The Coming Revolutions in Particle Physics

From the 1898–99 University of Chicago catalogue:

"While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice . . . . An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals."

Wilhelm Conrad Röntgen

RADIOACTIVITY, NEW PROPERTY OF MATTER

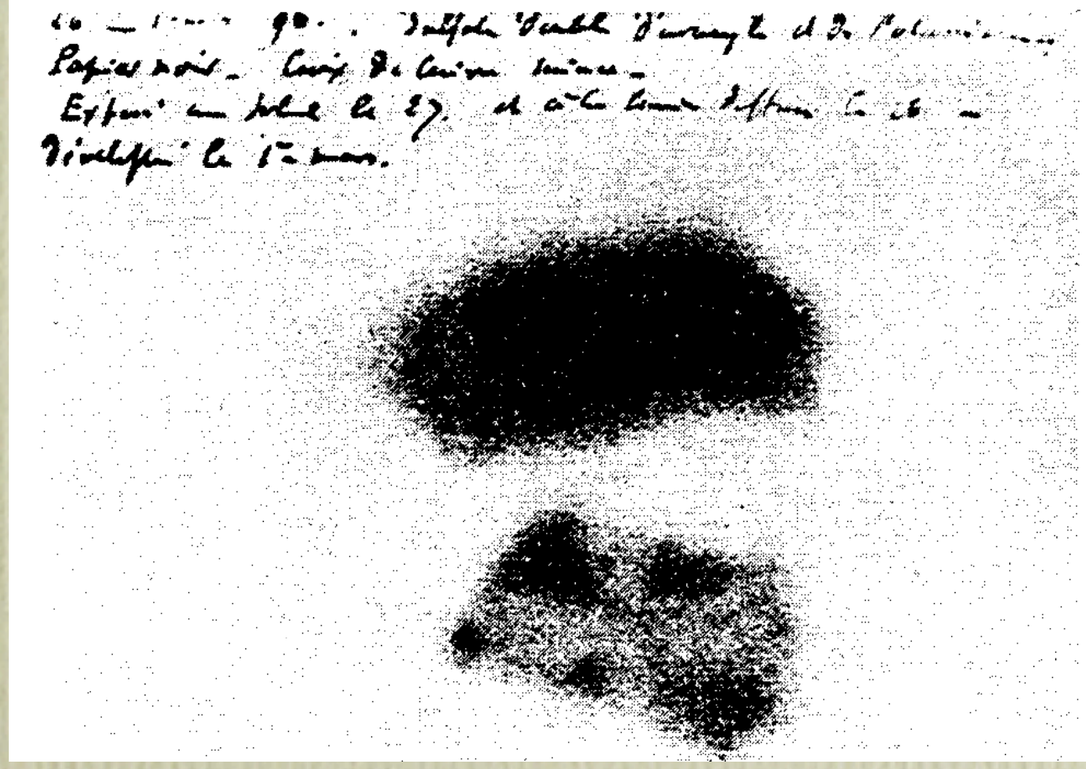
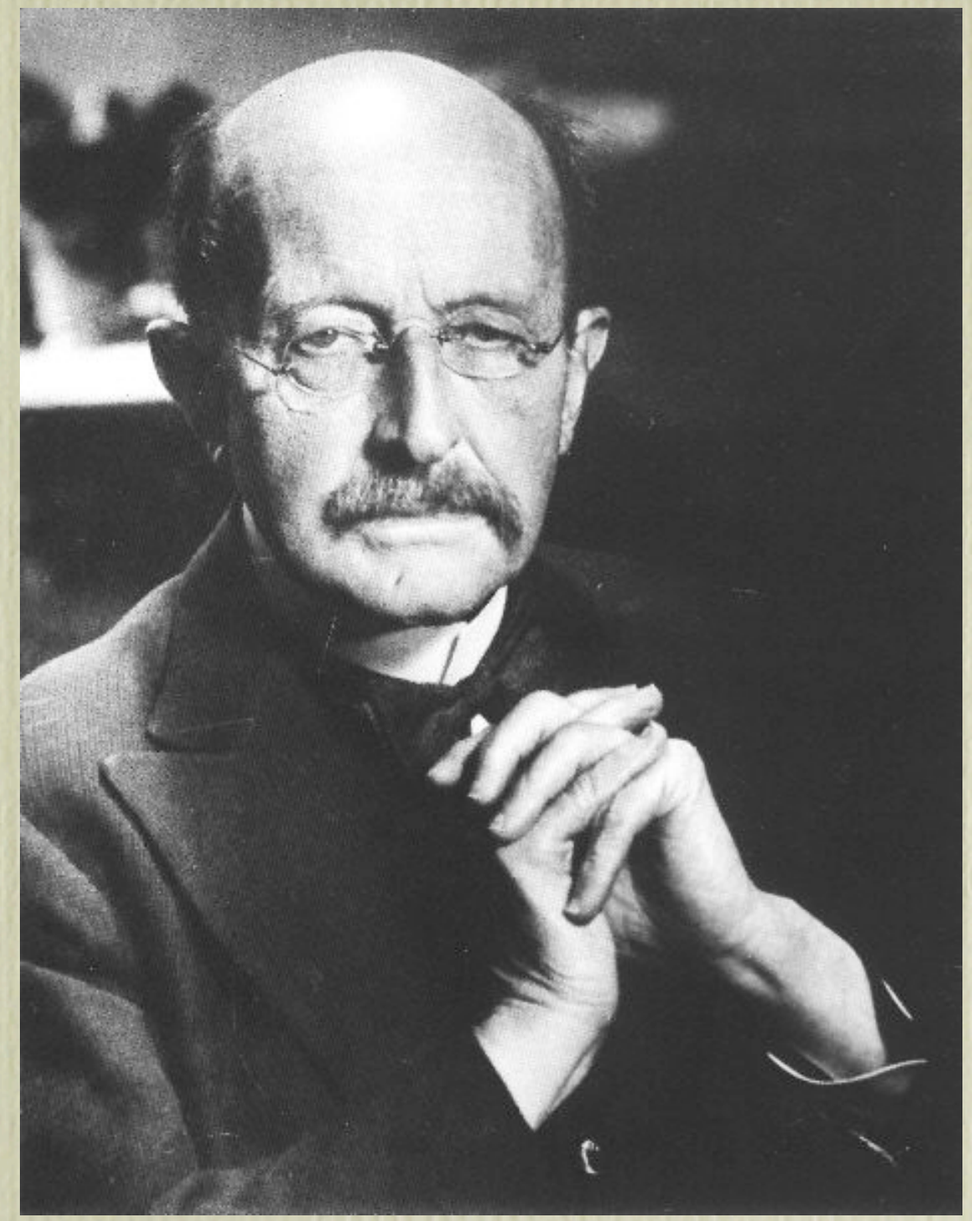


Fig.1.

Henri Becquerel

Marie & Pierre Curie

J. J. Thomson



Max Planck

The atomic hypothesis of Democritus, sung by Lucretius (ca. 50 BCE)

... many things have elements in common, but
differently combined ...
... It is most important
Both with what other elements they are joined,
In what position they are held together,
And their reciprocal movement. The same atoms
Constitute ocean, sky, lands, rivers, sun,
Crops, bushes, animals; these atoms mingle
And move in different ways and combinations.
Look—in my lines here you can see the letters
Common to many of the words, but you know
Perfectly well that resonance and meaning,
Sense, sound, are changed by changing the
arrangement.
How much more true of atoms than of letters!

