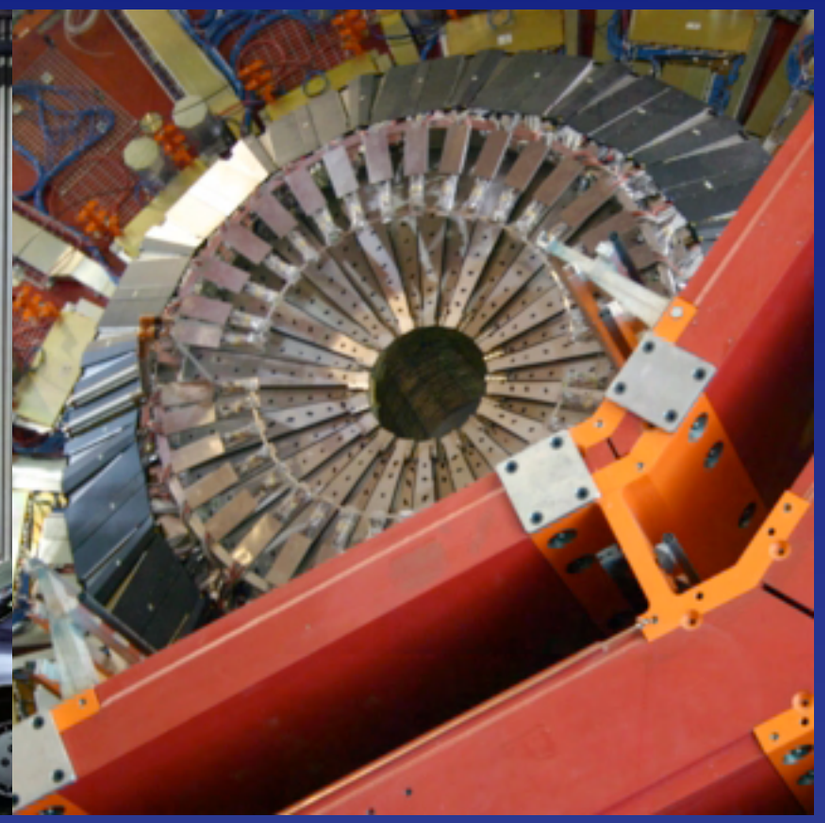
The Coming Revolutions in Particle Physics

Chris Quigg



Fermilab Auditorium Lecture · 18 January 2008

A Decade of Discovery Past

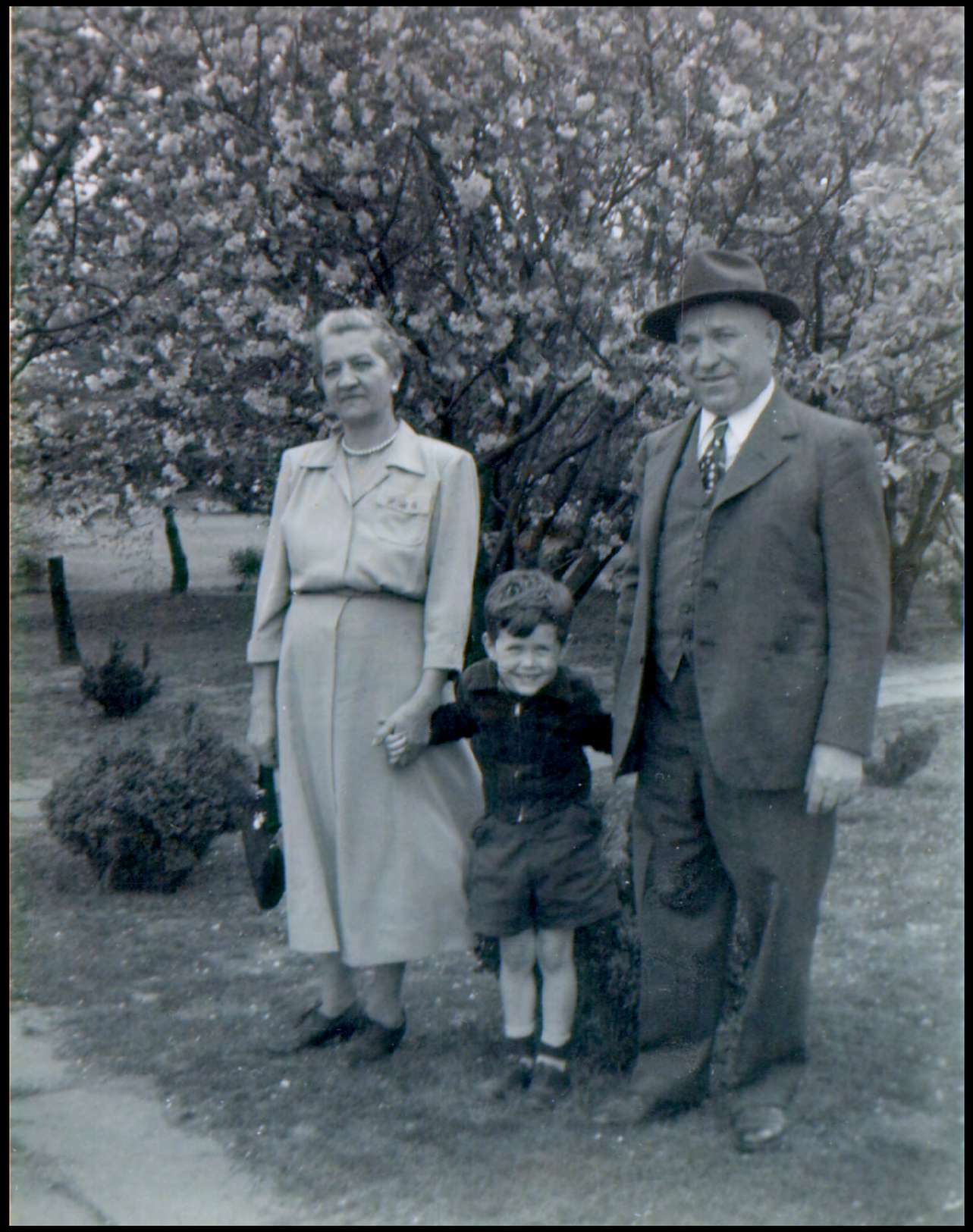
A new law of nature: electroweak theory

Neutrinos have mass: they morph

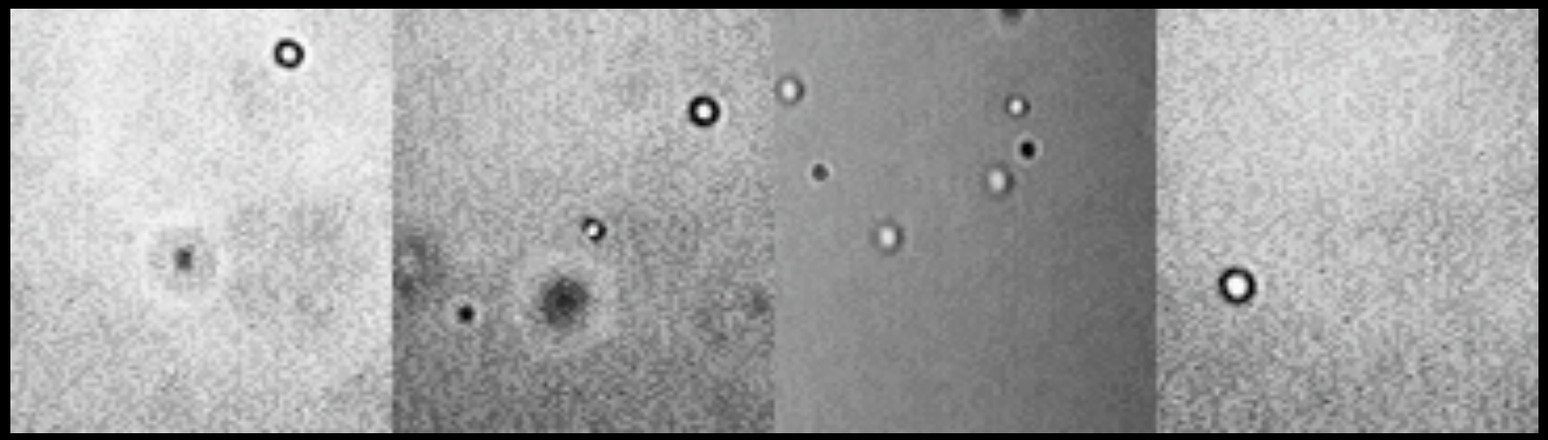
Top quark: very heavy, highly ephemeral

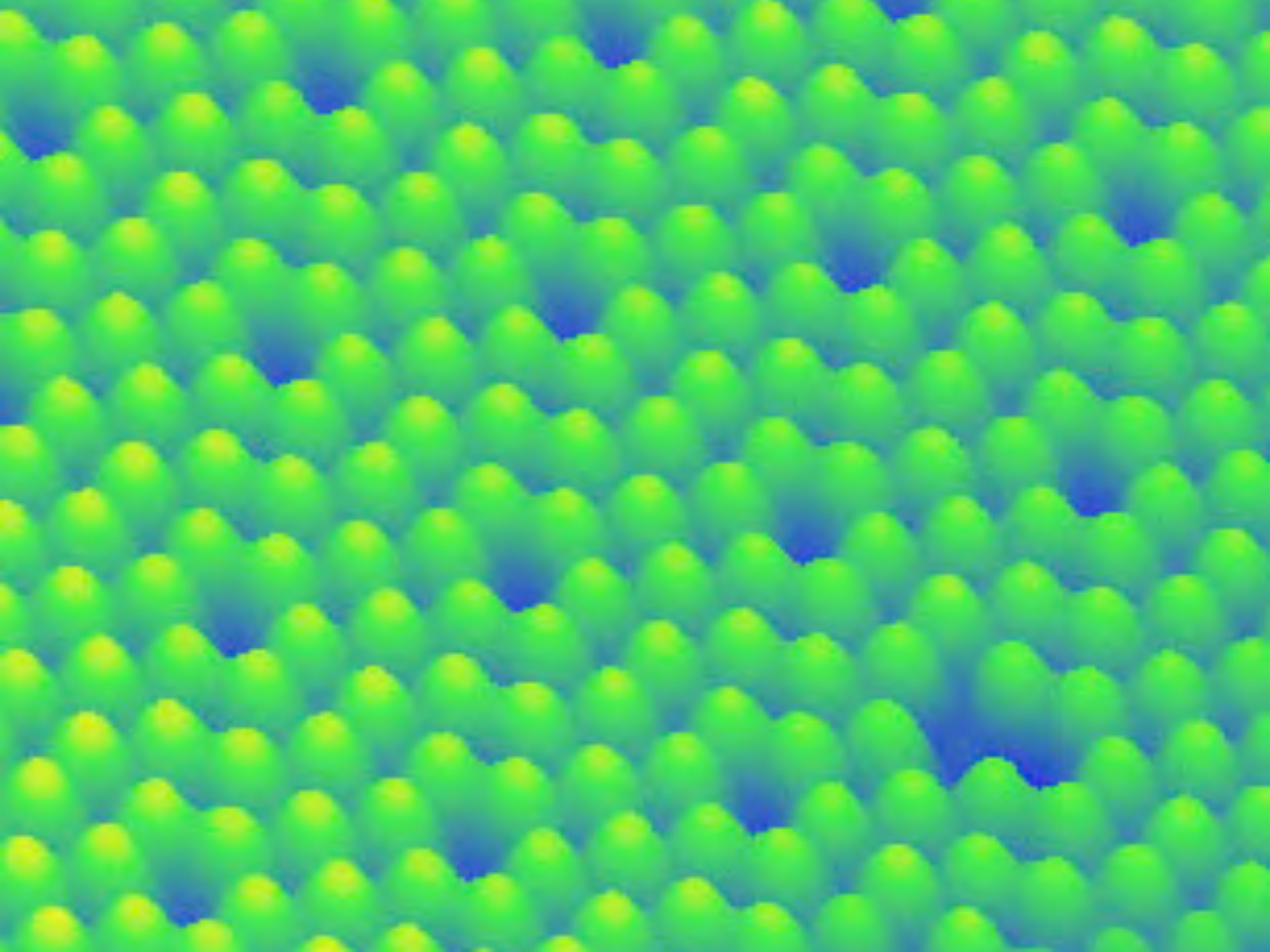
An imperfect mirror: matter/antimatter

Novel forms of matter and energy (dark)



To explain a complicated visible by a simple invisible





Great Lesson of XXth 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

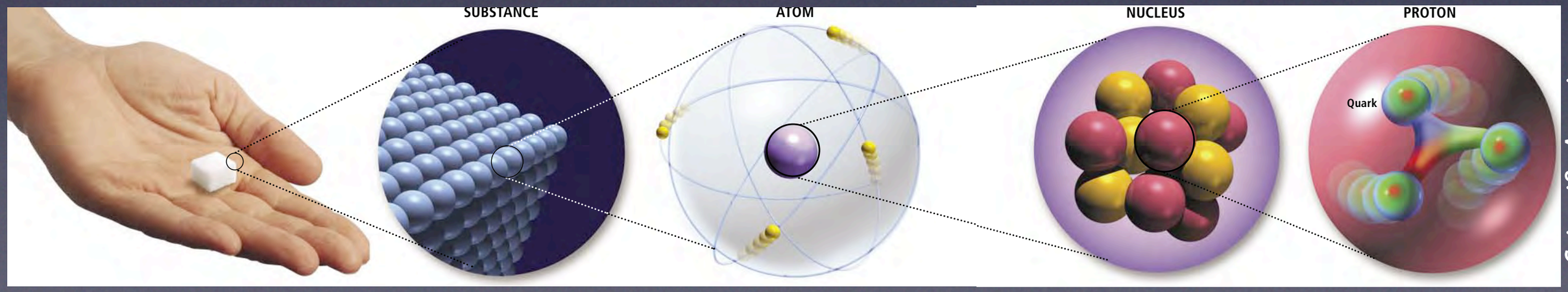
nanonanophysics

Fermilab's Tevatron Collider & Detectors

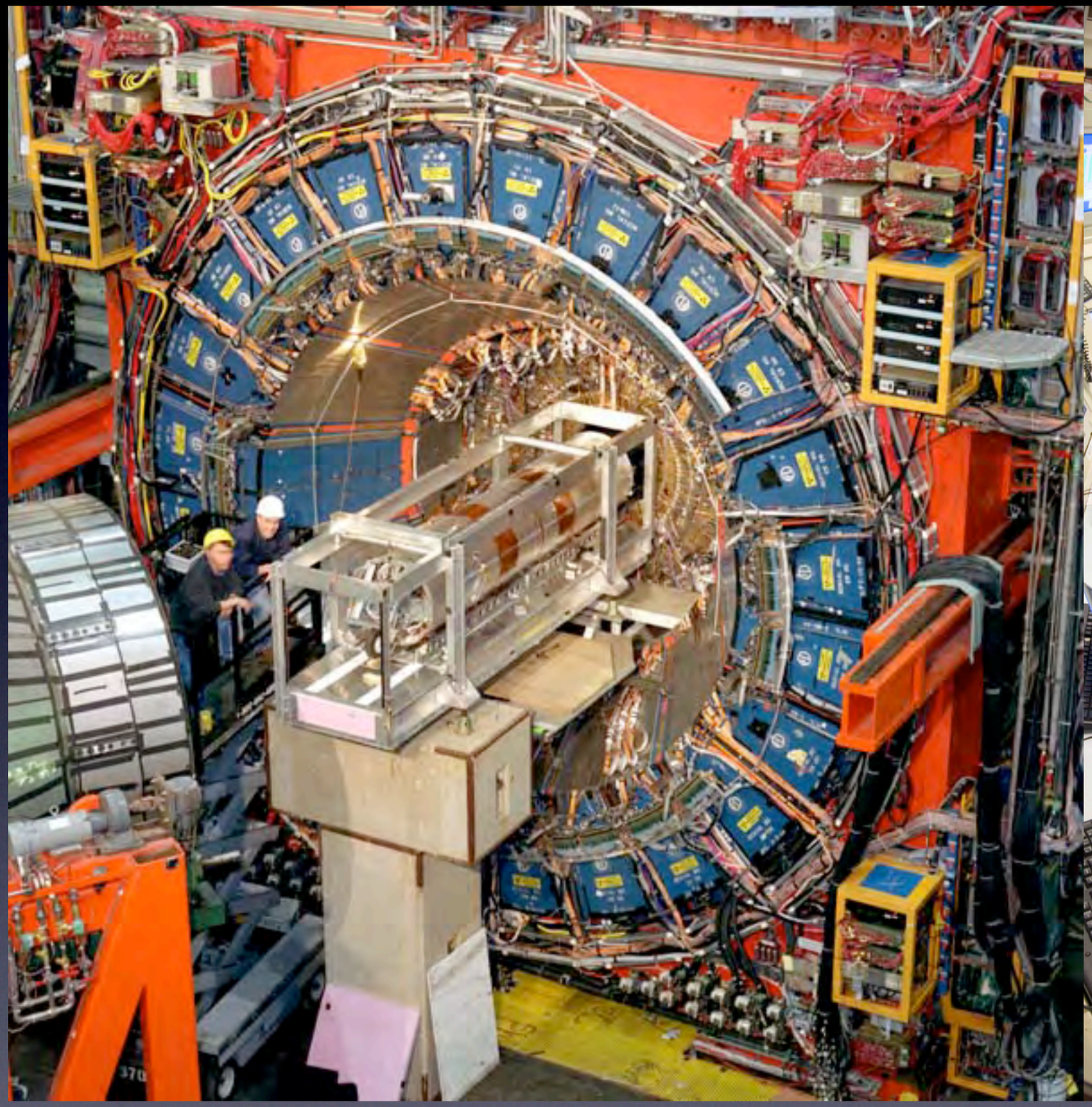
900-GeV protons: $c - 586$ km/h
980-GeV protons: $c - 495$ km/h
Improvement: 91 km/h!

