The Coming Revolutions in Particle Physics

Chris Quigg
Fermilab

Moti Lal Rustgi Memorial Lecture

University at Buffalo · October 18, 2002

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."

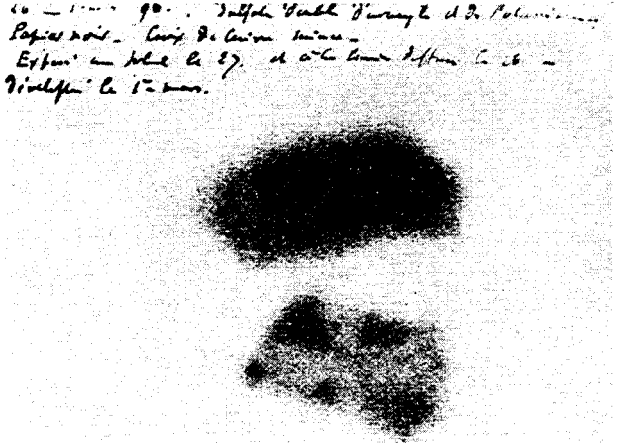
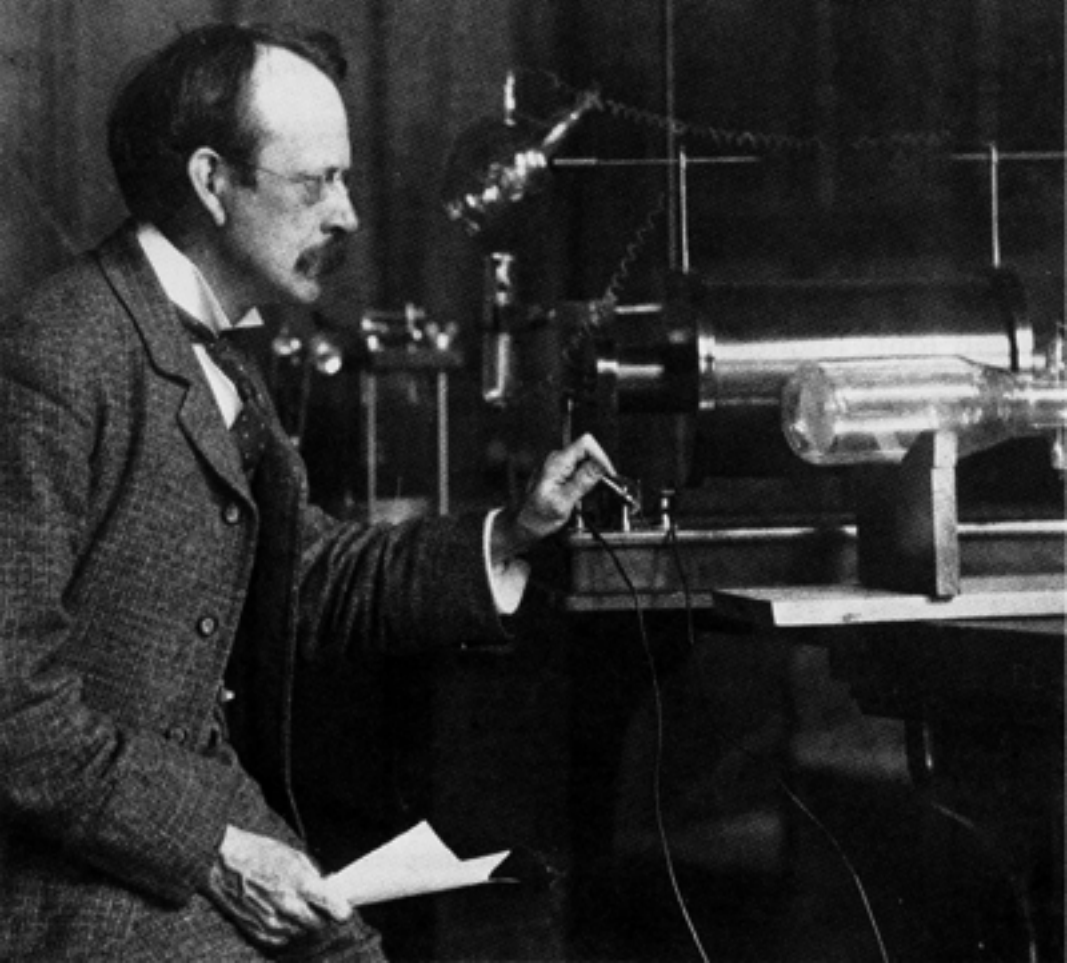


Fig.1.



Galileo's Three Revolutions

Galileo's Three Revolutions

Eppur si muove . . .

Galileo's Three Revolutions

Eppur si muove . . .

- ▷ Completing the Copernican Revolution

  Humans do not occupy a privileged location in the Universe

Galileo's Three Revolutions

Eppur si muove . . .

- ▷ Completing the Copernican Revolution

  Humans do not occupy a privileged location in the Universe

Cimenti . . .

Galileo's Three Revolutions

Eppur si muove . . .

▷ Completing the Copernican Revolution

Humans do not occupy a privileged location in the Universe

Cimenti . . .

▷ Rejecting Authority:

Learning to read Nature by doing experiments

Galileo's Three Revolutions

Eppur si muove . . .

▷ Completing the Copernican Revolution

Humans do not occupy a privileged location in the Universe

Cimenti . . .

▷ Rejecting Authority:

Learning to read Nature by doing experiments

The minute particular . . .

Galileo's Three Revolutions

Eppur si muove ...

▷ Completing the Copernican Revolution

Humans do not occupy a privileged location in the Universe

Cimenti ...

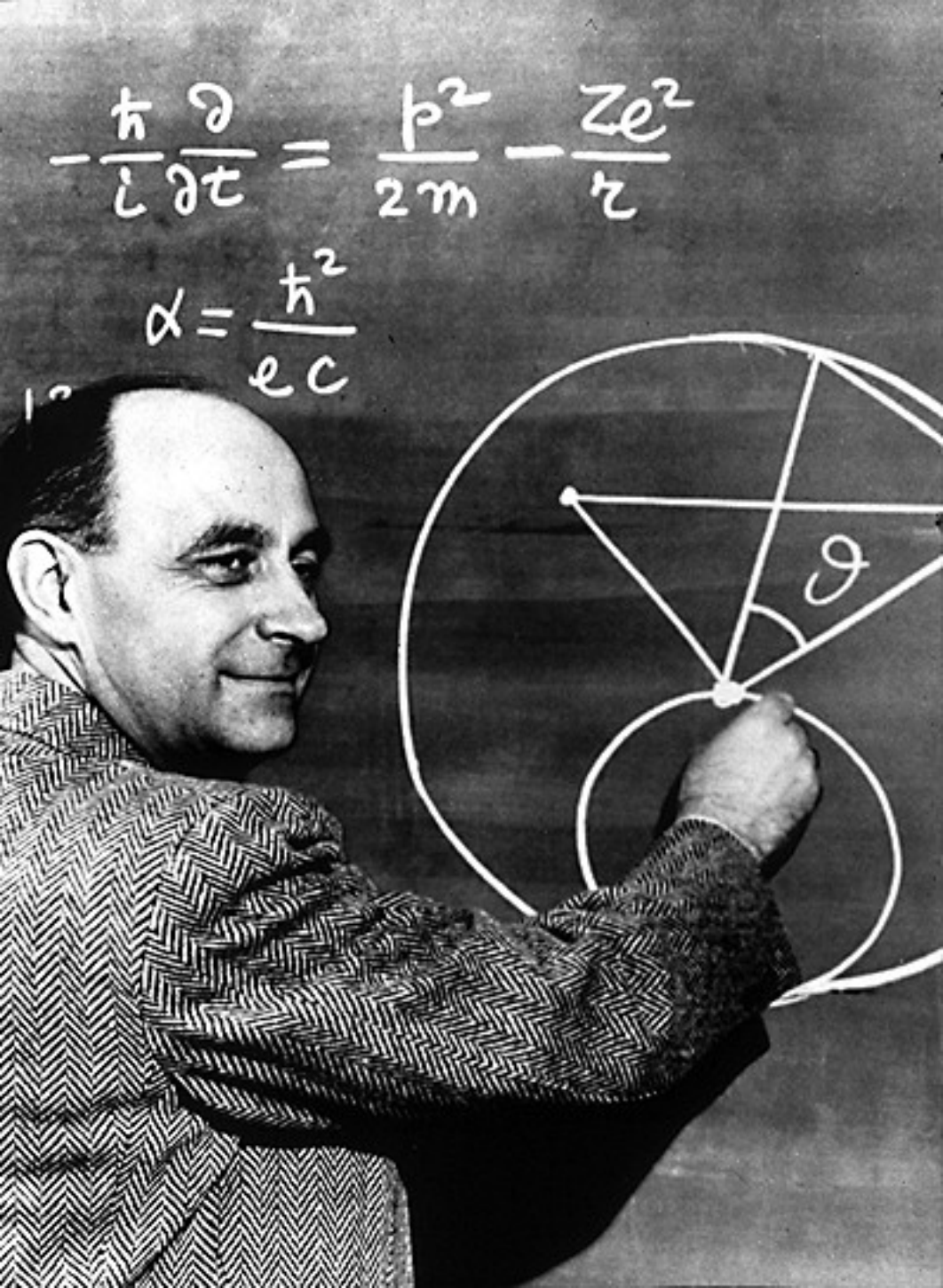
▷ Rejecting Authority:

Learning to read Nature by doing experiments

The minute particular ...

▷ Not asking general questions and receiving limited answers,

but asking limited questions and finding general answers


$-\frac{\hbar}{i}\frac{\partial}{\partial t} = \frac{p^2}{2m} - \frac{Ze^2}{r}$
$\alpha = \frac{\hbar^2}{ec}$
ϑ

The World's Most Powerful Microscope

Fermilab's Tevatron Collider and Detectors

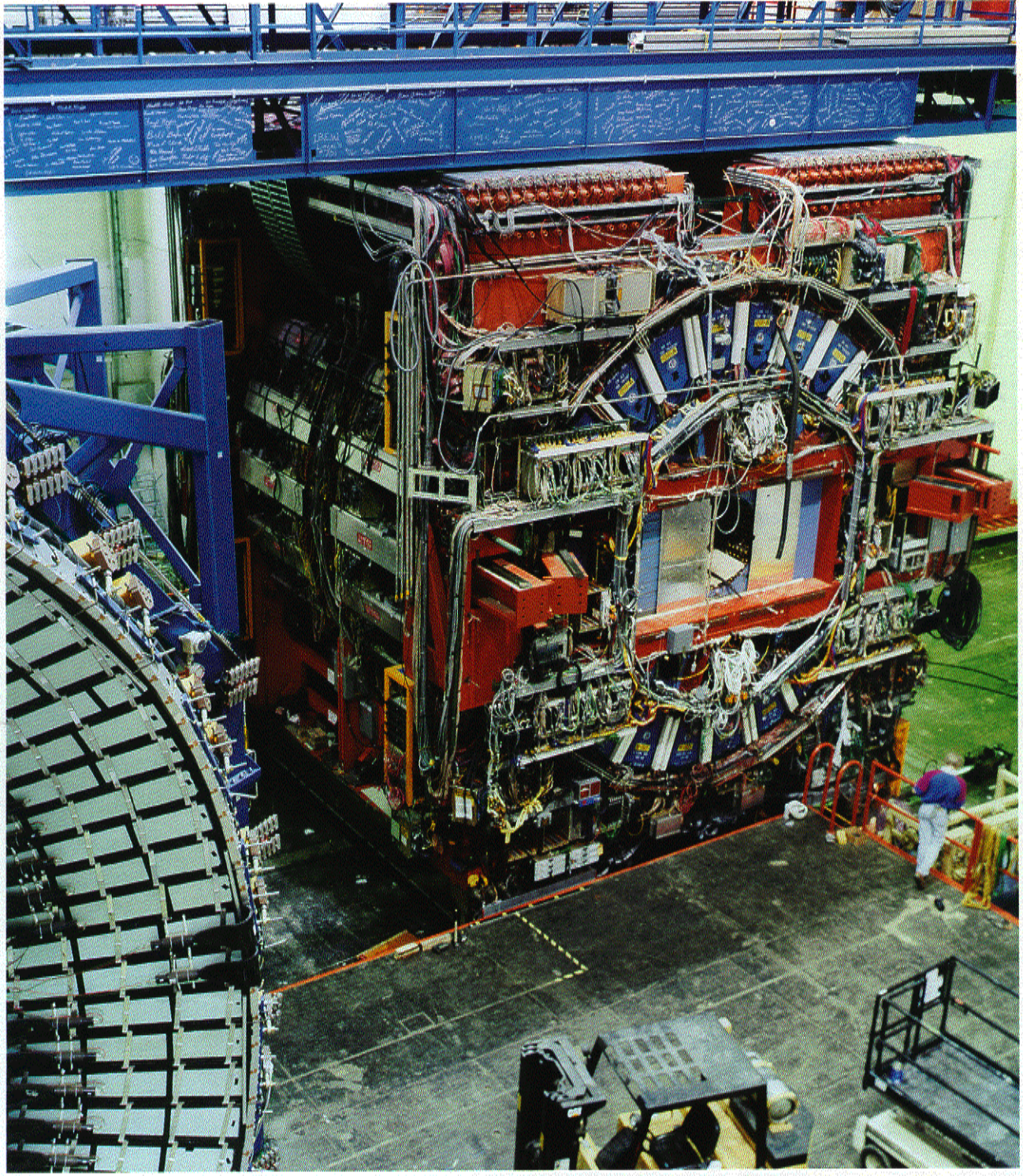
900-GeV protons: c - 364 mph

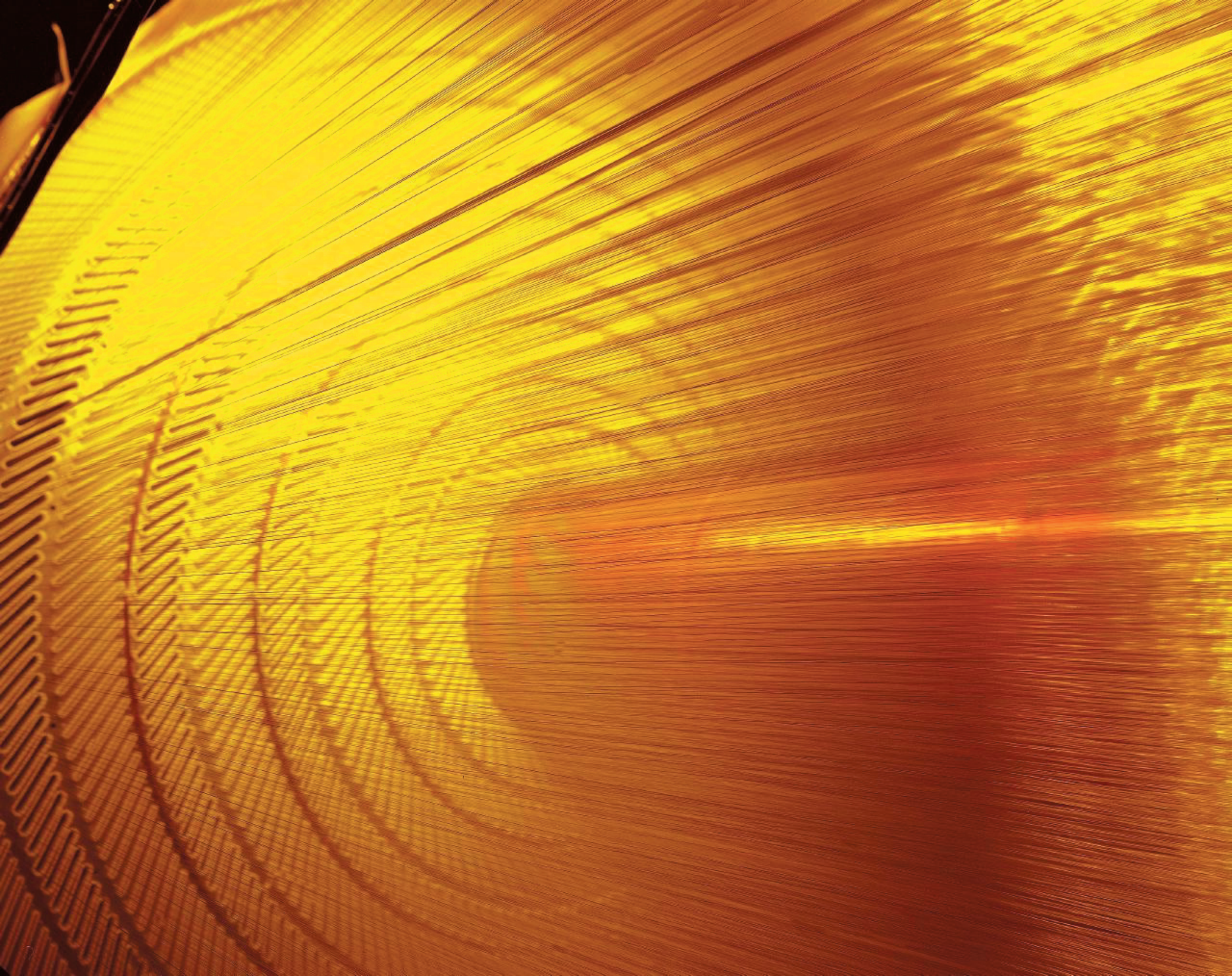
1-TeV protons: c - 295 mph

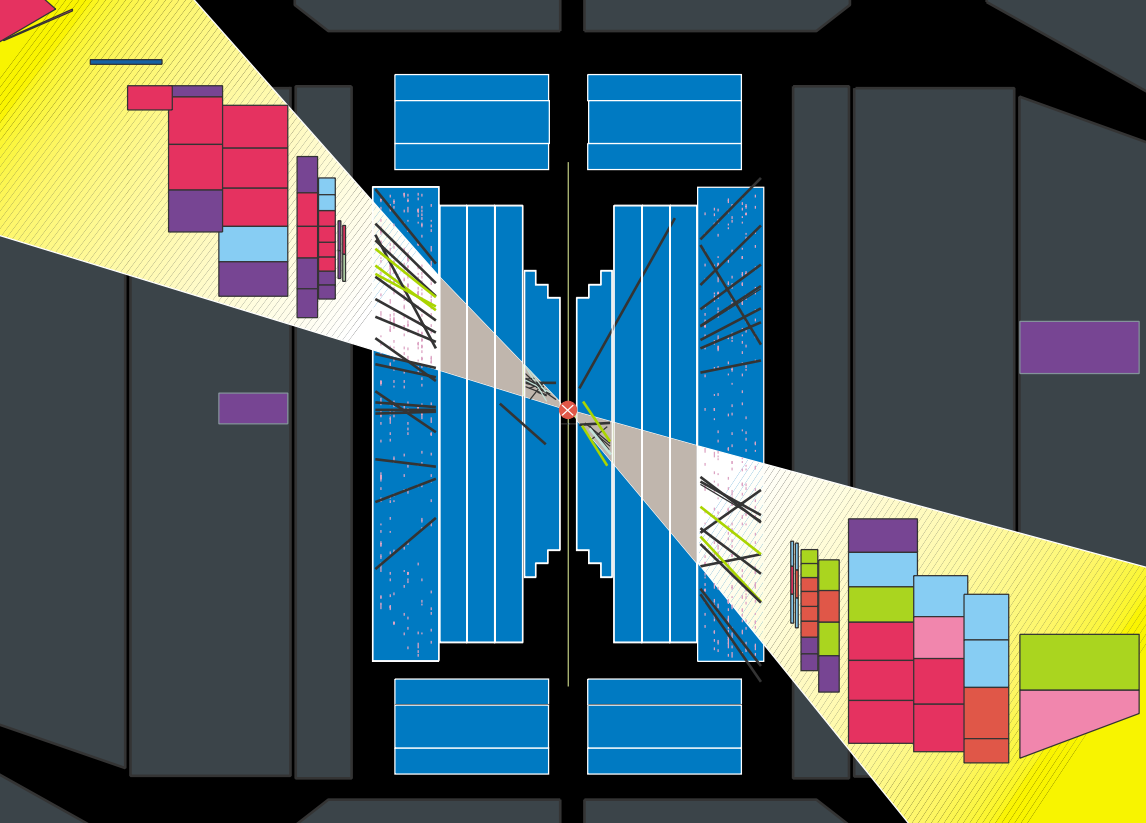
Improvement: 69 mph!