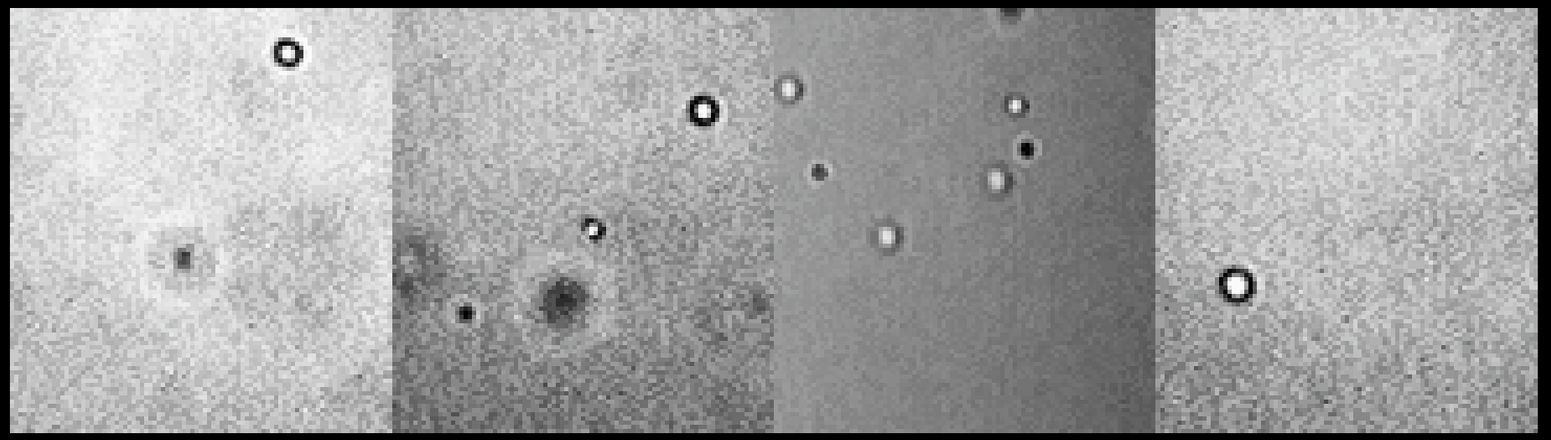
On the Nature of Things, I.815

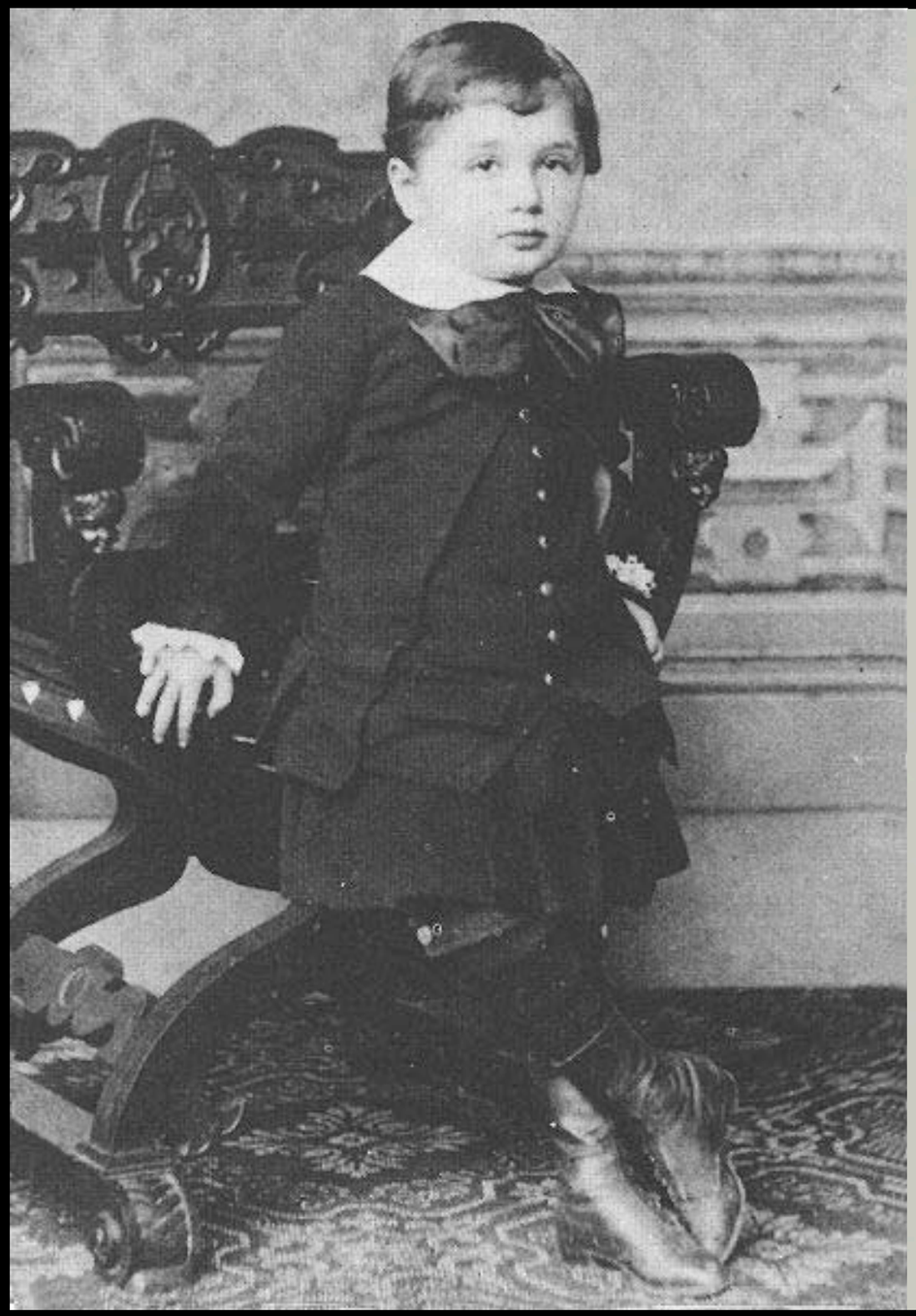
Jean Perrin, *Atoms* (1913)

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





5. *Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen;*

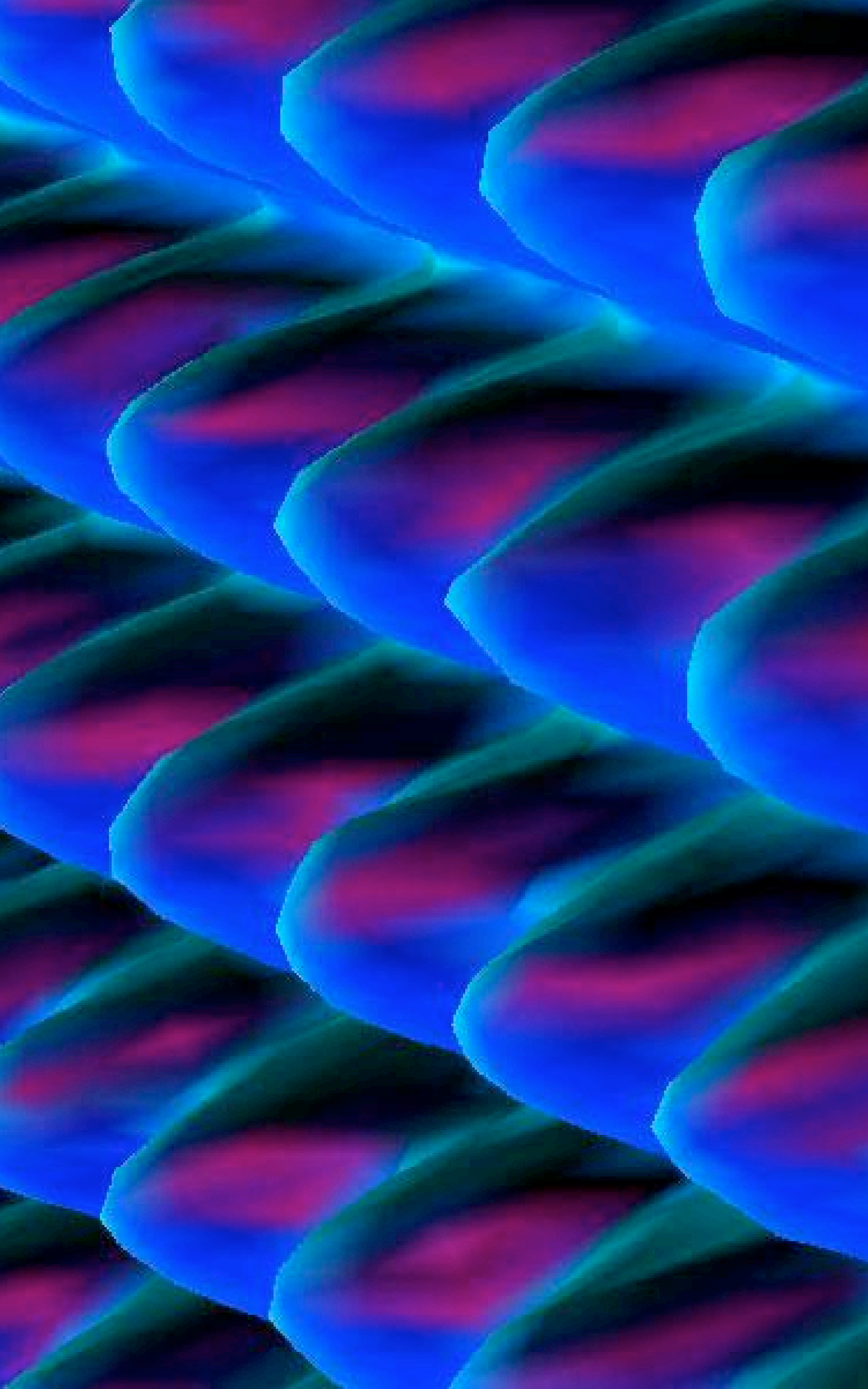
von A. Einstein.

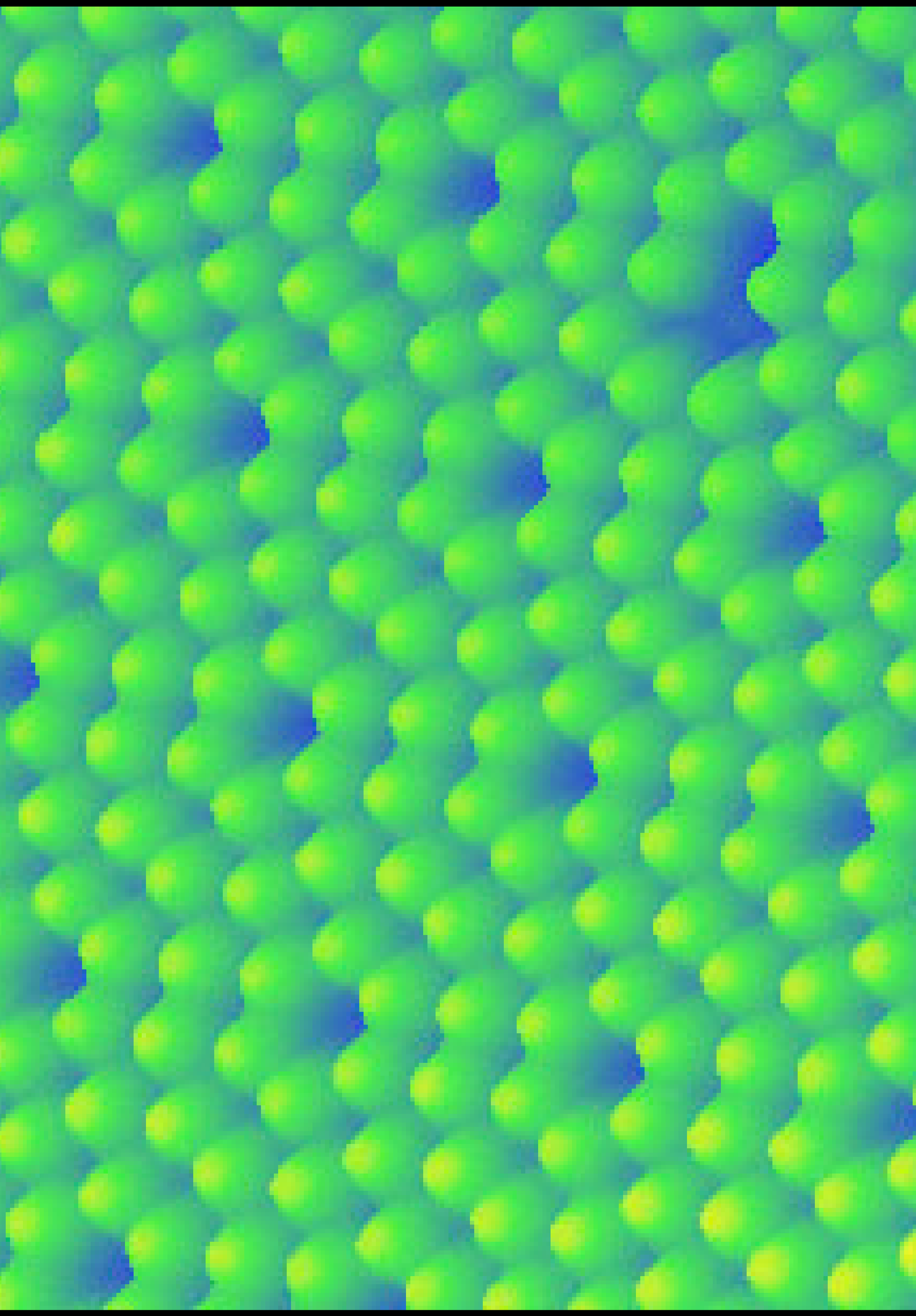
In dieser Arbeit soll gezeigt werden, daß nach der molekularkinetischen Theorie der Wärme in Flüssigkeiten suspendierte Körper von mikroskopisch sichtbarer Größe infolge der Molekularbewegung der Wärme Bewegungen von solcher Größe ausführen müssen, daß diese Bewegungen leicht mit dem Mikroskop nachgewiesen werden können. Es ist möglich, daß die hier zu behandelnden Bewegungen mit der sogenannten „Brownschen Molekularbewegung“ identisch sind; die mir erreichbaren Angaben über letztere sind jedoch so ungenau,
[1] daß ich mir hierüber kein Urteil bilden konnte.

Wenn sich die hier zu behandelnde Bewegung samt den für sie zu erwartenden Gesetzmäßigkeiten wirklich beobachten läßt, so ist die klassische Thermodynamik schon für mikroskopisch unterscheidbare Räume nicht mehr als genau gültig anzusehen und es ist dann eine exakte Bestimmung der wahren Atomgröße möglich. Erwiese sich umgekehrt die Voraussage dieser Bewegung als unzutreffend, so wäre damit ein schwerwiegendes Argument gegen die molekularkinetische Auffassung
[2] der Wärme gegeben.

§ 1. Über den suspendierten Teilchen zuzuschreibenden osmotischen Druck.

