Hadron Modifications in Dense Nuclear Matter

G. Musulmanbekov

JINR

genis@jinr.ru

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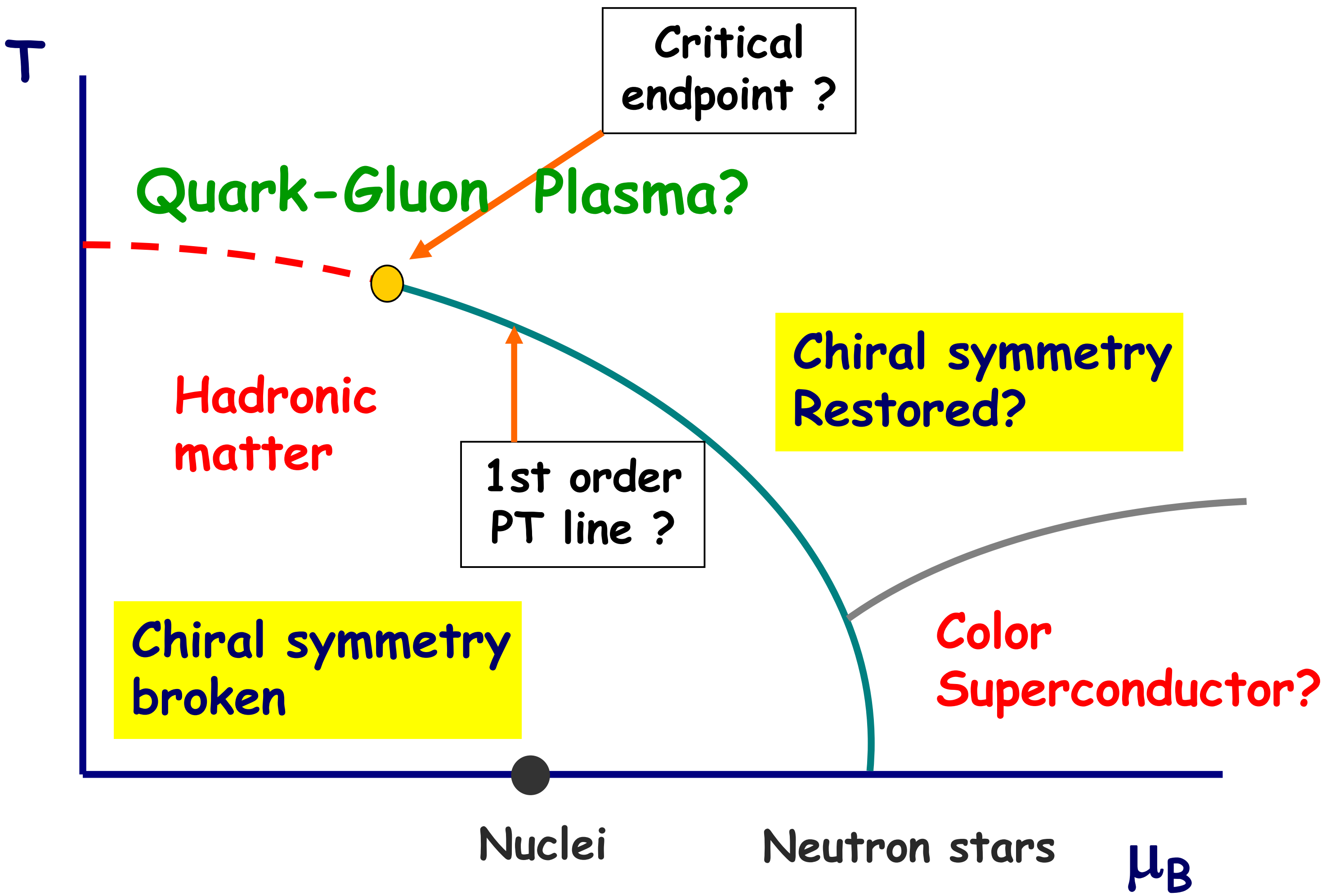
- Hadrons in Nuclei
  - Strongly correlated quark model (SCQM) of the hadron structure
  - Building the nuclear structure
- Hadron modifications in a dense nuclear matter
- Understanding of exp. effects in HIC
  - Enhanced strangeness production
  - Horn-effect
  - Enhancement of dilepton mass spectra in the range 0.2 – 0.6
- Conclusion

Motivation

- How nuclear matter behave under high compression?
- How hadron structures are modified in a dense matter?
- What observables are the possible signals of these modifications?

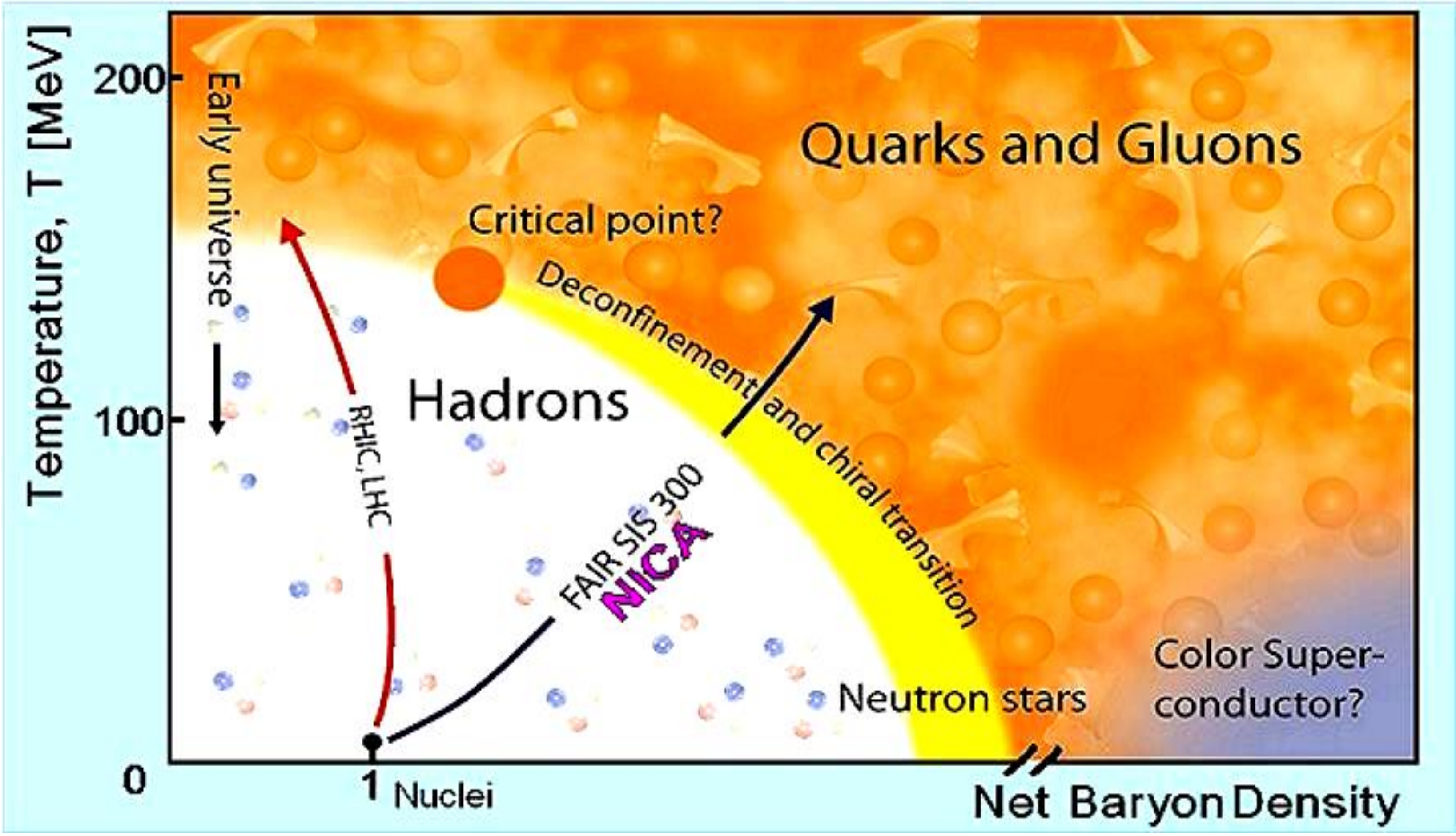
Motivation

- Does hadronic matter transit into QGP?



Motivation

- Does hadronic matter transit into QGP?



Toy Model:

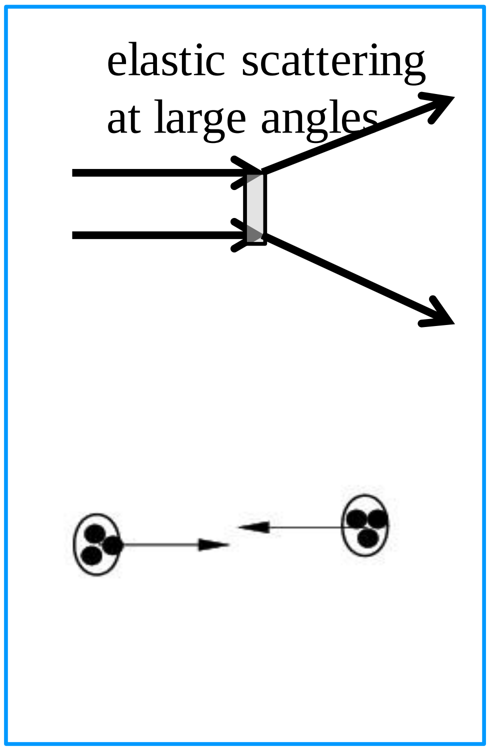
Strongly Correlated Quark Model

G. Musulmanbekov, 1995

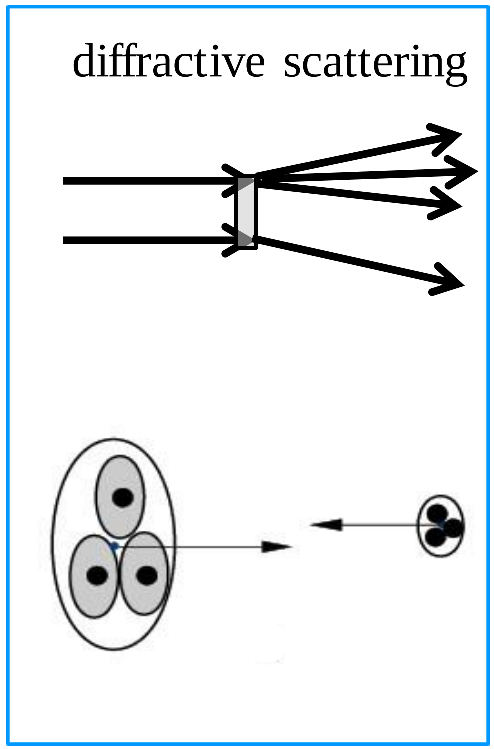
Strongly Correlated Quark Model

Motivations

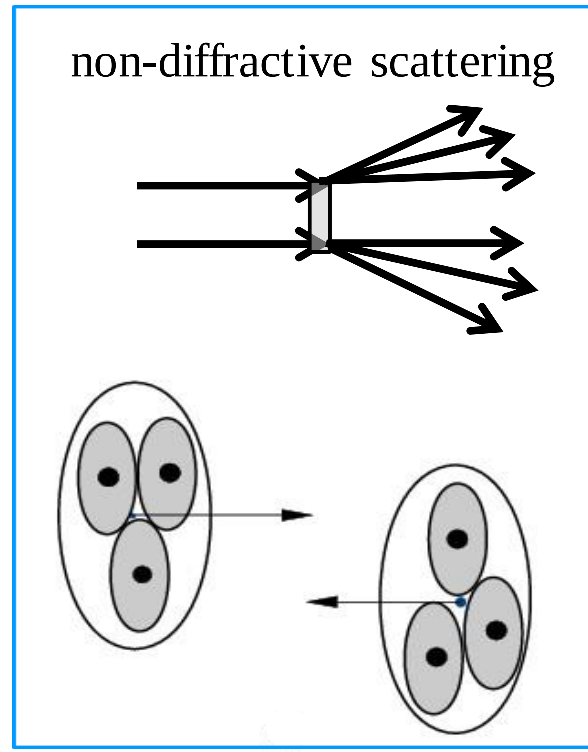
pp – interactions at high energies



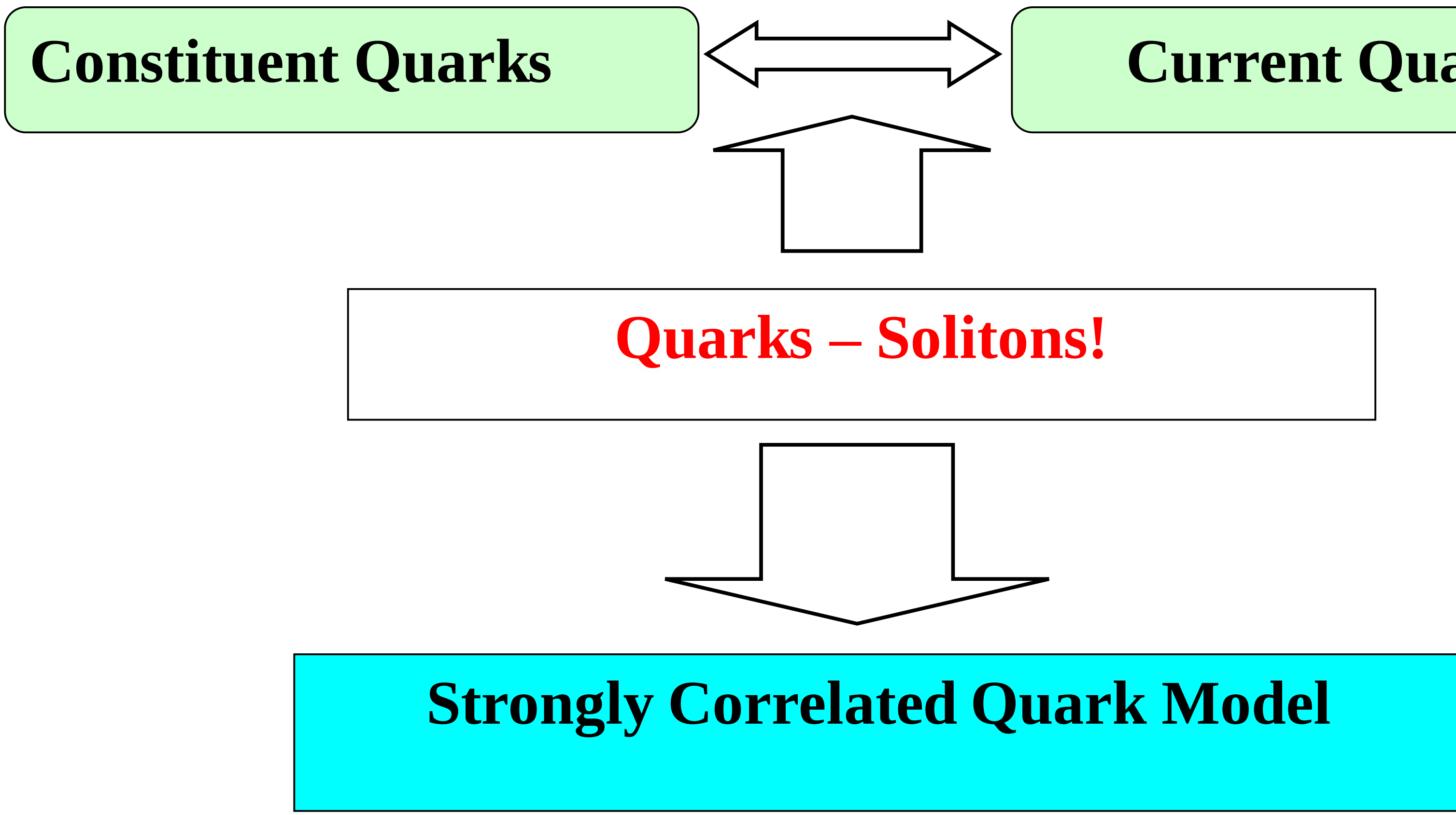
small-small quark configurations



intermediate-small quark configurations

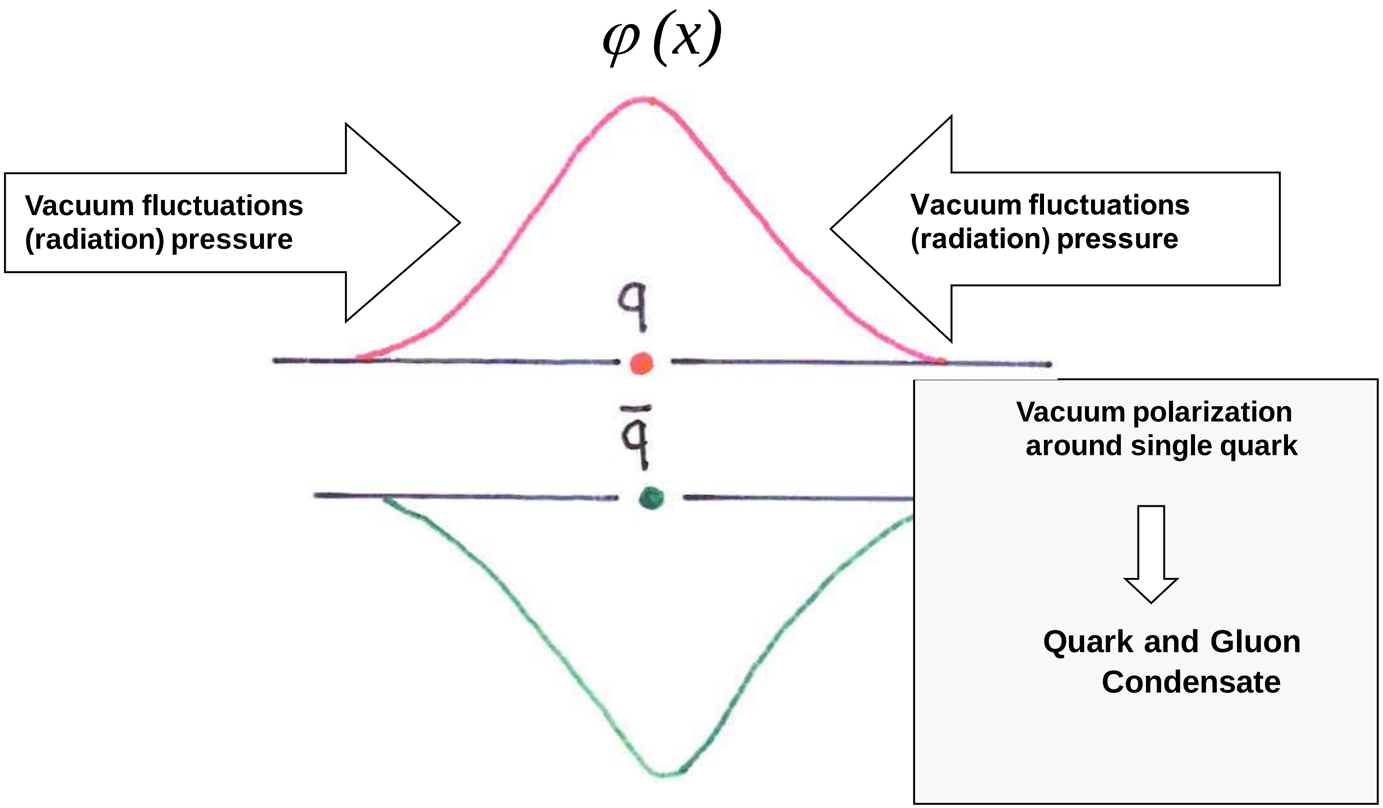


large-large quark configurations


Constituent Quarks
Current Quarks
Quarks – Solitons!
Strongly Correlated Quark Model

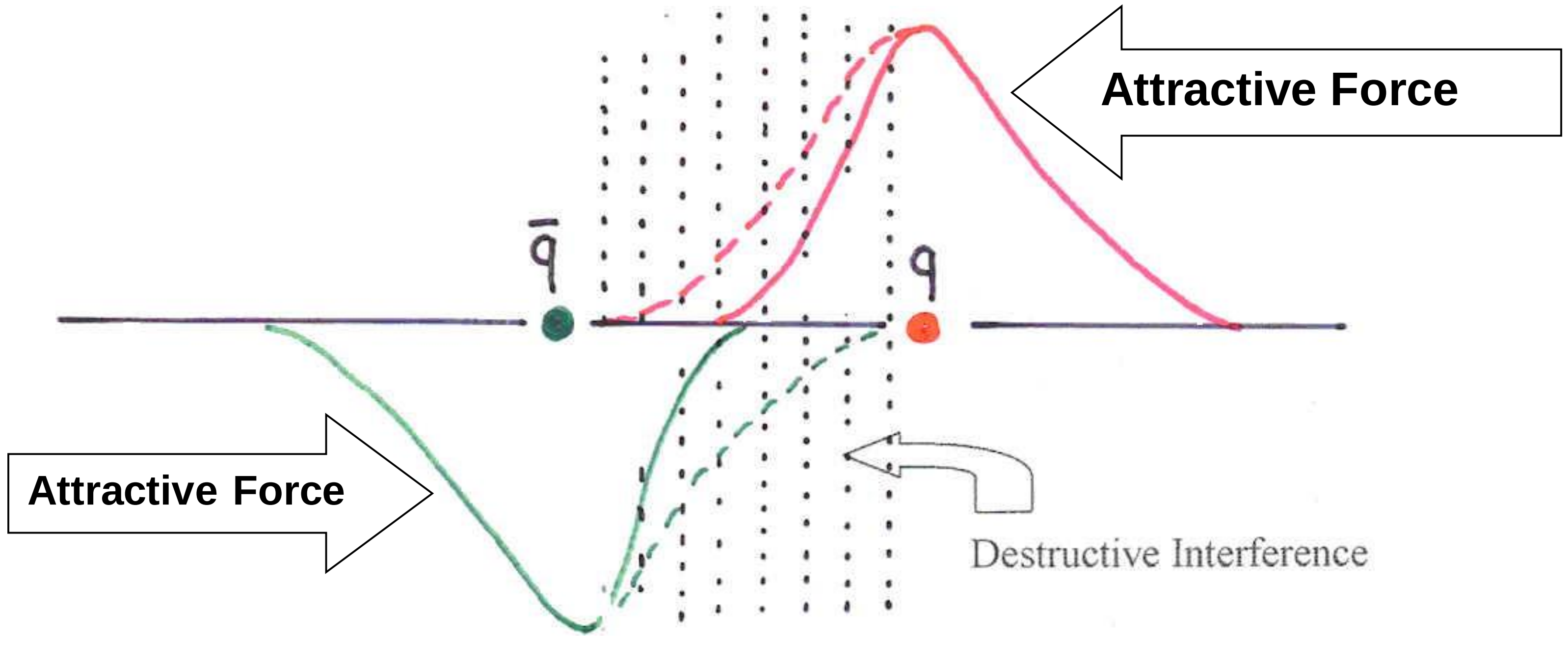
Strongly Correlated Quark Model

(SCQM)



Strongly Correlated Quark Model

(SCQM)



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,

***β = β(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.

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:

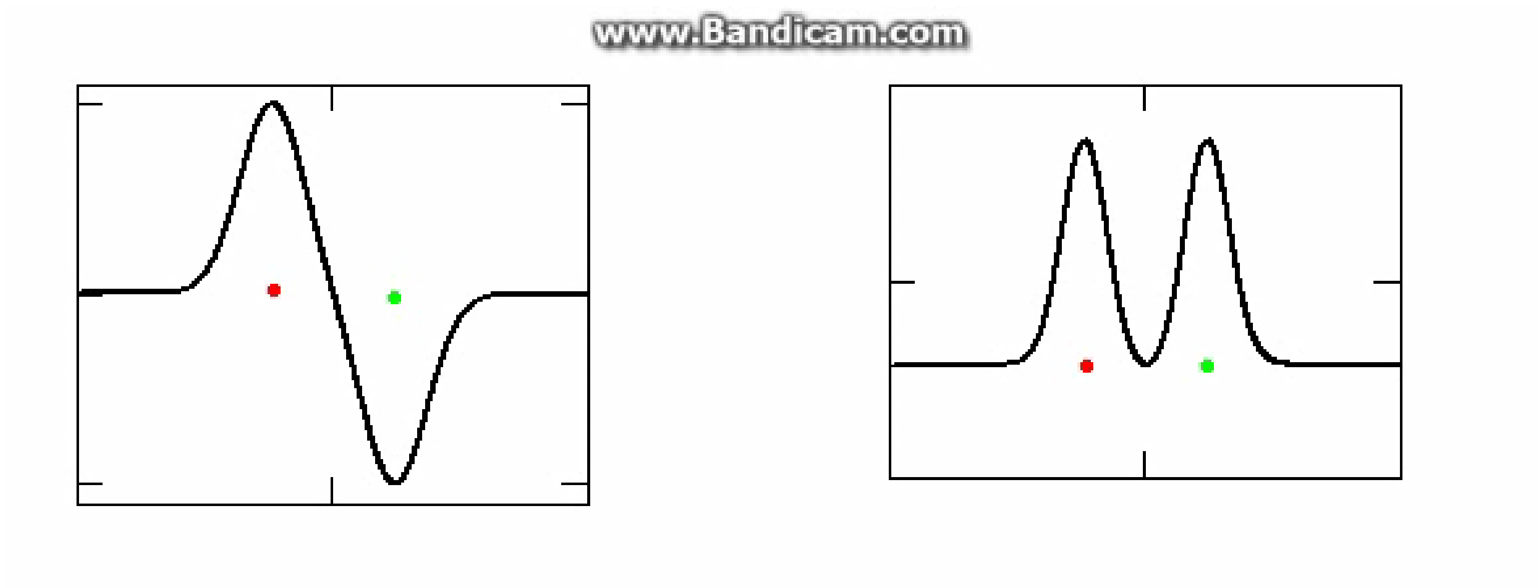
$$\phi(x,t)_{s-as} = 4\tan^{-1}\left[\frac{\sinh\left(ut/\sqrt{1-u^2}\right)}{u\cosh\left(x/\sqrt{1-u^2}\right)}\right]$$

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

is identical to our quark-antiquark system;

Breather – quark-antiquark pair
Meson

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



What is Chiral Symmetry and its Breaking?

- Chiral Symmetry

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

- The order parameter for symmetry breaking is quark or *chiral* condensate:

  $<\psi\psi> \simeq - (250\ \text{MeV})^3, \quad \psi = u,d$

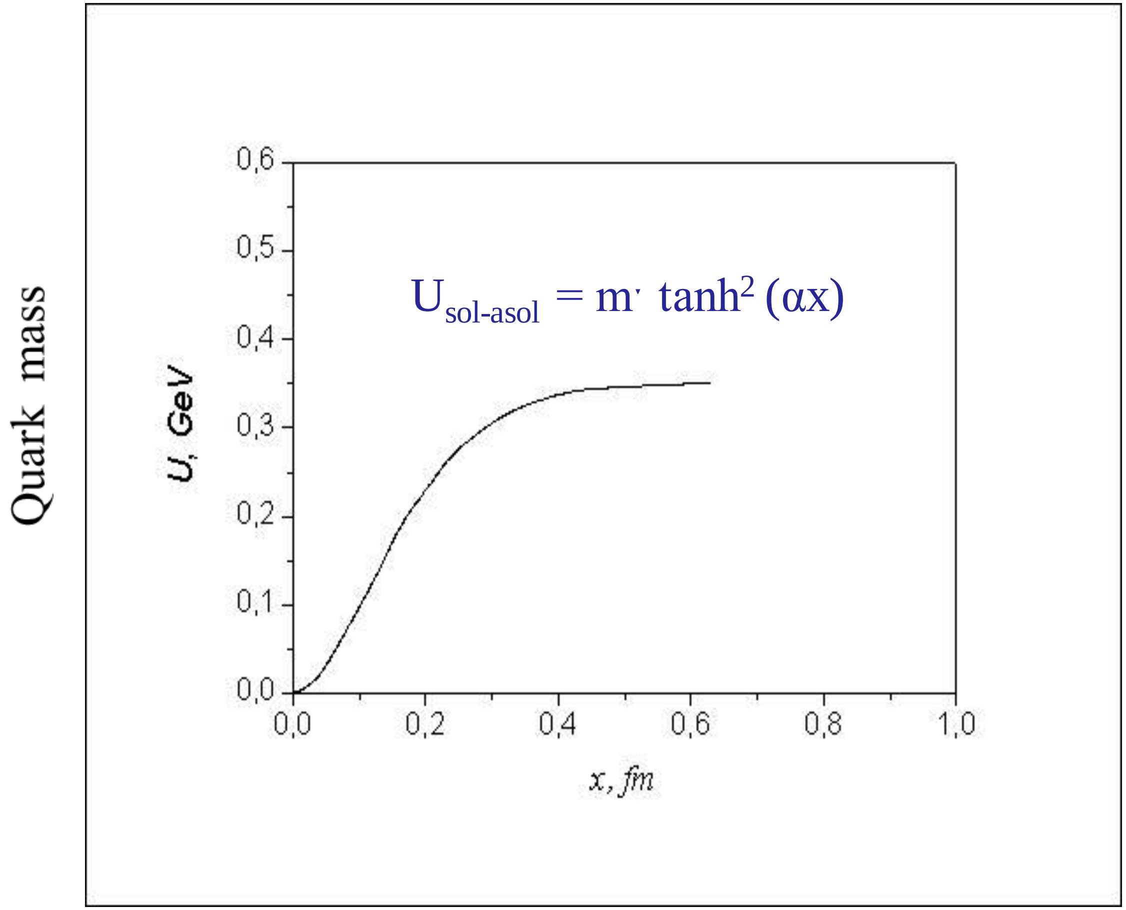
- As a consequence massless valence quarks (u, d) acquire dynamical masses which we call constituent quarks

  $$M_C \approx 350 - 400\ \text{MeV}$$

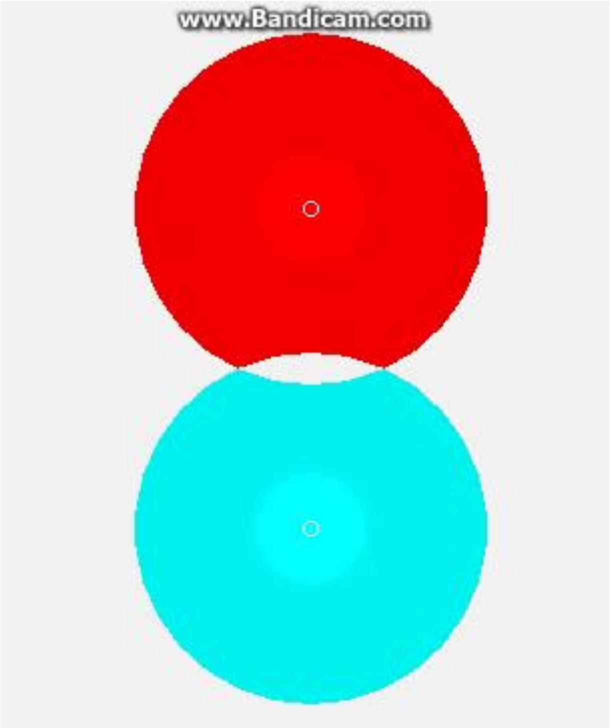
Quark Potential

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

W. Troost, CERN Report, 1975;
P. Vinsarelly, Acta Phys. Aust. Suppl., 1976



quark-antiquark pair
Meson

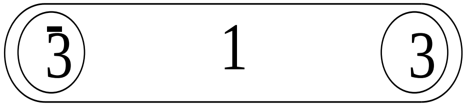


Generalization to the 3 – quark system (baryons)

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

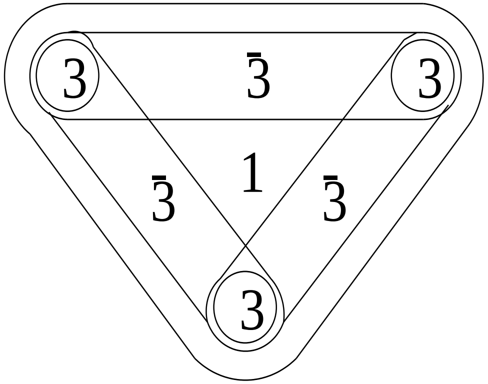
$$q \Rightarrow SU(3) \Leftrightarrow RGB \qquad \bar{q} \Rightarrow SU(\bar{3}) \Leftrightarrow CMY$$

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



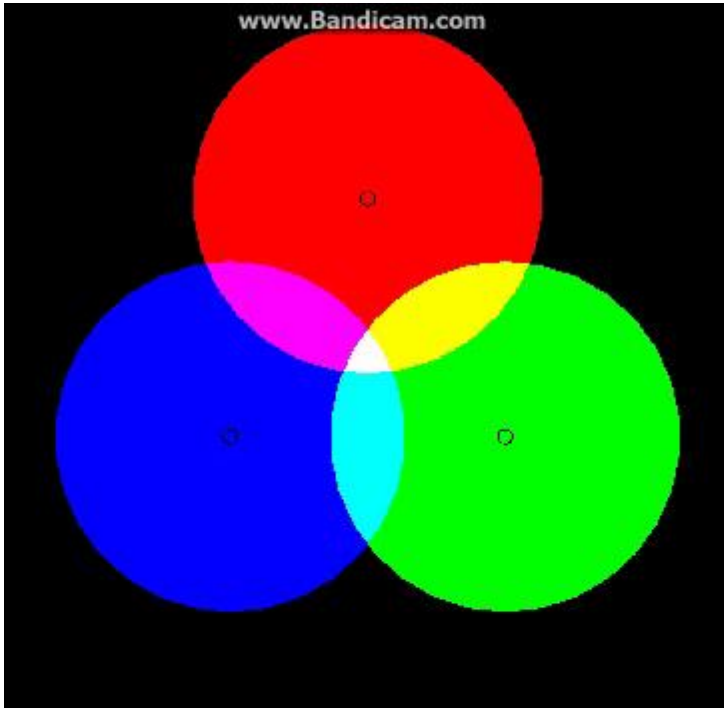
$$qq \to 3 \times 3 = 6 \oplus \bar{3} \qquad \Rightarrow \qquad \bar{q} \to qq$$

