Experimental search for a signal on new phases of Strongly interacting Matter : Hot , Dense Matter and Quark Gluon Plasma.

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First School on LHC Physics: ALICE week
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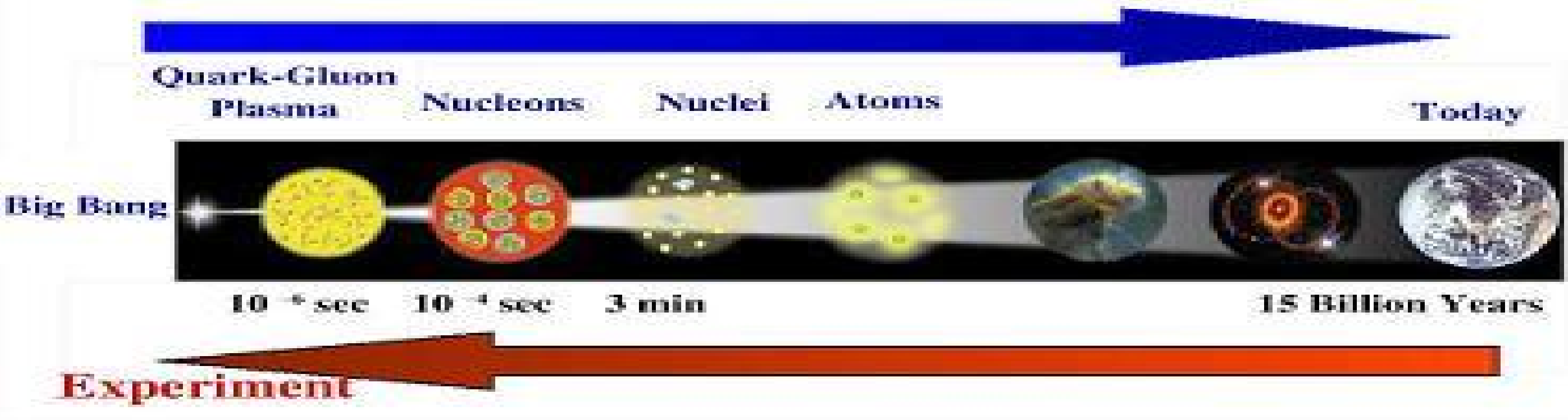
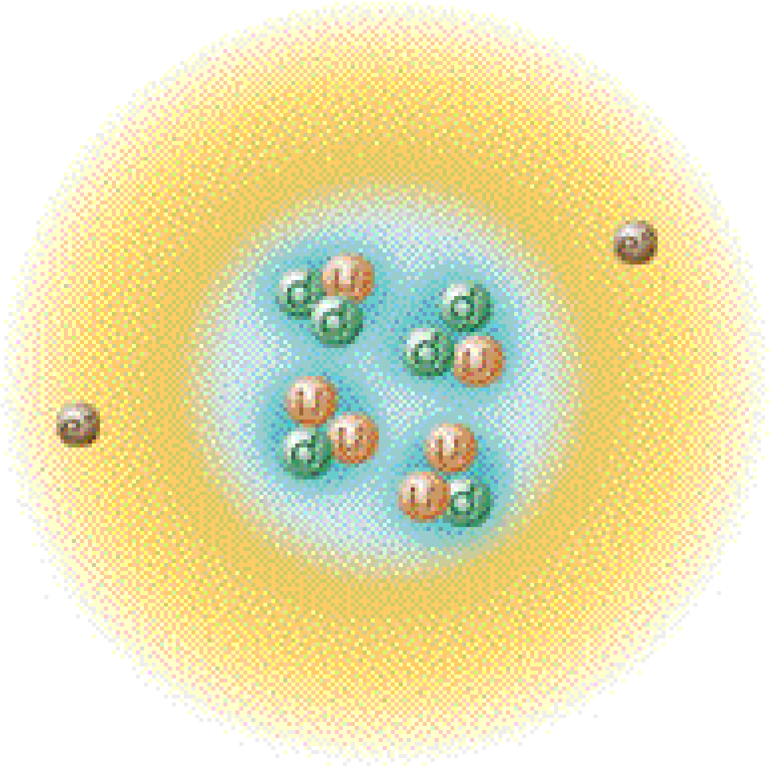
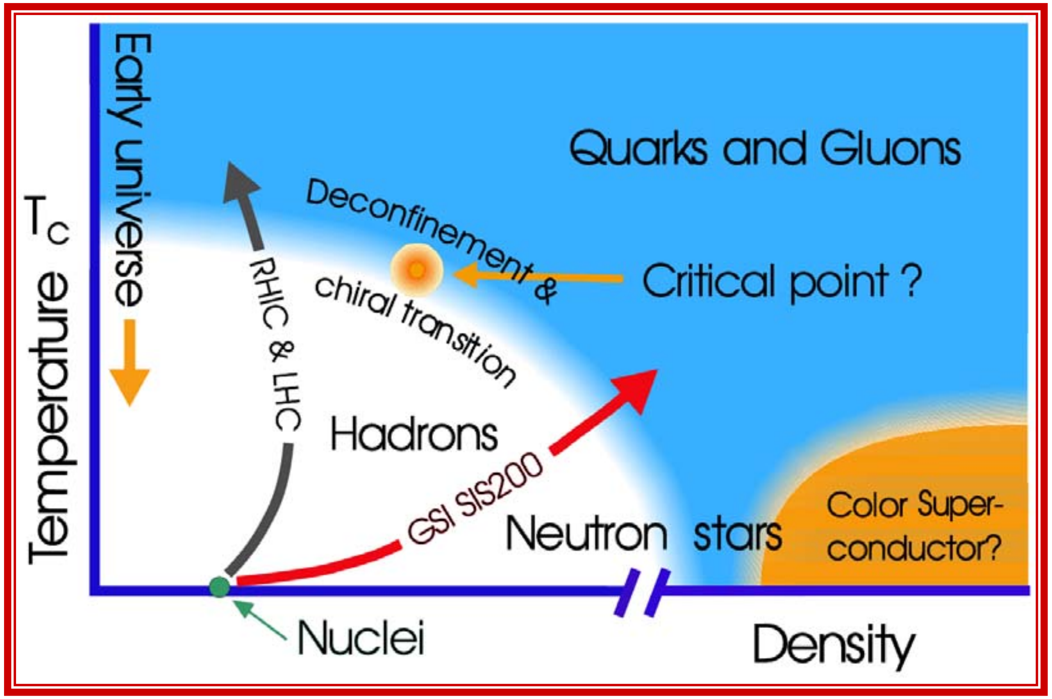
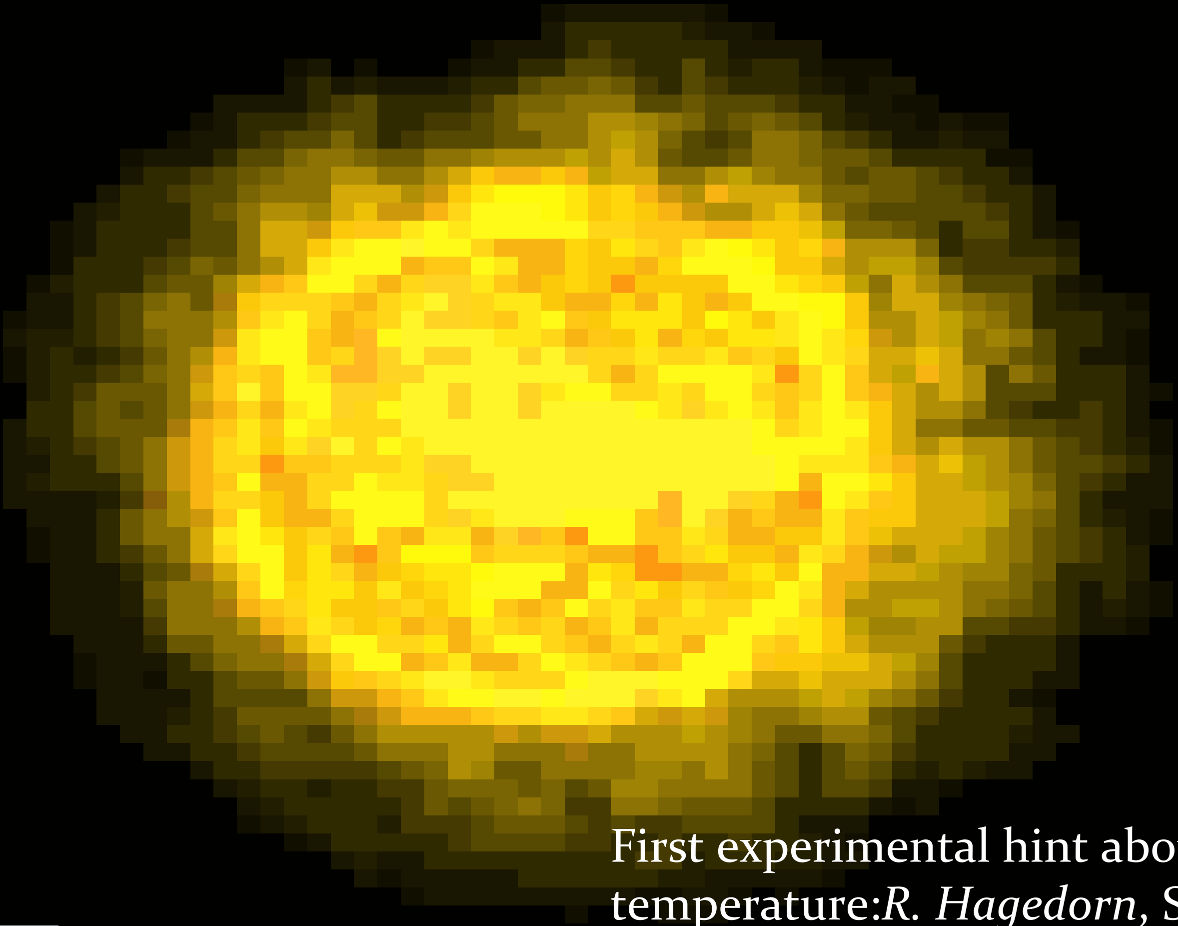

Quark-Gluon Plasma
Nucleons
Nuclei
Atoms
Today
Big Bang
10^{-6} sec
10^{-4} sec
3 min
15 Billion Years
Experiment




Early universe
T_c
Temperature
Quarks and Gluons
Deconfinement &
chiral transition
Critical point ?
RHIC & LHC
Hadrons
GSI SIS200
Neutron stars
Color Super-conductor?
Nuclei
Density