Im Teilvolumen V^* einer Flüssigkeit vom Gesamtvolumen V seien z-Gramm-Moleküle eines Nichtelektrolyten gelöst. Ist das Volumen V^* durch eine für das Lösungsmittel, nicht aber für die gelöste Substanz durchlässige Wand vom reinen Lösungs-





The World's Most Powerful Microscope where nanonanophysicists work!

Tevatron Collider at Fermilab and its detectors

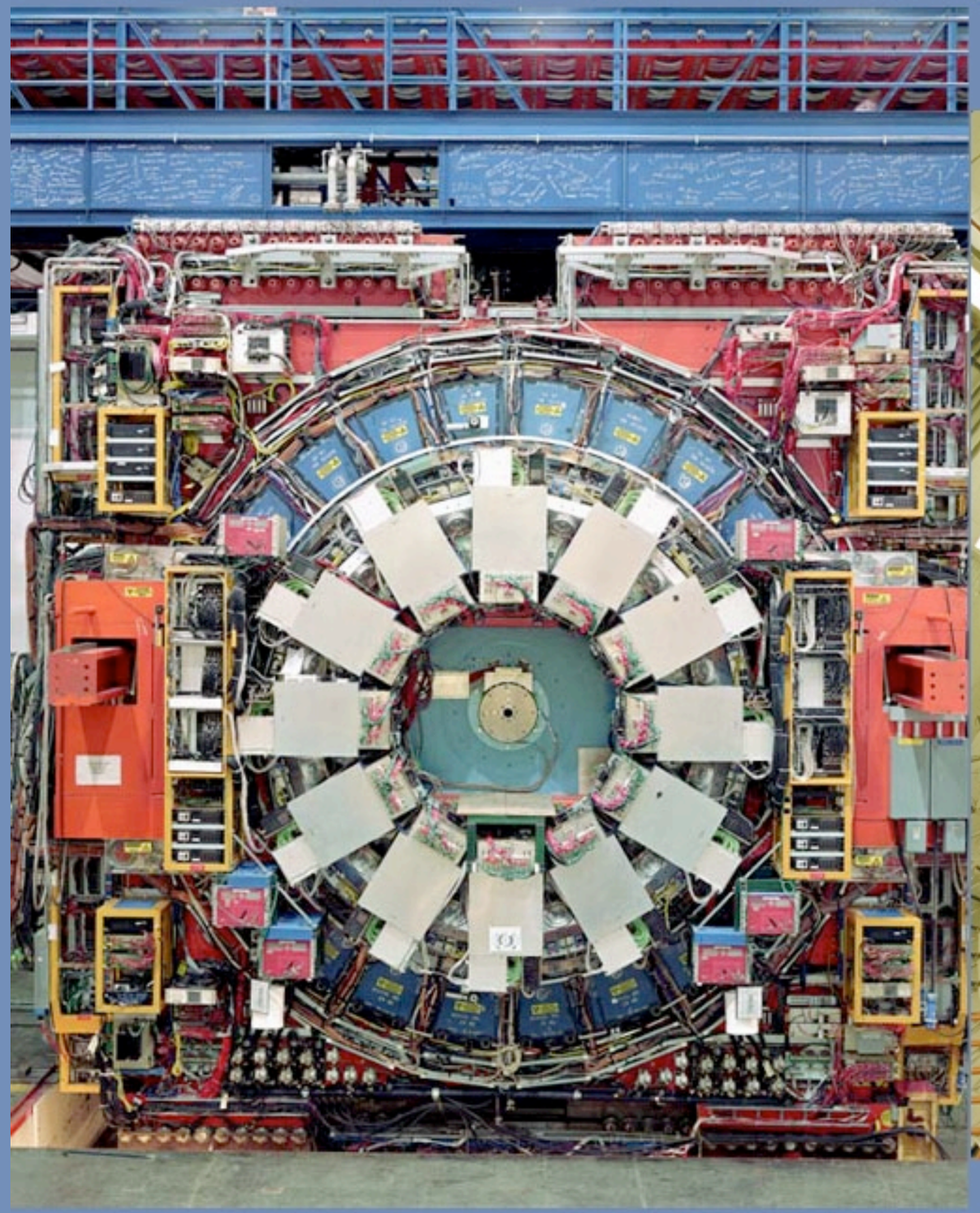
protons on antiprotons (1 TeV)

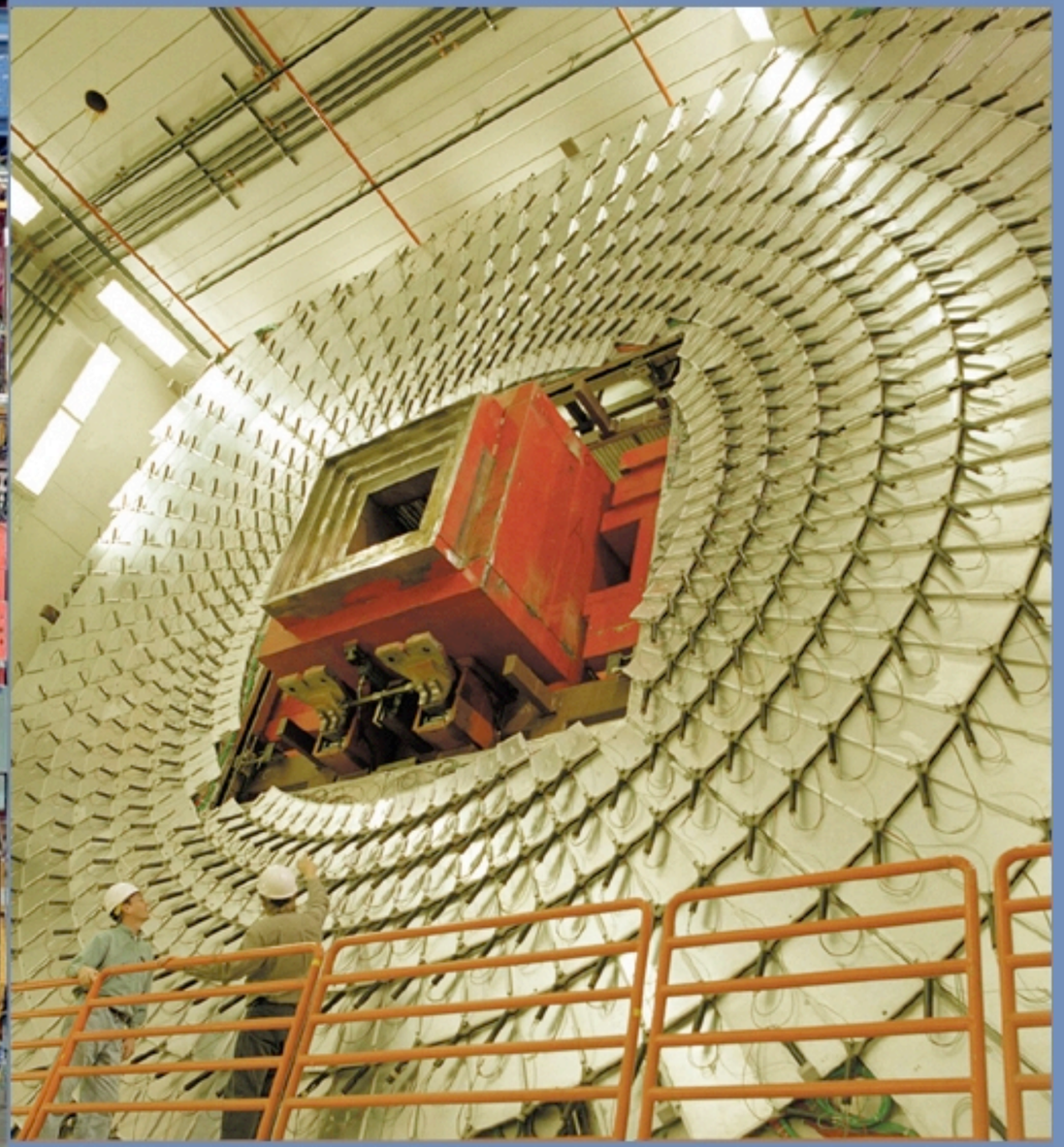
speed of light : $c \approx 10^9$ km/h

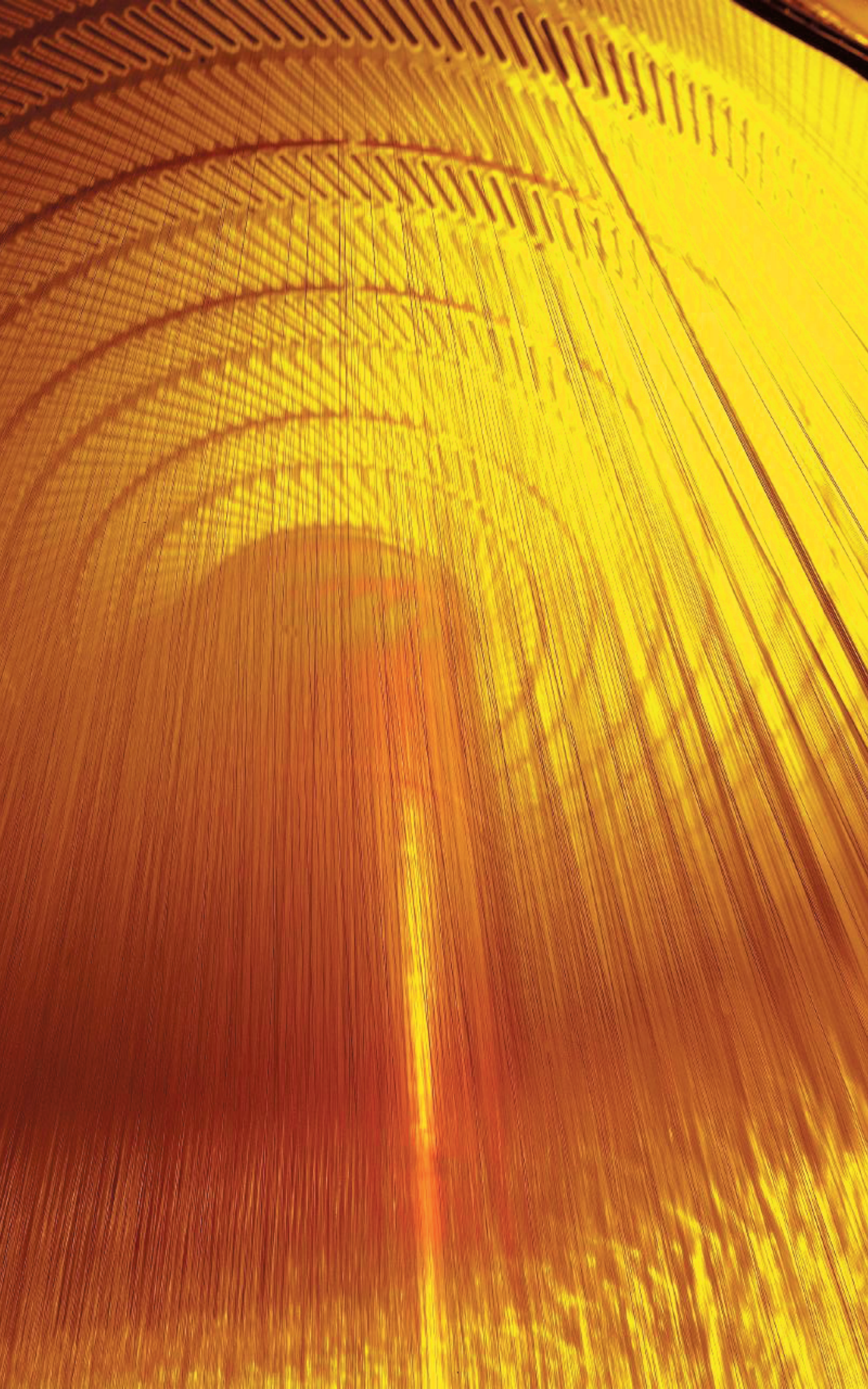
... of the protons & antiprotons : $c - 495$ km/h

