

# The Coming Revolutions in Particle Physics



Chris Quigg

## 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.”



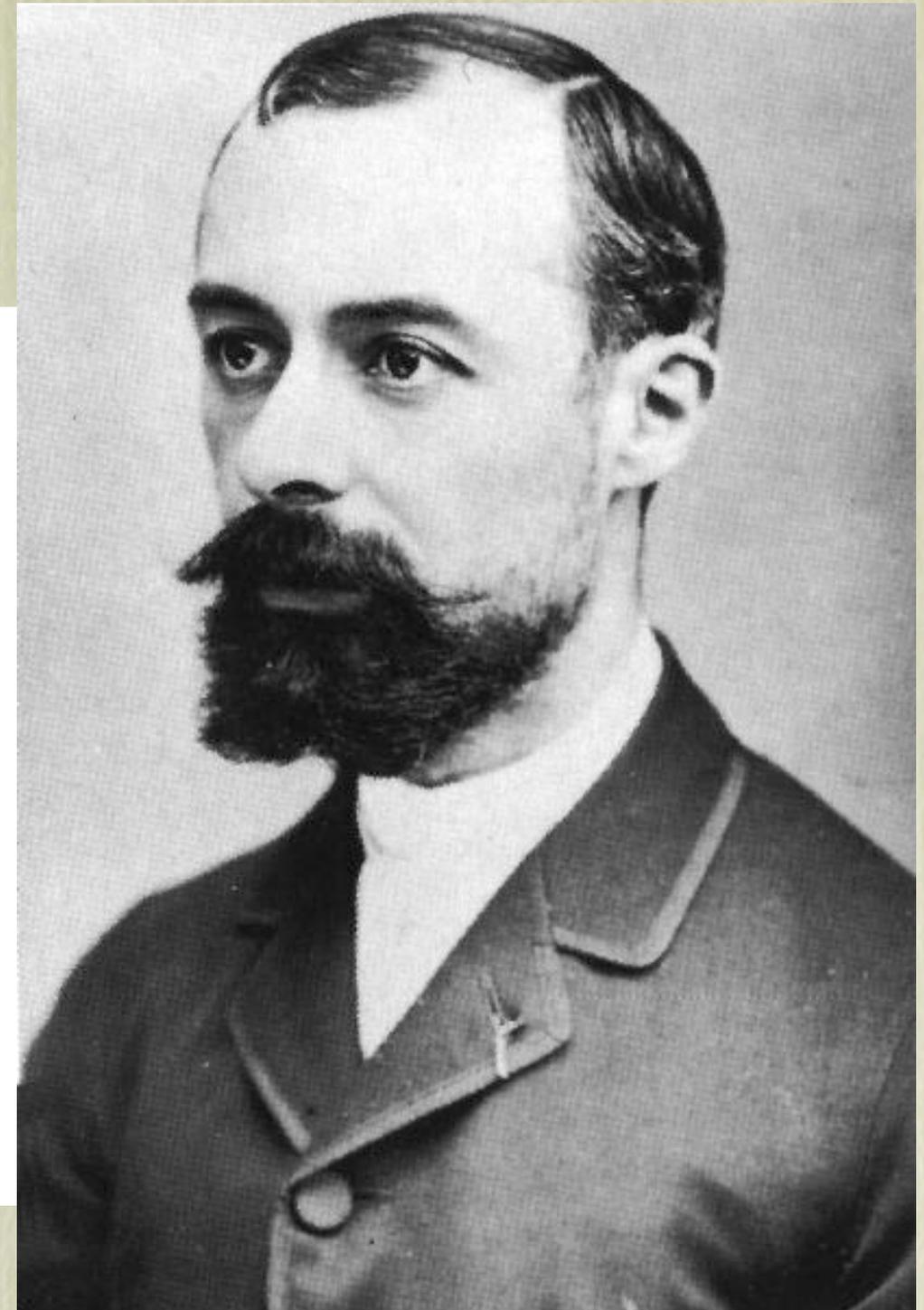
Wilhelm Conrad Röntgen

RADIOACTIVITY, NEW PROPERTY OF MATTER

46 - 1896 - 90. Sulfate double d'uranyle et de Potassium  
Papier noir - Couche de laque blanche -  
Exposé au soleil le 27, et à la lumière diffuse le 28 -  
Révélation le 1<sup>er</sup> Mars.



Fig.1.



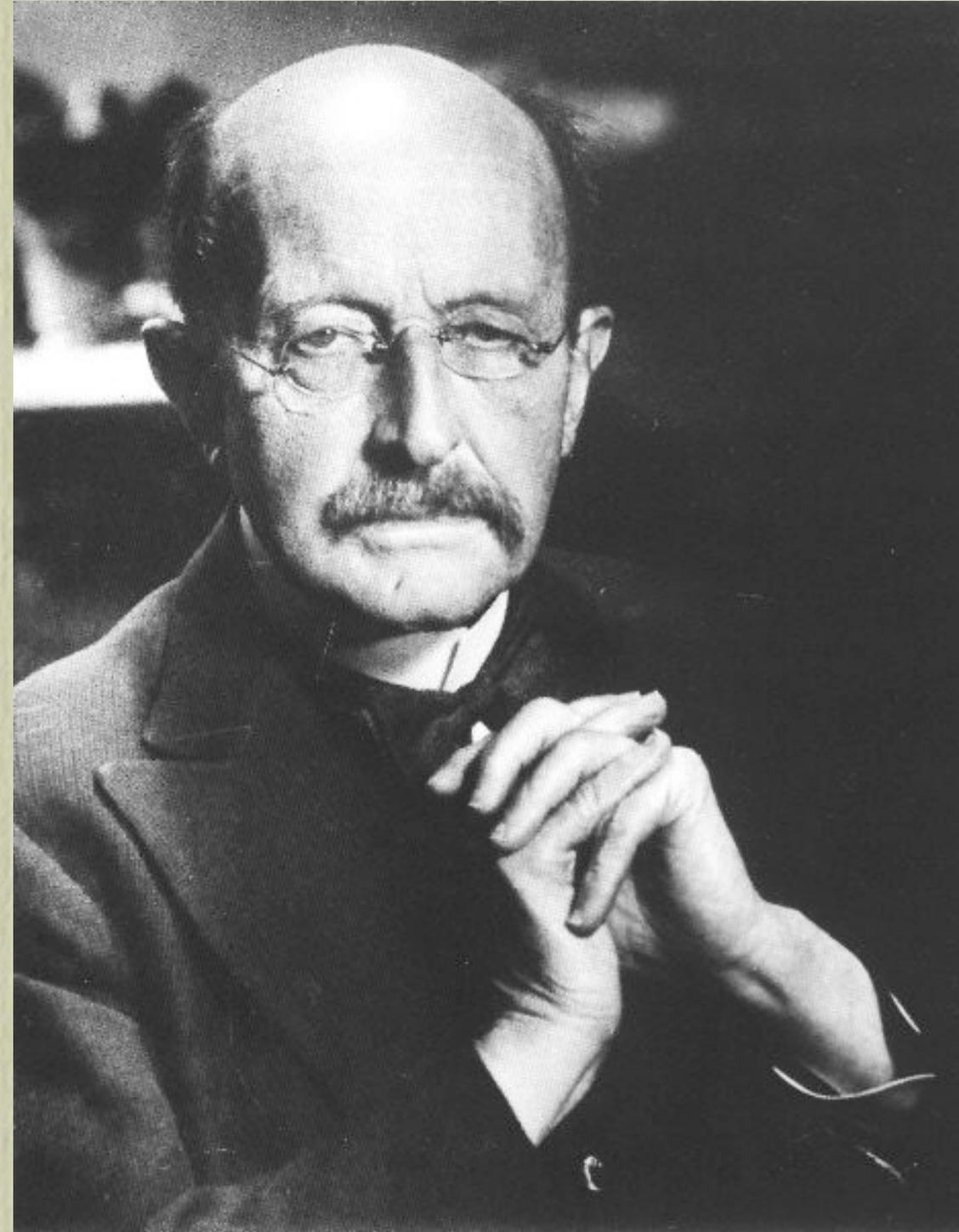
Henri Becquerel



Marie & Pierre Curie



J. J. Thomson



Max Planck

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

... many things have elements in common, but  
differently combined ...

... It is most important

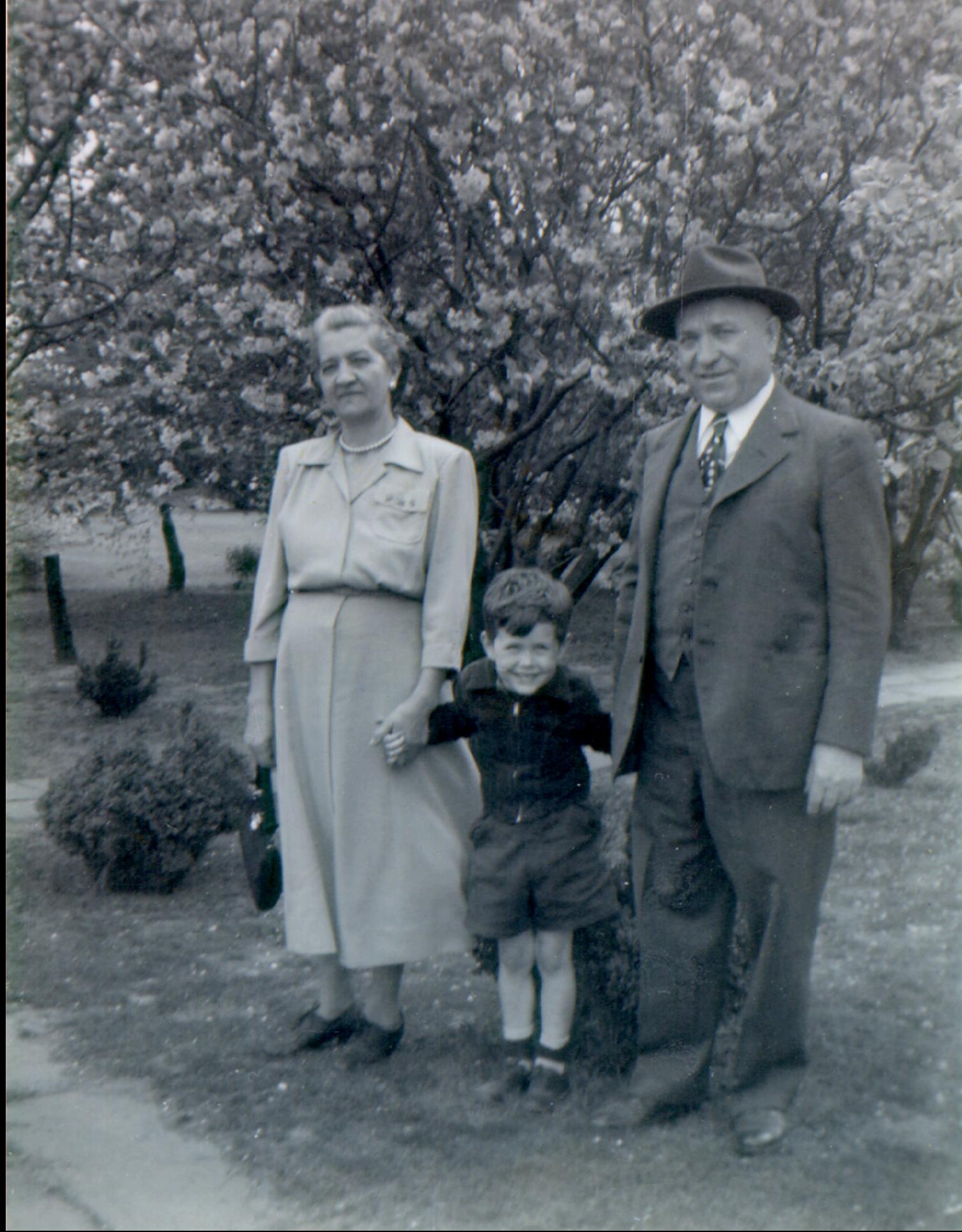
Both with what other elements they are joined,  
In what position they are held together,  
And their reciprocal movement. The same atoms  
Constitute ocean, sky, lands, rivers, sun,  
Crops, bushes, animals; these atoms mingle  
And move in different ways and combinations.

