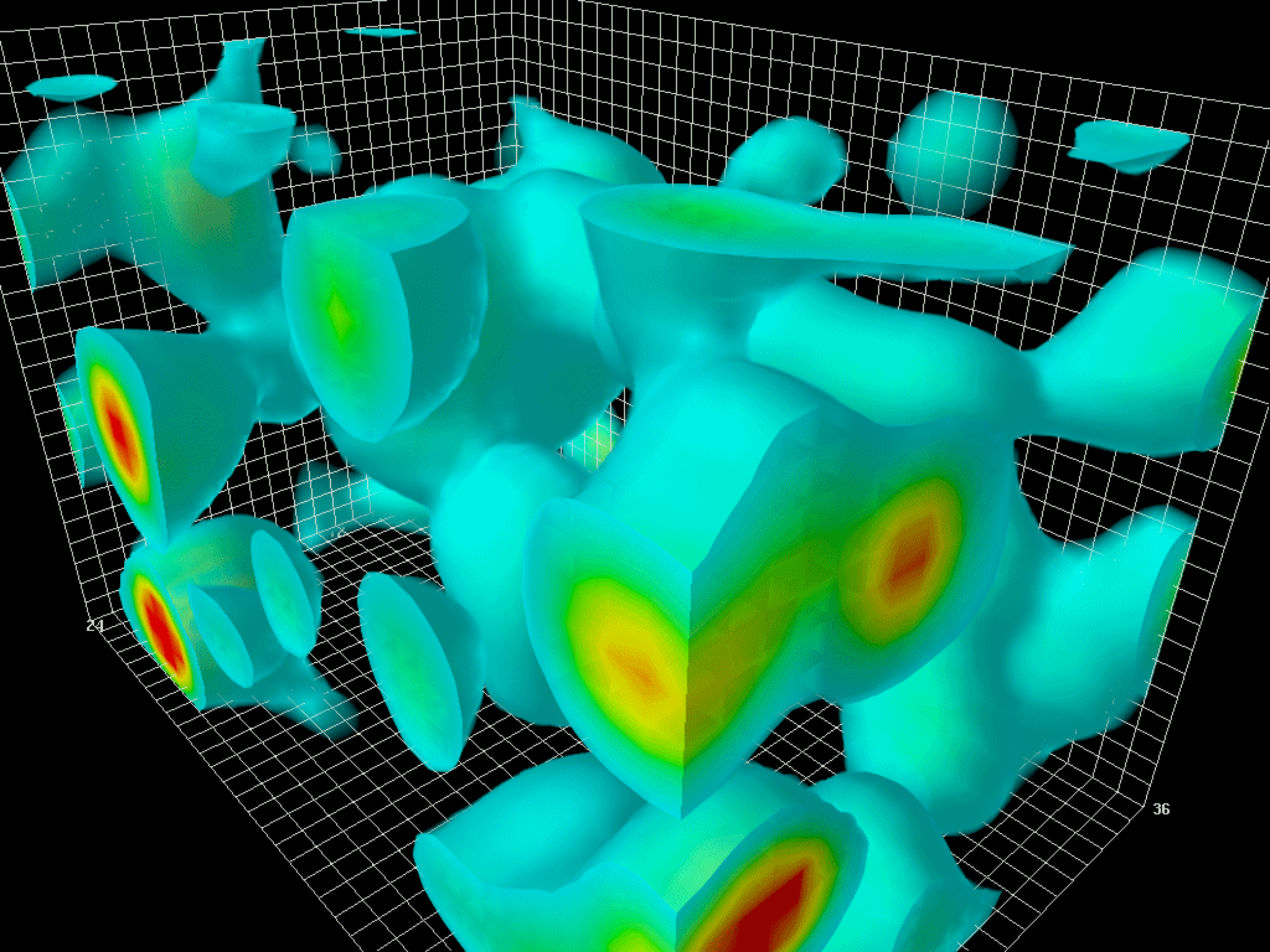
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Weight, Weight—Do Tell Me!!!

QCD and the Origin of Mass

Andreas S. Kronfeld
Fermilab & IAS TU München

Stanford University Online High School
February 5, 2016

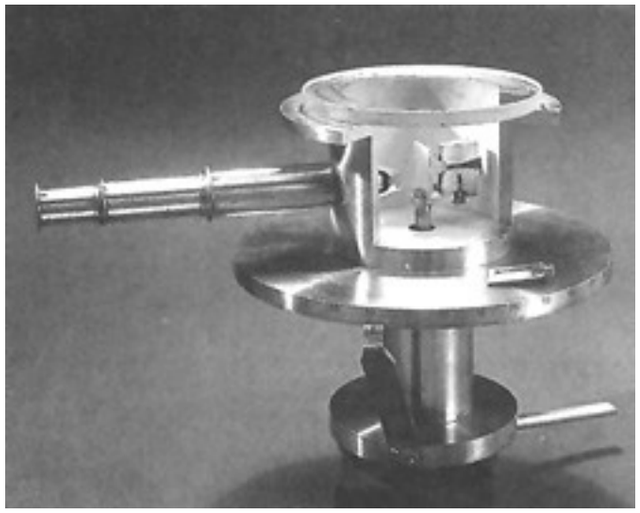
title with apologies to Chicago Public Radio

further reading: arXiv:1209.3468

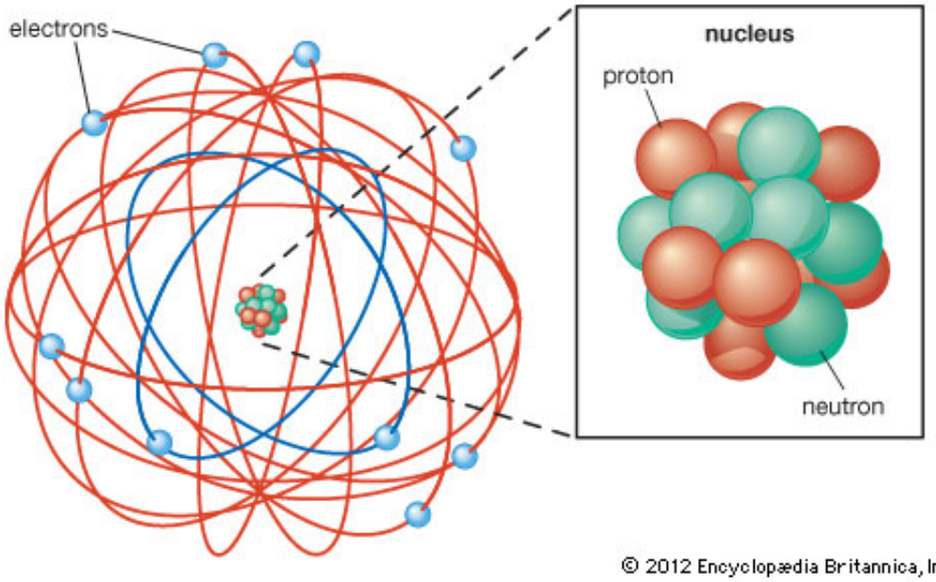
Where Does Mass Come From?

Atoms

- The density of a gold atom is about 20 gm cm^{-3}:
- Geiger-Marsden experiment:



- Rutherford model:
  - some very light electrons ($m_e/M_p = 0.00054$);
  - a lot of empty space;
  - and a **heavy nucleus**.



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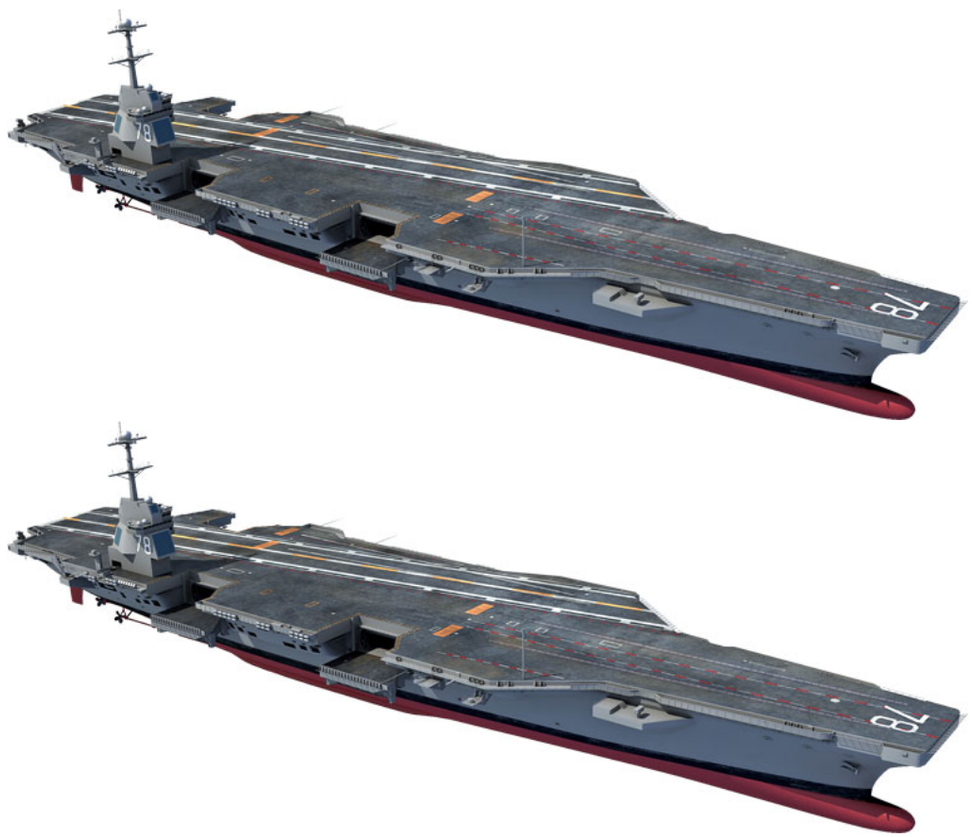
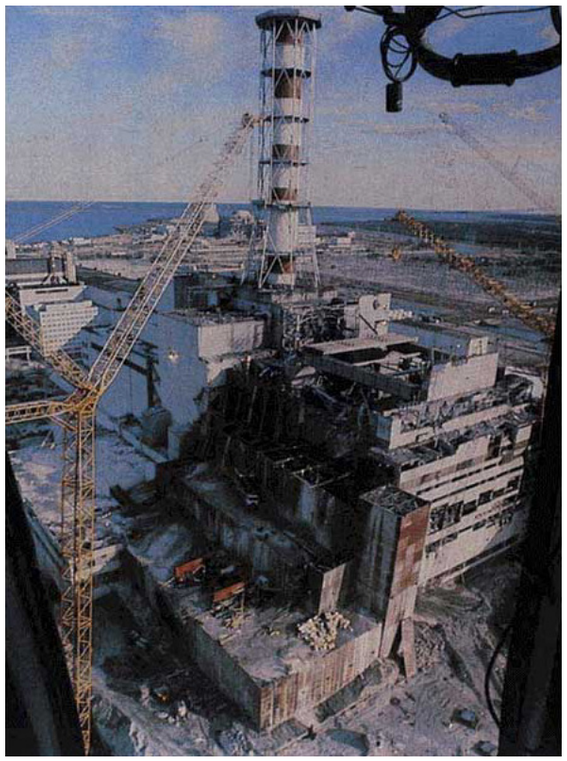
- The density of an atomic nucleus ranges from around 20×10^{13} gm cm^{-3} (Au) to 60×10^{13} gm cm^{-3} (proton).

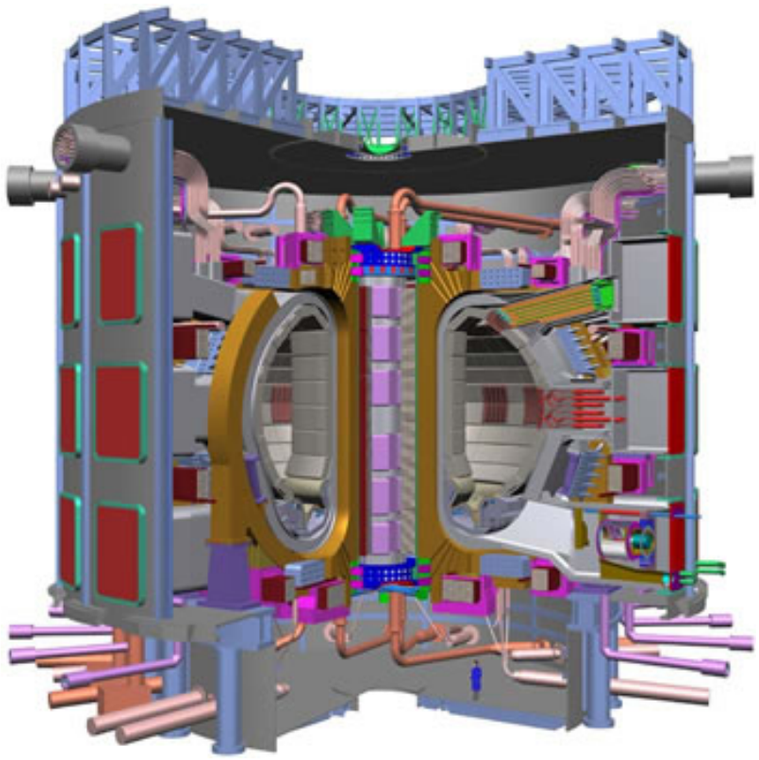


- Deeper scattering says nuclei = **protons** + **neutrons** ☛ nucleons.