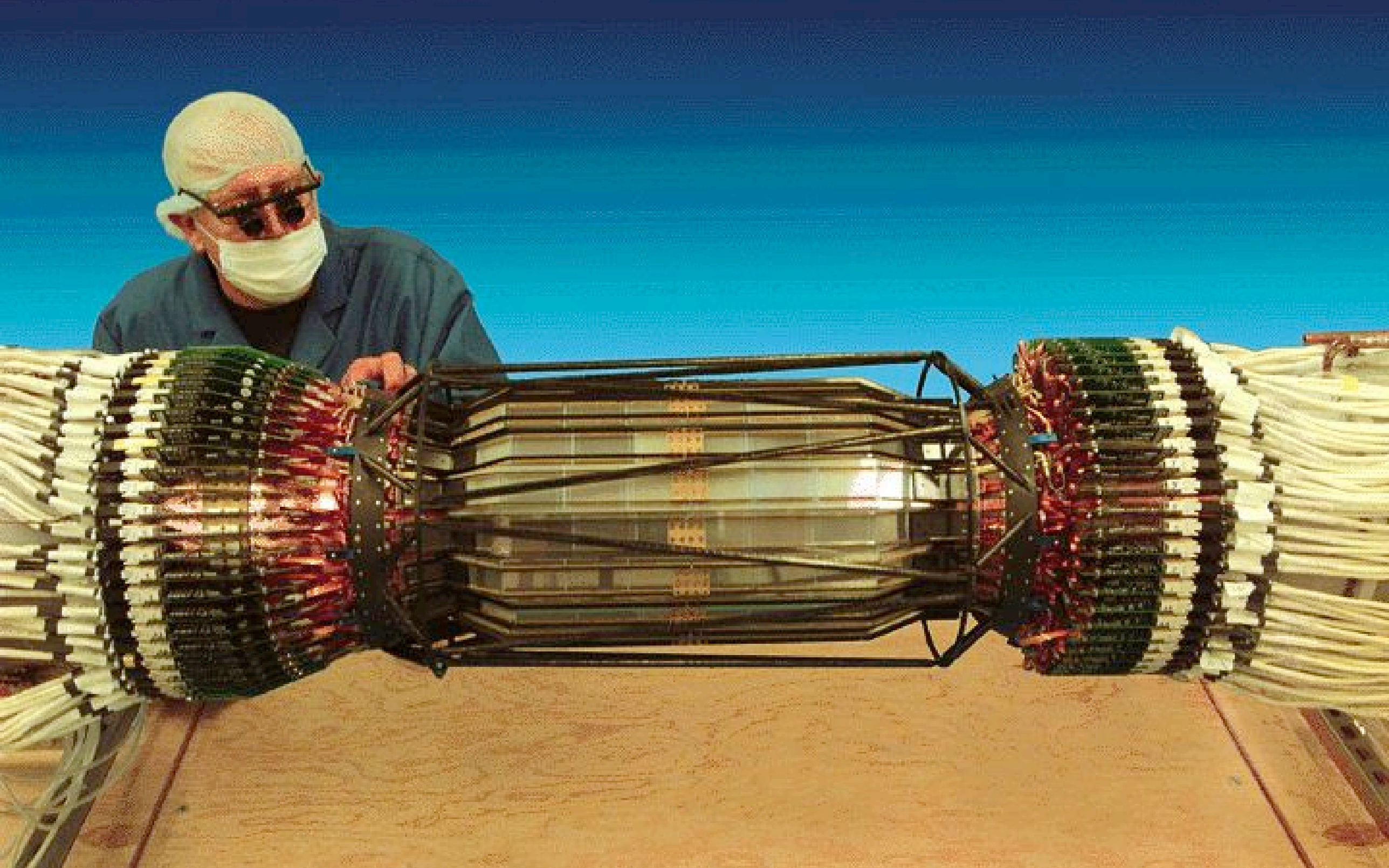
Protons pass my window 45 000 times a second

10 millions collisions per second







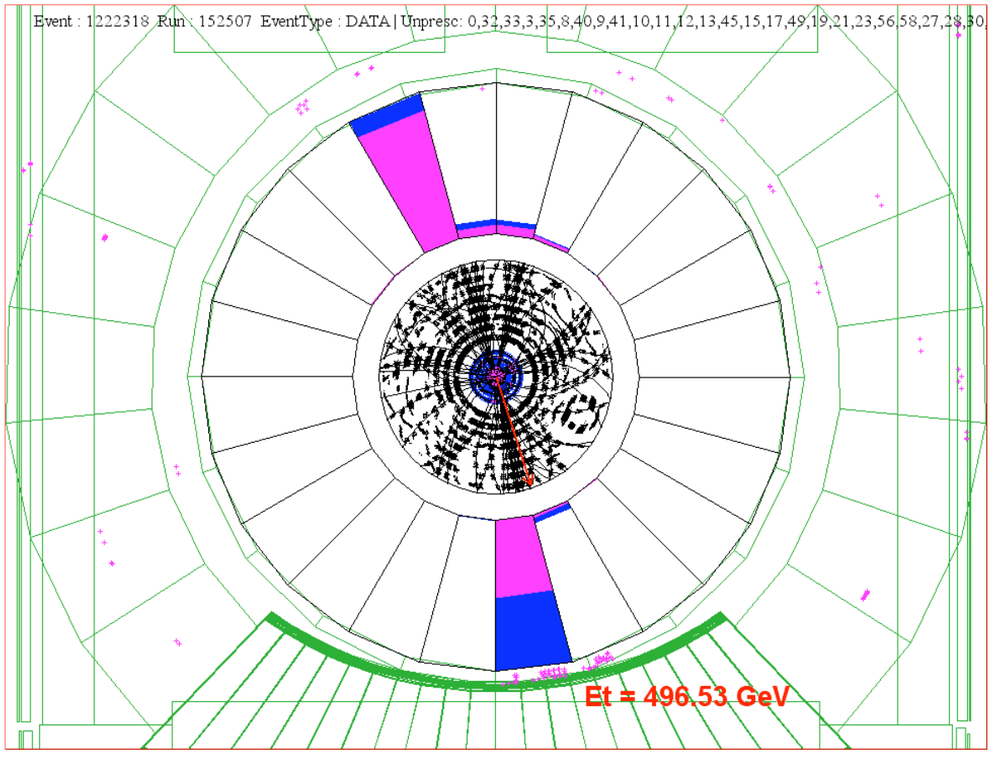


Run 152507 event 1222318

Dijet Mass = 1364 GeV (corr)

cos θ* = 0.30

z vertex = -25 cm

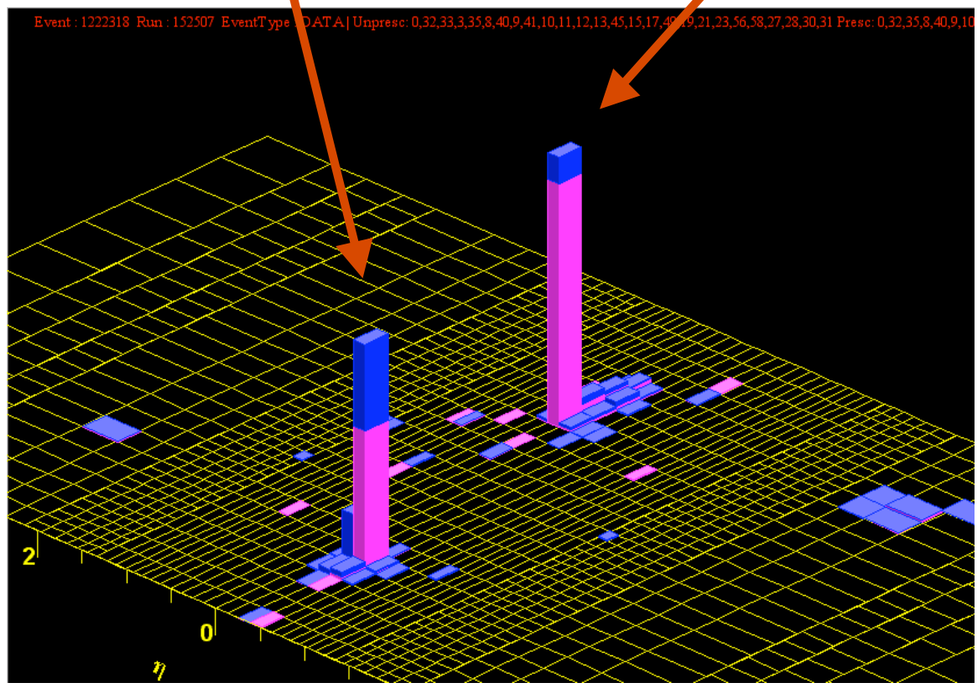


J2 E_T = 633 GeV (corr)
546 GeV (raw)

