

The Coming Revolutions in Particle Physics

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Citizens' Task Force · I March 2007



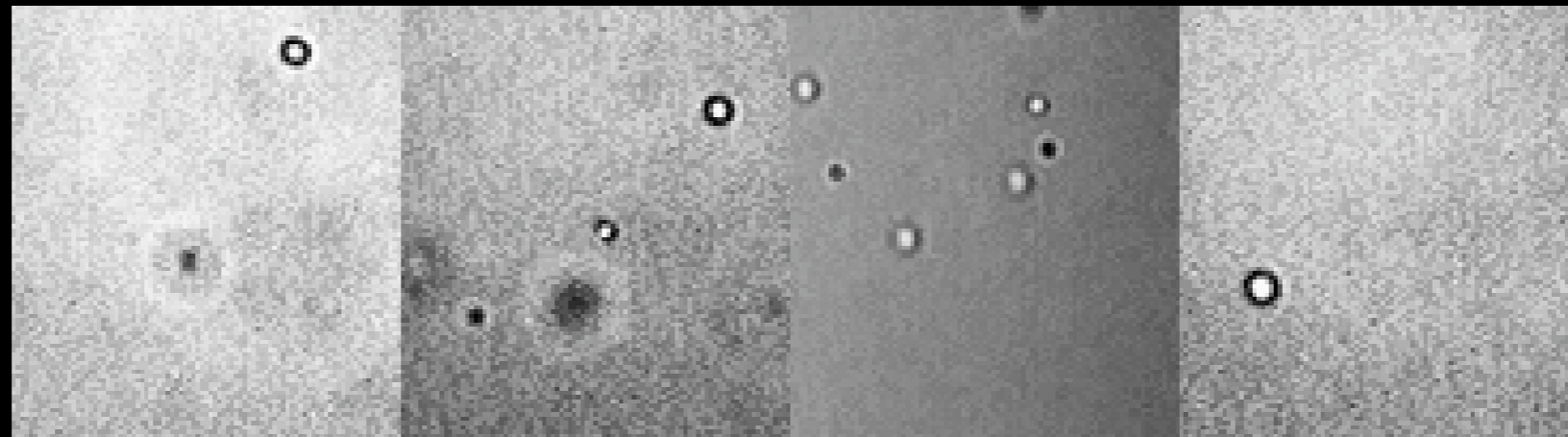
Jean Perrin, *Atoms* (1913)

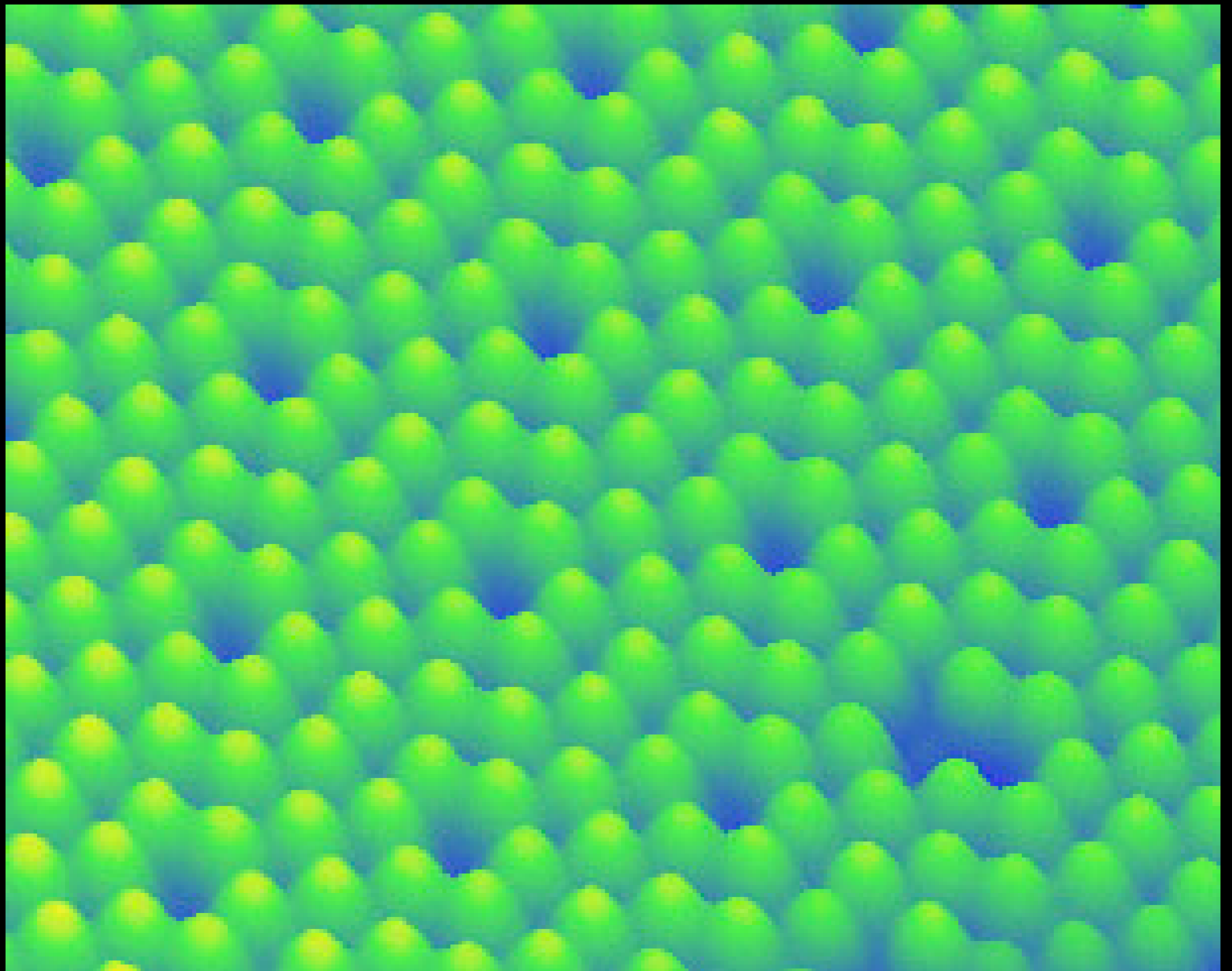
Studying a machine, we don't limit ourselves to thinking about the visible parts, which are the only objective reality we can establish short of taking the machine apart. We observe the visible parts as best we can, but we also try to guess what hidden gears and levers might explain the machine's movements.

To divine in this way the existence or the properties of objects that we haven't yet experienced directly—to *explain a complicated visible by a simple invisible*—that is the kind of intuitive intelligence to which, thanks to men such as Dalton or Boltzmann, we owe the doctrine of atoms ...



*Nobel Prize 1926
for his work on the discontinuous structure of matter*





The Great Lesson of Twentieth-Century Science

The human scale of space & time is not
privileged for understanding Nature . . .
and may even be disadvantaged





The World's Most Powerful Microscopes

nanonanophysics

Fermilab's Tevatron Collider & Detectors

900-GeV protons: $c - 586$ km/h

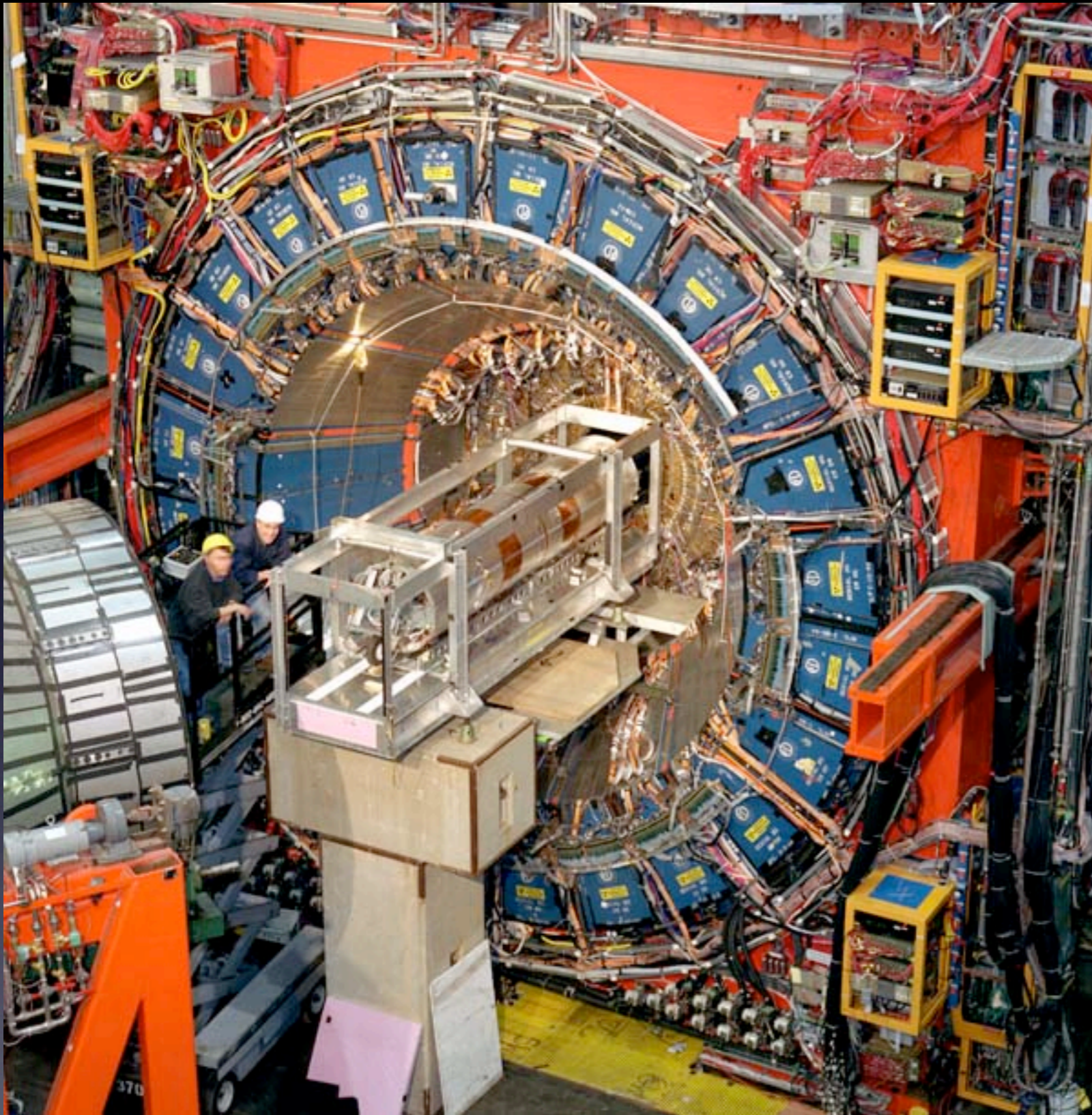
980-GeV protons: $c - 495$ km/h

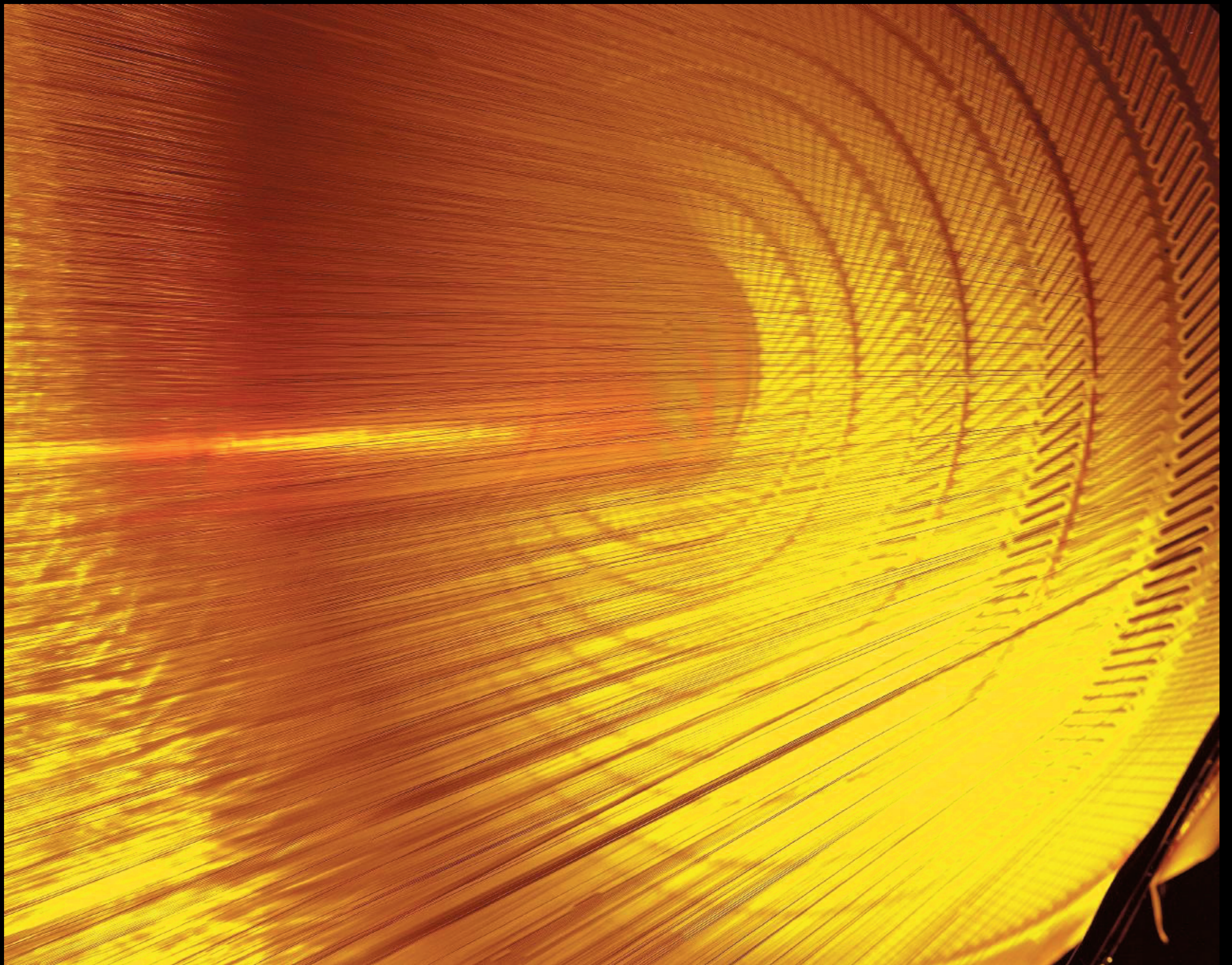
Improvement: **91 km/h!**

Protons, antiprotons pass my window 45 000 times / second

... **achieved** working toward $20 \times$ increase in luminosity
 $\Rightarrow 10^7$ collisions / second