- The energy released in nuclear reactions is puny compared to Einstein's total $E = Mc^2$ of the nucleons.



fission: 0.11%



fusion: 1%

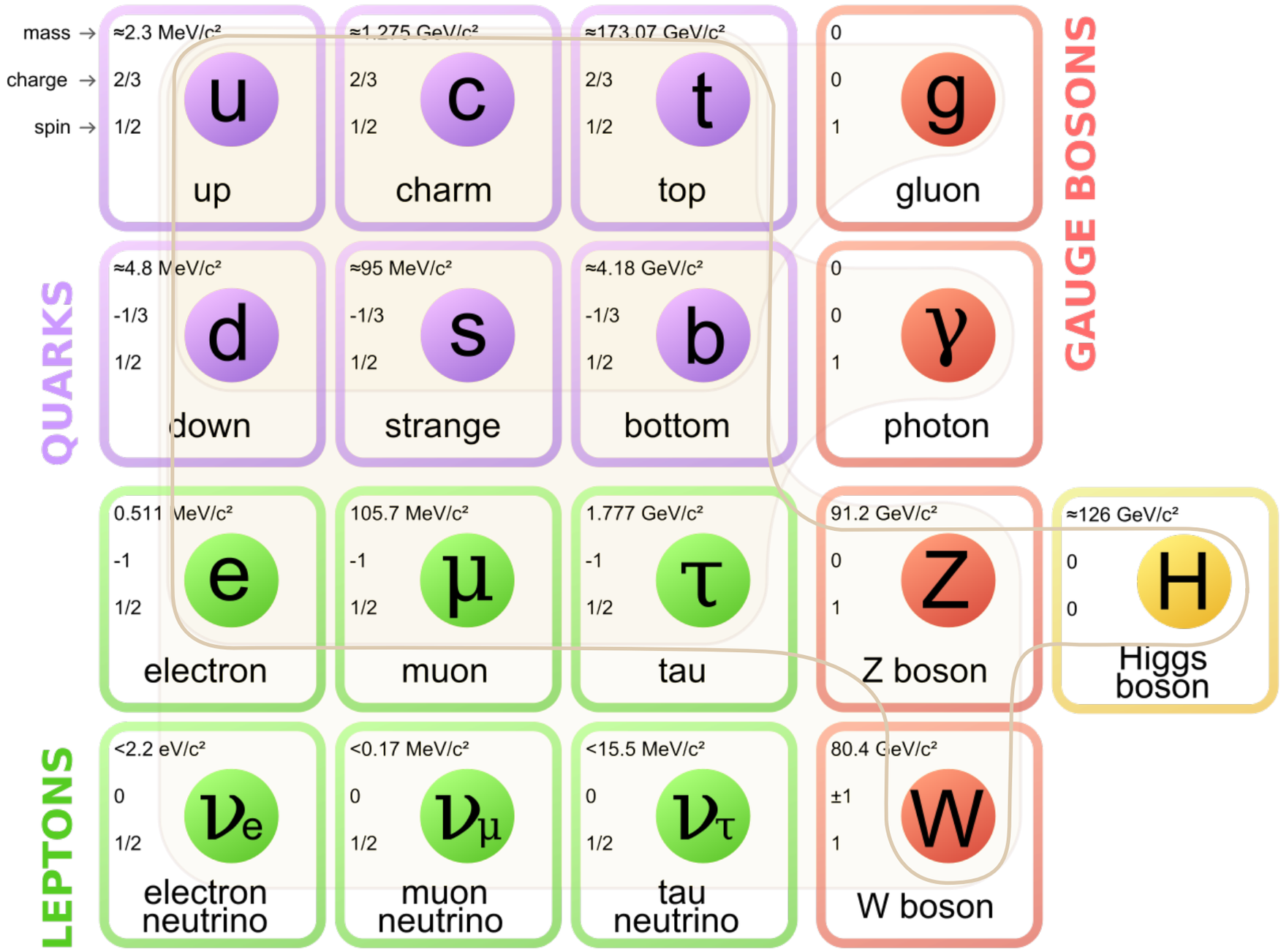
- The origin of mass of the atomic nuclei lies beyond nuclear chemistry.

Your mass comes from something inside protons & neutrons.

Particles, Waves, Forces

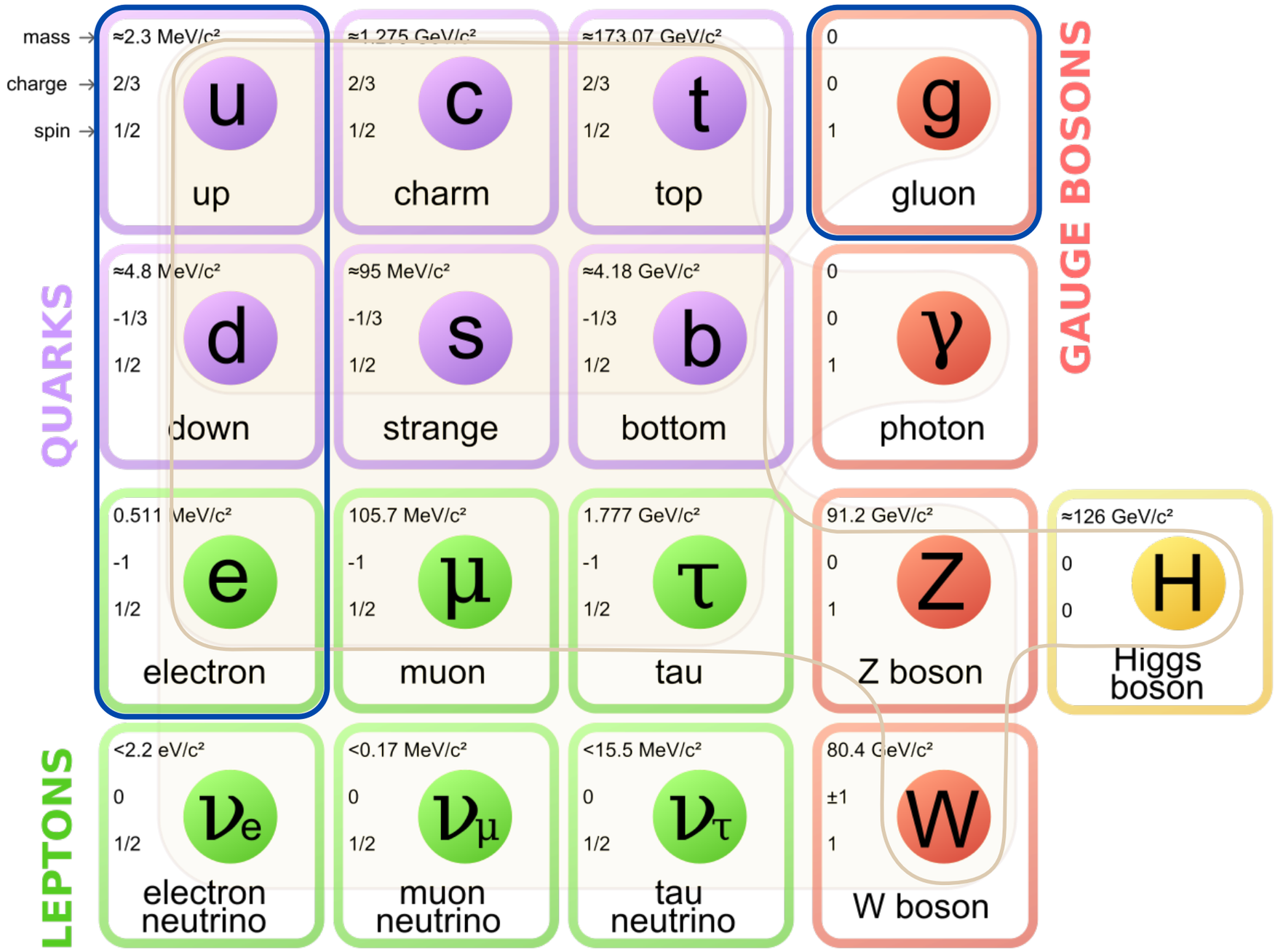
The Elementary Particles

wikimedia



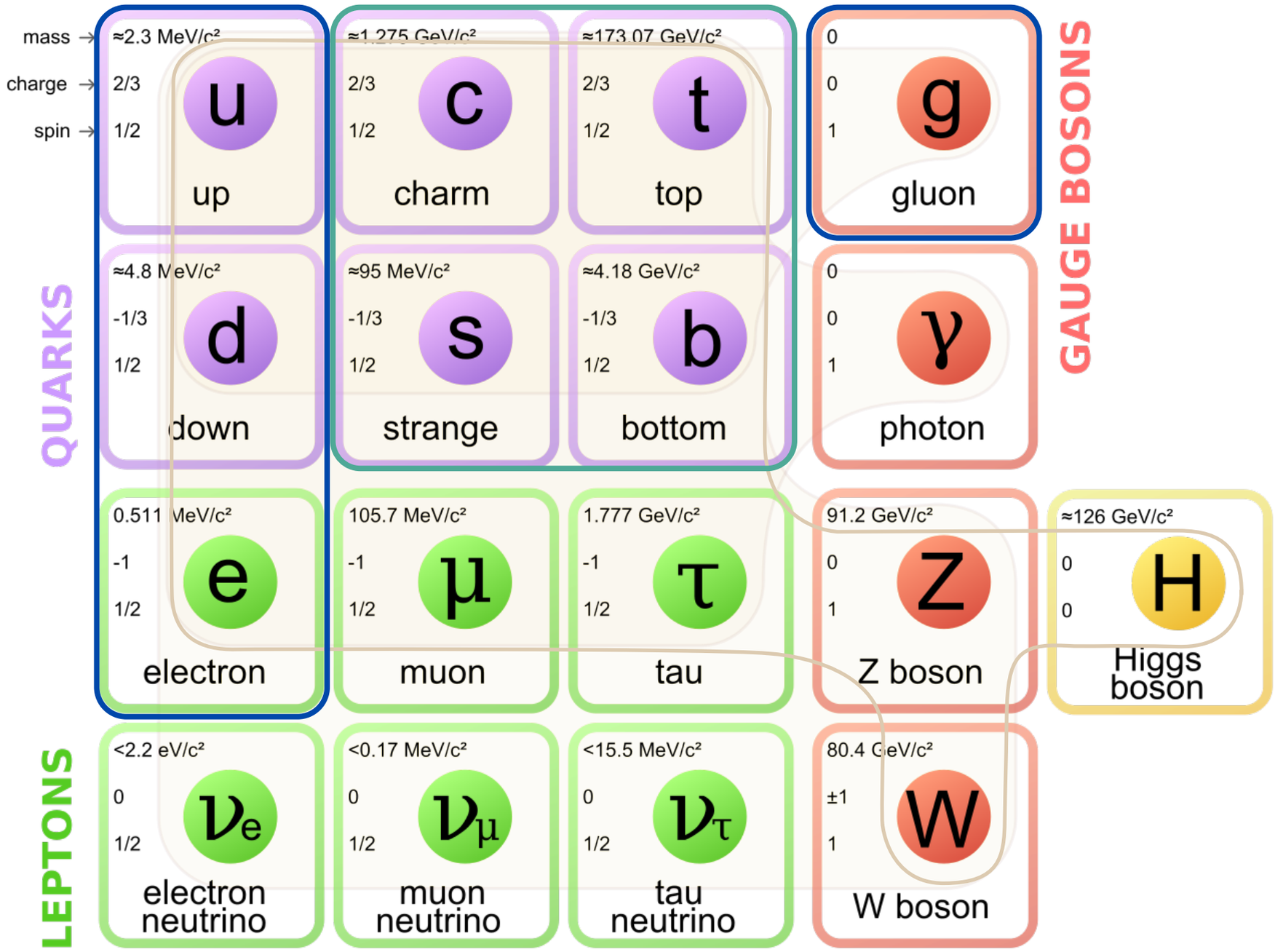
The Elementary Particles

wikimedia



The Elementary Particles

wikimedia



Hadrons

- **Baryons** consist of three quarks:
  - a proton is made of two u quarks and a d quark;
  - a neutron is made of one u quark and two d quarks;
  - many other baryons known as $\Delta = uud,\ \Lambda = uds,\ \Xi = uss, \ldots.$
- **Mesons** consist of a quark and an antiquark:
  - $\pi^- = \bar{u}_\downarrow d_\uparrow,\ \rho^- = \bar{u}_\uparrow d_\uparrow,\ K^- = \bar{u}s,\ K^0 = \bar{s}d,\ B = \bar{u}b,\ \Upsilon = \bar{b}b, \ldots.$
- Quarks (or aces) to describe plethora; partons to explain scattering.

