From Heavy-Ion Collisions to Quark Matter

Lecture 1

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CERN summer student programme 2014

Prelude

Official CERN summer student photo 1998

Acknowledgments

Lots of input (slides, graphics, discussion) from

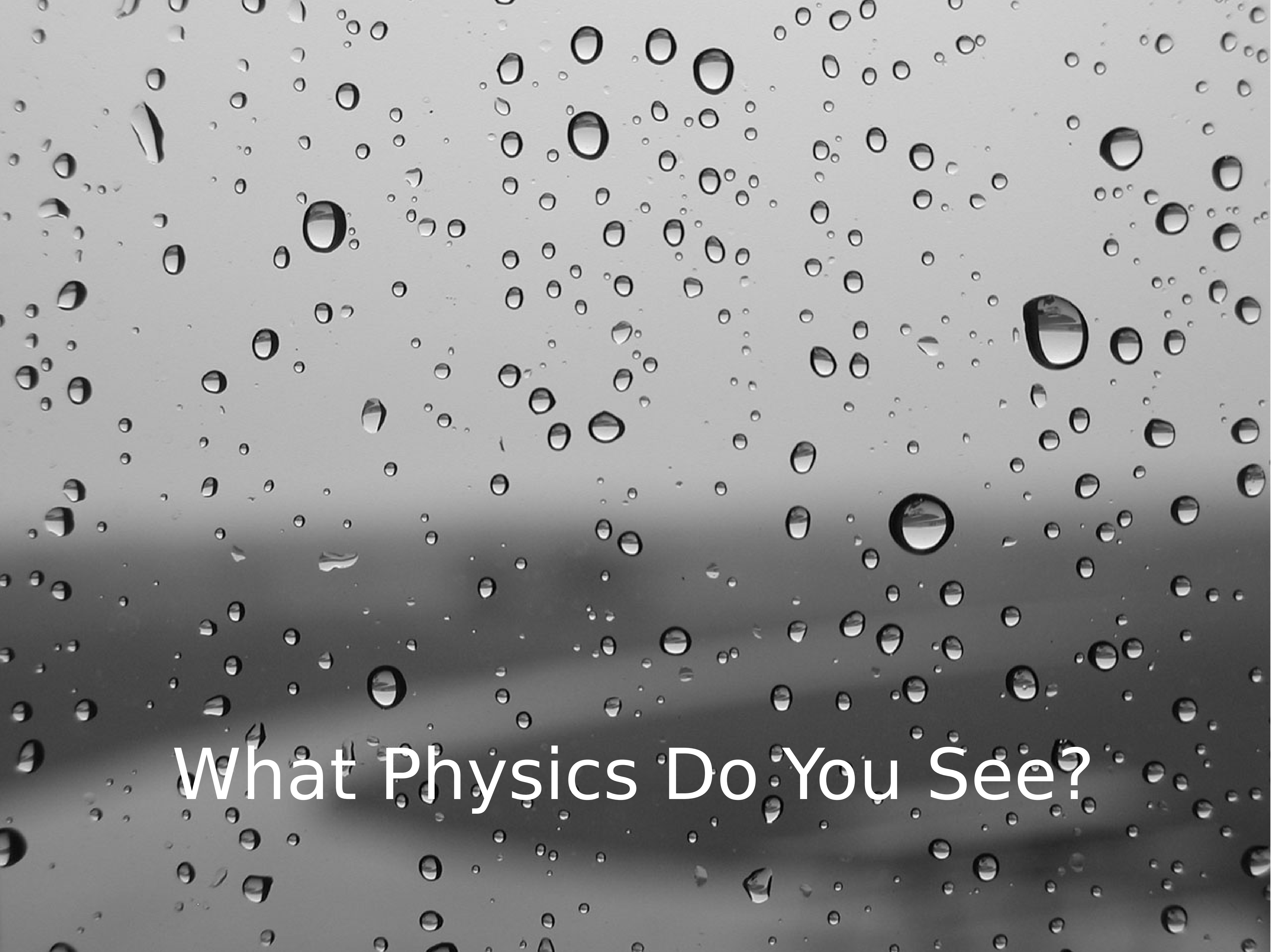
Federico Antinori
Tom Hemmick
Peter Jacobs
Jamie Nagle
Carlos Lourenco
Klaus Reygers
Enrico Scomparin
Kai Schweda
Peter Steinberg

My approach to these lectures

- The field of heavy-ion physics and QCD matter is vast, spanning experimental and theoretical concepts from nuclear, particle and condensed matter physics
- Many phenomena of the field are not yet understood on fundamental level
  - This is an opportunity for, and at the same time a barrier to newcomers to sort out what is really known and what not
- I do not aim to cover every topic in 3 lectures
  - Instead I will discuss a few topics, which are well established
    - Lecture 1: Introduction and background to the field
    - Lecture 2: Measurements mainly related to bulk properties
    - Lecture 3: Measurements mainly related to hard probes
- I am not an expert in all topics. Ask questions in the discussion session. Those I do not understand we figure out offline

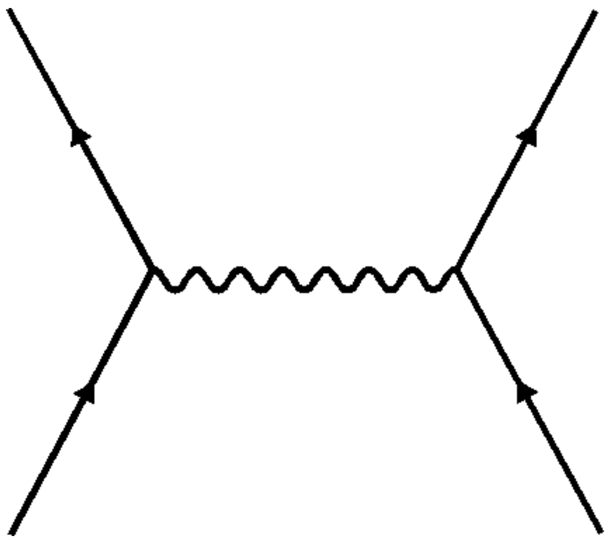
References

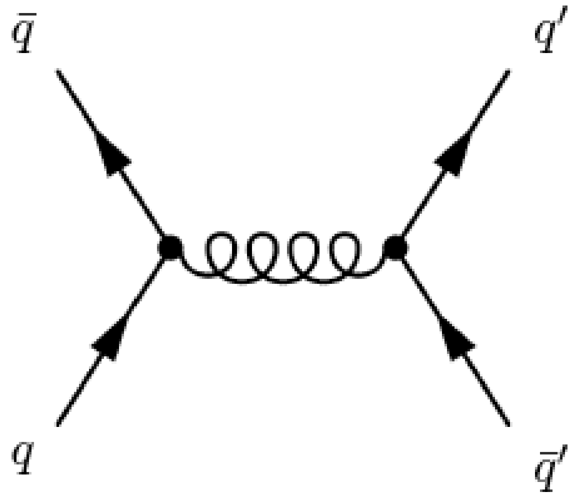
- QCD
  - QCD and jets: CTEQ web page and summer school lectures
  - Handbook of perturbative QCD, Rev. Mod. Phys. 67 (1995) 157
  - QCD and collider physics,
    Ellis, Sterling, Webber, Cambridge University Press (1996)
- Heavy-ion physics
  - Results from the Relativistic Heavy Ion Collider,
    Mueller and Nagle, Ann. Rev. Nucl. Part. Sci. 56, 93 (2006)
  - First results from Pb+Pb collisions at the LHC,
    Mueller, Schukraft, Wyslouch, arXiv:1202.3233
  - New developments in relativistic viscous hydrodynamics,
    Romatschke, Int. J. Mod. Phys E 19 (2010) 1
  - The theory and phenomenology of QCD-based jet quenching,
    Majumber and van Leeuwen, arXiv:1002.2206
  - Gauge/string duality, hot QCD and heavy ion collisions,
    Casalderrey-Solana et al., arXiv:1101.0618
  - Relativistic Heavy Ions, Stock et al., Springer (2010)



What Physics Do You See?

Physics beyond the diagram

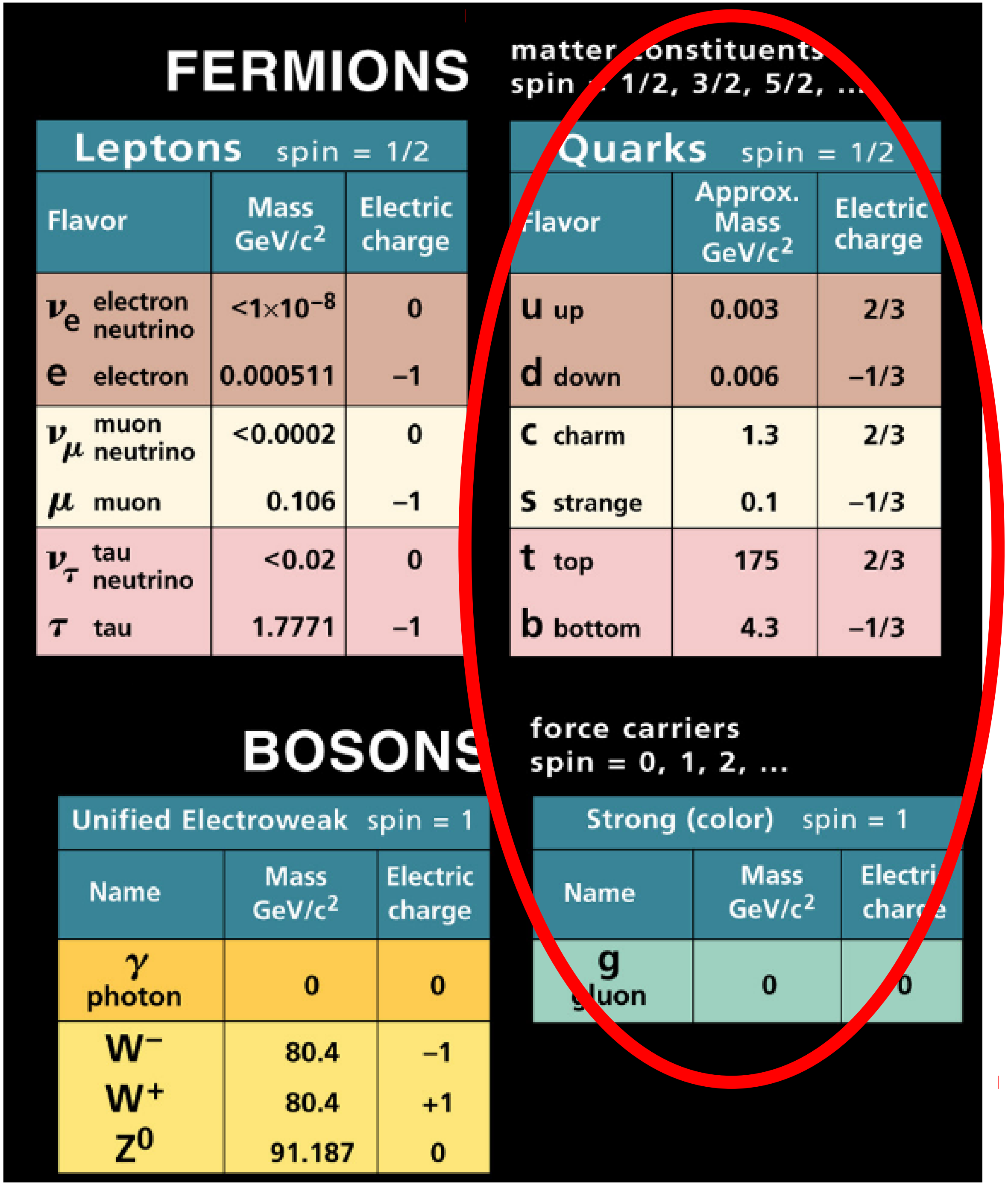




- The water droplets on the window demonstrate a principle
- True beautiful and complex physics emerges in systems whose underlying dynamics is given by QED

- Does QCD exhibit equally beautiful properties when looked at as bulk matter
- Answer (as we will see): YES!

The standard model and QCD



FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

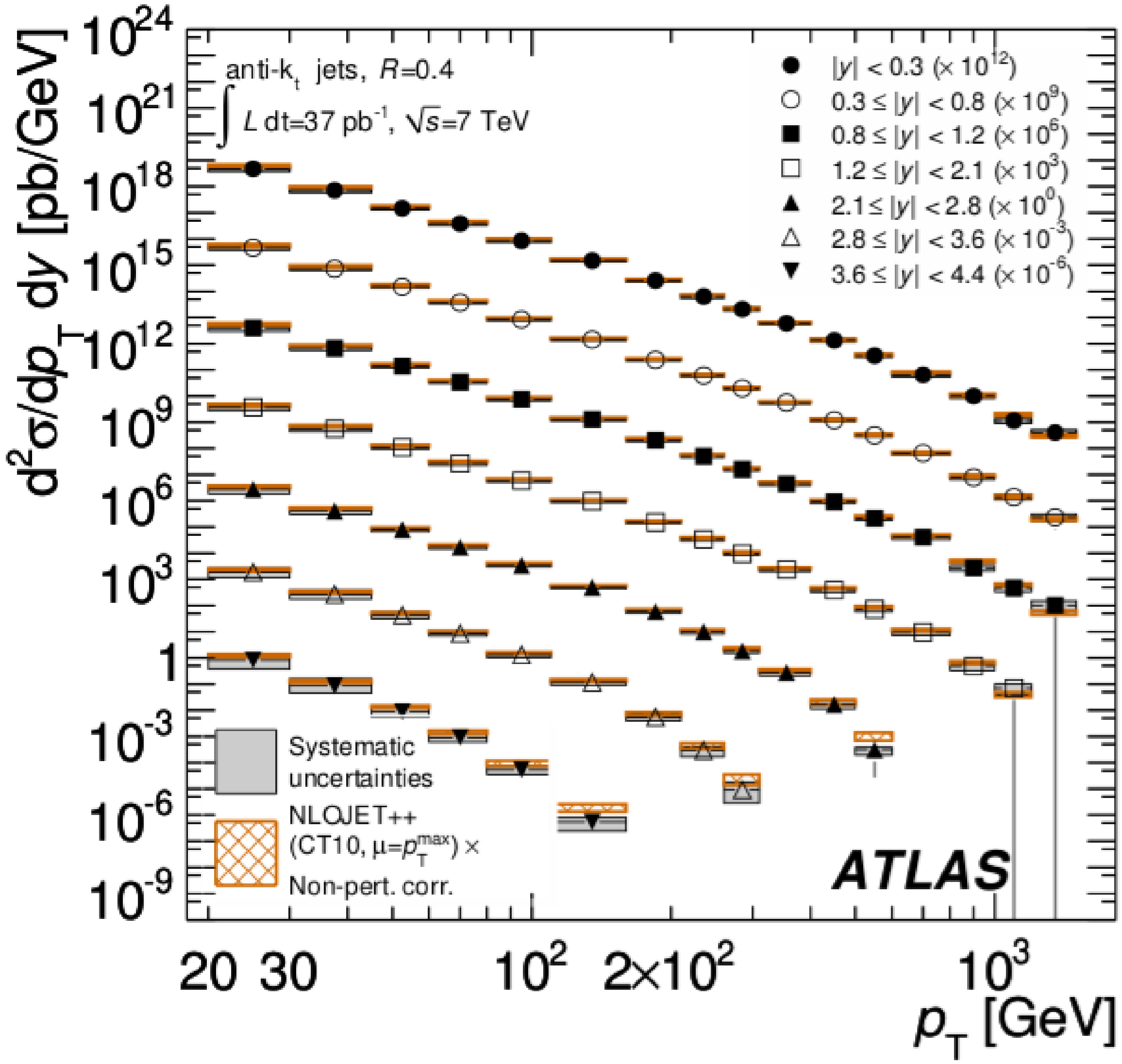
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

- Strong interactions
  - Binds quarks into hadrons
  - Binds nucleons into nuclei
- Described by QCD
  - Interactions between quarks and gluons carrying color charge
  - Mediated by gluons, the strong force carriers

The standard model and QCD



ATLAS, Phys.Rev. D86 (2012) 014022

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  - e.g. pQCD vs production of high energy jets

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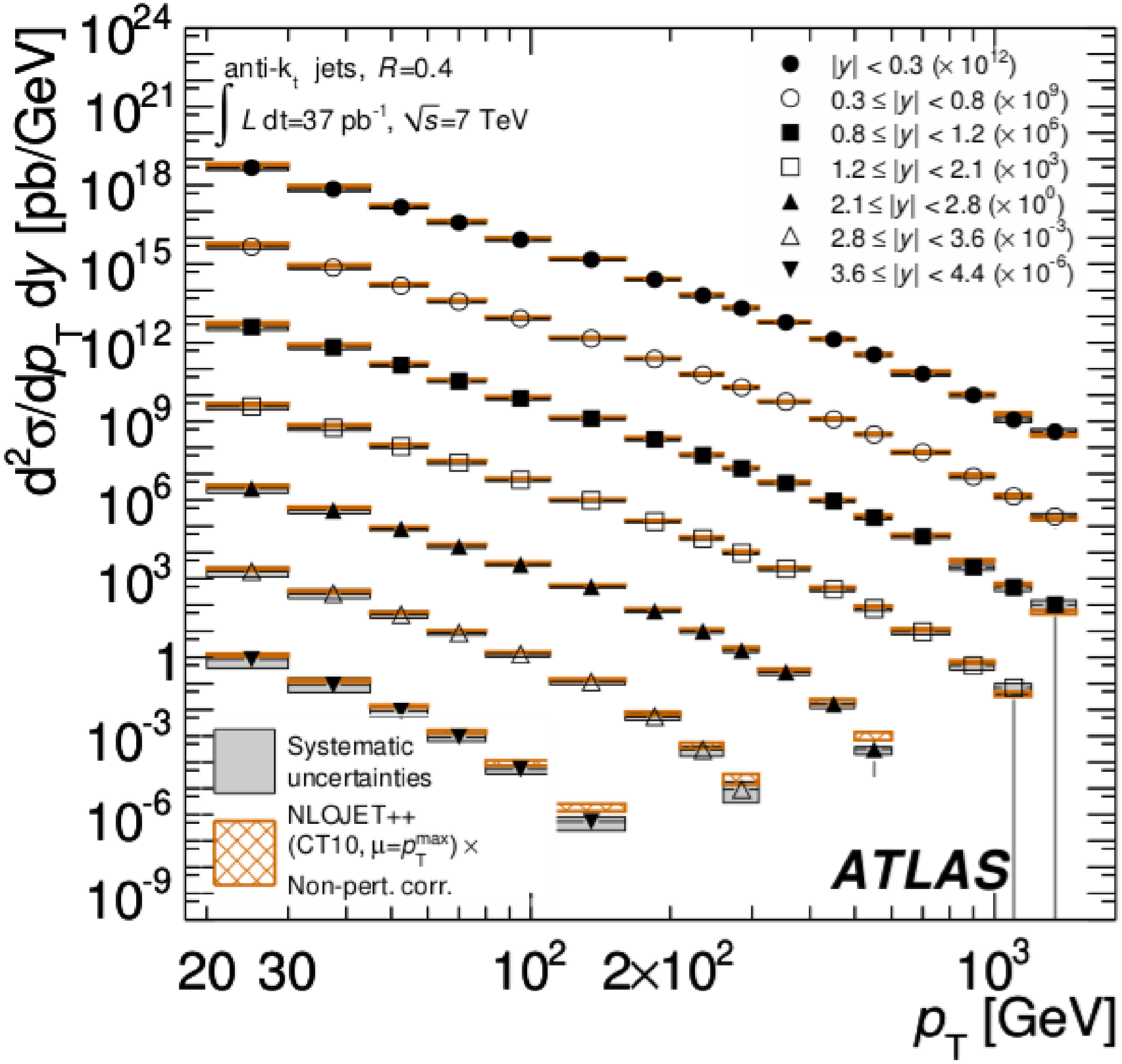

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- Strong interactions
  - Binds quarks into hadrons
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- Described by QCD
  - Interactions between quarks and gluons carrying color charge
  - Mediated by gluons, the strong force carriers
- Very successful theory
  - e.g. pQCD vs production of high energy jets
- But with outstanding puzzles!

Two puzzles in QCD:

i) hadron masses

- A proton is thought to be composed out of uud
- The proton mass is about 938.3 MeV/c
- Sum of bare quark masses is only about 12 MeV
- How is the extra mass generated?

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- Sum of bare quark masses is only about 12 MeV
- How is the extra mass generated?

ii) confinement

- Nobody ever succeeded in detecting an isolated quark
- Instead, quarks seem to be confined within hadrons
- It looks like one half of the fundamental fermions are not directly observable. Why?

Quantum Chromo Dynamics (QCD)

Elementary fields: **Quarks** **Gluons**

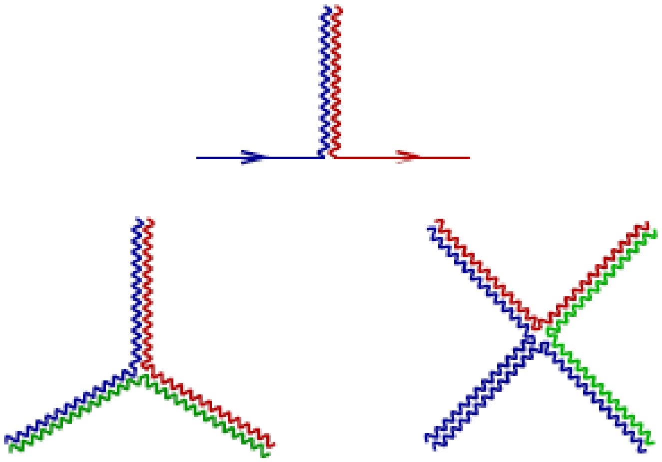
$$(q_\alpha)^a_f \begin{cases} \text{color} & a = 1, \ldots, 3 \\ \text{spin} & \alpha = 1, 2 \\ \text{flavor} & f = u, d, s, c, b, t \end{cases} \qquad A^a_\mu \begin{cases} \text{color} & a = 1, \ldots, 8 \\ \text{spin} & \epsilon^\pm_\mu \end{cases}$$

Dynamics: Generalized Maxwell (Yang-Mills) + Dirac theory

$$\boxed{\mathcal{L} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}}$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

$$i\not{D} q = \gamma^\mu \left(i\partial_\mu + g A^a_\mu t^a \right) q$$



Quantum Chromo Dynamics (QCD)

Same basic structure as
QED (electro-magnetism) ...

Gluons

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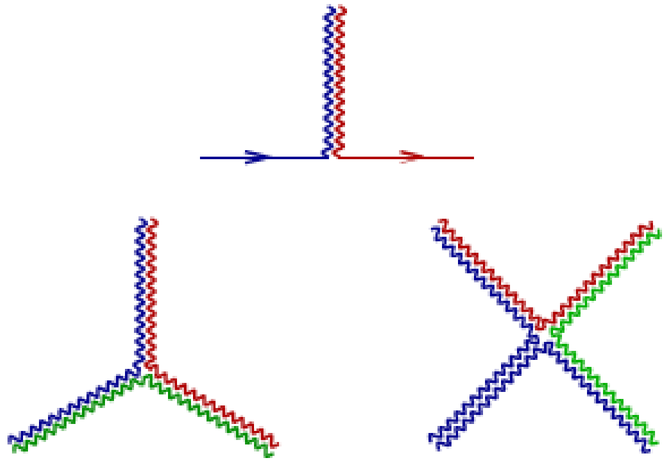

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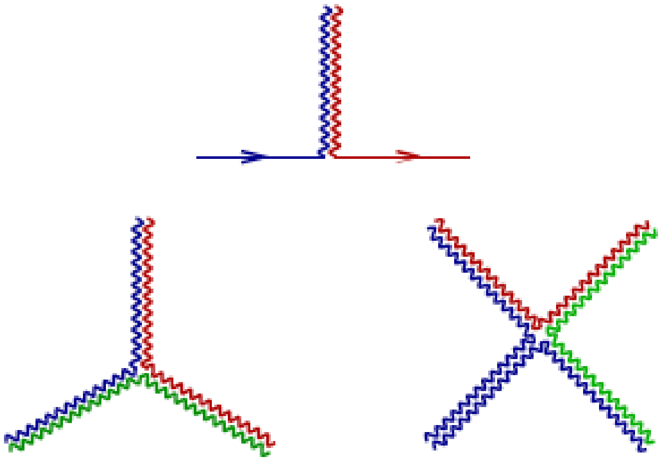

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Dynamics: Generalized Maxwell (Yang-Mills)

... so they interact also among themselves, generating much more complex structures

$$\boxed{\mathcal{L} = \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}}$$

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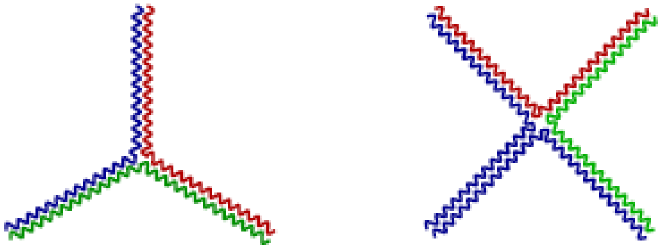
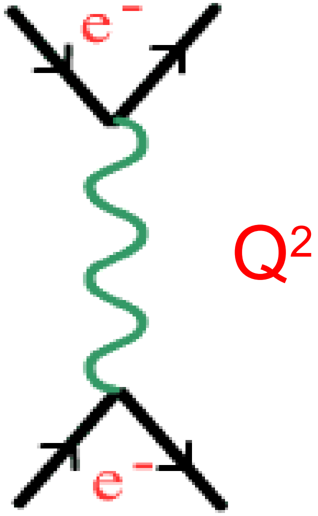


Field theory: “Running” of the coupling

Consider the interaction of two elementary particles



Momentum transfer Q^2:
Small $Q^2 \Rightarrow$ large distance scales
Large $Q^2 \Rightarrow$ small distance scales

Quantum mechanics:
Virtual pairs (loops) screen the bare interaction
resulting in momentum dependent interaction strength

“Running” of the coupling: QED vs QCD

$$\alpha \equiv \frac{g^2}{4\pi}$$

QED:

$$\frac{1}{\alpha\left(Q^2\right)} \approx \frac{1}{\alpha\left(\mu^2\right)} \overset{\text{negative}}{-} \frac{1}{3\pi} \log \frac{\left|Q^2\right|}{\mu^2}$$

Smaller |Q^2| (larger distance) ⇒ weaker coupling
(similar to screening of charge in di-electric material)

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= (33-12)/12π = positive!

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negative

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QCD:

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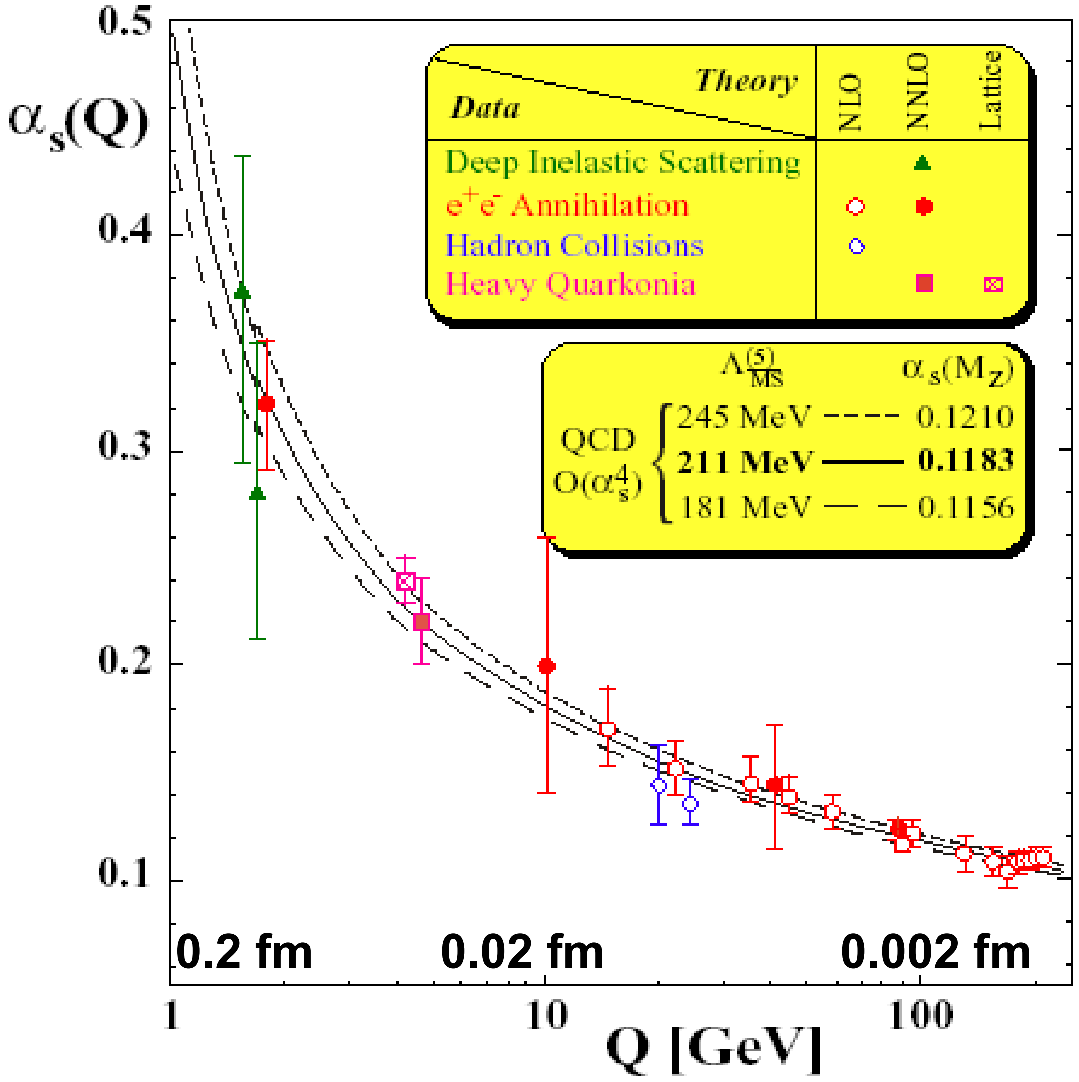
= (33-12)/12π = positive!

Smaller |Q^2| (larger distance) ⇒ stronger coupling
(so called anti-screening stronger than screening)

And that makes a huge difference!

