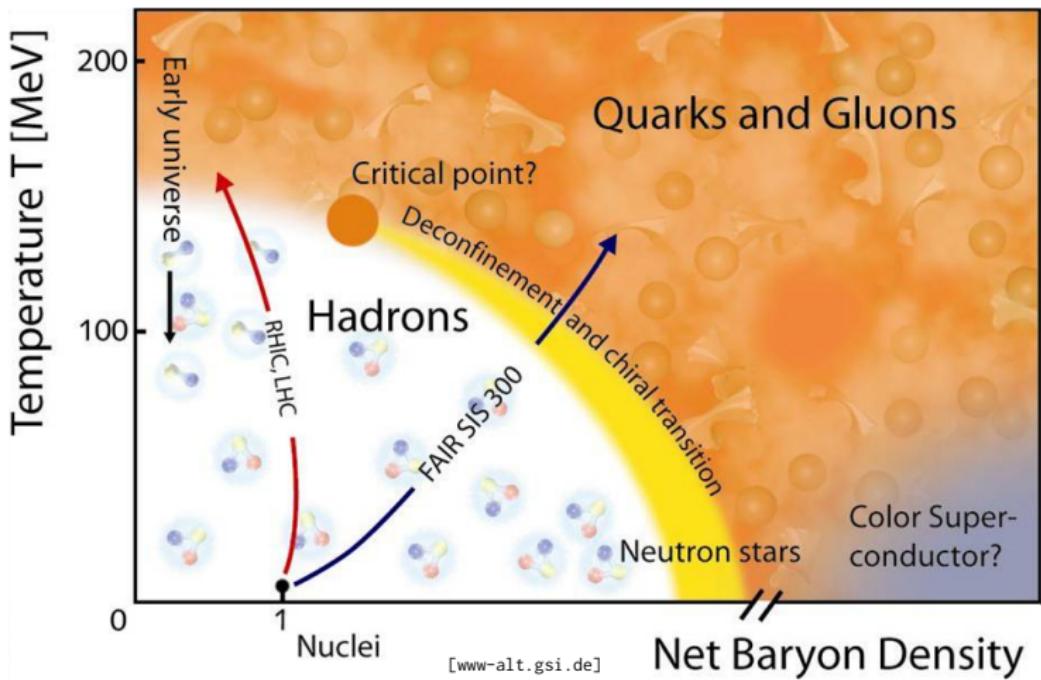


The QCD Phase Diagram

Ralf-Arno Tripolt



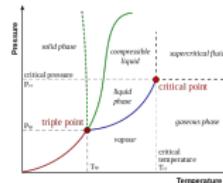
Outline



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introduction

- ▶ phases, phase transitions and thermodynamics

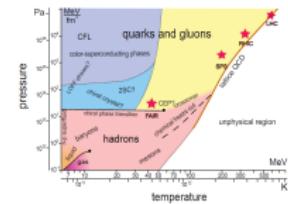


introduction to QCD

- ▶ QCD basics and symmetries

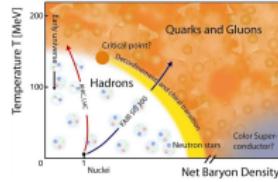
QCD phase diagram from theory

- ▶ different approaches and results



QCD phase diagram from experiment

- ▶ early universe, neutron stars and heavy ion collisions



What is a Thermodynamic Phase?

Matter may exist in different phases, throughout which all physical properties, like density, index of refraction, magnetisation and chemical composition, are essentially uniform and homogeneous.

homogeneous or inhomogeneous?



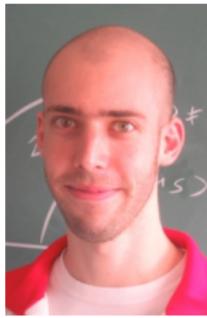
[wikipedia.org]

...it depends on the scale

More on Inhomogeneous (Chiral Symmetry Breaking) Phases



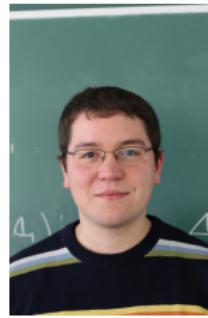
Michael Buballa



Stefano Carignano



Jamil Arif



Marco Schramm



Daniel Nowakowski

[S. Carignano, D. Nickel, M. Buballa, PRD (2010)]

[S. Carignano, M. Buballa, arXiv:1203.5343]

[M. Buballa, S. Carignano, D. Nickel, Phys. Atom. Nucl. 75 (2012)]

[M. Buballa, S. Carignano, arXiv:1210.7155]

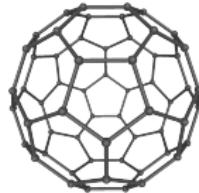
Thermodynamic Equilibrium



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In thermodynamic equilibrium there are no net flows of matter or of energy, no phase changes, and no unbalanced potentials (or driving forces).

However, a system may not reach this stable equilibrium due to energy barriers - such a quasi-equilibrium is metastable.

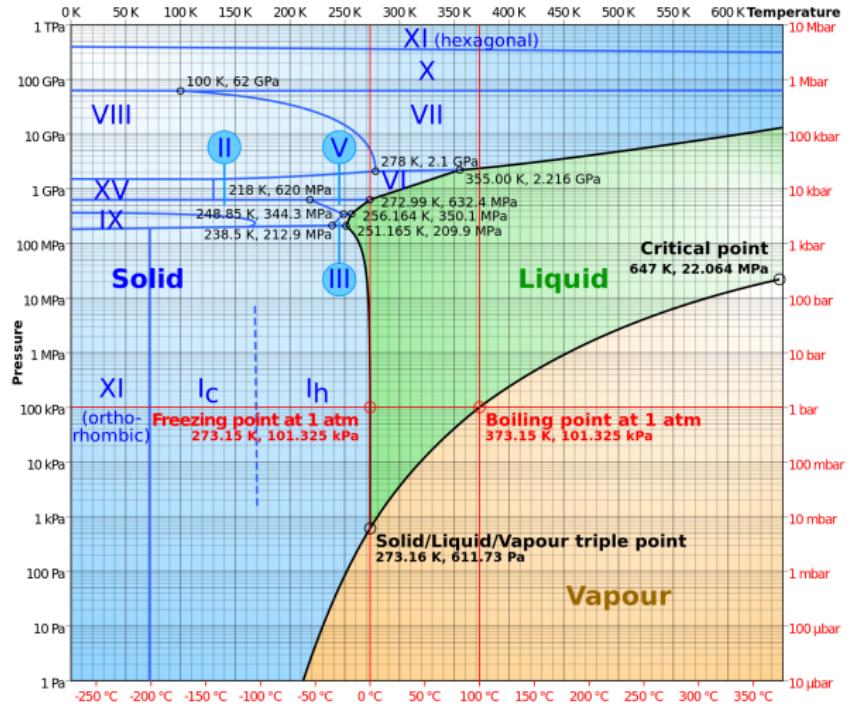


[wikipedia.org]

The Phase Diagram of Water



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[wikipedia.org/wiki/Phase_diagram]

Is There a Critical Point?



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THE
ANNALS 290 *M. de la Tour on the* [APRIL,
OR
PHILOSOPHY. ARTICLE IX.
—
NEW SERIES.
JANUARY TO JUNE, 1823.

An Account of some Results obtained by the combined Action of Heat and Compression upon certain Fluids, such as Water, Alcohol, Sulphuric Ether, and the rectified Oil of Petroleum.
By M. le Baron Cagniard de la Tour.*

The last experiment was made with a glass tube about one-third full of water ; this tube lost its transparency, and broke a few seconds afterwards. It appears that at a high temperature water is capable of decomposing glass by combining with its alkali ; this suggests the idea that some other result interesting to chemistry may, perhaps, be obtained by increasing the applications of this process of decomposition.