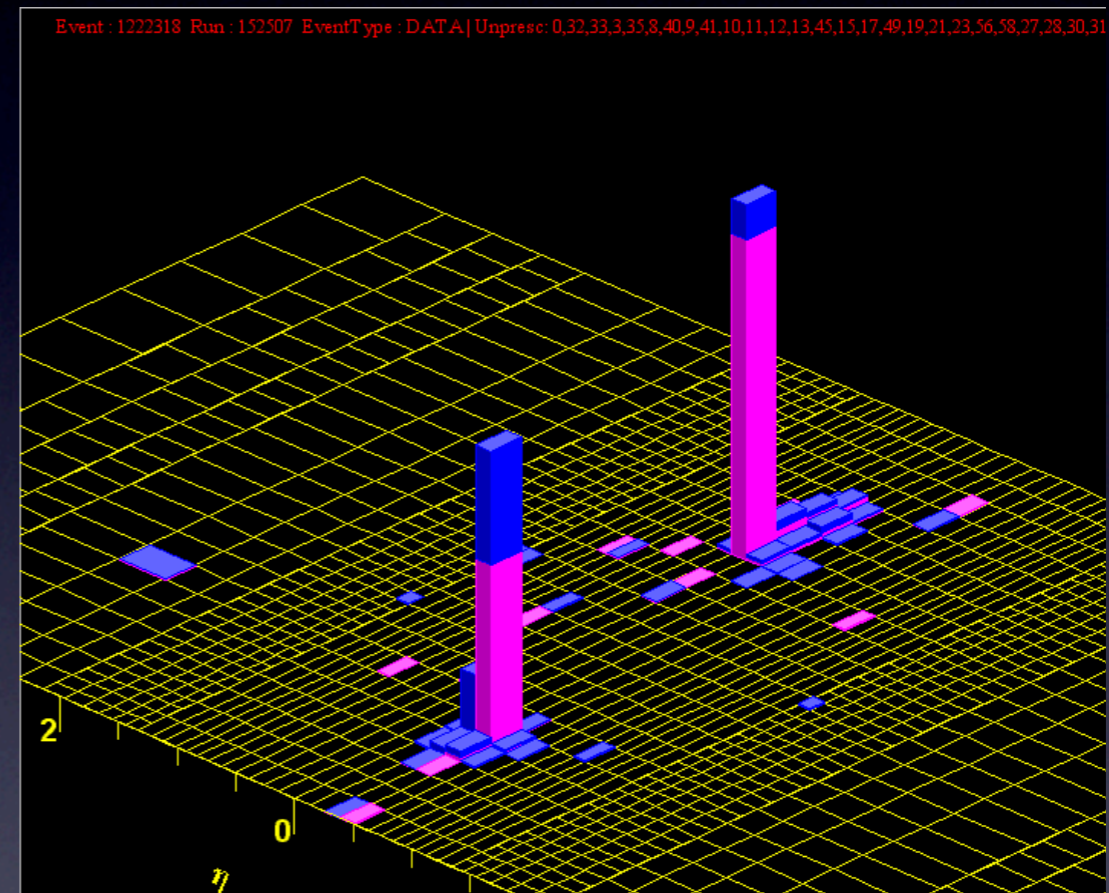
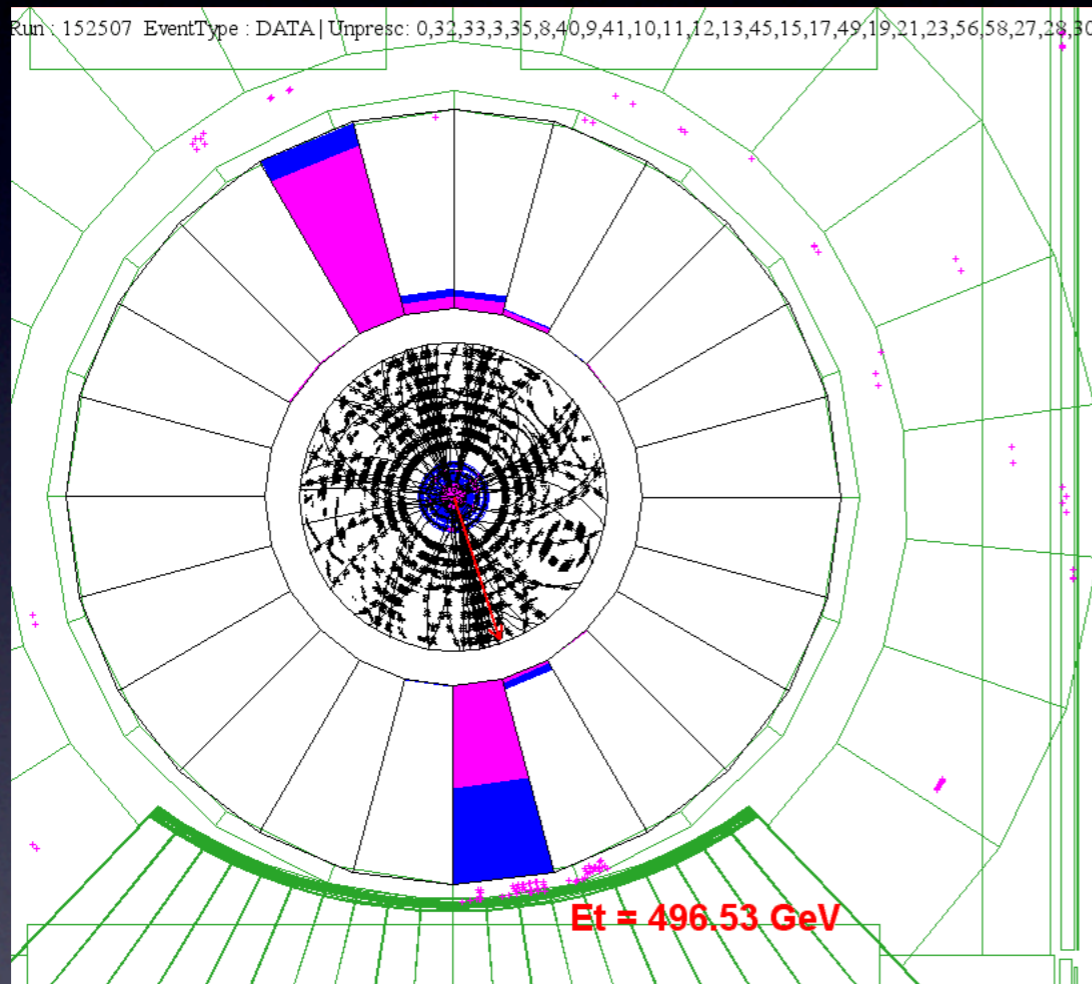
CERN's Large Hadron Collider, 7-TeV protons: $c - 10$ km/h



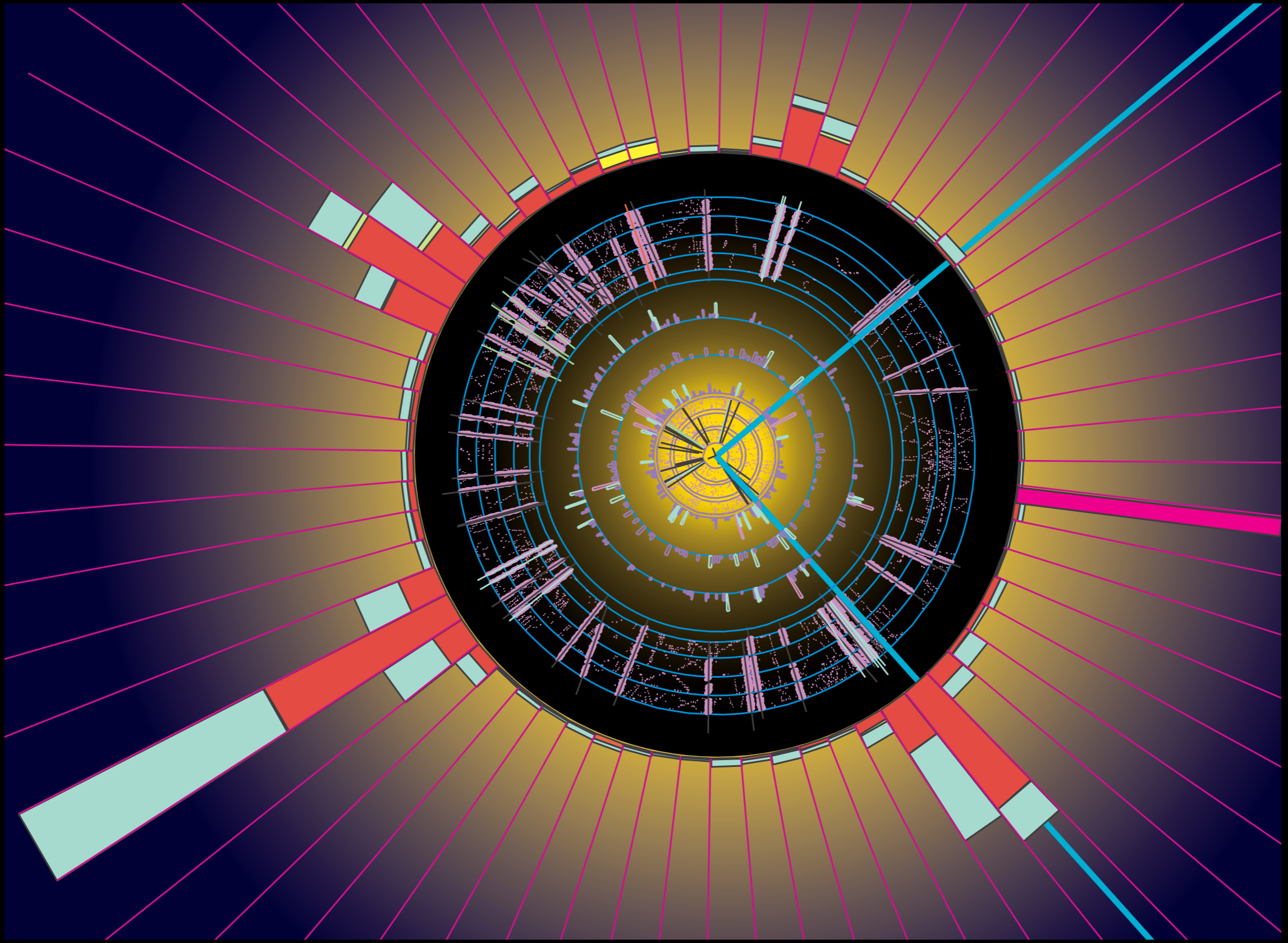


The World's Most Powerful Microscopes

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CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $q\bar{q} \rightarrow \text{jet} + \text{jet}$