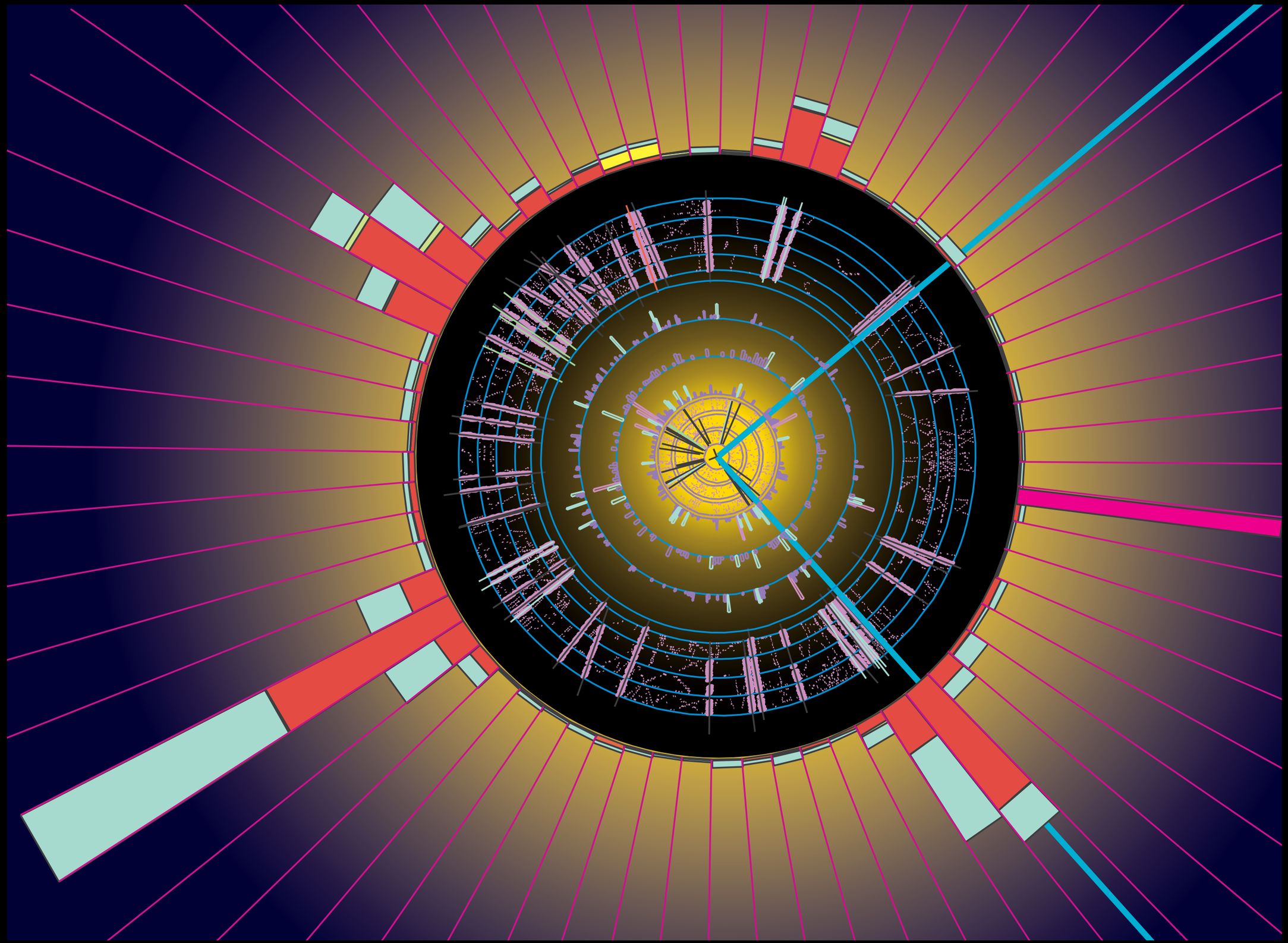
J2 η = -0.30 (detector)
= -0.19 (correct z)

J1 E_T = 666 GeV (corr)
583 GeV (raw)

J1 η = 0.31 (detector)
= 0.43 (correct z)



CDF Run 2 Preliminary

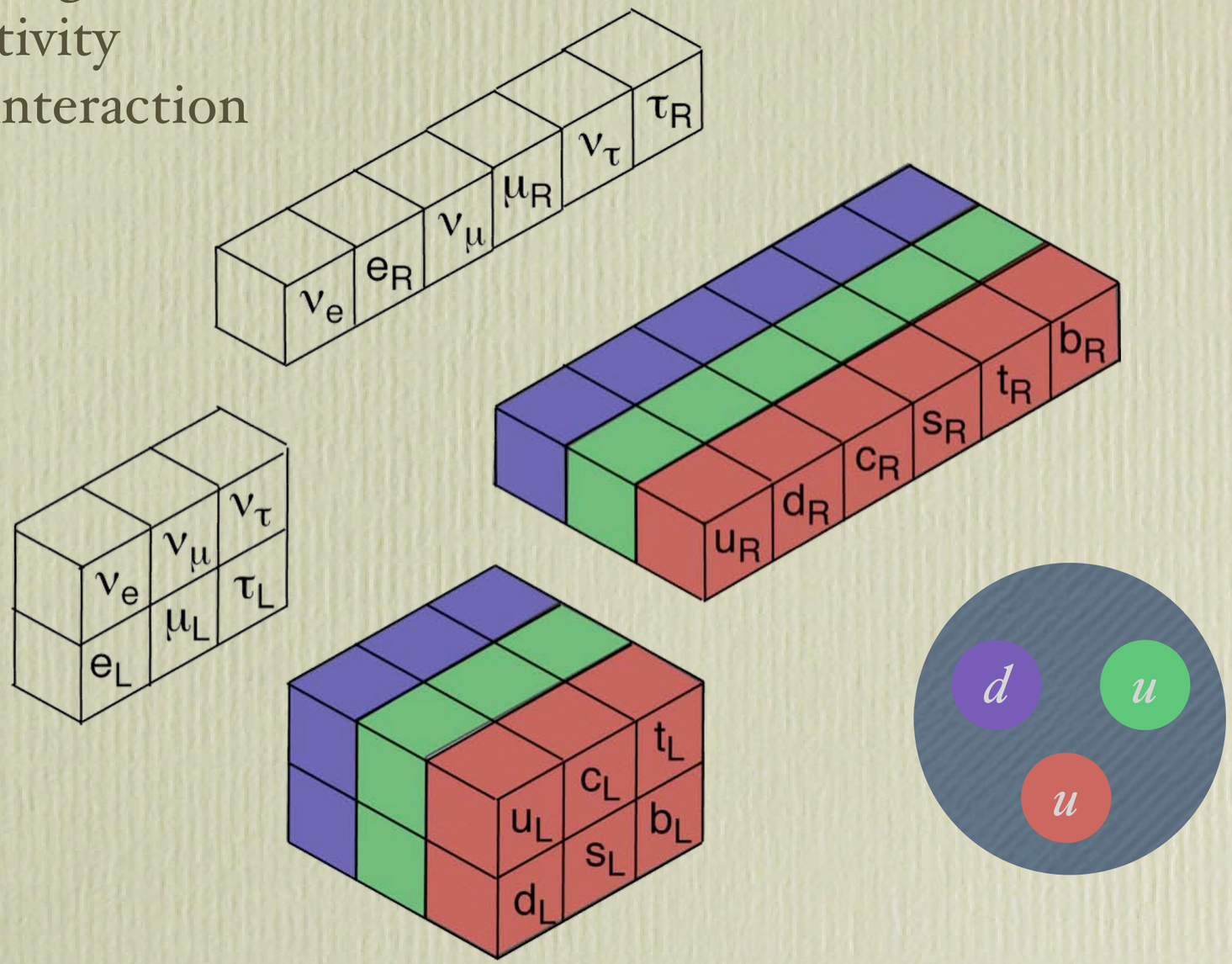


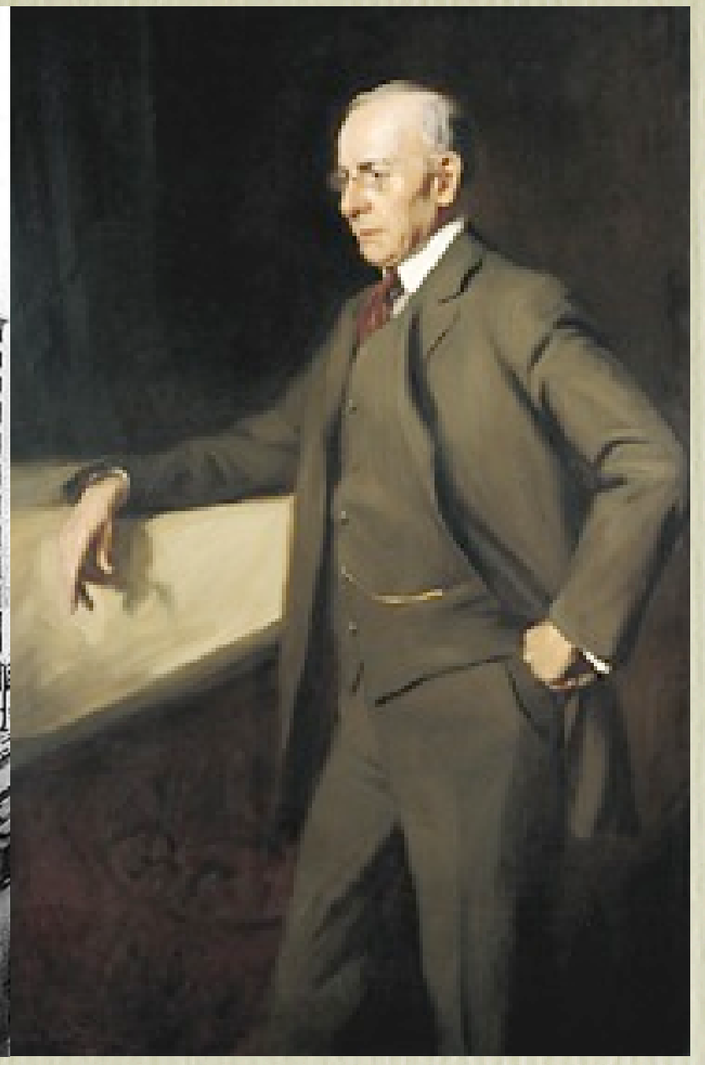
Particle accelerators are time machines ...

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)

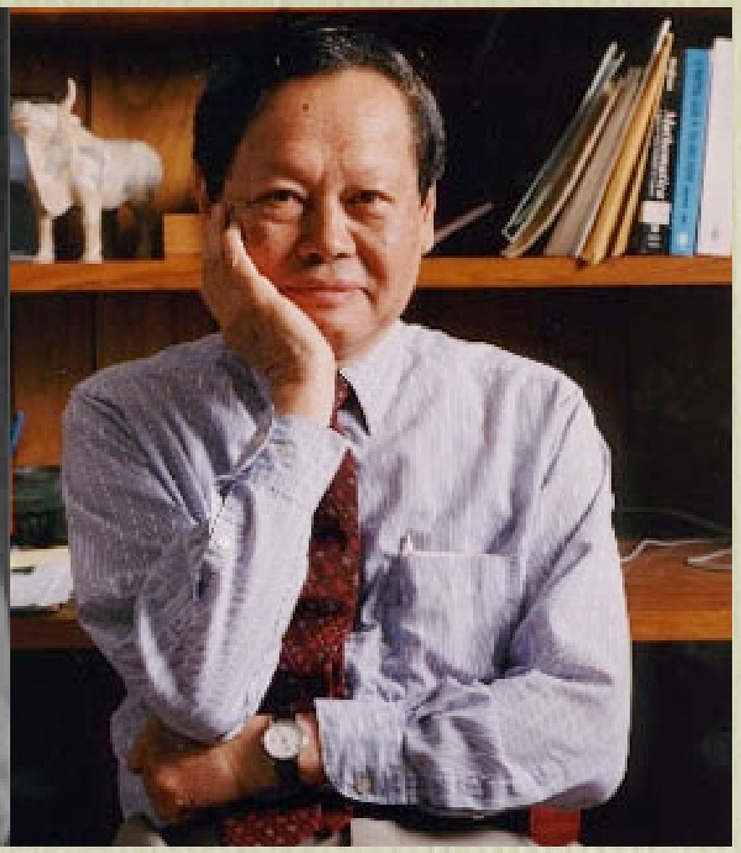
gravitation
electromagnetism
radioactivity
strong interaction





Louis Sullivan, architect (1896)