$$qqq \Rightarrow$$



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

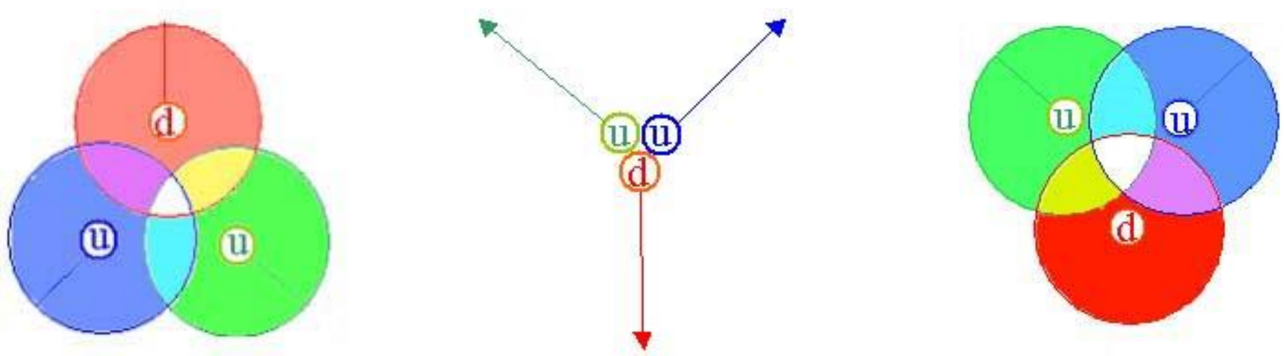
$SU(3)_{color}$ - RGB



Interplay between constituent and current quark states

Chiral Symmetry Breaking ⟺ Restoration

t = 0, $x = x_{max}$ | t = T/4, x = 0 | t = T/2, $x = -x_{max}$



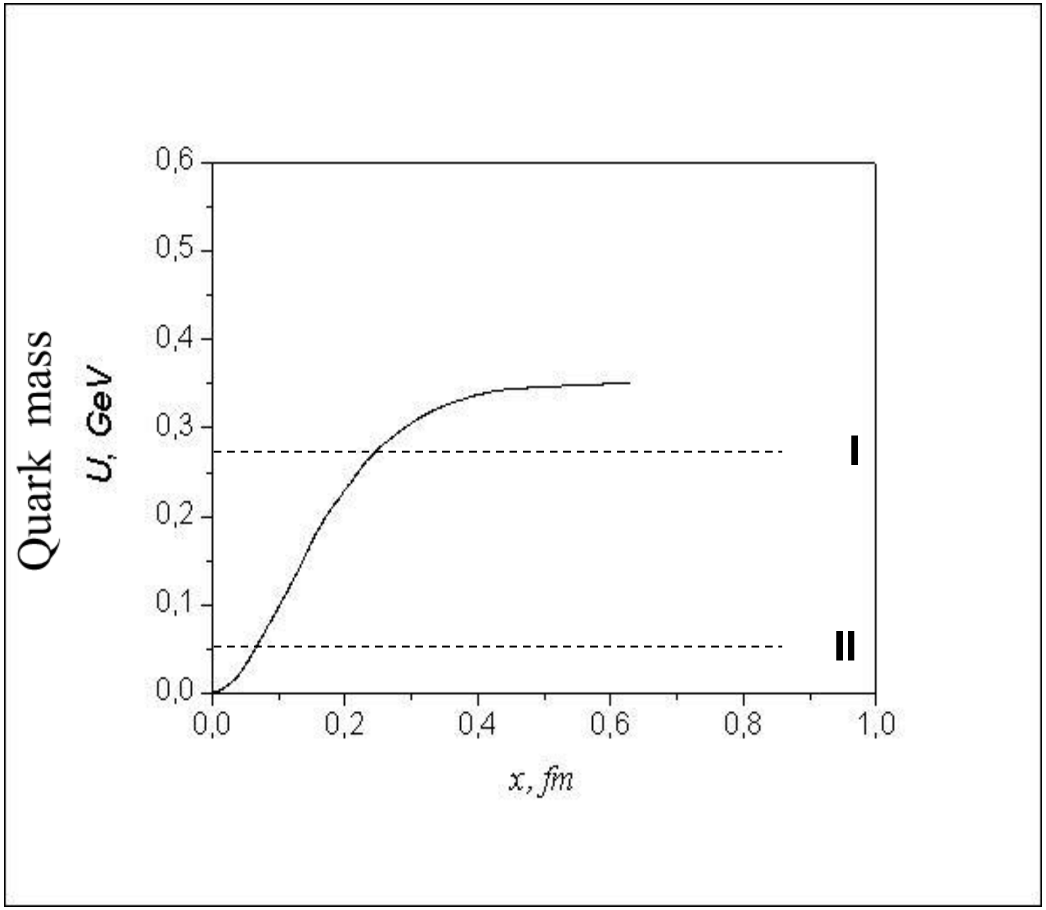
Constituent quaks | current quarks | Constituent quarks

Asymptotic freedom

During the valence quarks oscillations:

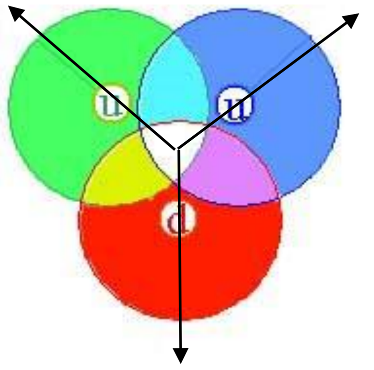
$$|B\rangle = a_1|q_1q_2q_3\rangle + a_2|q_1q_2q_3\bar{q}q\rangle + a_3|q_1q_2q_3g\rangle + \ldots$$

Quark Potential



U(x) > I – constituent quarks
U(x) < II – current (relativistic) quarks

Nucleon



Quark color wave function

$$\psi(x)_{Color} = \sum_{i=1}^{3} a_i(x)\left|c_i\right\rangle$$

Where $\left|c_i\right\rangle$ **are orthonormal states with *i, j* = R,G,B**

$$\left\langle c_i \middle| c_j \right\rangle = \delta_{ij}$$

Nucleon wave function

$$\psi(x)_{Color} \rightarrow \frac{1}{\sqrt{6}} \sum_{ijk} e_{ijk}\left|c_i\right\rangle\left|c_j\right\rangle\left|c_k\right\rangle$$

Parameters of SCQM for the Nucleon

- Parameters of Quark potential $U_{sol\text{-}asol} = m \cdot \tanh^2(\alpha x)$

  1. Mass of Consituent Quark

$$m = M_{Q(\overline{Q})}(x_{\max}) = \frac{1}{3}\left(\frac{m_\Delta + m_N}{2}\right) \approx 360 MeV,$$

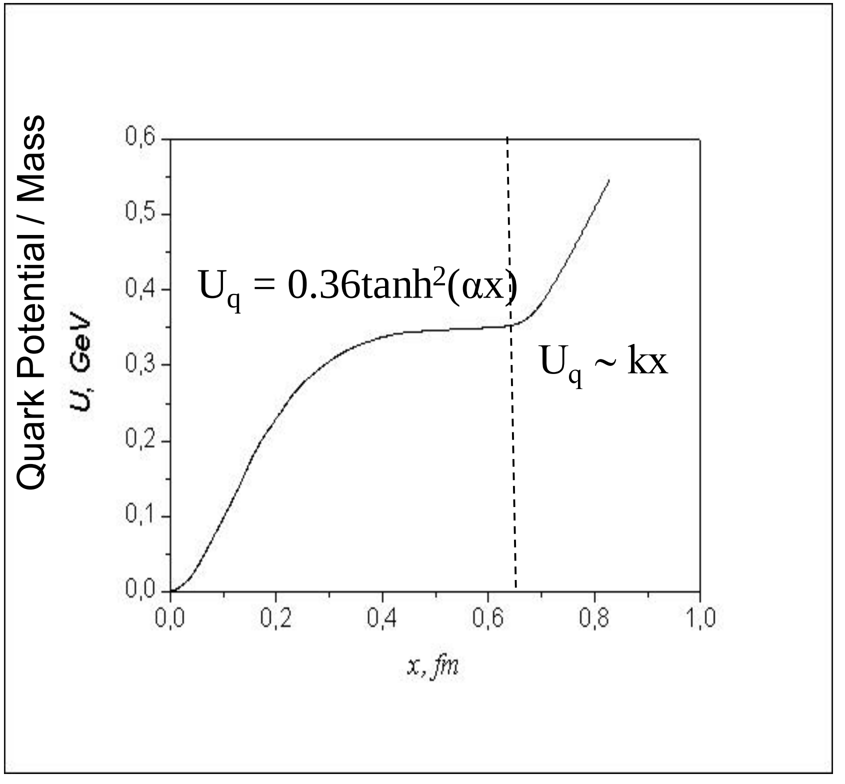
  2. Amplitude of VQs oscillations : $\alpha = x_{max} = 0.64\ fm$,

- Constituent quark sizes (parameters of gaussian distribution): $\sigma_{x,y} = 0.24\ fm$, $\sigma_z = 0.12\ fm$

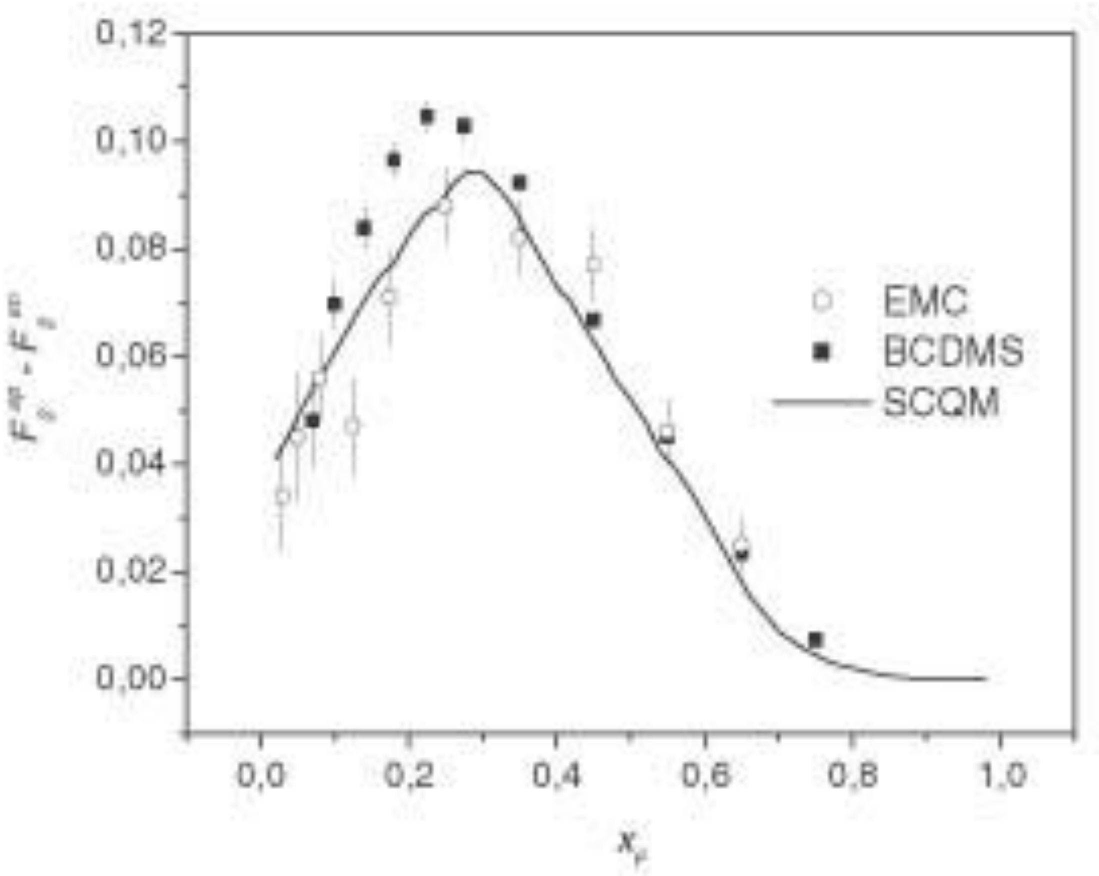
- Parameters 2 and 3 are derived from the calculations of Inelastic Overlap Function (IOF) and σ_{tot} in $\bar{p}\,p$ and pp – collisions.

"The wave packet solution of time-dependent Schrodinger equation for harmonic oscillator moves in exactly the same way as corresponding classical oscillator"
E. Schrodinger, 1926

Quark Potential



Structure Function of Valence Quarks in Proton



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

$$A^{\mu}(x) \rightarrow A^{\mu}(x) + \partial^{\mu}\theta(x)$$

Therefore, during quark oscillation its

color charge

momentum

mass

are continuously varying functions of time.

