

# The Discovery of Asymptotic Freedom & The Emergence of QCD

David Gross

*Nobel Lecture*  
*December 8, 2004*

# The Weak and the Strong

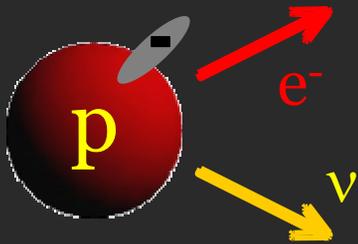
The forces operating in the nucleus are of two kinds:

## WEAK INTERACTIONS

Responsible for radioactivity

## STRONG INTERACTIONS

Responsible for holding the nucleus together



Fermi theory

Meson theory

# QUANTUM FIELD THEORY

# The Strong Interactions Were Especially Intractable

- Which particles are elementary:  
 $p, n, \pi, \dots, K, \Sigma, \Lambda, \rho, \dots$
- What are the Dynamics?
- How to calculate?

DYSON: *“The correct theory will not be found in the next hundred years.”* (1960)

# A Revolution Was Needed

# The Attack on Field Theory

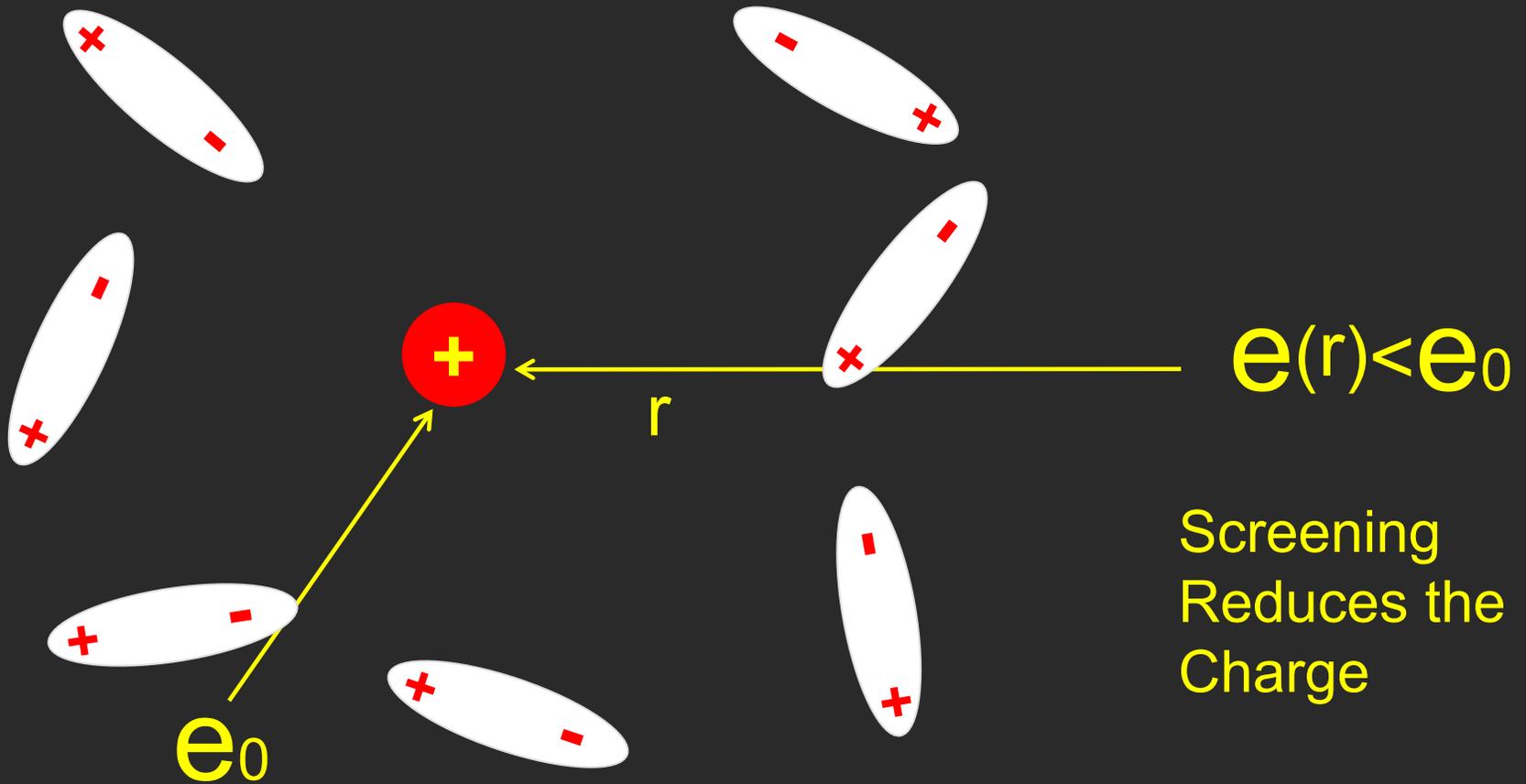
## NUCLEAR DEMOCRACY

All hadrons are equally fundamental

## BOOTSTRAP THEORY

General principles determine a unique S-Matrix

# Screening in Q.E.D.



$$\beta(e) \equiv -\frac{d \ln e(r)}{d \ln(r)} > 0$$

**FORCE IS STRONGER  
AT SHORT DISTANCES**

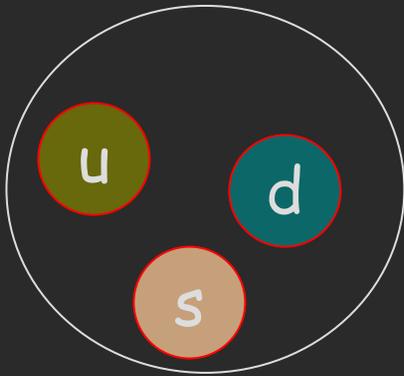
We reach the conclusion that within the limits of formal electrodynamics a point interaction is equivalent, for any intensity whatever, to no interaction at all. *We are driven to the conclusion that the Hamiltonian method for strong interaction is dead* and must be buried, although of course with deserved honor.

*Landau (1960)*

# Patterns & Symmetries

Hadrons looked as if they were made of QUARKS

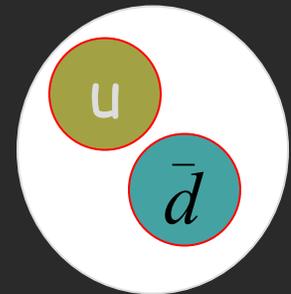
Gell-Mann  
& Zweig '64



baryons

3 DIFFERENT  
FLAVORS:

up, down & strange



mesons

And each quark came in 3 identical colors:

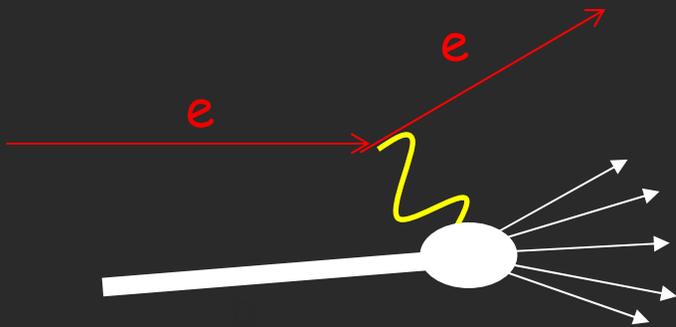


**BUT QUARKS COULD NOT BE SEEN  
THEREFORE THEY WERE UNREAL  