Reminder on Thermodynamics



thermodynamic potentials:

energy: $E(S, V, N)$

$$dE = T dS - P dV + \mu dN$$

free energy: $F(T, V, N) = E - TS$

$$dF = -S dT - P dV + \mu dN$$

enthalpy: $H(S, P, N) = E + PV$

$$dH = T dS + V dP + \mu dN$$

free enthalpy: $G(T, P, N) = E - TS + PV$

$$dG = -S dT + V dP + \mu dN$$

Legendre transformations w.r.t. $-\mu N$ give further potentials, e.g.:

grand potential: $\Omega(T, V, \mu) = E - TS - \mu N$ $d\Omega = -S dT - P dV - N d\mu$

some important relations following from this:

$$\blacktriangleright \mu = (\partial G / \partial N)_{T,P} = G/N$$

$$\blacktriangleright \Omega = -PV$$

second law of thermodynamics (Clausius, 1865):

- ▶ a closed system with fixed energy E and fixed external parameters (V, N) tends to maximise its entropy S

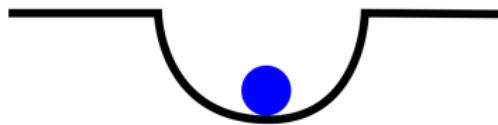
it follows that G is minimal for fixed T and P in equilibrium:

$$\begin{aligned} S(E_A, V_A) &= S_A(E_A, V_A) + S_B(E - E_A, V - V_A) \\ &= S_A + S_B(E, V) - \frac{\partial S_B(E_B, V_B)}{\partial E_B} E_A - \frac{\partial S_B(E_B, V_B)}{\partial V_B} V_A \\ &= \text{const.} + S_A - \frac{E_A}{T} - \frac{PV_A}{T} \\ &= \text{const.} - G_A/T \rightarrow \text{maximal} \end{aligned}$$

Equilibrium Conditions (II)

summary of extremal conditions for equilibrium:

	$V = \text{const.}$	$p = \text{const.}$
$S = \text{const.}$	$E \rightarrow \min.$	$H \rightarrow \min.$
$T = \text{const.}$	$F, \Omega \rightarrow \min.$	$G \rightarrow \min.$



[wikipedia.org]

Equilibrium Conditions at Phase Transitions

consider two phases, vapour (A) and water (B):

$$E = E_A + E_B = \text{const.},$$

$$V = V_A + V_B = \text{const.},$$

$$N = N_A + N_B = \text{const.},$$

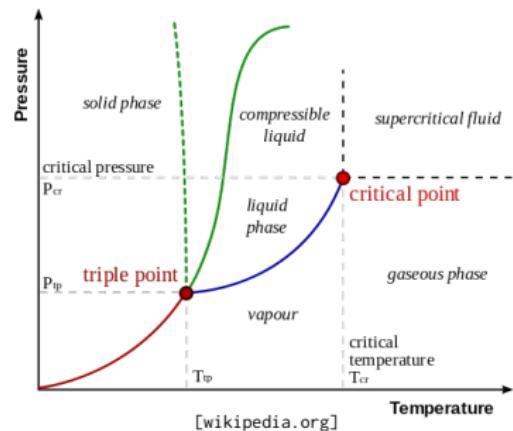
the entropy is maximal in equilibrium,

$$S(E_A, V_A, N_A) = S_A + S_B \rightarrow \max.$$

from $\partial S / \partial E_A = 0$, $\partial S / \partial V_A = 0$ and

$\partial S / \partial N_A = 0$ it follows that, in equilibrium,

$$T_A = T_B, \quad P_A = P_B, \quad \mu_A = \mu_B$$



The Clausius-Clapeyron Equation

consider vapour (A) and water (B) along phase-transition line:

$$\mu_A(T, P(T)) = \mu_B(T, P(T))$$

the total T -derivative gives, with $d\mu = -s dT + v dP$ (Duhem-Gibbs),

$$\begin{aligned} \left(\frac{\partial \mu_A}{\partial T}\right)_P + \left(\frac{\partial \mu_A}{\partial P}\right)_T \frac{dP(T)}{dT} &= \left(\frac{\partial \mu_B}{\partial T}\right)_P + \left(\frac{\partial \mu_B}{\partial P}\right)_T \frac{dP(T)}{dT} \\ (v_A - v_B) \frac{dP(T)}{dT} &= s_A - s_B, \end{aligned}$$

with $s = S/N$ and $v = V/N$; for a fixed pressure P we have $\Delta s = \Delta h/T$, so

$$\frac{dP(T)}{dT} = \frac{\Delta h}{T \Delta v}$$

The Clausius-Clapeyron Equation for QCD

to express the Clausius-Clapeyron equation in terms of μ and T , we use the grand potential $\Omega(\mu, T(\mu))$, where Ω , S and N are now taken to be divided by V :

$$\Omega_A(\mu, T(\mu)) = \Omega_B(\mu, T(\mu)),$$

taking the total μ -derivative and using $d\Omega = -SdT - Nd\mu$ gives

$$\begin{aligned} \left(\frac{\partial \Omega_A}{\partial \mu} \right)_T + \left(\frac{\partial \Omega_A}{\partial T} \right)_\mu \frac{dT(\mu)}{d\mu} &= \left(\frac{\partial \Omega_B}{\partial \mu} \right)_T + \left(\frac{\partial \Omega_B}{\partial T} \right)_\mu \frac{dT(\mu)}{d\mu} \\ \frac{dT(\mu)}{d\mu} (S_A - S_B) &= -(N_A - N_B) \\ \frac{dT(\mu)}{d\mu} &= -\frac{\Delta N}{\Delta S} \end{aligned}$$

order parameter ψ :

is a (macroscopic) quantity that changes characteristically at a phase transition,
e.g. M/M_0 for paramagnetic \leftrightarrow ferromagnetic or $(n - n_c)/n_c$ for liquid \leftrightarrow gas;
it is zero in one phase (usually above the critical point), and non-zero in the other.

order of phase transitions - modern classification:

- ▶ ψ changes discontinuously: first-order
- ▶ ψ changes continuously: second-order

order of phase transitions - Ehrenfest classification:

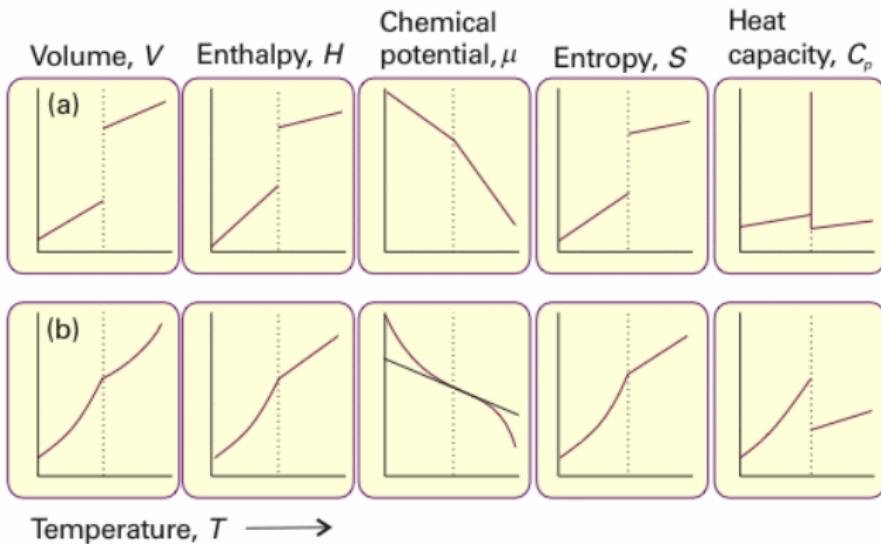
- ▶ $\partial F/\partial y$ changes discontinuously: first-order
- ▶ $\partial F/\partial y$ is continuous but $\partial^2 F/\partial y^2$ discontinuous: second-order

Classification of Phase Transitions (II)



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first-order (a) and second-order (b) phase transitions:



[www.chem.queensu.ca]

