Quark-Gluon Matter

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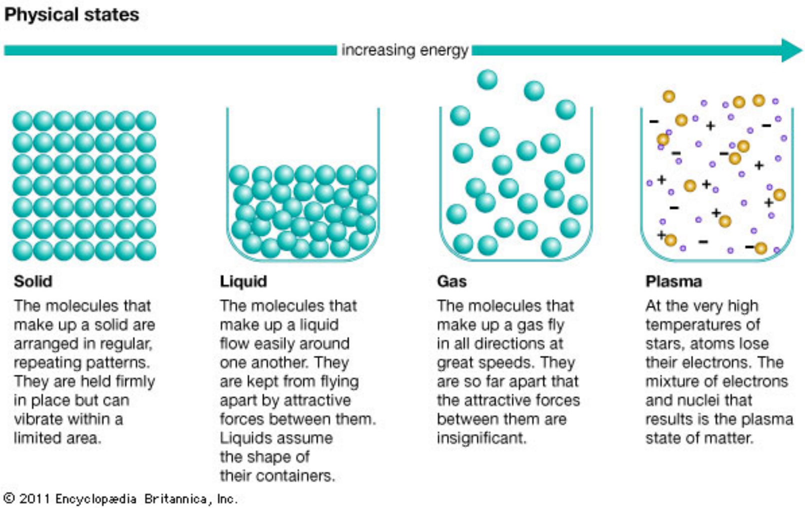
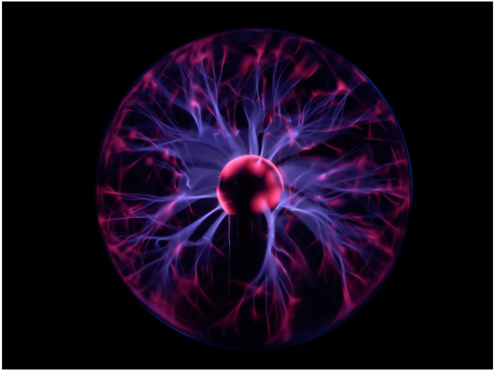
states of matter

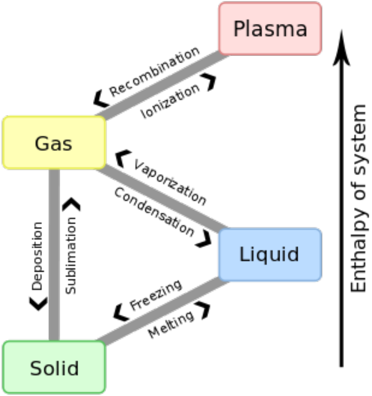


plasma



- emerge from gases by further supply of energy
- charge-carrying ions and electrons become separated
- electrons move freely
- 99% of the visible matter is in a plasma state!

phase transitions



- conversion of phases through pressure and temperature
- in '**phase transitions**' the material properties change drastically
- phases are displayed '**phase diagrams**'

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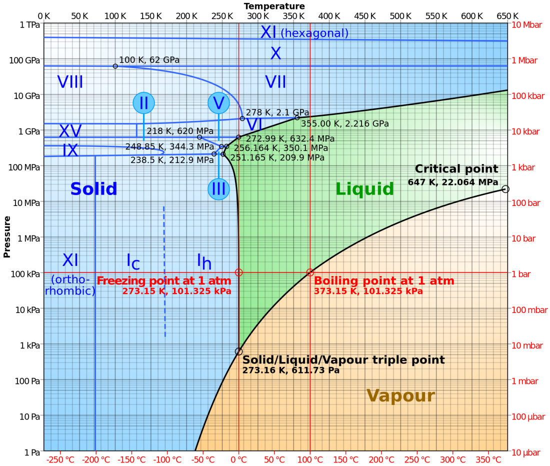
water (H_2O)



12 crystalline (ice) und 3 amorphous (glas) phases known

phase diagram determined by chemical forces

→ **electromagnetic interaction**

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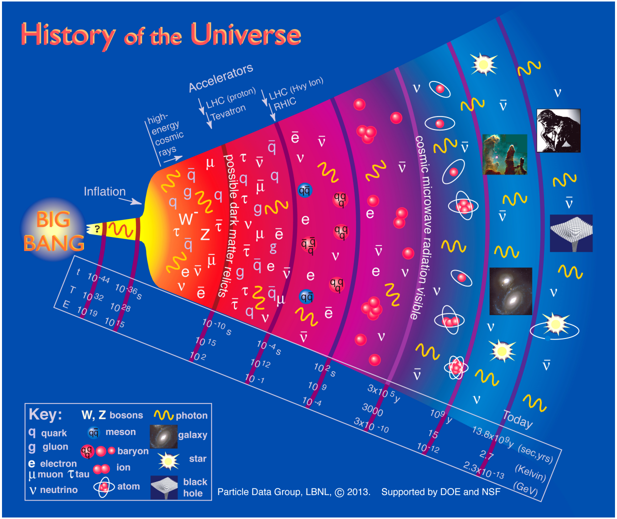
what happens **ultimately** to matter under heating and compression?