$\rho_c \geq 7\text{-}10\ \rho$

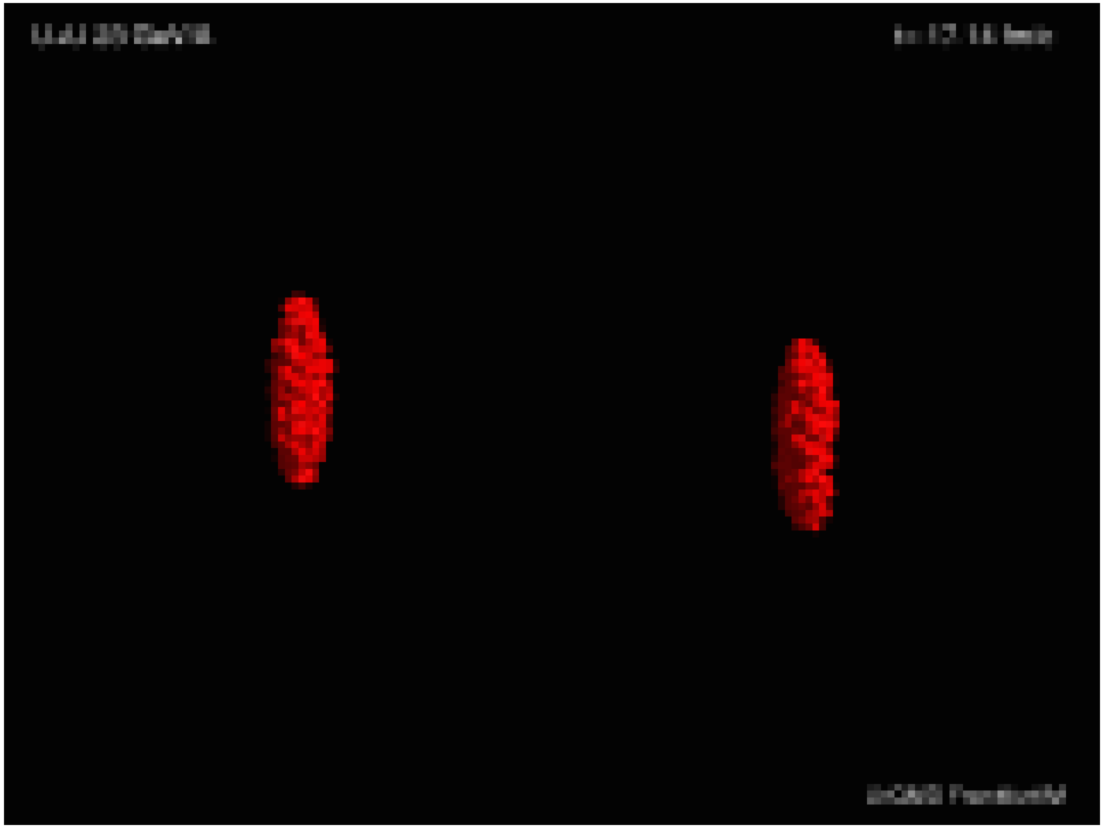


First experimental hint about critical temperature:*R. Hagedorn*, Suppl. Nuovo. Cimento **3** 1965, 3, p. 147.

$T_c \geq 5\ T$

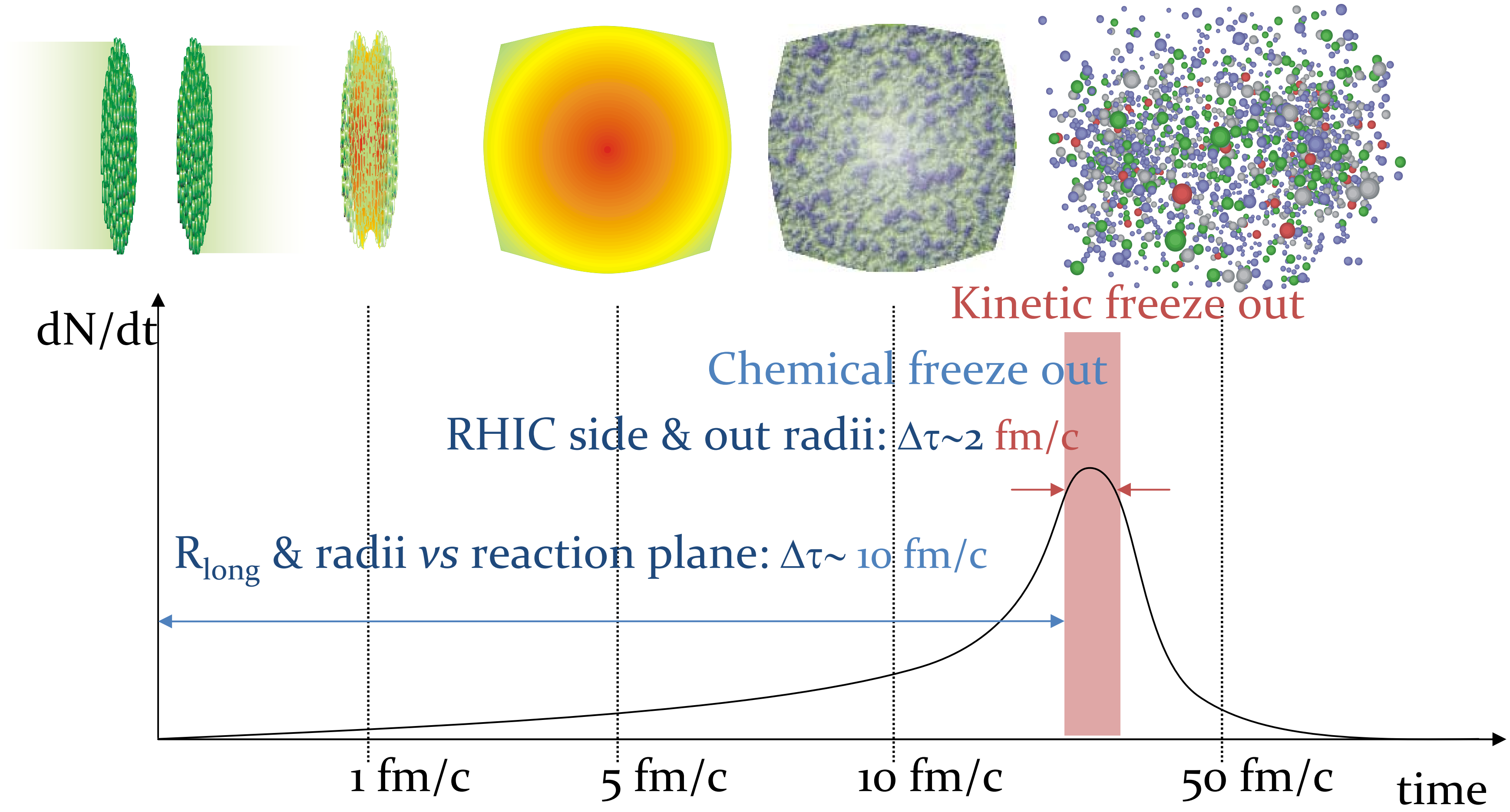
Where could be QGP formed ?

Central collisions of ultrarelativistic heavy ions



$$b \rightarrow 0$$

Expected evolution of HI collision vs RHIC data



initial state

pre-equilibrium

QGP and
hydrodynamic expansion

hadronization

hadronic phase
and freeze-out

Kinetic freeze out

Chemical freeze out

RHIC side & out radii: Δτ~2 fm/c

R_{long} & radii *vs* reaction plane: Δτ~ 10 fm/c

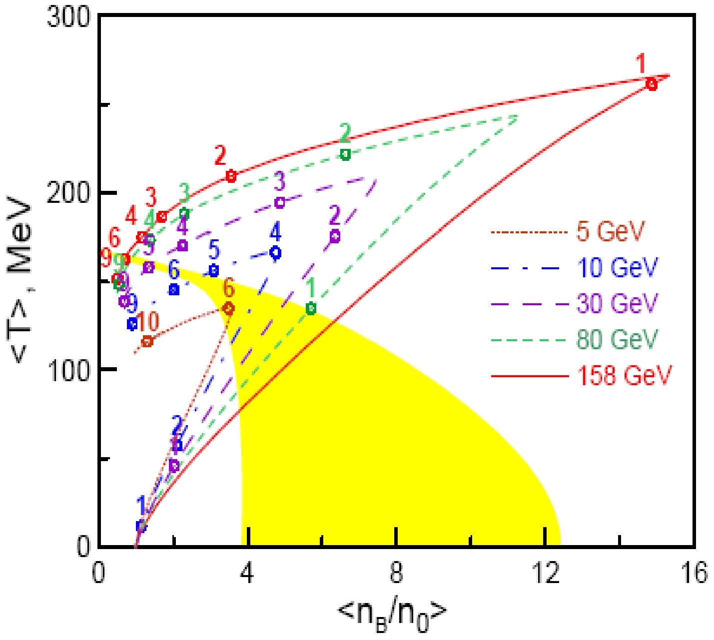
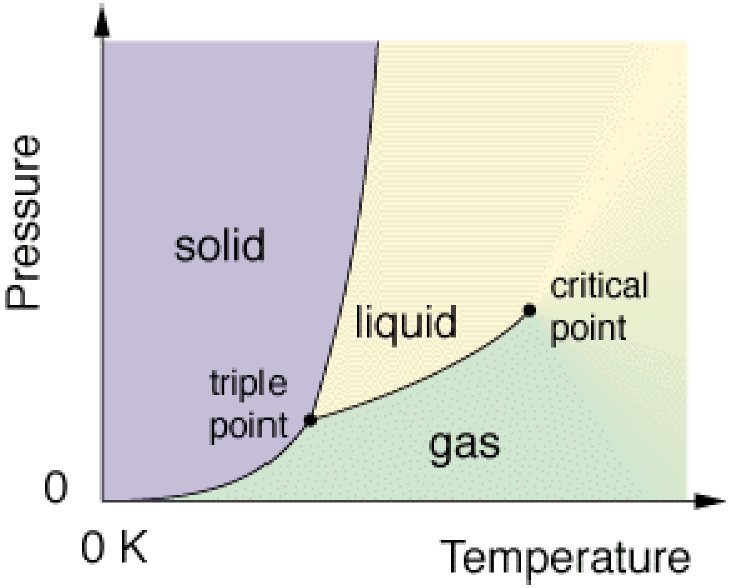


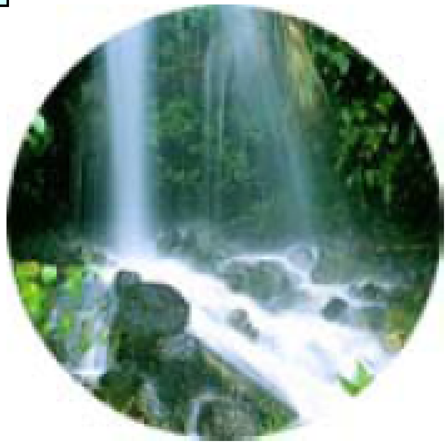
Figure Dynamical trajectories for central $Au + Au$ collisions in $T - n_B$ (left panel) for various bombarding energies calculated within the relativistic 3-fluid hydrodynamics]. Numbers near the trajectories are the evolution time moment. Phase boundaries are estimated in a two-phase bag model.