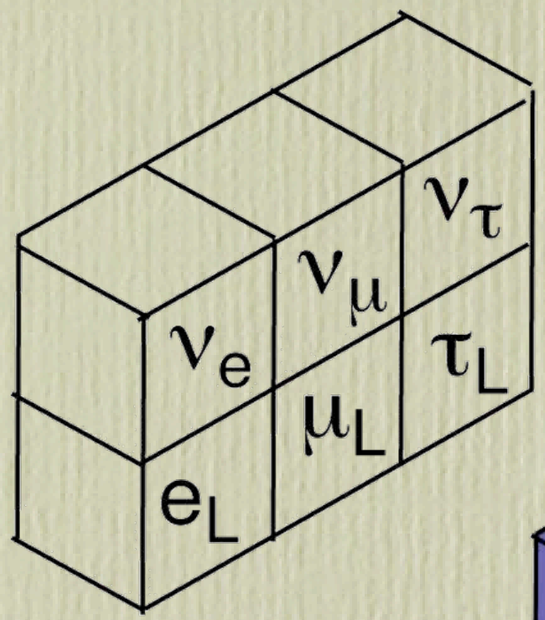
Form follows function



Robert Mills (1954) Yang Chen Ning

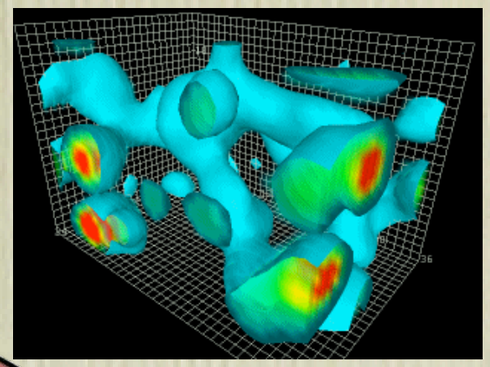
Function follows form

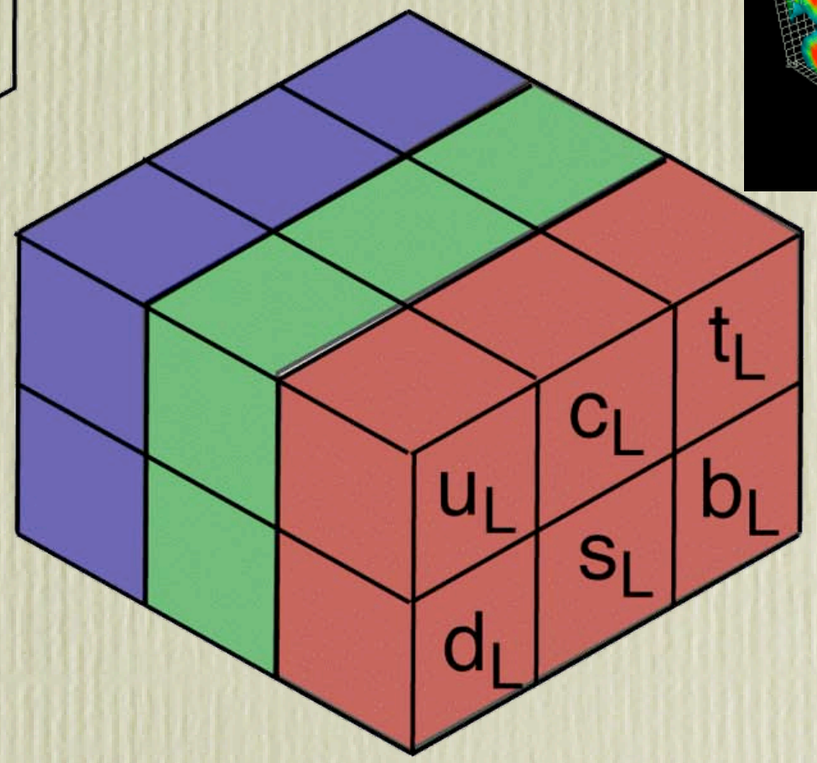
Interactions follow from symmetry



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

Quantum chromodynamics (QCD):
symmetry among quarks
red, green, blue





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

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

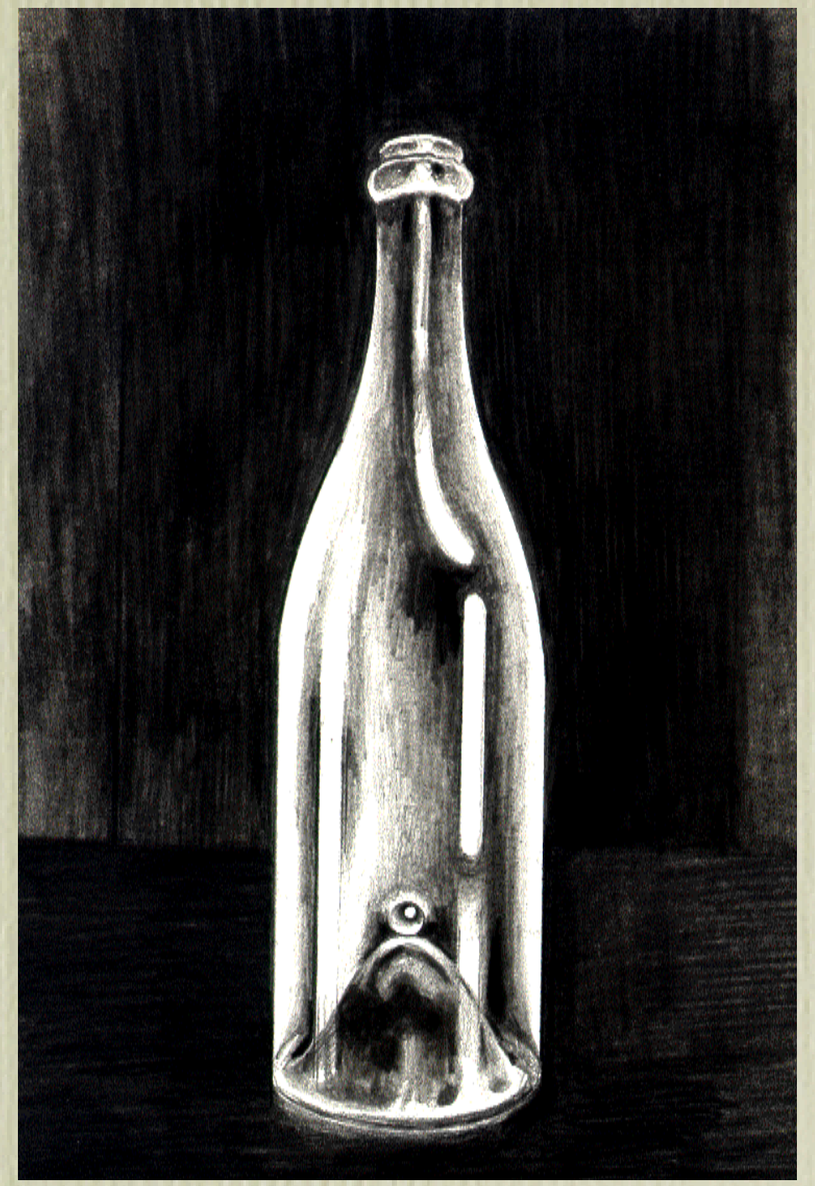
proton mass would be little changed ...
but the proton would outweigh the neutron

lightest nucleus: the 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



Spontaneous symmetry breaking

A mysterious new force hides electroweak symmetry

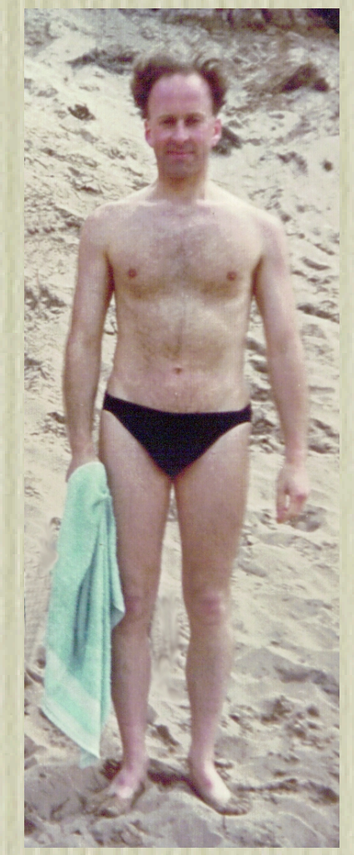
- New kind of force? Higgs field?
- New force from a new symmetry?
- Residual force from strong dynamics?
- Echo of extra spacetime dimensions?

Which path has nature taken?

Experiments at 1 TeV will tell

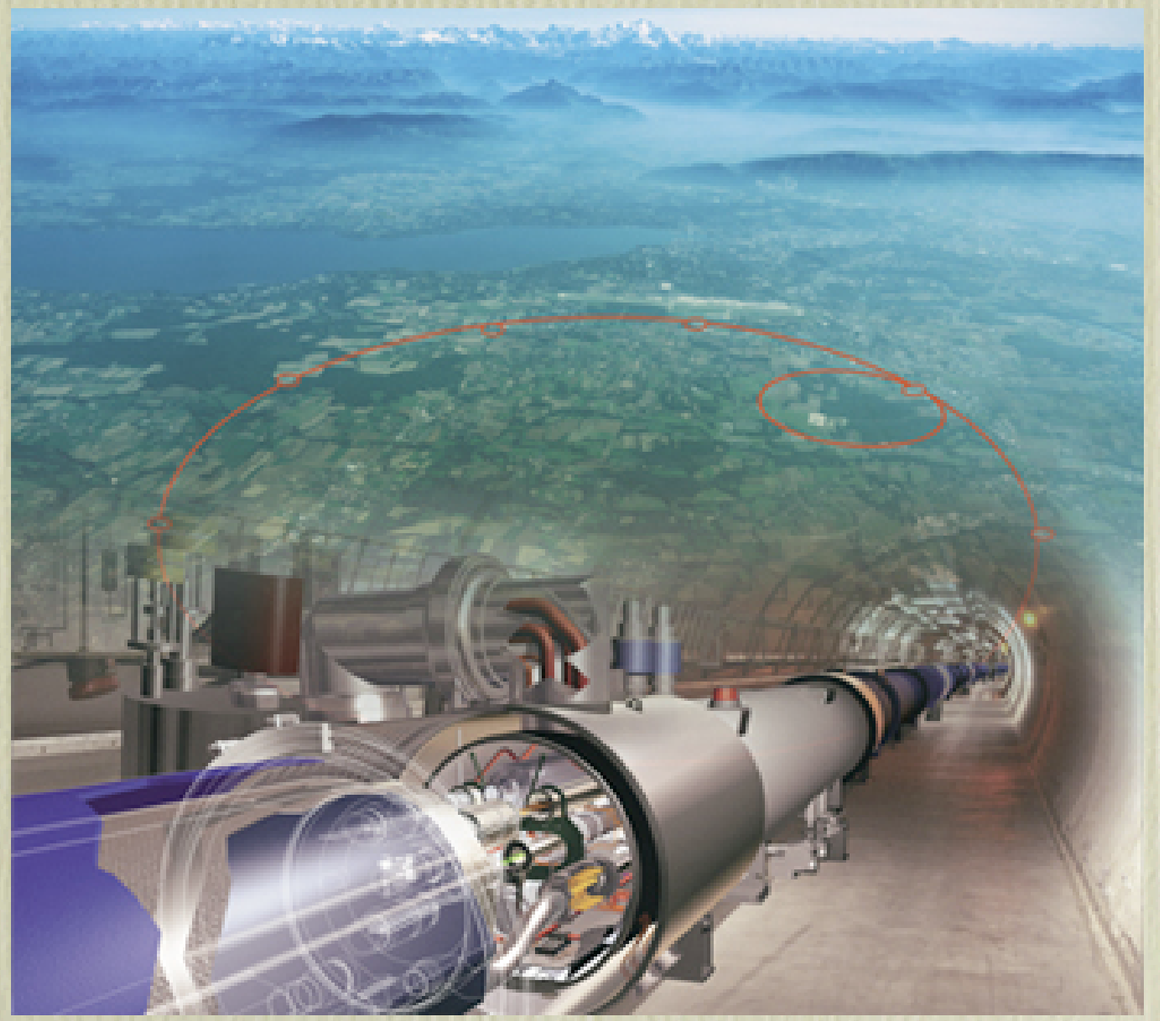
Searching for the *agent provocateur* of electroweak symmetry breaking

« the search for the Higgs boson »



Coming to CERN/Geneva in 2007: the LHC proton–proton collider at 7+7 TeV

speed of protons: c – 10 km/h



Fabiola Gianotti (ATLAS) : « If we do not find the Higgs boson,
that means that the theory is just wrong! »

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Stereo
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Revolution: the meaning of identity

- What sets quark & lepton masses?
- What makes matter – antimatter symmetry imperfect?
- New kinds of matter show us pattern? dark matter, superpartners, ...

