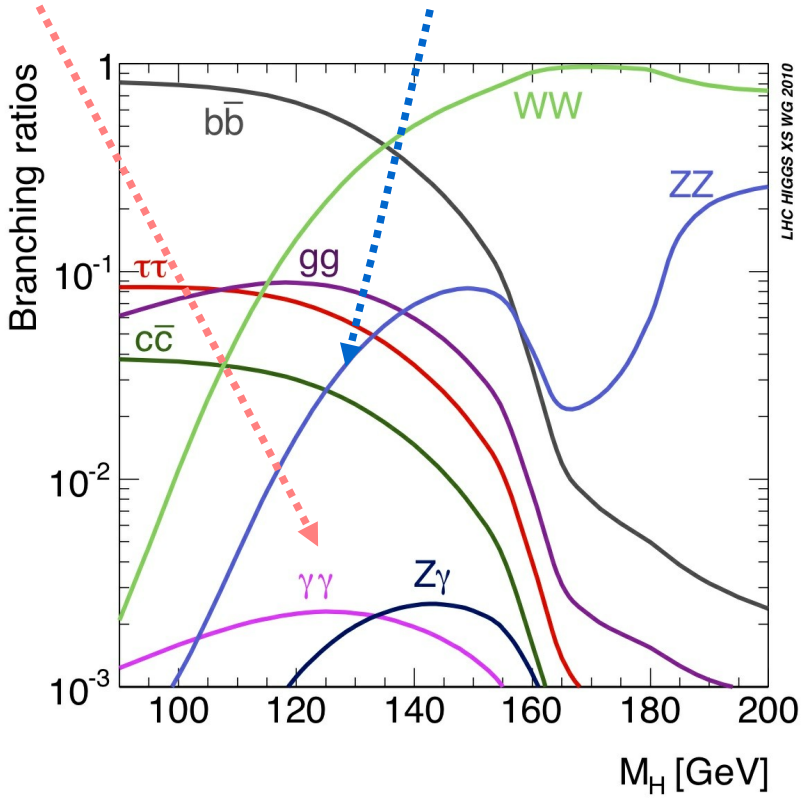
~ one week



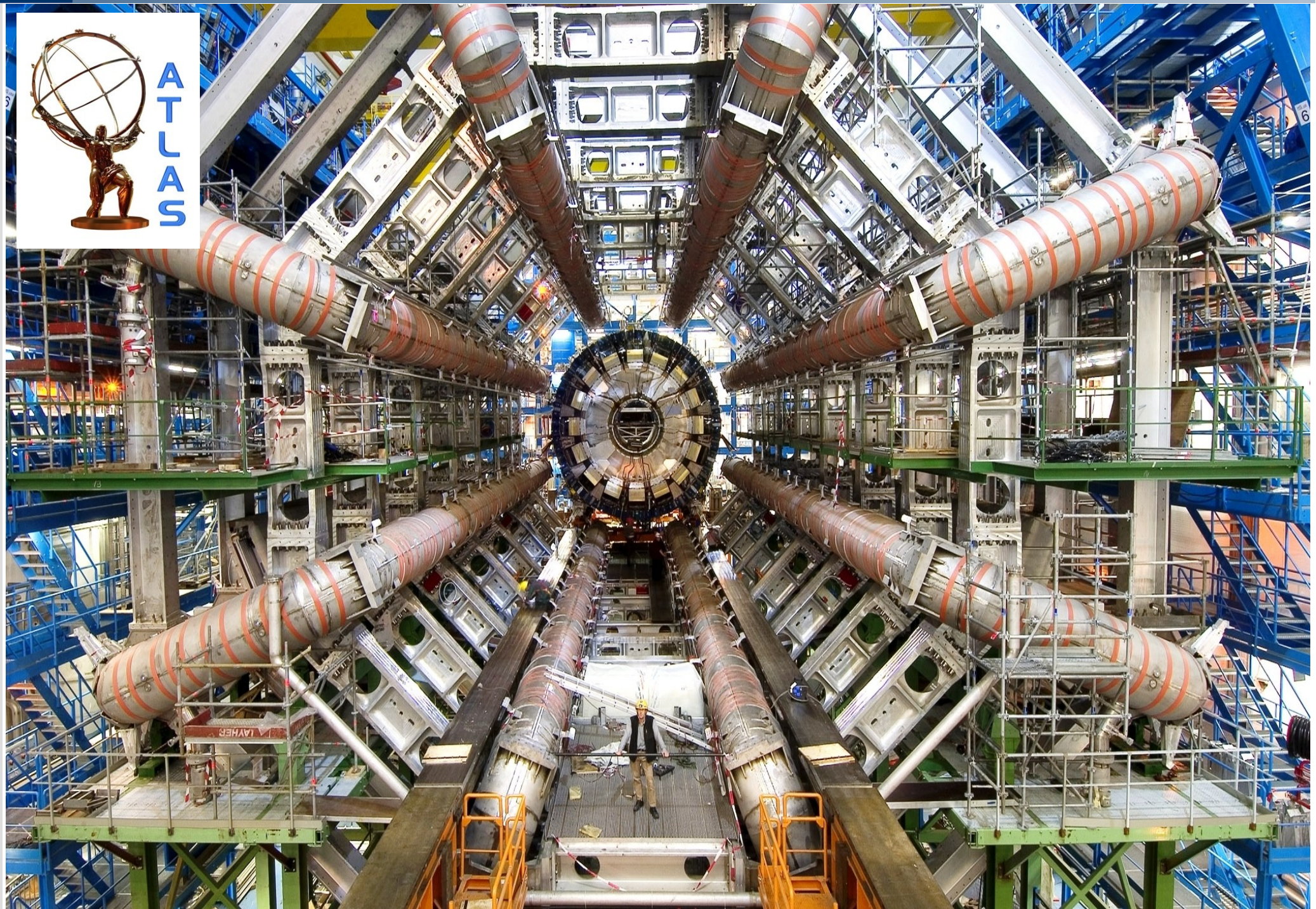
$$\text{Number of potential collisions per unit area} = \frac{N_1 N_2}{A}$$

