The Coming Revolutions in Particle Physics

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The Great Lesson of Twentieth-Century Science

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

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."

RADIOACTIVITY, NEW PROPERTY OF MATTER

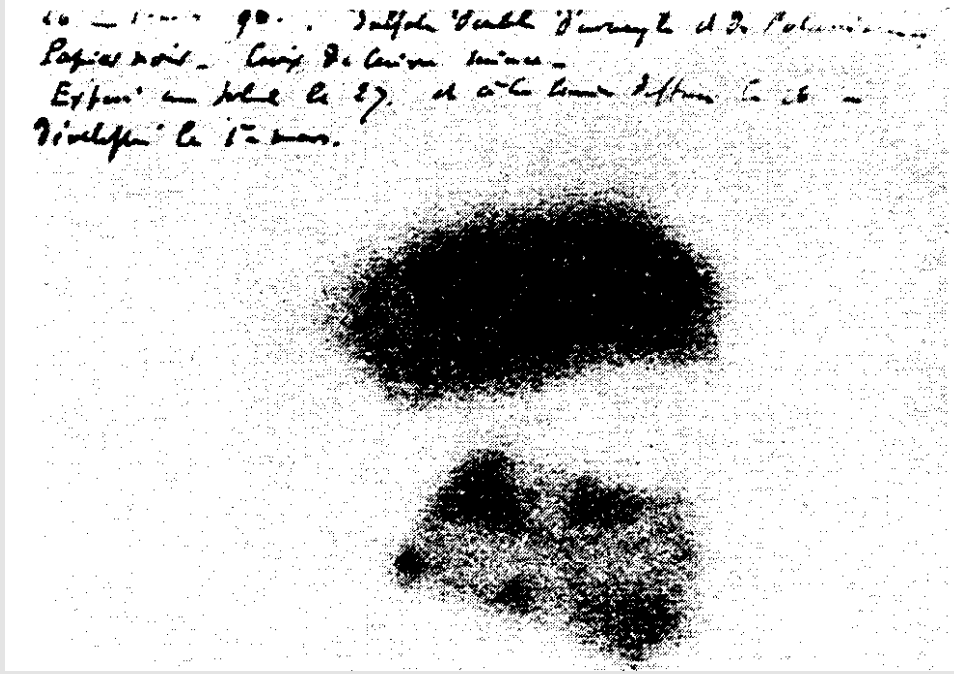
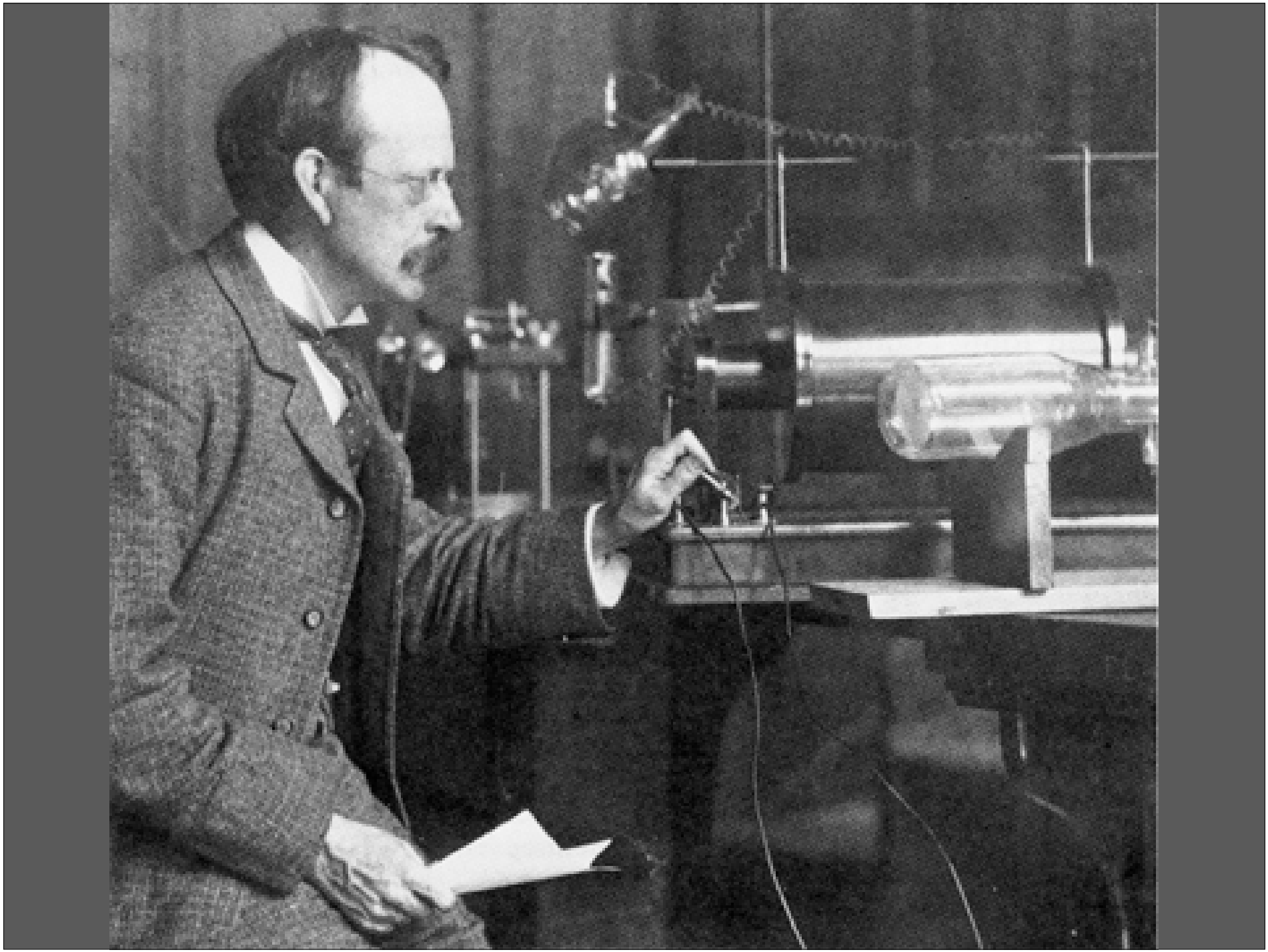
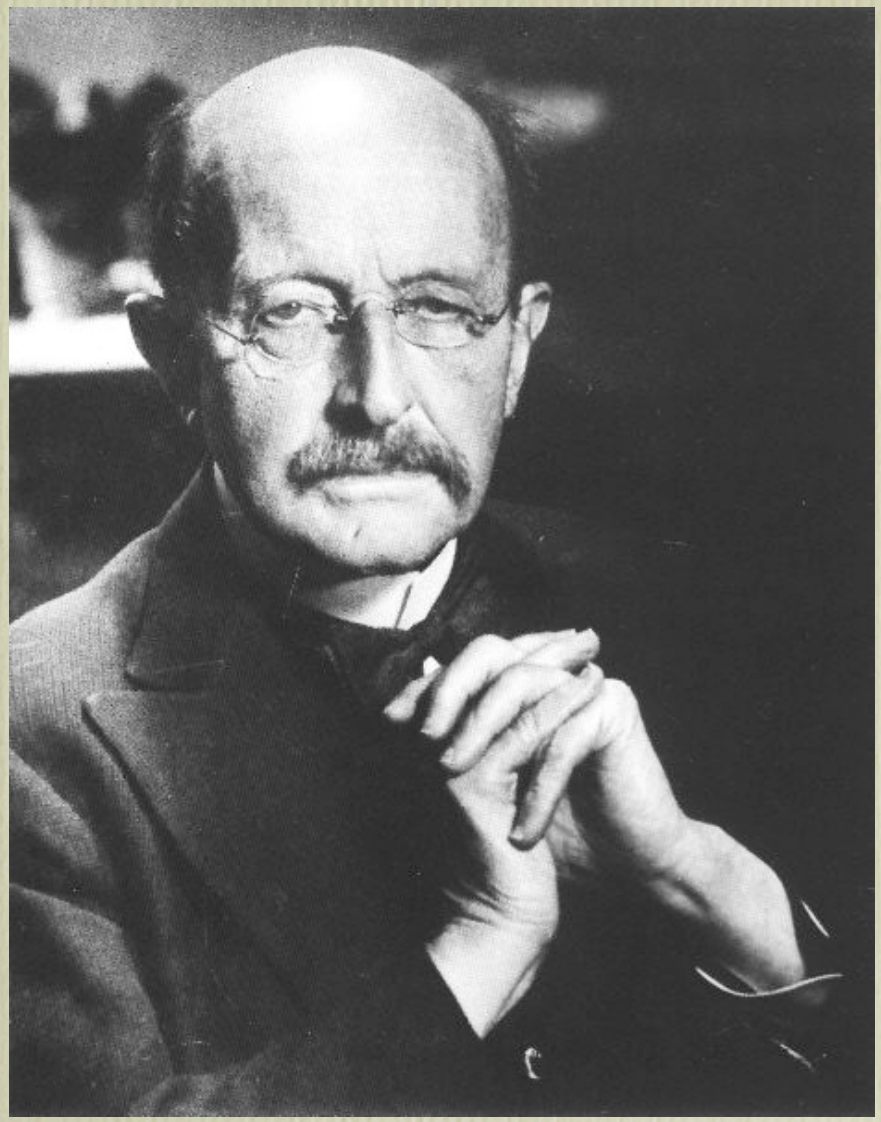


Fig.1.