“Running” of the coupling: QCD



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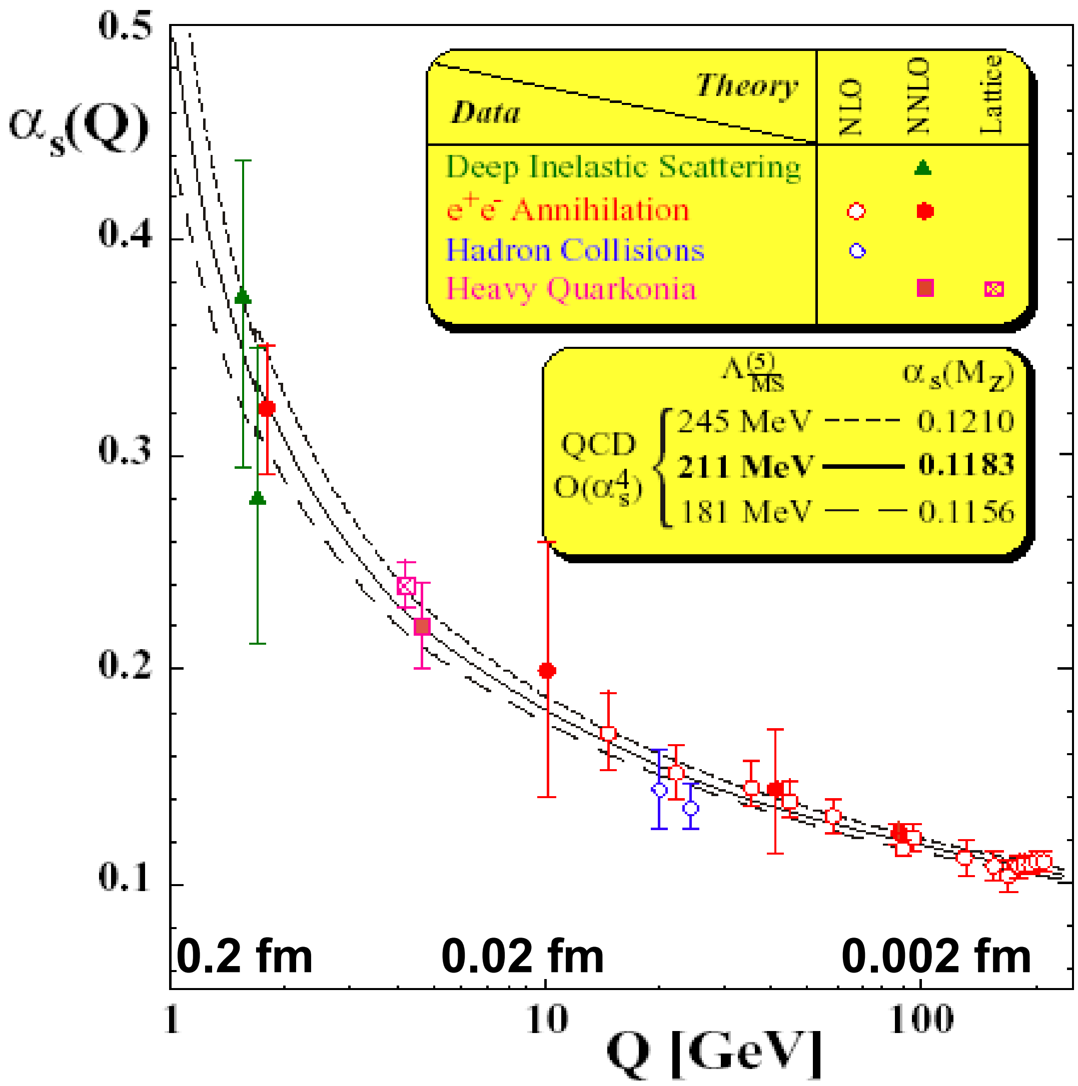
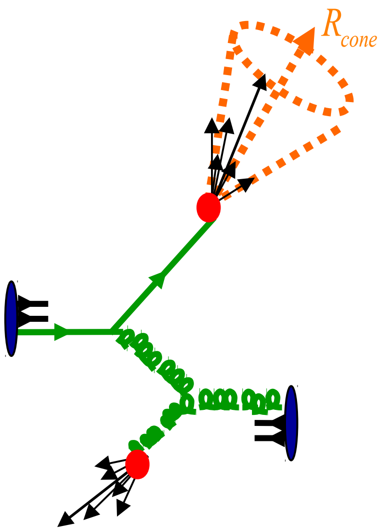


Asymptotic freedom



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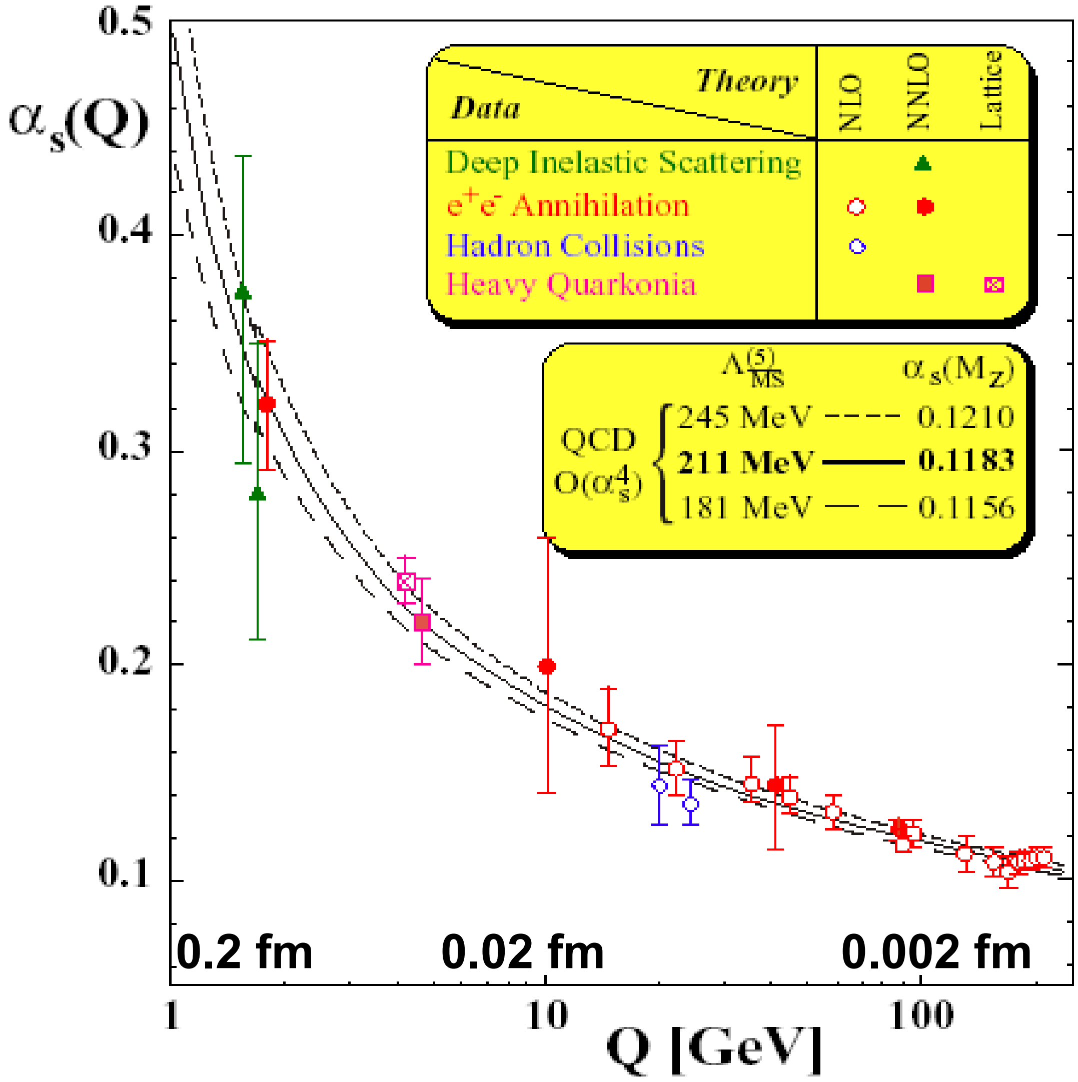

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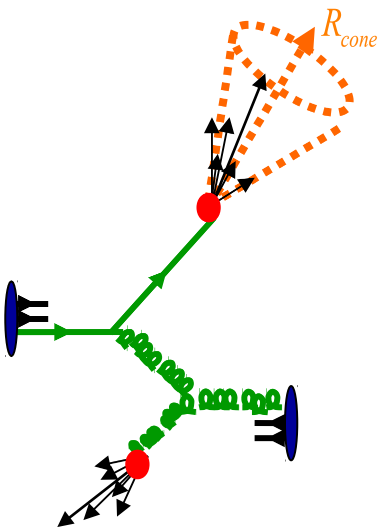

2004 Nobel Prize

PHYSICAL REVIEW D VOLUME 8, NUMBER 10 15 NOVEMBER 1973

Asymptotically Free Gauge Theories. I*

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(Received 23 July 1973)

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

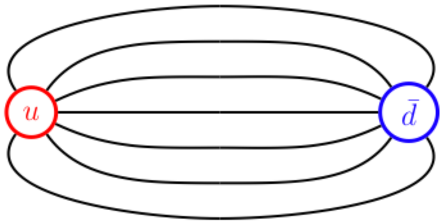
Reliable Perturbative Results for Strong Interactions?*

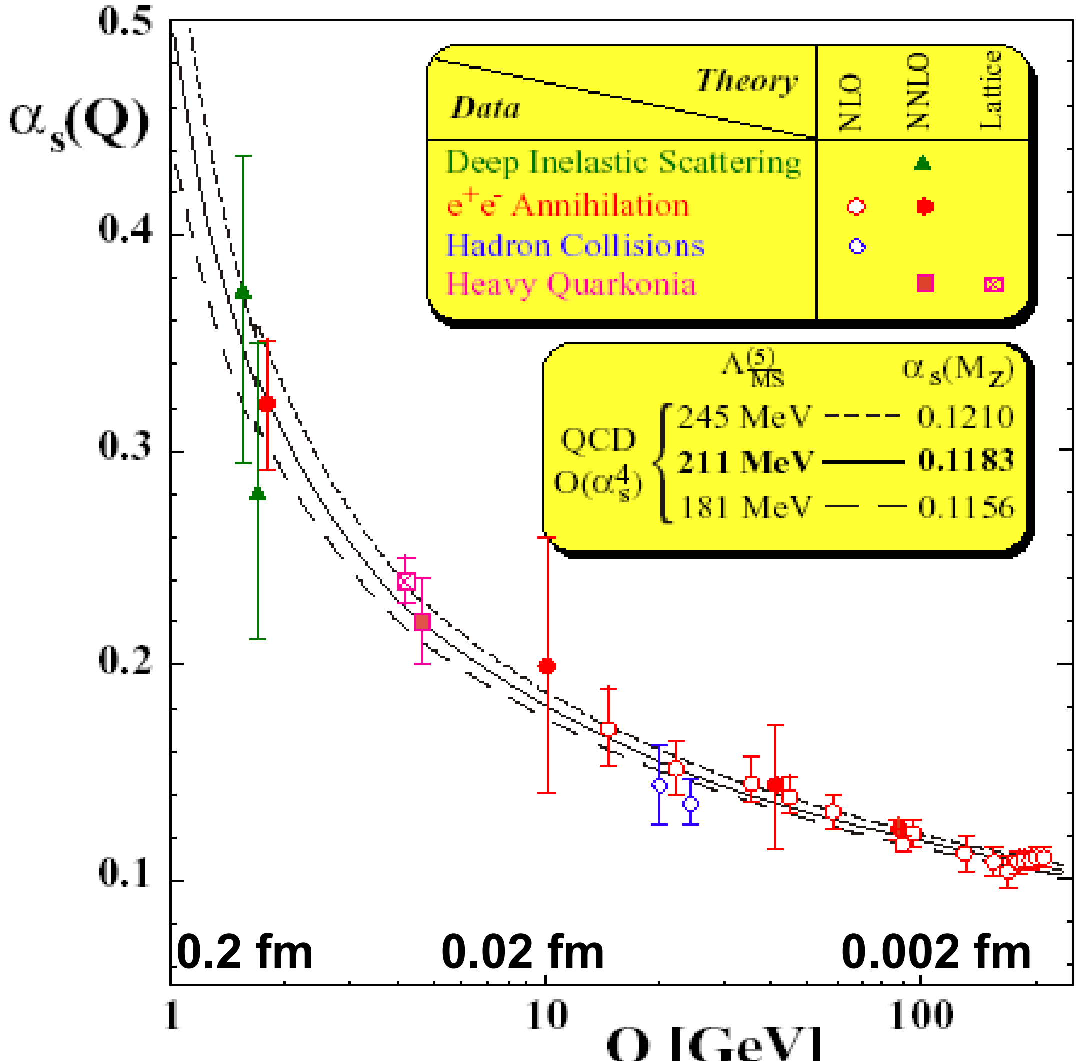
H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138

(Received 3 May 1973)

“Running” of the coupling: QCD

Confinement





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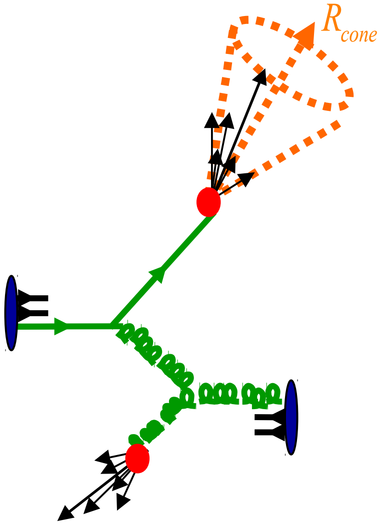

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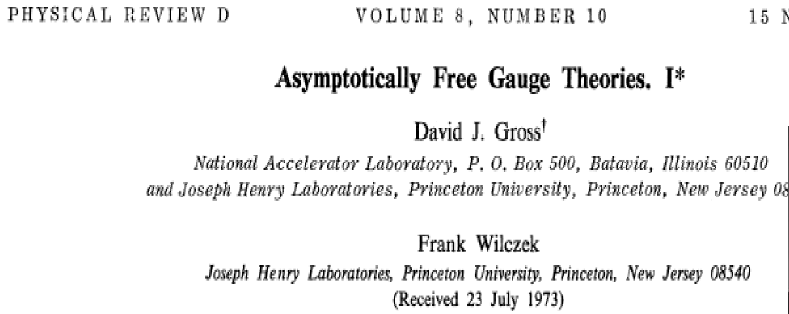

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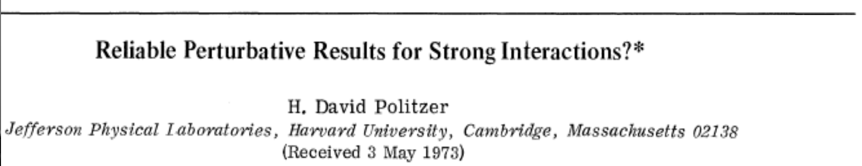

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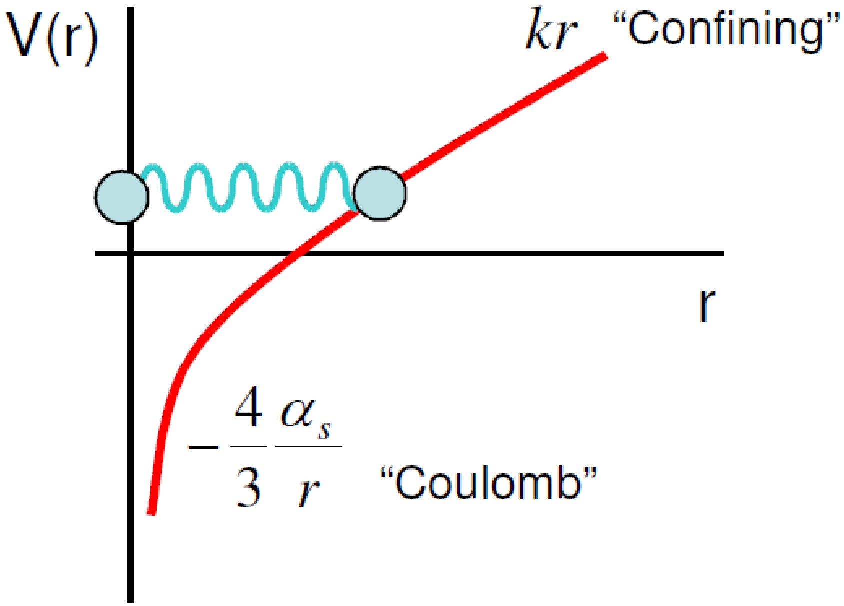
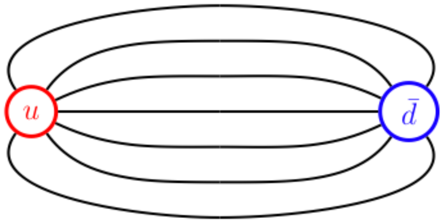
From a confined world ...

- The increase of the interaction strength (for a $q\bar{q}$ pair) can be approximated by the Cornell potential

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + K\,r$$

- Kr parametrizes the effects of confinement
- When r increases, the color field can be seen as a tube
- At large r, it become energetically favorable to convert the stored energy into a new $q\bar{q}$ pair
- Confinement cannot be described perturbatively, but with lattice QCD or bag models inspired by QCD





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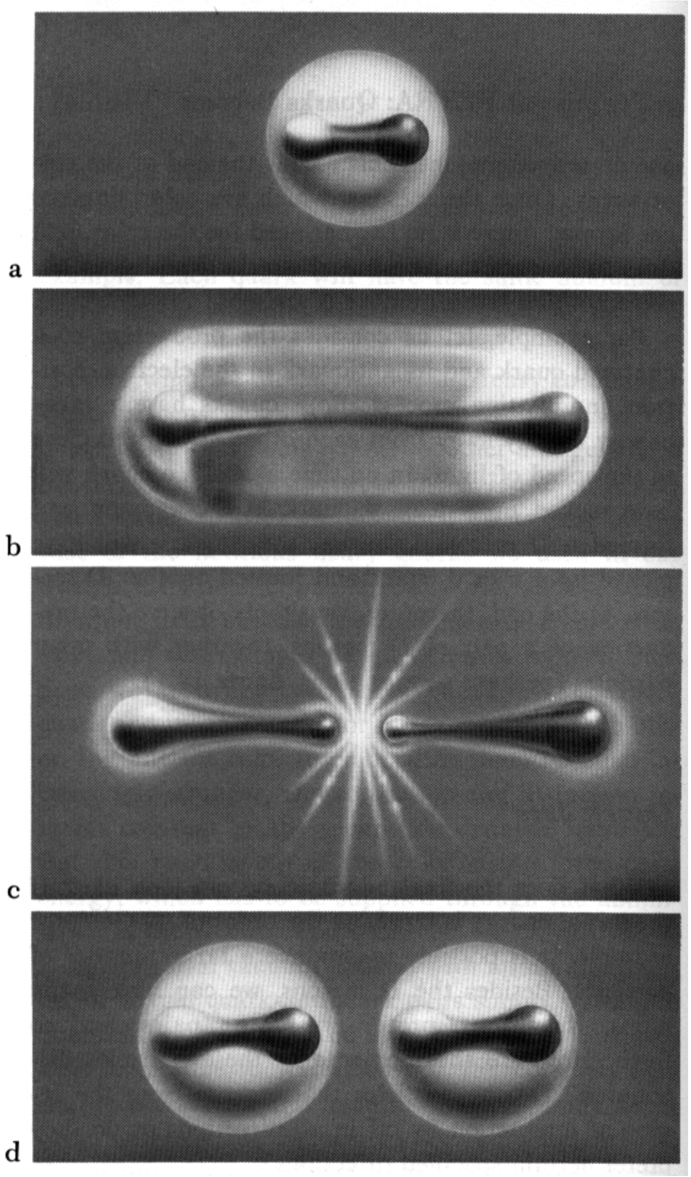

(Illustration from Fritzsch)

... to deconfinement

- Since the interactions between quarks and gluons become weaker at small distances, it might be possible to create a deconfined phase of matter composed out of a large number of free quarks and gluons

- First ideas in the mid 1970's

Experimental hadronic spectrum
and quark liberation
Cabibbo and Parisi, PLB59 (1975) 67

Superdense matter: Neutrons or
asymptotically free quarks?
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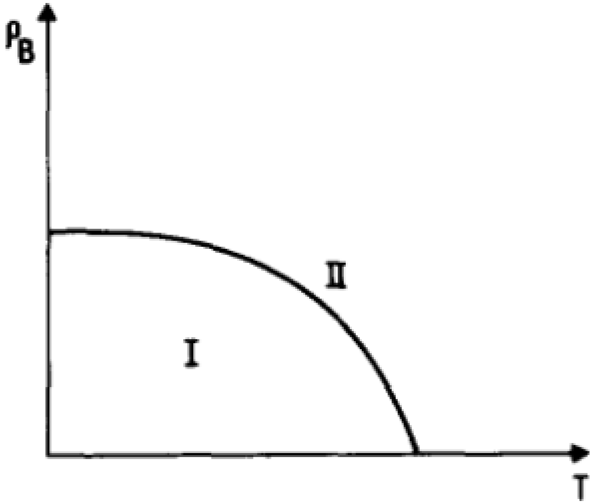

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

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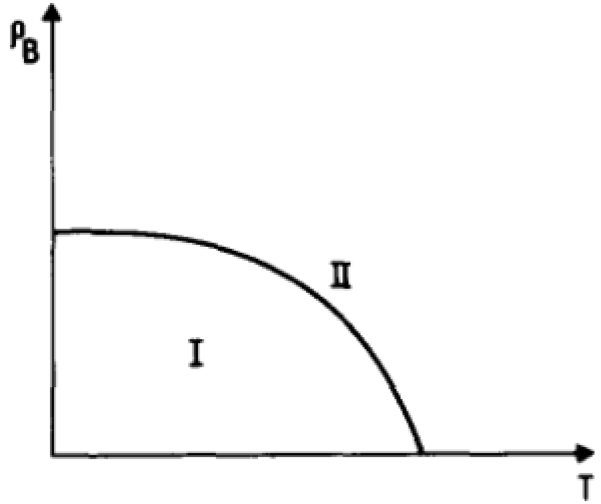

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Phase transition
at large T

We expect models of this kind to give rise to a phase transition at a temperature $kT \approx m_\pi$, the high temperature phase being one where quarks can move freely in space.

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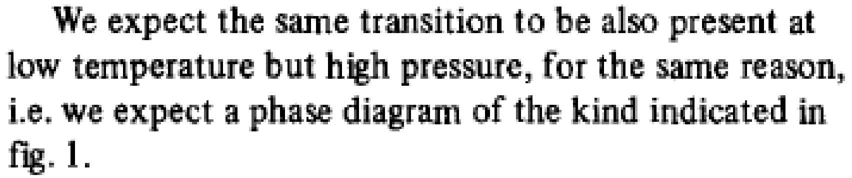
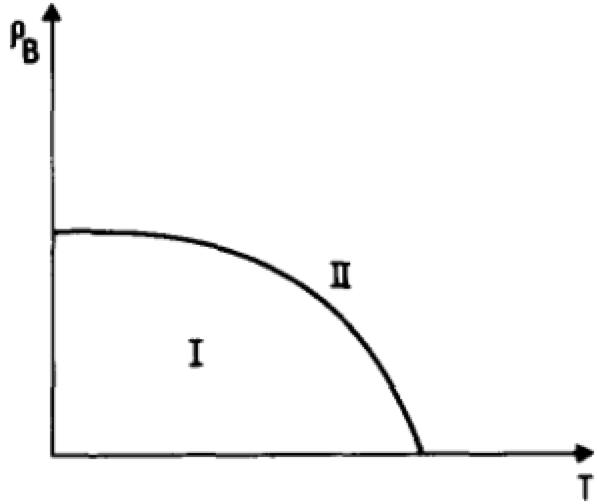


We expect the same transition to be also present at low temperature but high pressure, for the same reason, i.e. we expect a phase diagram of the kind indicated in fig. 1.



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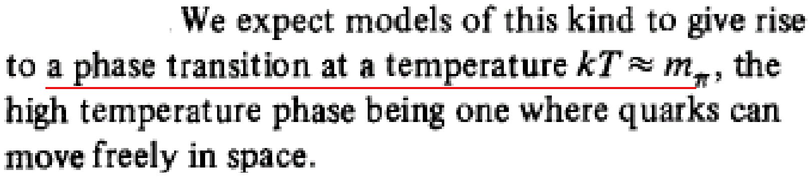
Phase transition at large T and/or ρ_B



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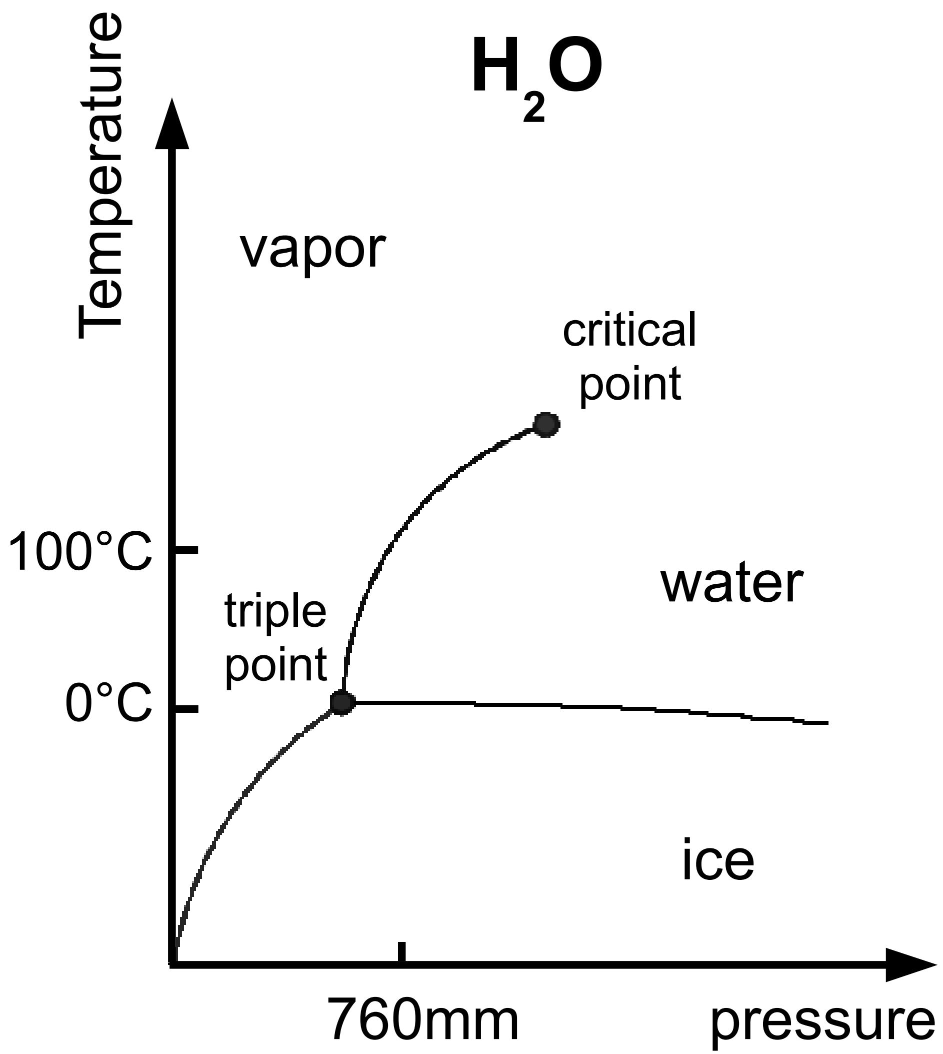
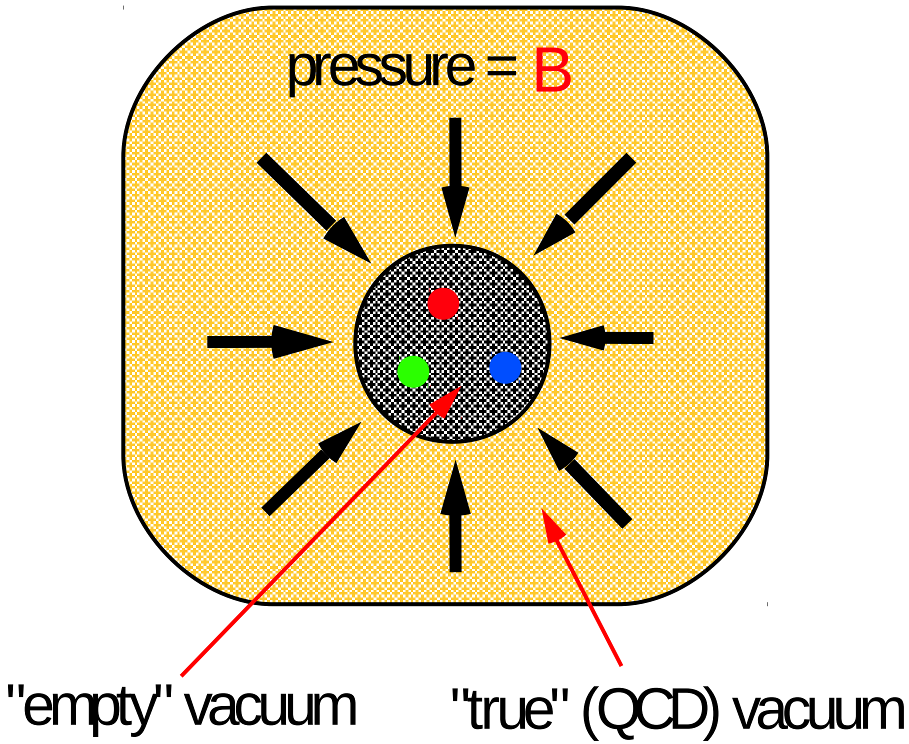
Reminder: Phase diagram



Building intuition: The MIT Bag model

- The MIT bag model assumes that quarks are confined within bags of perturbative (empty) vacuum of radius R, in which they are free to move
- The QCD (true) vacuum exerts a confining bag pressure B
- The bag pressure is obtained by balancing the vacuum with the kinetic pressure of the quarks
- B ≈ (200 MeV)^4 with N=3 quarks in R=0.8fm

Bag model of a hadron:



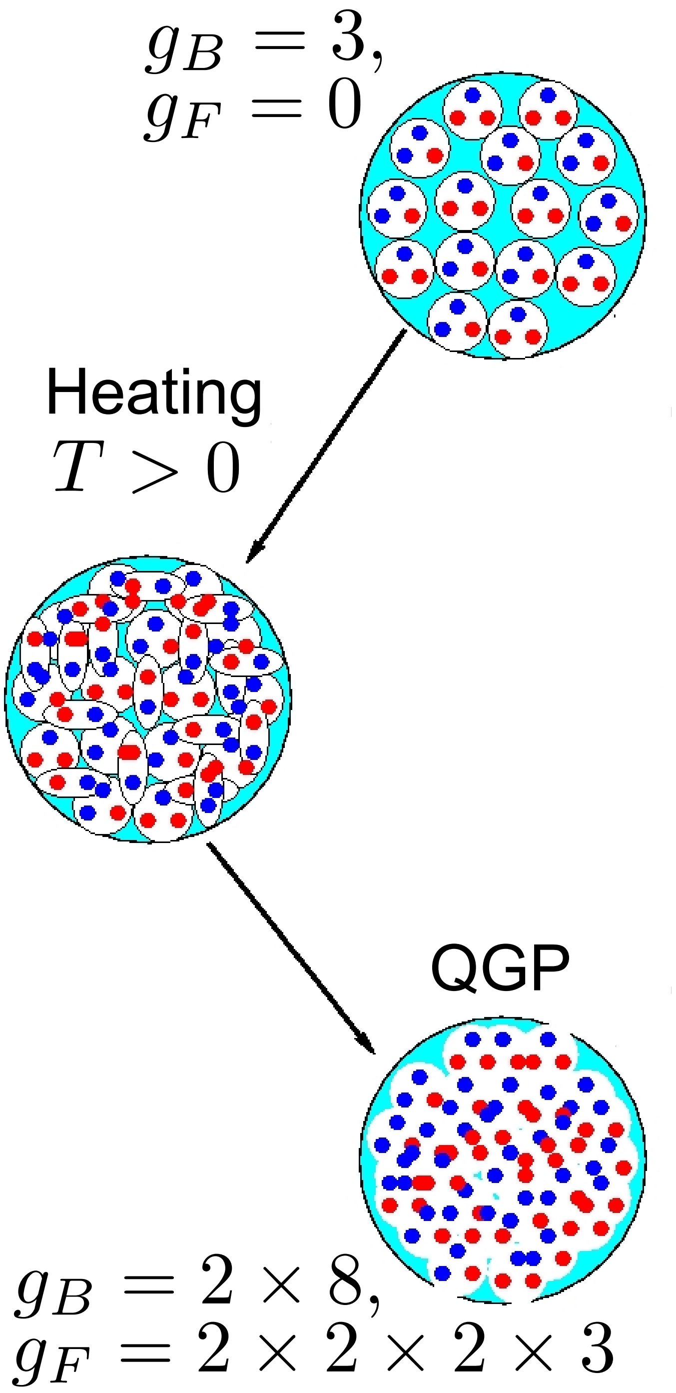
B = "bag constant" $B^{1/4} \approx$ 200 MeV

Chodos et al., PRD 10 (1974) 2599

Deconfinement: A toy model

- Heat matter so much that individual hadrons start to overlap
- From statistical mechanics for an ideal gas

$$p = \frac{\epsilon}{3} = \left(g_B + \frac{7}{8} g_F\right) \frac{\pi^2 T^4}{90}$$



$g_B = 3,$
$g_F = 0$

$T > 0$

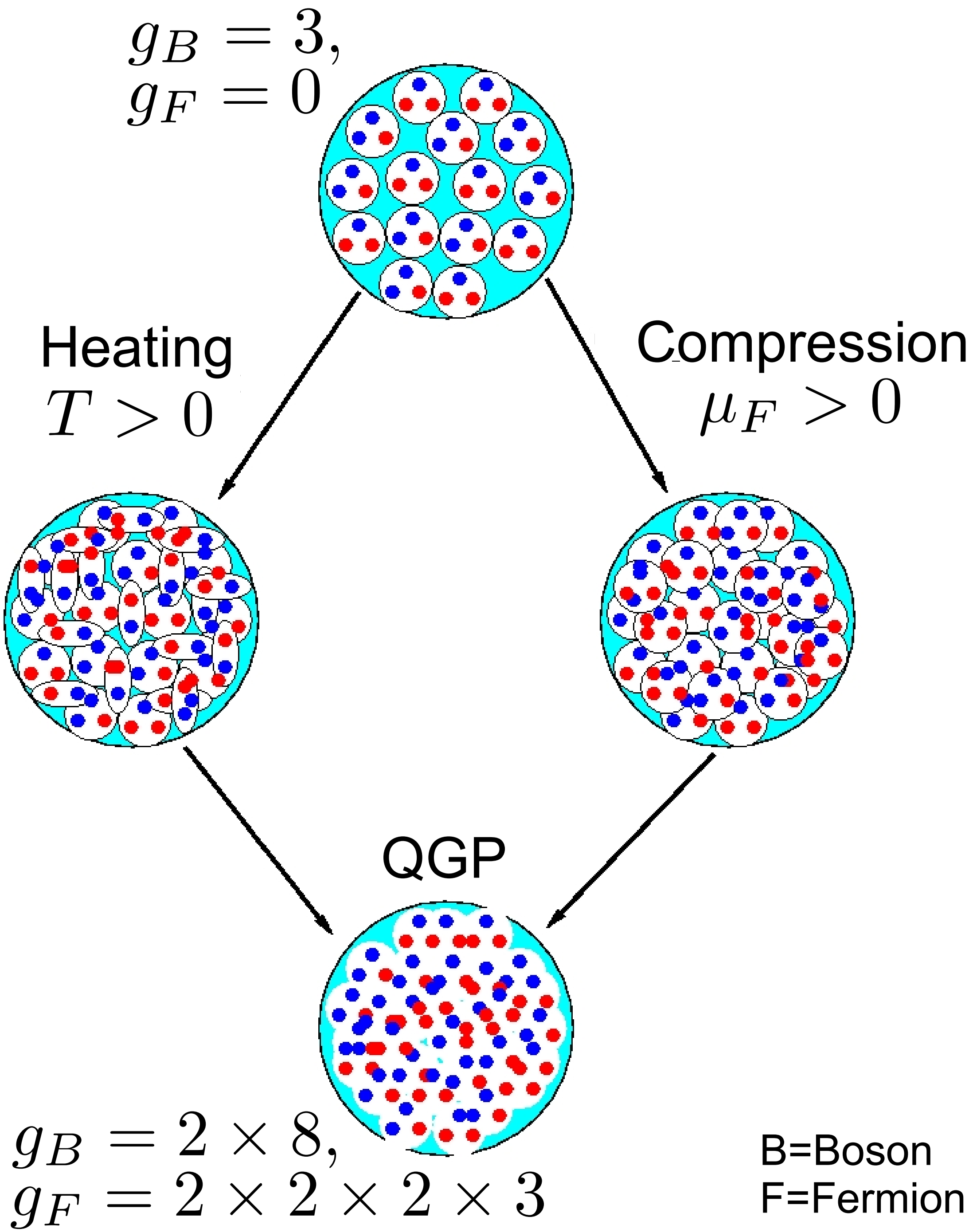
$g_B = 2 \times 8,$
$g_F = 2 \times 2 \times 2 \times 3$