early universe

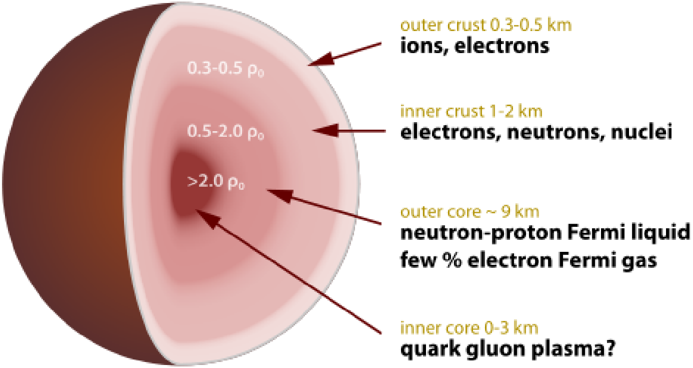


what happens **ultimately** to matter under heating and compression?

neutron stars

(R. Tolman, R. Oppenheimer, G. Volkoff (1939))

inner structure



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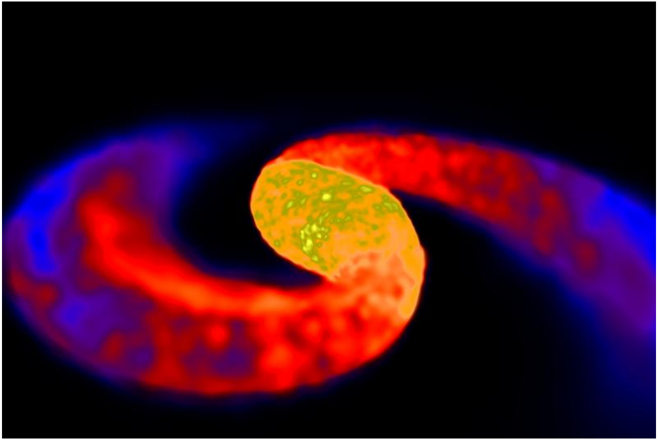
what happens **ultimately** to matter under heating and compression?

neutron star mergers



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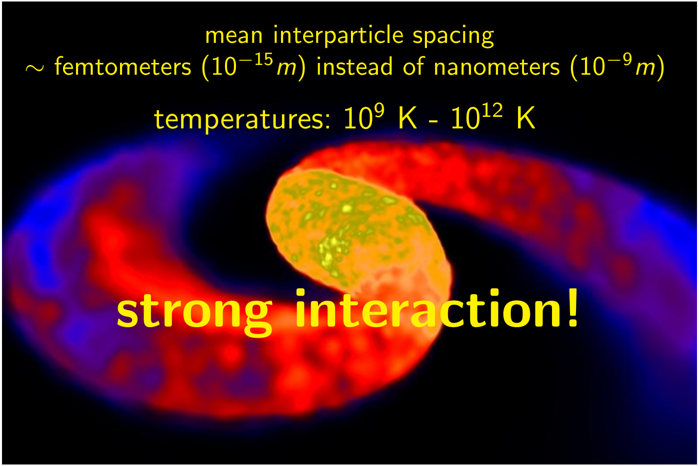
neutron star mergers



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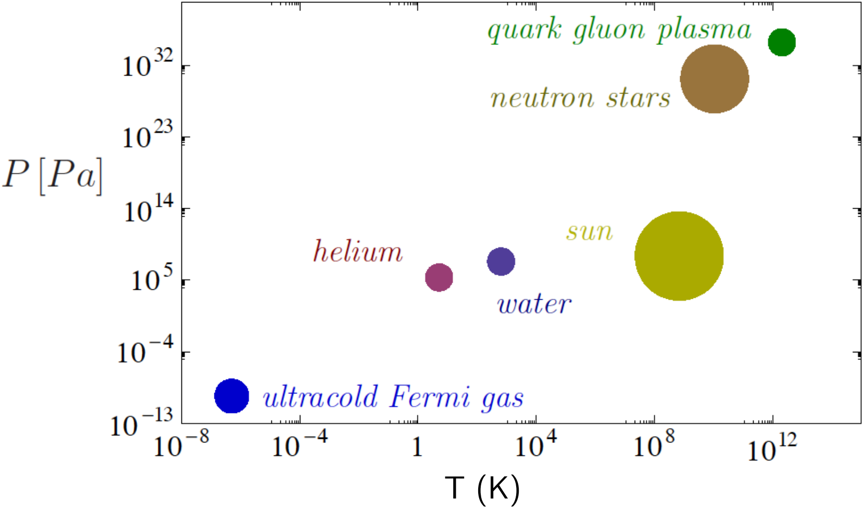
matter under extreme conditions