MATHEMATICAL ENTITIES**

Han-Nambu &  
Greenberg '64

# Berkeley: S-Matrix Theory

I derived (with Callan) some relations-sum rules abstracted From the quark-gluon model.



# Harvard: Algebra of Currents

These could be tested in deep-inelastic lepton-hadron scattering experiments (SLAC 1968)

$$\text{Spin} = \frac{1}{2} \Rightarrow$$

$$R = \frac{\sigma_L}{\sigma_T} \rightarrow 0$$

1. Hadrons were made of point like constituents.
2. The charged constituents were quarks. Quarks are real.

# The Plan:

1. Scaling  $\rightarrow$  Asymptotic Freedom

C. Callan & D.G., 1973

2. There are no Asymptotically Free Field Theories

S. Coleman & D.G., 1973

The one exception:  
Non-Abelian Gauge Theories.

With F. Wilczek we determined to close the last hole in the argument (Non-Abelian gauge theories)

We Found

$$\beta(g) = -\frac{g^3}{16\pi^2} \left( \frac{11}{3} N_C - \frac{4}{3} \frac{N_F}{2} \right)$$

Number of colors, quarks

March  
1973

Instead of: *No field theory can explain scaling*

There exists a unique field theory that explains scaling

**ASYMPTOTICALLY FREE GAUGE THEORY !**

## Ultraviolet Behavior of Non-Abelian Gauge Theories\*

David J. Gross† and Frank Wilczek

*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540*

(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.<sup>1</sup> In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

The UV behavior of renormalizable field theories can be discussed using the renormalization-group equations,<sup>2,3</sup> which for a theory involving one field (say  $g\phi^4$ ) are

$$[m\partial/\partial m + \beta(g)\partial/\partial g - n\gamma(g)]\Gamma_{\text{asy}}^{(n)}(\mathbf{g}; P_1, \dots, P_n) = 0. \quad (1)$$