Classification of Phase Transitions (III) - Critical Exponents and Universality

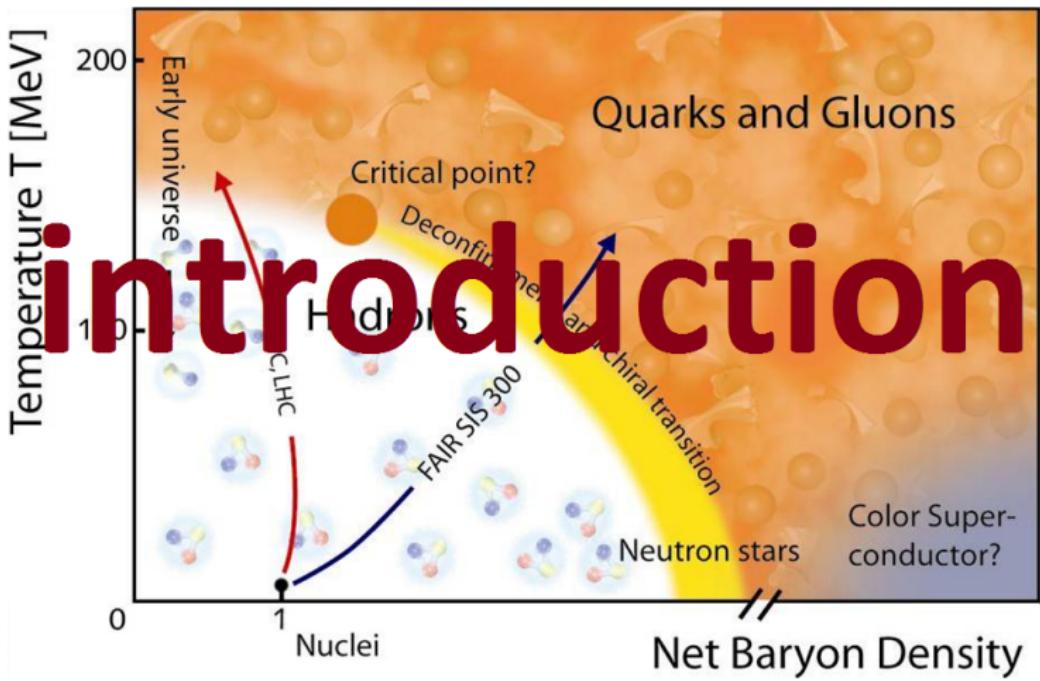
critical exponents describe the behaviour of physical quantities near continuous (second order) phase transitions and are universal, i.e. they do not depend on the details of the physical system

most important critical exponents, $t = (T - T_c)/T_c > 0$:

- ▶ specific heat: $C = -T \partial^2 F / \partial T^2 \propto t^{-\alpha}$
- ▶ susceptibility: $\chi = \partial^2 F / \partial J^2 \propto t^{-\gamma} \propto t^{-\nu(2+\eta)}$
- ▶ correlation length: $\langle \psi(x)\psi(y) \rangle \sim e^{-(x-y)/\xi}, \xi \propto t^{-\nu}$

universality classes:

in general, microscopic theories which have the same global symmetries, have equal critical exponents and form broad universality classes, e.g. 3D Ising model:
 $\eta \approx 0.04$ and $\nu \approx 0.63$



Introduction to QCD - Basics of Quantum Chromodynamics

QCD Lagrangian:

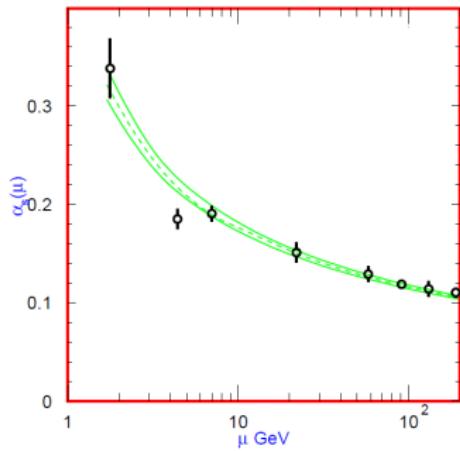
$$\mathcal{L}_{QCD} = -\frac{1}{2} G_{\mu\nu} G^{\mu\nu} + \sum_q \bar{q} (i\gamma^\mu D_\mu - m_q) q$$

with the covariant derivative $D_\mu = \partial_\mu - igA_\mu$

and the gluon field strength

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$

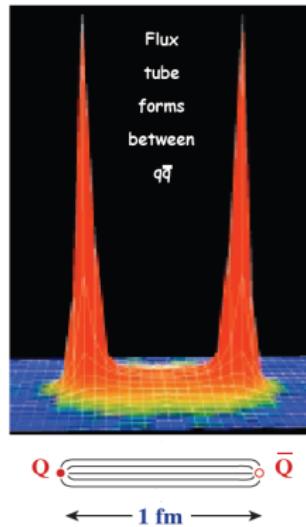
running coupling:



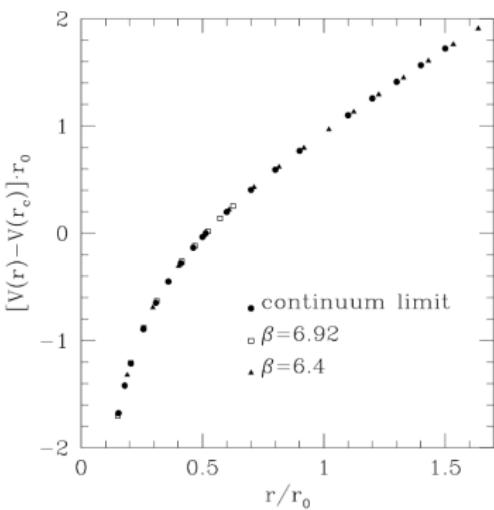
[W.M. Yao, et al., J. Phys. G33, 1 (2006)]

Introduction to QCD - Quark Confinement

Lattice QCD shows flux tube and linear potential for static quarks:



[G. Bali et al., PRD 51, 5165 (1995), arXiv:9409005]



[S. Necco and R. Sommer, NPB 622 (2002), arXiv:0306005]

Introduction to QCD - Center Symmetry and Confinement (I)



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boundary conditions at finite temperature:

$$q(t + 1/T, \vec{x}) = -q(t, \vec{x}), \quad A_\mu(t + 1/T, \vec{x}) = A_\mu(t, \vec{x})$$

this constrains the possible gauge transformations $g(t + 1/T, \vec{x}) = h g(t, \vec{x})$

gluons respect the $Z(\text{SU}(3))$ center symmetry:

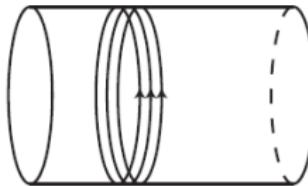
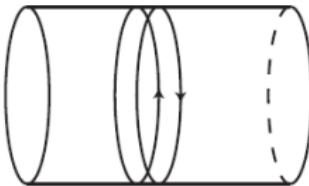
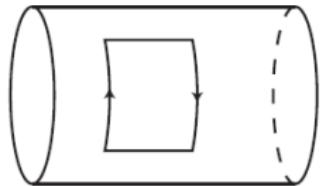
$$A'_\mu(t + 1/T, \vec{x}) = h A'_\mu(t, \vec{x}) h^\dagger \Rightarrow h = z \mathbb{1}, \quad z = \exp(i2\pi n/3), \quad n = 1, 2, 3$$

dynamical quarks break center symmetry:

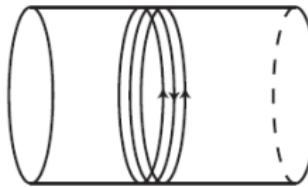
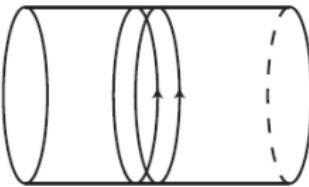
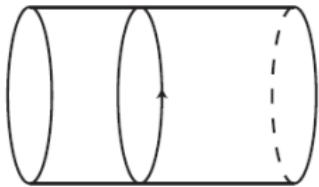
$$q'(t + 1/T, \vec{x}) = g(t + 1/T, \vec{x}) q(t + 1/T, \vec{x}) = -z g(t, \vec{x}) q(t, \vec{x}) = -z q'(t, \vec{x})$$