Relation SCQM to QCD

We reduce interaction of color quarks via **non-Abelian** fields to its **E-M** analog:

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

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

Spin in SCQM

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

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

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:

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

Total angular momentum created by this Pointing's vector

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

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 $\mathbf{E}_{\mathbf{ch}}$ and $\mathbf{B}_{\mathbf{ch}}$ create around VQ color analog of Pointing's vector (circulating flow of energy)

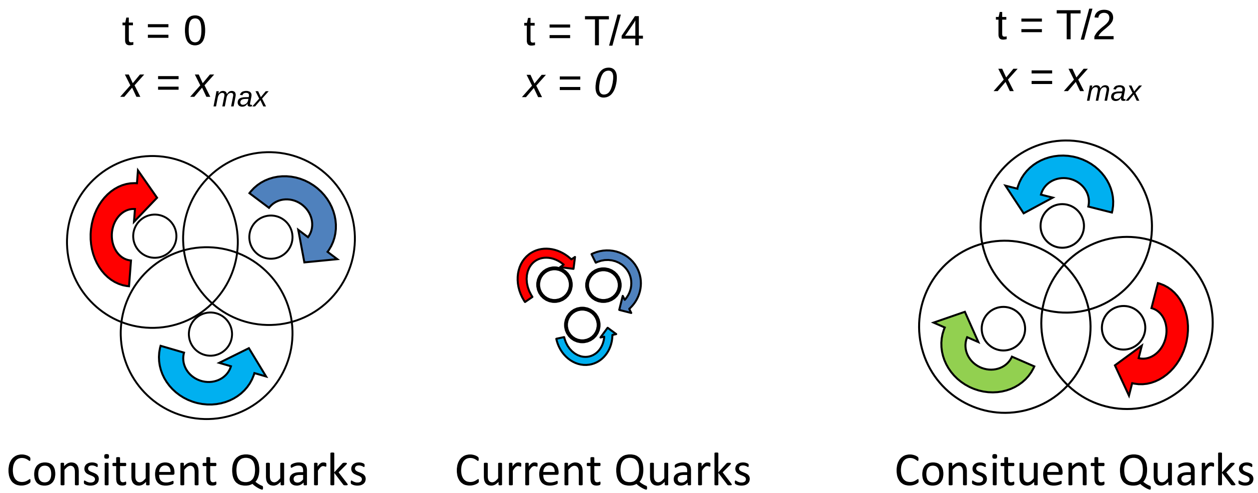
$$\mathbf{S}=\varepsilon_0 c^2 \mathbf{E}_{\mathbf{ch}} \times \mathbf{B}_{\mathbf{ch}}.$$

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

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

is associated with the intrinsic spin of the constituent quark.

Quarks – Oscillating Vortices

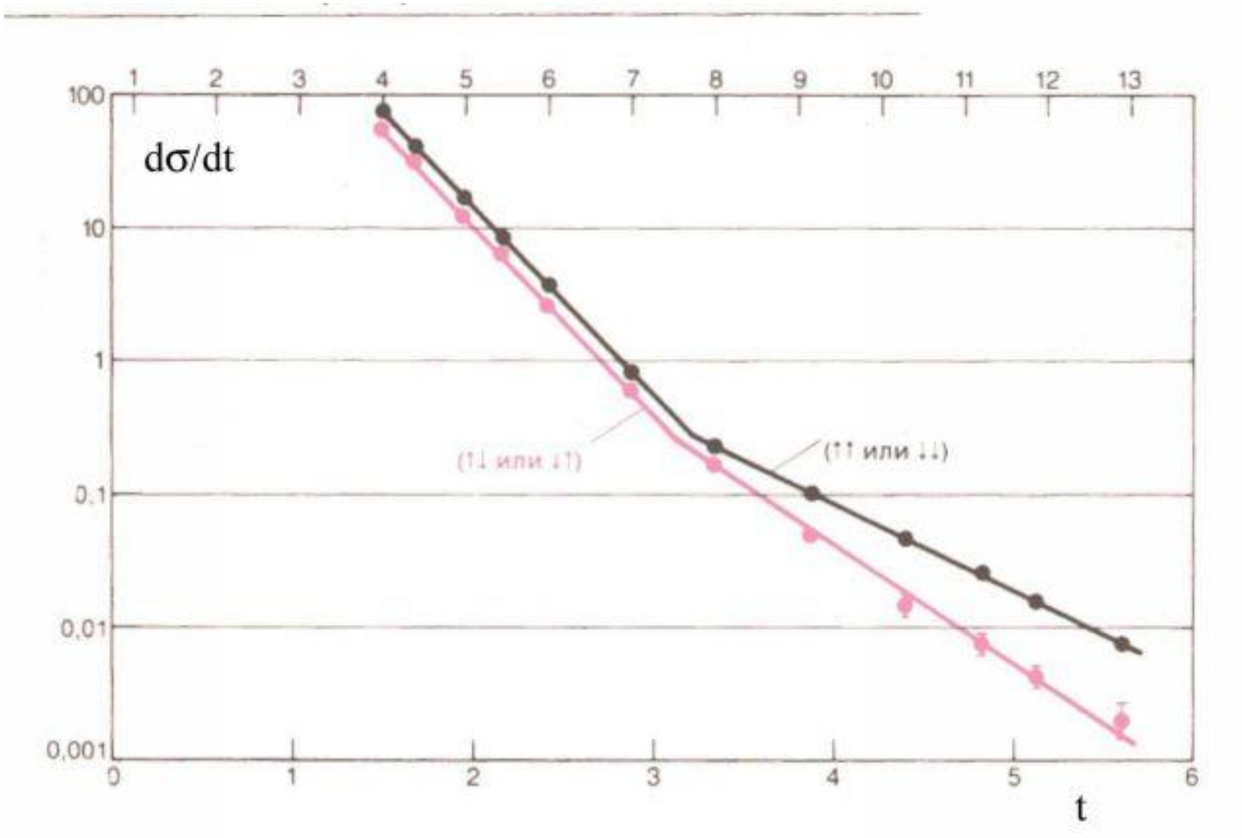


- In the current quark state E_{ch} and B_{ch} are concentrated in a **small radius shell** around VQ.
- And so is for the vortices around VQs.

Polarized proton-proton collisions

anti-parallel spins

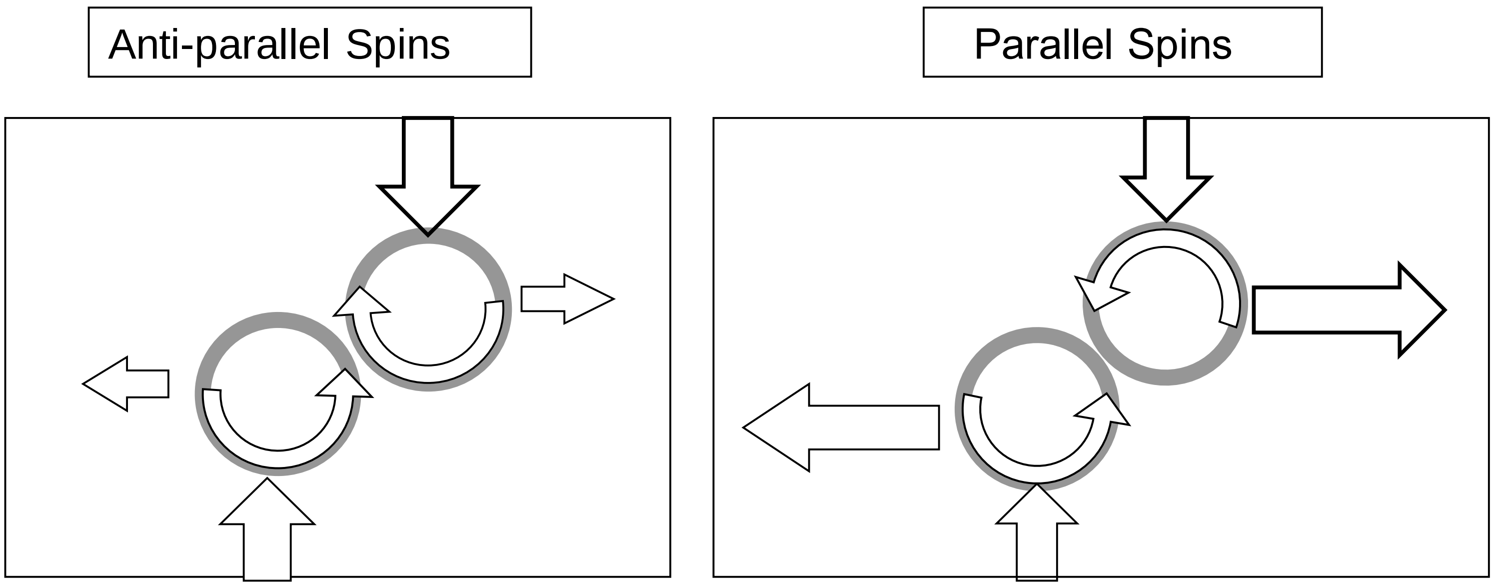
parallel spins



“Krish” - effect

Collision of Vorticing Quarks

Spin Asymmetries



"Krish" - effect

Summary on Quarks in Hadrons

- Constituent quarks are identical to solitons.
- Quarks and gluons inside nucleons are strongly correlated;
- Hadronic matter distribution inside hadrons is fluctuating quantity;
- Nucleons are not spherically symmetric (deformed).