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*





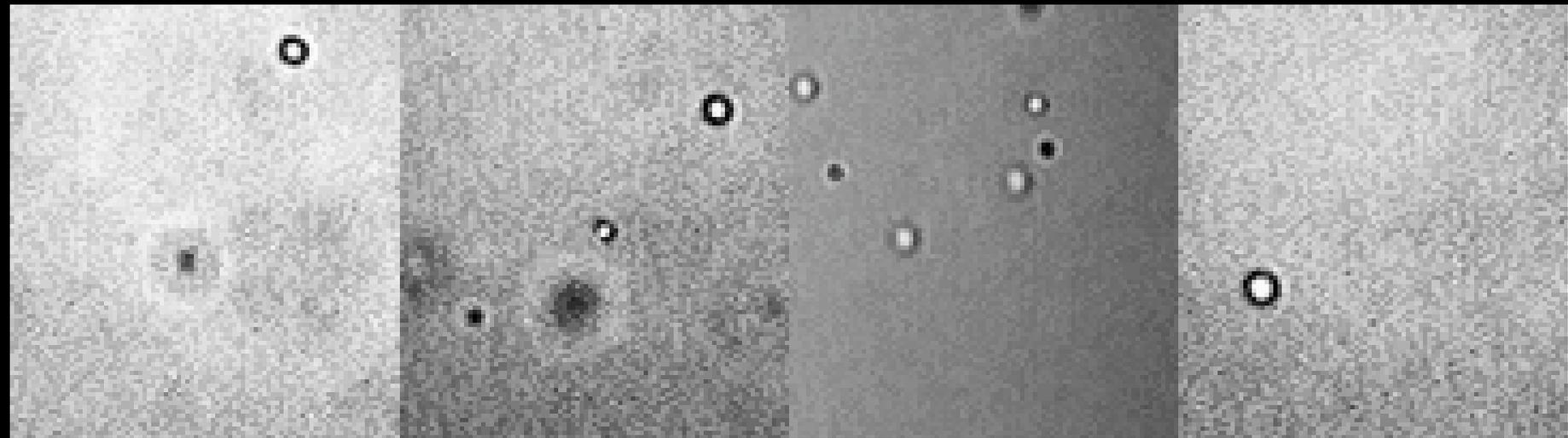
## Jean Perrin, *Atoms* (1913)

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*





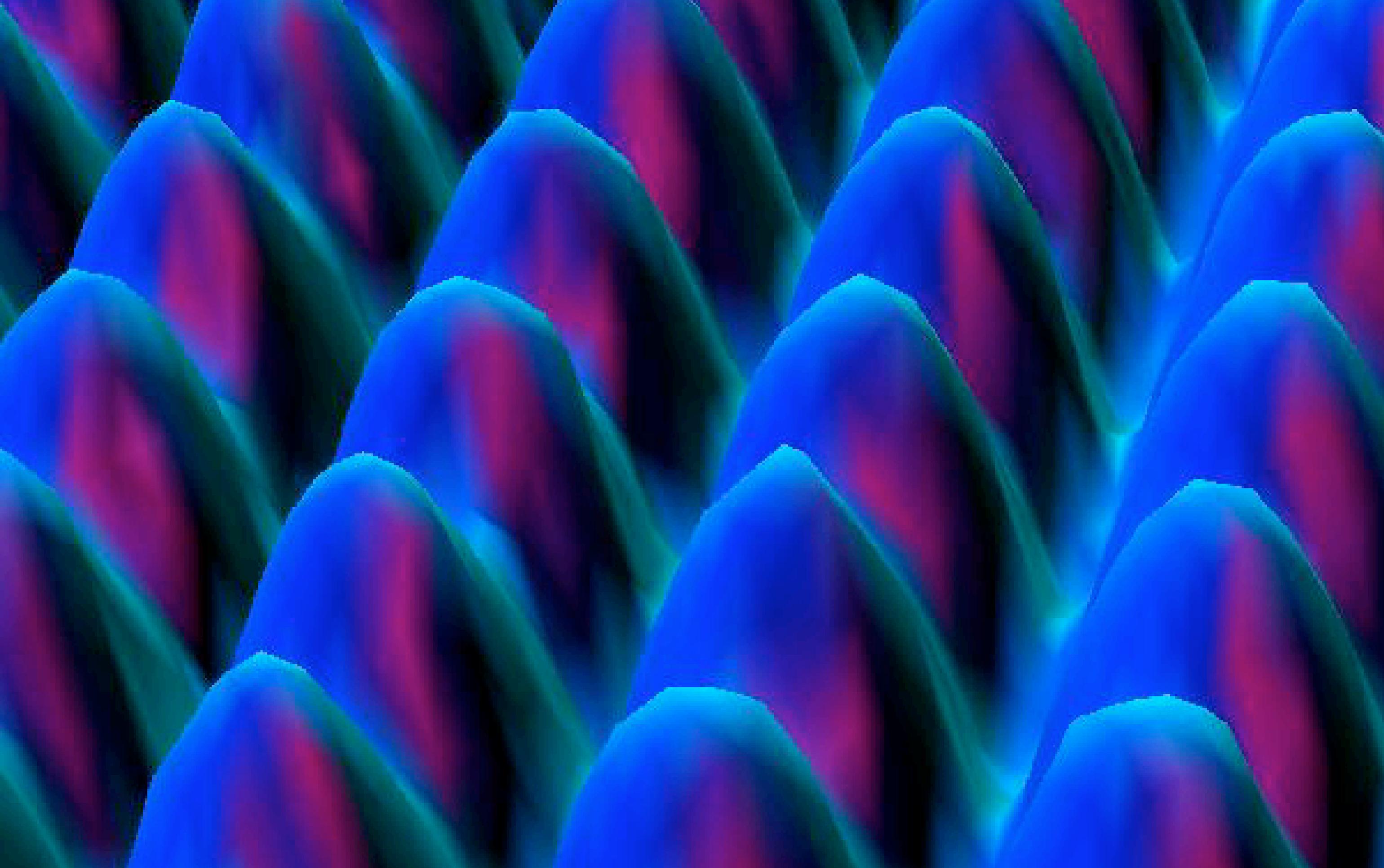
5. *Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen;*  
von A. Einstein.

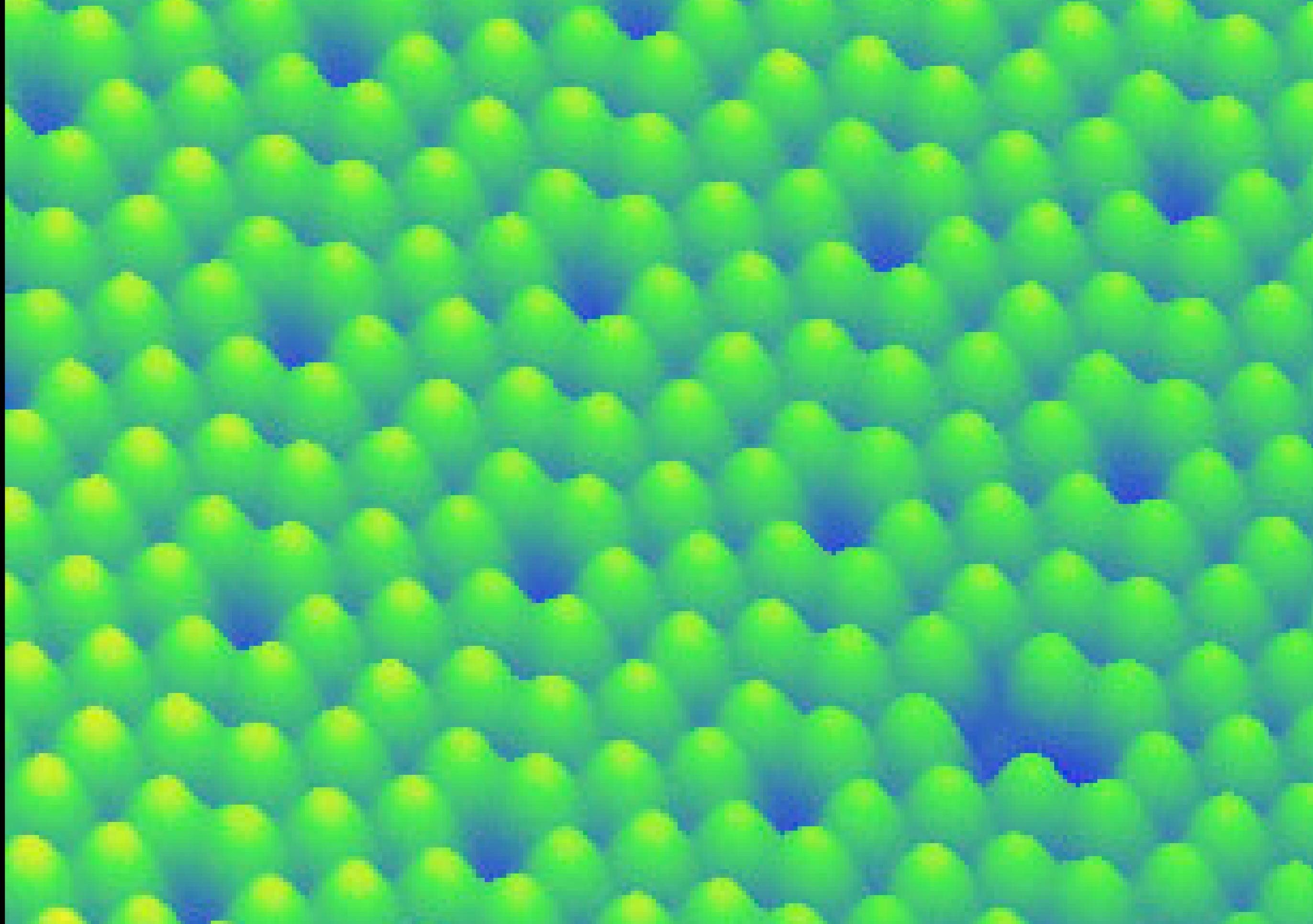
In dieser Arbeit soll gezeigt werden, daß nach der molekularkinetischen Theorie der Wärme in Flüssigkeiten suspendierte Körper von mikroskopisch sichtbarer Größe infolge der Molekularbewegung der Wärme Bewegungen von solcher Größe ausführen müssen, daß diese Bewegungen leicht mit dem Mikroskop nachgewiesen 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, daß ich mir hierüber kein Urteil bilden konnte.

(1) 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 der Wärme gegeben.

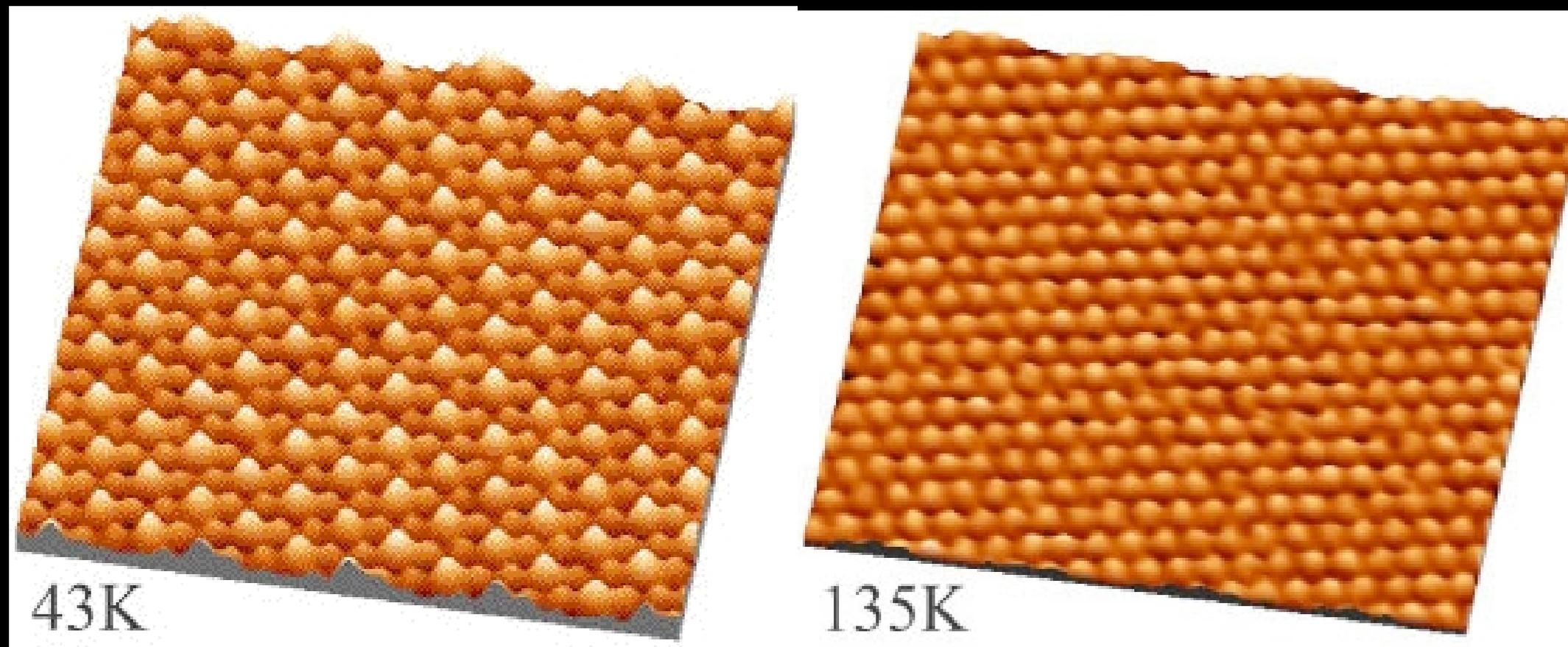
§ 1. *Über den suspendierten Teilchen zuschreibenden osmotischen Druck.*

Im Teilvolumen  $V^*$  einer Flüssigkeit vom Gesamtvolumen  $V$  seien  $x$ -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-