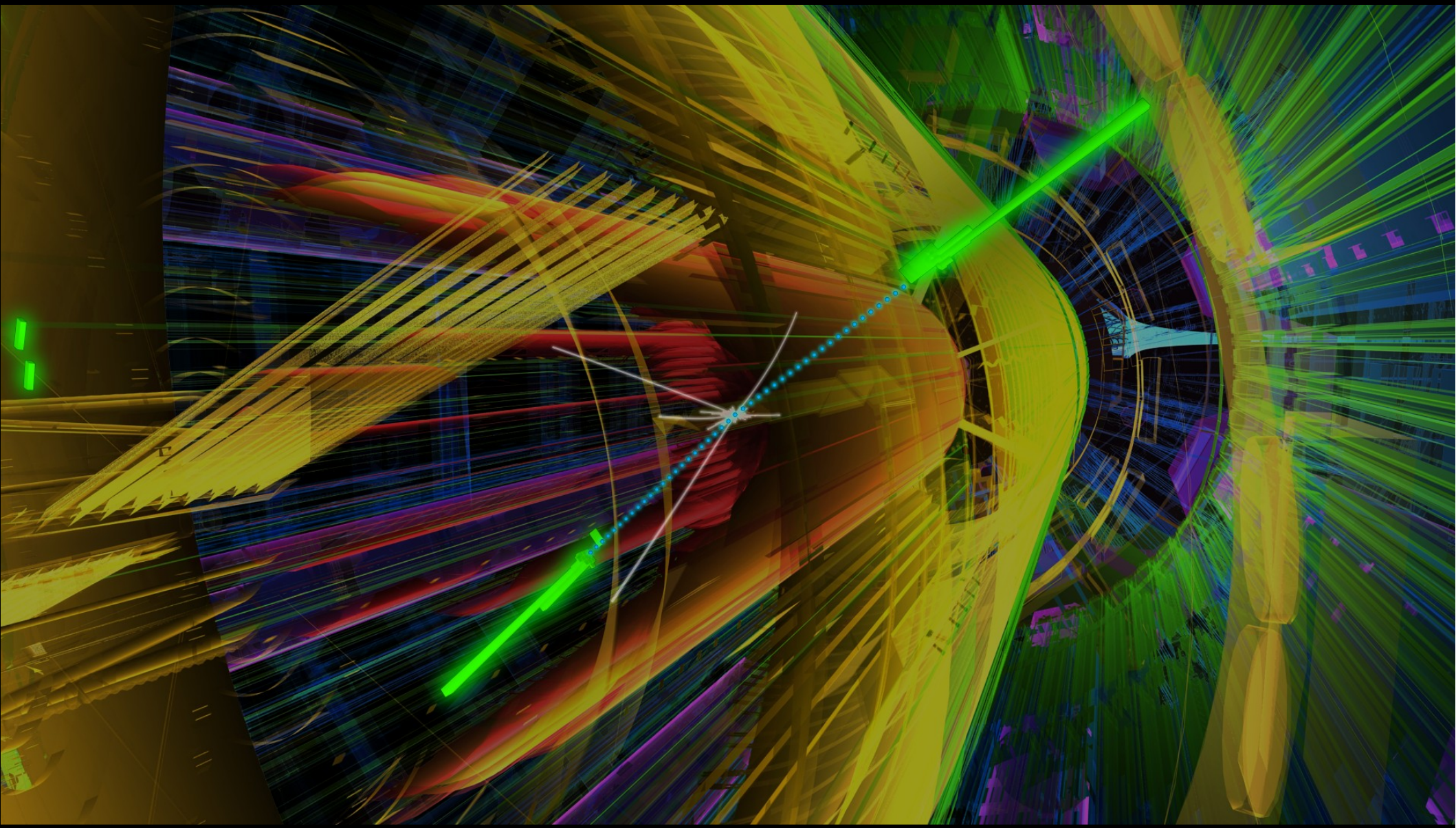
Feynman Diagrams: Physics turns into Art
Quantitative Description of Particle Collisions



