Discovering the Nucleus of the Indivisible

Blueprint for the ~~Legacy of~~ Fundamental Physics

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Briefly:

PANDORA'S BOX?

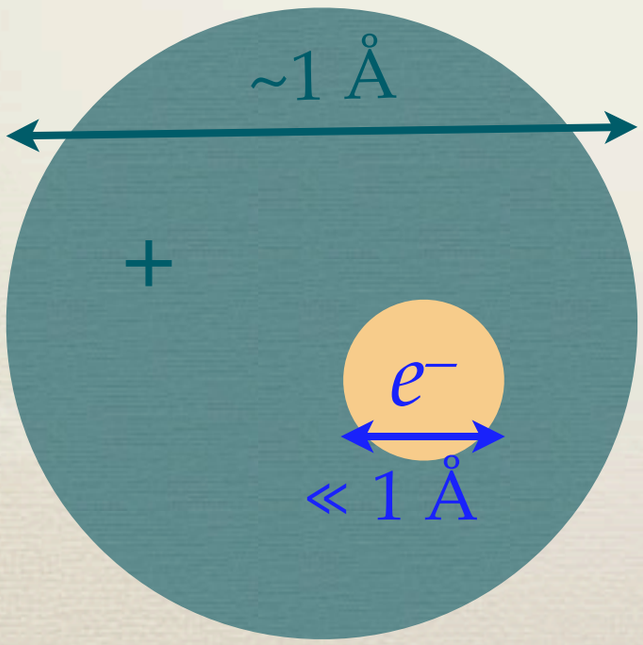
- Rutherford's discovery
  - First: e^- & "plum pudding" model
  - Test: using α^{++}-rays and Rutherford's formula
  - Planetary model of the atoma *…and quantum physics*
- Collision experiments
  - Nuclei have a structure; consist of nucleons
  - Nucleons have a structure, consist of quarks
  - Quarks and leptons have no structure, as best as we know.
- So, what now?
  - Theoretical developments way ahead of experiments
  - Waiting experiments are not fully complementary
  - New ideas?

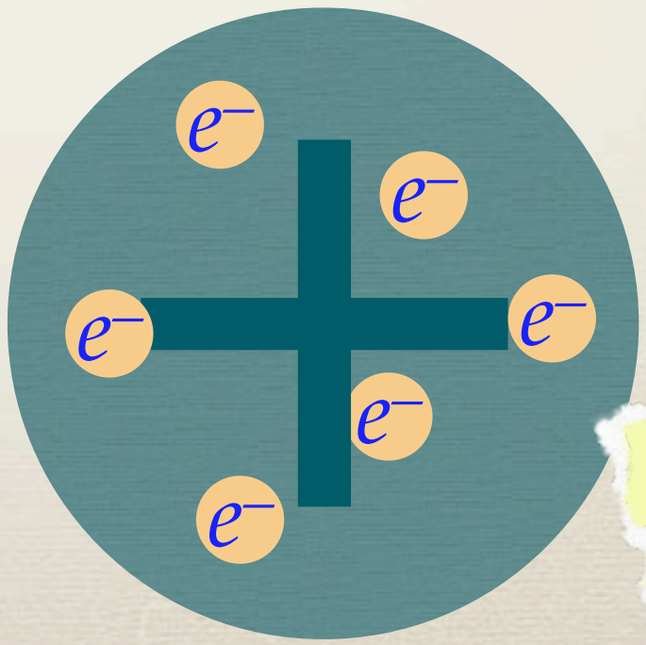
Pre 1909:

- 2 ½ millennia ago: Democritus & Leucippus, …
- 18th–19th century chemists (John Dalton, 1801–1803)…
- 1897: Joseph J. Thomson discovered:
  - cathode rays = beams of *electrons*,
  - ~2 000 times lighter that the lightest atom.

Cavendish Laboratory at Cambridge University

- An atom is neutral and of ~1 Å size.
  - So:



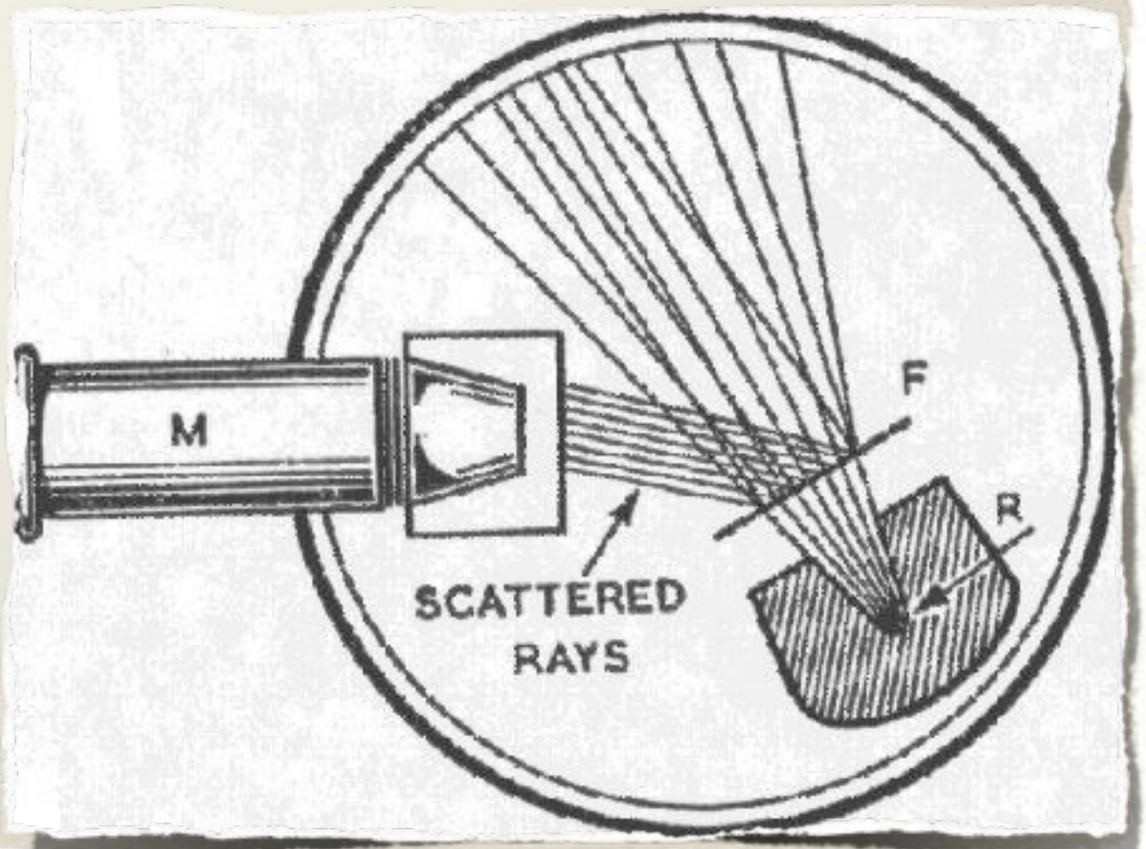


"plum pudding"

Pre 1909:

Manchester Literary and Philosophical Society (""Lit & Phil"), where John Dalton introduced atomism a century earlier…

- Ernest Rutherford
  - Student of J.J. Thomson, but situated in Manchester
  - Defined α-rays (w/ Paul Villard) 1899–1900,
  - …proved α-particles to be Helium ions (w/Thomas Royds, 1907)…
  - …used these α-particles (w/Hans Geiger & Ernest Marsden) to bombard a gold foil…
  - …than record and study the scattering pattern.



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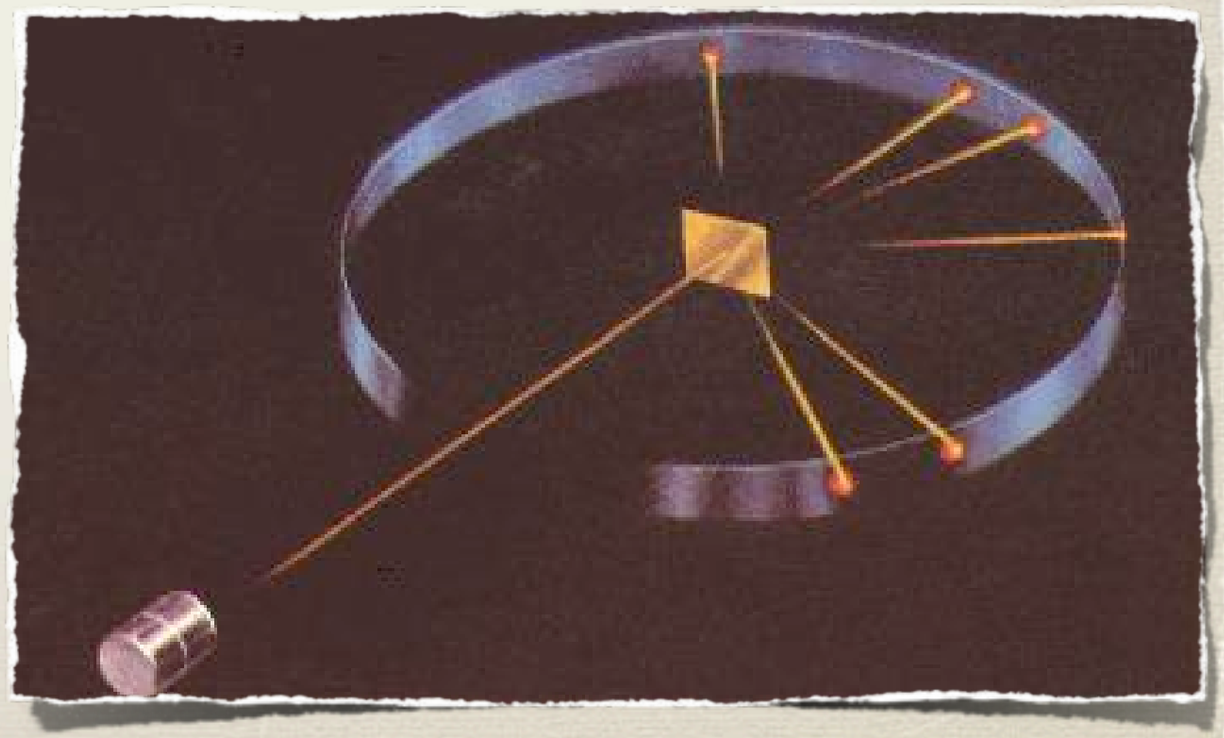
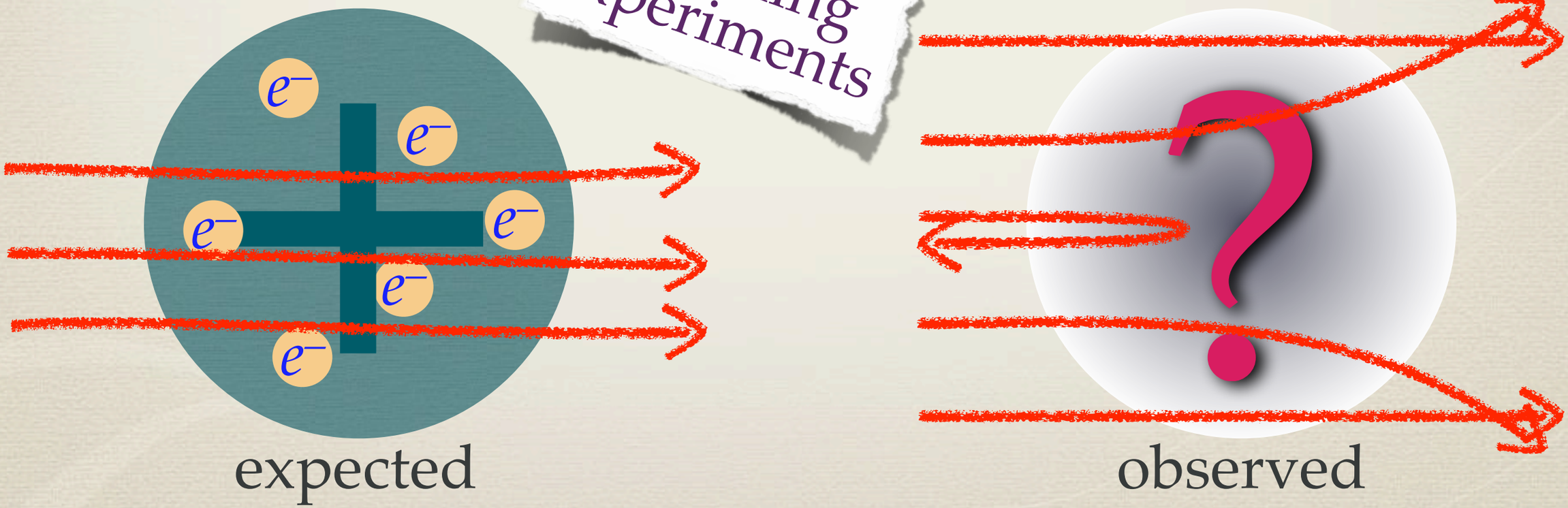