Nanophysics ...  
lead on silicon



José Gómez-Rodríguez et al., Madrid



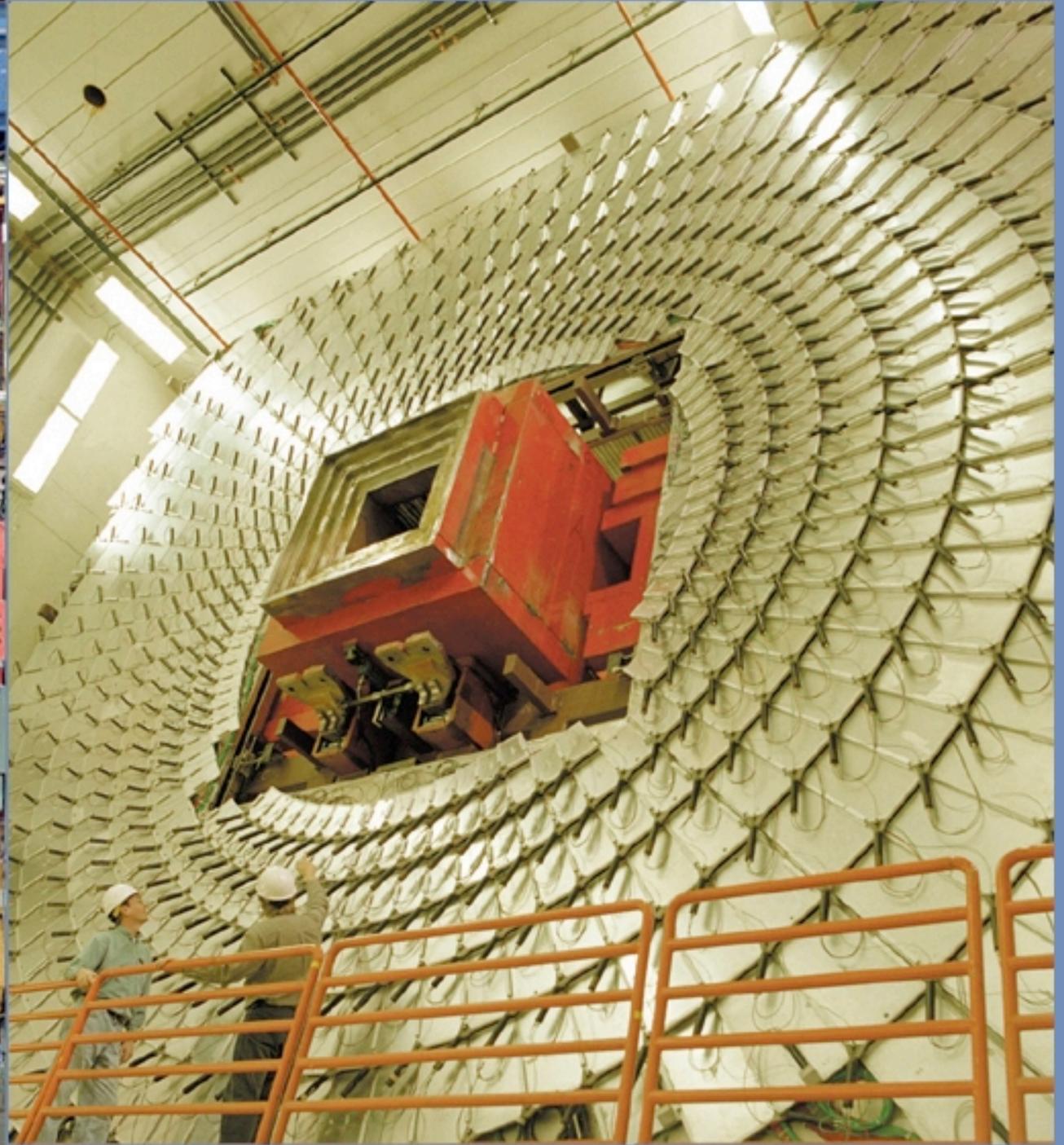
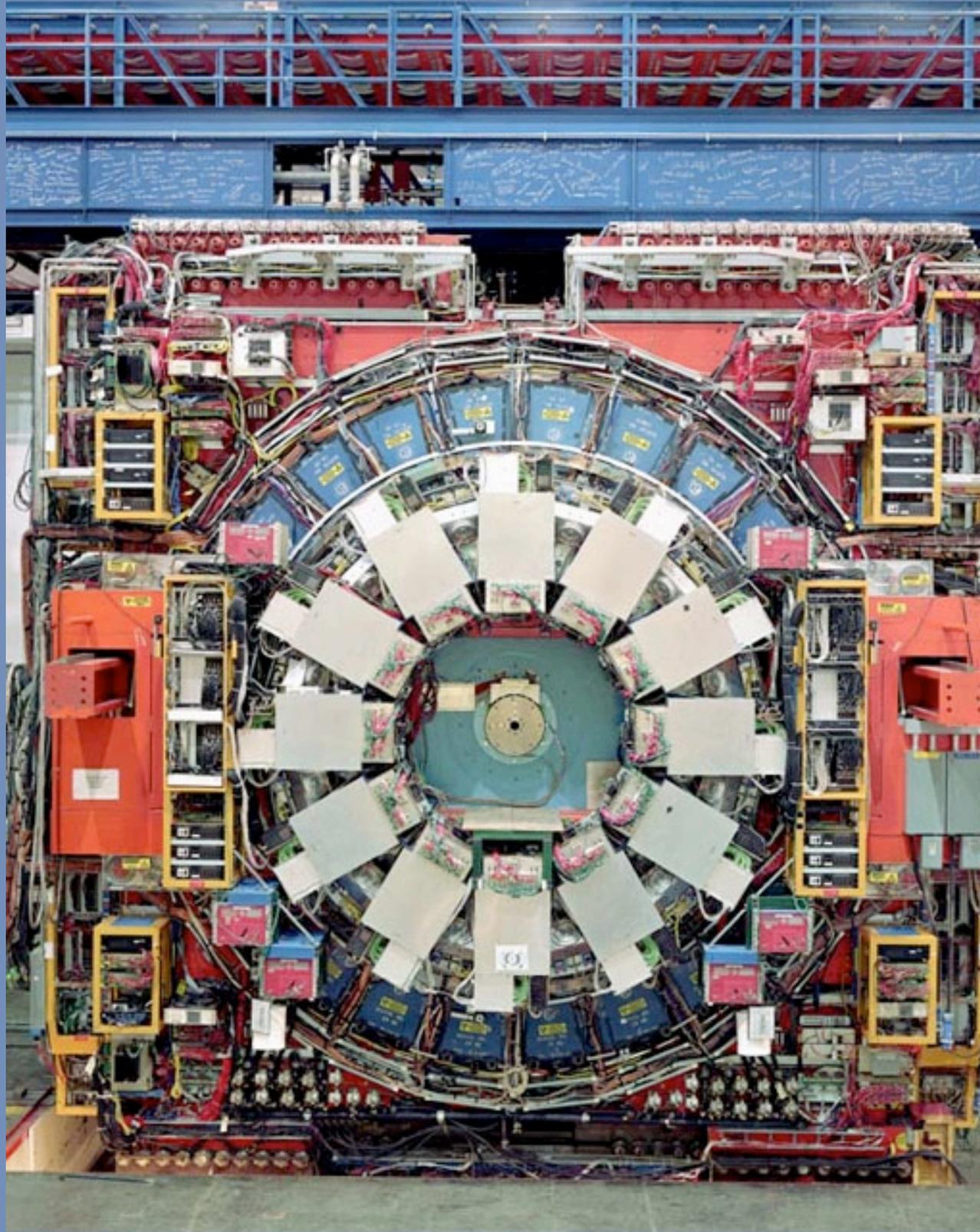
# The World's Most Powerful Microscope where nanonano physicists work!

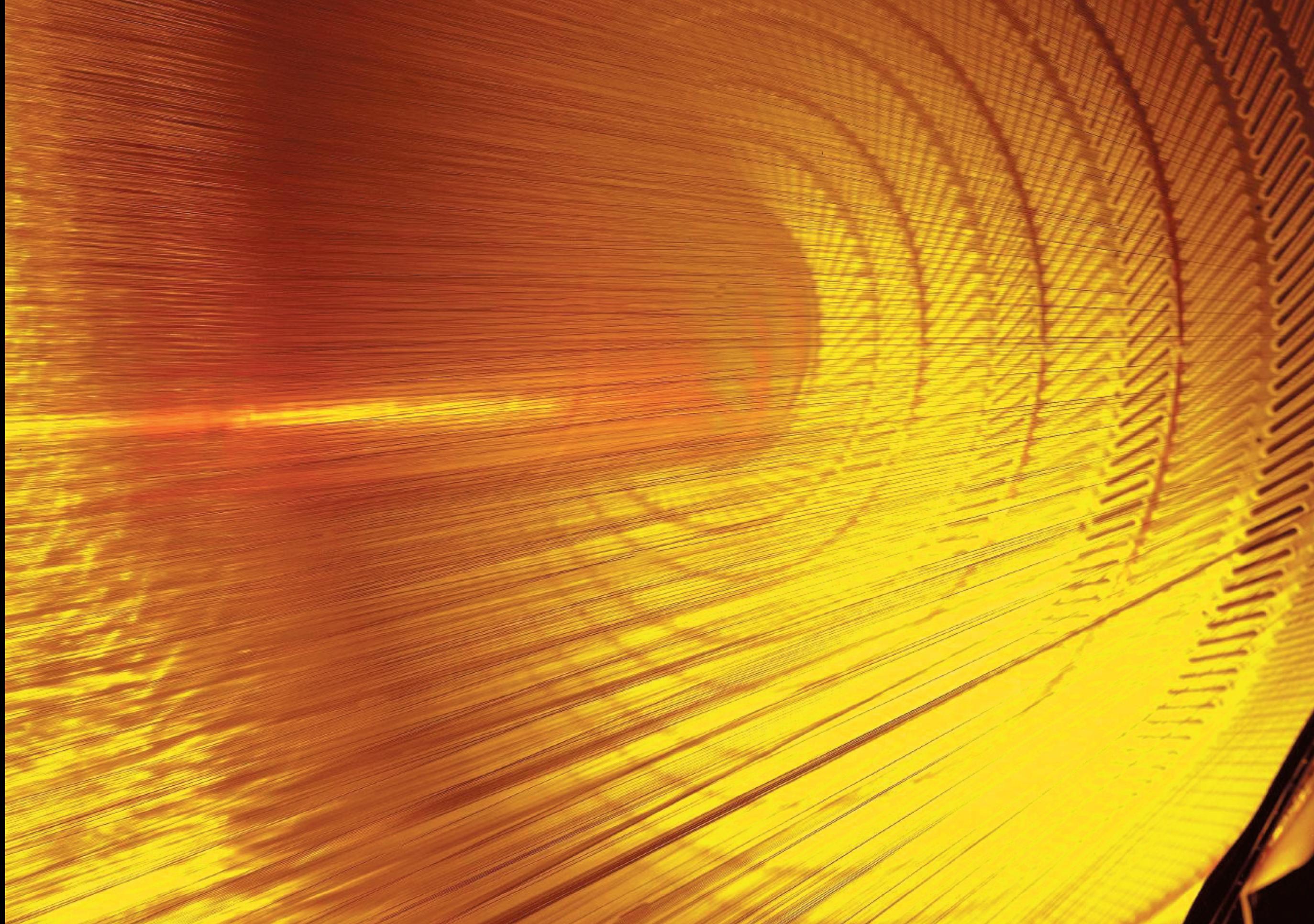
Tevatron Collider at Fermilab and its detectors  
protons on antiprotons (1 TeV)

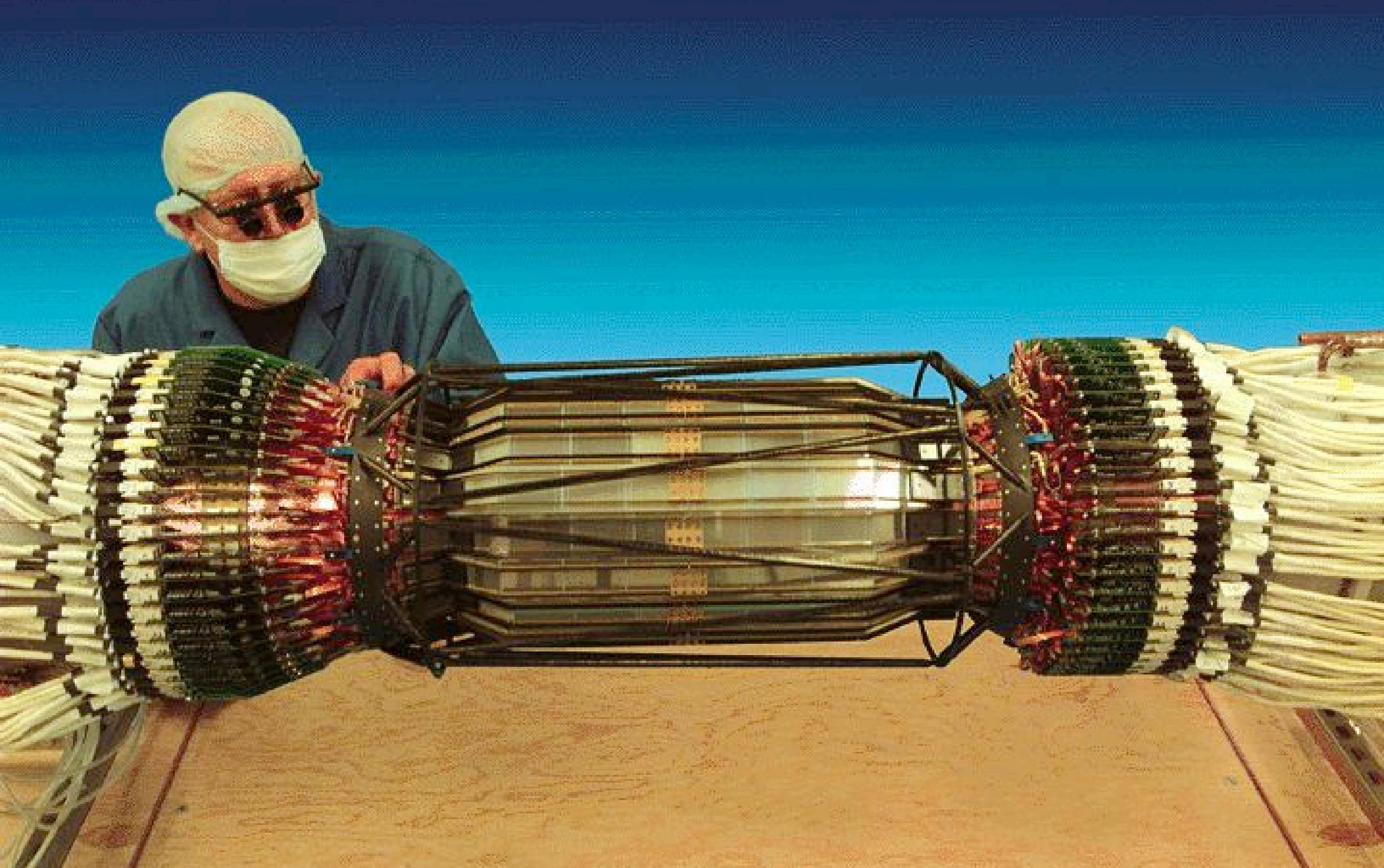
speed of light :  $c \approx 10^9$  km/h

