Types of Mixed Nuclear Matter

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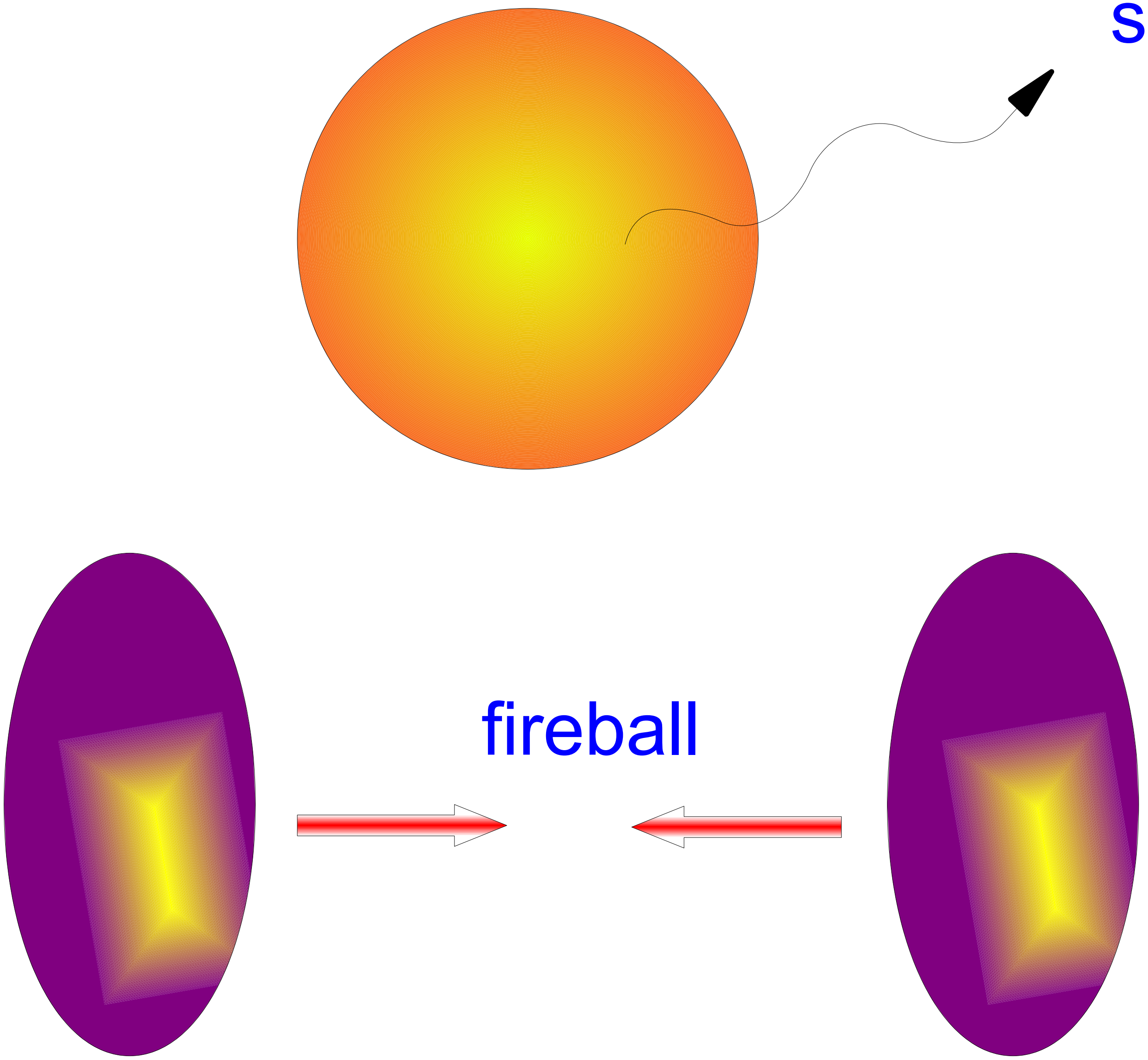
Mixtures