A Decade of Discovery Past

- Electroweak theory: a law of nature

Successes: charm, neutral currents, W & Z bosons;
Quantum field theory tested at 1/1000

Tested from few x 10^{-17}cm to 10^{+22} cm

Origin: Coulomb's law — tabletop experiments

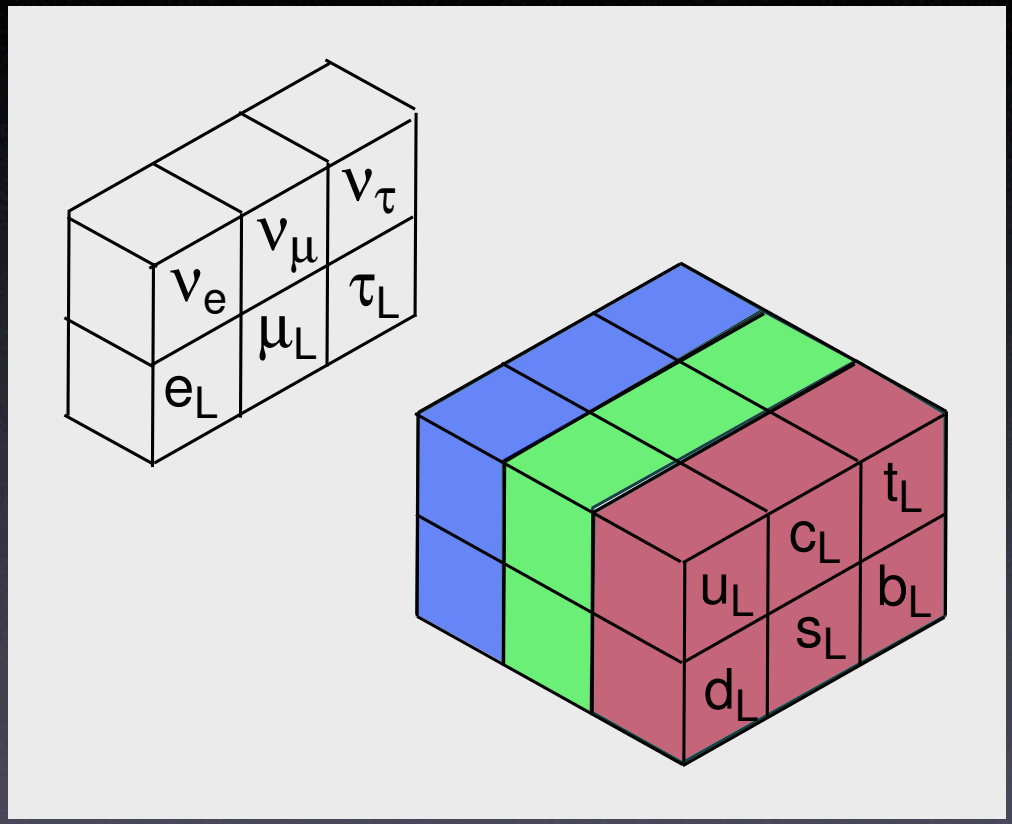
Smaller: Atomic physics → QED; high-energy → EW

Larger: Massless photon in planetary, … measurements

A Decade of Discovery Past

- Electroweak theory: a law of nature
- Quarks & leptons small: < 1 nanonanometer
- Neutrino flavor oscillations
- Quantum Chromodynamics: strong interaction
- Top quark discovery
- Flat universe: dark matter and dark energy

Symmetries imply interactions - function follows form?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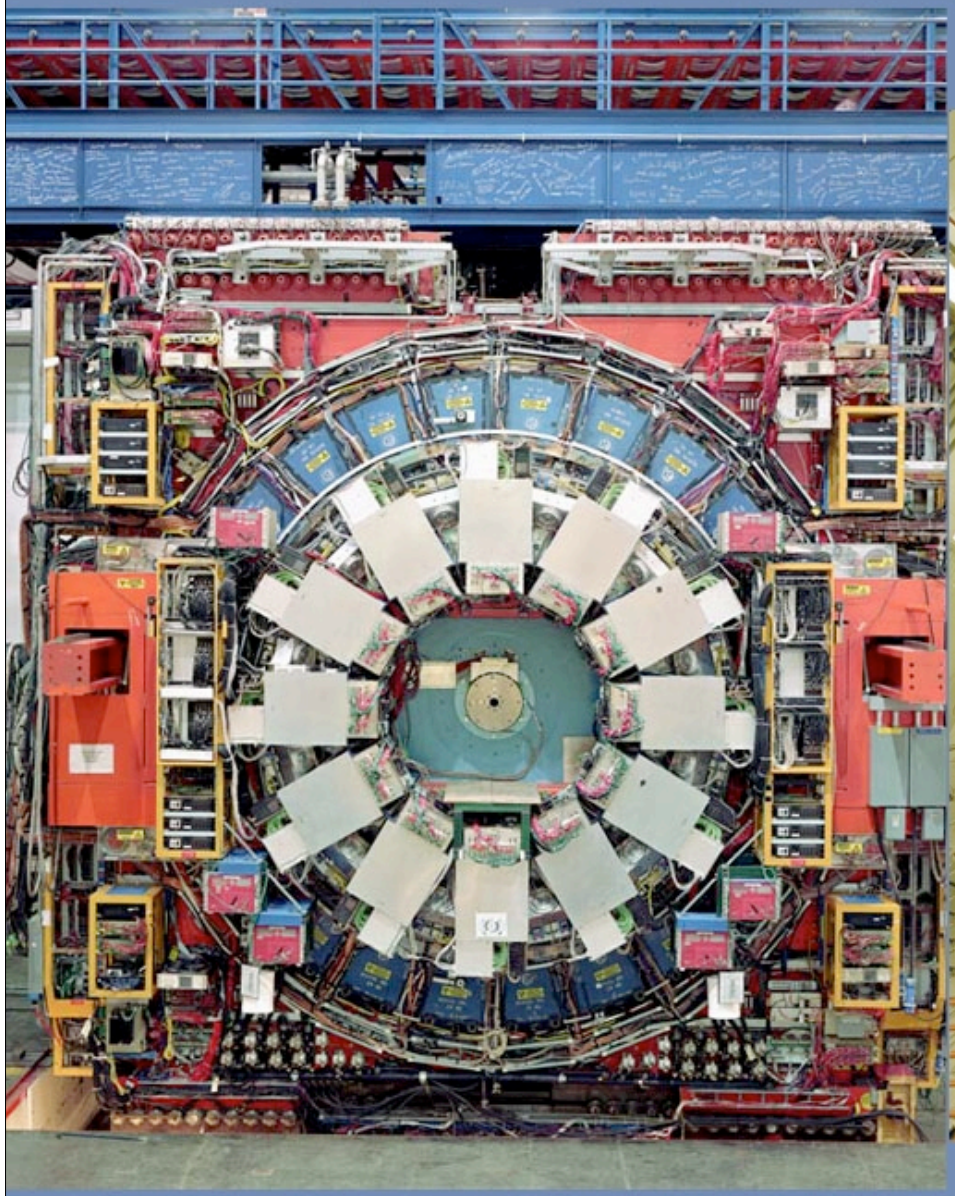
The World's Most Powerful Microscope