Overview : QCD Phase Diagram

T. Hatsuda
(Univ. Tokyo)

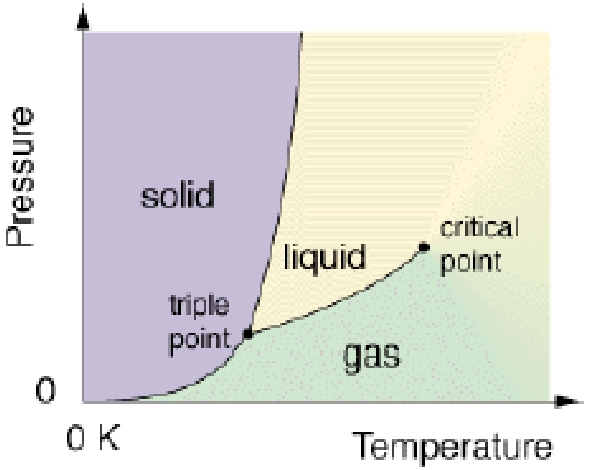
H_2O



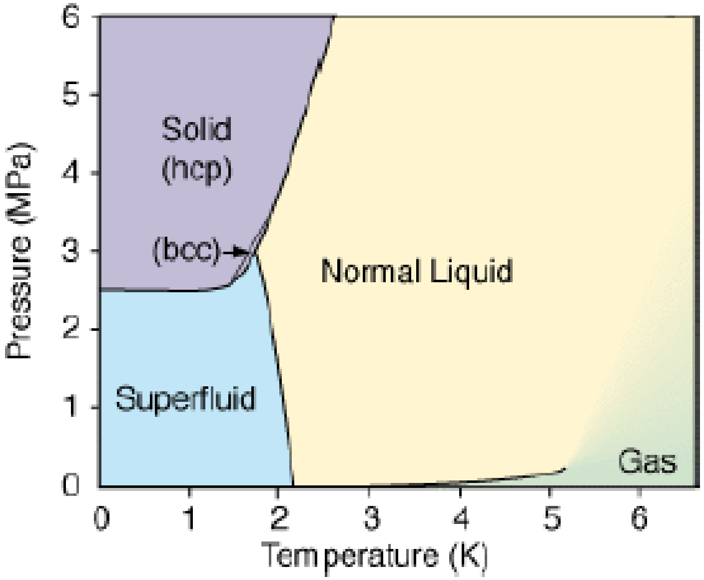


Quantum phases of ^{3}He & ^{4}He

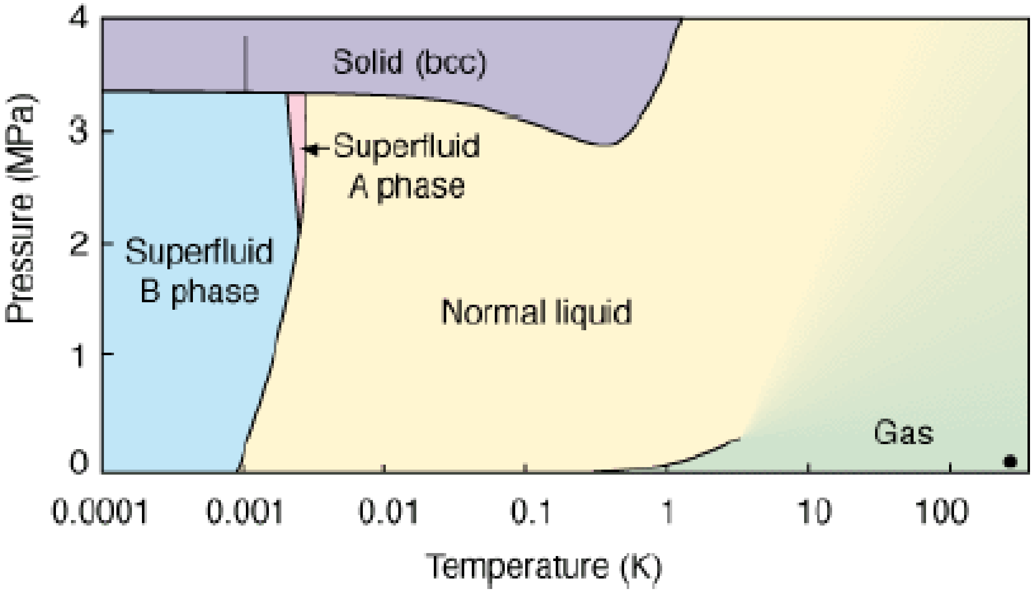
H_2O



^{4}He

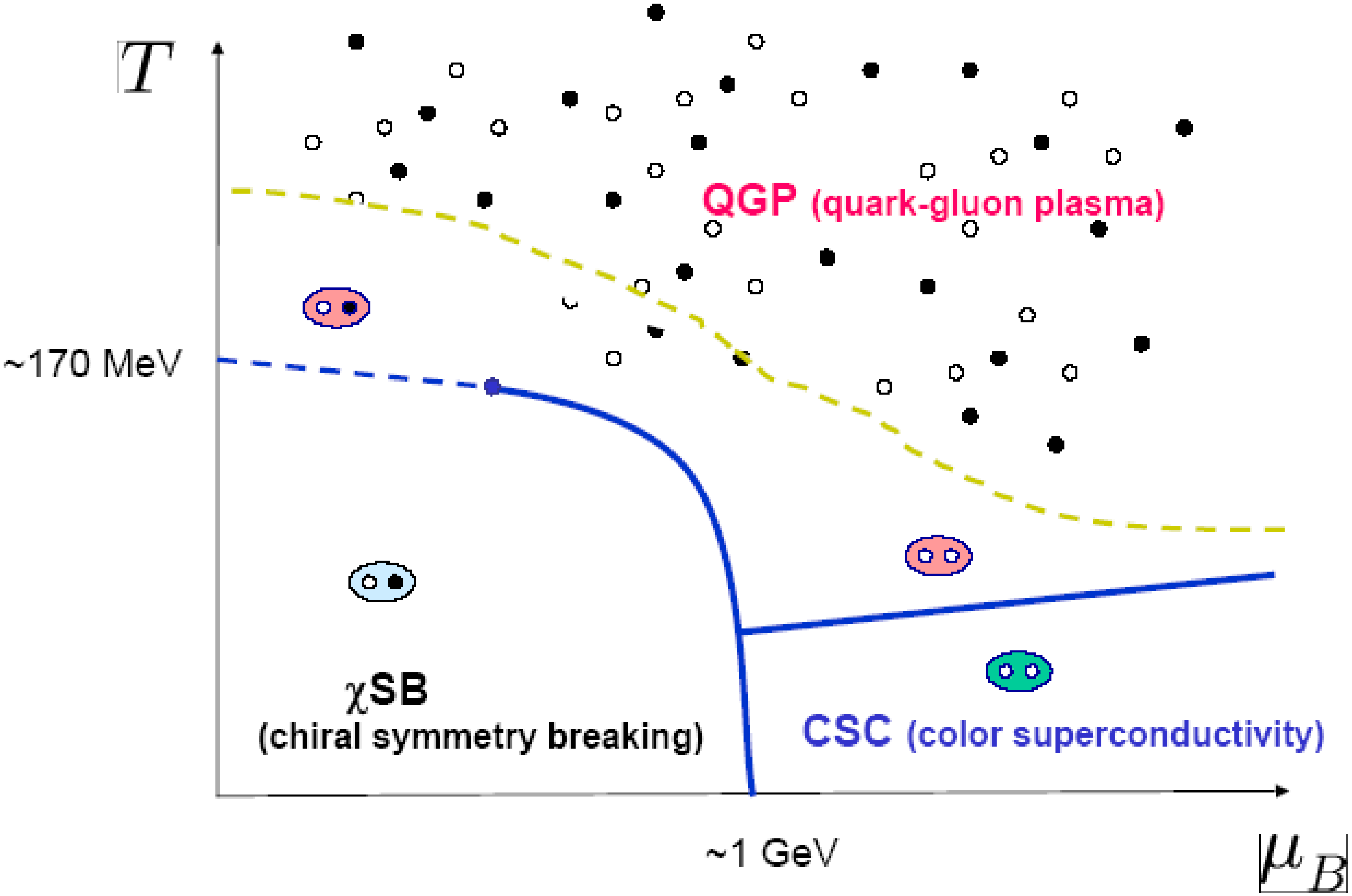


^{3}He

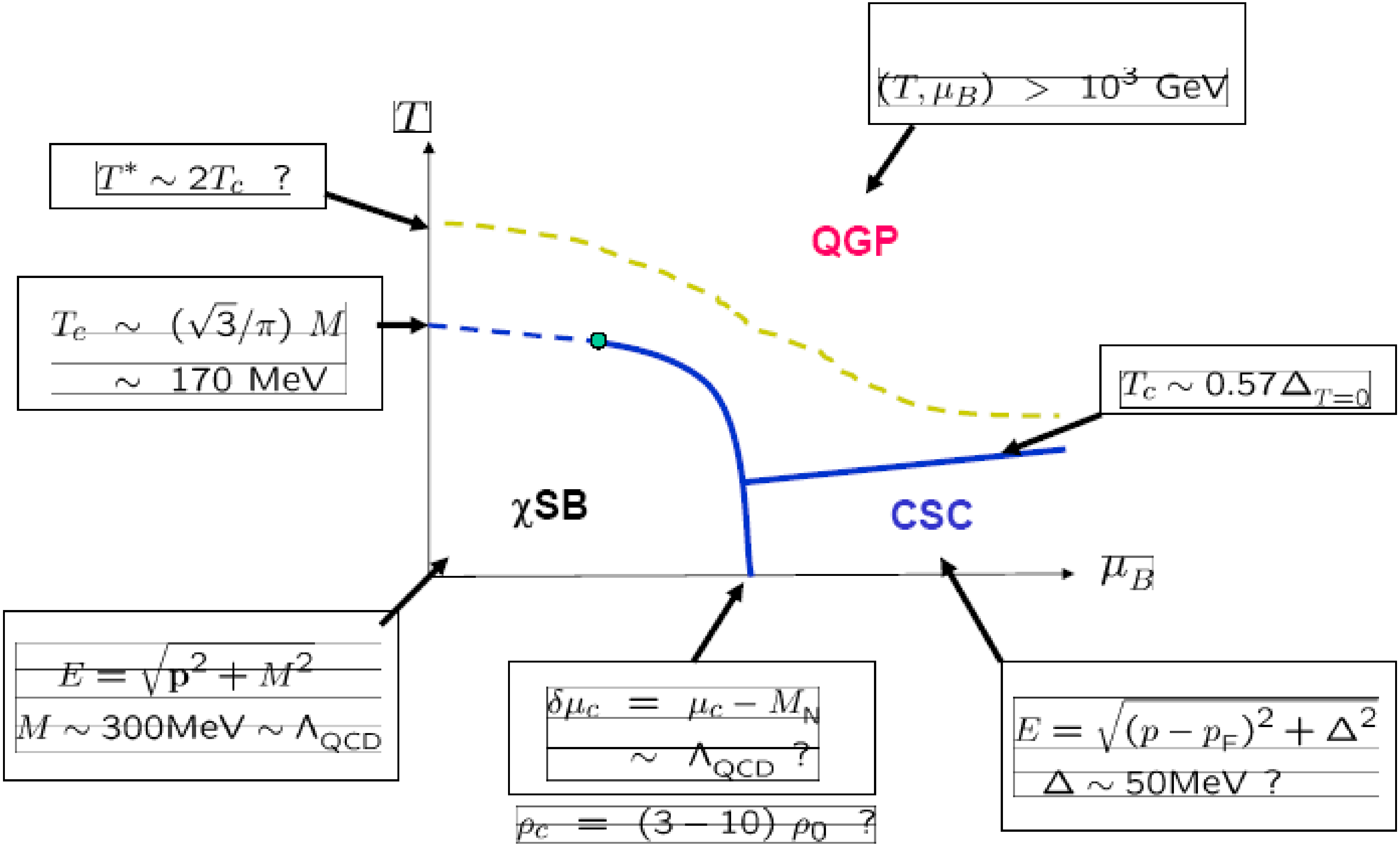


http://boojum.hut.fi/research/theory/typicalpt.html

Phases in QCD ? – a schematic picture --



Scale of each “phase”