B=Boson
F=Fermion

Deconfinement: A toy model

- Heat or compress matter so much that individual hadrons start to overlap
- From statistical mechanics for an ideal gas

$$p = \frac{\epsilon}{3} = \left(g_B + \frac{7}{8} g_F\right) \frac{\pi^2 T^4}{90} + g_F \left(\frac{\mu_F^2 T^2}{12} + \frac{\mu_F^4}{24\pi^2}\right)$$



$g_B = 3,$
$g_F = 0$

Heating
$T > 0$

Compression
$\mu_F > 0$

QGP

$g_B = 2 \times 8,$
$g_F = 2 \times 2 \times 2 \times 3$

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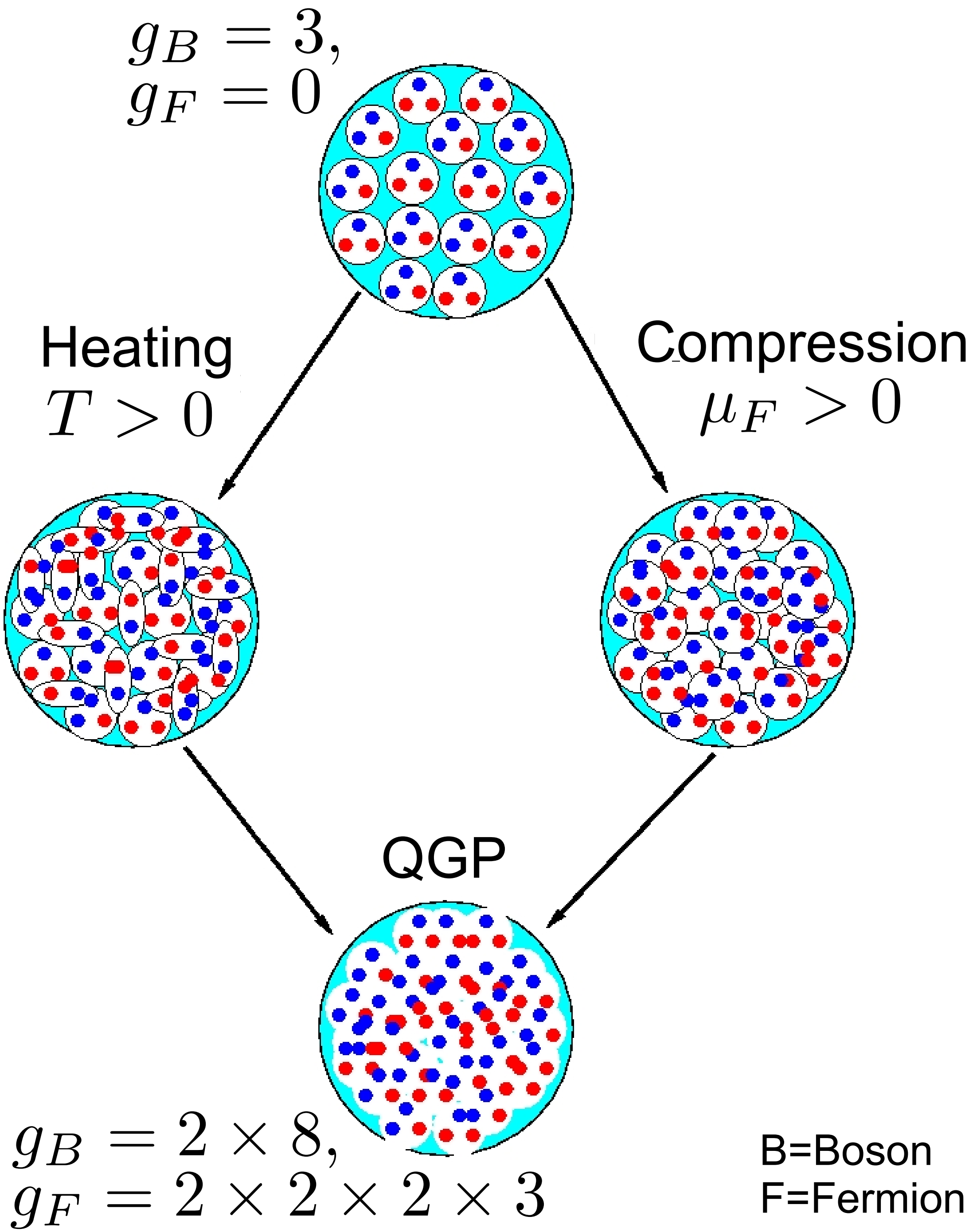
- Condition for QGP: Pressure ≥ B

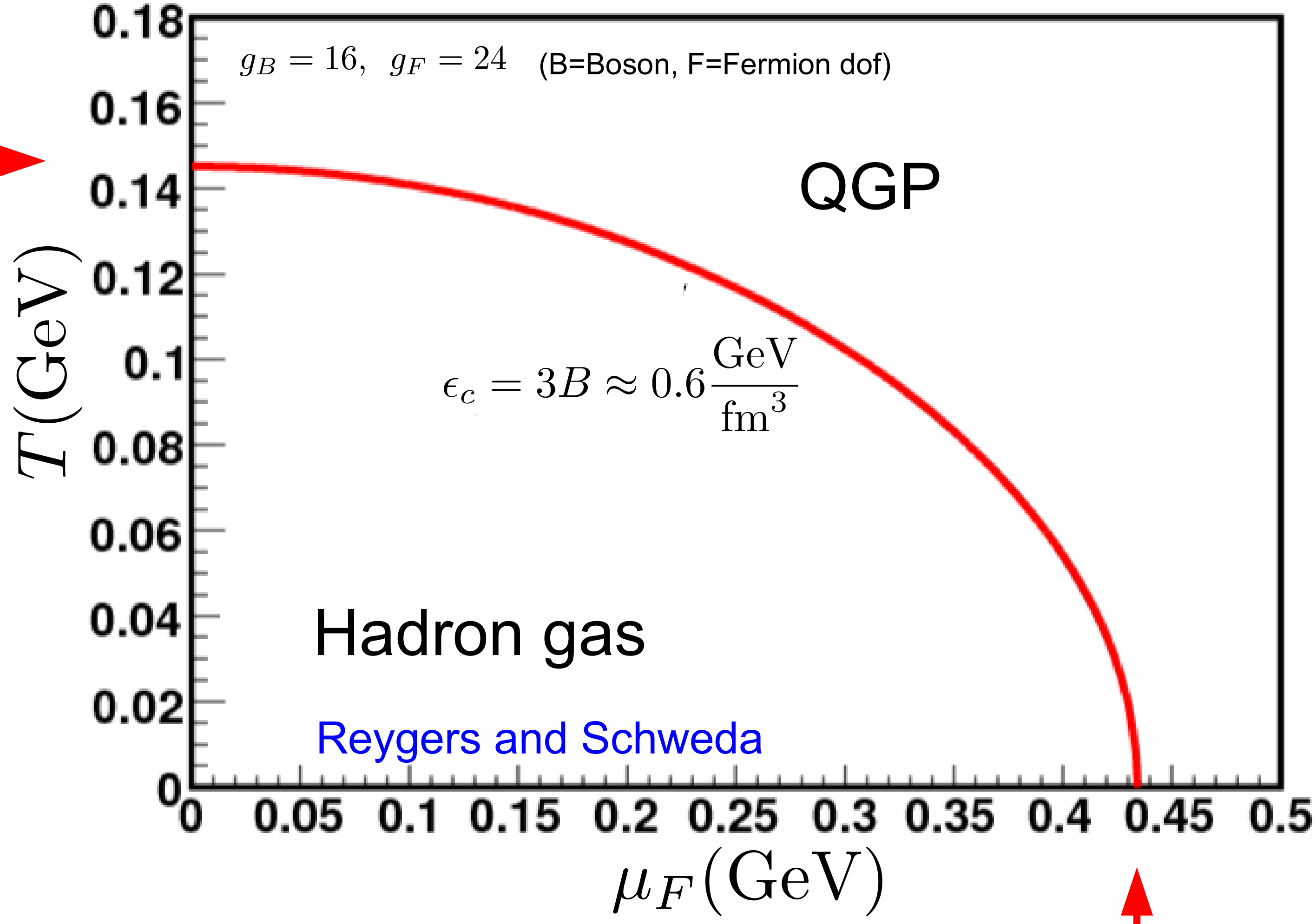
$$p = \frac{\epsilon}{3} \overset{!}{=} B \Rightarrow T_c(\mu_F)$$



Phase diagram of non-interacting QGP

$T_c \approx 2 \cdot 10^{12}\mathrm{K}$

(10⁵ times core of sun)



Reygers and Schweda

- Condition for QGP: Pressure ≥ B

$$p = \frac{\epsilon}{3} \overset{!}{=} B \Rightarrow T_c(\mu_F)$$

$n_c^B = 0.72\mathrm{fm}^{-3}$

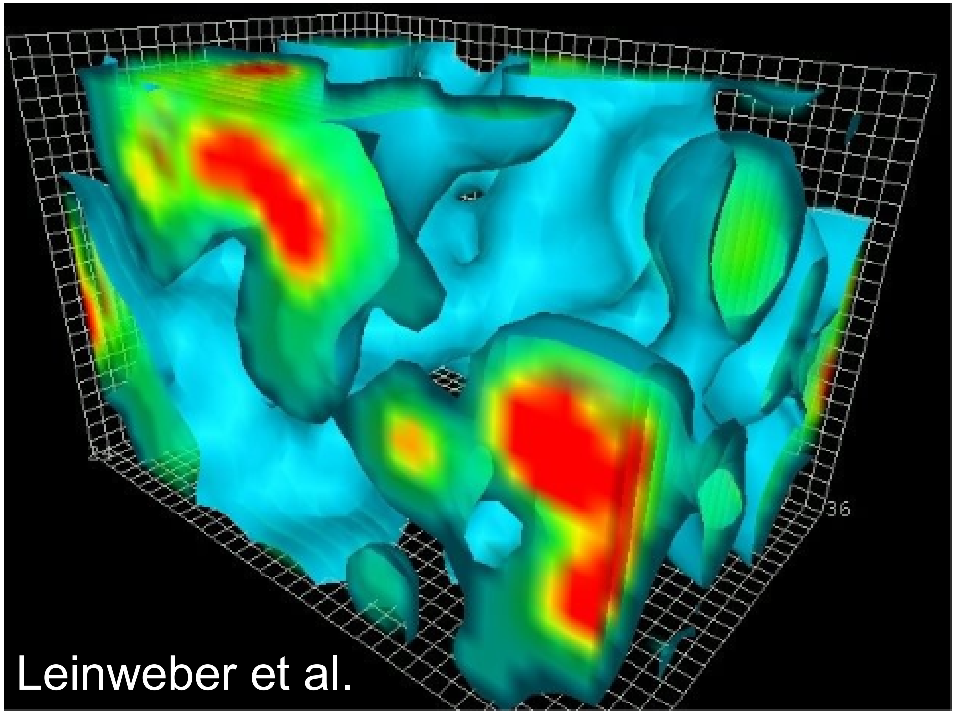
(5 x nucleus)

Lattice QCD

- As QCD is asymptotically free at small distances, cannot use perturbation theory to calculate properties of e.g. hadrons
- Instead solve QCD numerically by putting fields on a space-time lattice (lattice QCD)
- First principle non-perturbative calculation
- Computationally demanding as lattice needs to be big, e.g. 16^3x32

JUGENE in Jülich
(294,912 cores, ~ 1 PetaFLOPSS

Snapshot of fluctuating quark and gluon fields on a discrete space-time lattice



Leinweber et al.

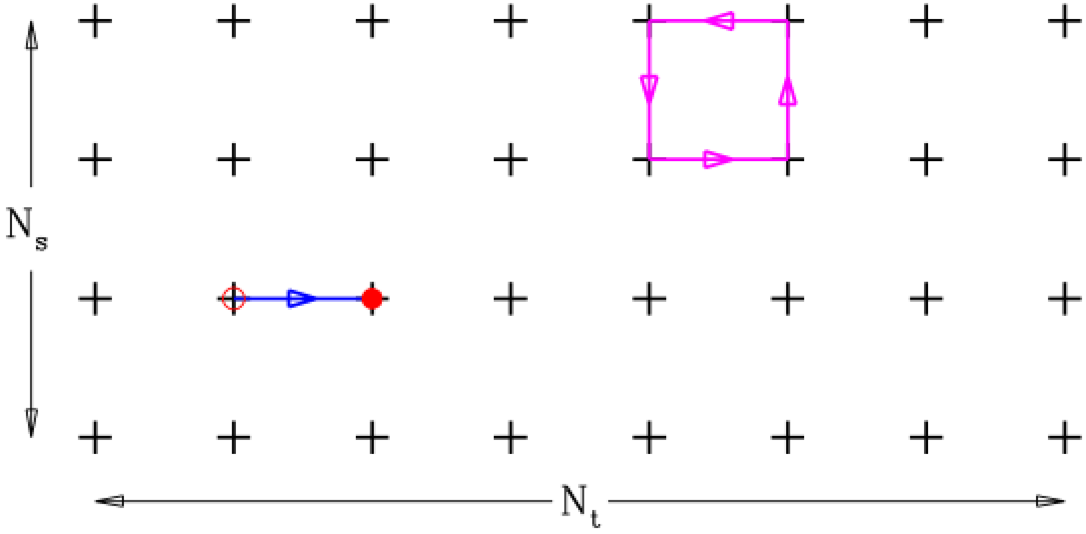
Lattice QCD: the approach

- Solve path integrals numerically in discretised Euclidean space-time

$$e^{i\,S} \to e^{-S_E}$$

Lattice spacing $a, \quad a^{-1} \sim \Lambda_{\mathrm{UV}}, \quad x_\mu = n_\mu a$

Finite volume $L^3 \cdot T, \quad N_s = L/a, \quad N_t = T/a$



(anti)quarks: $\psi(x), \overline{\psi}(x)$

gluons: $U_\mu(x) = \mathrm{e}^{aA_\mu(x)} \in \mathrm{SU}(3)$

field tensor: $P_{\mu\nu}(x) = U_\mu(x)U_\nu(x+a\hat{\mu}) U_\mu^\dagger(x+a\hat{\nu})U_\nu^\dagger(x)$

$$\boxed{S[U,\overline{\psi},\psi] = S_{\mathrm{G}}[U] + S_{\mathrm{F}}[U,\overline{\psi},\psi]}$$

(see, e.g. Wittig)

Lattice QCD: the approach

- Solve path integrals numerically in discretised Euclidean space-time

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- Physical results
  - Continuum limit (a → 0)
  - Infinite volume limit (V → ∞)
  - Set scale(s) using data e.g. hadron mass(es)

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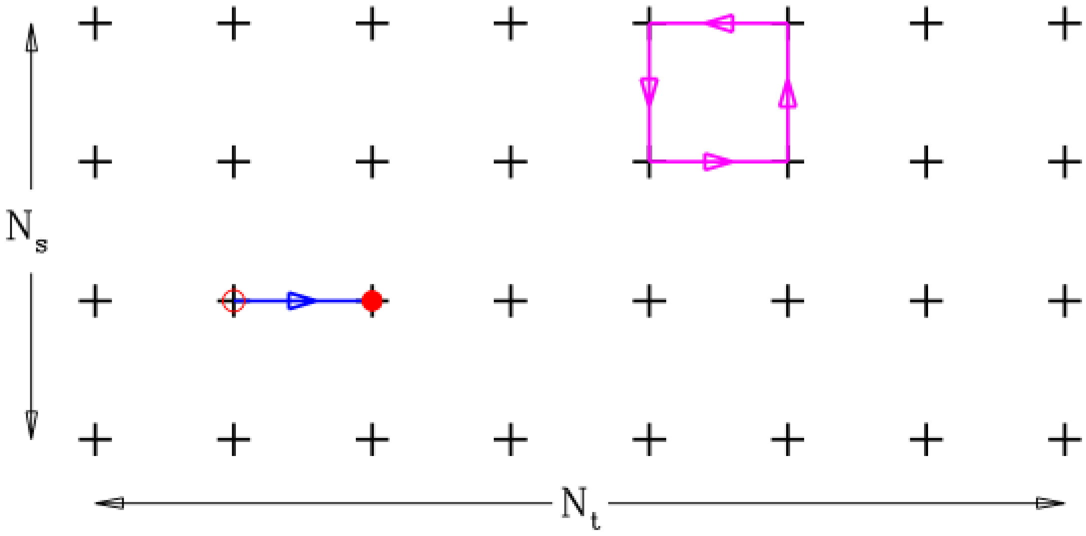

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Lattice QCD: the approach

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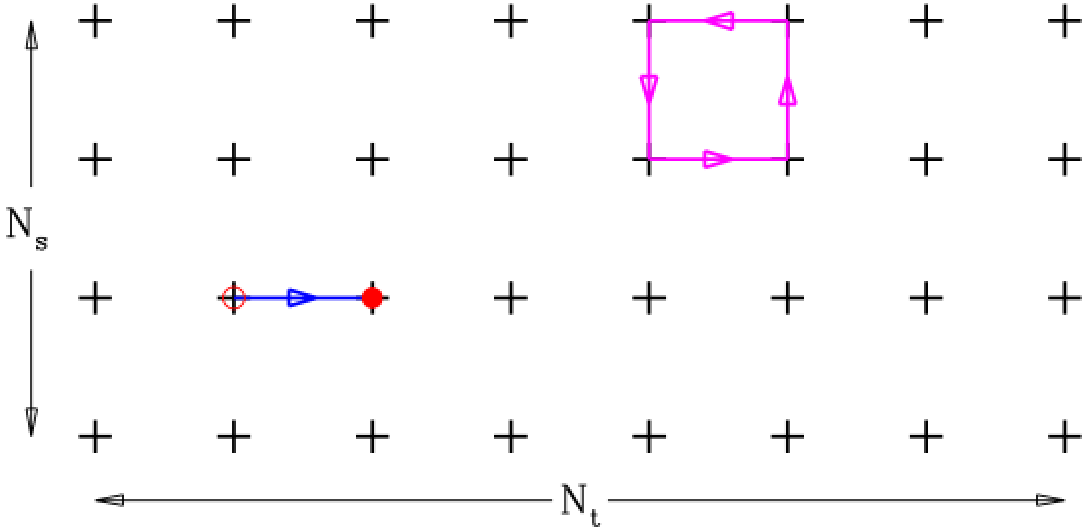
$$e^{i\,S} \rightarrow e^{-S_E}$$

- Physical results
  - Continuum limit (a → 0)
  - Infinite volume limit (V → ∞)
  - Set scale(s) using data e.g. hadron mass(es)

- Problems of approach
  - Fermion doubling
  - Sign problem for finite μ
  - Small physical quark masses computationally demanding

Lattice spacing $a, \quad a^{-1} \sim \Lambda_{\mathrm{UV}}, \quad x_\mu = n_\mu a$

Finite volume $L^3 \cdot T, \quad N_s = L/a, \quad N_t = T/a$



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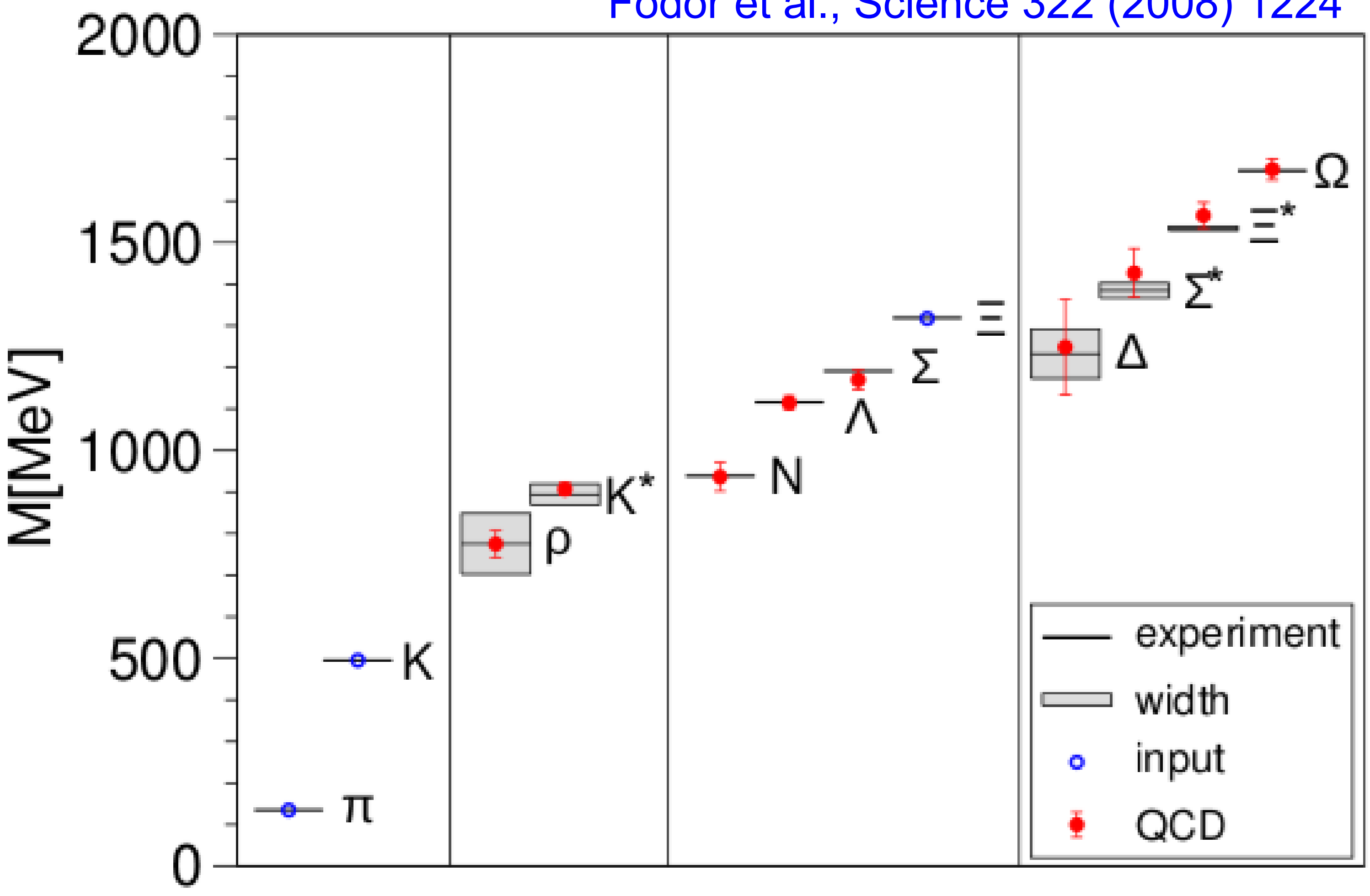
(see, e.g. Wittig)

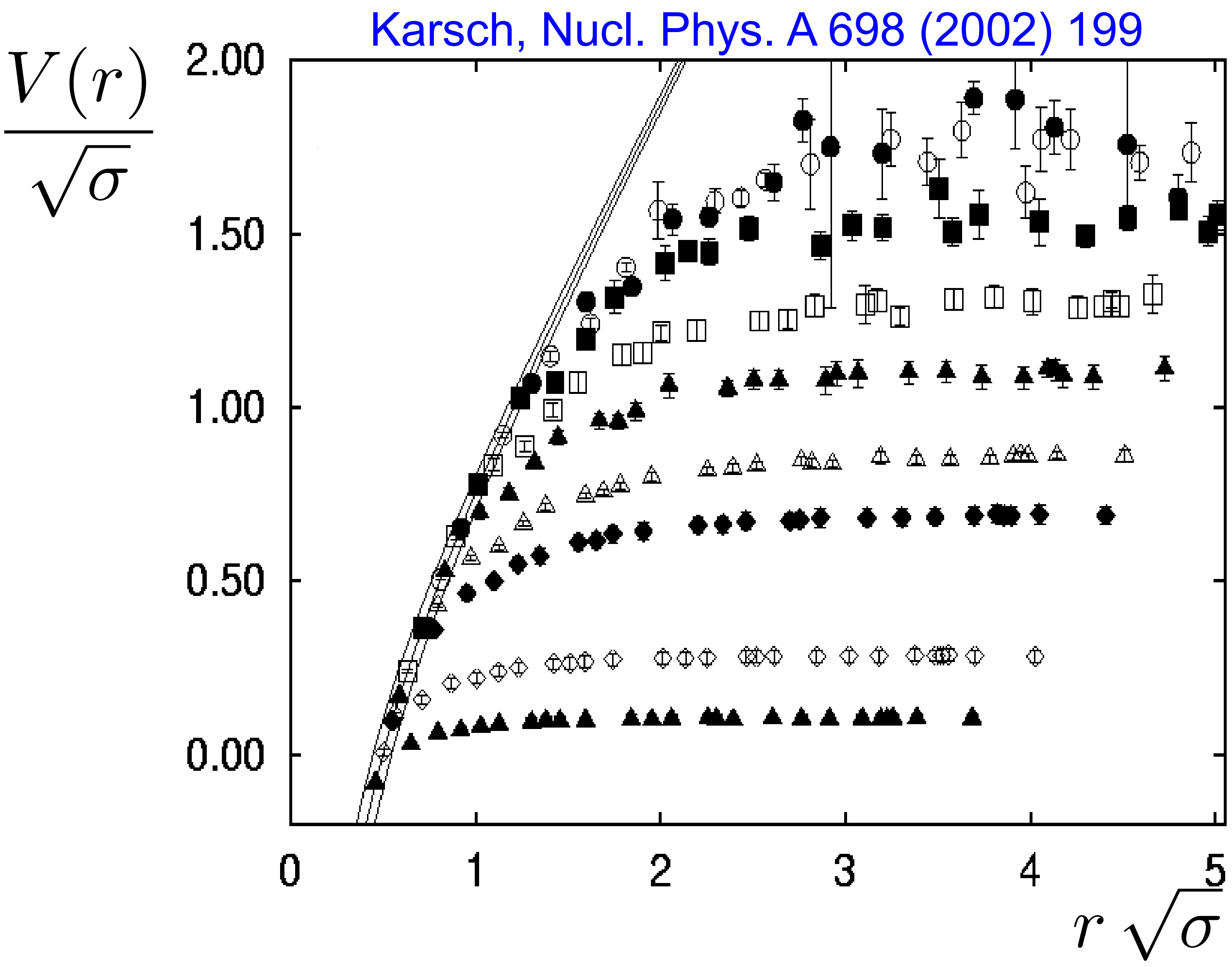
Lattice QCD: hadron spectrum

Fodor et al., Science 322 (2008) 1224

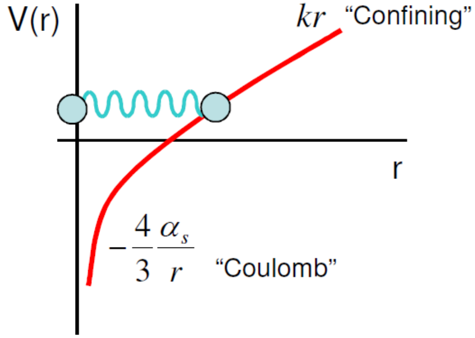


Full calculation using 2 quark flavors
in excellent agreement with experimental data

Lattice QCD: Static potential (μ=0)


Karsch, Nucl. Phys. A 698 (2002) 199

T=0



Lattice calculation (for a heavy quark pair) exhibits screening of long range confining potential with increasing temperature

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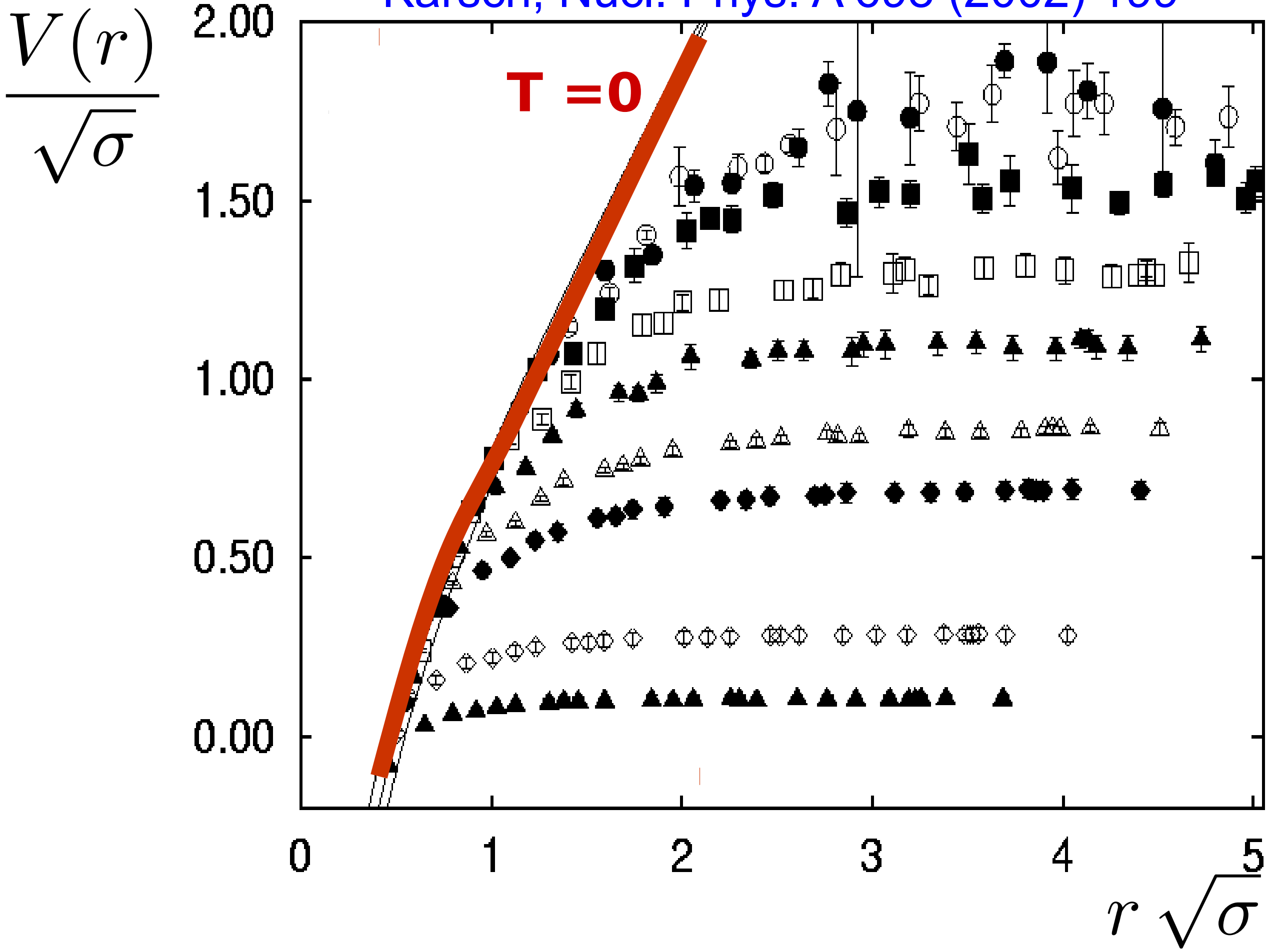

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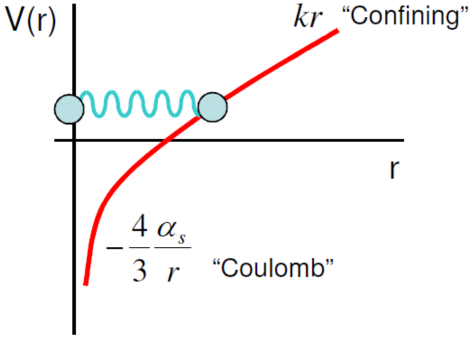

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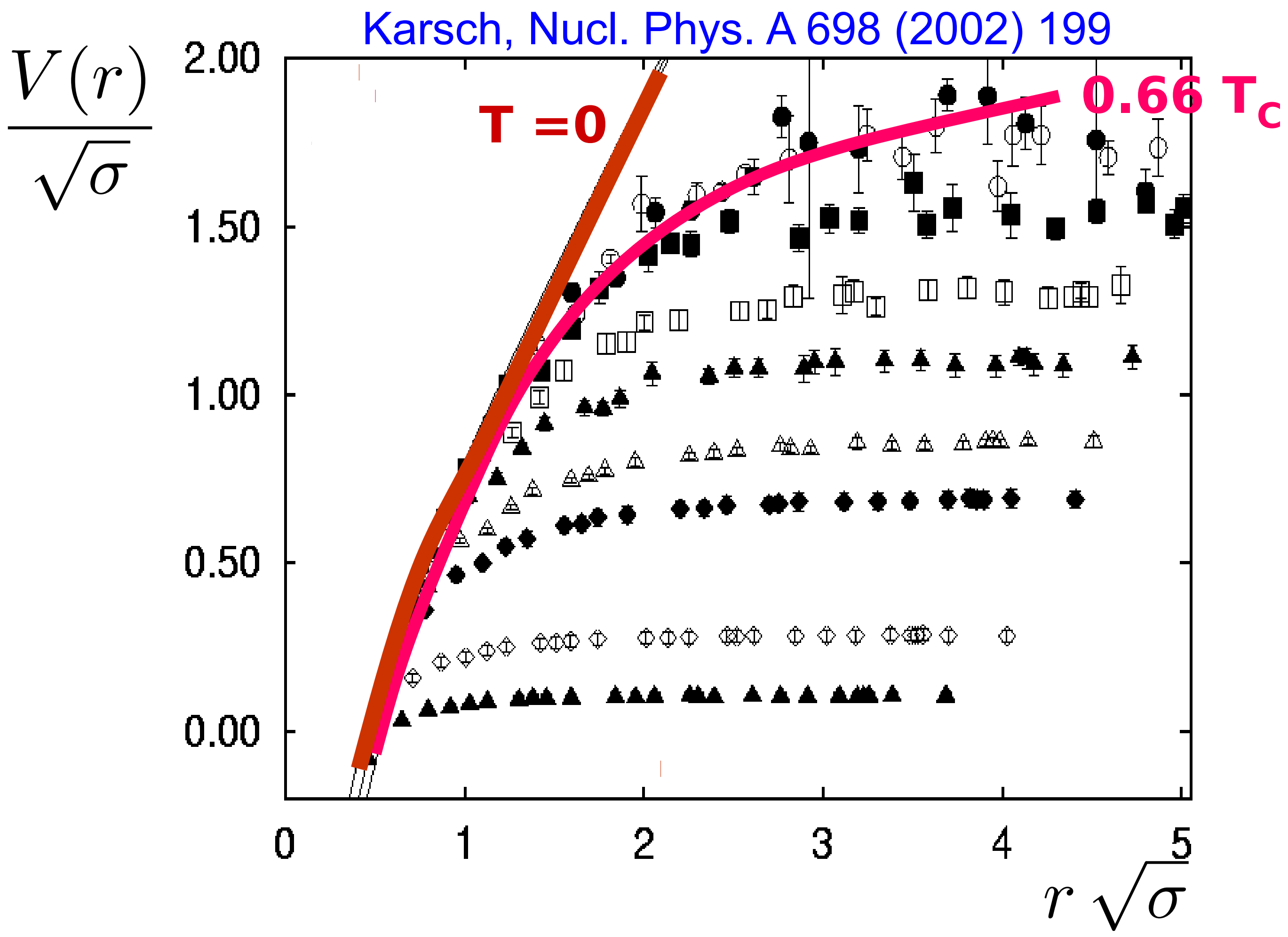