Introduction to QCD - Center Symmetry and Confinement (II)

thermal quark excitations respecting center symmetry:



thermal quark excitations breaking center symmetry:



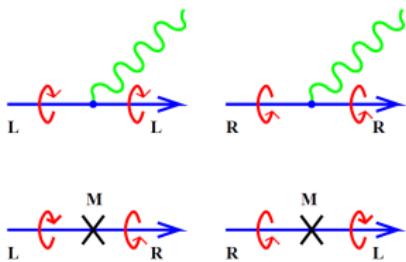
[K. Fukushima, Ann. Phys. 304, 72 (2003), hep-ph/0204302]

Introduction to QCD - Chiral Symmetry

chiral symmetry $SU(N_f)_L \times SU(N_f)_R$ is conserved for massless quarks:

$$\mathcal{L} = \bar{q}_L(i\cancel{D})q_L + \bar{q}_R(i\cancel{D})q_R$$

$$+ \bar{q}_L M q_R + \bar{q}_R M q_L$$



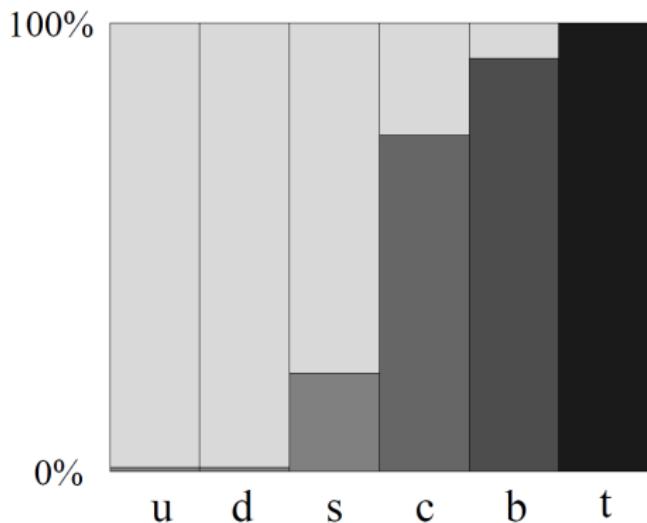
[T. Schaefer, Lecture on The Phases of QCD, NC State U.]

symmetry is spontaneously broken, $SU(N_f)_L \times SU(N_f)_R \rightarrow SU(N_f)_V$:

$$\langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \approx -(230 \text{ MeV})^3$$

Introduction to QCD - Consequences of the Non-Perturbative Vacuum

dynamical mass generation vs. Higgs mass:



[P. Braun-Munzinger, J. Wambach, arXiv:0801.4256]

Introduction to QCD - Summary of QCD symmetries

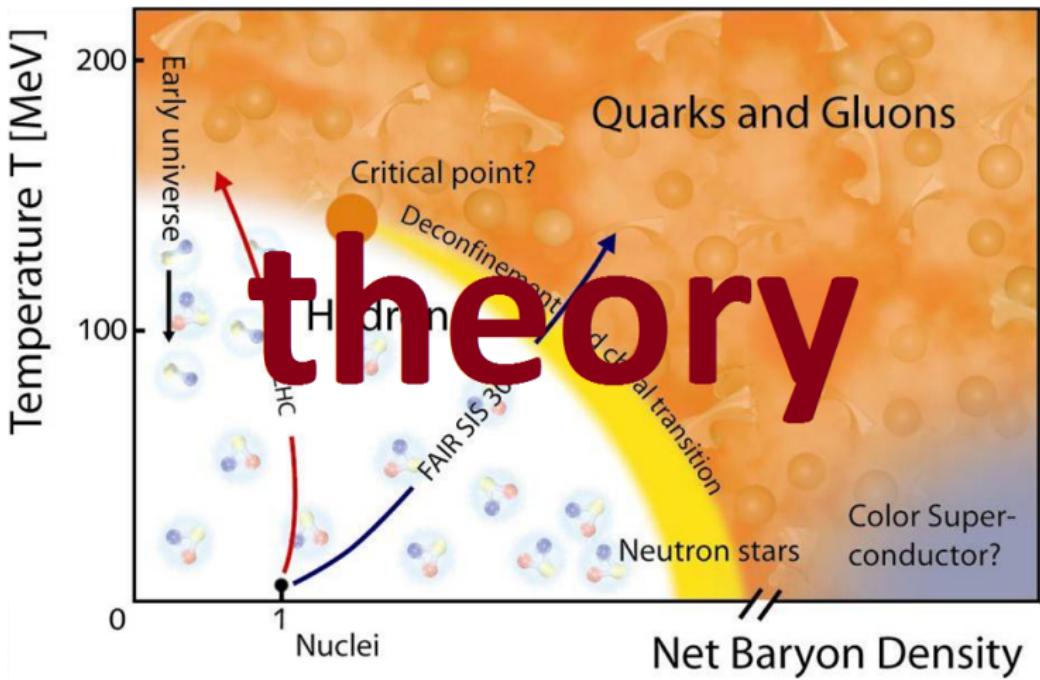
symmetry	vacuum	high T	low T , high μ	order parameter	consequences
(local) color $SU(3)$	unbroken	unbroken	broken	diquark condensate	color super- conductivity
$Z(3)$ center symmetry	unbroken	broken	broken	Polyakov loop	confinement/ deconfinement
scale invariance	anomaly			gluon condensate	scale (Λ_{QCD}), running coupling
chiral symmetry $U_L(N_f) \times U_R(N_f) = U_V(1) \times SU_V(N_f) \times SU_A(N_f) \times U_A(1)$					
$U_V(1)$	unbroken	unbroken	unbroken	—	baryon number conservation
flavor $SU_V(N_f)$	unbroken	unbroken	unbroken	—	multiplets
chiral $SU_A(N_f)$	broken	unbroken	broken	quark condensate	Goldstone bosons, no degenerate states with opposite parity
$U_A(1)$	anomaly			topological susceptibility	violation of intrinsic parity

[CBM Physics Book, 2011]

The QCD Phase Diagram from Theory



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The QCD Phase Diagram from Theory - Standard-Lore Phase Diagram

hadron gas:

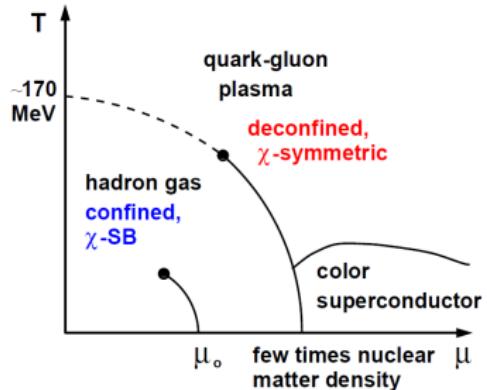
- ▶ moderate temperatures and densities
- ▶ quarks and gluons are confined
- ▶ chiral symmetry is spontaneously broken

quark-gluon plasma:

- ▶ very high temperatures and densities
- ▶ deconfined quarks and gluons
- ▶ chiral symmetry is restored