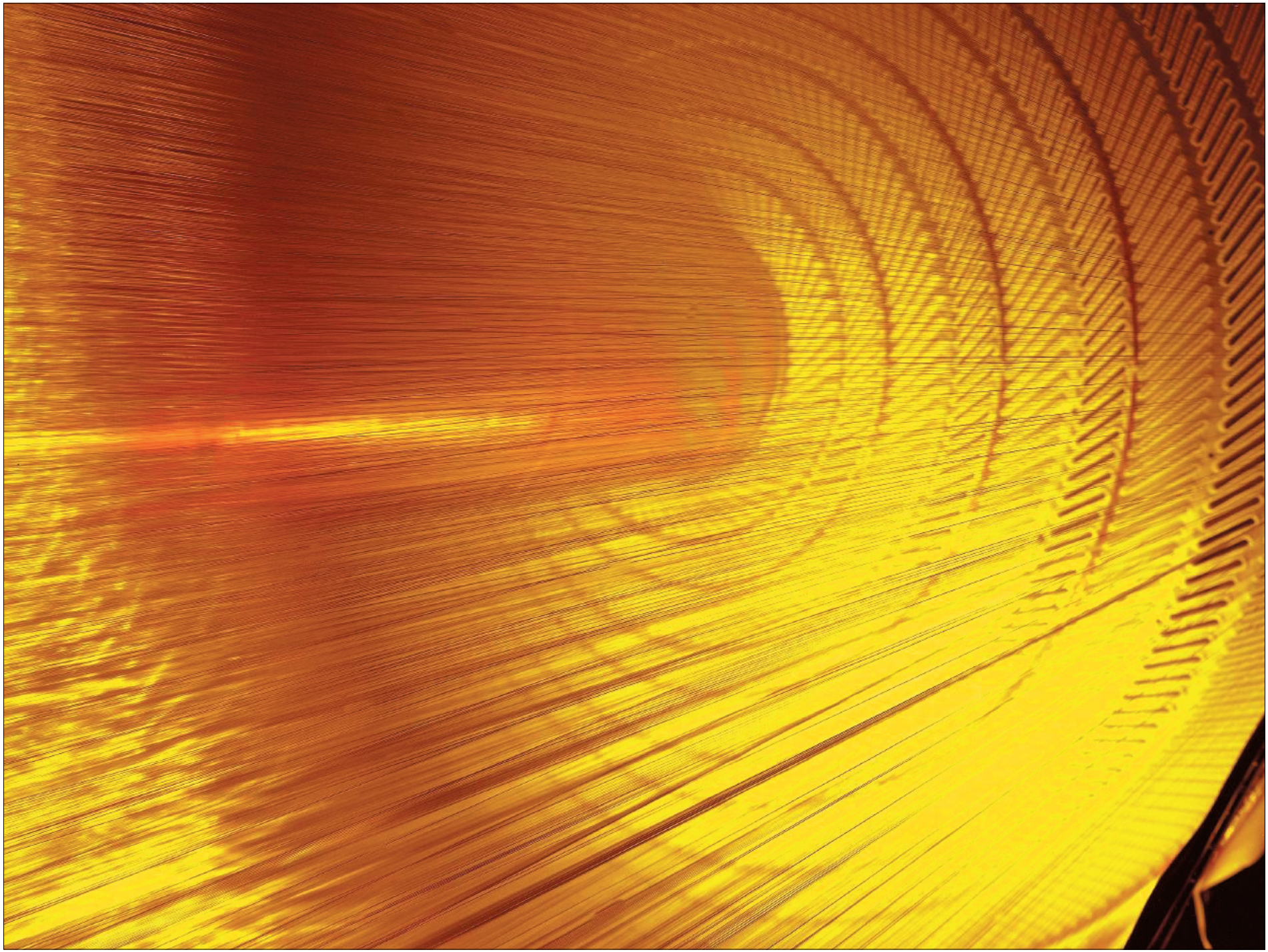
Fermilab's Tevatron Collider & Detectors

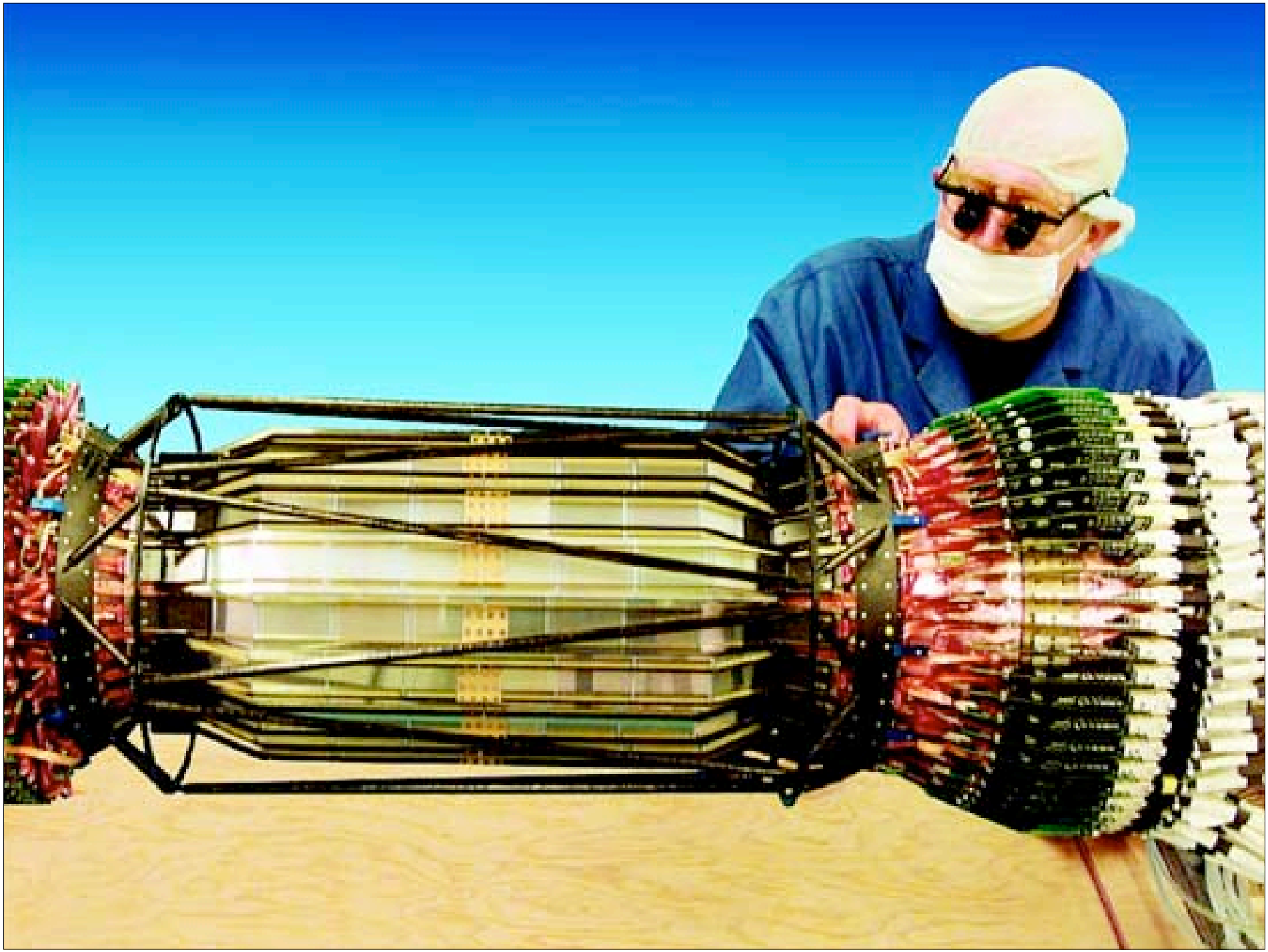
1-TeV protons, antiprotons
307 mph slower than speed of light
(recent improvement by 56 mph)

10 million collisions per second

CERN's Large Hadron Collider:
7 x energy · 300 mph faster!