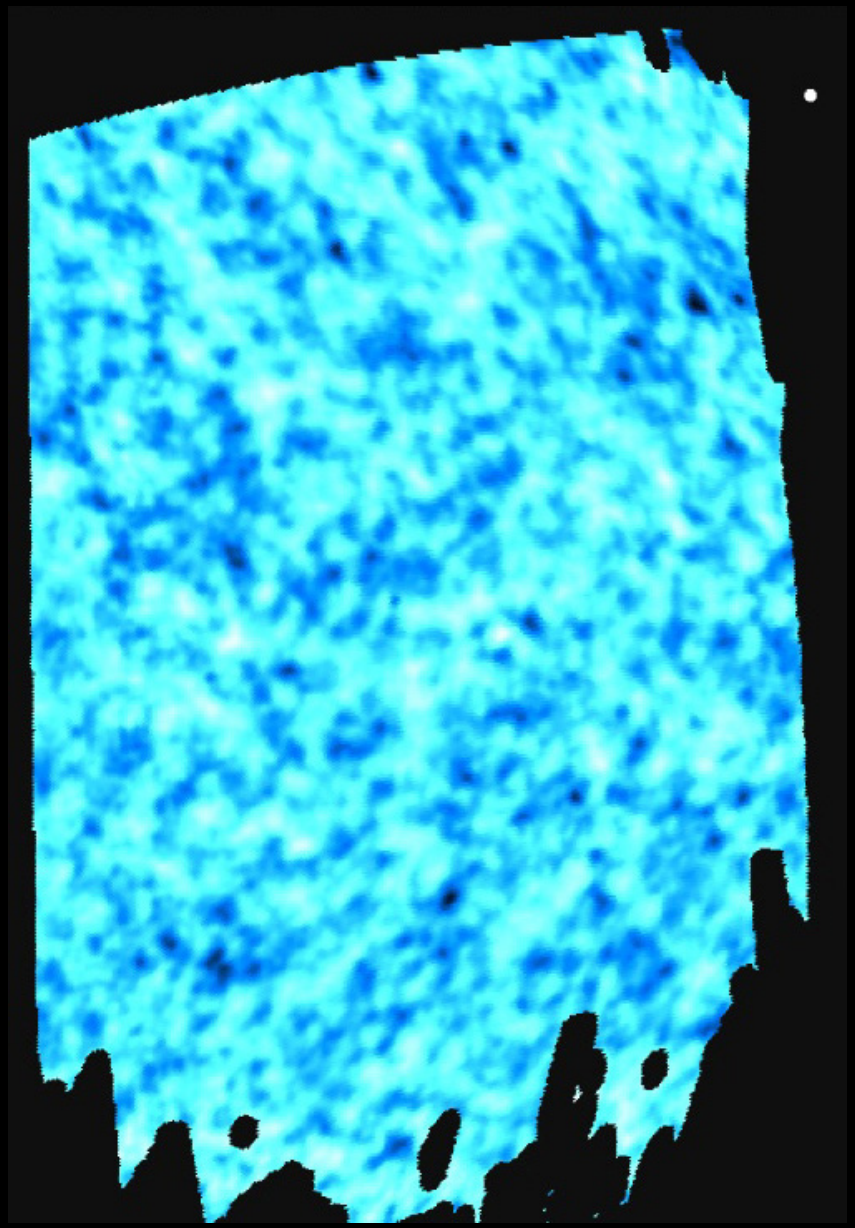
Protons pass my window 45,000 times per second

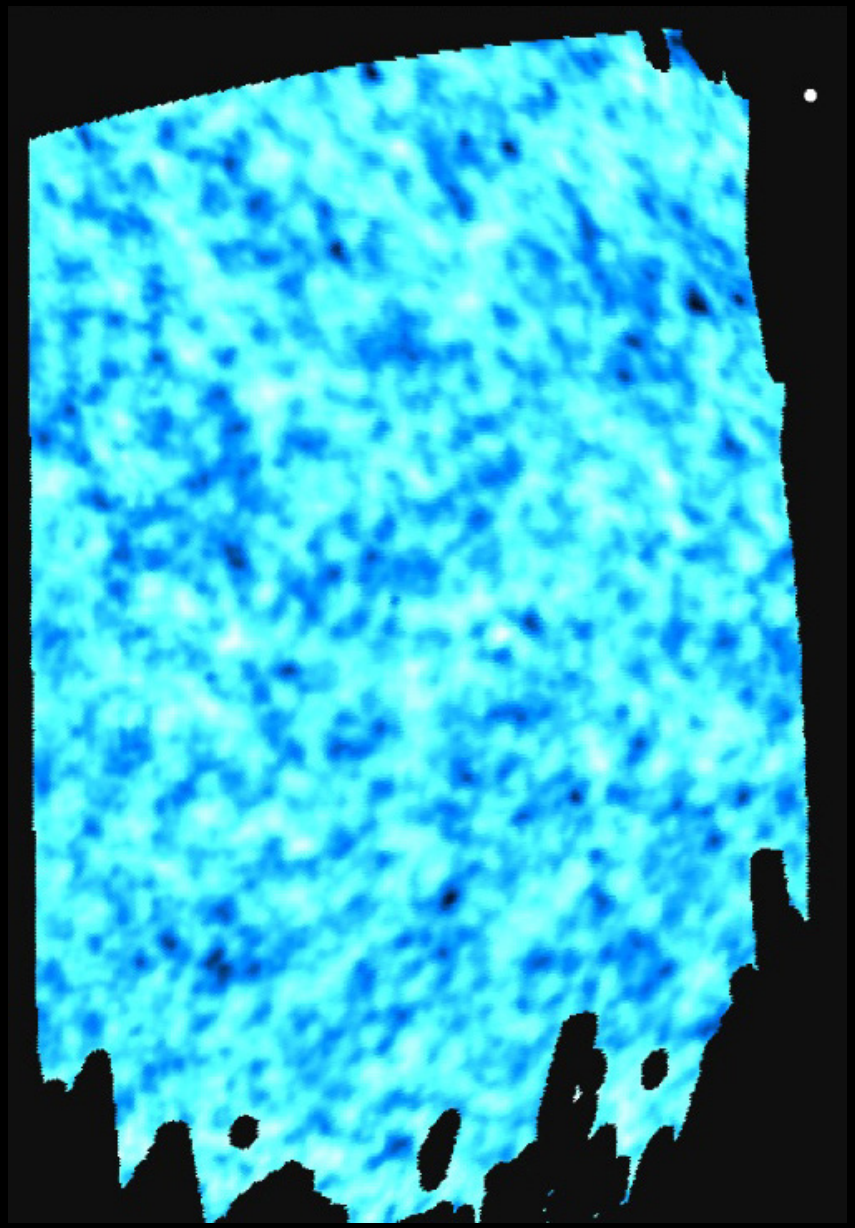
Large Hadron Collider at CERN, $c-6$ mph

