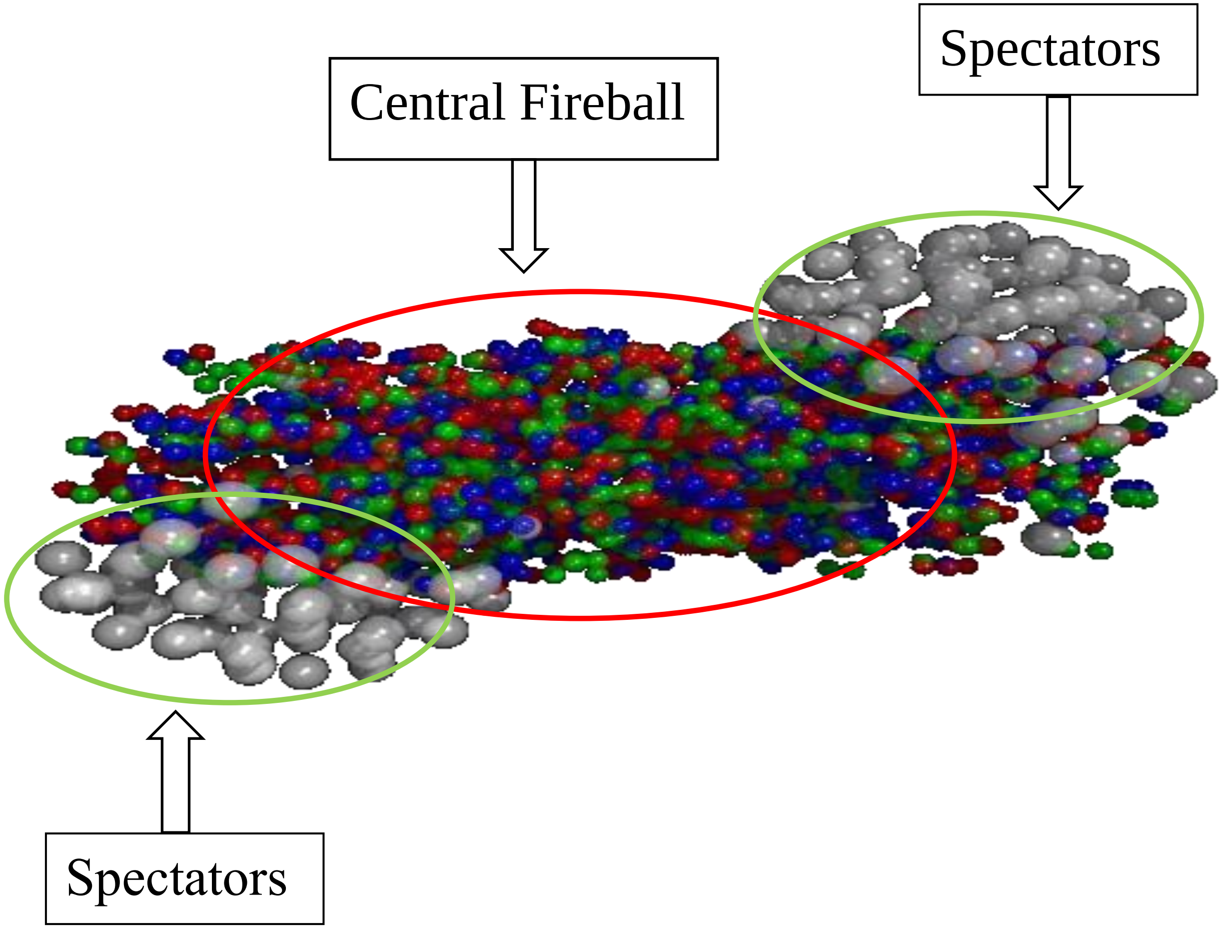
Hadron Modifications in Dense Nuclear Matter

G. Musulmanbekov
JINR
genis@jinr.ru

BM&N Meeting 2023

Heavy Ion Collision (HIC)

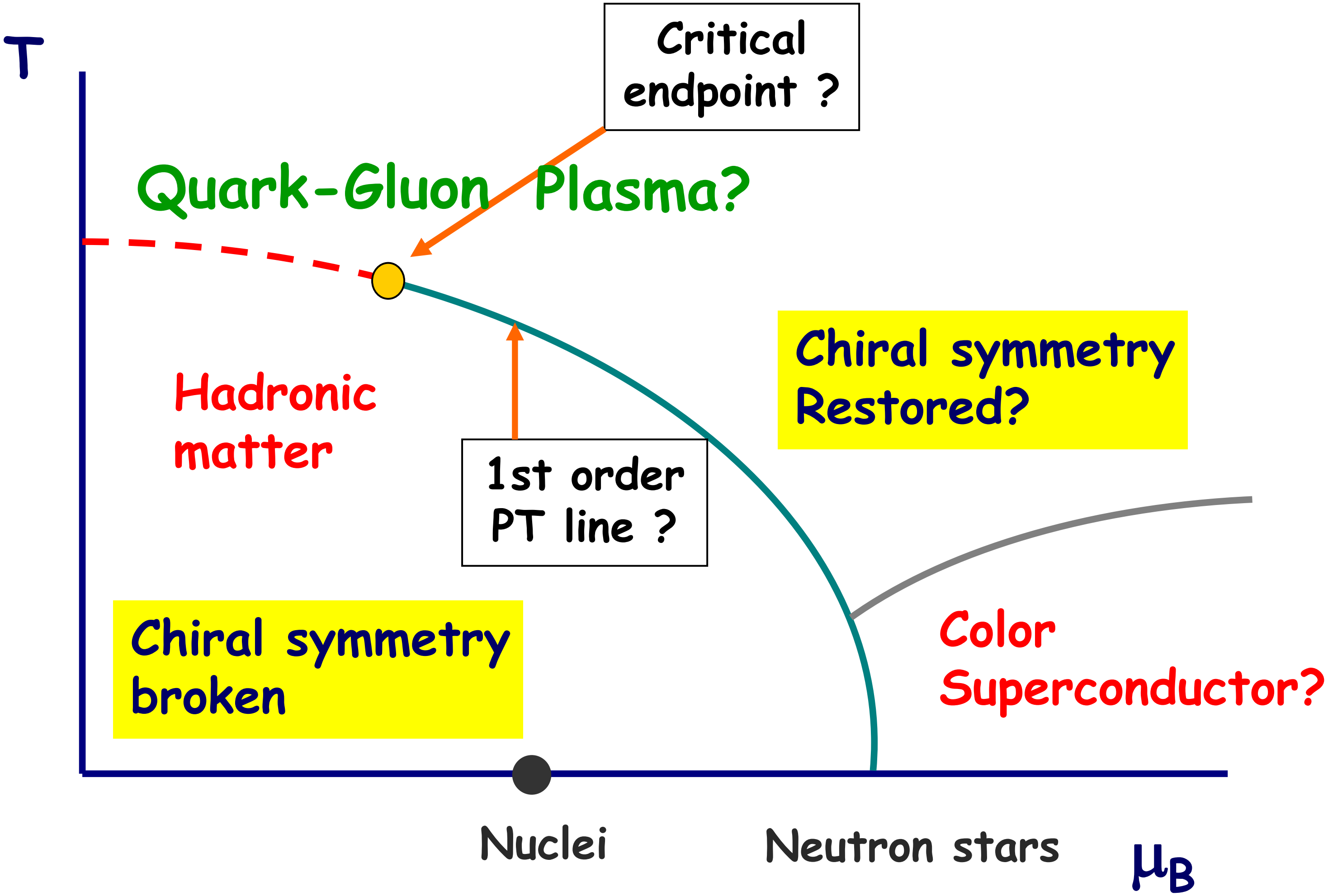


Central Fireball

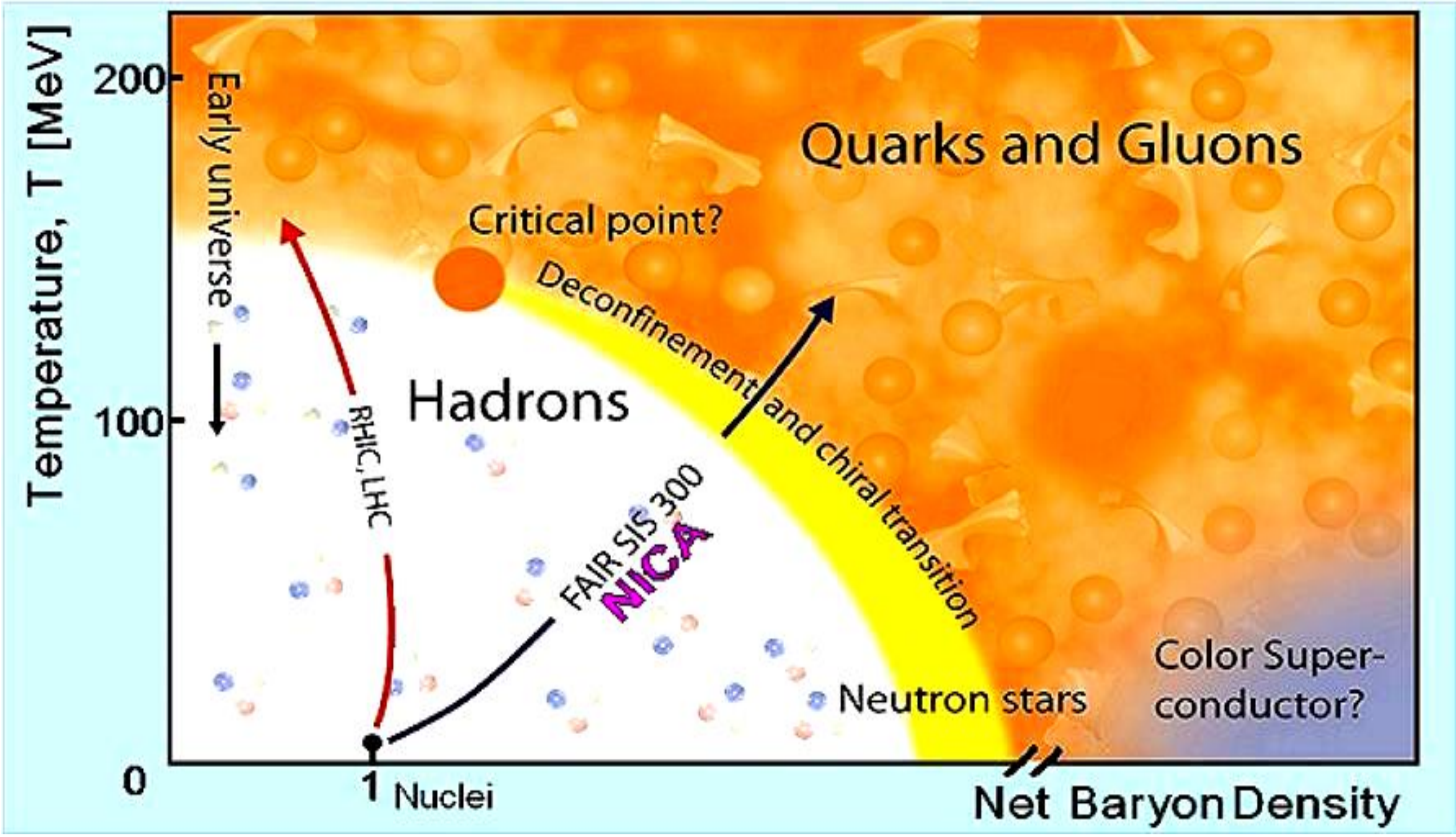
Spectators

Spectators

QGP Transition?



QGP Transition?



Content

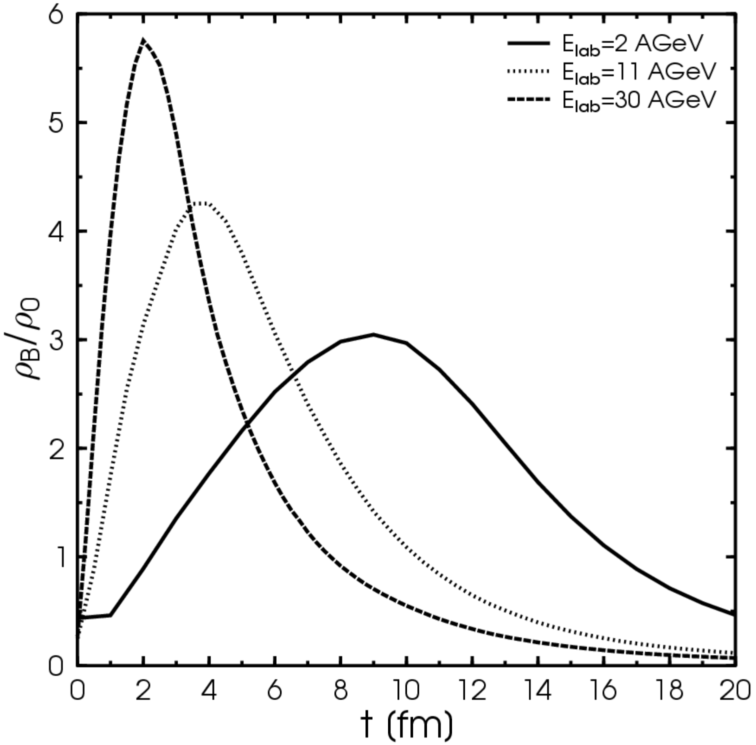
- Motivation
- Nuclear compression, EoS
- Observables related to modification of hadron properties in HIC
- Hadron modifications in a dense nuclear matter
  - Strongly correlated quark model (SCQM) of the hadron structure
- Understanding of exp. effects in HIC
- Conclusion

Motivation

- How much of nuclear collision energy is converted into compression?
- How hadrons structures are modified in a dense nuclear matter?
- Which observables are sensitive to dynamics of HIC?

Motivation

Baryon density evolution
in central Au+Au/Pb+Pb



- How much of nuclear collision energy is converted into compression?
- What is the impact of this compression on hadron properties?

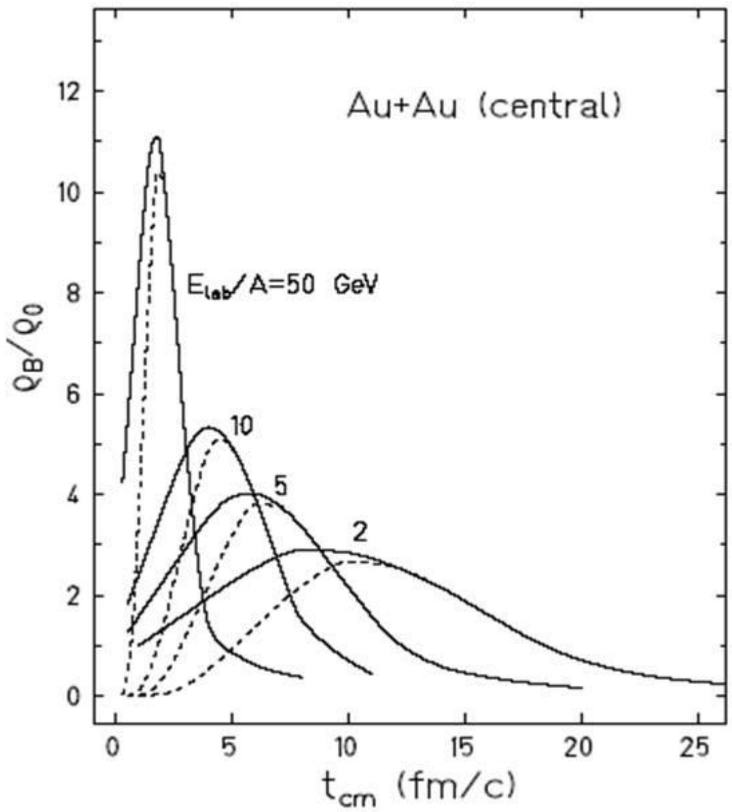
Motivation

Baryon density in HIC

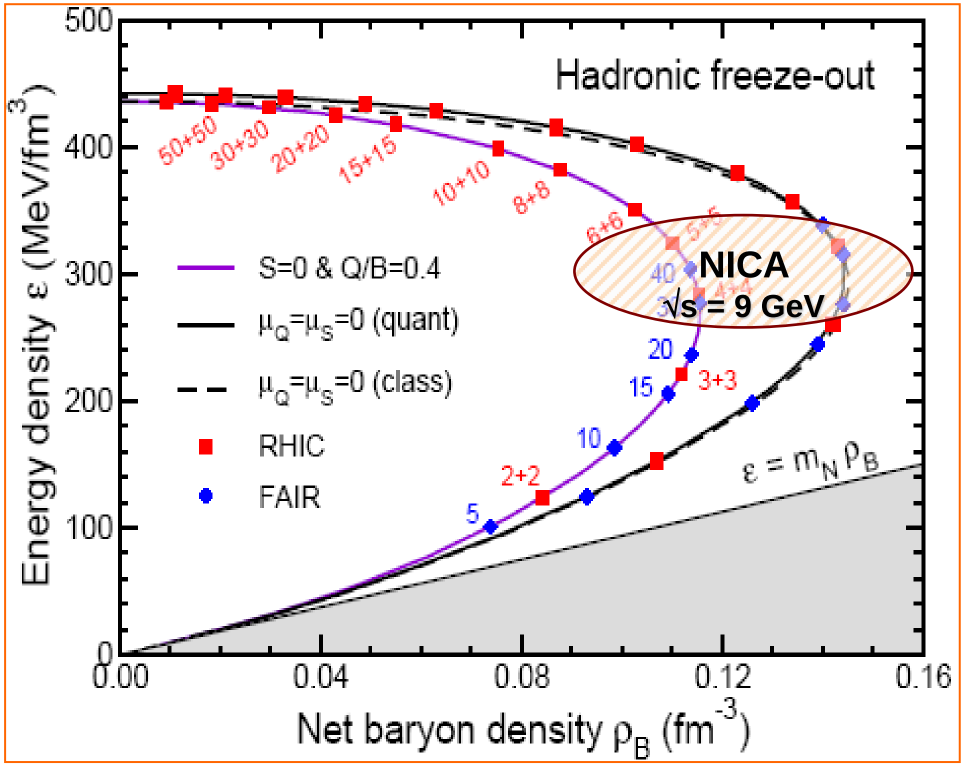
Baryon density evolution

At NICA energies $\rho/\rho_0 \sim 2 - 8$

QGSM model



Baryon density at freeze-out



Motivation

Fundamental questions in study of HIC

1. **How much of nuclear collision energy is converted into compression,**

or

How much the nucleus can be compressed?