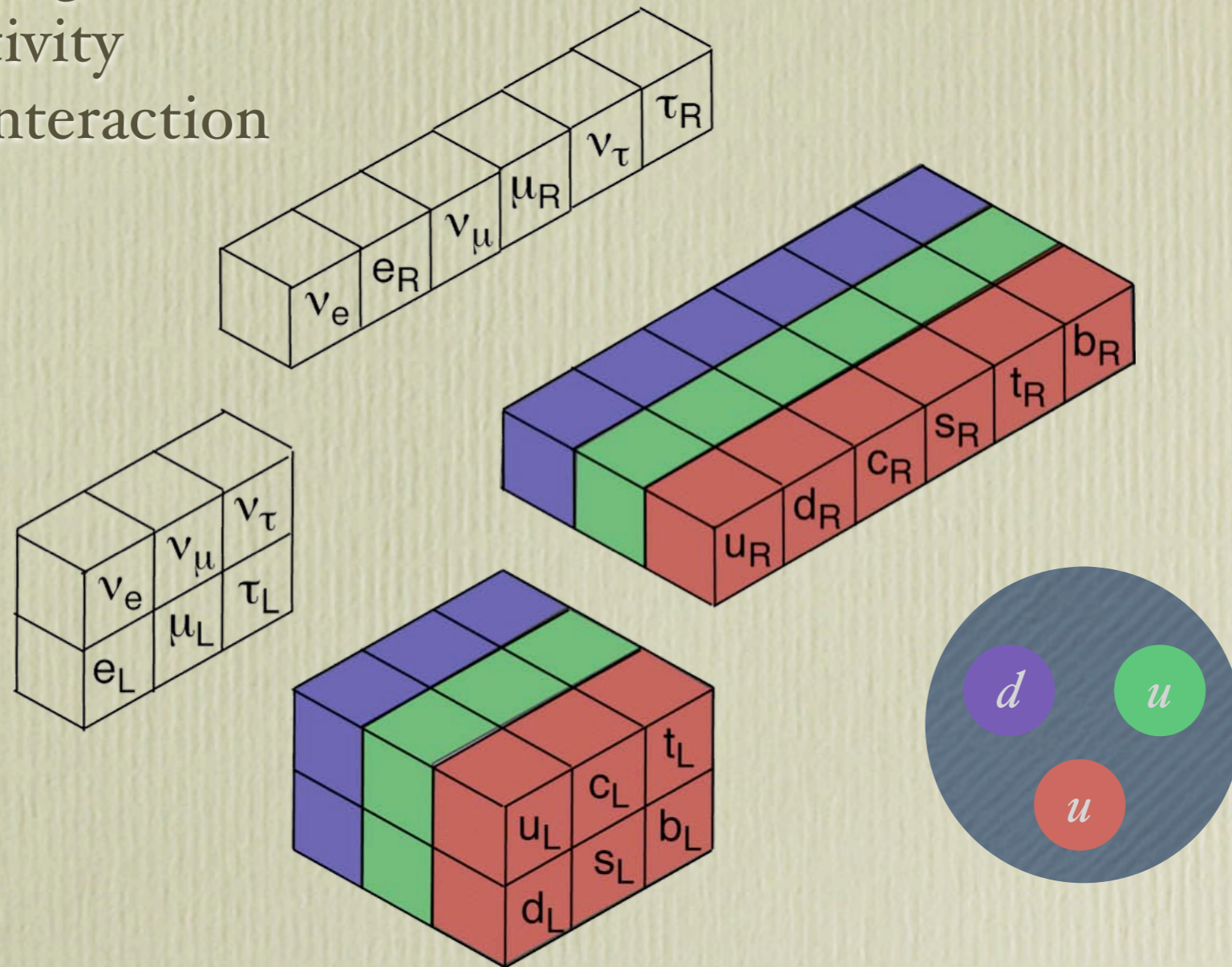


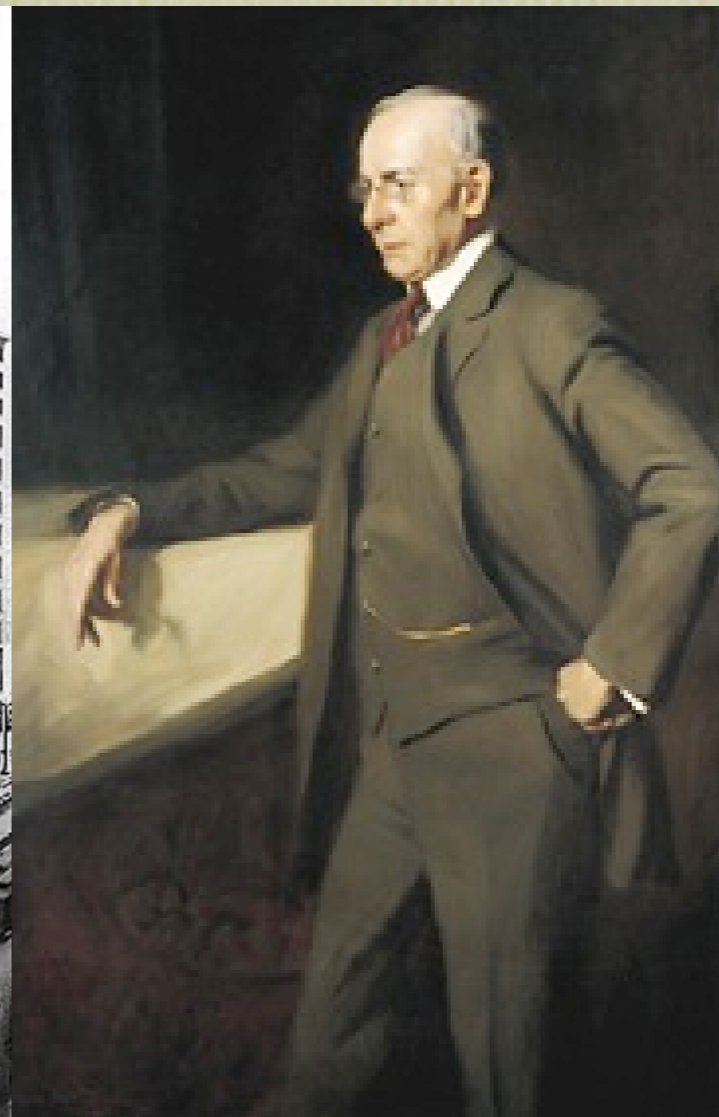
Particle accelerators are time machines ...

Not to replicate the early universe,
but to create conditions
that allow us to discover
something of the laws that prevailed
in the early universe.

(now back to 1 picosecond)

gravitation
electromagnetism
radioactivity
strong interaction





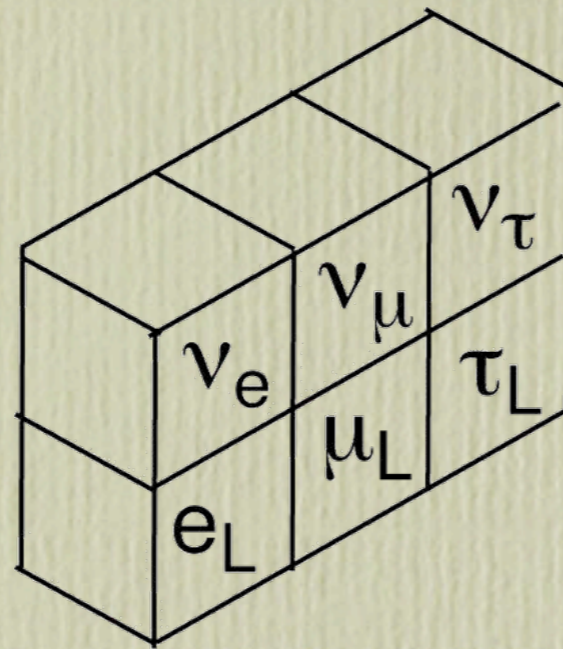
Louis Sullivan, architect (1896)
Form follows function



Robert Mills (1954) Chen Ning Yang

Function follows form

Interactions follow from symmetry



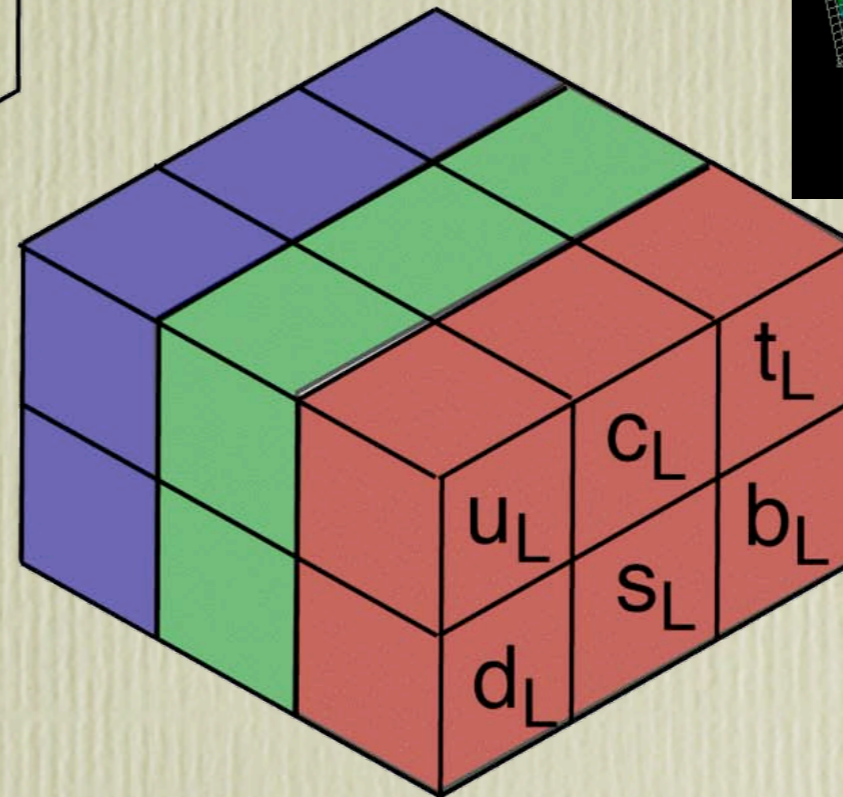
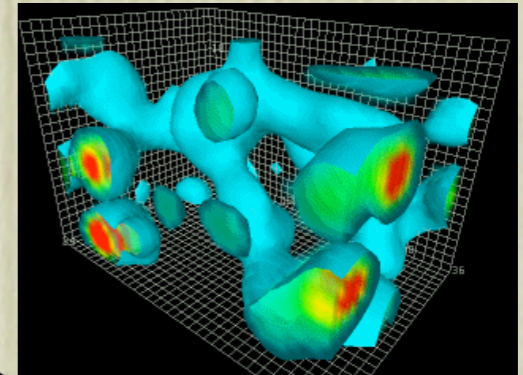
Electroweak theory:
family symmetry
 $u \leftrightarrow d ; \nu \leftrightarrow e ; \dots$ (hidden)

W and Z bosons; photon

Quantum chromodynamics (QCD):
symmetry among quarks

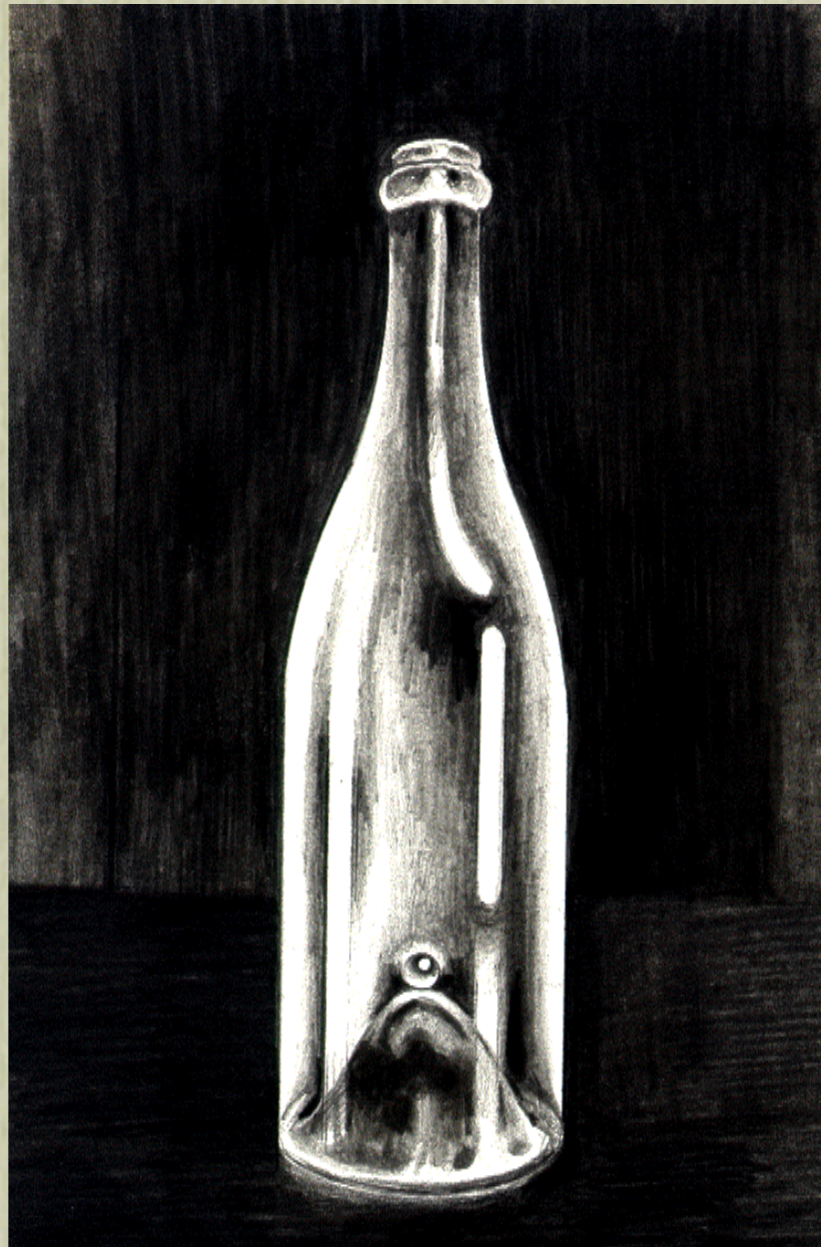
red, green, blue

gluons



A symmetry among quarks and leptons ...
... would have to be a hidden symmetry
leptoquarks

Symmetry of laws
doesn't necessarily mean
symmetry of outcomes



Spontaneous symmetry breaking

How we know where to look:
a thought experiment (1977)

Imagine scattering two W bosons
(not yet discovered at the time)

*Electroweak theory makes sense if
something happens
at energies around 1 TeV
... the Fermi scale*

Either the Higgs boson, which
hides the electroweak symmetry
or ... strong WW scattering

Other arguments also point to the Fermi scale

Keeping the Higgs boson light
Unifying the strong, weak, and
electromagnetic interactions
Dark matter candidates

We suspect these may all be related!

