The Physics of Relativistic Heavy Ion Collisions

18th National Nuclear Physics Summer School

July 23 - August 5, 2006

Indiana University, Bloomington, IN

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Lectures July 31-August 3, 2006

Associate Professor Jamie Nagle
University of Colorado, Boulder

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Lecture #1

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Acknowledgements

Lots of input (slides, graphics, discussion) from

Tom Hemmick
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Thomas Ullrich
Bill Zajc

The New York Times
ON THE WEB

NATIONAL DESK | January 13, 2004, Tuesday

Newly Found State of Matter Could Yield Insights Into Basic Laws of Nature

By JAMES GLANZ (NYT) 866 words
Late Edition - Final , Section A , Page 19 , Column 2

ABSTRACT - Scientists from Brookhaven National Laboratory say fleeting, ultradense state of matter, comparable in some respects to bizarre kind of subatomic pudding, has been discovered deep within core of ordinary gold atoms; some scientists describe finding as breakthrough in understading powerful, immensely complex forces that hold together building blocks of atomic nuclei: protons and neutrons (M)

NATIONAL DESK | January 14, 2004, Wednesday

Tests Suggest Scientists Have Found Big Bang Goo

By JAMES GLANZ (NYT) 832 words
Late Edition - Final , Section A , Page 12 , Column 3

DISPLAYING FIRST 50 OF 832 WORDS - At least three advanced diagnostic tests suggest that an experiment at the Brookhaven National Laboratory has cracked open protons and neutrons like subatomic eggs to create a primordial form of matter that last existed when the universe was roughly one-millionth of a second old, scientists said here on Tuesday. ......

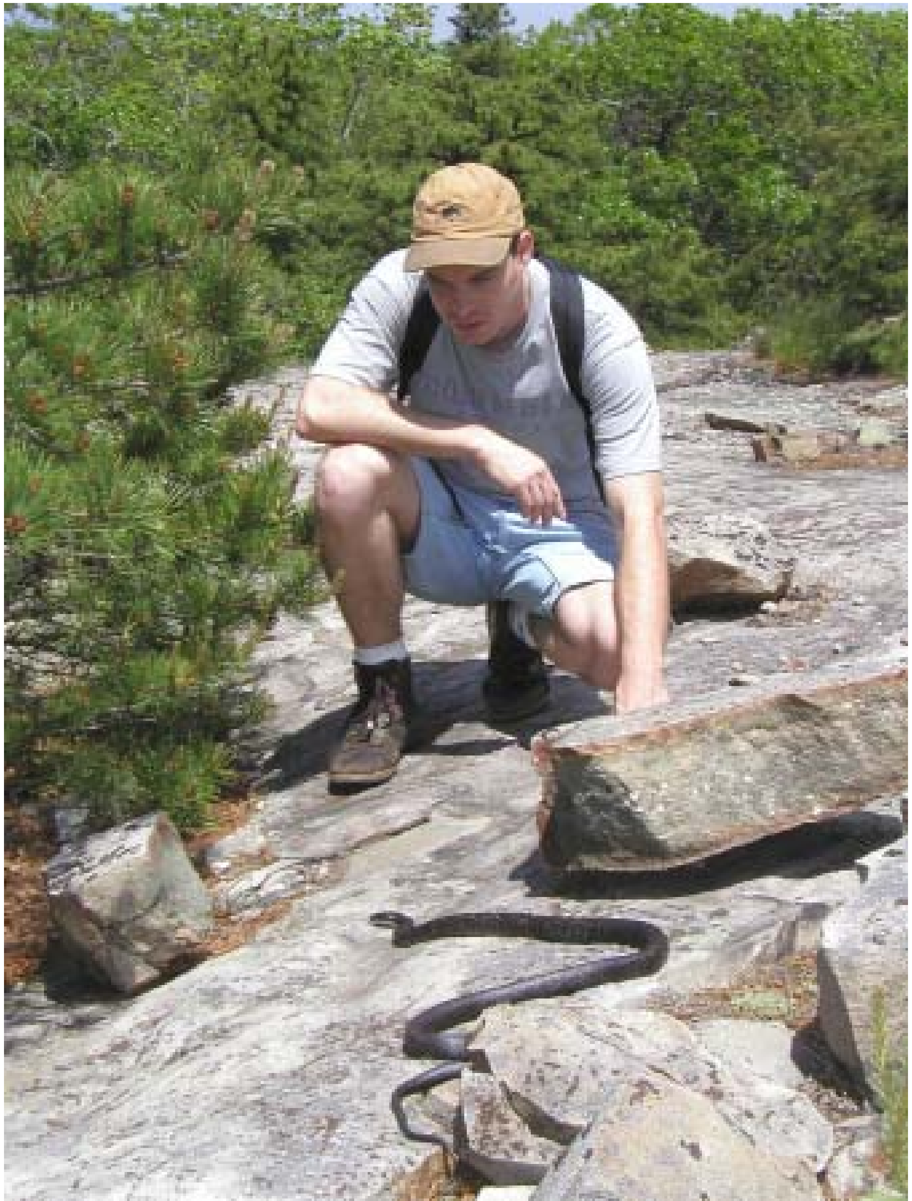
SCIENCE DESK | January 20, 2004, Tuesday

Like Particles, 2 Houses of Physics Collide

By JAMES GLANZ (NYT) 1356 words
Late Edition - Final , Section F , Page 1 , Column 1

DISPLAYING FIRST 50 OF 1356 WORDS - ... What, has this thing appear'd again ... I have seen ... -- "Hamlet," Act I, Scene ... A bland and bulky conference center in this city's fogbound downtown was transformed in recent days into the Elsinore of particle physics. The ghost that continually appeared, disappeared and appeared again during...

Curiosity



Going Back to School…

Many times as a field advances and matures, people forget the basic principles and only focus on the latest detailed measurements and theoretical developments.

In these lectures, I hope to talk in detail about the basics and then connect these to the latest and greatest results (from select topics).

Very broad subject area, and thus focus on a few topics and unfortunately leave out many other important ones.

QCD
and the
Quark Gluon Plasma

1973 = Birth of QCD

Gross, Politzer, Wilczek


PHYSICAL REVIEW D VOLUME 8, NUMBER 10 15 NOVEMBER 1973

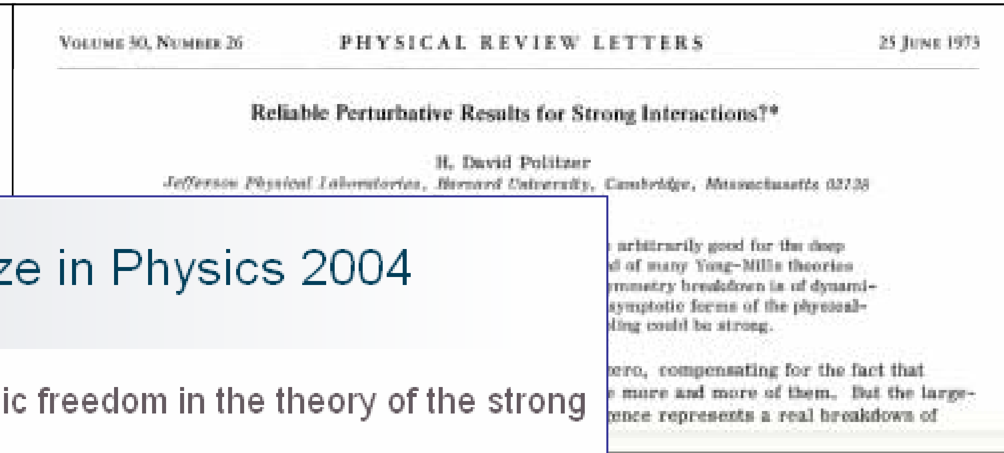
Asymptotically Free Gauge Theories. I*

David J. Gross†

National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510
and Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

Frank Wilczek

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


VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

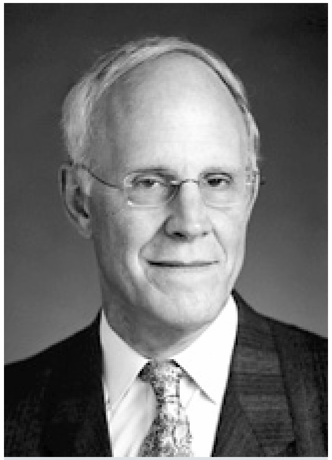
Reliable Perturbative Results for Strong Interactions?*

H. David Politzer

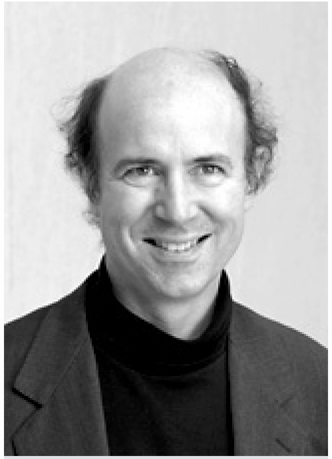
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138

The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

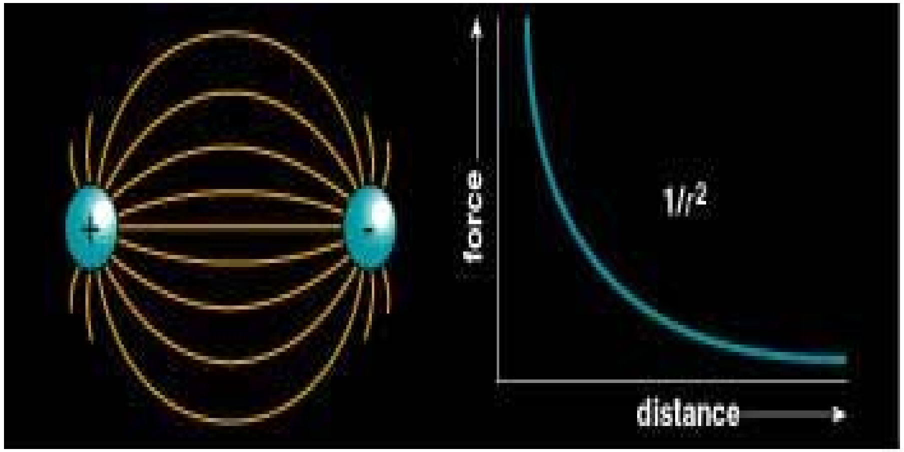

David J. Gross

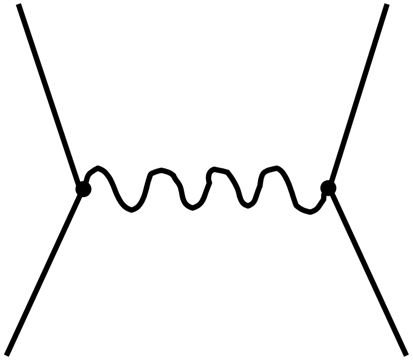

H. David Politzer

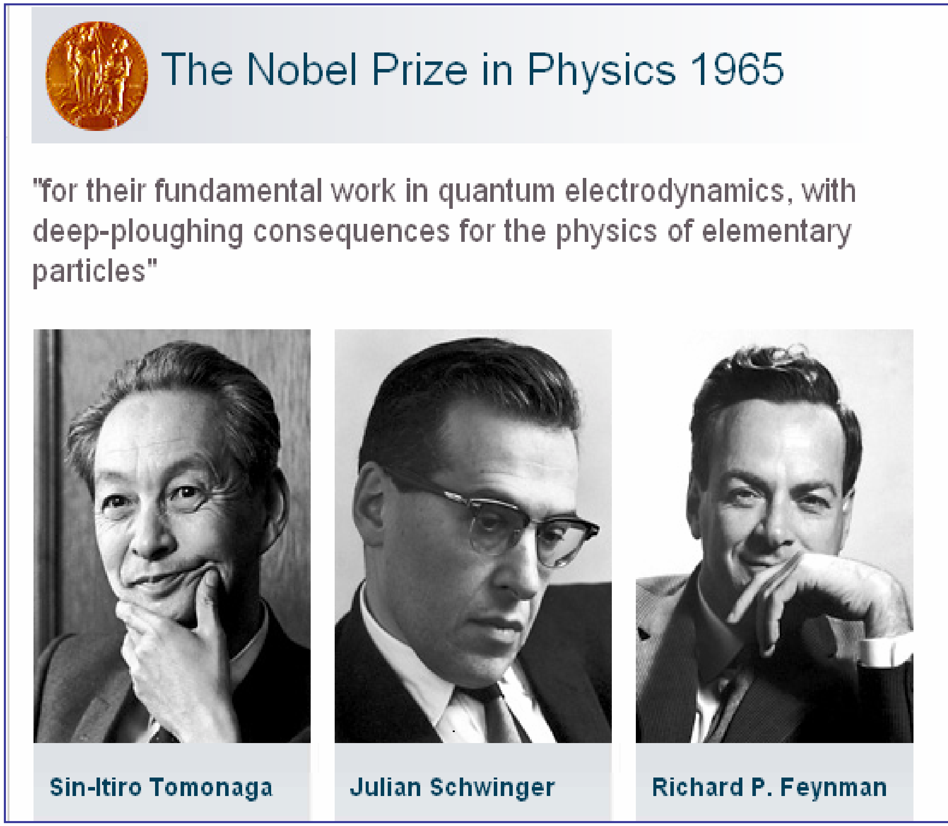

Frank Wilczek

Quantum Electrodynamics (QED)