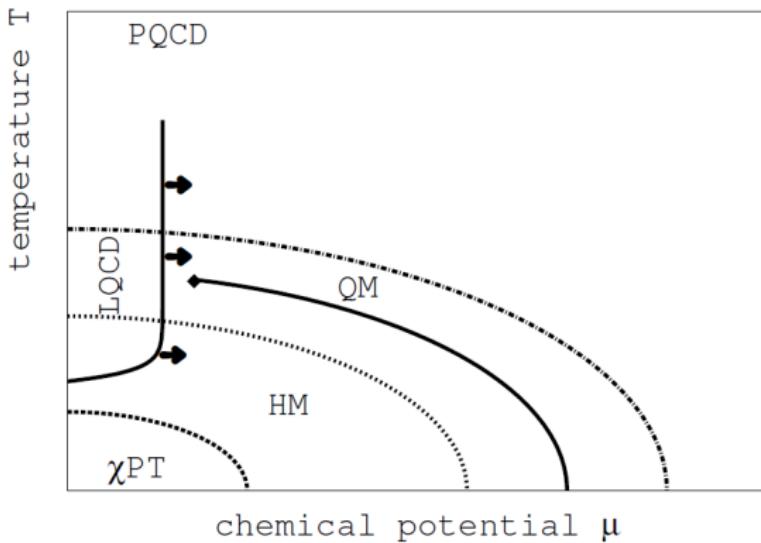
color superconductor:

- ▶ $T < 100$ MeV and very high densities
- ▶ quarks form bosonic pairs in analogy to BCS theory



[CBM physics book (2011)]

The QCD Phase Diagram from Theory - Overview of Theoretical Approaches



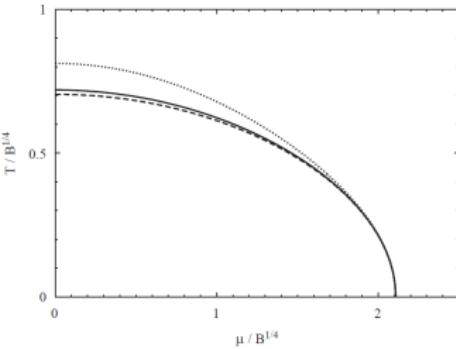
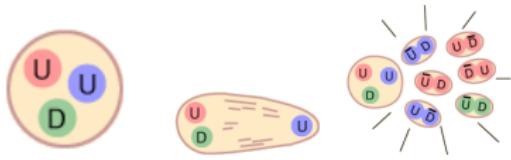
[CBM Physics Book, 2011]

The QCD Phase Diagram from Theory - Models (I) - MIT Bag Model

Bag Model (Chodos et al., 1974):

- ▶ simple implementation of confinement
- ▶ weakly interacting quarks are confined to a spherical cavity with radius $R \sim \Lambda_{\text{QCD}}^{-1} \approx 1 \text{ fm}$
- ▶ cost in energy density for creating the cavity is the bag constant B
- ▶ for a free gas of massless quarks and gluons,

$$p_{\text{QGP}} = 37 \frac{\pi^2}{90} T^4 + \mu_q^2 T^2 + \frac{\mu_q^4}{2\pi^2} - B$$



The QCD Phase Diagram from Theory - Models (II) - NJL and QM Models

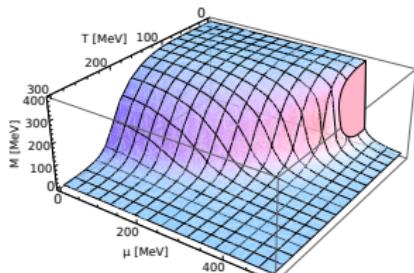


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NJL model

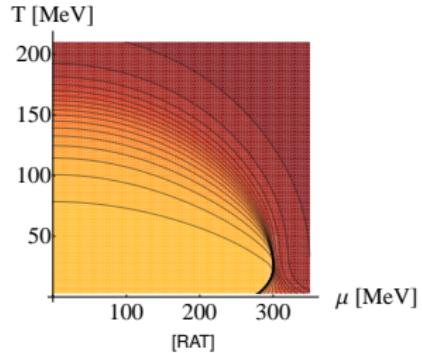
(Nambu and Jona-Lasinio, 1961):

$$\mathcal{L}_{\text{NJL}} = \bar{q}(i\gamma^\mu \partial_\mu - m_q)q + G [(\bar{q}q)^2 + (\bar{q}i\gamma_5 \vec{\tau} q)^2]$$



quark-meson model:

$$\begin{aligned}\mathcal{L}_{\text{QM}} = & \bar{q}(i\gamma^\mu \partial_\mu - h(\sigma + i\gamma_5 \vec{\tau} \vec{\pi}))q \\ & + \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \pi)^2 - U(\sigma, \vec{\pi})\end{aligned}$$



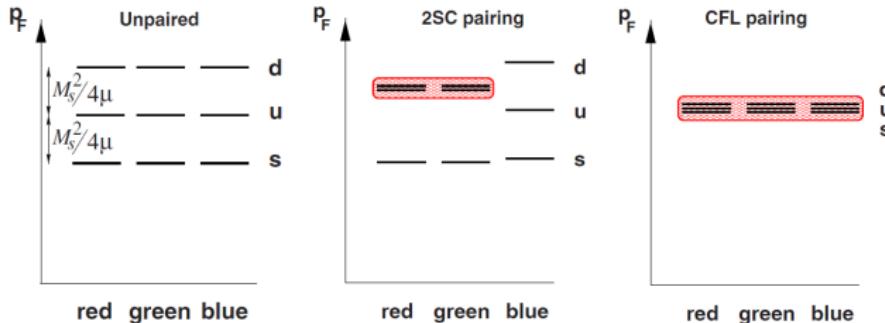
The QCD Phase Diagram from Theory - Models (III) - Color Superconducting Phases



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consider quark matter at $T = 0$ and large density n_q :

- ▶ quarks near the Fermi surface interact only weakly
- ▶ attractive single-gluon exchange channel leads to formation of Cooper pairs
- ▶ 2SC: only quarks of two colors (e.g. red and green) participate in pairing
- ▶ CFL: all colors and flavors pair with each other



[M.Alford, A.Schmitt, Rev.Mod.Phys.80 (2008)]

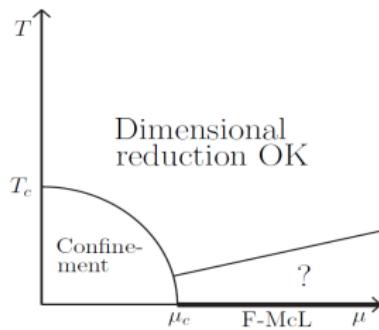
The QCD Phase Diagram from Theory - Perturbative QCD and Chiral Perturbation Theory



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Perturbative QCD:

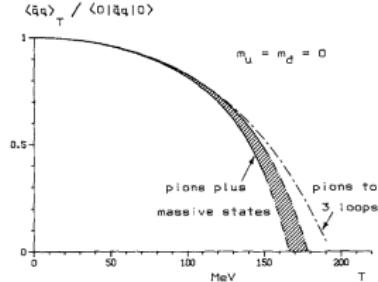
- ▶ expansion in α_s for high energies and
- ▶ quarks and gluons are relevant degrees of freedom



[A. Vuorinen, Phys.Rev. D68, 054017 (2003)]

Chiral Perturbation Theory:

- ▶ expansion in terms of energies and (Goldstone boson) masses for low momenta
- ▶ stable (light) hadrons are relevant degrees of freedom



[P. Gerber, H. Leutwyler, Nucl. Phys. B321, 387 (1989)]

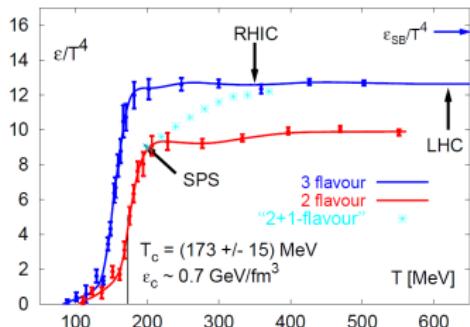
The QCD Phase Diagram from Theory - Lattice QCD

→ talk by D. Scheffler on *Lattice QCD*, 15.11.2012

- ▶ full QCD is solved from first principles on a discrete Euclidean space-time grid
- ▶ predicts a cross-over from hadronic matter to QGP for $\mu_q = 0$ at $T_c \approx 170$ MeV
- ▶ confinement and chiral transition seem to appear at exactly the same temperature for $\mu_q = 0$

problems:

- ▶ most lattice calculations still use unrealistically large light-quark masses
- ▶ fermion-sign problem at finite μ_q



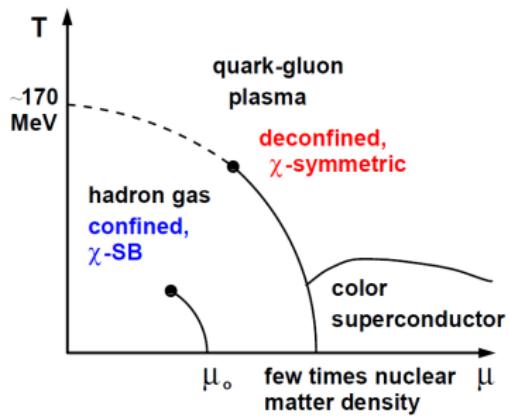
[F.Karsch, E.Laermann, arXiv:0305025]

The QCD Phase Diagram from Theory - Summary

→ talk by S. Finkbeiner on *Fluctuations and the QCD phase boundary - theory*, 6.12.2012

what to expect:

- ▶ bag model predicts that T_c decreases with increasing μ_q
- ▶ models (e.g. NJL, QM) predict first-order transition for low T and large μ_q
- ▶ lattice results indicate cross over at small μ_q
- ▶ together, this implies the existence of a critical endpoint



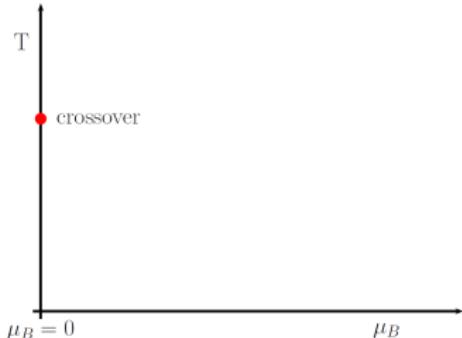
[CBM physics book (2011)]

The QCD Phase Diagram from Theory - Summary

what to expect:

- ▶ bag model predicts that T_c decreases with increasing μ_q
- ▶ models (e.g. NJL, QM) predict first-order transition for low T and large μ_q
- ▶ lattice results indicate cross over at small μ_q
- ▶ together, this implies the existence of a critical endpoint

what we really know:

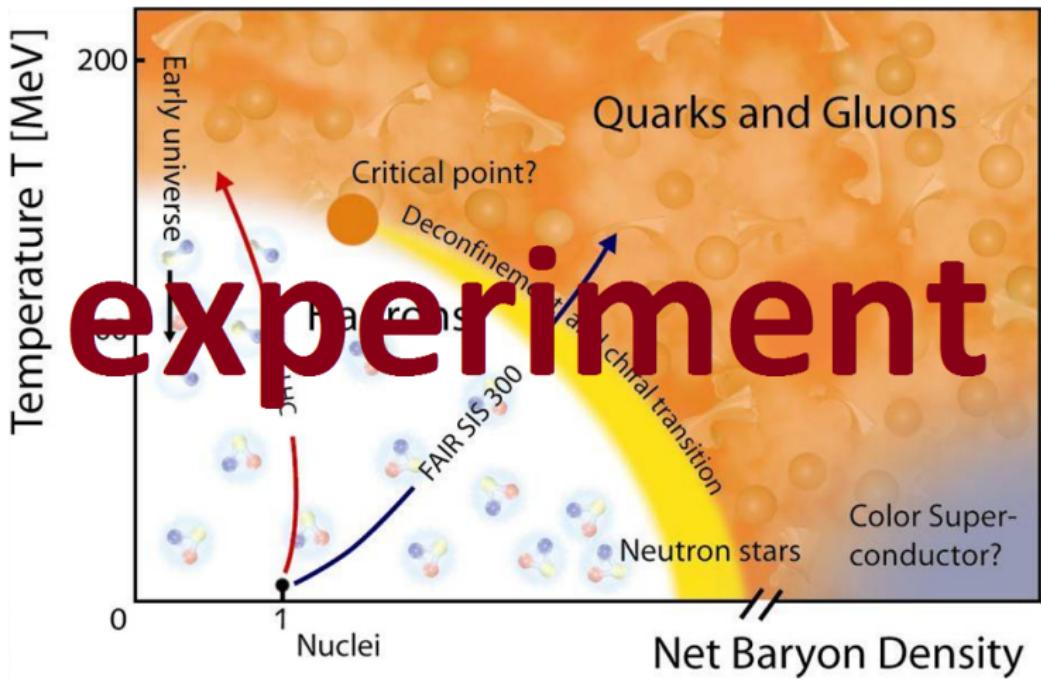


[M.Nahrgang, M.Bleicher, arXiv:1111.3771]

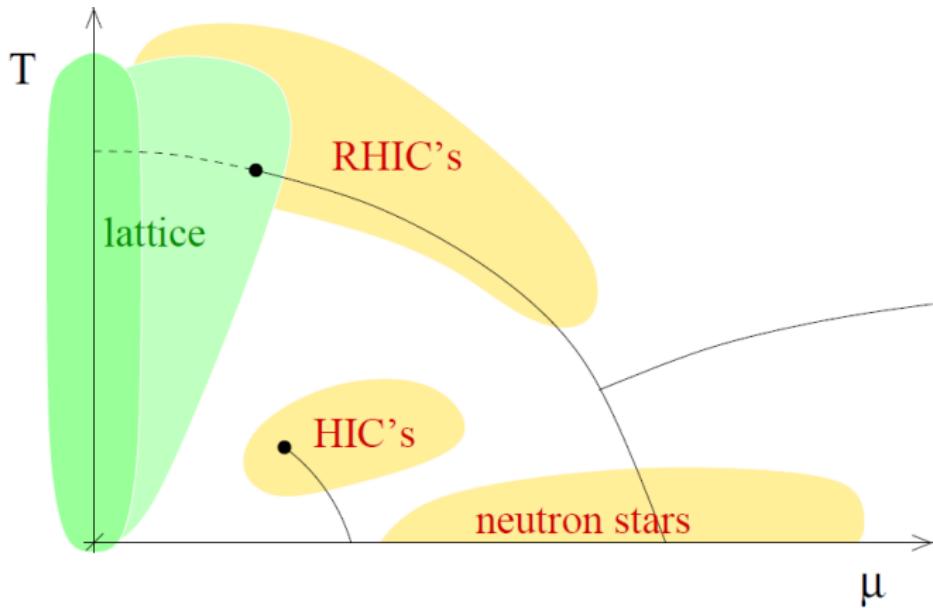
The QCD Phase Diagram from Experiment



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The QCD Phase Diagram from Experiment - Overview

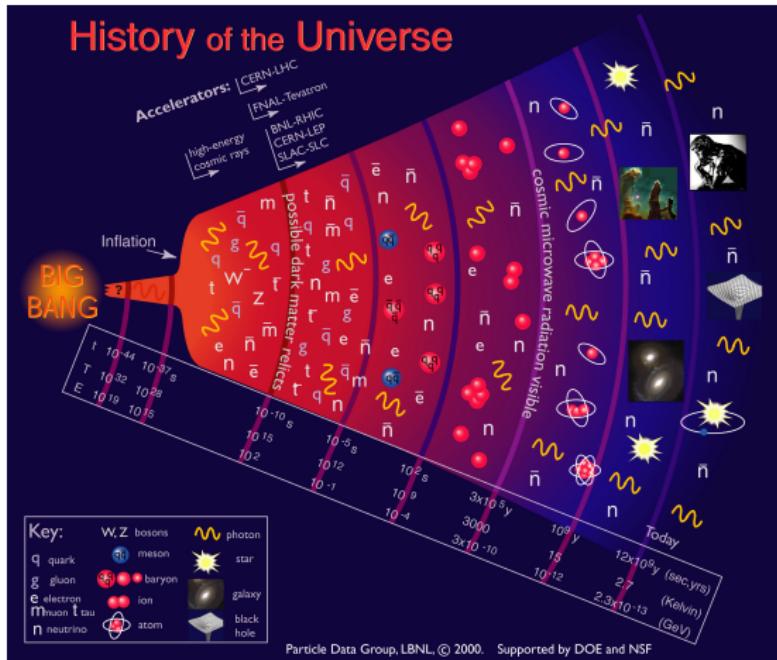


[T. Schaefer, Lecture on The Phases of QCD, NC State U.]