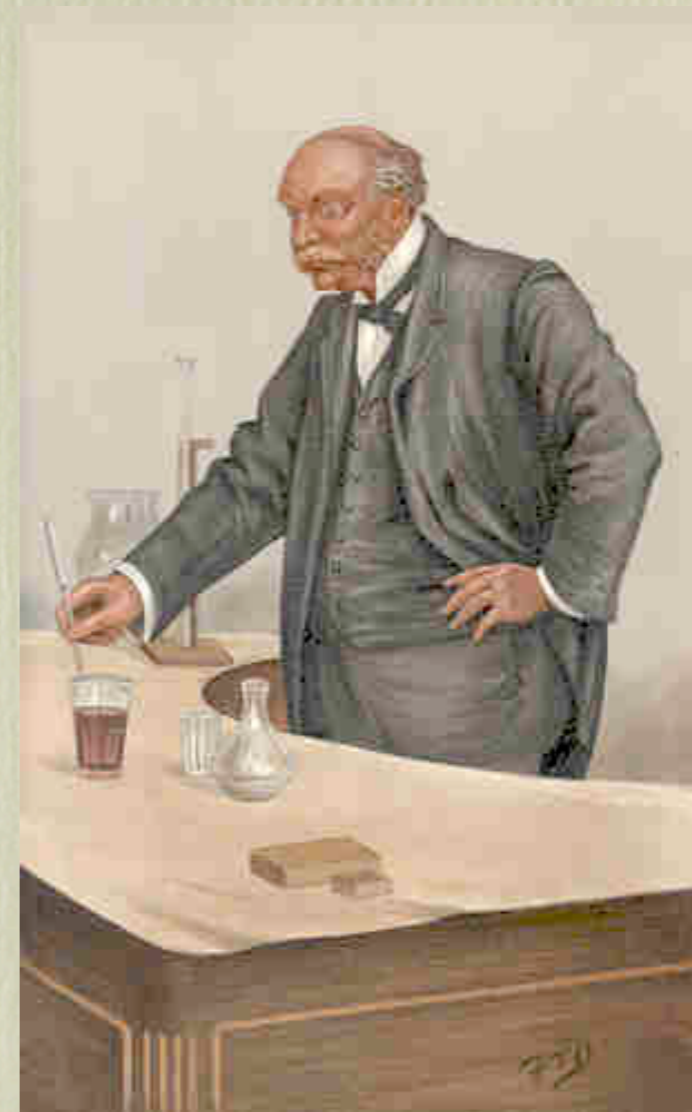
Dark Matter Precedent: Discovery of the Noble Gases

“Nitrogen” from atmosphere
1/2% heavier than extracted
from N-bearing compounds.

Hypothesis: unknown
ingredient in the air.

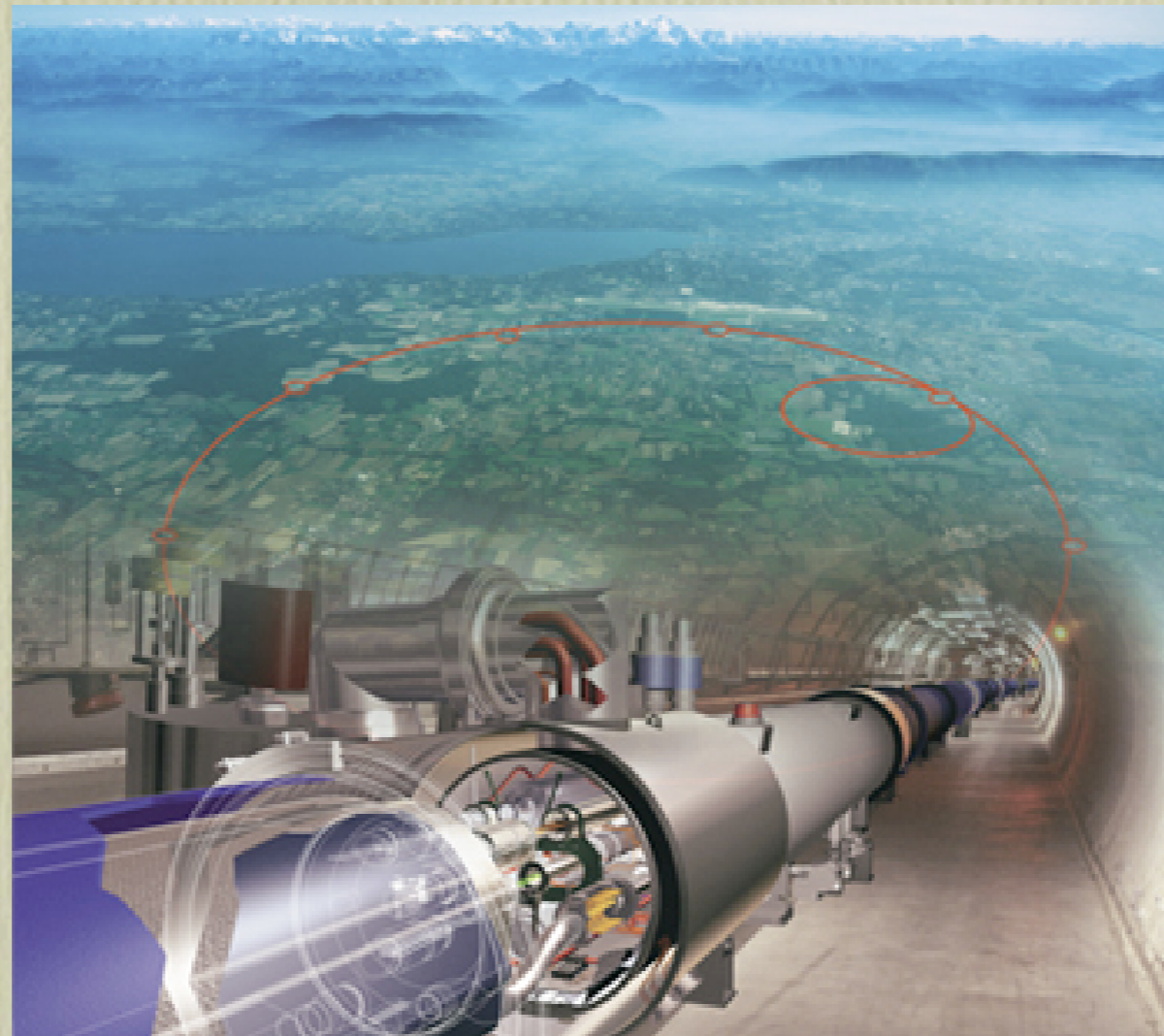
“... the improbability that a
gas surrounding us on all
sides, and present in
enormous quantities, could
have remained so long
 unsuspected.”

*A lot of dark matter (not
like us) needed to account for
large-scale motion*



Lord Rayleigh

Coming to CERN this year:
Large Hadron Collider
proton-proton collider at 7+7 TeV
speed of protons: $c - 10$ km/h





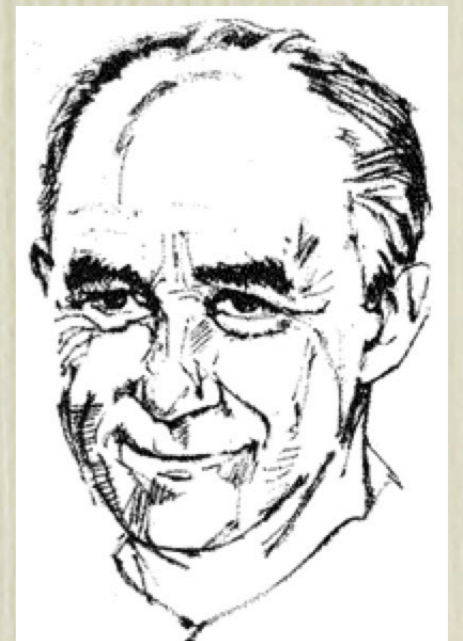
What the LHC is *not* really for ...

1. Find the Higgs boson,
the Holy Grail of particle physics,
the source of all mass in the Universe.
2. Celebrate.
3. Then particle physics will be over.

We are not ticking off items on a shopping list ...

We are exploring a vast new terrain
... and reaching the Fermi scale

*We do not know what the new wave
of exploration will find*



Revolution:

Understanding the everyday

- Why atoms?
- Why chemistry?
- Why stable structures?
- What makes life possible?

If the electroweak symmetry were not hidden ...

massless quarks and leptons

proton mass would be little changed ...
but the proton would outweigh the neutron

lightest nucleus: neutron — no hydrogen atom

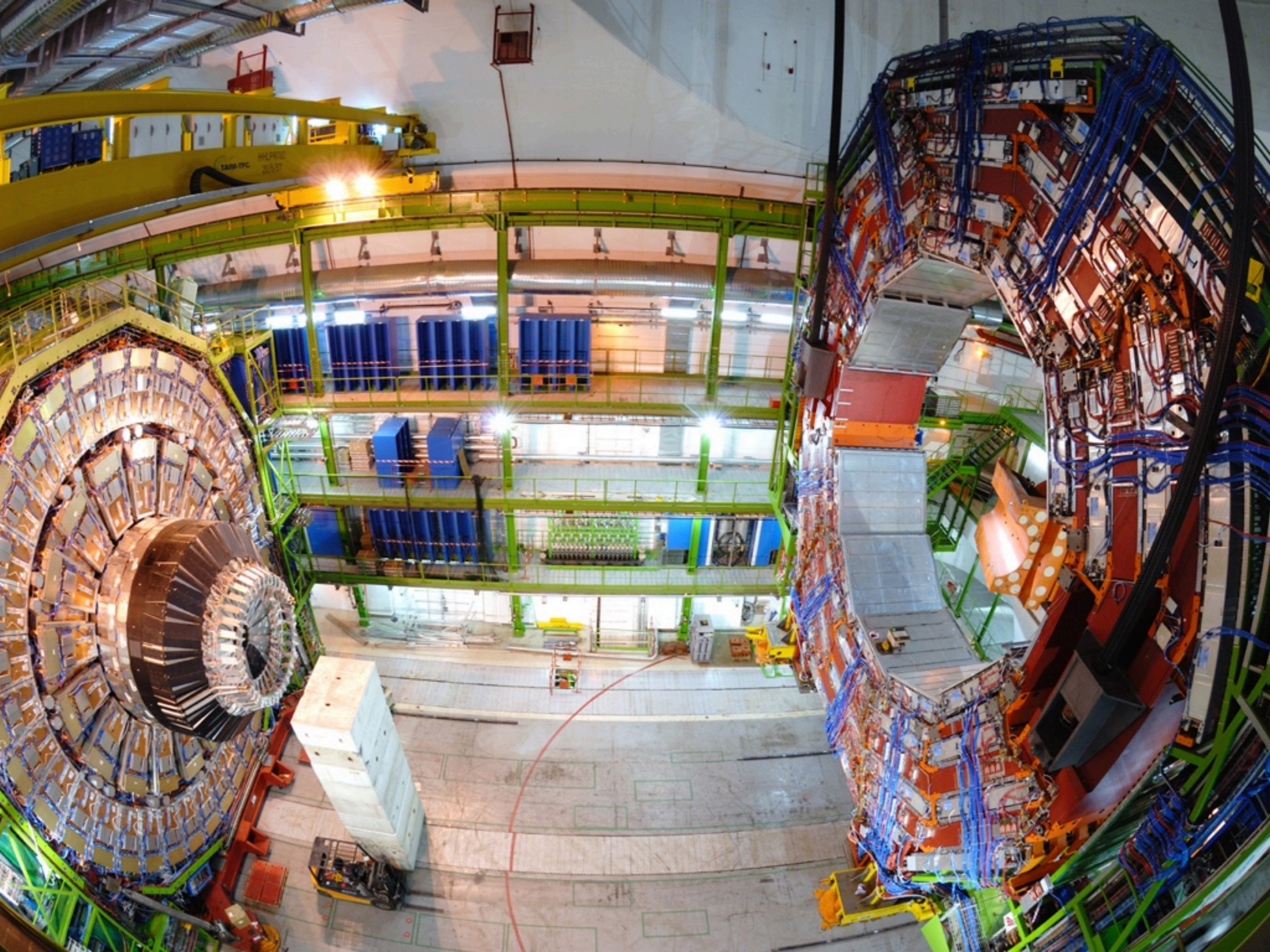
some light elements produced in the big bang