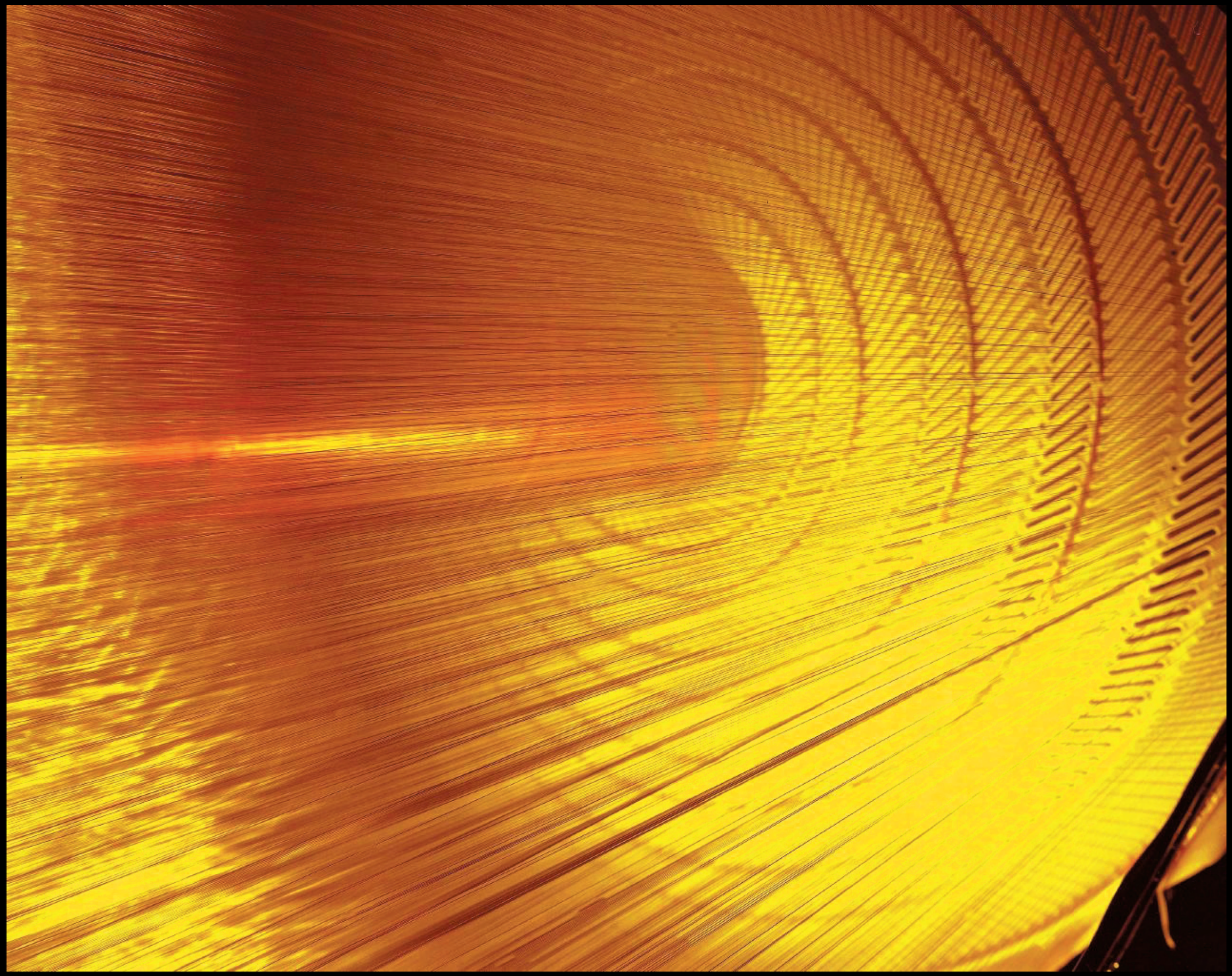
Protons, antiprotons pass my window 45 000 times / second