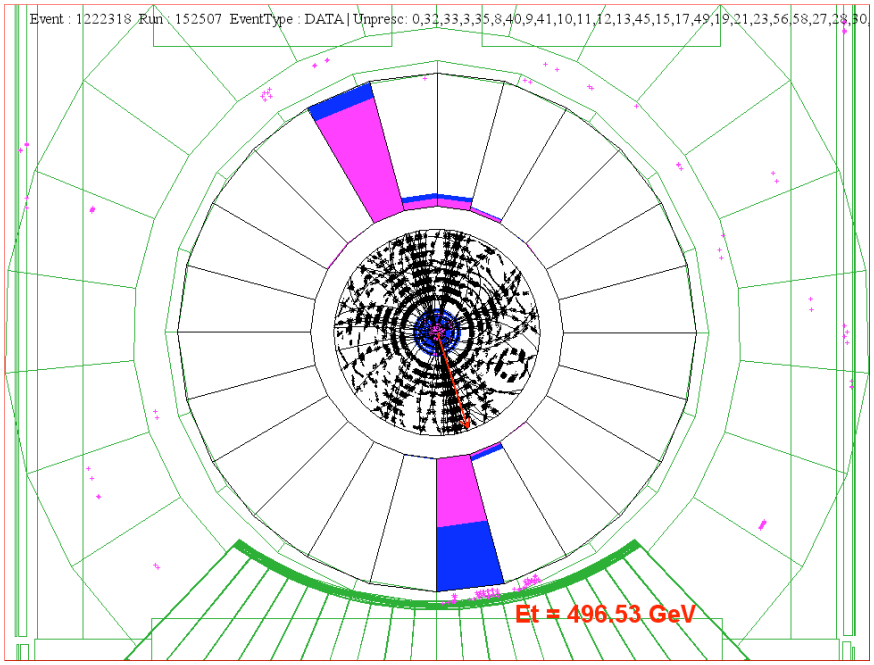


Run 152507 event 1222318

Dijet Mass = 1364 GeV (corr)

cos θ* = 0.30

z vertex = -25 cm

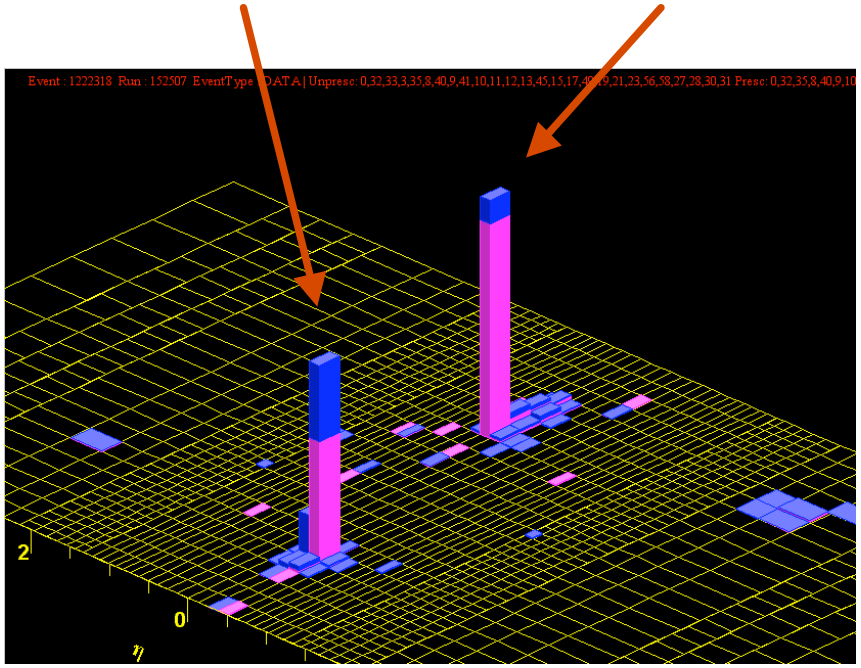


J2 E_T = 633 GeV (corr)
546 GeV (raw)

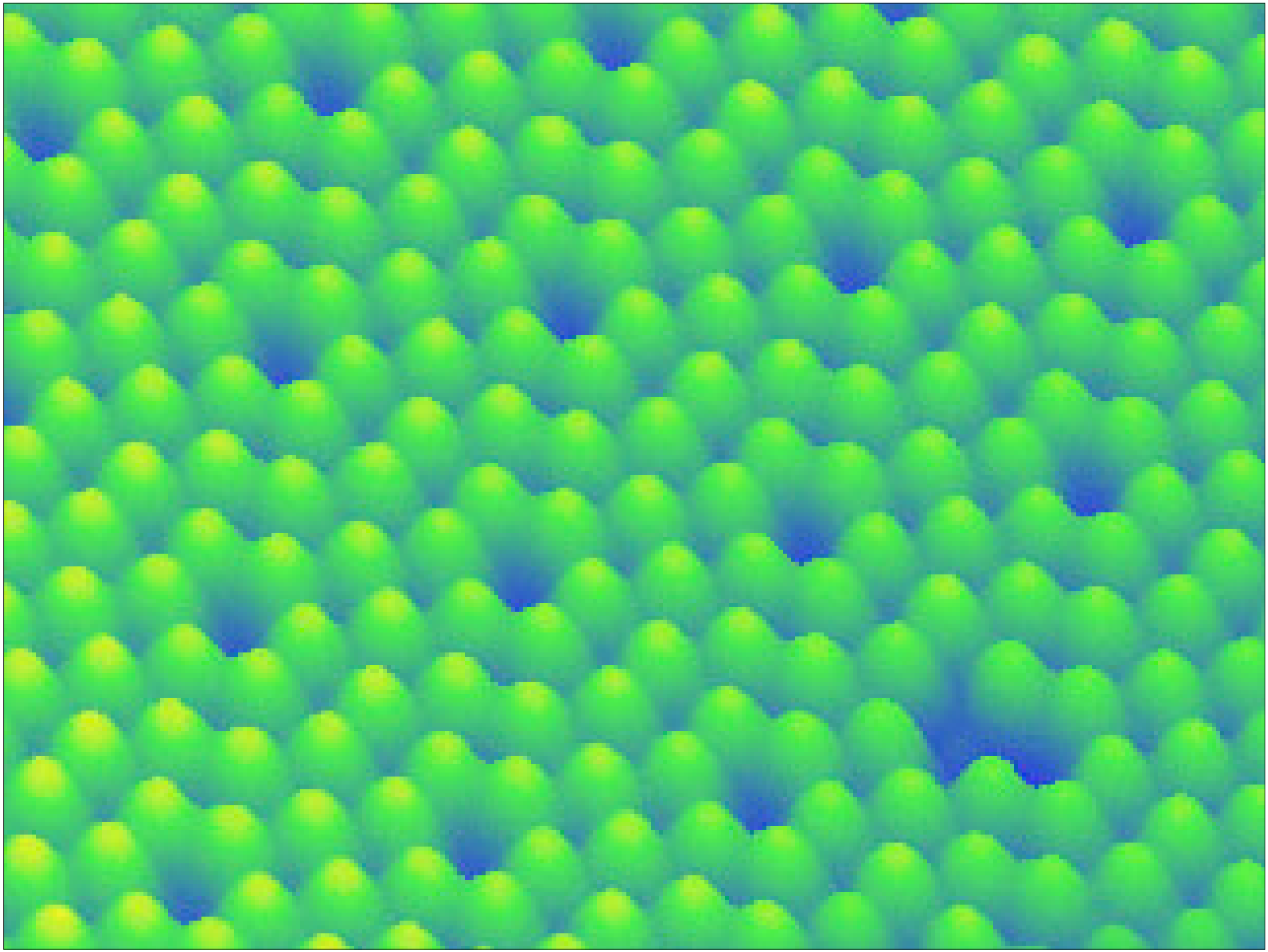
J2 η = -0.30 (detector)
= -0.19 (correct z)