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

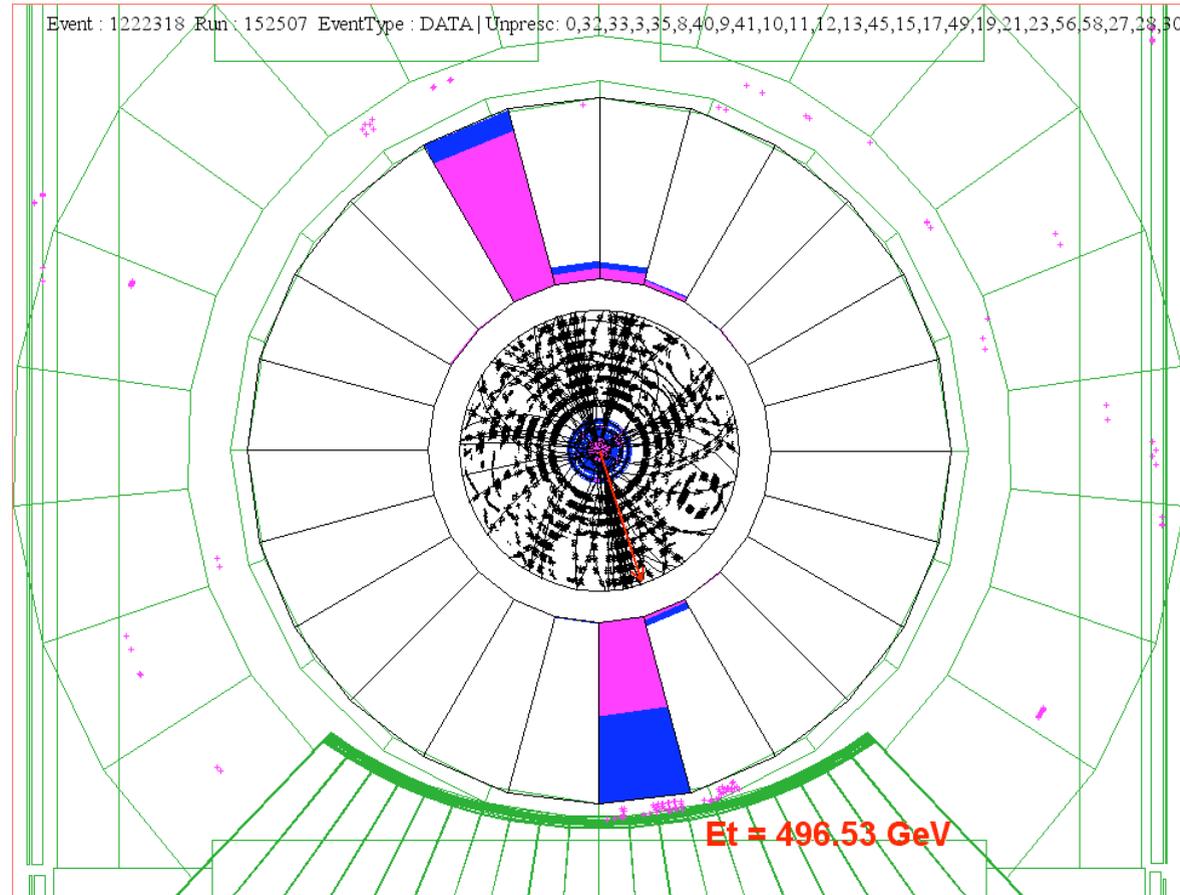
Protons pass my window 45 000 times a second  
10 millions collisions per second





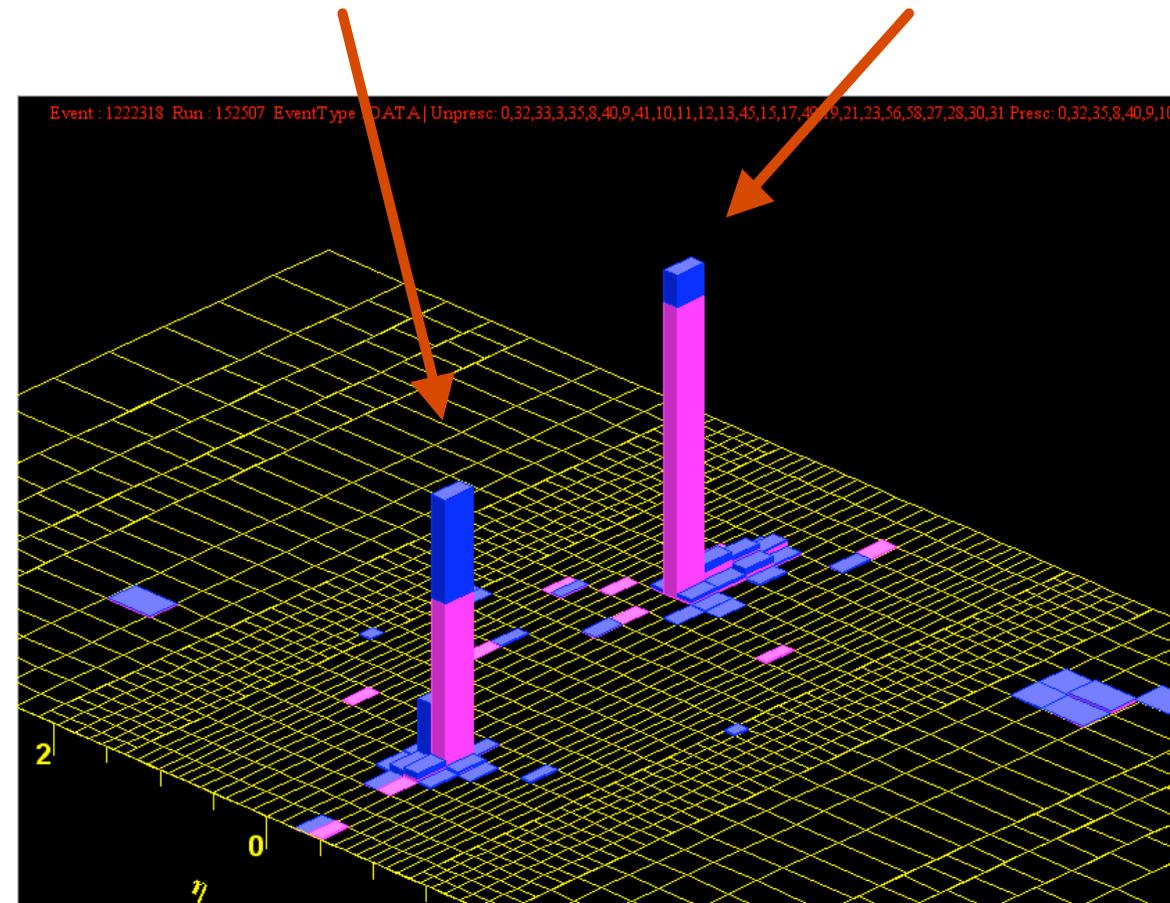


Run 152507 event 1222318  
Dijet Mass = 1364 GeV (corr)  
 $\cos \theta^* = 0.30$   
z vertex = -25 cm

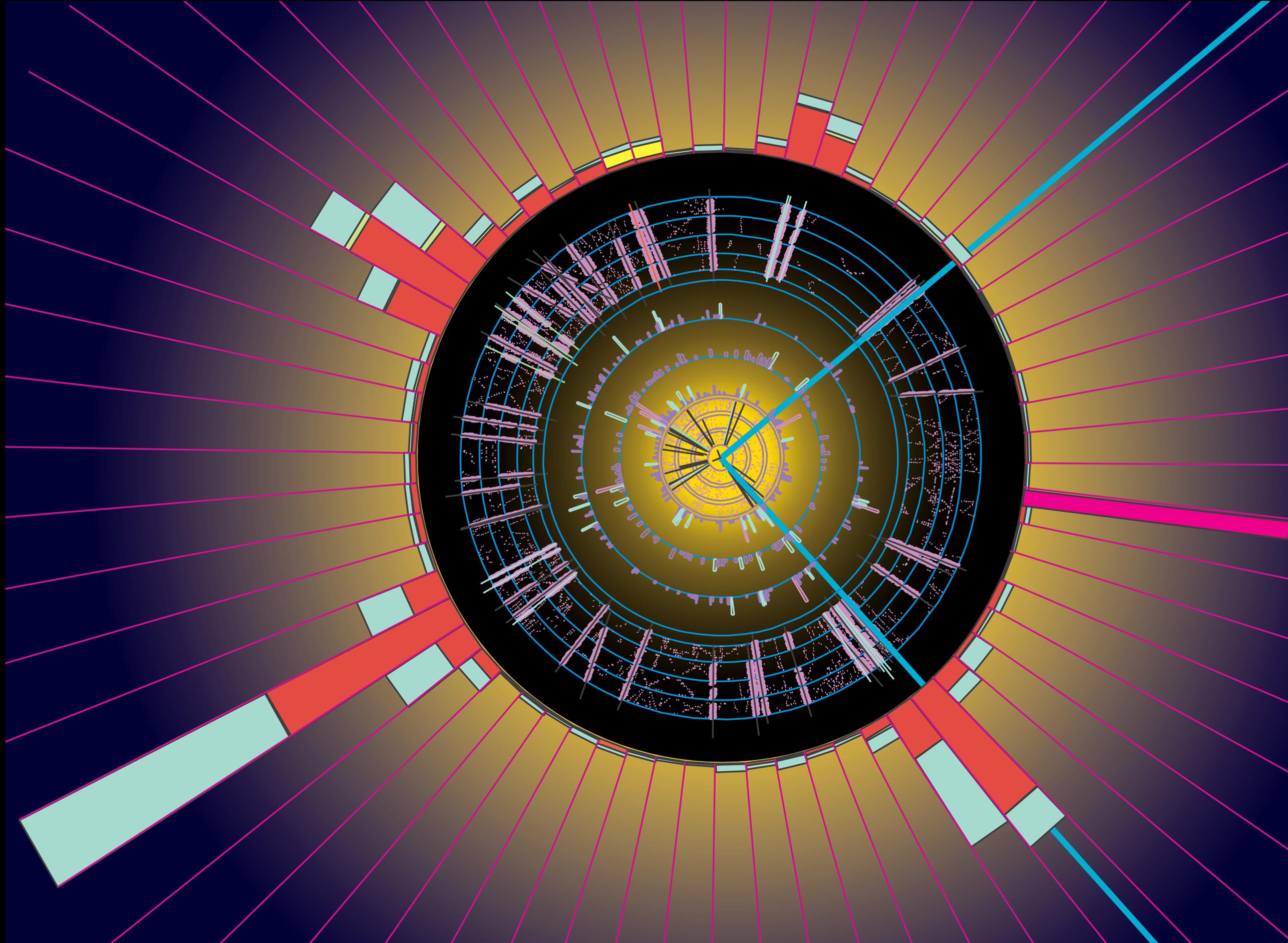


J2  $E_T = 633$  GeV (corr)  
546 GeV (raw)  
J2  $\eta = -0.30$  (detector)  
= -0.19 (correct z)

J1  $E_T = 666$  GeV (corr)  
583 GeV (raw)  
J1  $\eta = 0.31$  (detector)  
= 0.43 (correct z)