The QCD Phase Diagram from Experiment - Early Universe

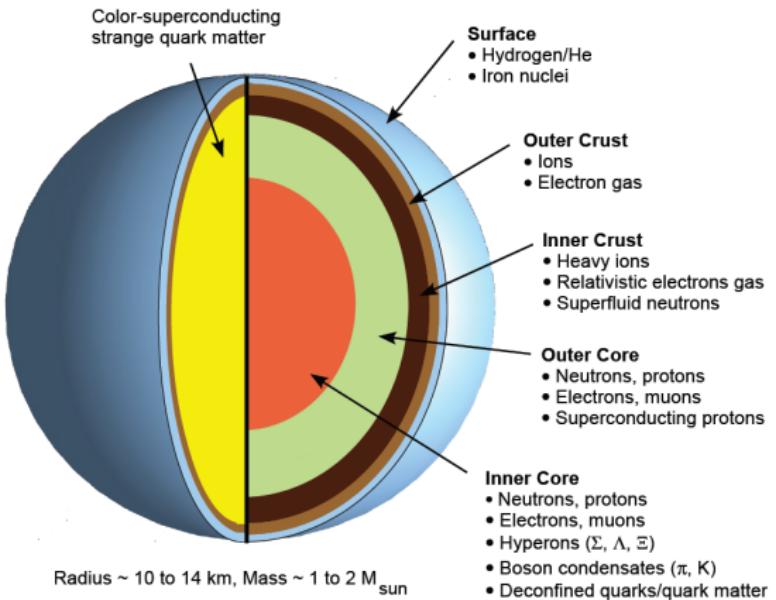


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The QCD Phase Diagram from Experiment - Neutron Stars

- ▶ density around five times nuclear saturation density
- ▶ temperature reaches a few keV
- ▶ possibility to study strongly interacting matter under extreme conditions not available in the laboratory



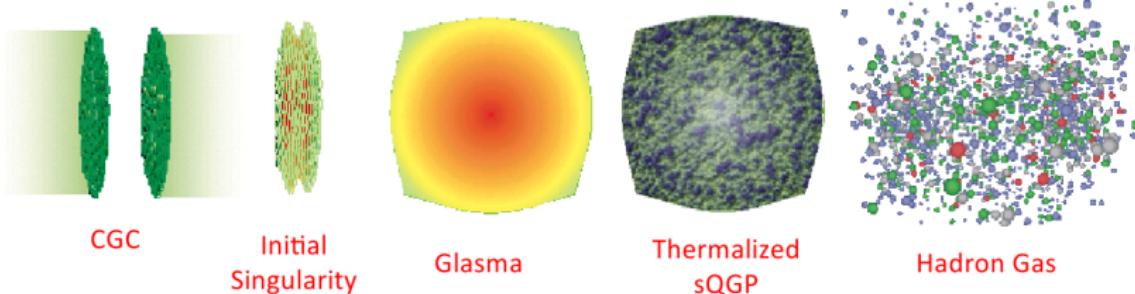
[CBM physics book (2011)]

The QCD Phase Diagram from Experiment - Heavy Ion Collisions (I)

→ talk by D. Nowakowski on *Hydrodynamics - theory*, 22.11.2012

stages of a heavy-ion collision:

- ▶ color glass condensate: dense, weakly-interacting, contracted gluon-walls
- ▶ plasma: immediately after the collision, chromo E and B fields have only longitudinal components forming flux tubes along the collision axis
- ▶ sQGP: strongly coupled QGP, not a perturbatively describable plasma
- ▶ chemical freeze-out: inelastic collisions stop, composition of hadrons is fixed
- ▶ thermal freeze-out: interaction rates insufficient for thermal equilibrium



The QCD Phase Diagram from Experiment - Heavy Ion Collisions (II)

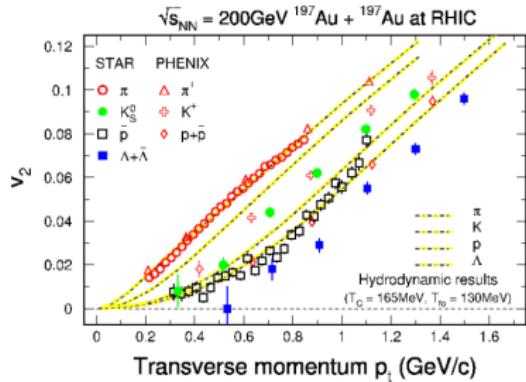
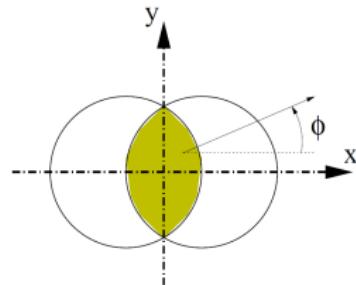
→ talk by NN on *Collective flow at RHIC and LHC - experimental data*, 29.11.2012



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evidence for quark gluon plasma:

- ▶ the Fourier coefficient $v_2 = \langle \cos(2\Phi) \rangle$ of the distribution of the momenta of produced particles can be compared to predictions from hydrodynamical calculations
- ▶ close agreement implies that the quark-gluon matter produced at RHIC flows collectively like a liquid with negligible η/s , i.e. is a strongly coupled QGP



[P. Braun-Munzinger, J. Wambach, arXiv:0801.4256]

[J. Adams, et al. (STAR), Phys. Rev. C72, 014904 (2005)]

[P. Huovinen et al., Phys. Lett. B503, 58 (2001)]

The QCD Phase Diagram from Experiment - Heavy Ion Collisions (III)

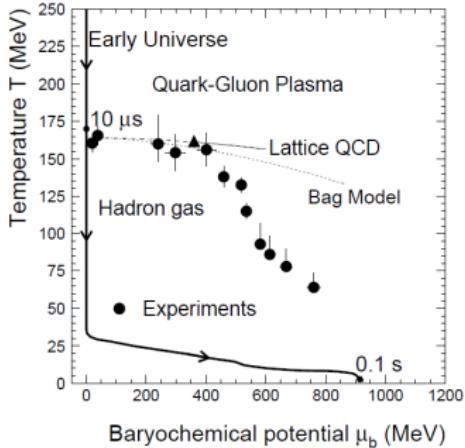


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→ talk by G. Dentinger on *Thermal fits of hadron yields and the QCD phase diagram*, 8.11.2012

evidence for a phase transition:

- ▶ information about the location of the freeze-out point is obtained by measuring the ratios of particle yields, and fitting to a statistical model with T and μ_B as parameters
- ▶ at least for small μ_B the extracted temperature is closely linked to the (calculated) phase boundary



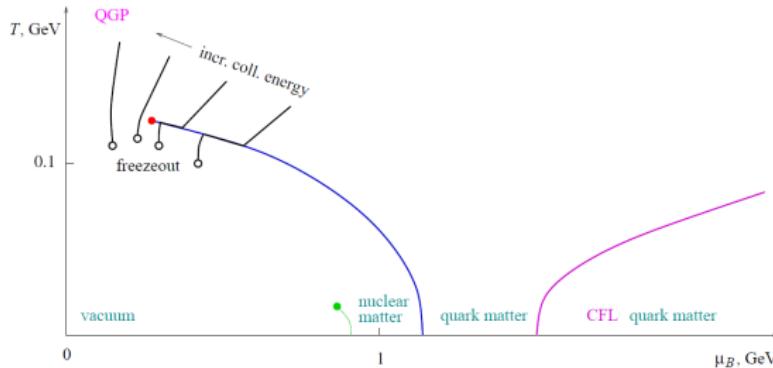
[P. Braun-Munzinger, J. Wambach, arXiv:0801.4256]