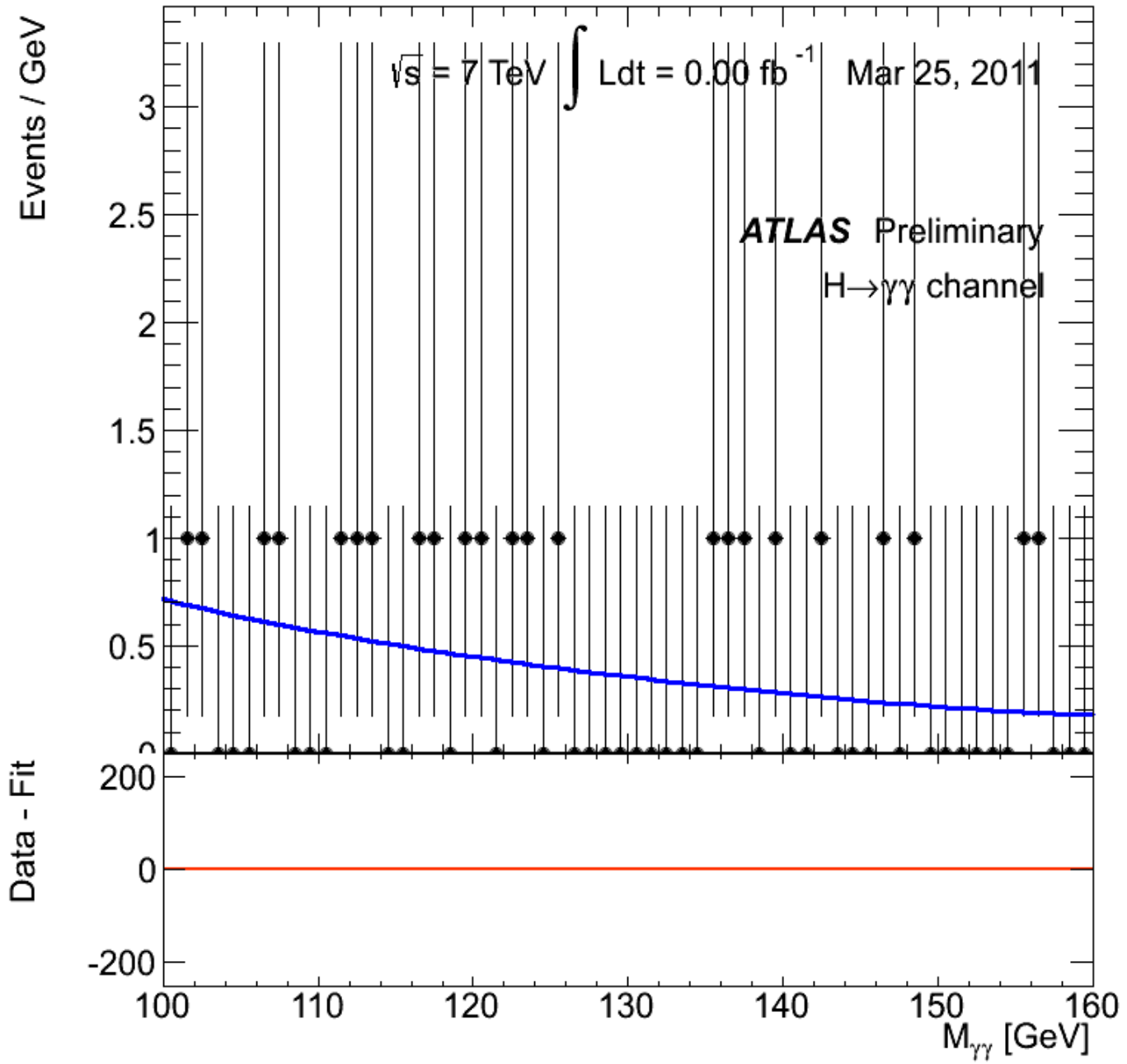


ATLAS

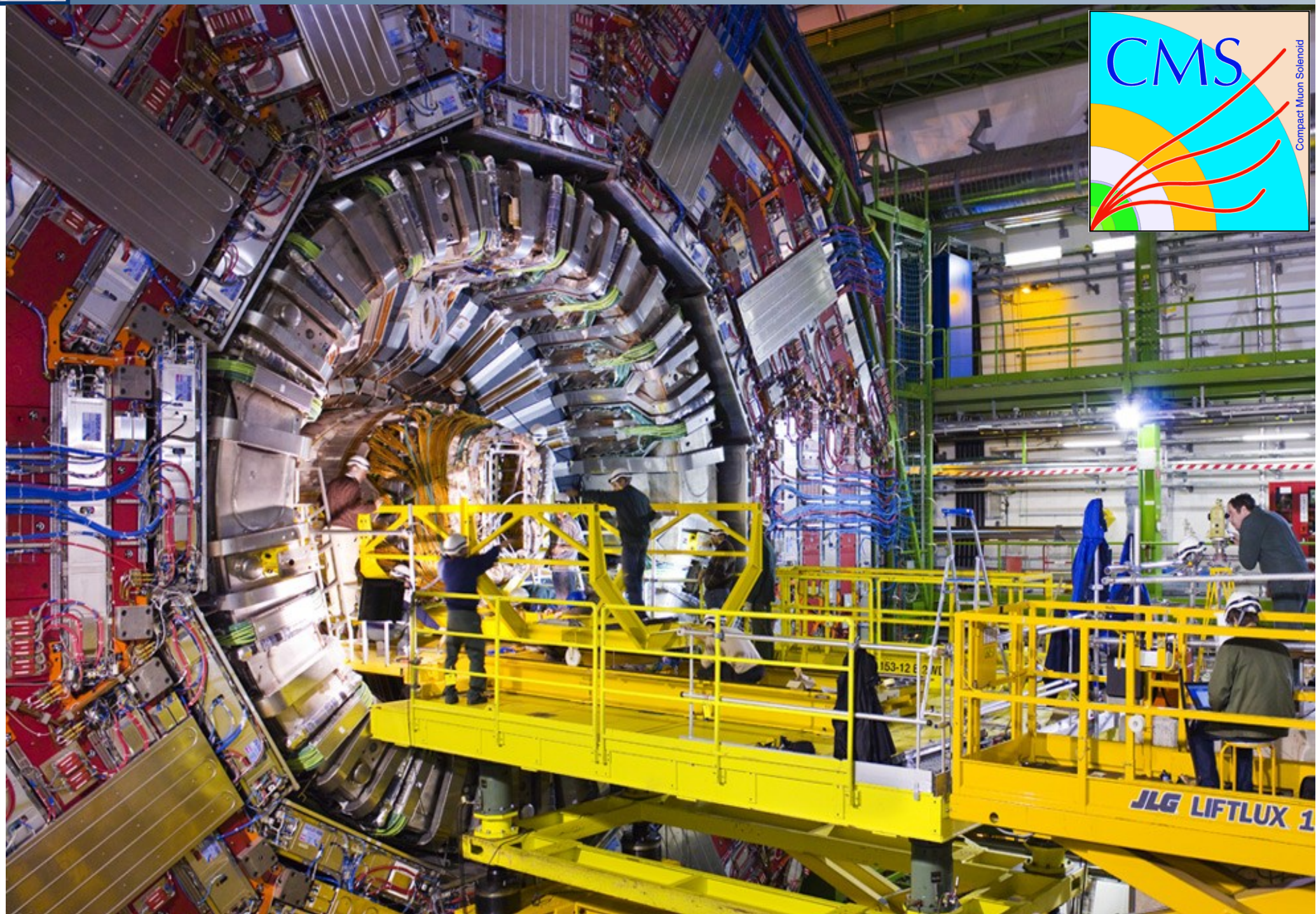


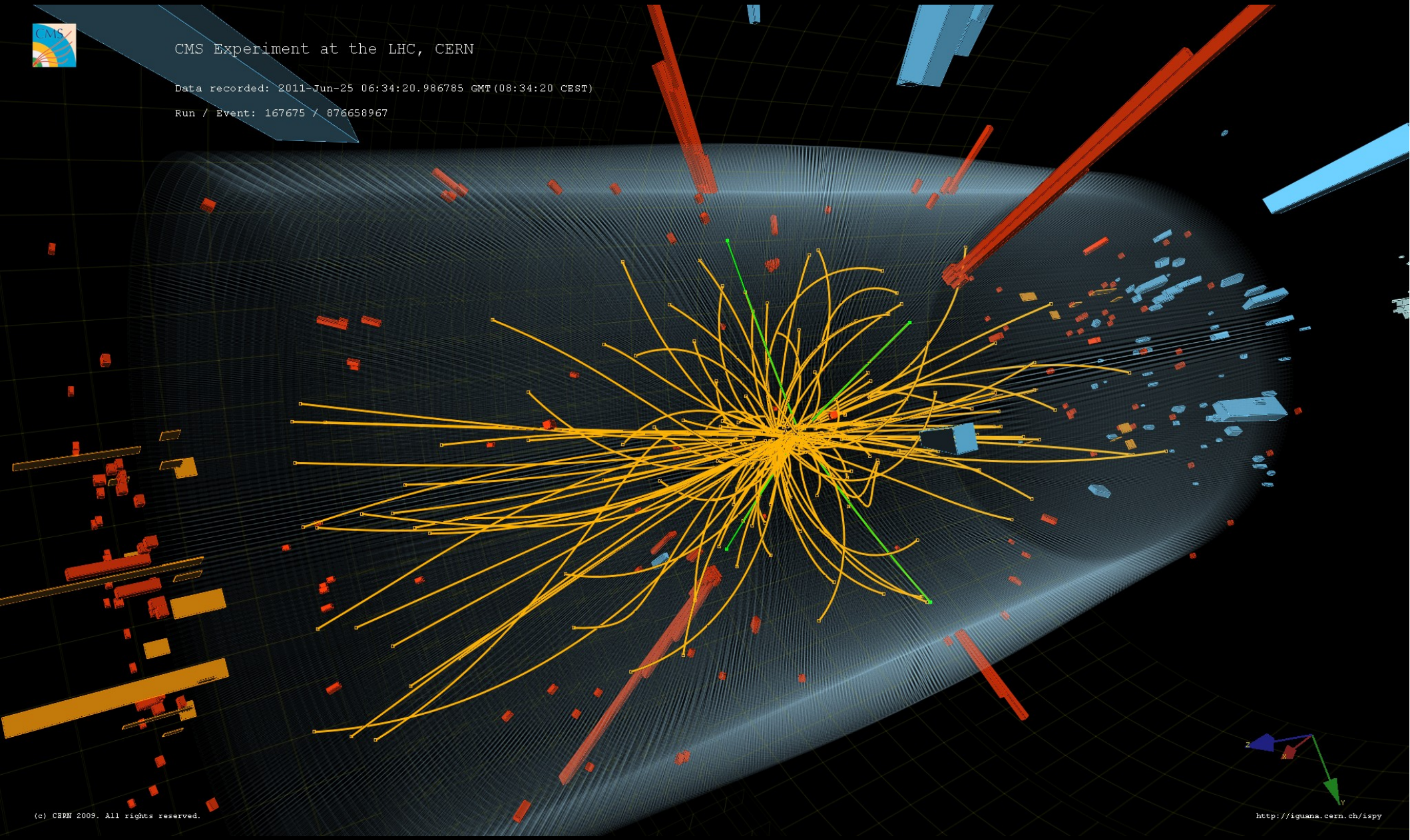