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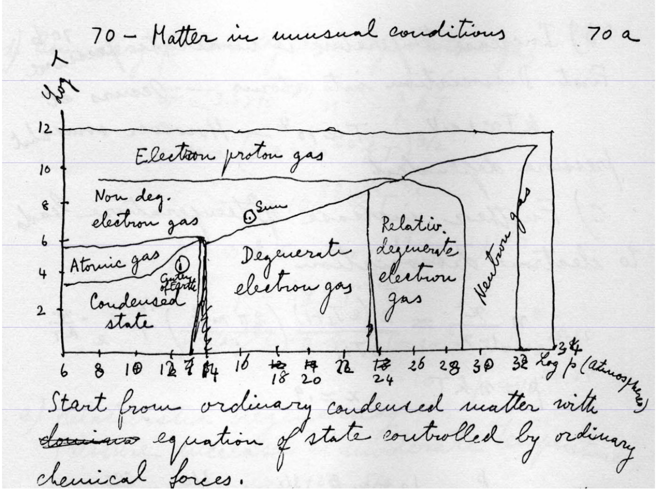
initial speculations

E. Fermi: Notes on Thermodynamics and Statistics (1953)



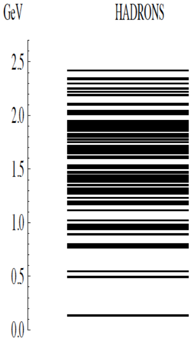
courtesy: G. Baym

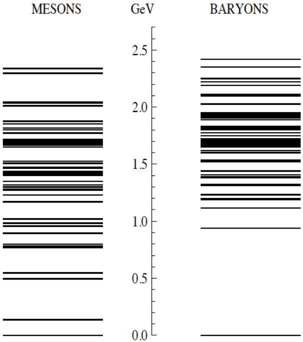
for the thermodynamics (partition function) the **excitation spectrum** is needed

L. Boltzmann (1871)

$E = mc^2$ (Einstein (1905)

$\hbar$ (Planck ...(1900)





Particle Data Group 2014

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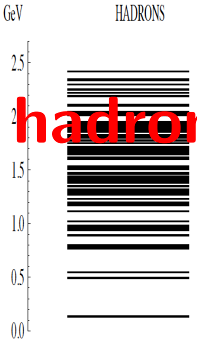
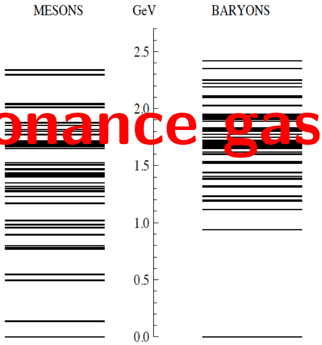
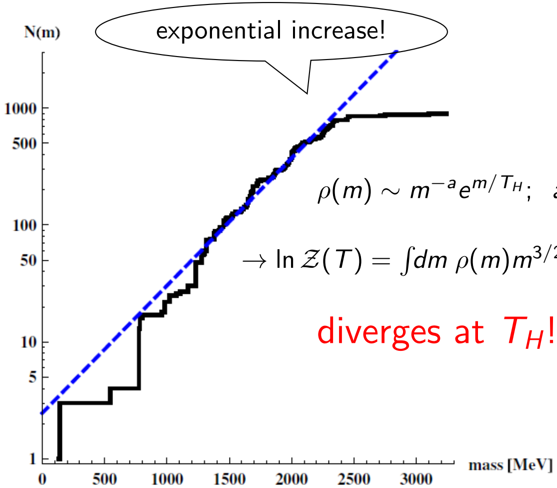




hadron-resonance gas

Particle Data Group 2014

for the thermodynamics (partition function) the **excitation spectrum** is needed



$$\rho(m) \sim m^{-a} e^{m/T_H}; \quad a \sim 5/2$$

$$\rightarrow \ln \mathcal{Z}(T) = \int dm\, \rho(m) m^{3/2} e^{-m/T}$$

diverges at T_H!