Field theory for electromagnetic interactions
Exchange particles (photons) do not have electric charge
Flux is not confined - U(r) α 1/r and F(r) α 1/r^2





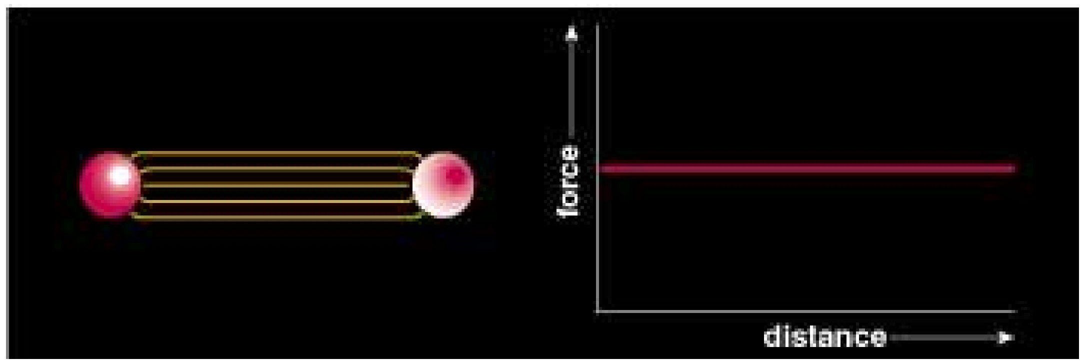


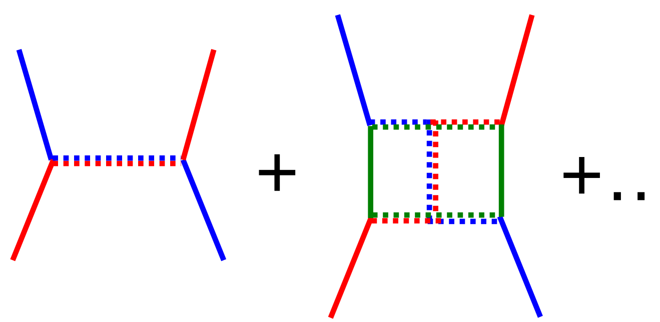
Quantum ChromoDynamics (QCD)

Field theory for strong (nuclear) interactions

Exchange particles (gluons) do have “color” charge

Flux is confined - U(r) α r and F(r) = constant





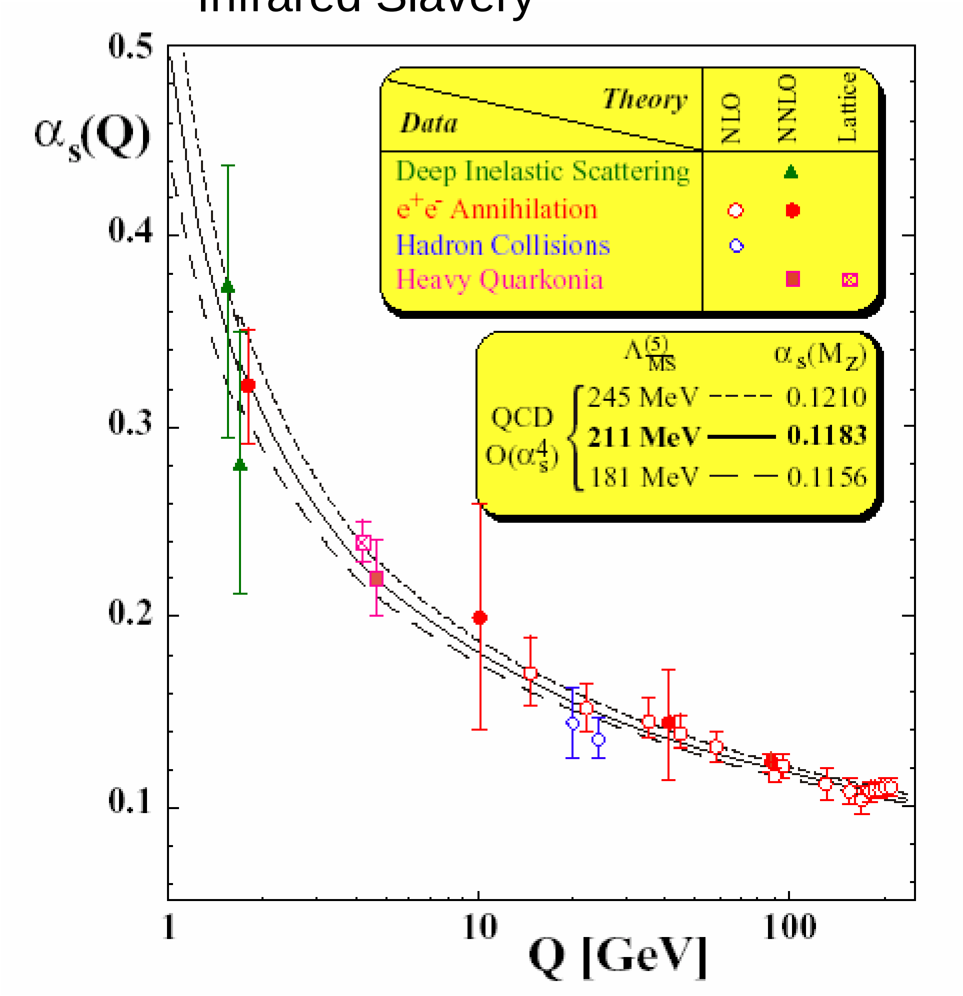
QCD Looks Simple, but Is Not

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi}\left(i\gamma_{\mu} D^{\mu} - m\right)\psi$$

$$F^{a}_{\mu\nu} = \partial_{\mu} A^{a}_{\nu} - \partial_{\nu} A^{a}_{\mu} + g f^{abc} A^{b}_{\mu} A^{c}_{\nu}$$

Running Coupling Constant

Infrared Slavery



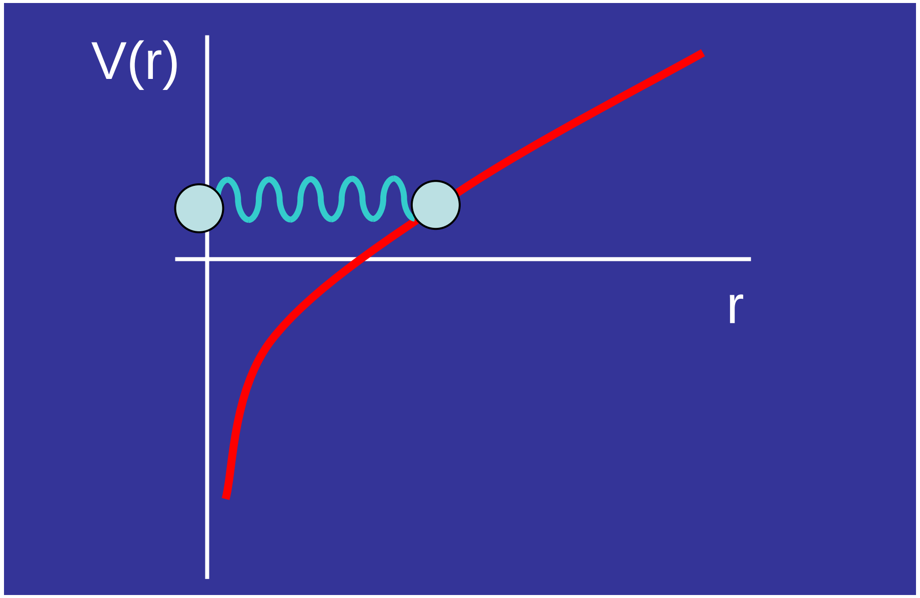
Asymptotic Freedom

0.2 fm 0.02 fm 0.002 fm

Free Quarks?

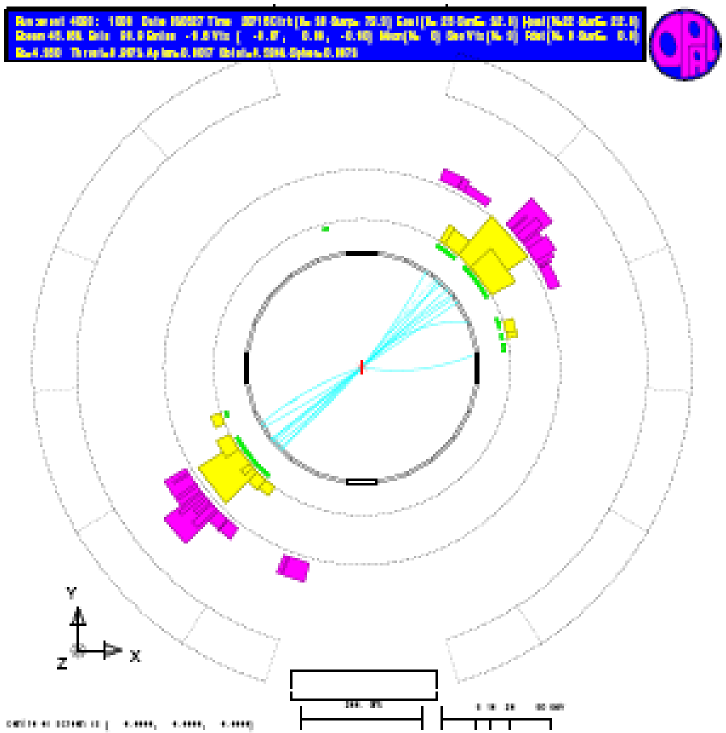
No one has ever seen a free quark.
QCD is a "confining" gauge theory,
with an effective potential:

$$V = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

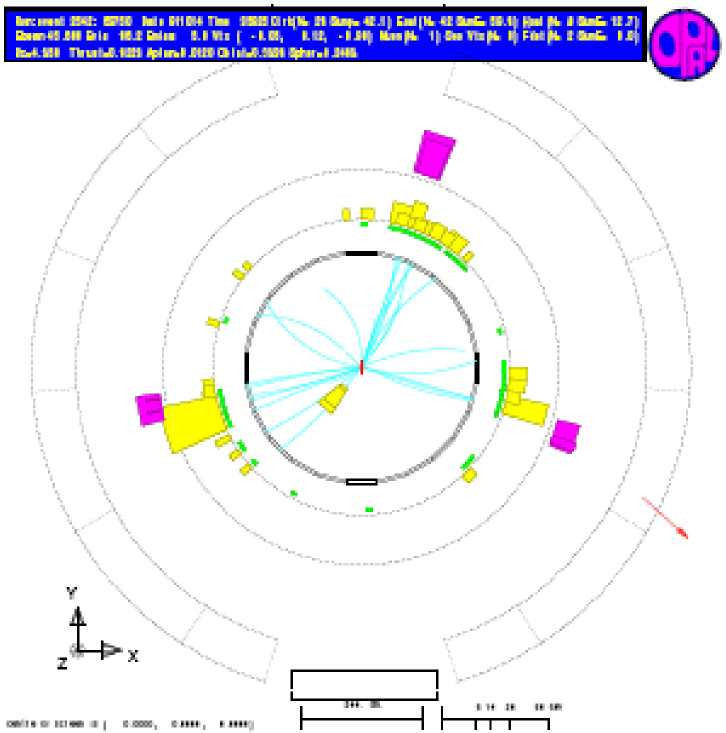


“Seeing” the Gluon

A two jet event

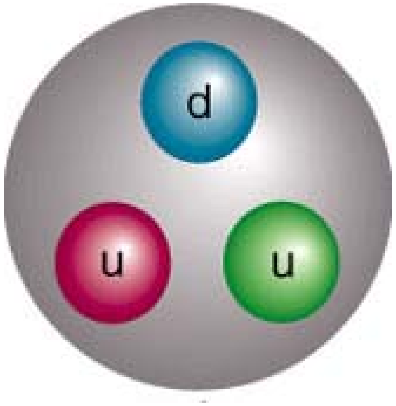


A three jet event

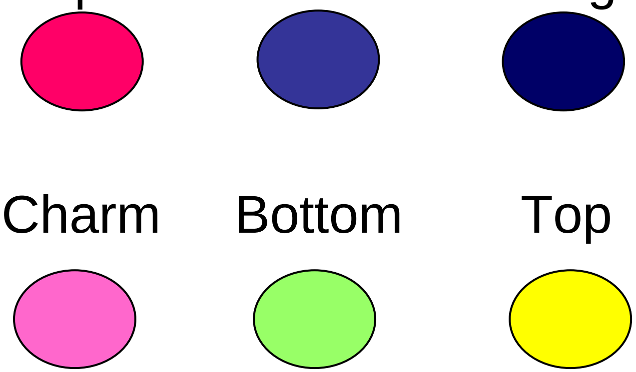


Quarks, Gluons and the Strong Interaction

Proton is a composite object
made of quarks and gluons.