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

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



CDF Run 2 Preliminary



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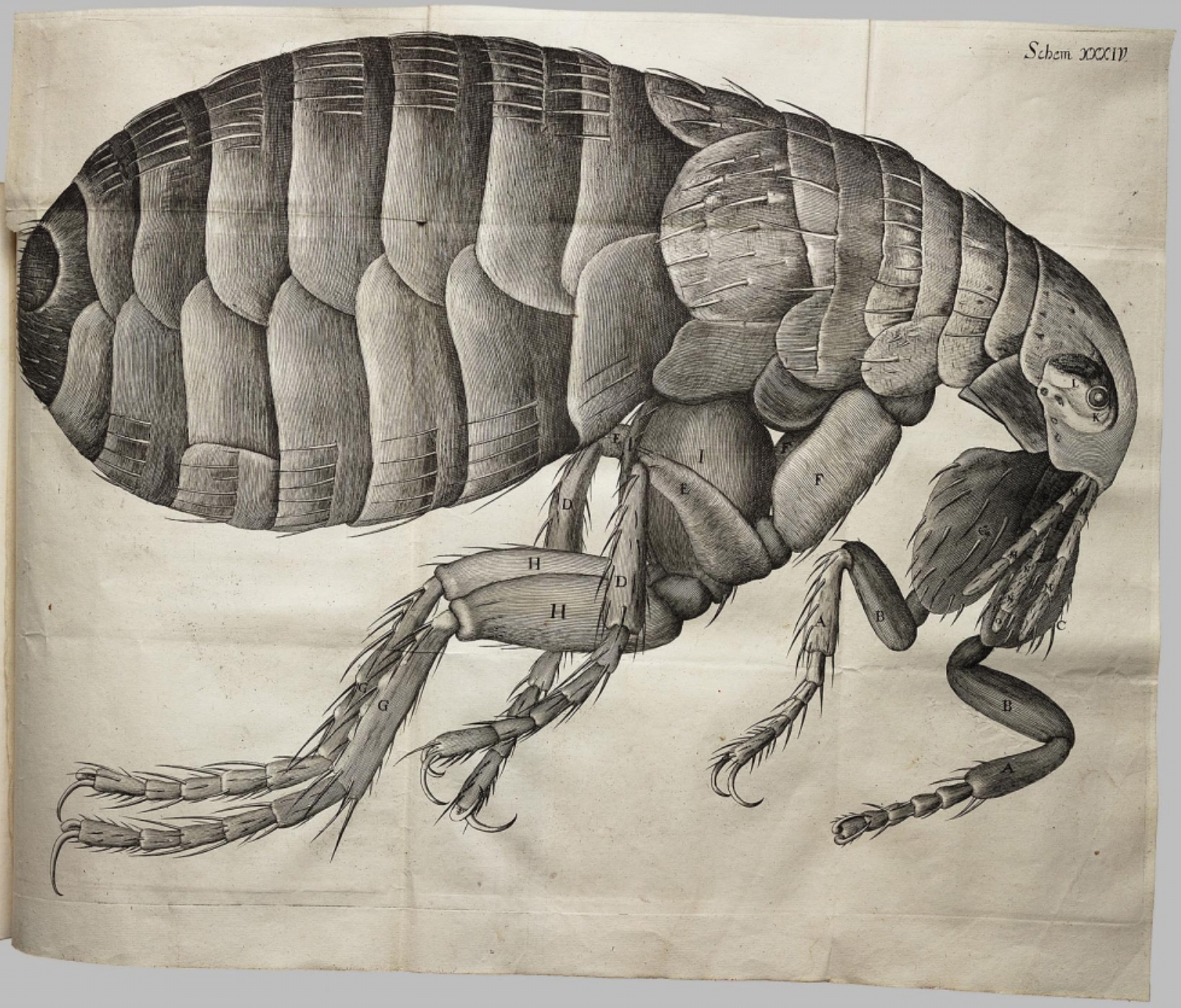
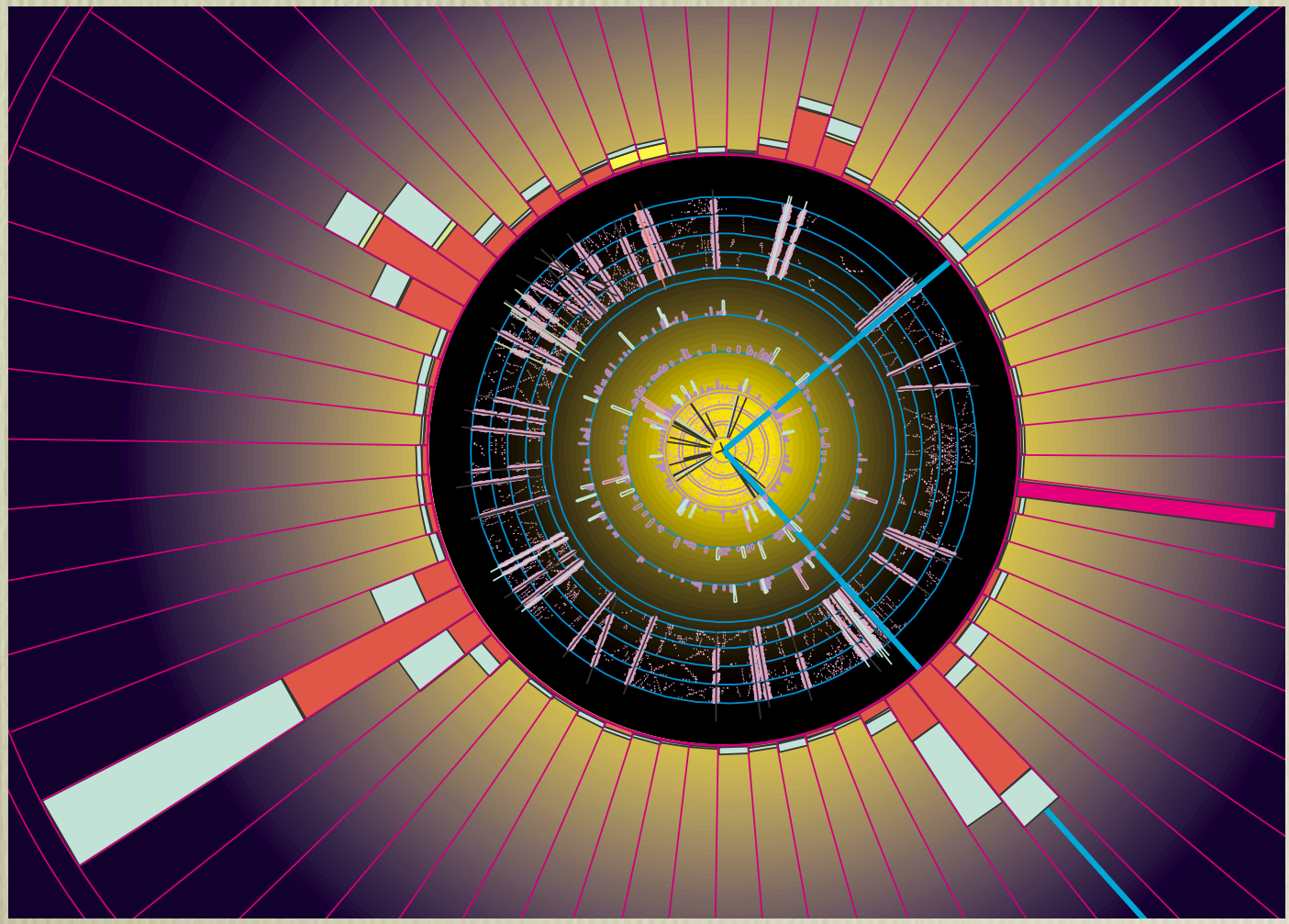


Accelerators
Create New Forms of Matter



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)

Revolution:
Understanding the Everyday

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

Symmetry is sameness

Sameness is not our world

Symmetry in the laws of nature ...
not necessarily in the manifestations

If symmetry were not hidden ...