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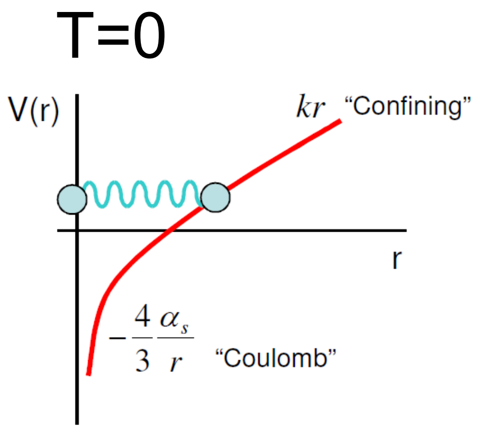

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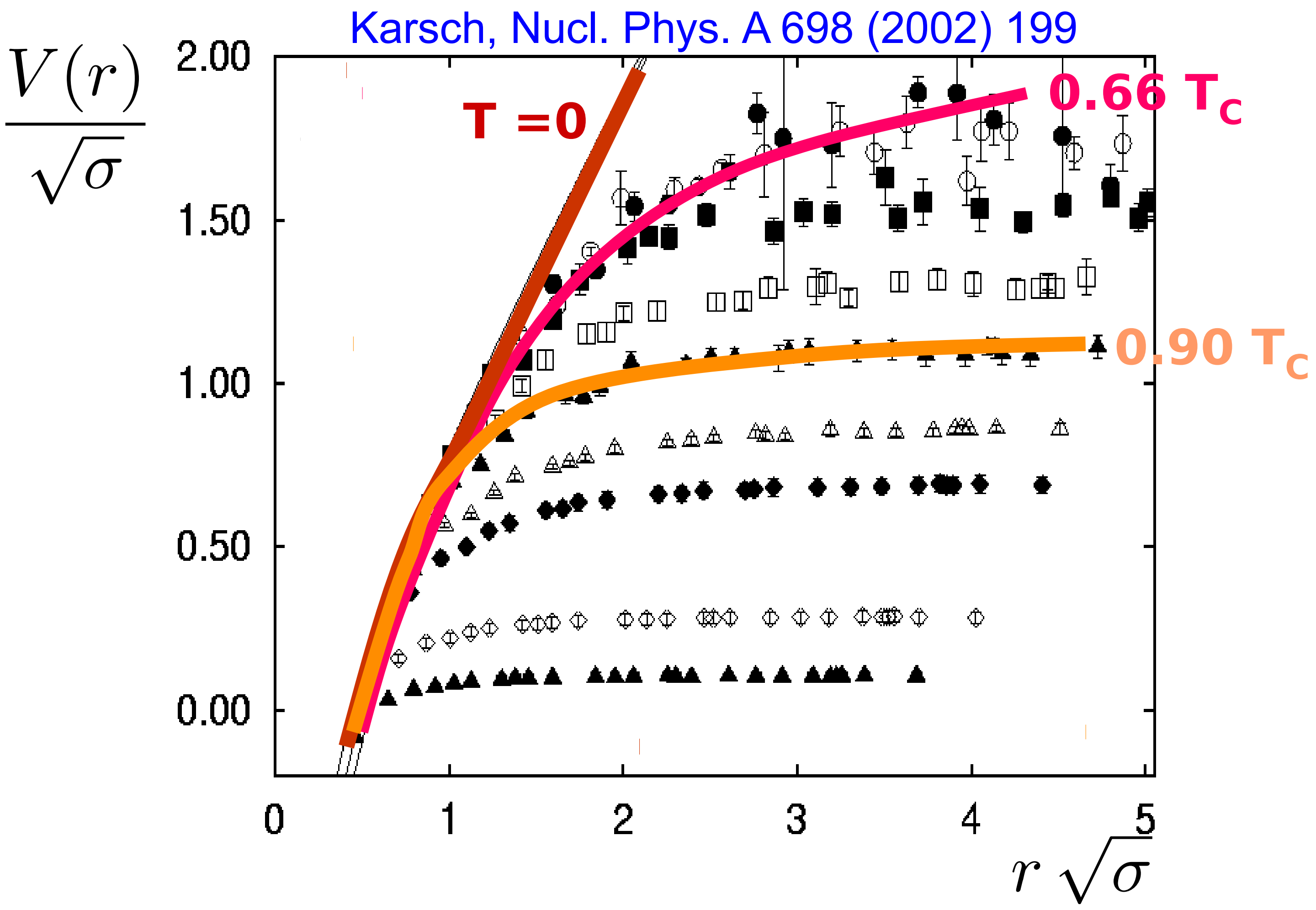

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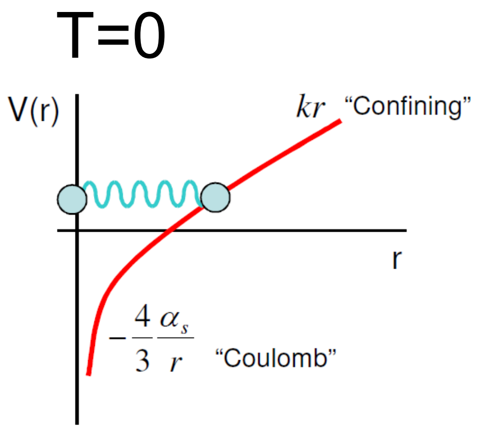

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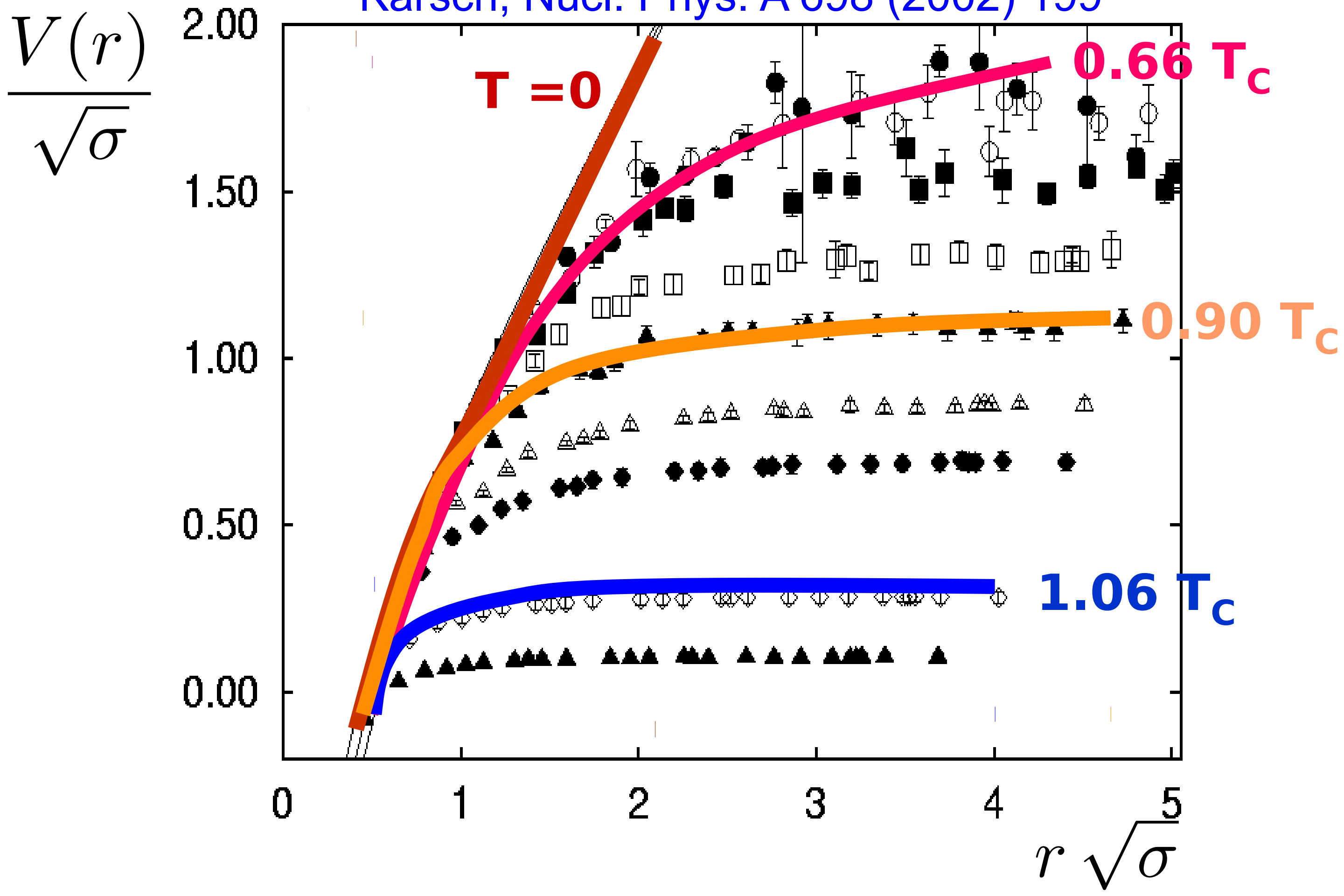

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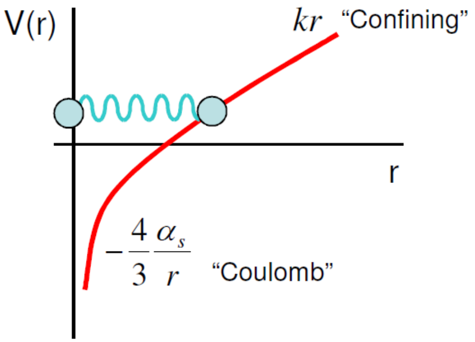

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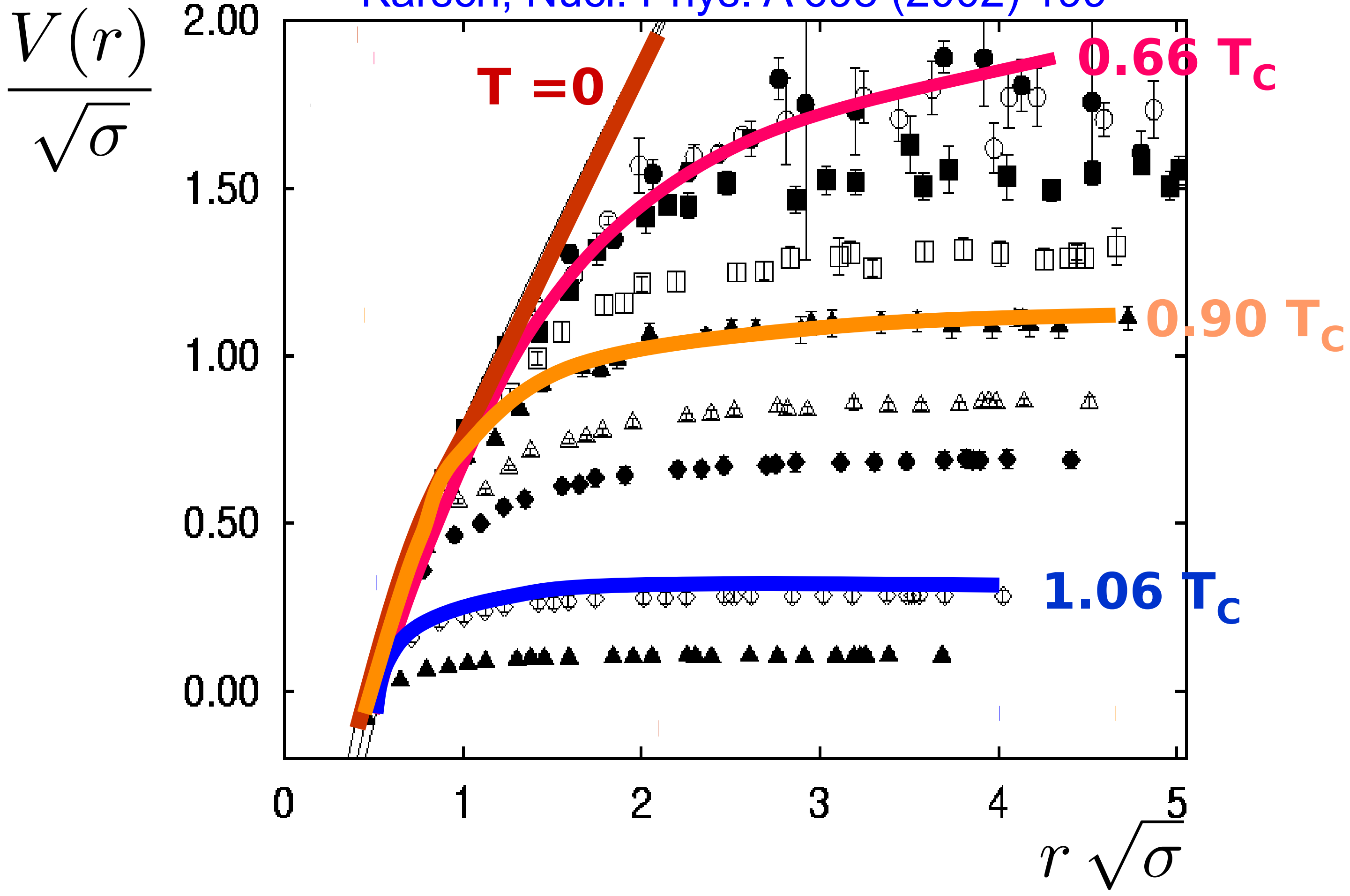

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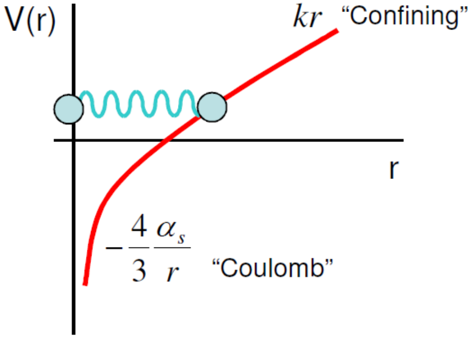
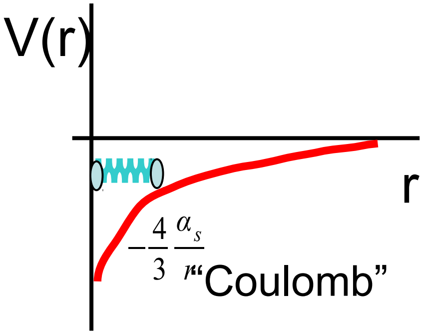


T=T_c



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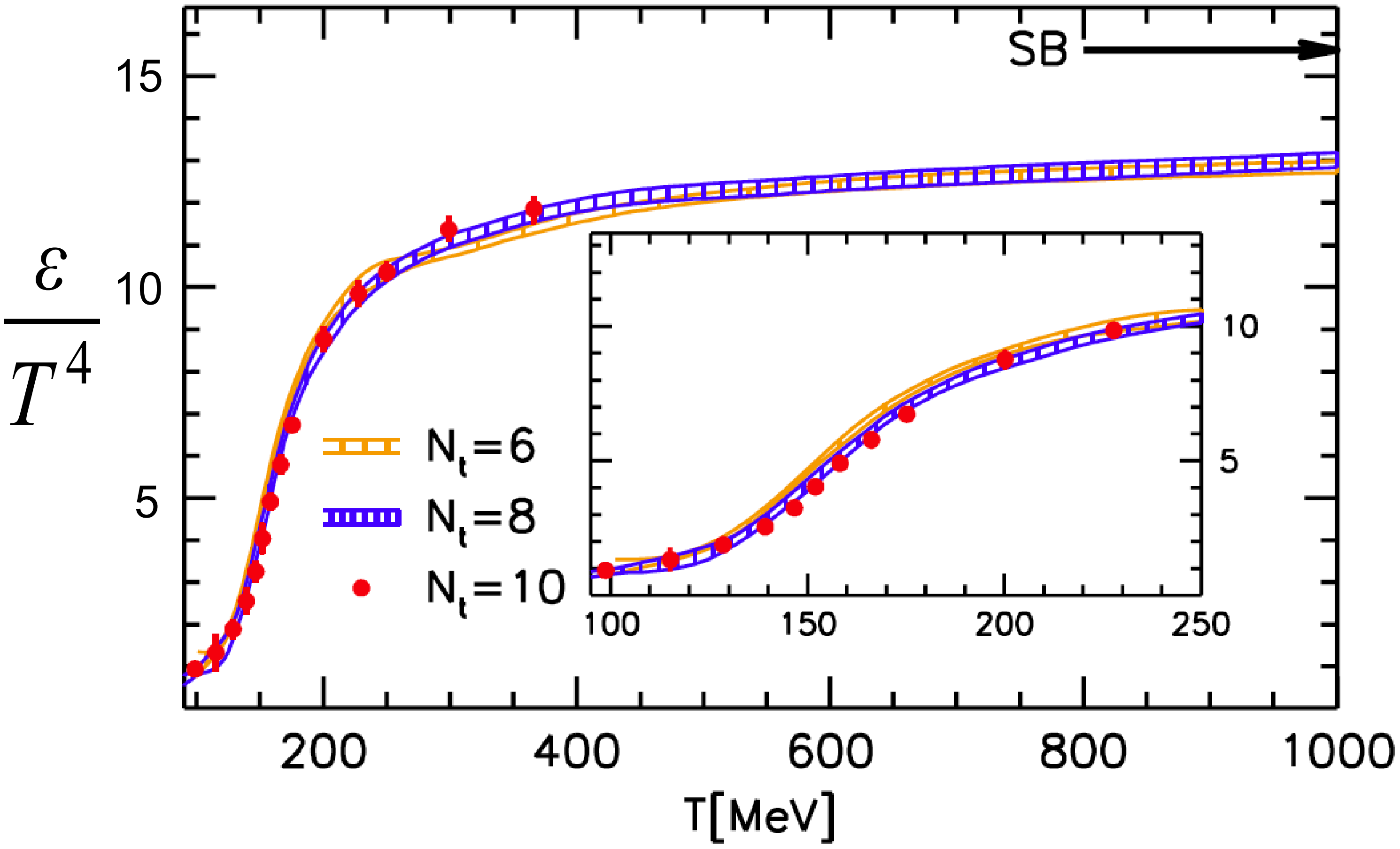
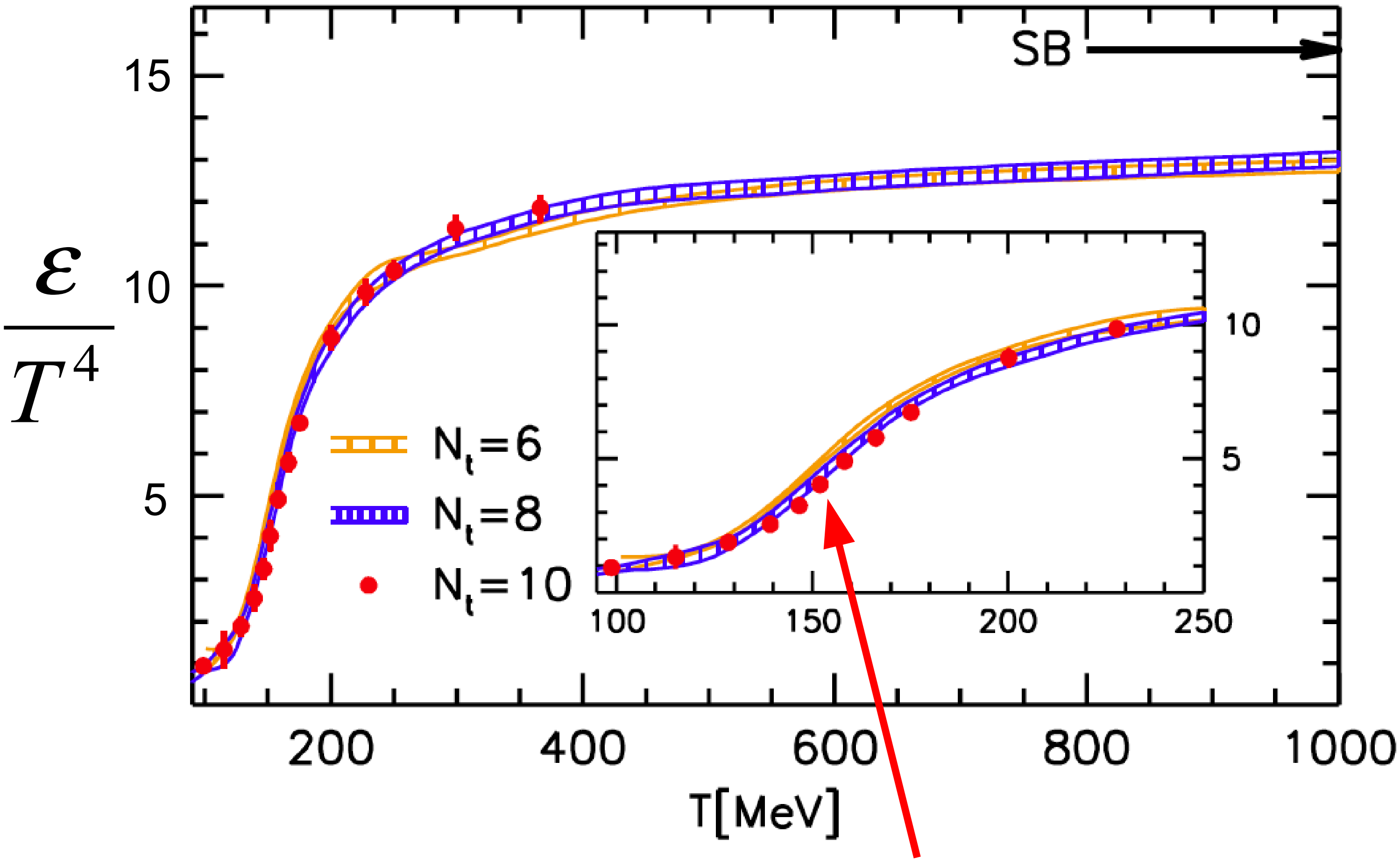
Lattice QCD: Energy density (μ=0)

Fodor et al., JHEP 11 (2010) 077



Transition temperature region between 140 and 200 MeV, with wide range of energy density between 0.2 and 1.8 GeV/fm^3

Lattice QCD: Energy density (μ=0)



Fodor et al., JHEP 11 (2010) 077

Cross-over, not sharp phase transition
(like ionization of atomic plasma)

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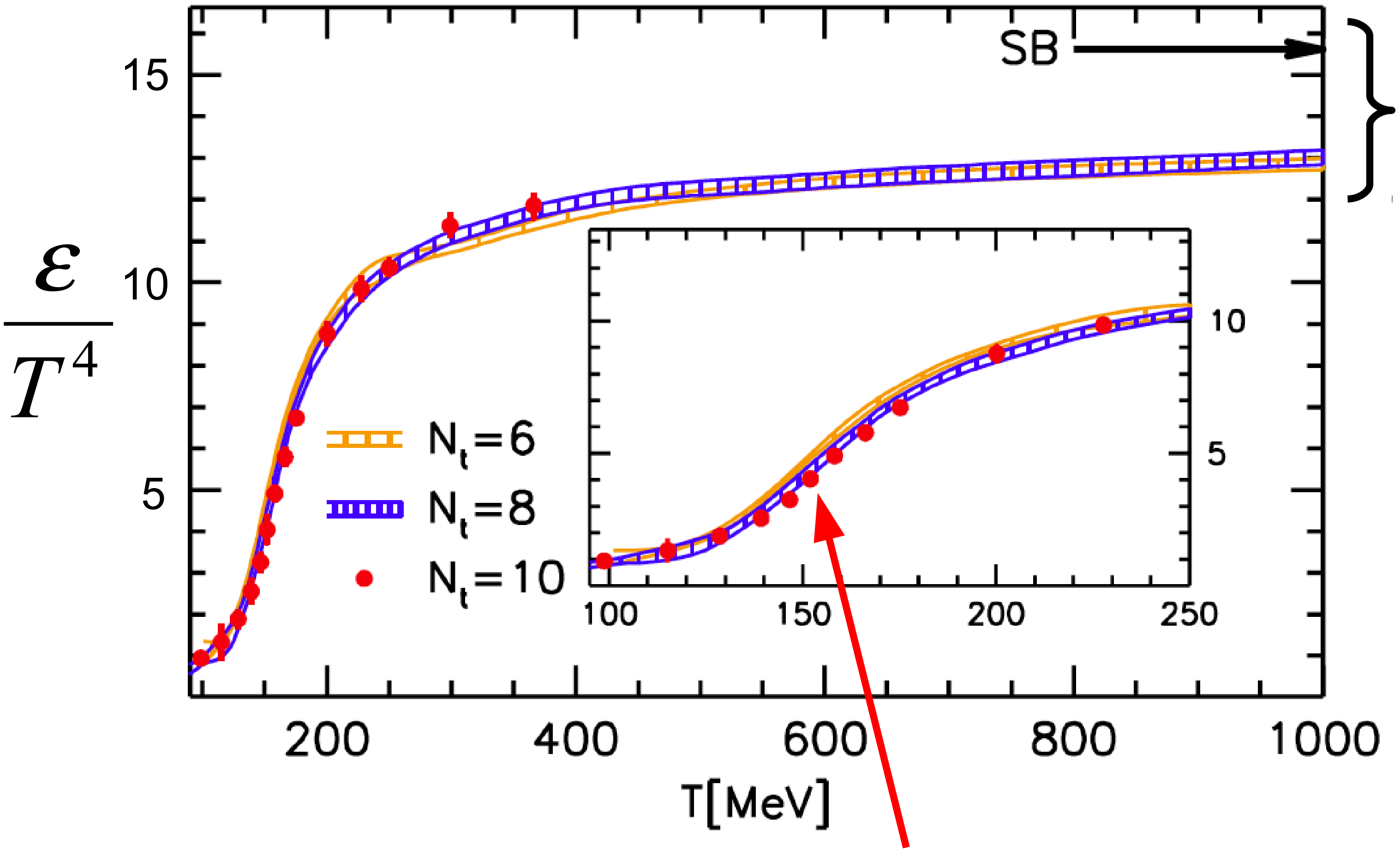
Fodor et al., JHEP 11 (2010) 077



Slow convergence to ideal gas (SB) limit

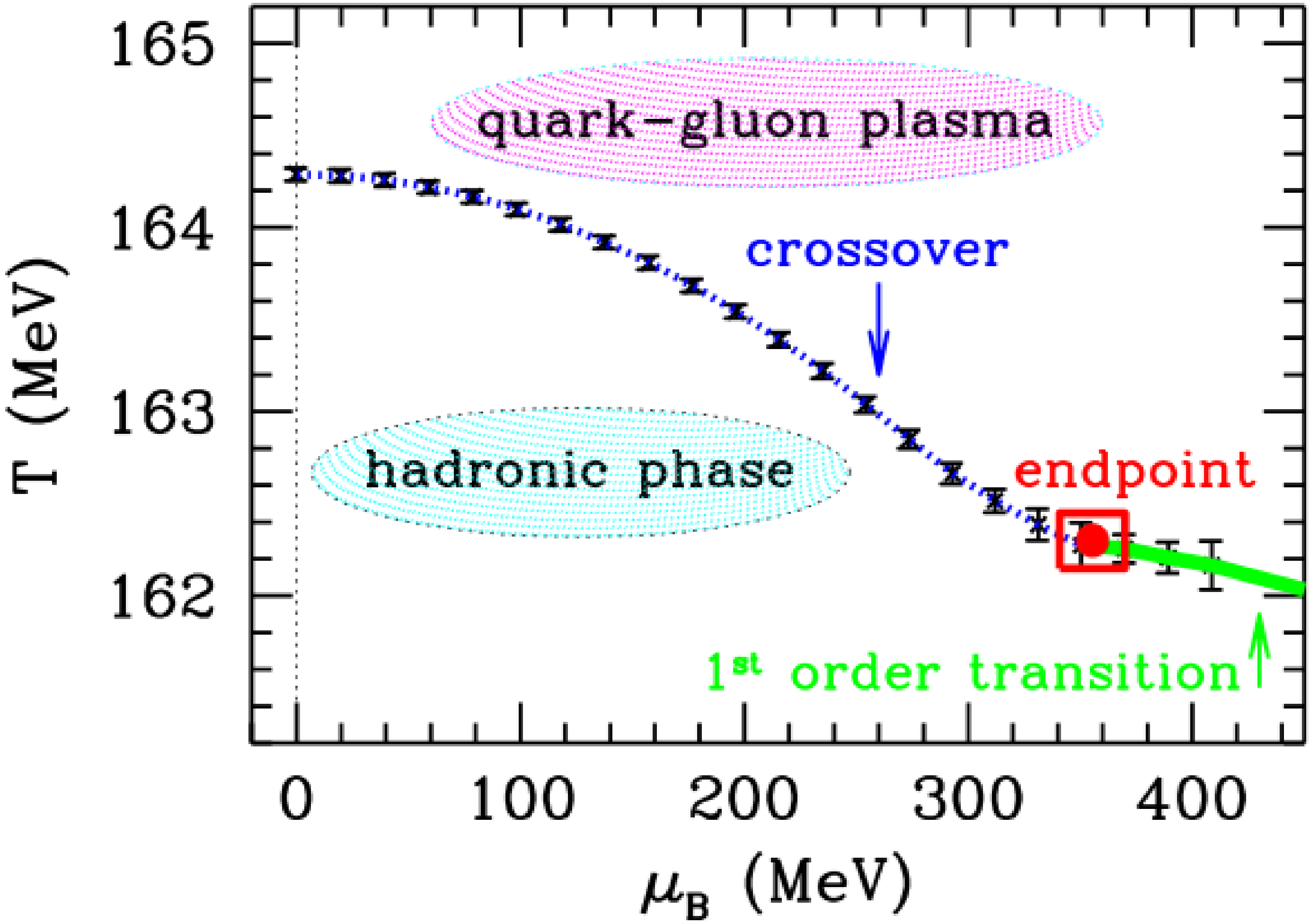
What carries the energy?
Complex bound states of q and g?
Strongly coupled plasma?