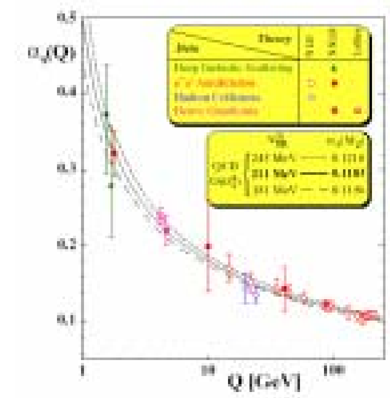
"Three quarks on a lark." James Joyce

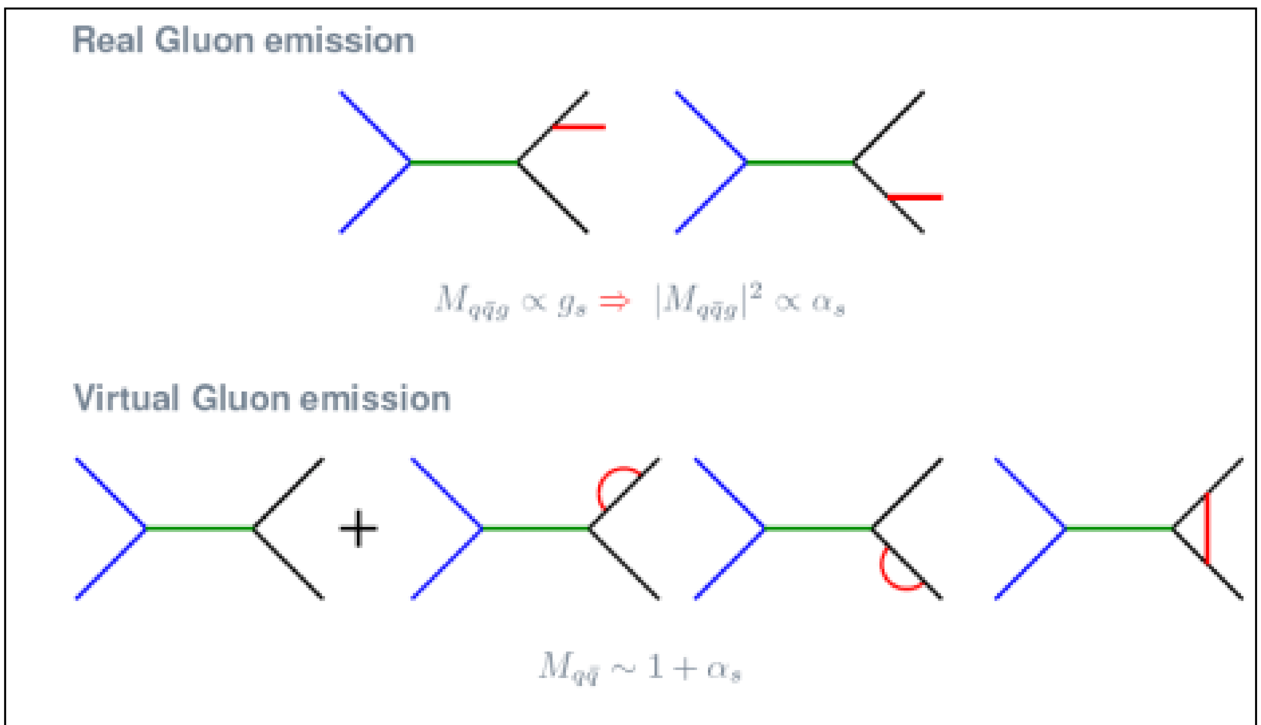


Perturbative QCD

For processes where coupling is small, one can do a perturbative expansion (to a given order) and expect increasingly accurate results.

Note that there are still many tricky issues in pQCD calculations.

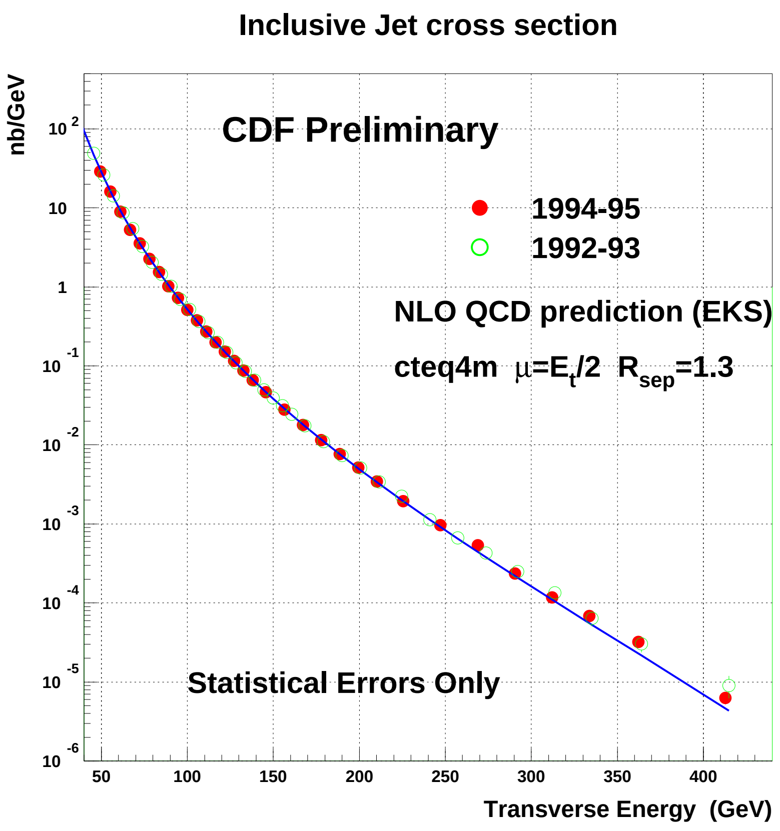


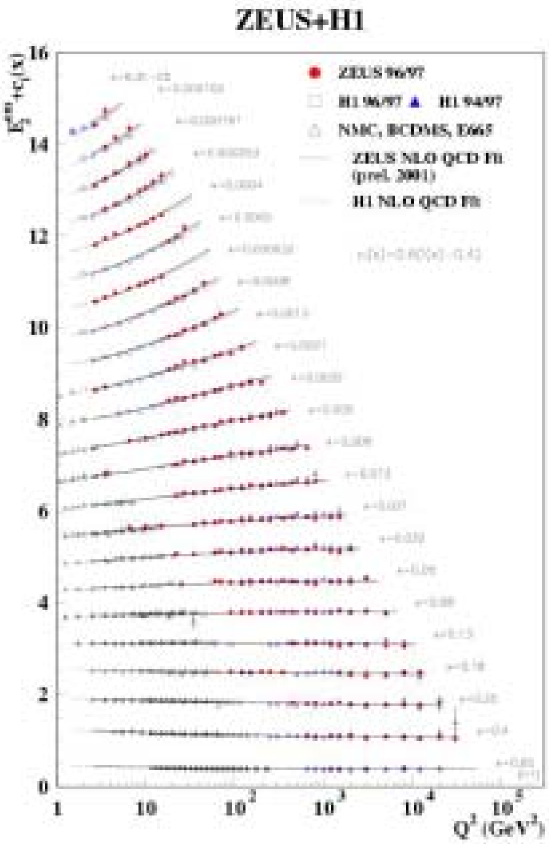


Perturbative QCD Successes

High Energy
Jet Observations

Deep Inelastic Scattering
DGLAP

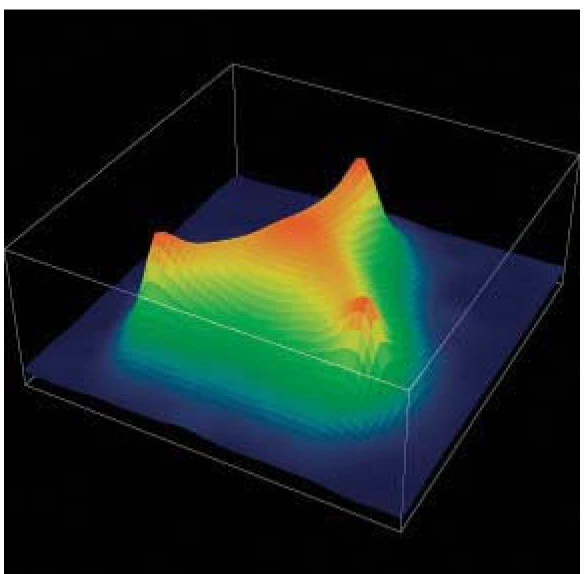


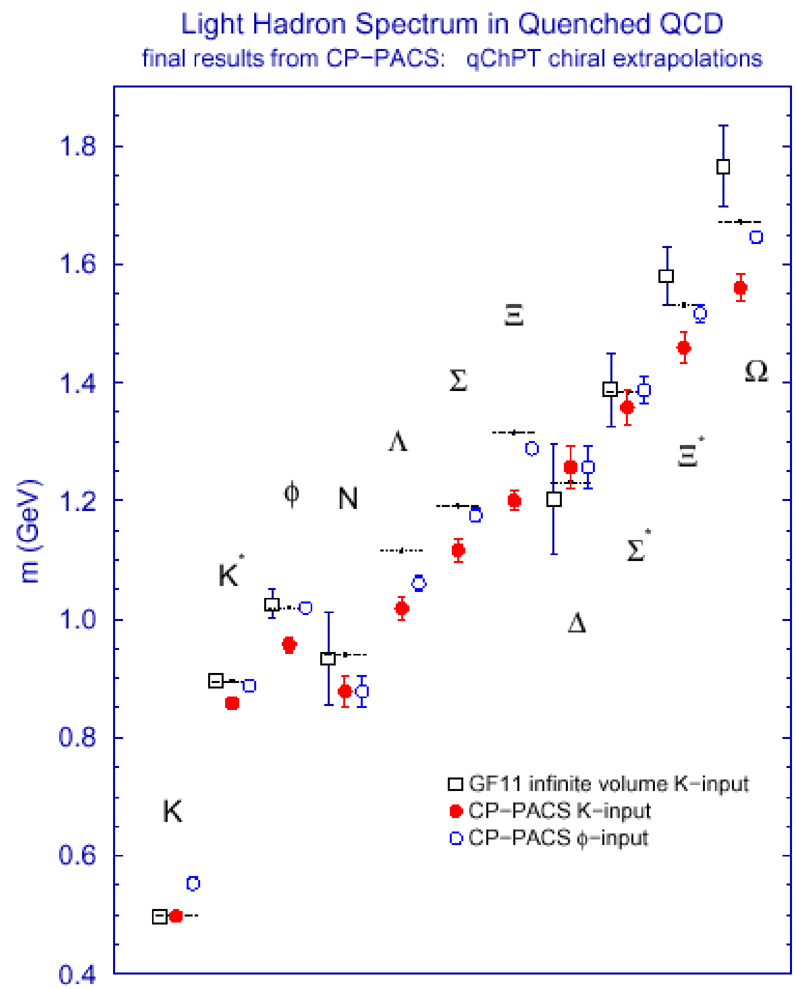


Non-Perturbative Lattice QCD Results

Using lattice QCD we can calculate the various hadron masses.

Agreement at 10% level, excluding π^0.