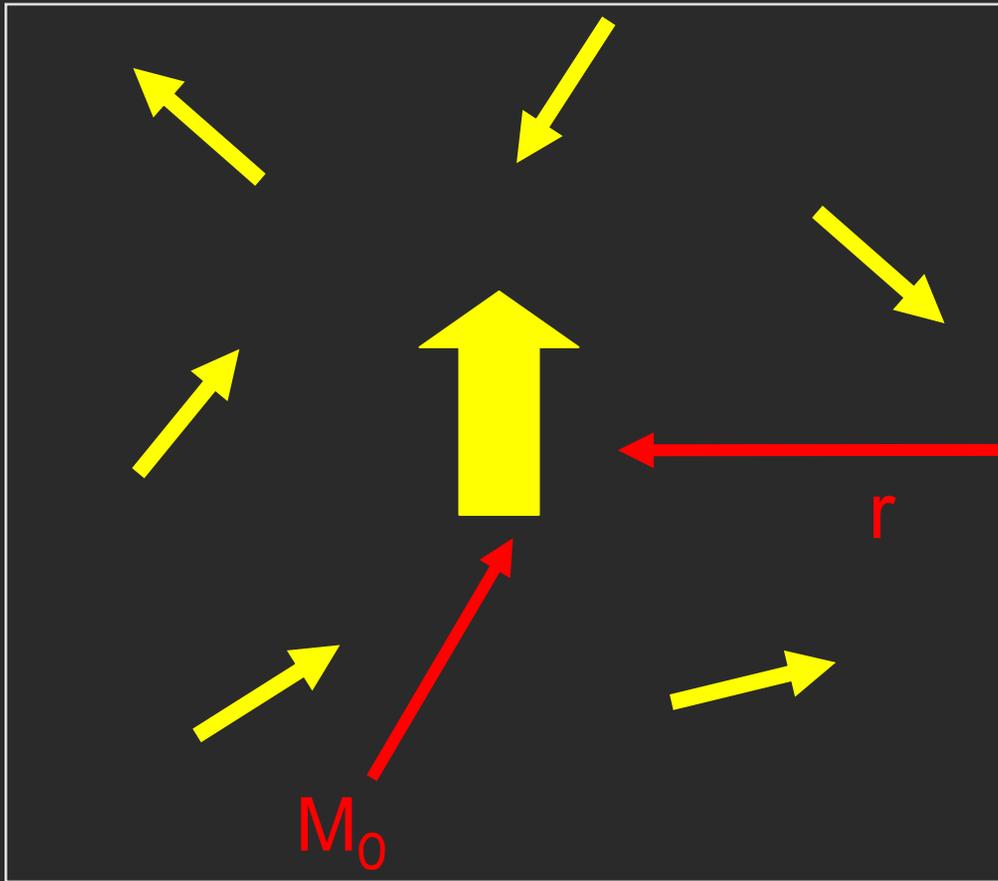
$\Gamma_{\text{asy}}^{(n)}$  is the asymptotic part of the one-particle-irreducible renormalized  $n$ -particle Green's function,  $\beta(g)$  and  $\gamma(g)$  are finite functions of the renormalized coupling constant  $g$ , and  $m$  is either the renor-

We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such *asymptotically free* theories will exhibit Bjorken scaling.

We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field theoretic understanding.

D. J. Gross and F. Wilczek, *Phys. Rev.Lett.* 30, 1343 (1973)

# The Anti-screening of QCD



$M(r)$   
Anti-Screening  
Increases the  
Charge.