CDF Run 2 Preliminary

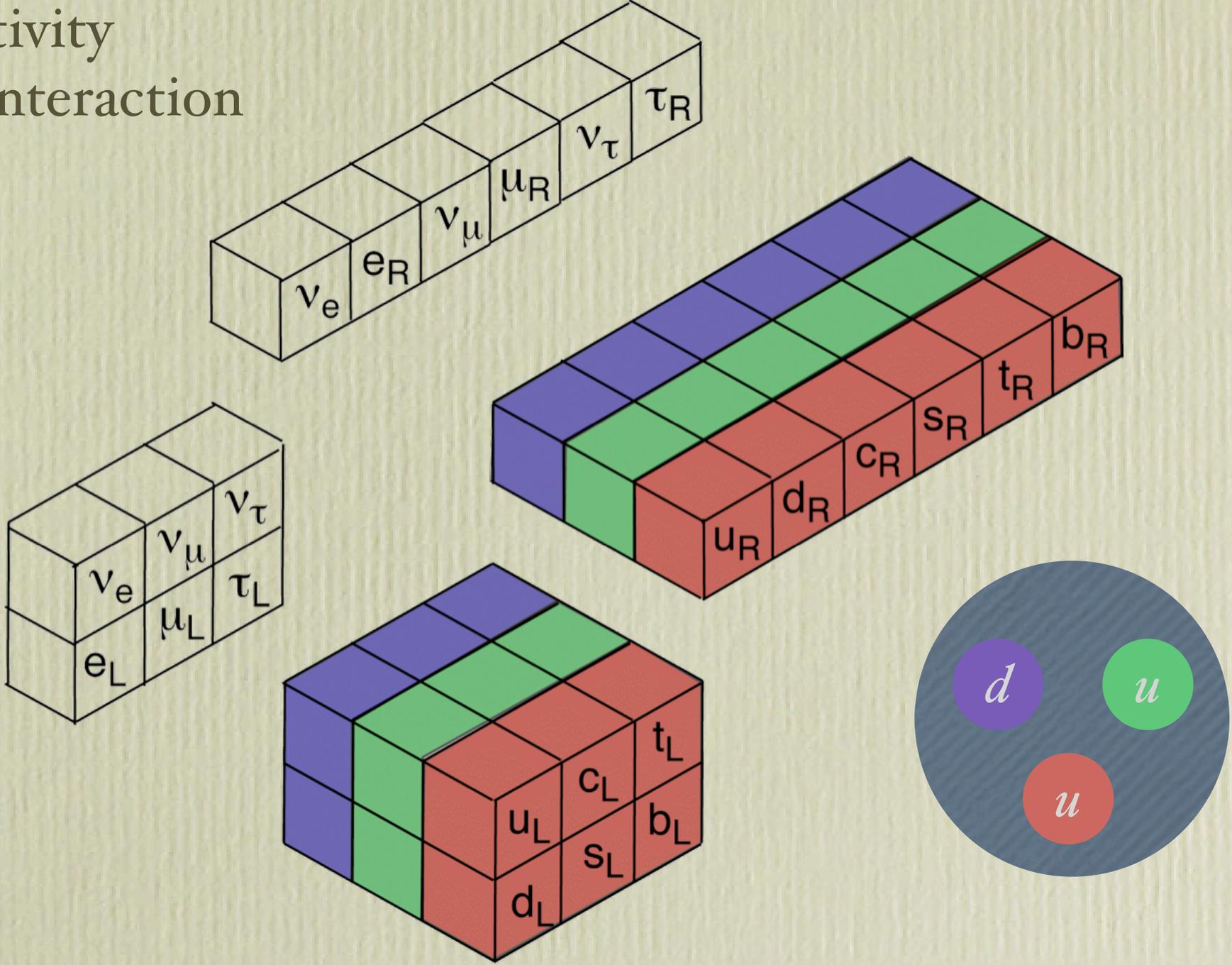


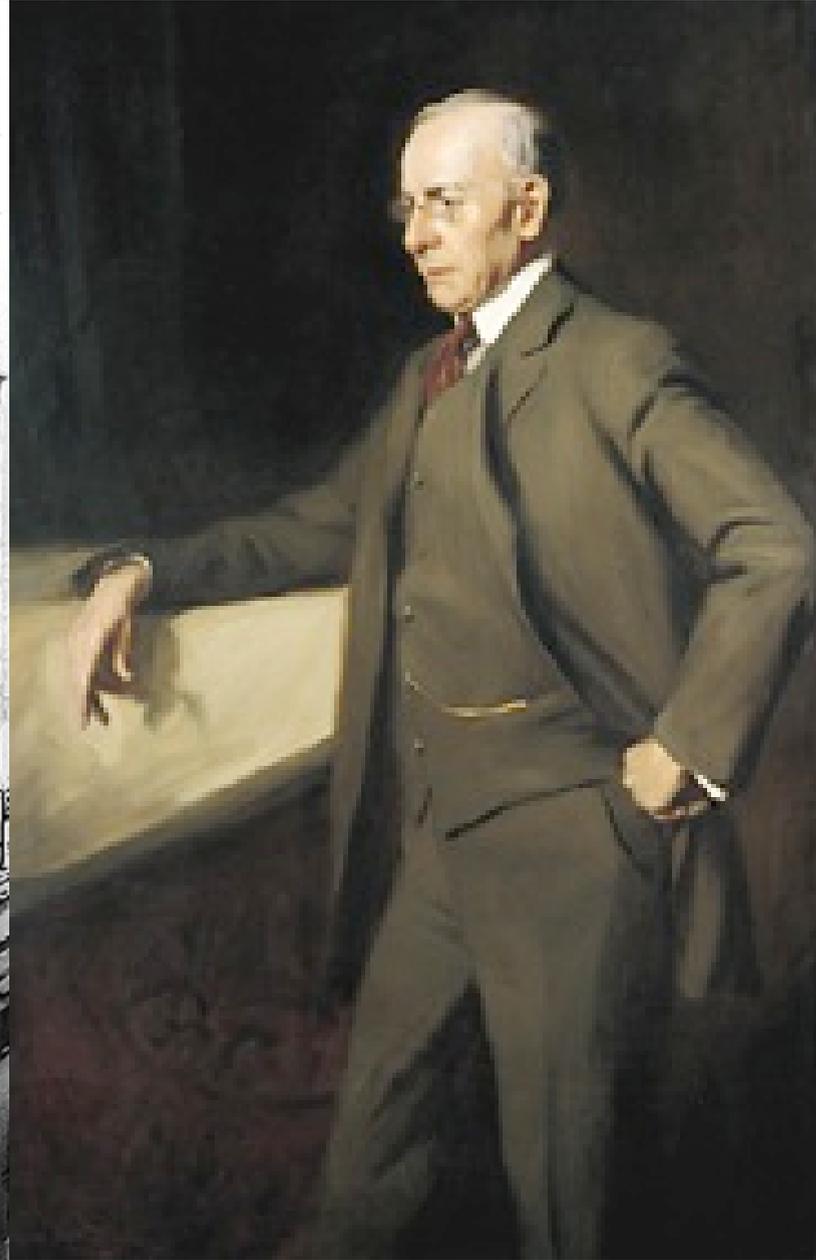
# Particle accelerators are time machines ...

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.

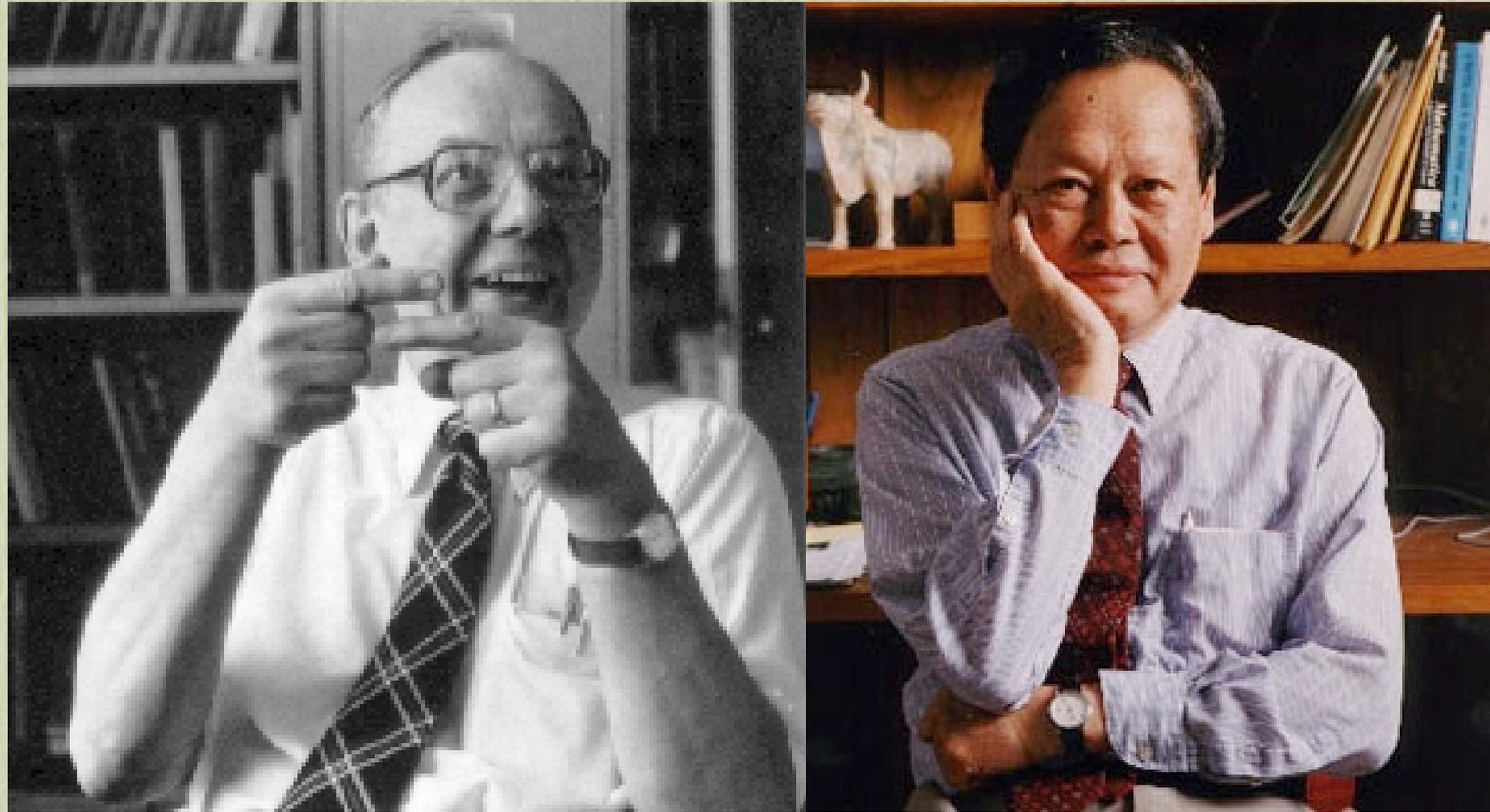
(now back to 1 picosecond)

gravitation  
electromagnetism  
radioactivity  
strong interaction





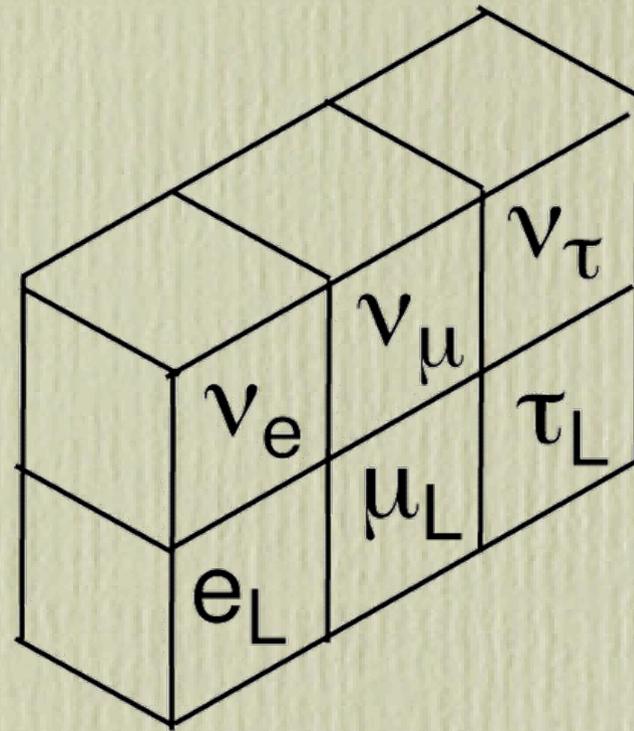
Louis Sullivan, architect (1896)  
Form follows function