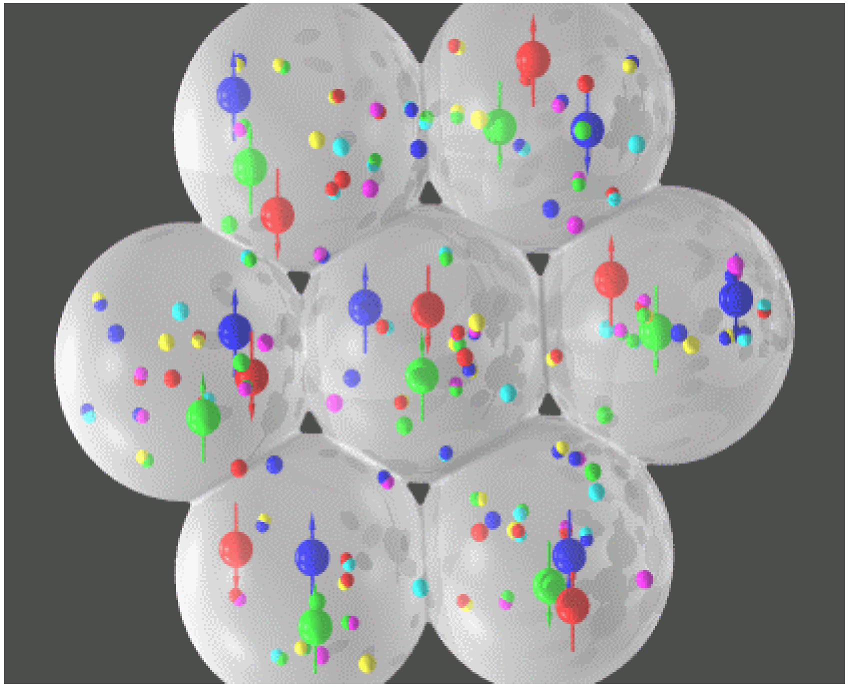


Lattice Limitations

Computations are costly in terms of computer equipment and time.

Also, lattice results determine equilibrium properties and do not address well dynamical quantities.

Heating Up Nuclear Matter



Limiting Temperature

The very rapid increase of hadron levels with mass yields an exponential level density

$\equiv$ ——

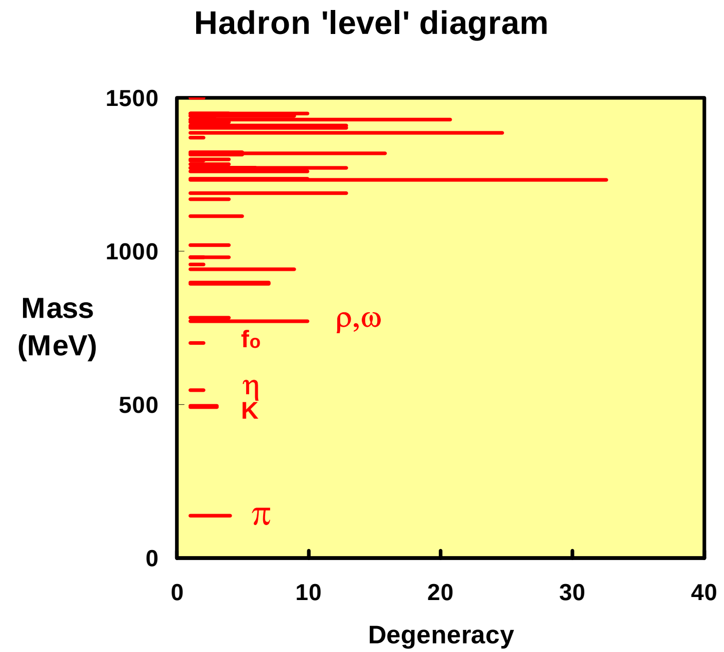
$\Rightarrow \int$ —

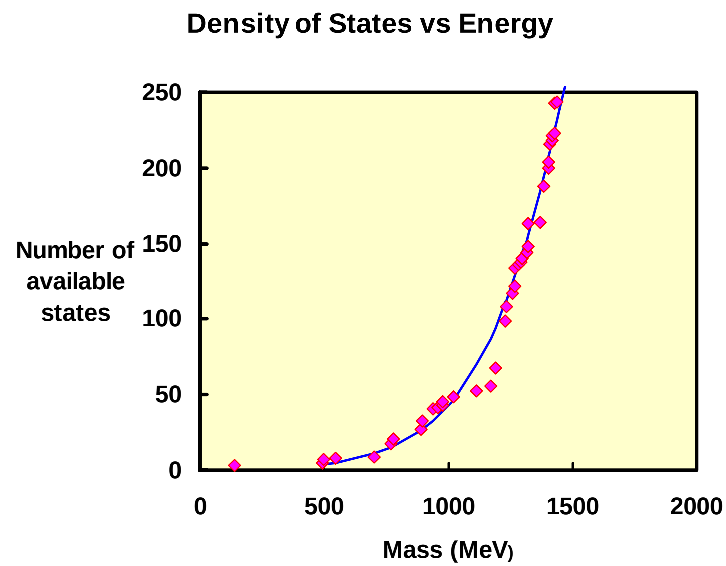
$\int$ —— – —

and would thus imply a "limiting temperature"

T_H ~ 170 MeV

Hagedorn, S. Fraustchi, Phys.Rev.D3:2821-2834,1971

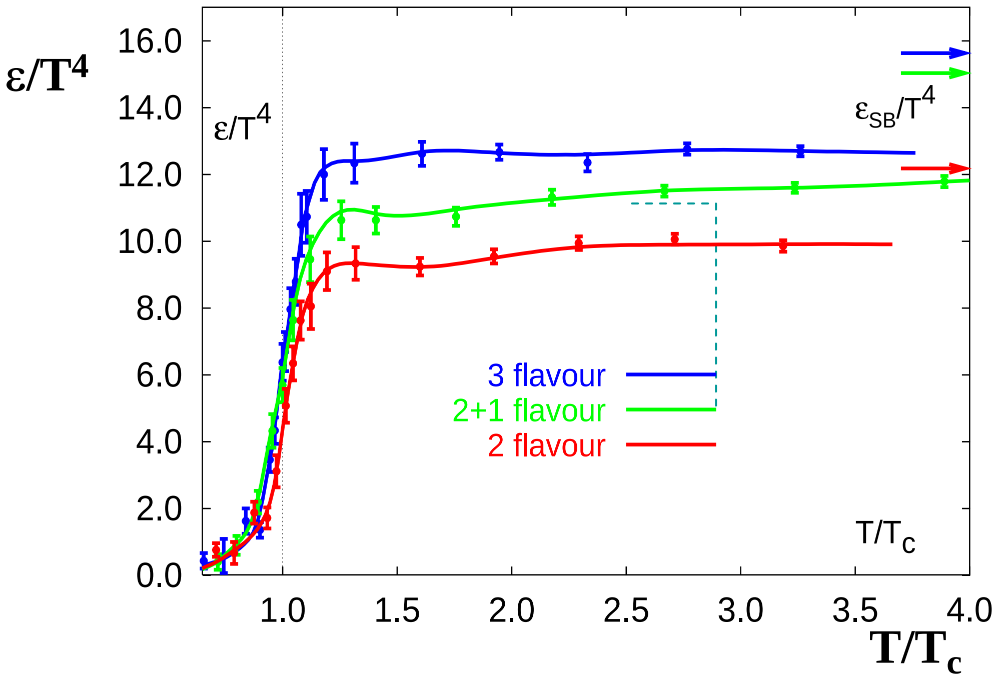




No Limiting Temperature

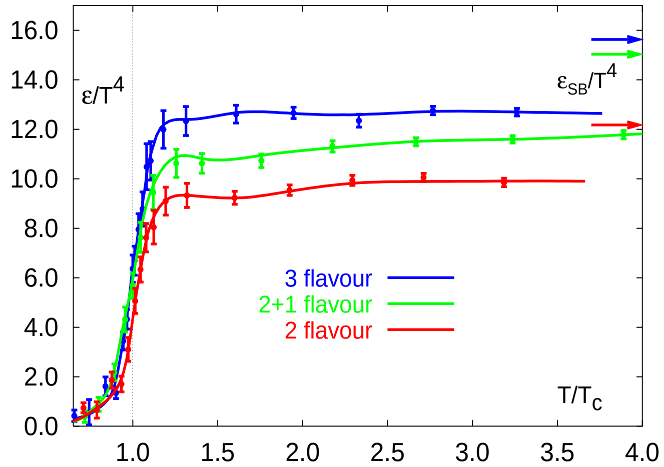
Lattice QCD results indicate that as one increases the energy input (bunsen burner heat), it is very hard to move the temperature above ~ 170 MeV.

However, eventually the temperature does exceed the "limiting temperature" !



(F. Karsch, hep-lat/0106019)

Where is the Energy Going?



Input energy is not increasing the kinetic energy per particle, but instead going into the rearrangement of the constituents of the matter (i.e. a phase transition).

Phase Transition: **T = 150-200 MeV ~ 10^{12} ^{0}F**
ε ~ 0.6-1.8 GeV/fm^3

If there is a period where all energy goes into rearrangement with no temperature increase, it is a first order phase transition with latent heat (and a mixed phase).

Melting the Hadrons

Can we melt the hadrons and liberate these quark and gluon degrees of freedom?

$$\varepsilon = g\frac{\pi^2}{30}T^4$$

Energy density for "g" massless d.o.f.

$$\varepsilon = 3\cdot\frac{\pi^2}{30}T^4$$

Hadronic Matter: quarks and gluons confined
For T ~ 200 MeV, 3 pions with spin=0

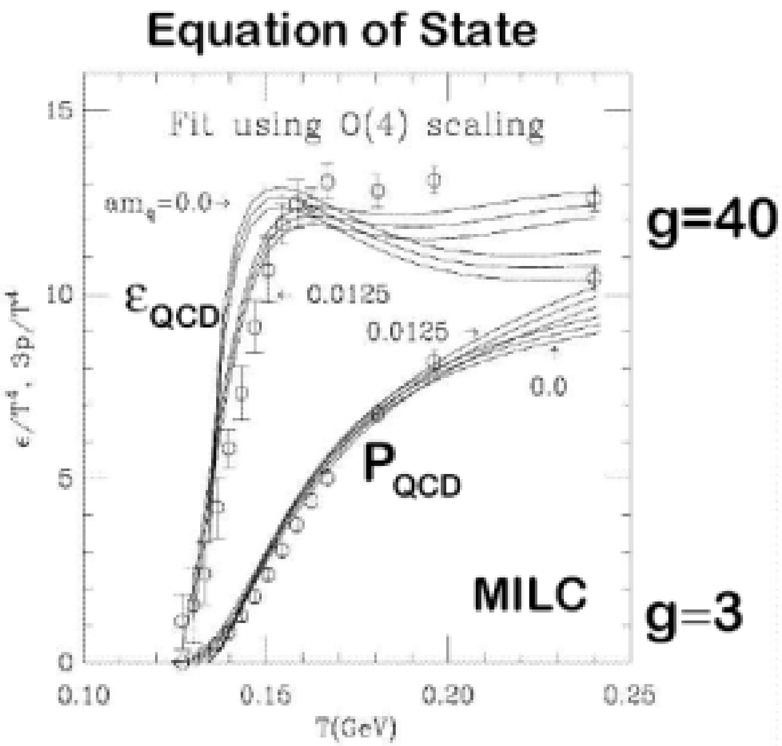
$$\varepsilon = \left\{2\cdot 8_g + \frac{7}{8}\cdot 2_s\cdot 2_a\cdot 2_f\cdot 3_c\right\}\frac{\pi^2}{30}T^4$$

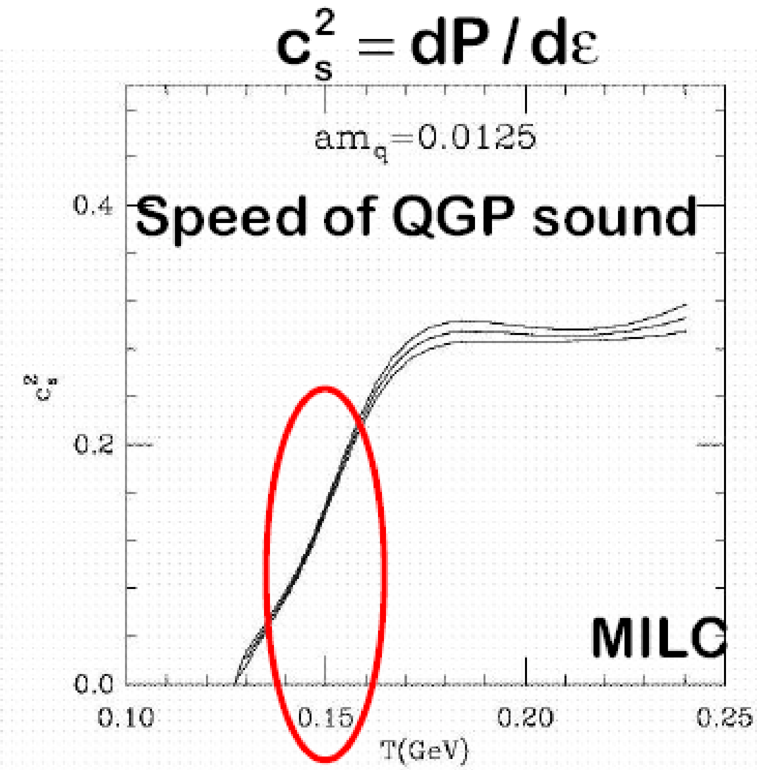
Quark Gluon Matter:
8 gluons;
2 quark flavors, antiquarks,
2 spins, 3 colors

$$\varepsilon = 37\cdot\frac{\pi^2}{30}T^4$$

37 !