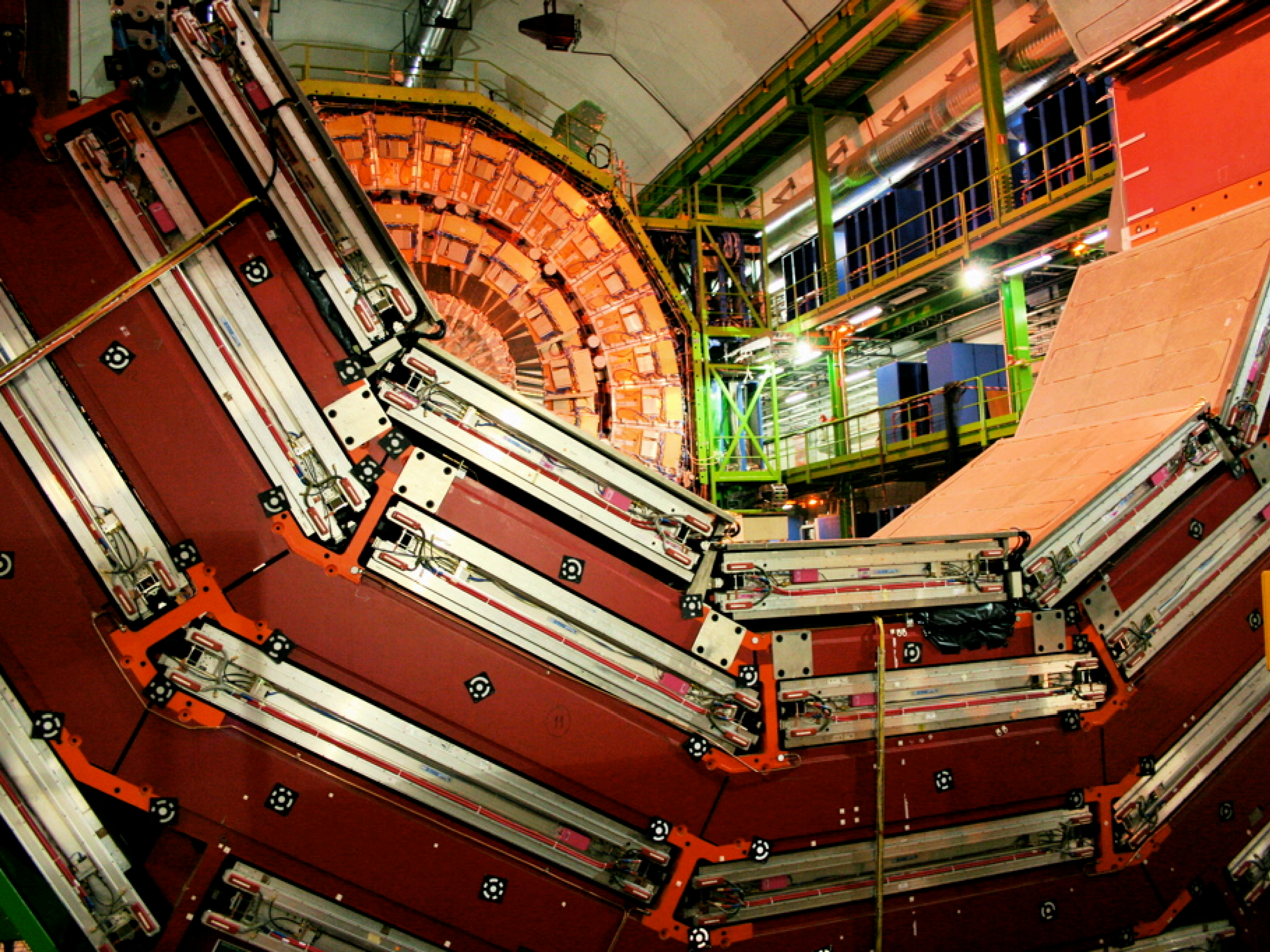
but the radius of atoms is infinite

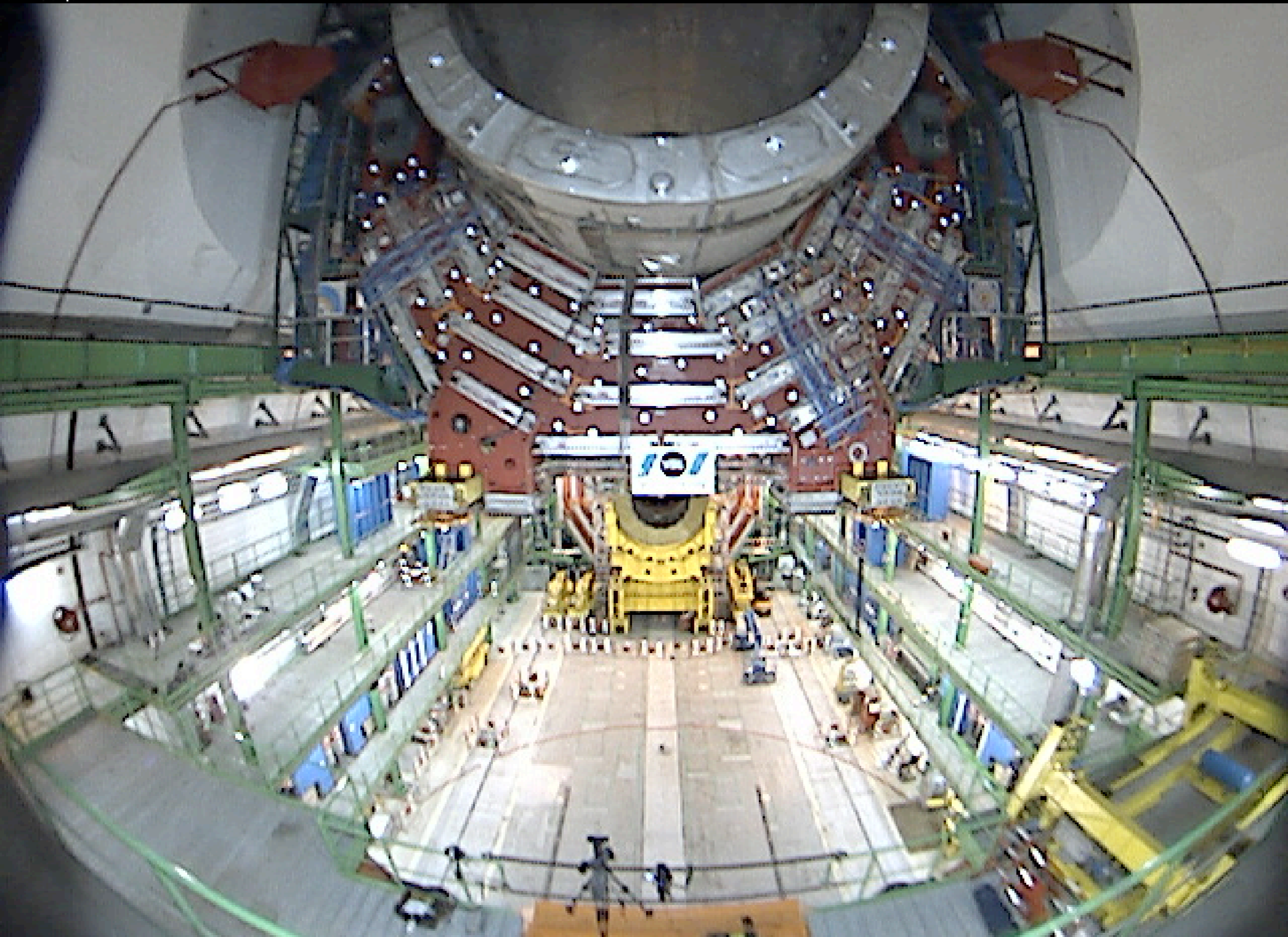
no chemistry, no liquids, no solids

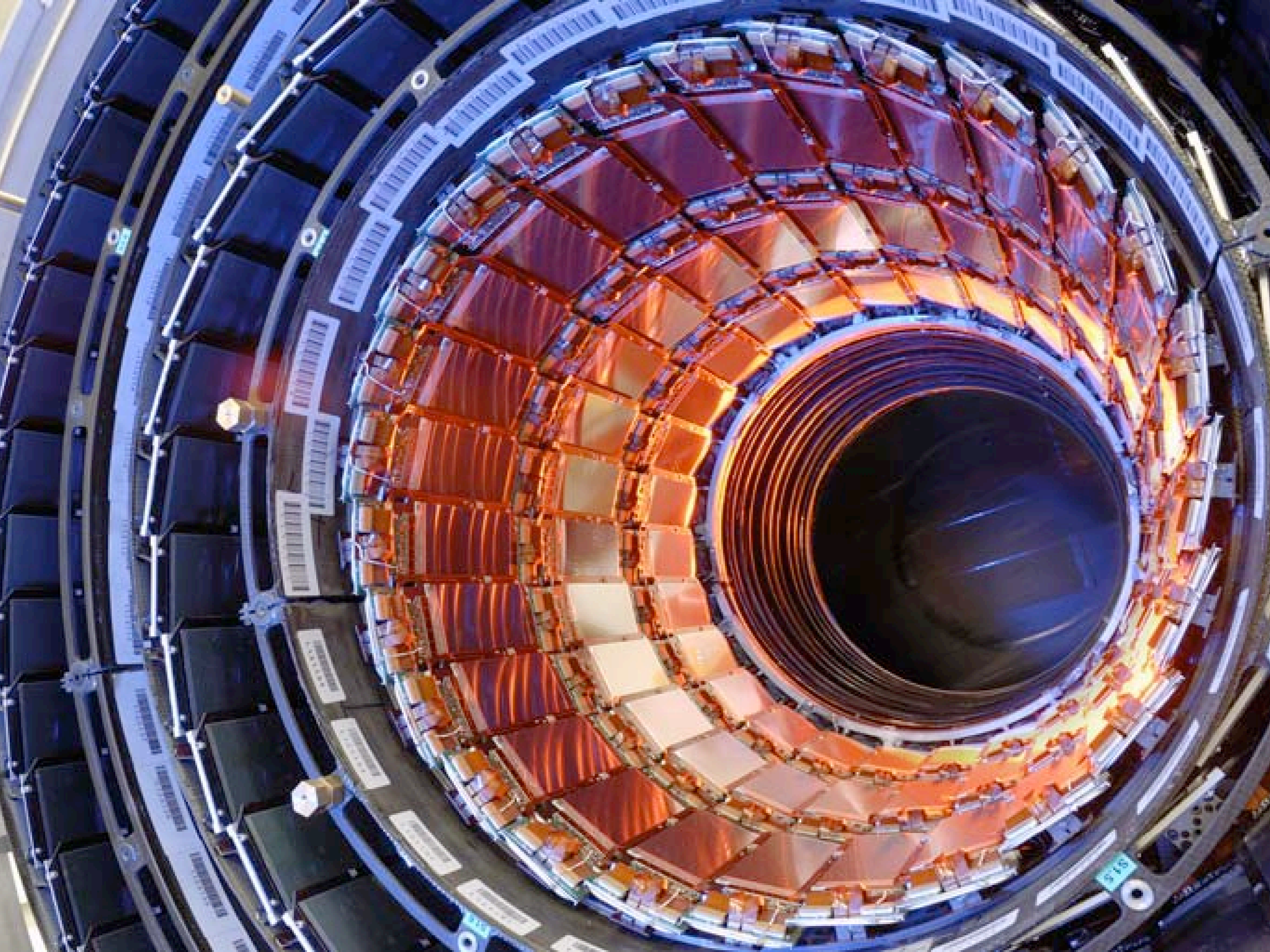


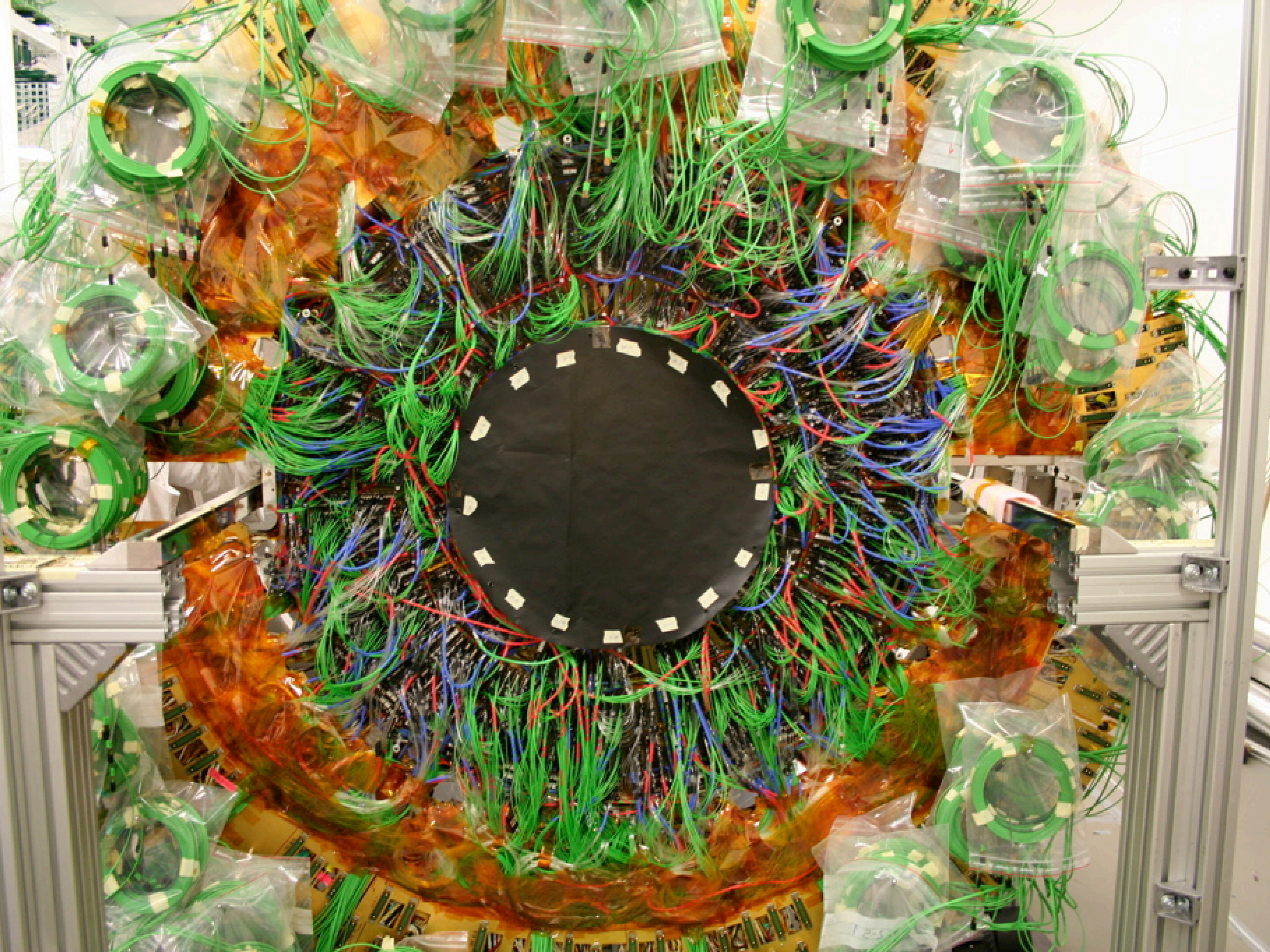


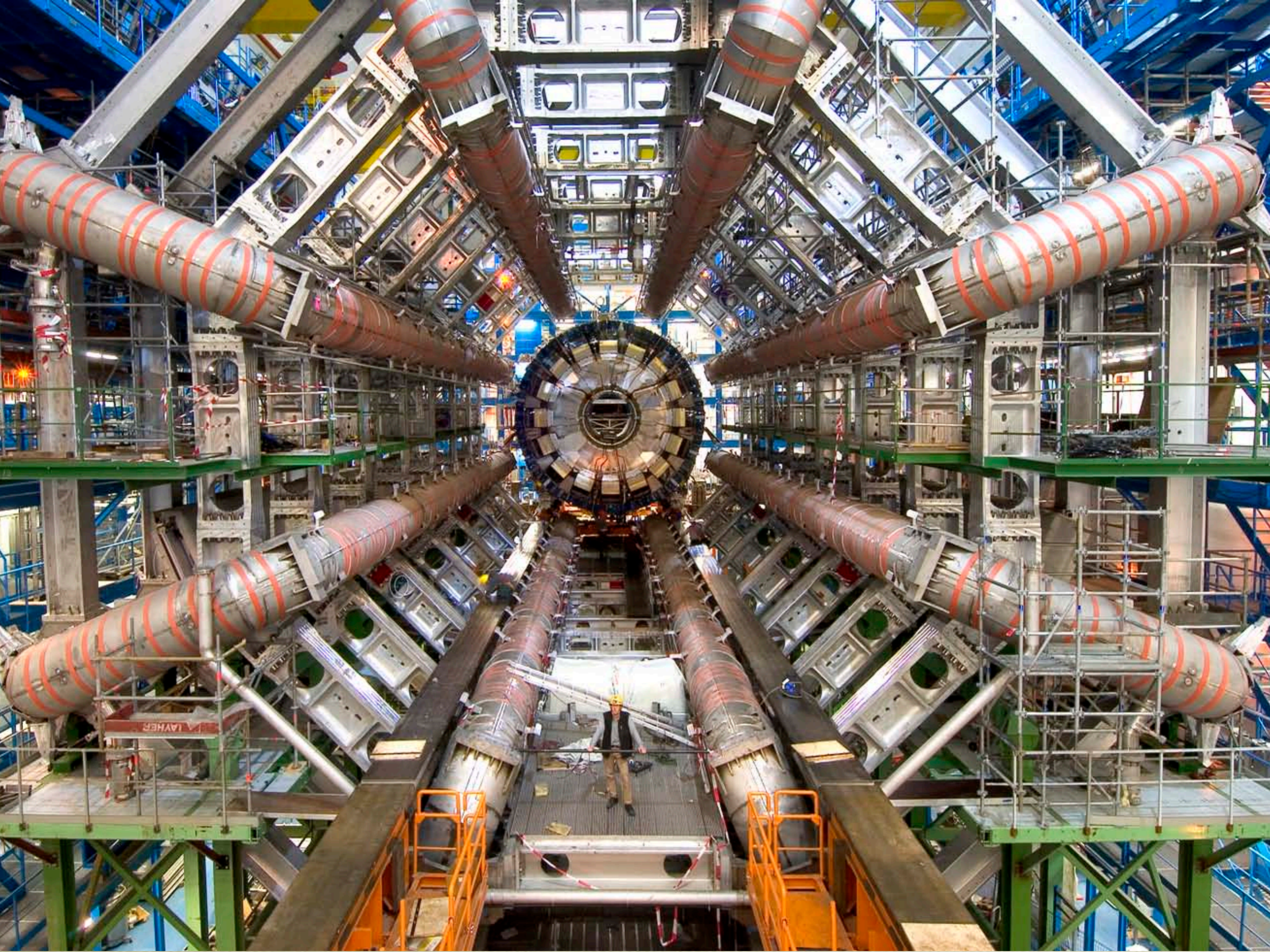


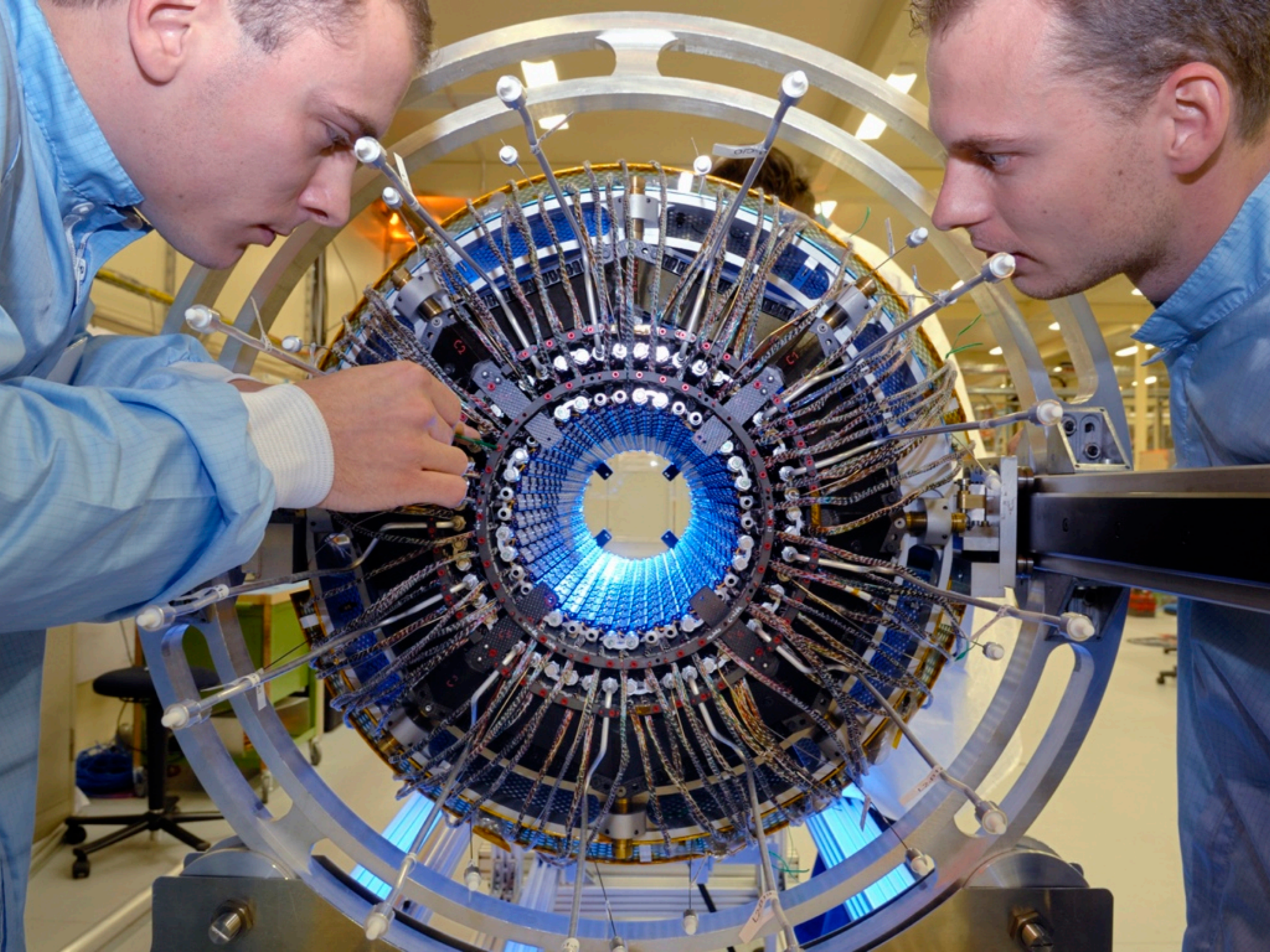














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“It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion.”