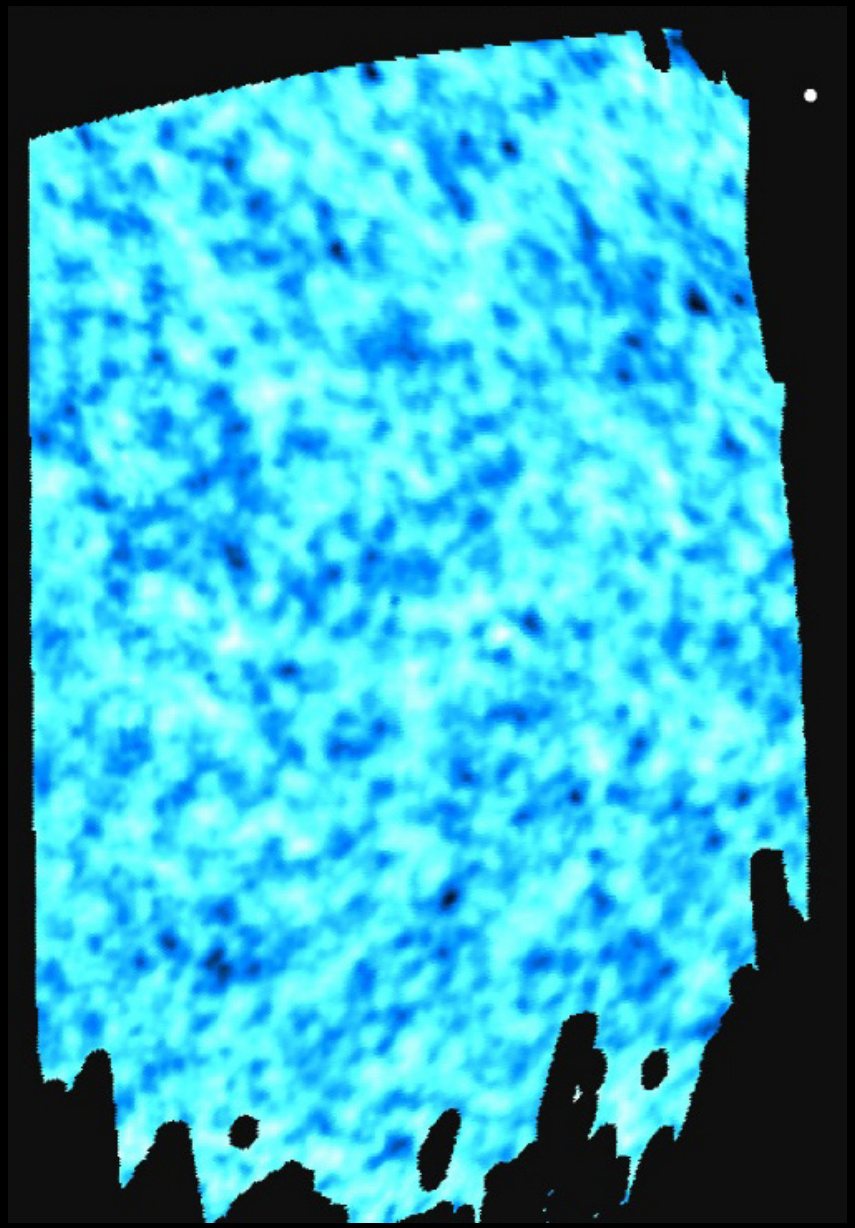


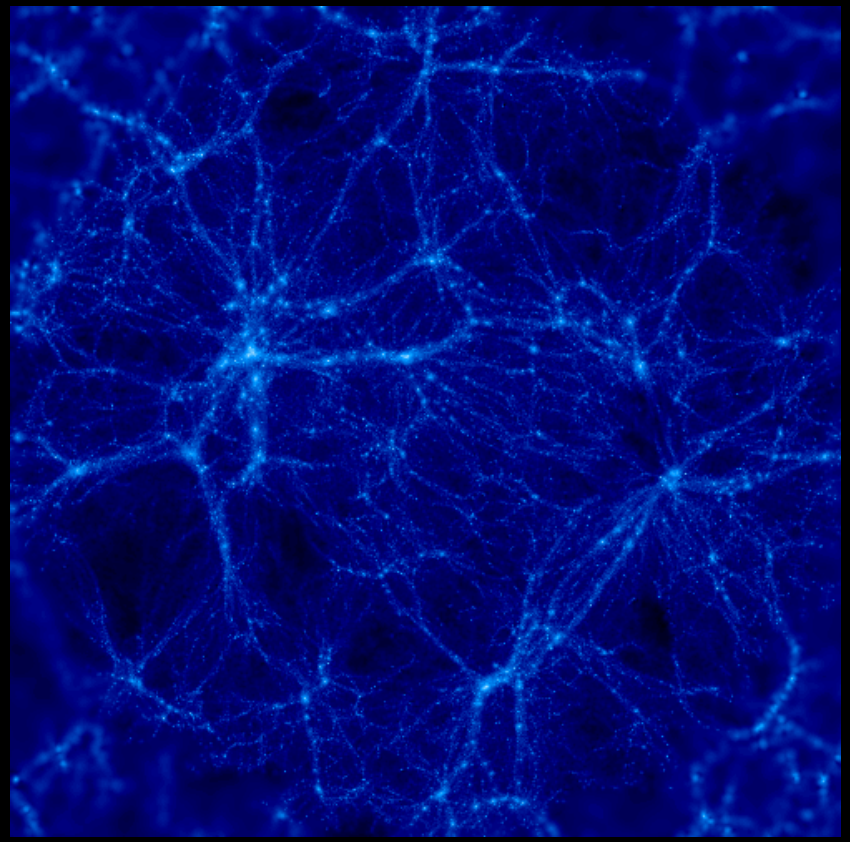


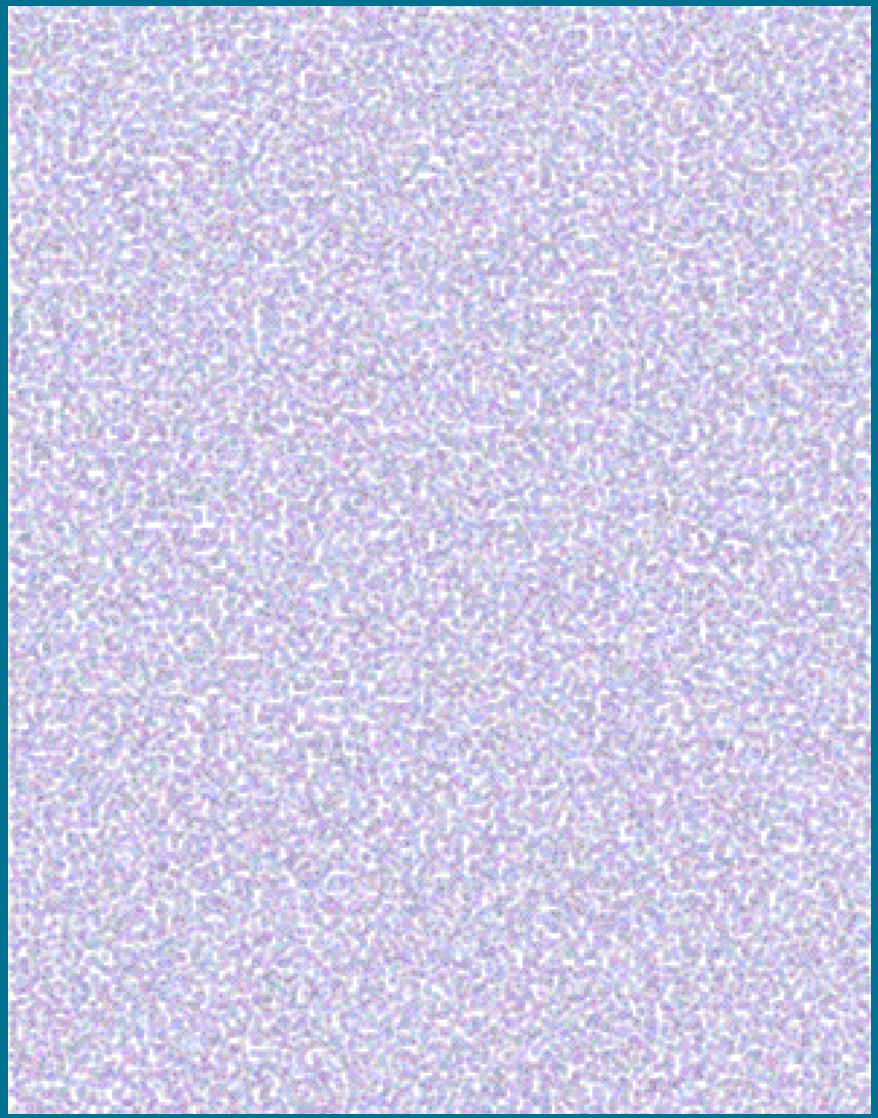


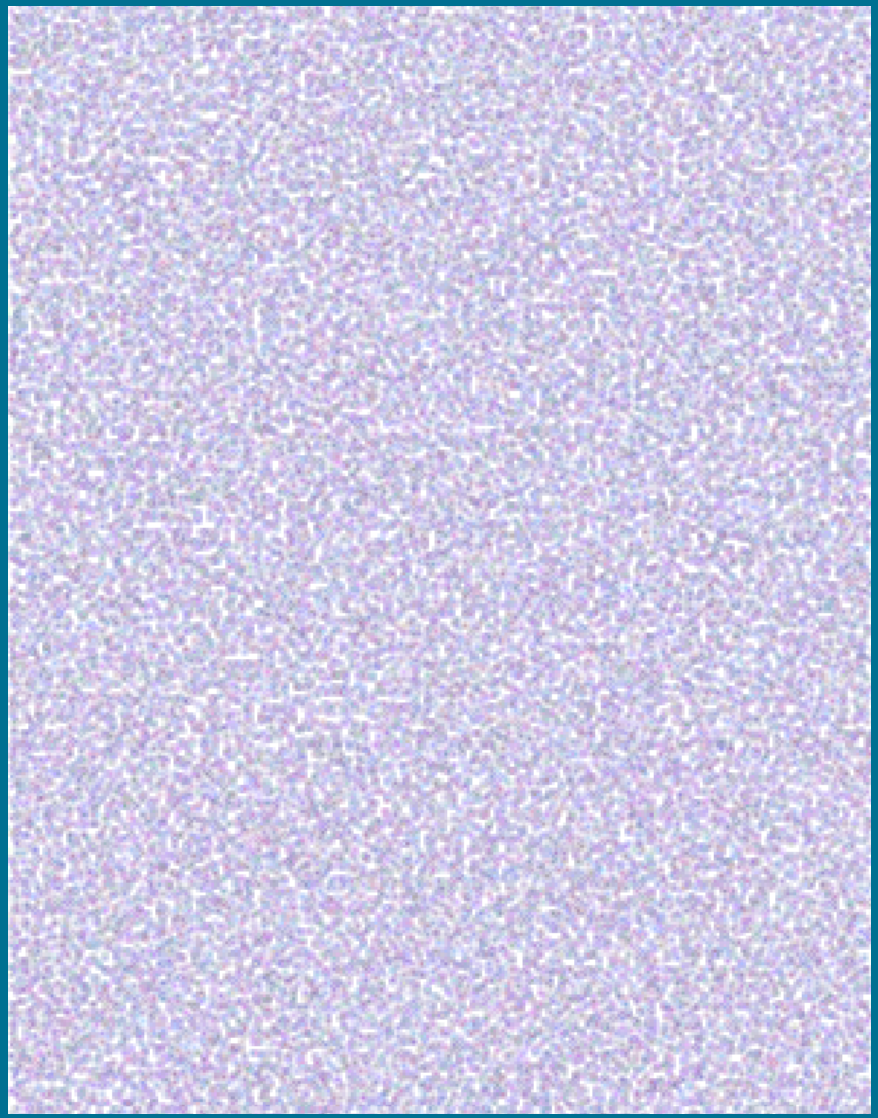


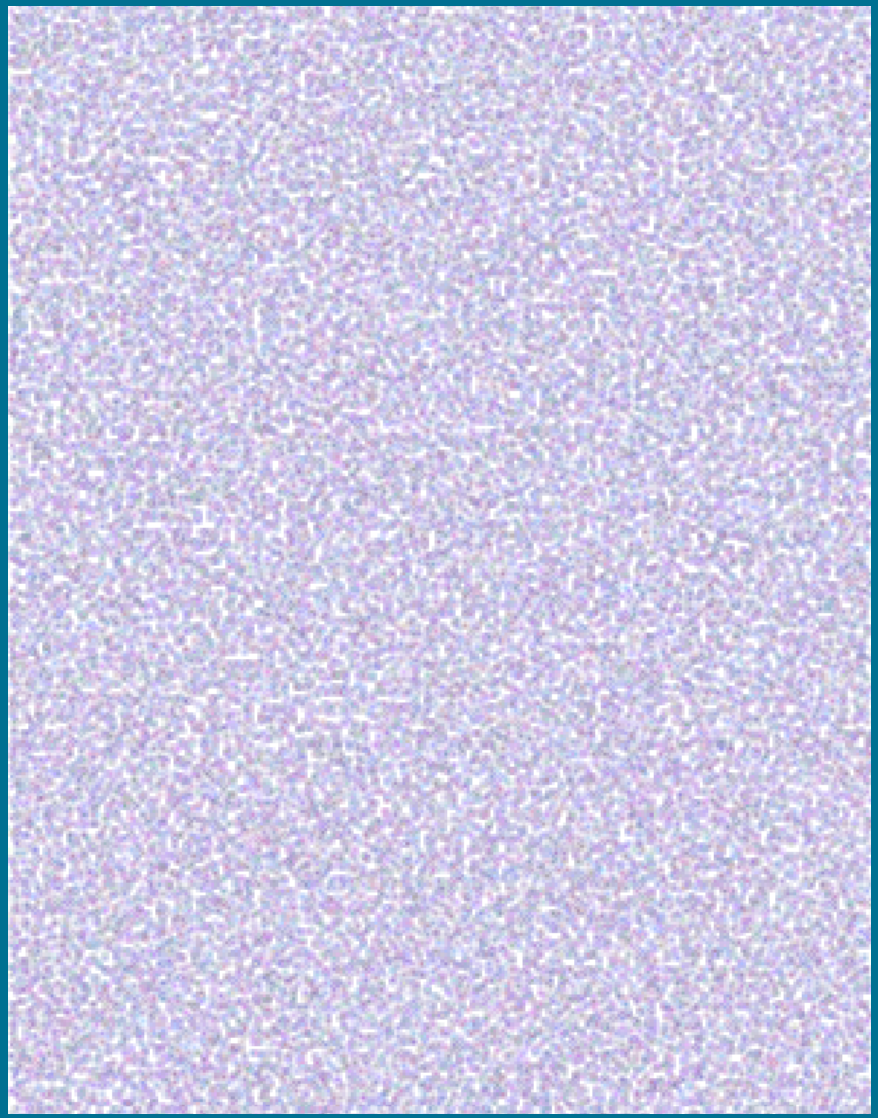












Atoms are small!

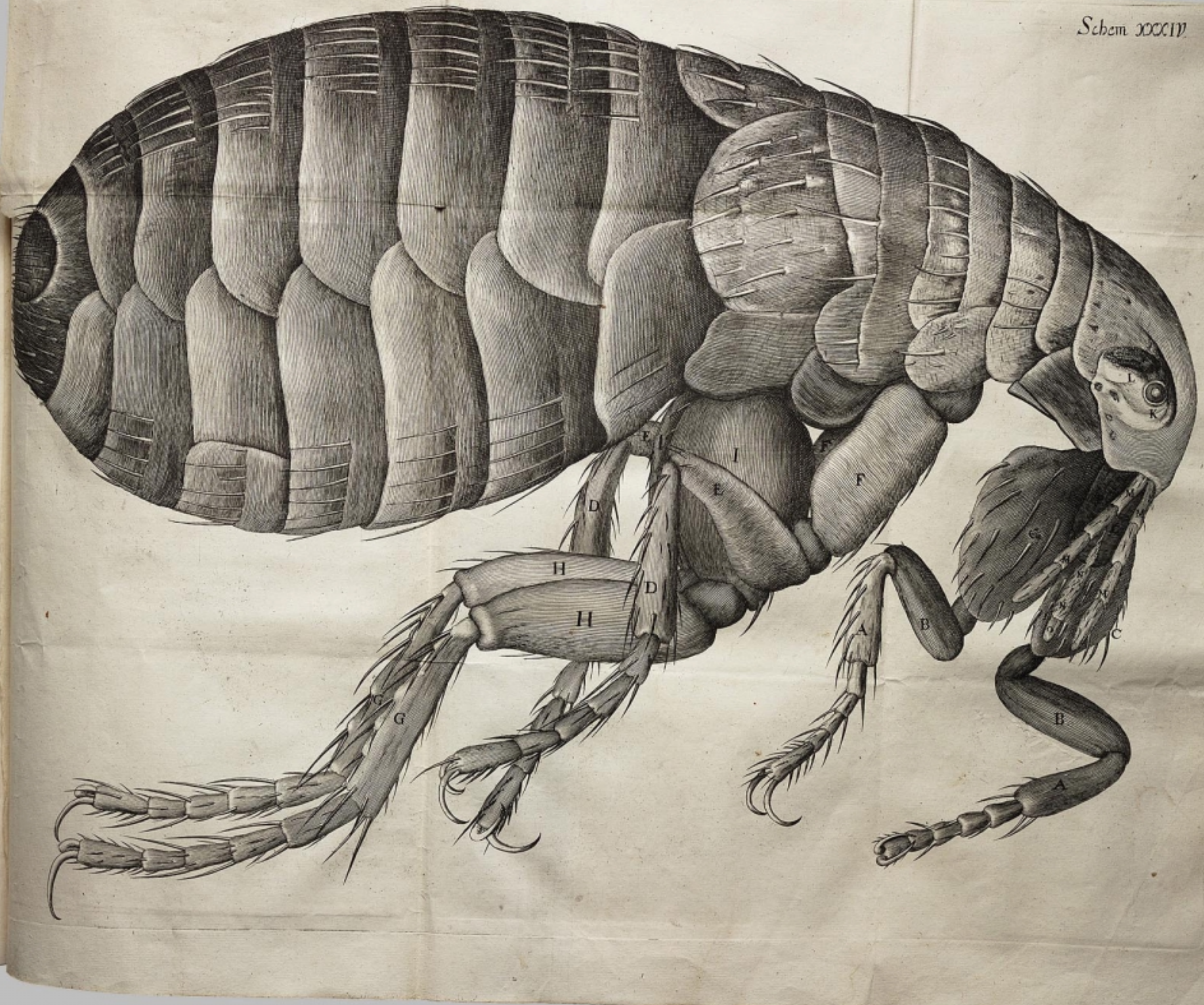
$\sim 10^{-10}$ meter

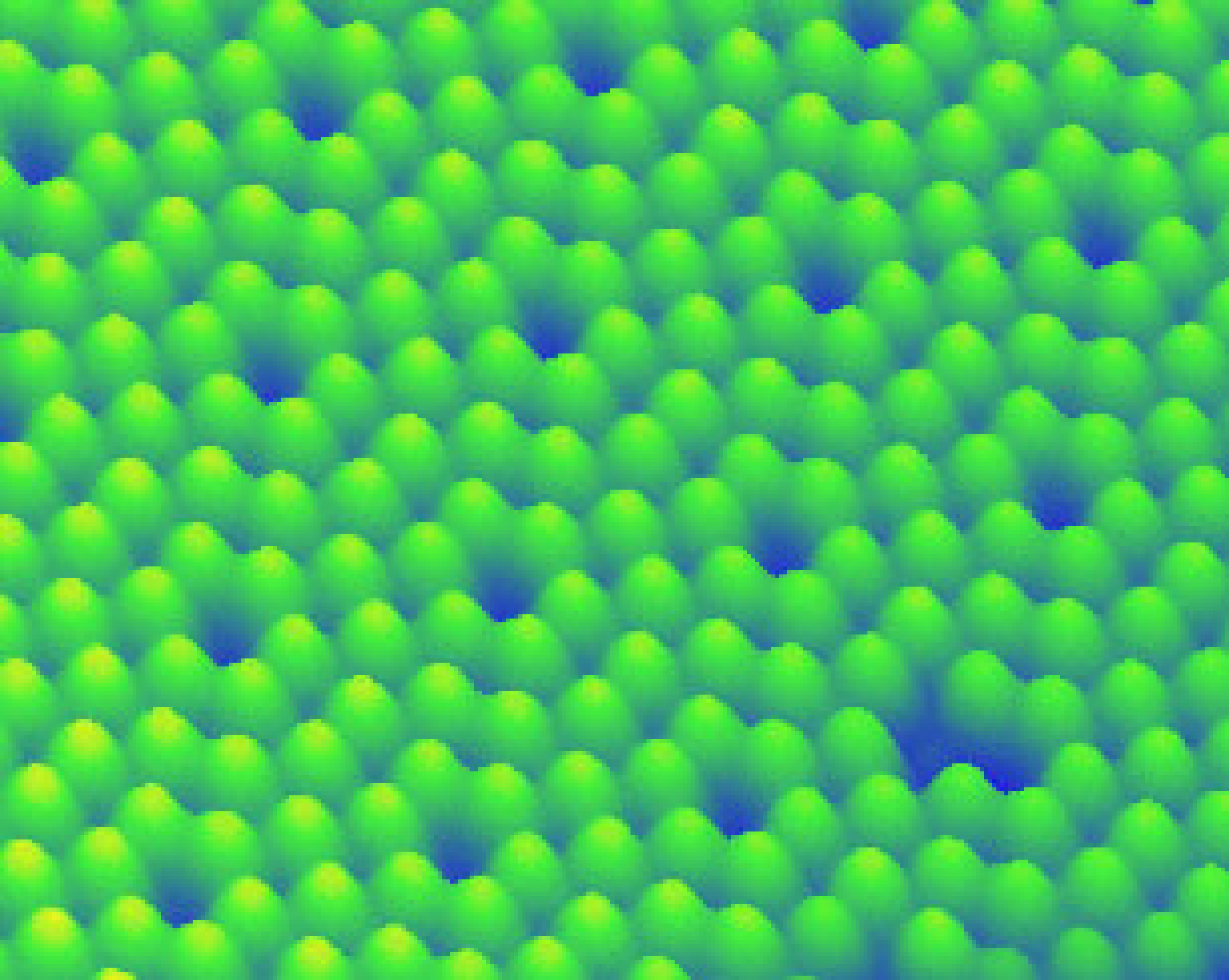
Wavelength of green light:

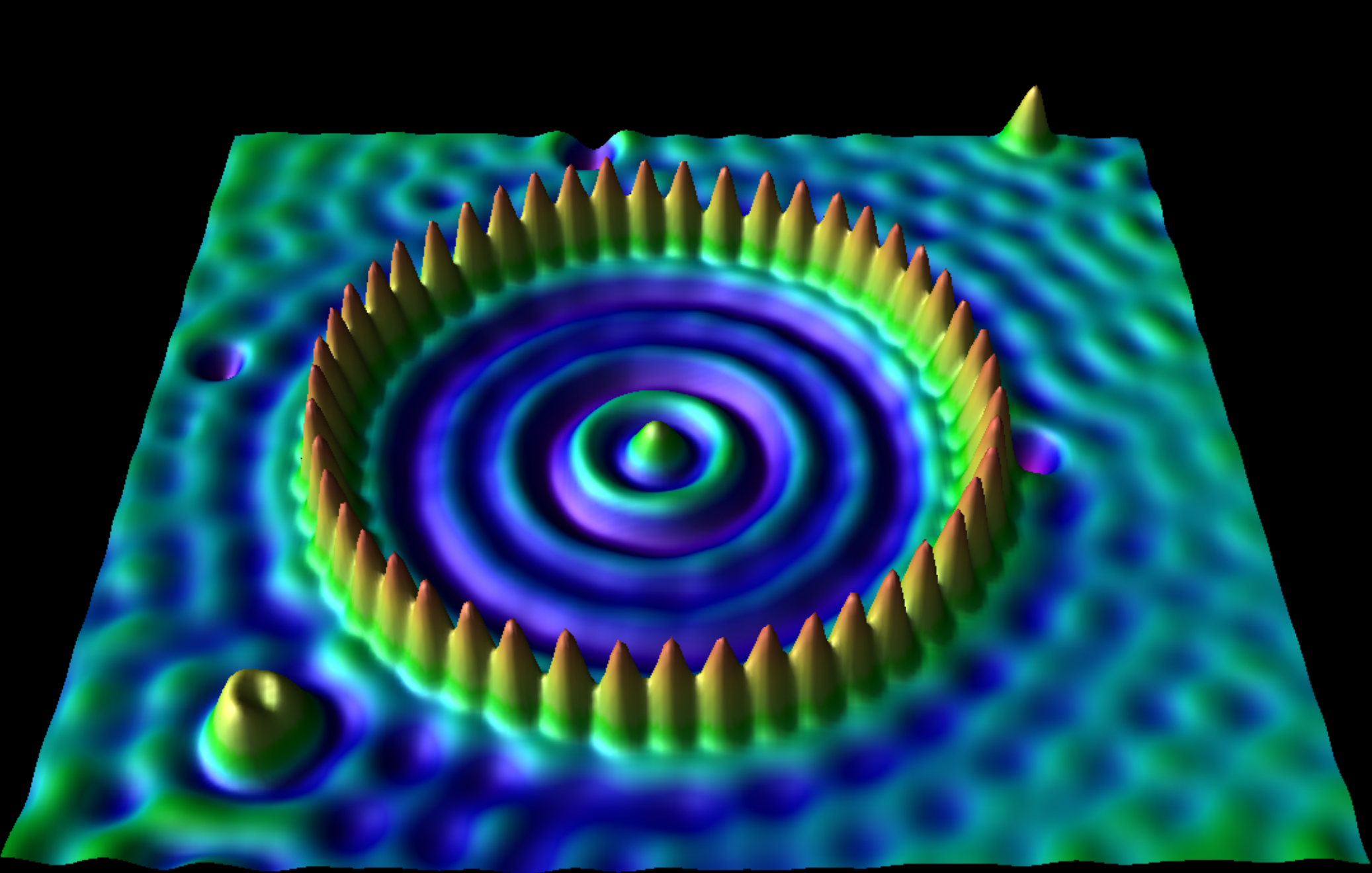
$\sim 5 \cdot 10^{-7}$ meter

Atoms are far too *small* to be seen

Schem XXXIV



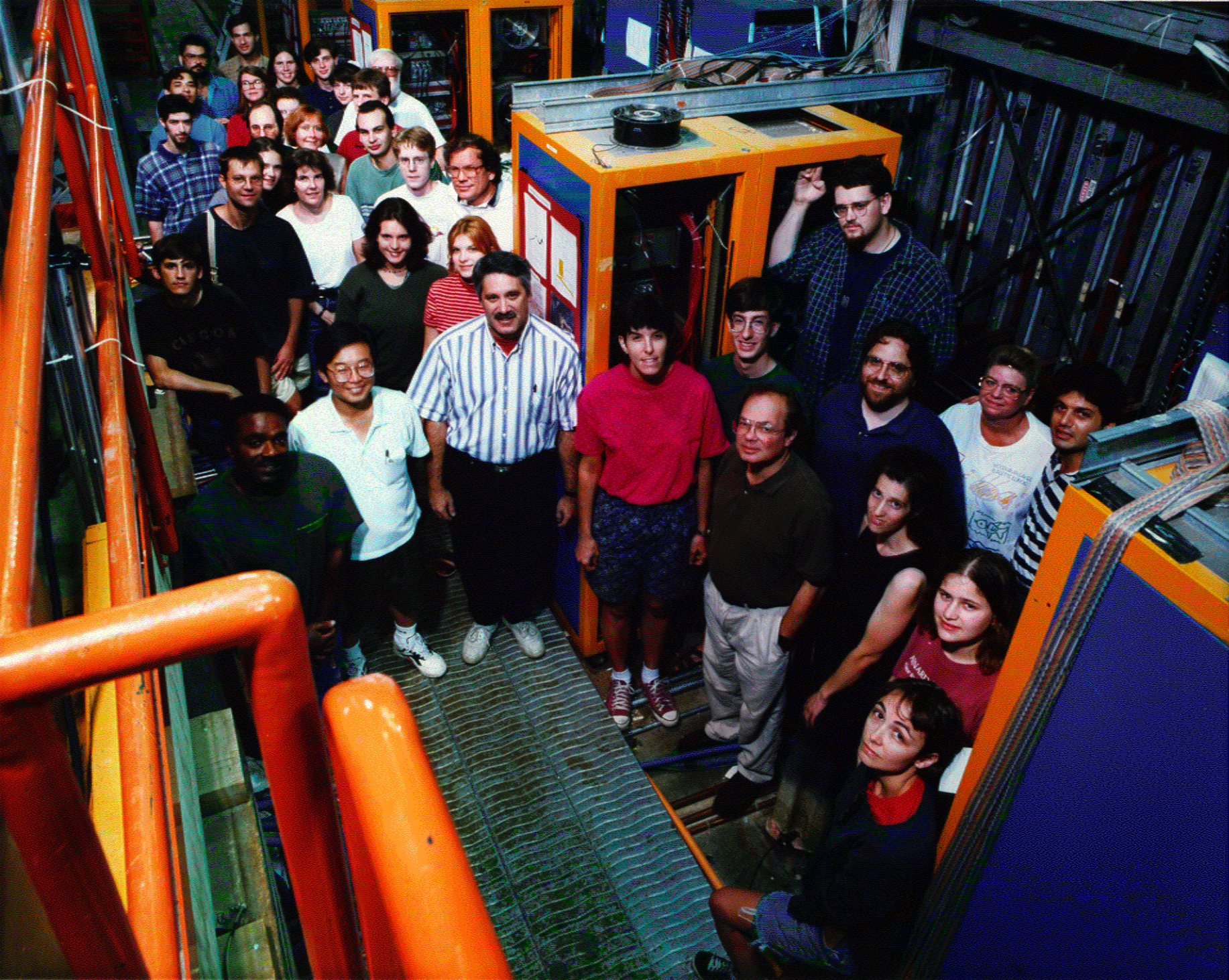


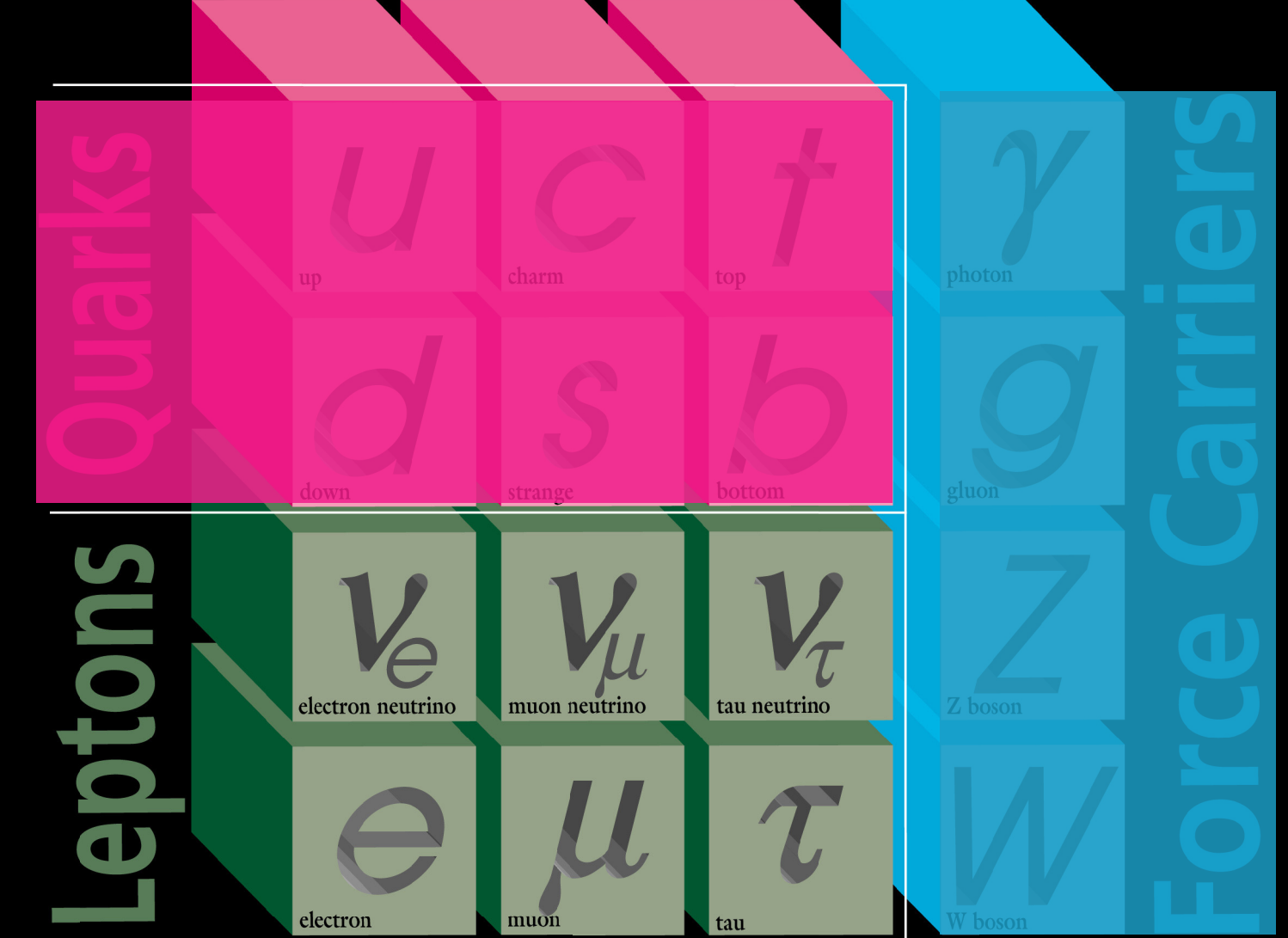


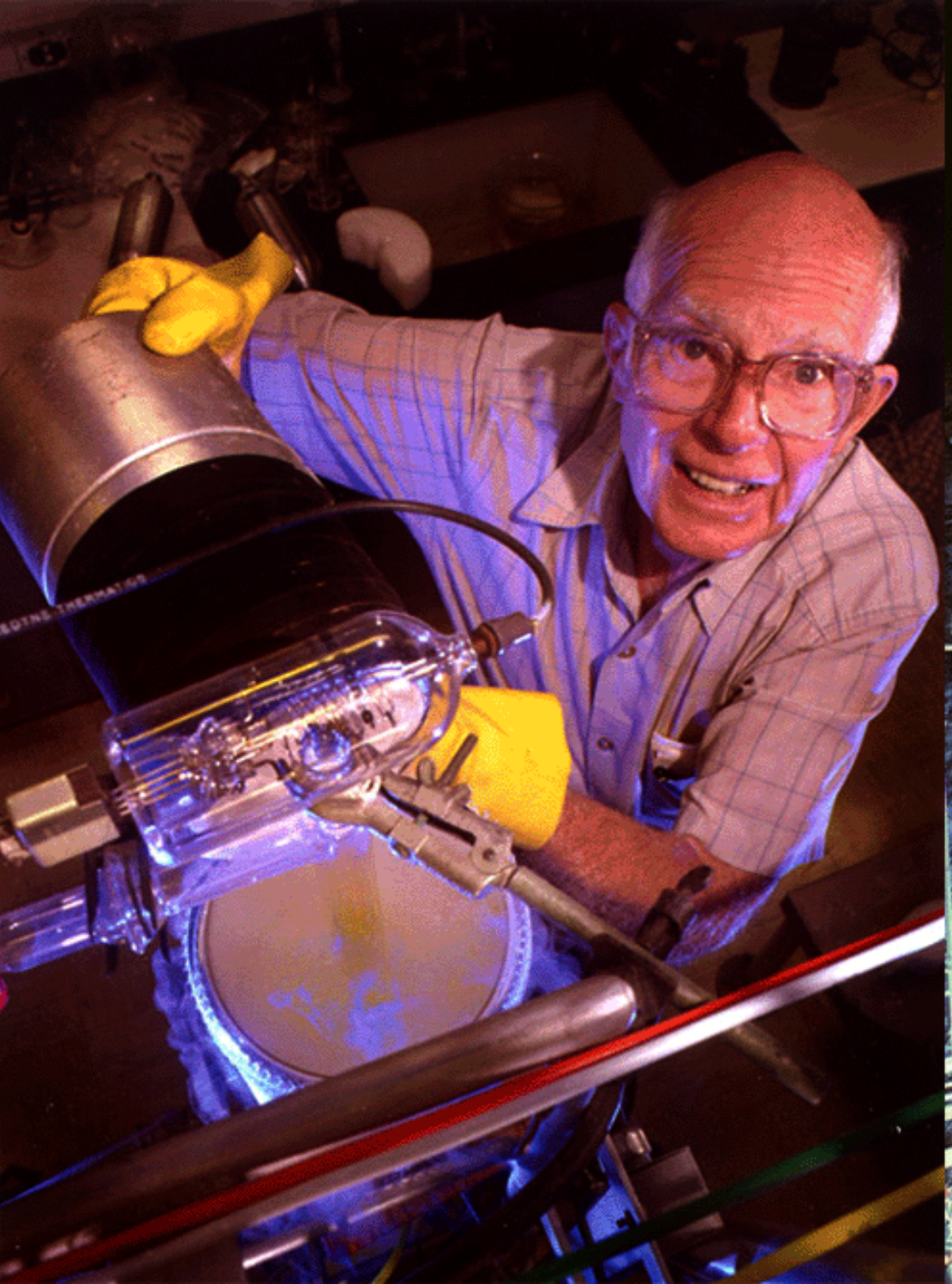
Neutrinos . . .

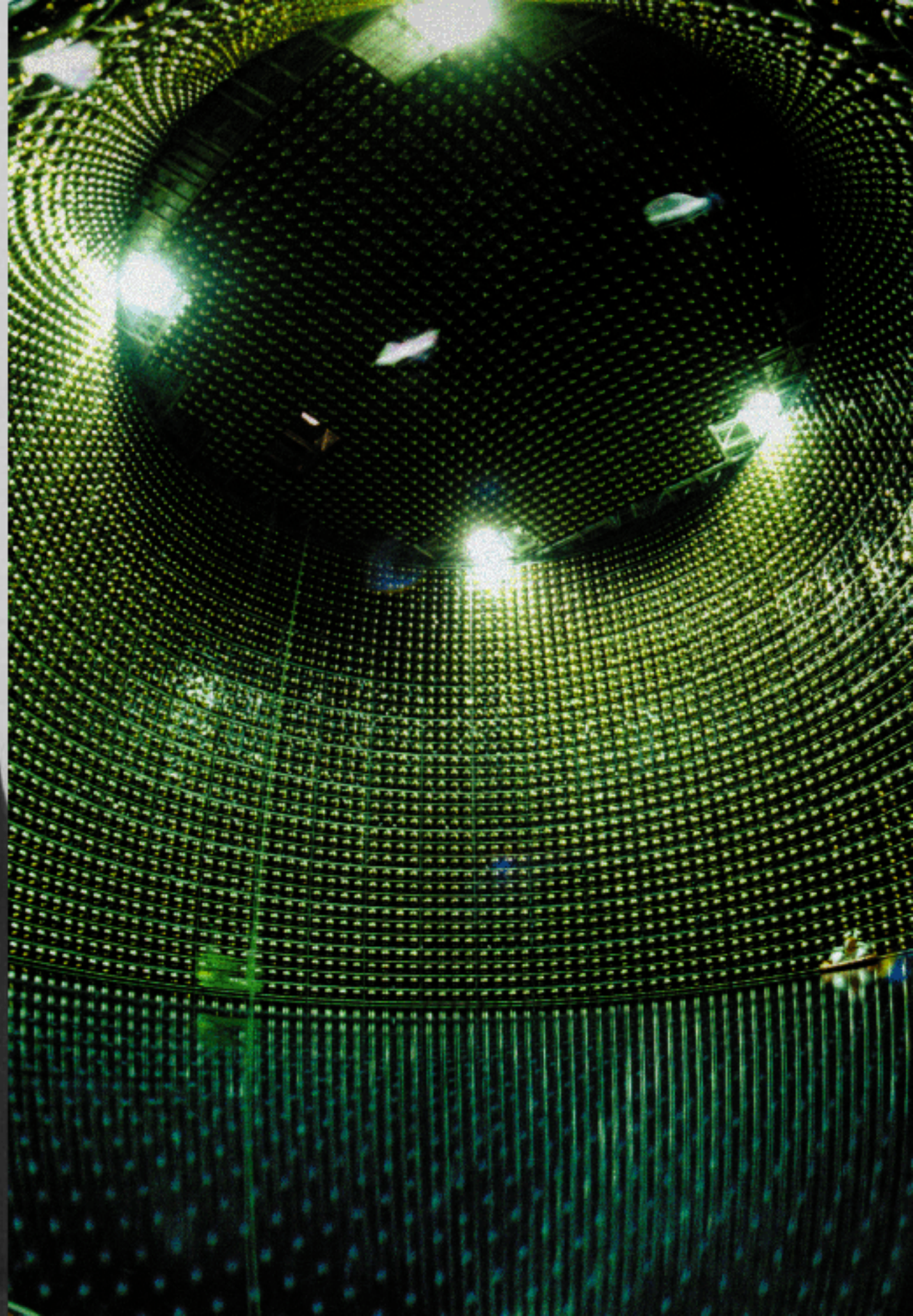
- are tiny subatomic particles
- carry no electric charge
- have (almost) no mass; move (nearly) at the speed of light
- hardly interact at all

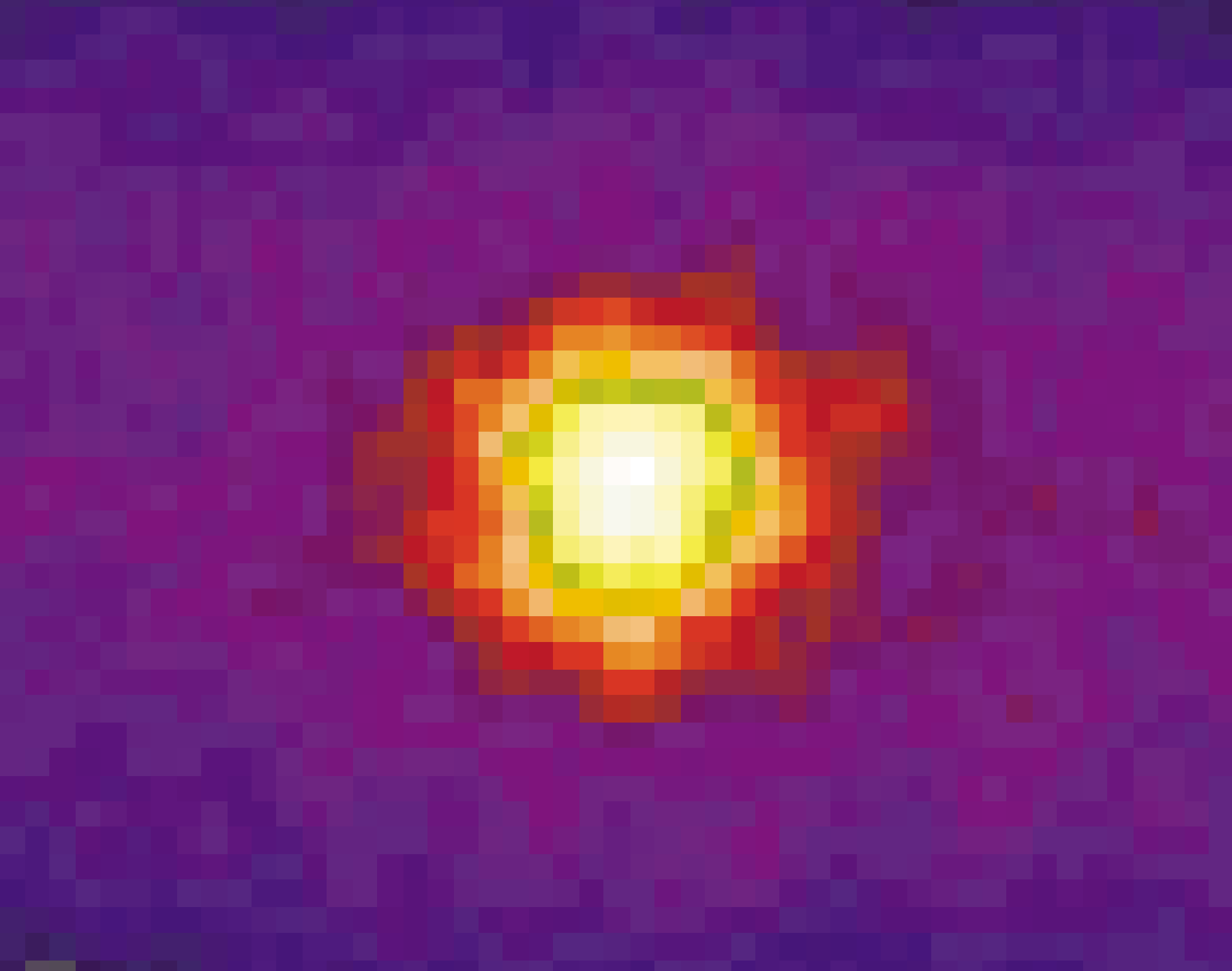
- *Each second,* a hundred trillion neutrinos made in the Sun pass through your body.
- *Each second,* about a thousand neutrinos made in Earth's atmosphere by cosmic rays pass through your body.
- Inside your body are more than ten million neutrino fossils from the Big Bang.
- Other neutrinos reach us from natural (radioactive decays of elements inside the Earth) and artificial (nuclear reactors) sources.