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



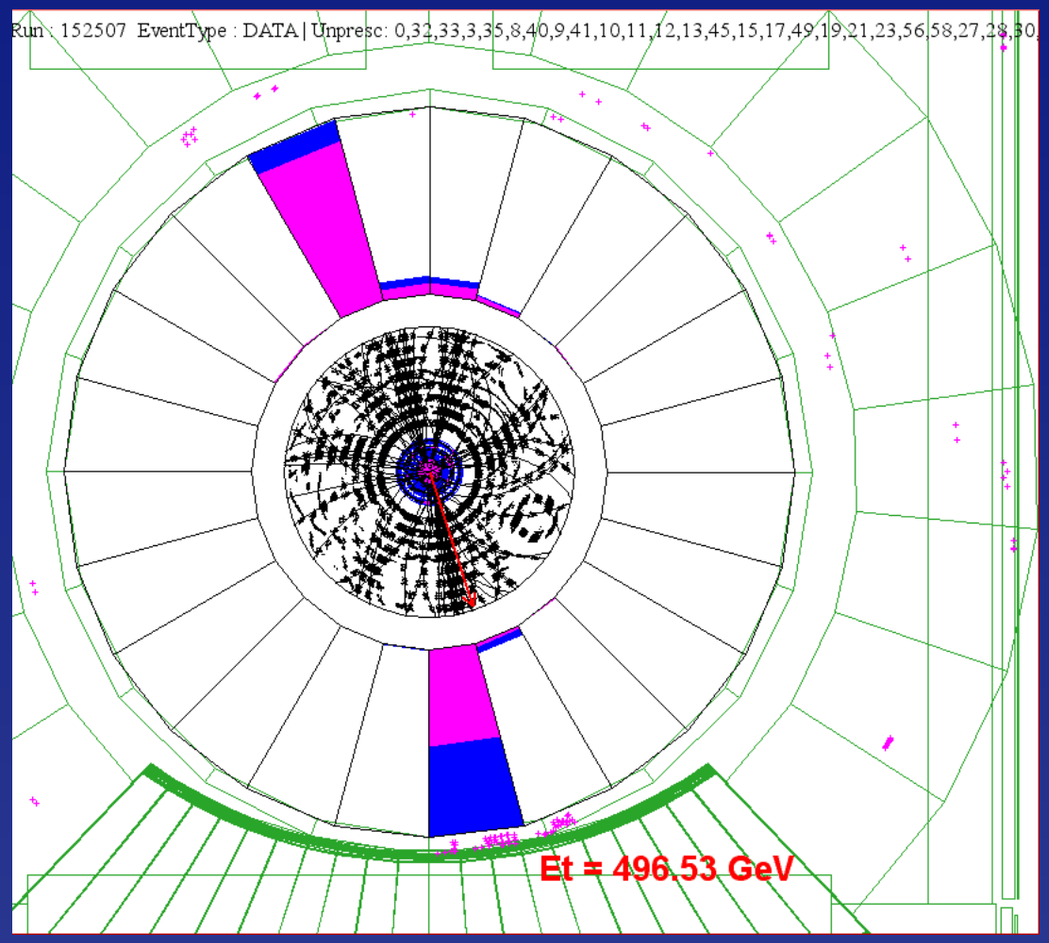
Scientific American

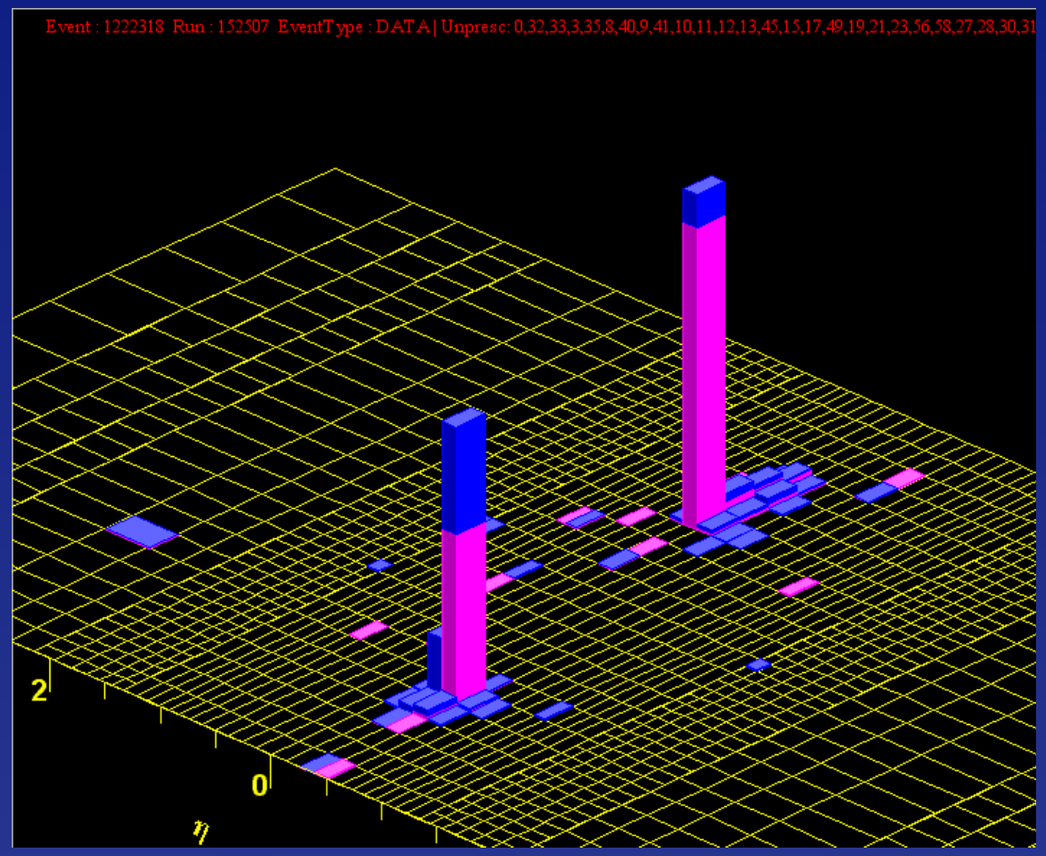




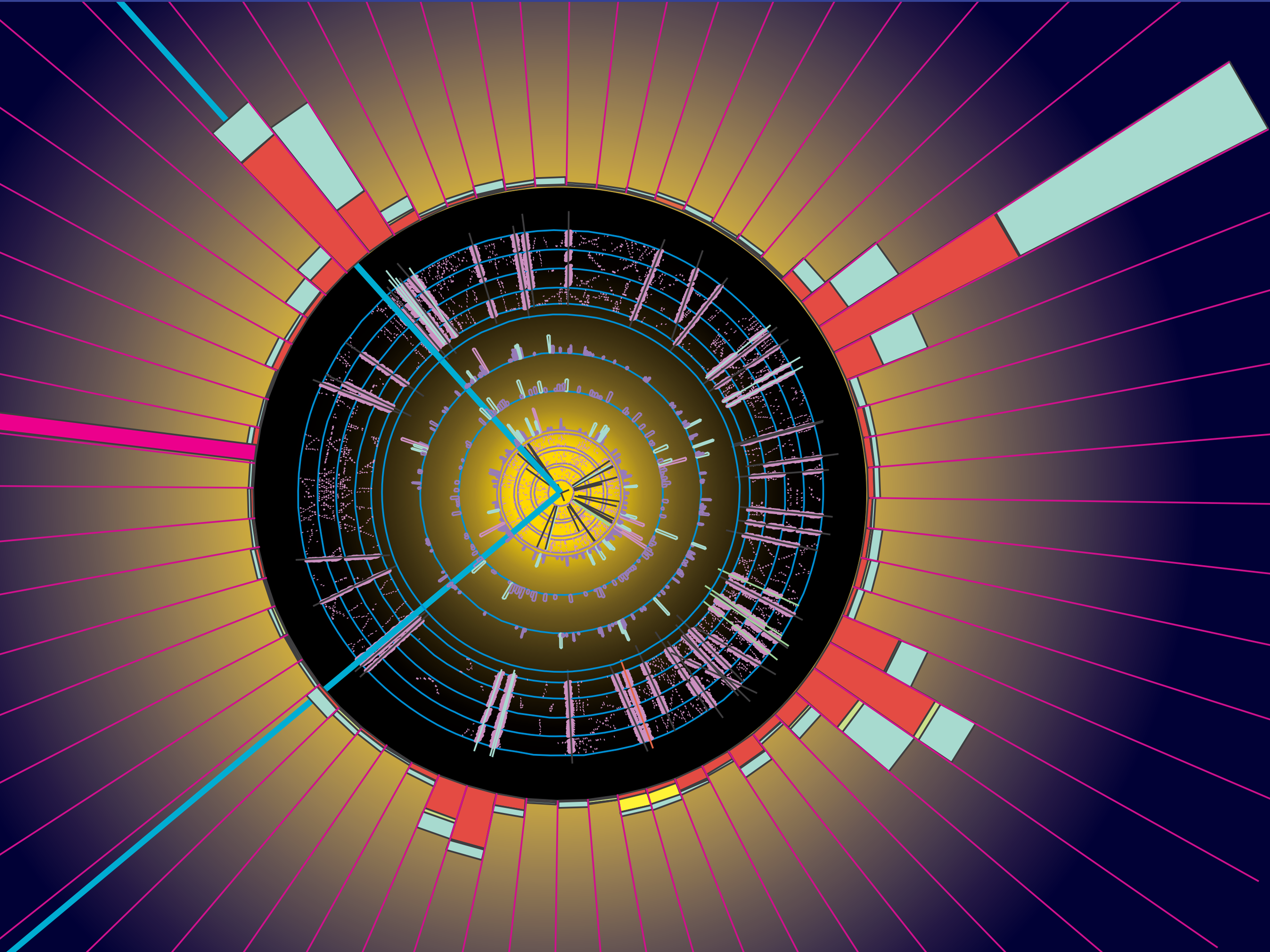
The World's Most Powerful Microscopes

nanonanophysics

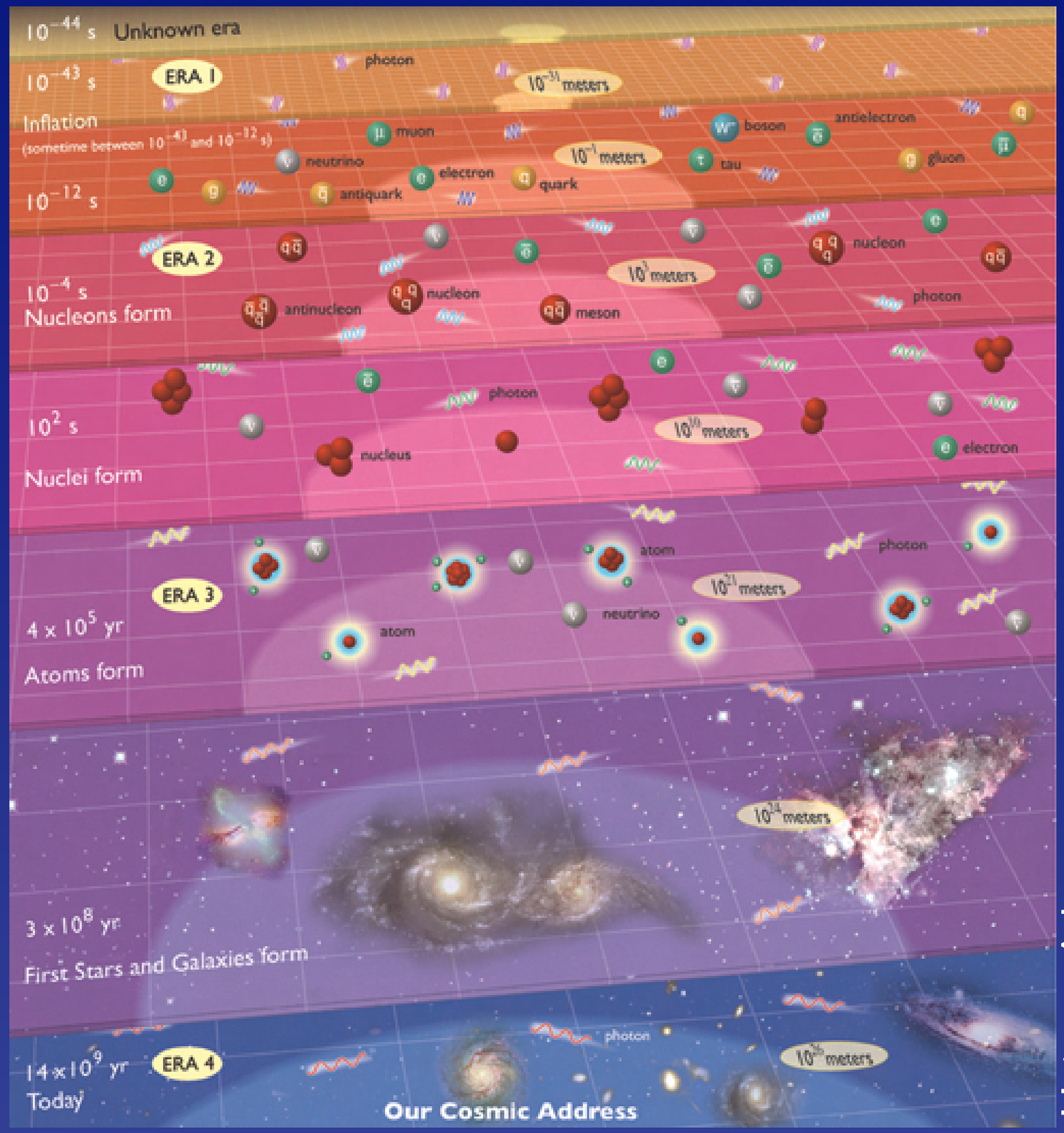




CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $\boxed{q\bar{q} \to \text{jet} + \text{jet}}$



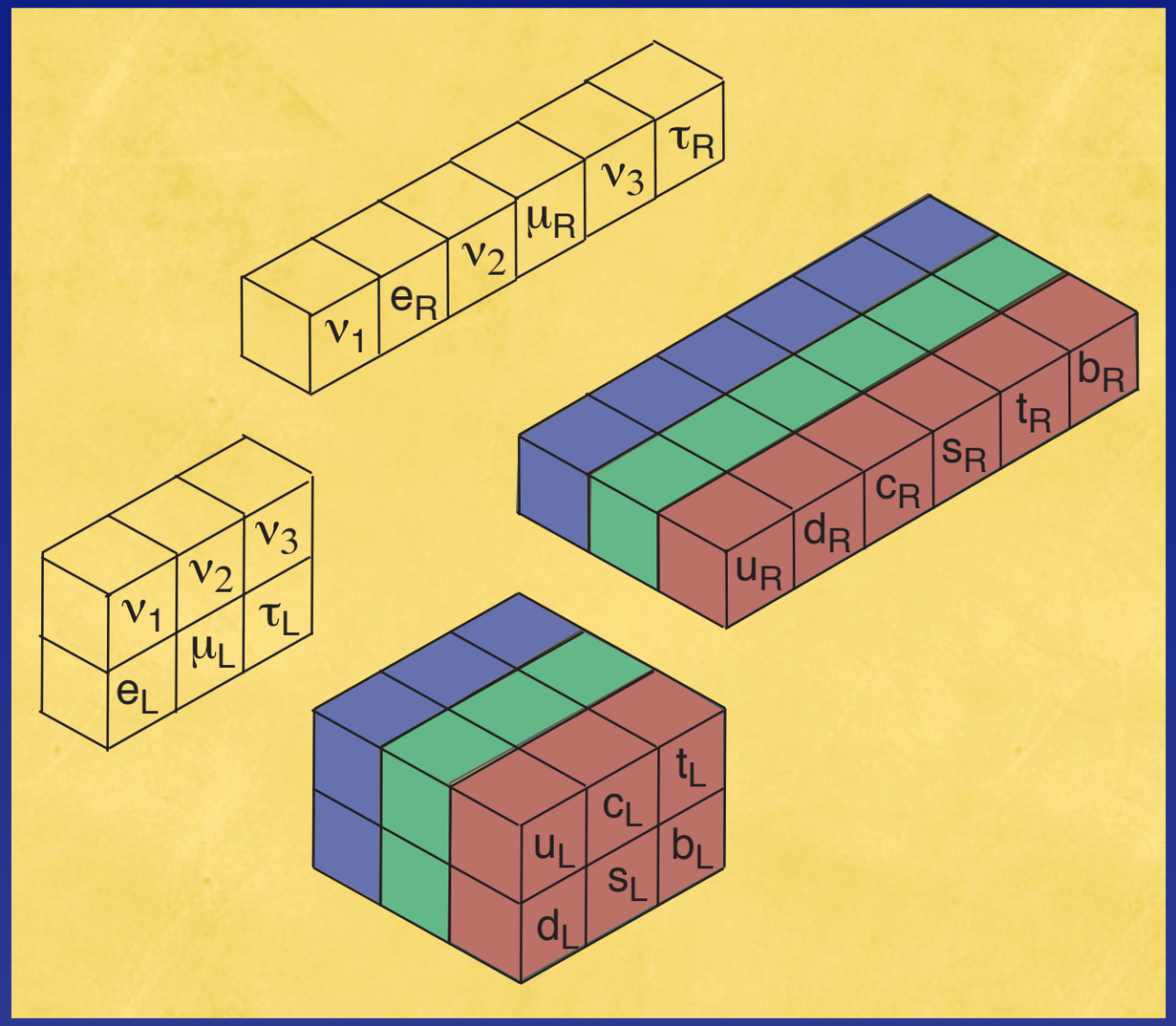
Accelerators as time machines …

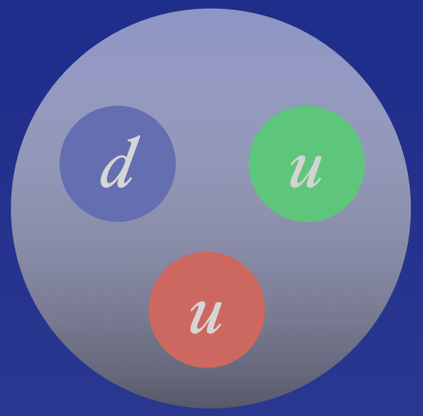


UniverseAdventure.org

Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) quarks and leptons

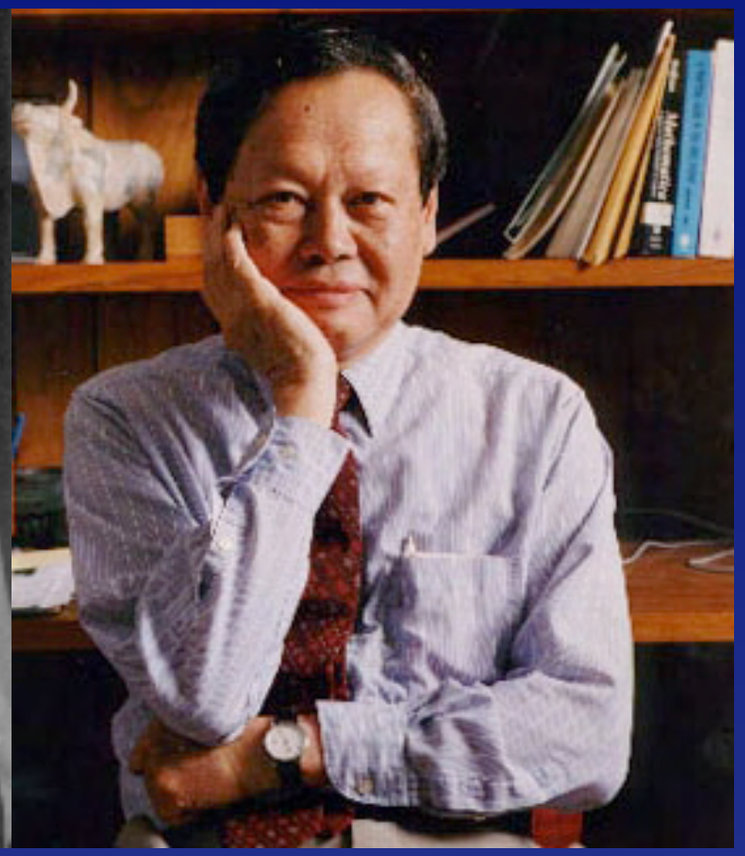




Gravitation, electromagnetism, radioactivity, strong interaction

Louis Sullivan, architect (1896)