1909–1911:

- Ernest Rutherford (+ Hans Geiger & Ernest Marsden)
  - template experiment
  - mathematical analysis
  - planetary model

} legacy of the 20th century Physics

smashing experiments



expected

observed

1911: Manchester Literary and Philosophical Society
110 years after J. Dalton's *indivisible* atoms

- Rutherford:

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2/4\pi\epsilon_0}{2m_\alpha v_0^2}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

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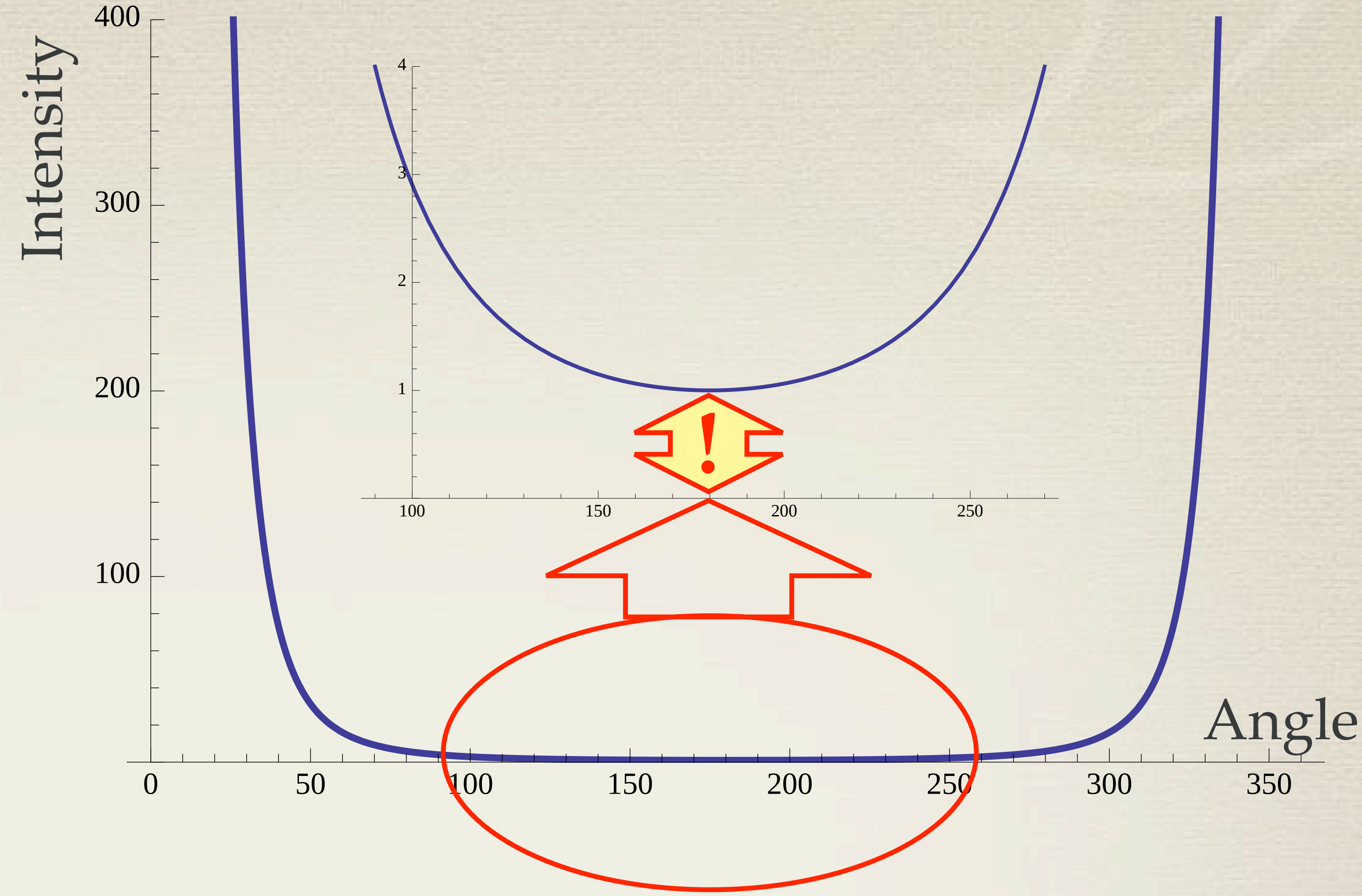
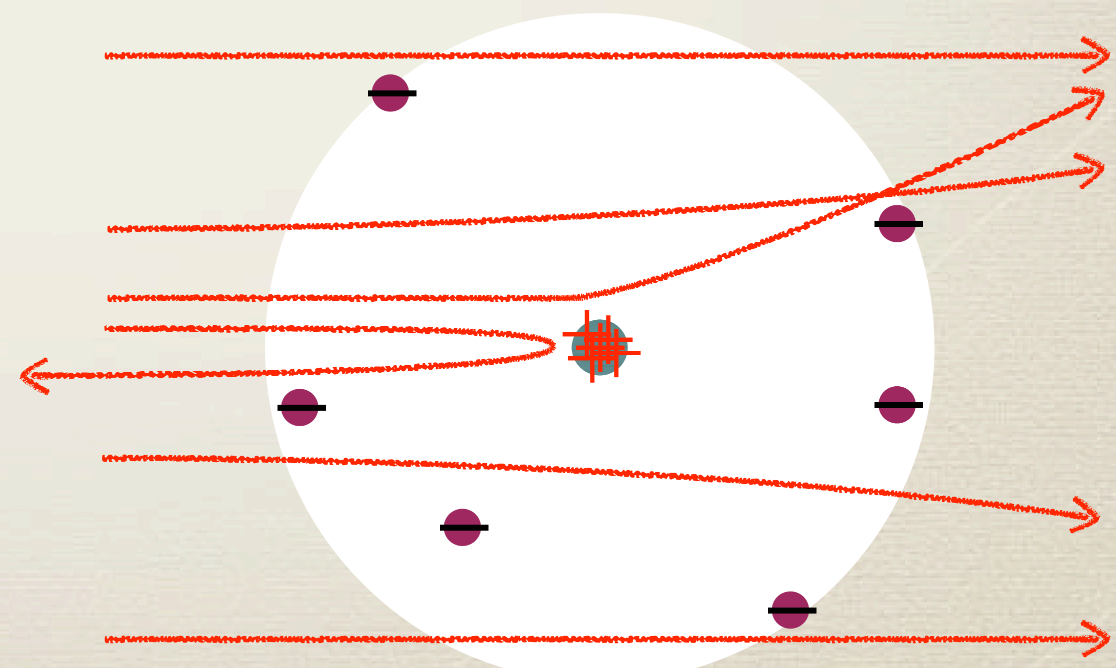
- describes that:
  - vast majority of α-particles passes unhindered
  - a few α-particles deflect a little from their direction
  - a teeeeeeeensy few α-particles ricochet “straight back”!?!