$$\beta(e) \equiv -\frac{d \ln e(r)}{d \ln(r)} < 0$$

**FORCE IS WEAKER  
AT SHORT DISTANCES**

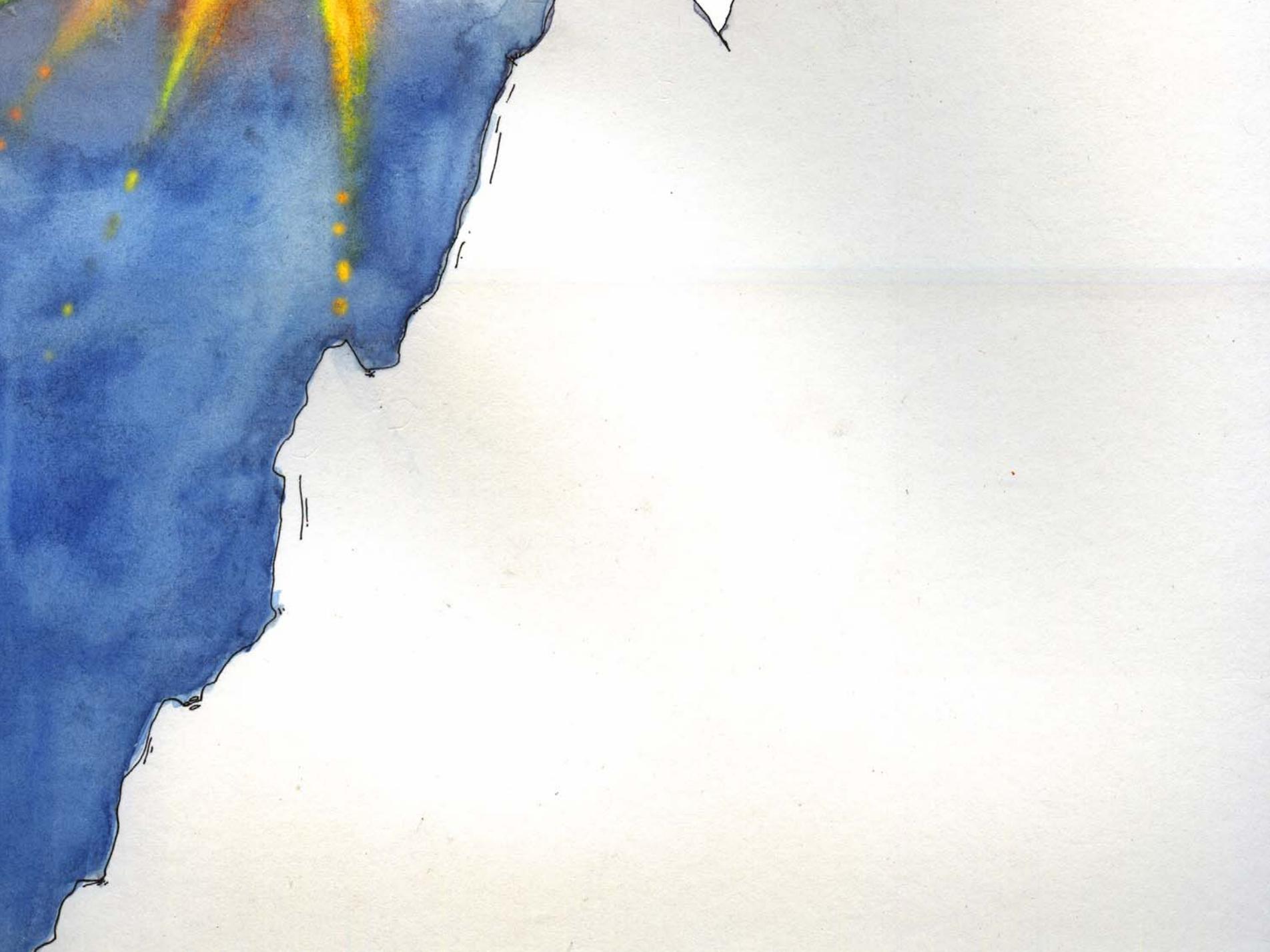
Dynamics ---- Non-Abelian Gauge Theory --- Gluons

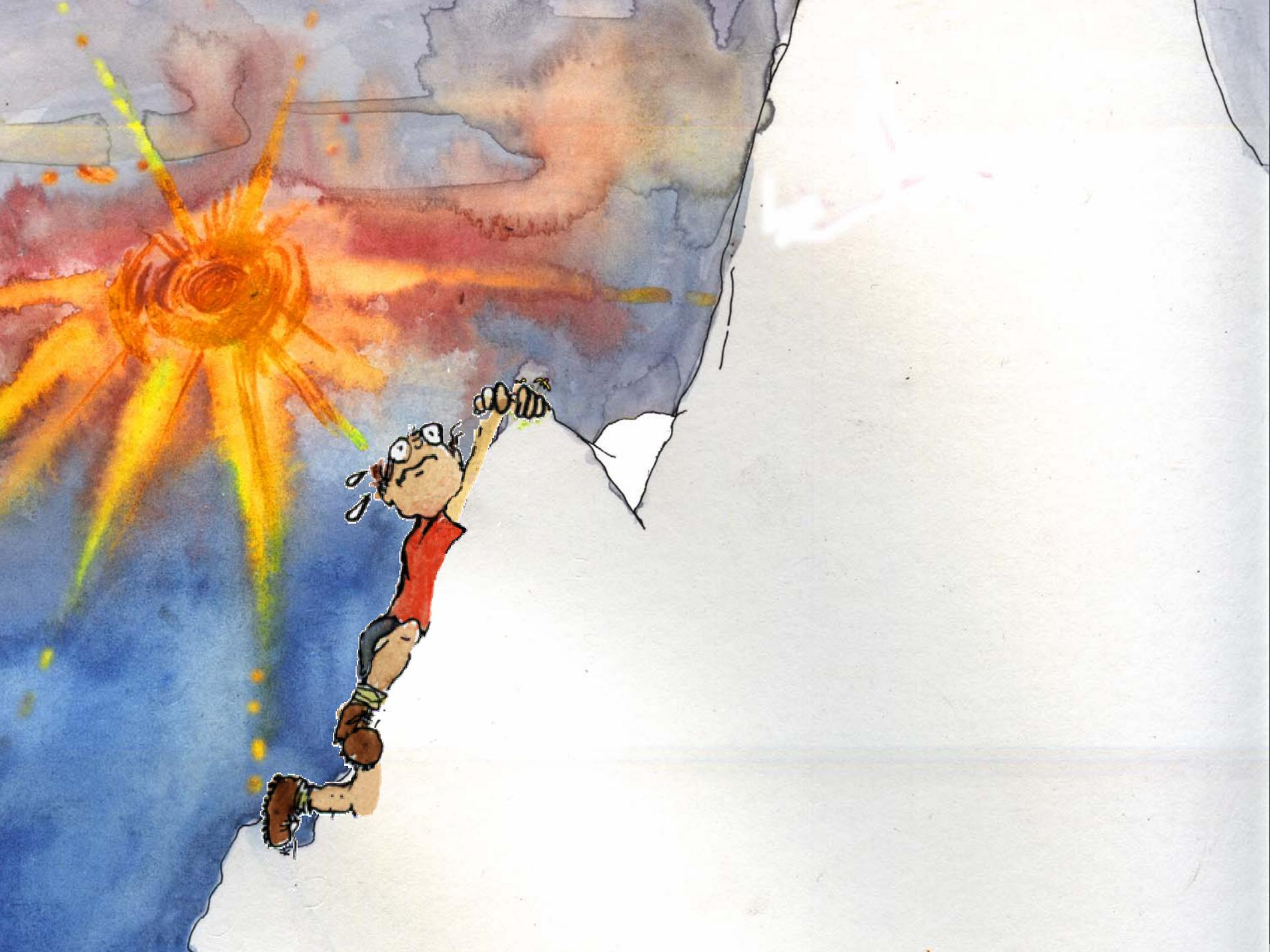
Charged Matter --- Exp --- Quarks & 3 Colors