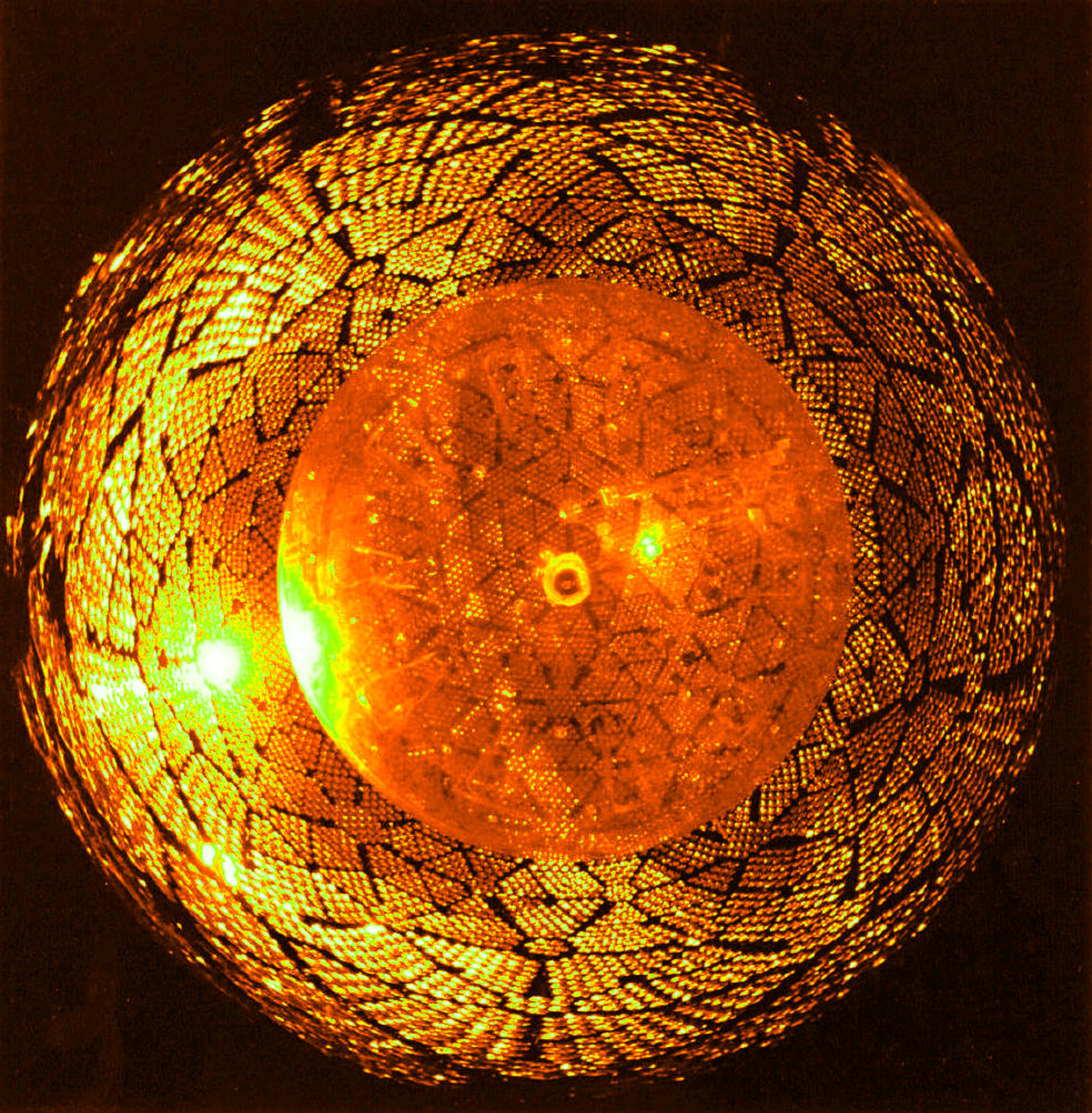



Quarks
up
charm
top
down
strange
bottom
Leptons
electron neutrino
muon neutrino
tau neutrino
electron
muon
tau
Force Carriers
photon
gluon
Z boson
W boson