Lattice Equation of State (EoS)





Speed of sound drops near transition ("soft point in EoS") and actually goes to zero in first order transition.
Sound wave transmits energy. In true mixed phase, all energy is absorbed into rearranging constituents.

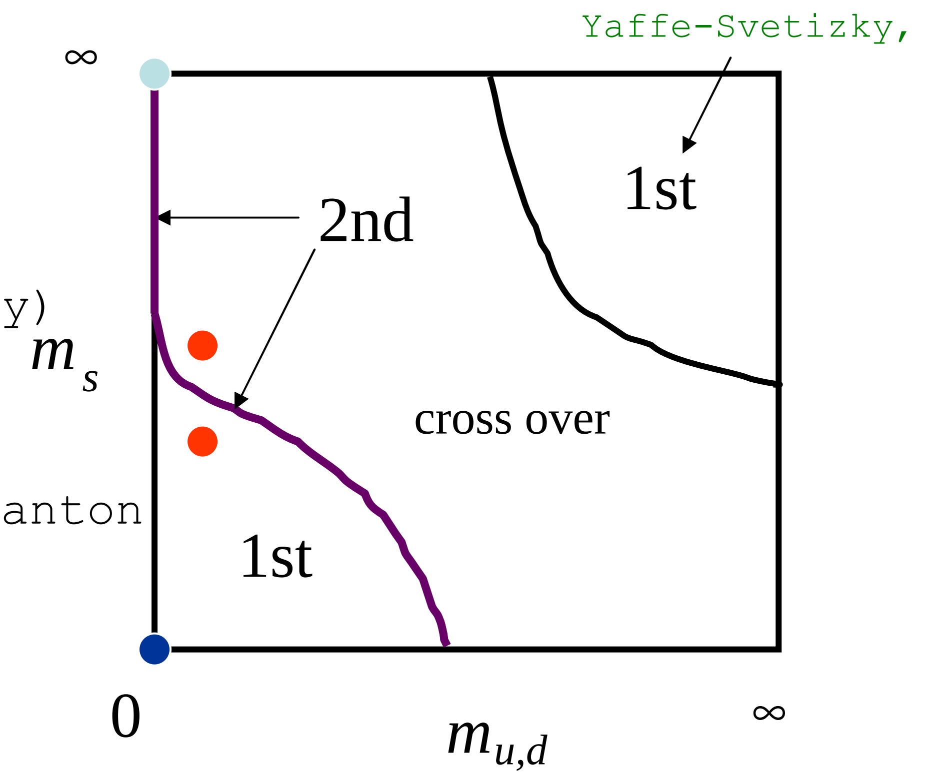
Transition Order?

Pisarski and Wilczek, Phys.Rev.D ('84)

- $N_f = 2$ ($m_s = \infty$, $m_{u,d} = 0$ □
  2nd order (O(4) universality)

- $N_f = 3$ ($m_s = 0$, $m_{u,d} = 0$)
  1st order (fluctuation/instanton

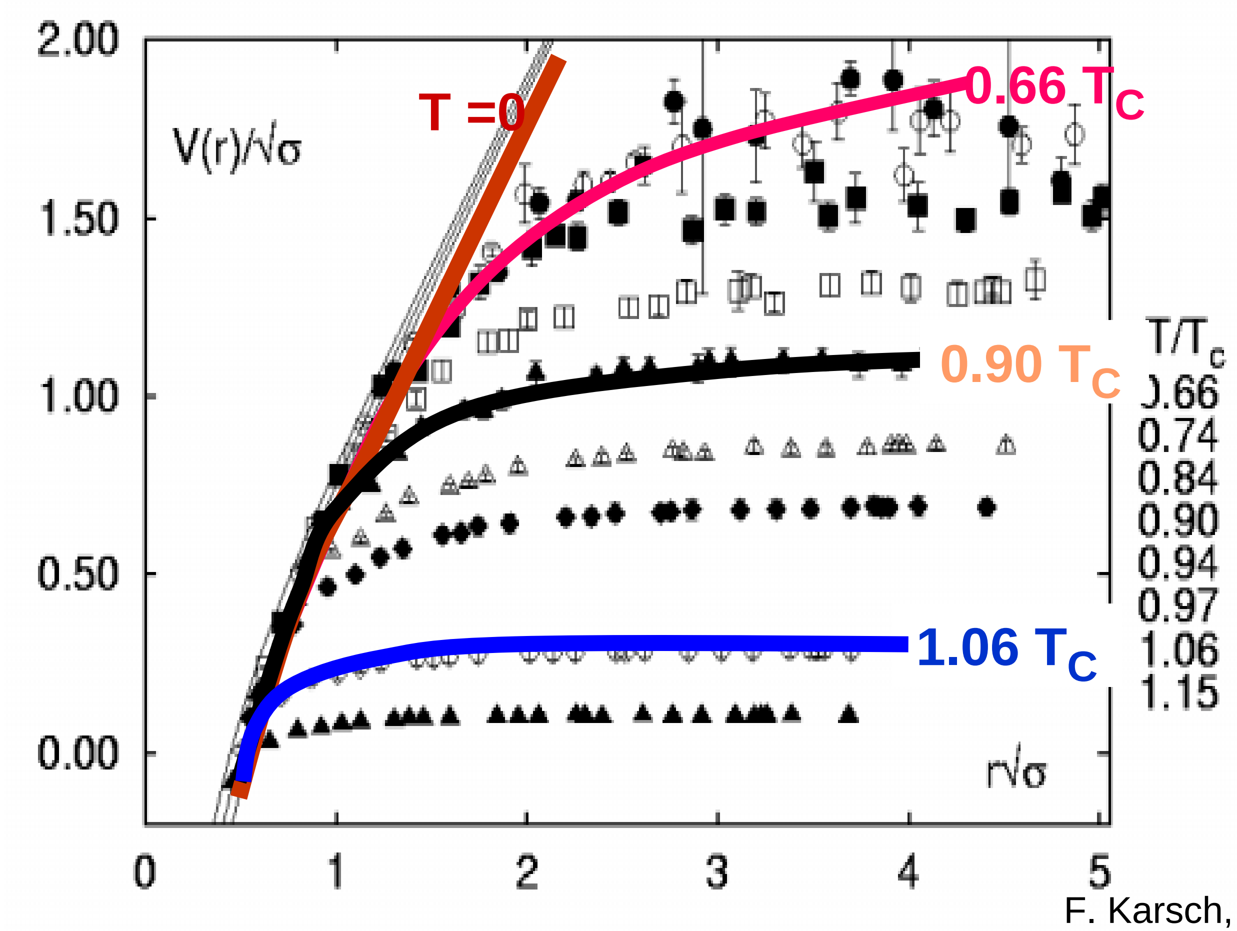
- $N_f = 2+1$ ($m_s >> m_{u,d} \neq 0$)
  1st order or crossover



Most recent lattice QCD results for a realistic strange quark mass favor a smooth cross over transition for zero net baryon density, but this may not be the final word.

Lattice Thermodynamics

Lattice QCD (for heavy quarks as a test) show a screening of the long range confining potential gradually as one passes the transition temperature.



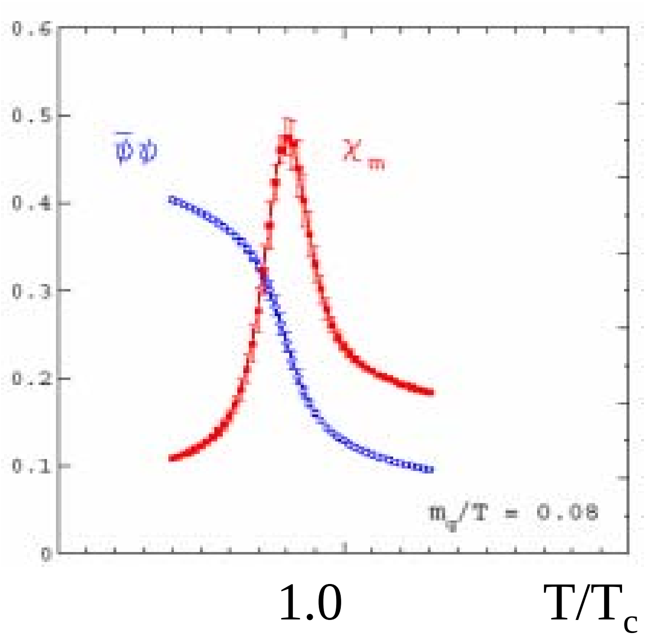
F. Karsch, hep-ph/0103314

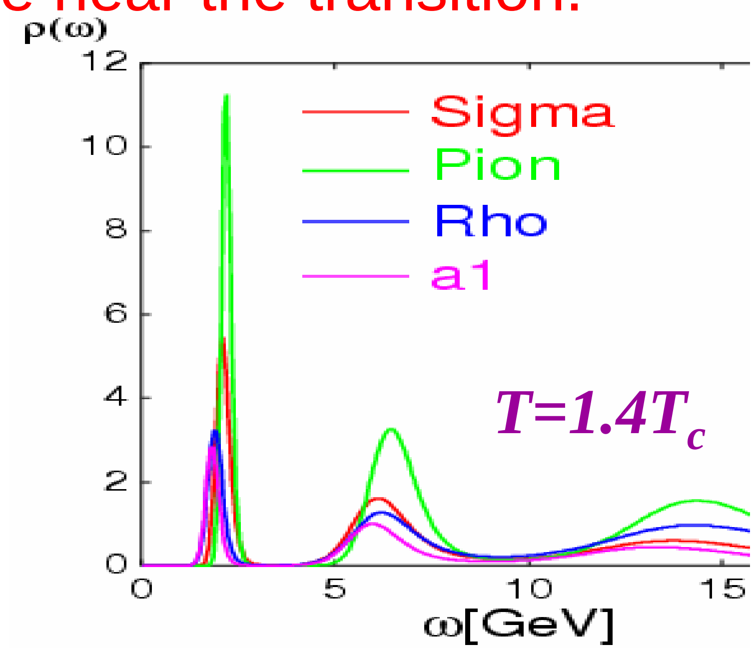
Approximate Chiral Symmetry

Up and Down quarks have very small neutral current masses (< 15 MeV). These masses are of interest to electroweak symmetry breaking (i.e. Higgs).

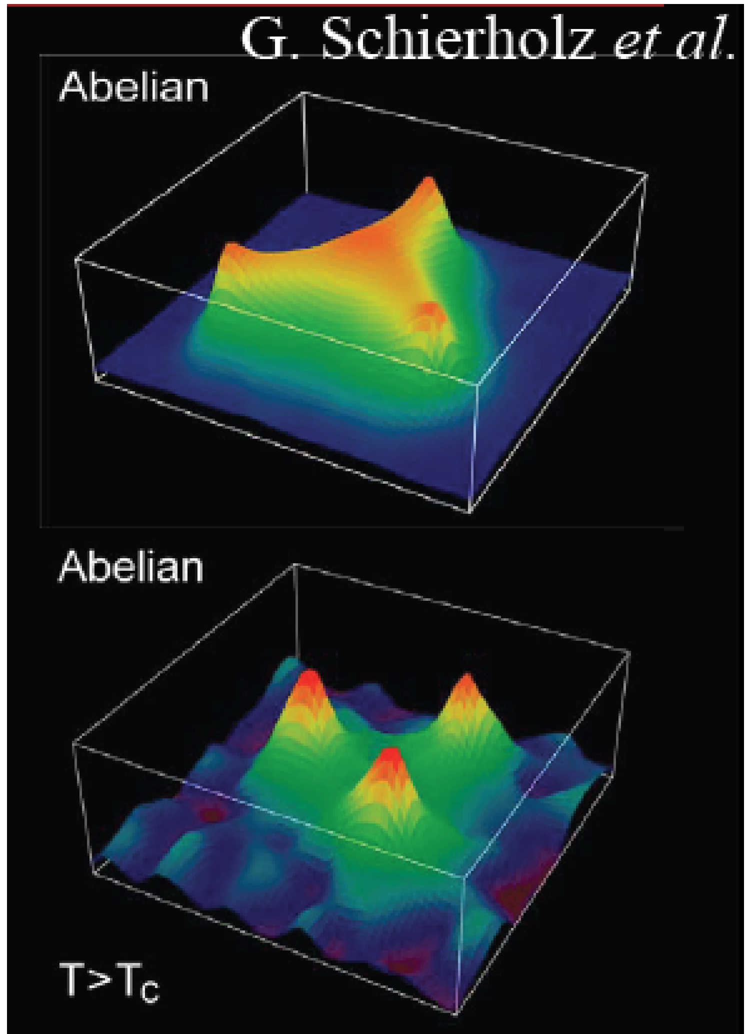
However, there is spontaneous breaking of chiral symmetry in the QCD vacuum we live in. A condensate of qqbar pairs results in the observed hadronic masses.