— Cecil Powell
1950 Nobel Prize: π

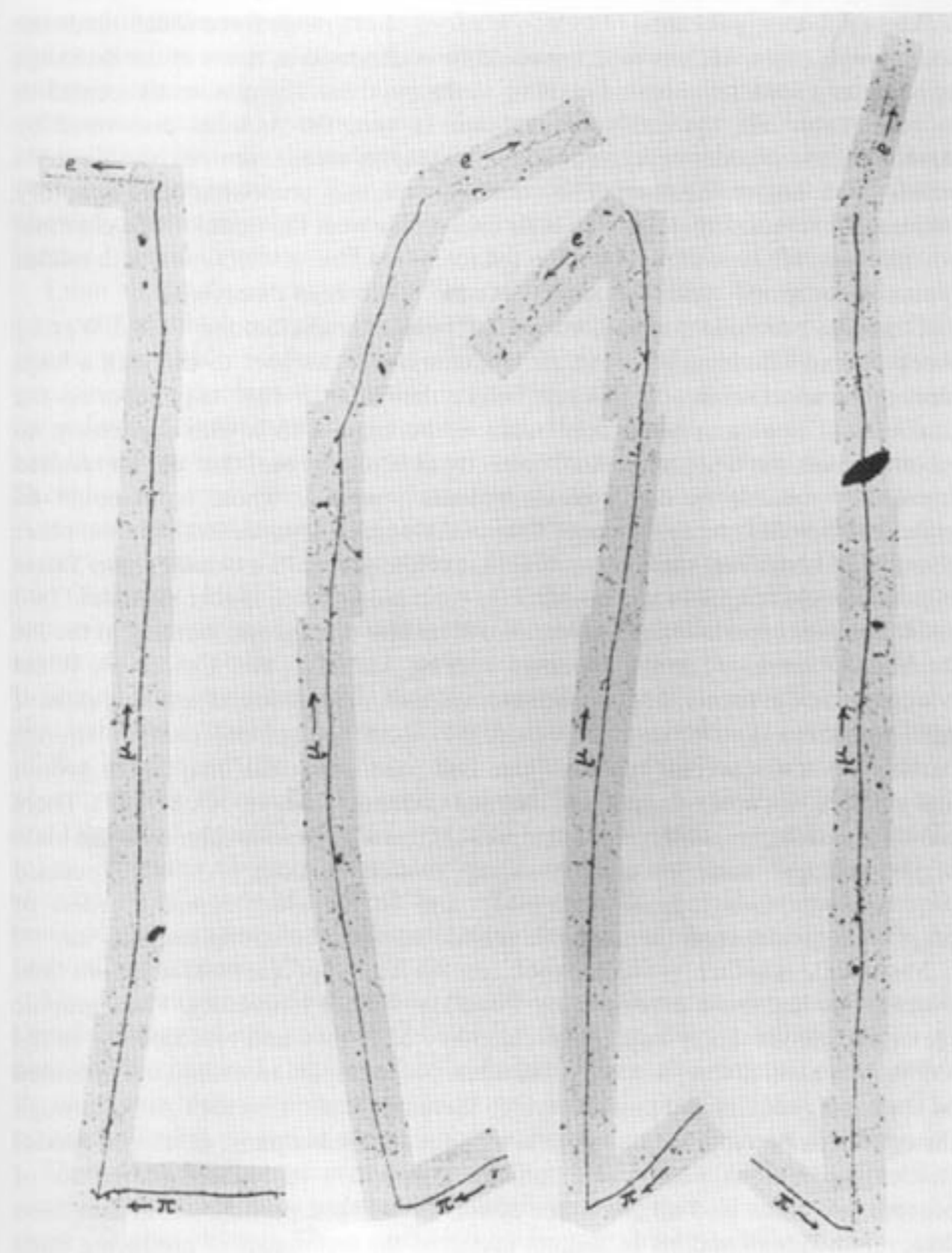


Figure 1.6. Four examples of the decay of a pion into a muon, followed by the subsequent decay of the muon into an electron. These processes were discovered by Powell and his collaborators using nuclear emulsions. (From C. F. Powell, P. H. Fowler and D. H. Perkins (1959). *The study of elementary particles by the photographic method*, page 245, Plate 8-5, Oxford: Pergamon Press.)