1. Nuclear matter with multiquark clusters
2. Multicomponent quark – hadron matter
3. Stratified quark – hadron mixture
4. Stratified hadron – hadron mixture
5. Heterophase quark – hadron matter

What is the state?



signal

fireball

Typical scales

Characteristic distance

$$a \sim \frac{1}{\rho^{1/3}} \sim 1\,\mathrm{fm} = 10^{-13}\,\mathrm{cm}$$

Fireball radius

$$R \sim 10\,\mathrm{fm} = 10^{-12}\,\mathrm{cm}$$

Local equilibration time

$$t_{loc} \sim \frac{a}{v} \sim 10^{-23}\,\mathrm{s}$$

Total equilibration time

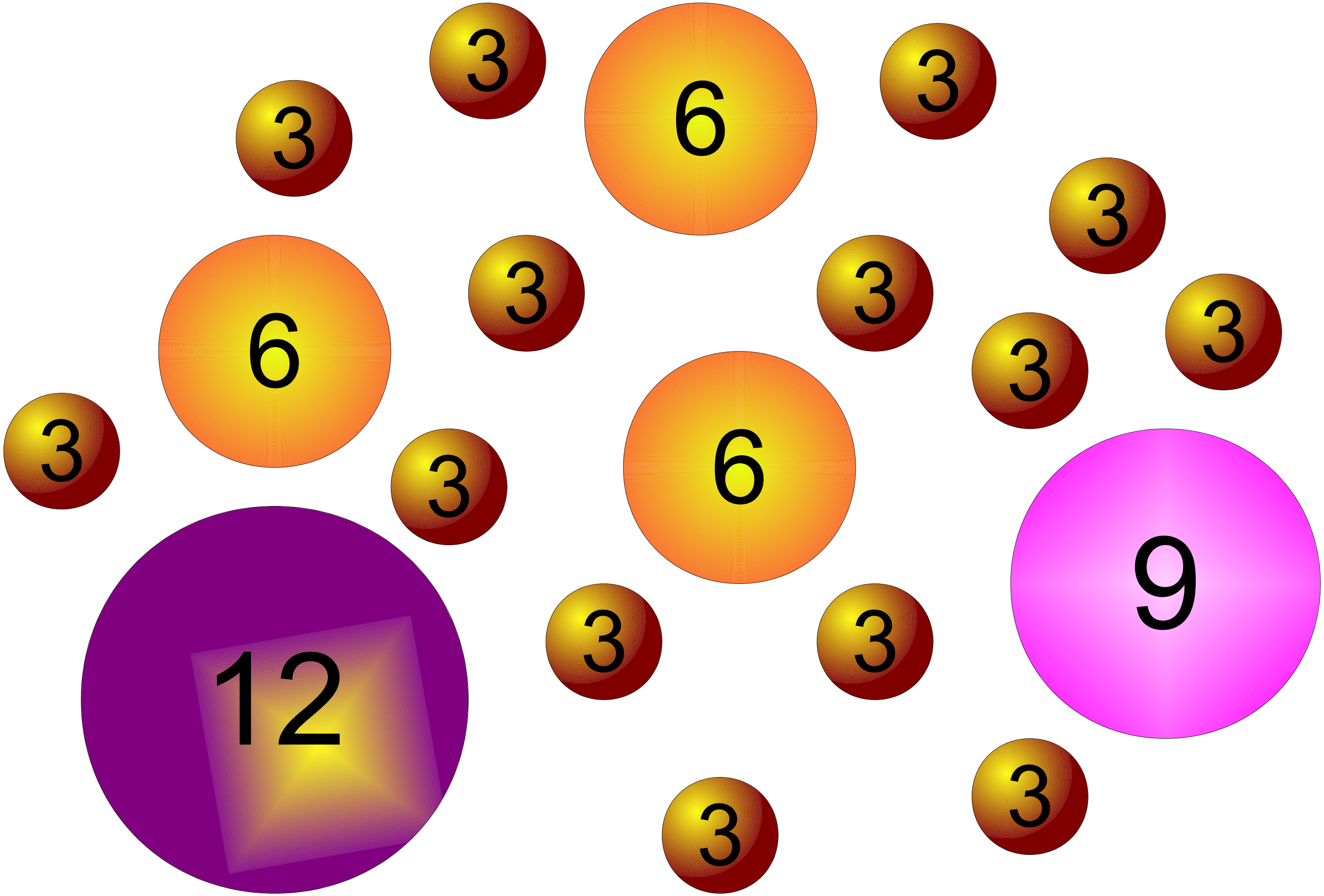
$$t_{eq} \sim \frac{R}{v} \sim 10^{-22}\,\mathrm{s}$$