At high temperature this condensate goes away and thus hadronic masses should change near the transition.

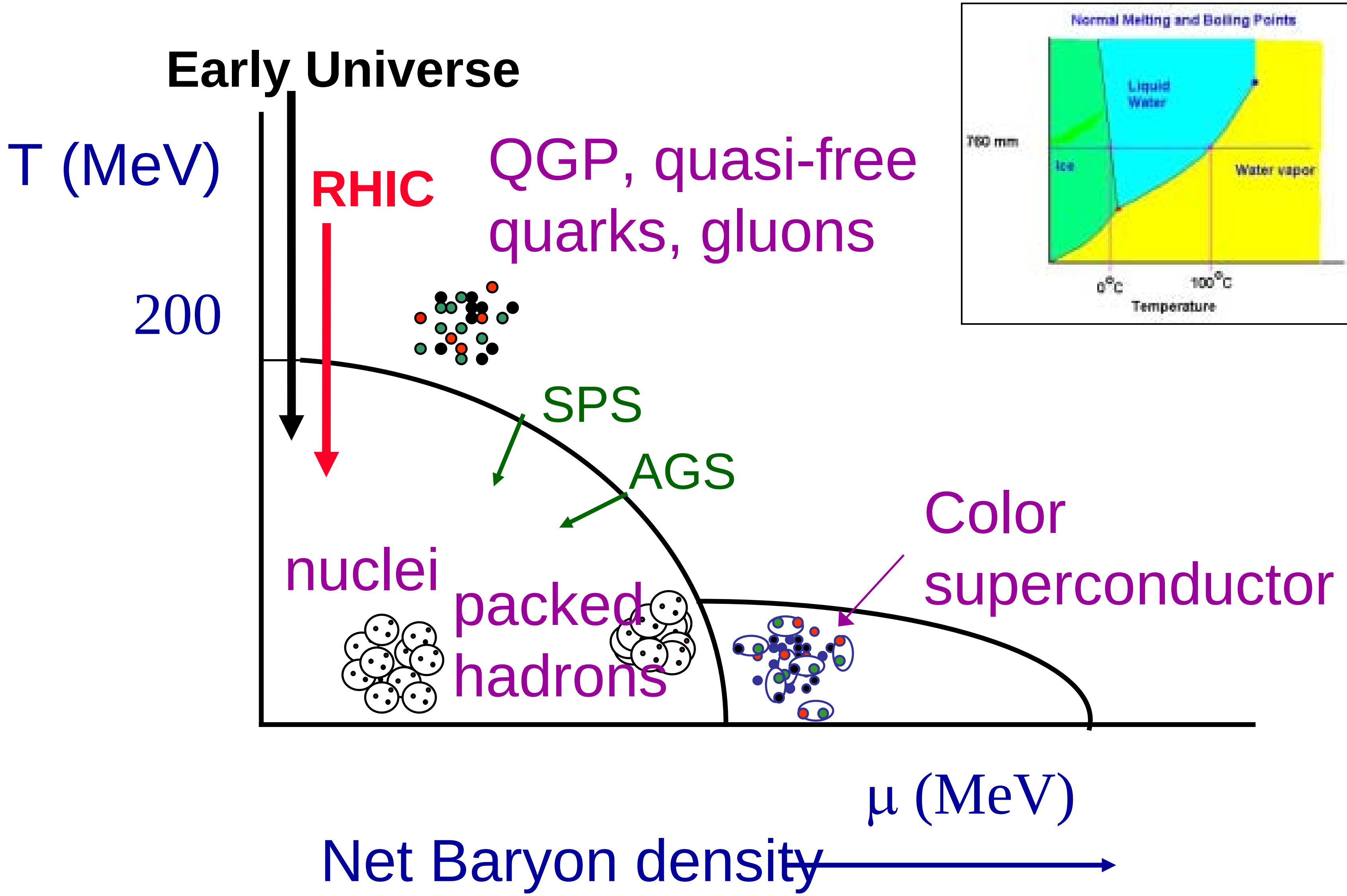




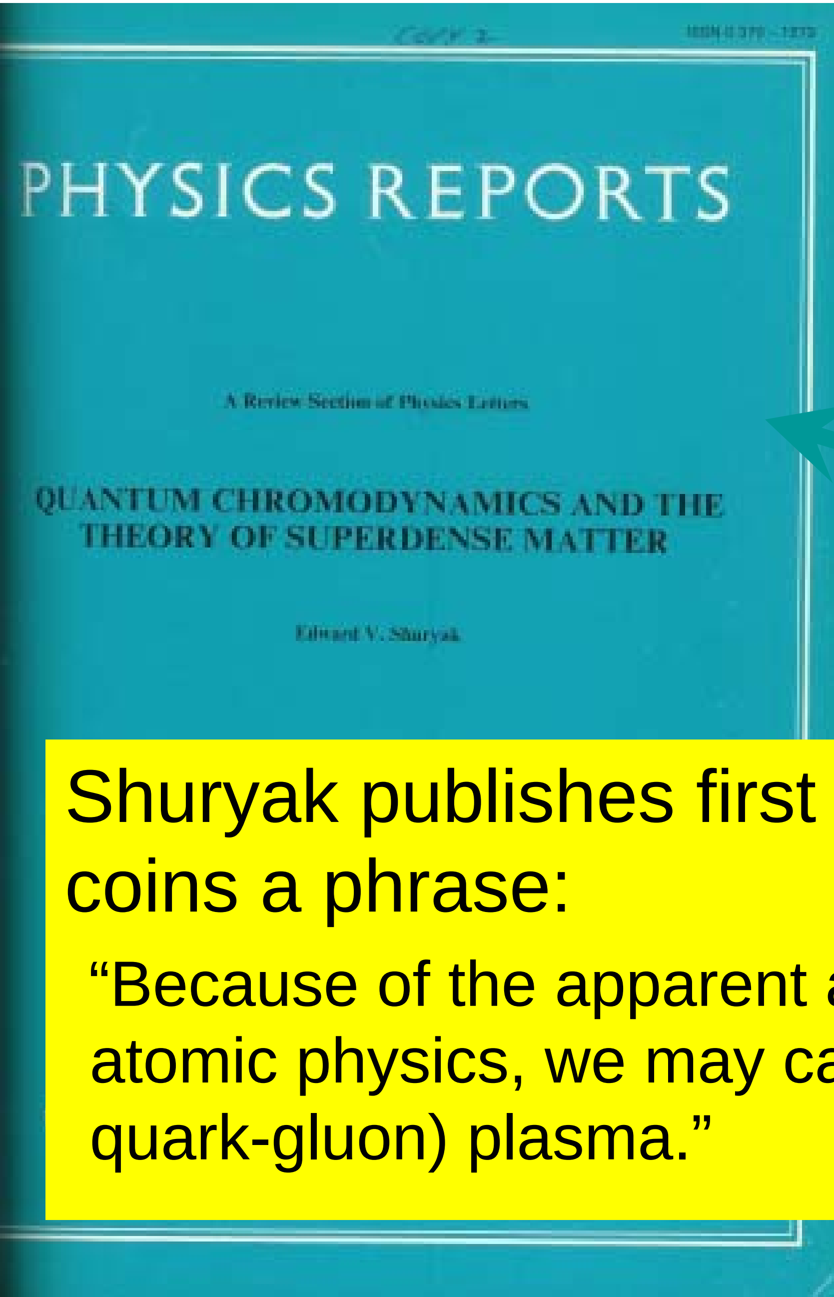
Color Flux Tubes

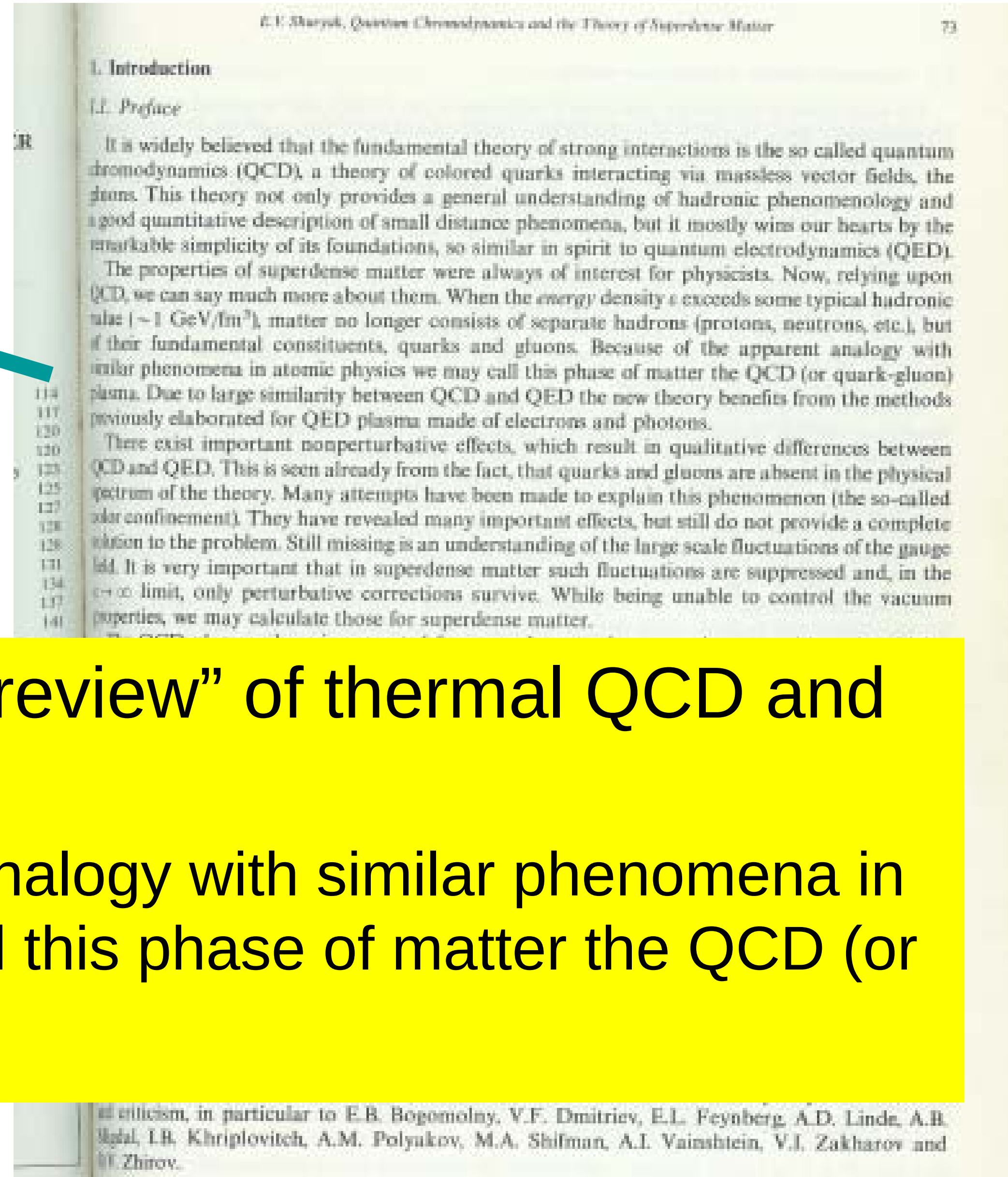


Phase Transition



Birth of a Name





E.V. Shuryak, Quantum Chromodynamics and the Theory of Superdense Matter 73

1. Introduction

1.1. Preface

It is widely believed that the fundamental theory of strong interactions is the so called quantum chromodynamics (QCD), a theory of colored quarks interacting via massless vector fields, the gluons. This theory not only provides a general understanding of hadronic phenomenology and a good quantitative description of small distance phenomena, but it mostly wins our hearts by the remarkable simplicity of its foundations, so similar in spirit to quantum electrodynamics (QED).