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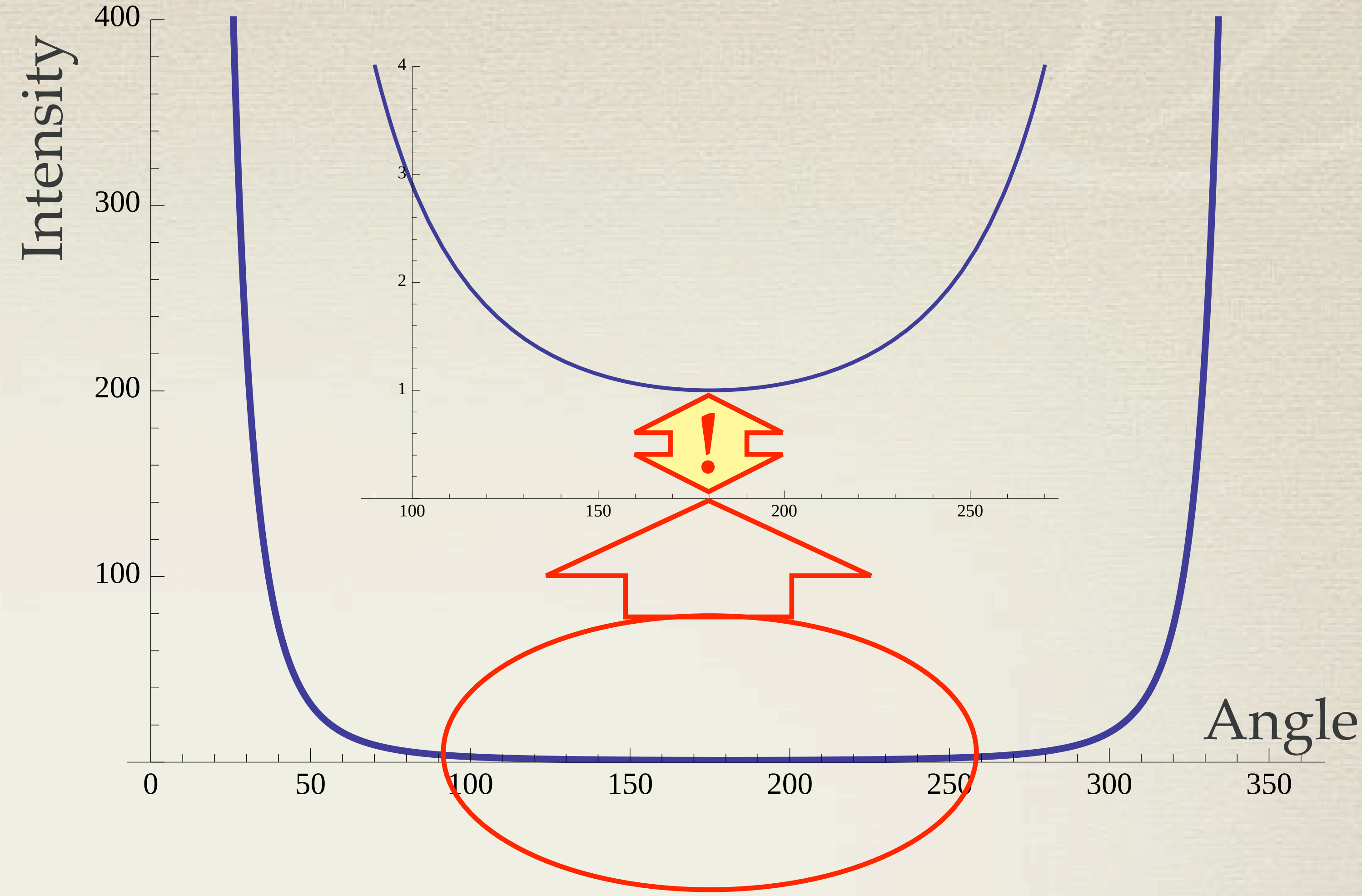
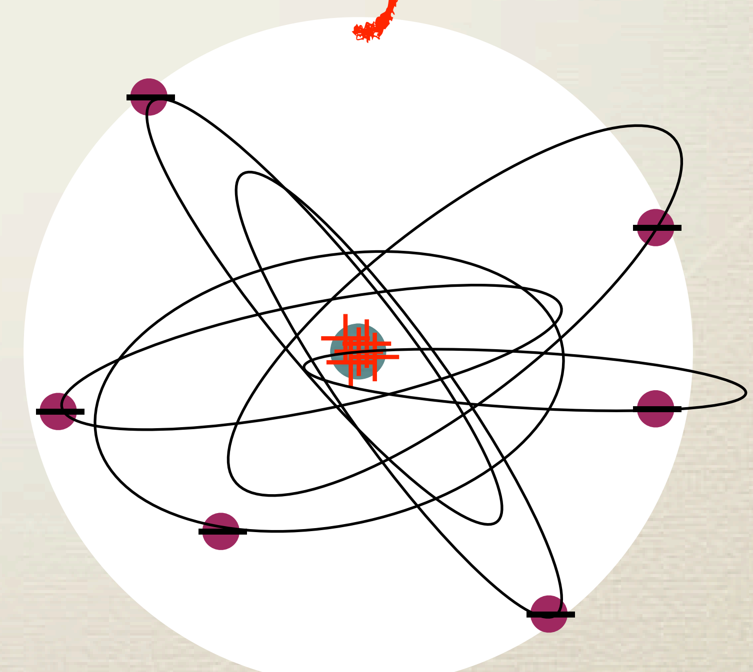