One particularly appealing model is based on three triplets of fermions, with a  $SU_3$  color gauge group to provide the strong interactions.

# QCD



















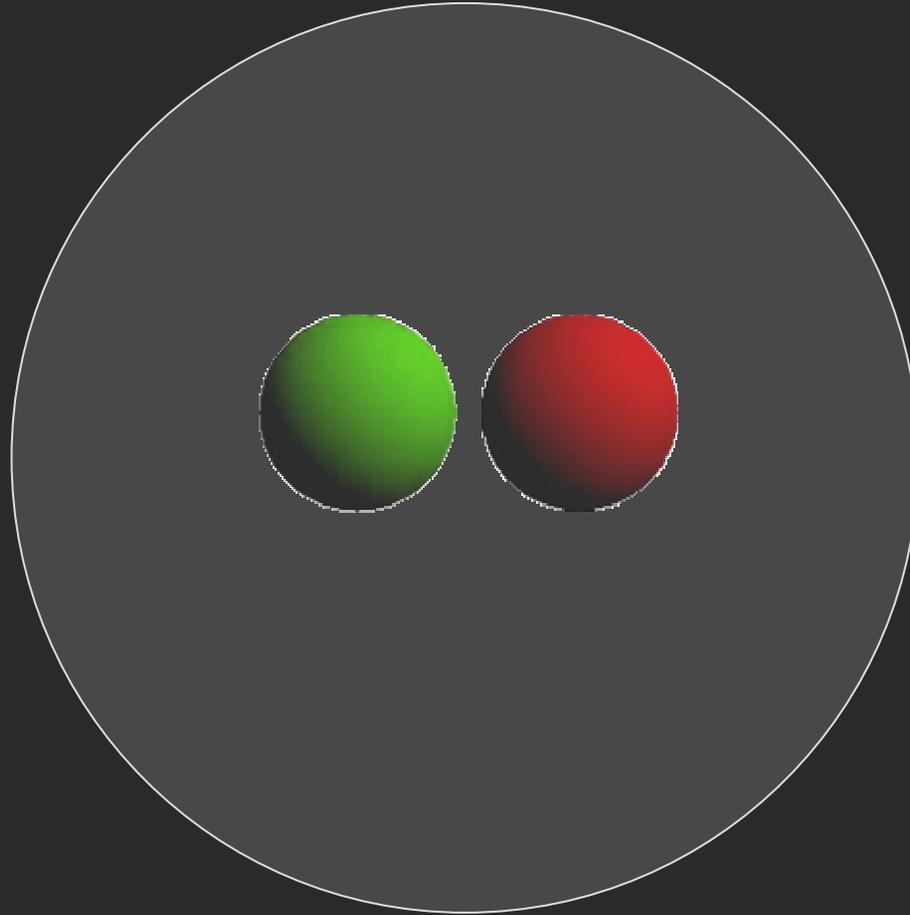
“At first, sight this would appear to be ridiculous since it would imply the existence of massless, strongly coupled vector mesons. However, in asymptotically free theories these naïve expectations might be wrong. There may be little connection between the ‘free’ Lagrangian and the spectrum of states. The infrared behavior of Greens functions in this case is determined by the strong-coupling limit of the theory.