Mendele'ev didn't know about noble gases

Neutrinos (ν)...

are tiny subatomic particles

carry no electric charge

have (almost) no mass,
move (nearly) at the speed of light

hardly interact at all

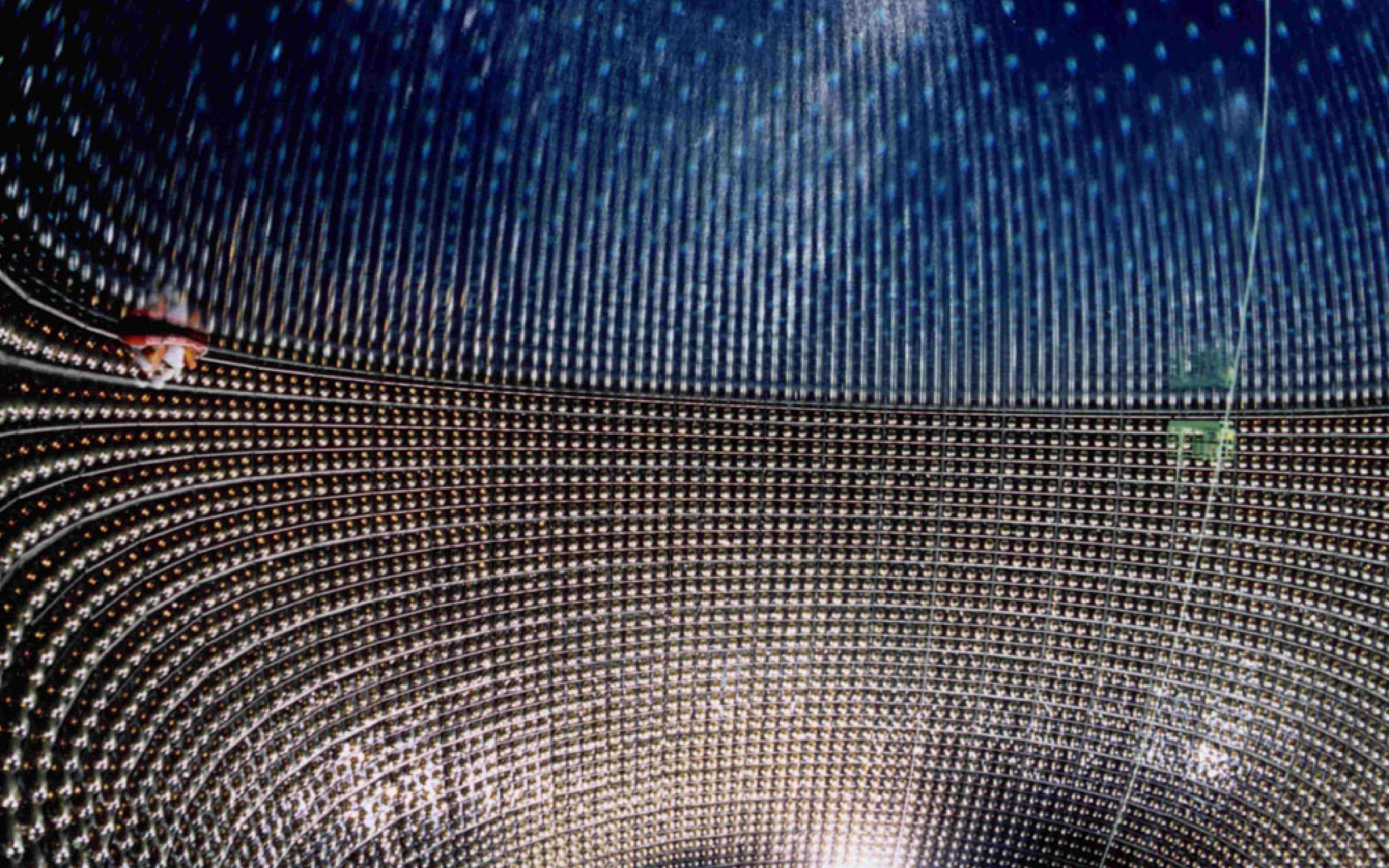
Each second ...

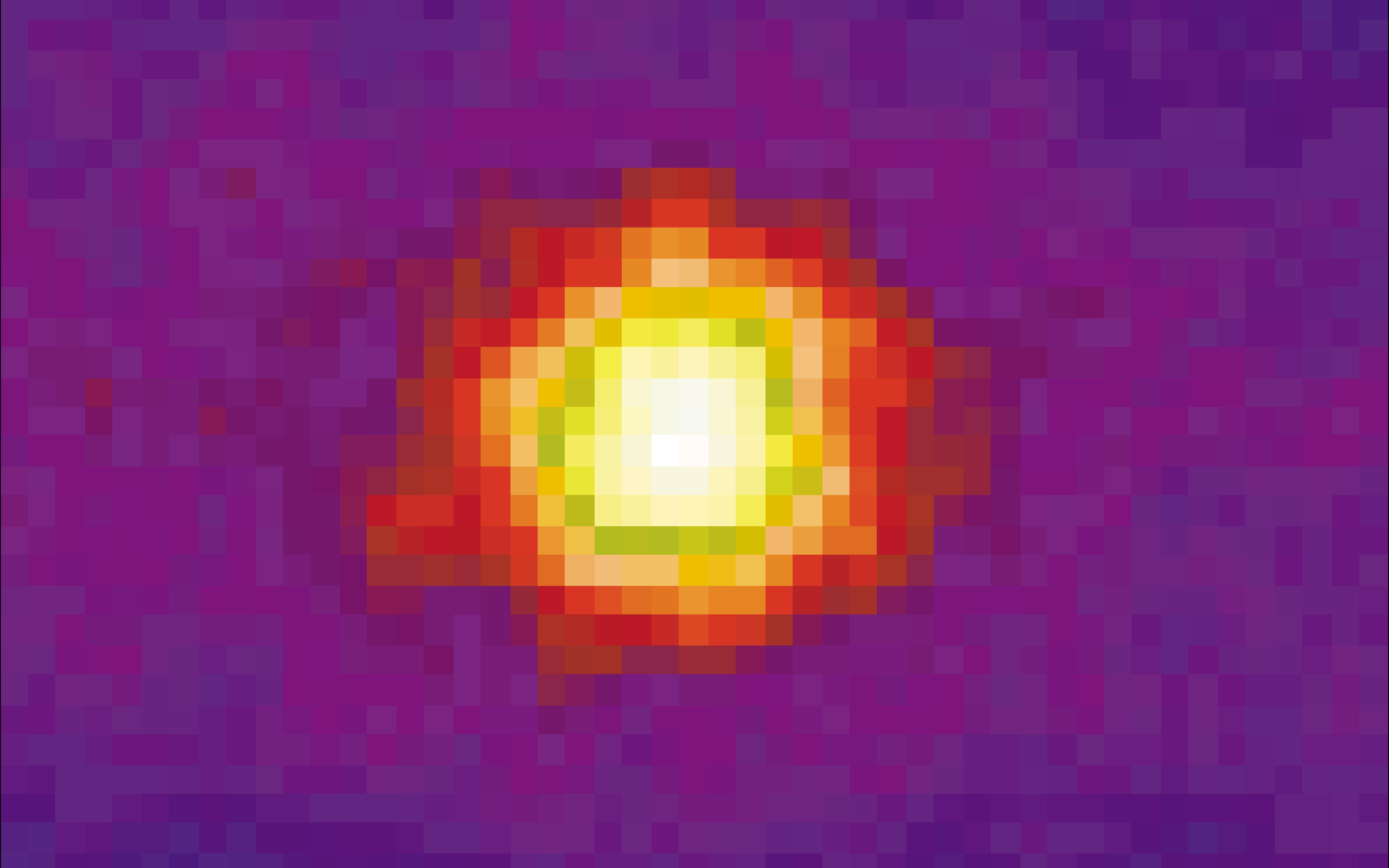
100 trillion neutrinos produced in the Sun pass through your body

1000 neutrinos made in Earth's atmosphere by cosmic rays pass through your body

Inside your body are more than 10 million neutrino fossils from the Big Bang

Other neutrinos reach us from natural (radioactive decay of elements inside the Earth) and artificial (nuclear reactors) sources





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 Physics rejoins Gr

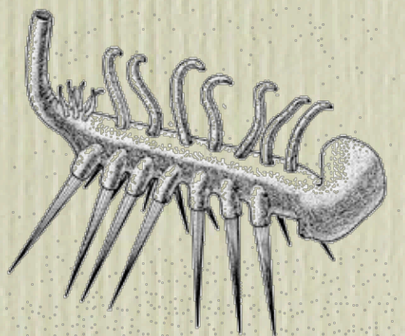
A Chronic Dull Headache ...

