Asymptotic Freedom:

From Paradox to Paradigm

Paradox 1:

Quarks are Born Free,
But Everywhere They
are in Chains

The quark model “works” ...

... but its rules are very strange.

Quarks behave independently when they're close, but they can't be pulled apart. An unprecedented hypothesis: CONFINEMENT!

Hard-hit quarks accelerate rapidly, without radiating away energy. The strongest force of nature "turns off": FREEDOM!

Paradox 2:

Quantum Mechanics and Special Relativity Both Work

Special relativity puts space and time on the same footing, but quantum mechanics treats them very differently. This leads to a creative tension ...

Dirac: from uncertainty to antiparticles

Feynman-Schwinger-Tomonoga: the reality of virtual particles (QED)

'tHooft-Veltman: the vast scope of virtual particles (electroweak gauge theory)

Landau's Paradox

Screening by virtual particles wipes out interactions

The demise of quantum field theory was widely proclaimed - and welcomed!

Paradox Lost:

Asymptotic Freedom

Some very special quantum field theories have **anti**-screening (asymptotic freedom).

One of these theories is uniquely well suited to accommodating quarks. It **predicts** gluons. This is quantum chromodynamics (QCD).

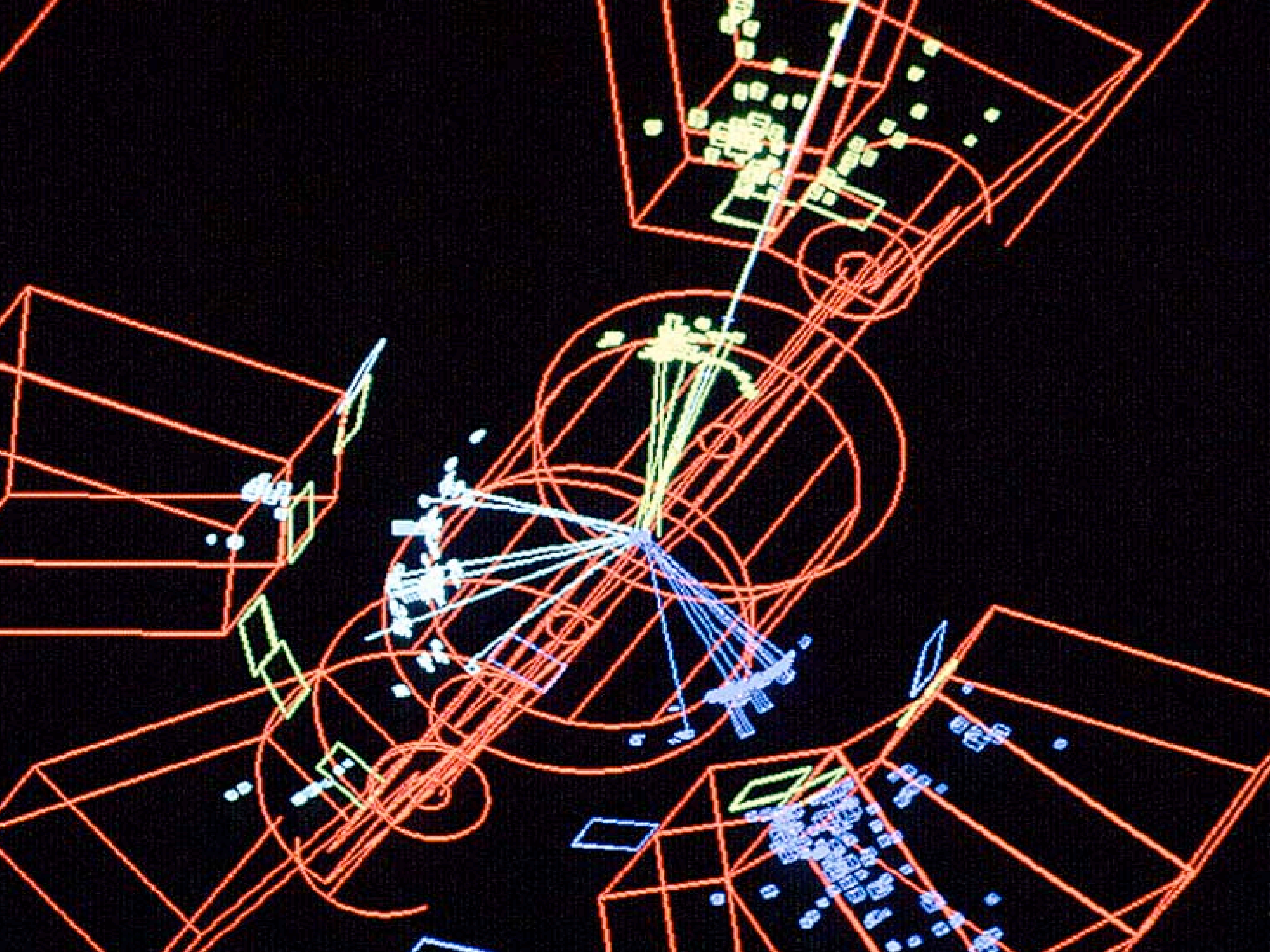
Antiscreening explains how the same basic interaction can appear either powerful or feeble, depending on circumstances.