2011 → 2012 The Higgs Hunt: H → γγ

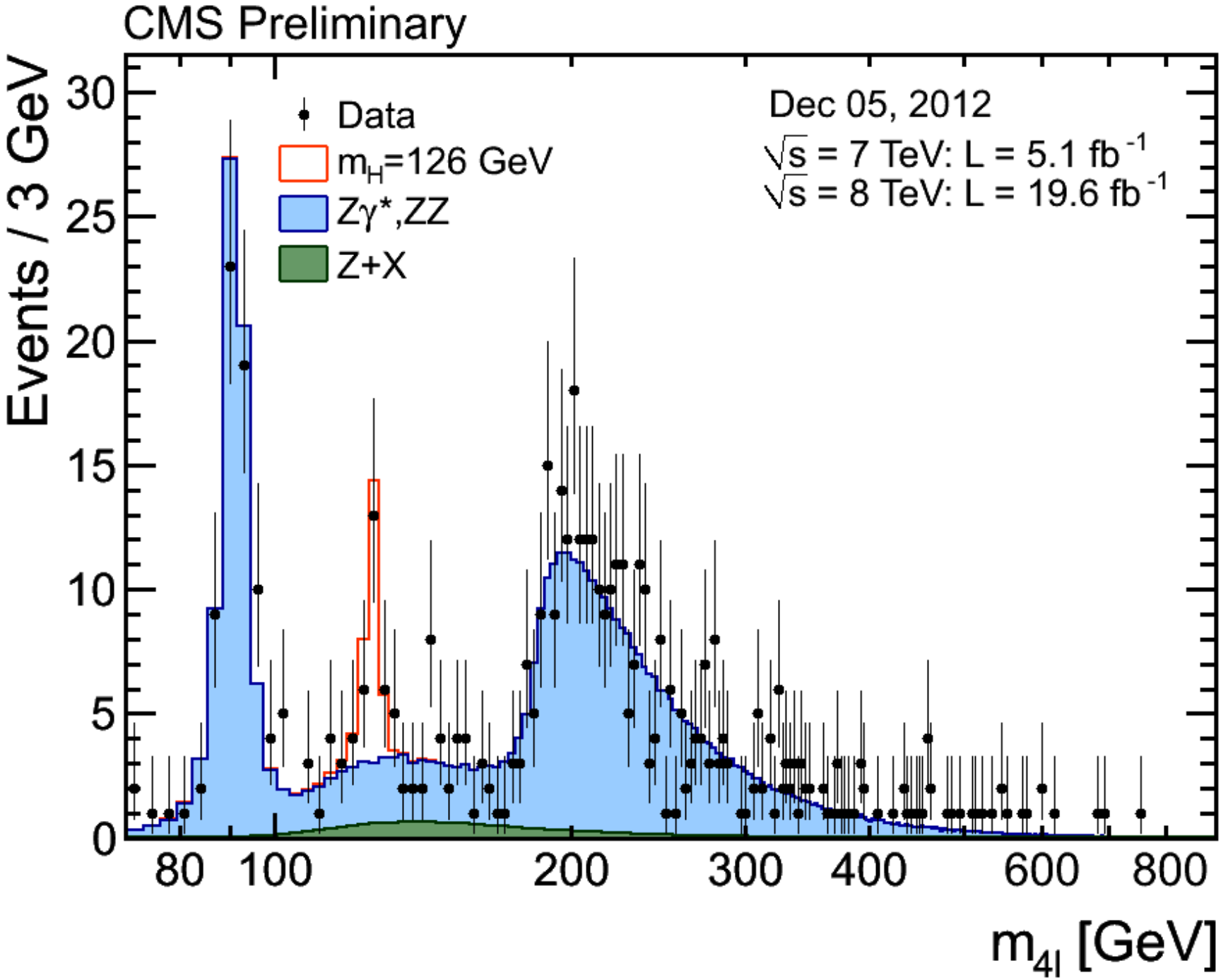


CMS

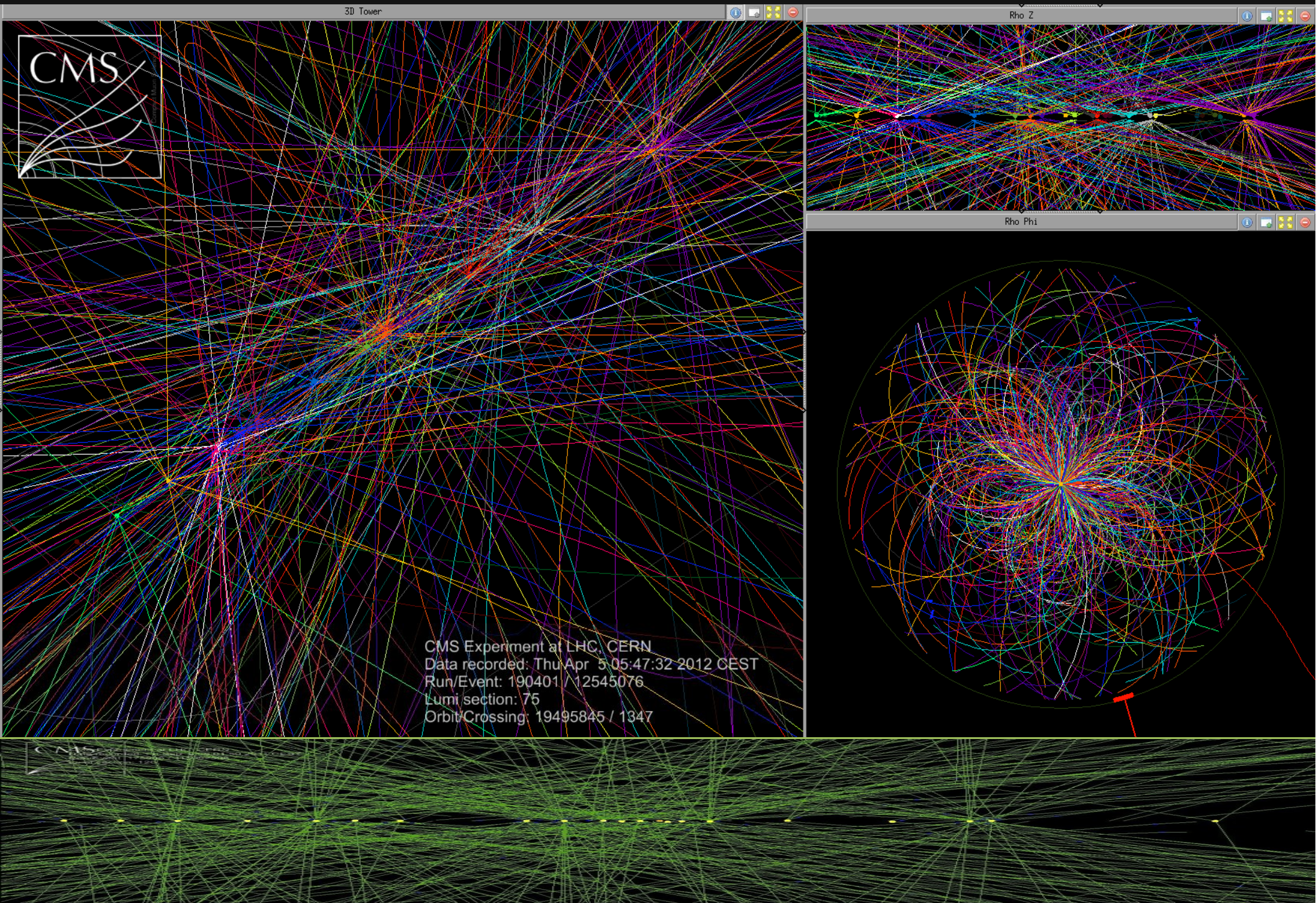



CMS Experiment at the LHC, CERN
Data recorded: 2011-Jun-25 06:34:20.986785 GMT(08:34:20 CEST)
Run / Event: 167675 / 876658967
(c) CERN 2009. All rights reserved.
http://iguana.cern.ch/ispy