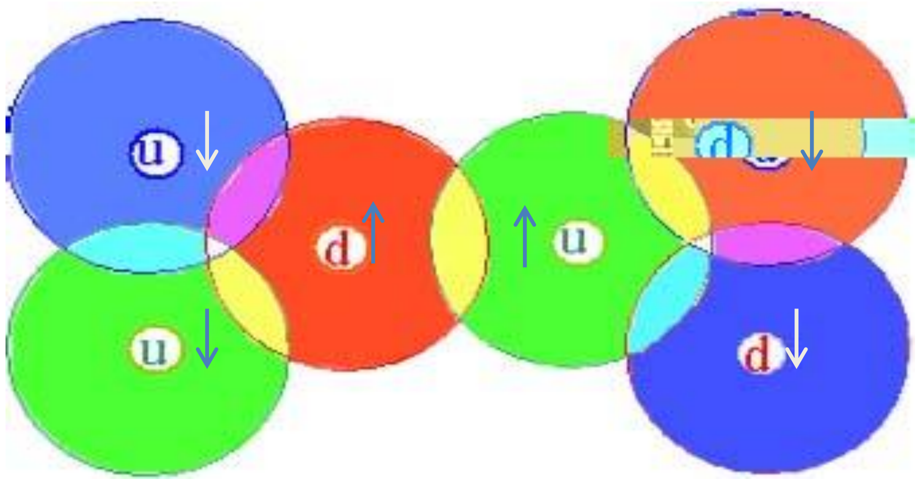
Quark Arrangement inside Nuclei

Strongly Correlated Quark Model

↓

Crystal-like arrangement of Nuclear Structure

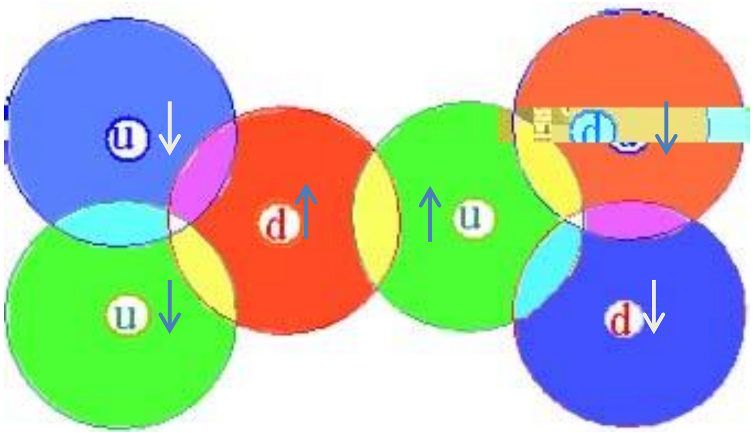
Two Nucleon System in SCQM



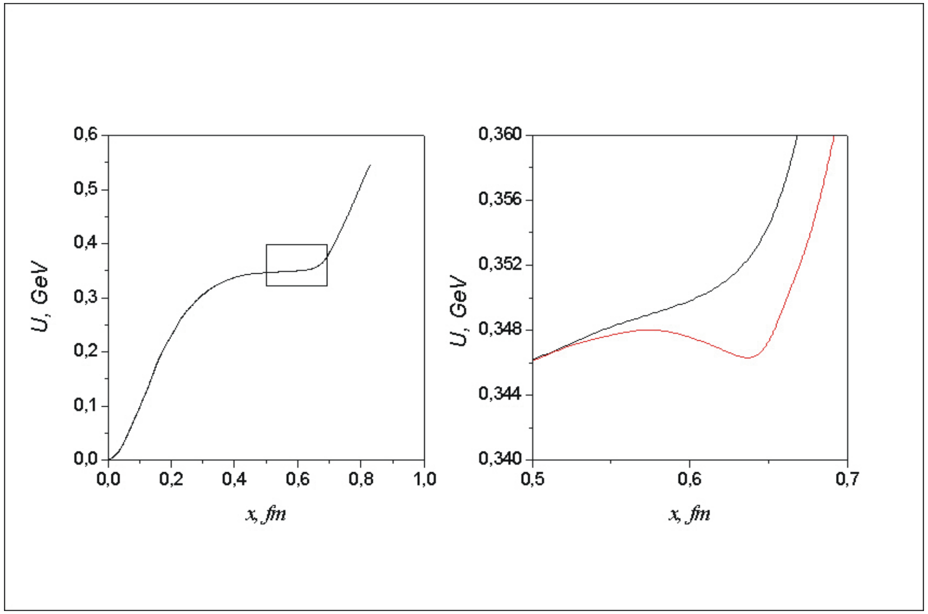
Selection rules for binding two quarks of neighboring nucleons at a junction:

- $SU(3)_{Color}$ – of different colors
- $SU(2)_{Flavor}$ – of different flavors
- $SU(3)_{Spin}$ – of parallel spins