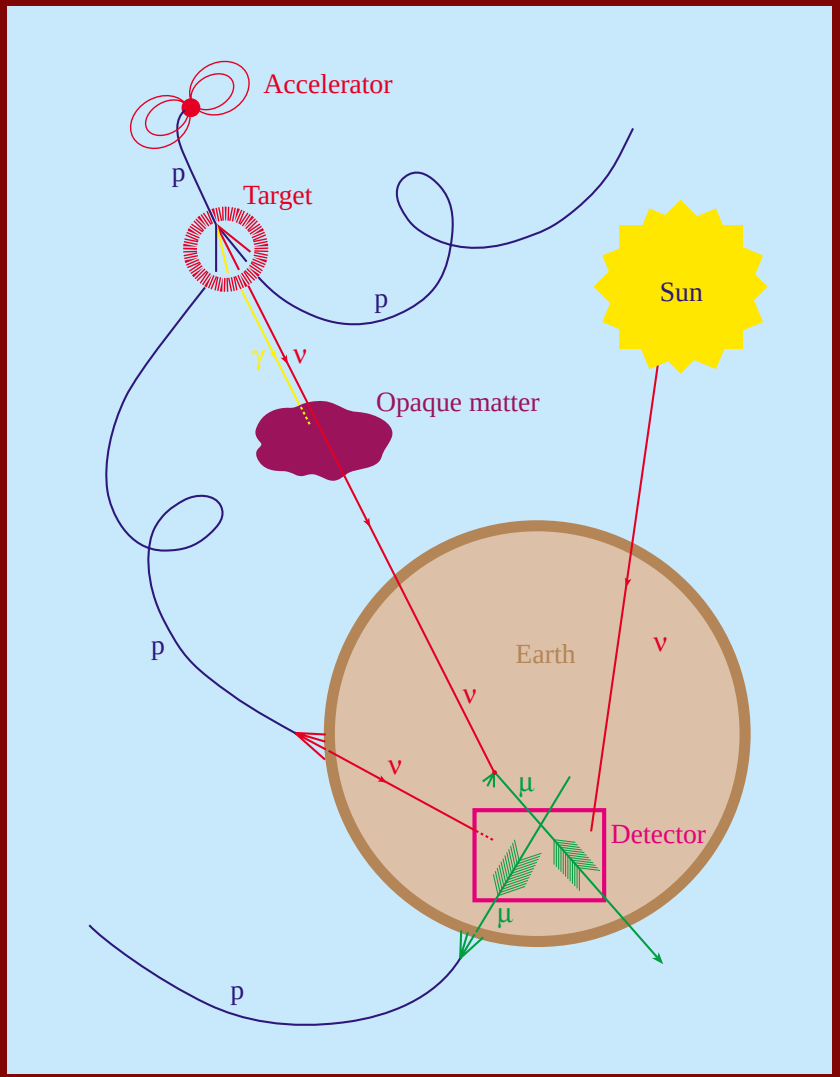


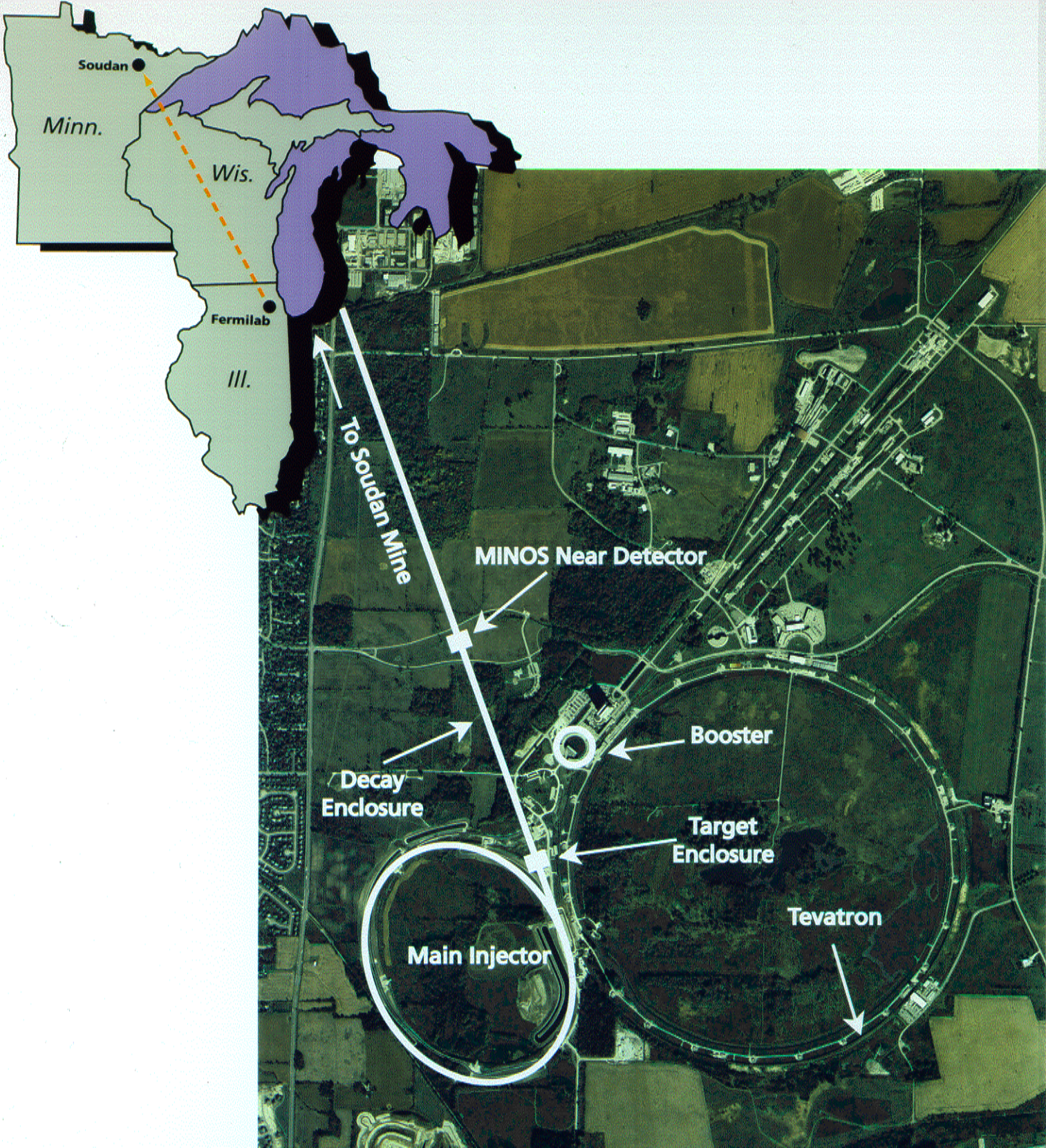


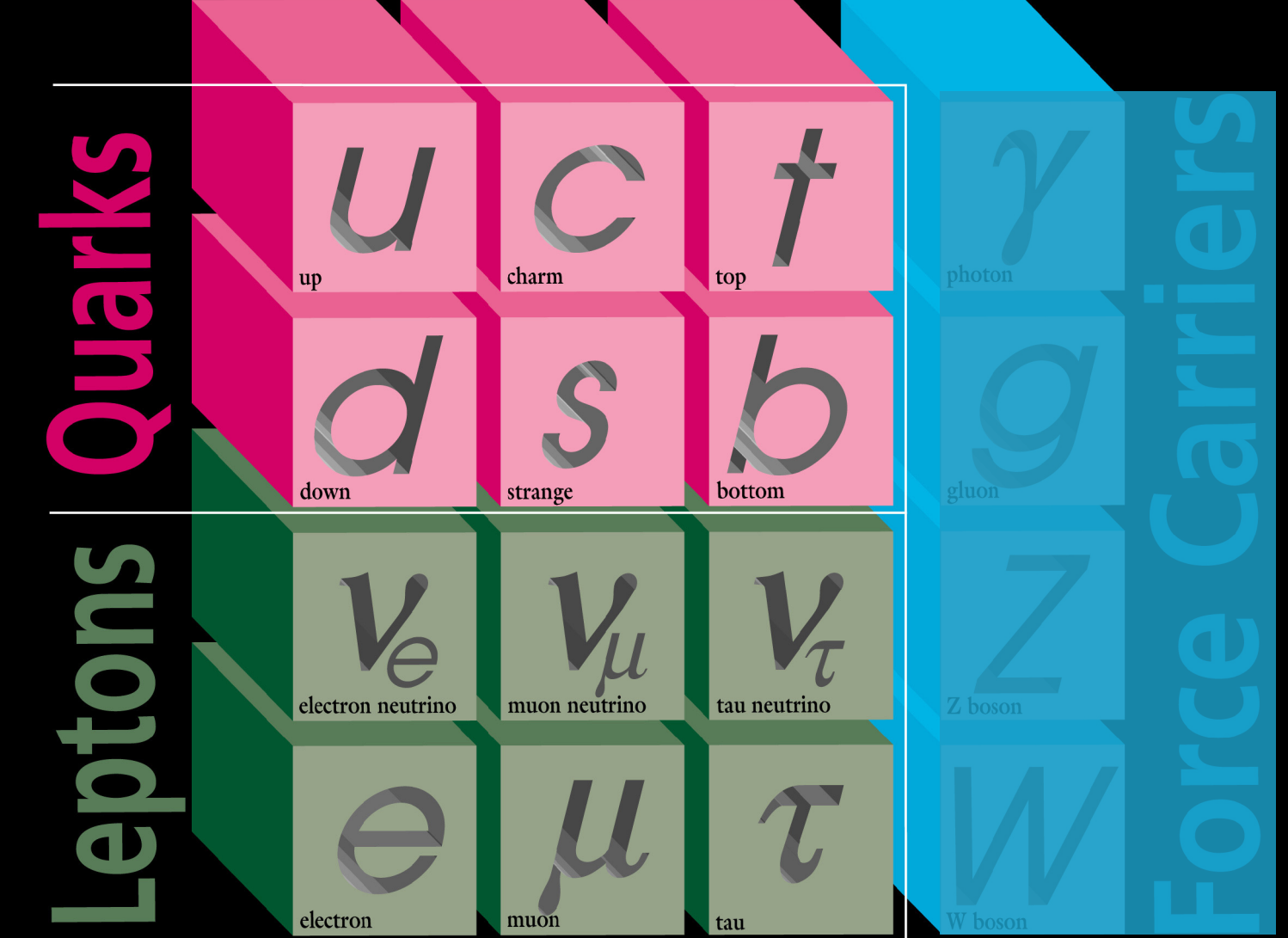


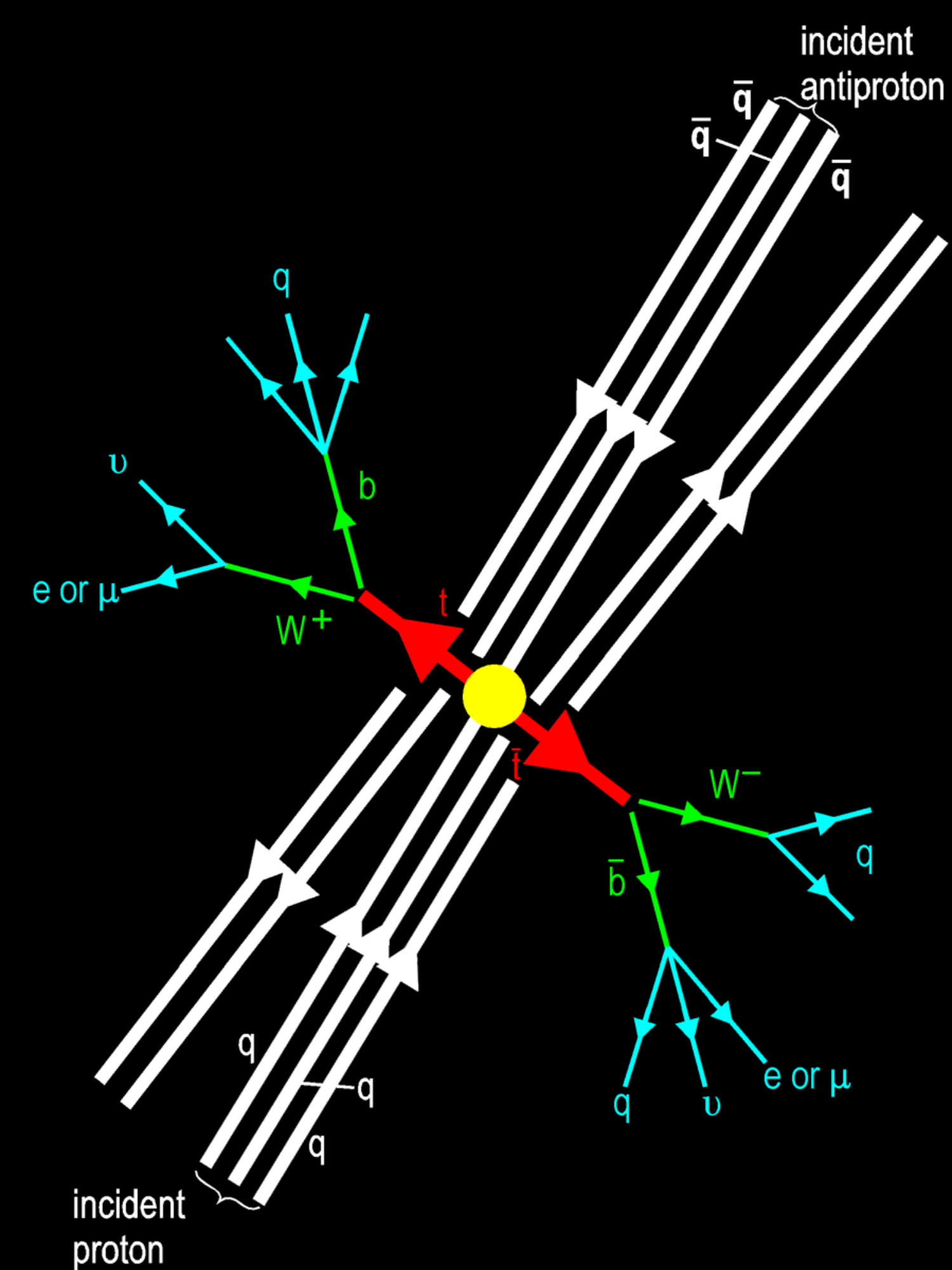


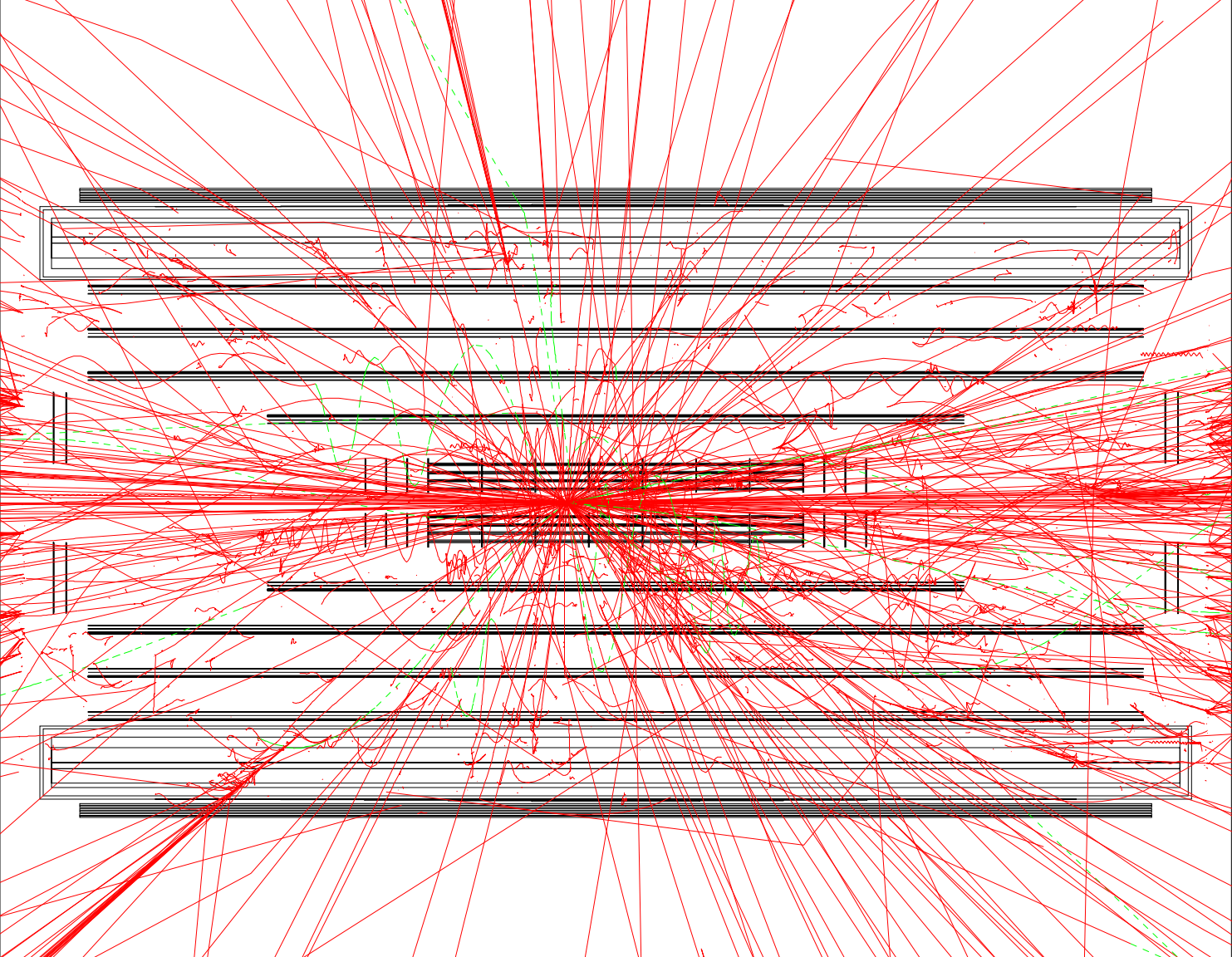
Cosmic Rays Produce Neutrinos in the Atmosphere

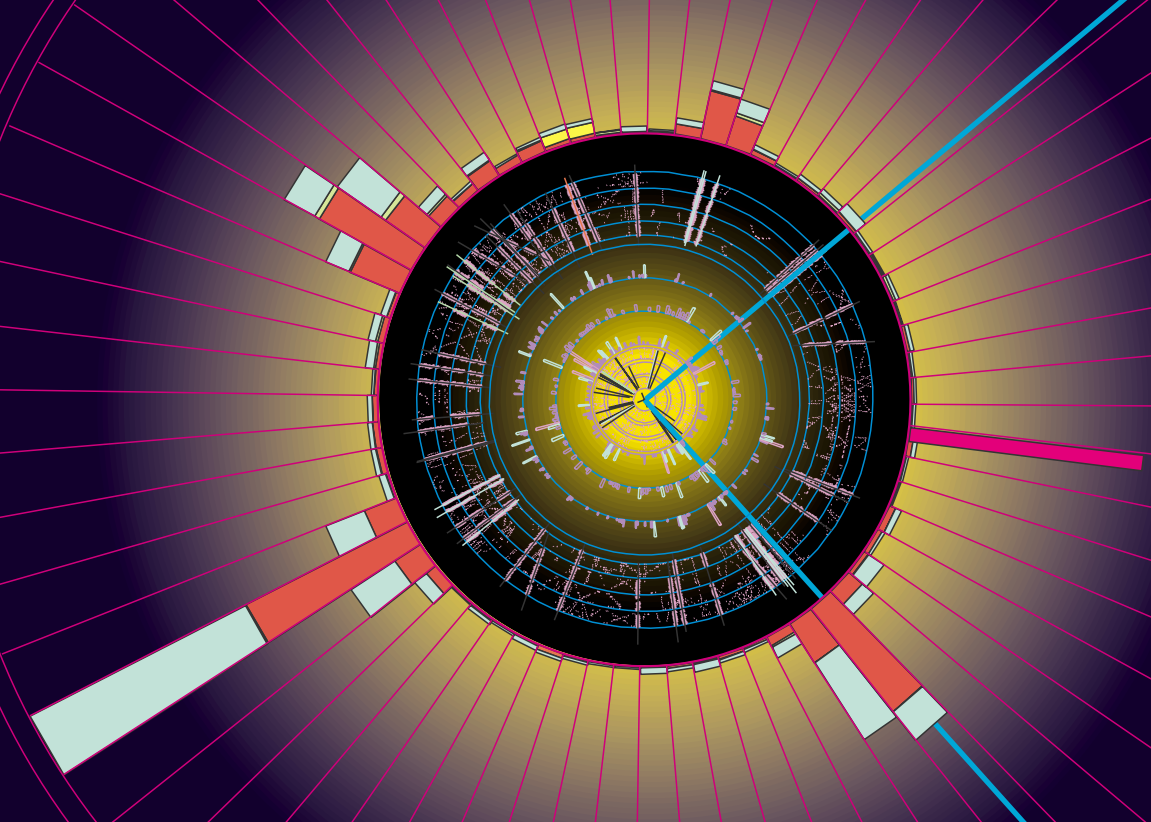


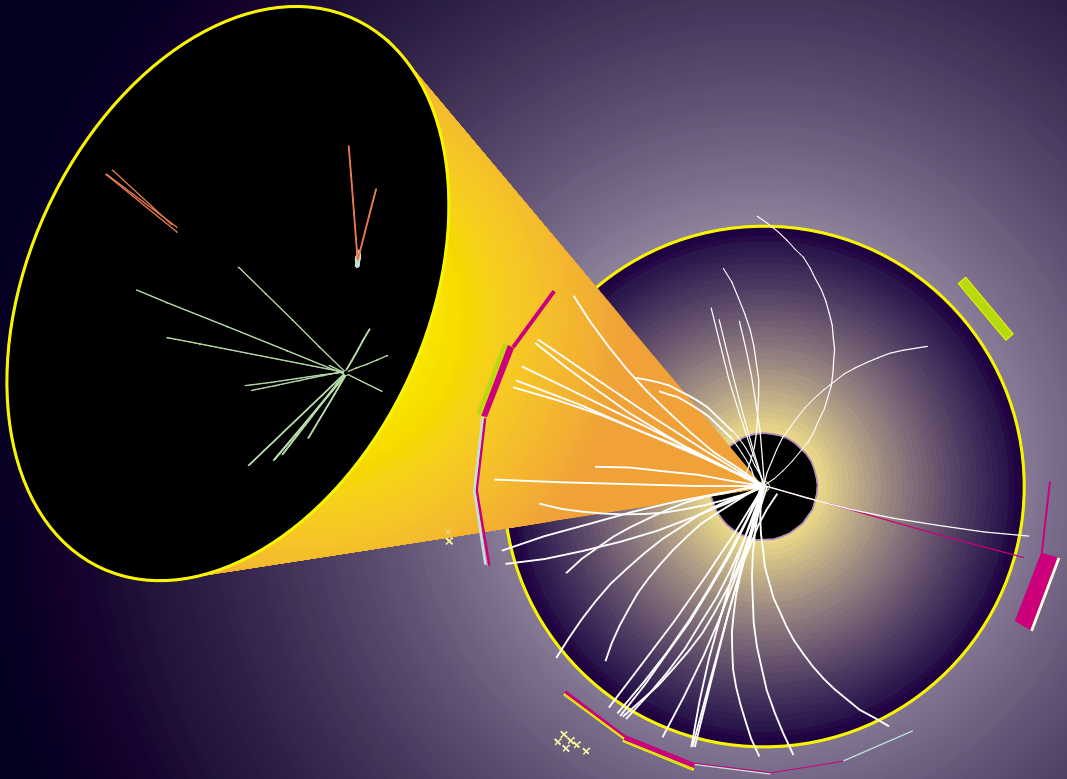

Soudan
Minn.
Wis.
Fermilab
Ill.
To Soudan Mine
MINOS Near Detector
Booster
Decay Enclosure
Target Enclosure
Tevatron
Main Injector

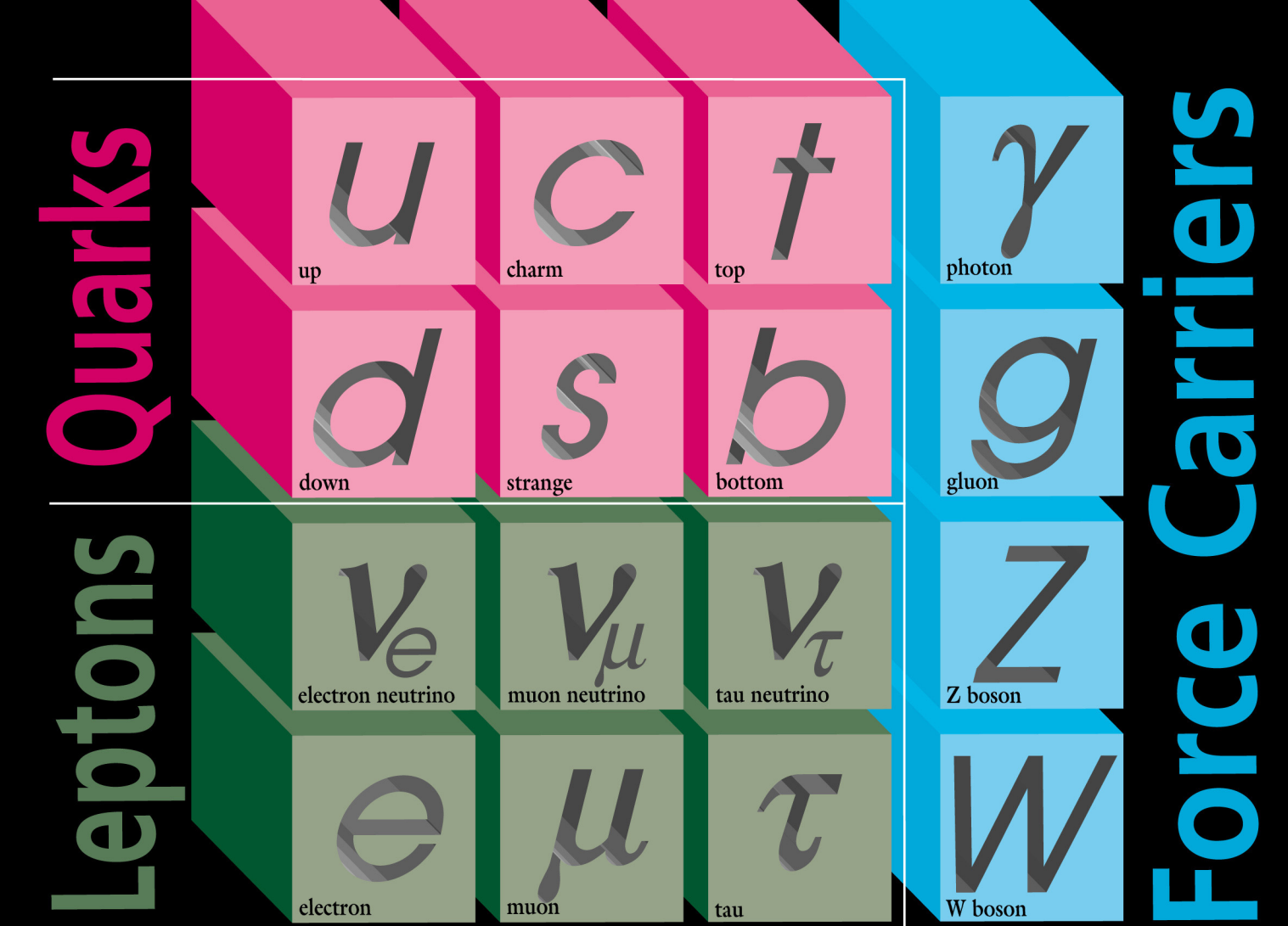

Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
d
down
s
strange
b
bottom
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
g
gluon
Z
Z boson
W
W boson


incident
antiproton
$\bar{q}$
$\bar{q}$
$\bar{q}$
q
b
υ
e or μ
W^+
t
$\bar{t}$
W^-
$\bar{b}$
q
q
e or μ
q
υ
q
q
q
incident
proton