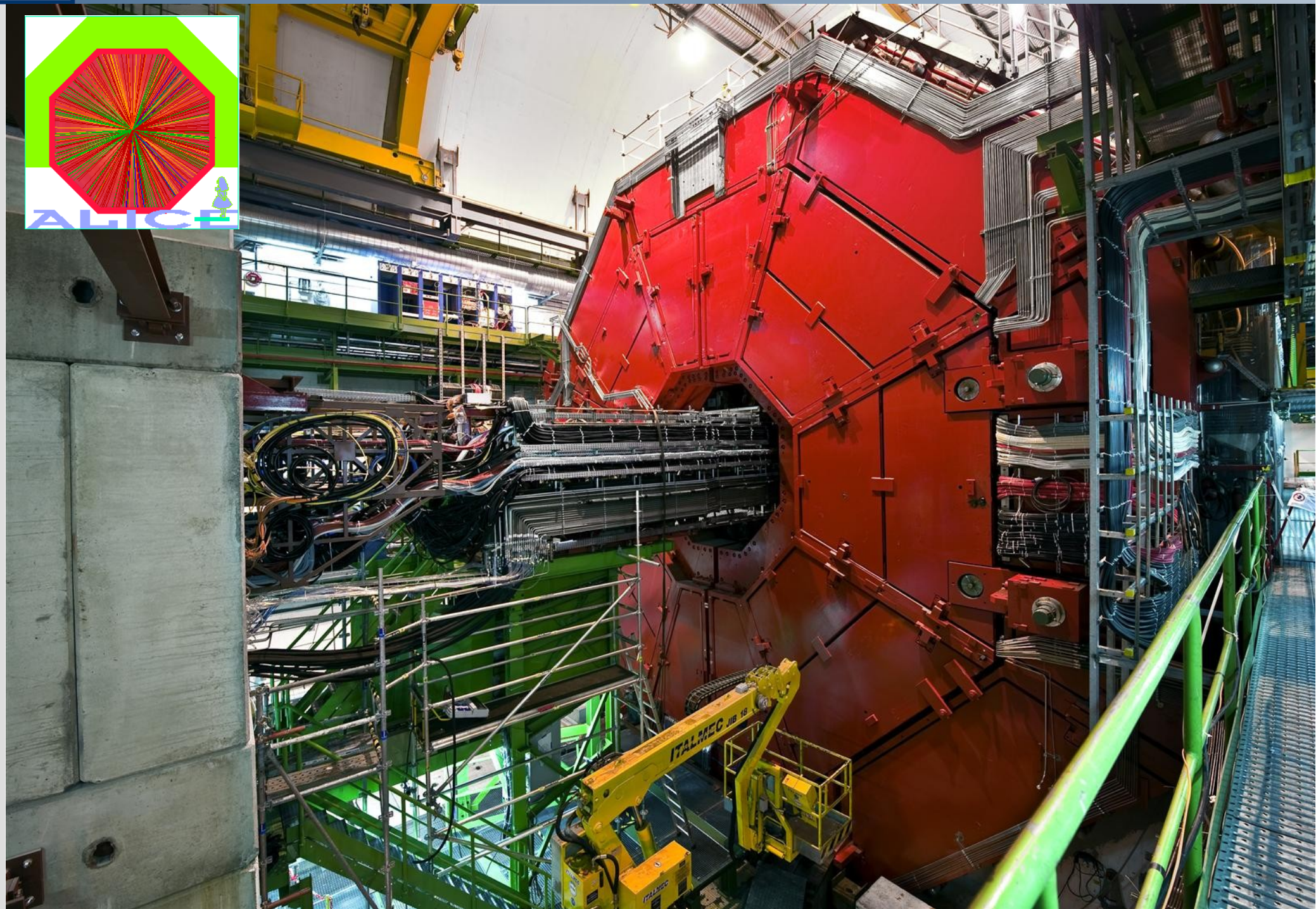
2011 → 2012 The Higgs Hunt: H → 4l



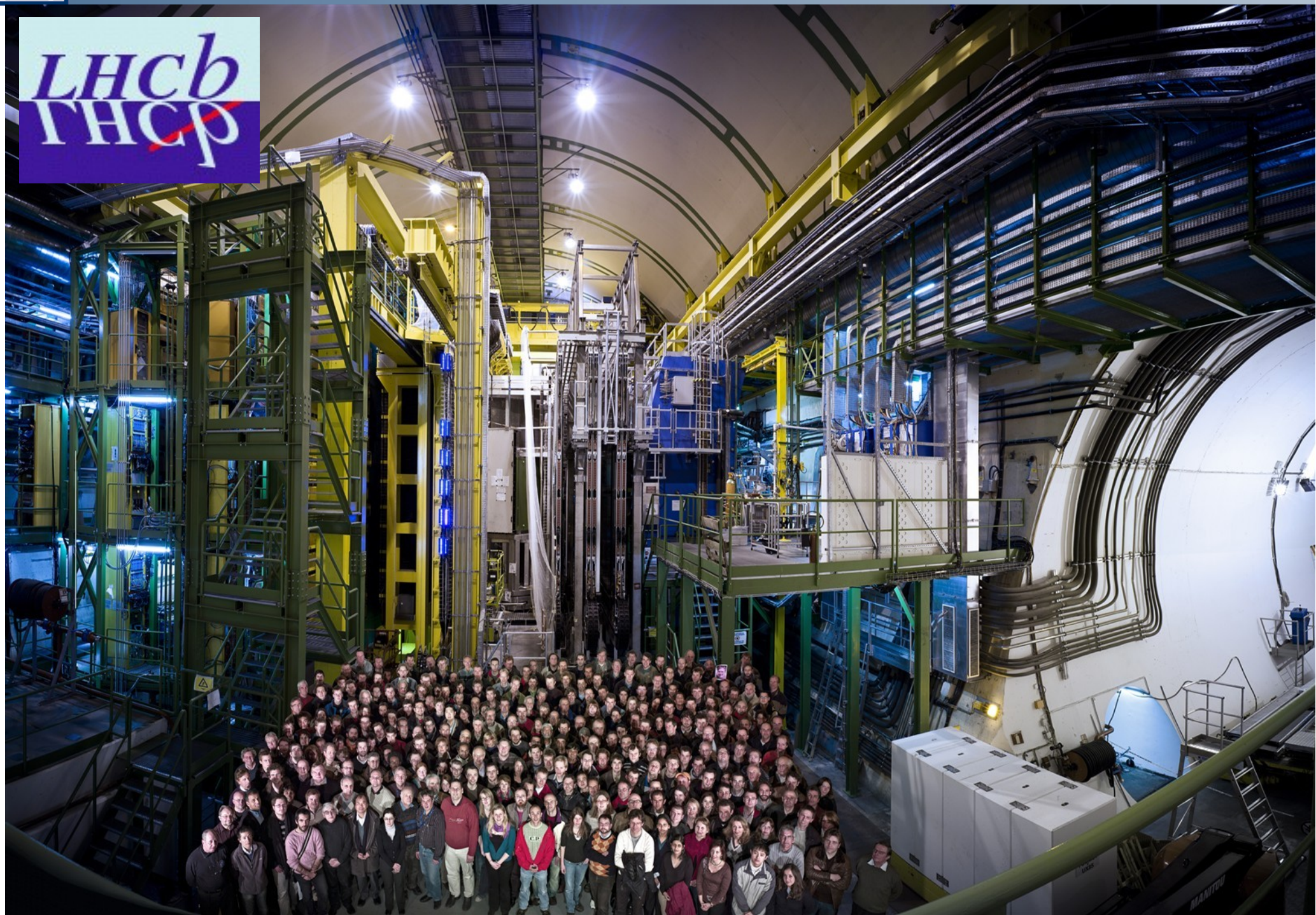
Disentangling of multiple Collision Events



ALICE



LHCb



CERN - Conseil Europeén pour la Recherche Nucléaire
Today: European Global Organization for Nuclear Research

- 1951: CERN's mission:
  - A) provide resources and common infra-structure related to pure scientific and fundamental character
  - B) Promote peace and collaboration platform, education and sharing of scientific results among nations

- 20 member states + observers: India, Israel, Japan, Russian Federation, USA, Turkey, European Commission and UNESCO
- One of Geneva's largest organisations:
  ~ 2500 full-time employers, > 9000 visiting scientists
- A small world of its own → extraterritorial (neither CH/FR)
- Cradle of the World-Wide-Web: http://www.cern.ch
- GRID - One of the world's most power-full data processing networks
- World's home of High-Energy Physics and Nobel-Prize Winners
- More info:

Formal Contacts with CERN

Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Belarus. Belgium, Bolivia, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Cuba, Cyprus, Czech Republic, Denmark, Ecuador, Egypt. Estonia, France, Finland, Georgia, Germany, Ghana, Greece, Hungary, Iceland, India, Iran, Ireland, Israel, Italy, Japan, Jordan, Korea, Latvia, Lebanon, Lithuania, Macedonia, Madagascar, Malaysia, Malta, Mexico, Montenegro, Mozambique, New Zealand, Netherlands, Norway, Pakistan, Palestine, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russia, Rwanda, Saudi Arabia, Serbia, Singapore, Slovenia, Slovak Republic, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Taiwan, Thailand, Tunisia, Turkey, United Arab Emirates, United Kingdom, Ukraine, USA, Uzbekistan, Venezuela, Vietnam, European Union, Unesco

What are long-, medium- and short-term benefits?
… why we must spend money for science?

Long-Term - World is becoming a Knowledge-based Society/Economy

- Research: Seeking and finding answers to questions about the Universe
- Technology: Advancing the frontiers of technology
- Collaborating: Bringing nations together through science
- Education: Training the scientists & engineers of tomorrow

Medium-Term: Fundamental Research enables applied Science, e.g.