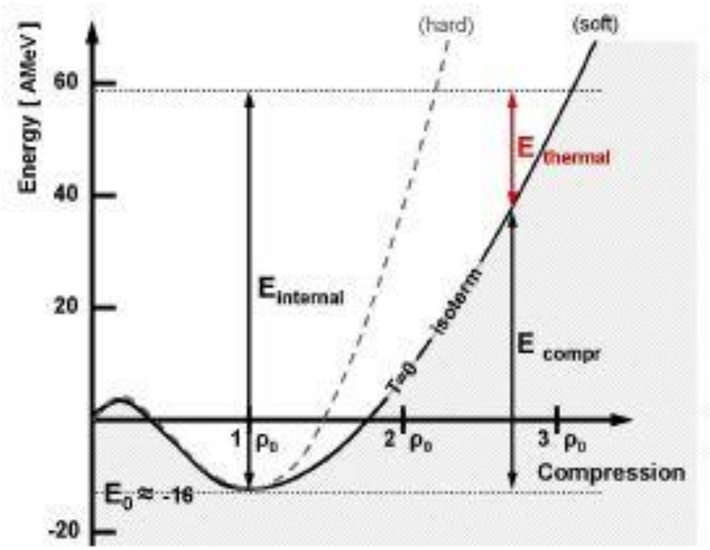
2. **What is the impact of this compression on hadron properties,**

or

How are the hadron properties modified in a dense nuclear matter?

Motivation

How much of nuclear collision energy is converted into compression?



Equation of State, EoS

$$E(\rho,T) = E_{therm}(\rho,T) + E_{compr}(\rho,T=0) + E_0\,(\rho_0) + E_{sym}\,(\rho,T)$$

$\chi = -(1/V)dV/dP$ – compessibility

$K = 1/\chi = (9/\rho)\,d(E_{compr}/A)/d\eta^2$ – incompessibility

$\eta = \rho/\rho_0$

EoS of a dense hadronic matter is still **unknown!**

How are the hadron properties modified in a dense nuclear matter?

Baryonic matter under compression

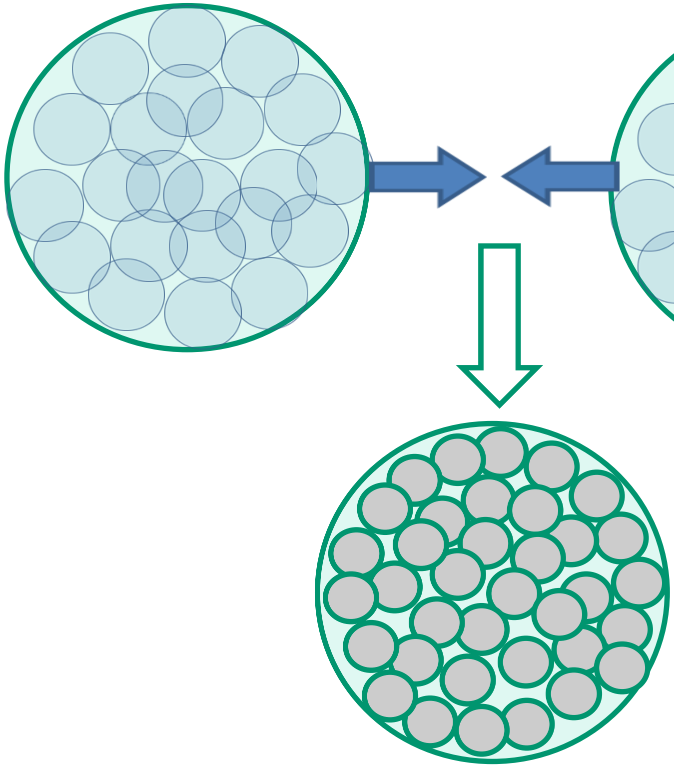
Heavy ion head-on collision

$V_A = V_N A$

$\rho = \rho_0$

$V_A = V_N A$

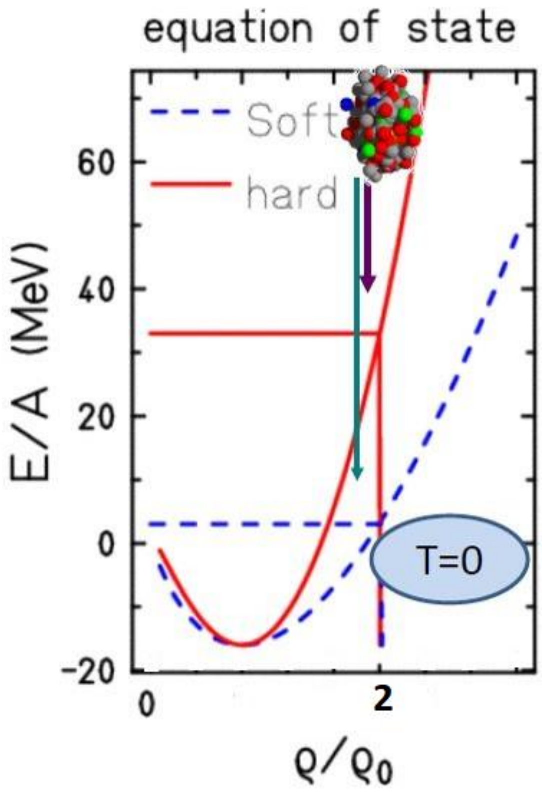
$\rho = \rho_0$



$\rho/\rho_0 = 2$

$V_A = V_{N*} 2A$

$r_{N*} = 0.79\, r_N$

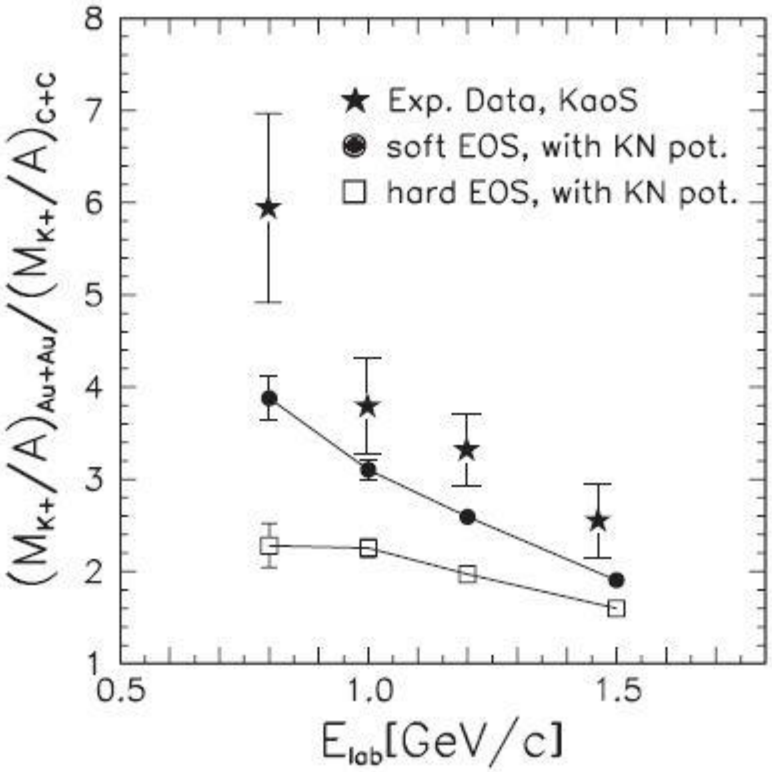


Enhanced yield of K^+ in subthreshold kaon production

KaoS at SIS

Transport models with NN-interactions

- **underestimate yield of K^+**
- **overestimate yield of K^-**



J. Phys. G: Nucl. Part. Phys. 27 (2001) 275

RQMD:

- **K^+ N repulsive potential**
- **K^- N attractive potential**
- **Momentum dependent Skyrme forces**
- **Compression parameter**
  - ✓ **soft: K ~ 200 MeV**
  - ✓ **hard: K ~ 380 MeV**

Conclusion:

Nuclear EoS is more ‘**soft**’ than ‘**stiff**’, i.e. nuclear matter is essentially compressible!

The Question:

How are baryons and mesons **modified** inside a **dense, compressed** hadronic matter?

Heavy Ion Collisions (HIC)
Observables

Particle yields (π, K, φ, Λ, Σ, Ξ, Ω)

Energy range: $\sqrt{s} < 11$ *GeV* *most interesting!*

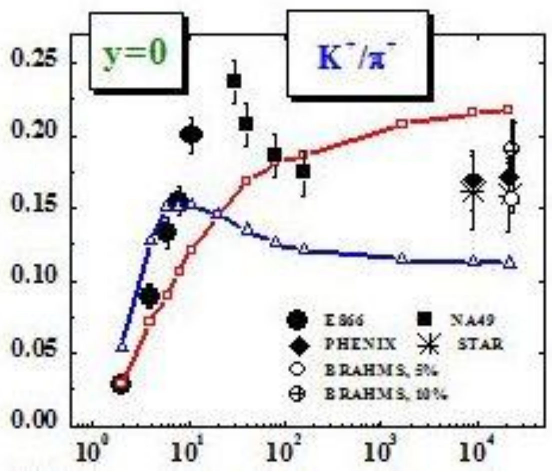
What Experiment tells us

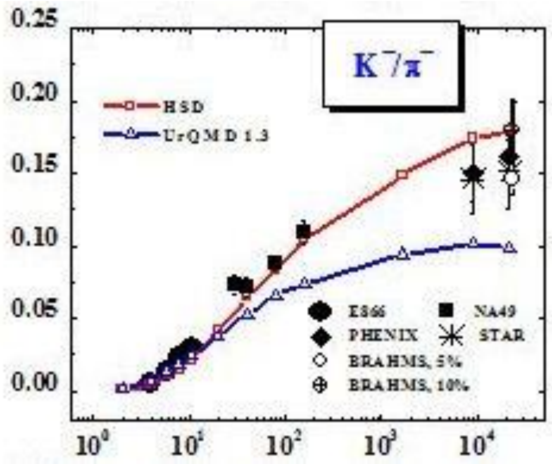
- **Enhanced (subthreshold) yield** of K^+, φ, Λ, Ξ^-, Ω
- **Horn-effect** – irregular behavior of K^+/π^+
- **Enhanced yield of dileptons**

Exp.: KaoS, HADES, AGS, NA49, STAR, PHENIX (RHIC)

Projects: FAIR/CBM, NICA/MPD, BM&N

Excitation functions of K^+/π^+ and K^-/π^- ratios





Phys.Rev. C69 (2004) 015202 PRL 92 (2004) 013302

- Clear evidence for “horn” structure in K^+/π^+ at ~30 A GeV !

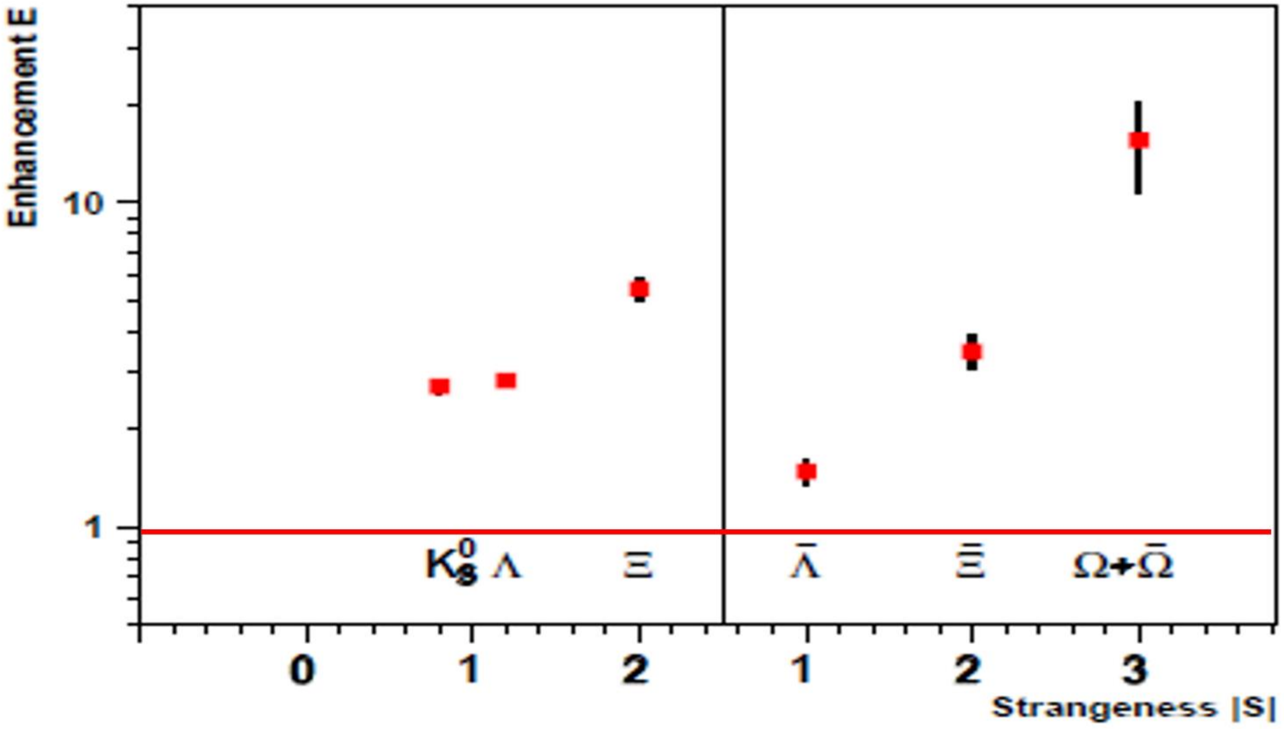
- Non-horn structure in K^-/π^-

- “horn” was not reproduced by transport models

Enhancement of strangeness

Hyperons

PbPb vs pBe SPS

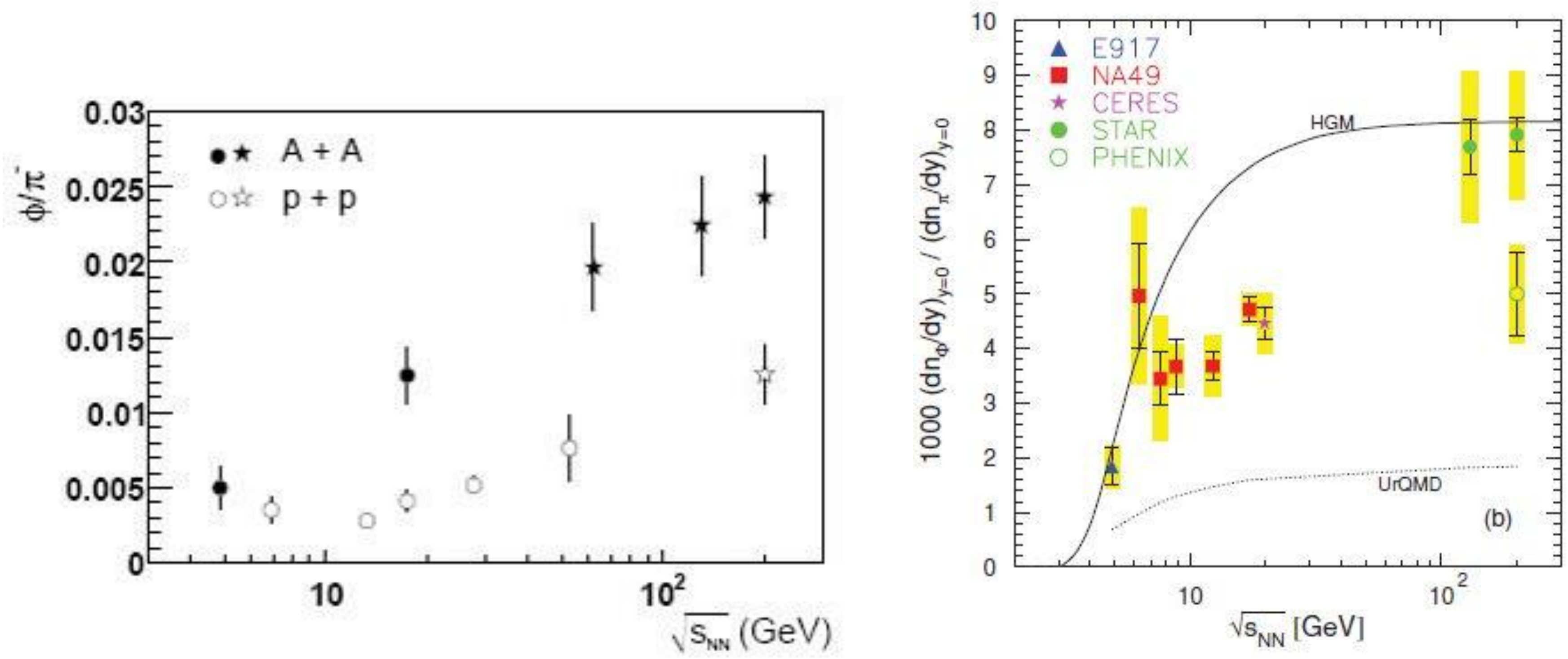


is not reproduced by transport models

Enhancement of strangeness

φ-mesons

φ/π^-



is not reproduced by transport models

Enhanced yield of dileptons in HIC

Dilepton channels in transport models

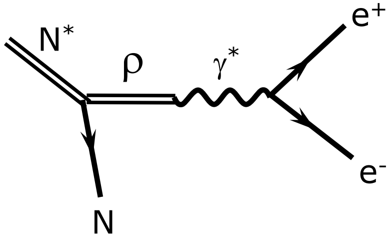
$$\mathbf{BB \to RX}$$

$$\mathbf{mB \to RX}$$

$$\mathbf{R \to e^+e^-X}$$

$$\mathbf{R \to mX,\ m \to e^+e^-X}$$

$$\mathbf{R \to R'X,\ R' \to e^+e^-X}$$



i	Dilepton channel	
1	Dalitz decay of π^0:	$\pi^0 \to \gamma e^+e^-$
2	Dalitz decay of η:	$\eta \to \gamma e^+e^-$ (or $\mu^+\mu^-$)
3	Dalitz decay of ω:	$\omega \to \pi^0 e^+e^-$
4	Dalitz decay of Δ:	$\Delta \to N e^+e^-$
5	direct decay of ω:	$\omega \to e^+e^-$
6	direct decay of ρ:	$\rho \to e^+e^-$
7	direct decay of ϕ:	$\phi \to e^+e^-$
8	direct decay of J/Ψ:	$J/\Psi \to e^+e^-$
9	direct decay of Ψ':	$\Psi' \to e^+e^-$
10	Dalitz decay of η':	$\eta' \to \gamma e^+e^-$
11	pn bremsstrahlung:	$pn \to pn e^+e^-$
12	$\pi^\pm N$ bremsstrahlung:	$\pi^\pm N \to \pi N e^+e^-$, where $N = p$ or n