Cross-over, not sharp phase transition (like ionization of atomic plasma)

Transition temperature region between 140 and 200 MeV, with wide range of energy density between 0.2 and 1.8 GeV/fm^3

Lattice QCD: phase diagram

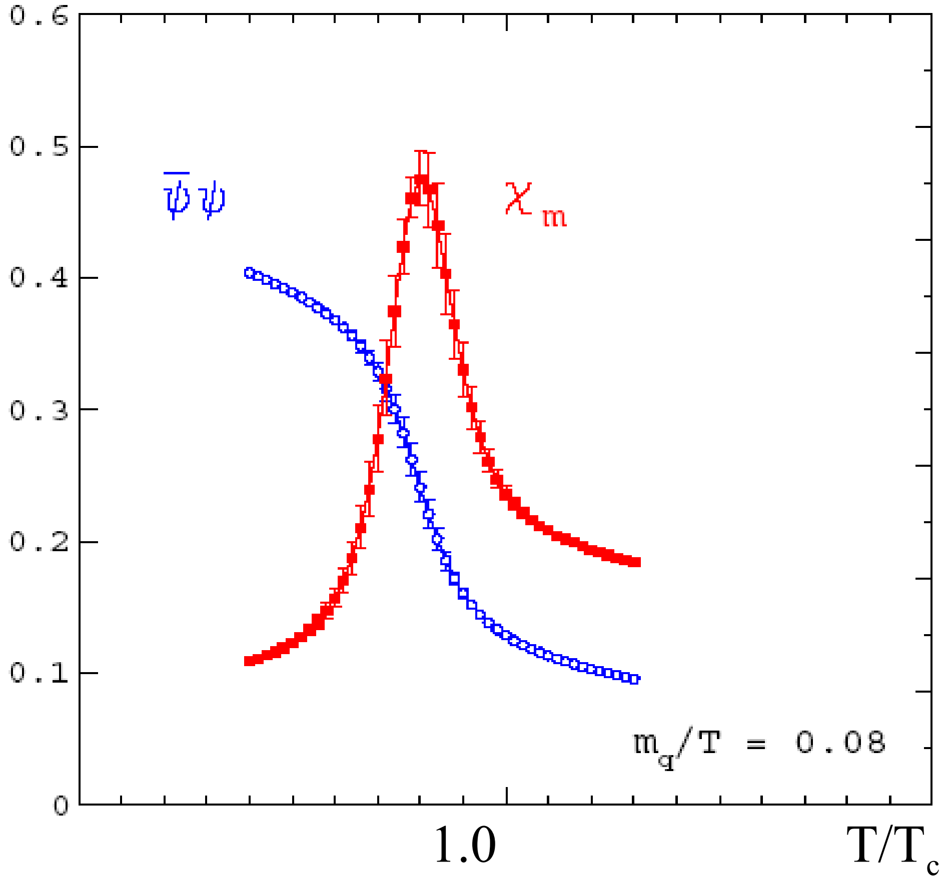
Fodor and Katz, JHEP 0404 (2004) 050



- Finite μ calculations complicated and computationally demanding
- Some calculations suggest a critical endpoint at T=162 MeV, μ_B=340 MeV with large theoretical uncertainties
- Critical endpoint existence and exact location is an open question

Restoration of bare masses

Satz, arXiv:0803.1611



Restoration of bare masses

- Up and down quarks have very small (<10 MeV) bare masses (generated from the coupling to the Higgs)
- Confined quarks however require about 300 MeV dynamically through the effect of the strong interactions
- Deconfinement should be accompanied by a restoration of the masses to the bare masses of the Lagrangian
- Usually called "Partial restoration of chiral symmetry)
- Effective quark mass from <$\bar{\psi}\psi$> computed on lattice confirms expected behavior

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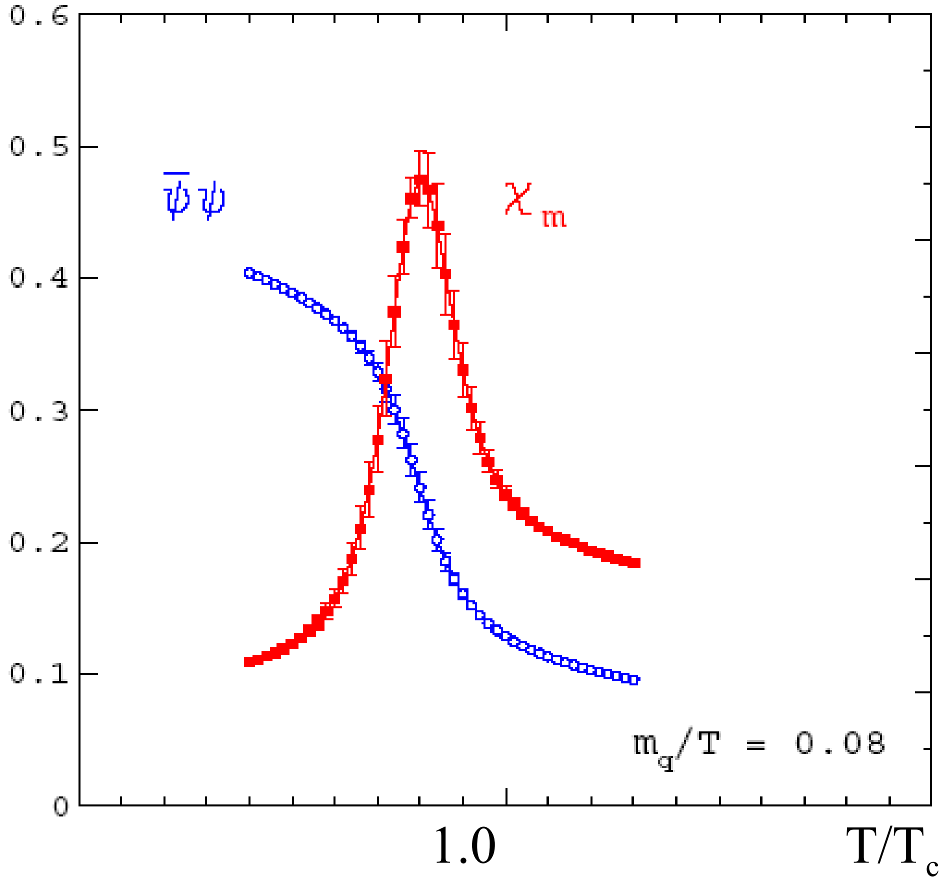

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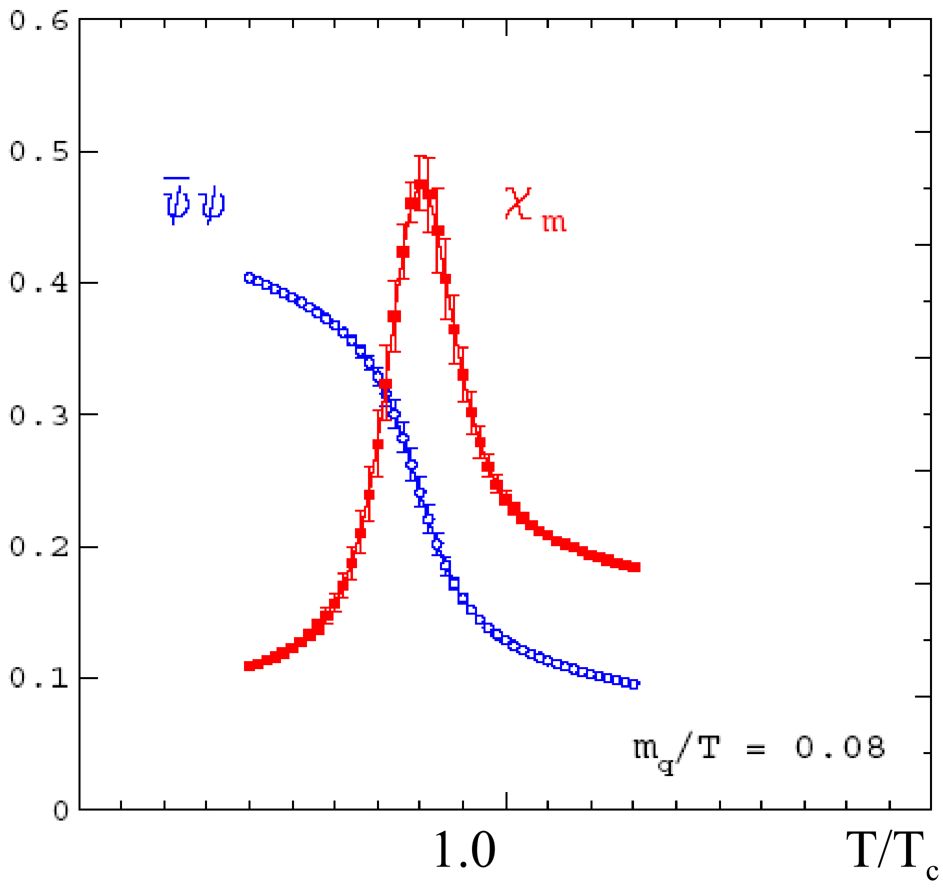

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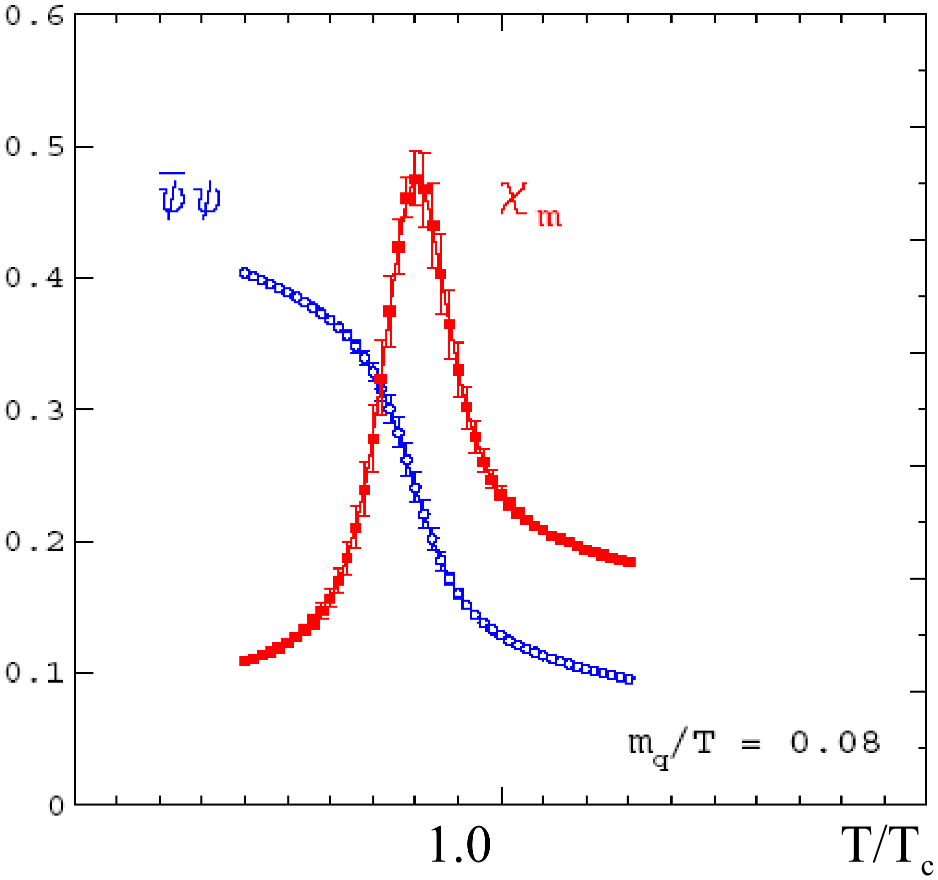

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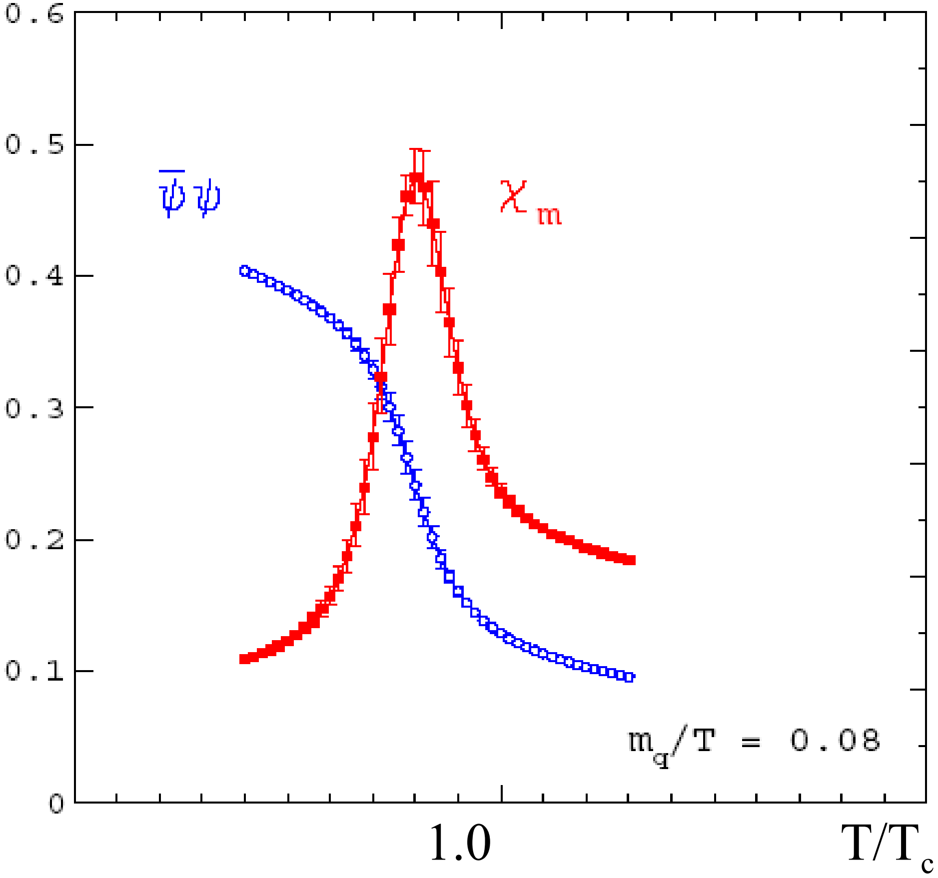
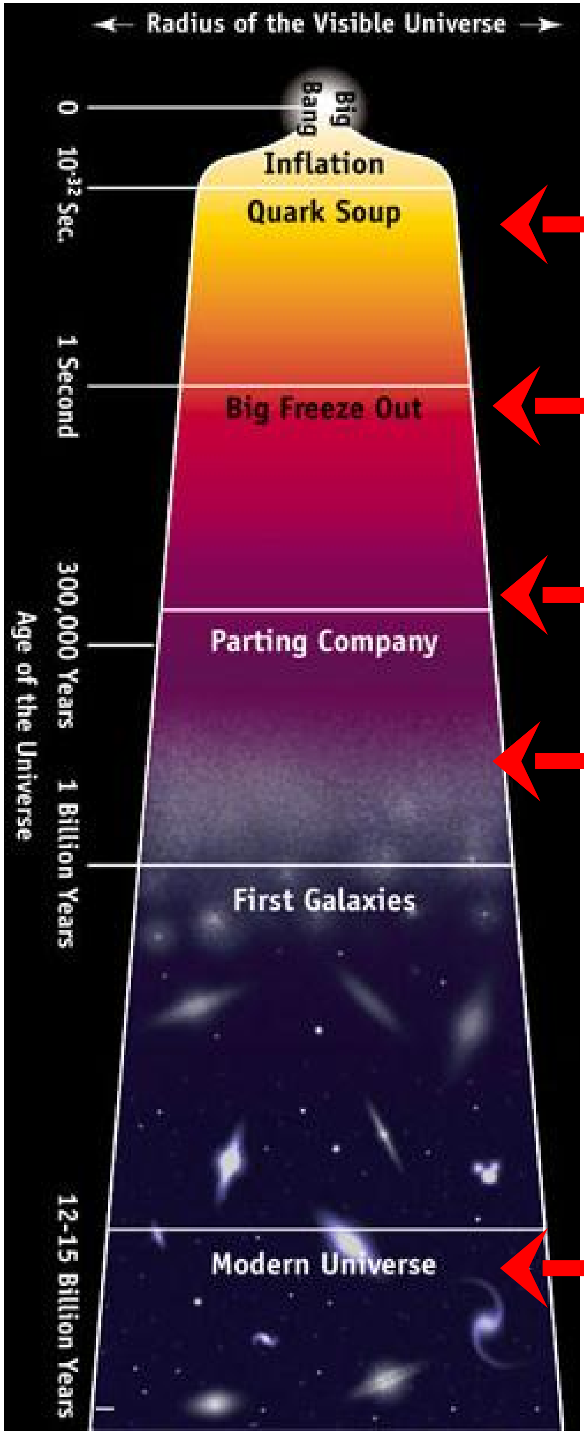


Satz, arXiv:0803.1611

Brief history of time



Too hot for quarks to bind!

Standard Model (N/P) Physics

Quark Gluon Plasma

Too hot for nuclei to bind

Nuclear/Particle (N/P) Physics

Hadron Gas

Nucleosynthesis builds nuclei up to He

Nuclear Force…Nuclear Physics

Universe too hot for electrons to bind

E-M…Atomic (Plasma) Physics

E/M Plasma

Today’s Cold Universe

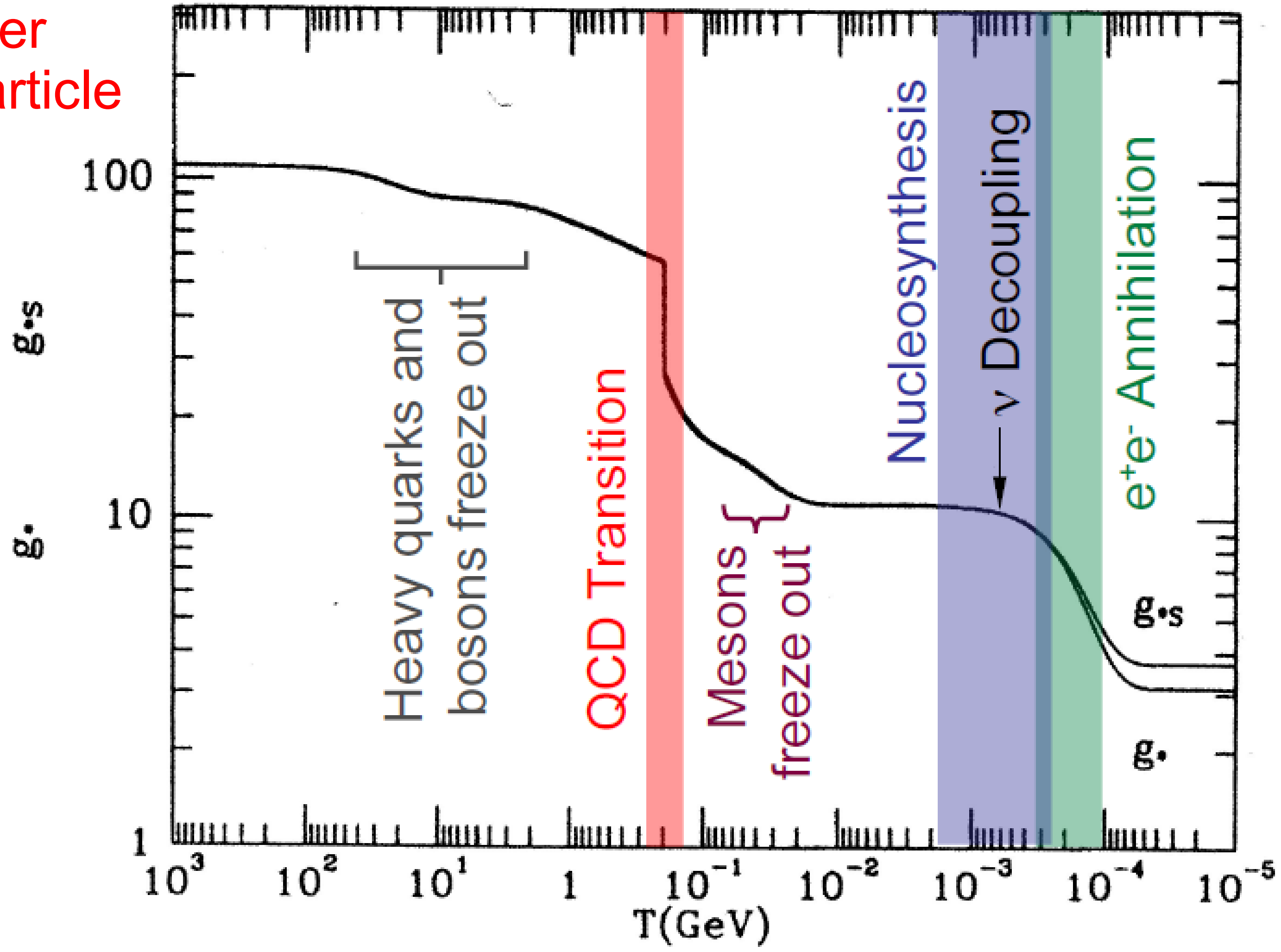
Gravity…Newtonian/General Relativity

Solid Liquid Gas

Natural appearance of QCD phase transition

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

Effective degrees of freedom per relativistic particle



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.

Natural appearance of QCD phase transition

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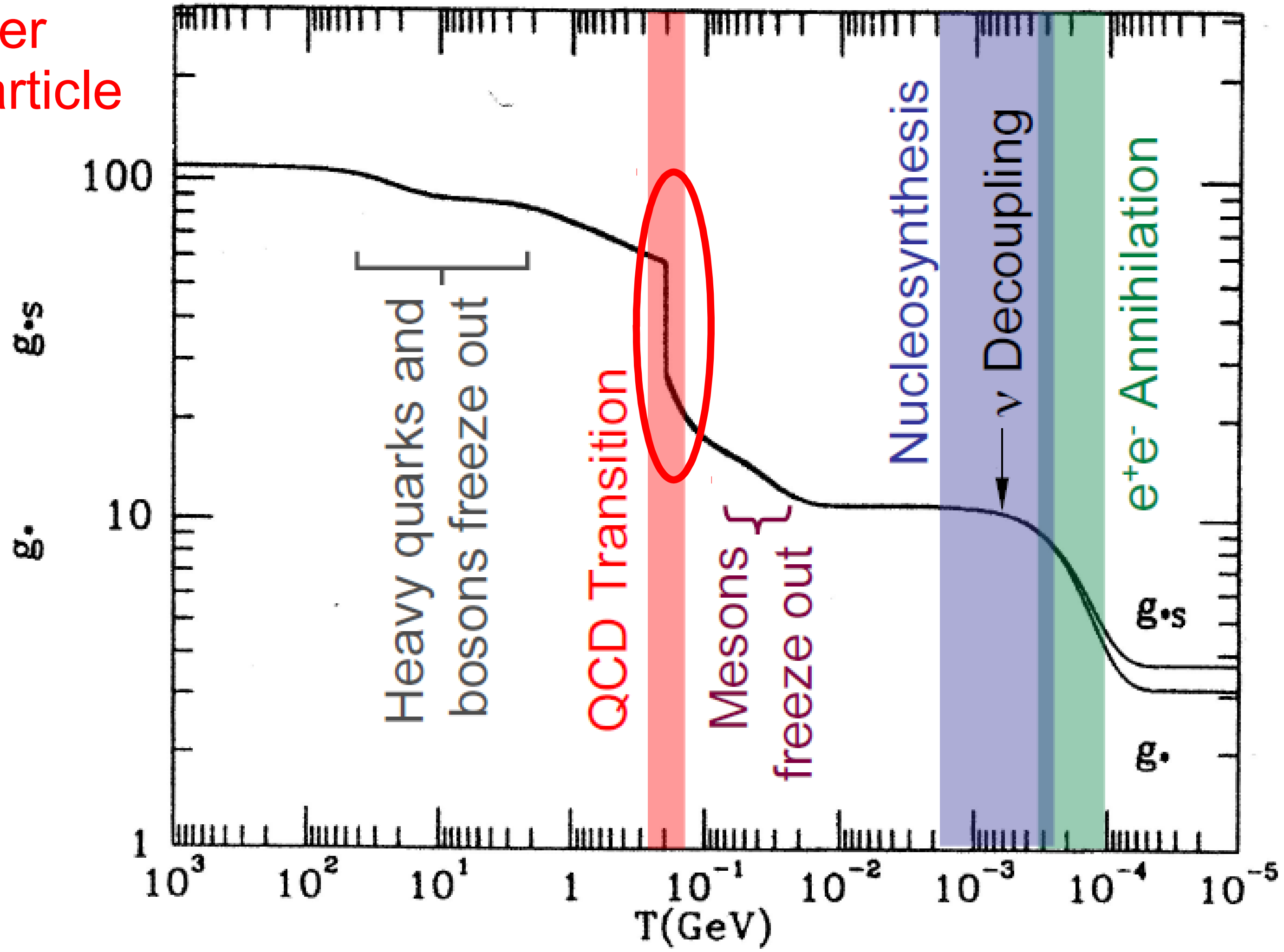

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The Early Universe,
Kolb and Turner

Exploration of QCD matter: what are the questions?

Exploration of QCD matter: what are the questions?

- What is the nature of QCD matter at finite temperature?
  - What is its phase structure?
  - What is its equation of state?
  - What are its effective degrees of freedom?
    - Is it a trivial gas of non-interacting quarks and gluons?
    - Or more like a fluid of interacting quasi particles?
  - Is it described by lattice QCD or does it require new approaches?
- What are the dynamics of QCD matter at finite temperature?
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  - Is chiral symmetry restored at high temperature, and how?
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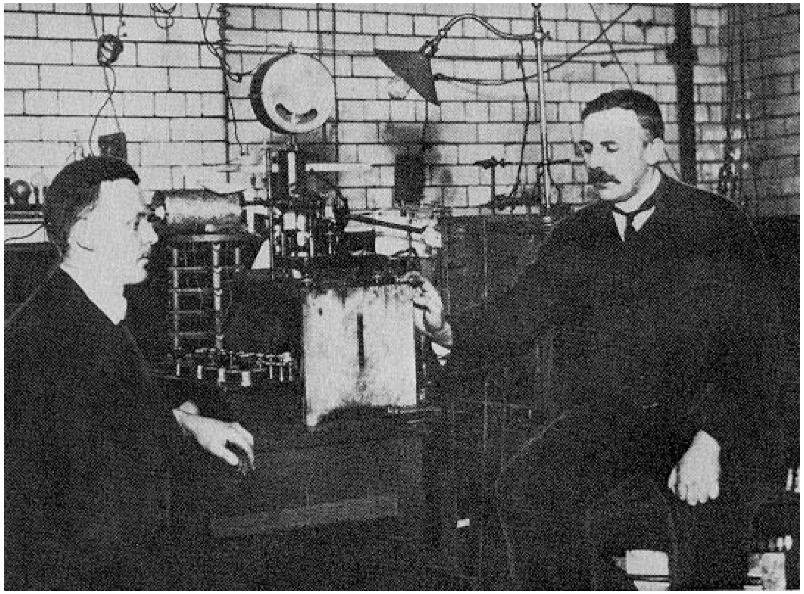
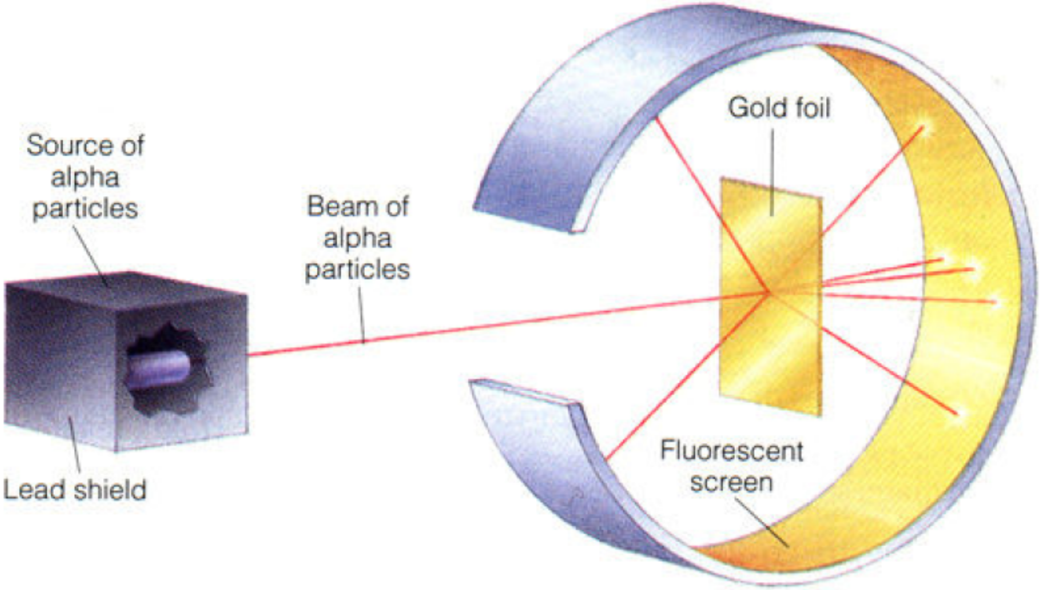
Can we study hot QCD matter experimentally?

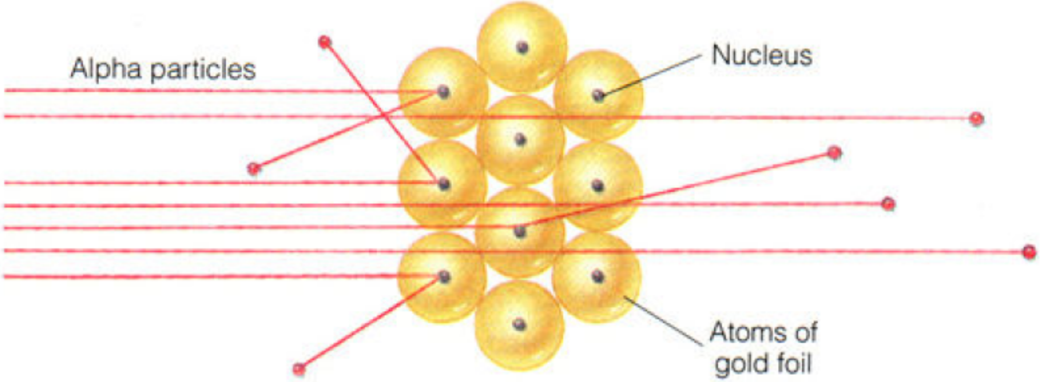
Exploring the structure of atoms

The first exploration of subatomic structure, by Rutherford, used Au atoms as targets and α particles as *probes*



<u>Interpretation:</u>
Positive charge is concentrated in a tiny volume with respect to the atomic dimensions





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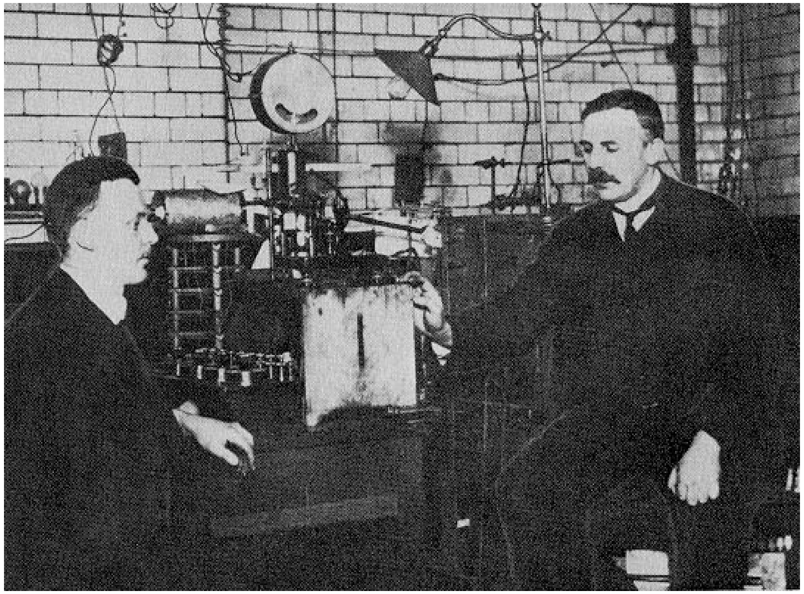
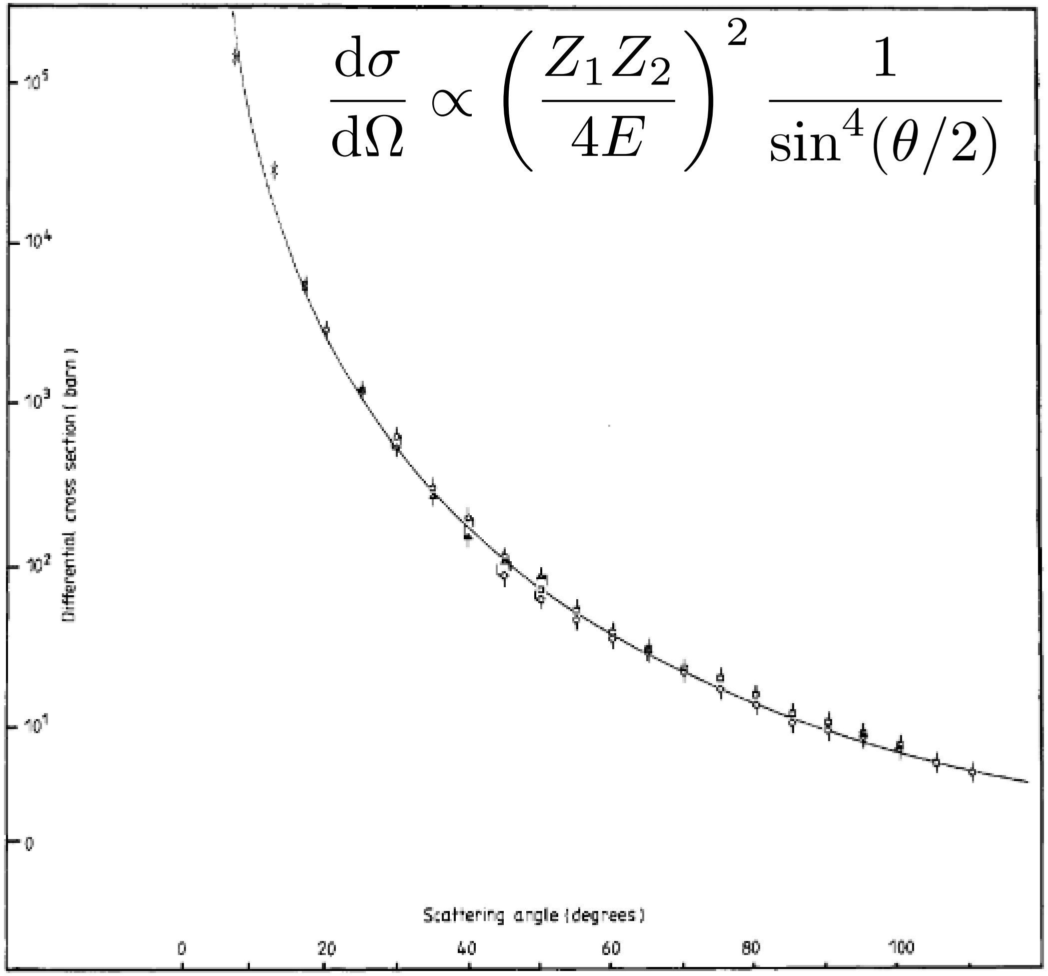


Interpretation:
Positive charge is concentrated in a tiny volume with respect to the atomic dimensions

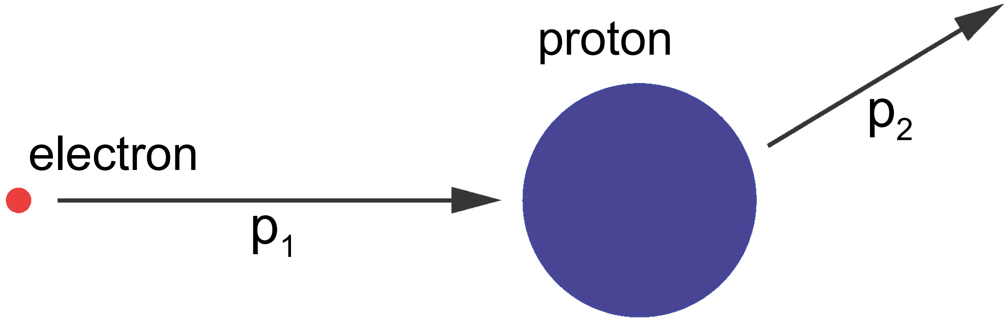


$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \left(\frac{Z_1 Z_2}{4E}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