*It may be very well that this infrared behavior is such so as to suppress all but color singlet states, and that the colored gauge fields as well as the quarks could be ‘seen’ in the large-Euclidean momentum region but never produced as real asymptotic states.”*

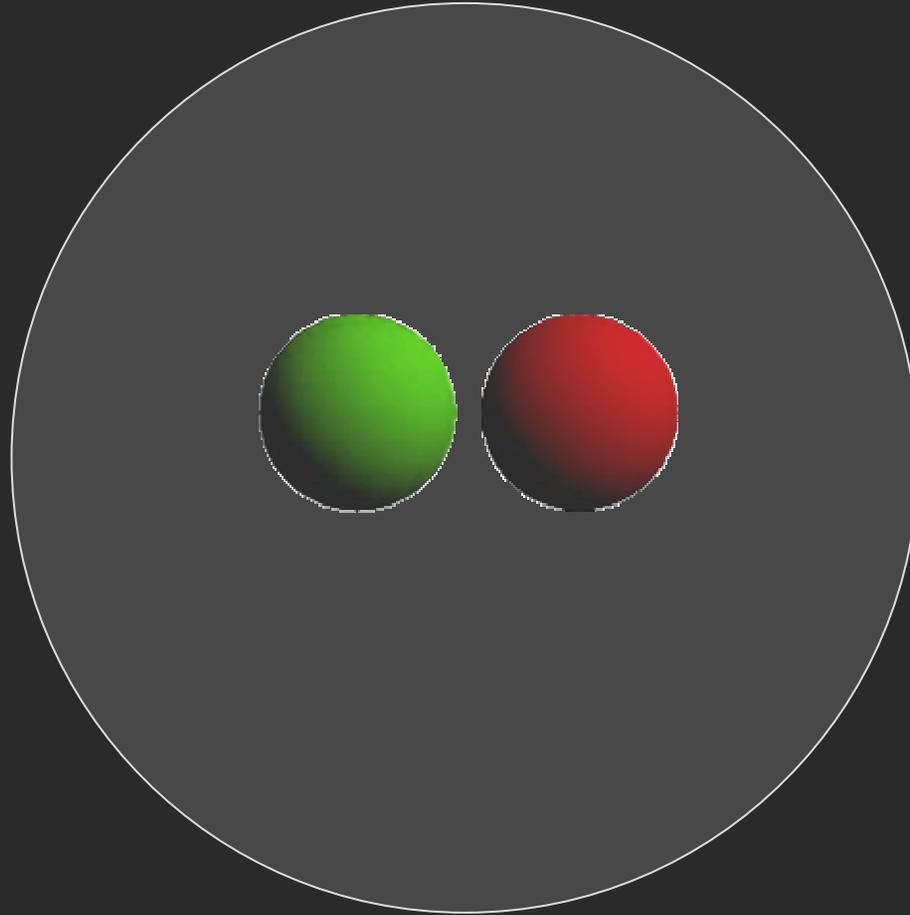
**INFRARED SLAVERY → CONFINEMENT**

*Phys. Rev. D8 30, 3633 (2973)*

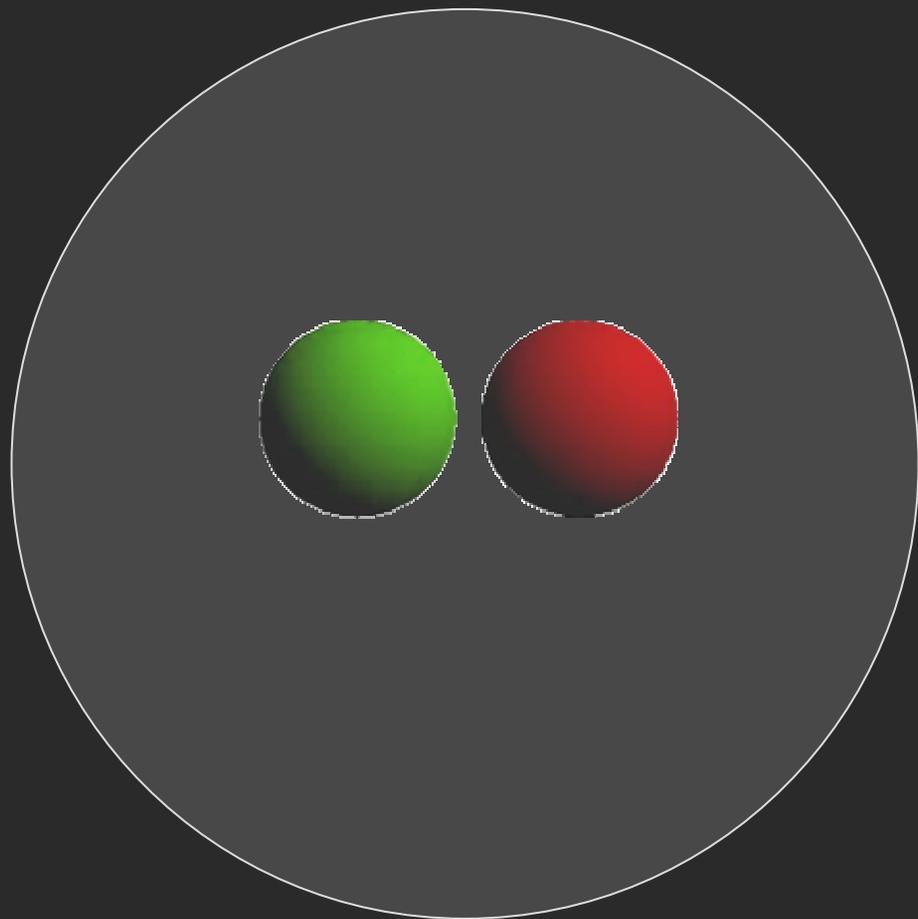
# Asymptotic Freedom



# Asymptotic Freedom



At short distances, quarks behave freely...





At large distances the quarks are confined.

# Experimental Confirmation

In QCD:

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow e^+e^-)} \rightarrow \sum_{\text{QUARKS}} Q_i^2$$