Enhanced yield of dileptons in HIC

Dilepton channels in transport models

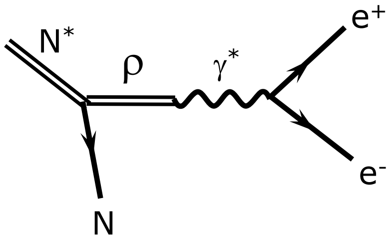
$$\mathbf{BB \to RX}$$

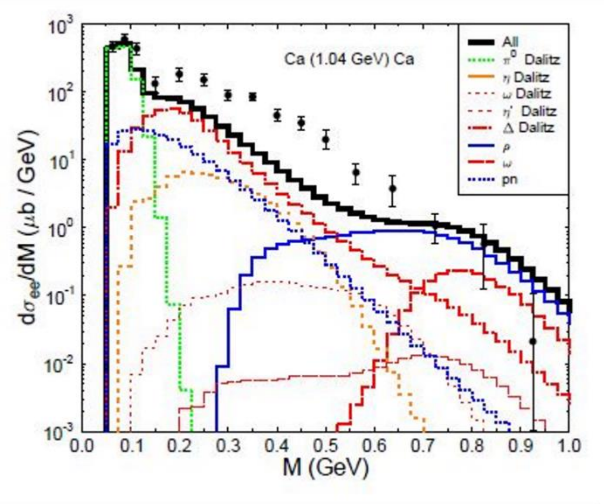
$$\mathbf{mB \to RX}$$

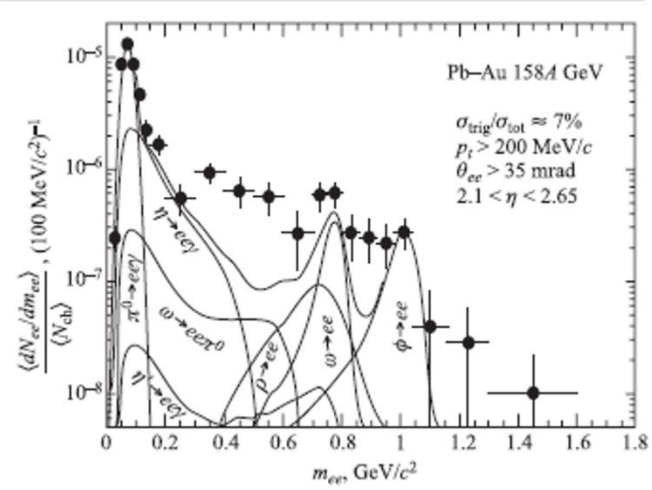
$$\mathbf{R \to e^+e^-X}$$

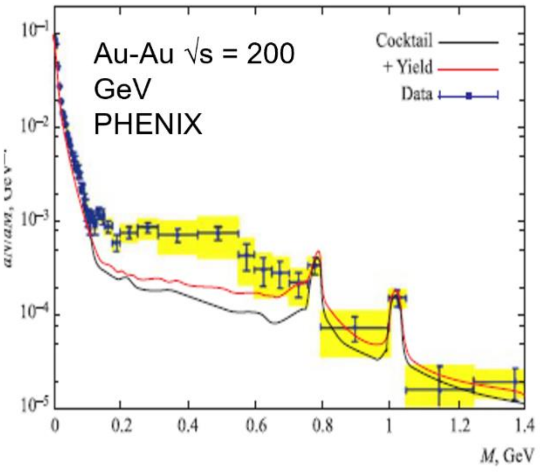
$$\mathbf{R \to mX,\ m \to e^+e^-X}$$

$$\mathbf{R \to R'X,\ R' \to e^+e^-X}$$









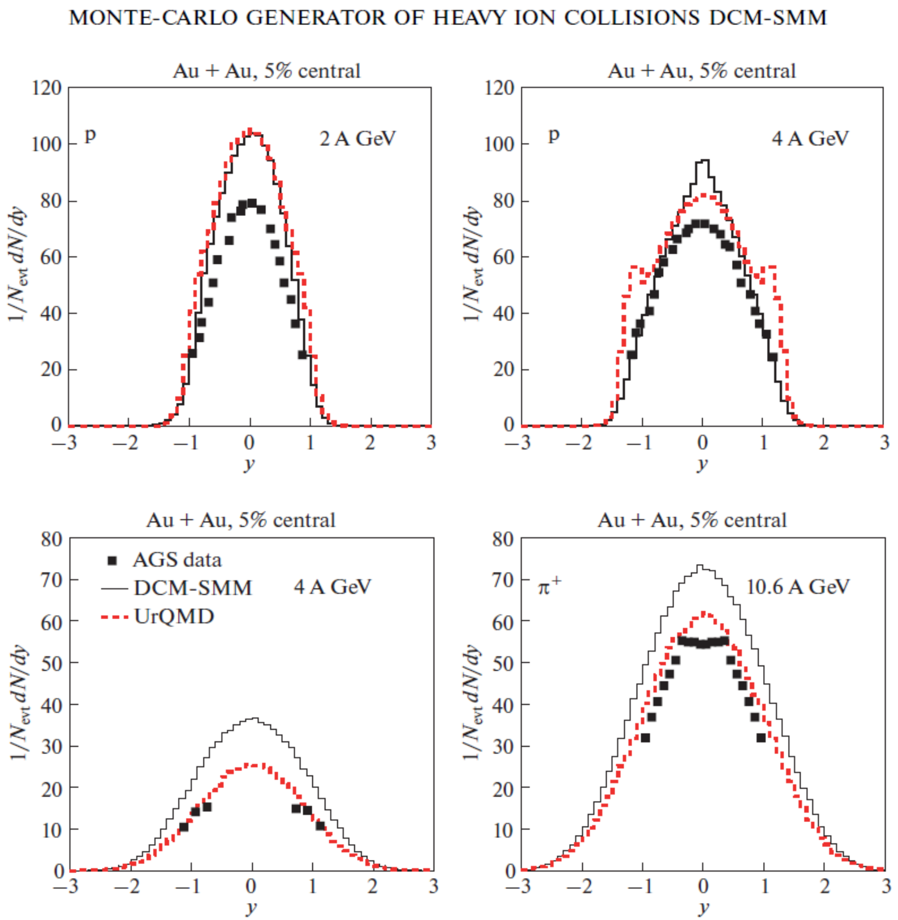
Interpretations:

ρ decay width-broadenning

P mass-dropping

Overestimation of pions yield in transport models for HIC

Partcle production in DCM-QGSM-SMM



Interpretations:

Overestimation of paticle multiplication in binary collisions in HIC

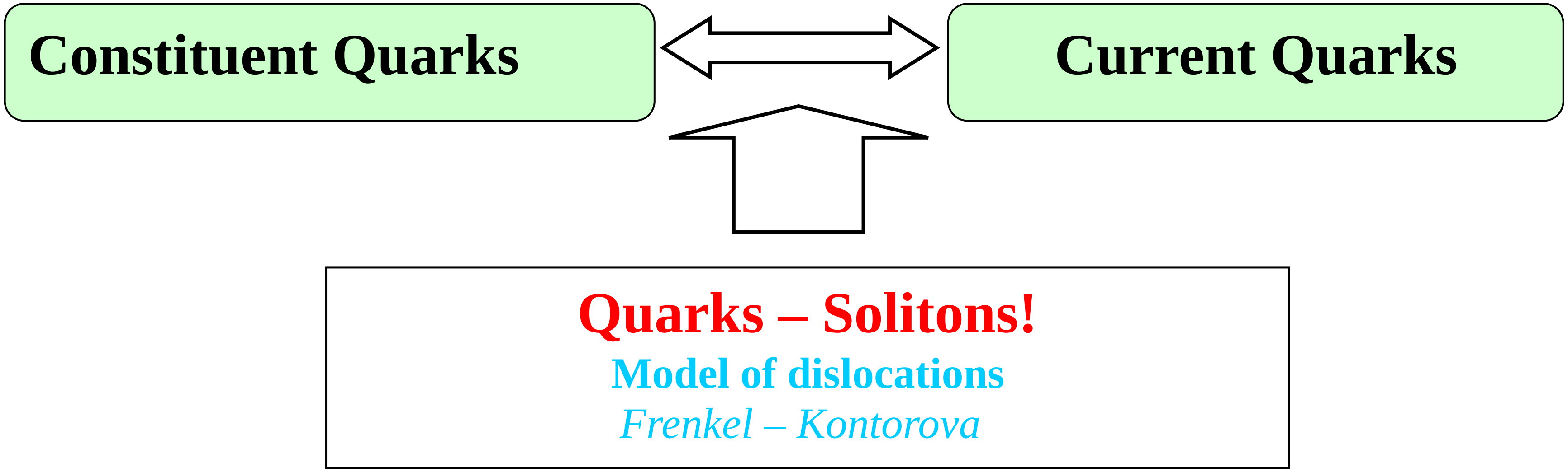
How are baryons and mesons **modified** inside a **dense, compressed** hadronic matter?

Model:

Strongly Correlated Quark Model

G. Musulmanbekov, PEPAN Lett., vol. 18, p.548, 2021

Strongly Correlated Quark Model



Constituent Quarks

Current Quarks

Quarks – Solitons!

Model of dislocations

Frenkel – Kontorova

Constituent Quarks – Topological Solitons

SCQM ≡ Breather Solution of Sine- Gordon equation

$$\partial_\mu \partial^\mu \phi(x,t) + \sin\phi(x,t) = 0$$

Breather – oscillating soliton-antisoliton pair:

$$\phi(x,t)_{s-as} = 4\tan^{-1}\left[\frac{\sinh\left(ut/\sqrt{1-u^2}\right)}{u\cosh\left(x/\sqrt{1-u^2}\right)}\right]$$

$$\varphi(x,t)_{s-as} = \frac{\partial\phi(x,t)_{s-as}}{\partial x}$$

is identical to our quark-antiquark system;

The Strongly Correlated Quark Model

Hamiltonian of the Quark – AntiQuark System

$$H = \frac{m_{\bar{q}}}{(1-\beta_{\bar{q}}^{\,2})^{1/2}} + \frac{m_q}{(1-\beta_q^{\,2})^{1/2}} + V_{\bar{q}q}(2x)$$

$m_{\bar{q}}$ m_q - are the current masses of quarks,

$\beta = \beta(x)$ – the velocity of the quark (antiquark),

$V_{\bar{q}q}$ - *is the quark–antiquark potential.*

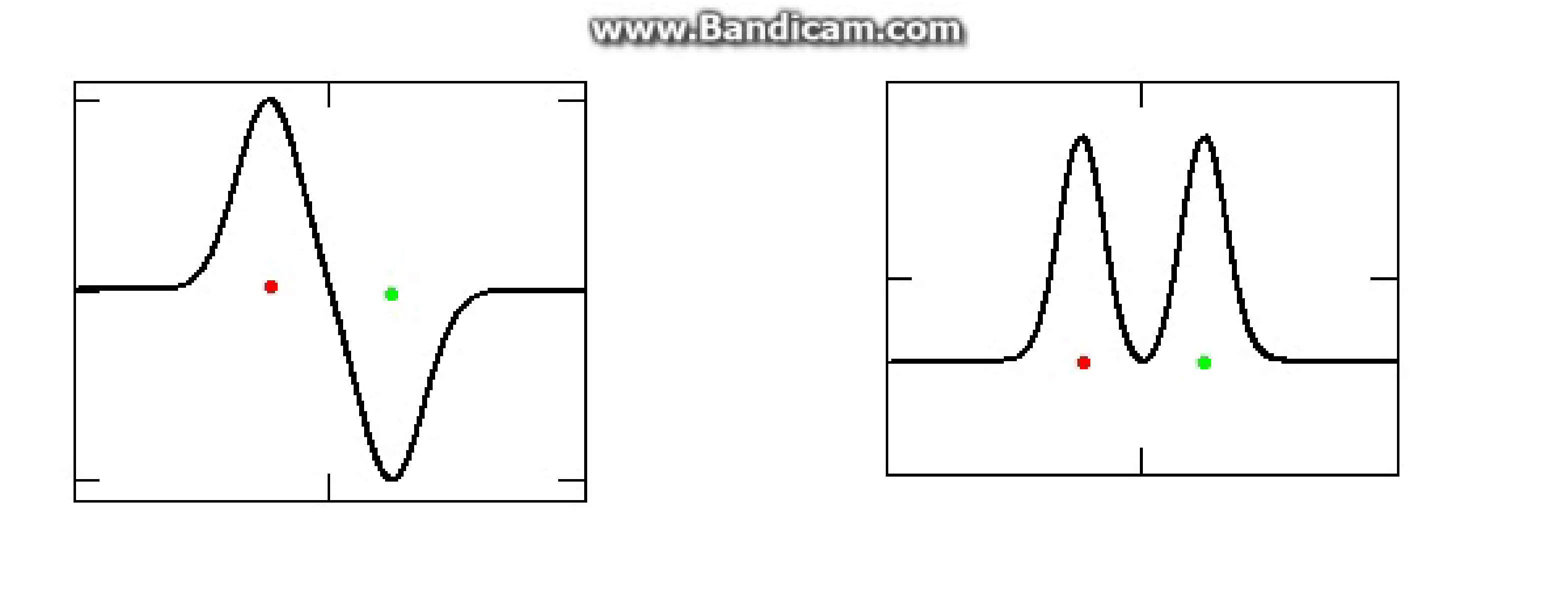
$$H = \left[\frac{m_{\bar{q}}}{(1-\beta_{\bar{q}}^{\,2})^{1/2}} + U(x)\right] + \left[\frac{m_q}{(1-\beta_q^{\,2})^{1/2}} + U(x)\right] = H_{\bar{q}} + H_q$$

$U(x) = \frac{1}{2} V_{\bar{q}q}(2x)$ is the potential energy of a single quark/antiquark.

H_q is Hamiltonian of a single quark/antiquark.