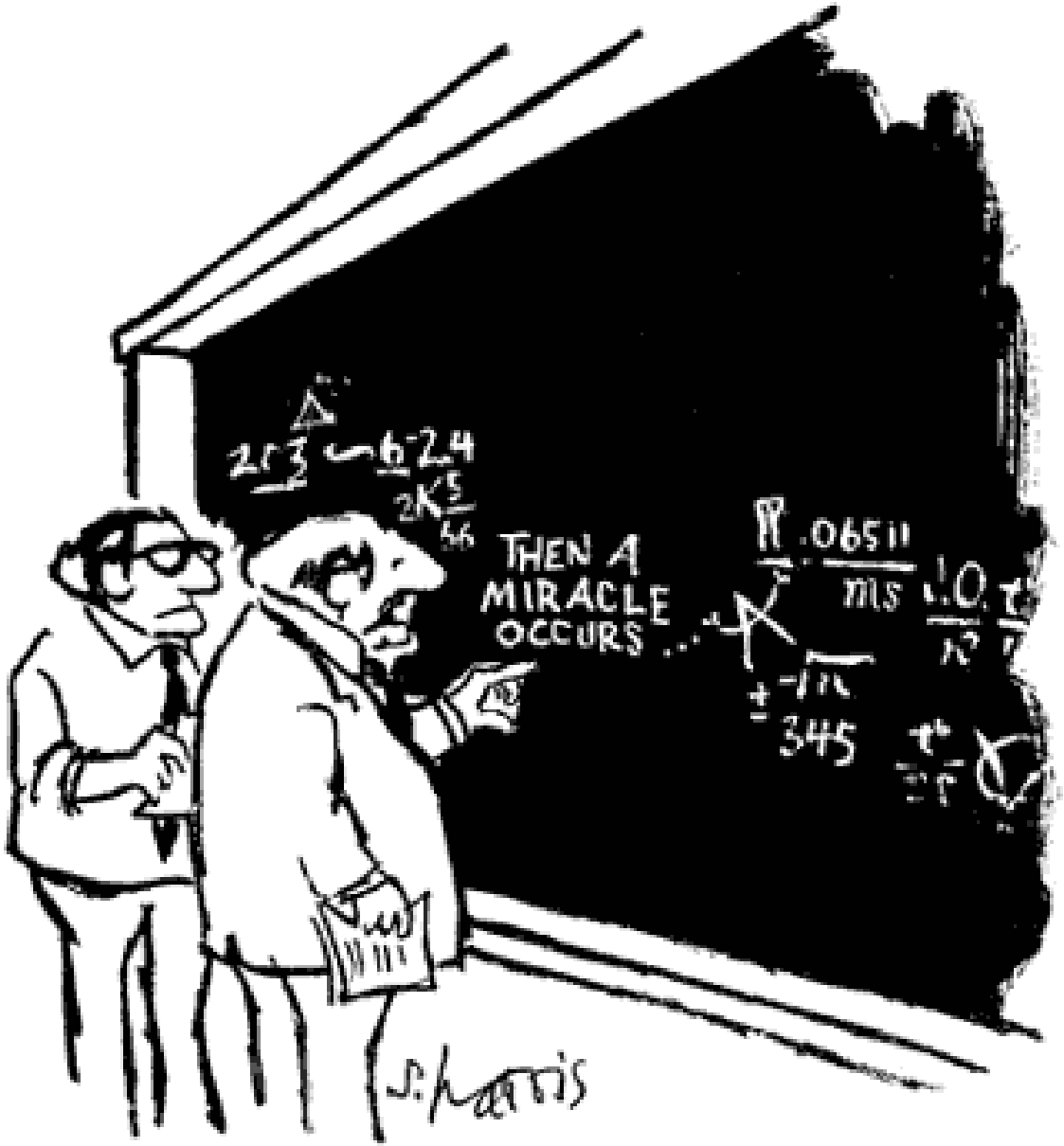
- Quantum-Mechanics → Semi-Conductor → Transistors → Computer
- General Theory of Relativity (Einstein) → Satellites → GPS

Short-Term: Advancements in industry....

- Accelerator, Magnet, Cryogenics, Detectors & Instrumentation, Electronic
  → Biology and Medicine: NMR & PET scanners, Ion therapy/cancer treat
- Information Technology: WWW, GRID, Genome Analysis, …

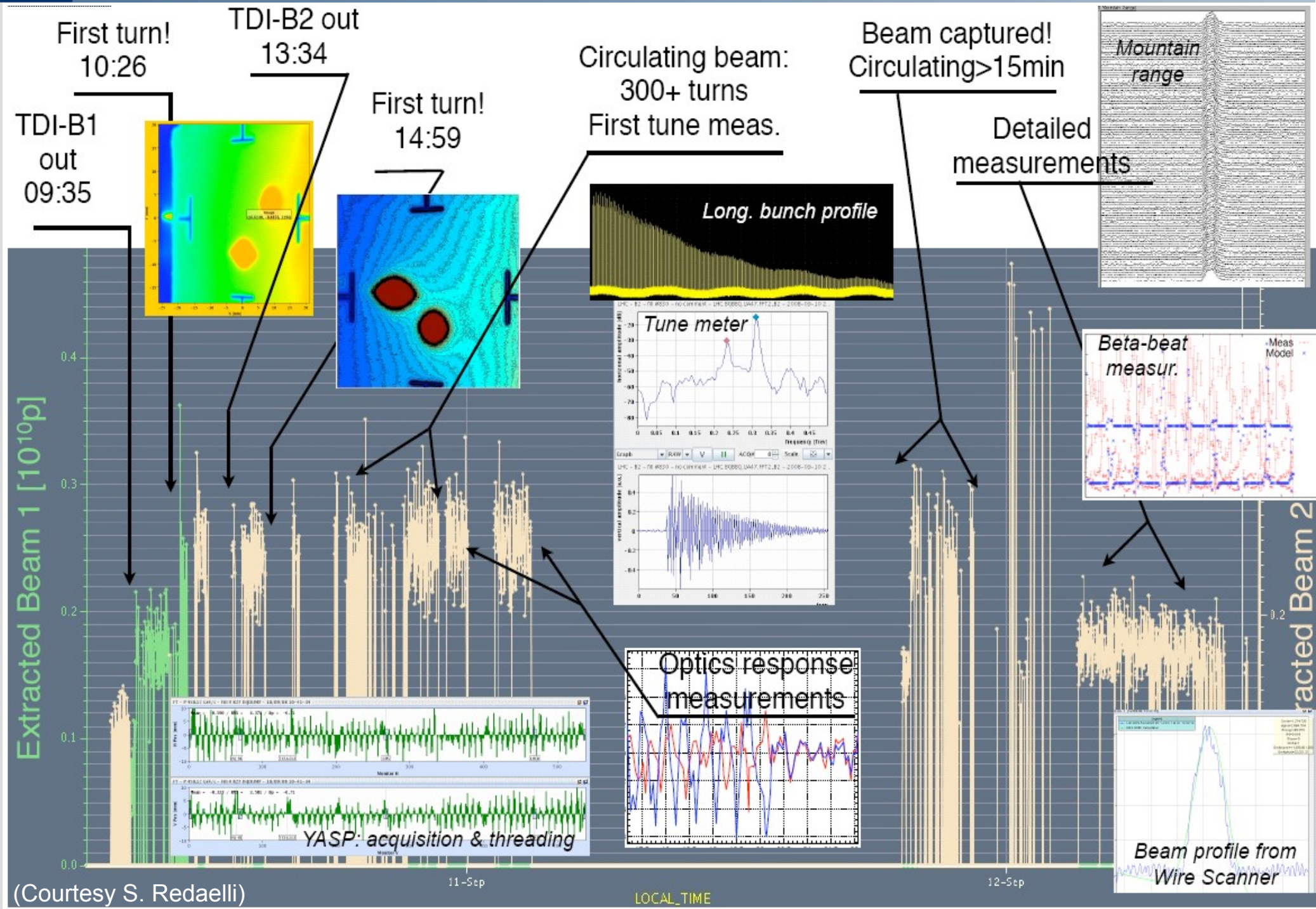

Thank You!