$(T, \mu_B) > 10^3$ GeV

$T^* \sim 2T_c$?

$$T_c \sim (\sqrt{3}/\pi)\ M \sim 170\ \text{MeV}$$

$T_c \sim 0.57\Delta_{T=0}$

$$E = \sqrt{\mathbf{p}^2 + M^2}$$

$M \sim 300\text{MeV} \sim \Lambda_{\text{QCD}}$

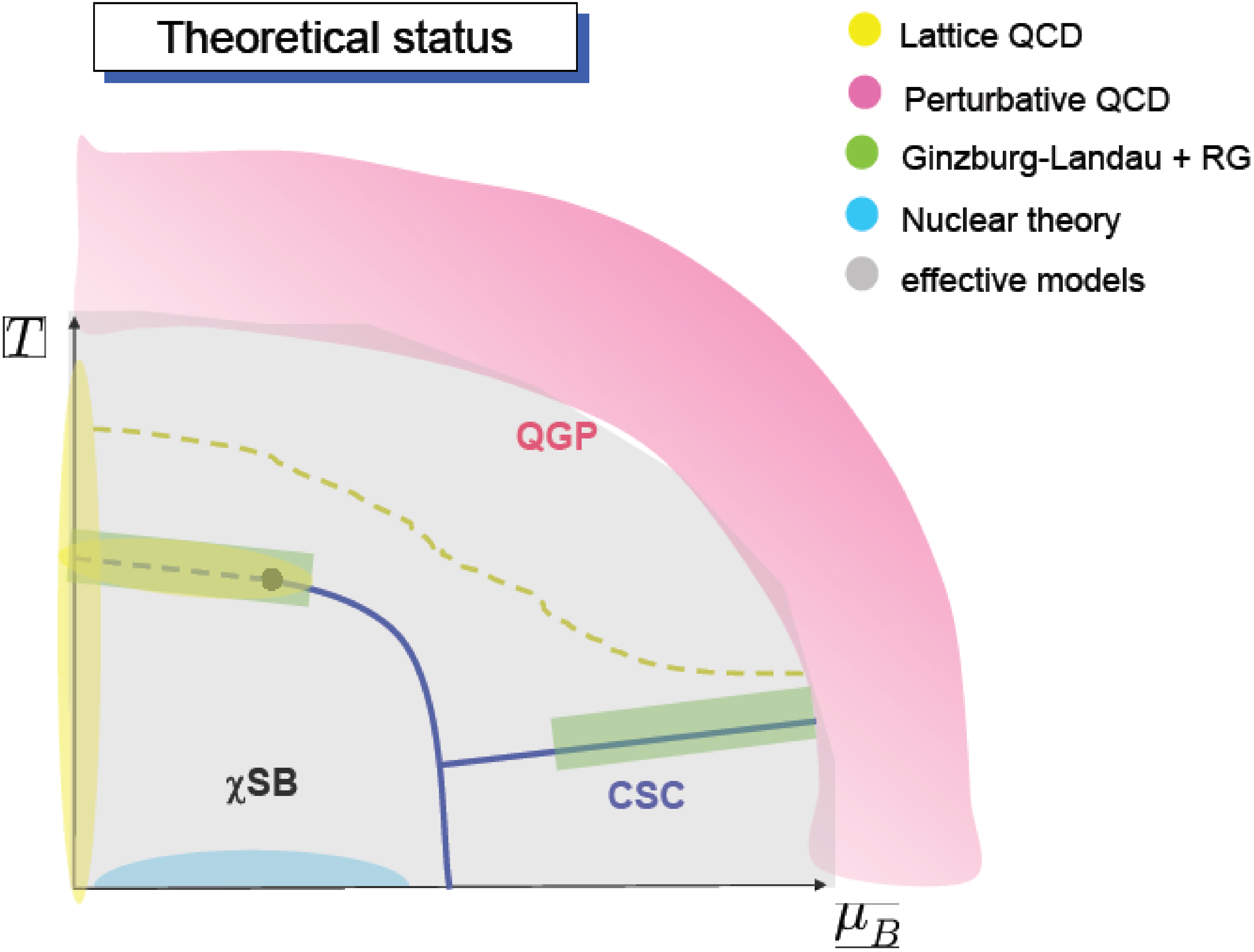
$$\delta\mu_c = \mu_c - M_N \sim \Lambda_{\text{QCD}}\ ?$$

$\rho_c = (3-10)\ \rho_0$?

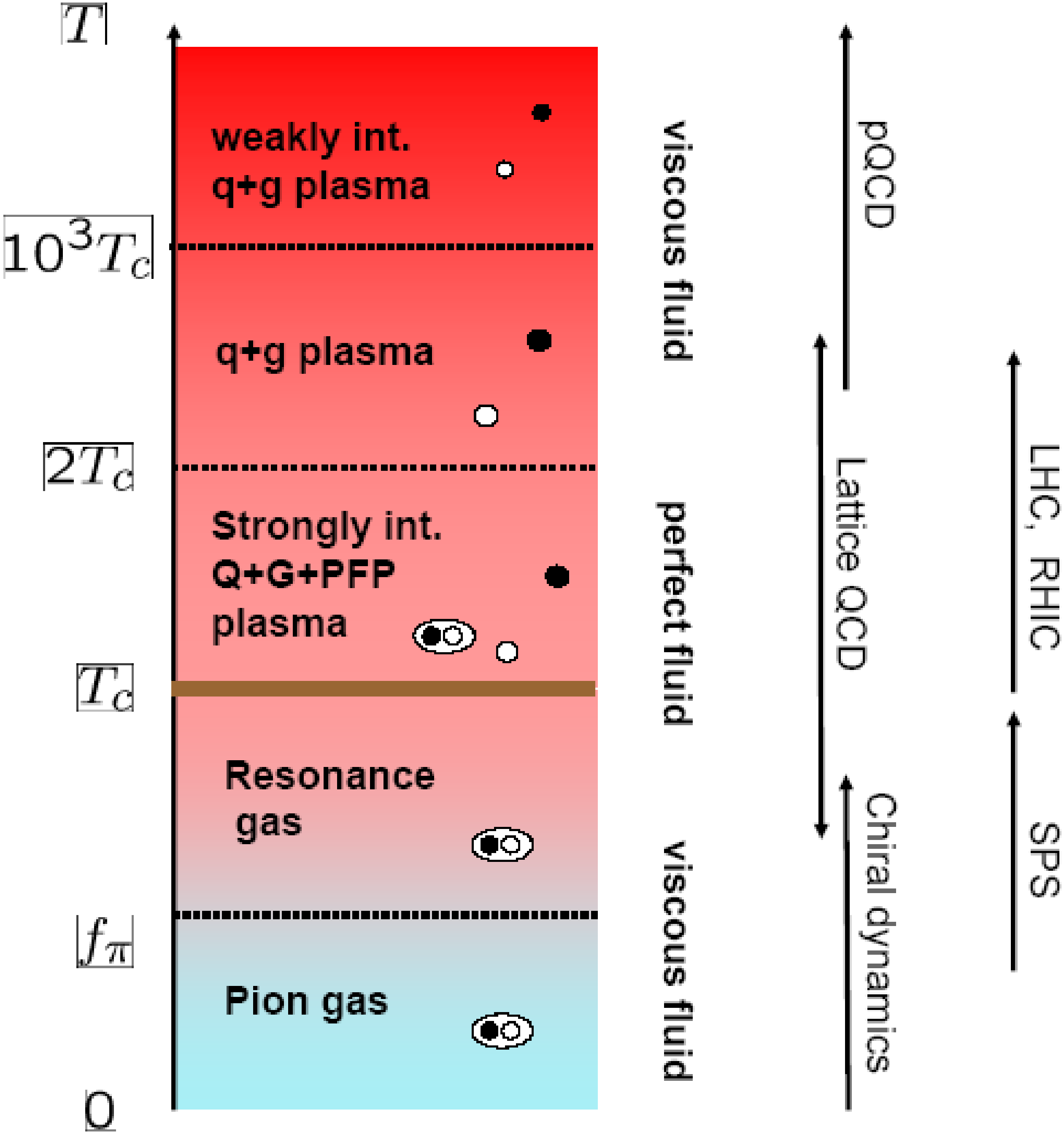
$$E = \sqrt{(p - p_F)^2 + \Delta^2}$$

$\Delta \sim 50$MeV ?