Breather – quark-antiquark pair
Meson

$\varphi(x,t)$ $\varepsilon(x,t)$



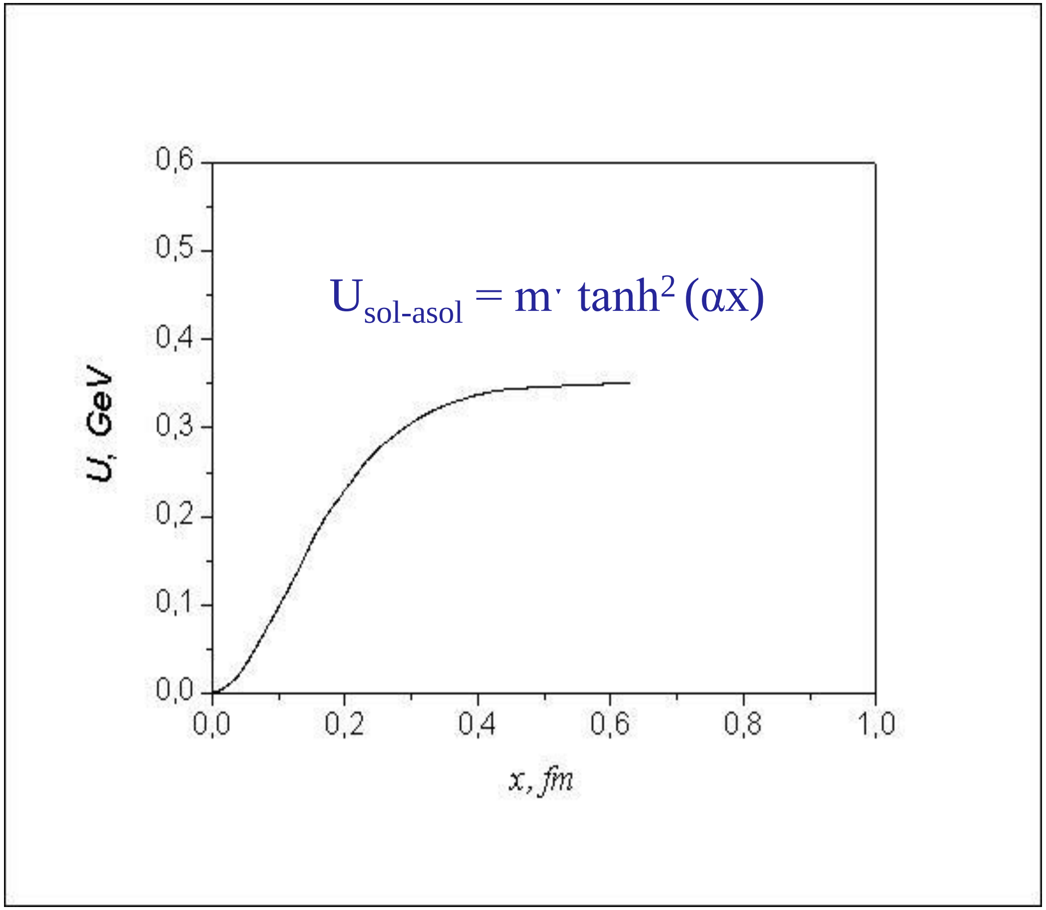
Breather demonstrates Chiral Symmetry **Breaking** and It’s **Restoration**

Quark Potential

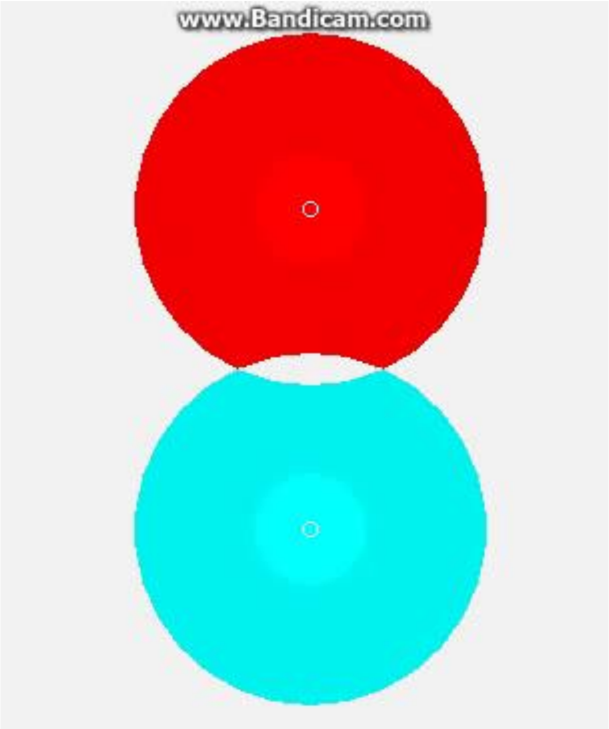
Potential in soliton-antisoliton system: $U_{sol\text{-}asol} = m\cdot\tanh^2(\alpha x)$

W. Troost, CERN Report, 1975;

P. Vinsarelly, Acta Phys. Aust. Suppl., 1976



quark-antiquark pair
Meson

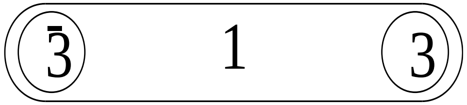


Generalization to the 3 – quark system (baryons)

$$SU(3)_{Color}$$

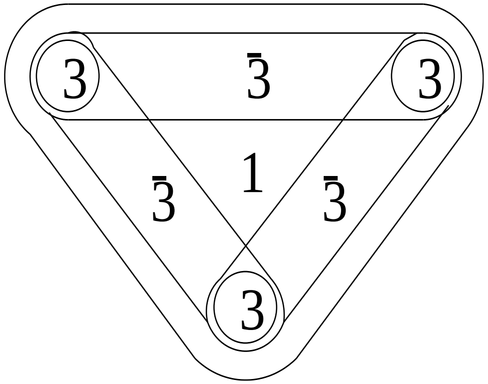
$$q \Rightarrow SU(3) \Leftrightarrow RGB \qquad \bar{q} \Rightarrow SU(\bar{3}) \Leftrightarrow CMY$$

$$\bar{q}q \quad \Rightarrow$$



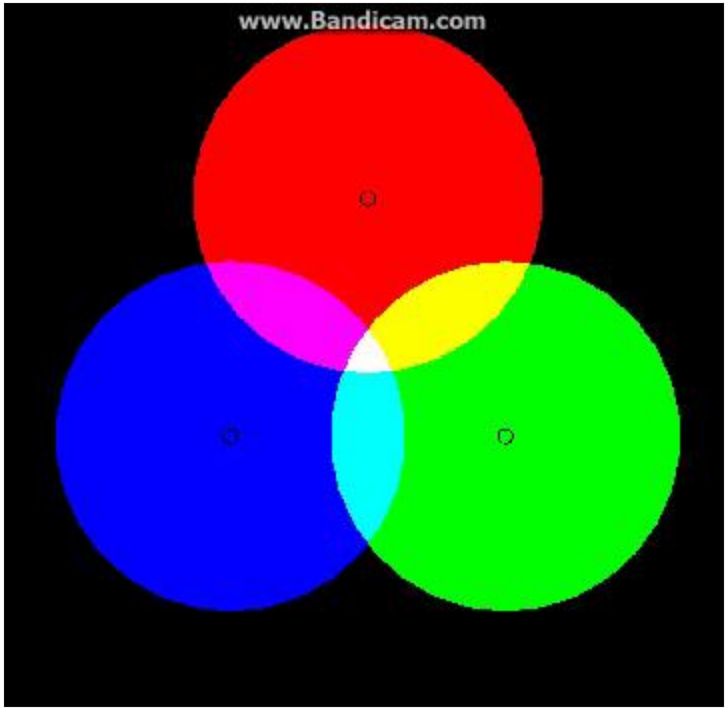
$$qq \rightarrow 3\times 3 = 6 \oplus \bar{3} \qquad \Rightarrow \qquad \bar{q} \rightarrow qq$$

$$qqq \Rightarrow$$



Nucleon - SU(3)$_{color}$ singlet

SU(3)$_{color}$ - RGB

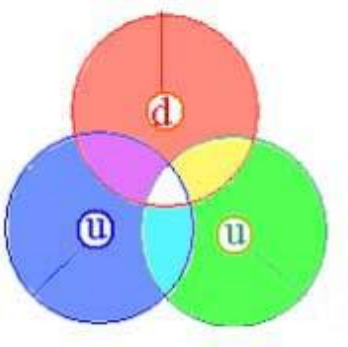


Interplay between constituent and current quark states

Chiral Symmetry Breaking $\Longleftrightarrow$ Restoration

t = 0

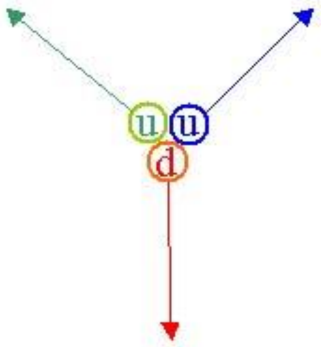
$x = x_{max}$



Constituent quaks

$t = T/4$

$x = 0$

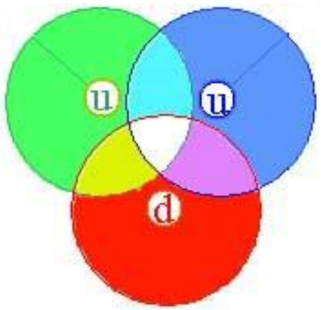


current quarks

Asymptotic freedom

$t = T/2$

$x = -x_{max}$

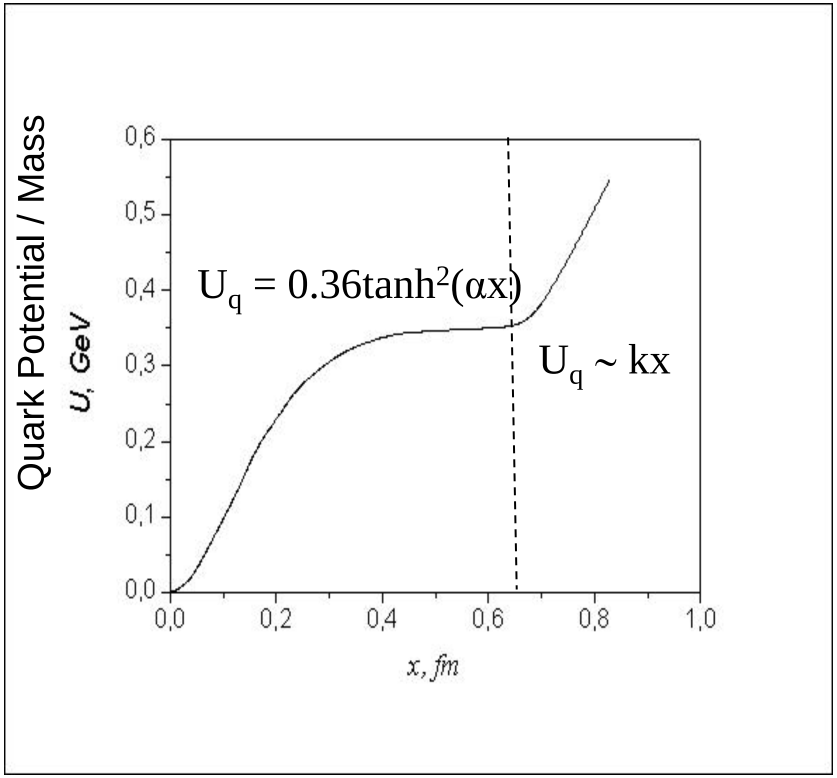


Constituent quarks

During the valence quarks oscillations:

$$|B\rangle = a_1|q_1q_2q_3\rangle + a_2|q_1q_2q_3\bar{q}q\rangle + a_3|q_1q_2q_3g\rangle + \dots$$

Quark Potential



$U_q = 0.36\tanh^2(\alpha x)$

$U_q \sim kx$

SCQM $\Longrightarrow$ The Local Gauge Invariance Principle

Destructive Interference of color fields ≡ Phase rotation of the quark w.f. in color space:

$$\psi(x)_{Color} \rightarrow e^{ig\theta(x)}\psi(x)$$

Phase rotation in color space $\Longrightarrow$ quark dressing (undressing) ≡ the gauge transformation

$$A^{\mu}(x) \rightarrow A^{\mu}(x) + \partial^{\mu}\theta(x) \qquad A = \{\varphi, \mathbf{A}\}$$

Therefore, during quark oscillation its

color charge

momentum

mass

are continuously varying functions of time.

Relation SCQM to QCD

Considering a single color quark oscillation we reduce interaction of color quarks via **non-Abelian** fields to its **E-M** analog (dropping color indexes) :

$$A_a^{\mu}(x) \to A^{\mu}(x)$$

$$F_a^{\mu\nu} = \partial^{\mu} A_a^{\nu} - \partial^{\nu} A_a^{\mu} - \lambda f^{abc} A_b^{\mu} A_c^{\nu} \to F_{ch}^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu}$$

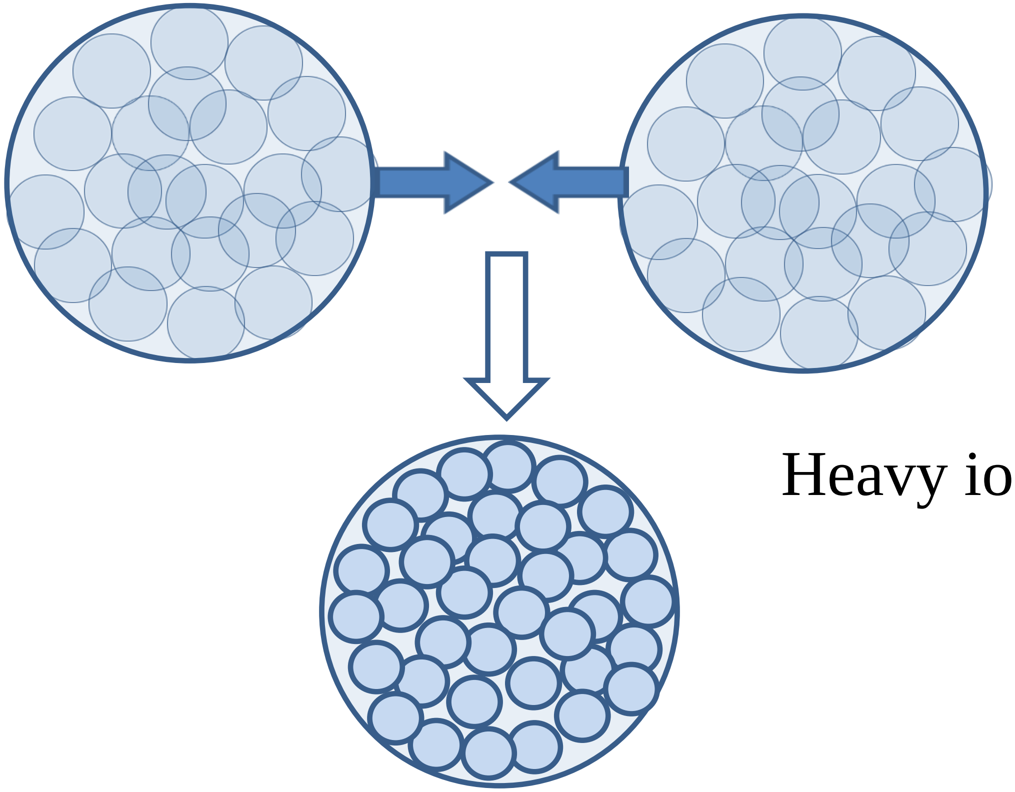
Summary on SCQM

- Constituent quarks are identical to topological solitons.
- Their masses are formed by quark-antiquark condensate (according to CSB)
- Quarks inside nucleons are strongly correlated;
- Hadronic matter distribution inside hadrons is fluctuating quantity;
- Nucleon is non-spherical (deformed) object.

Hadron modifications in a dense nuclear matter

Baryonic matter under compression

Heavy ion head-on collision



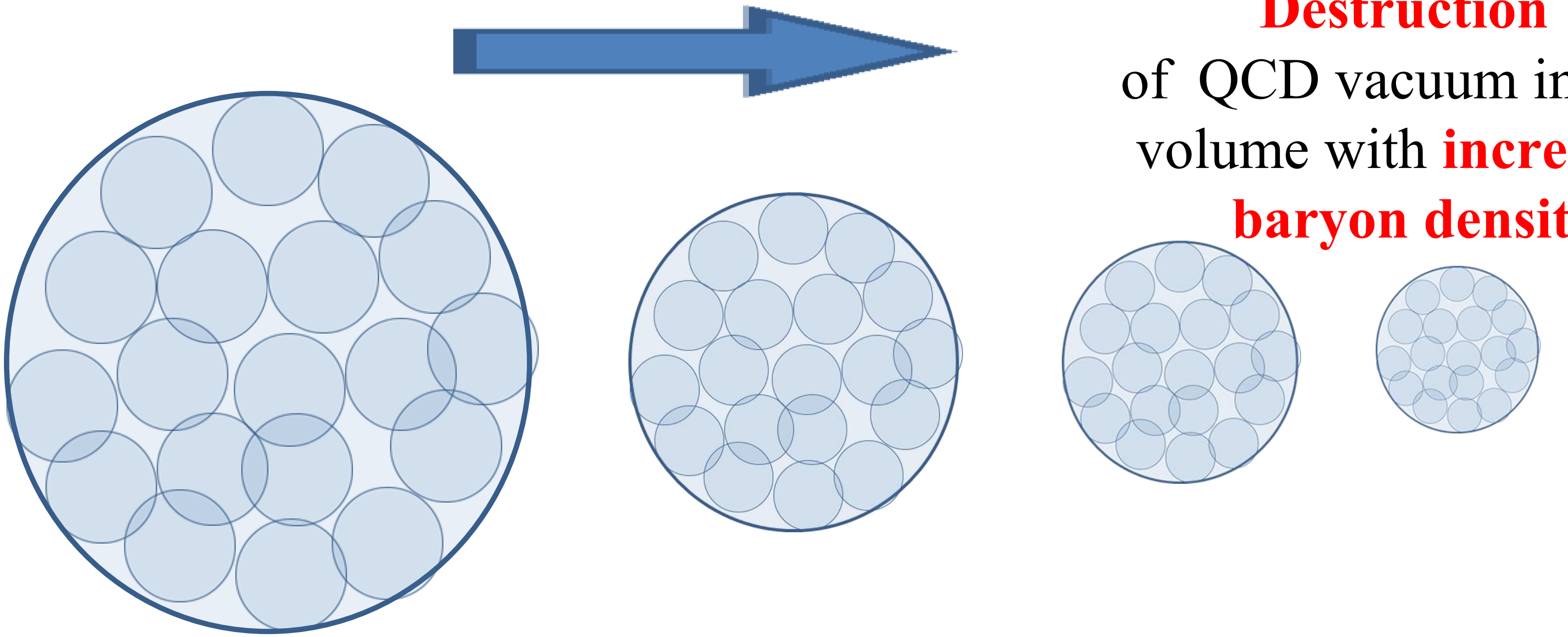
Destruction of
QCD vacuum
in intersection
volume

Heavy ion head-on collision

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression (neutron star/HIC)