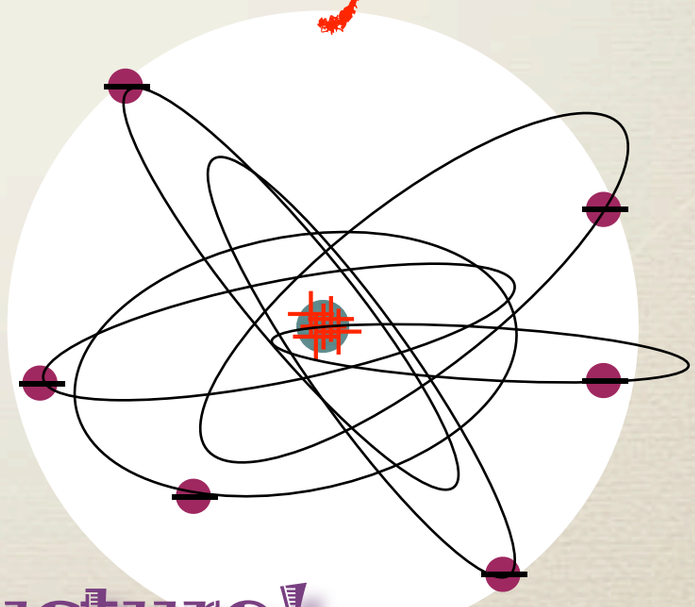
Planetary model



1911:

- Rutherford's experiment, analysis & result
  - Nixed his former advisor's "plum pudding" model;
  - proved that the atom (formerly ***named*** as indivisible),
    - …the smallest portion of any element…
    - …is in fact mostly void;
  - ushered the planetary model
    - …where negative electrons…
    - …orbit the positive nucleus…
    - …held by Coulomb's force,
    - just as planets are held by…
    - …Newton's force of gravity.

Planetary model

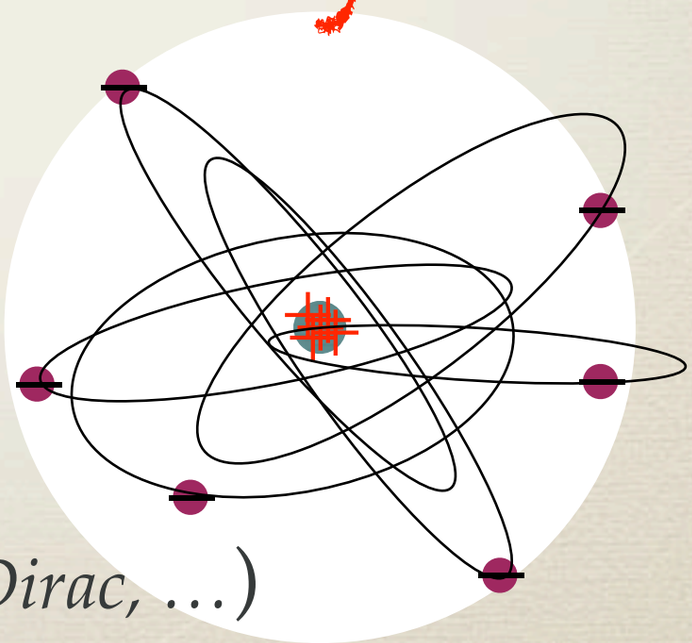


A remarkable repetition in structure!

1911:

- Rutherford's planetary model of the atom
  - also opened Pandora's box of new questions.
  - *"… the stability of the atom proposed need not be considered at this stage…"* – wrote Rutherford in his 1911 paper
- Niels Bohr
  - May 1911, PhD
  - 6 months with Thomson,
  - March 1912 with Rutherford,
  - …angular momentum is an integral multiple of $\hbar$ …
  - **Quantum physics** (*Planck, Einstein, Bohr, Compton, Heisenberg, Schrödinger, Dirac, …*)