Form follows function

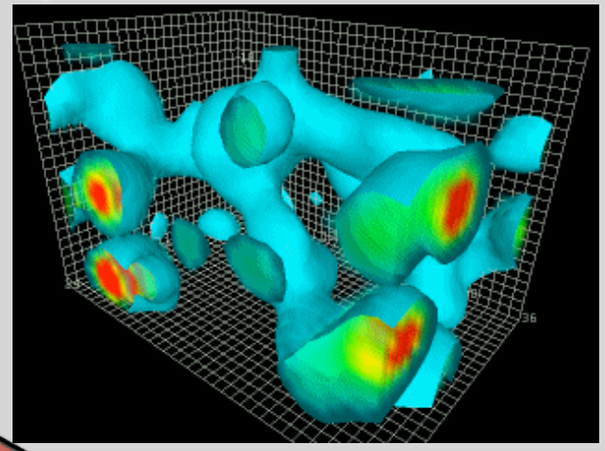


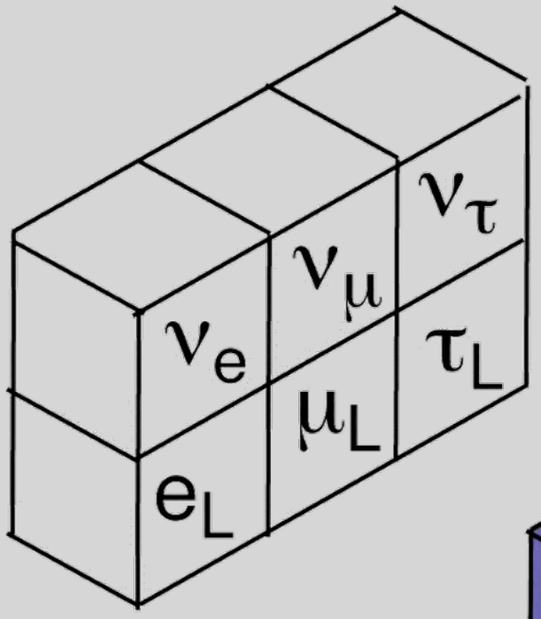
Robert Mills (1954) Yang Chen Ning

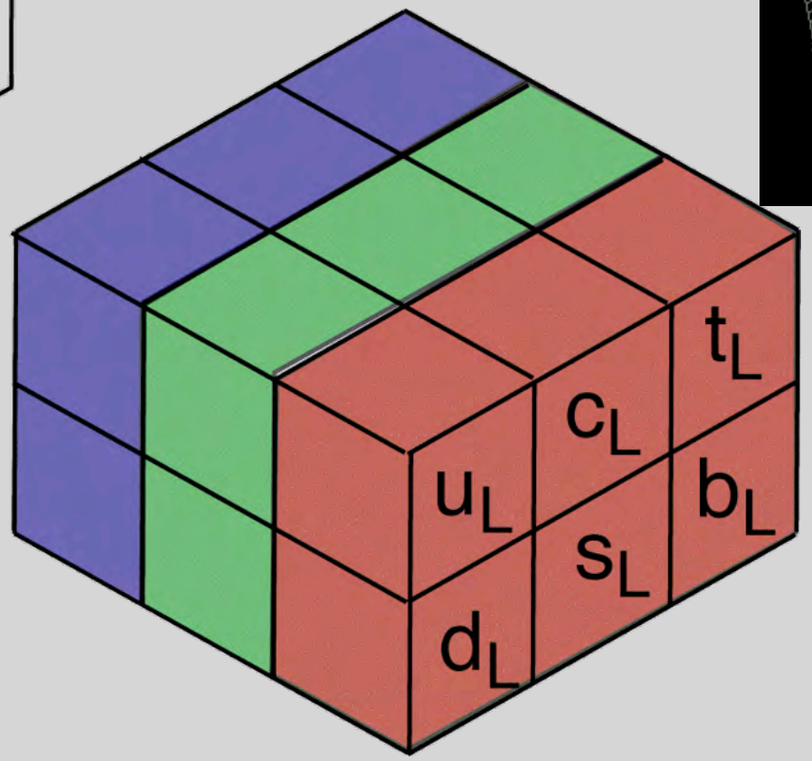
Function follows form

Interactions follow from symmetry

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





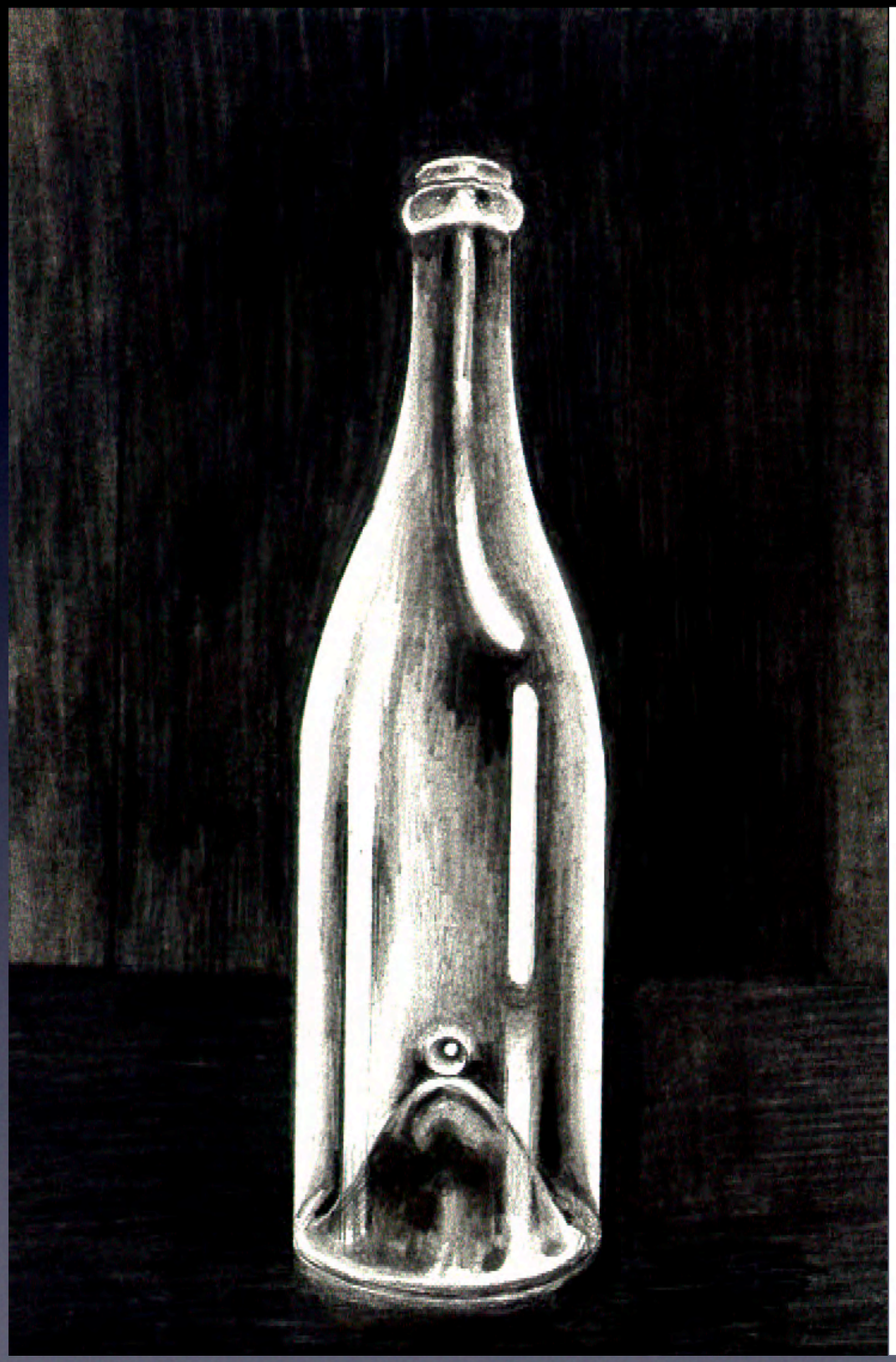


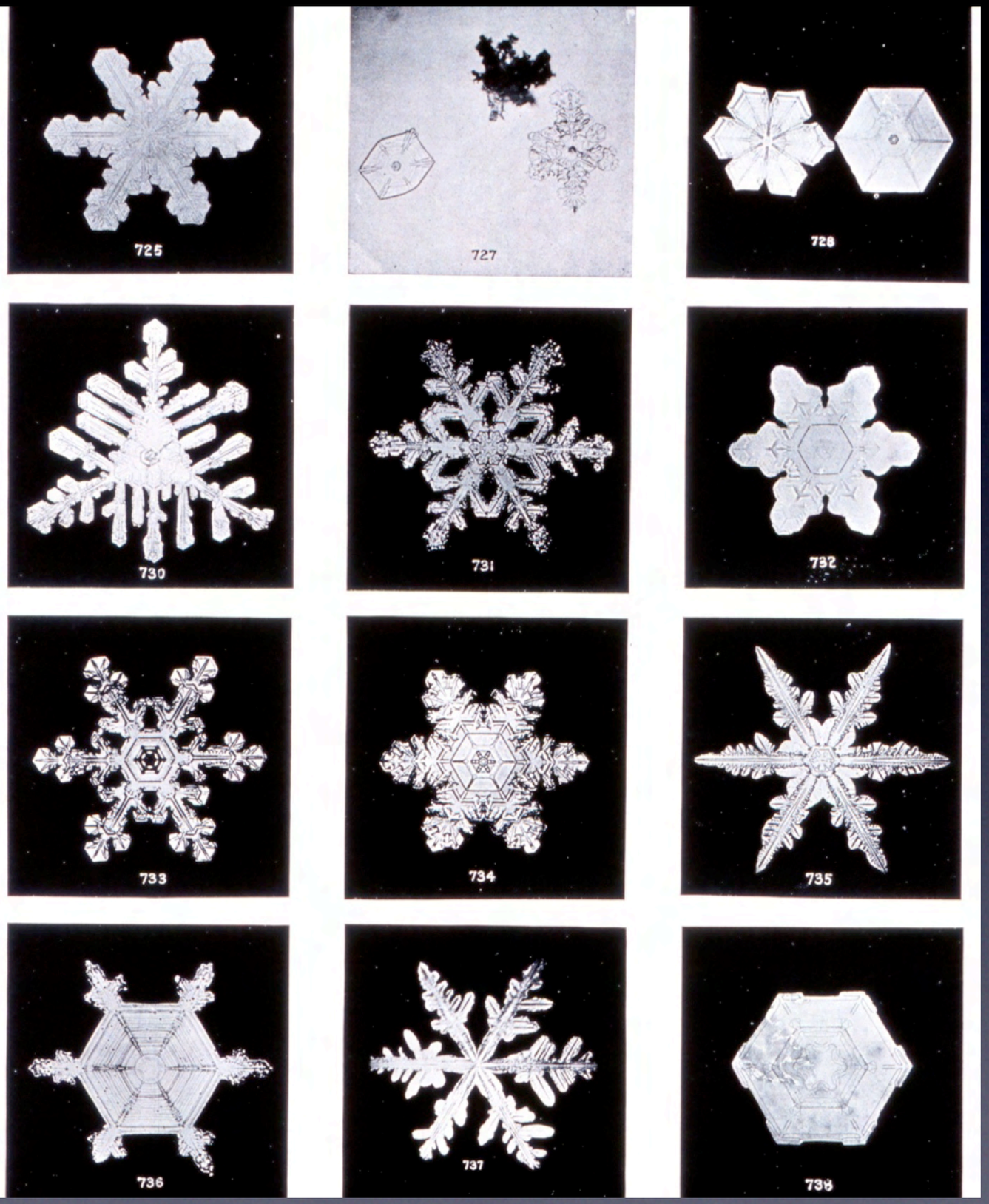
Electroweak theory:
family symmetry
$u \leftrightarrow d$; $\nu \leftrightarrow e$; …

(hidden)

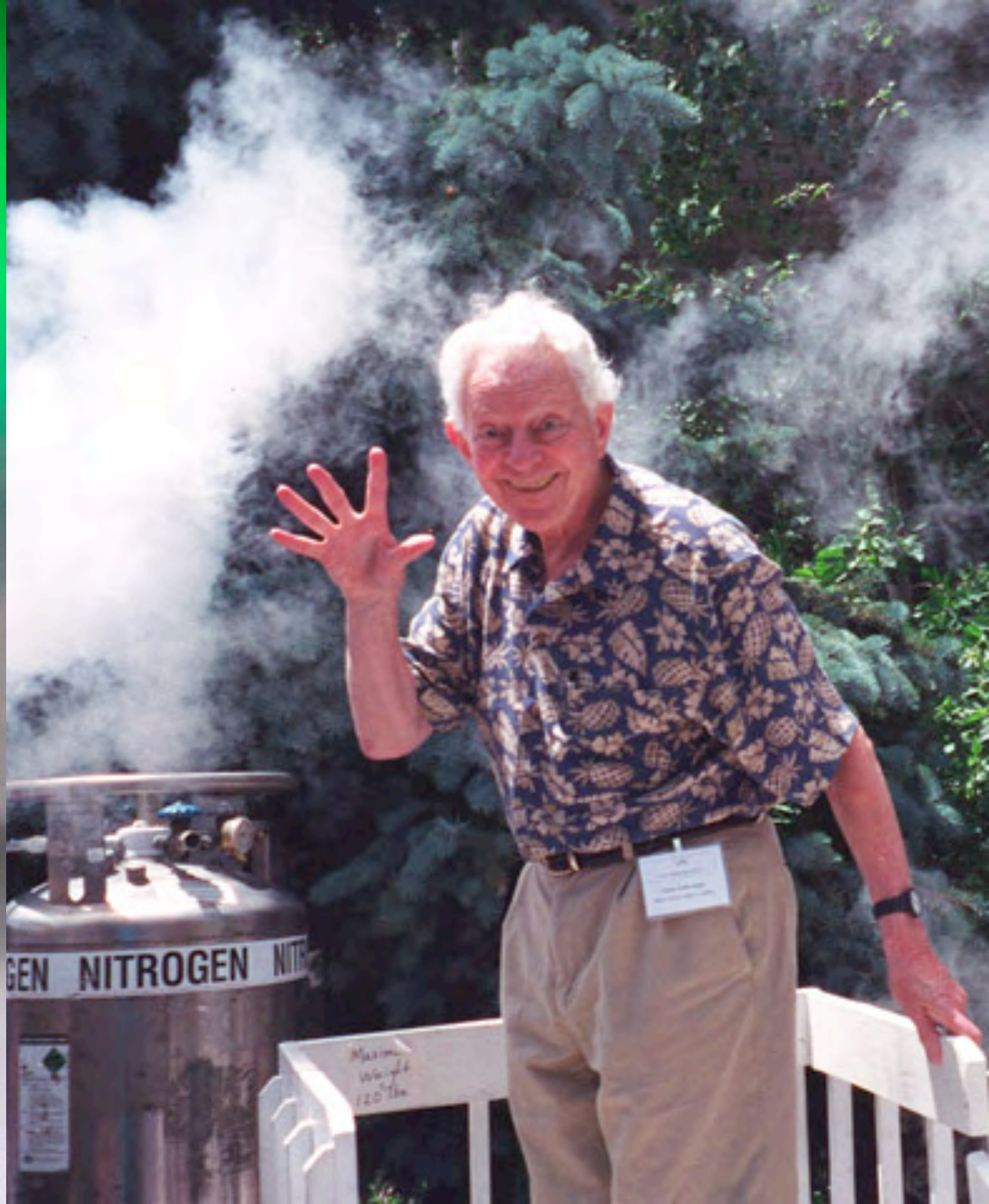
A symmetry among quarks and leptons …
… would have to be a hidden symmetry

Symmetry of laws $\not\Rightarrow$ symmetry of outcomes





Studies among the Snow Crystals ... by Wilson Bentley, via NOAA Photo Library


GEN NITROGEN NIT

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?

Revolution:

Understanding the Everyday

- Why are there atoms?
- Why chemistry?
- Why stable structures?

Imagine a world without a Higgs mechanism

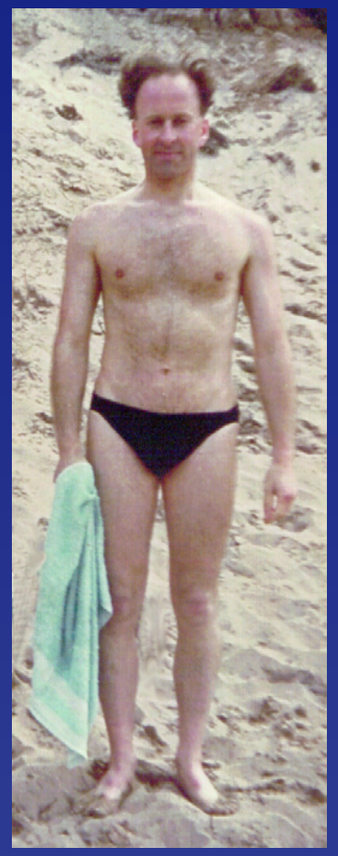
If electroweak symmetry were not hidden …

- Massless quarks and leptons
- QCD confines quarks into color-singlet hadrons
- *Nucleon mass little changed*
- QCD breaks EW symmetry, gives tiny *W*, *Z* masses; weak-isospin force doesn't confine
- *p outweighs n:* rapid β-decay
  ⇒ lightest nucleus is *neutron* … no hydrogen atom
- Some light elements from BBN, but ∞ Bohr radius
- No atoms means no chemistry, no stable composite structures like liquids, solids, …

… character of the physical world would be profoundly changed

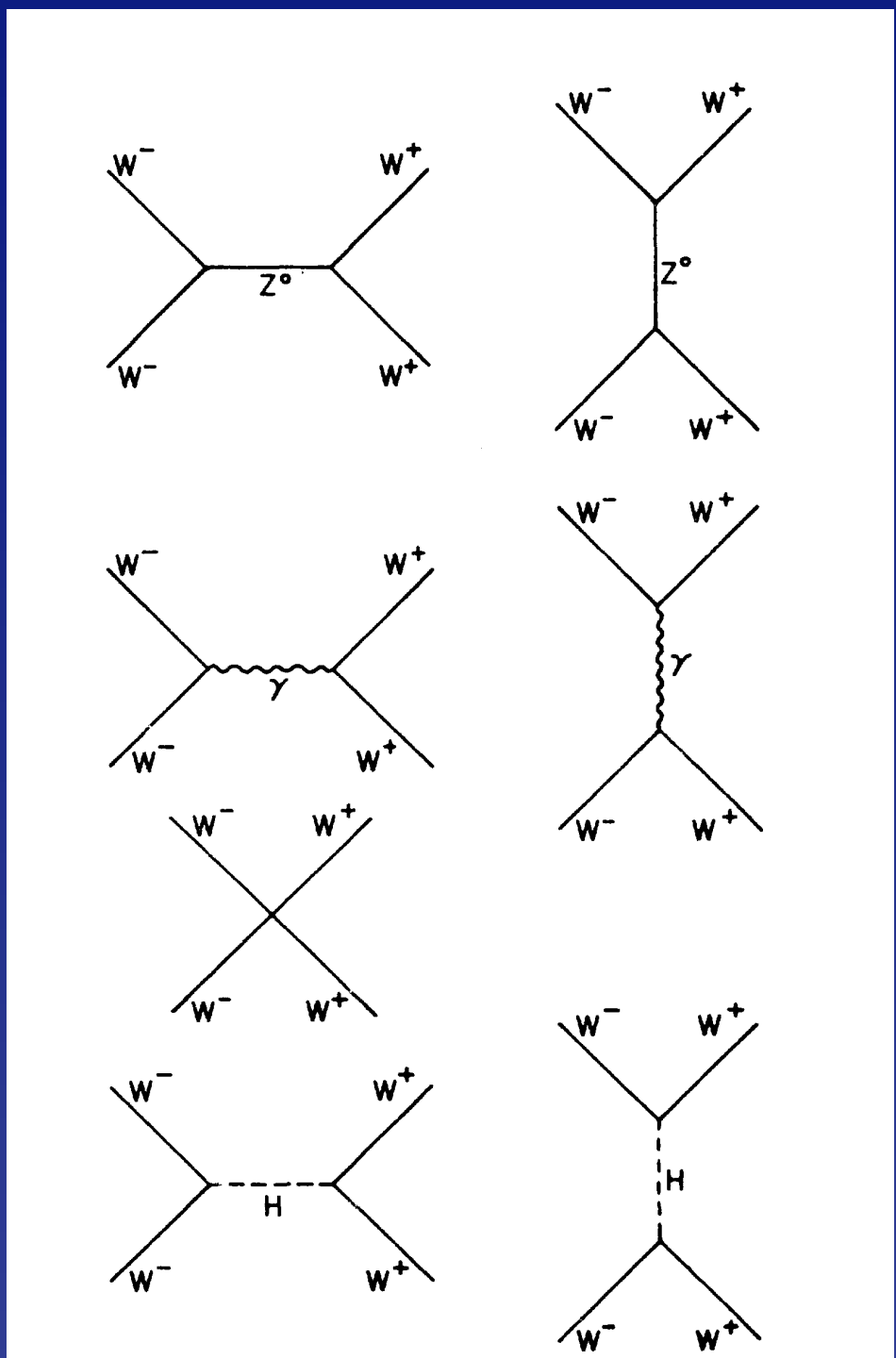
Searching for the *agent provocateur* of electroweak symmetry breaking