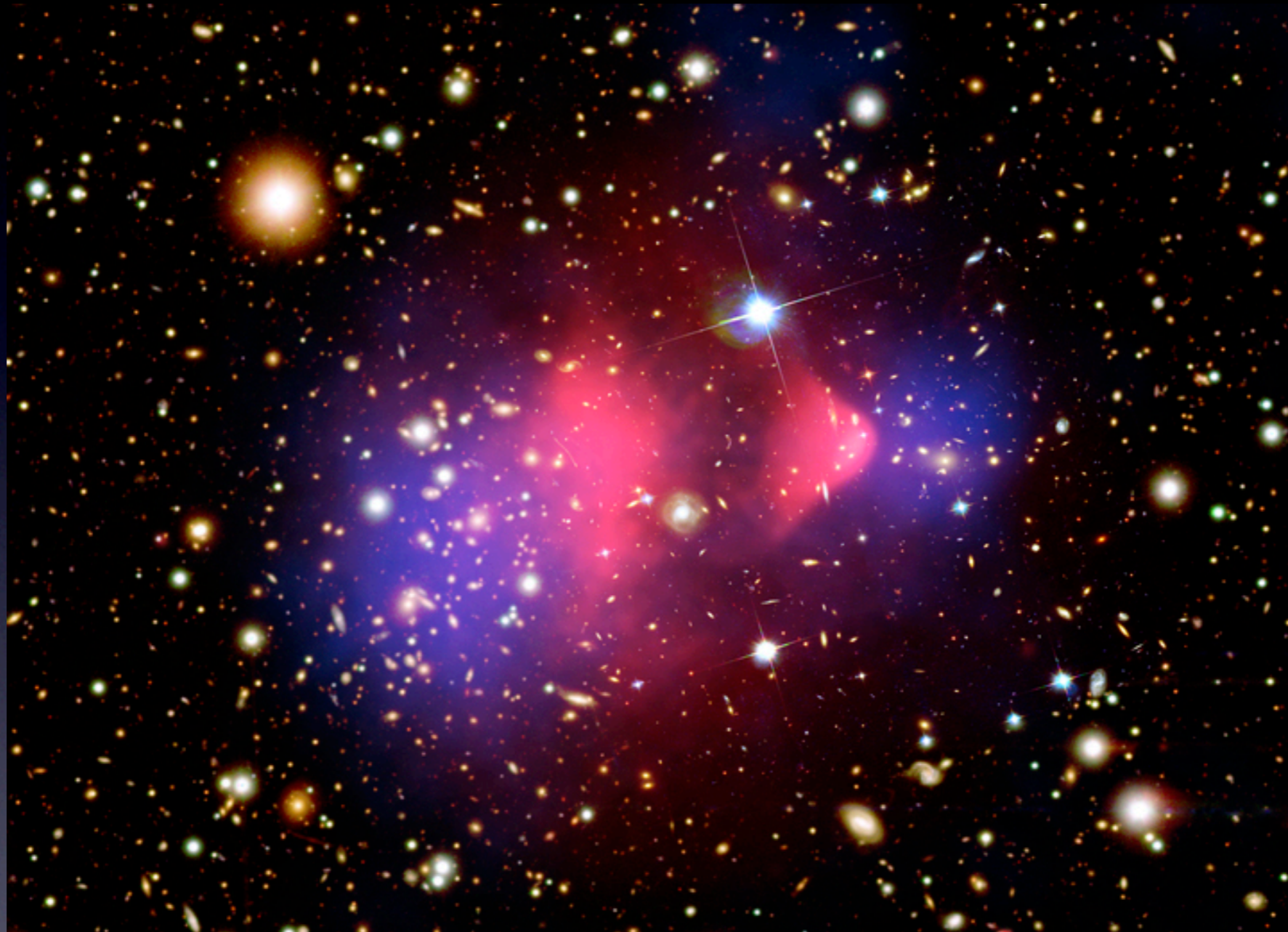
Revolution: the meaning of identity

- What makes a top quark a top quark and an electron an electron?
- What means the slightly different behavior of matter and antimatter?
- Neutrino oscillations a new take:
key to matter excess in Universe?
- New kinds of matter show us pattern?
dark matter, superpartners, ...

Mendele'ev didn't know about noble gases

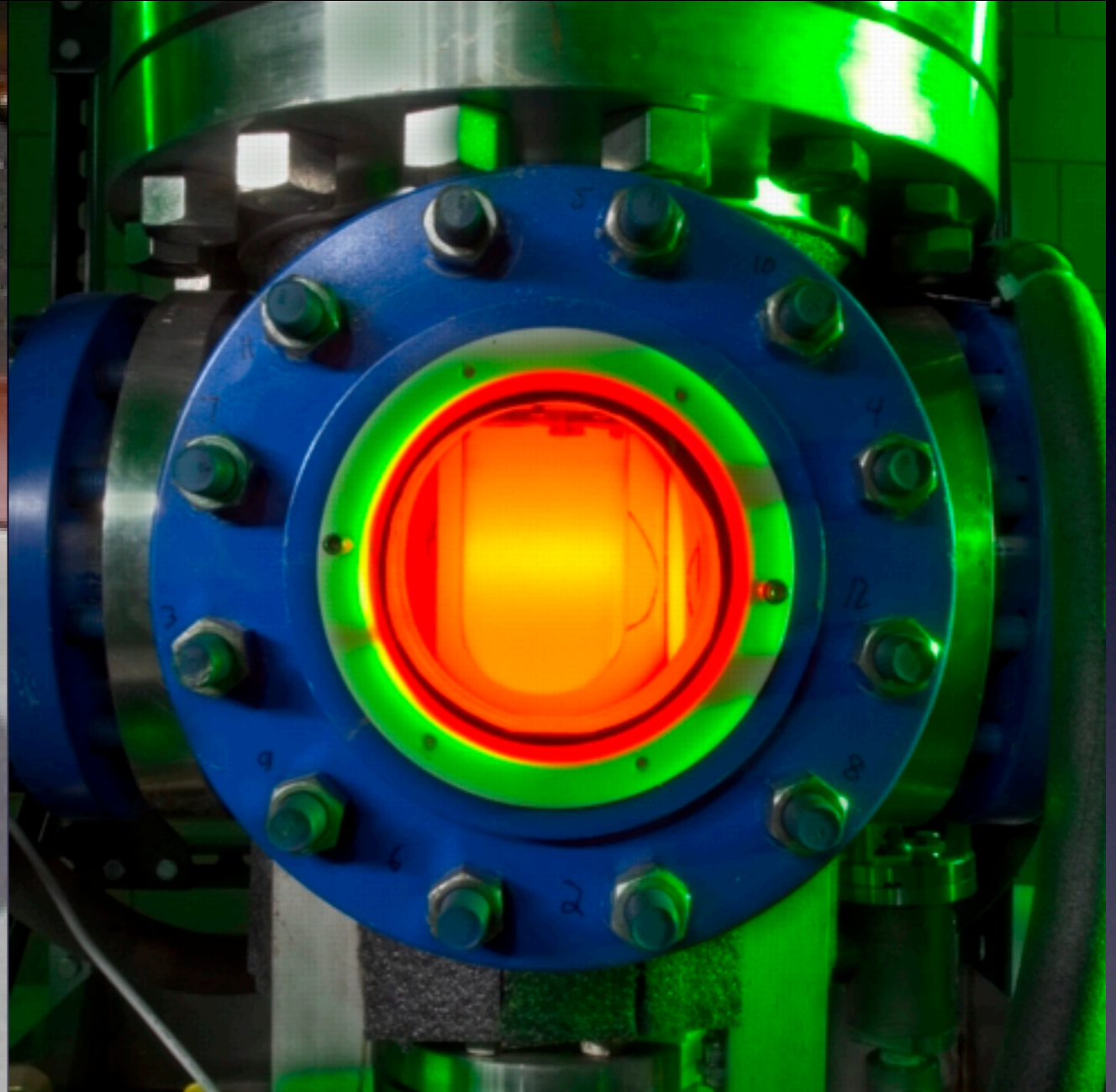
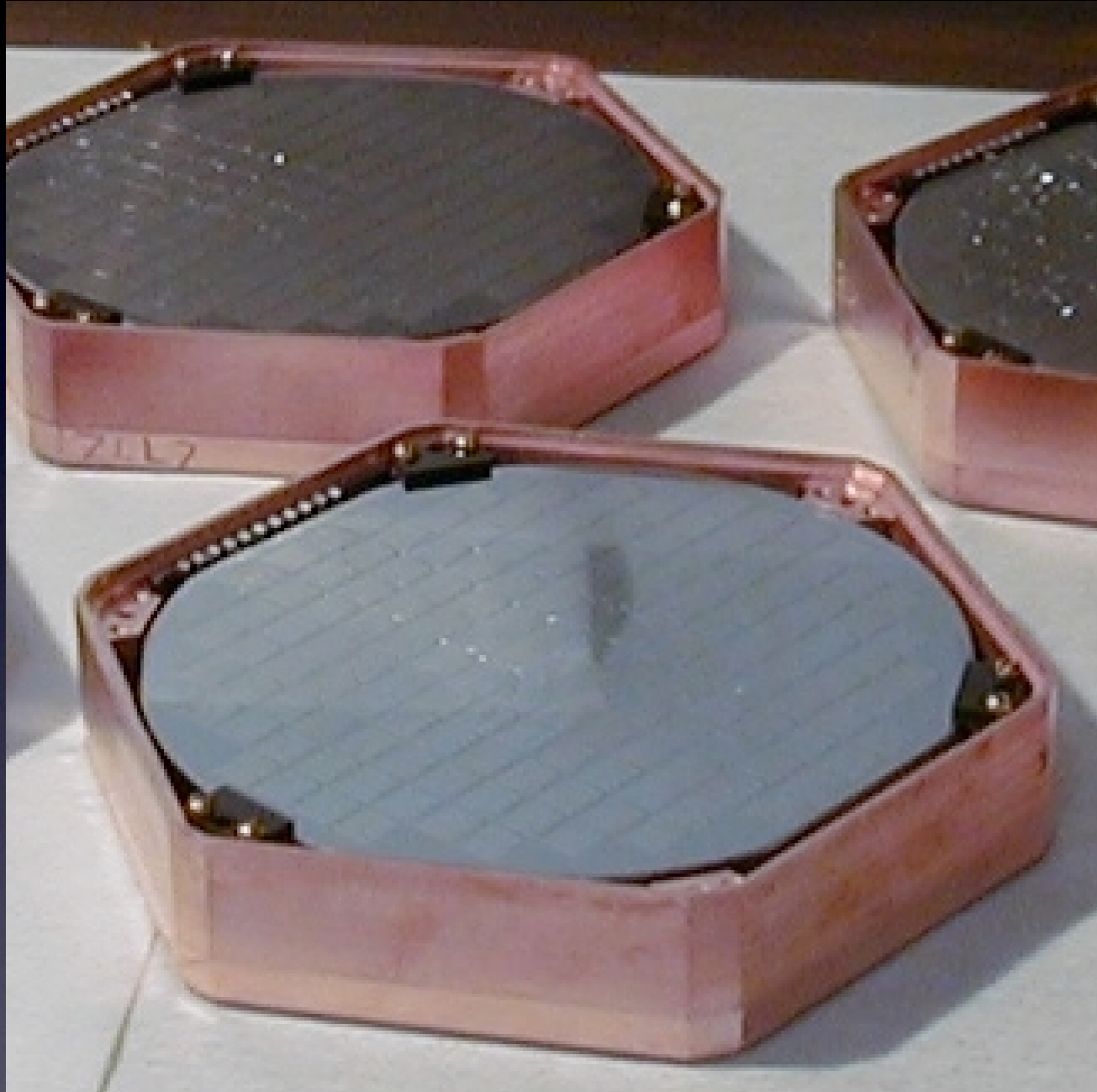


If dark matter is weakly interacting ...



... in many extensions to EW theory, mass: 0.1–1 TeV

Search for relics, produce in colliders



Revolution:

Unity of Quarks & Leptons

- What do quarks and leptons have in common?
- Why are atoms neutral?
- Which quarks with which leptons?
- Extended quark–lepton families:
proton decay!

Gravity rejoins Particle
rejoins Physics

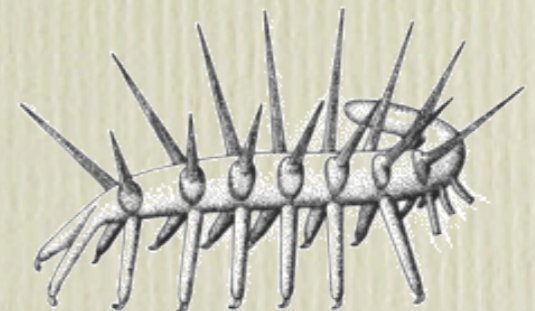
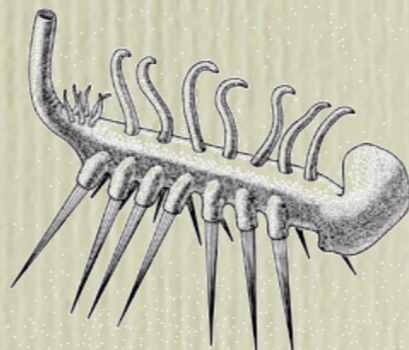
A Chronic Dull Headache ...