Higher compression: ρ → $2\rho_0$, $3\rho_0$, …

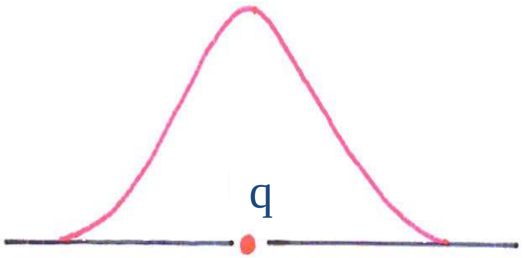


Destruction of QCD vacuum inside a volume with **increasing baryon density**

Hadron modifications in a dense nuclear matter

1. Constituent quark under compression

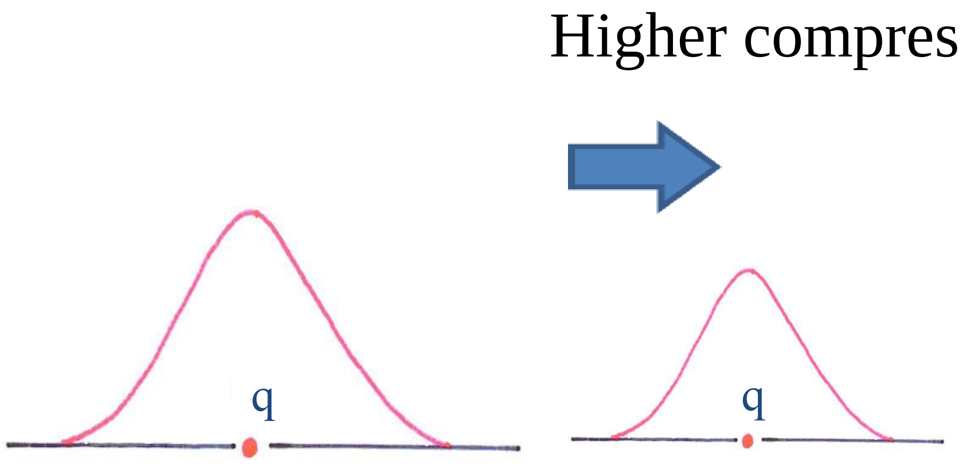
Higher compression



Quark condensate around valence quark, $\langle \psi\psi \rangle$

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

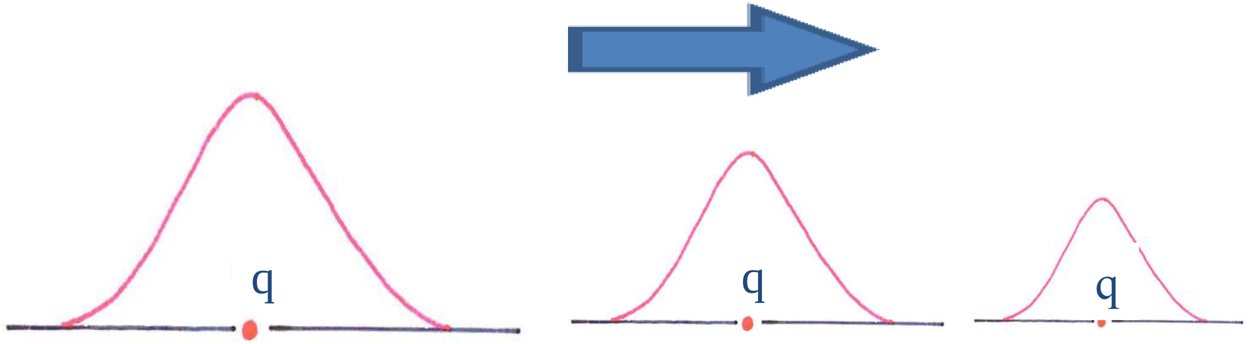


Higher compression

Quark condensate around valence quark, <ψψ>, is decreasing

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

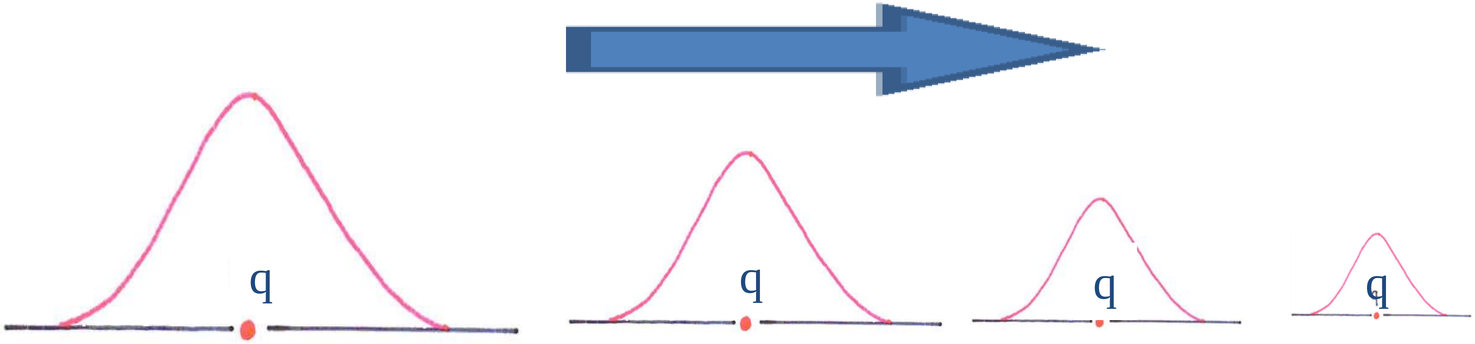


Higher compression

Quark condensate around valence quark, <ψψ>, is decreasing

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression



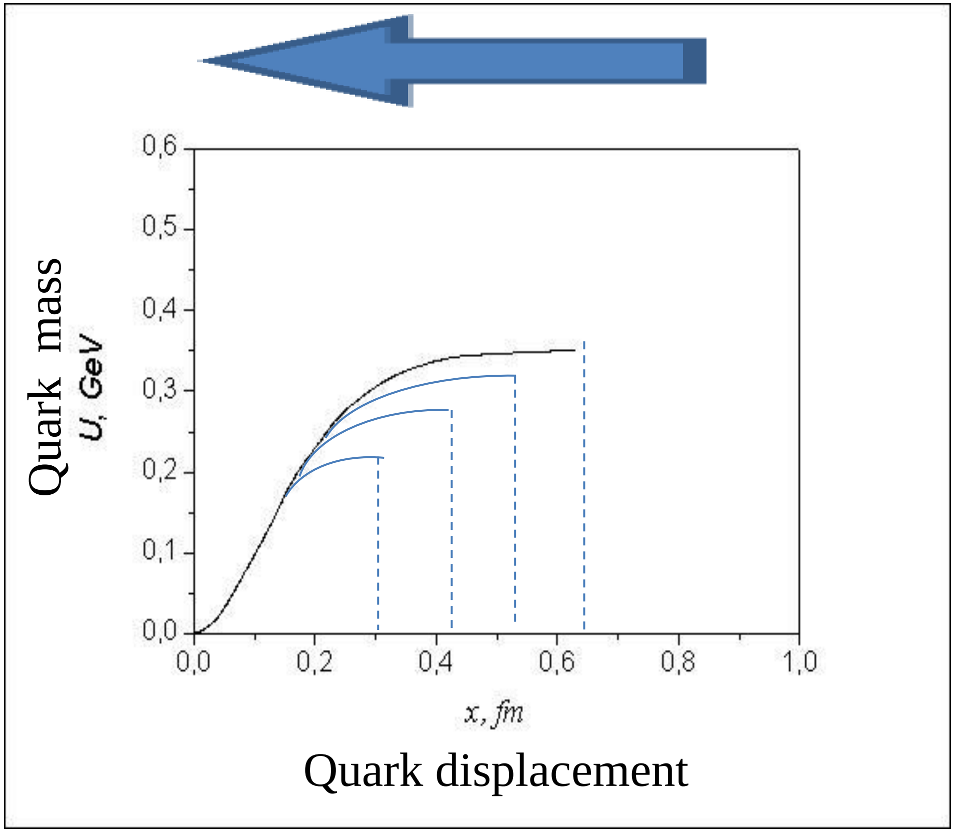
Higher compression

Quark condensate around valence quark, $\langle\psi\psi\rangle$, is decreasing

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression



Decreasing nucleon dimension

Decreasing quark displacement

Decreasing nucleon mass

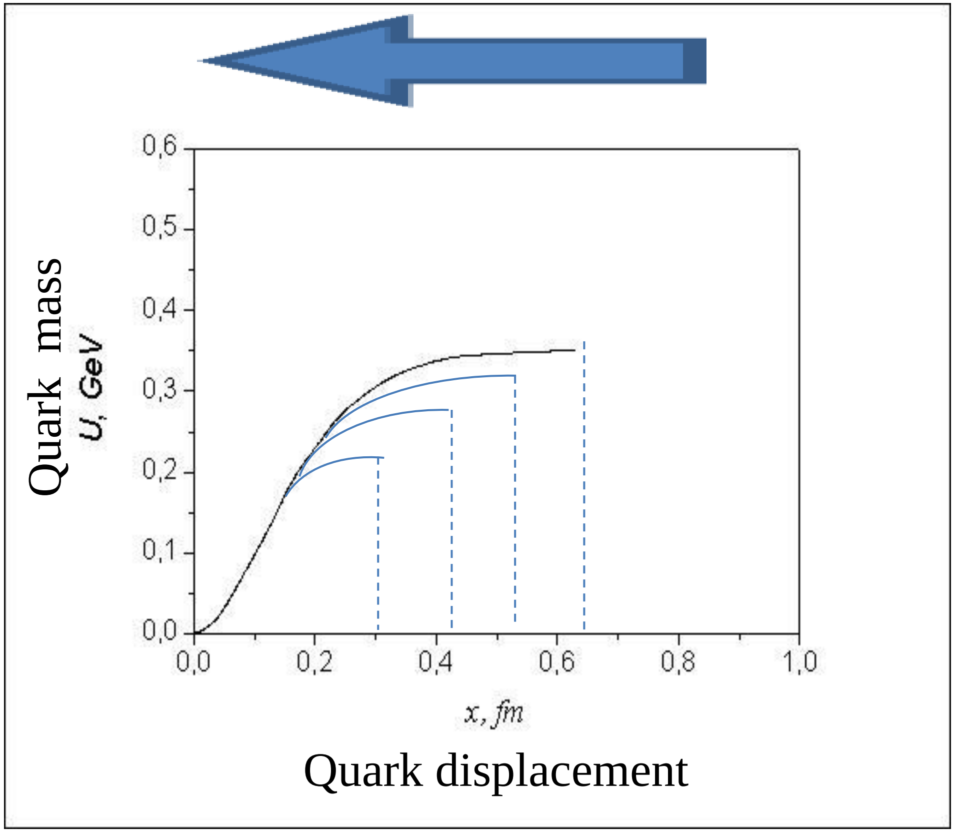
Collapse of nucleon

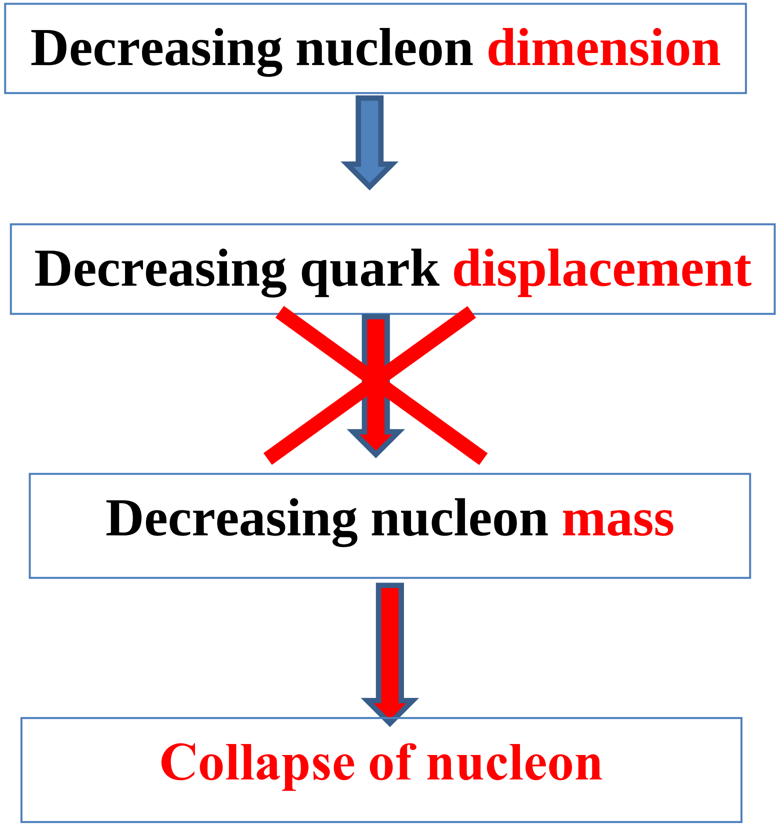
$$r \rightarrow 0.5R_A\,, \quad m_r \rightarrow 0.6m_R$$