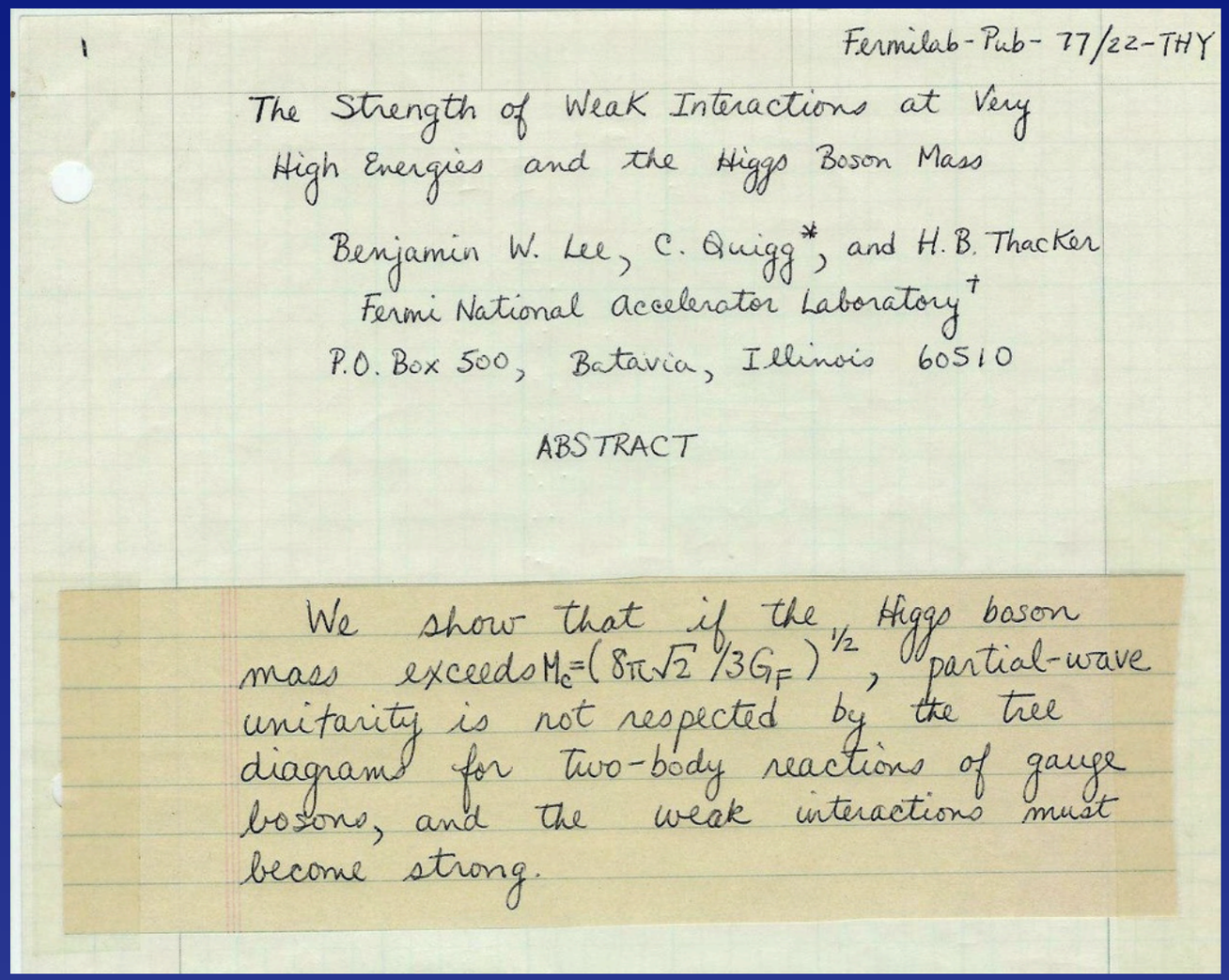
« the search for the Higgs boson »



Peter Higgs

Thought experiment





Fermilab-Pub-77/22-THY

The Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass

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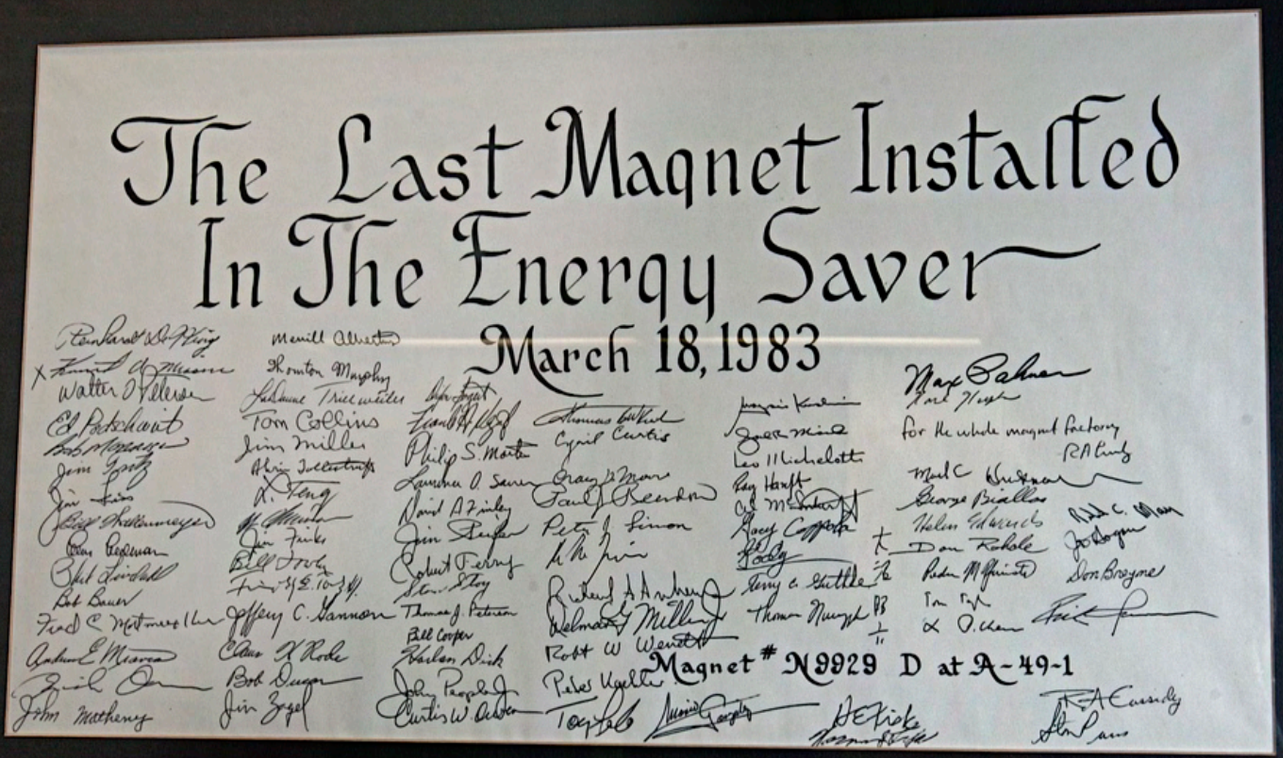
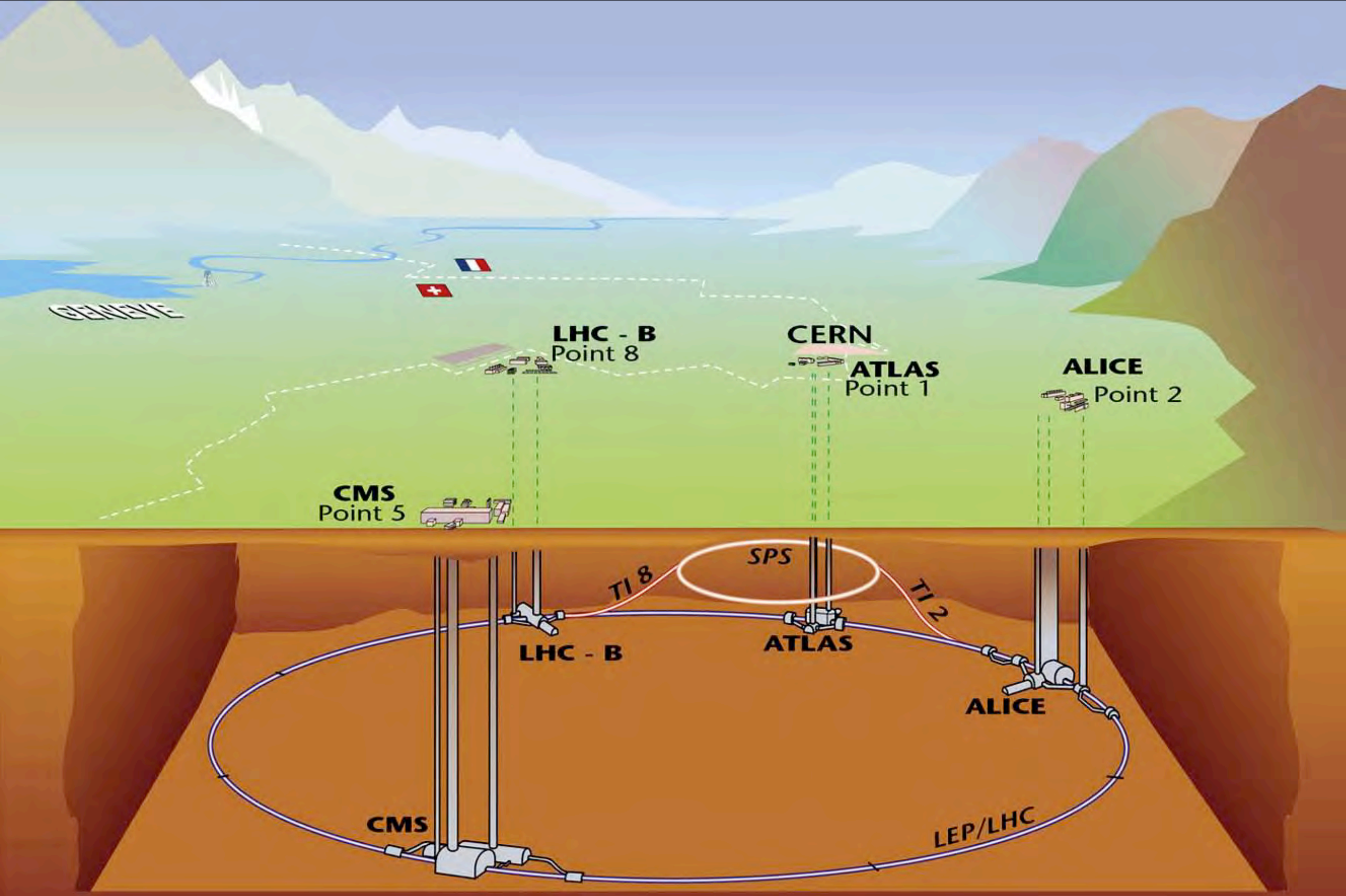
Fermi National Accelerator Laboratory†
P.O. Box 500, Batavia, Illinois 60510

ABSTRACT

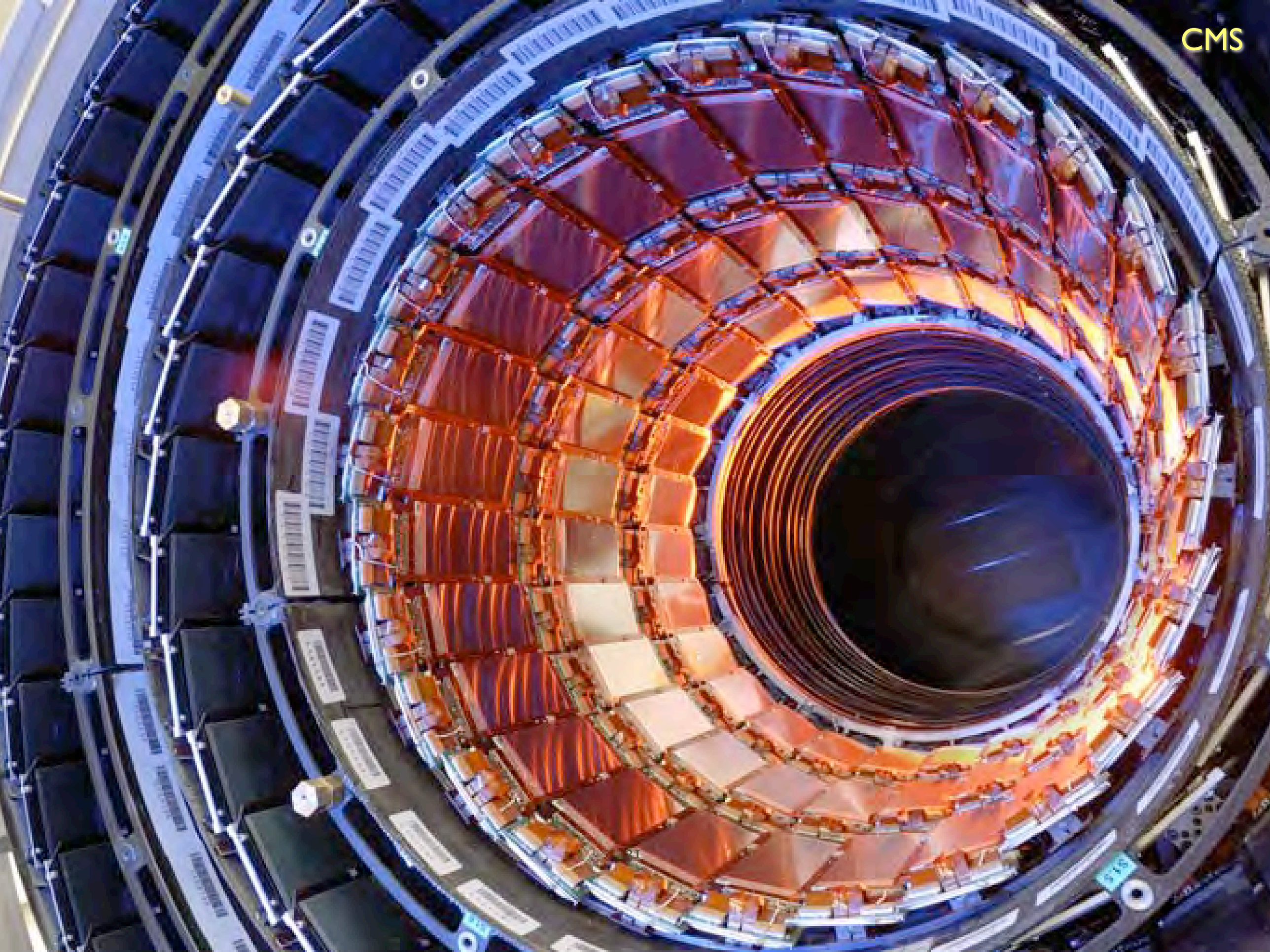
We show that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, partial-wave unitarity is not respected by the tree diagrams for two-body reactions of gauge bosons, and the weak interactions must become strong.