- Quark masses don't add up to hadron masses:

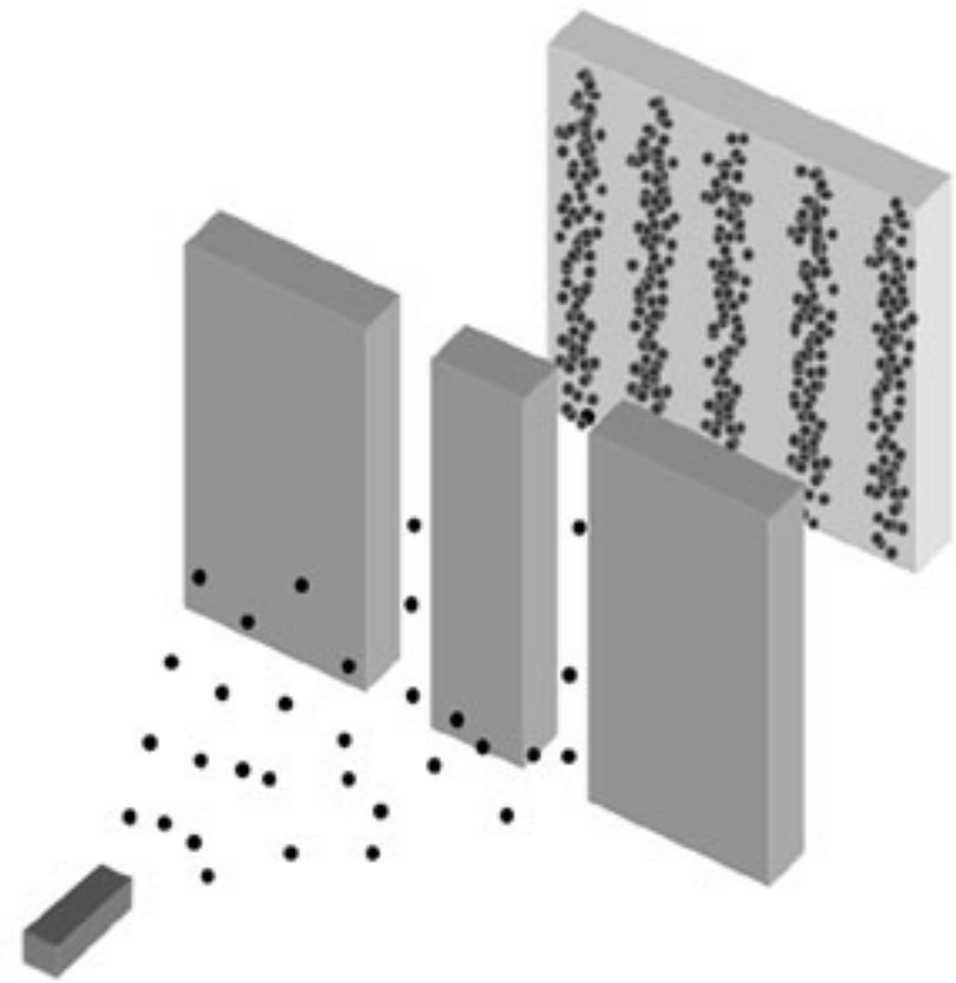
$$
\begin{aligned}
2m_u + m_d &= 9.4\ \mathrm{MeV}/c^2 < 938.3\ \mathrm{MeV}/c^2 = M_p \\
m_u + 2m_d &= 11.9\ \mathrm{MeV}/c^2 < 939.6\ \mathrm{MeV}/c^2 = M_n \\
m_u + m_d &= 7.1\ \mathrm{MeV}/c^2 < 139.6\ \mathrm{MeV}/c^2 = M_\pi
\end{aligned}
$$

- What produces the additional mass?

From now on, usually use "God-given" units with $c = \hbar = 1$.

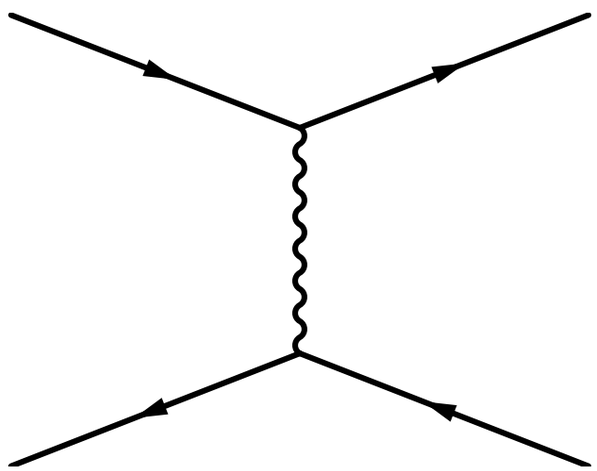
Quantum Fields

- Electrons—and everything else in the chart—are simultaneously **particles** and **waves**:
  - double slit experiment.
- There's some math for that:
  - quantum field theory;
  - field = few numbers at every point in space.
- Explore all possible paths, staying close to "classical".



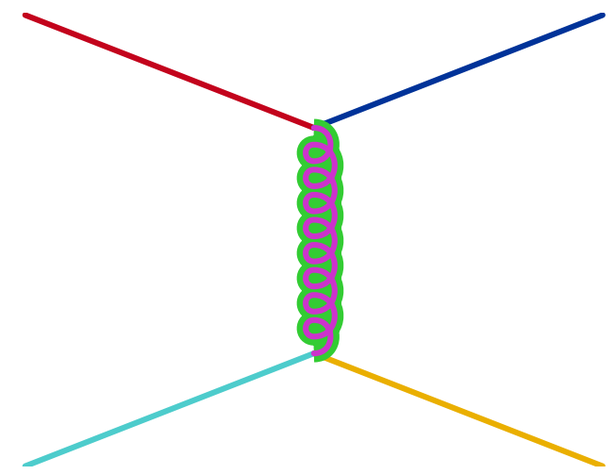
Forces from Boson Exchange

- Quantum electrodynamics:



- atoms held together by exchanging photons;
- electric charge feels the photons.
- U(1) symmetry.

- Quantum chromodynamics:



- hadrons held together by exchanging gluons
  - quarks' color feels the gluons.
  - SU(3) symmetry.

Rotations: Commute or Not Commute?

Rotations: Commute or Not Commute?

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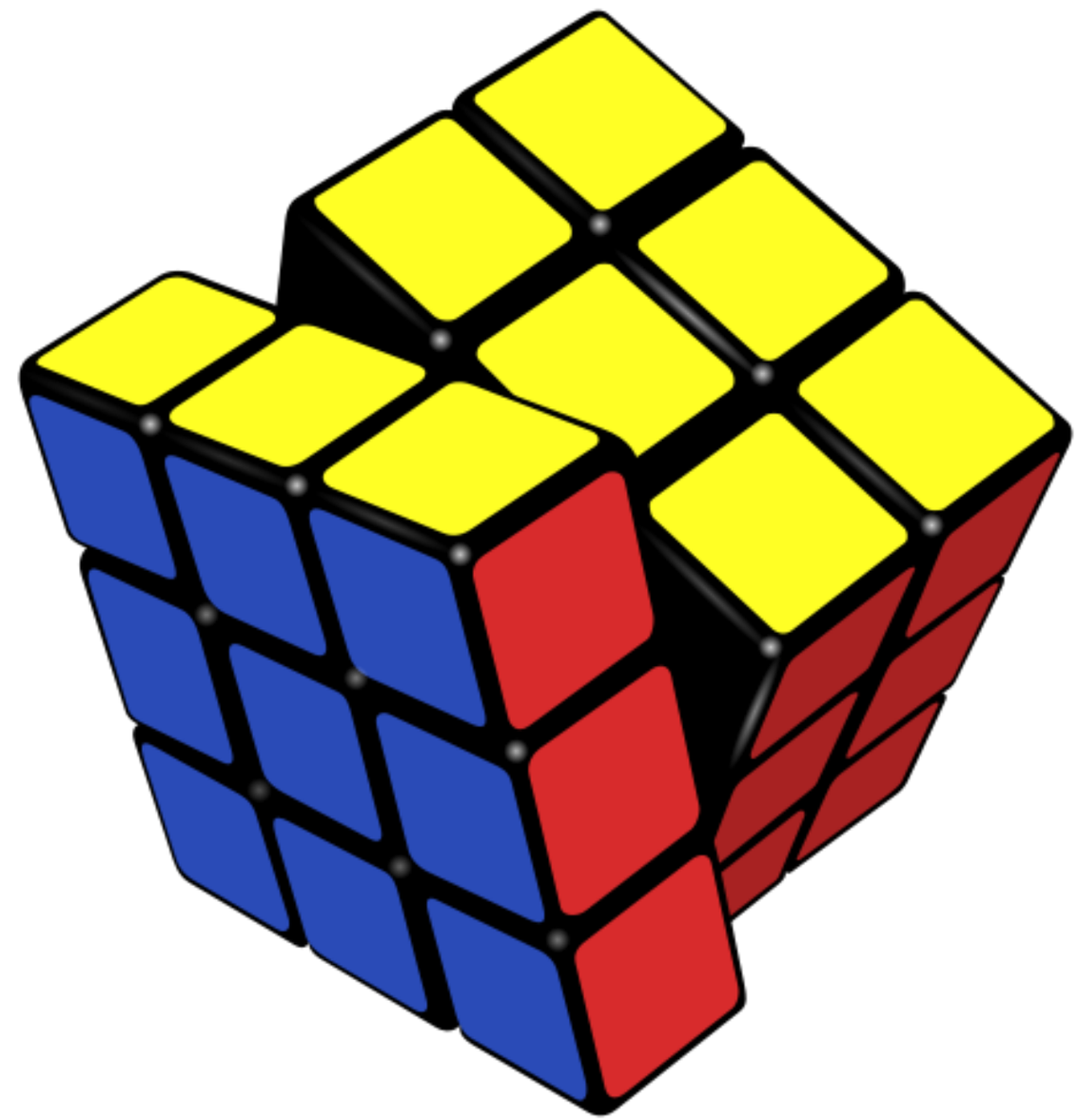
U(1)

$45^\circ + 90^\circ = 90^\circ + 45^\circ$

Rotations: Commute or Not Commute?