T.D. Cohen et al. JPG 39, 2012

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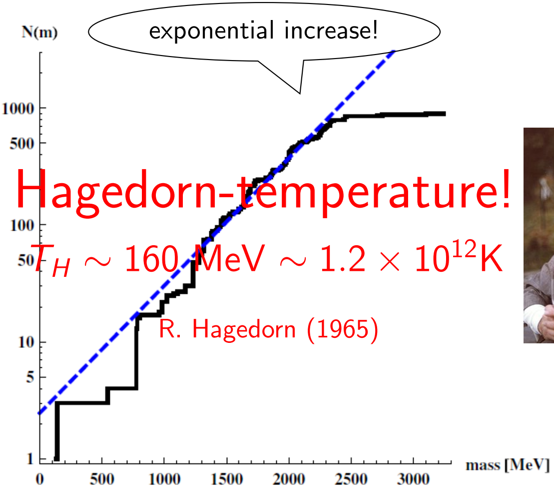
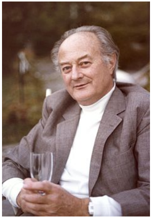
for the thermodynamics (partition function) the **excitation spectrum** is needed



Hagedorn-temperature!

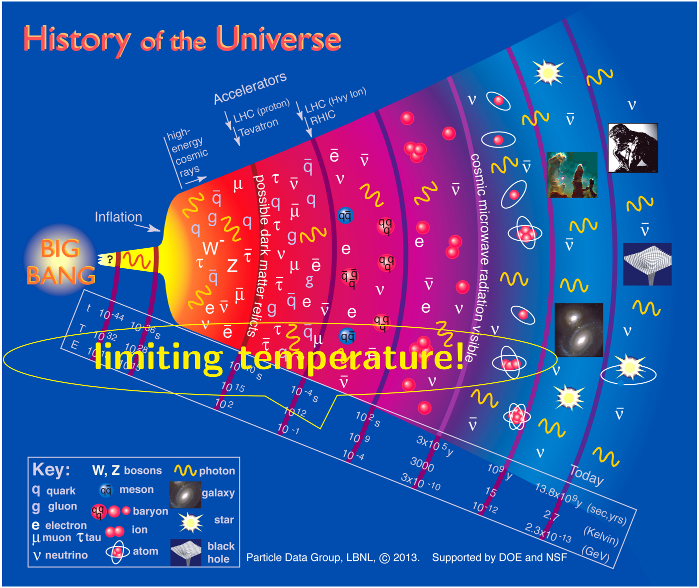
$T_H \sim 160$ MeV $\sim 1.2 \times 10^{12}$K

R. Hagedorn (1965)



T.D. Cohen et al. JPG 39, 2012

how can that be?



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how can that be?

VOLUME 25, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1970

ULTIMATE TEMPERATURE AND THE EARLY UNIVERSE*

Kerson Huang and Steven Weinberg
Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 5 August 1970)

The early history of the universe is discussed in the context of an exponentially rising density of particle states.

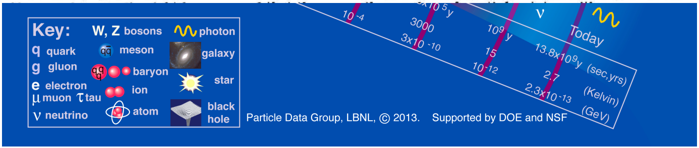
There are now plausibe theoretical models[1] for the thermal history of the universe back to the time of helium synthesis, when the temperature was 0.1 to 1 MeV. Our present theoretical apparatus is really inadequate to deal with much earlier times, say when $T \gtrsim 100$ MeV, and in lieu of any better ideas it is usual to treat the matter of the very early universe as consisting of a number of species of essentially free particles. But how many species?

$B=\frac{5}{2}$.

(2) If particles fall on families of parallel linearly rising Regge trajectories, their masses take discrete values $m_1, m_2, \cdots$, where

$$\alpha' m_n^2 + \alpha_0 = n. \qquad (2)$$

Here $\alpha' \approx 1\ \mathrm{GeV}^{-2}$ is the universal Regge slope and α_0 is a number, of order unity, characterizing the family. The extension of the Veneziano model[7] to multiparticle reactions requires[8] that



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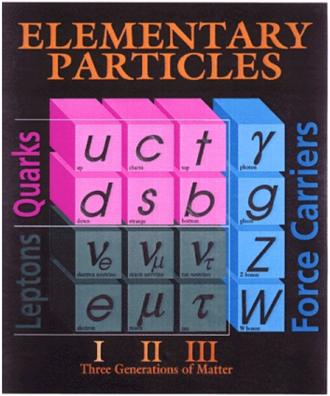
in the 1960's it became clear that hadons have substructure

hadrons consist of quarks and gluons

Quantumchromodynamics (H. Fritzsch et al. 1973)