The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value (~ 1 GeV/fm^3), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

There exist important nonperturbative effects, which result in qualitative differences between QCD and QED. This is seen already from the fact, that quarks and gluons are absent in the physical spectrum of the theory. Many attempts have been made to explain this phenomenon (the so-called color confinement). They have revealed many important effects, but still do not provide a complete solution to the problem. Still missing is an understanding of the large scale fluctuations of the gauge field. It is very important that in superdense matter such fluctuations are suppressed and, in the $\varepsilon \to \infty$ limit, only perturbative corrections survive. While being unable to control the vacuum properties, we may calculate those for superdense matter.

...criticism, in particular to E.B. Bogomolny, V.F. Dmitriev, E.L. Feynberg, A.D. Linde, A.B. Migdal, I.B. Khriplovitch, A.M. Polyakov, M.A. Shifman, A.I. Vainshtein, V.I. Zakharov and V.F. Zhirov.

Shuryak publishes first “review” of thermal QCD and coins a phrase:

“Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma.”

Physics goals of RHIC

• Achieve highest energy densities in extended matter for relatively long times

•Learn the dynamics of high density matter: energy deposition, stopping, formation of excitations, onset of equilibration, hadronization, freezeout

•Search for collective effects beyond individual pp scattering, or pA scattering

•Study role of new degrees of freedom

•Produce and study quark-gluon plasma with large A at E above a few GeV/fm^3

•Extract nuclear equation of state, application to astrophysics

G. Baym, 1/95

What are the properties of matter at extremely high energy, or baryon, density? From nuclear matter scales (ρ_0=0.16/fm^3, E_0=0.15GeV/fm^3) to orders of magnitude beyond?

•What are its effective degrees of freedom? From nucleonic to hadronic to quark-gluon.

•What are the states of matter? Recognizable quark-gluon plasma? Strangelets? ...?

•What is the structure of qcd on large distance scales? Phase transitions? Monopoles?

•Surprises!

Terra incognita

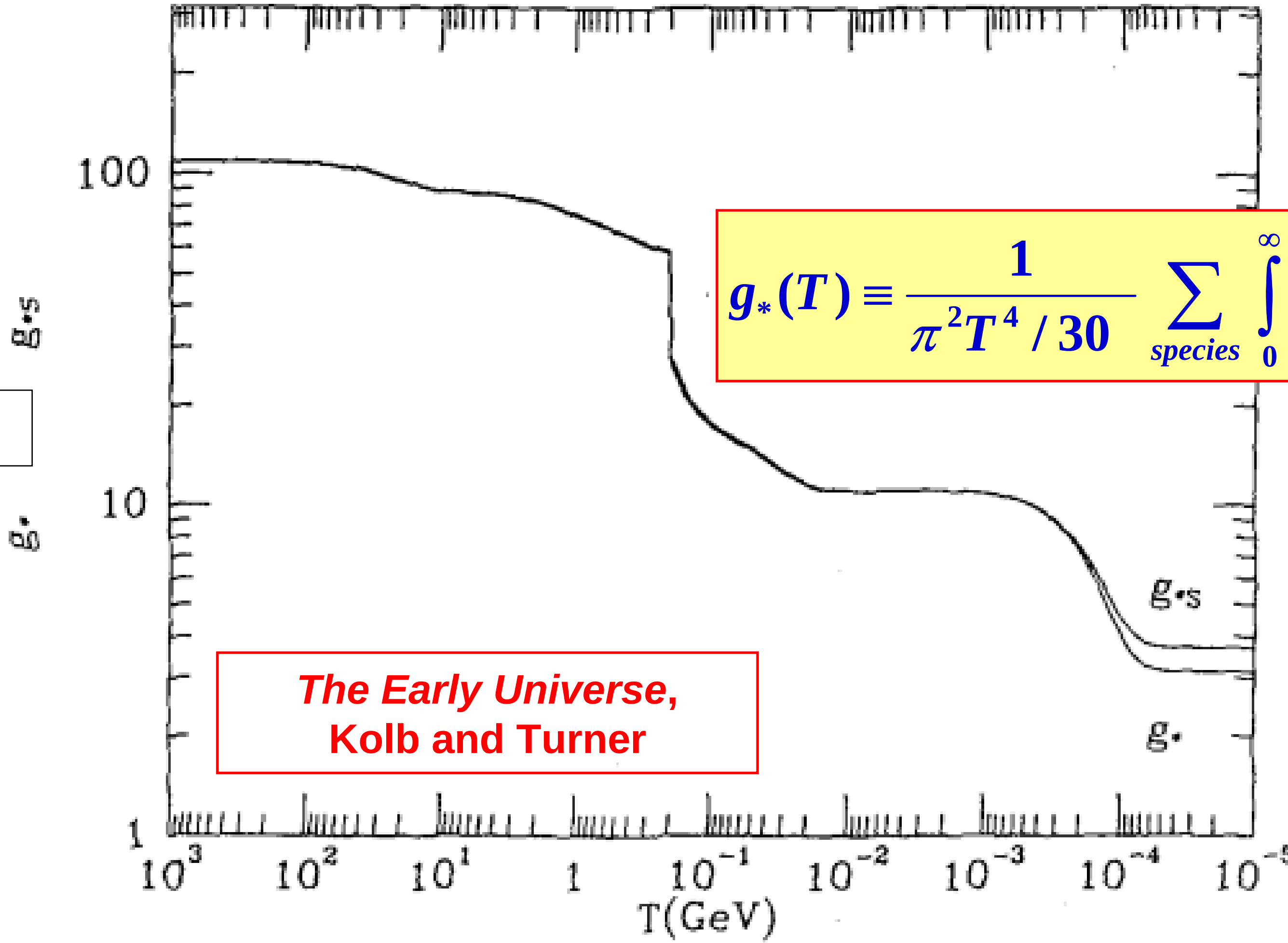
G. Baym, 1/95

QCD
and
Cosmology

First attempt at QGP formation *was* successful !

g

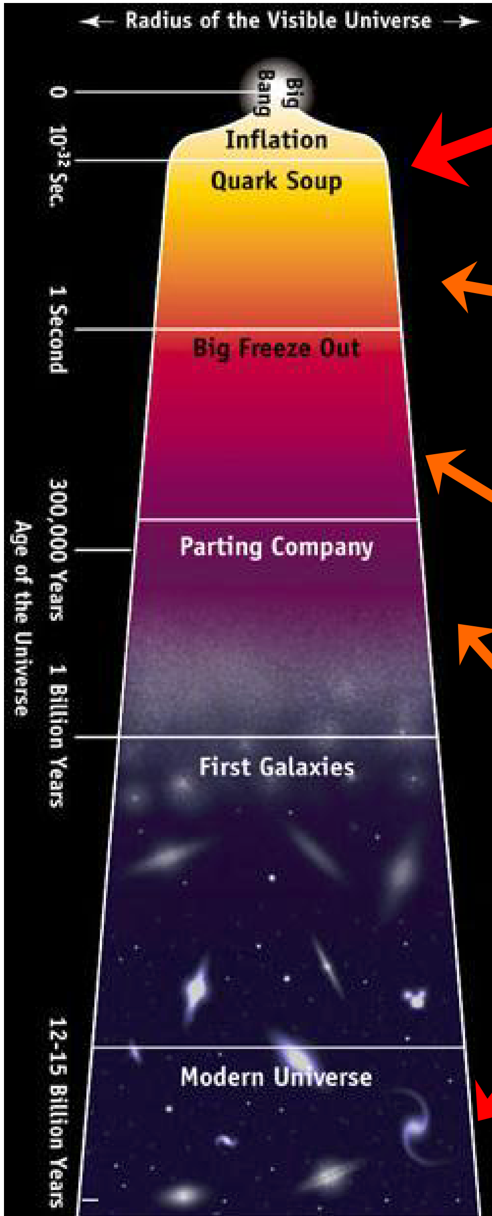
$$g_*(T) \equiv \frac{1}{\pi^2 T^4/30} \sum_{species} \int_0^\infty \frac{E_i(p)}{e^{(E_i-\mu_i)/T_i} \pm 1} \frac{d^3p}{(2\pi)^3}$$



***The Early Universe*, Kolb and Turner**

Fig. 3.5: The evolution of $g_*(T)$ as a function of temperature in the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ theory.

Brief History of Time



Too hot for quarks to bind!!!

Standard Model (N/P) Physics

Too hot for nuclei to bind

Nuclear/Particle (N/P) Physics

Nucleosynthesis builds nuclei up to He

Nuclear Force…Nuclear Physics

Universe too hot for electrons to bind

E-M…Atomic (Plasma) Physics

Today's Cold Universe

Gravity…Newtonian/General Relativity

Quark Gluon Plasma

Hadron Gas

E/M Plasma

Solid Liquid Gas

Cosmology Connection

"A first-order QCD phase transition that occured in the early universe would lead to a surprisingly rich cosmological scenario."

"Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets."

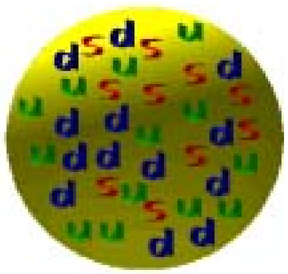
Ed Witten
Phys. Rev. D (1984)
Over 1000 citations

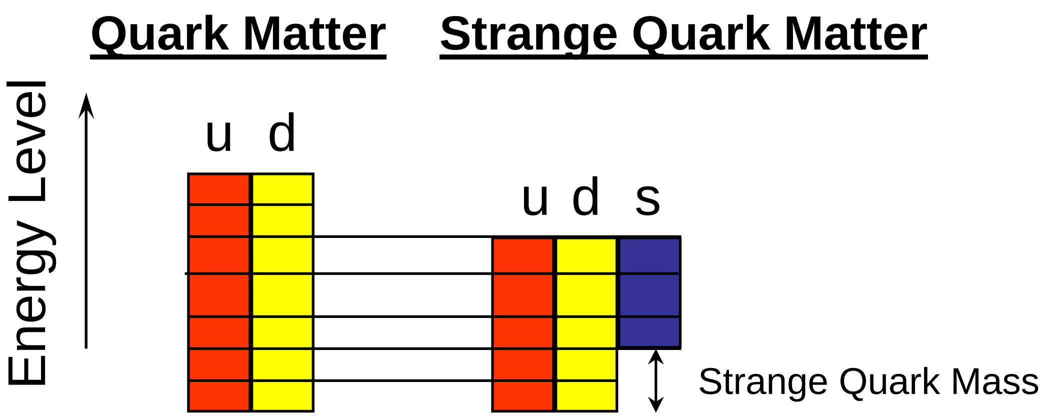
Strange Quark Matter

- Matter of roughly equal numbers of up, down and strange quarks.

- Strange Quark Matter could be more stable that Fe^{55} and thus be the ground state of nuclear matter.

- If stable, it could be a source of baryonic dark matter.





Strange Stars

Matter of roughly equal u, d, s stays electrically neutral and thus SQM objects can have very large baryon number.

Stars with quark matter cores have a different density profile.

Also, at the point of a phase transition, they can exhibit interesting behaviour (e.g. spin up).

There are some candidates, but nothing definitive yet.


BBC NEWS

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Wednesday, 10 April, 2002, 23:26 GMT 00:26 UK

Quark stars point to new matter

RX J1856.5-3754: Its size, just 11 km across, and temperature profile mean it cannot be a neutron star

By Richard Black
BBC science correspondent

Astronomers believe they have found their first quark stars - super-dense objects that are formed when the remnants of old stars collapse in on themselves.

Theorists have long suspected the existence of these weird objects, which are denser than neutron stars but are not compact enough to become black holes.