Theoretical status



A modern “picture” of hot QCD



T

10^3T_c

$2T_c$

T_c

f_π

0

weakly int.
q+g plasma

q+g plasma

Strongly int.
Q+G+PFP
plasma

Resonance
gas

Pion gas

viscous fluid

perfect fluid

viscous fluid

pQCD

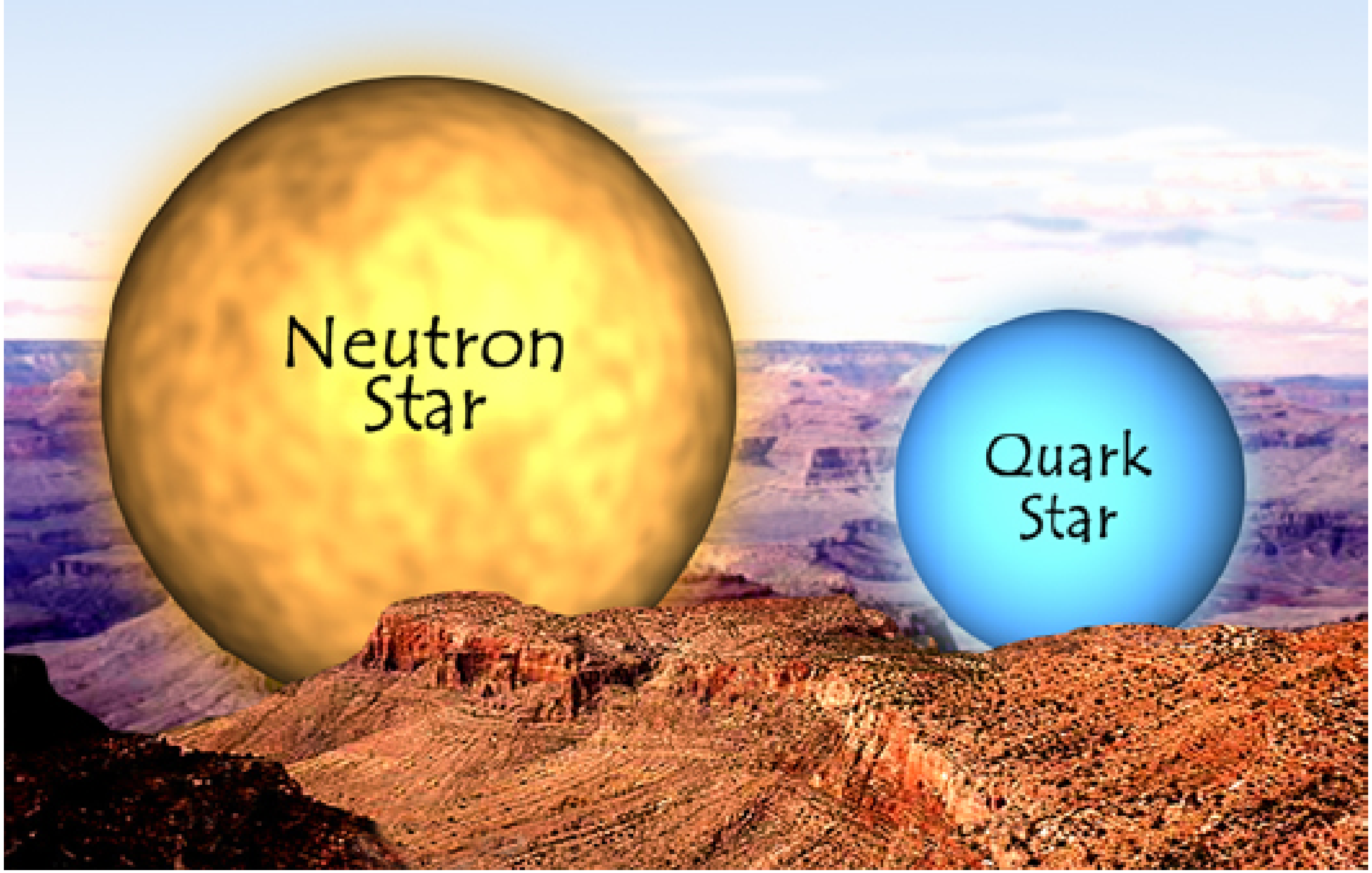
Lattice QCD

Chiral dynamics

LHC, RHIC

SPS

Phases in dense QCD



Baade-Zwicky ('34) **N. Itoh ('70), E. Witten ('84)**

http://chandra.harvard.edu/resources/illustrations/neutronStars.html

The estimate of QGP parameters

J. D. Bjorken, Phys. Rev. 1983, **D27**, p. 140.

$$\varepsilon_{BJ} = \frac{Energy}{Volume} = \frac{\frac{dE}{d\eta}}{\pi R_0^2 A^{2/3}} = \frac{m_T \frac{dN}{d\eta}}{\pi R_0^2 A^{2/3} c\tau_0}$$

The density of energy
(transverse flow neglected)

$\pi R^2_o A^{2/3}$ Transverse size of the smallest nucleous

$\tau_o \sim 1\ fm/c$ formation time

$dE_T/d\eta = m_T dN/d\eta$ Mean energy of the particle, multiplied on the number of particles

$m_T = \sqrt{p_T^2 + m^2}$ Transverse mass (energy)

The mean free path ~ 0.5 fm at $\varepsilon_{BJ} \sim 2$ GeV/fm^3

The temperature and density of nuclear matter are among the main parameters of equation of state determining the phase transition mechanism. To obtain the temperature of secondary hadrons in the experiment one usually estimates the value of the inclusive spectrum slope.

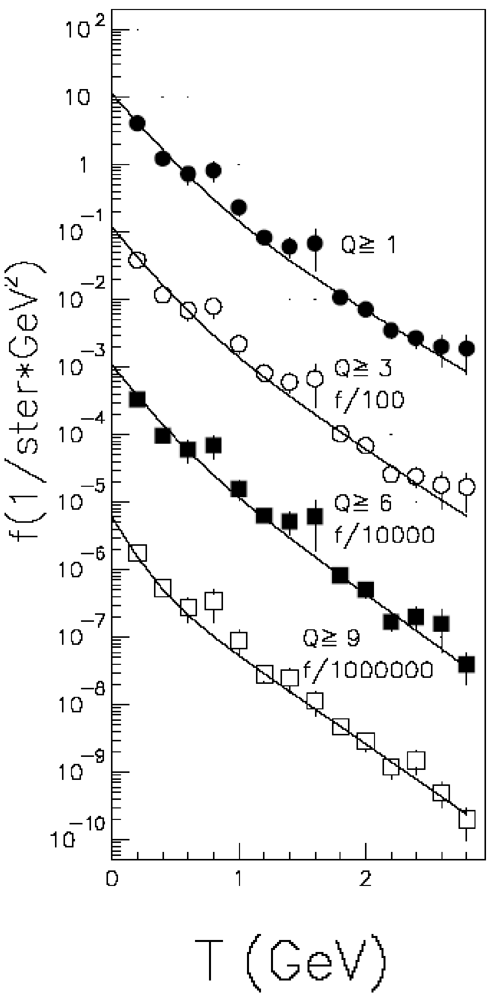
To define the temperature, , the invariant inclusive spectra of

π^--mesons as a function of their kinetic energies T in the lab system for

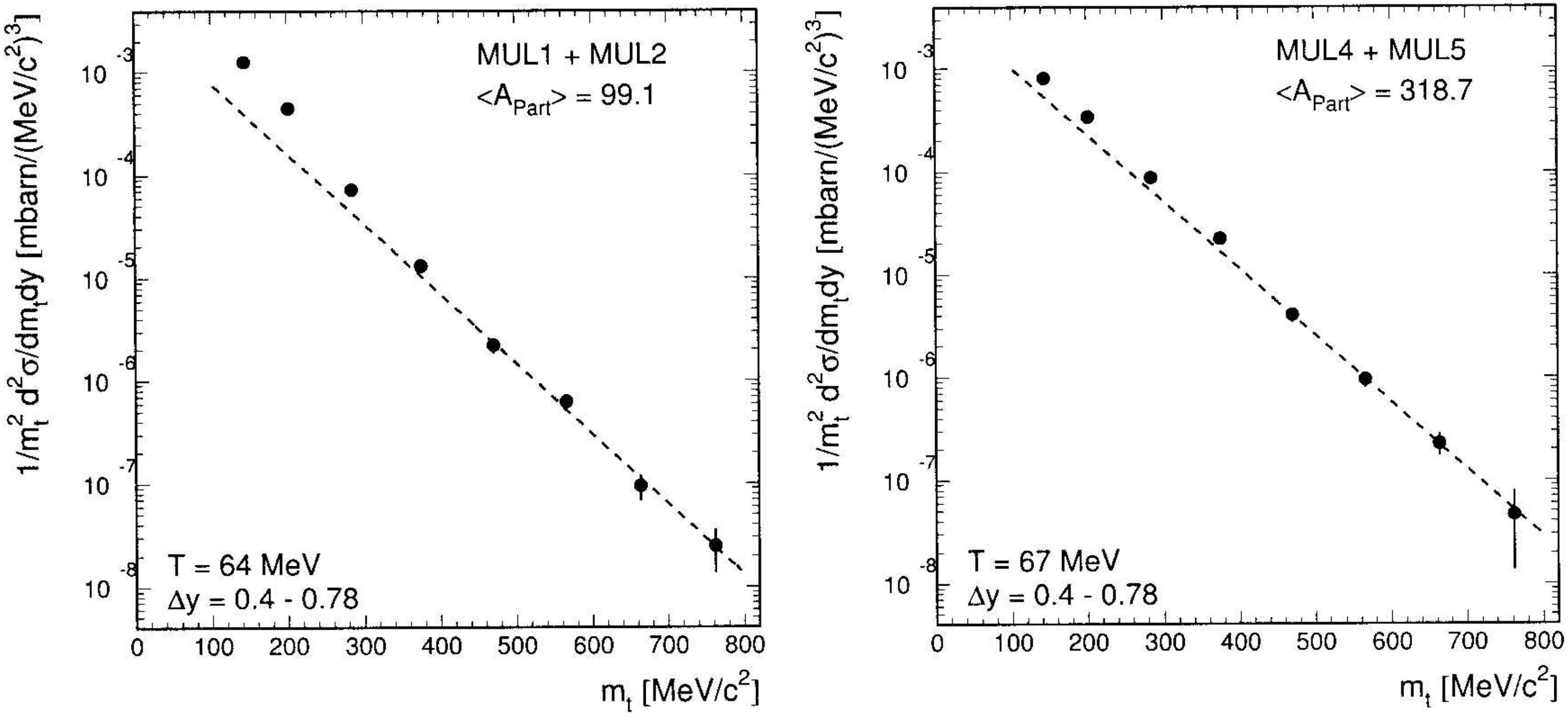
^{12}CC interactions at the momentum 4.2 A GeV/c with different values of Q are

used. The spectra are fitted by the expressions of the form $\sum_{i=1}^{n} a_i \exp(-b_i T)$

the inverses of slopes $T_i = 1/b_i$



$$f = \frac{E}{\sigma}\frac{d^3\sigma}{dp^3} = \frac{E}{\sigma p^2}\frac{d^2\sigma}{dp\,d\Omega} = \frac{E}{p^2}\frac{d^2N}{dp\sin\theta d\theta d\varphi} = \frac{E}{4\pi p^2}\frac{dN}{dp} = \frac{1}{4\pi p}\frac{dN}{dT}$$



mt spectrum of π- and η- mesons prodused in AuAu interactions at 0.8 A GeV (TAPS)

How could we identify experimentally QGP?