Hoppenau and Eggers, Eur.J.Phys. 6 (1985) 86

Exploring the structure of protons

Deep inelastic scattering experiments at SLAC in the 1960s established the quark-parton model:



The angular distribution of the scattered electrons reflects the distribution of charge inside the proton

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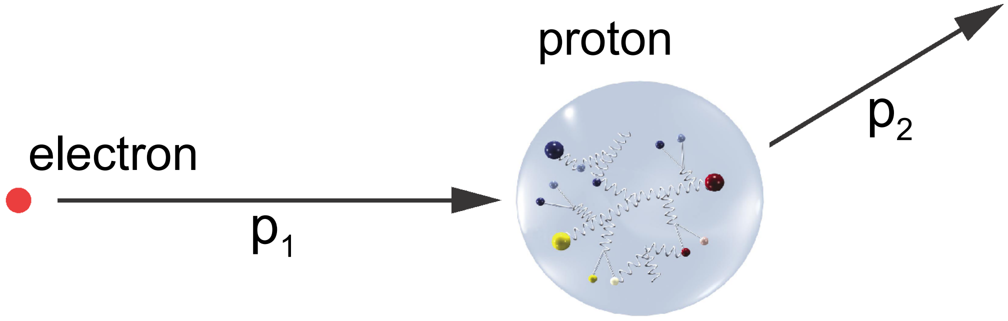

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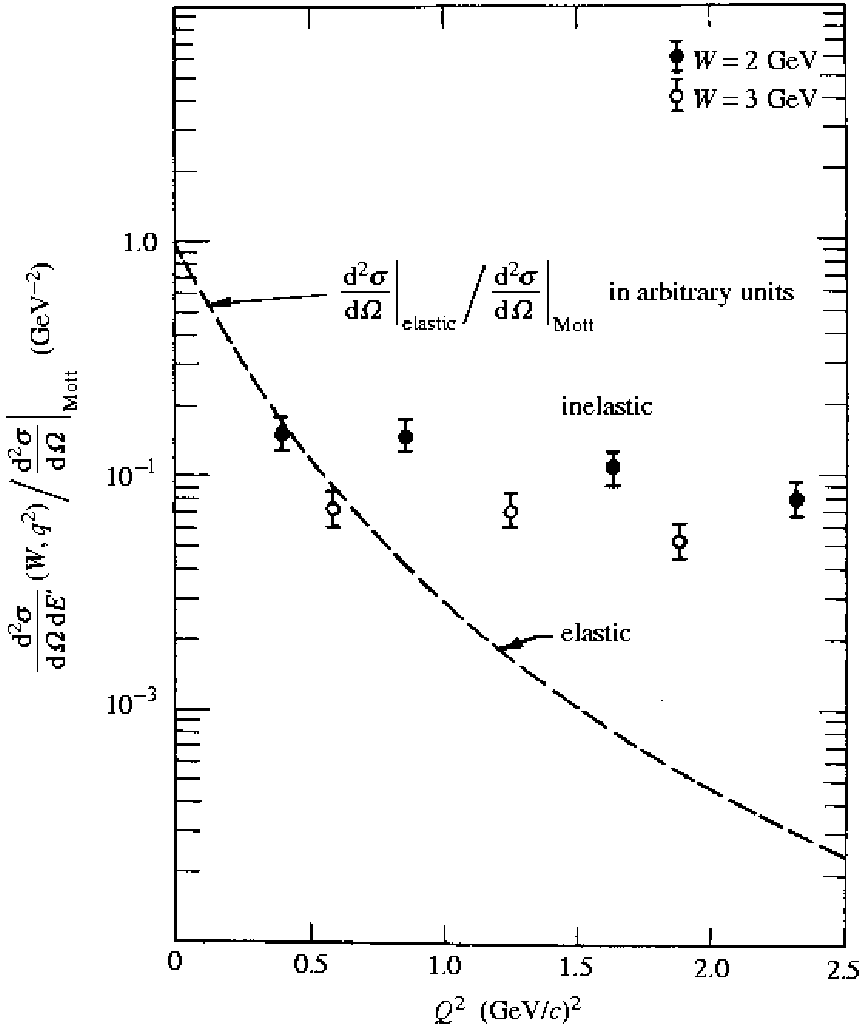

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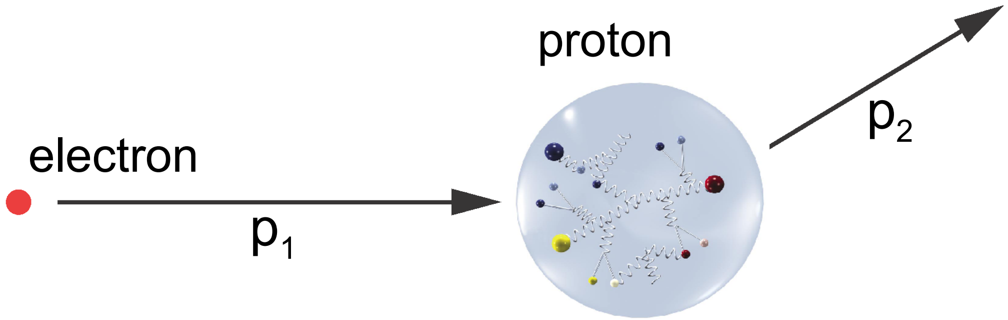

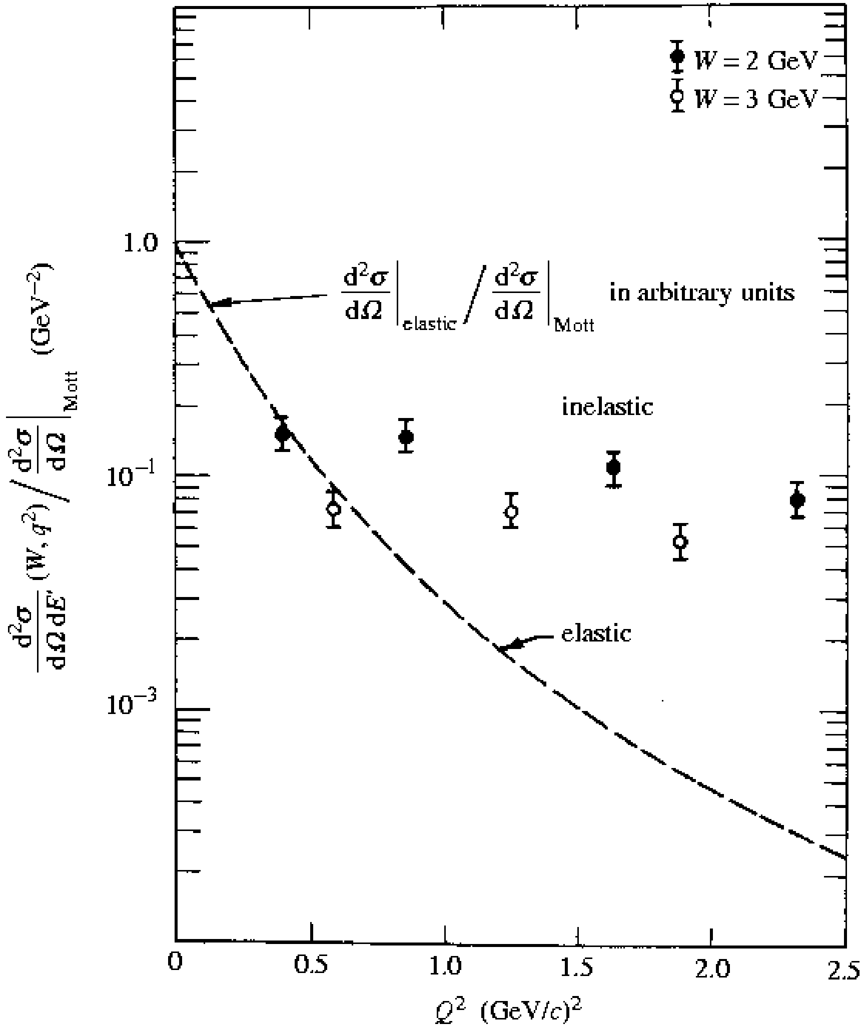

The angular distribution of the scattered electrons reflects the distribution of charge inside the proton

Approximately constant form factor
⇒scattering on point-like constituents
⇒quarks

1990 Nobel Prize in Physics

Exploring the structure of QCD matter

In analogy, we study the QCD matter produced in HI collisions by measuring how it affects well understood probes, as a function of the temperature of the system

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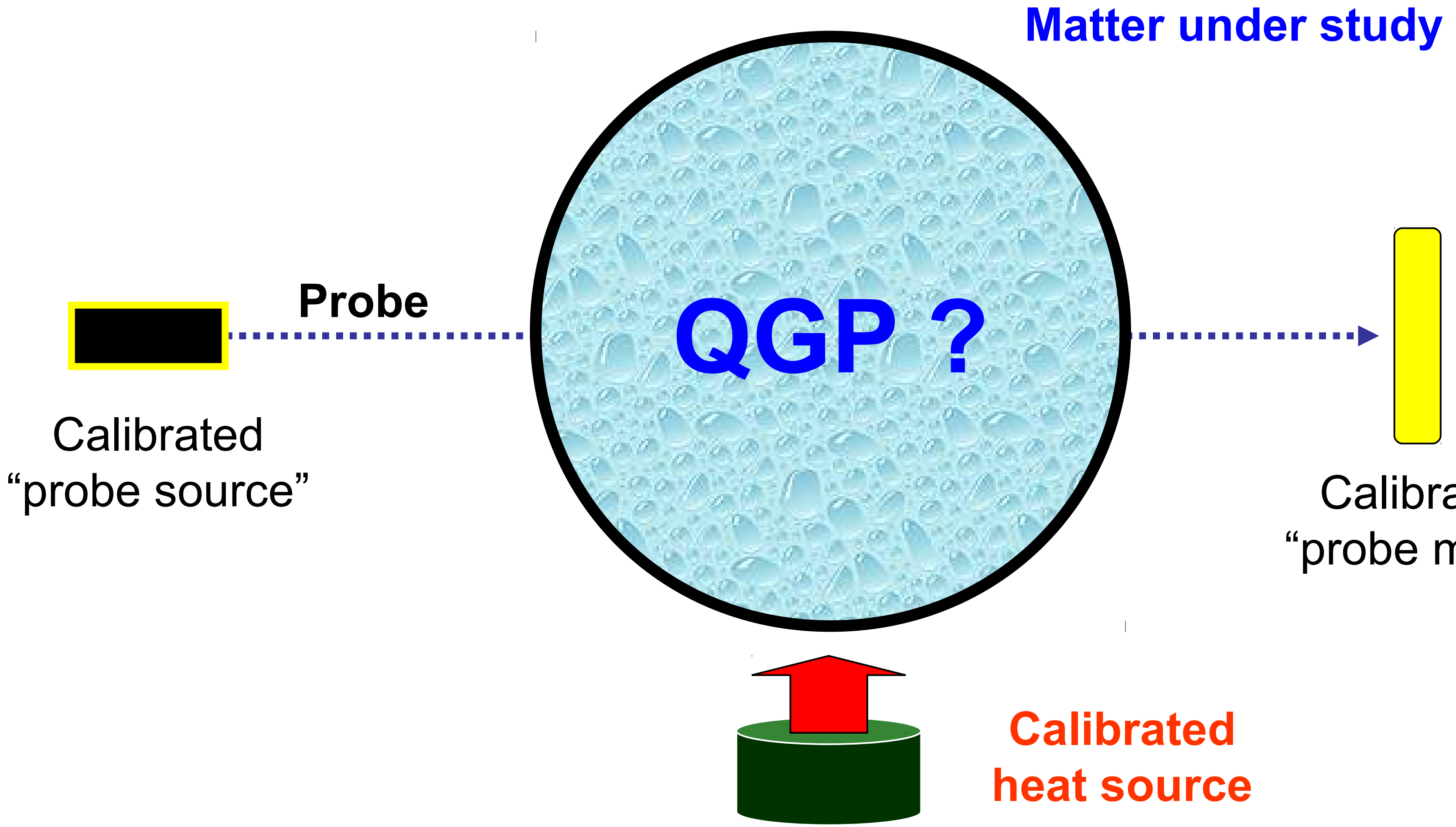
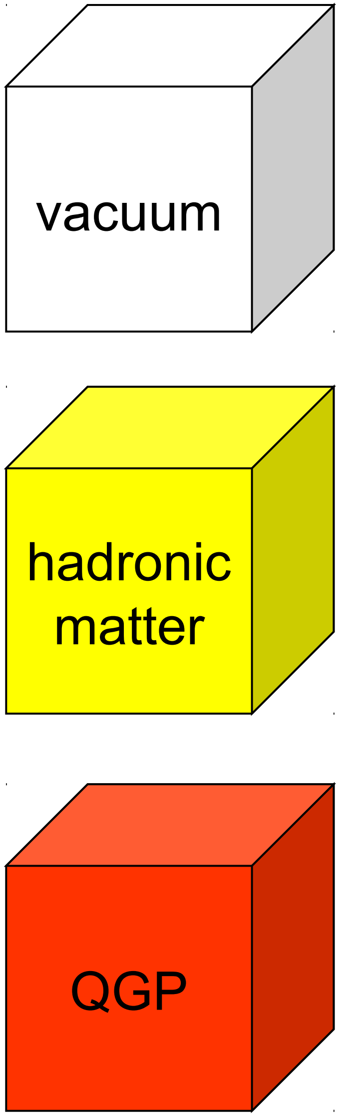
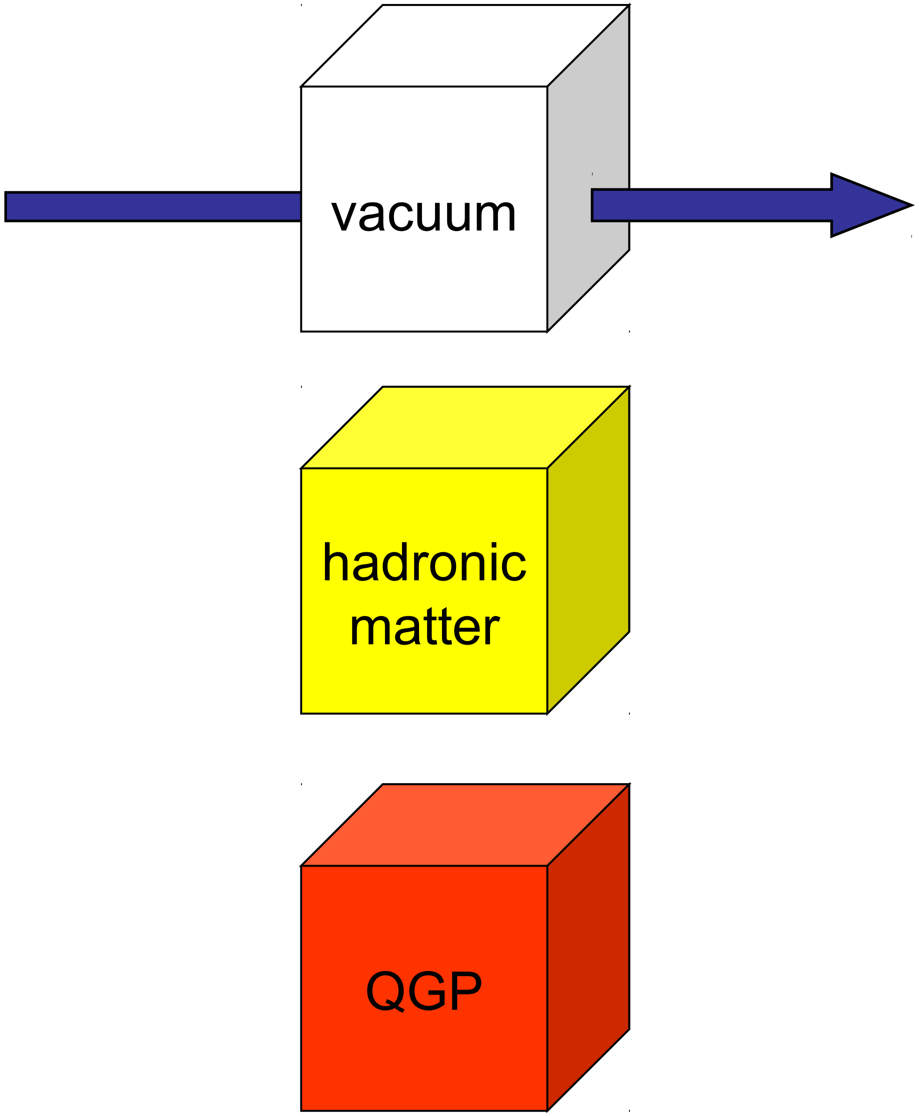


Good probes of QCD matter



Good QCD probes should be:

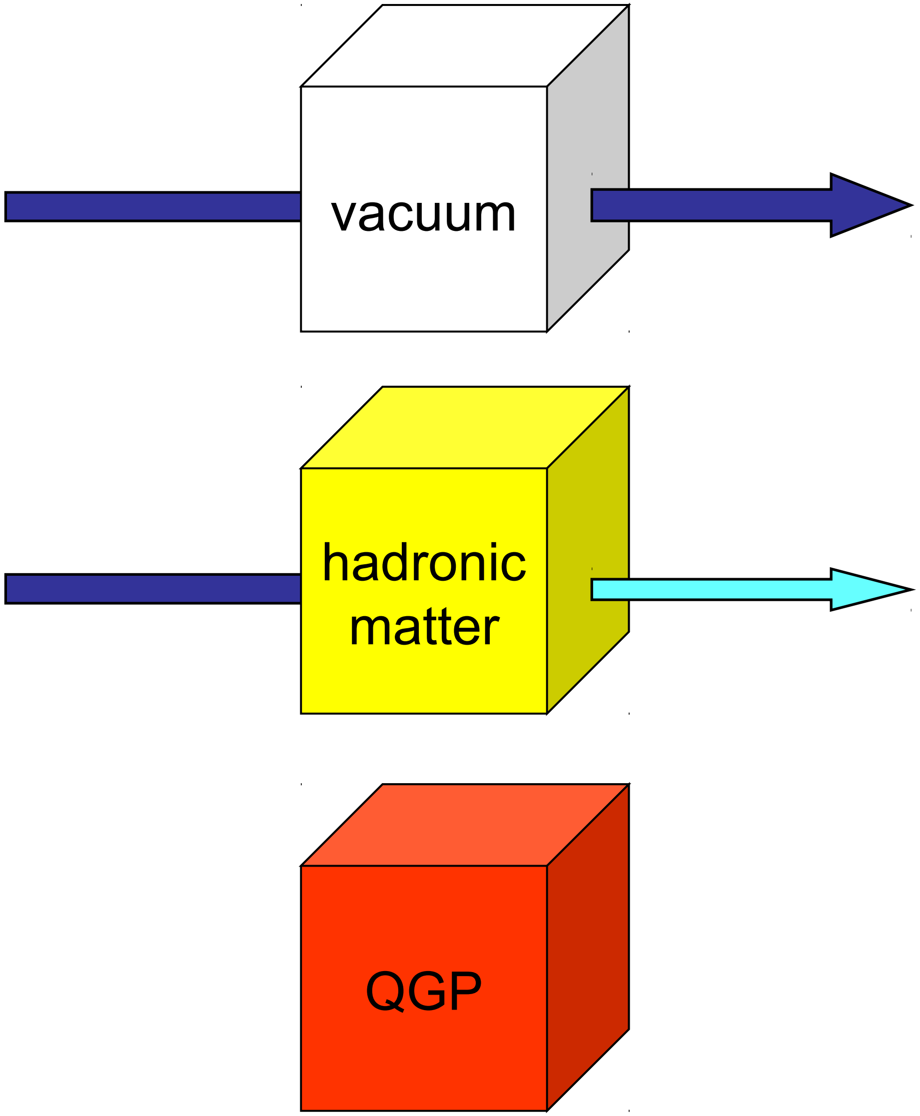
Good probes of QCD matter



Good QCD probes should be:

Well understood in “pp collisions”

Good probes of QCD matter



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Affected by hadronic matter,
in a well understood way, which
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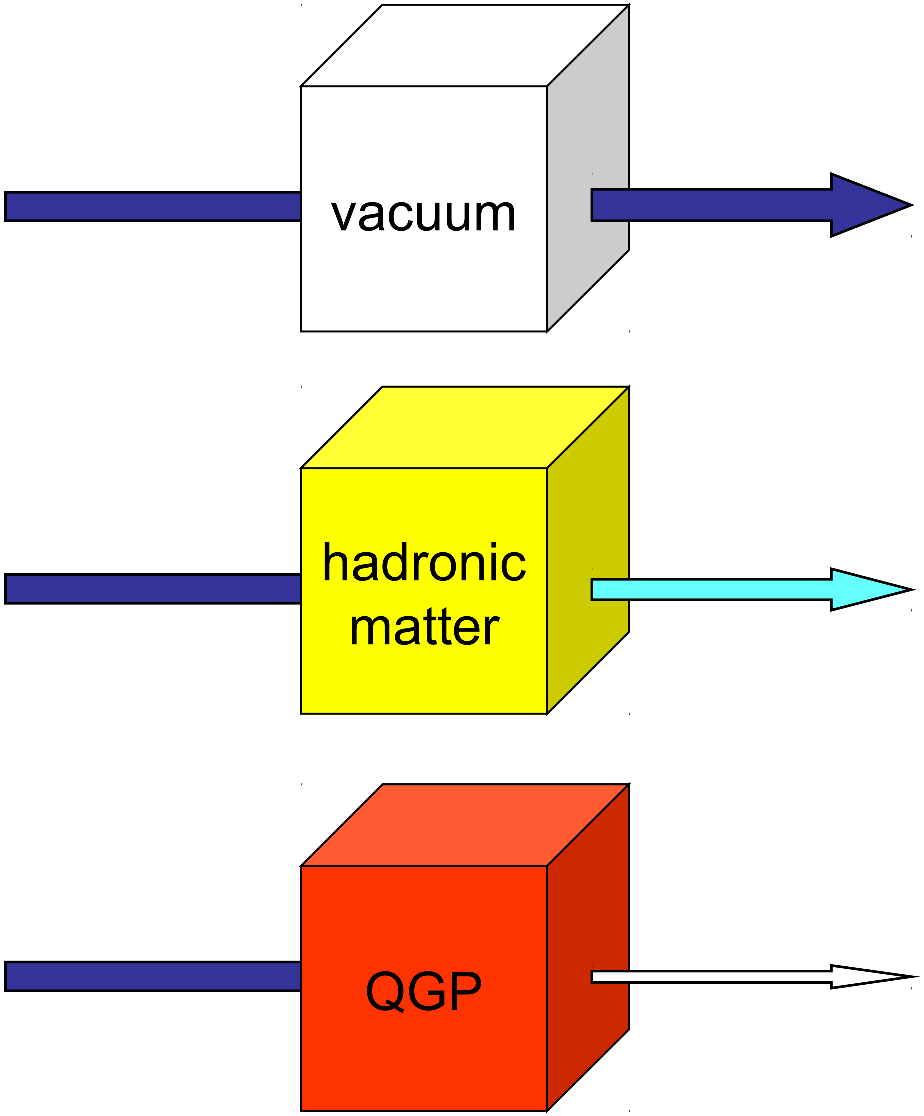
Good probes of QCD matter



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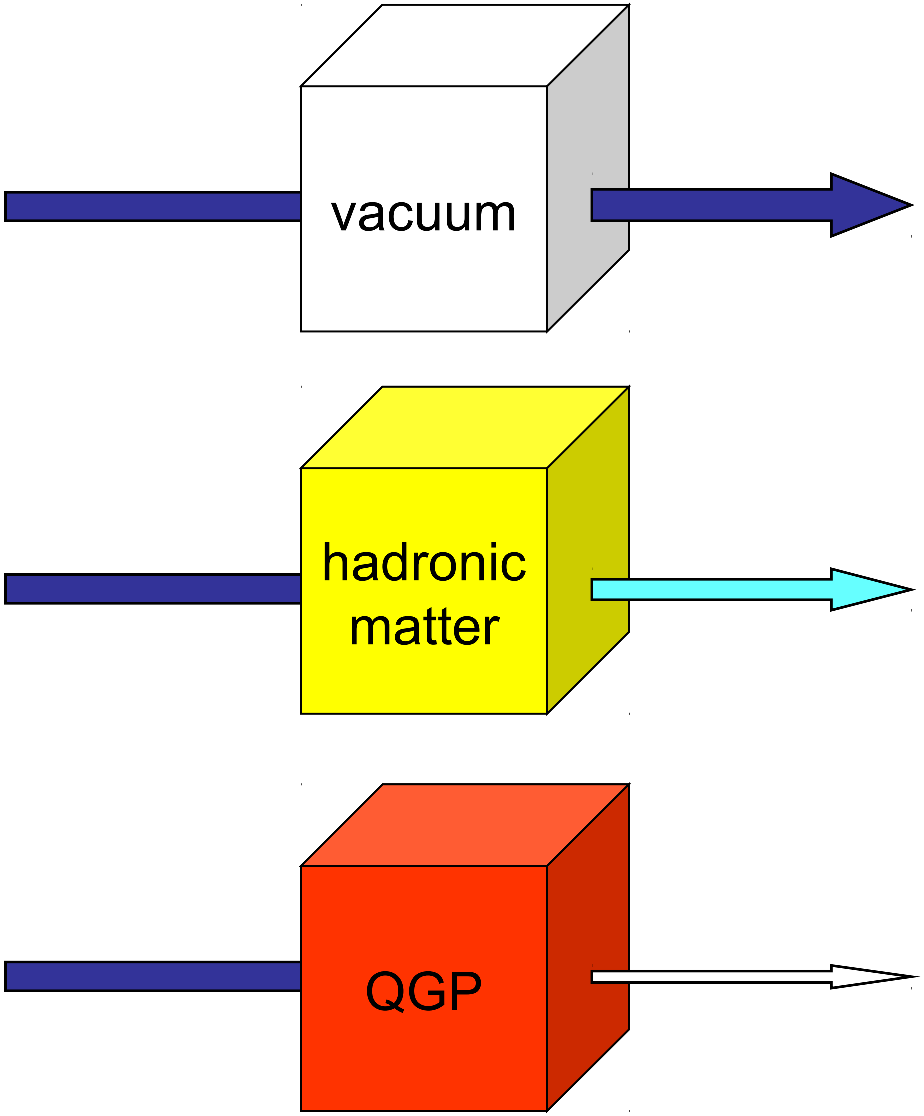

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Strongly affected by the dense and
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Jets and heavy quarkonia (J/ψ, χ_c, Υ, Υ', etc)
should be good QCD matter probes !

Good probes of QCD matter

Good probes of QCD matter

The “probes” must be produced together with the system they probe!

They must be created very early in the collision evolution, so that they exist before the QGP might be formed:

⇒ hard probes, such as jets and quarkonia

We must have “trivial” probes, not affected by the dense QCD matter, to serve as baseline reference :

⇒ photons, Drell-Yan dimuons

We must have “trivial” collision systems, to understand how the probes are affected in the absence of “new physics” :

⇒ pp, p-nucleus, light ion collisions

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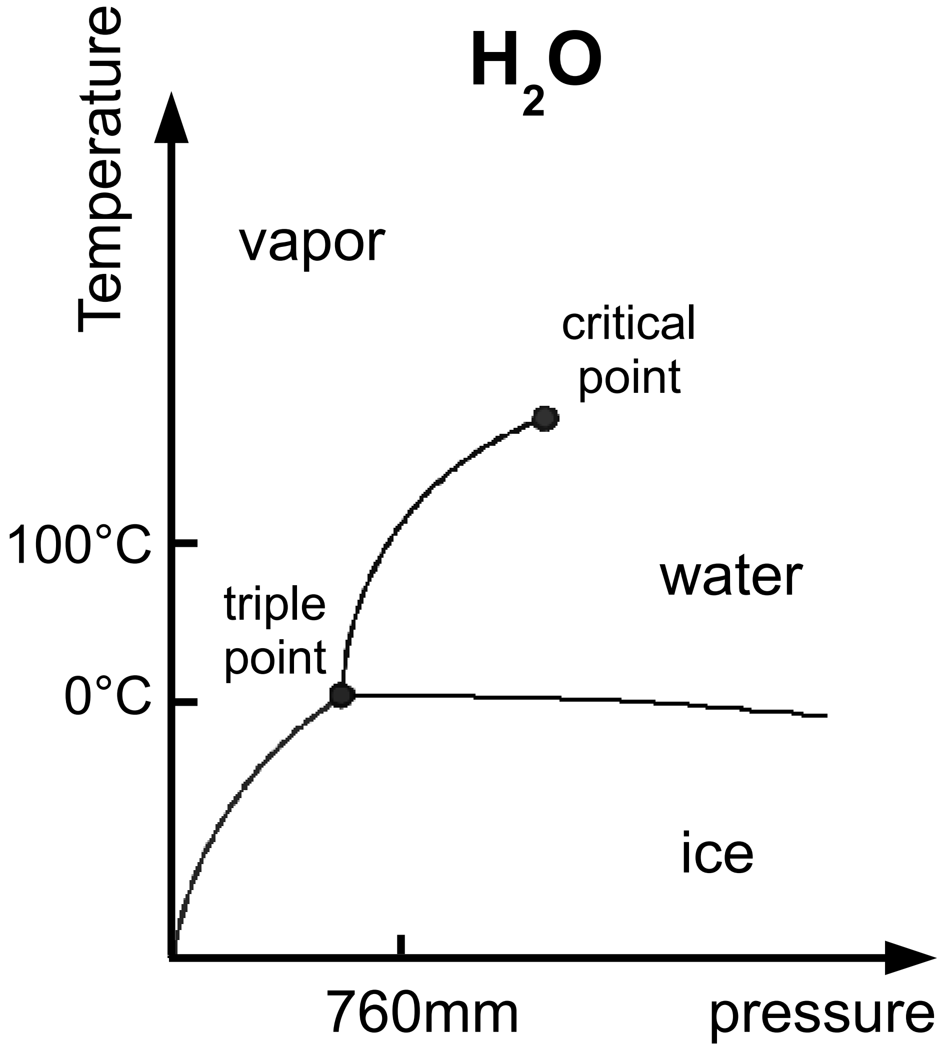

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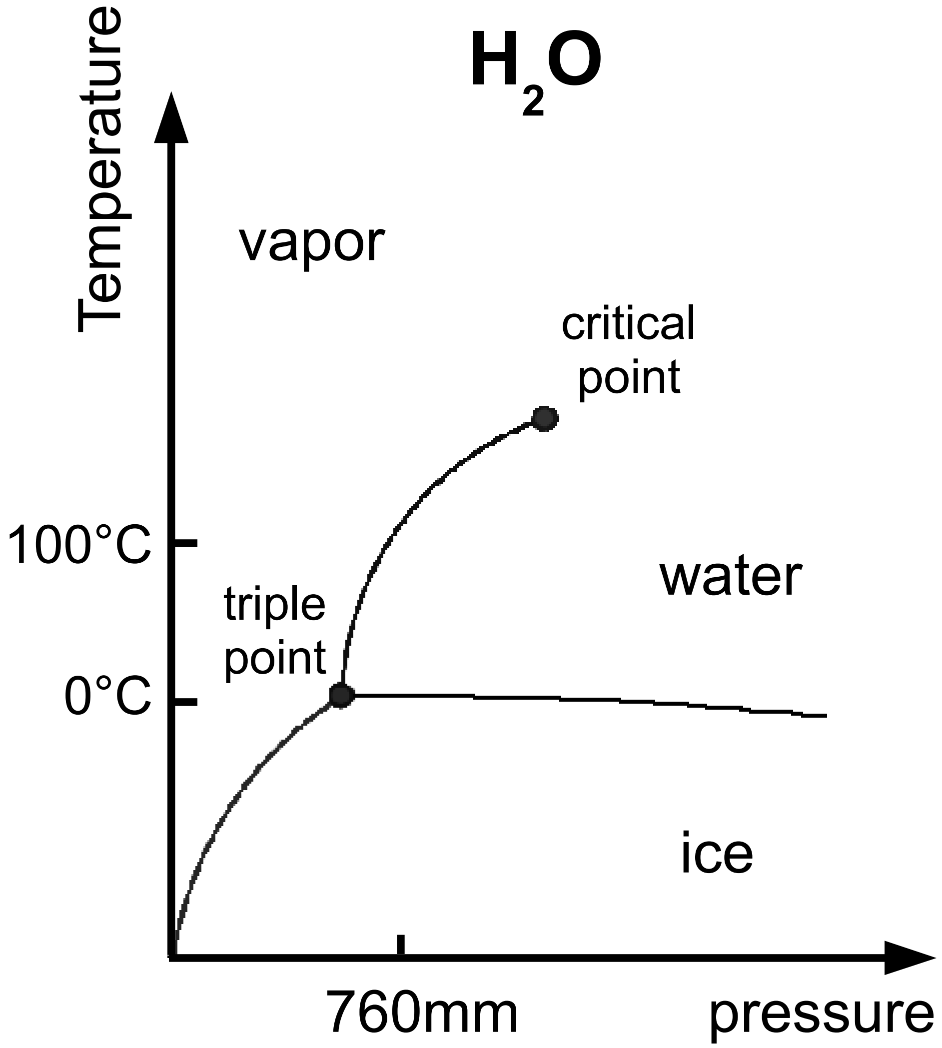