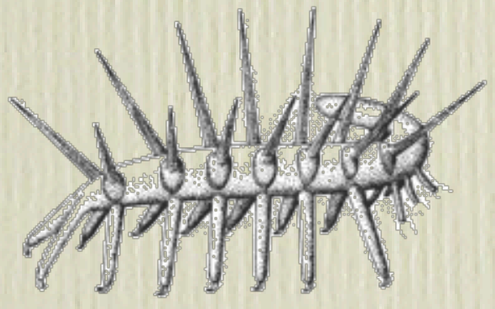
... for thirty years

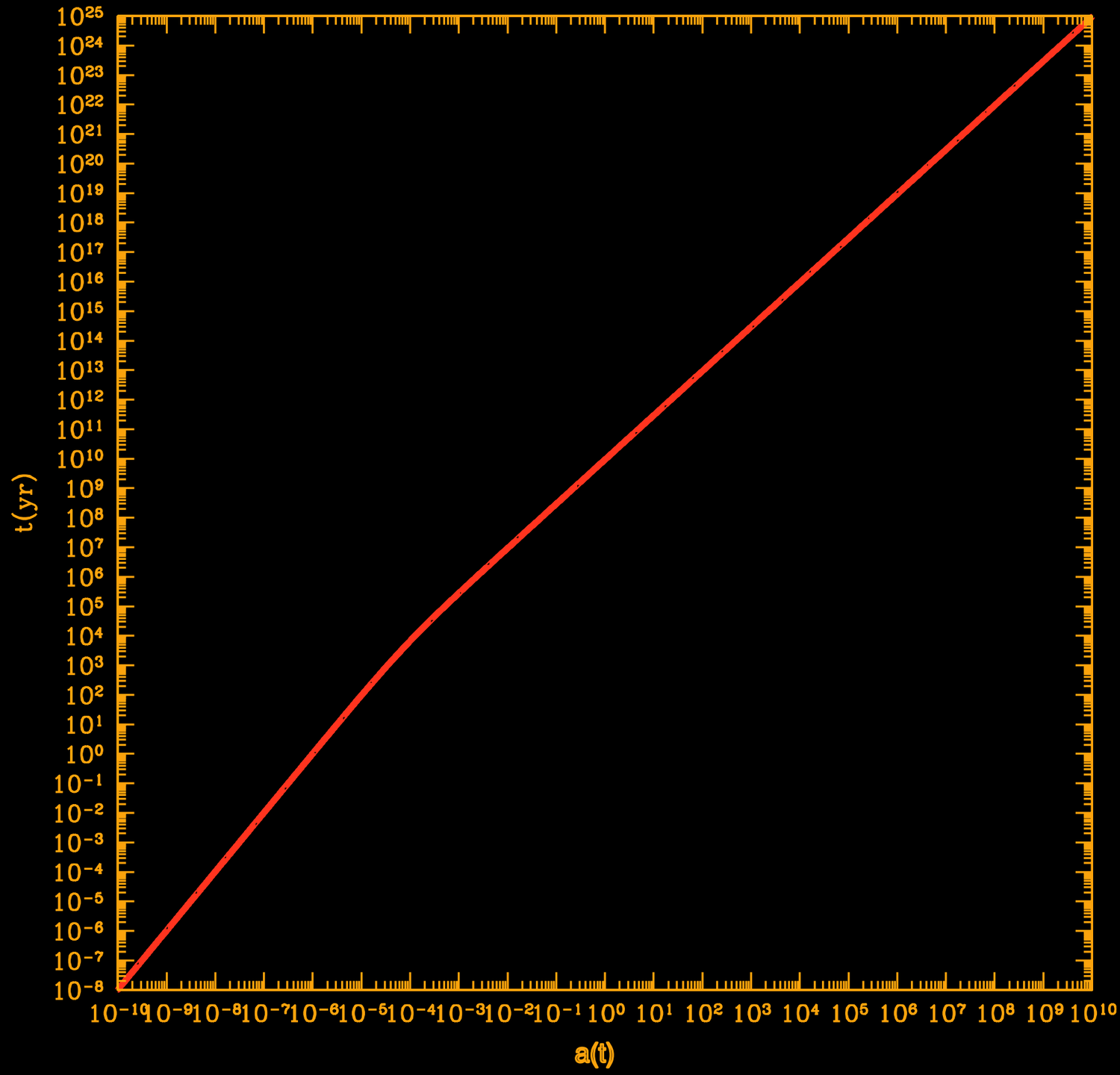
- Higgs field fills all of space with energy density 10^{25} g/cc
- But empty space weighs next to nothing: $< 10^{-29}$ g/cc
- Evidence that vacuum energy is present (accelerating universe) recasts problem

Implications for ...
the fate 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]



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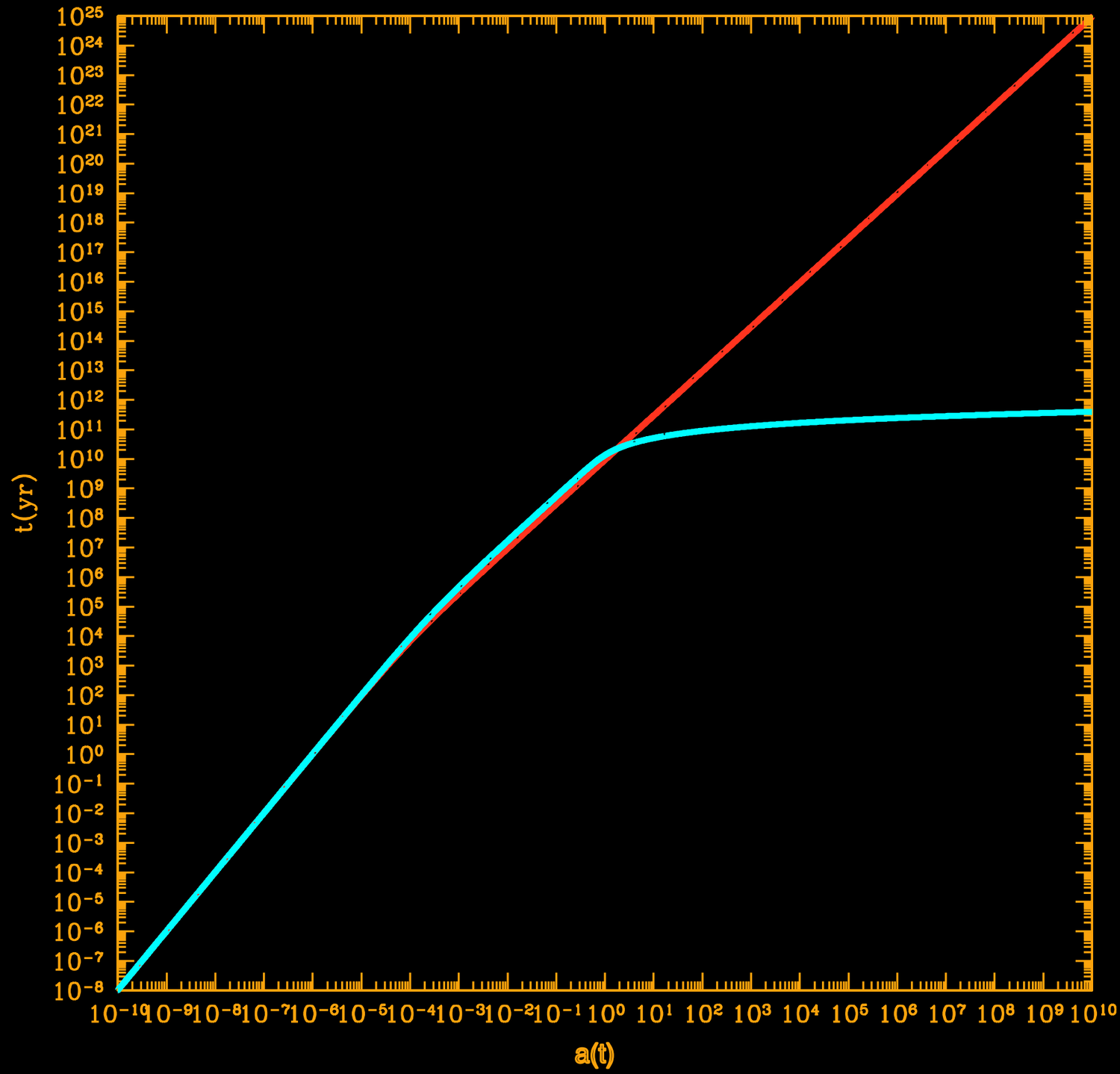
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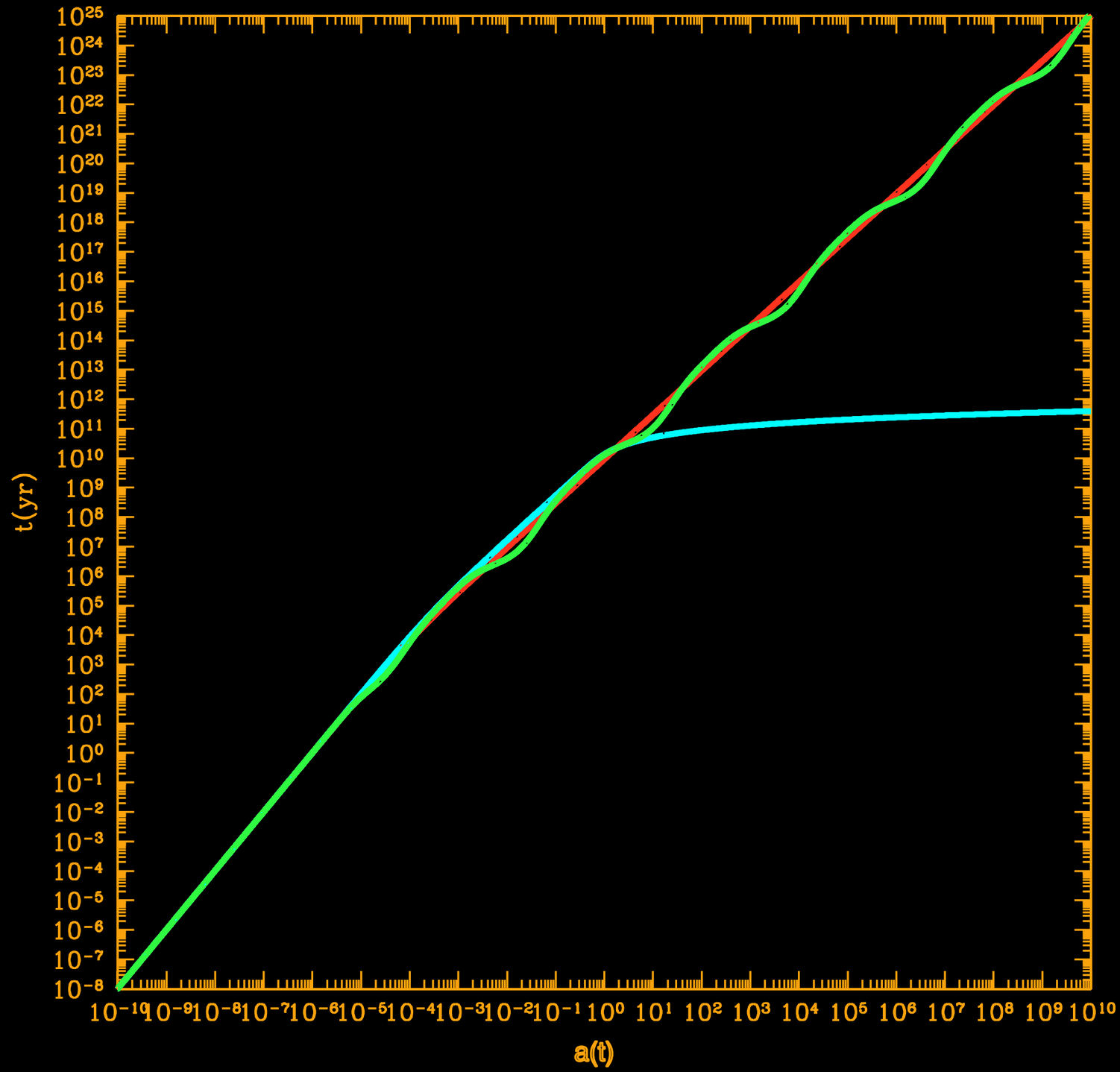
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a(t)

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 1 000 000 000 000 000 eV for other forces we know)
- *n* extra dimensions: $1/r^{2+n}$

Explain a complicated visible
by a simple invisible ...