The Last Magnet Installed
In The Energy Saver
March 18, 1983
Magnet # N9929 D at A-49-1



E540 - V10/09/97

CMS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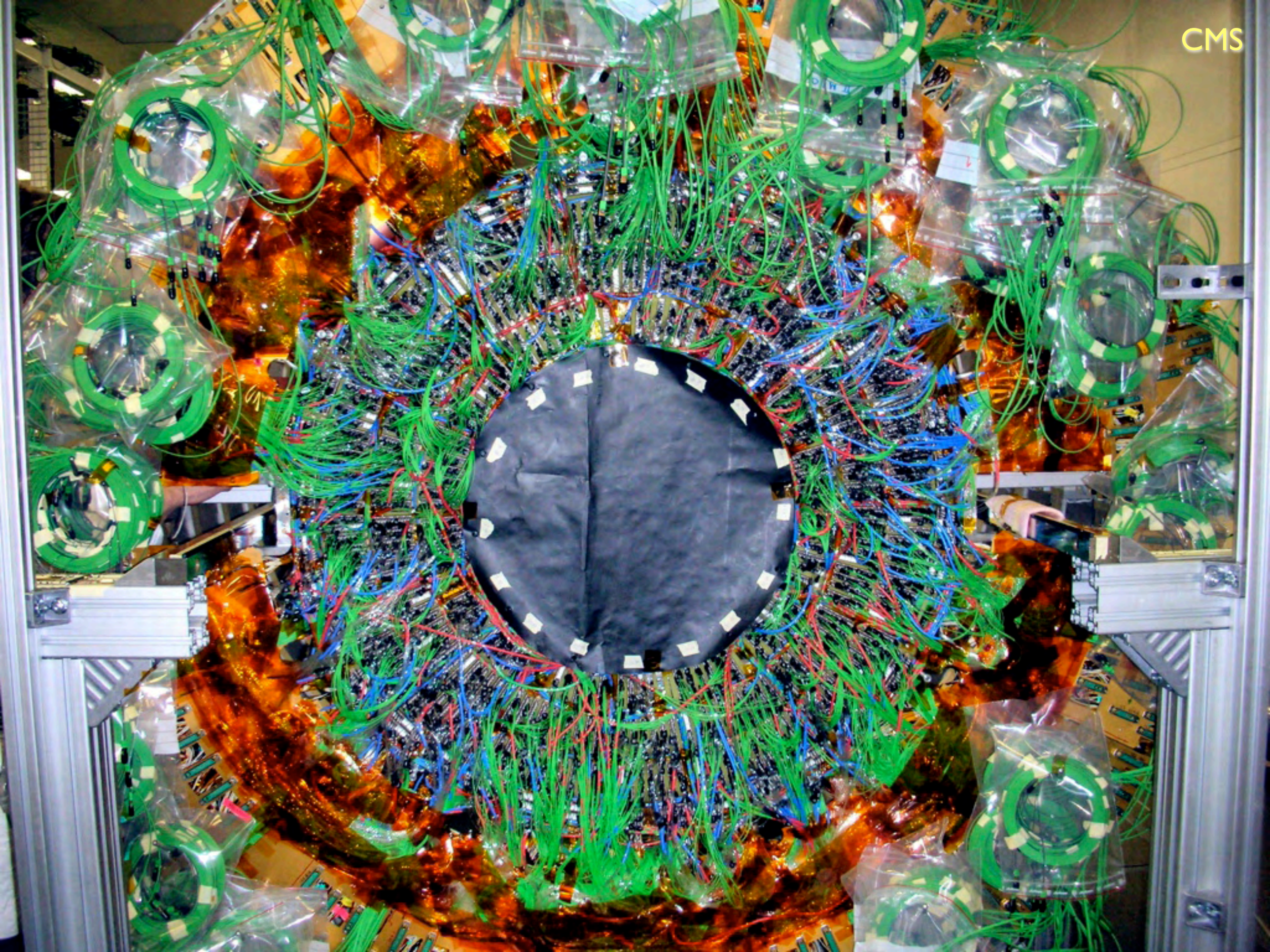
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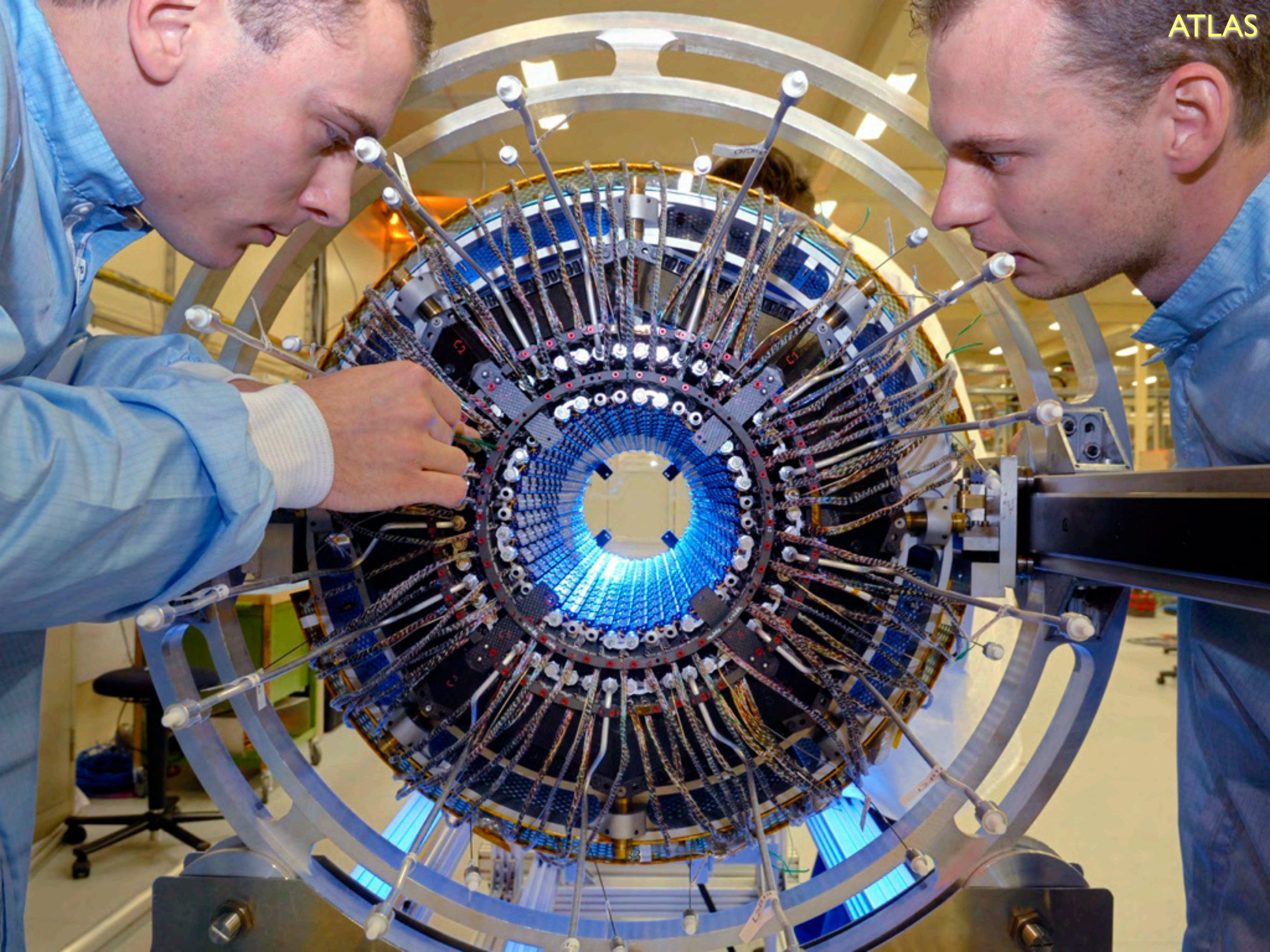
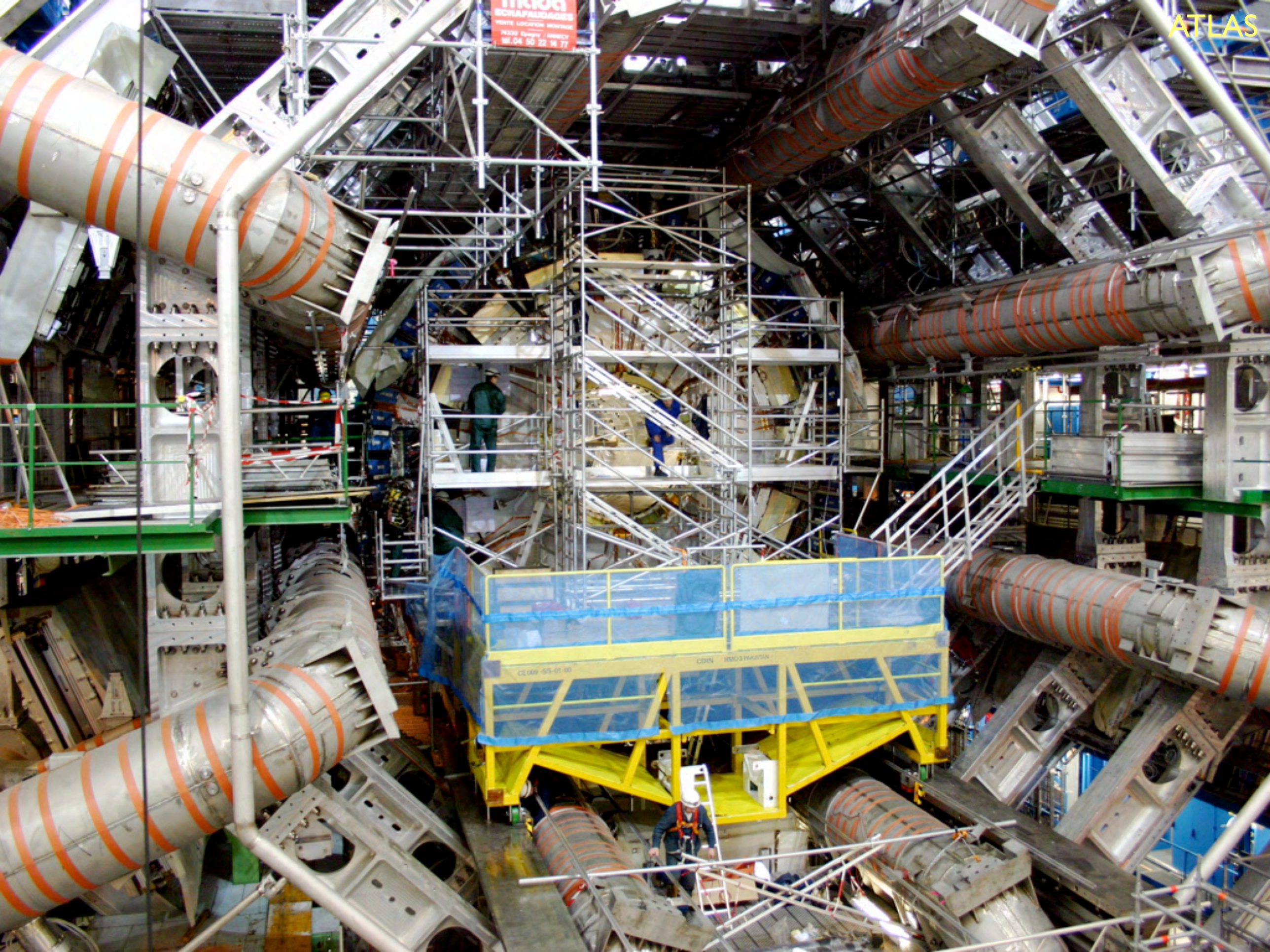

ATLAS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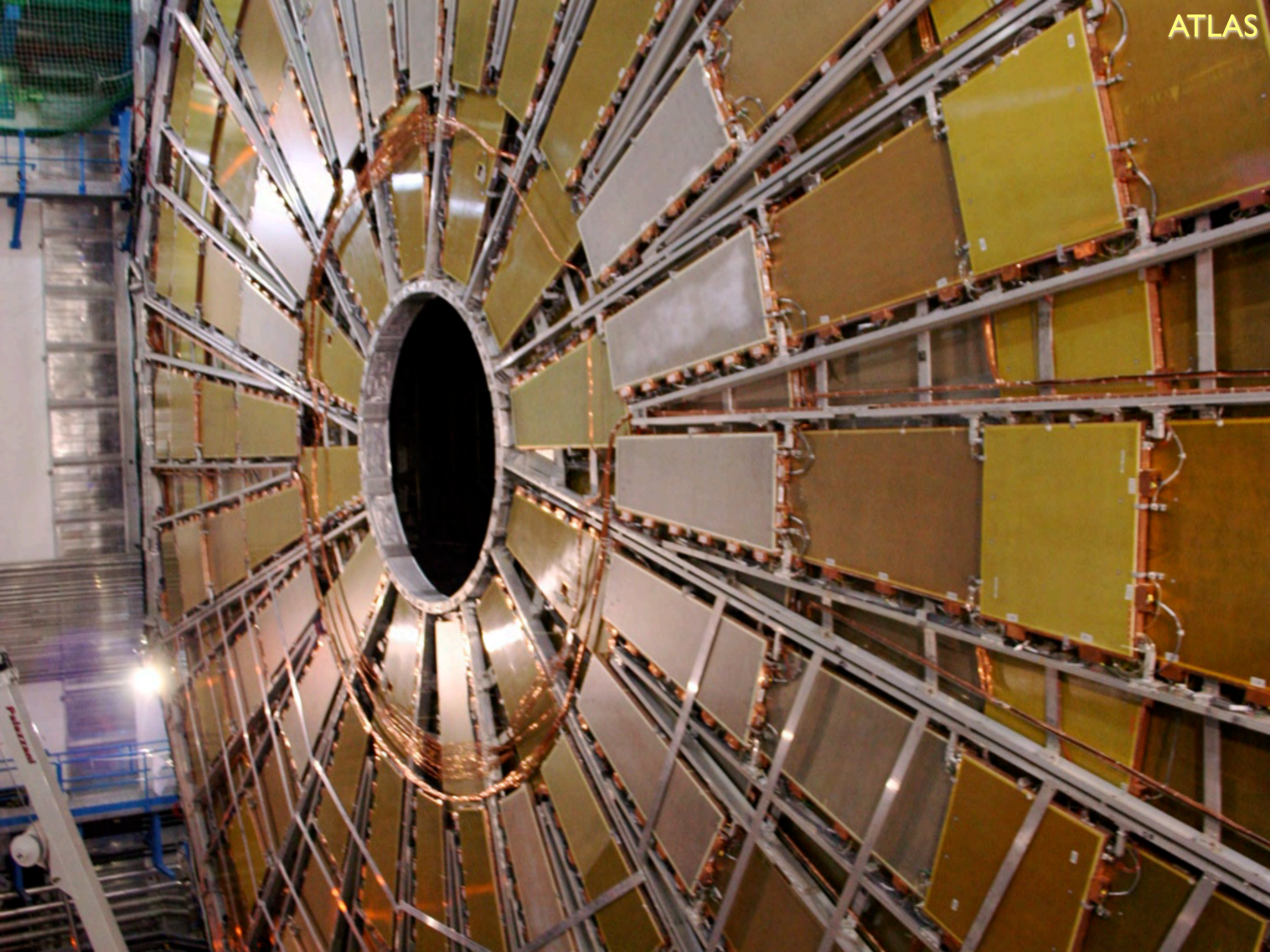
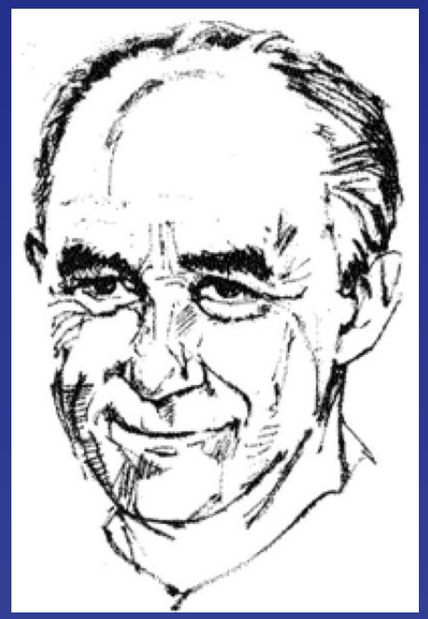