U(1)



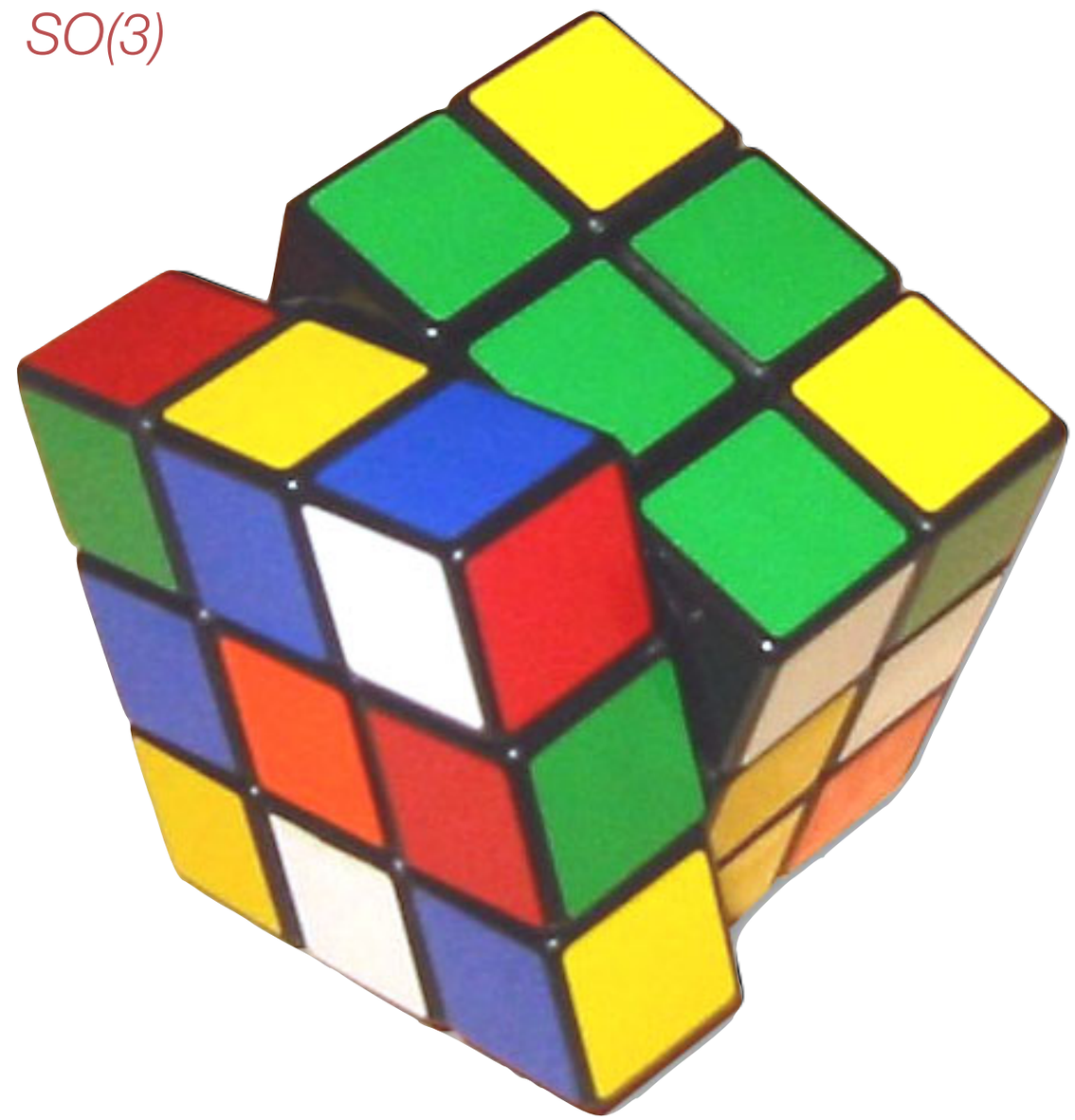
$45^\circ + 90^\circ = 90^\circ + 45^\circ$

Rotations: Commute or Not Commute?

U(1)

$45^\circ + 90^\circ = 90^\circ + 45^\circ$

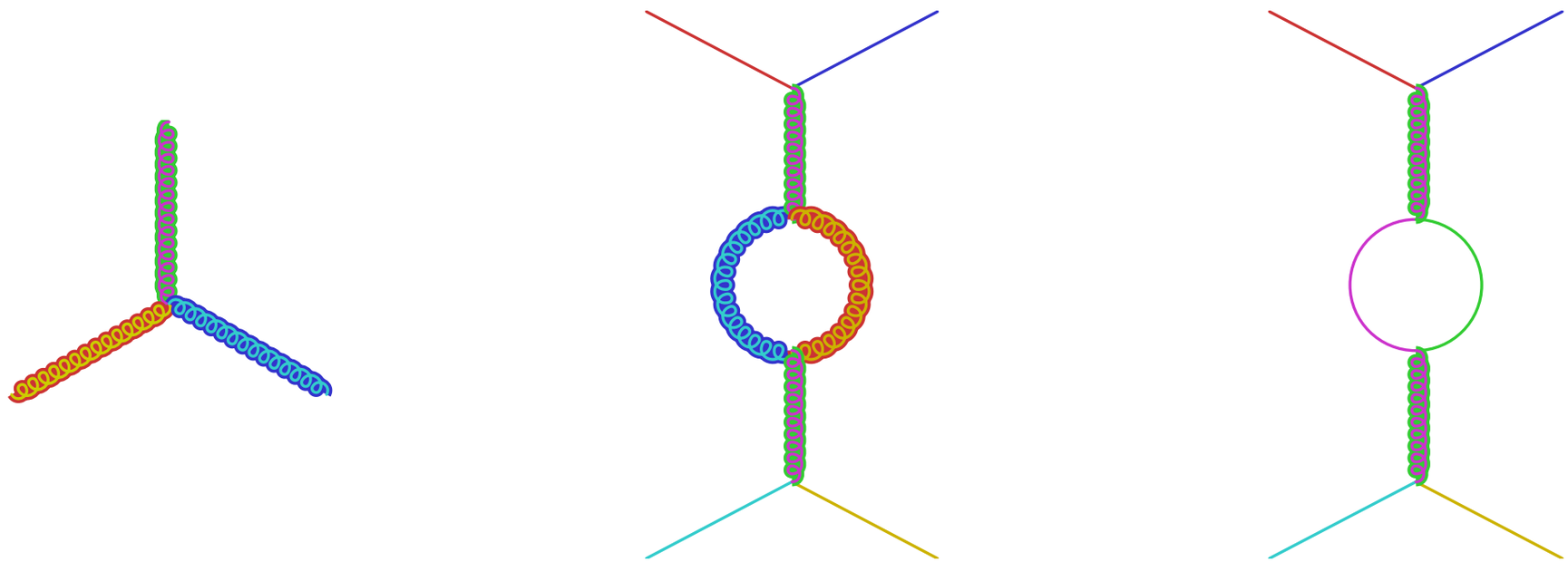
SO(3)



$R_x(90^\circ)R_y(90^\circ) \neq R_y(90^\circ)R_x(90^\circ)$

Gluons Carry Color

- … so they interact with each other!



- This simple change makes QCD completely different from QED:
  - asymptotic freedom: $F(r) = -\frac{1}{r^2}\frac{1}{1-\beta_0 \ln(r\Lambda)}$, for r small enough;
  - new physics energy scale Λ.

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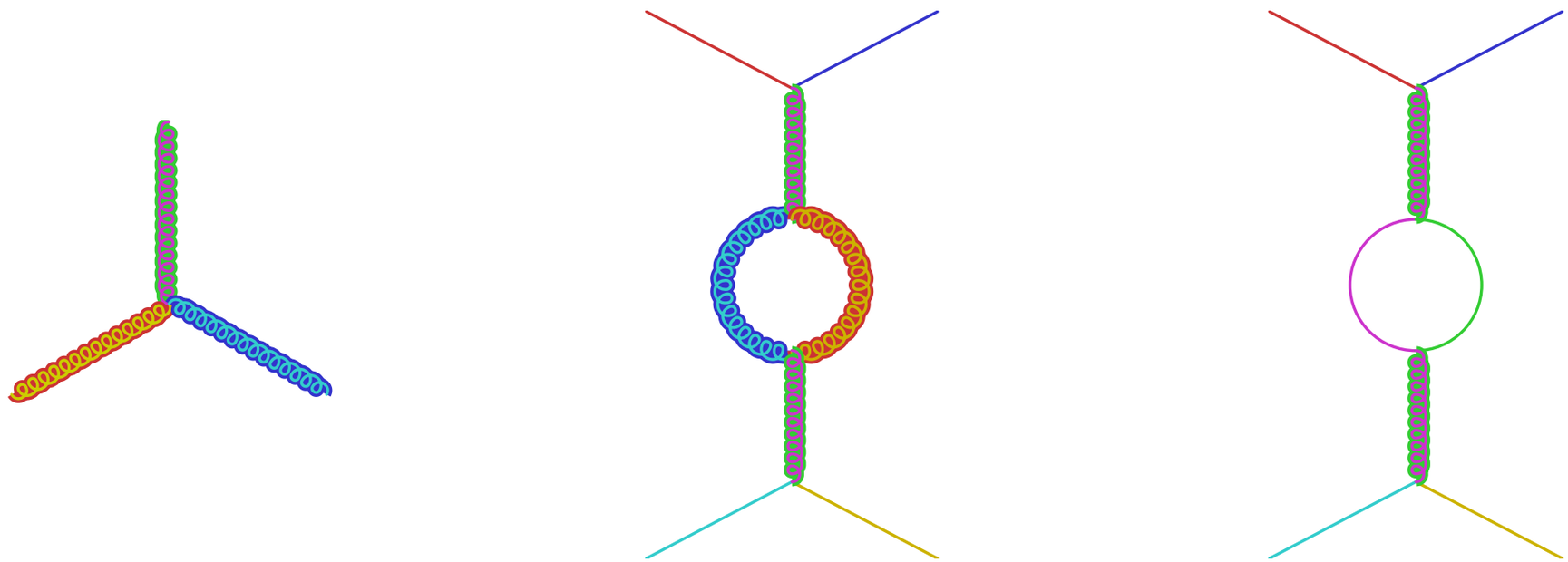

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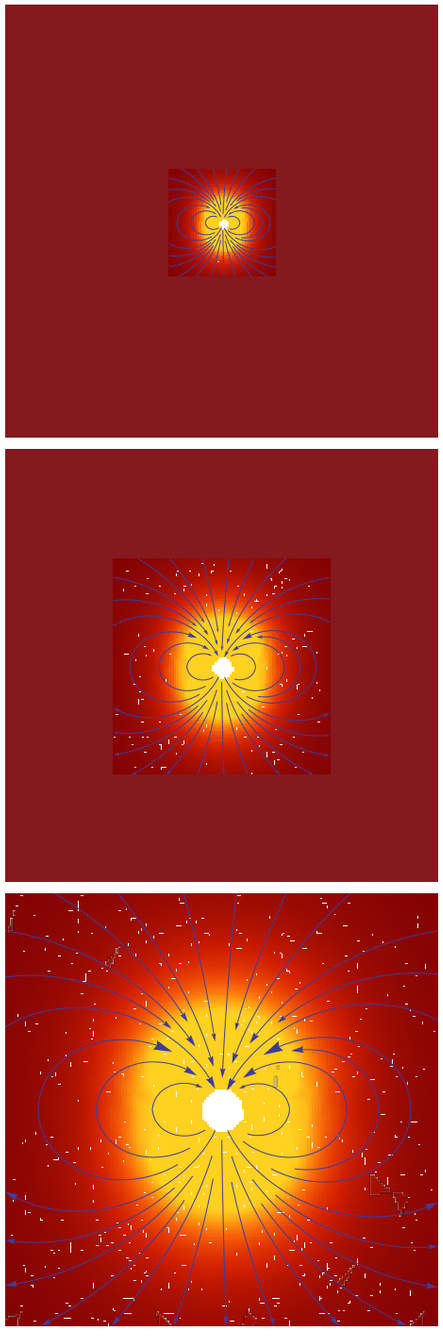
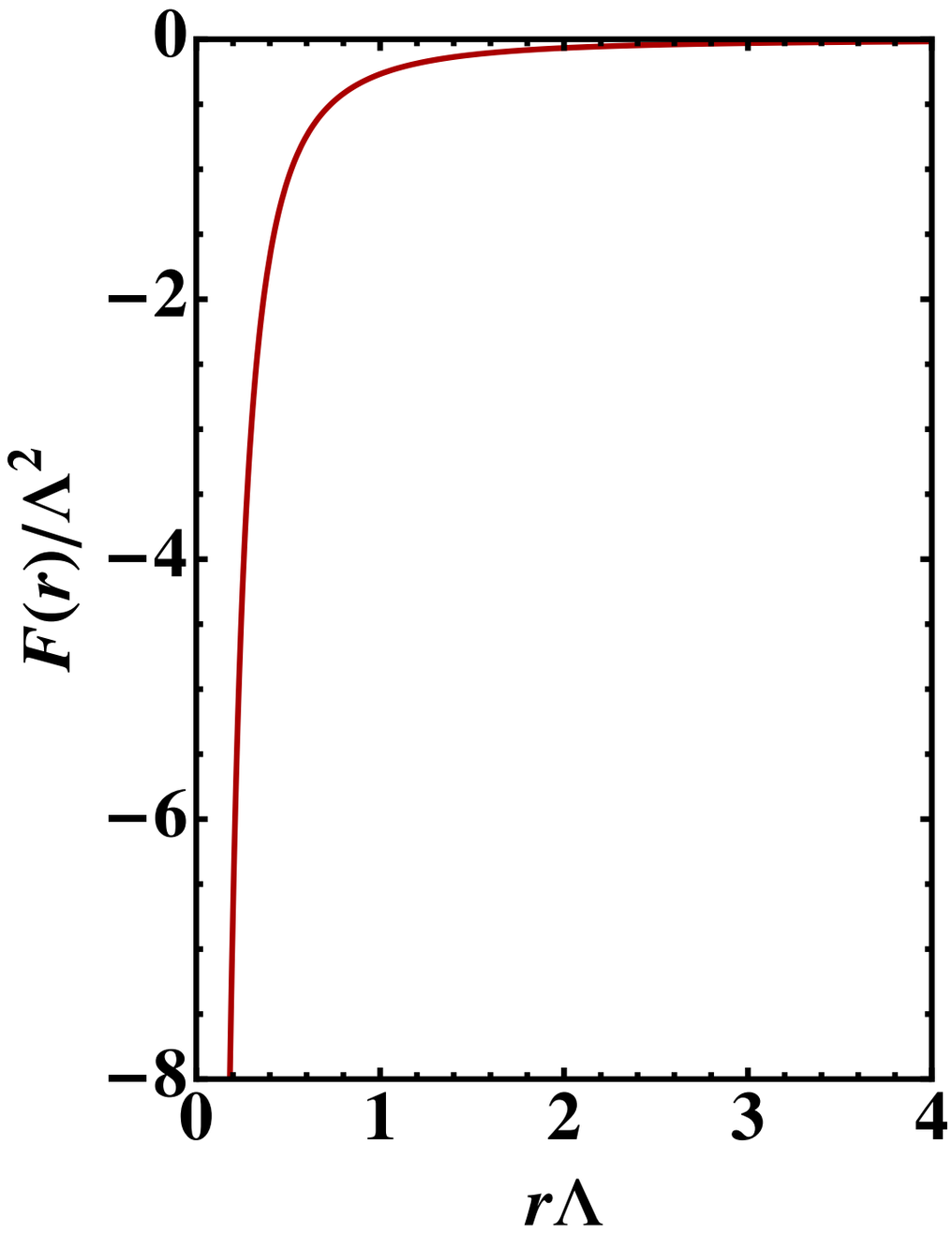
running coupling $\alpha_s(r)$