Robert Mills (1954) Yang Chen Ning

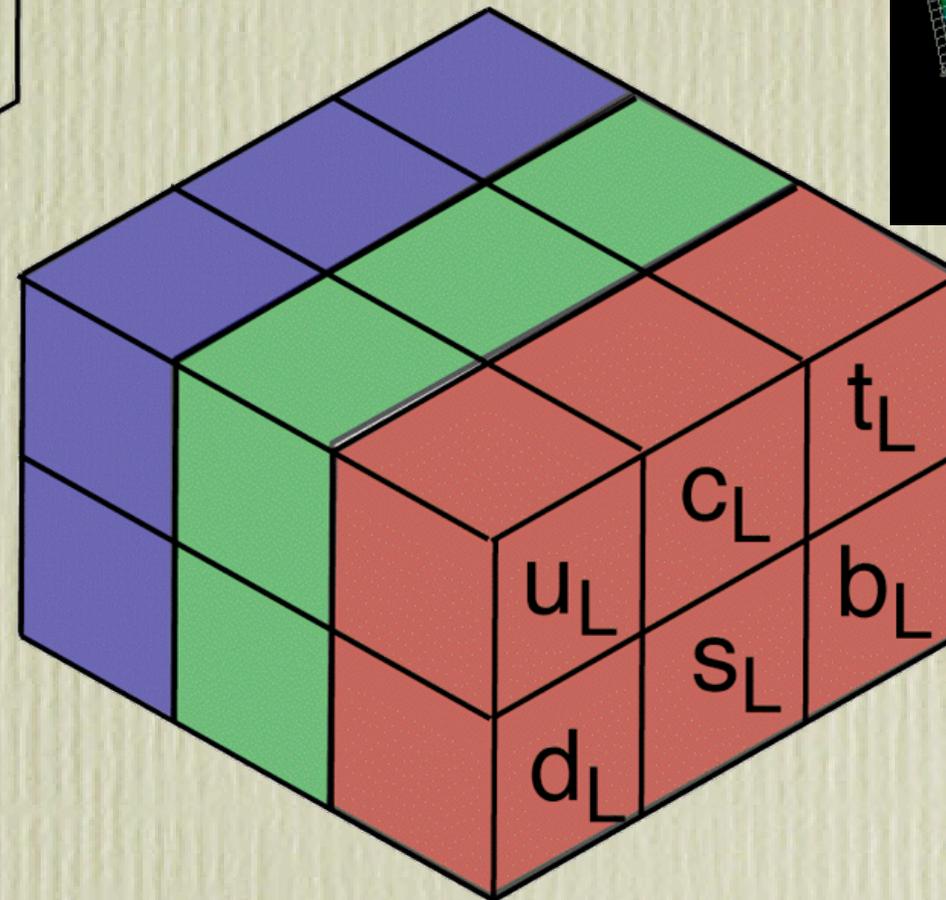
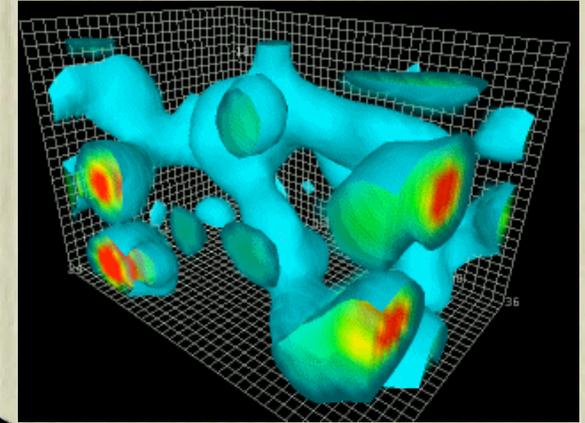
Function follows form

Interactions follow from symmetry



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

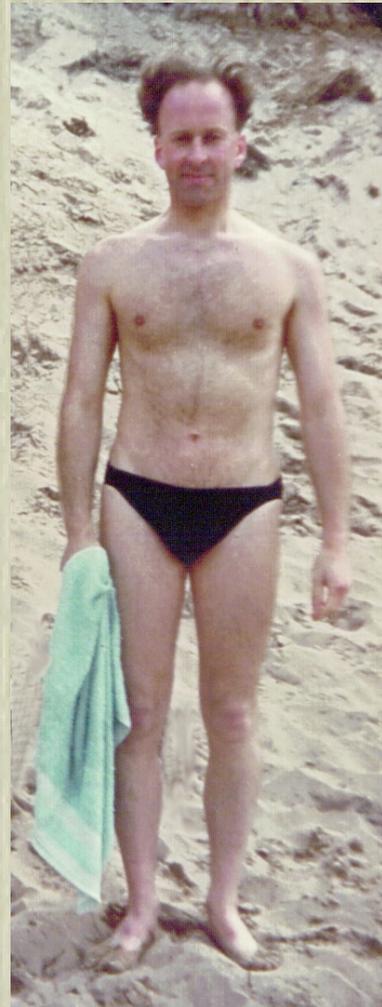
- New kind of force? Higgs field?
- New force from a new symmetry?
- Residual force from strong dynamics?
- Echo of extra spacetime dimensions?

Which path has nature taken?

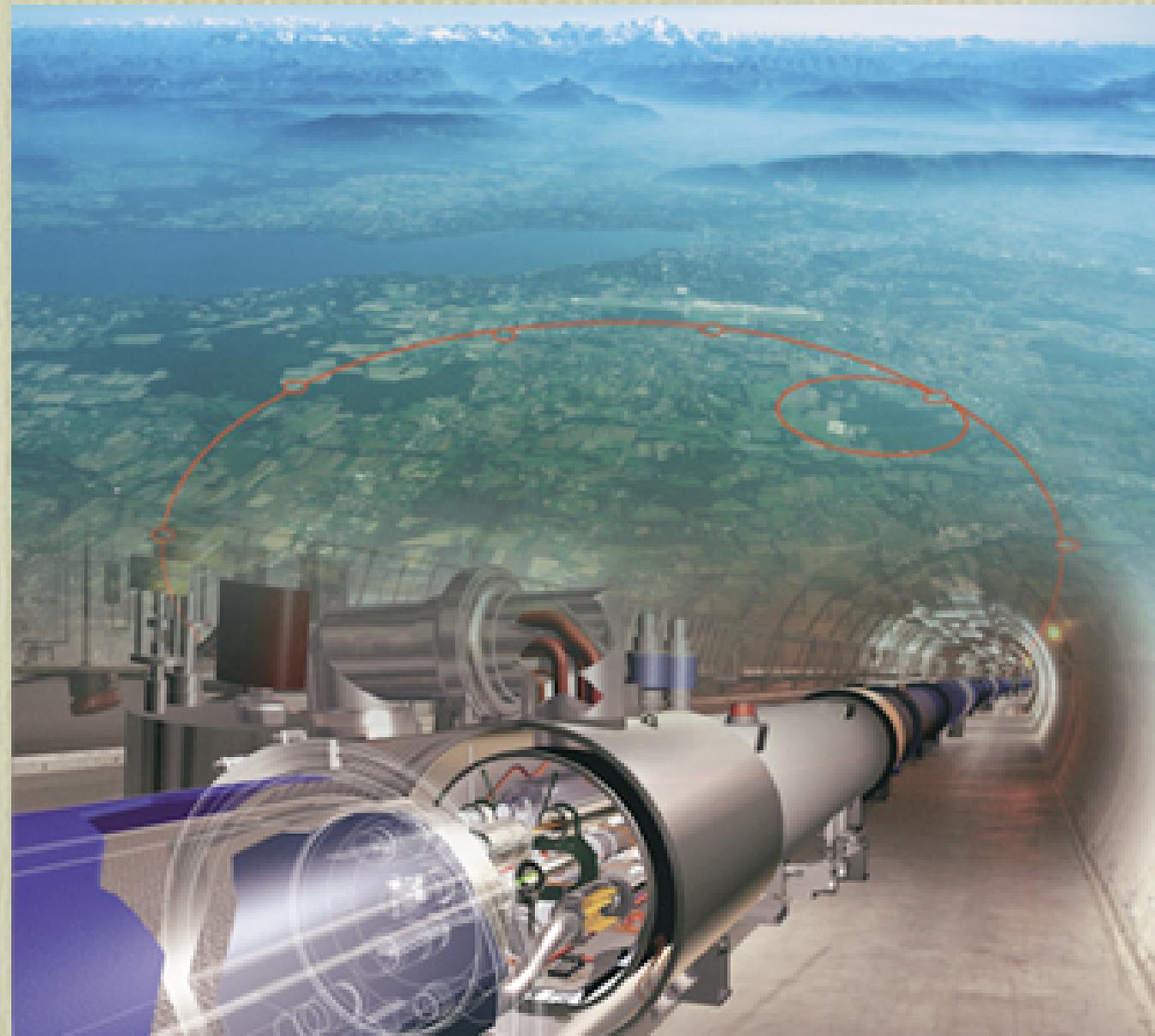
Experiments at 1 TeV will tell

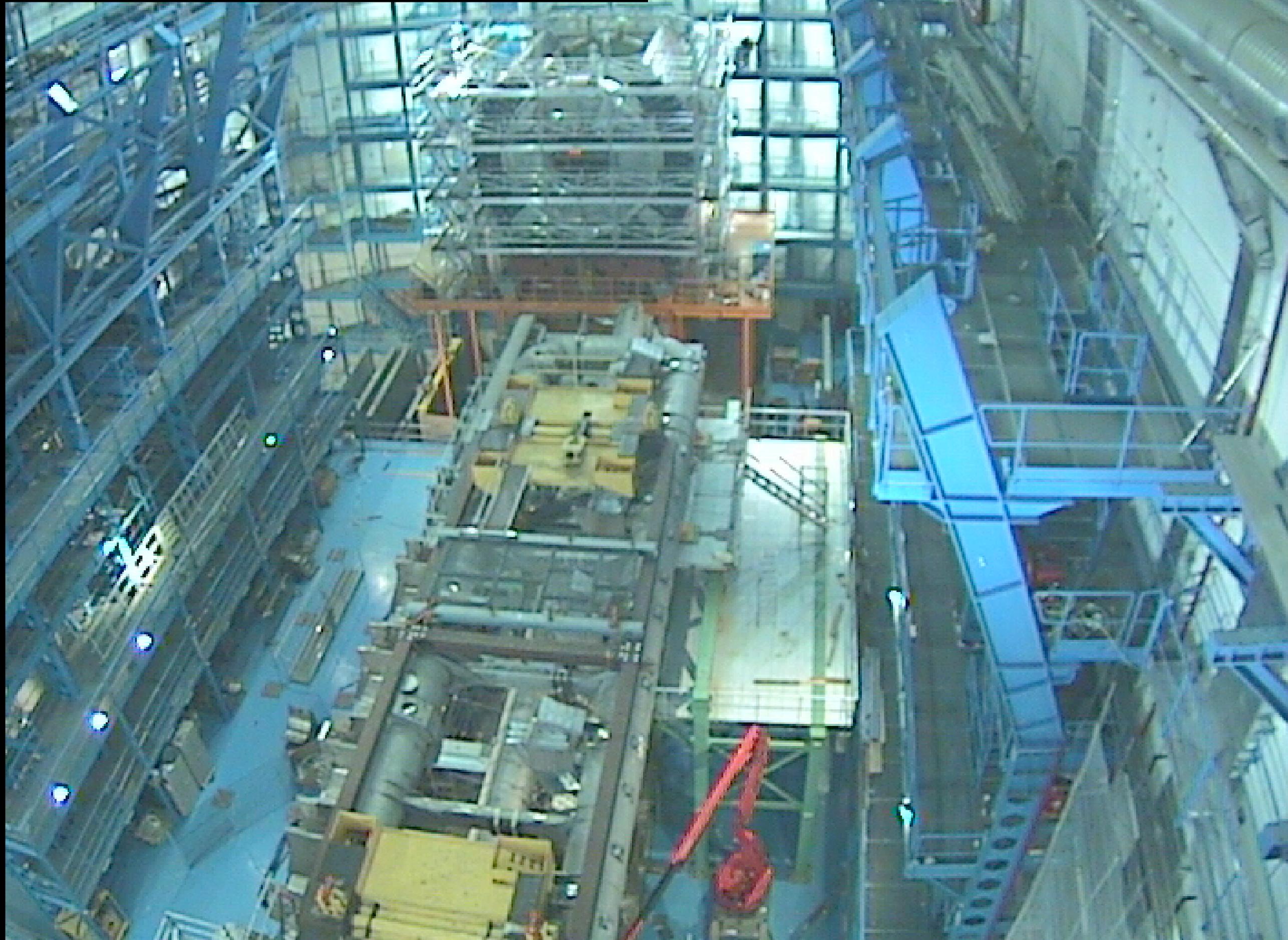
# Searching for the *agent provocateur* of electroweak symmetry breaking

« the search for the Higgs boson »



Coming to CERN 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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# HIGGS BOSON

Compact Disc  
Digital Audio  
Stereo



Produced by  
Gareth Young  
and Higgs Boson  
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# Revolution: the meaning of identity

- What sets quark & lepton masses?
- What is CP violation is telling us?
- Neutrino observations a new take:  
key to matter excess in Universe?
- New kinds of matter show us pattern?  
dark matter, superpartners, ...