Some of the traditional QGP signatures

- **Dilepton production**: A quark and an anti-quark can interact via a virtual photon γ^* to produce a lepton and an anti-lepton l^+l^- (often called dilepton). Since the leptons interact only via electromagnetic means, they usually reach the detectors with no interactions, after production. As a result dilepton momentum distribution contains information about the thermodynamical state of the medium.
- **Thermal Radiation**: Similar to dilepton production, a photon and a gluon can be produced via $q + {}^{-}q \rightarrow \gamma + g$. Since the electromagnetic interaction isn't very strong, the produced photon usually passes to the detectors without any interactions after production. And just like dilepton, the momentum distribution of photons can yield valuable information about the momentum distributions of the quarks and gluons that make up the plasma, giving us a window into its thermodynamical properties.
- **Strangeness Enhancement**: Production of strange quarks requires a larger amount of energy compared to ordinary u and d quarks. The high energy densities in QGP are conducive for sś production, leading to an enhancement in the number of strange particles as compared to the strangeness production in p+p collisions.

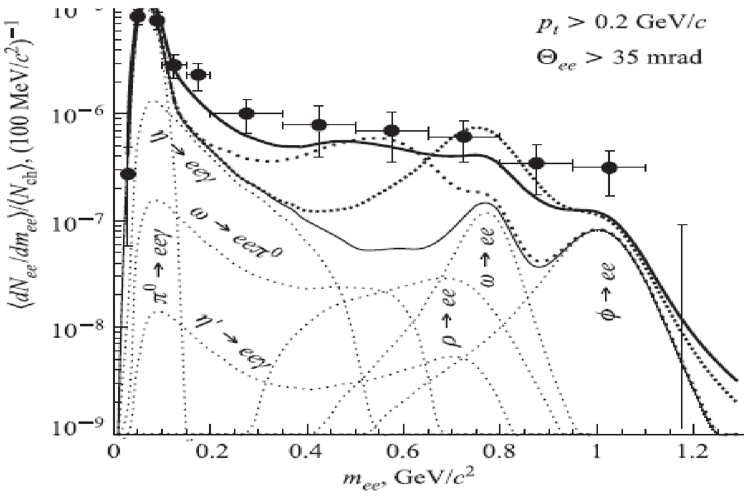
Some of the traditional QGP signatures

- ***J/Ψ* suppression**: In a Quark-Gluon-Plasma (QGP), color screening due the presence of free quarks and gluons (similar to Debye screening seen in QED), the *J/ Ψ* particle — a bound state of charm and anti-charm quarks $\bar{c}c$ — can dissociate. This leads to a suppression of *J/ Ψ* production, a classic signature.
- **HBT:** The Hanbury-Brown-Twiss effect — first used to measure the diameter of a star is also used in high energy nuclear experiments, by measuring the space-time (or energy-momentum) correlation of identical particles emitted from an extended source. In ultrarelativistic heavy ion collisions, an HBT measurement can yield information about size and the matter distribution of the sources
- **Jet suppression**: In nucleon collisions, energetic partons (jets) can be produced via hard scatterings. In presence of deconfined matter, they interact strongly, leading to energy loss GeV/fm, mostly due to gluon bremsstrahlung processes. This results in a decrease in the yield of high energy particles or jet suppression.
- **Flow (radial and elliptic)** .

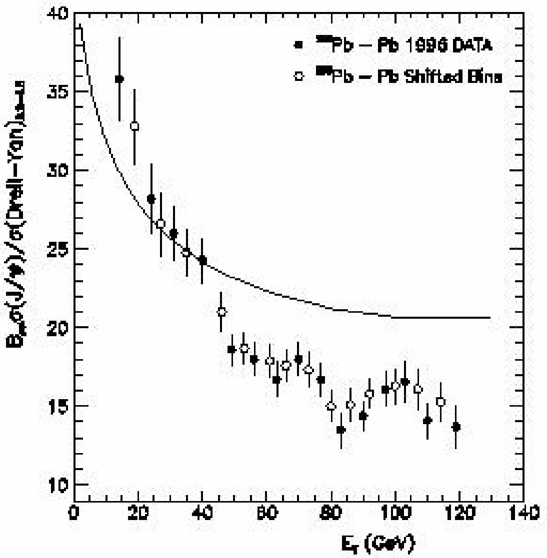
- Properties of hadrons are expected to change in hot and/or dense baryon matter |. This change concerns hadronic masses and widths, first of all for the σ meson as the chiral partner of pions, which characterizes a degree of chiral symmetry violation and can serve as a «signal» of its restoration as well as the mixed phase formation. Lepton decays in matter of vector mesons (particularly ρ and ω) are also very attractive.

The presence of in-medium modification of ρ mesons has been proved in the CERES experiments (see Fig.). The observed essential enhancement of low mass ($0.2 \lesssim M \lesssim 0.7$) lepton pairs, as compared to free hadron decays, is due to the influence of hot and dense nuclear matter on properties of the ρ-meson spectral function. Unfortunately, poor resolution in the di-electron mass does not allow discrimination of different physical scenarios of this effect in the CERES experiments.

Fig. 2. The e^+e^- invariant spectra from central Pb + Au (40A GeV) collisions . . Thin solid and dotted lines are hadronic cocktail and calculation results for free ρ mesons, respectively. Appropriate thick solid and dash-dotted lines are calculated in the Rapp–Wambach and Brown–Rho scenarios. Contributions of different channels are shown as well

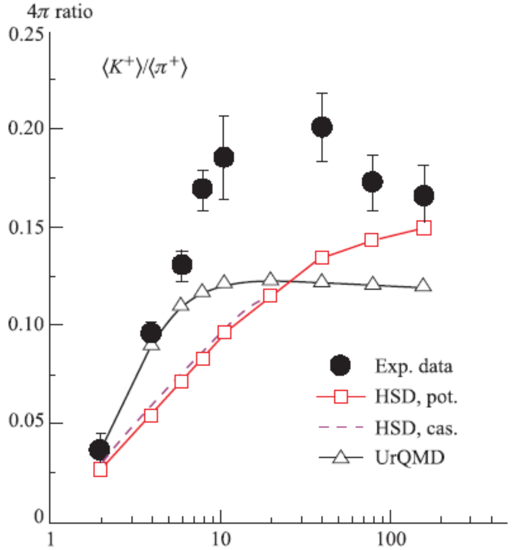


J/ψ-suppression



The ratio of the J/ψ to Drell-Yan cross-sections has been measured by NA38 and NA50 SPS CERN as a function of the centrality of the reaction estimated, for each event, from the measured neutral transverse energy Et [M.C. Abreu et al., Phys.Let. B 1999, 450, p. 456; M.C. Abreu et al., Phys.Let. B, 1997, 410, p. 337; M.C. Abreu et al. Phys.Let. B, 1997, 410, p. 327; M. C. Abreu et al. By NA50 Collaboration, Phys.Lett.B, 2001, 499, pp. 85-96].

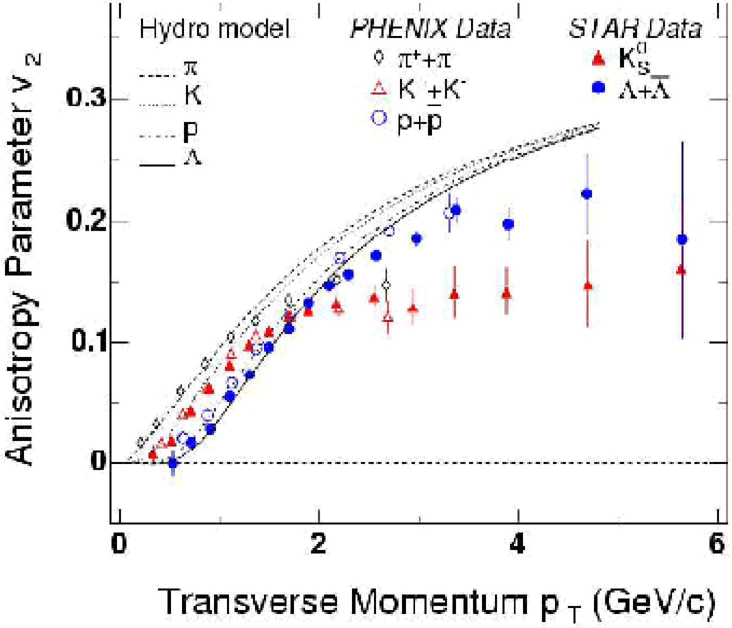
- Strangeness enhancement is an intriguing point of physics of heavy-ion collisions, being one of the first proposed signals of quark–gluon plasma formation. An important experimental finding is the observation of some structure («horn») in the energy dependence of reduced strangeness multiplicity at $E_{\text{lab}} \sim 30A$ GeV, predicted in as a signal that the formed excited system came into a deconfinement phase. As an example, in Fig. the K^+/π^+ average multiplicity ratio is displayed as a function of the bombarding energy. The «horn» structure is well visible and is getting even more prominent if the recent measurement of $\langle K^+\rangle/\langle\pi^+\rangle \simeq 0.22$ at $E_{\text{lab}} = 20A$ GeV is additionally plotted and the bombarding energy is presented in the logarithmic scale (which is quite natural when RHIC data are supplemented). It is of great interest that these global characteristics are not explained by modern transport theory (UrQMD, HSD models). While the average pion and kaon multiplicities are well reproduced at the SIS and SPS energies, the above-mentioned models essentially underestimate the K/π ratio in the AGS energy domain. It is remarkable that the divergence between the transport theory and experiment starts just at the Nuclotron energy. This increases interest in future experiments at the Nuclotron.