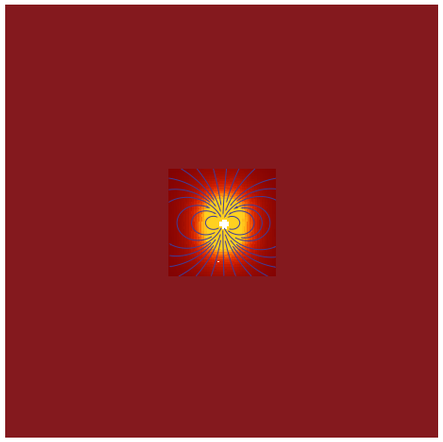
Forces in QED and QCD

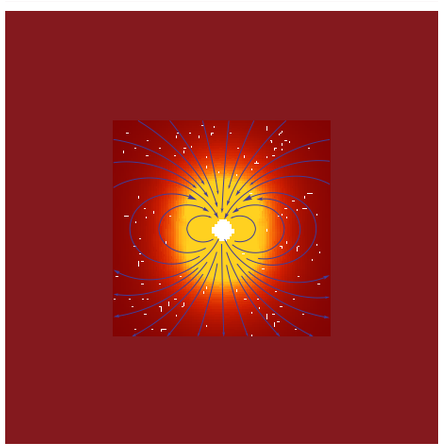


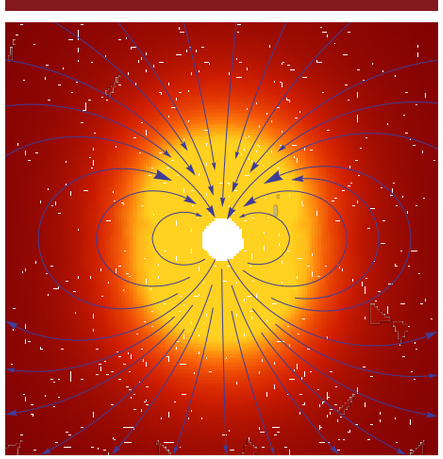
- QED:
  - $F(r) = -\alpha_s/r^2$;
  - (high school).



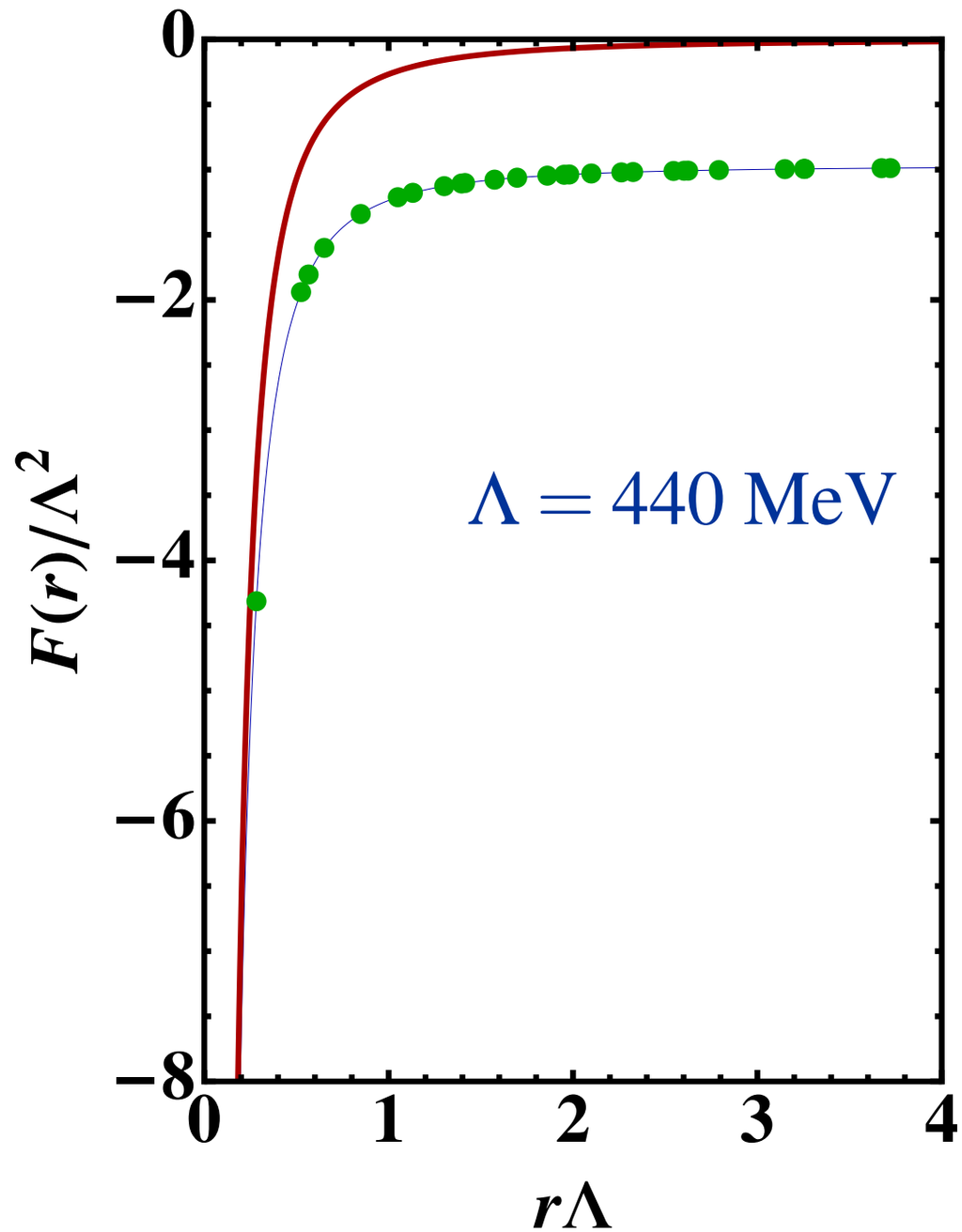
Forces in QED and QCD

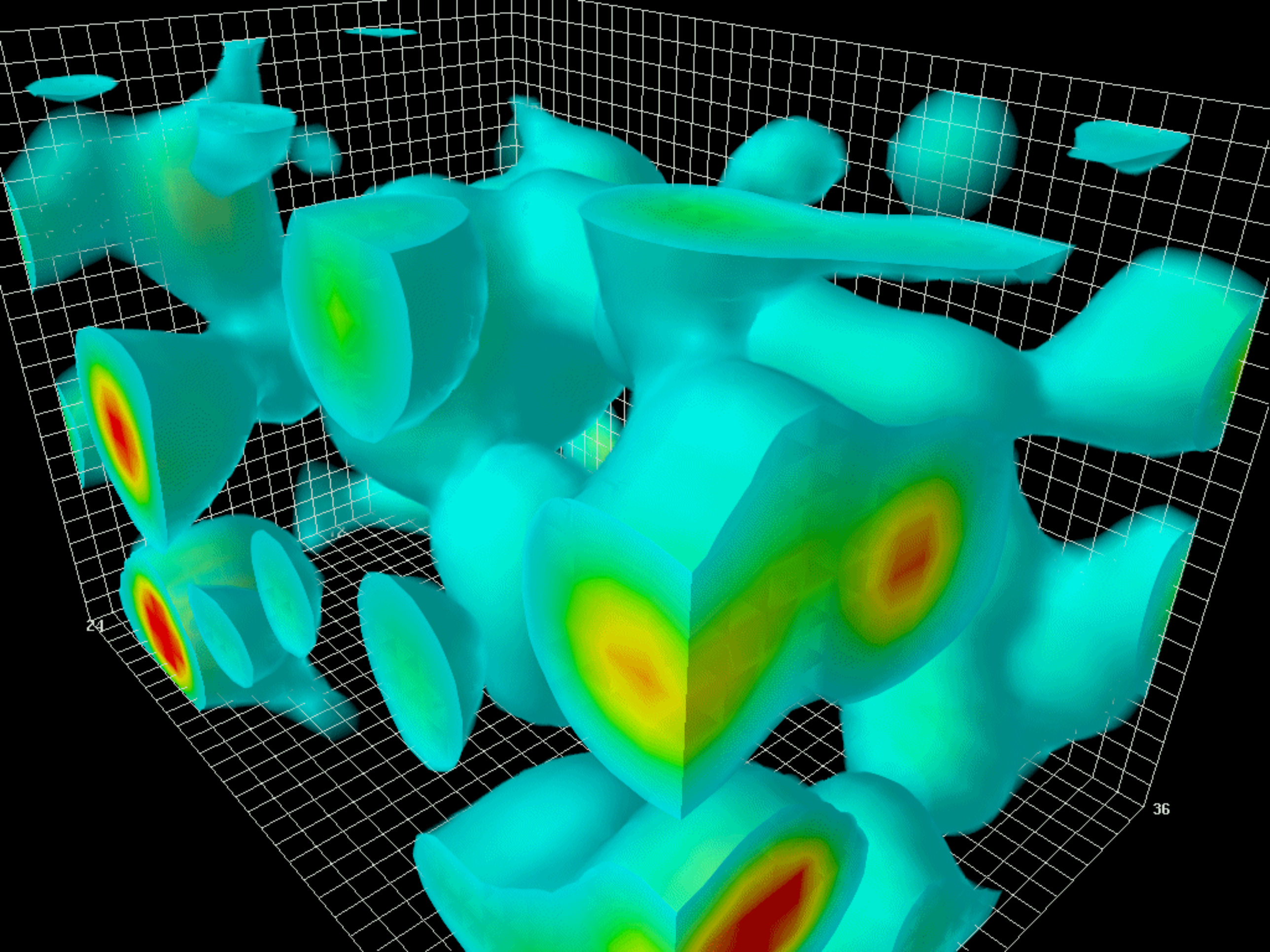






- QED:
  - $F(r) = -\alpha_s/r^2$;
  - (high school).
- QCD computation:
  - data points;
  - (recent research).
- QCD fit:
  - $F(r) = -\Lambda^2 - \alpha_s/r^2$.