ATLAS

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



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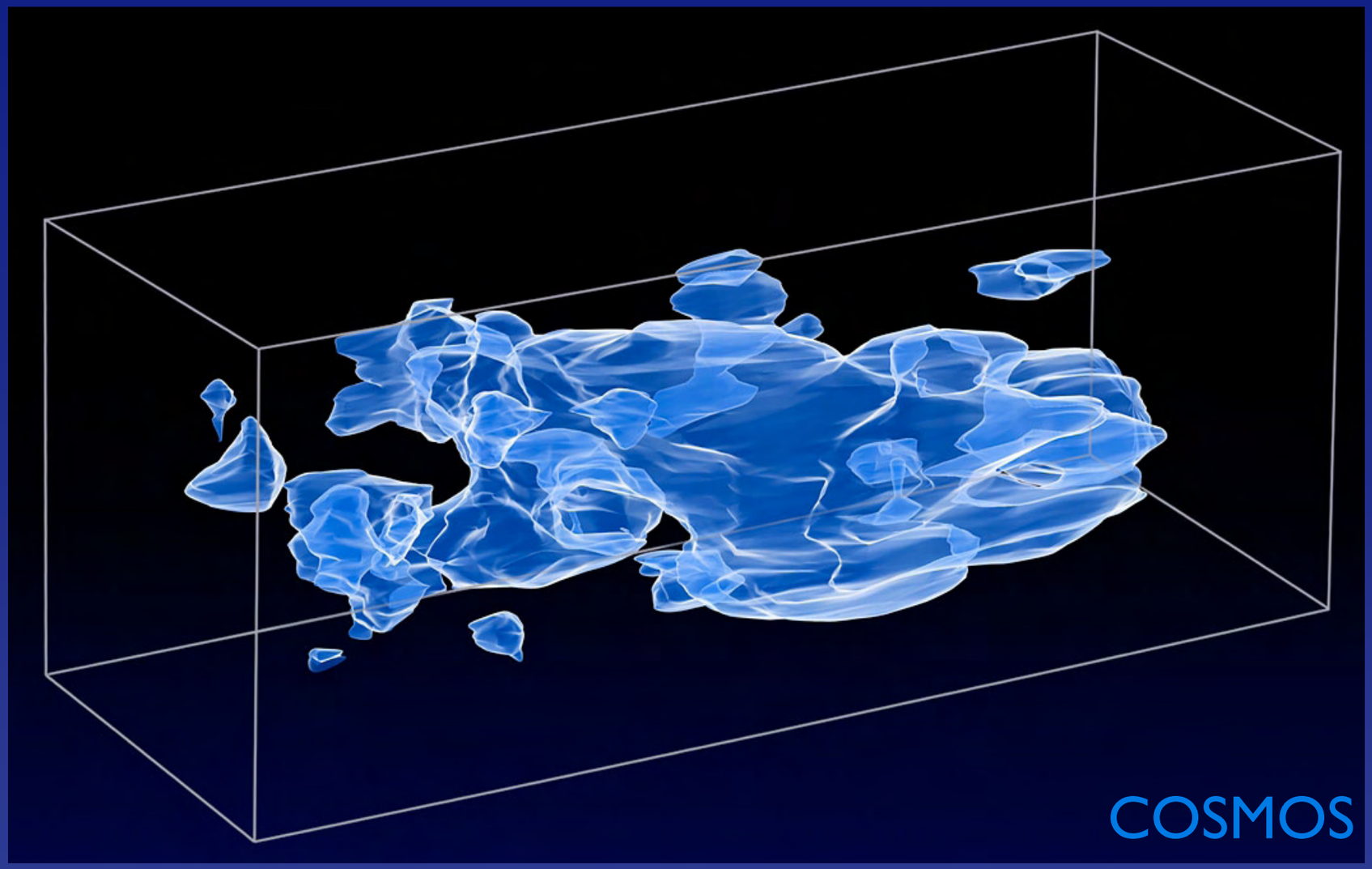
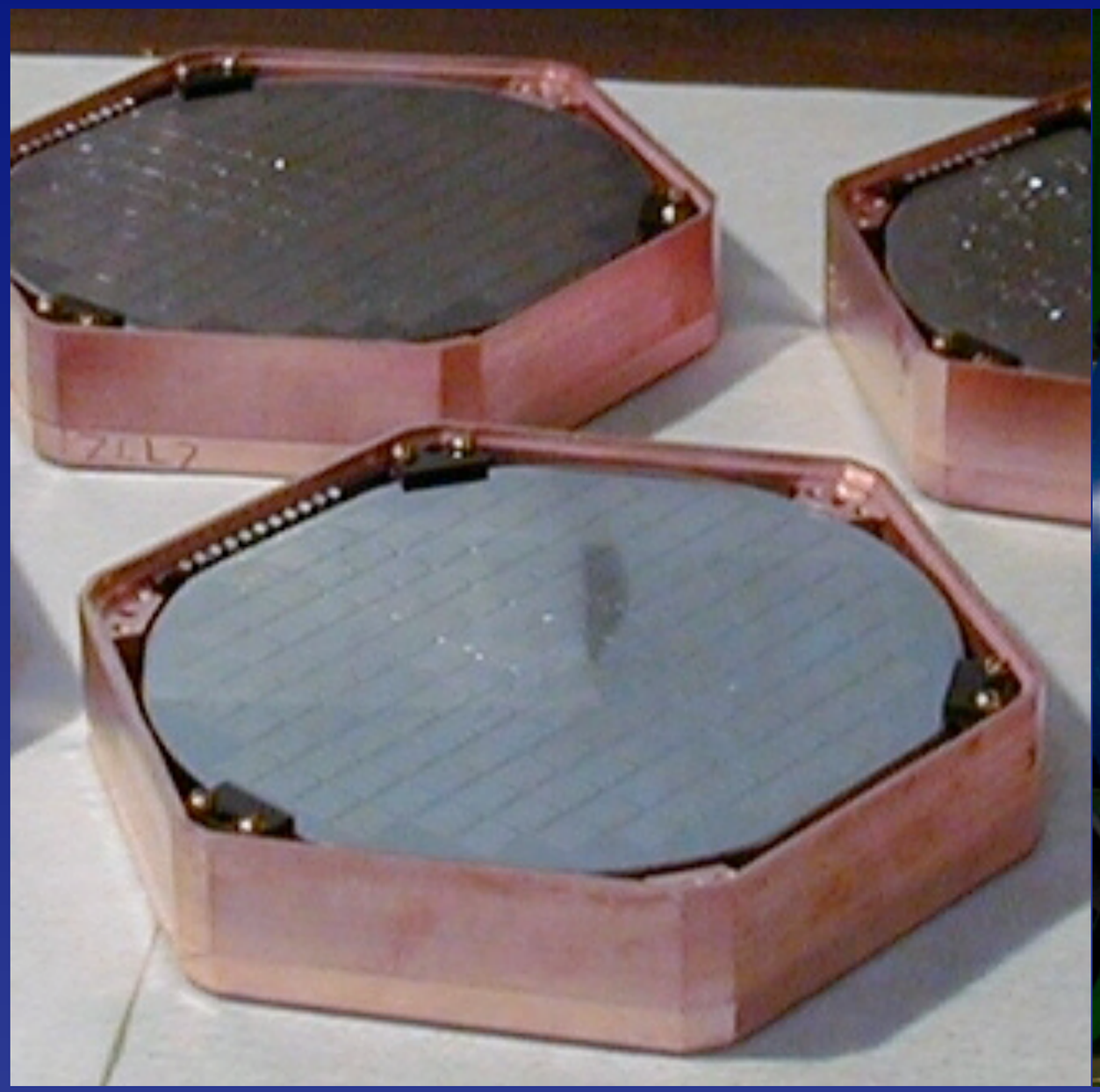
More New Physics on the Fermi Scale?

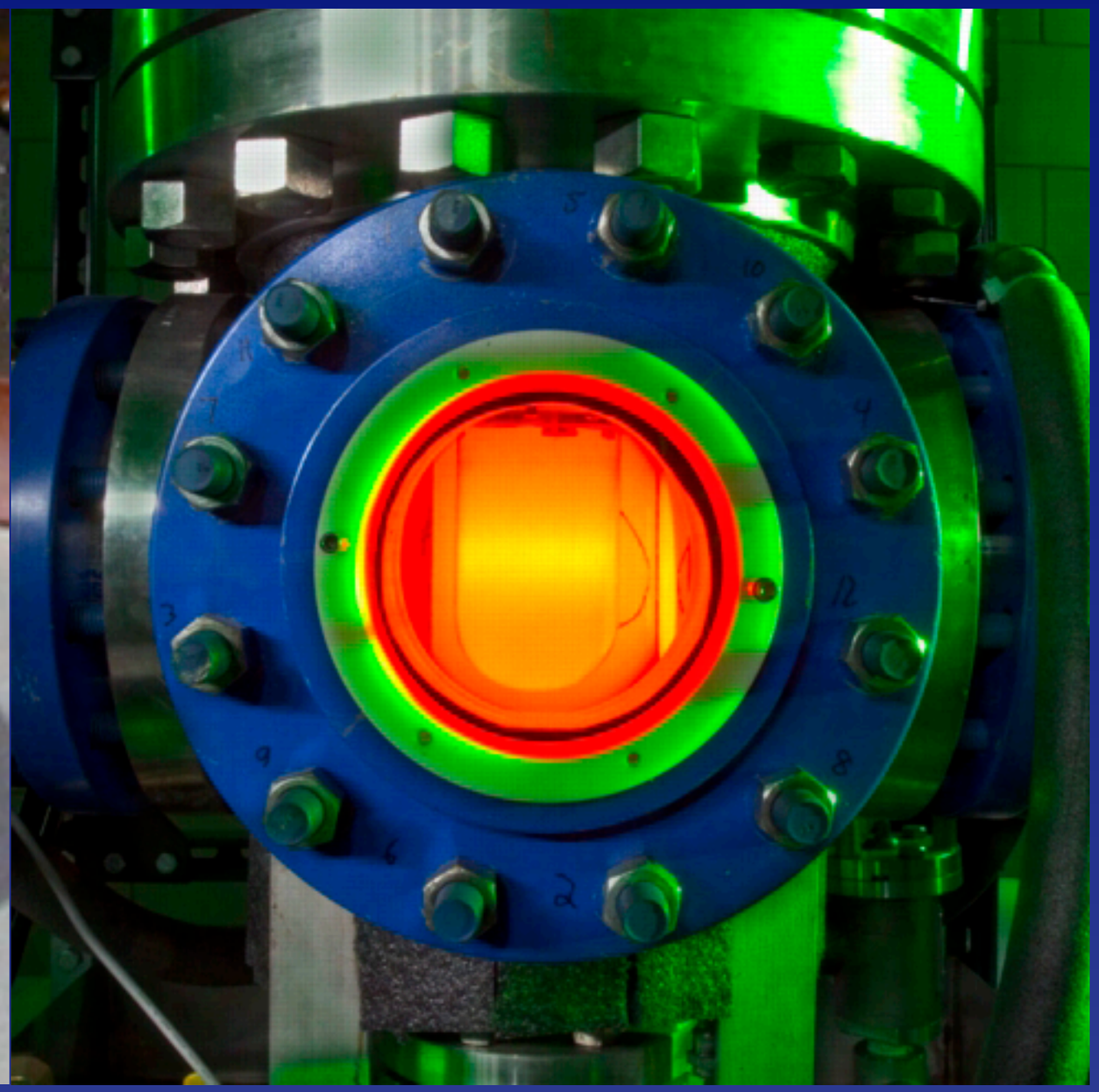
If dark matter interacts weakly …



… its likely mass is 0.1 to 1 TeV: *Fermi scale*

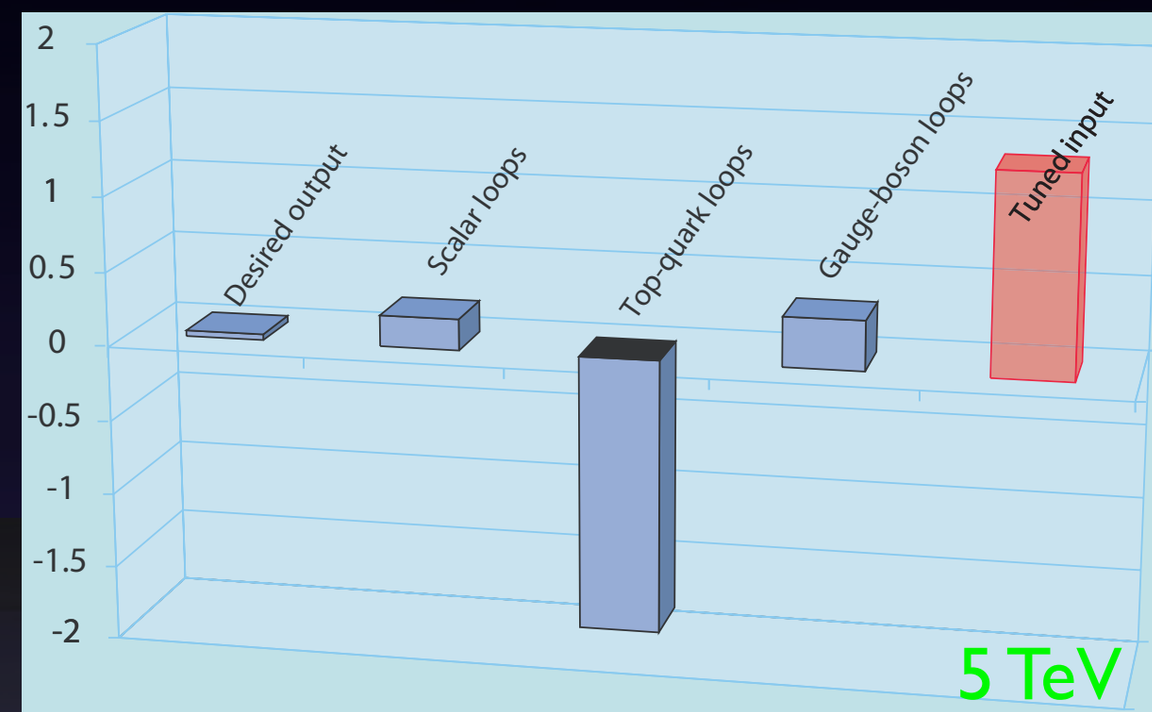
Dark matter relics of the big bang?