→ Standard Model of particle physics



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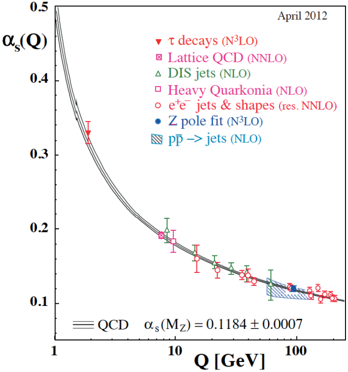
QCD similar to Quantumelectrodynamics

but gluons are selfinteracting!

asymptotic freedom at short distances



D. Gross & F. Wilczek, D. Politzer 1973

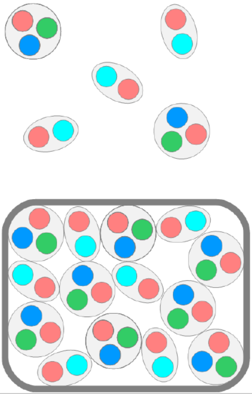
color confinement at large distances

quark-hadron transition

vacuum perfect paramagnet

$\mu_0^c = \infty;\ \epsilon_0^c = 0$

$\rightarrow$ MIT bag model



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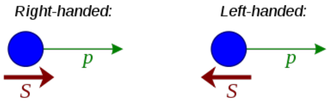
Chiral symmetry of the strong interaction

for vanishing quark masses QCD has an extra chiral symmetry



left- and right-handed quarks do not interact!

$\rightarrow$ **parity doublets** in the hadron spectrum

but

chiral symmetry is **sponateously broken** by the Nambu-Goldstone mechanism

the symmetry of the theory is not the symmetry of the ground state!

in QCD quarks condense $\langle \bar{q}q \rangle \neq 0$

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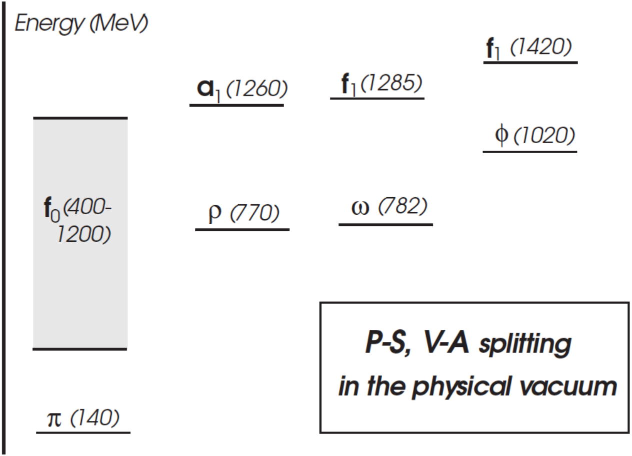
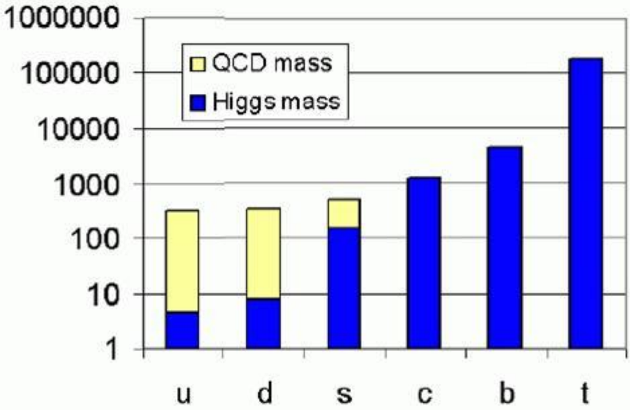
spontaneously broken chiral symmetry



Goldstone mode

quark-mass generation



u, d quarks acquire most of their mass from χSB!