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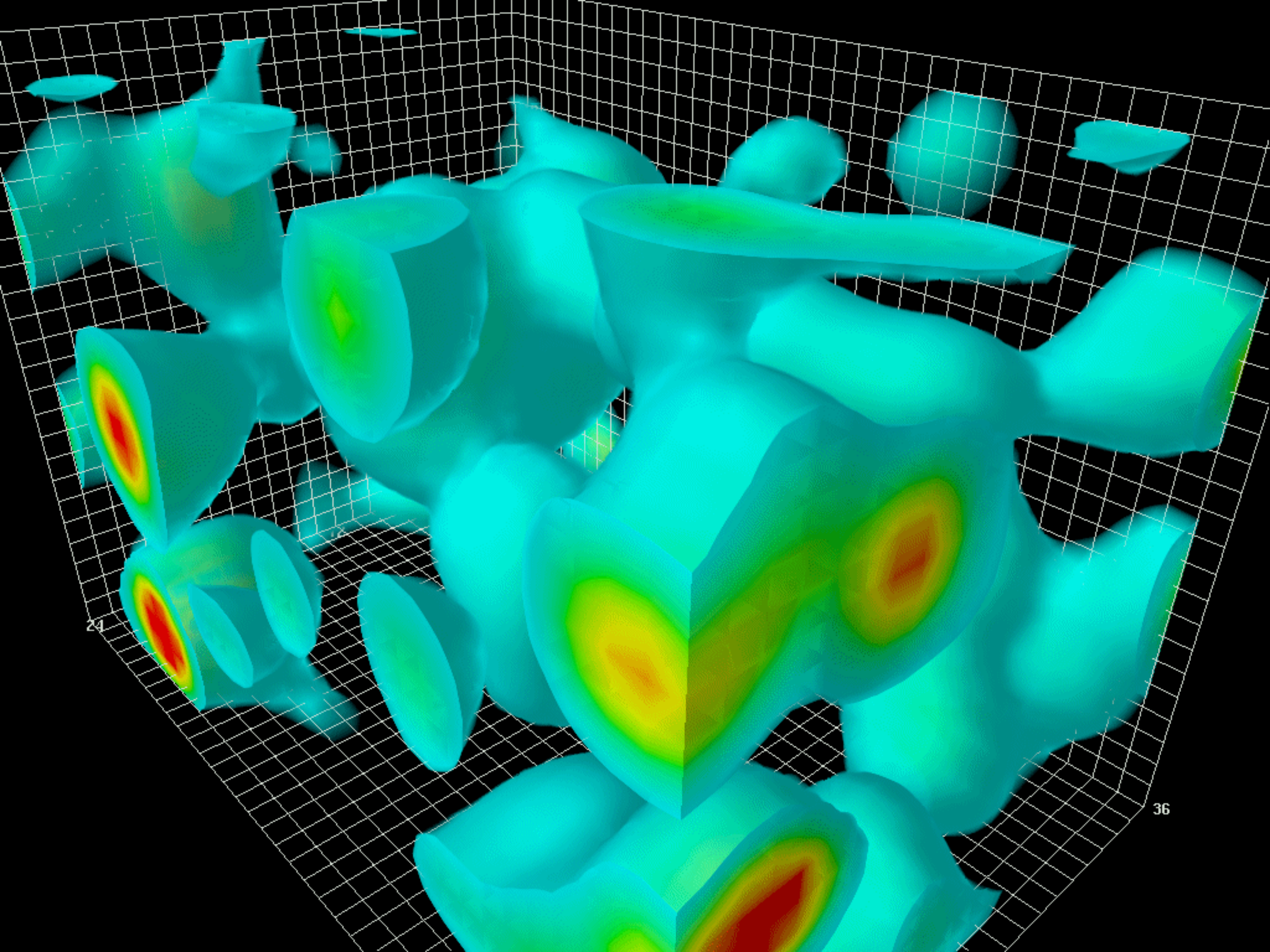
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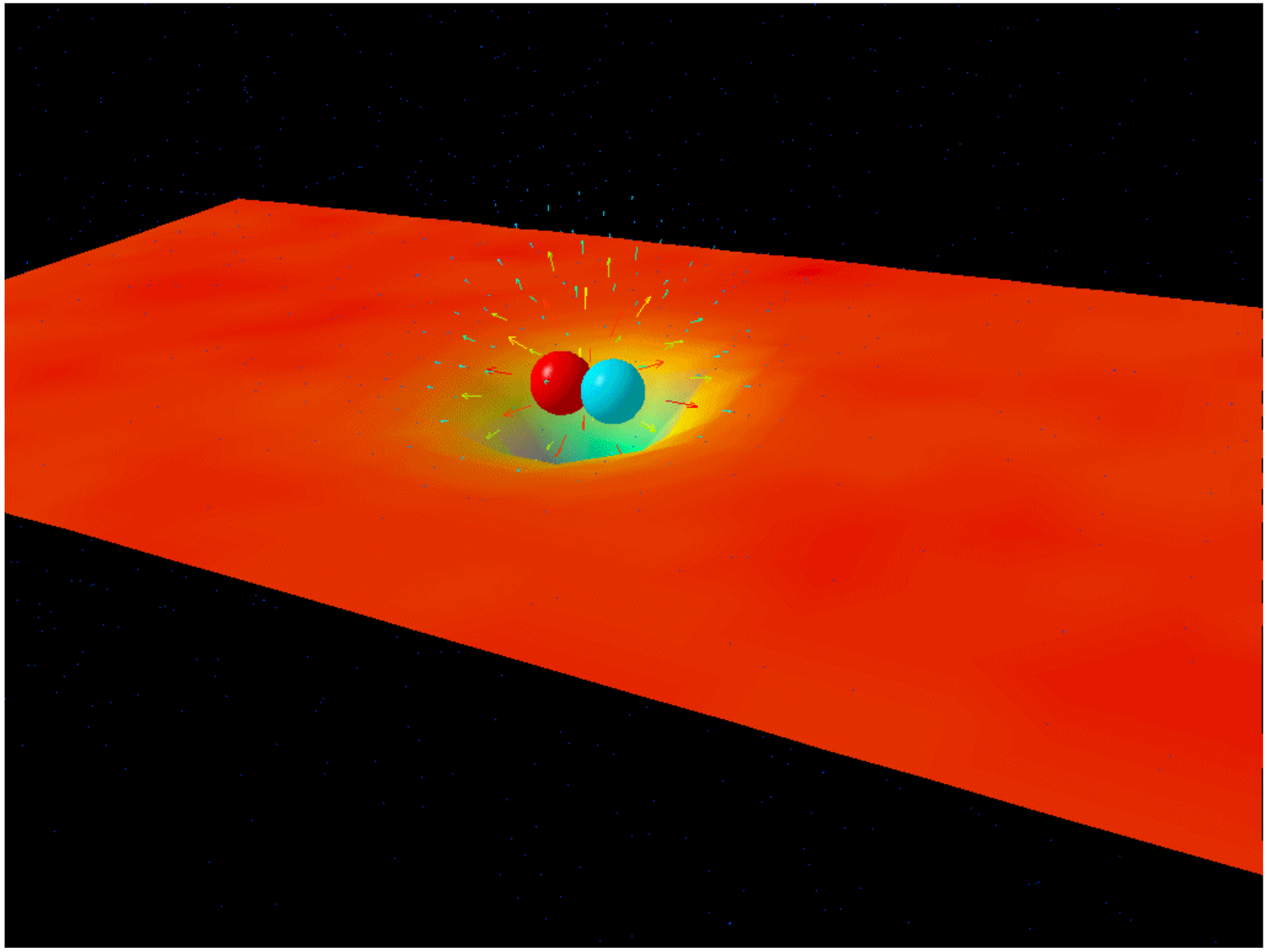
Field Between Quark and Antiquark



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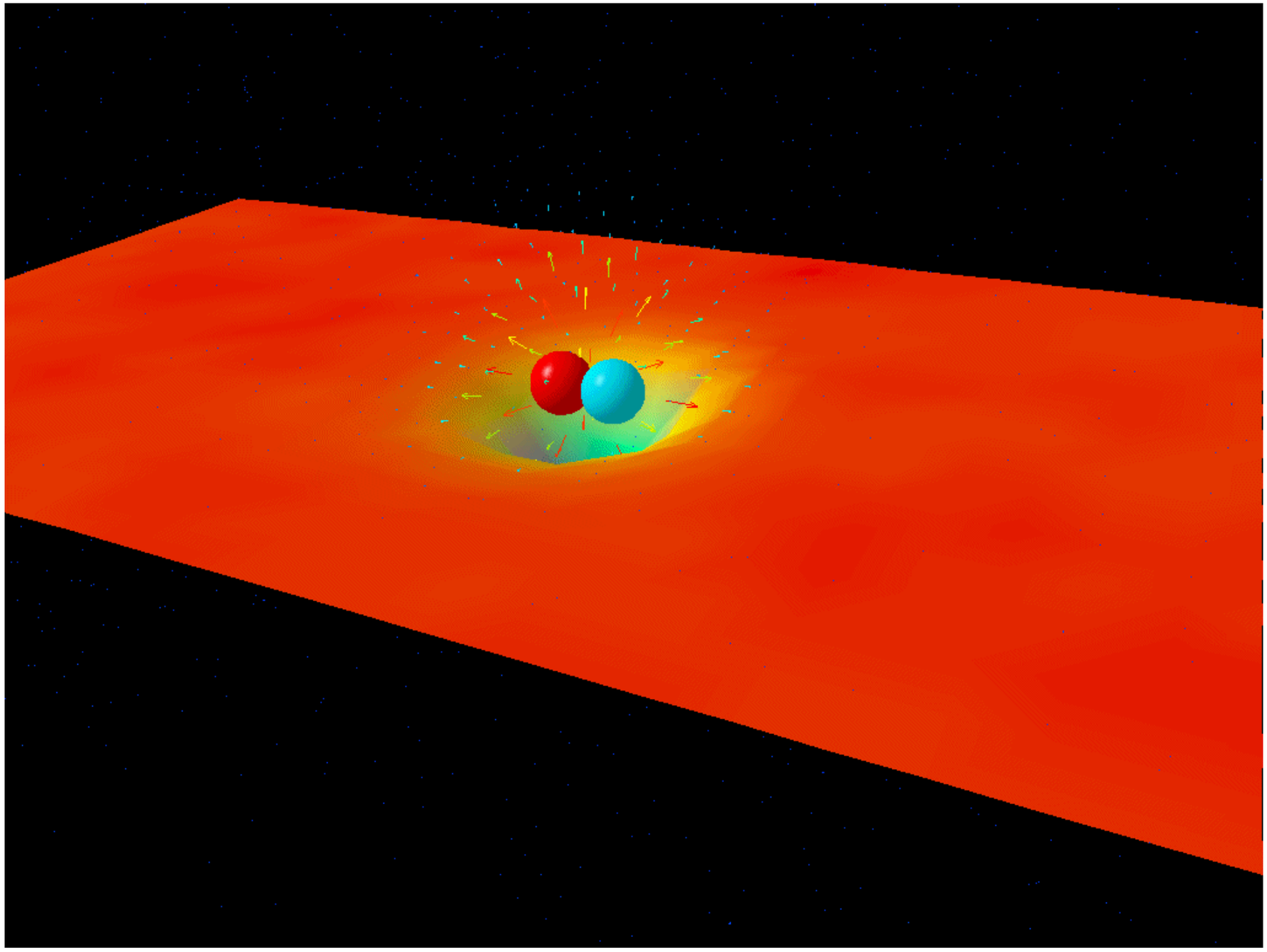
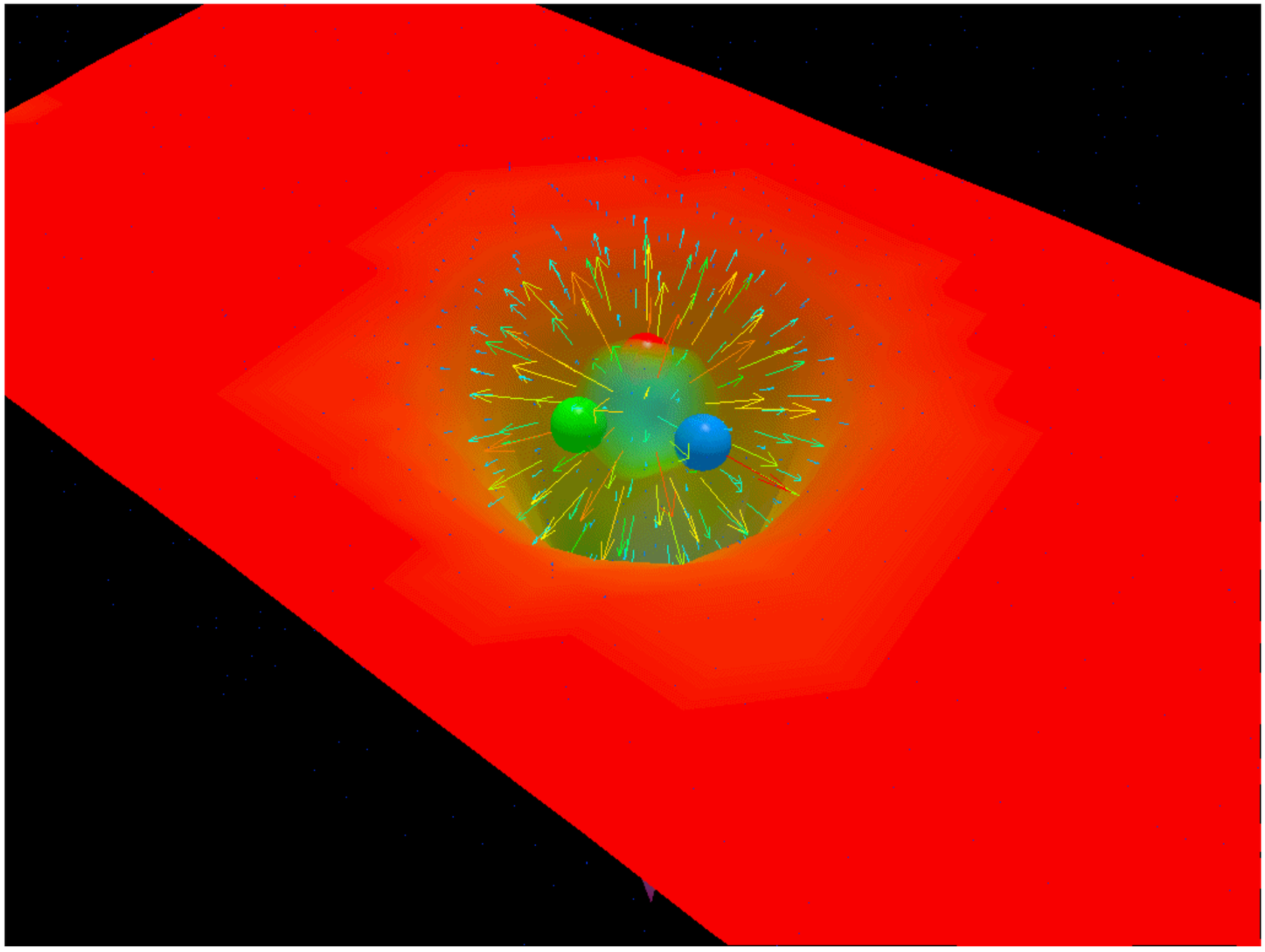