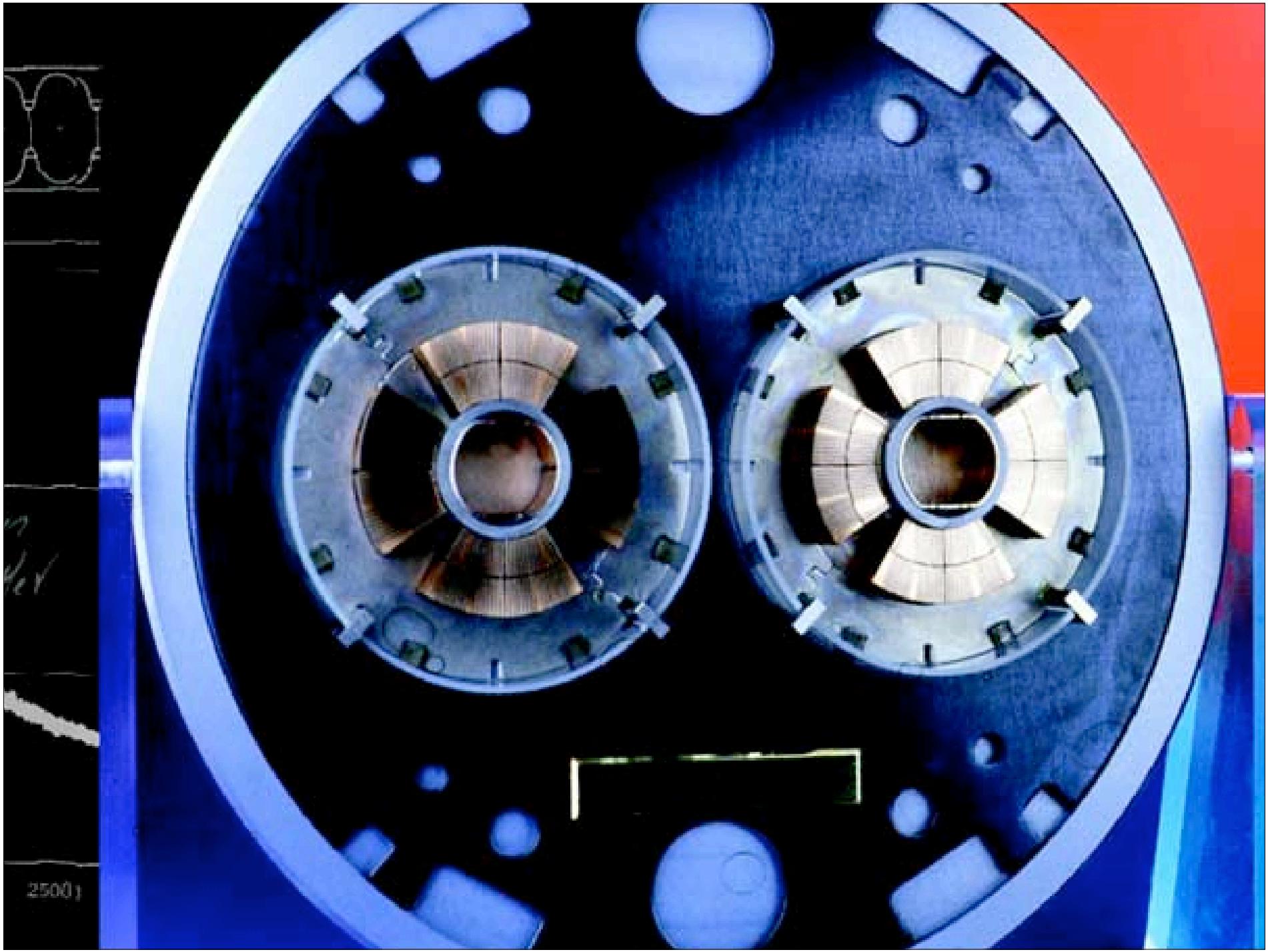
- Massless quarks & leptons
- Quarks confined by QCD
- Proton outweighs neutron
- Rapid beta decay: no hydrogen atom
- (Probably) some light elements, but "atoms" are huge: no chemistry, no stable composite structures

A Mysterious New Force hides electroweak symmetry

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

Which path has Nature taken?

Experiments at 1 TeV will tell

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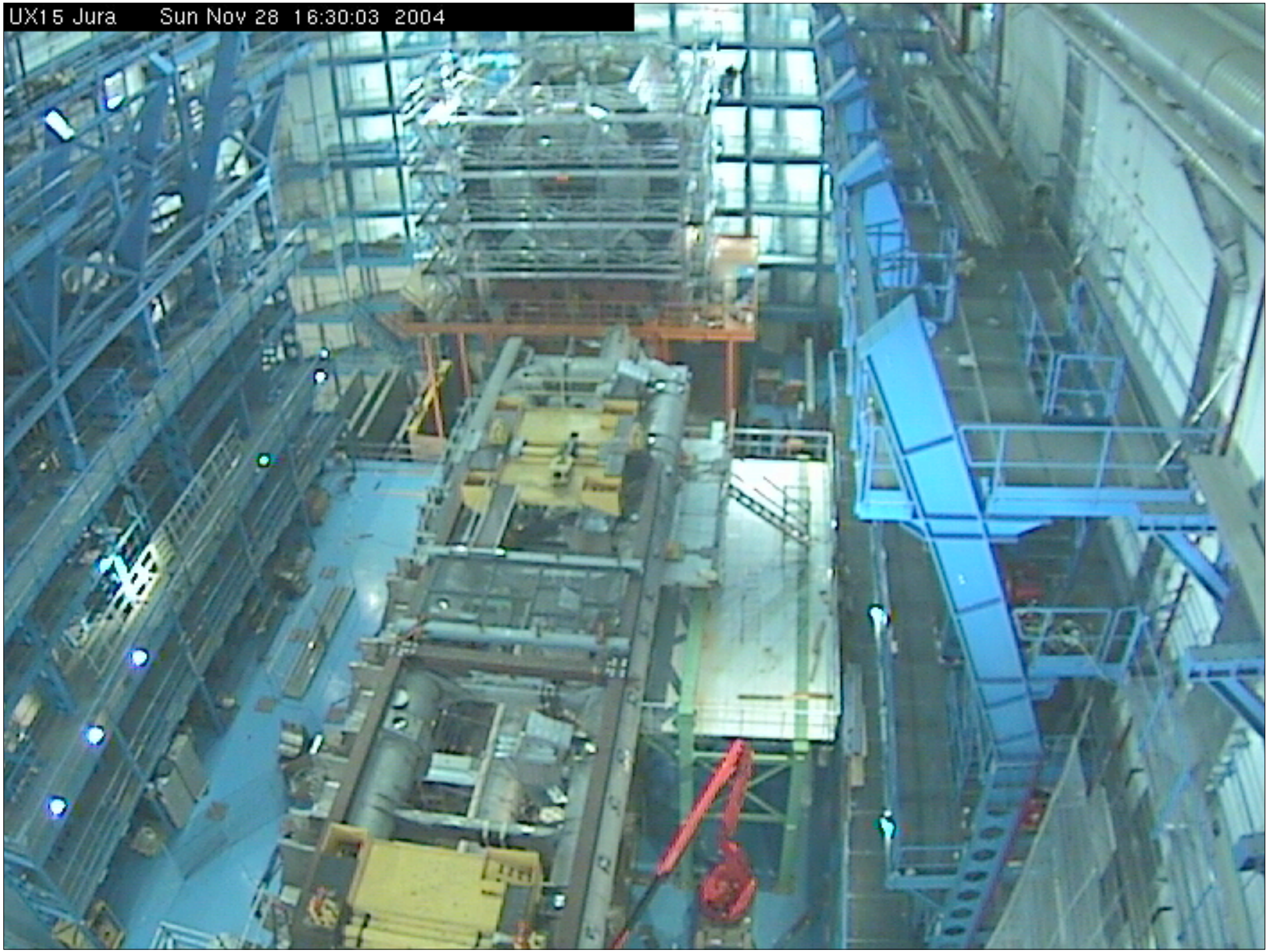
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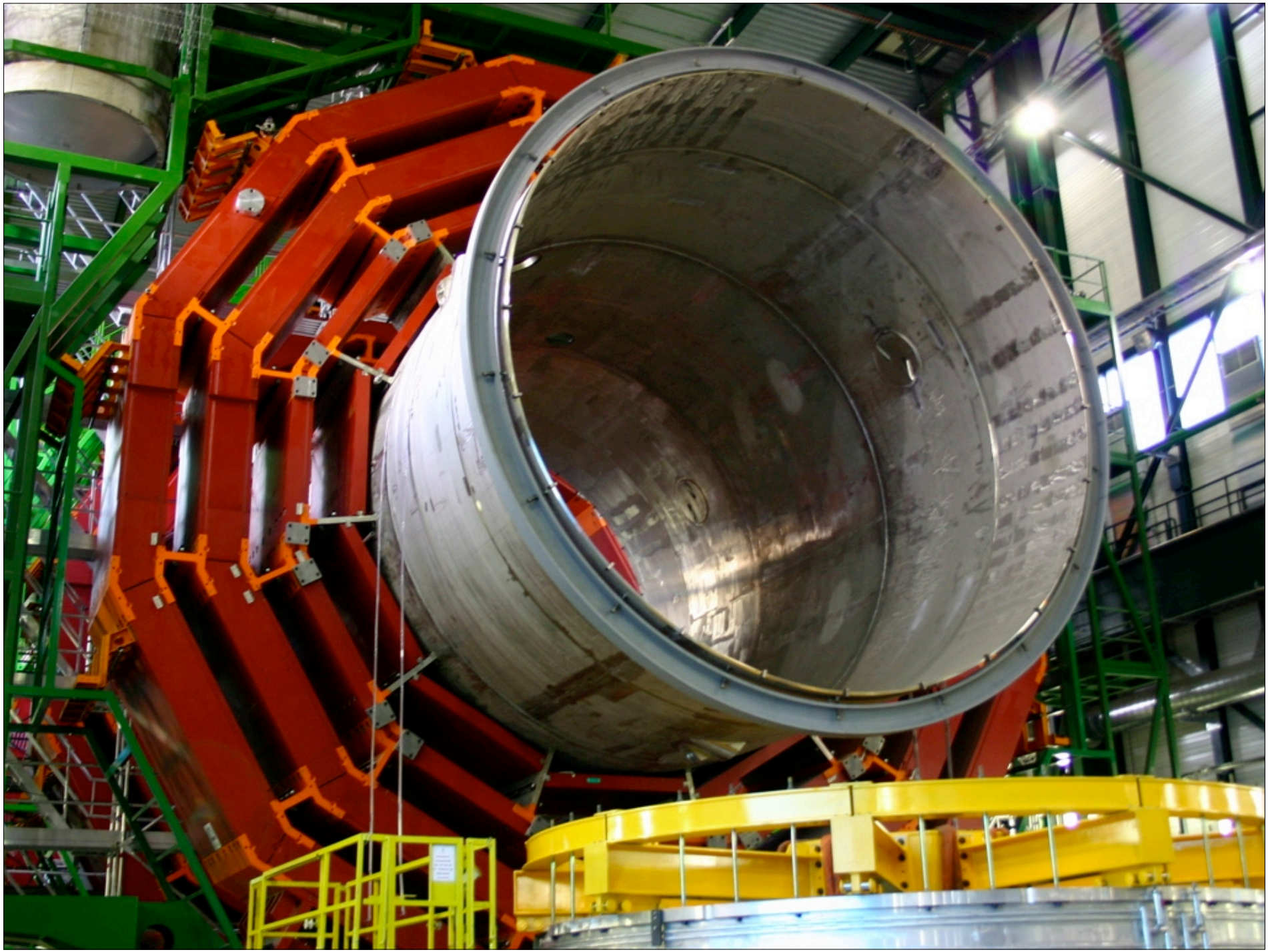