'constituent mass'

$$\textit{NJL model}: \quad M_q = m_q - 2G\langle \bar{q}q \rangle$$

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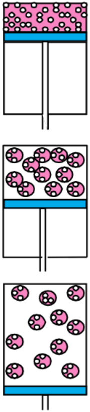
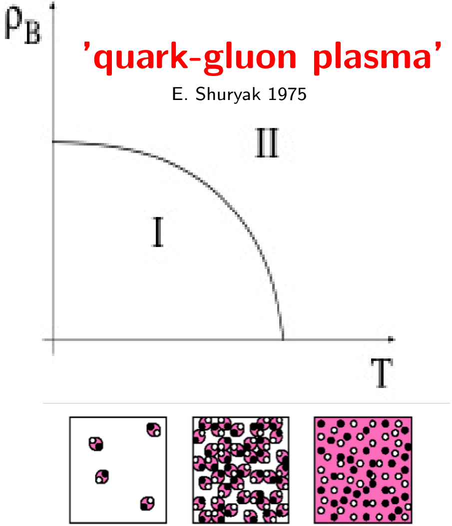
'early' phase diagram

N. Cabibo & G. Parisi, J.C. Collins & M.J. Perry 1975

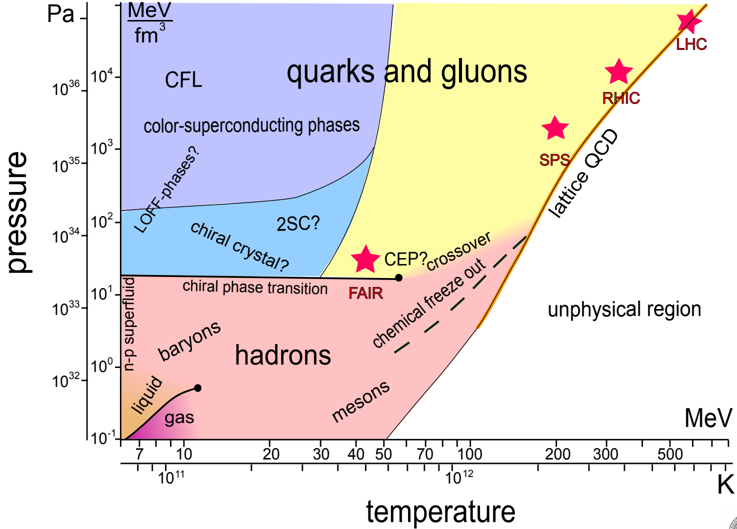


'quark-gluon plasma'

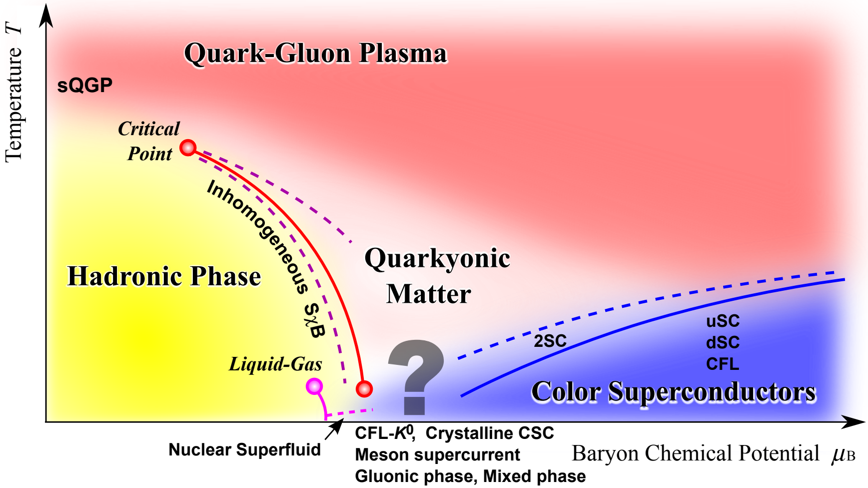
E. Shuryak 1975



'modern' QCD phase diagram



another representation



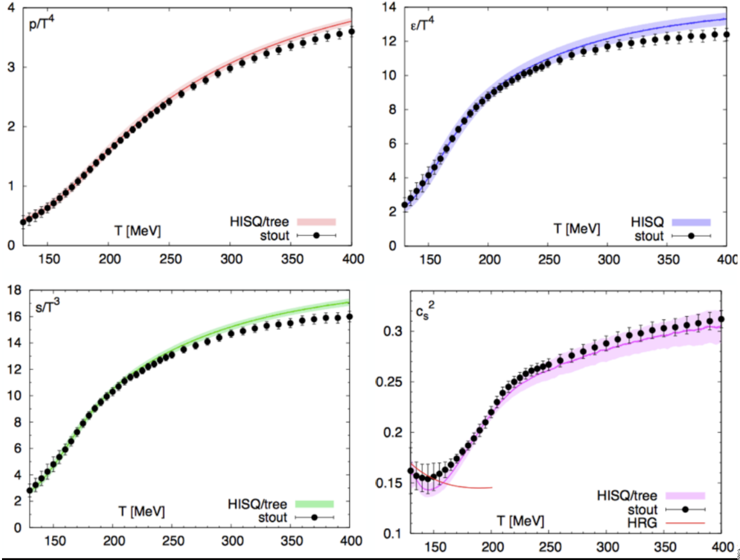
T (K)

exact computation of thermodynamic quantities

at finite temperature and vanishing density
with 'Monte-Carlo Methods'