Tri-Tip aka Baryon



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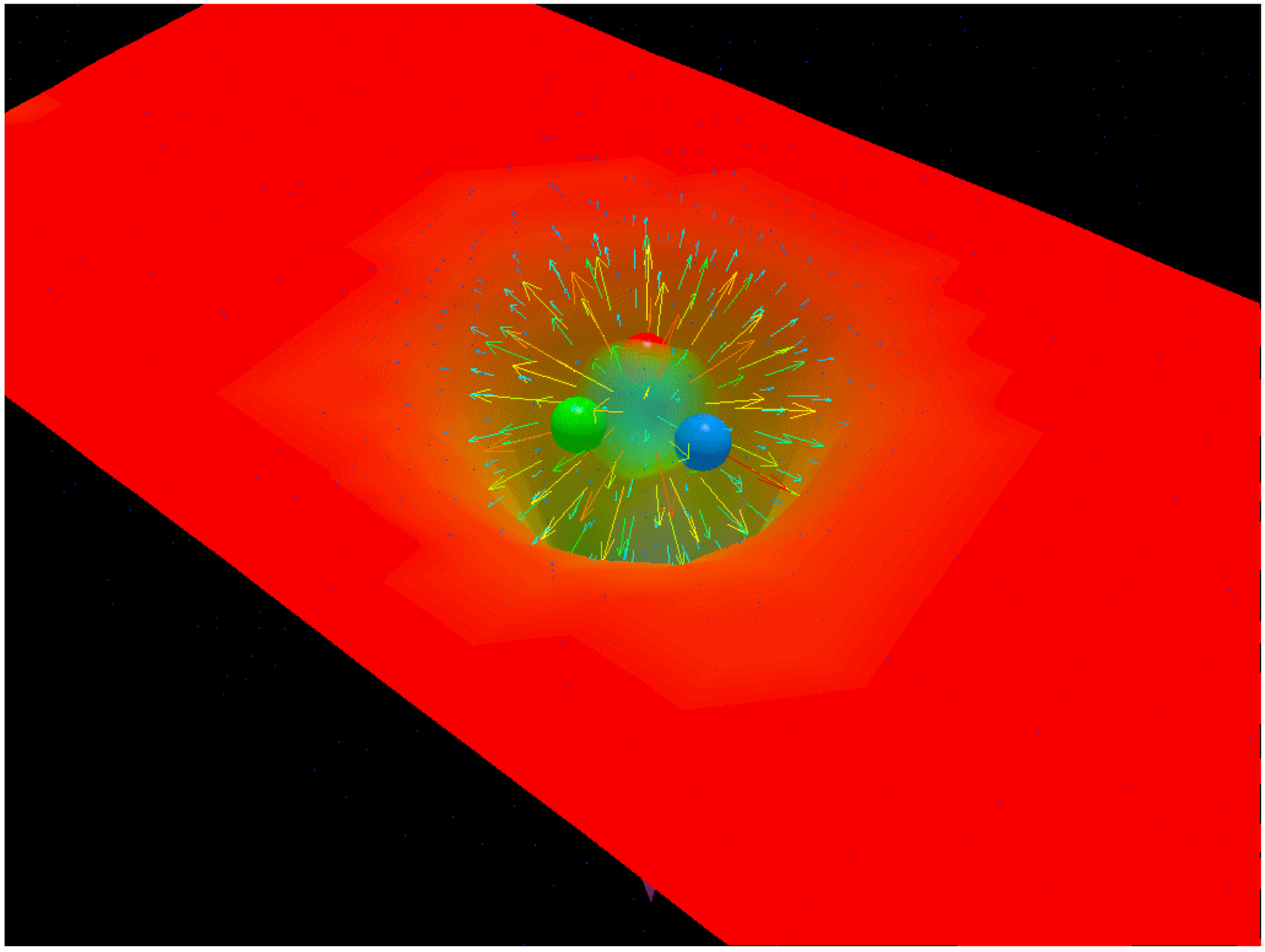


A Sausage-shaped Flux Tube

Meson

Baryon

Alles hat ein Ende,
doch diese Wurst hat drei!

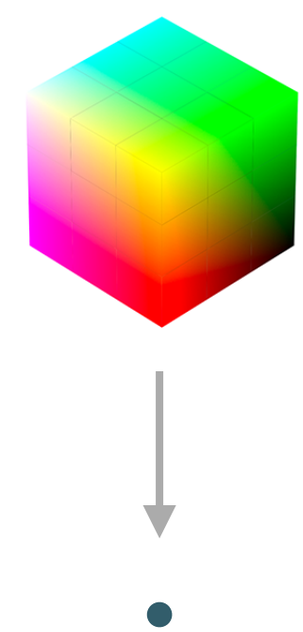
- In QCD, quantum fluctuations produce a new, dynamical energy scale Λ.
- Everything stems from Λ and SU(3) symmetry:
  - QCD coupling $\alpha_s(r) \sim 1$ at distance $r \sim \Lambda^{-1}$;
  - sausage thickness $\propto \Lambda^{-1}$;
  - nucleon mass $\propto \Lambda$.
- An amazing phenomena: does Nature use it anywhere else?

How Do We “Compute”? Lattice QCD

QCD on a Supercomputer

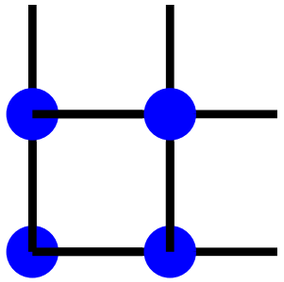
- QCD interactions accumulate in a nonlinear way:
  - solve the basic equations on supercomputers.

- But each field has an uncountable infinity of information:
  - makes it “hard to count”.



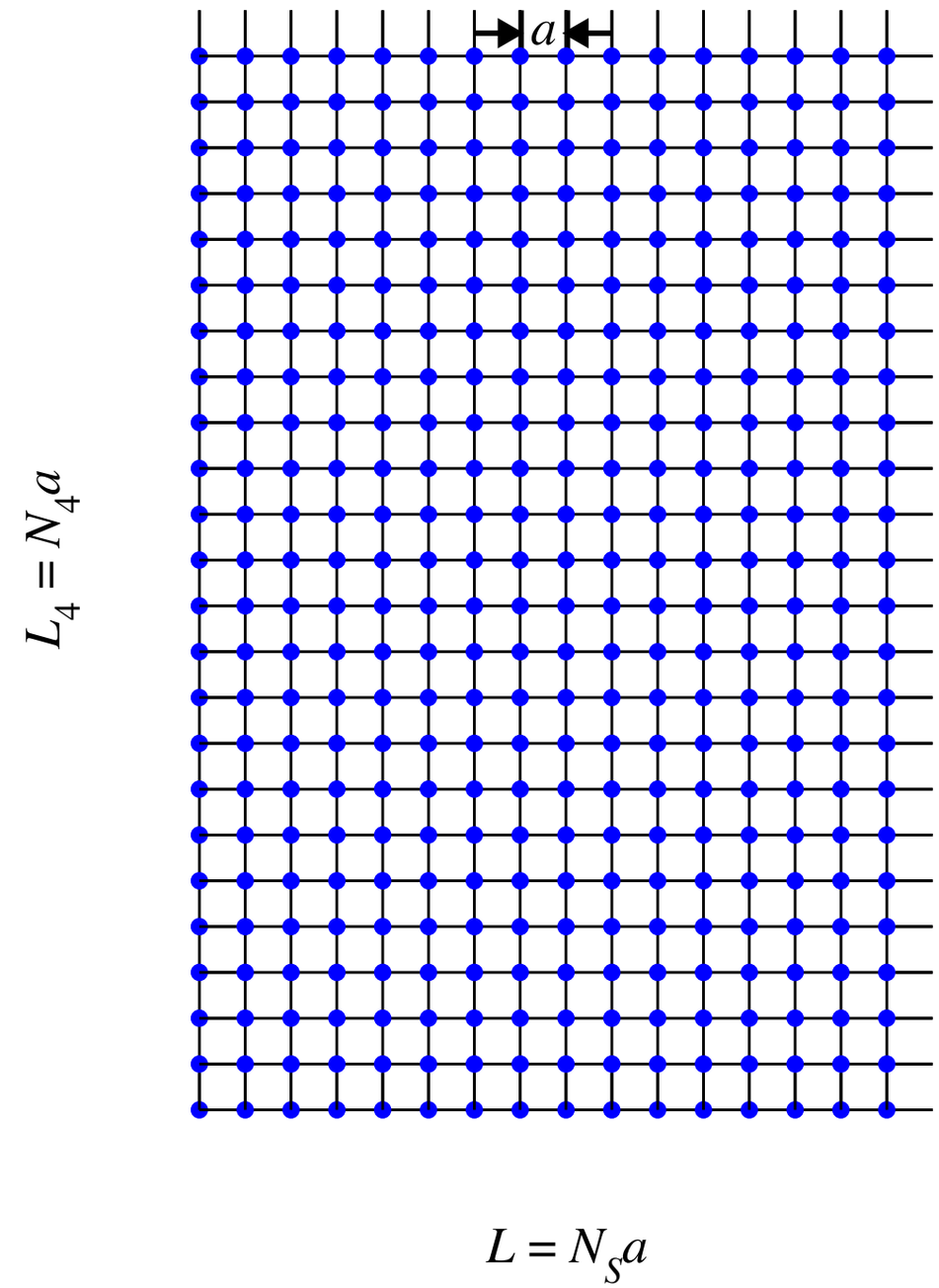
- Make the infinity “countable” by associating the whole field inside a block of spacetime with a single field variable.

Lattice Gauge Theory



quarks on sites
gluons on links

- Lattice:
  - arrange blocks on a regular grid, a much smaller than Λ^{-1};
  - preserve SU(3) symmetry.
- Finite spatial volume:
  - smaller than the universe;
  - L much larger than Λ^{-1}.



Program the computer to explore all paths,
with the right weight for quantum mechanics.