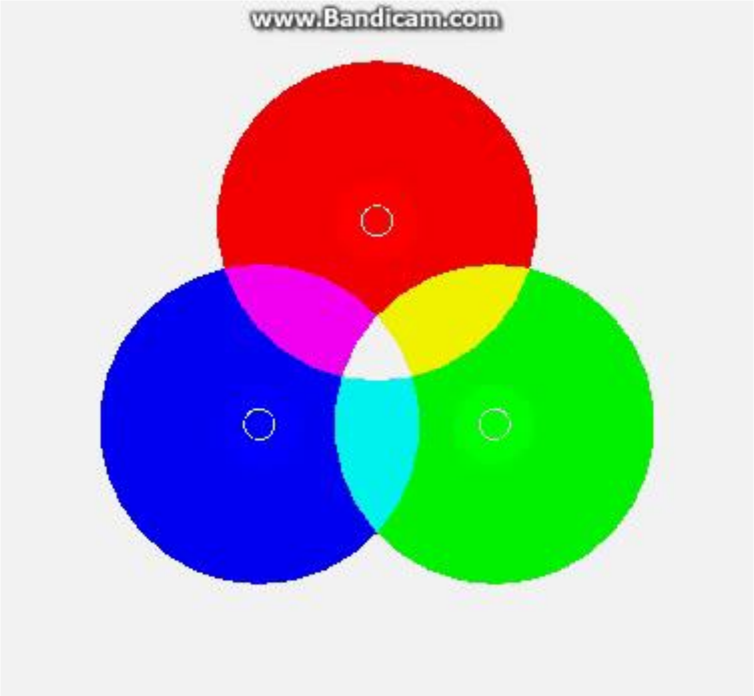
Two Nucleon System in SCQM



Quark Potential Inside Nuclei

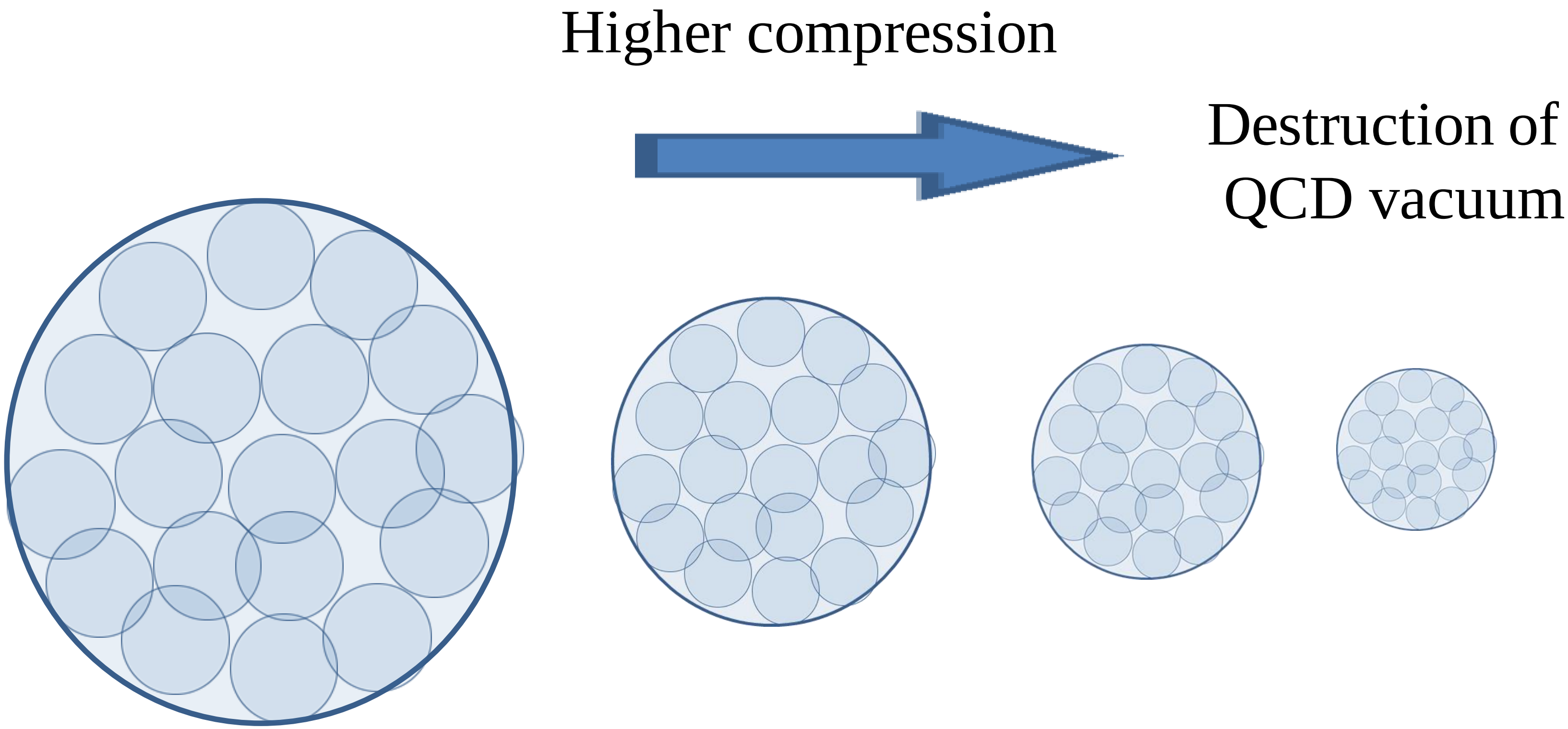


Quarks inside nucleus



Hadron modifications in a dense nuclear matter

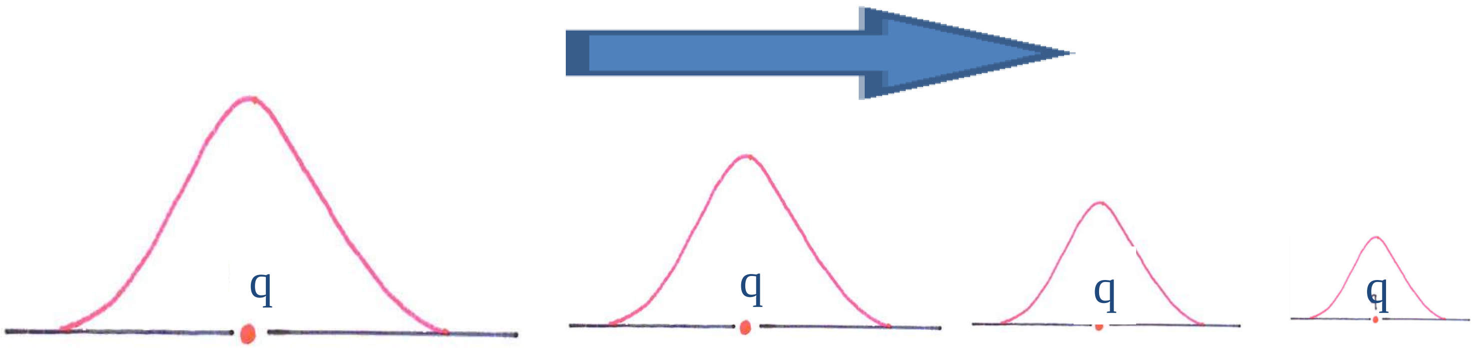
1. Baryonic matter under compression



Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression

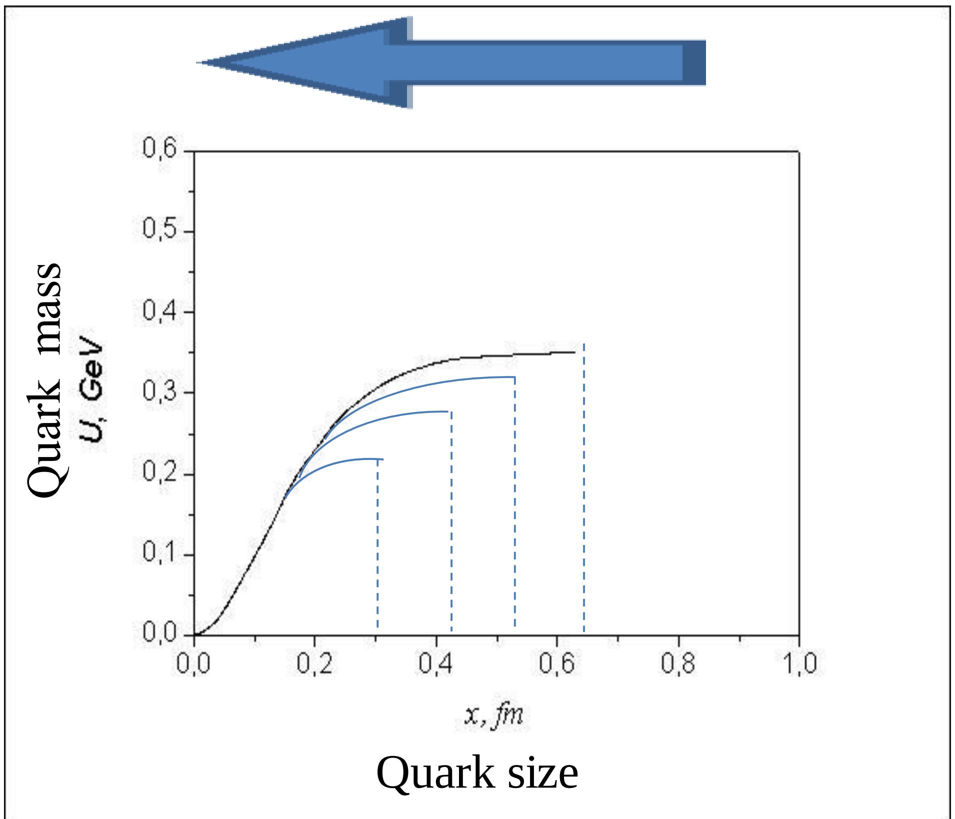


Quark condensate around valence quarks, <ψψ>

Hadron modifications in a dense nuclear matter

1. Baryonic matter under compression

Higher compression



Decreasing nucleon dimension

↓

Decreasing quark condensate

↓

Decreasing quark/nucleon mass

↓

Up to repulsive nucleon core

Baryonic matter under compression

Higher compression makes nucleons to convert into

- **delta-isobars**
- **hyperons**
- **higher mass resonances**

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

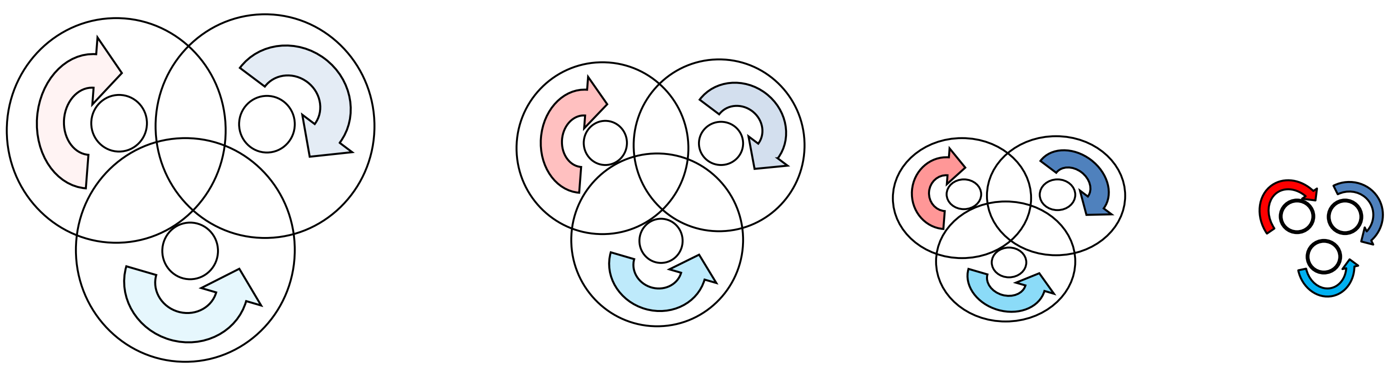
- the **heavier** quark content of a baryon, the **less** spatial dimensions it occupies

Scenario to avoid collapse

Higher compression

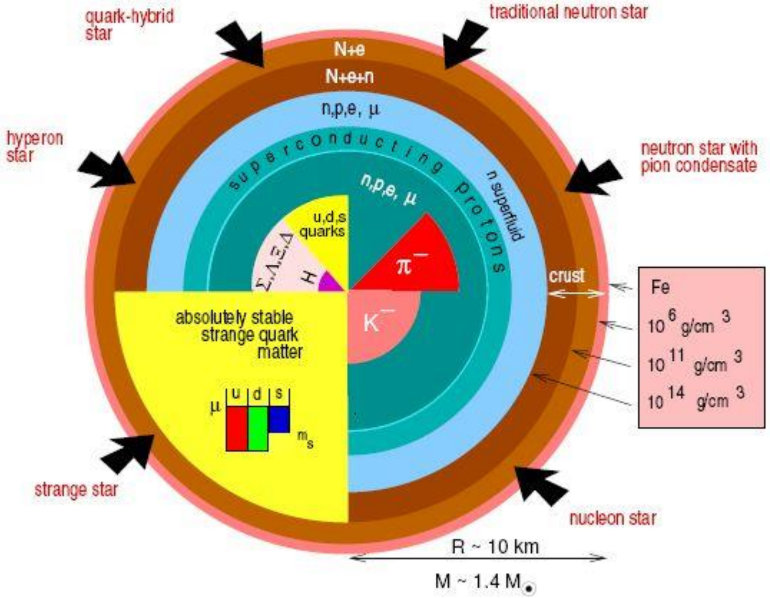
$$n, p \Rightarrow \Delta$$

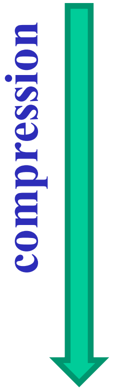
$$u, d \Rightarrow s, c, \ldots \quad n, p \Rightarrow \Lambda, \Sigma, \Xi, \Omega, \ldots$$



Hadronic gas → **Hadronic liquid**

Neutron star





Gravitational compression

NS core

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: $\rho, \omega, \varphi, K^{*}, \ldots$ - incompressible (effective cores)
- ρ, ω – '**melting**': mass dropping and width-widening;
  dilepton spectra
- Fireball 'cooling' → increased π – yield

Hadrons in a high dense and temperature medium

Model Consequences

1. **Baryons** transform to isobars then to 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-widening;

5. **Fireball evolution:**

Hadron-Resonance Liquid → Hadron-Resonance Gas

Hadrons in a high dense and temperature medium

1. **Hadrons** – **topological solitons?**

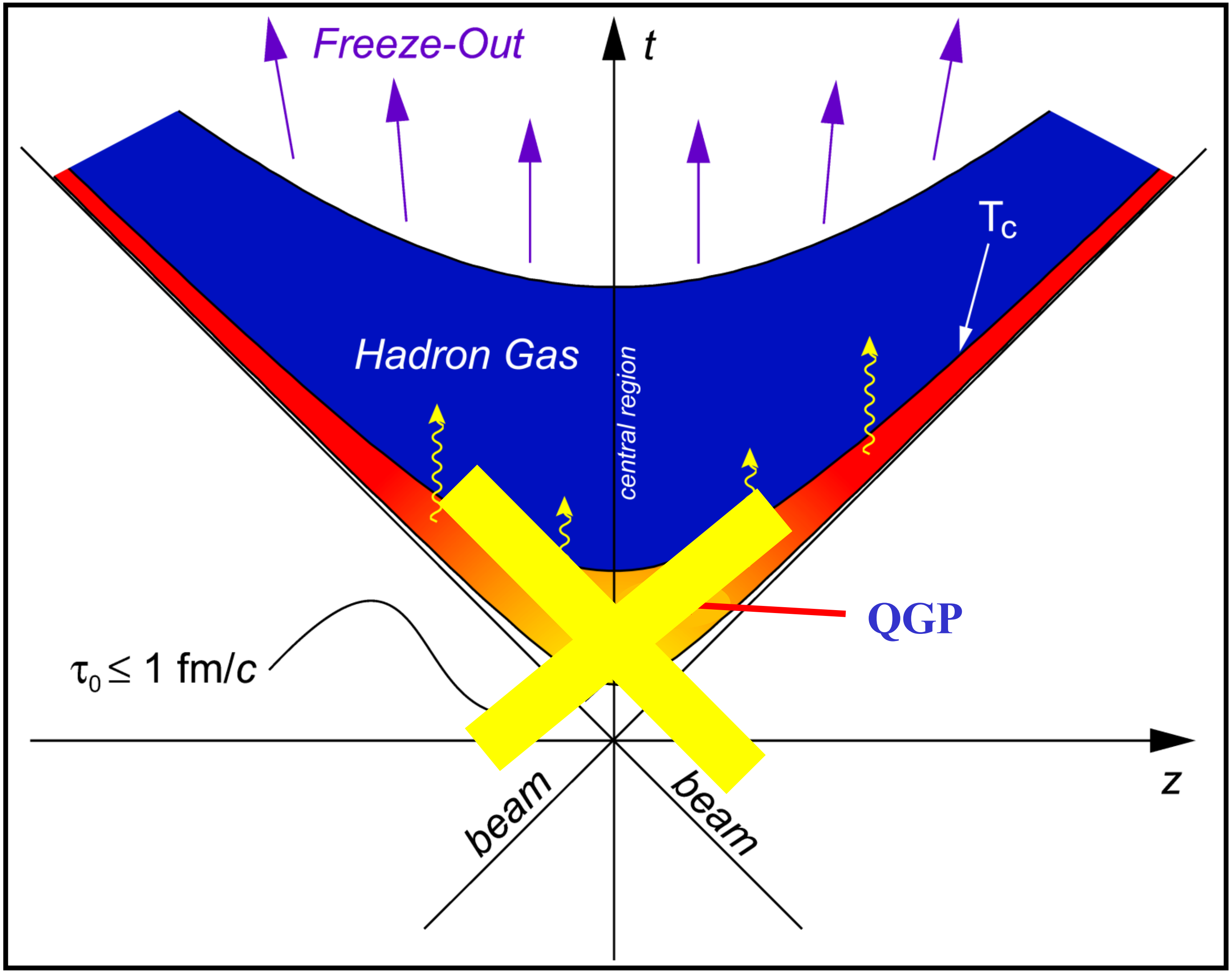
   ⇓

2. Conservation of topological charge

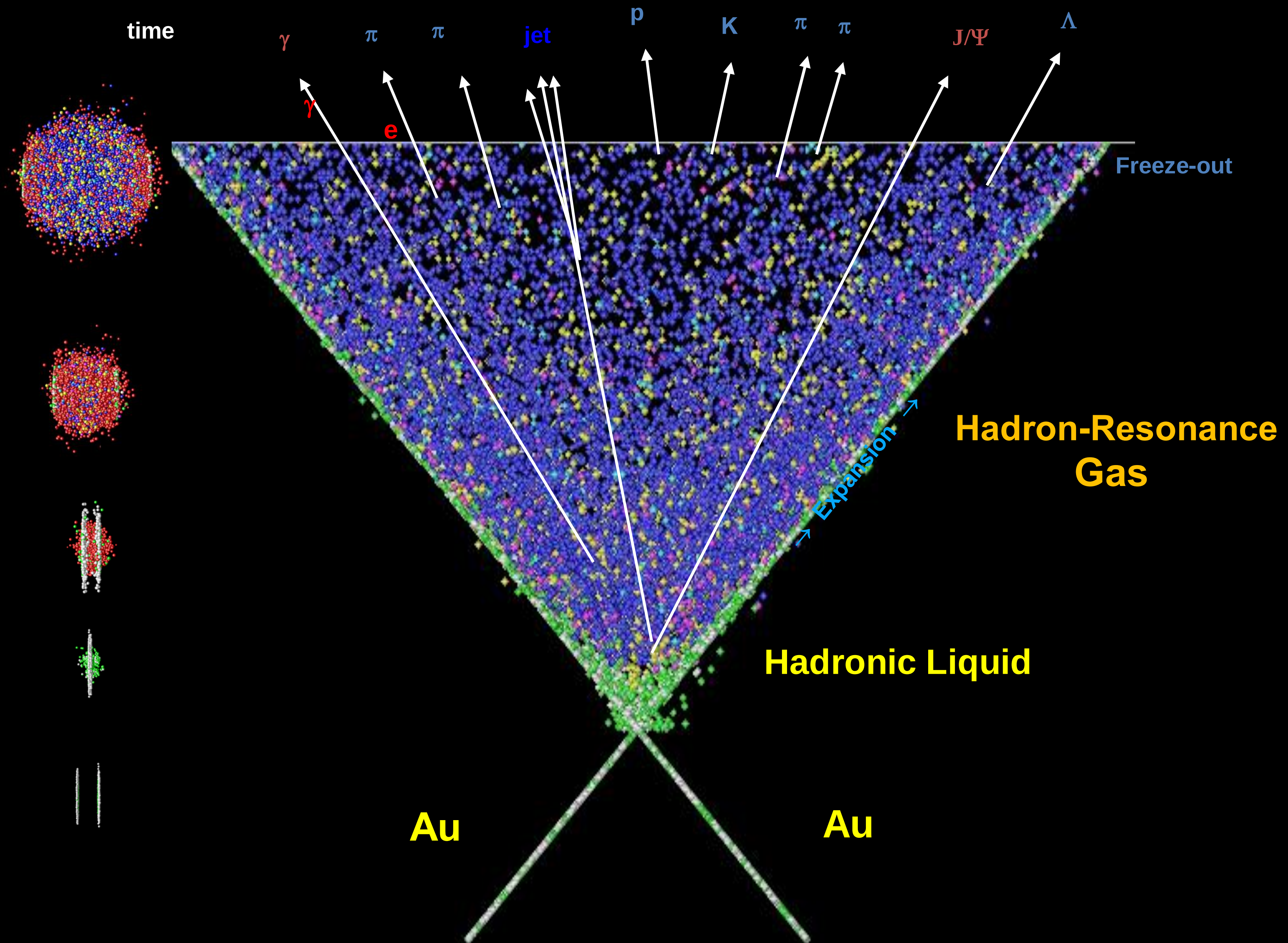
   ⇓

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

Space-time Evolution of HIC



Space-time Evolution of HIC



Experiments

Energy range: $\sqrt{s} = 3 - 11$ *GeV* ***most interesting!***

- **Enhanced yield of K^+, φ, (multi)strange baryons**

experiments: KaoS, AGS, NA49 at low energies of SPS, (BES RHIC)