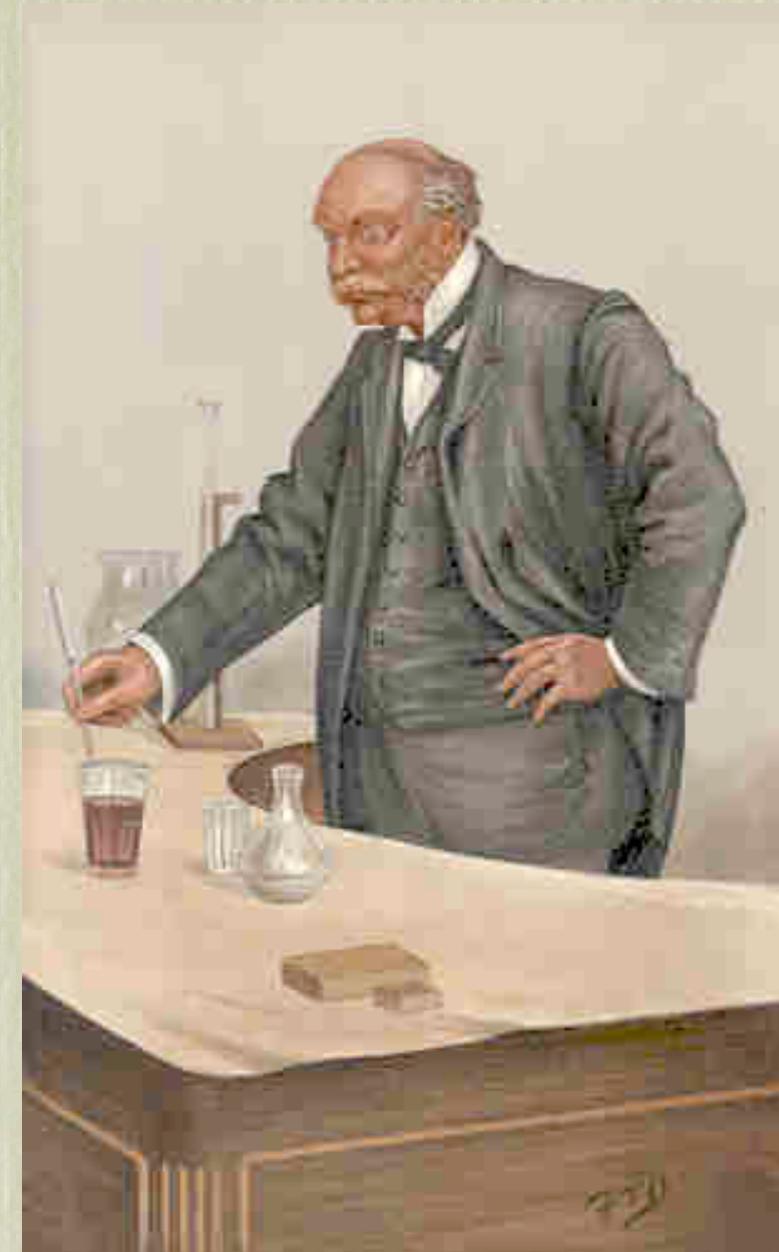
Mendele'ev didn't know about noble gases

# 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.”



Lord Rayleigh

# Neutrinos ( $\nu$ )...

are tiny subatomic particles

carry no electric charge

have (almost) no mass,

move (nearly) at the speed of light

hardly interact at all

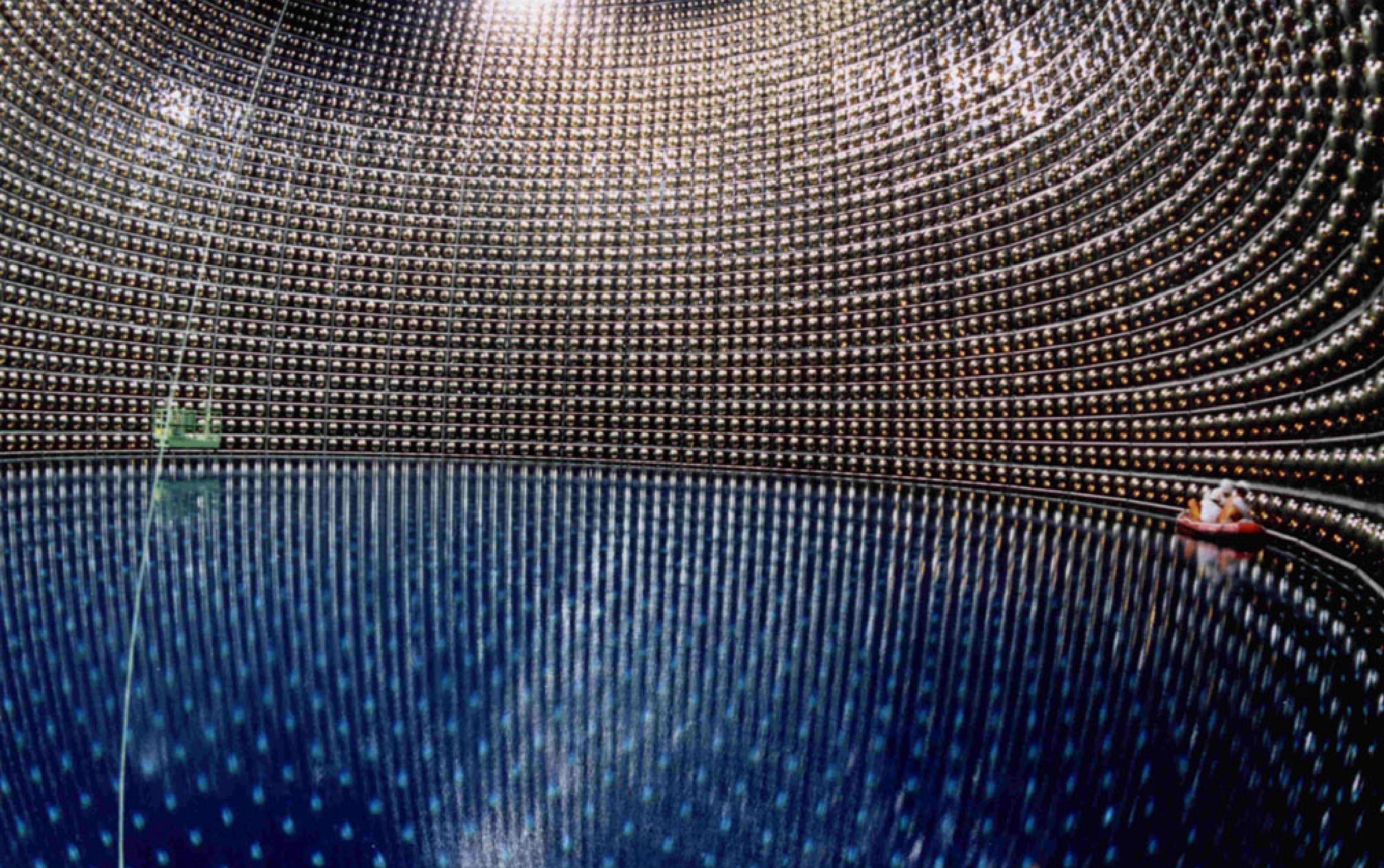
# Each second ...

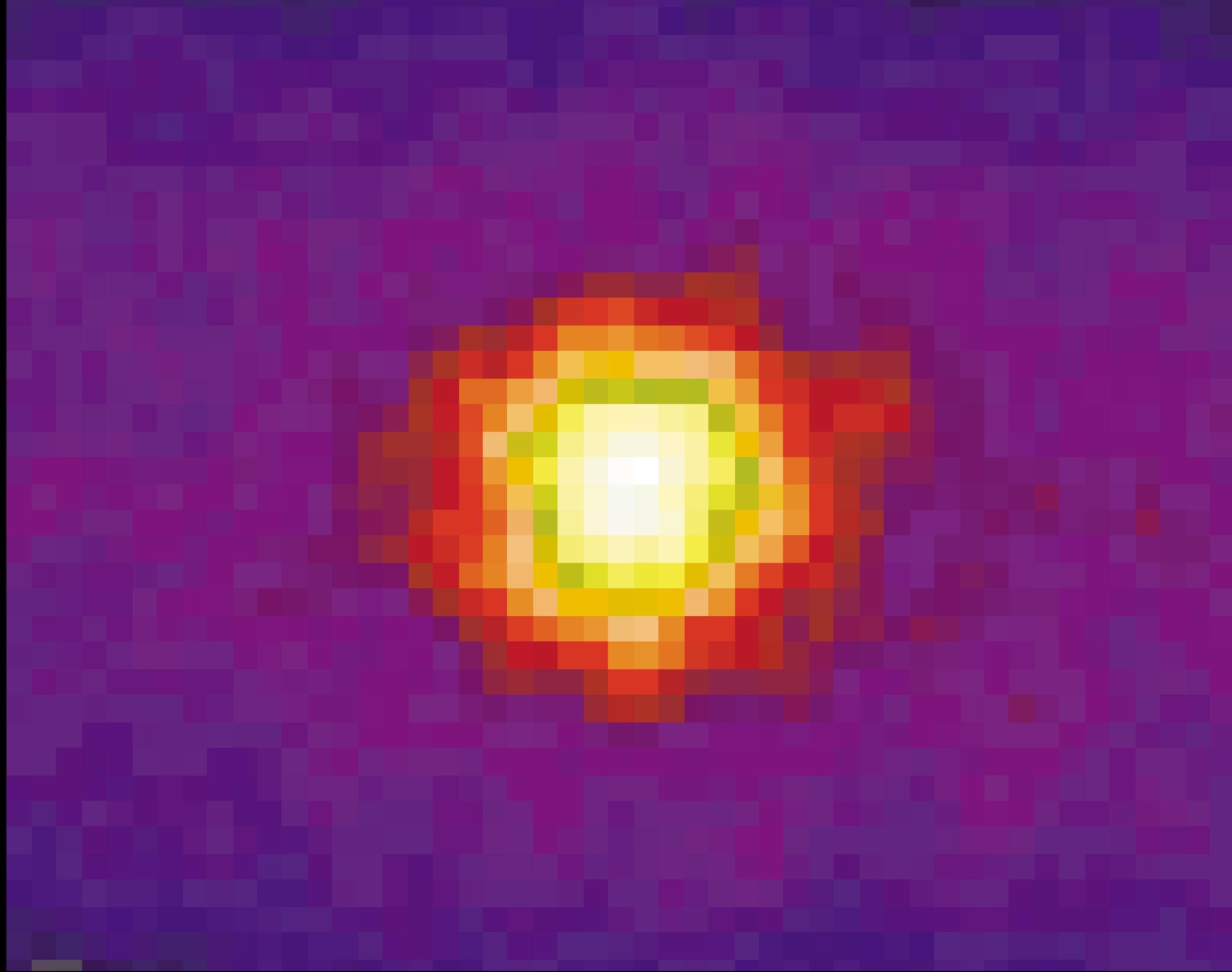
**100 trillion** neutrinos produced in the Sun pass through your body

**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

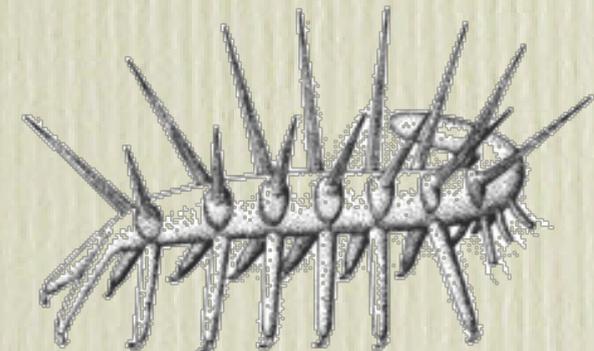
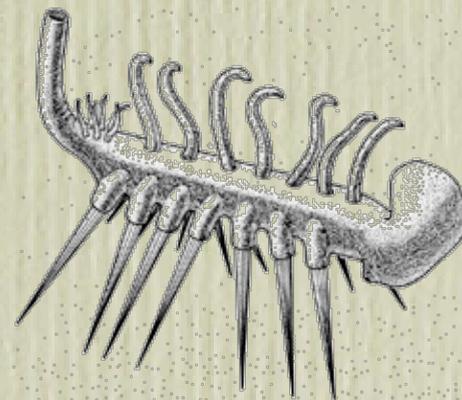
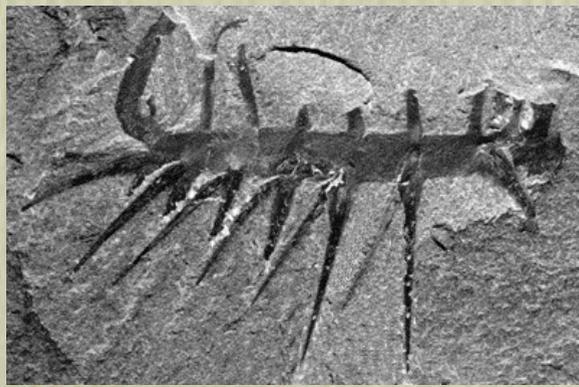
# A Chronic Dull Headache ...