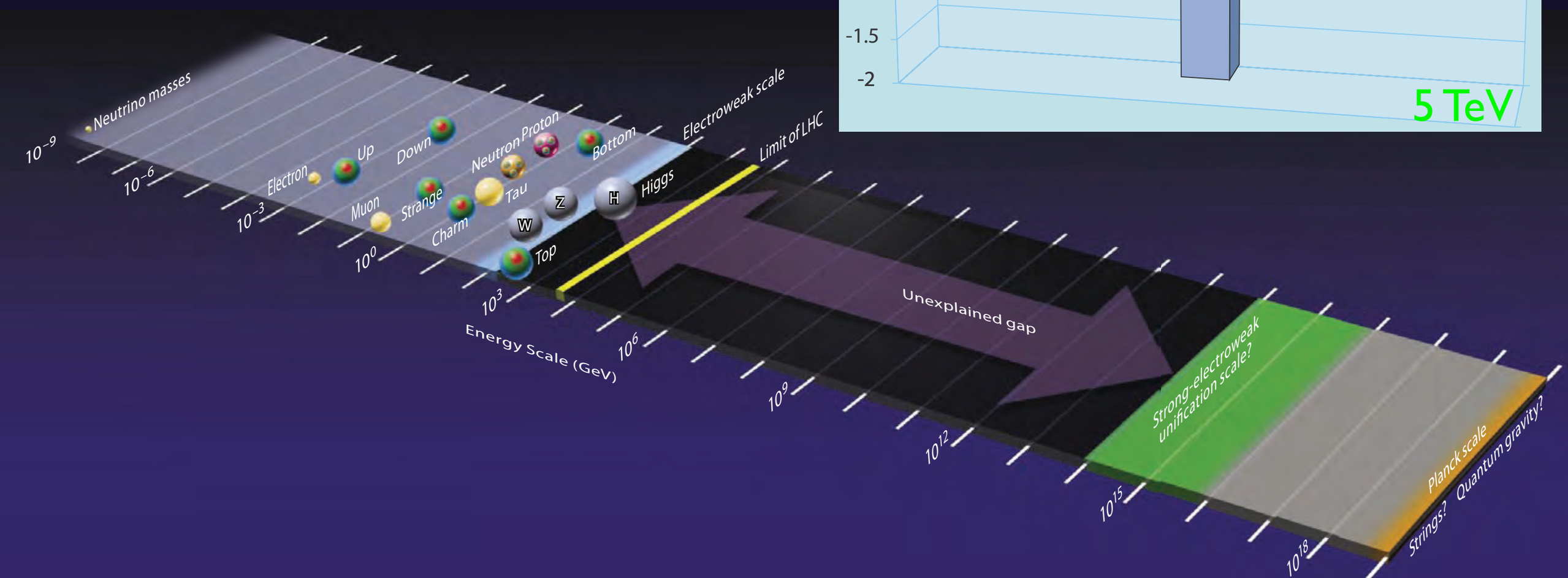




Does M_H < 1 TeV make sense?

The peril of quantum corrections – hierarchy problem





How to separate electroweak, higher scales?

Traditional: change electroweak theory to understand why M_H, electroweak scale $\ll M_{\text{Planck}}$

To resolve hierarchy problem: extend standard model on the 1-TeV scale …

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

composite Higgs boson

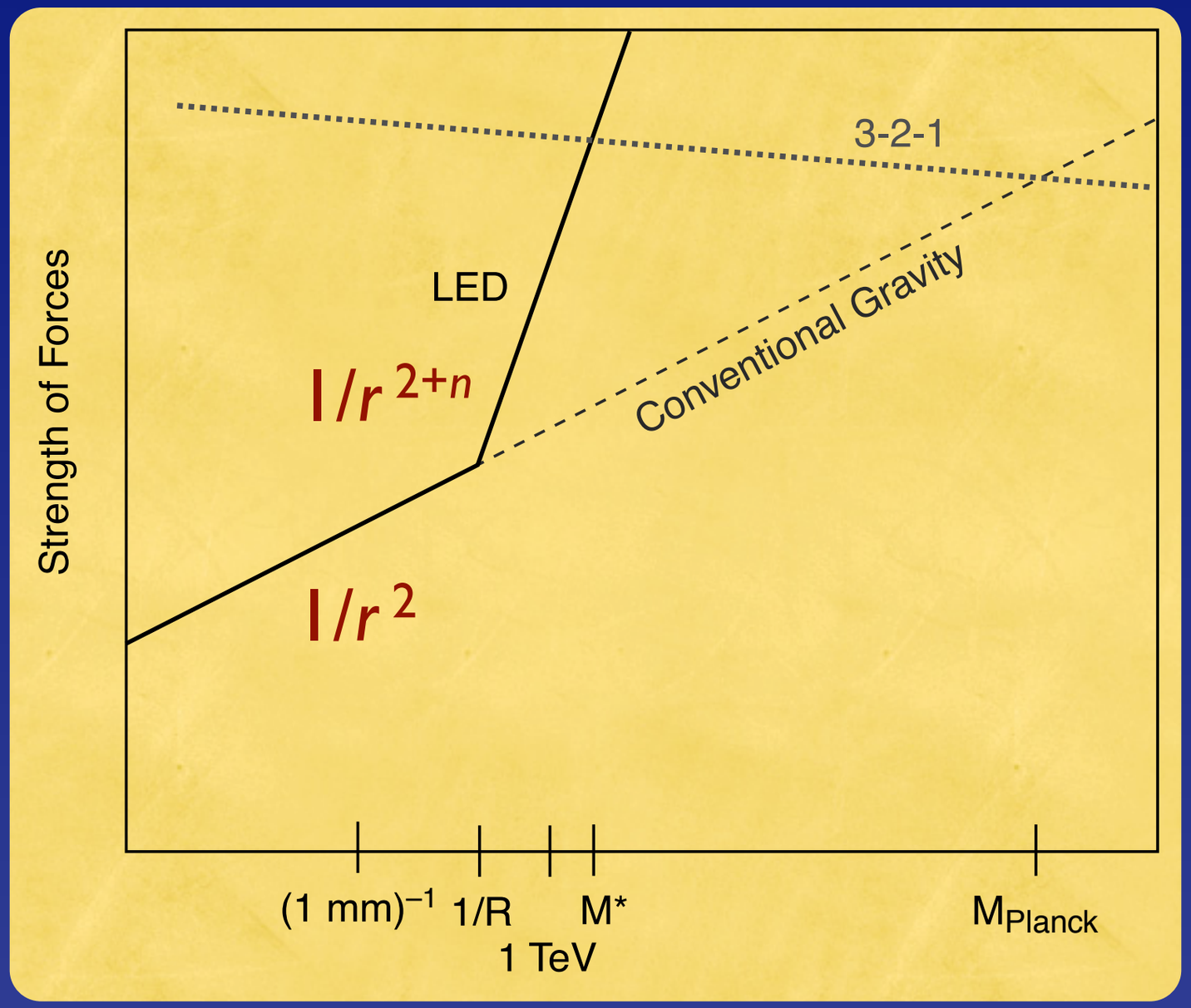
technicolor / topcolor

supersymmetry

…

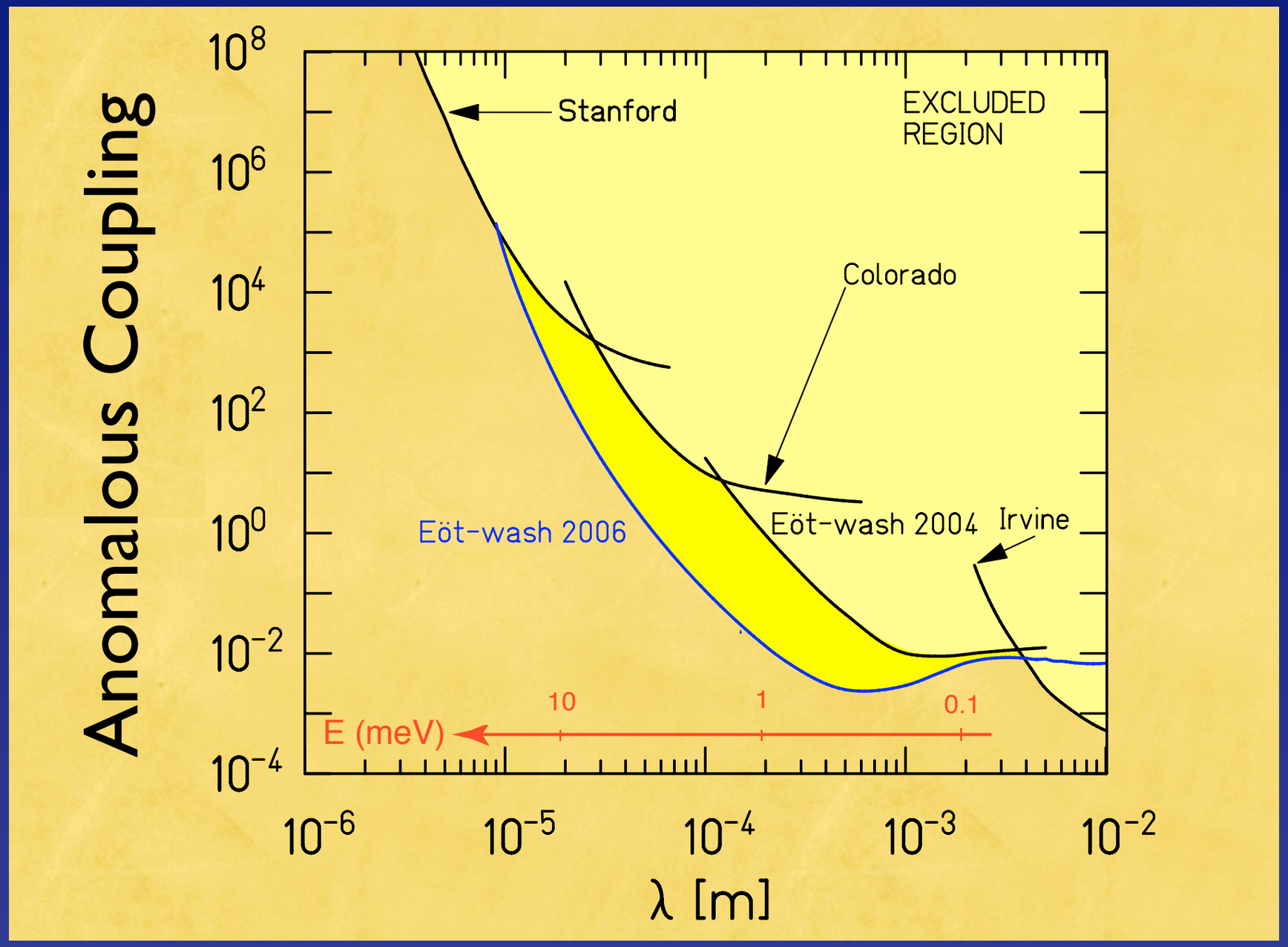
Ask instead why gravity is so weak, why $M_{\text{Planck}} \gg$ electroweak scale

Suppose at scale *R* … gravity propagates in 4+*n* dimensions



M_{Planck} would be a mirage!

Gravity follows Newtonian force law down to $\lesssim$ 1 mm



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
- New evidence that vacuum energy is present (accelerating universe)

Revolution: the meaning of identity

- What makes a top quark a top quark and an electron an electron?
- Slightly different behavior of matter and antimatter means what?
- 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

KATRIN aims at 0.2 eV

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!

Connections …

?

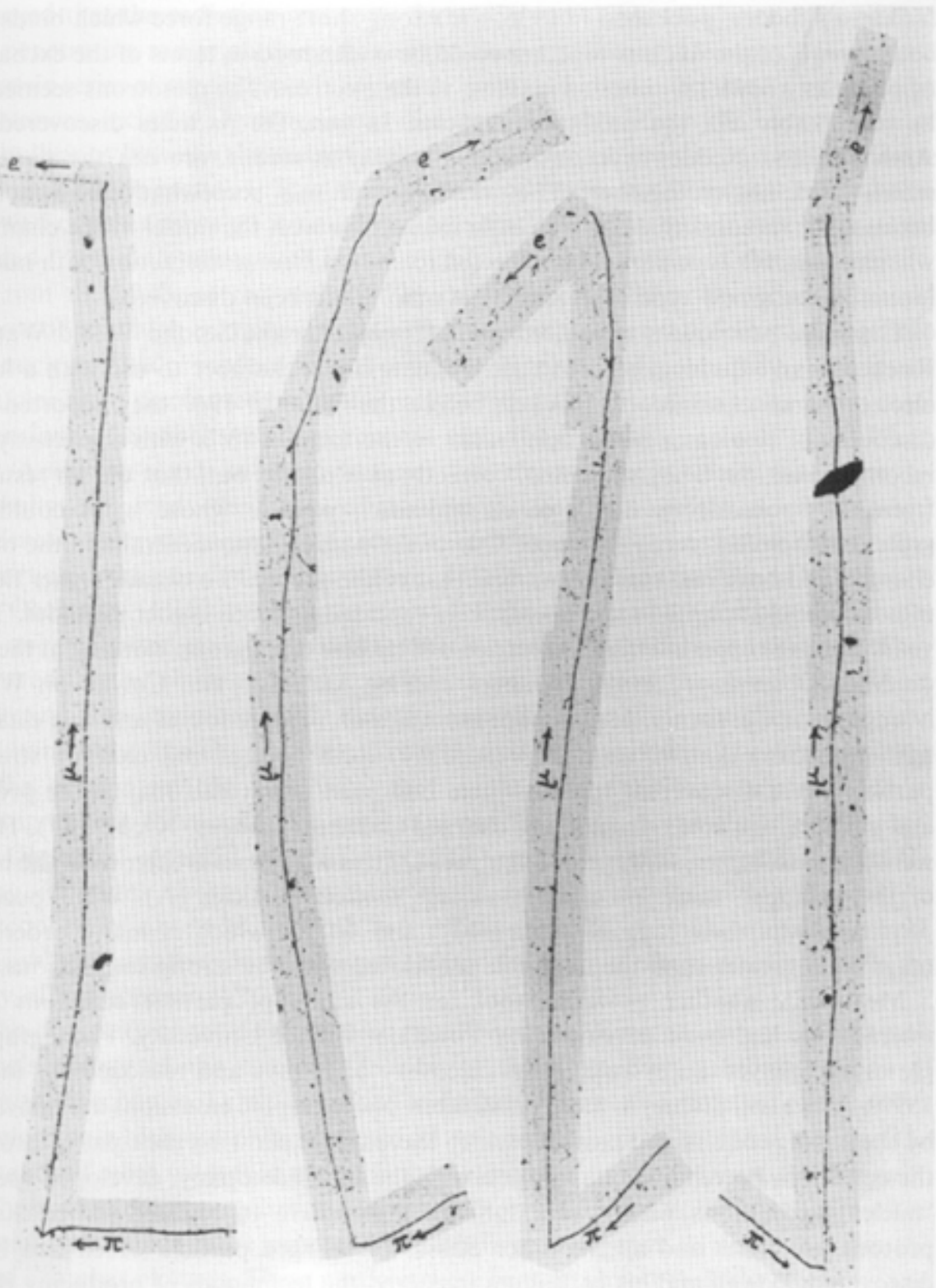


Figure 1.6. Four examples of the decay of a pion into a muon, followed by the subsequent decay of the muon into an electron. These processes were discovered by Powell and his collaborators using nuclear emulsions. (From C. F. Powell, P. H. Fowler and D. H. Perkins (1959). *The study of elementary particles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

"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

Thanks to …

Eric Weeks for the film of Brownian motion
www.physics.emory.edu/~weeks

Derek Leinweber for the QCD lava lamp
www.physics.adelaide.edu.au/~dleinweb/

Angela Gonzales for the pearl in a bottle

J. D. Jackson for the photo of Peter Higgs