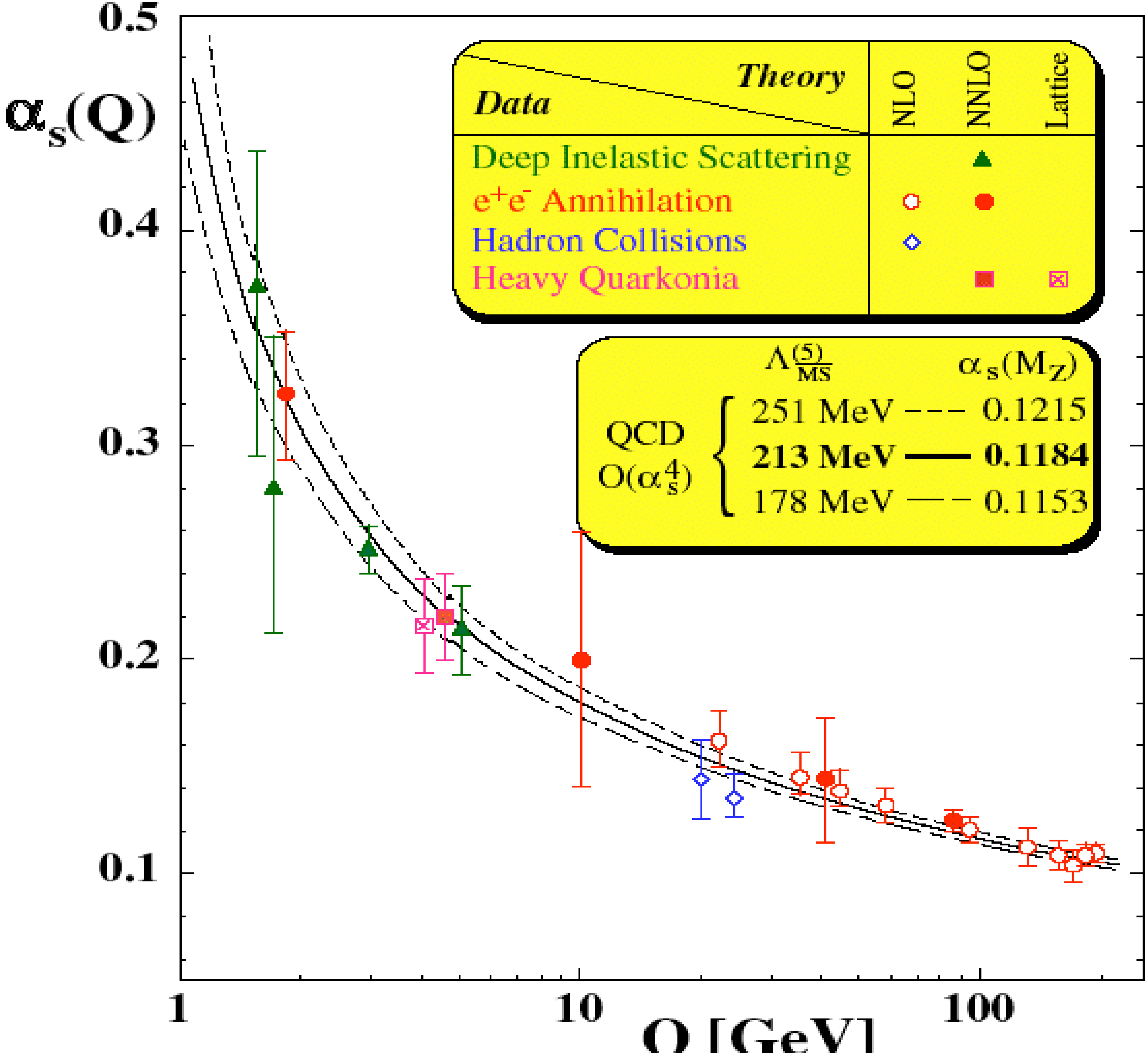
The interaction is feeble at small separations, powerful at large separations. (Confinement!)