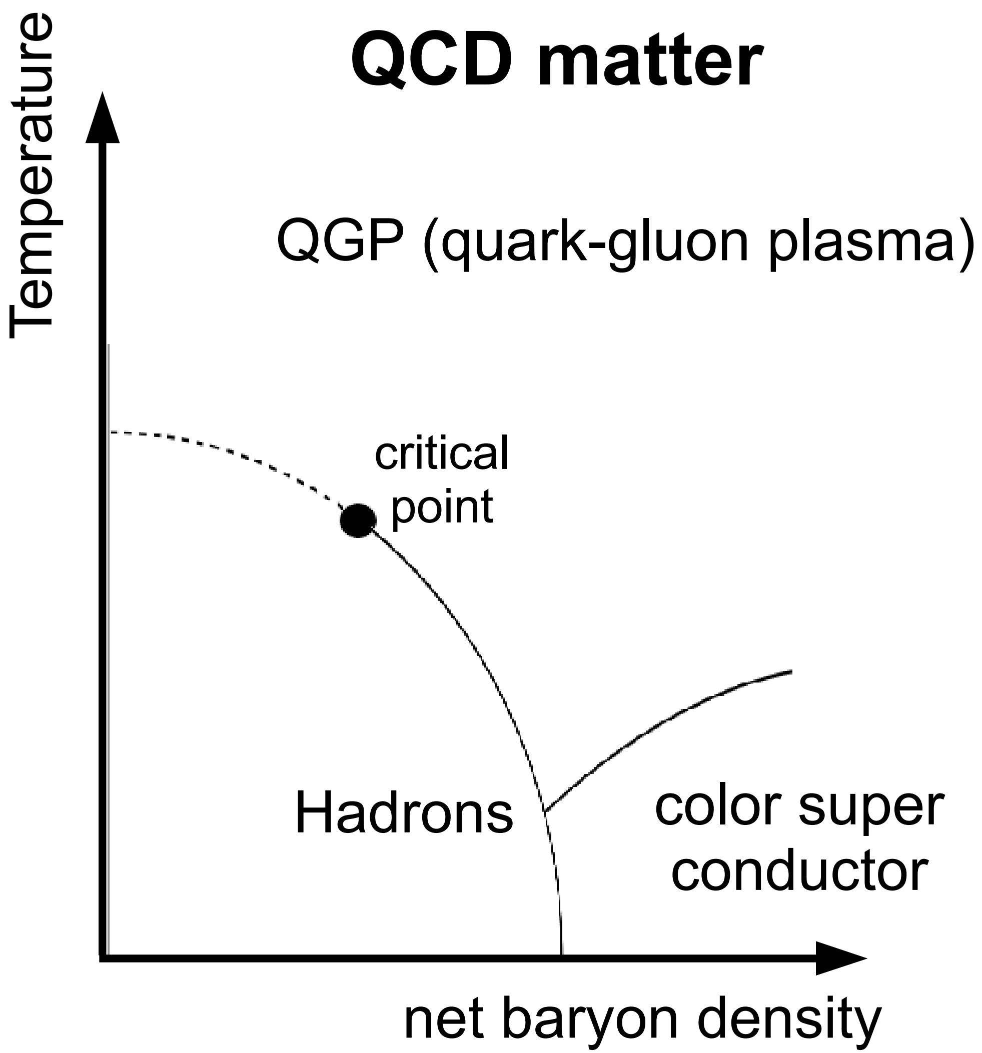

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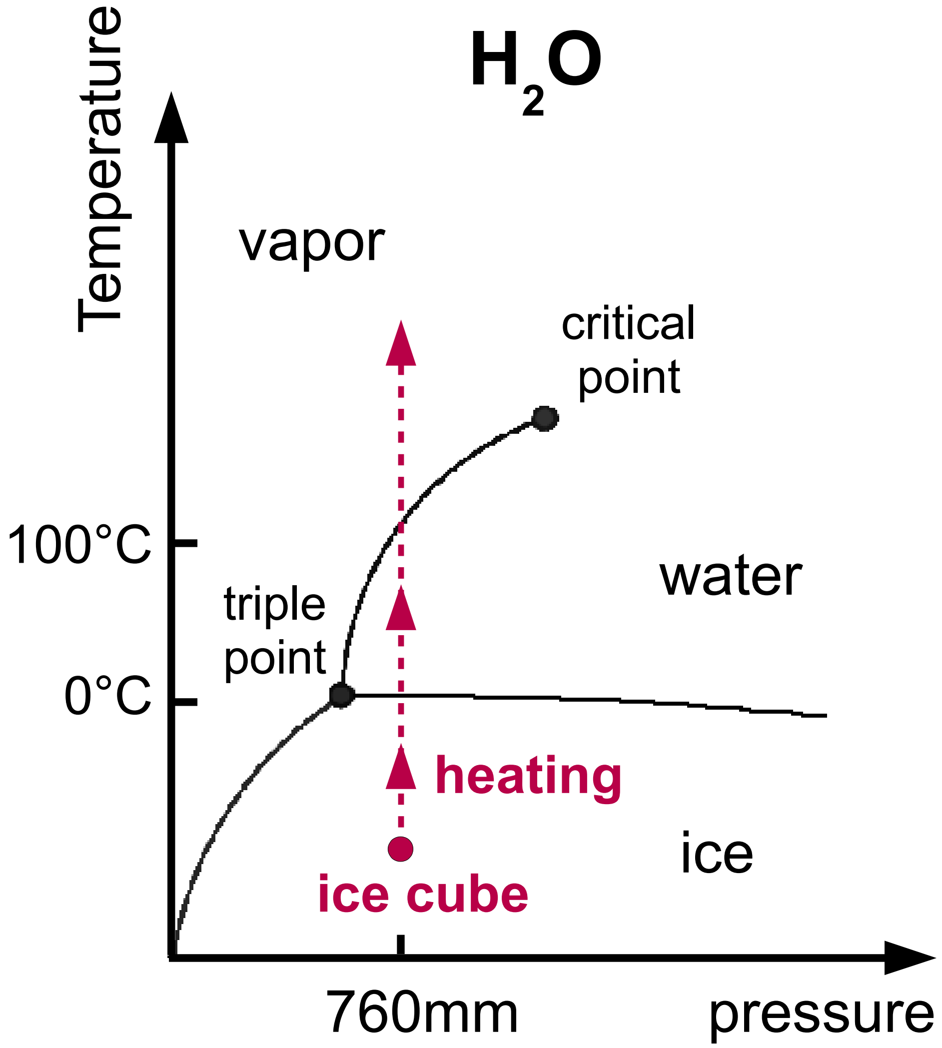

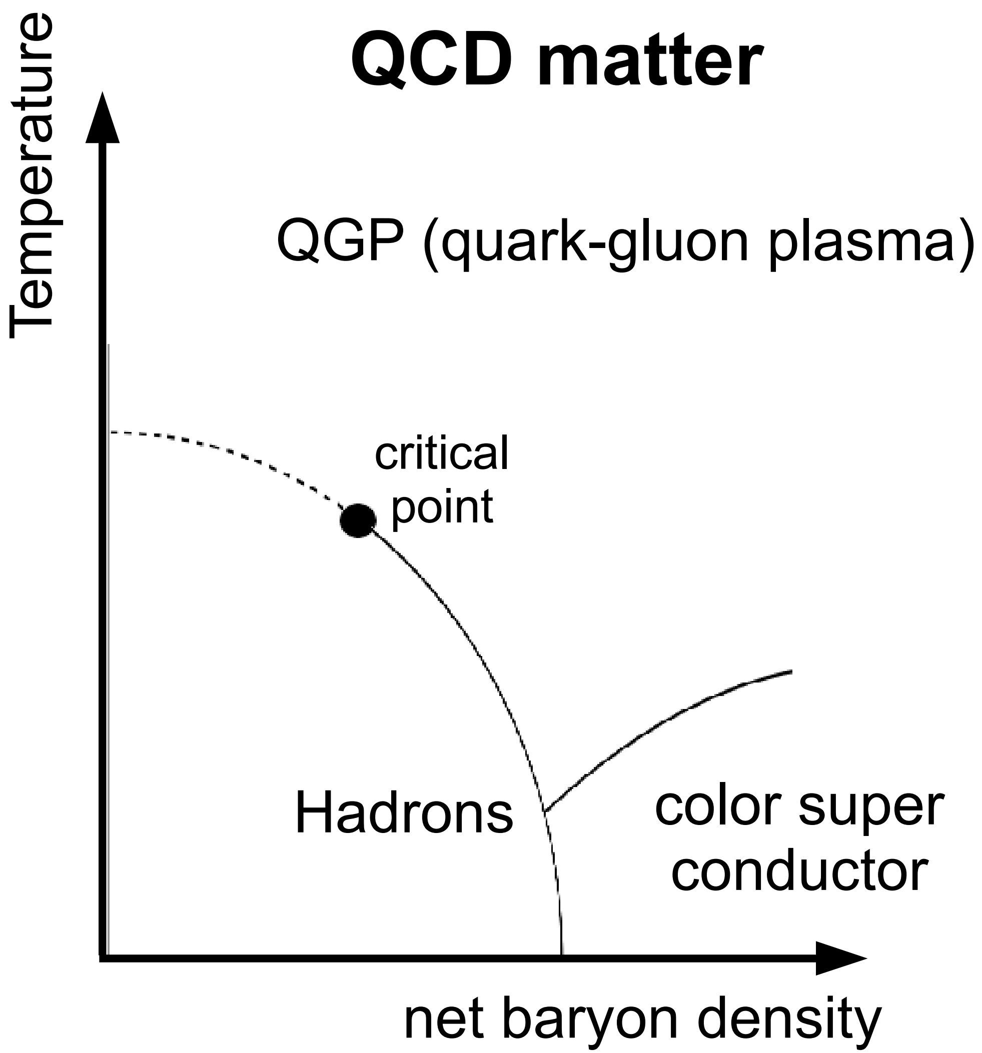

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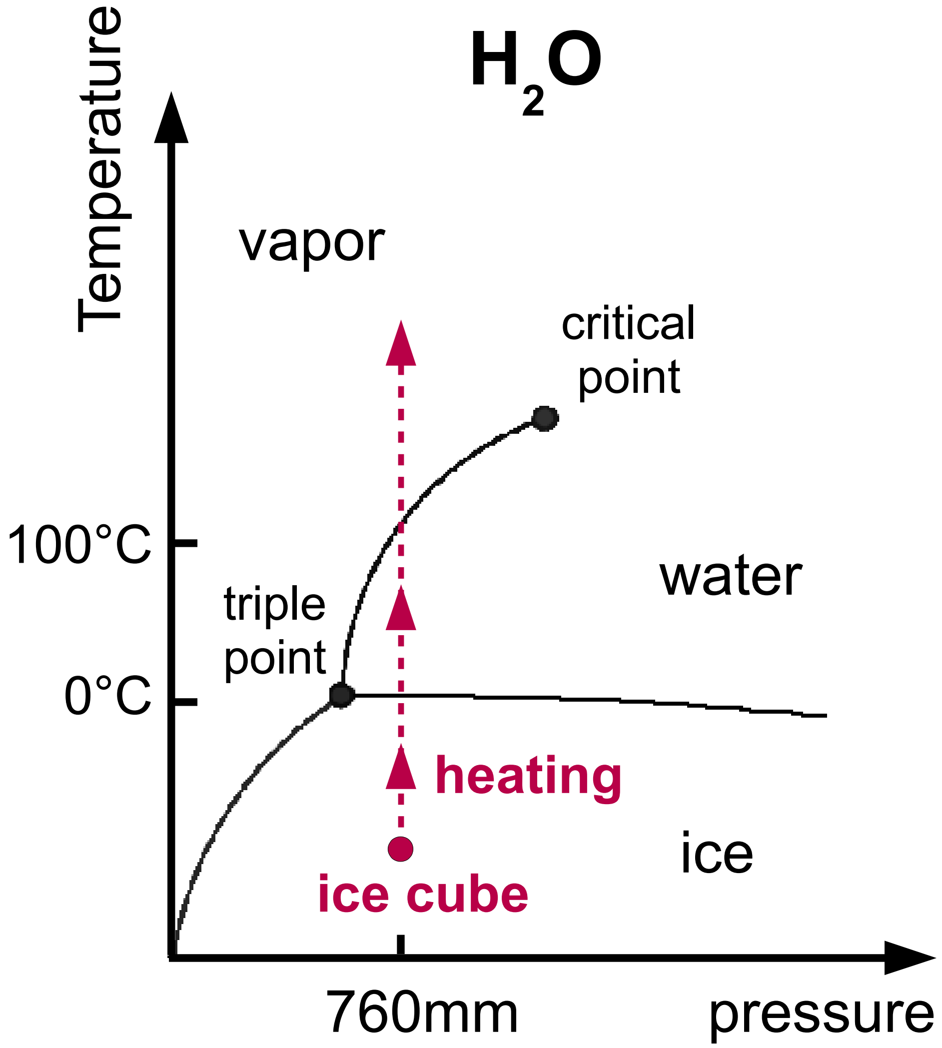

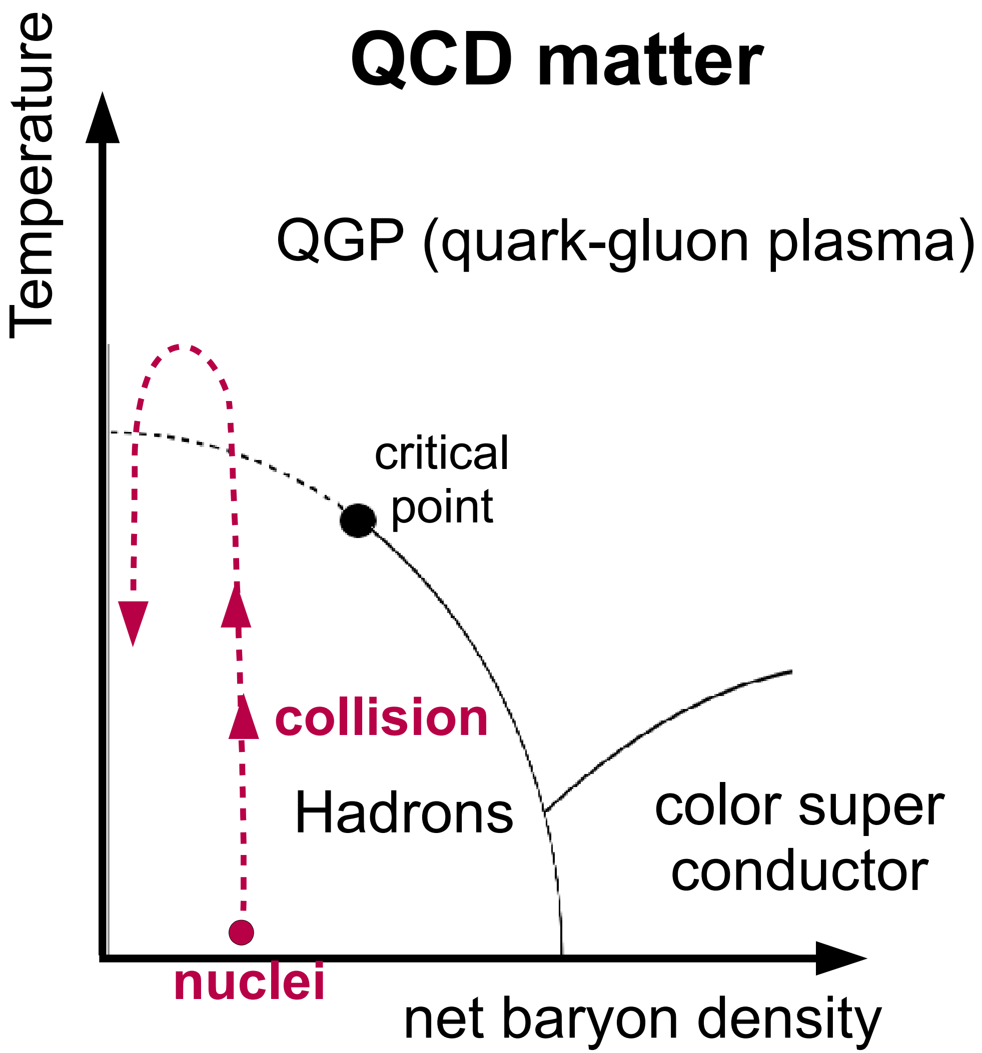

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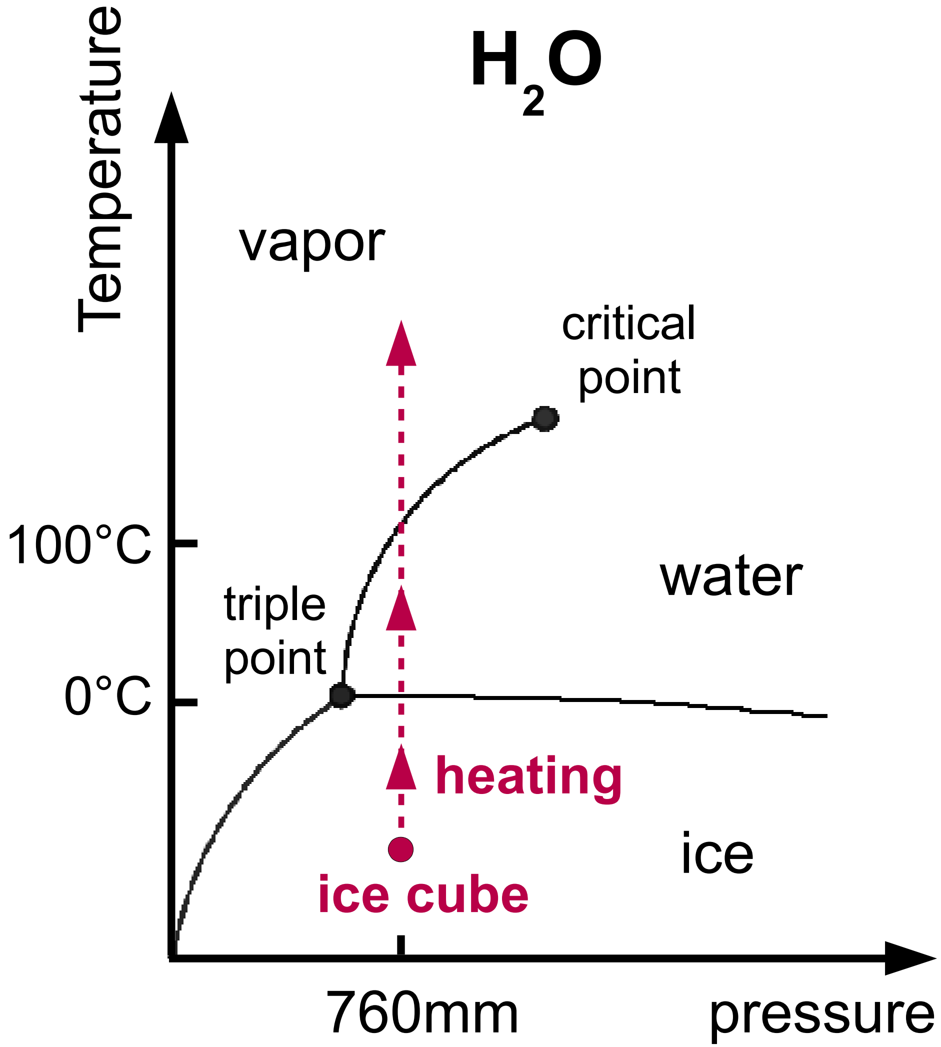

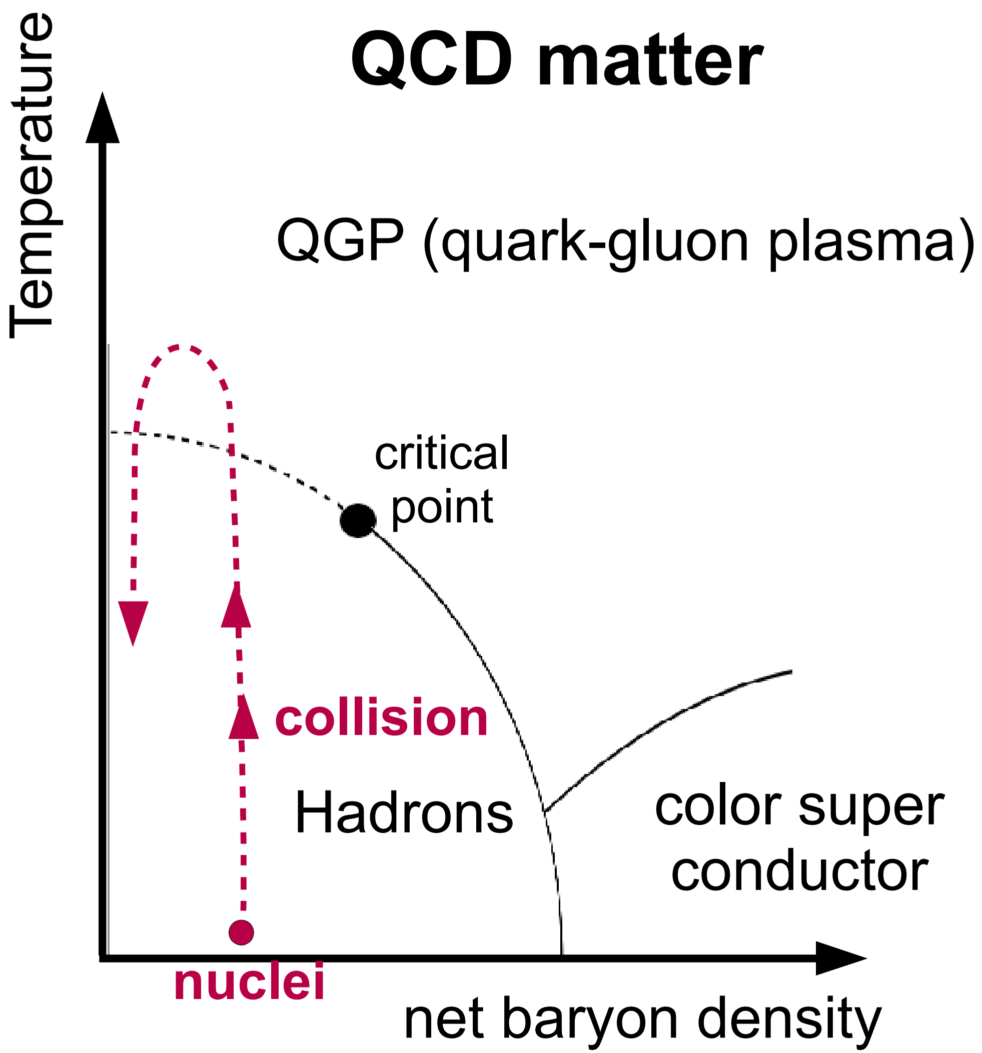

Experimental study of QCD phase diagram by colliding nuclei head-on to convert cold nuclear matter into a fireball of partons

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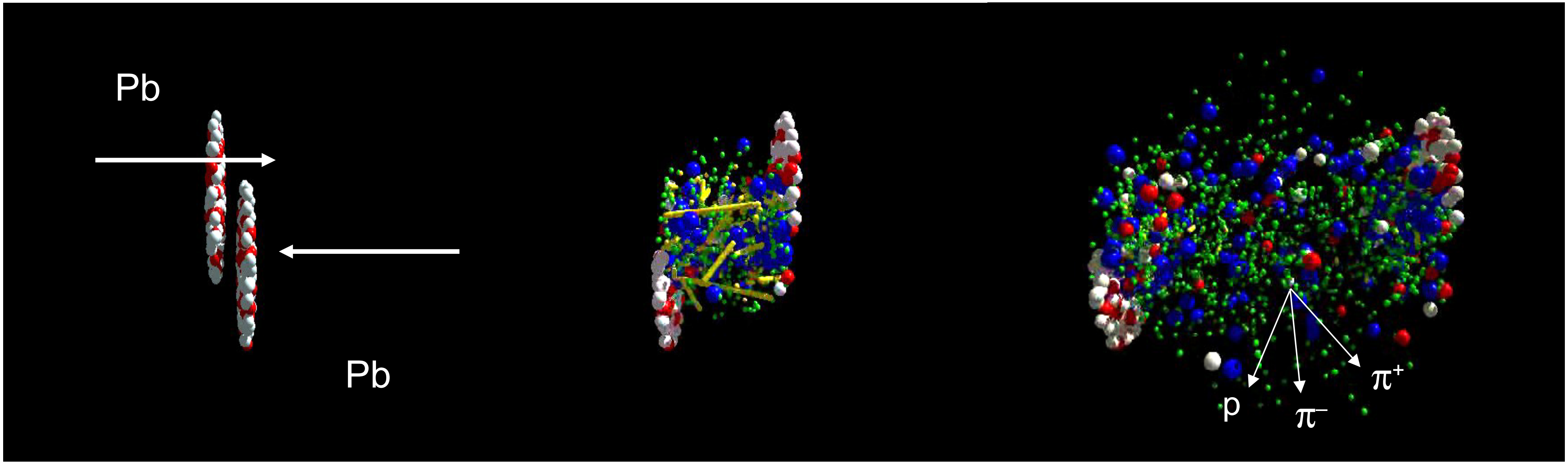
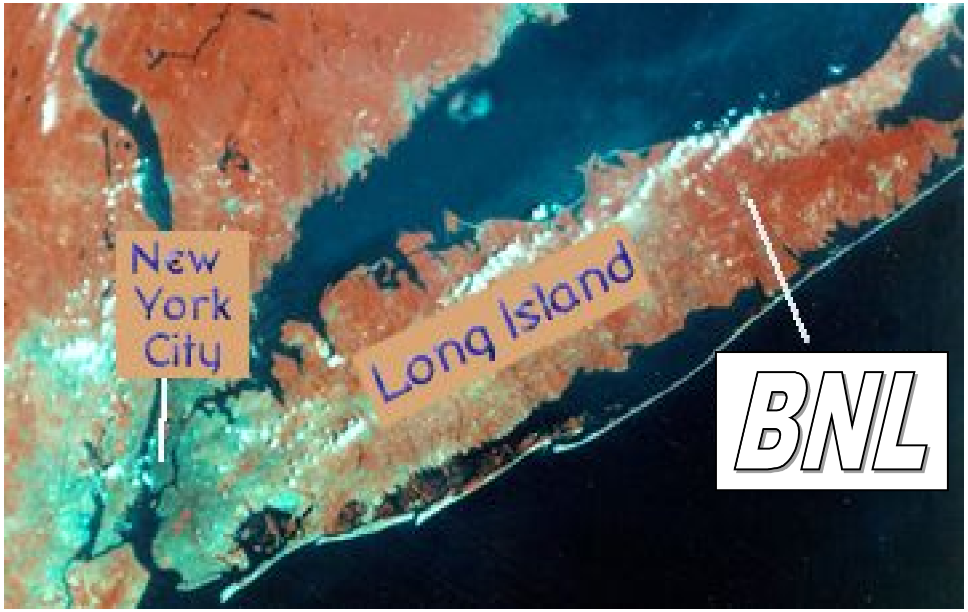


Experimental study of QCD phase diagram by colliding nuclei head-on to convert cold nuclear matter into a fireball of partons

Two main laboratories for heavy-ion collisions



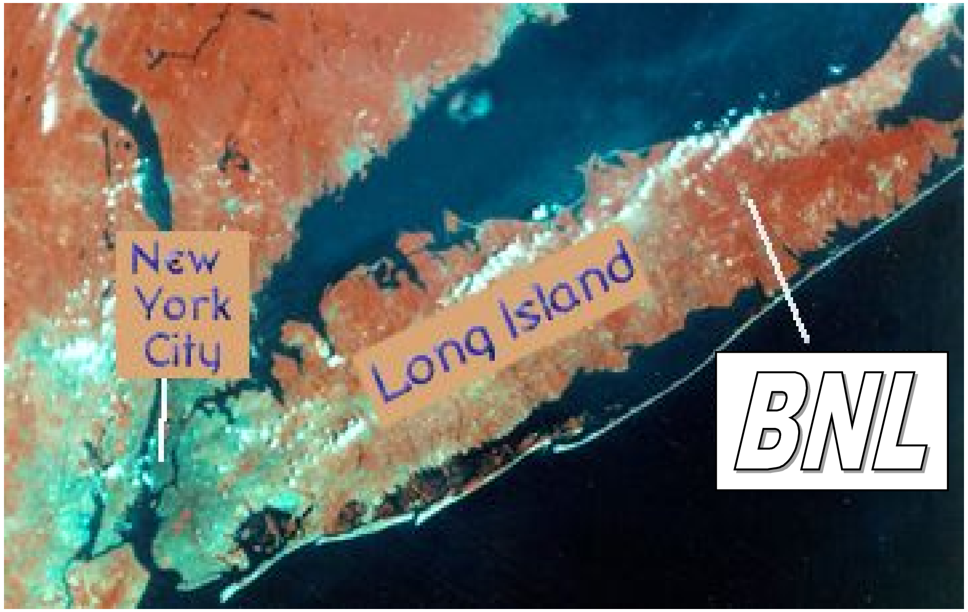
AGS : 1986 – 2000

- Si and Au beams ; √s ~ 5 GeV
- only hadronic variables

RHIC : 2000 – ?

- He3, Cu, Au beams ;
  up to √s = 200 GeV
- 4 experiments (only two remain)

Two main laboratories for heavy-ion collisions



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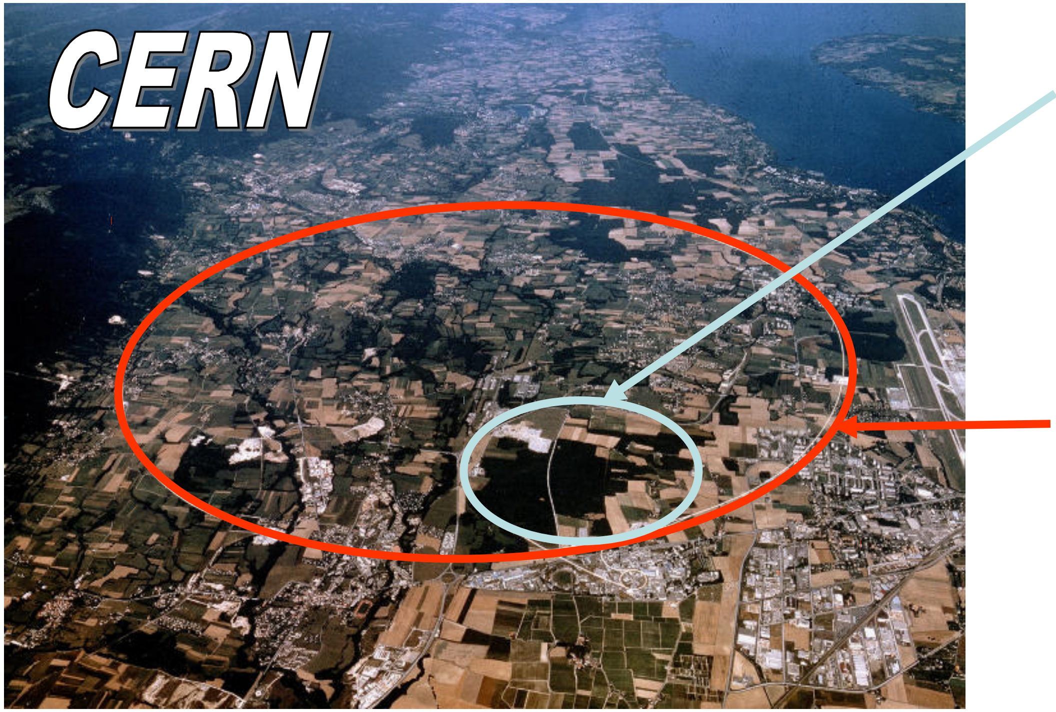


SPS : 1986 – 2003 + 2009 – ?

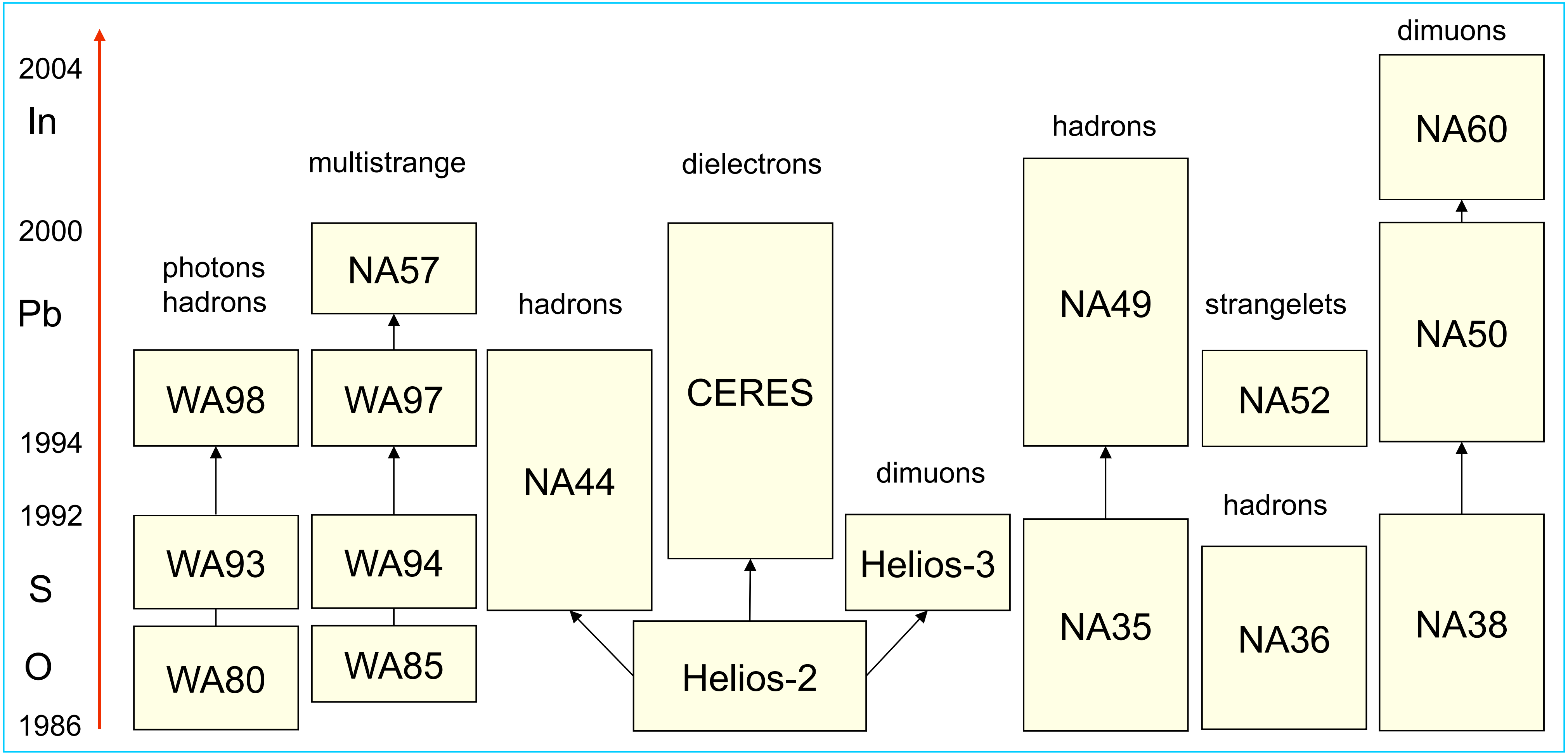
- O, S, In, Pb beams ; √s ~ 20 GeV
- hadrons, photons and dileptons

LHC : 2009 – ?