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Revolution:
The Meaning of Identity

- 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.

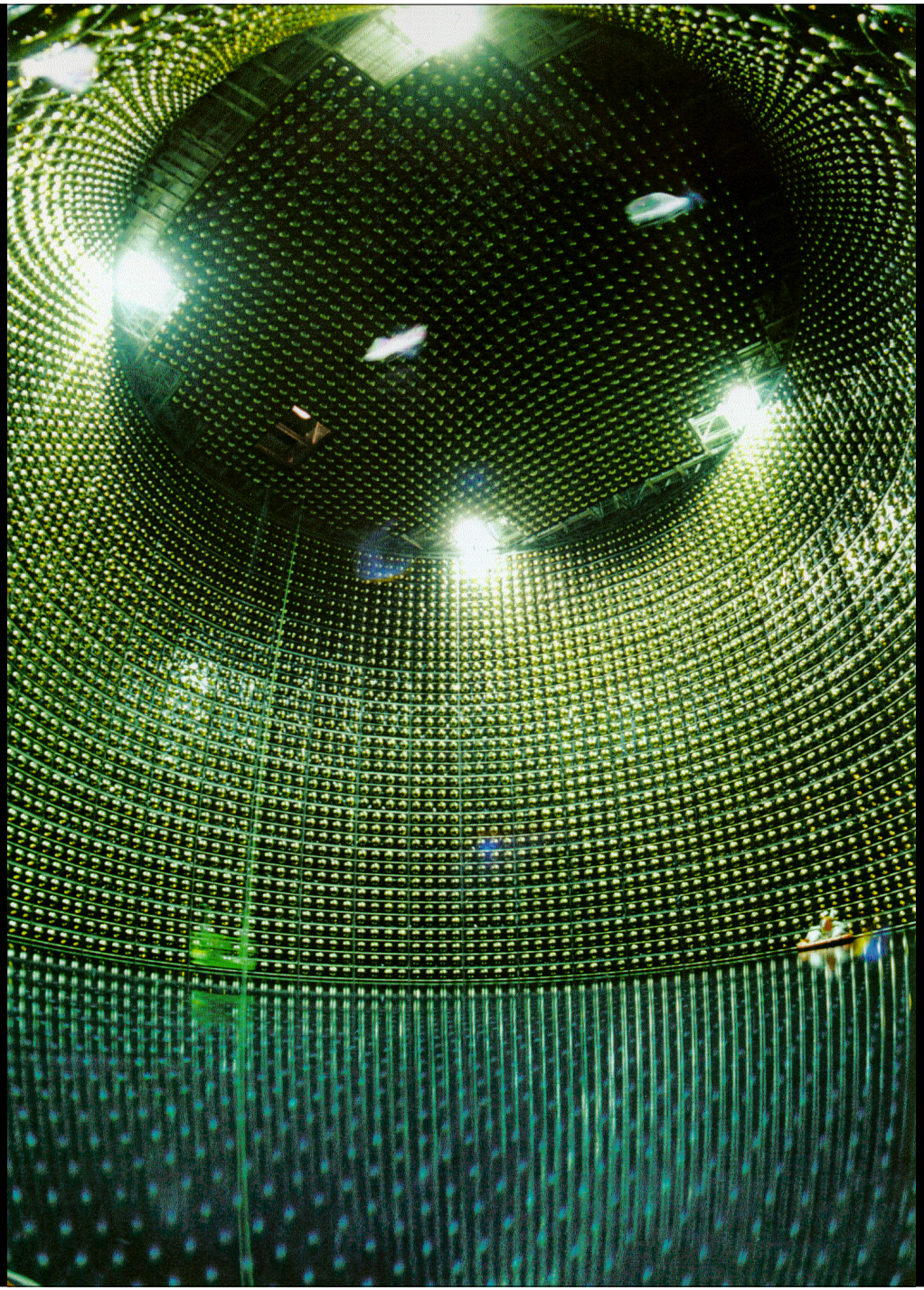
Hypothesis: unknown ingredient in the air.

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

Lord Rayleigh

Revolution:
Unity of Quarks & Leptons

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



Gravity rejoins Particle Physics rejoins

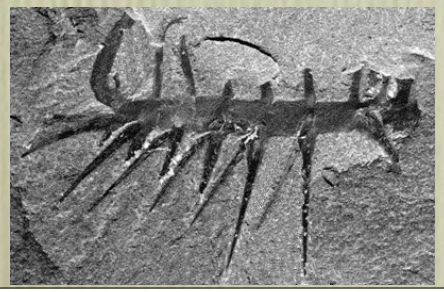
A Chronic Dull Headache ...

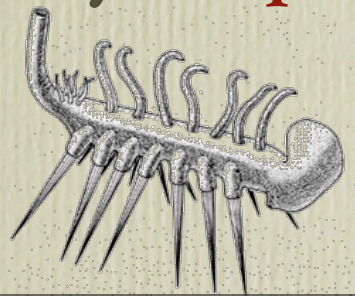
... for thirty years

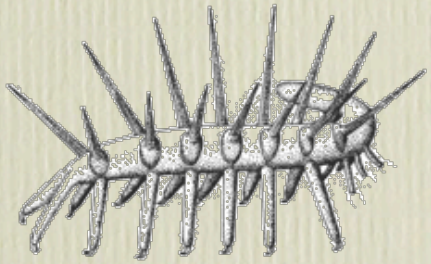
- Higgs field fills all of space with energy density 10^{25} g/cc
- But empty space weighs next to nothing: $< 10^{-29}$ g/cc
- Evidence that vacuum energy is present (accelerating universe) recasts problem