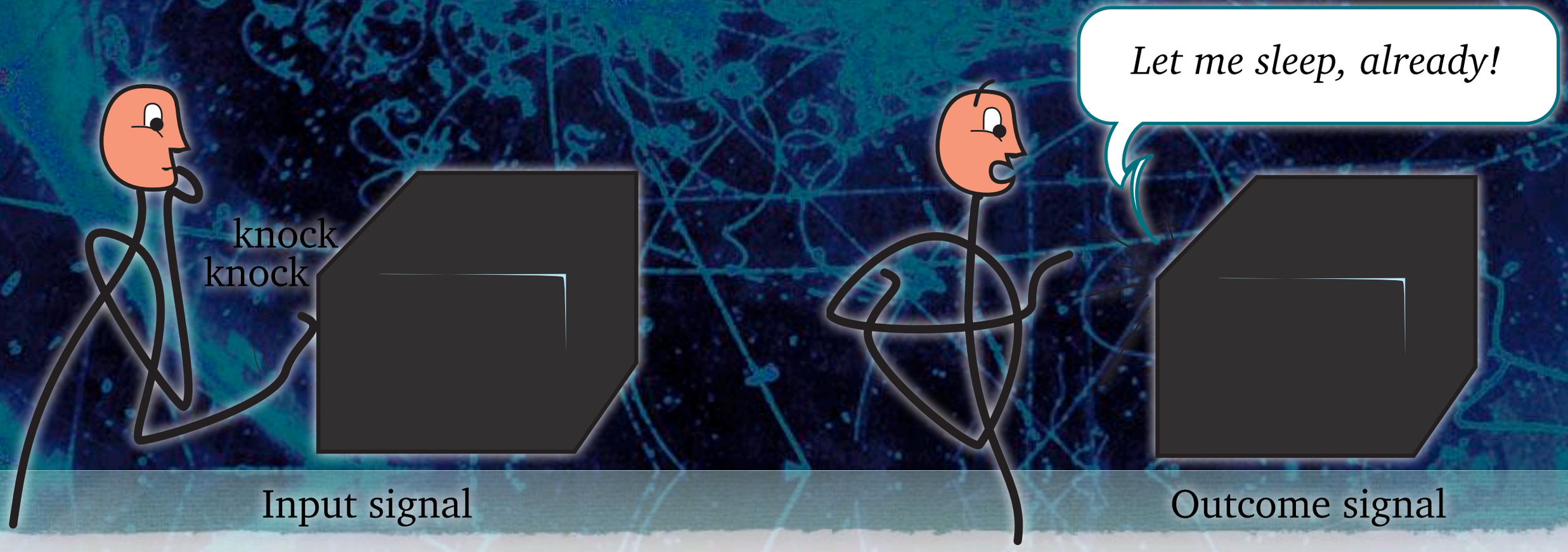
Planetary model



However, that's not all, Folks!

Conceptual shift in understanding

Legacy in experimenting methods



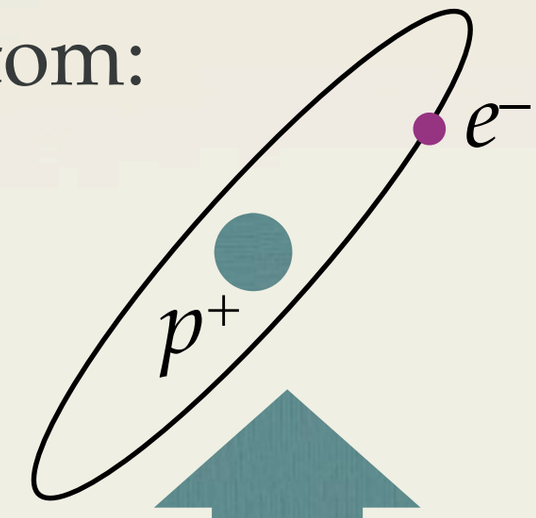
Divisibility & Atom Structure

- divisibility implies (sub)structure:

Divisibility & Atom Structure

- Indivisibility implies not the lack of (sub)structure:
  - Hydrogen atom:

Not divisible by chemical processes!



Thus, quite literally, a Hydrogen atom is never ***really*** divided.

Not a chemical process!

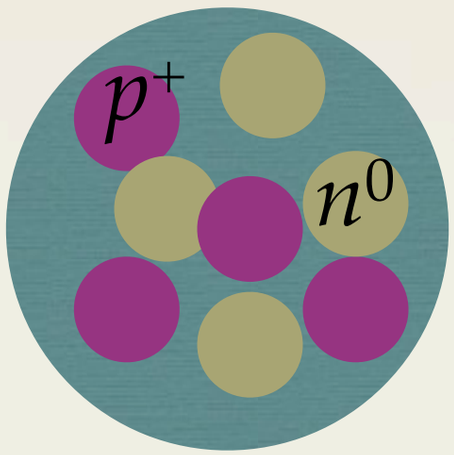
Nevertheless, it evidently does have a (sub)structure.

Recombination
("*all by themselves*")

Divisibility & the Structure of Matter

- Indivisibility implies not the lack of (sub)structure:
  - Atomic nuclei:

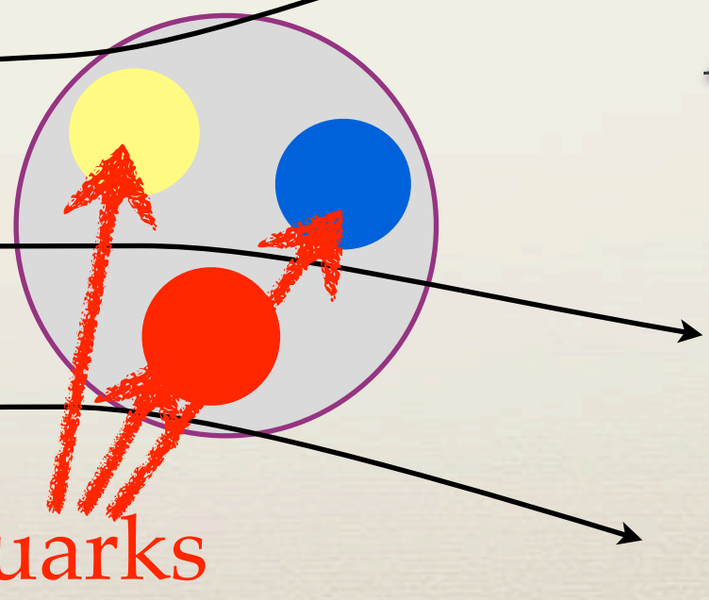
    Not divisible by chemical/atomic processes.



    Nevertheless, there is a (sub)structure.

  - Proton, neutron:

    Not divisible by any known process.