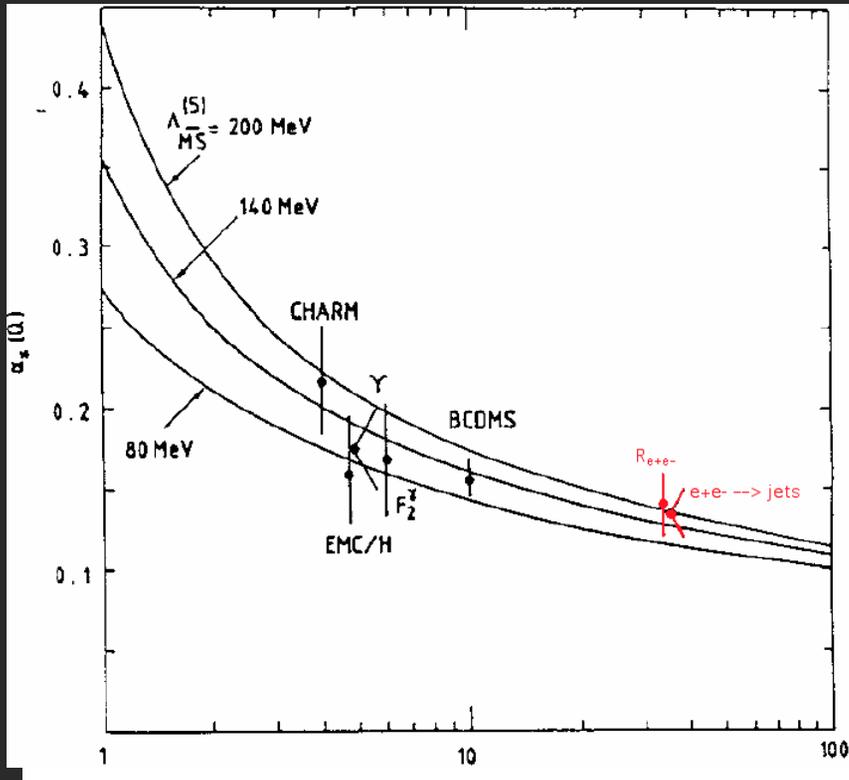
Measures the  
Number and  
charges  
of quarks

4 quarks  $\Rightarrow$   
3 quarks  $\Rightarrow$

TIFF (Uncorrupted  
are needed t

# World summary of $\alpha_s$

1989



$$\alpha_s(M_z) = 0.110^{+0.006}_{-0.008} \text{ (NLO)}$$

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989

2004

Zur Anzeige wird der QuickTime™  
Dekompressor „TIFF (LZW)“  
benötigt. (LZW)  
benötigt.

$$\alpha_s(M_z) = 0.1182 \pm 0.0027 \text{ (NNLO)}$$

S. Bethke, hep-ex/0407021

# World summary of $\alpha_s$

Zur Anzeige wird der QuickTime™  
-Dekompressor „TIFF (LZW)“  
benötigt.

# World summary of $\alpha_s(M_Z)$

Can all the strong interactions be described by QCD with one single coupling  $\alpha_s$ ?