'Lattice QCD'

lattice QCD results



H.T. Ding 2013

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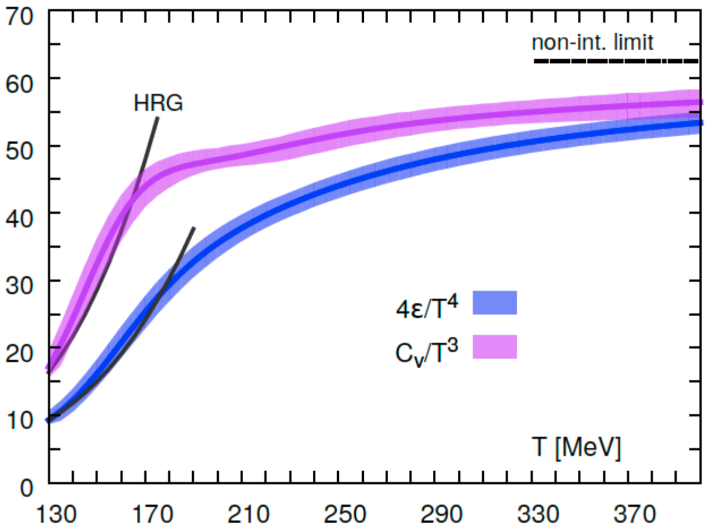
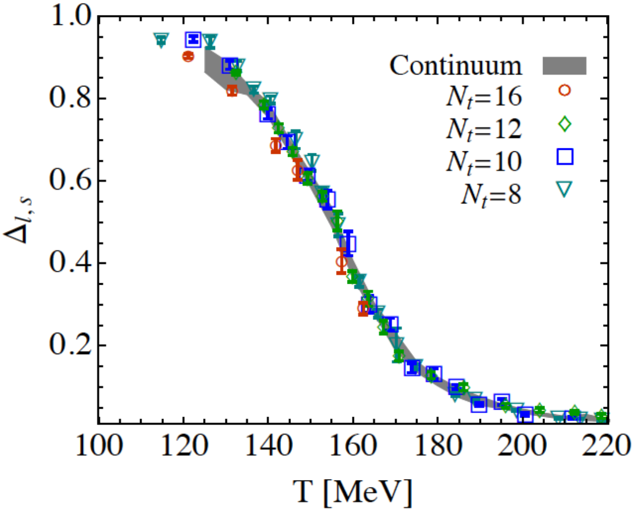
lattice QCD results



H.T. Ding 2013

lattice QCD results

chiral condensate



S. Borsanyi et al. 2011

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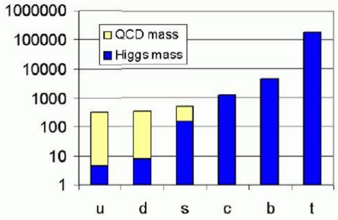
'dropping masses'

as the chiral condensate diminishes with increasing temperature and density quarks loose their 'constitutent' mass'



if the hadron mass is directly related to the quark mass
hadrons should become lighter as well

$$m_h^* \propto m_h^0 \left(\langle \bar{q} q \rangle\right)^\alpha$$

G. E. Brown and M. Rho 1991

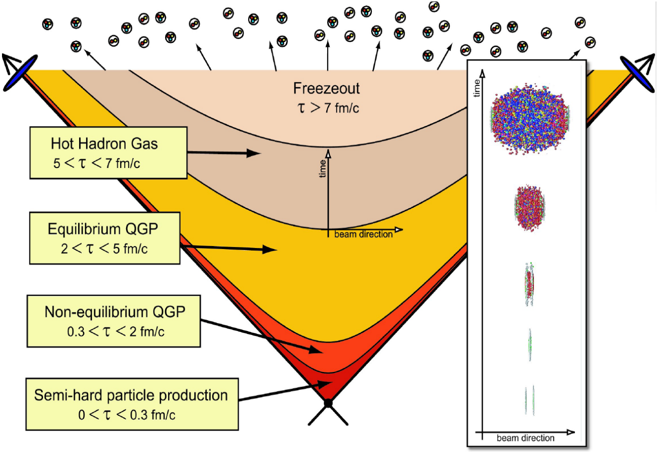
this can be tested with photons!