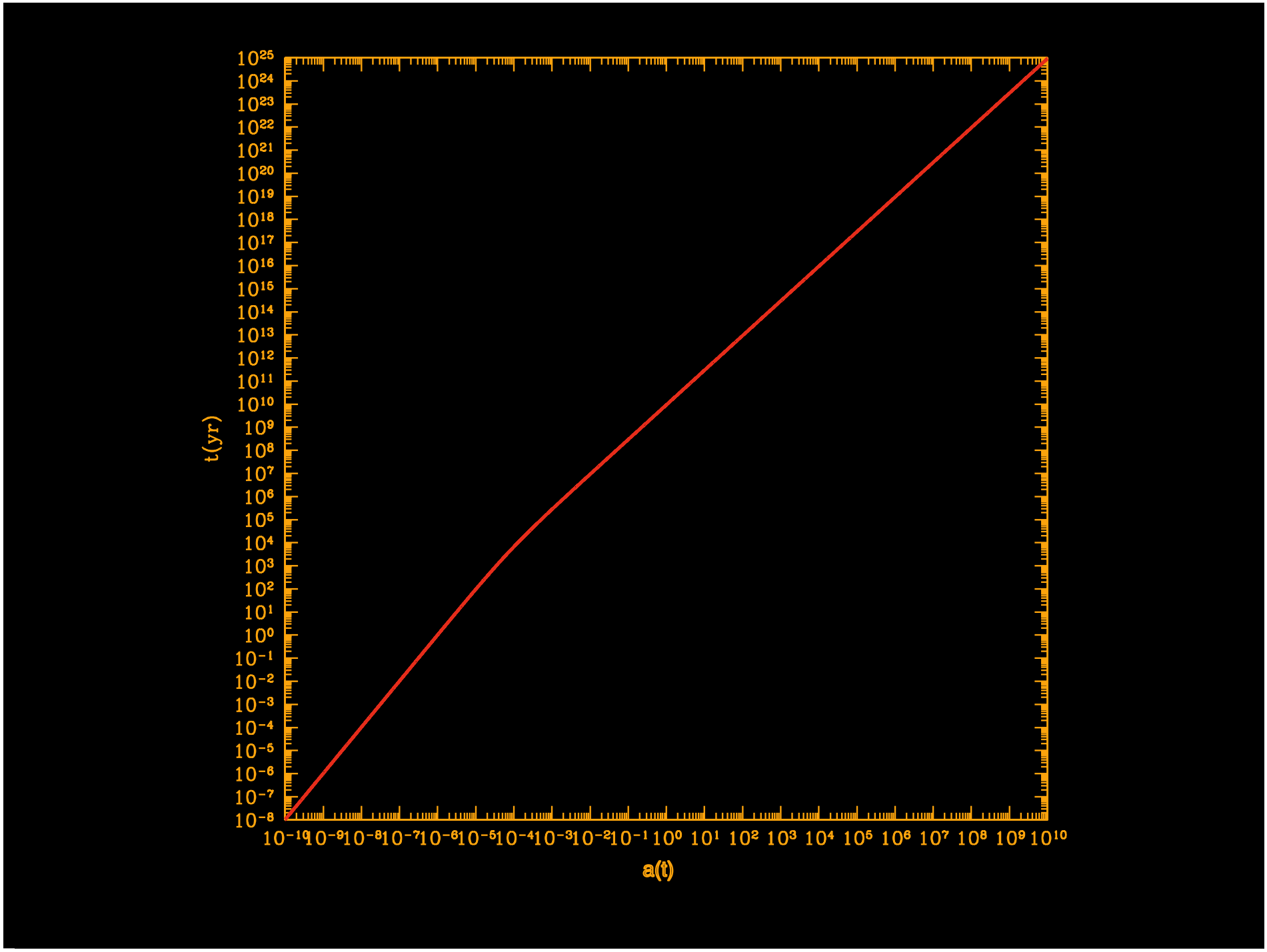
Implications for ...
The Fate of the Universe

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





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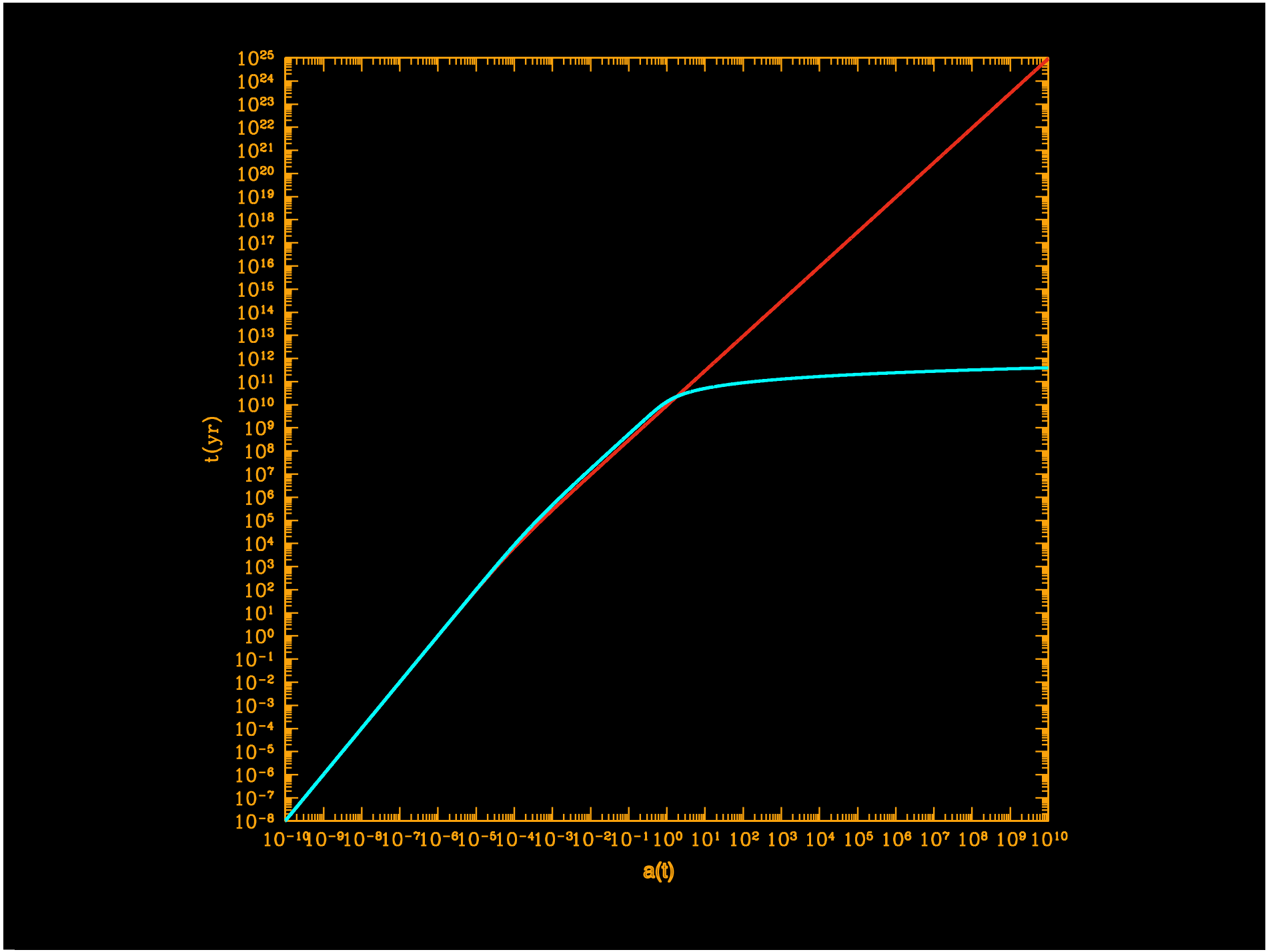
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Energy scale hierarchies ...

- Electroweak: 1 TeV
- Gravity ("Planck"): EW $\times 10^{16}$
- Traditional: why EW scale so small?
- Recent: why is gravity so weak?

Revolution:
New Conception of Spacetime

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

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

A New Decade of Discovery

- Higgs boson search & study
- Rare quark decays; neutrino oscillations
- Proton decay
- Top quark as a tool
- Exploration! extra dimensions? new forces? supersymmetry?
- Composition of universe; dark matter ID

Prepare for Many Revolutions

- Energy frontier experiments
- High-sensitivity experiments
- Experiments with “found beams”
- Astrophysical observations

Diversity & scale diversity ...

Beyond the Large Hadron Collider

International Linear Collider
electron-positron @ 1 TeV
30 km long
superconducting acceleration

(definitive design by 2008/2009)

Beyond the International Linear Collider

? Neutrino Factory ?

muon storage ring

or

? Very Large Hadron Collider ?

or

? Multi-TeV Linear Collider ?

diverse, exploratory R&D

In a decade or two, we can hope to ...

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish neutrinos = antineutrinos
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, ...)
Observe neutron's EDM, pursue electron's
Use top quark as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine the unifying symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly massless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

... learn the right questions to ask ...

... and rewrite the textbooks!