The interaction does not interfere with violent deflections. (Freedom!) Nor does it induce them.

Paradigm 1:

The Hard Reality of Quarks and Gluons





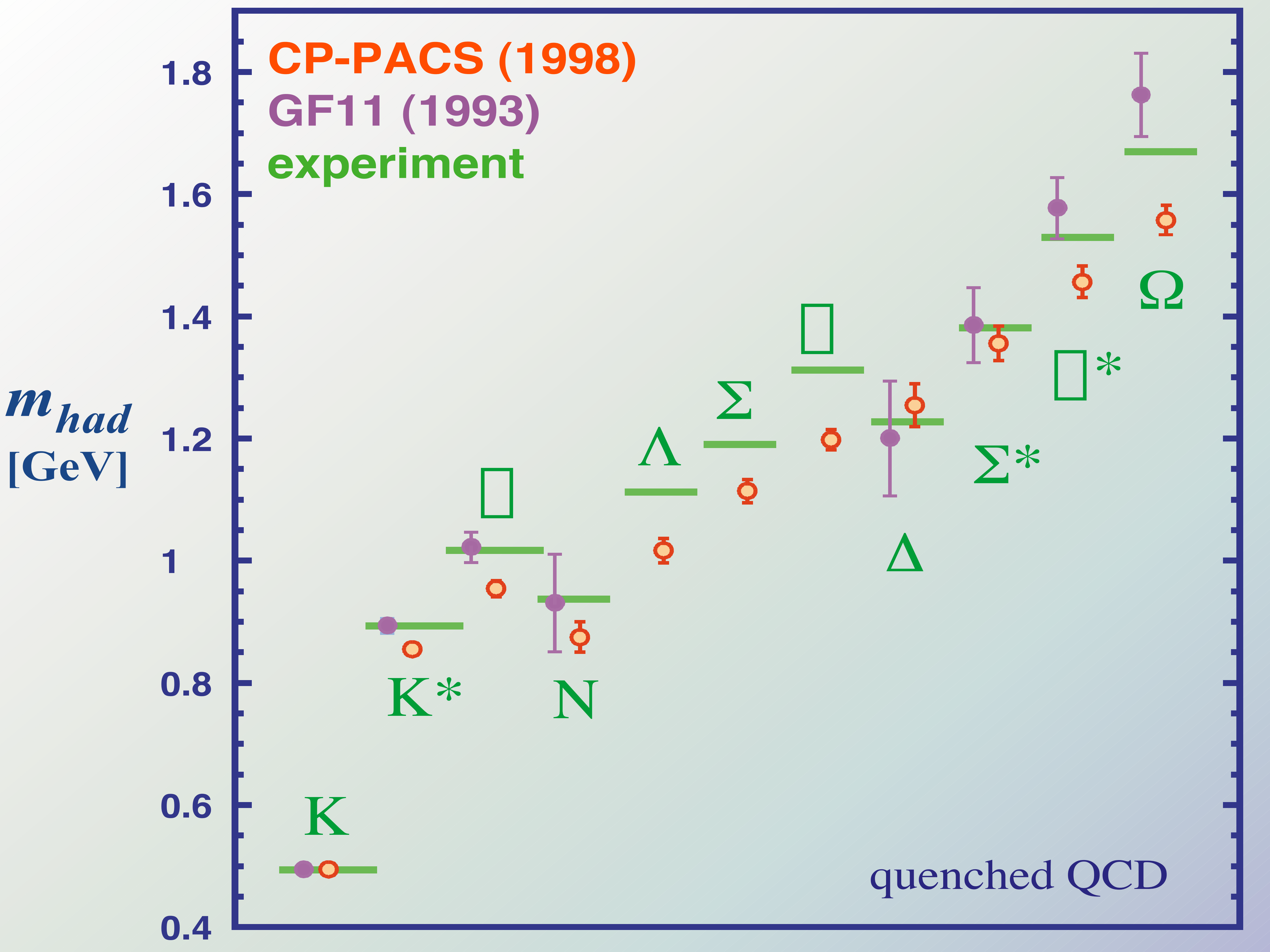
0.5
0.4
0.3
0.2
0.1
$\alpha_s(Q)$
Theory
Data
NLO
NNLO
Latice
Deep Inelastic Scattering
e^+e^- Annihilation
Hadron Collisions
Heavy Quarkonia
$\Lambda^{(5)}_{\overline{MS}}$
$\alpha_s(M_Z)$
QCD
$O(\alpha_s^4)$
251 MeV 0.1215
213 MeV 0.1184
178 MeV 0.1153
1
10
100
Q [GeV]