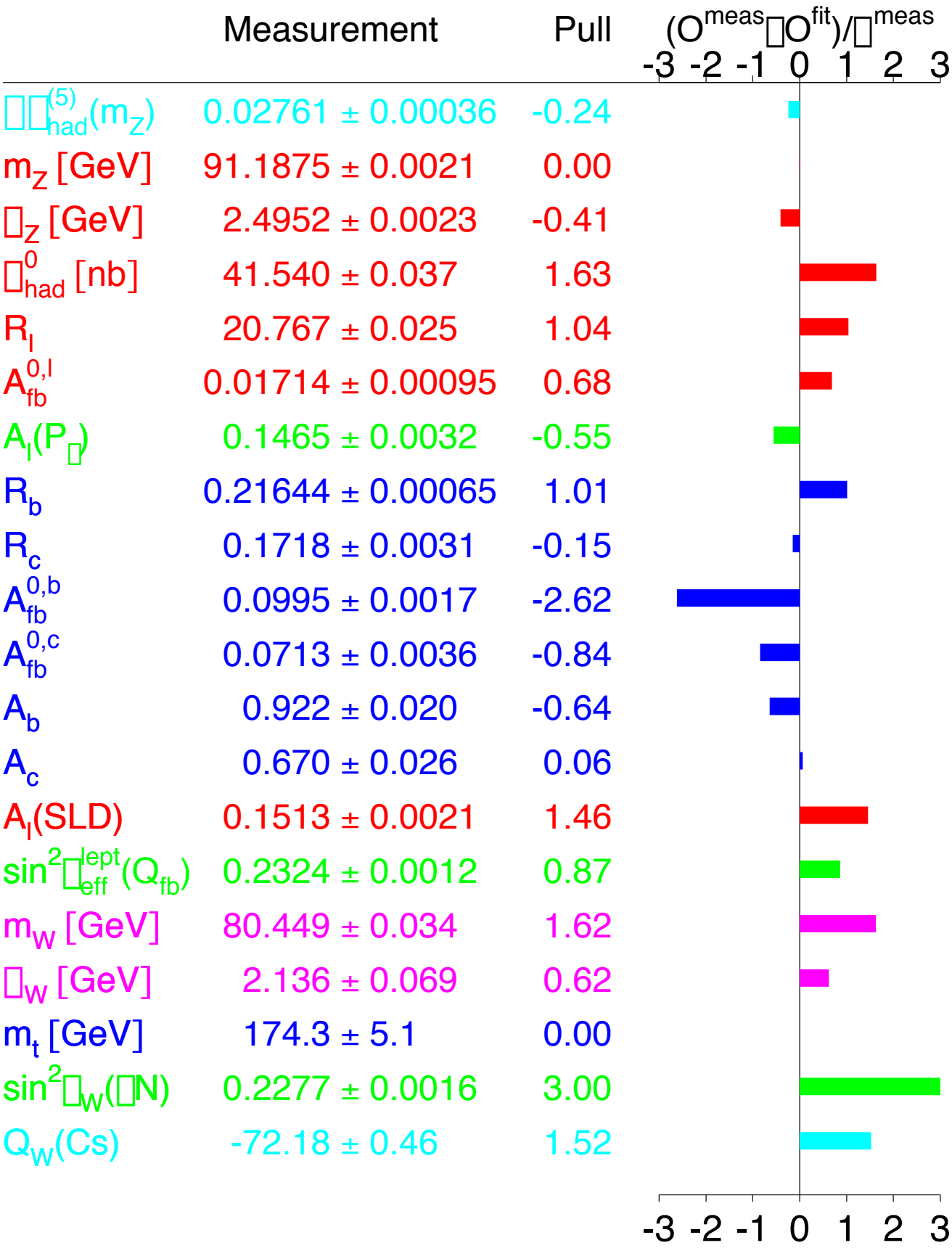






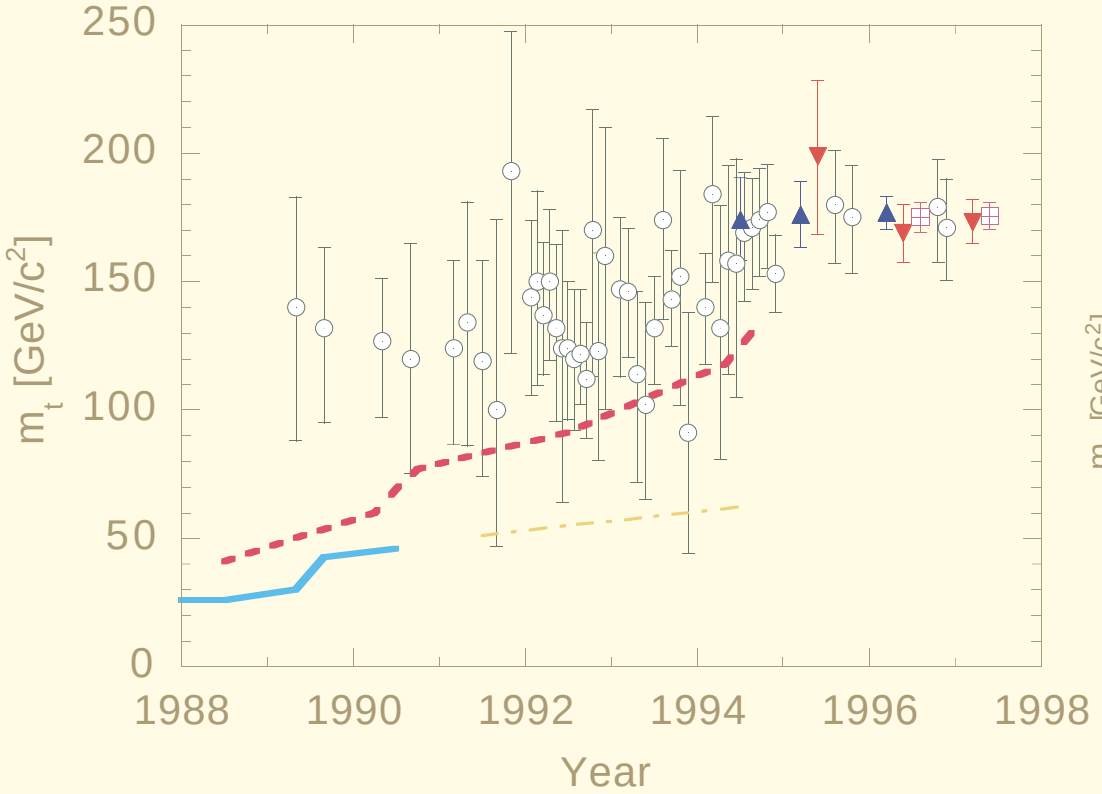

Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson

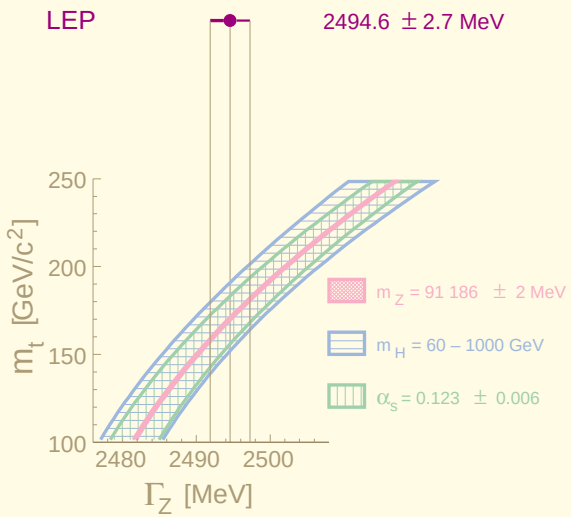
Summer 2002

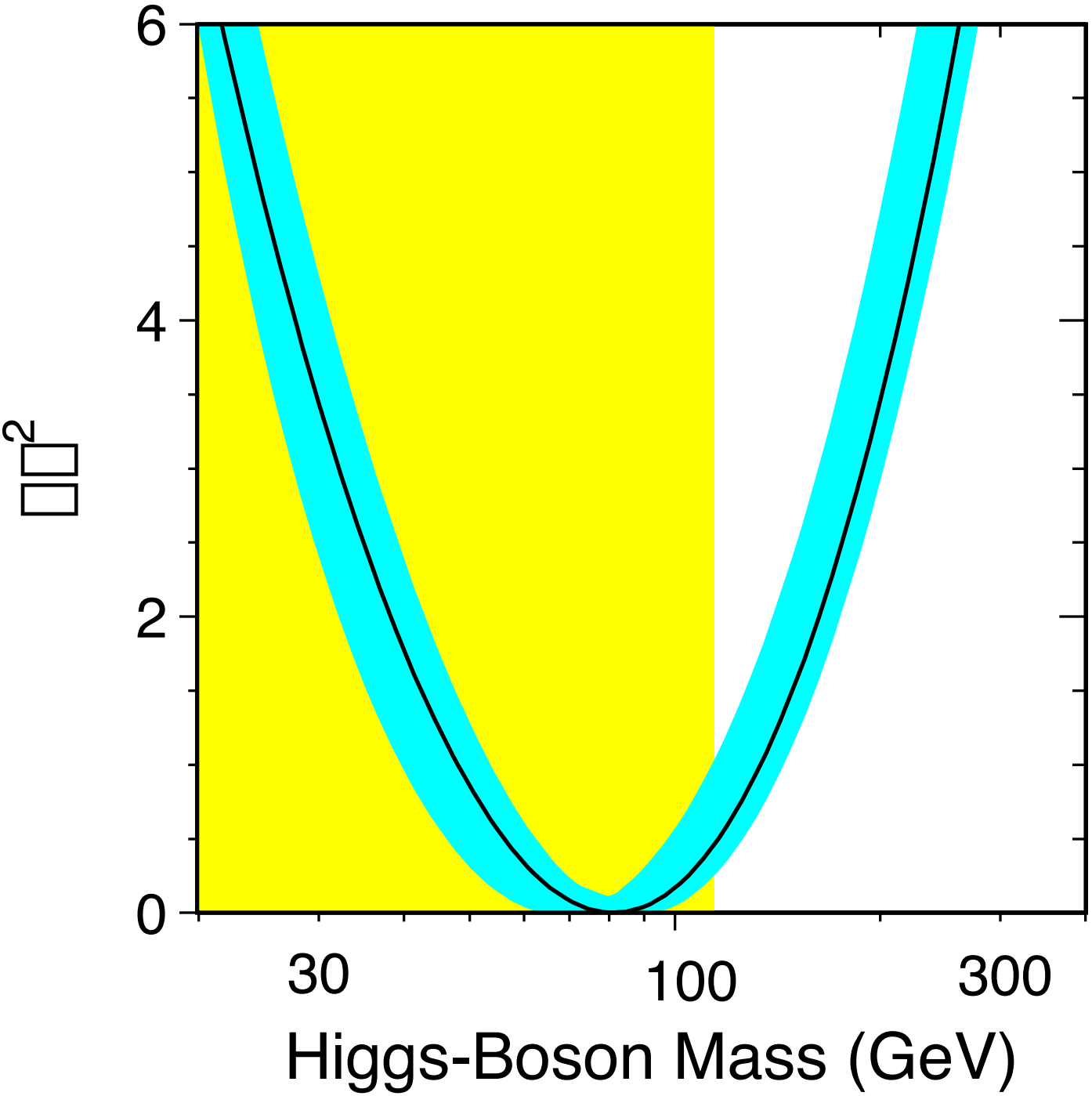

Measurement
Pull
(O^meas − O^fit)/σ^meas
-3 -2 -1 0 1 2 3
Δα(5)had(mZ) 0.02761 ± 0.00036 -0.24
mZ [GeV] 91.1875 ± 0.0021 0.00
ΓZ [GeV] 2.4952 ± 0.0023 -0.41
σ0had [nb] 41.540 ± 0.037 1.63
Rl 20.767 ± 0.025 1.04
A0,lfb 0.01714 ± 0.00095 0.68
Al(Pτ) 0.1465 ± 0.0032 -0.55
Rb 0.21644 ± 0.00065 1.01
Rc 0.1718 ± 0.0031 -0.15
A0,bfb 0.0995 ± 0.0017 -2.62
A0,cfb 0.0713 ± 0.0036 -0.84
Ab 0.922 ± 0.020 -0.64
Ac 0.670 ± 0.026 0.06
Al(SLD) 0.1513 ± 0.0021 1.46
sin2θlept eff(Qfb) 0.2324 ± 0.0012 0.87
mW [GeV] 80.449 ± 0.034 1.62
ΓW [GeV] 2.136 ± 0.069 0.62
mt [GeV] 174.3 ± 5.1 0.00
sin2θW(νN) 0.2277 ± 0.0016 3.00
QW(Cs) -72.18 ± 0.46 1.52
-3 -2 -1 0 1 2 3

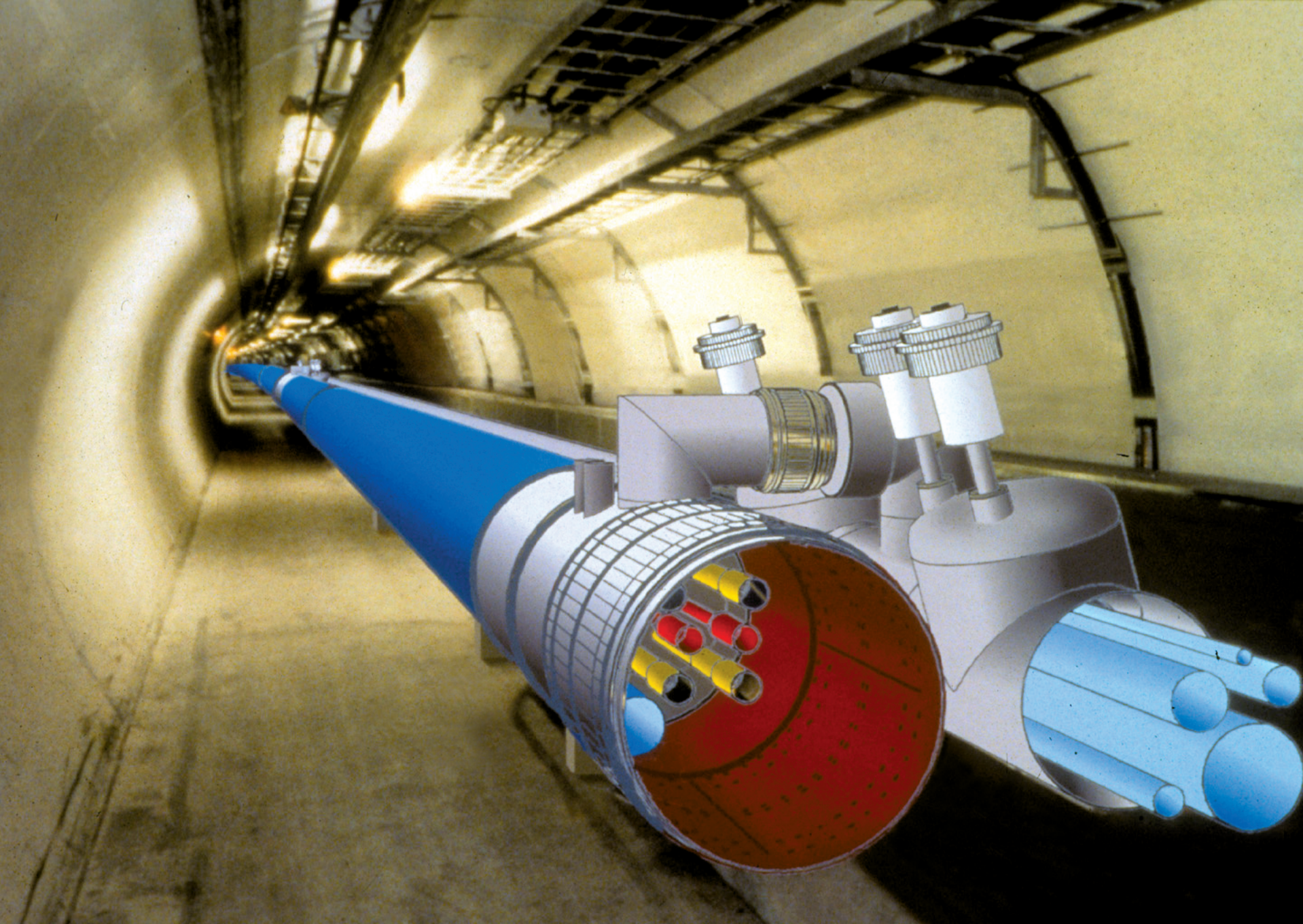
Precision measurements to determine unknown parameters . . .