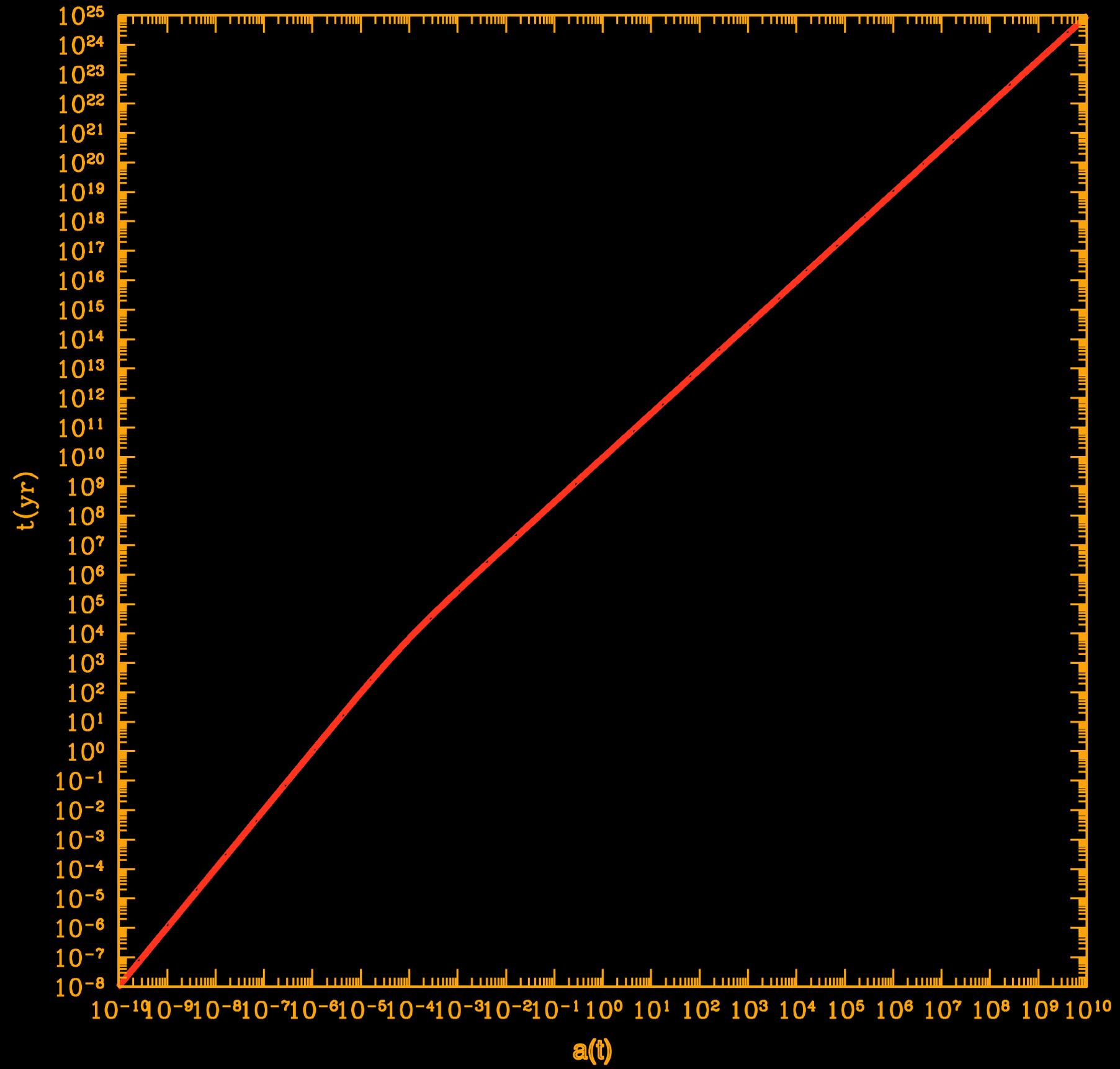
## ... for thirty years

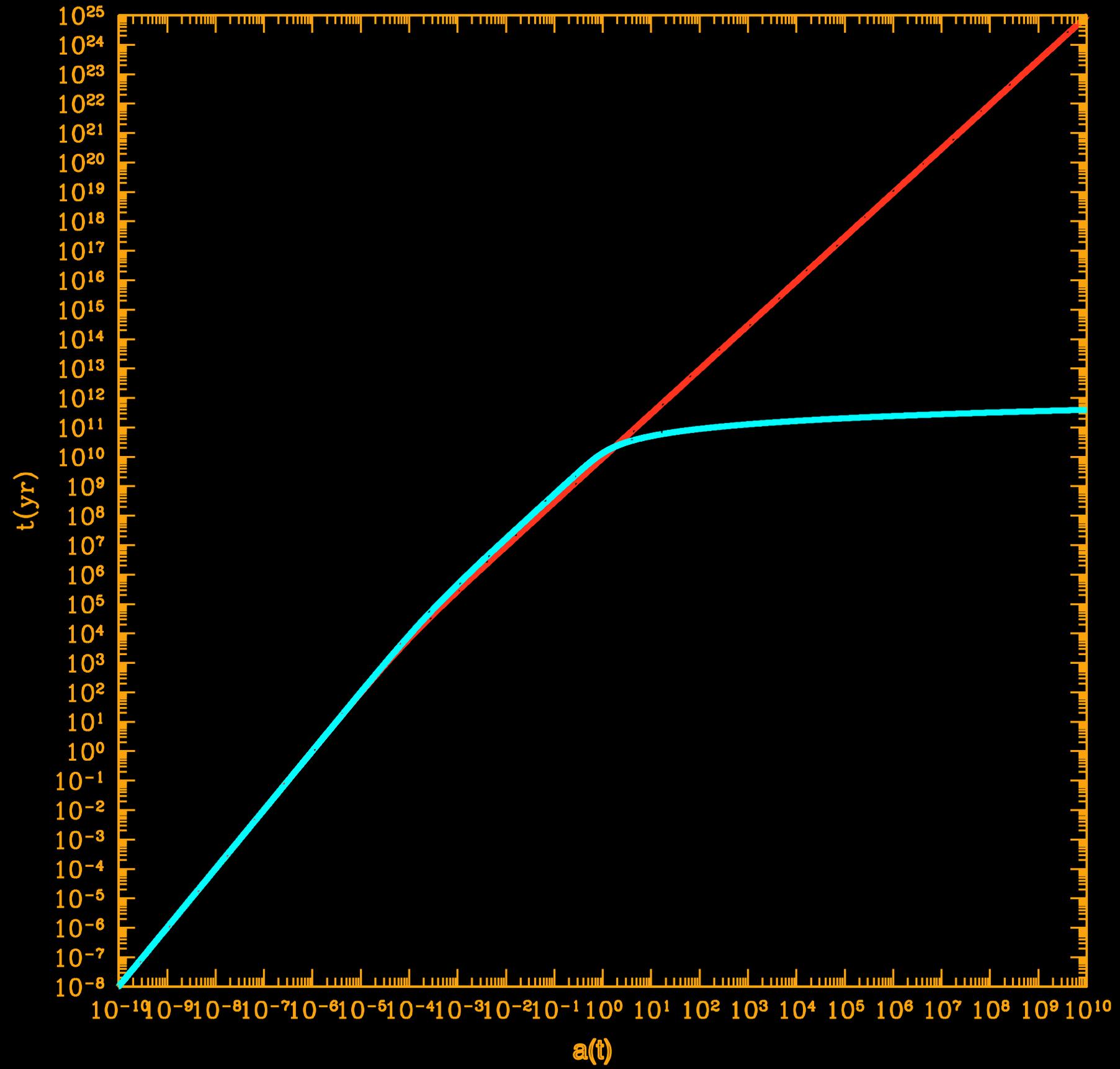
- Higgs field fills all of space with energy density  $10^{25}$  g/cc
- But empty space weighs next to nothing:  $< 10^{-29}$  g/cc
- Evidence that vacuum energy is present (accelerating universe) recasts problem

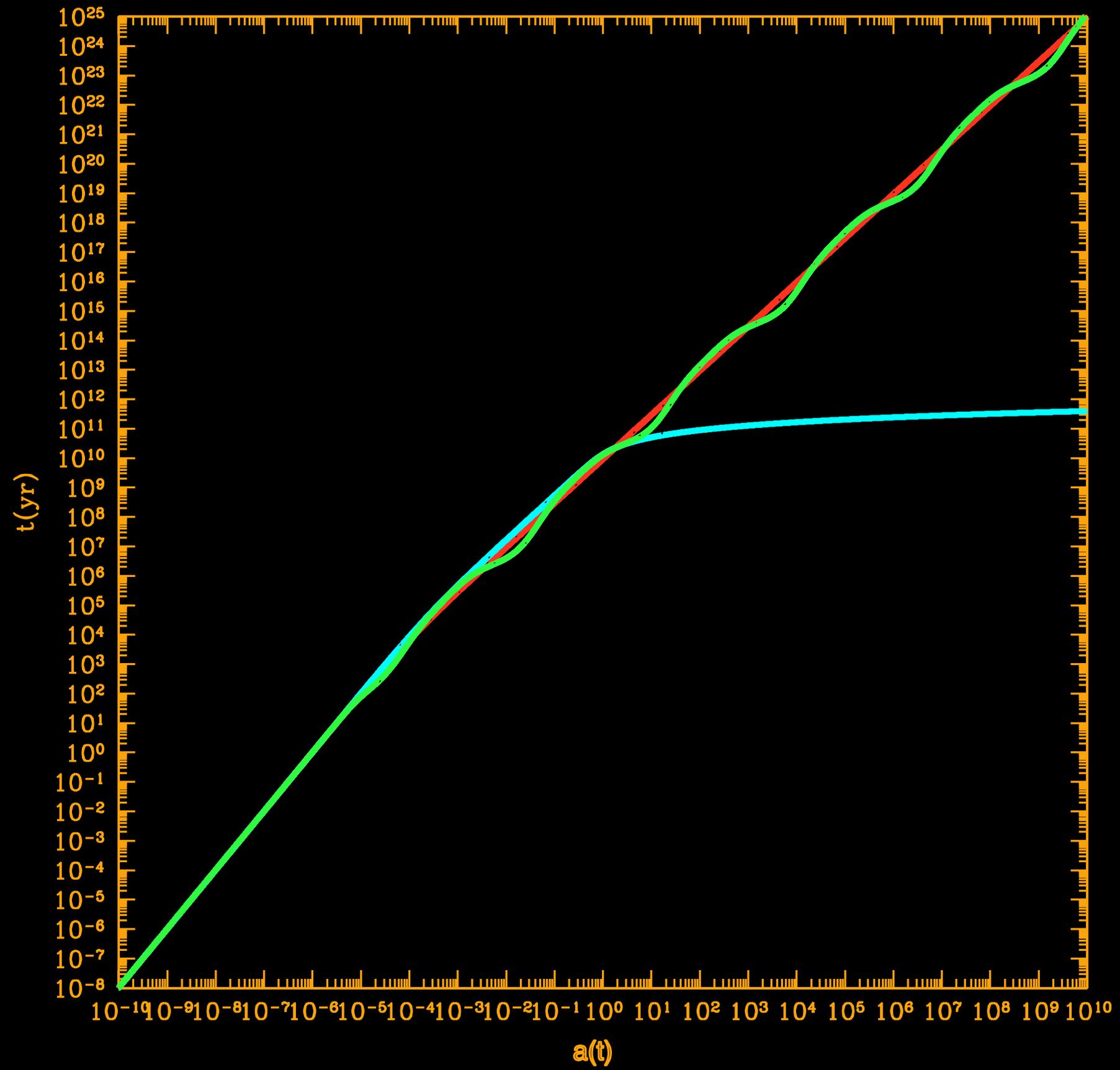
# Implications for ... the fate of the universe

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









# Revolution:

## New Conception of Spacetime

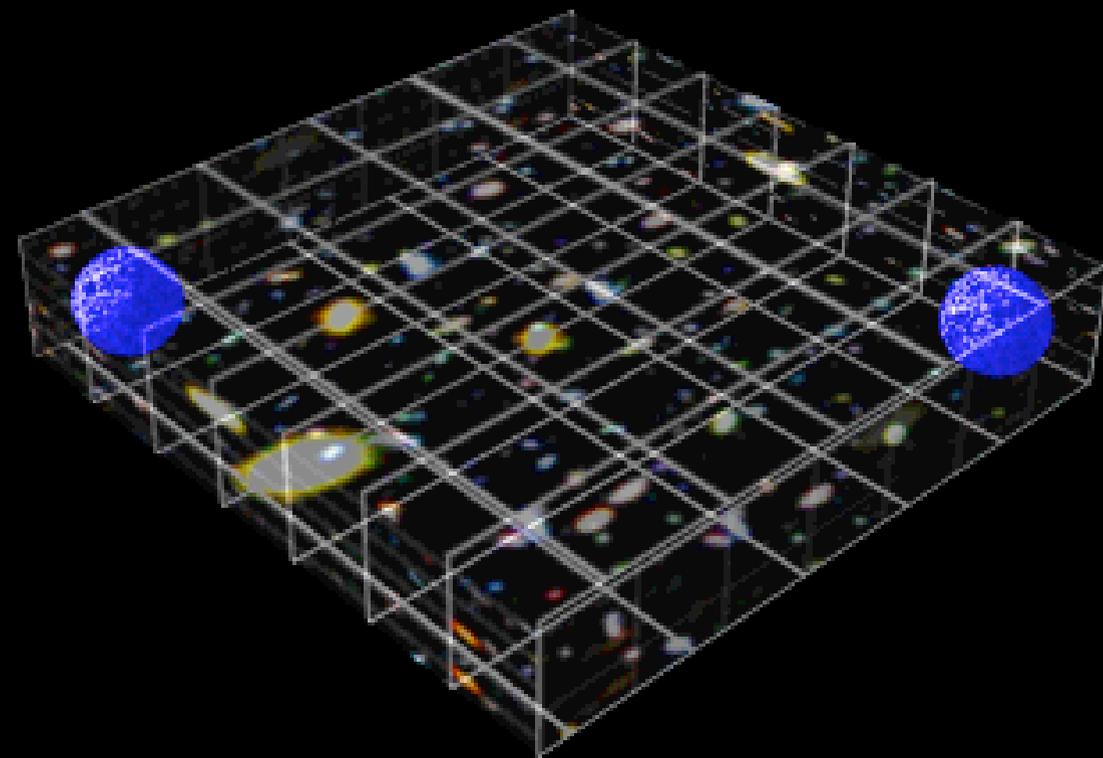
- More space dimensions?
- What is their size? their shape?
- How do they influence our world?
- How can we map them?

(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:  $1/r^{2+n}$



*Explain a complicated visible  
by a simple invisible ...*

## Thanks to ...

Eric Weeks for the film of Brownian motion  
[www.physics.emory.edu/~weeks](http://www.physics.emory.edu/~weeks)

Derek Leinweber for the QCD animation

Angela Gonzales for the pearl in a bottle

J. D. Jackson for the photo of Peter Higgs

Liubo Borissov for the animation