☛ High-capability computer,
e.g., IBM Blue-Gene Q

High-capacity cluster
at Fermilab ☛

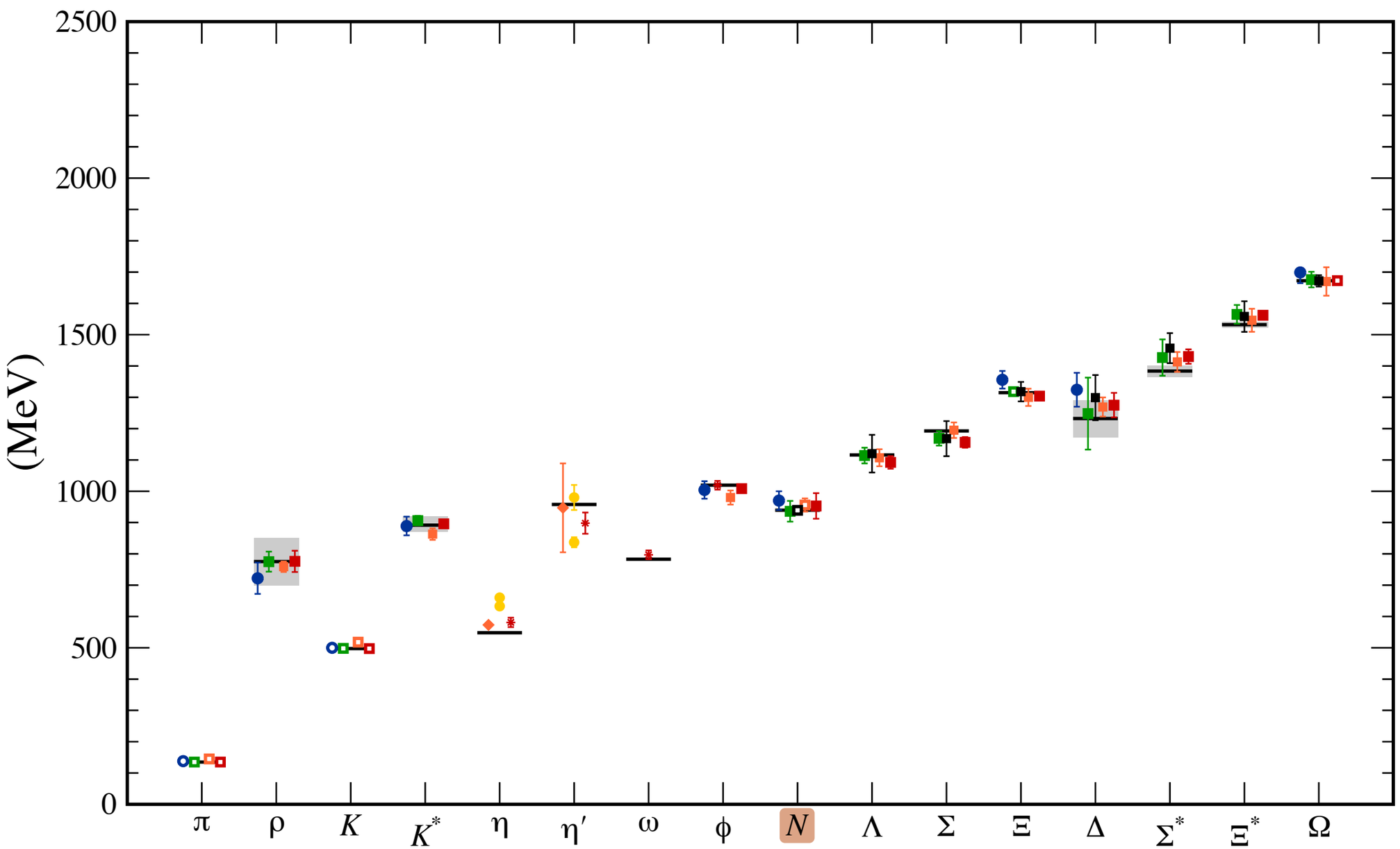
- Qualitative or semi-quantitative information shown so far.

- We physicists insist on being quantitative.

- Can we calculate a wide variety of hadron masses, and find agreement with lab measurements?

π…Ω: BMW, MILC, PACS-CS, QCDSF; ETM (2+1+1);
η-η′: RBC, UKQCD, Hadron Spectrum (ω).

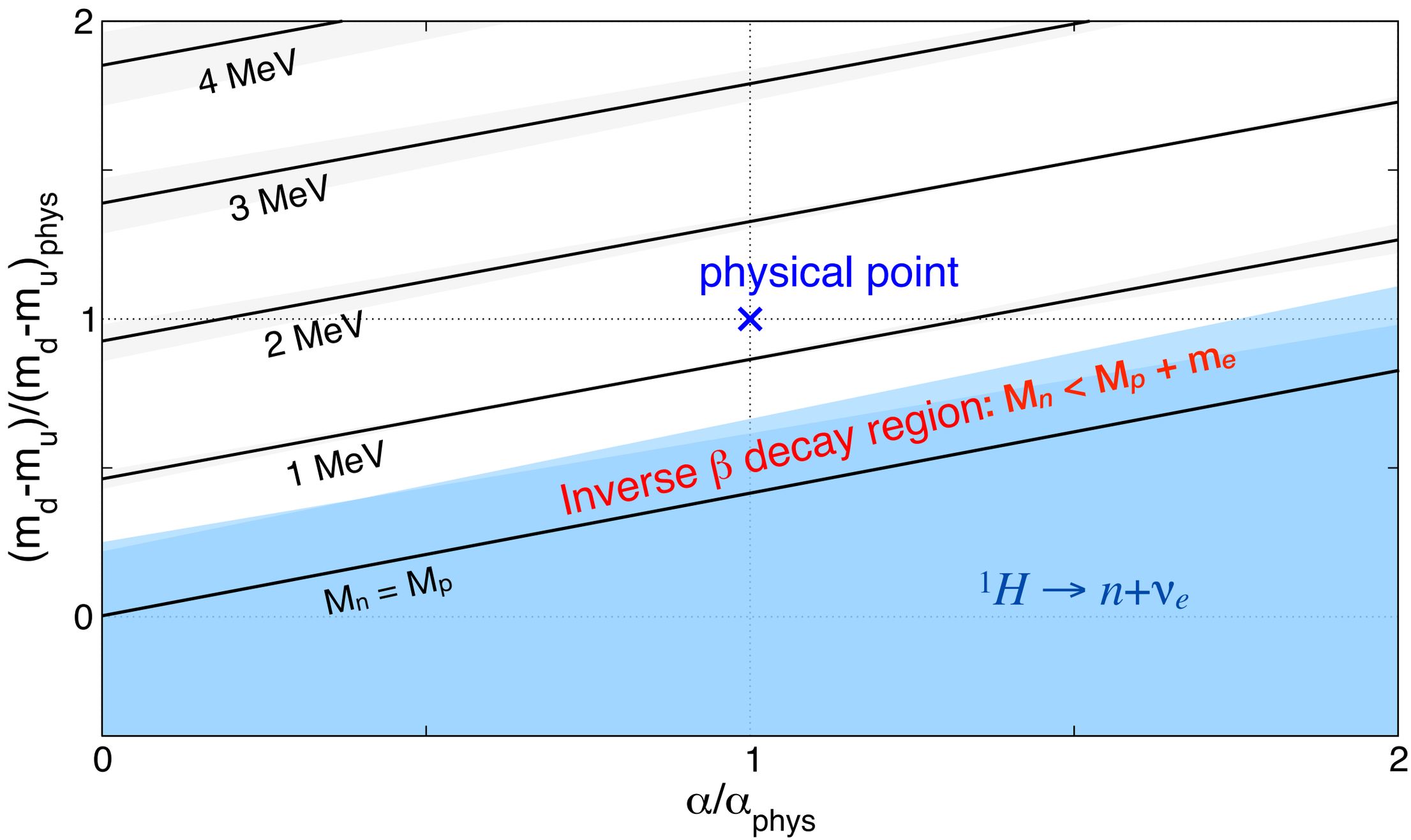
QCD Hadron Spectrum



Simulating Alternative Universes

- With the supercomputer, we can change the inputs and ask
  - what happens if the electron mass changes?
  - what happens if the up and down quark masses change?
  - what happens if the strength of electromagnetism changes?
- Our universe: $m_e \approx 0.5$ MeV
  $m_u \approx 2.3$ MeV $\quad M_n - M_p = 1.3$ MeV
  $m_d \approx 4.7$ MeV

Neutron-Proton Mass Difference



In the blue region, biochemistry (as we know it)

is impossible.

Summary & Outlook

The Origin of Everyday Mass

- QCD has a reductionist origin: peering into nuclei and hadrons one found quarks and gluons.

- Yet QCD is fascinating for its emergent phenomena:

  - out of the gluon-gluon interaction there emerges a powerful force;

  - a new energy scale, Λ, generated by quantum fluctuations;

  - this energy is the origin of (almost all) everyday mass.

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  - this energy is the origin of (almost all) everyday mass.

$$M_N = E_\Lambda / c^2$$

Industrial Lattice QCD

- Practitioners are engaged in this research to address the frontier:
  - What are the properties of hadrons with more exotic quarks?
  - Do lab measurements of these particles deviate from the expectations of the Standard Model?
  - Do they provide, for example, new interactions that break the matter-antimatter symmetry?
  - How did the early universe behave when it was so hot the hadrons "melted" into a quark-gluon plasma—the Primordial Soup?
- and many, many more questions!

Acknowledgments

- KITP for hosting “Lattice Gauge Theory for the LHC and Beyond”
- Animations © 2003, 2004, Derek Leinweber, CSSM, University of Adelaide, Australia
- You (and your mass) for your attention.

Backup

July 4, 2012

The New York Times

SCIENCE

Physicists Find Elusive Particle Seen as Key to Universe

EL PAÍS

¡La partícula de Higgs por fin!

theguardian

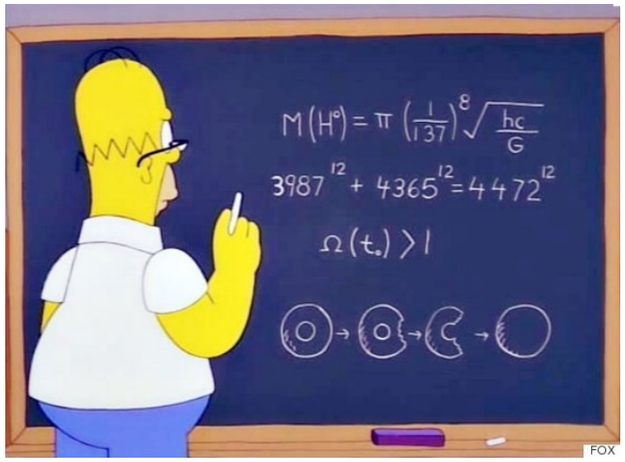
Higgs boson

Higgs boson discovery: now the real work begins

Süddeutsche Zeitung

4. Juli 2012, 11:22 Uhr Cern

Physikern gelingt Durchbruch bei Suche nach Higgs-Boson



A Higgs boson walks into a church.
The priest says, “We don’t allow Higgs bosons in here!”
The Higgs boson says, “Without me, how can you have mass?”

—Brian Malow, the science comedian

Mass and Higgs

- Quarks, leptons, and *W* & *Z* bosons drag through the Higgs field.

- Higgs bosons are **cool**, because they are the **snowflakes**.

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small drag ⇒ small mass: e, u, d, s, μ

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Mass and Higgs

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small drag ⇒ small mass: e, u, d, s, μ

medium drag ⇒ medium mass: c, τ, b

what a drag ⇒ large mass: W, Z, t, H

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Elementary Particle Music

- Quark, Strangeness, and Charm—Hawkwind
- Higgs Boson Blues—Nick Cave and the Bad Seeds
- Tomorrow—Bob Seger and the Silver Bullet Band

QCD and Cosmology

- Baryogenesis—at the end of inflation, $t \sim 10^{-32}$ s (?), the matter-antimatter asymmetry should arise. (A primordial asymmetry would be washed out by electroweak sphalerons at $\sim 10^{-36}$ s.)

- After inflation, $t \sim 10^{-32}$ s (?), the elementary particles "as we know them" exist, but the temperature is easily high enough for QGP.

- Hadrons form at $t \sim 10^{-6}$ s and the QGP is gone at $t \sim 1$ s. For the next 9 s the remaining antibaryons annihilate with baryons.

- For $t \sim 3$–$20'$, nucleons fuse into deuterons, tritons, He^3, He^4, and Li^7.

- After 377,000 years, atoms form.