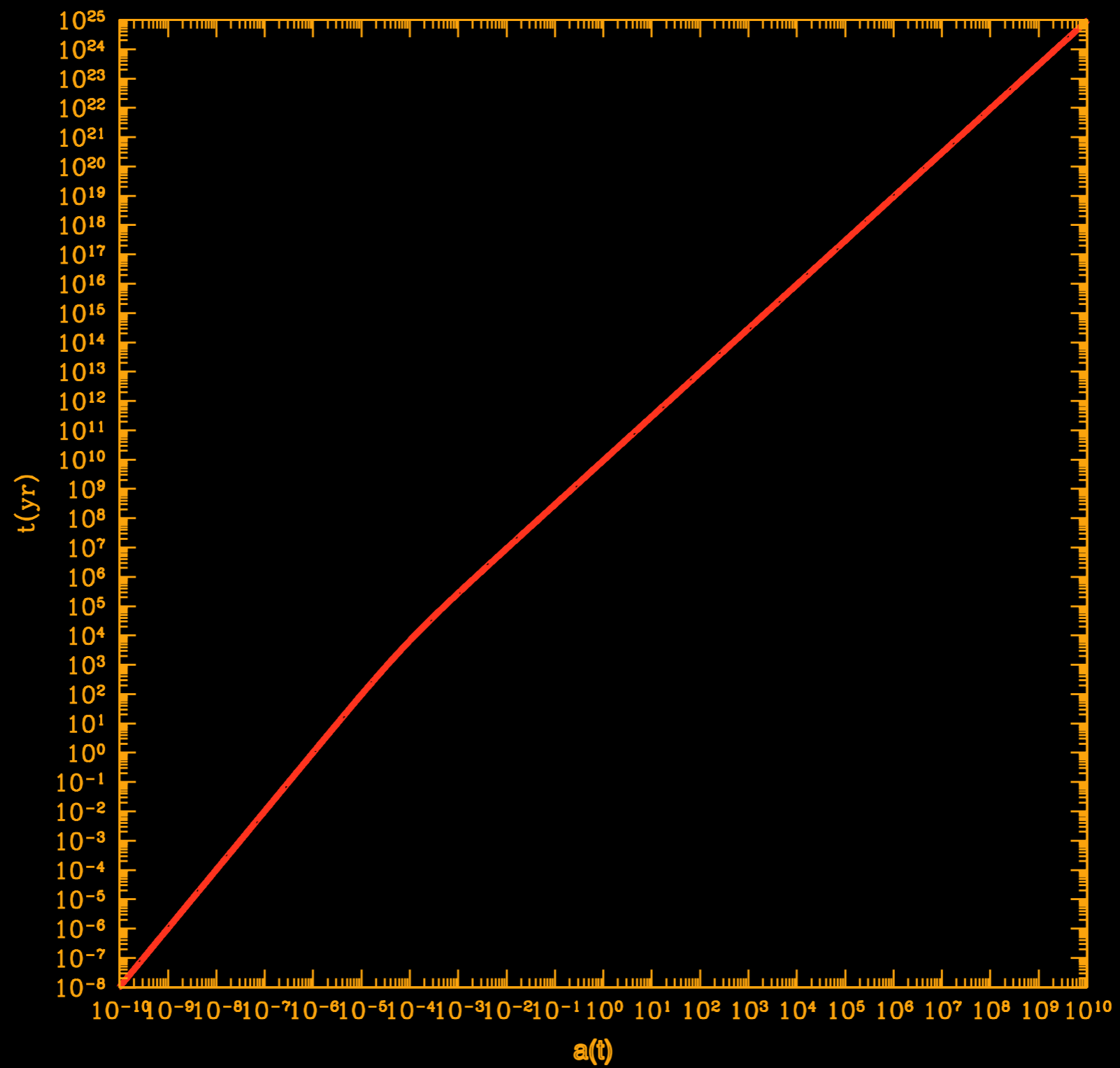
... for thirty years

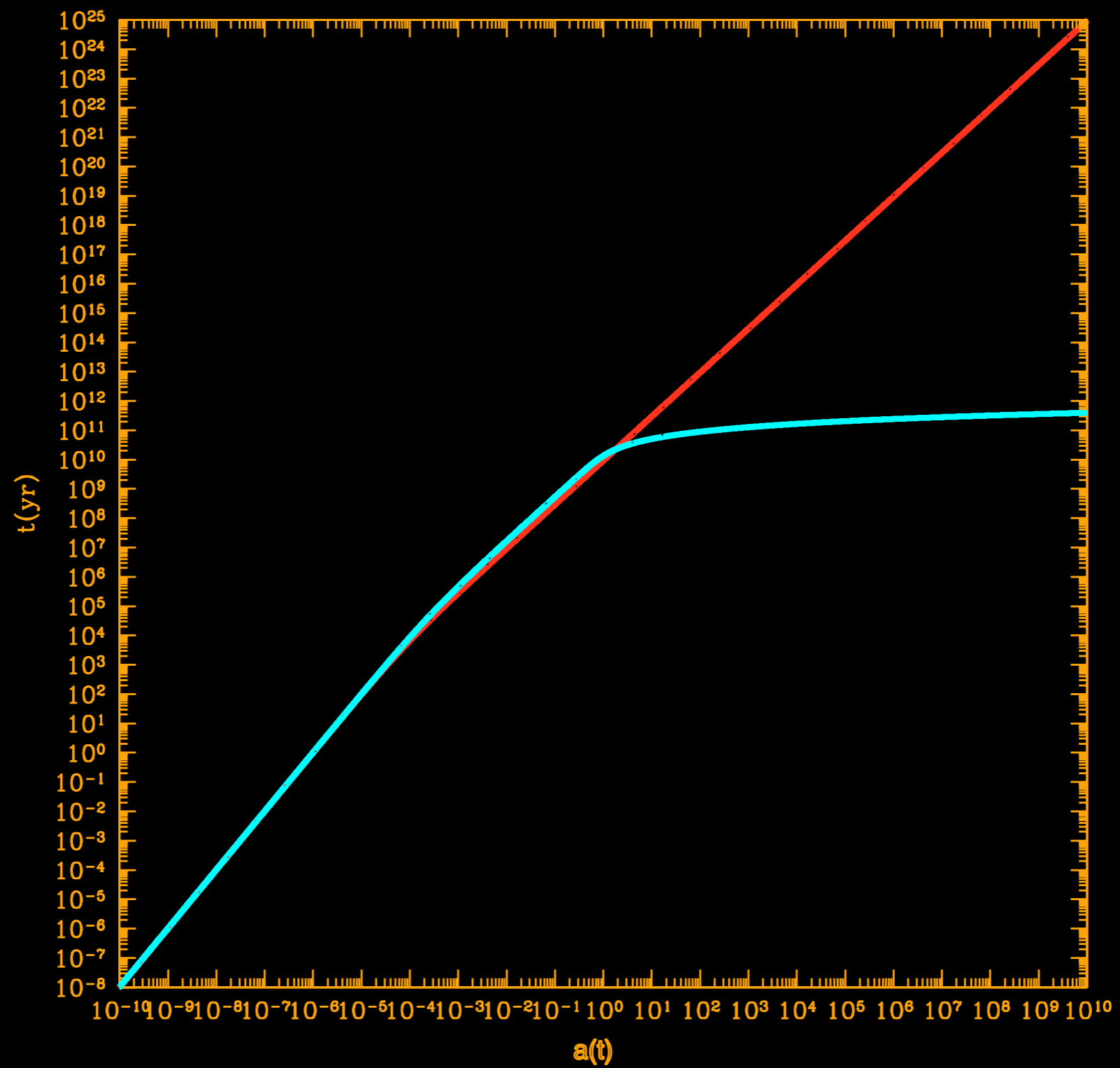
- Higgs field fills all of space with energy density 10^{25} g/cc
- But empty space weighs next to nothing: $< 10^{-29}$ g/cc
- Evidence that vacuum energy is present (accelerating universe) recasts problem

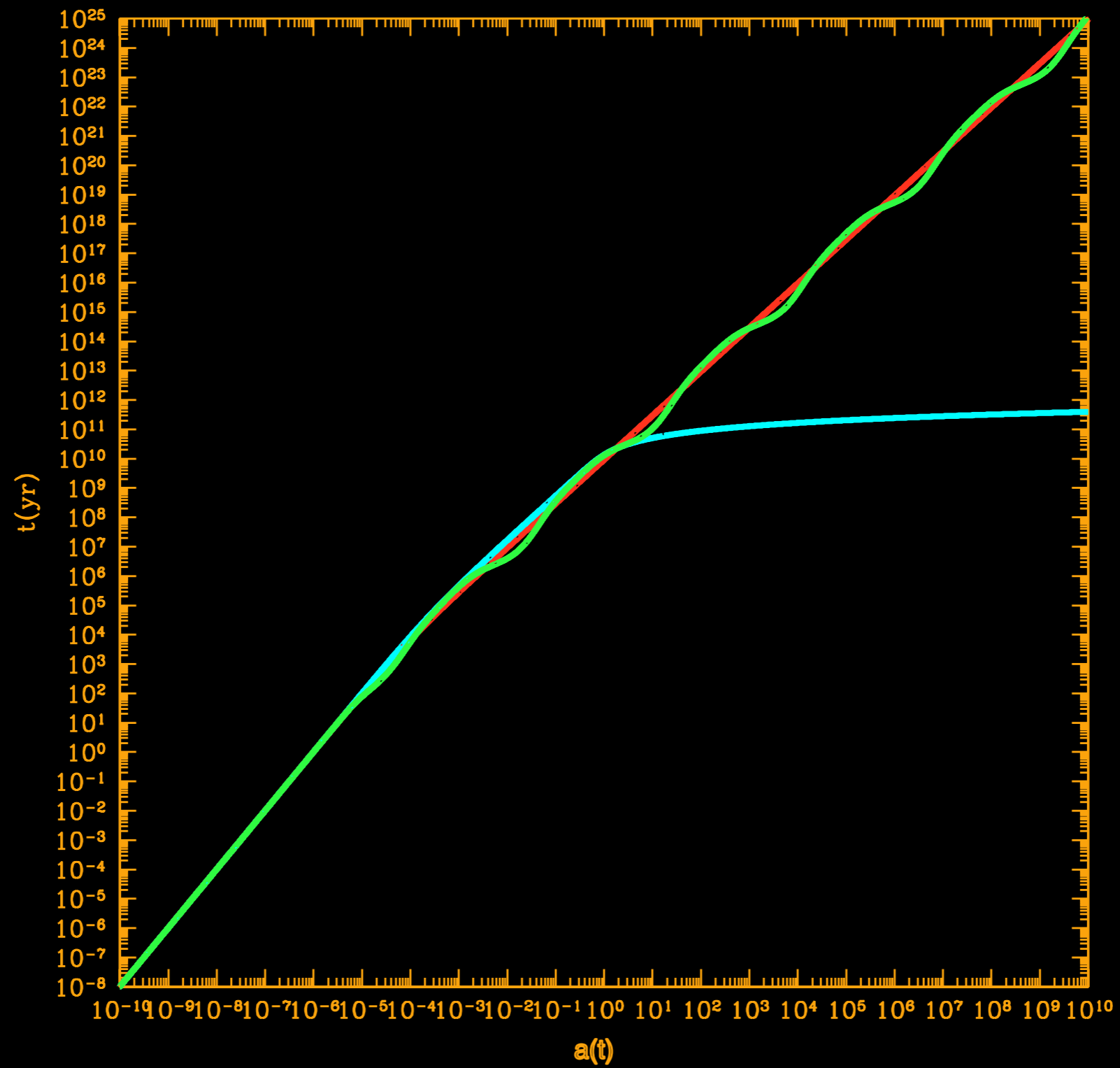
Implications for ... the future of the universe

- The fossil record is sparse ...
- We read it imperfectly, influenced by our world-view (of the moment)
- Enrich fossil record **[observations]**
- Improve theory **[experiments]**









Revolution:

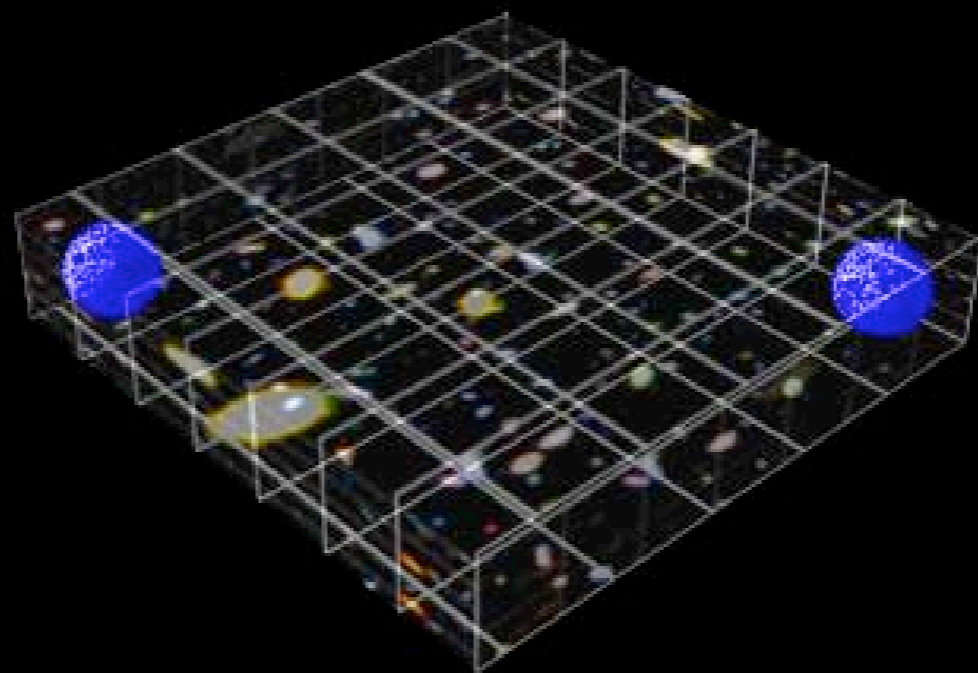
New Conception of Spacetime

- More space dimensions?
- What is their size? their shape?
- How do they influence our world?
- How can we map them?

(string theory requires 9 or 10)

Is Newton's Law True Forever?

- Inverse square law for gravity is tested over a large, but finite, range
- Not tested below 0.1 mm, equivalently above 0.01 eV (compare 1 000 000 000 000 eV for other forces we know)
- n extra dimensions: $1/r^{2+n}$



A Step Beyond ...

International Linear Collider

30-kilometer long electron-positron collider
an ideal complement to the LHC

Higgs boson, dark matter, and more

We will try to make the ILC
Fermilab's future star