- Pb beams ; up to √s = 5500 GeV
- ALICE, CMS and ATLAS

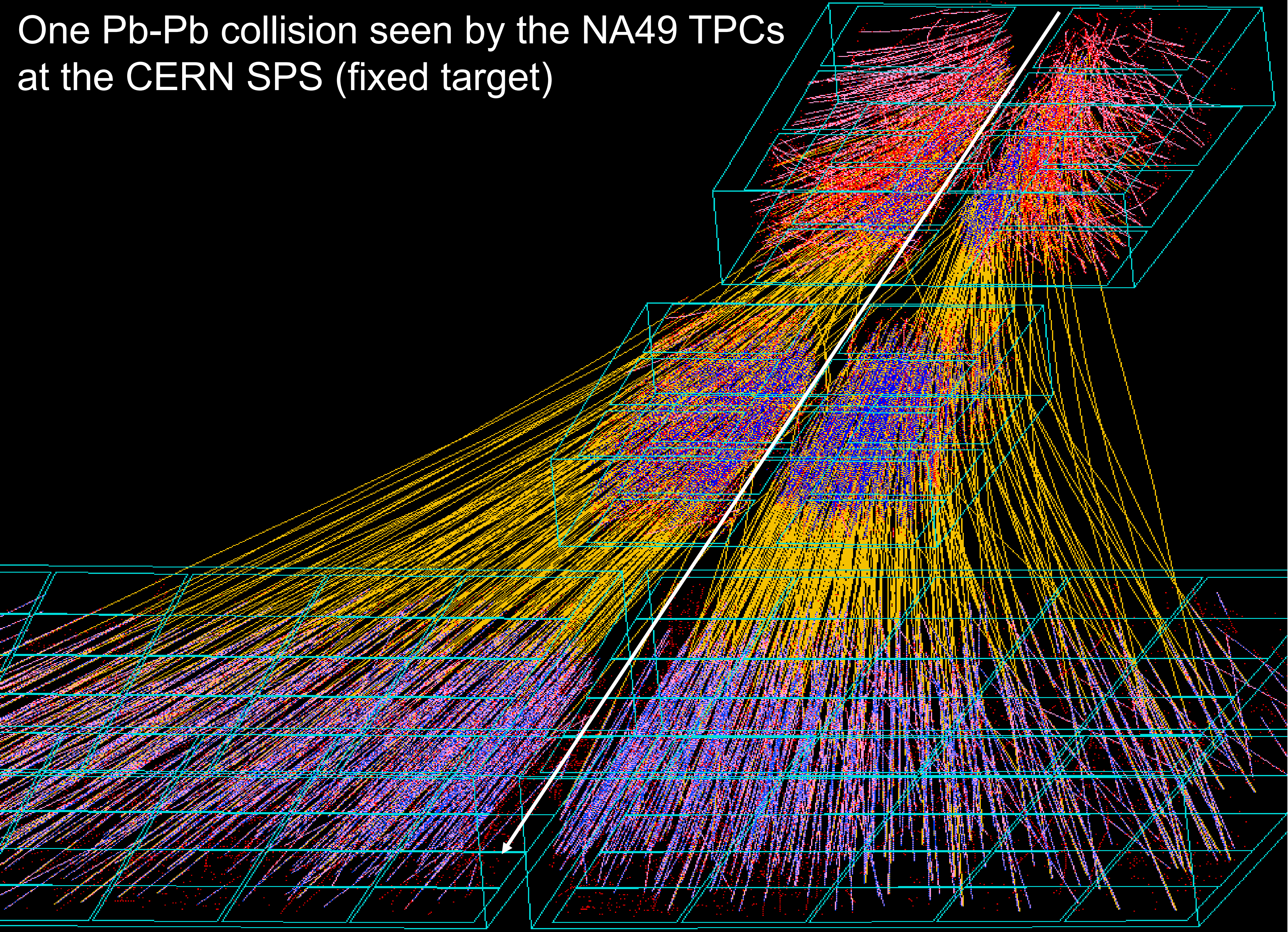
The CERN SPS physics program

Between 1986 and 2003, many experiments studied high-energy nuclear collisions at the CERN SPS, to probe hot QCD matter



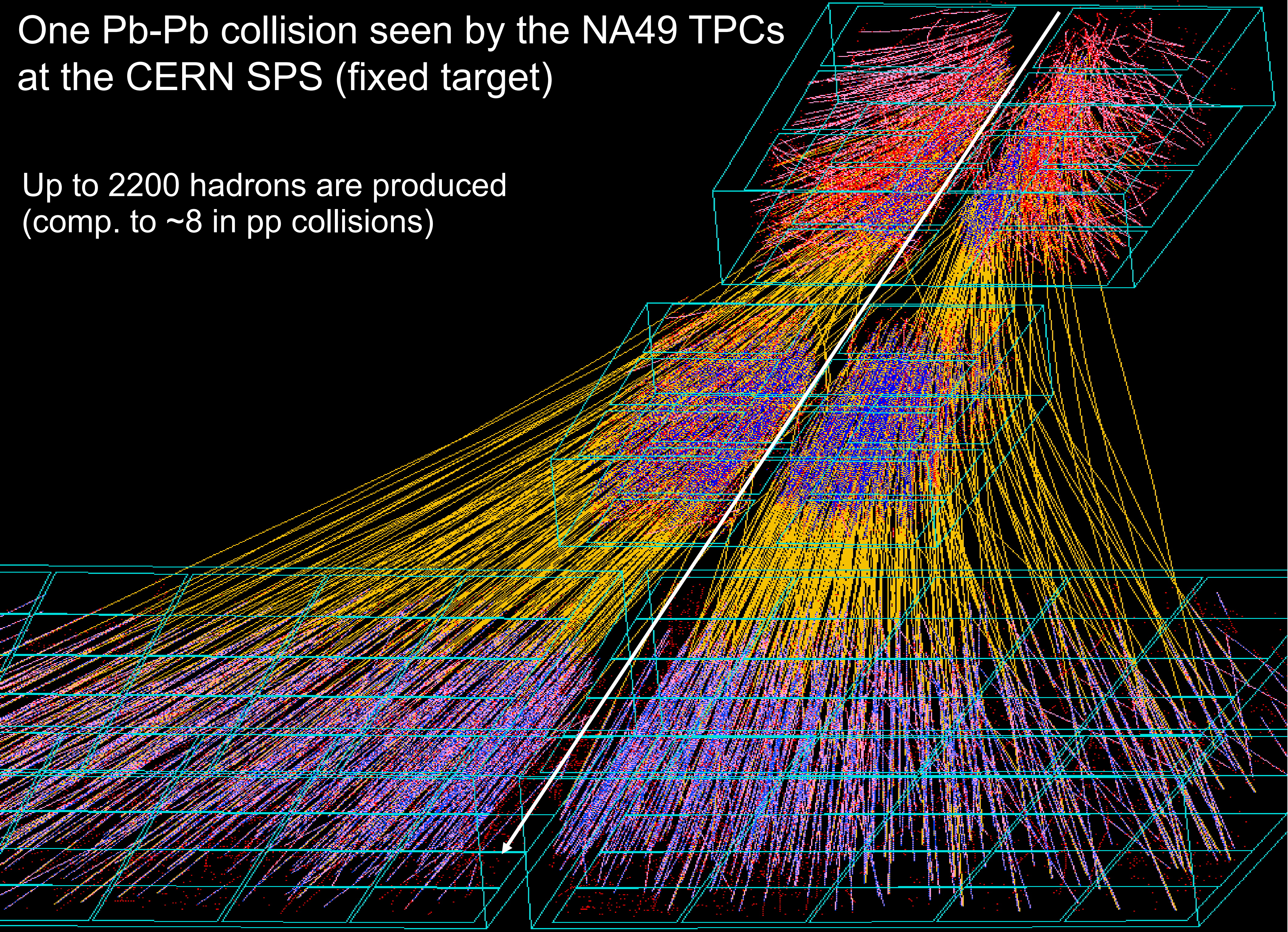
Scientific statement, 2000

One Pb-Pb collision seen by the NA49 TPCs at the CERN SPS (fixed target)

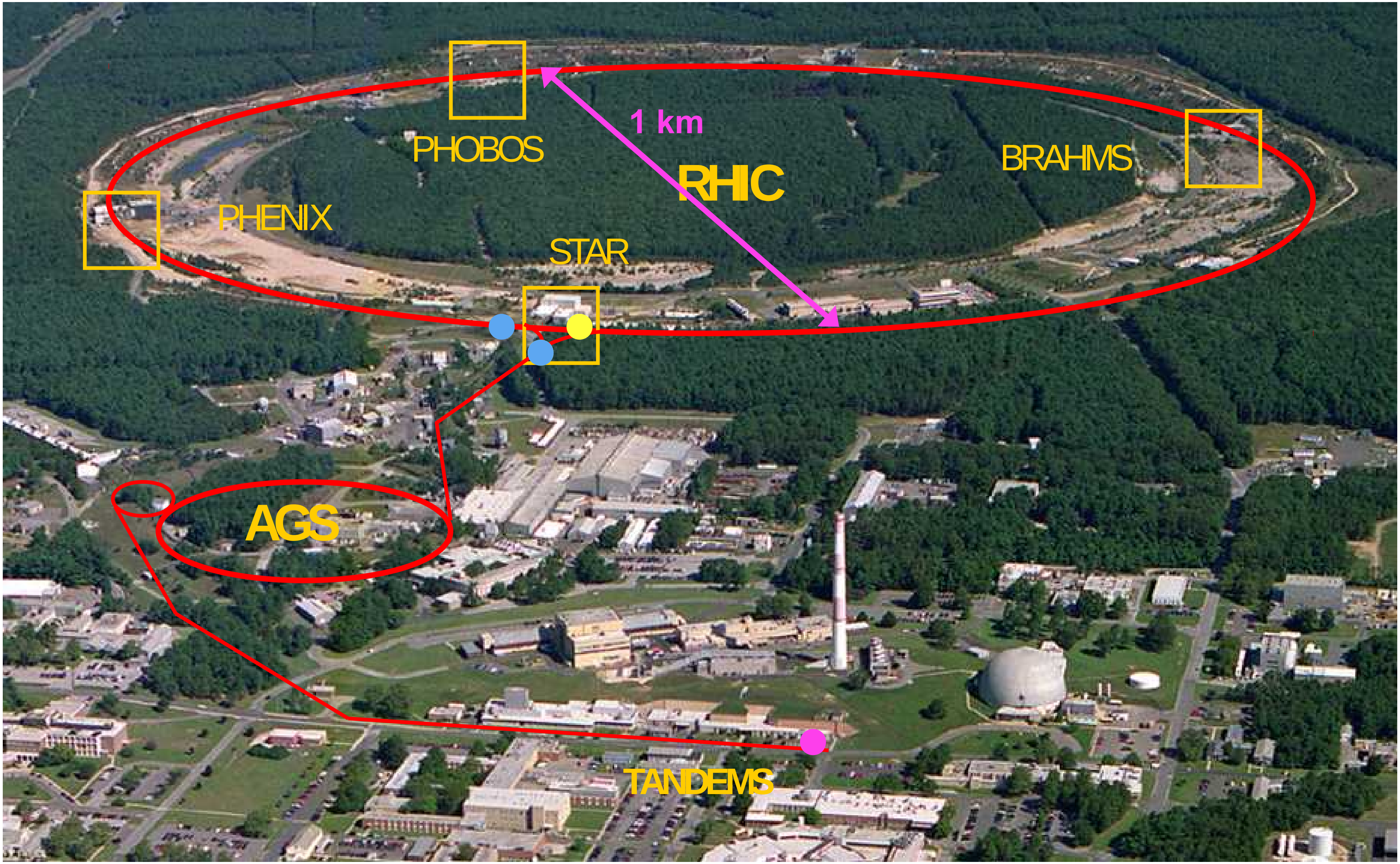


One Pb-Pb collision seen by the NA49 TPCs at the CERN SPS (fixed target)

Up to 2200 hadrons are produced
(comp. to ~8 in pp collisions)

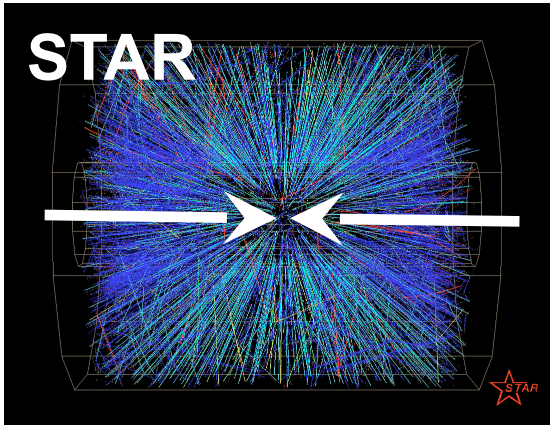


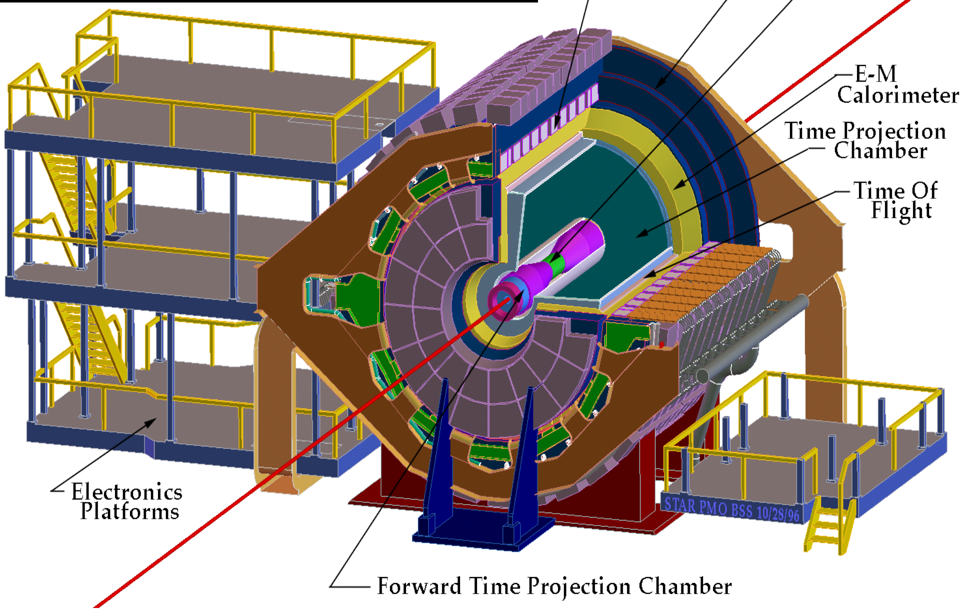
The Relativistic Heavy Ion Collider (RHIC)

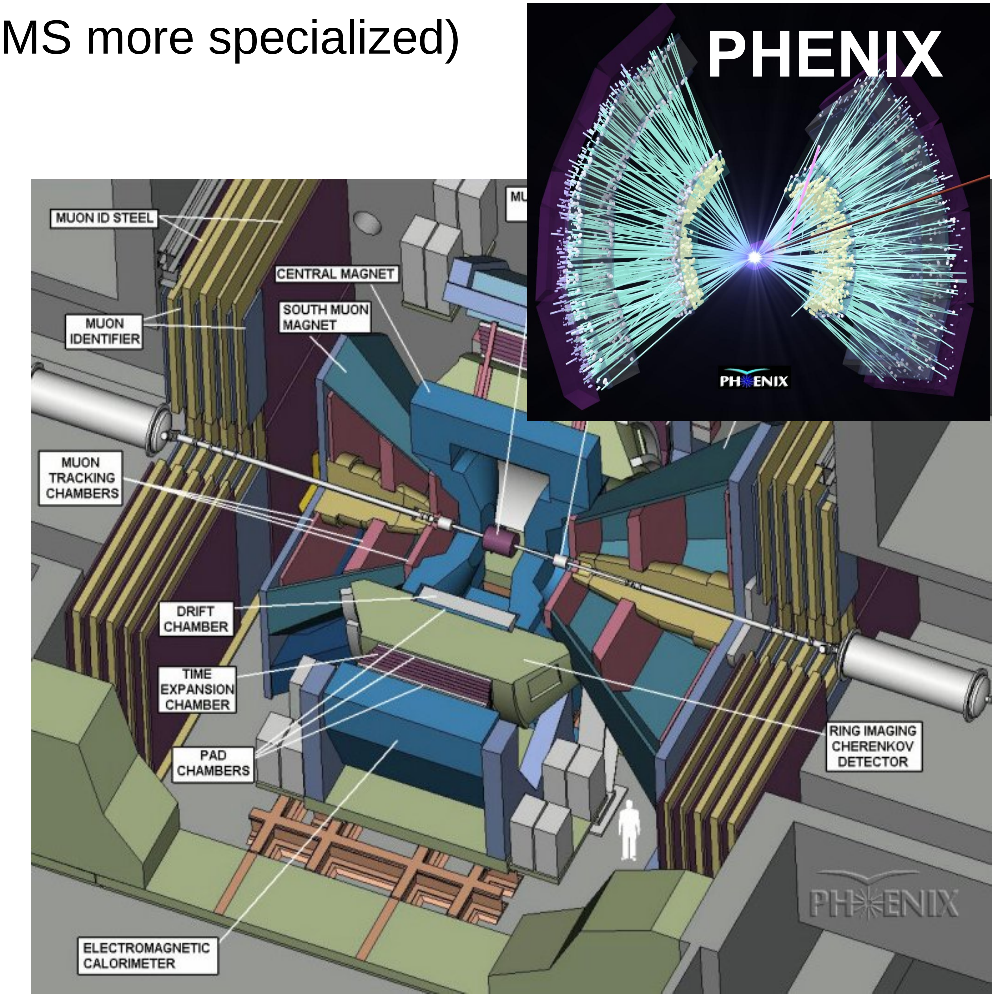


STAR and PHENIX at RHIC

(PHOBOS, BRAHMS more specialized)







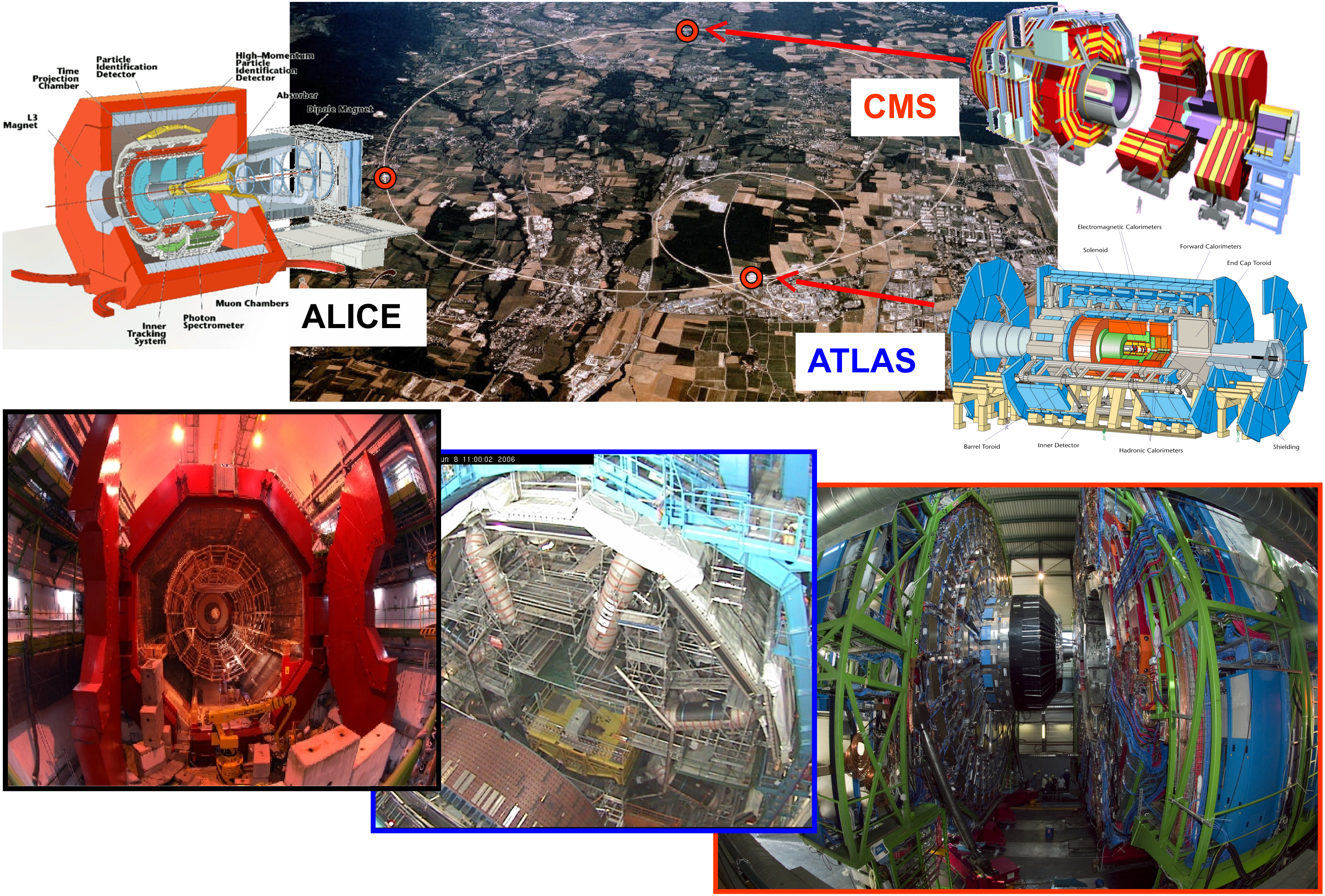
2π coverage, $-1<\eta<1$
for tracking + (coarse) EMCal
PID by TOF, dE/dx

Optimized for acceptance
(correlations, jet-finding)

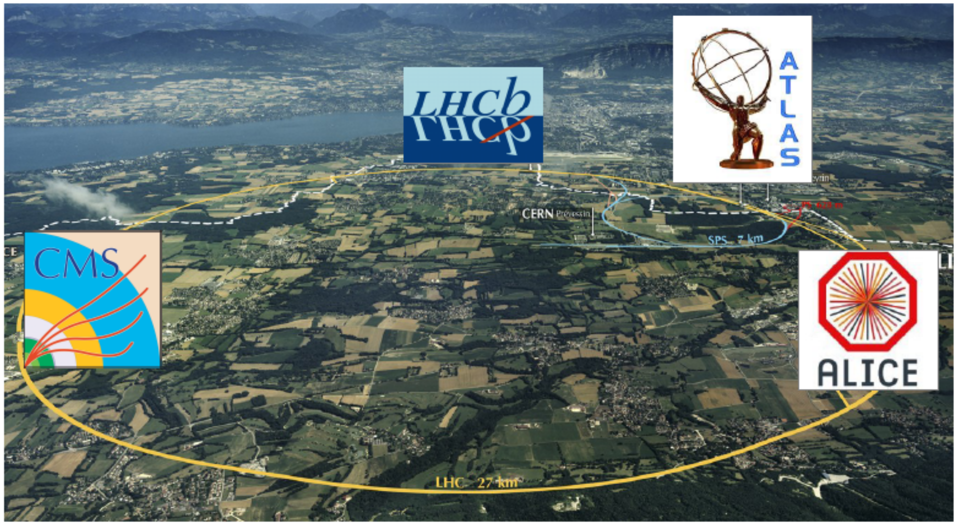
Partial coverage 2x0.5π, $-0.35<\eta<0.35$
Finely segmented calorimeter
+ forward muon arm, PID by RICH

Optimized for high-pt π^0, γ, e, J/ψ
(EMCal, high trigger rates)

LHC: The large ~~hadron~~ heavy-ion Collider



(Heavy-)Ion data-taking experiments at the LHC



- ALICE dedicated HI experiment
  - Low-p_T tracking, PID, mid-rapidity
- ATLAS/CMS large HEP experiments
  - Large acceptance, full calorimetry
- LHCb (recorded pPb data)
  - Forward tracking, PID, calorimetry

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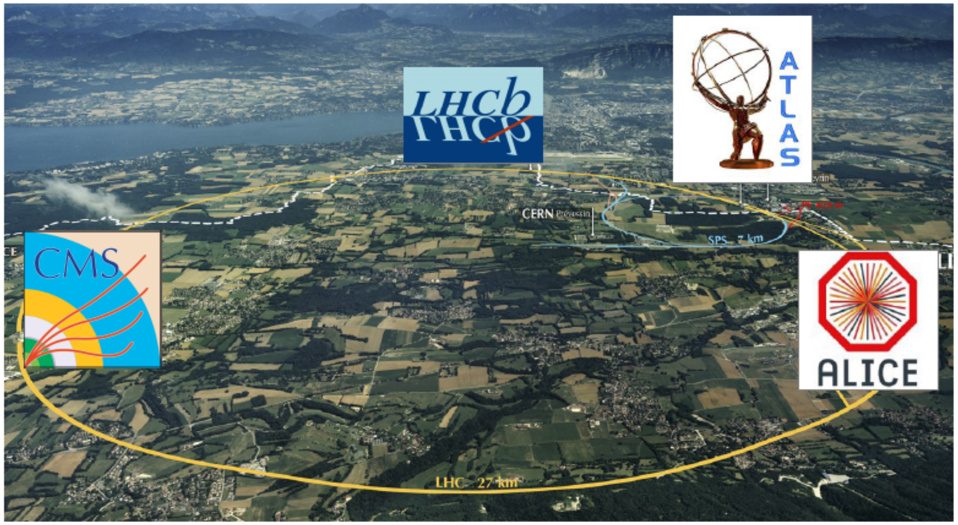
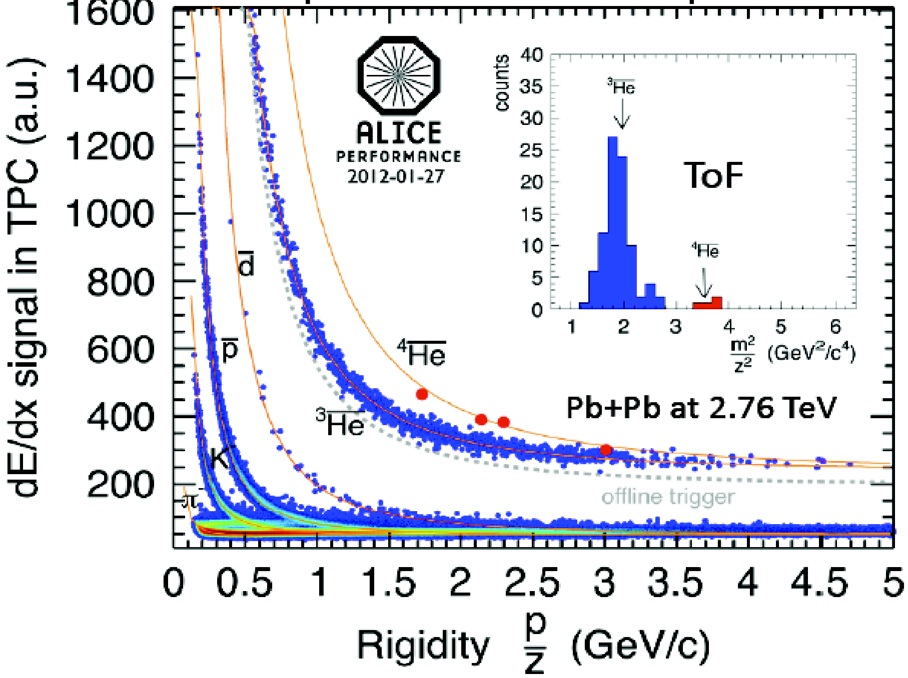


Example ALICE: PID capabilities



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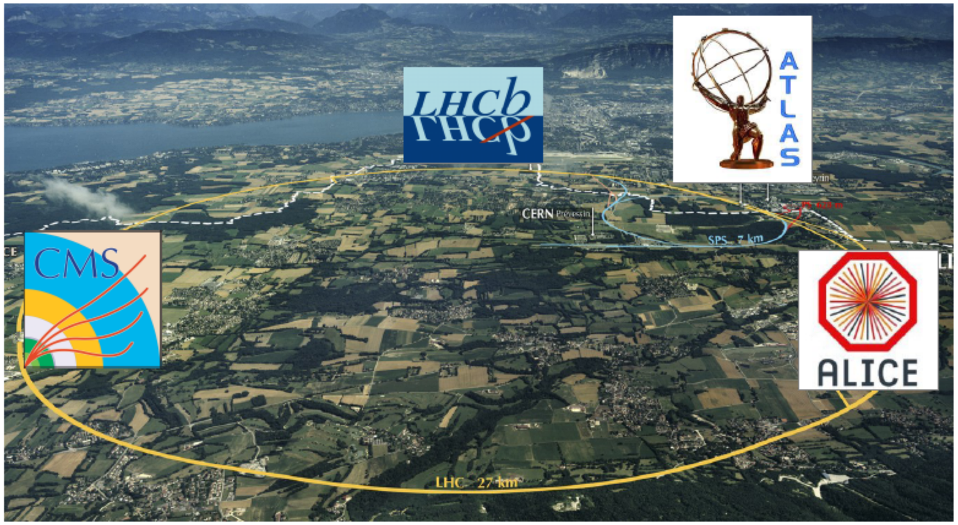

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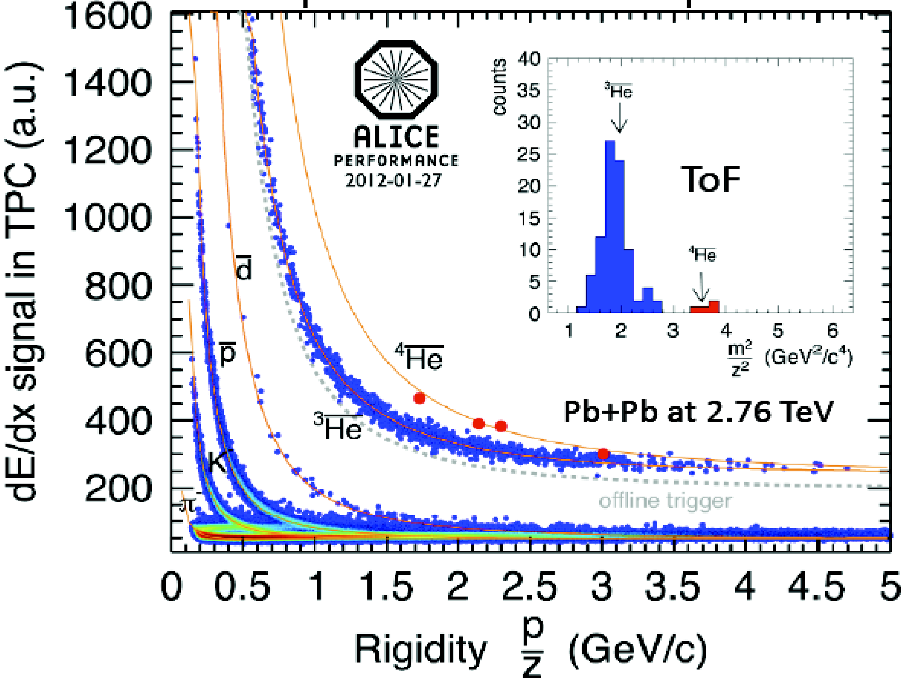

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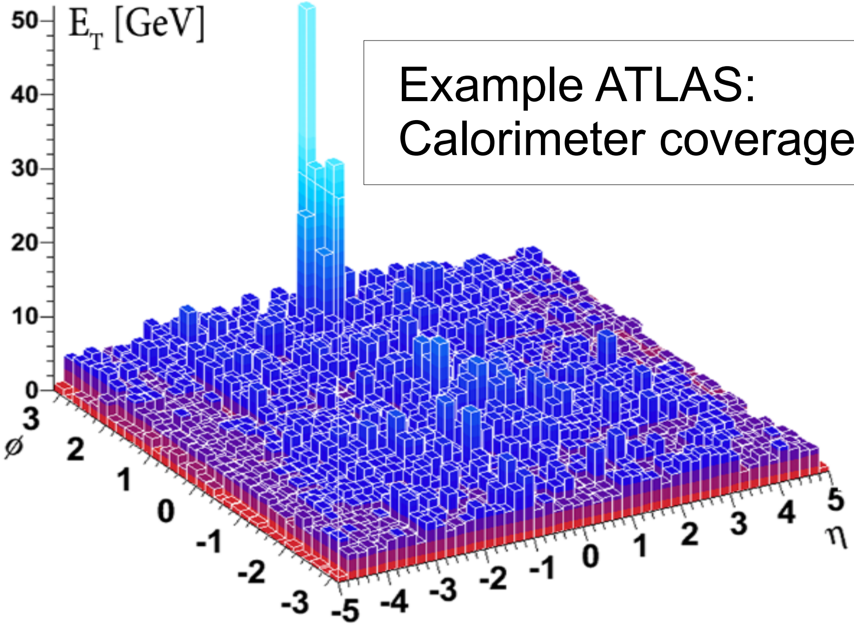

Example ATLAS:
Calorimeter coverage

Summary

- The QCD phase structure is rich with many fundamental and open questions
- Heavy-ion collisions attempt to create and probe QCD matter at high temperature and energy density
- The scientific approach is conceptually similar to previous scattering experiments, and relies on a series of well calibrated probes and set of collision systems

In the next two lectures we will look at a set of important results obtained from heavy-ion collisions at RHIC and LHC

If you have questions about today's lecture please send them to “cloizides at lbl dot gov”