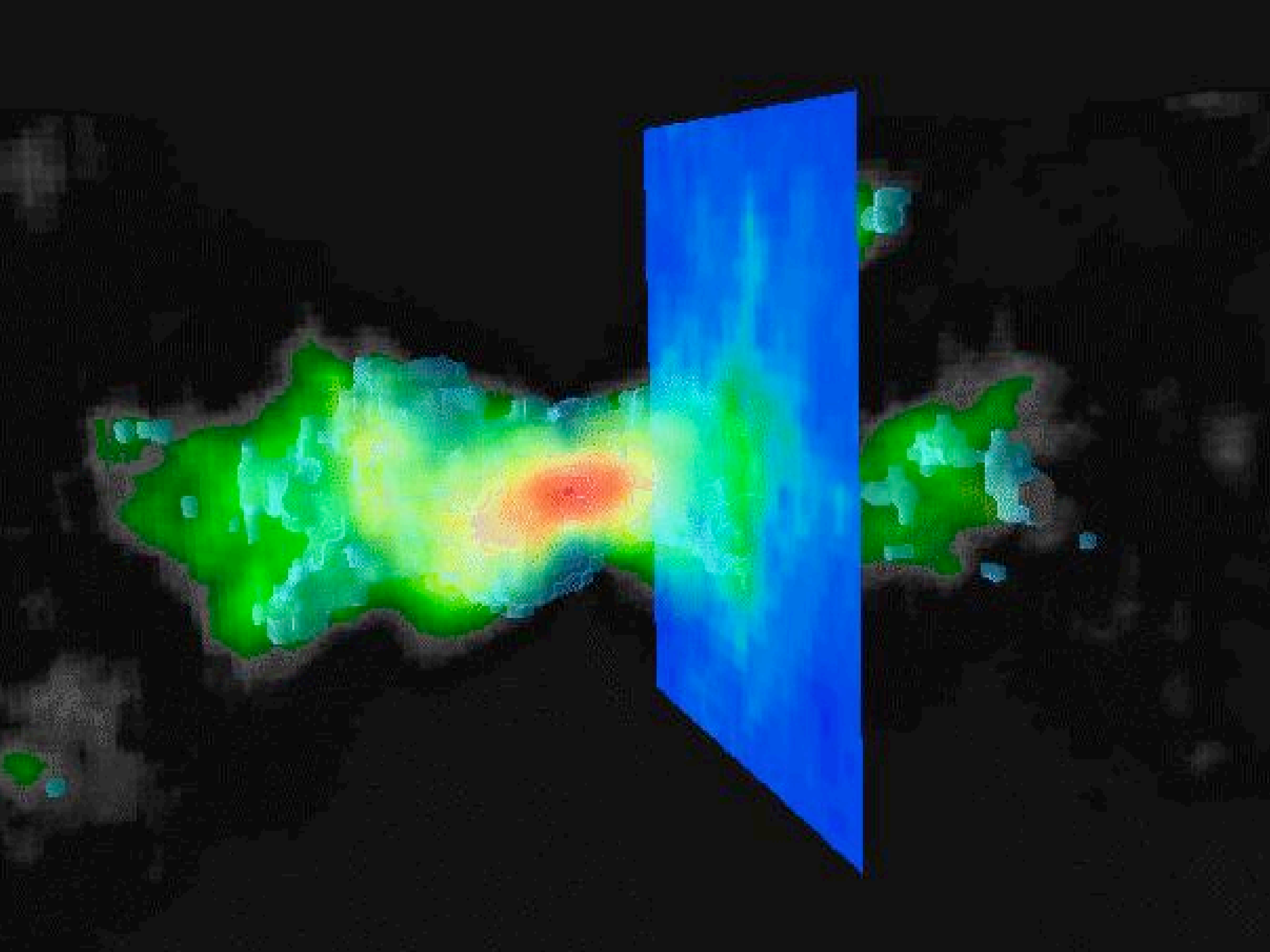
Paradigm 2:

Mass Comes From Energy

Einstein's Second Law:

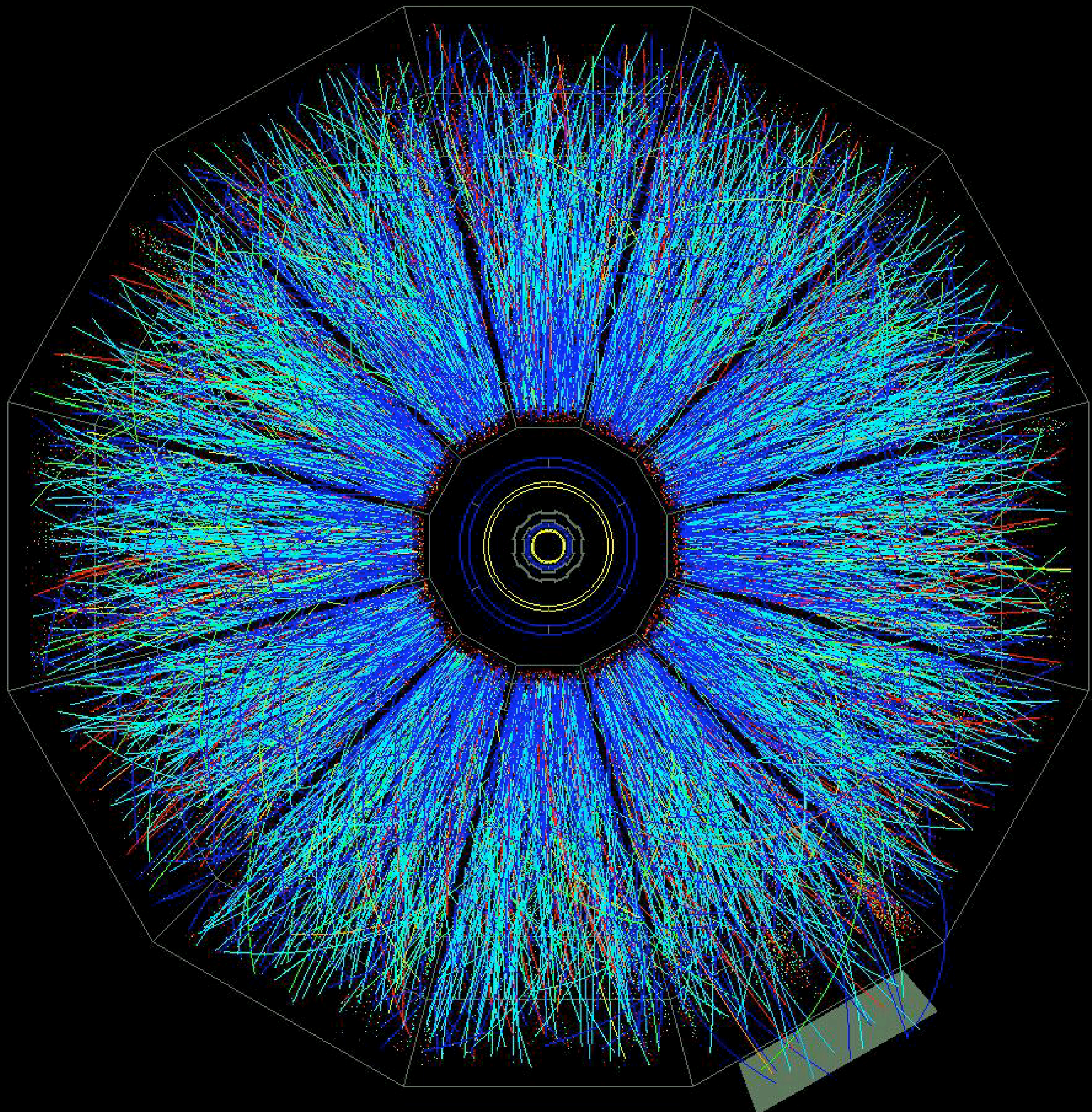
$$m=E/c^2$$


CP-PACS (1998)
GF11 (1993)
experiment
m had
[GeV]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
K
K*
N
Λ
Σ
Δ
Σ*
Ω
quenched QCD



Paradigm 3:

The Early Universe Is Simple



STAR

Paradigm 4:

Symmetry Rules

$$\begin{pmatrix} u & u & u \\ d & d & d \end{pmatrix}^{L}_{1/6}$$

$$\begin{pmatrix} \nu \\ e \end{pmatrix}^{L}_{-1/2}$$

$$\left(u \quad u \quad u \right)^{R}_{2/3}$$

$$\left(d \quad d \quad d \right)^{R}_{-1/3}$$

$$\left(e \right)^{R}_{-1}$$

$$SU(3) \times SU(2) \times U(1)$$

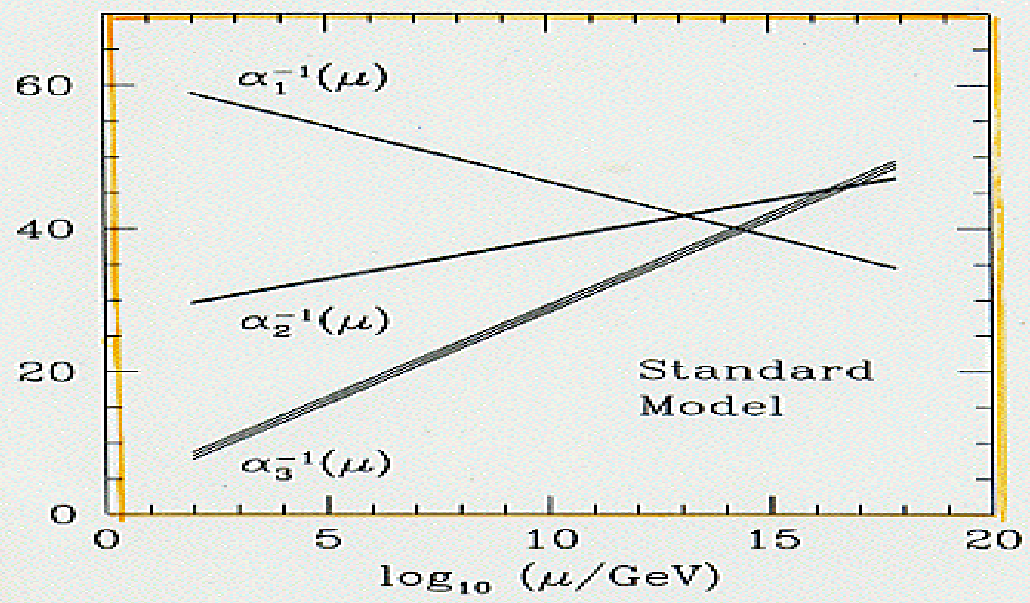
mixed, not unified

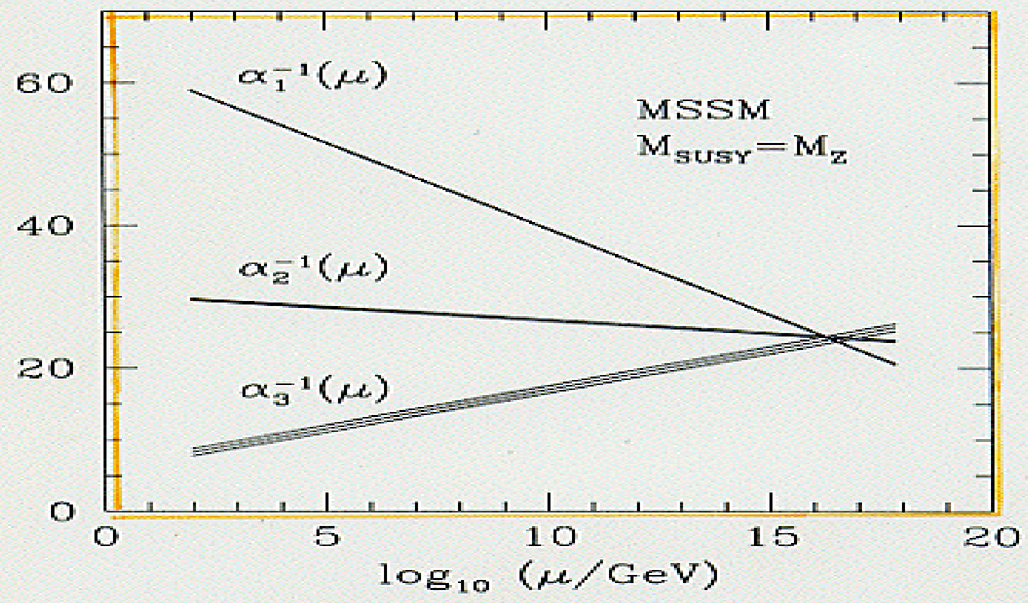
No ν^R

	B	R	G	P	O
u	+	−	−	+	−
u	−	+	−	+	−
u	−	−	+	+	−
d	+	−	−	−	+
d	−	+	−	−	+
d	−	−	+	−	+
ν	+	+	+	−	+
e	+	+	+	+	−
u^c	−	+	+	−	−
u^c	+	−	+	−	−
u^c	+	+	−	−	−
d^c	−	+	+	+	+
d^c	+	−	+	+	+
d^c	+	+	−	+	+
e^c	−	−	−	+	+
ν^c	−	−	−	−	−

$$Y = \frac{1}{4}(P+O) - \frac{1}{6}(B+R+G)$$

Unification of gauge couplings...





Gravity fits too! (roughly)

Frontiers of Symmetry

Unification → Proton Decay, Supersymmetry

Supersymmetry → World x2, Dark Matter

QCD T-protection → Axions, Dark Matter

Gauge Symmetry Breaking → Higgs sector

The Greatest Lesson

If we work to understand,
then we can understand.

Credits

hadron tables: Particle Data Group

jet event: L3 collaboration

running coupling plot: S. Bethke

pion fields: G. Kilcup

QCD “lava lamp”: D. Leinweber

little bang: STAR collaboration

technical assistance: C. Suggs