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression





Decreasing nucleon dimension

Decreasing quark displacement

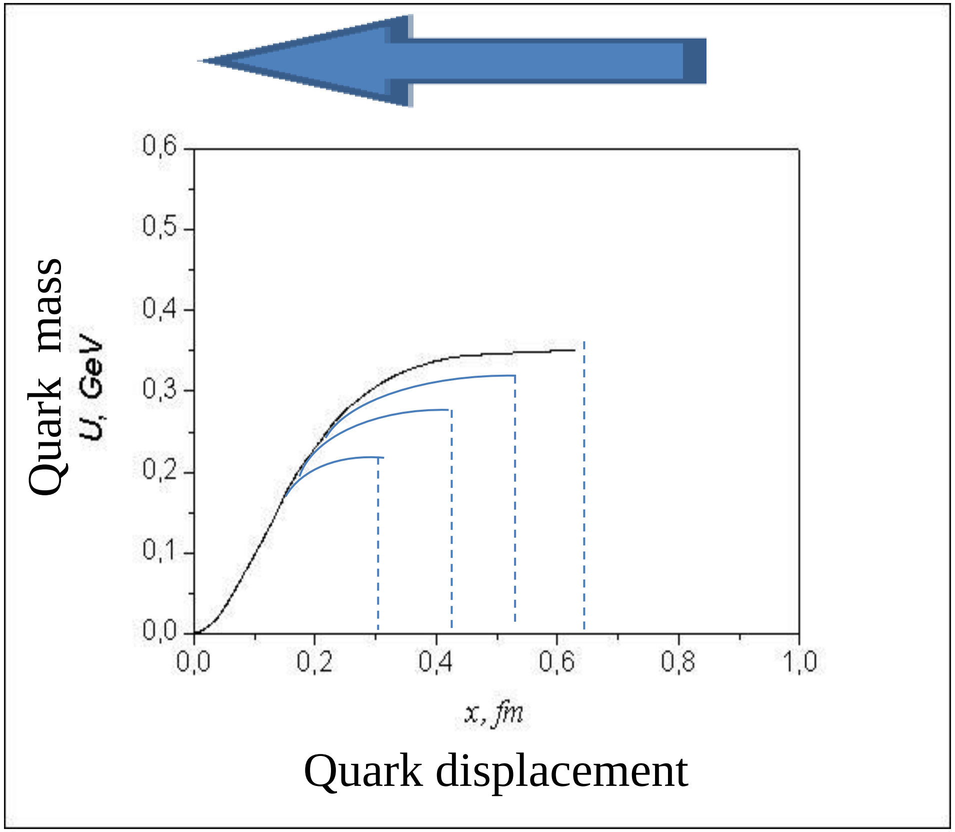
Decreasing nucleon mass

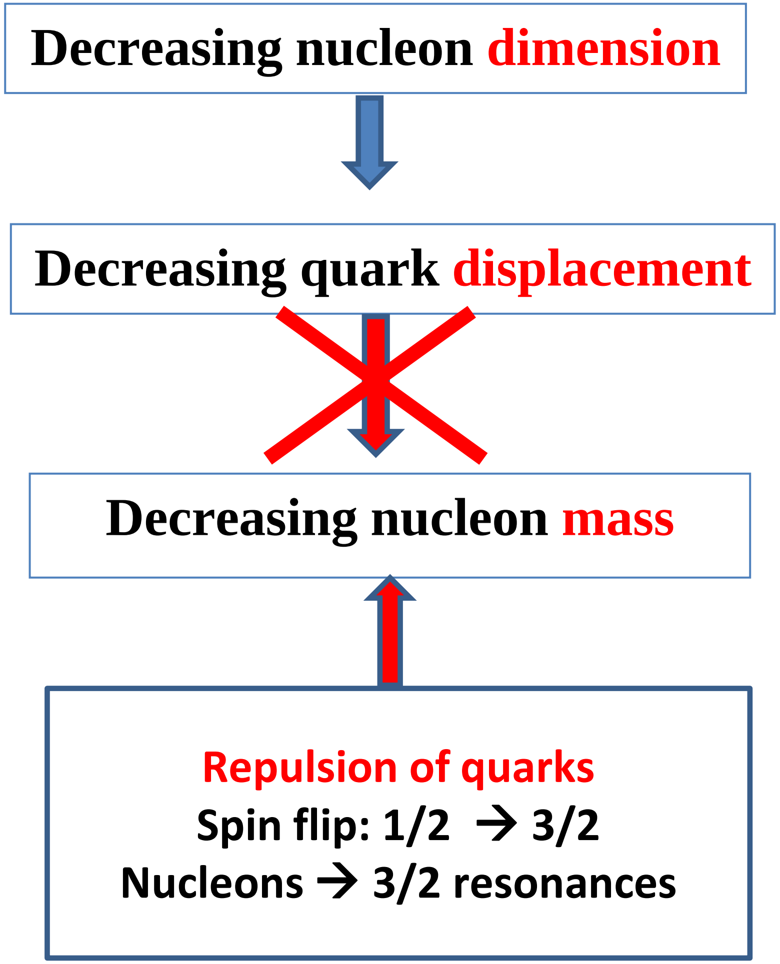
Collapse of nucleon

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression





Decreasing nucleon dimension

Decreasing quark displacement

Decreasing nucleon mass

Repulsion of quarks

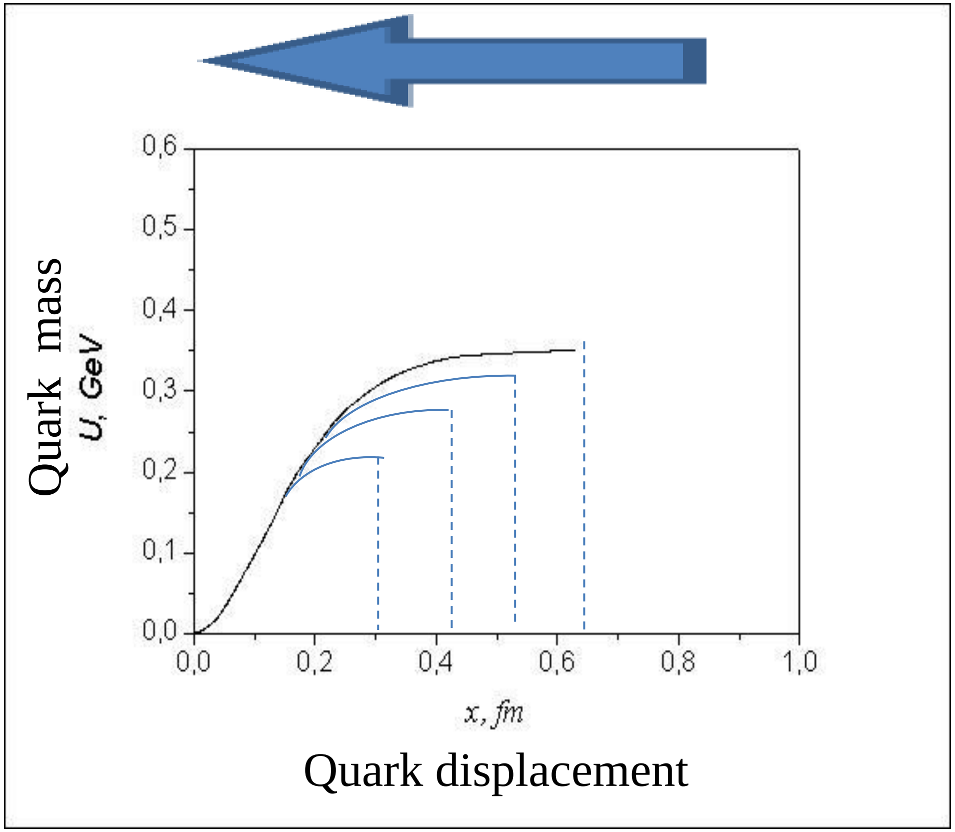
Spin flip: 1/2 → 3/2

Nucleons → 3/2 resonances

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression



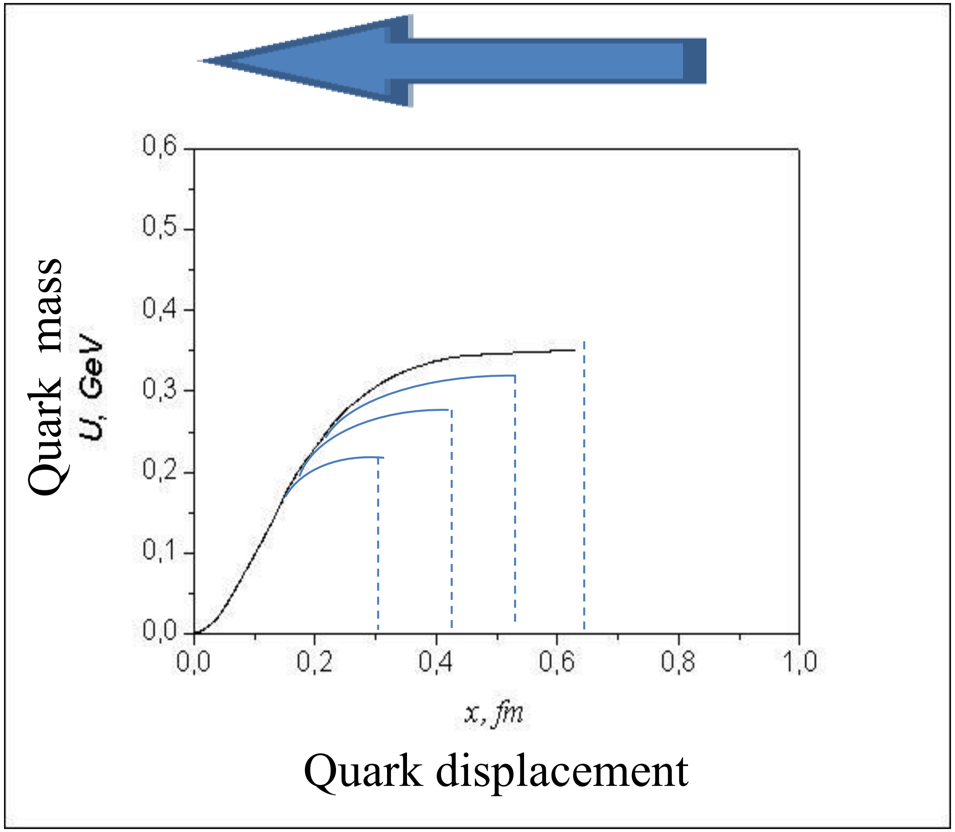
Baryon resonances are compressed up to the ‘hard-core’

without decreasing of masses

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression



Quark mass

Quark displacement

Baryonic matter under compression

High compression forces nucleons to convert into

- **Delta isobars**
- **Hyperons and their resonances**
- **higher mass resonances**

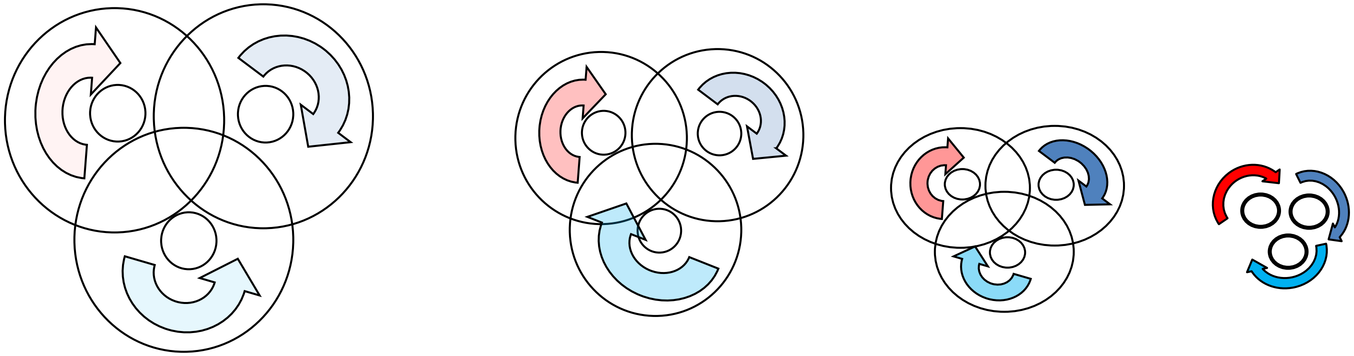
Scenario of nucleon modification

Higher compression

$n, p \rightarrow \Delta$

$u,d \rightarrow s, c, \ldots$

$n, p \rightarrow \Lambda, \Xi, \Omega, \ldots$



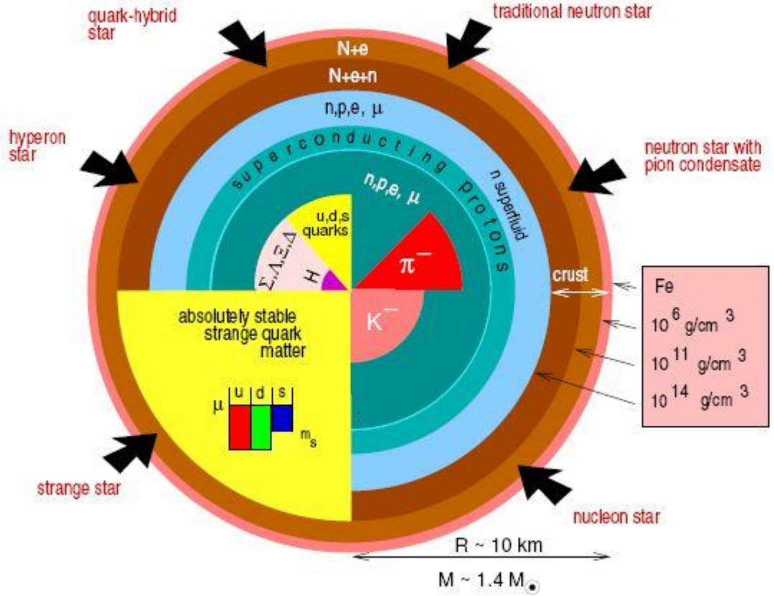
Spin flip 1/2 → 3/2

Hadronic gas → **Hadronic fluid**

Neutron star

Gravitational compression

NS core



compression

Neutrons?

Δ- isobars

Hyperons

…

Hadron modifications in a dense nuclear medium

1. Hadronic matter at high density and temperature

Particle production in a hot and dense fireball

- π - production is suppressed
- vector mesons: $\rho, \omega, \varphi, K^*, \ldots$ - are dominating
- ρ, ω – '**melting**': mass dropping and width-broadening;

  $m^* = m(1 - \alpha\rho/\rho_0)$
- Fireball 'cooling' → decay of resonances

Hadrons in a high dense and temperature medium

Model Scenario

1. **Baryons** transform to isobars and hyperons
2. **π–production** is suppressed
3. Particle generation inside hot and dense fireball is realized mainly via **vector mesons** $\boldsymbol{\rho, \omega, \varphi, K^*}$**, …**
4. $\boldsymbol{\rho, \omega}$ – '**melting**': mass dropping and width-broadening;