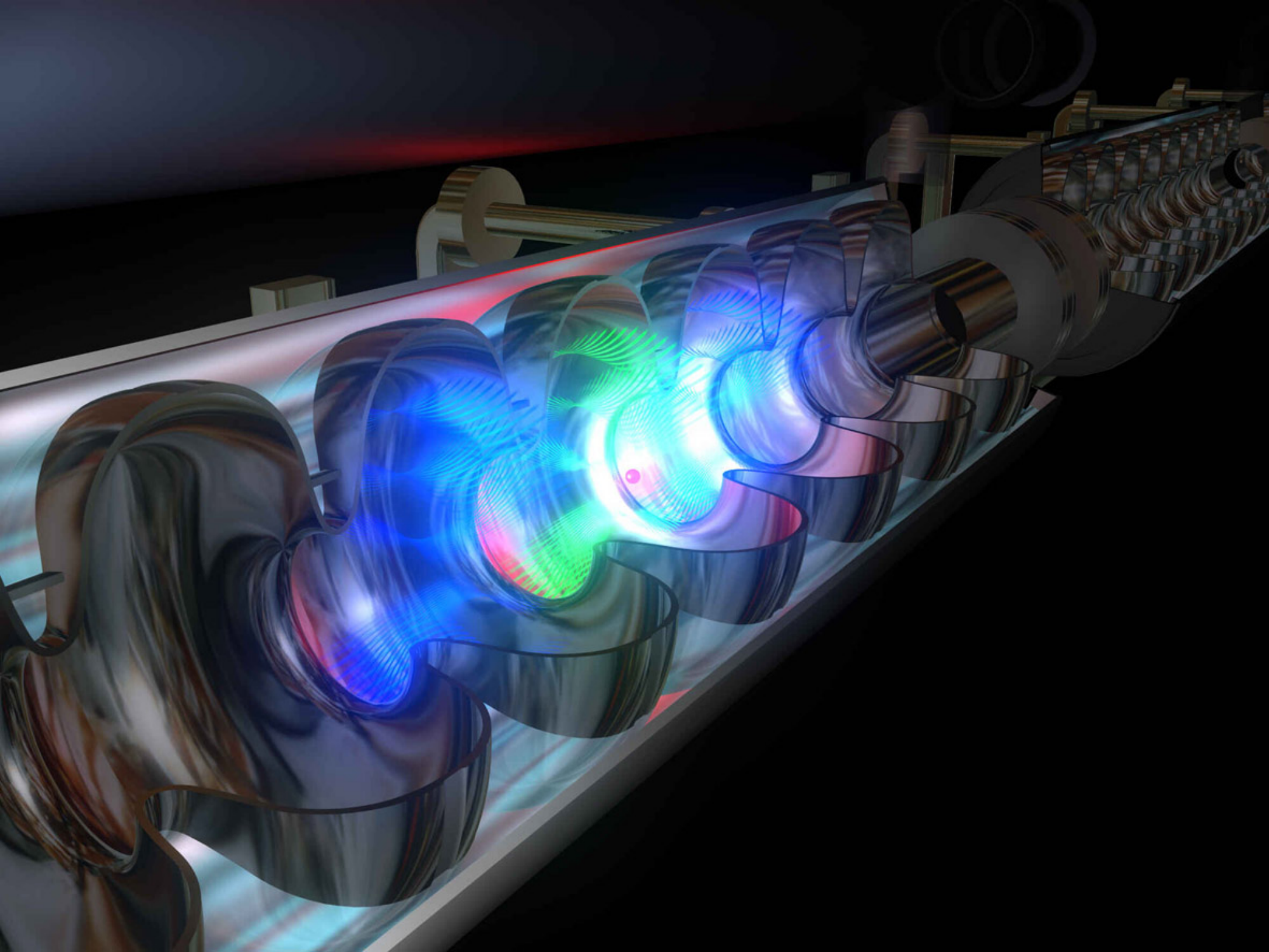
Inferring the top-quark mass through its rôle in quantum corrections:






6
4
2
0
$\Delta\chi^2$
30
100
300
Higgs-Boson Mass (GeV)



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Penumbra
Synthetic Spring
Neptune
Big Technology
I'm With You
Cooled
Faith (Yourself)
Travel
Perpetual Symmetry
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BOSON
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disc
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DDD
HP
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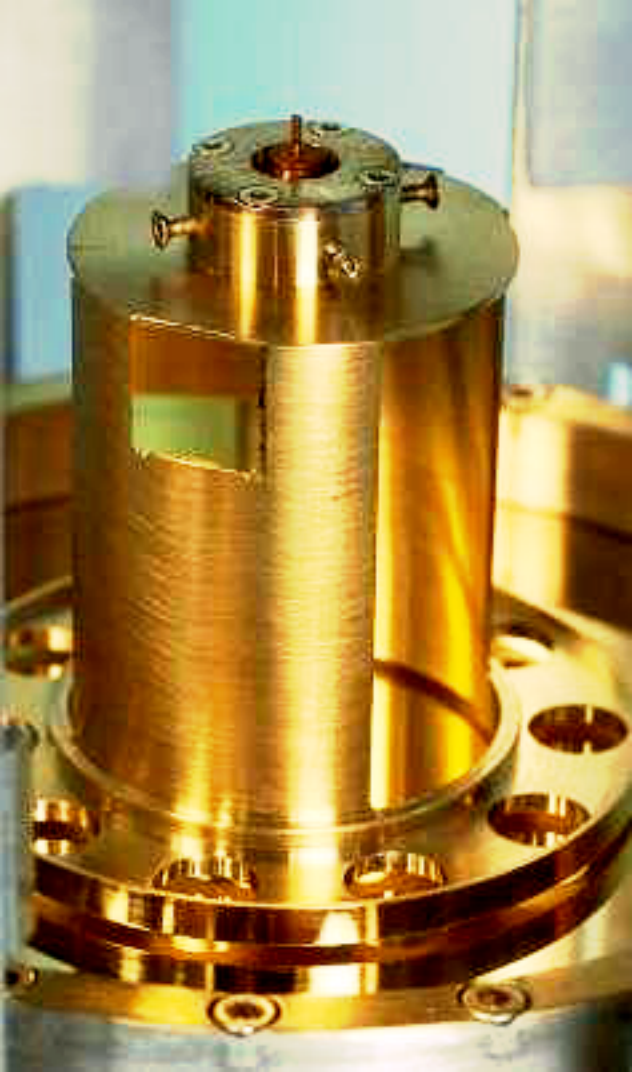
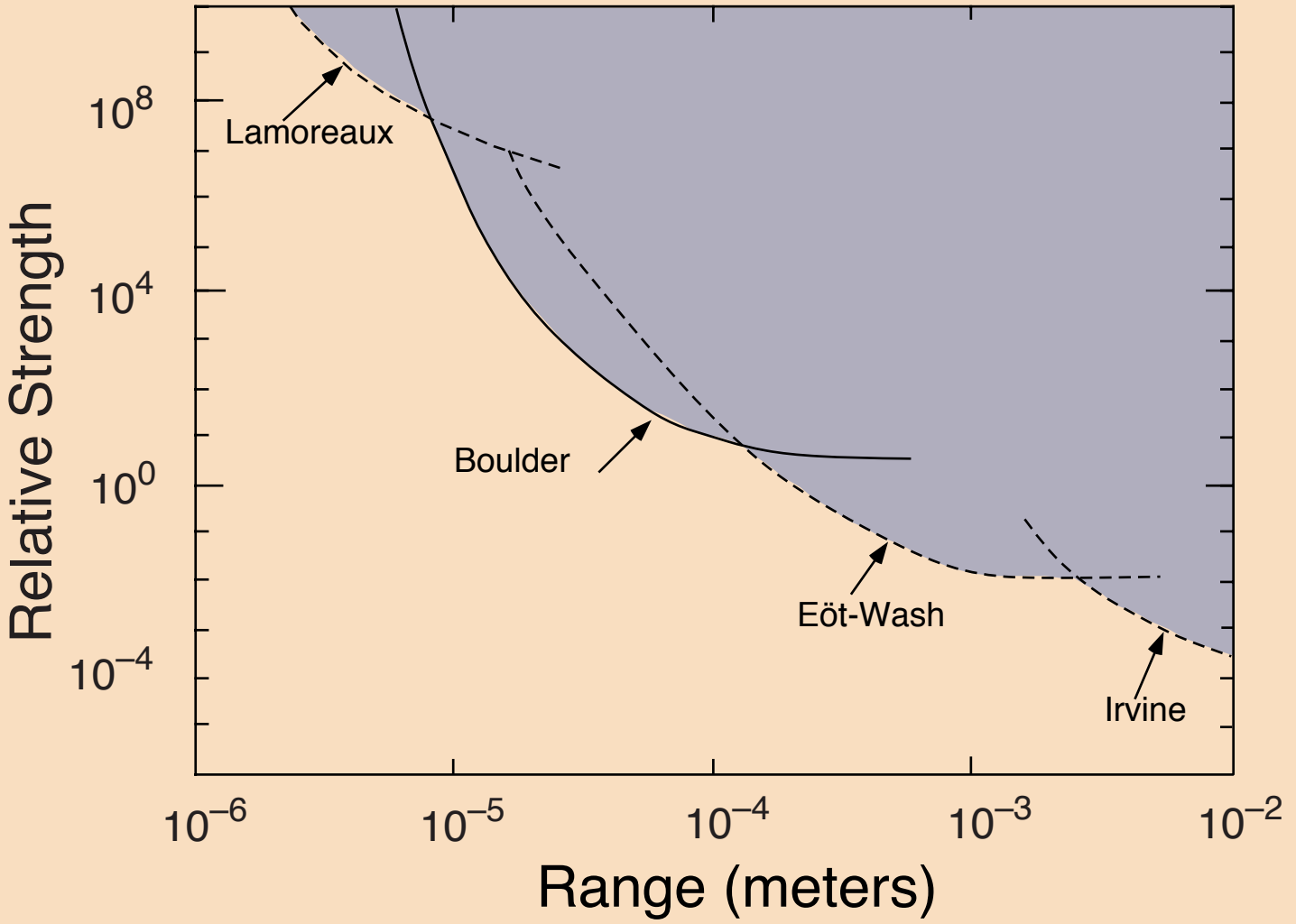
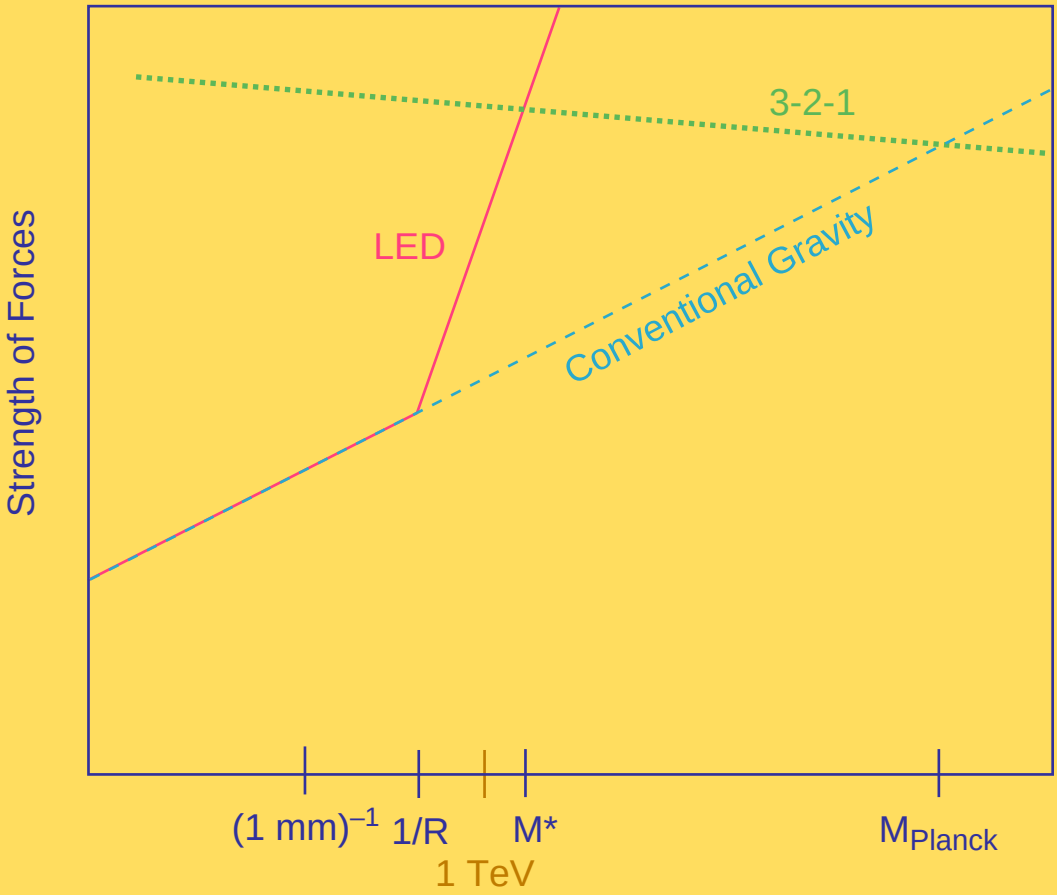


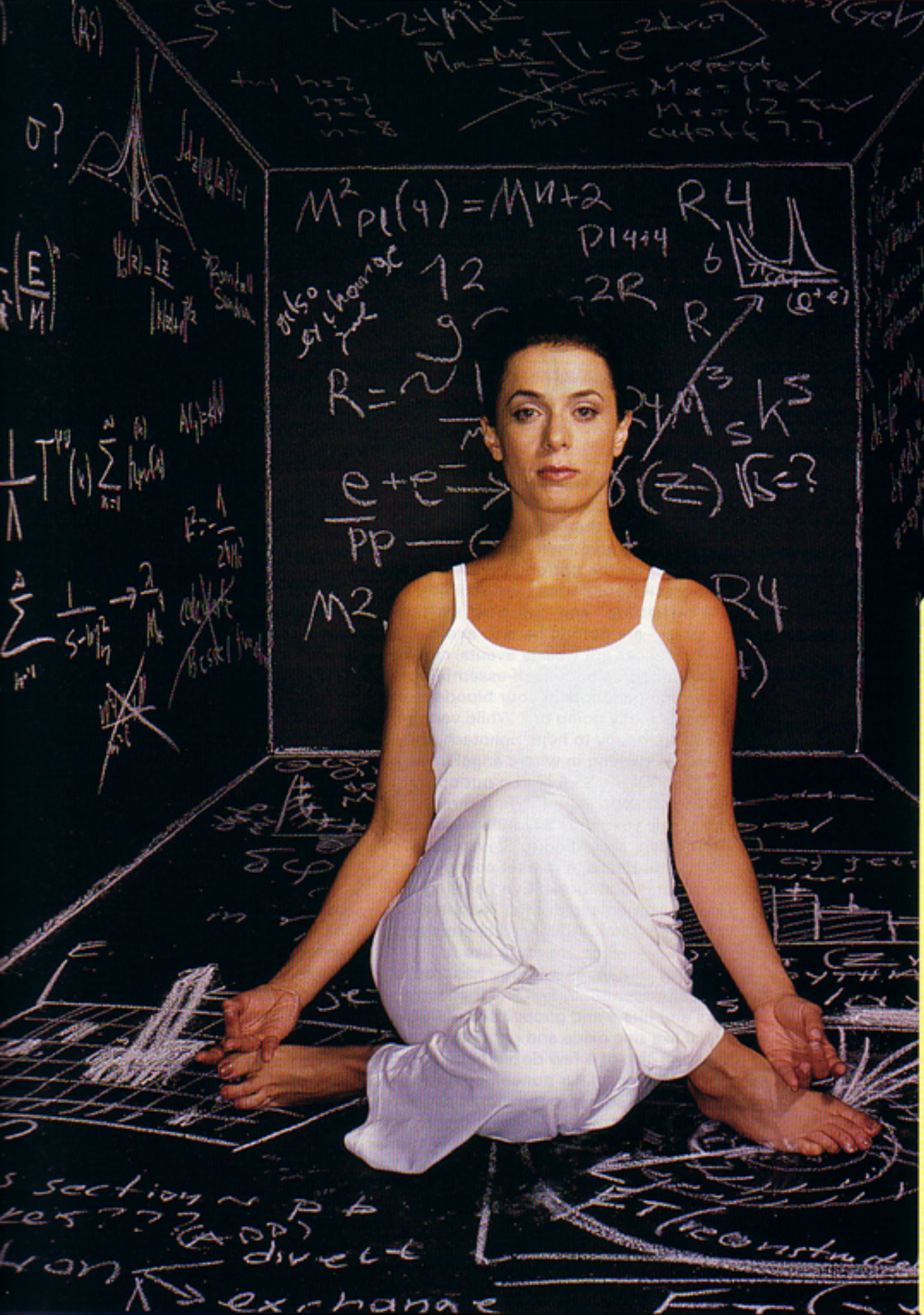

Relative Strength
10^{8}
10^{4}
10^{0}
10^{-4}
Lamoreaux
Boulder
Eöt-Wash
Irvine
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Range (meters)


Strength of Forces
3-2-1
LED
Conventional Gravity
(1 mm)$^{-1}$
1/R
M*
1 TeV
M_{Planck}


$M^2 = M^{n+2} R^n$
Amor

Gravitons ring extra dimensions . . .

(Video: Liubo Borissov, Columbia University, New York)



PEOPLE

Stretching Physics

Maria Spiropulu believes in a fifth dimension. The physicist, a researcher at the Fermi National Accelerator Laboratory, is harnessing the world's most powerful particle accelerator to smash protons and antiprotons together. If these collisions kick out less energy than predicted, then a few particles must have been blasted into another dimension. Or so the theory goes. "Think of it like a game of billiards," says Spiropulu, 32. "When you hit the balls, one of them goes vertical and never comes down." Her quest may resolve quantum physics' inconsistencies with Newtonian laws – and inch science closer to a unified theory that explains the formation of the universe and black holes. "Right now," she says, "we haven't a clue."
– Michael Behar

Elementarity

▷ Are quarks and leptons structureless?

Elementarity

- ▷ Are quarks and leptons structureless?

Symmetry

- ▷ Electroweak symmetry breaking and the 1-TeV scale
- ▷ Origin of gauge symmetries

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Unity

- ▷ Coupling constant unification
- ▷ Unification of quarks and leptons (new forces!); of constituents and force particles
- ▷ Incorporation of gravity

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Identity

- ▷ Fermion masses and mixings; CP violation; neutrino oscillations
- ▷ What makes an electron an electron and a top quark a top quark?

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▷ Fermion masses and mixings; CP violation; neutrino oscillations

▷ What makes an electron an electron and a top quark a top quark?

Topography

▷ What is the fabric of space and time? . . . the origin of space and time?

The Great Lesson of Science in the Twentieth Century

The human scale is not privileged for understanding Nature . . .

and may even be disadvantaged

Thanks to . . .

Liubo Borissov · *New York*
Timo Koerber · *Seattle*
Joseph Lykken · *Batavia*
Maria Spiropulu · *Chicago*

The Rustgi Family
Uli Baur · *Buffalo*
Michael Fuda · *Buffalo*

A Decade of Discovery Ahead

In the midst of a revolution in our conception of Nature, we deal with fundamental questions about our world, including

- Are the quarks and leptons elementary or composite?
- What are the symmetries of Nature, and how are they hidden from us?
- Are there new forms of matter, like the superpartners suggested by supersymmetry?
- Are there more fundamental forces?
- What makes an electron an electron and a top quark a top quark?
- What is the dimensionality of spacetime?

Nothing is too wonderful to be true,
if it be consistent with the laws of nature . . .
Experiment is the best test
Michael Faraday

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

- Understand electroweak symmetry breaking
- Observe the Higgs boson
- Measure neutrino masses and mixings
- Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
- Thoroughly explore CP violation in B decays
- Exploit rare decays (K, D, . . .)
- Observe neutron EDM, pursue electron EDM
- Use top 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 GUT symmetry
- Detect neutrinos from the universe
- Learn how to quantize gravity
- Learn why empty space is nearly weightless
- 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

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. . . and to learn the right questions to ask