The QCD Phase Diagram from Experiment - Heavy Ion Collisions (IV)

→ talk by P. Piasek on *Search for the QCD phase boundary with experiments*, 13.12.2012

approaching the critical endpoint:

- ▶ in the approximation of ideal hydrodynamics, entropy is conserved and the expanding fireball follows a trajectory of constant baryon per entropy ratio n/s
- ▶ T increases at phase transition since latent heat is released and the lower number of dof's in the hadronic phase would result in a smaller entropy

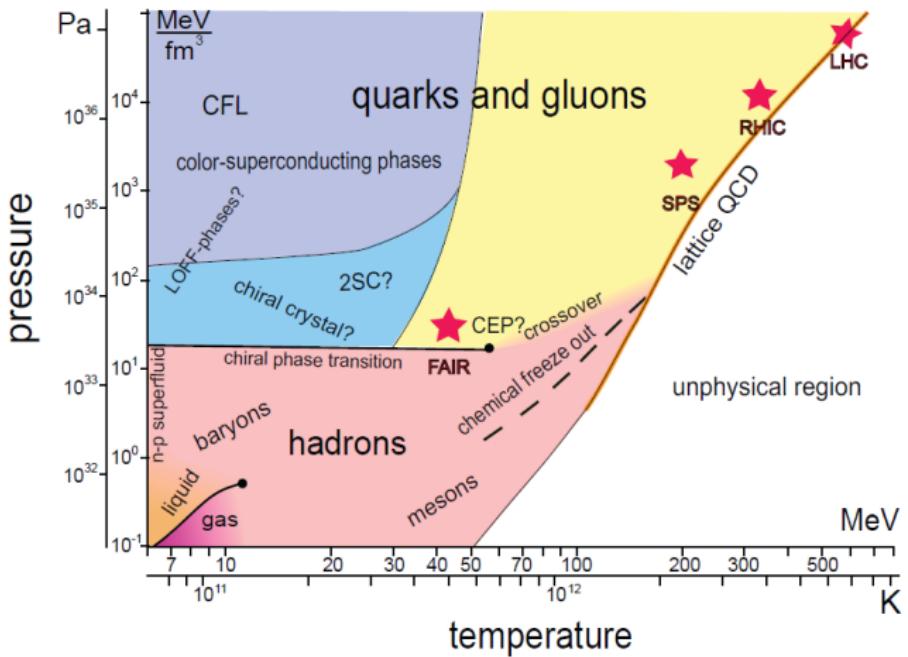


[M. Stephanov, arXiv:0402115 (2006)], [M. Stephanov, K. Rajagopal and E. Shuryak, arXiv:9806219]

Summary - Contemporary View of the QCD Phase Diagram



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[J. Wambach, K. Heckmann and M. Buballa, arXiv: 1111.5475]

Appendix



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Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model".

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

Leptons		spin = 1/2
Name	Mass GeV/c ²	Electric charge
e ⁻ electron	<1.10 ⁻³	0
e ⁻ electron neutrino	0.000511	-1
μ^- muon	<0.0002	0
μ^- muon neutrino	0.106	-1
τ^- tau	<0.02	0
τ^- tau neutrino	1.7771	-1

Quarks		spin = 1/2
Name	Approx. Mass GeV/c ²	Electric charge
u up	0.0053	2/3
d down	0.056	-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

Structure within the Atom

If the proton and neutrons in this atom were 10 cm across, the electron would be about 10 nm from the nucleus. If the nucleus were the size of a grain of sand, the entire atom would be about 10 km across.

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

Unified Electroweak		spin = 1
Name	Mass GeV/c ²	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/c ²	Electric charge
g gluon	0	0

Color-charged particles interact by exchanging gluons. Colorless particles do not interact with gluons. Color-charged particles can also interact with photons and Z bosons. These charges have nothing to do with the color of the particles. They are just labels to indicate the type of color charge for gluons. Just as electrons interact with photons, gluons, leptons, photons, and W and Z bosons have no strong interaction with each other.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. The confinement (binding) results from the exchange of gluons. The color charge of a quark is proportional to its mass. The stronger the binding between the quark and the gluon field between them increases. This energy eventually is converted into mass. This is why the mass of a hadron is much larger than the sum of the masses of the hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons and baryons.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged quarks. It is similar to the regular electrical interaction between charges, but it is much stronger and acts over a much shorter distance. It is also responsible for the binding of nucleons to form molecules and can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property	Interaction			
	Gravitational	Weak (Electroweak)	Electromagnetic	Strong
Acts on:	All	Flavor	Color Charge	See Results of Strong Interaction
Particles experiencing:	Quarks, Leptons	Electric Charge	Gluons	Mesons
Particles mediating:	Gravity	W ⁺ W ⁻ Z ⁰	Quarks, Gluons	Hadrons
Strength relative to electromagnetism:	10^{-38} to 10^{-18}	γ	Not applicable	Not applicable
Strength relative to two-body quark annihilation:	10^{-10} to 10^{-12}		25	20
Strength relative to two-proton in nucleus:	10^{-36}		60	

Mesons q-q-bar

Mesons are fermionic hadrons. There are about 100 types of mesons.

Symbol	Name	Quark	Antiquark	Mass	Spin
π^+	pion	u d	u -d	0.140	0
K^-	K meson	s u	s -u	0.494	0
ρ^+	rho	u d	u -d	0.770	1
B^0	B meson	d b	d -b	5.279	0
Ξ_c^0	Xi_c	c c	c -c	2.980	0

Particle Adventure
Visit the award-winning web feature the Particle Adventure at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:
The National Science Foundation
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Stanford Linear Accelerator Center
The University of California, Berkeley Department of Physics and Fields Institute
DURLE INDUSTRIES, INC.

CEP
Contemporary Physics Education Project. CPEP is a non-profit organization that develops educational materials for K-12 students and teachers. CPEP is funded by grants from the National Science Foundation, the Department of Energy, the National Laboratory Foundation, CA, NASA, the American Physical Society, and individuals. For more information, contact CPEPweb.org.

Baryons qqq and Antibaryons q-q-bar

Baryons are fermionic hadrons. There are about 100 types of baryons.

Symbol	Name	Quark	Blocks	Mass	Spin
p	proton	u u d	1	0.938	0
\bar{p}	antiproton	u u d	-1	0.938	0
n	neutron	u d d	0	0.940	0
Λ	lambda	u d s	0	1.116	0
Ξ^0	xi	u s s	-1	1.072	0

Matter and Antimatter
For every particle there is a corresponding antiparticle type, identical except for having the opposite charge. A charge is a measure of the amount of electric field it creates. Particles and antiparticles have identical mass and spin but opposite charge. Particles are represented by letters (e.g., e⁻, p, and q_u, q_d, q_s) but antiparticles are given with a bar over them (e.g., \bar{e}^+ , \bar{p} , and \bar{q}_u , \bar{q}_d , \bar{q}_s) are their own antiparticles.

Figures
These diagrams are artist's conception of physical processes. They are not to scale and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p + e^- + \bar{\nu}_e$
An neutron decays to a proton, an electron, and an electron antineutrino. The electron and electron antineutrino are emitted in different directions.

$e^+ e^- \rightarrow B^0 \bar{B}^0$
An electron and positron annihilate at high-energy can produce a B meson and an anti-B meson. Both can decay into a virtual Z boson or a virtual photon.

$p + p \rightarrow Z^0 + \text{assorted hadrons}$
Two protons colliding at high energy can produce a Z boson and various hadrons such as pions, kaons, and gluons. The Z boson will decay due to the interaction of matter.