**YES!**

$$\alpha_s(M_Z) = 0.1182 \pm 0.0027$$

Zur Anzeige wird der QuickTime™  
Dekompressor „TIFF (LZW)“  
benötigt.

# Implications of Asymptotic Freedom



QCD

QuickTime™ and a  
TIFF (Uncompressed) decompressor  
are needed to see this picture.

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# Consistency of Quantum Field Theory

NO DISEASES AT HIGH ENERGY

Asymptotic freedom →

The theory gets simpler at high energy

NO INFINITIES AT SHORT DISTANCES

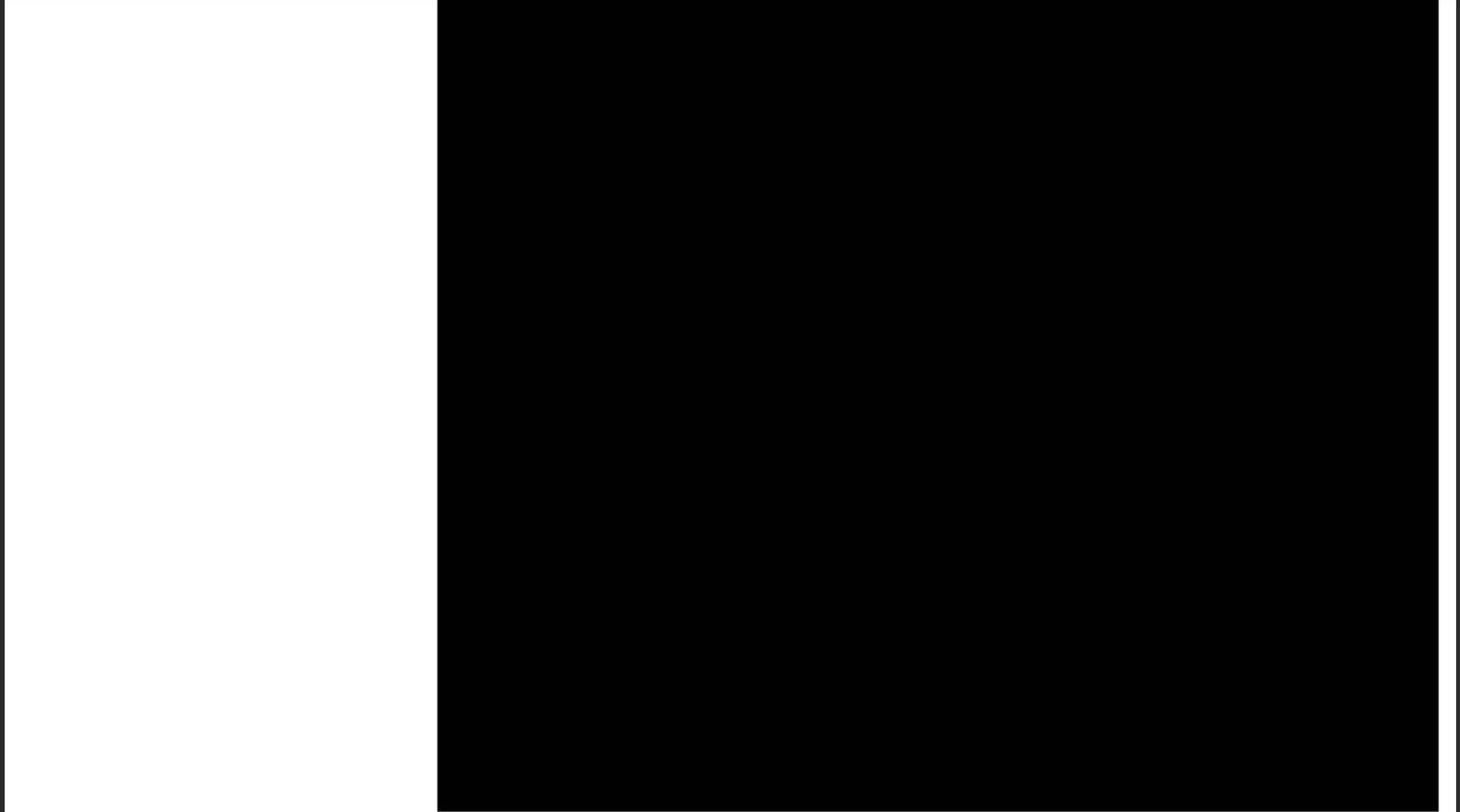
Asymptotic freedom → bare coupling = 0

NO ADJUSTABLE PARAMETERS

All observables are calculable in terms of the dynamically generated mass scale

One can extrapolate QCD to infinite energy and the universe to early times.

# Removes the Barrier to Unification



Thank You

**NACUBE**

Thank You

NACOBURIE