The Problem with Terminology or …
… why some have trouble with Physics



"I think you should be more explicit here in step two."

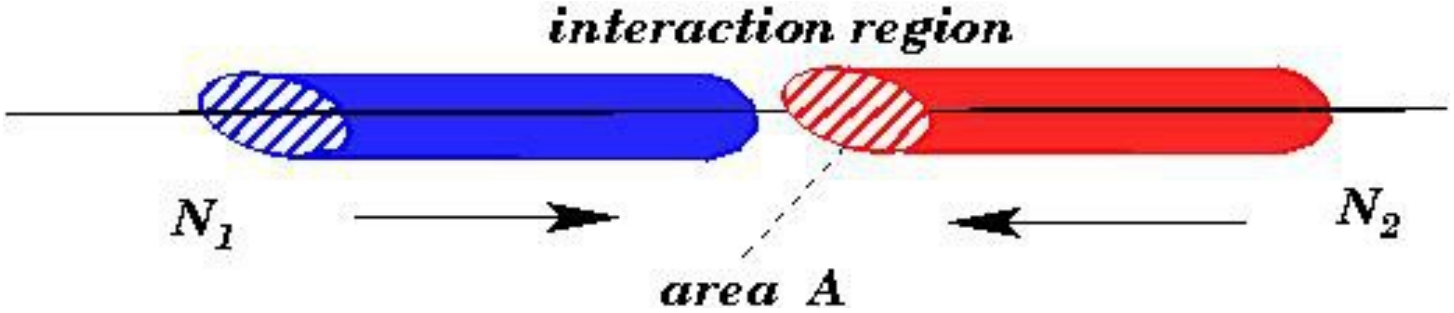
Beam Instrumentation provides the 'Eyes' and 'Ears' of an Accelerator
Example: 10th September 2008



(Courtesy S. Redaelli)

Luminosity: $dN_{event}/dt = L\,\sigma_{process}$

- Collider design:



$$L_{peak} \approx \frac{f_{rev} k_b \cdot N_b^2}{4\pi\sigma_x\sigma_y} \cdot F = \frac{f_{rev}\gamma k_b \cdot N_b^2}{4\pi\beta\epsilon_n} \cdot F$$

- N_b: number of particles per bunch,
- k_b: total number of bunches,
- σ_x, σ_y: hor./vert. r.m.s. beam size in IR,
- f_{rev}: revolution or repetition frequency,
- $F_{corr.}$: numerical correction factors (hour-glass, crossing angle, ...),
- ε: emittance (invariant of motion, ~"temperature of bunch")

$$\sigma_{x,y} = \sqrt{\frac{\epsilon\beta(s)}{\gamma}} + \ldots$$

Example: Squeezing in ATLAS Beam Envelope

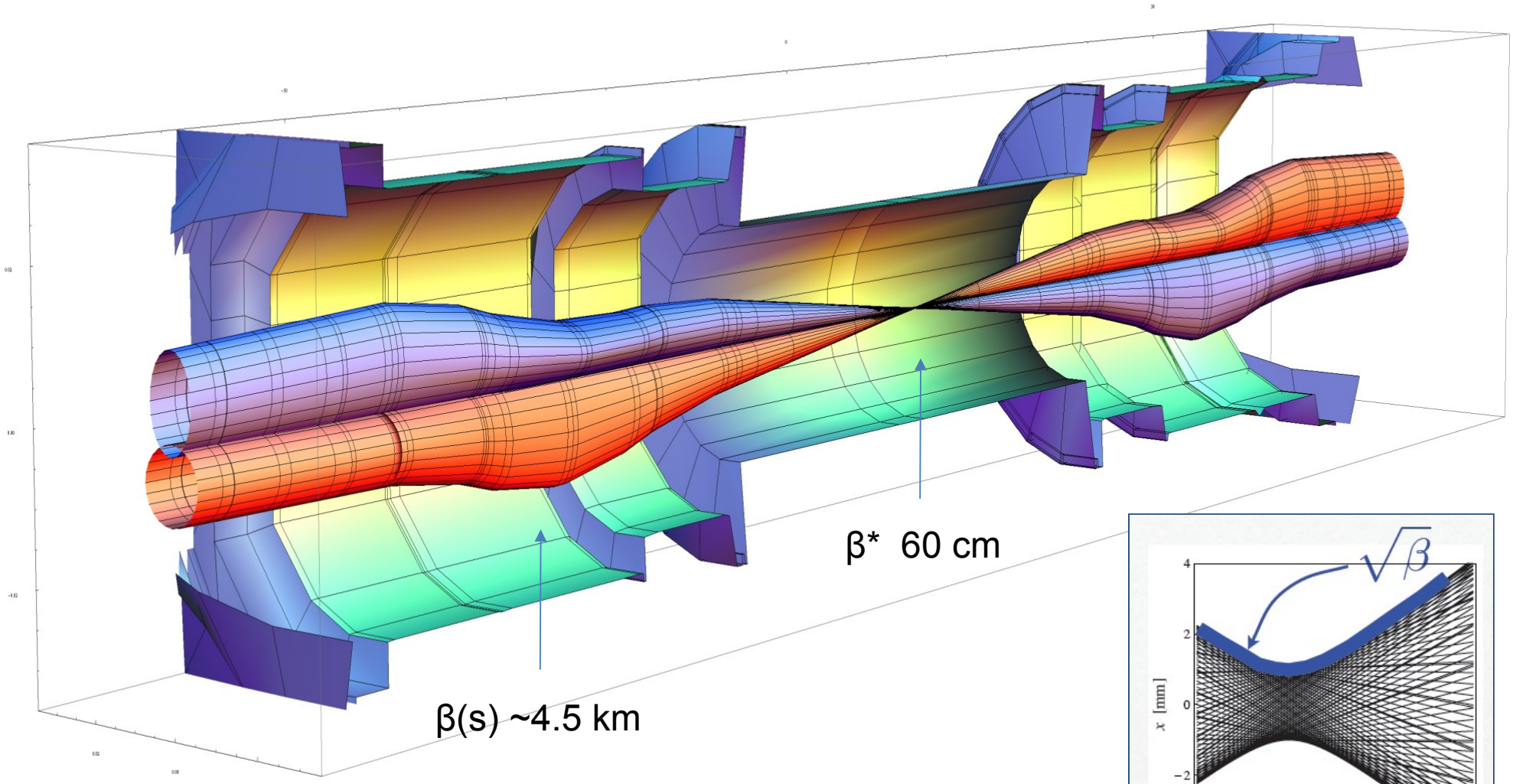


Image courtesy John Jowett