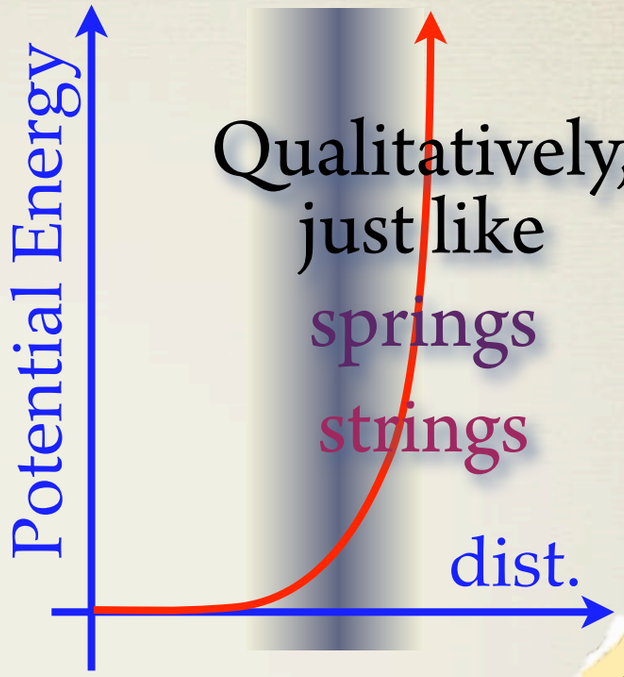


    Again, there is a (sub)structure.

    (Regardless of the fact that quarks cannot, in fact, be isolated!)

Divisibility & the Structure of Matter

- Indivisibility implies not the lack of (sub)structure:
  - Protons, neutrons, ***hadrons***:
  - bound states of (anti)quarks,
  - …which cannot be observed as sufficiently isolated particles.



(so as to be handled regardless of the rest)

Divisibility & the Structure of Matter

- Indivisibility implies not the lack of (sub)structure:
- But, why can we separate e^- and p^+, but not quarks?
  - Binding energy of H-atom = 13.6 eV.
  - Rest energy of e^- = 510,999 eV.
  - Ratio ≈ 0.000 0266 ≈ 1/37,573.

$$E_n = -\tfrac{1}{2}\alpha_e^2 m c^2$$

$$\alpha_e = \tfrac{1}{137}$$

- On the other hand,
  - Rest energy of u,d quarks = 1–6 MeV.
  - Binding energy in (u,d)-mesons is at least as big!
  - Ratio ≥1!!!

$$\alpha_s \sim 1$$

Divisibility & the Structure of Matter

- Fundamental physics of elementary particles…2011

Substance (spin-½ fermions)				
Gen.	**Leptons**		**Quarks**	
1.	ν_e	e^-	u	d
2.	ν_μ	μ^-	c	s
3.	ν_τ	τ^-	t	b

Interactions		(bosons)
γ	electromagnetic	(spin-1)
$W^\pm, Z^0$	weak nuclear	(spin-1)
gluons	strong nuclear interaction	(spin-1)
$\delta g_{\mu\nu}$	gravitation	(spin-2)

Higgs boson (spin-0): gives mass to the particles with which it interacts

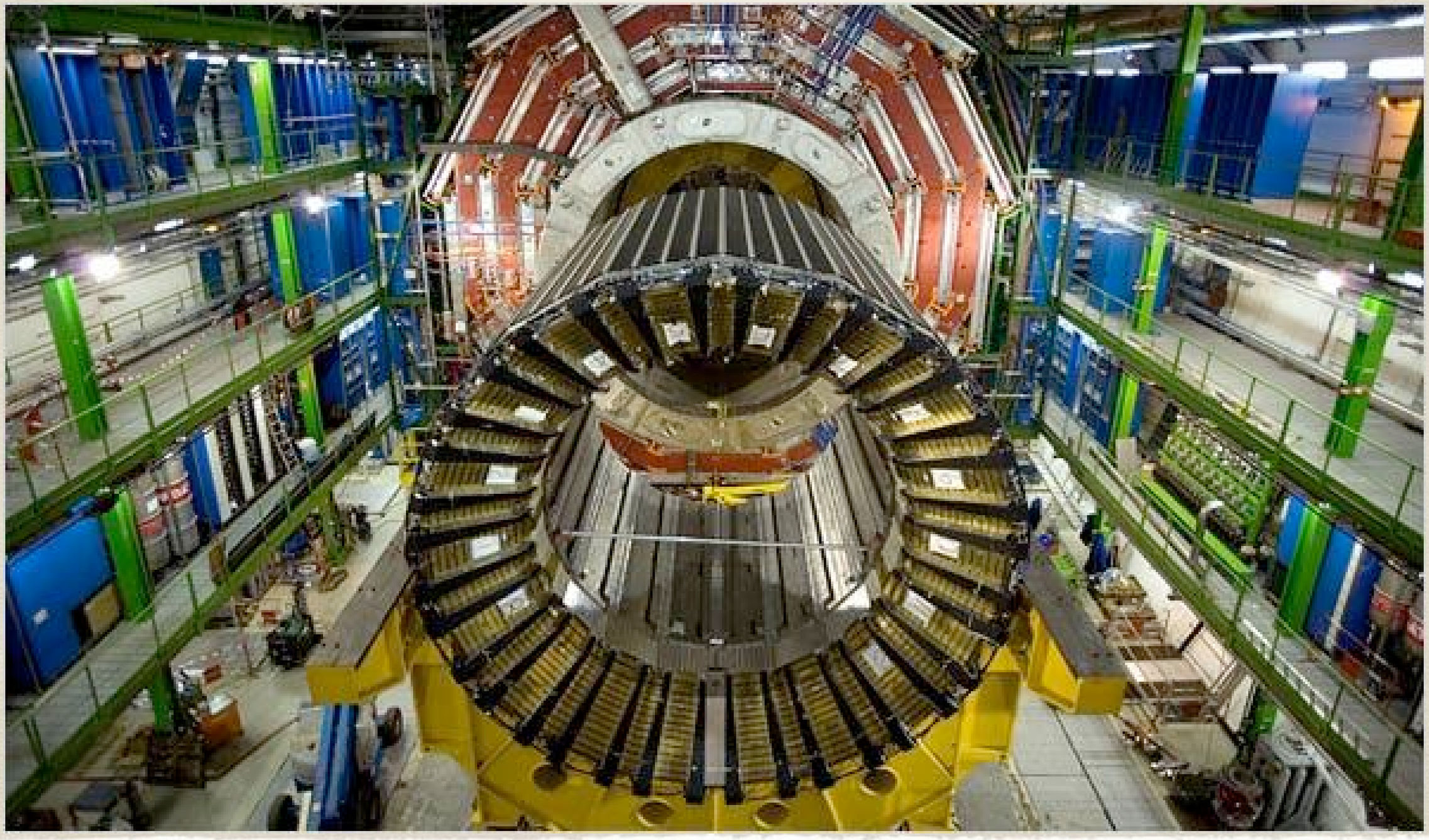
- …describes all tangible matter
  and all its fundamental interactions

- …in agreement with all experiments ever performed to date. (Except that the Higgs particle is still sought for…)
  (And, *perhaps… just very, very perhaps,* the impish neutrinos of the recent fervor…)

...& experiments

Template for most of EPP 20th century experiments

- Rutherford-esque colliding processes!