Heavy-ion collisions and photons

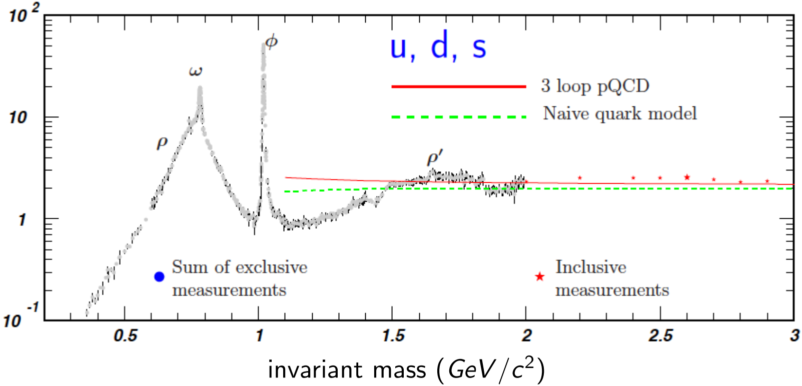
as compared to the size of the fireball photons have a long mean free path

$\rightarrow$ leave the interaction zone undisturbed

E. Feinberg 1976, E. Shuryak 1978



e^+e^-- annihilation in the vacuum



$$\text{quarks}: \quad \mathcal{R}^q = N_c \sum_i e_i^2 = 3\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right) = 2$$

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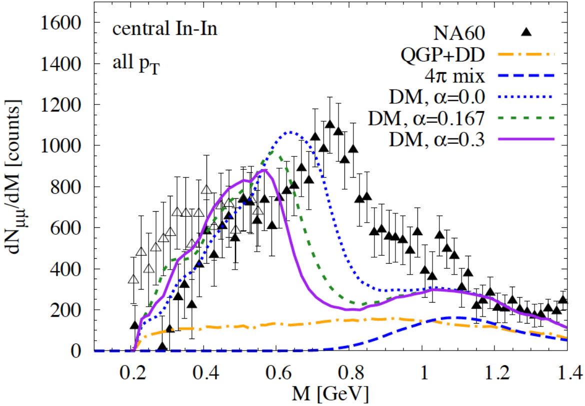
Dropping mass of the ρ-meson

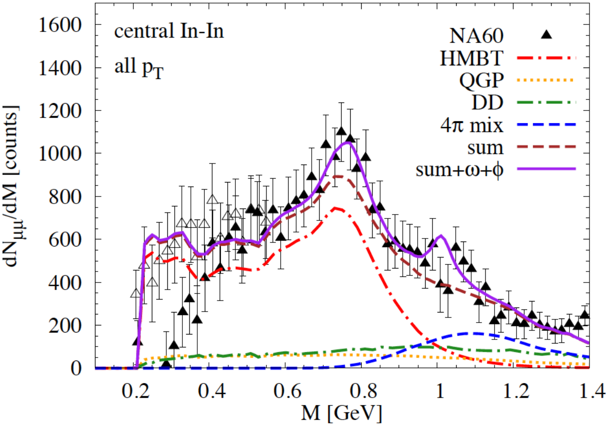
$$m_\rho^* = m_\rho^0 \left[1 - 0.15\rho_B/\rho_0\right] \left[1 - (T/T_c)^2\right]^\alpha$$



H. van Hees and R. Rapp 2006

S. Damjanovic et al. 2006

broadening of the ρ-meson



H. van Hees and R. Rapp 2006

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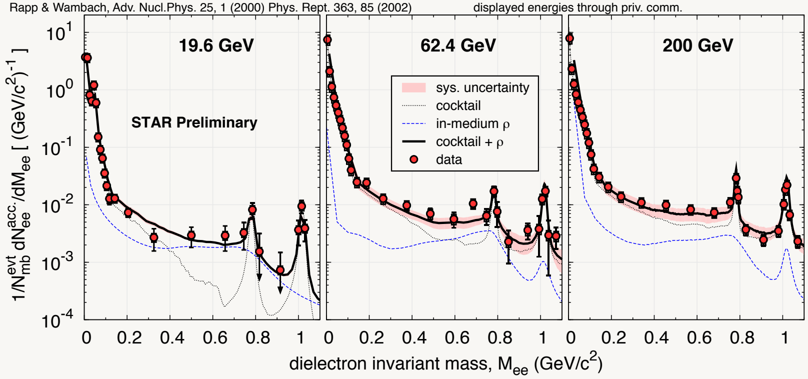
broadening of the ρ-meson

works also in other collision systems



F. Geurts et al. 2013

→ hadronic mass generation more complicated!

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thank you for your attention!

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