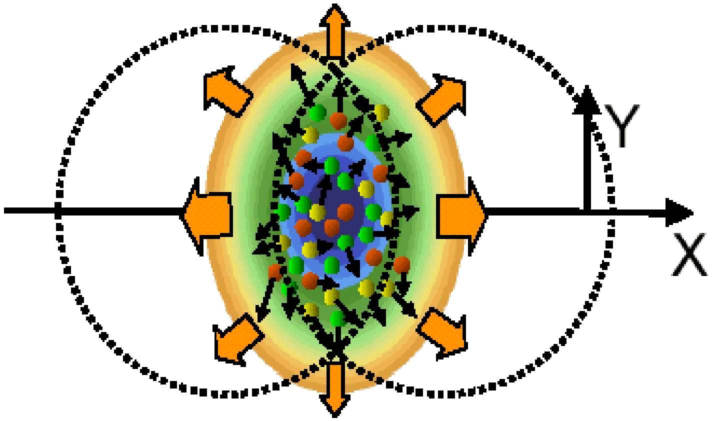


Energy dependence of the relative strangeness abundance of K^+ mesons . Curves are results of different transport calculations

elliptic flow --- `early signature´ of QGP

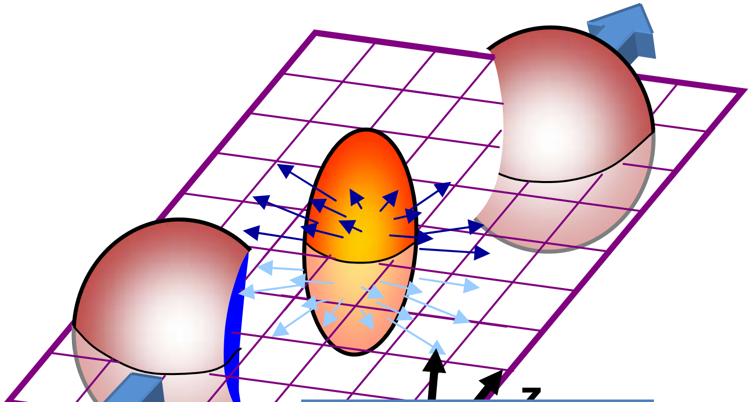
$$\frac{dN_h}{dp_T^2\,dy\,d\varphi}=\frac{dN_h}{dp_T^2\,dy}\frac{1}{\pi}(1+2v_1\cos\varphi+2v_2\cos 2\varphi+\ldots)$$

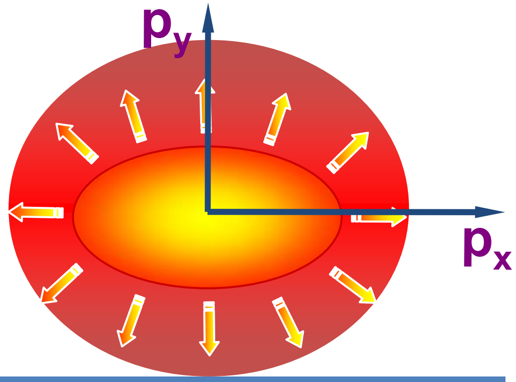




evidence for an early buildup of pressure and a fast thermalization of the quark-gluon system

A measure of the Pressure: Elliptic Flow





$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

Pressure

$c_s^2 = dP/d\varepsilon$

Mean free path

$$v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Obtained result cannot give possible to say surely that we have any experimental signal on Quark Gluon Plasma formation.

Why?

1. These results are model dependence;

2. These results could be explained by other ways.

What is a Problem ?

Before never physicists have had so difficult object as QGP which can't interact with our World and with our detectors due to Confinement .

It is absent complete theory of strong interactions --- quantitative QCD.

In any case QGP could be formed in central collisions , in events with huge multiplicity of secondary particles – enormous background .

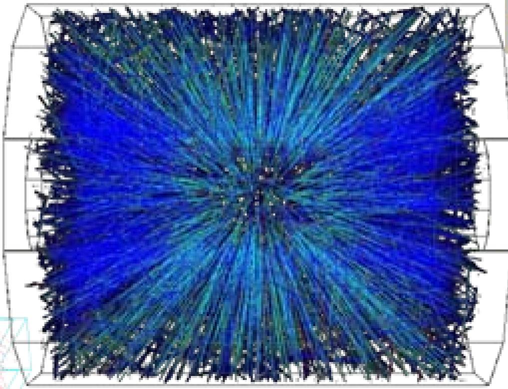
Traditional applied methods to process the data (single and multiparticle correlation methods, methods of effective mass , missing mass methods , HBT and others) are very sensitive to background information .

It is impossible to use 4π geometry detectors (because the volume of information is huge) which could give as some prompts to go forward surely.

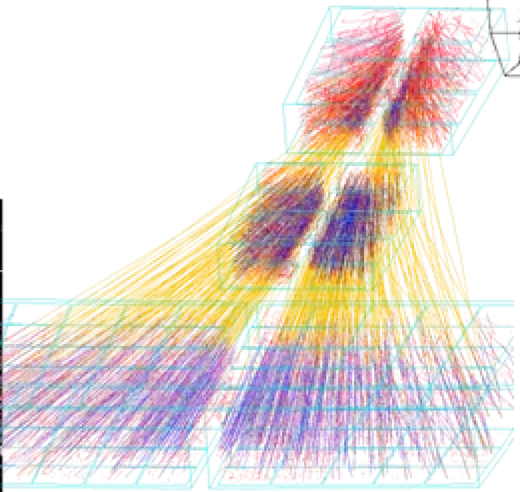
PbPb $\sqrt{s_{NN}}$= 5.5 TeV Alice LHC CERN


Alice event: 0, Run:0
Nparticles = 36276 Nhits = 1943104

Au+Au $\sqrt{s_{NN}}$ = 200 GeV STAR
RHIC BNL

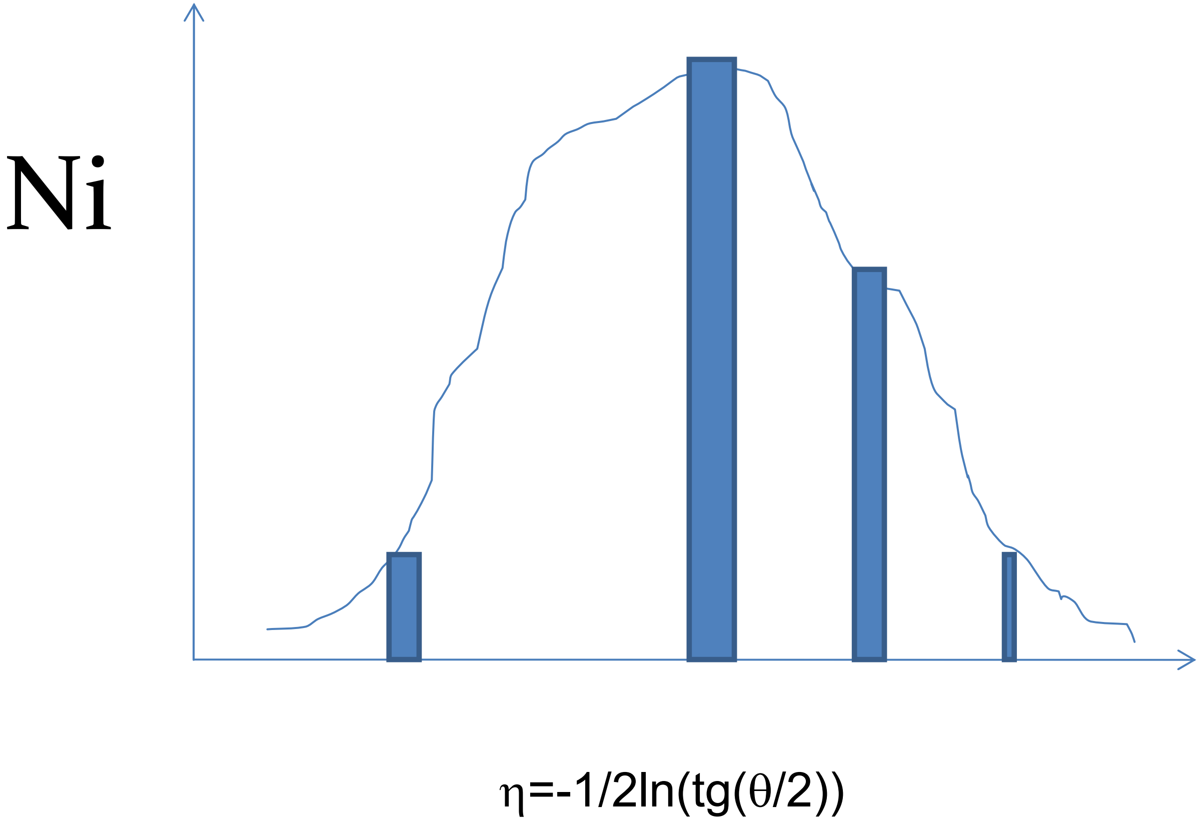


Pb+Pb $\sqrt{s_{NN}}$ = 17.3 GeV
NA 49 SPS CERN



π+A (~ 1 GeV)

What can see modern detectors ?