5. **Fireball cooling:**

Hadron-Resonance fluid → Hadron-Resonance Gas

Hadrons in a high dense and temperature medium

1. **Hadrons – topological solitons?**

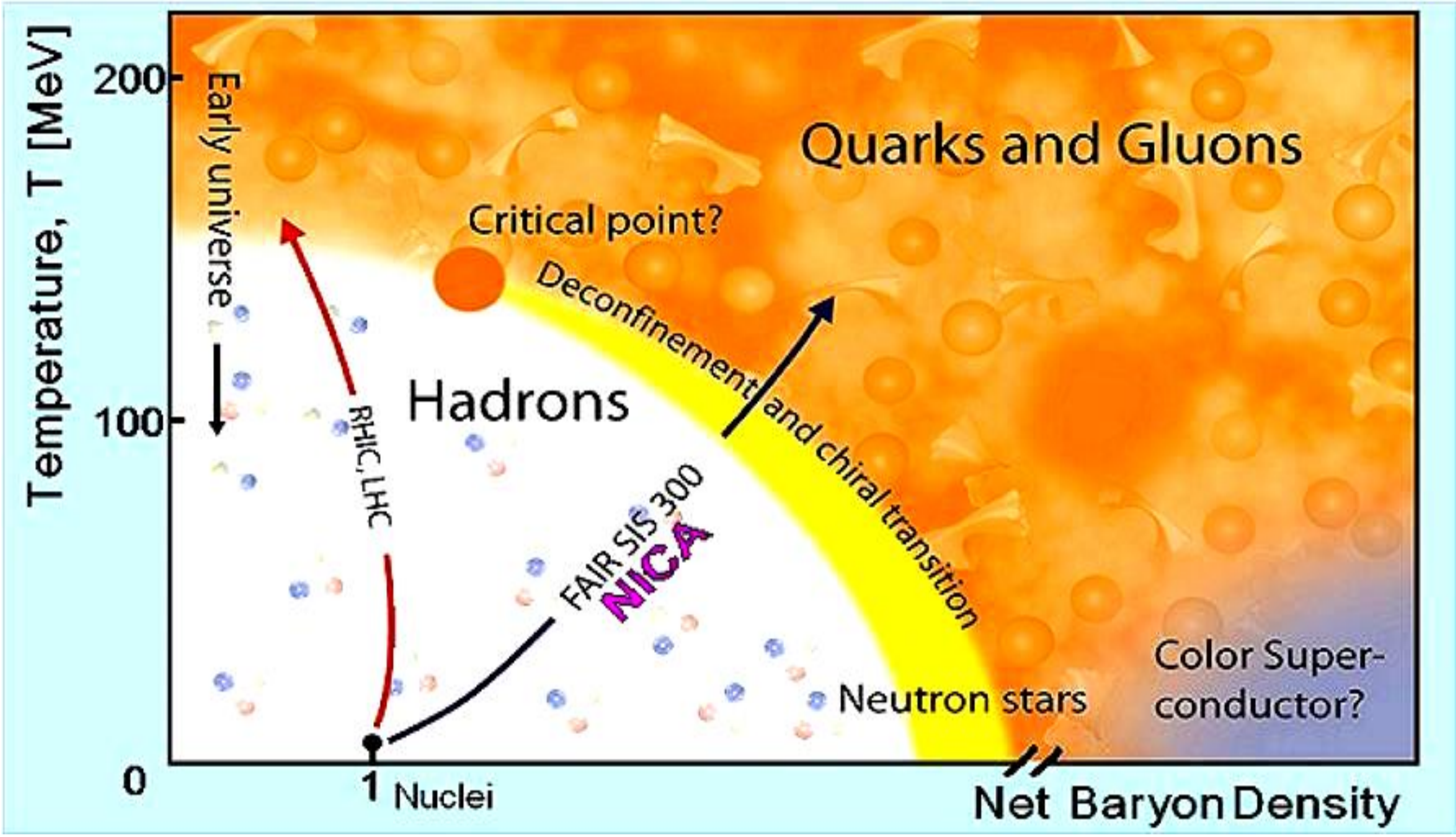
⇓

2. Conservation of topological charge

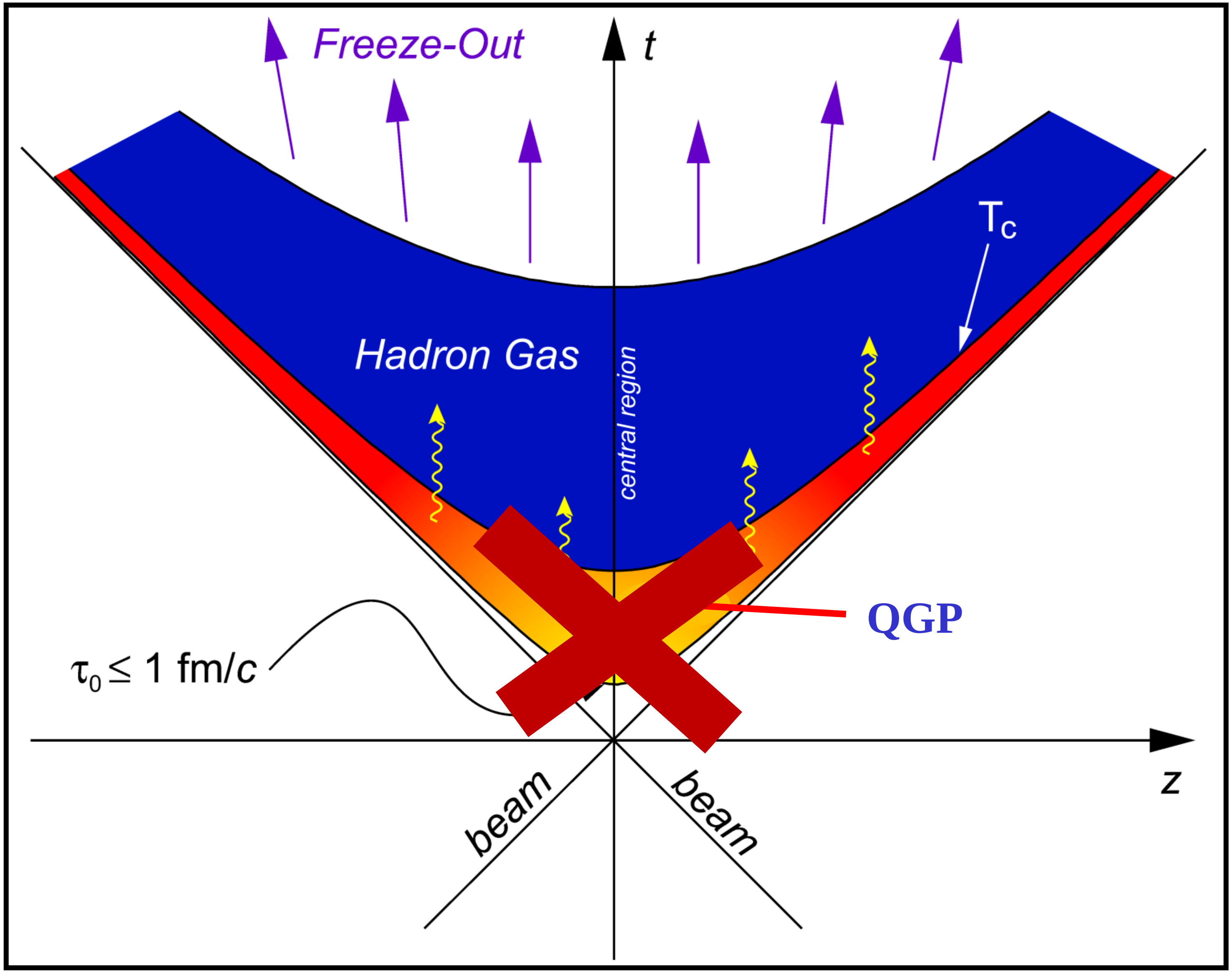
⇓

3. Deconfinement **is forbidden** → no room for QGP

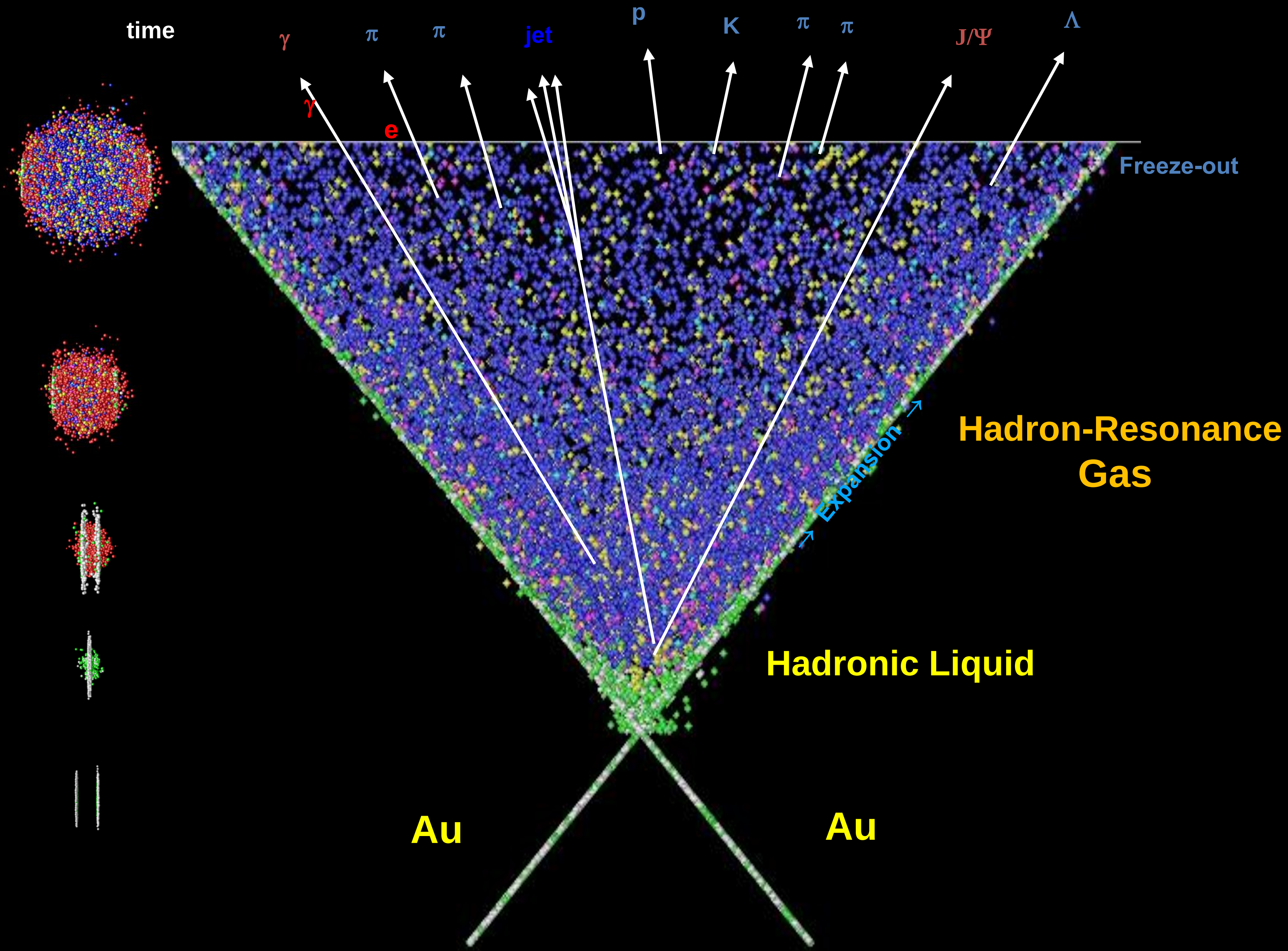
Does hadronic matter transit into QGP?



Space-time Evolution of HIC



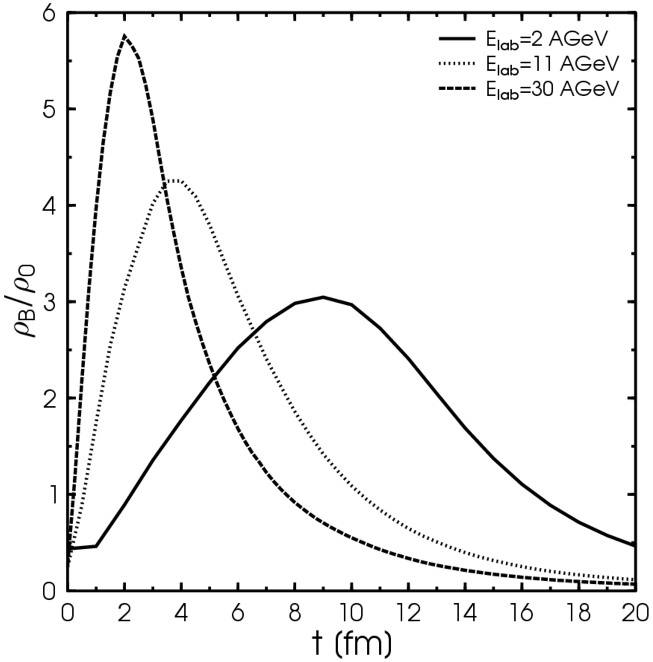
Space-time Evolution of HIC

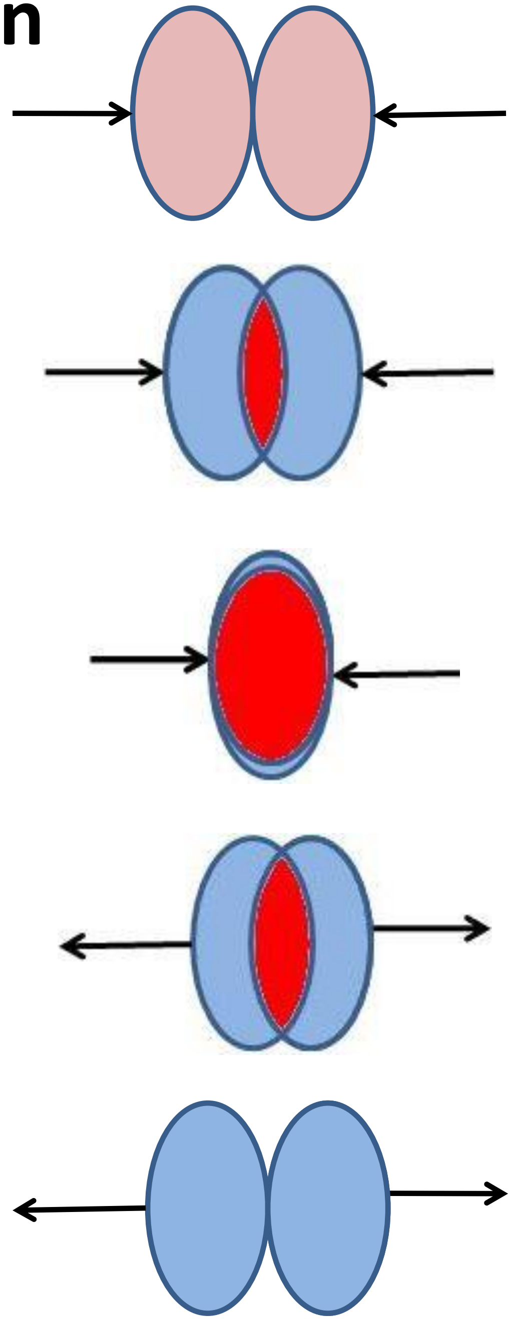


Thank you for your attention!

Requirements for nucleon → hyperon transition

Baryon density evolution
in central Au+Au/Pb+Pb





- In overlap region **nucleons are under compression** and forced to occupy much less space volume.

- **Overlap time in c.m.s**

$$\tau_o = [2R_A/(\gamma\beta)]\cdot b_{SP}$$

In **Bjorken scenario** $b_{SP} = 1$

- For central AuAu-collisions

'horn' location:

$$\tau_o \approx 3 - 4\ fm^{-1}$$

Above 'horn'

$$\tau_o \rightarrow 0$$

Initial stage of heavy ion collision

- Nucleons transformation to hyperons

$$P_{n\rightarrow hyp} \sim (\tau_o / \tau_{re})^c f(\rho/\rho_0)$$

τ_{ovelap} - overlap time

$\tau_{re} \sim 1\mathrm{fm}^{-1}$ - rearrangement time

c – adjustable parameter

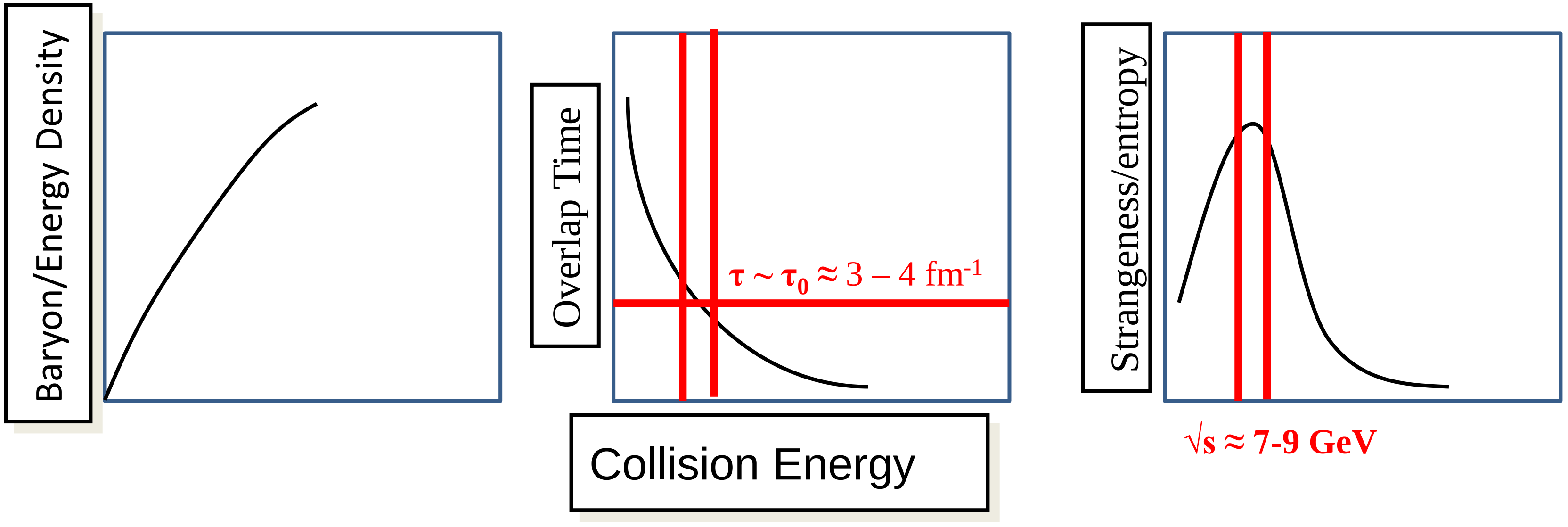
- Non-equilibrium kinetic mechanism

$$\sim 1/\lambda_{int} \sim \rho\sigma_{hN}$$

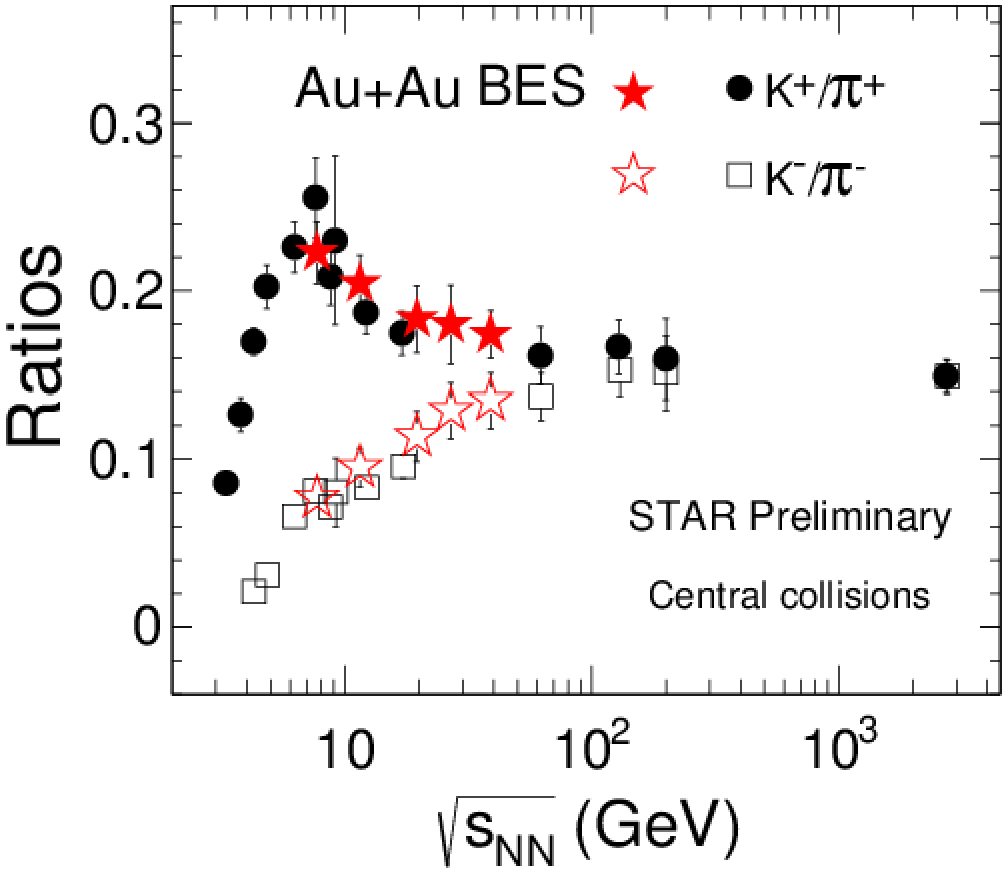
λ - mean free path

σ_{hB} - hadron-baryon cross section

Strangeness Enhancement Mechanism in HIC



But why 'horn' structure takes place for K^+/π^+ but not for K^-/π^- ?



Proton-to-hyperon transition channels

$$p = (uud), \quad u, d \to s$$

$$\left.\begin{aligned} p &\to \Sigma^{+}(\Sigma^{*+}) + K^{0}(K^{*0}) \\ &\to \Sigma^{0}(\Sigma^{*0}) + K^{+}(K^{*+}) \\ &\to \Lambda^{0} + K^{+}(K^{*+}) \end{aligned}\right\} S = -1$$

$$\left.\begin{aligned} &\to \Xi^{-}(\Xi^{*-}) + 2K^{+}(K^{*+}) \\ &\to \Xi^{0}(\Xi^{*0}) + K^{0}(K^{*0}) + K^{+}(K^{*+}) \end{aligned}\right\} S = -2$$

$$\left. \to \Omega^{-} + 2K^{+}(K^{*+}) + K^{0}(K^{*0}) \right\} S = -3$$

Only K^{+} and K^{0} are produced

No one K^{-} is created!

Neutron-to-hyperon transition channels

$$n(udd), \quad u,d \to s$$

$$\left.\begin{aligned} n(ddu) &\to \Sigma^- + K^+(K^{*+}) \\ &\to \Sigma^0 + K^0(K^{*0}) \\ &\to \Lambda^0 + K^0(K^{*0}) \end{aligned}\right\} S = -1$$

$$\left.\begin{aligned} &\to \Xi^0 + 2K^0(K^{*0}) \\ &\to \Xi^- + K^0(K^{*0}) + K^+(K^{*+}) \end{aligned}\right\} S = -2$$

$$\left.\to \Omega^- + 2K^0(K^{*0}) + K^+(K^{*+}) \quad \right\} S = -3$$

Only K^+ and K^0 are produced

No one K^- is created!

Stangeness Production in central HIC

AGS, NICA, CBM, low SPS: Kinetic + Transition mechanisms**:** nucleon transition to (multi)strange hyperons + kaons

$$1 \leq (\tau_o/\tau_{re})$$

top SPS, RHIC: Only kinetic mechanism

$$(\tau_o/\tau_{re}) \ll 1$$

$BB \rightarrow BYK^+$, $BB \rightarrow BBK^+K^-$,

$MB \rightarrow YK^+$, $MB \rightarrow BK^+K^-$

QCD – fundamental theory of strong interactions

- **Constituents of hadrons** – **quarks** of different flavors carrying spin, charge, color.
  - **flavors: u, d, s, c, b, t**
  - **spin: ½**
  - **charge: ⅓ , ⅔**
  - **color: SU(3)$_{\text{Color}}$** - *R, G, B*
- **Fields – gluons** $(R\bar{R}, G\bar{G}, B\bar{B}, RG, RB, GR, GB, BR, BG)$ perform interactions between quarks.
- **Nucleons –** 3–quark (**u/d**), color-singlet systems
- **Mesons –** quark-antiquark systems

Models of Hadrons

QCD is non-abelian theory → hard to derive the features of hadrons and nuclei from the first principles of QCD.

Hadronic processes with high Q^2

pQCD: $\alpha_S < 1$, $m_q \to 0$, chiral symmetry

Low energy hadron and nuclear physics

non-pQCD: $\alpha_S > 1$, $m_q \neq 0$, chiral symmetry breaking

- Low energy approx. of QCD
- QCD–inspired phenomenology
  - NR constituent quark models
  - Bag models
  - Chiral quark models
  - Soliton models

pQCD → non-pQCD

What is Chiral Symmetry and its Breaking?