- **Horn-effect – irregular behaviour of K^+/π^+**

experiments: NA49, STAR (BES RHIC)

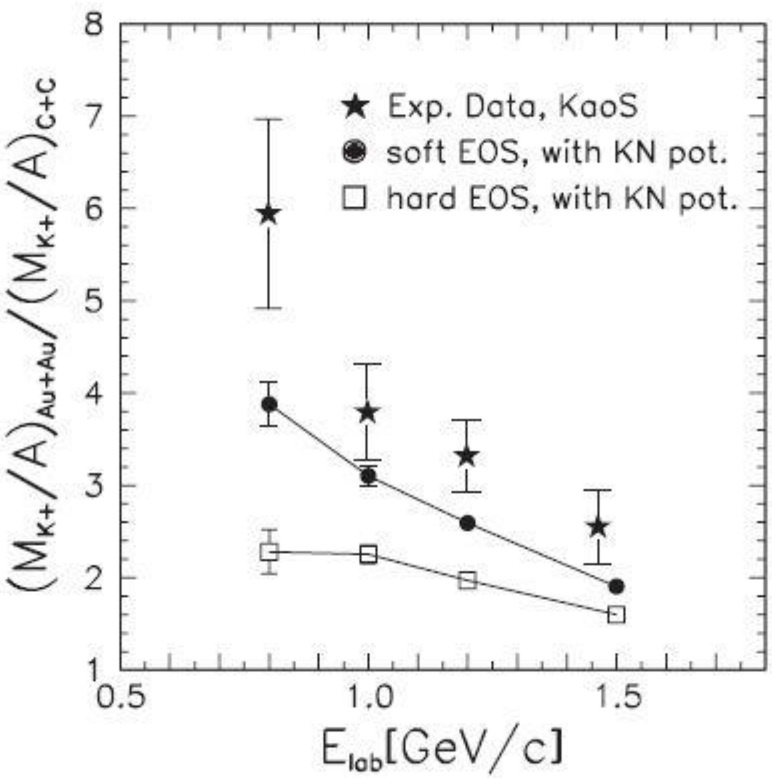
- **Dilepton production**

experiments: DLS, HADES, CERES, PHENIX

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

Enhanced yield of K^+ in subthreshold kaon production

KaoS at SIS



Transport models with NN-interactions

- **underestimate yield of K^+ by a factor of 6**
- **overestimate yield of K^-**

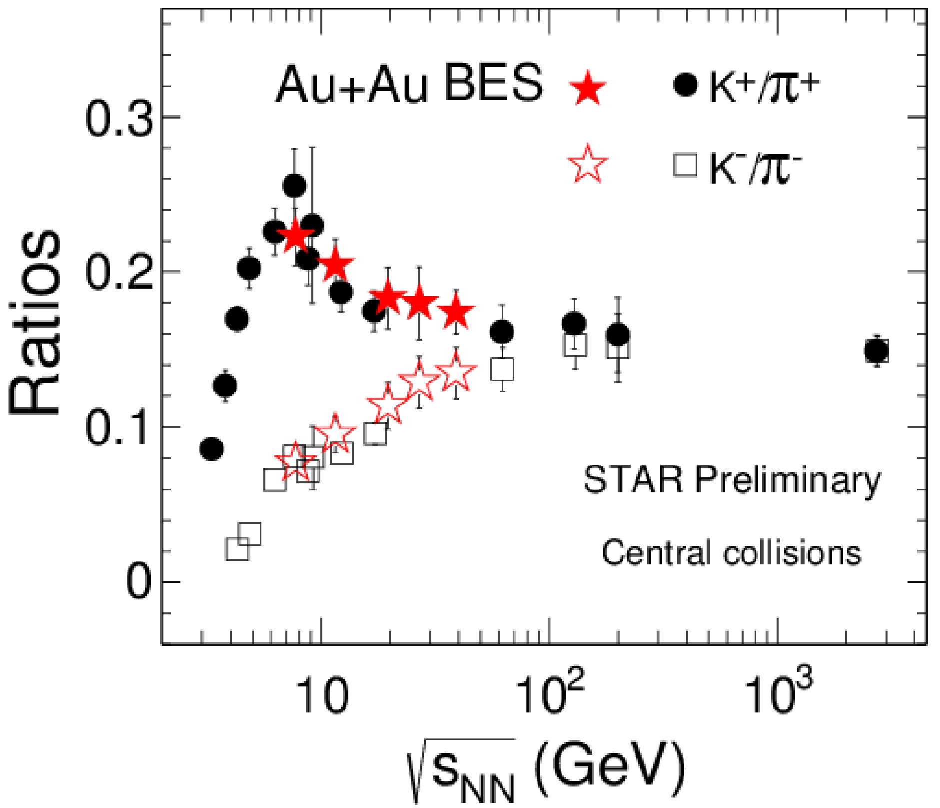
J. Phys. G: Nucl. Part. Phys. 27 (2001) 275

RQMD:

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

Enhansement of stangeness

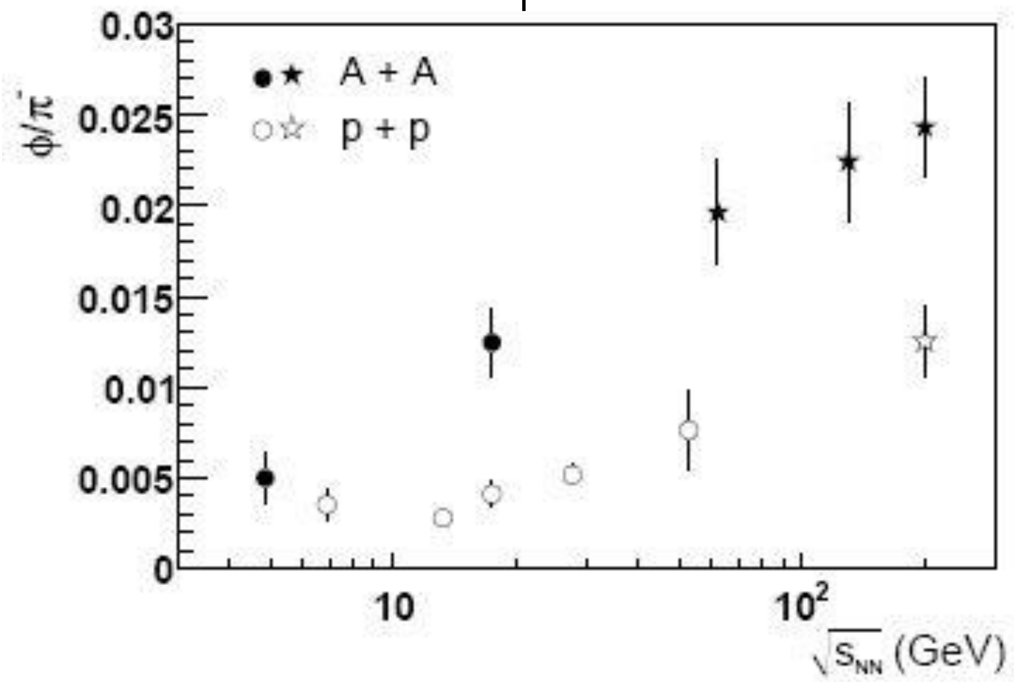
- Clear evidence for “horn” structure in K^+/π^+ at ~30 A GeV !
- Non-horn structure in K^-/π^-



Enhancement of strangeness

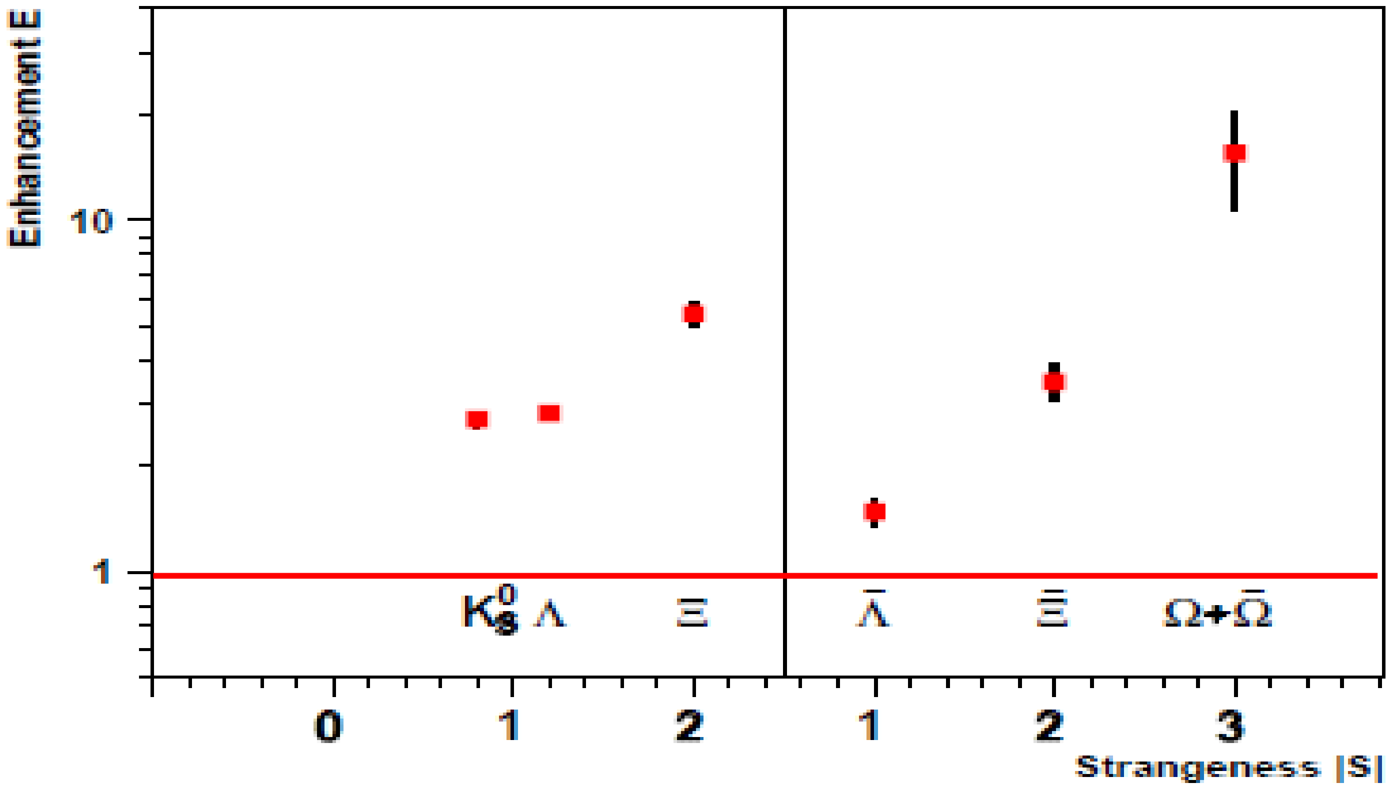
φ-mesons

φ/π⁻



Enhanced yield of hyperons

PbPb vs pBe SPS



Thank you for your attention!