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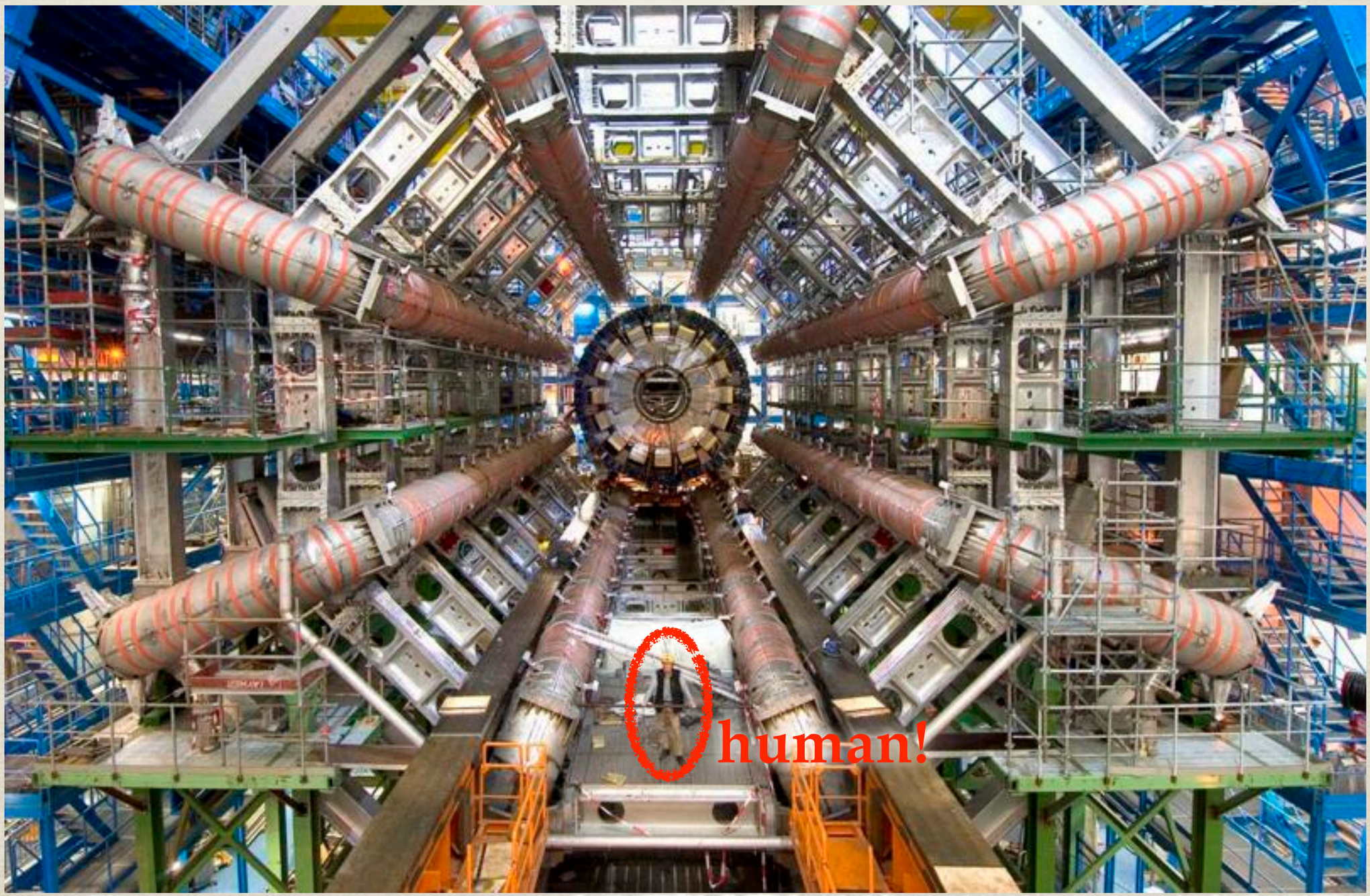

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- Rutherford-esque colliding processes!

- CERN is a
  - multi-national
  - multi-cultural
  - multi-social
  - multi-political
  - multi-financed
  - complex structure
- Really, really, really
  - ...expensive.
- *& Foreordained.*

You can't turn CERN on a dime!

...& experiments

- And then there are the "waiting experiments"
  - Deck out an abandoned mine with detectors…
  - …fill it with water (the price is right)…
  - …and wait.
    - The more time passes without registering an event,
      - the smaller the probability for the event to happen at all.
- Typically, not as complex/political/expensive/BIG as the smashing experiments…
- …but, they tend to produce "limits from one side,"
- …and they too are carefully planned/designed.

...& experiments

- You cannot plan/design for "accidental discoveries"
  - Thales noticed that amber (ήλεκτρον) attracts lint…
  - Alessandro Volta poked frog legs with various wires…
  - Hans Christian Ørsted saw the magnetic needle turn…
  - Henry Becquerel noticed materials to affect photo-plates…
  - …and there's nothing accidental about multi-complex experimentation as is being done nowadays.
- Needed: a radically new type of experiment
  - complementary to "waiting experiments"
  - more maneuverable than CERN, SLAC, FNAL, …
- A world of new discovery left to the Young!

Thanks!

See you, if virtually, at:

http://homepage.mac.com/thubsch/