- $m_q = 0$
- Chiral Symmetry

  $SU(2)_L \times SU(2)_R$ for $\psi_{L,R} = u, d$ – current quarks

- Chiral symmetry breaking ≡ quark or *chiral* condensate:

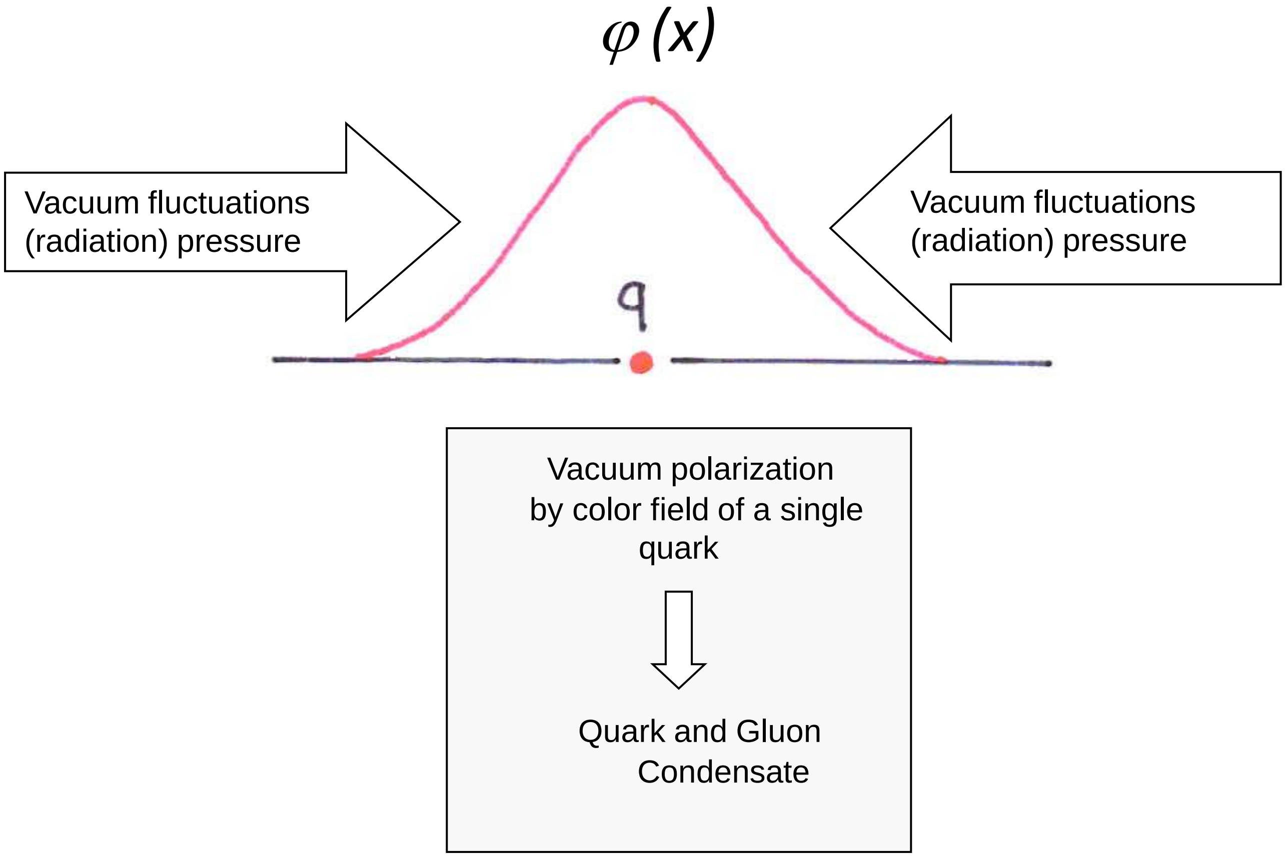
  $\langle \bar{\psi}\psi \rangle \simeq - (250\ \text{MeV})^3$, $\psi = u,d$

- As a consequence massless valence quarks (u, d) acquire dynamical masses which we call constituent quarks

  $M_C \approx 350 – 400\ \text{MeV}$

Strongly Correlated Quark Model

(SCQM)



Vacuum fluctuations (radiation) pressure

Vacuum fluctuations (radiation) pressure

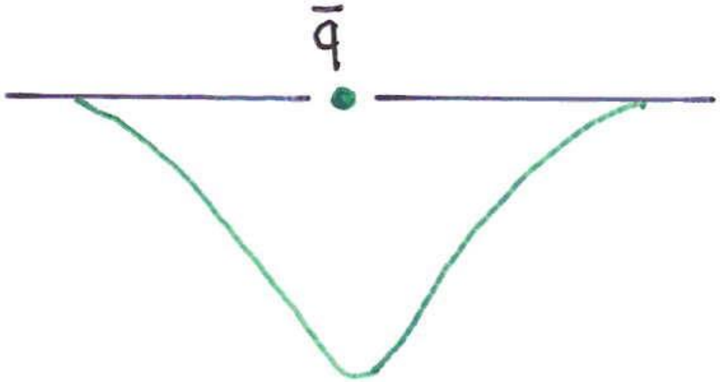
Vacuum polarization by color field of a single quark

Quark and Gluon Condensate

Strongly Correlated Quark Model

(SCQM)

$\varphi(x)$



Vacuum fluctuations
(radiation) pressure

Vacuum fluctuations
(radiation) pressure

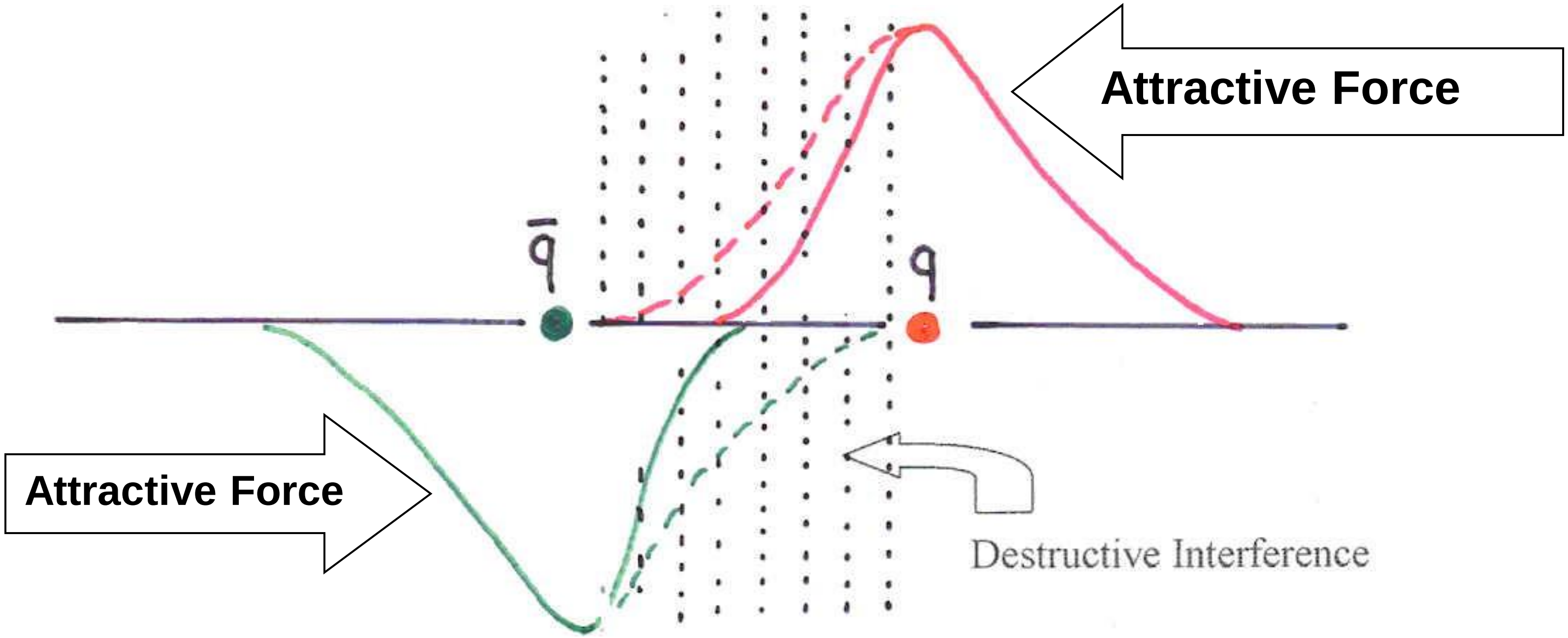
Vacuum polarization
by color field of a single
quark

⇩

Quark and Gluon
Condensate

Strongly Correlated Quark Model

(SCQM)



Inelastic Overlap Function

$$2Imf(s,b) = |f(s,b)|^2 + G_{in}(s,b),$$

$$\frac{1}{\pi}(d\sigma_{in}/db^2) = G_{in}(s,b).$$

$$\sigma_{in}(s) = \int G_{in}(s,\mathbf{b}) d^2\mathbf{b},$$

$$\sigma_{el}(s) = \int \left[1 - \sqrt{1 - G_{in}(s,\mathbf{b})}\right]^2 d^2\mathbf{b},$$

$$\sigma_{tot}(s) = 2\int \left[1 - \sqrt{1 - G_{in}(s,\mathbf{b})}\right] d^2\mathbf{b}.$$

$$d\sigma/dt = \pi[\int_0^\infty (1 - \sqrt{1 - G_{in}(s,b)}) J_0(b\sqrt{-t}) bdb]^2$$

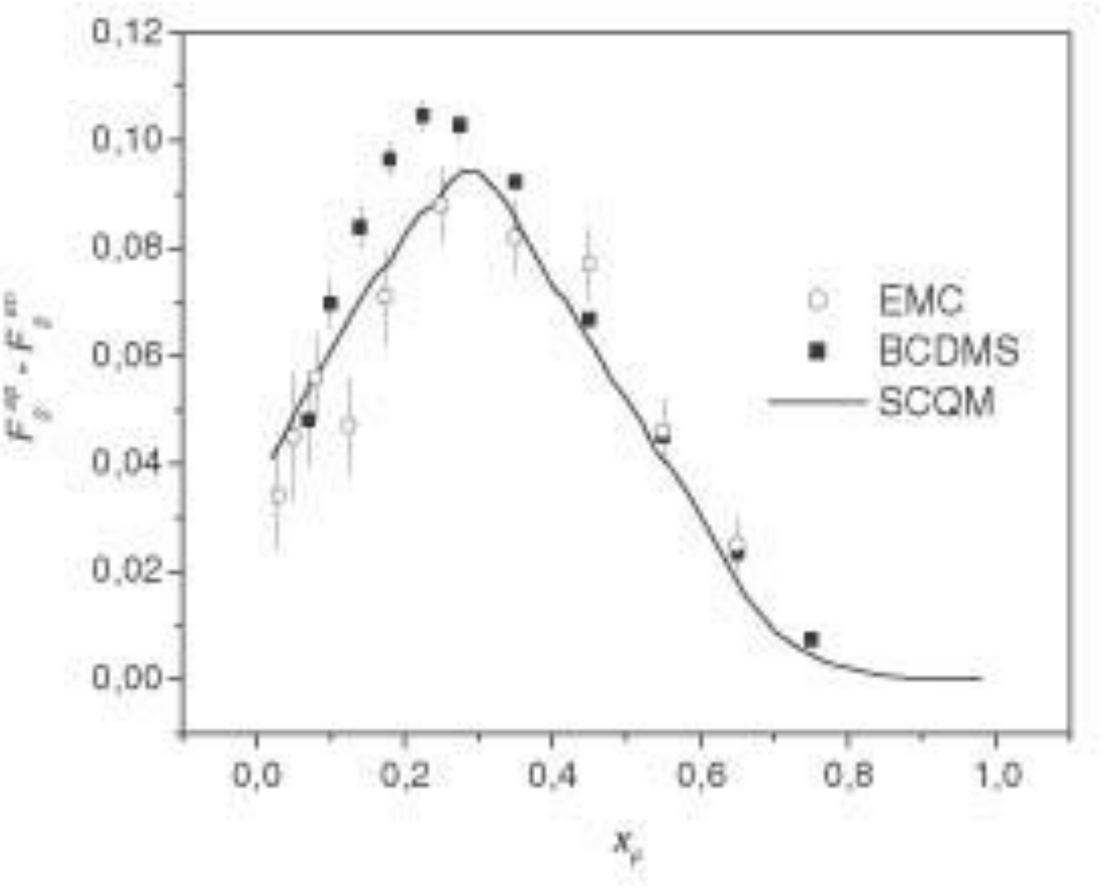
Monte-Carlo Simulation of Inelastic Events

$$\boldsymbol{M} = \sqrt{x_1 x_2 s} =$$

$$4M_{q_i}\gamma_{q_i}M_{p_j}\gamma_{p_j}\int \rho_{q_i}(\mathbf{r})\rho_{p_j}(\mathbf{r}-\mathbf{r}')\ d^3\mathbf{r} \geq m^2_{\pi_\perp},$$

+ energy – momentum conservation

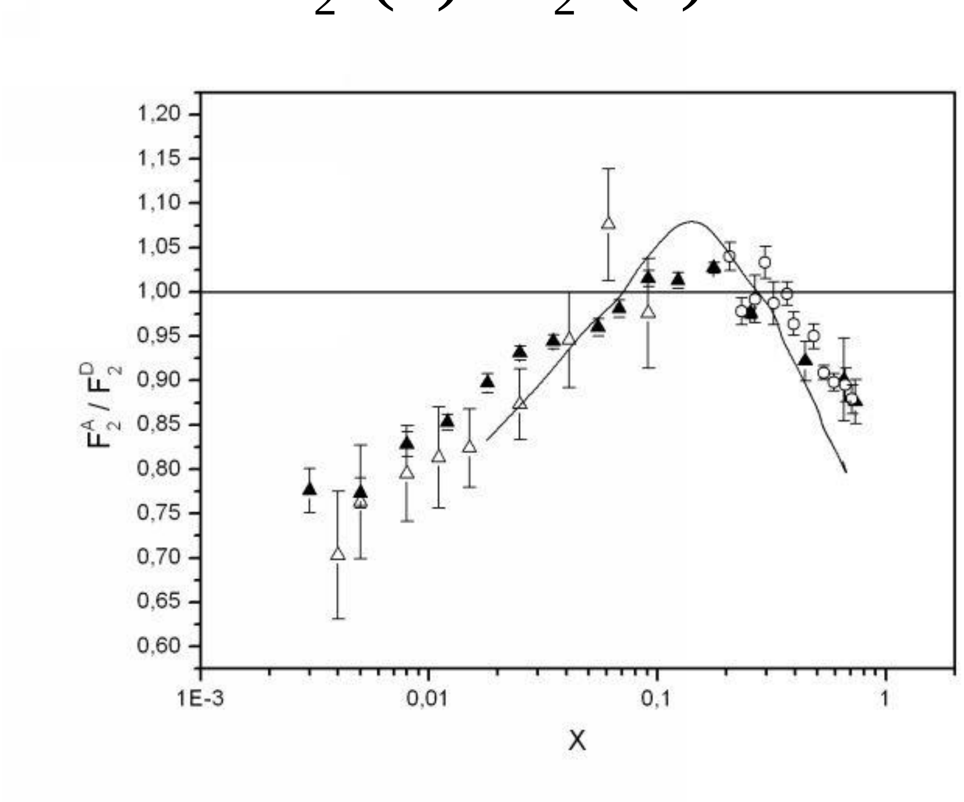
Structure Function of Valence Quarks in Proton



Comparison with experiments

1. EMC – effect

$$F_2^A(x)/F_2^D(x)$$



Spin in SCQM

Conjecture: spin of constituent quark is entirely analogous to the angular momentum carried by classical circularly polarized wave:

$$\mathbf{J_Q} = \mathbf{J_g} = \int_a^\infty d^3r\left[\mathbf{r}\times(\mathbf{E}\ \ \times\mathbf{B}\ \ )\right]$$

Classical analog of electron spin – *F.Belinfante 1939; R. Feynman 1964; H.Ohanian 1986; J. Higbie 1988.*

Electron surrounded by proper **E** and **B** fields creates circulating flow of energy:

$$\mathbf{S}=\varepsilon_0 c^2\mathbf{E}\times\mathbf{B}$$

Total angular momentum created by this Pointing's vector

$$\mathbf{s} = \mathbf{L} = (\ldots)\int_a^\infty d^3r\left[\mathbf{r}\times(\mathbf{E}\ \ \times\mathbf{B})\right]$$

is associated with the entire spin angular momentum of the electron.

Spin in SCQM

1. Now we accept that

$$A^{\mu} = \{\varphi, \mathbf{A}\}$$

and intersecting $\mathbf{E_{ch}}$ and $\mathbf{B_{ch}}$ create around VQ color analog of Pointing's vector (circulating flow of energy)

$$\mathbf{S} = \boldsymbol{\varepsilon_0} \mathbf{c^2} \mathbf{E_{ch}} \times \mathbf{B_{ch}}.$$

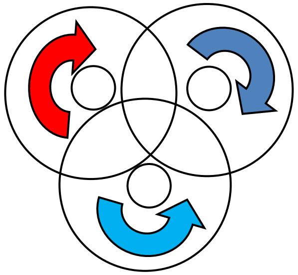
2. Total angular momentum created by this Pointing's vector

$$\mathbf{s_Q} = \mathbf{L_g} = (\ldots)\int_a^{\infty} d^3r\left[\mathbf{r} \times (\mathbf{E_{ch}} \times \mathbf{B_{ch}})\right]$$

is associated with the intrinsic spin of the constituent quark.

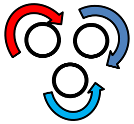
Quarks – Oscillating Vortices

t = 0
$x = x_{max}$



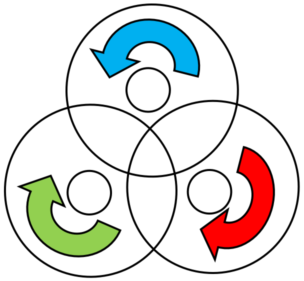
Consituent Quarks

t = T/4
$x = 0$



Current Quarks

t = T/2
$x = x_{max}$



Consituent Quarks

- In the current quark state E_{ch} and B_{ch} are concentrated in a **small radius shell** around VQ.
- And so is for the vortices around VQs.

Nucleon Transition into Hyperon Phase

How can nucleons be converted into hyperons?

- Inside highly compressed nuclear matter a strange quark-antiquark condensate is created.

And:

- ***u*** and ***d*** quarks in nucleons are replaced by ***s***-quarks,
- ***s***-antiquarks together with those ***u*** and ***d*** form kaons:

p, n → hyperons + kaons

- the **heavier** quark content of a baryon, the **less** spatial dimensions it occupies