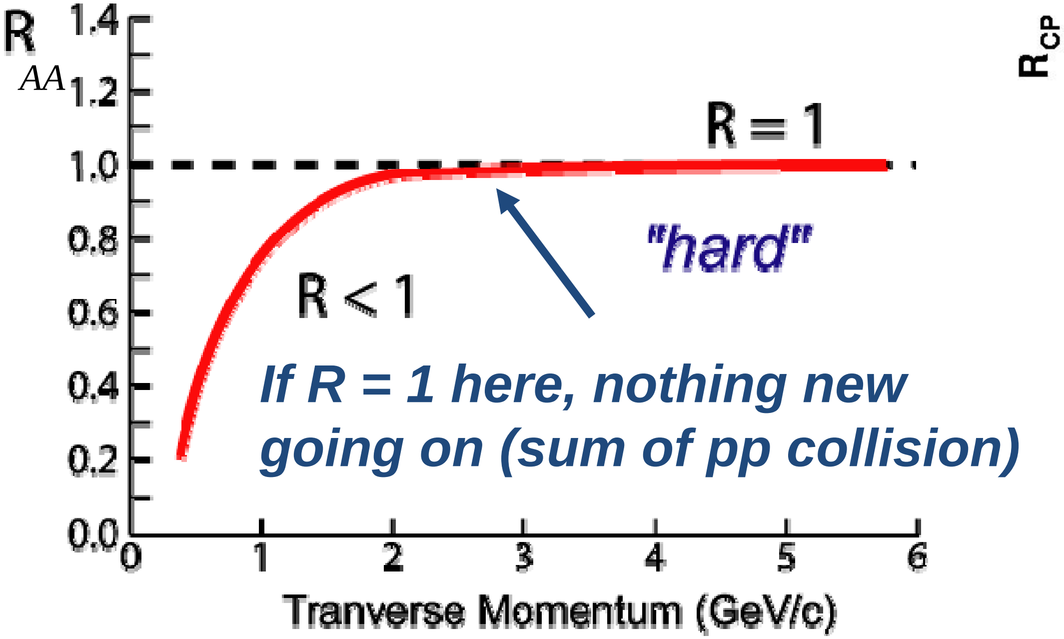


Nuclear Transparency Effect

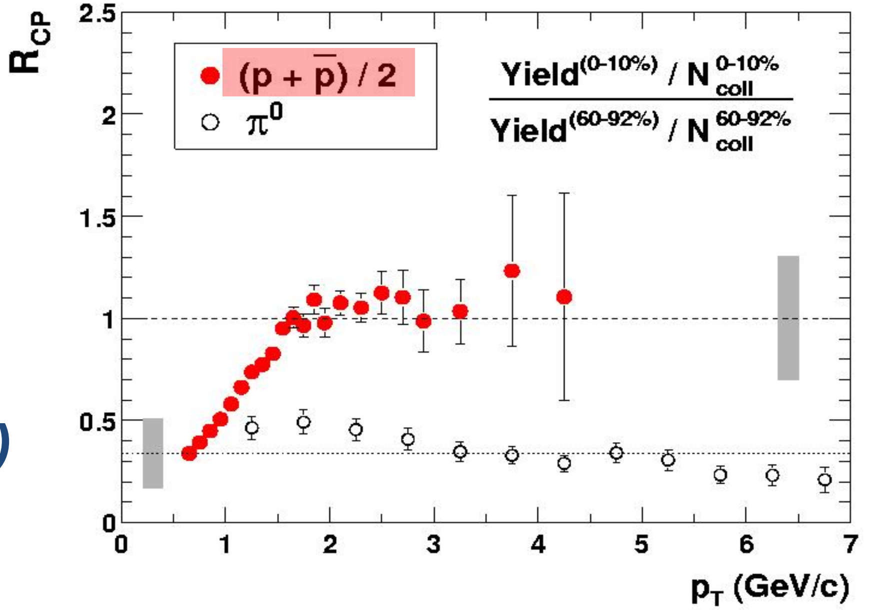
Light Nuclei Production

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{NN}/dp_T d\eta}$$



If R = 1 here, nothing new going on (sum of pp collision)



- Strong (Flat) suppression explained by jet quenching
- *Proton not suppressed ?!*

Nuclear Transparency

Transparency at different energies:

- Transparency is strongly energy dependent. At low incident energies ($E_i < 35$ MeV) the composite projectile are known to be strongly absorbed. But the situation dramatically changes at higher incident energies (E_i~200MeV/nucleon) The nucleon-nucleon (N-N) interaction is to exhibit a minimum in the total cross-section in the energy range $150 \leq E \leq 350$ MeV. This dip is ascribed to a falloff, due to increasing transparency.

Transparency at low energies:

- At low energies the effect of transparency can provide us with necessary information on the structure of the nucleus because transparency capability of different nuclei is different. At low energies, when colliding nuclei overcome the Coulomb barrier, form a cold residue at the end of the reaction “a fusion reaction”, which’s mass corresponds to the full system mass.

Transparency effect at medium and high energies:

- At middle and high energies the effect of transparency can provide us the necessary information on the states of nuclear matter because transparency capability of different states of nuclear matter must be different.

Transparency at ultra relativistic energies.

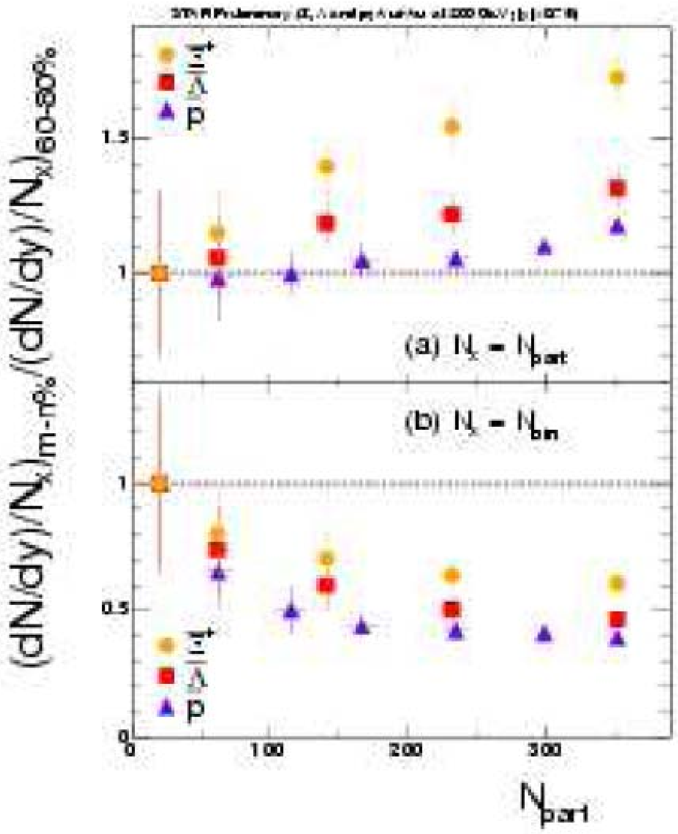
- At ultra relativistic energies transparency gives information on the states, phases and properties of strongly interacting matter. Strongly interacting matter is a system with nucleons, pions and nucleons and pion resonances

Experimental methods for determination of Transparency effect.

$$R = \frac{n_1}{n_2}$$

(here e.g., n_1 and n_2 could be heavy flavor particles yields with fixed values of p_T and η) as a function of centrality, the masses and energy it is possible to get necessary information on the properties of the nuclear matter. In such definition of R, appearance of transparency could be identified using the condition $R \to 1$. Using some statistical and percolation models and experimental data on the behaviour of the nuclear modification factors it is possible to get information on the appearance of the anomalous nuclear transparency as a signal of formation of the percolation cluster.

Recent data obtained by STAR RHIC BNL on the behavior of the nuclear modification factors of the strange particles as a function of the centrality in Au+Au- and p+p-collisions at sqrt(s_{NN}) = 200 GeV may help us to answer the questions that how the new phases of strongly interacting matter form? May we expect a signal on the formation of the intermediate nuclear system e.g., nuclear cluster? The strange particles could be formed as a result of quark coalescence in high density strongly interacting matter and on other hand they could be captured by this system intensively.



Light Nuclei Production

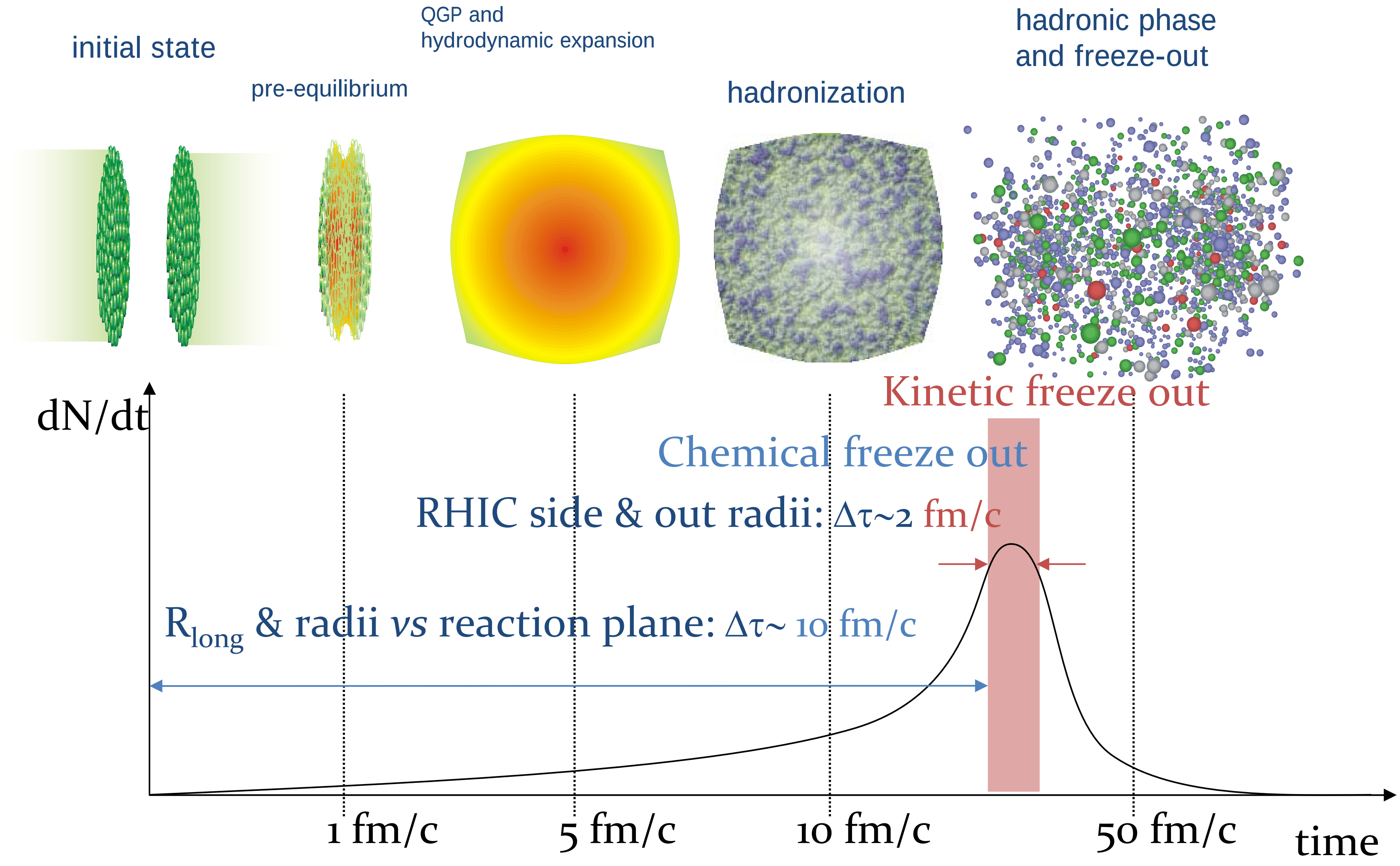
One of the ways to identify Quark-Gluon-Plasma could be to study the centrality dependence of the light nuclei production in heavy ion collisions. Observation of the regime change on the behavior of those distributions as a function of the centrality could be some signal of the appearance of the freeze out state. In this state light nuclei could be formed as a result of nuclear coalescence.

The coalescence parameter B_2 characterizes the probability that two nucleon with similar momentum form abound state.

$$B_2 = \frac{\left(E_d \frac{d^3 N_d}{dp_d^3}\right)}{\left(E_p \frac{d^3 N_p}{dp_p^3}\right)^2} \propto \frac{1}{V} \qquad (1)$$

here and are the deuteron, proton density in momentum space respectively, E_d and E_p the deuteron and proton energies respectively V is the volume of source size at freeze out.

Expected evolution of HI collision vs RHIC data



Kinetic freeze out

Chemical freeze out

RHIC side & out radii: $\Delta\tau \sim 2$ fm/c

R_{long} & radii *vs* reaction plane: $\Delta\tau \sim 10$ fm/c

Thank you