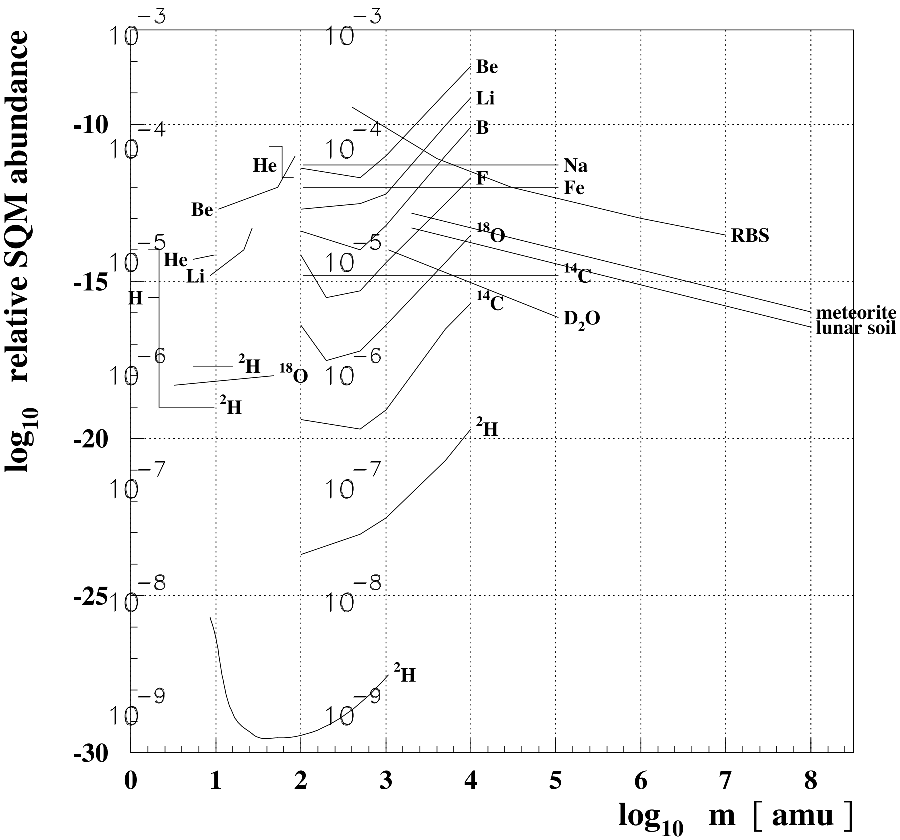
The observations were made by the orbiting Chandra X-ray Observatory, and were unveiled at an American space agency (Nasa) press briefing in Washington, US.

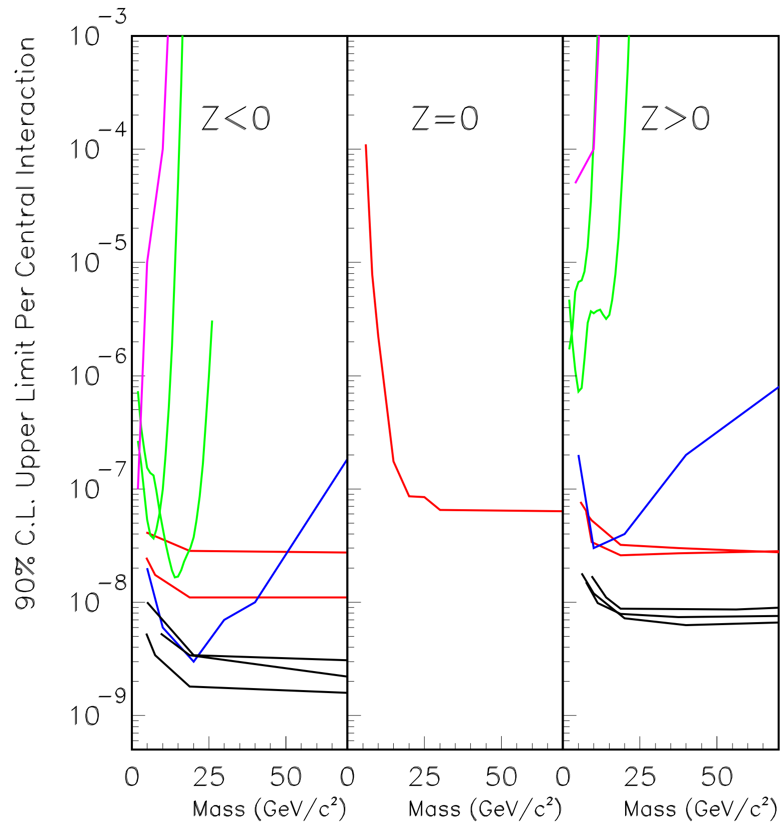
"If they are right, quark stars will provide them with stunning insights into the nature of matter"

Creating Strangelets

• Twenty years later, SQM still theoretically allowed.

• Experiments searches in terrestrial matter and nuclear reactions for small A< 100 SQM have yielded null results.



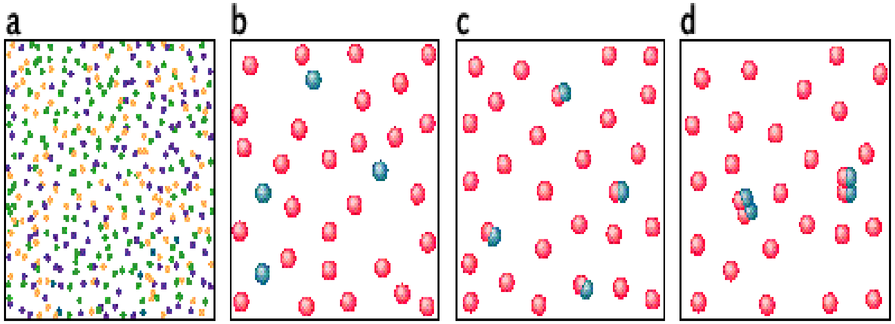


Supercooling and Bubbles

If the plasma-to-hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous early universe, thus impacting big bang nucleosynthesis (BBN).

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities? (200 MeV to 2 MeV)

This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content in the universe from BBN.

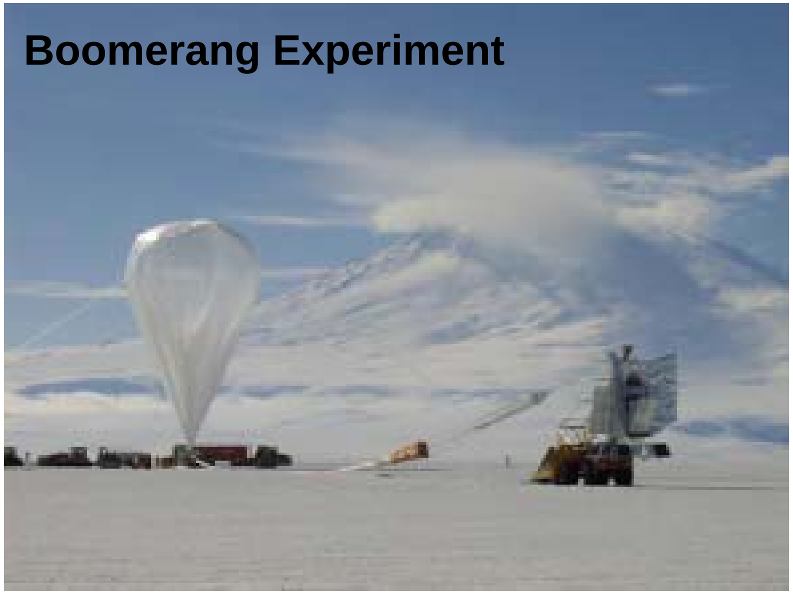


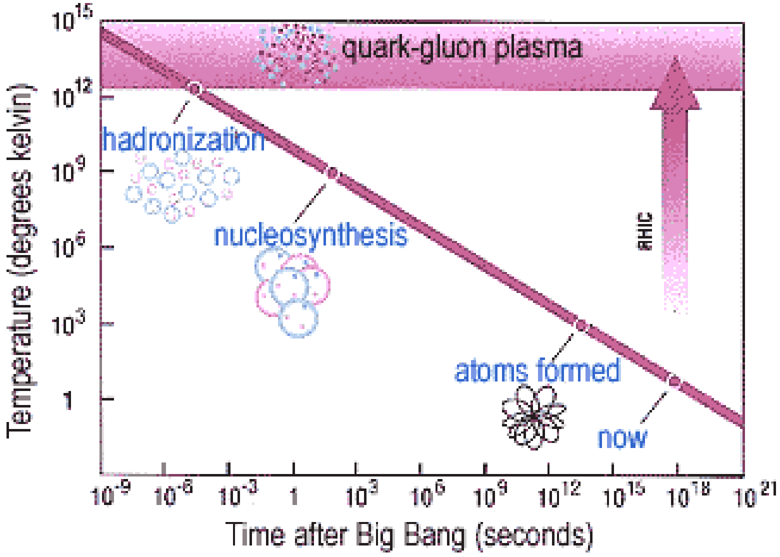
No BBN Problem

Physics Today, July 2001: Cosmic Microwave Background Observations

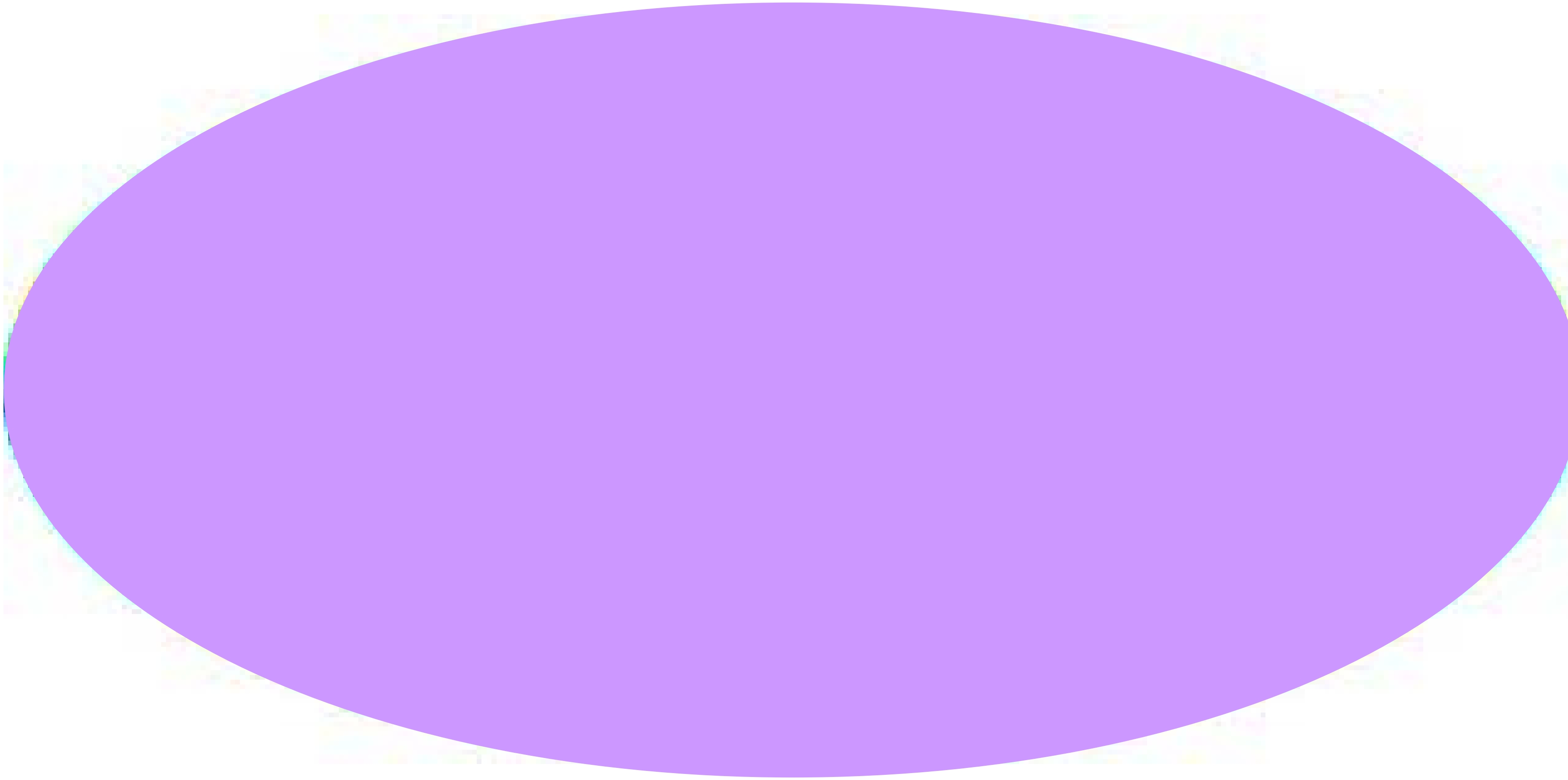
"The value deduced from the second harmonic in the acoustic oscillations for Ω_B=0.042 ± 0.008 (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium."

However, this confirmation of BBN does not rule out a first order phase transition in QCD because of the diffusion issue.





Flat Universe



WMAP Results
Age of the Universe = 13.8 billion years
Isotropic (1:100,000)
Total Energy = 0 (Universe is flat!)