Fireball lifetime

$$t_{\exp} \sim 10^{-22}\,\mathrm{s}$$

$$t_{loc} \ll t_{\exp}, \qquad t_{eq} \sim t_{\exp}$$

Multiquark admixture



Neutrons, protons, six–quark clusters, ...

Cluster probability

Cluster compositeness number z_i
(number of quarks in a cluster)

Density of clusters $\rho_i = \frac{N_i}{V}$

Total number N of quarks in volume V

Average density of matter $\rho = \frac{N}{V} = \sum_i z_i \rho_i$

Cluster probability $w_i = \frac{z_i \rho_i}{\rho}$

Cluster interactions

Interaction strength

$$\Phi_{ij} = \int \Phi_{ij}(\vec{r})\, d\vec{r} = 2\pi\hbar^2 \frac{a_{ij}}{m_{ij}}$$

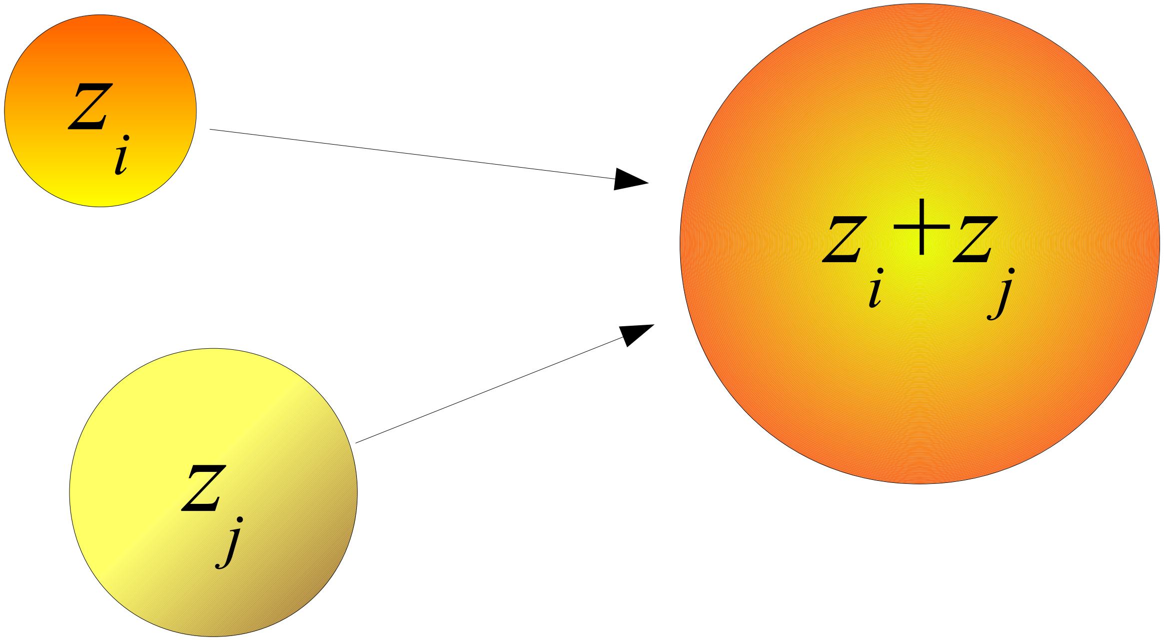
Scattering length

$$a_{ij}$$

Reduced mass

$$m_{ij} = \frac{m_i m_j}{m_i + m_j}$$

Reaction of fusion



Conservation of energy: $\sum_i E_i = const$

Conservation of compositeness number:

$$\sum_i z_i = const$$

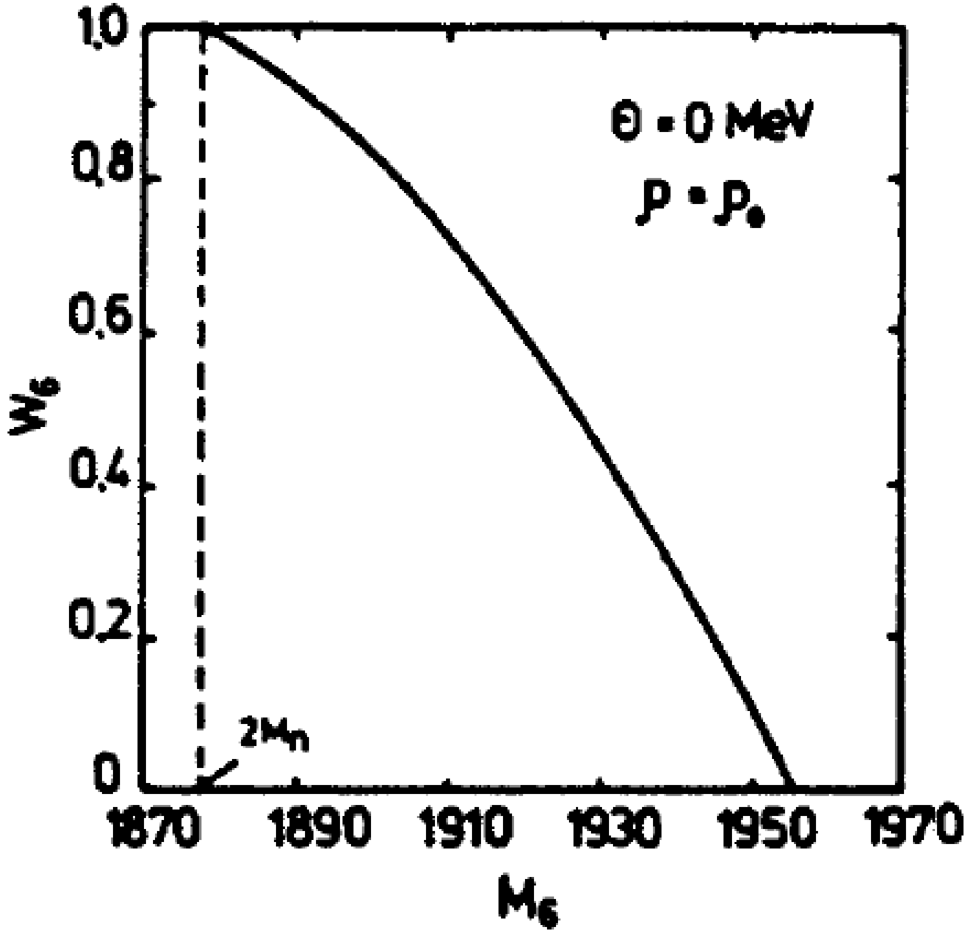
Interaction relations

$$\frac{\Phi_{ij}}{z_i z_j} = \frac{\Phi_{mn}}{z_m z_n}$$

All interactions can be expressed through a known nucleon – nucleon interactions

$$\boxed{\frac{\Phi_{ij}}{z_i z_j} = \frac{\Phi_{33}}{9}}$$

Φ_{33} Bonn potential

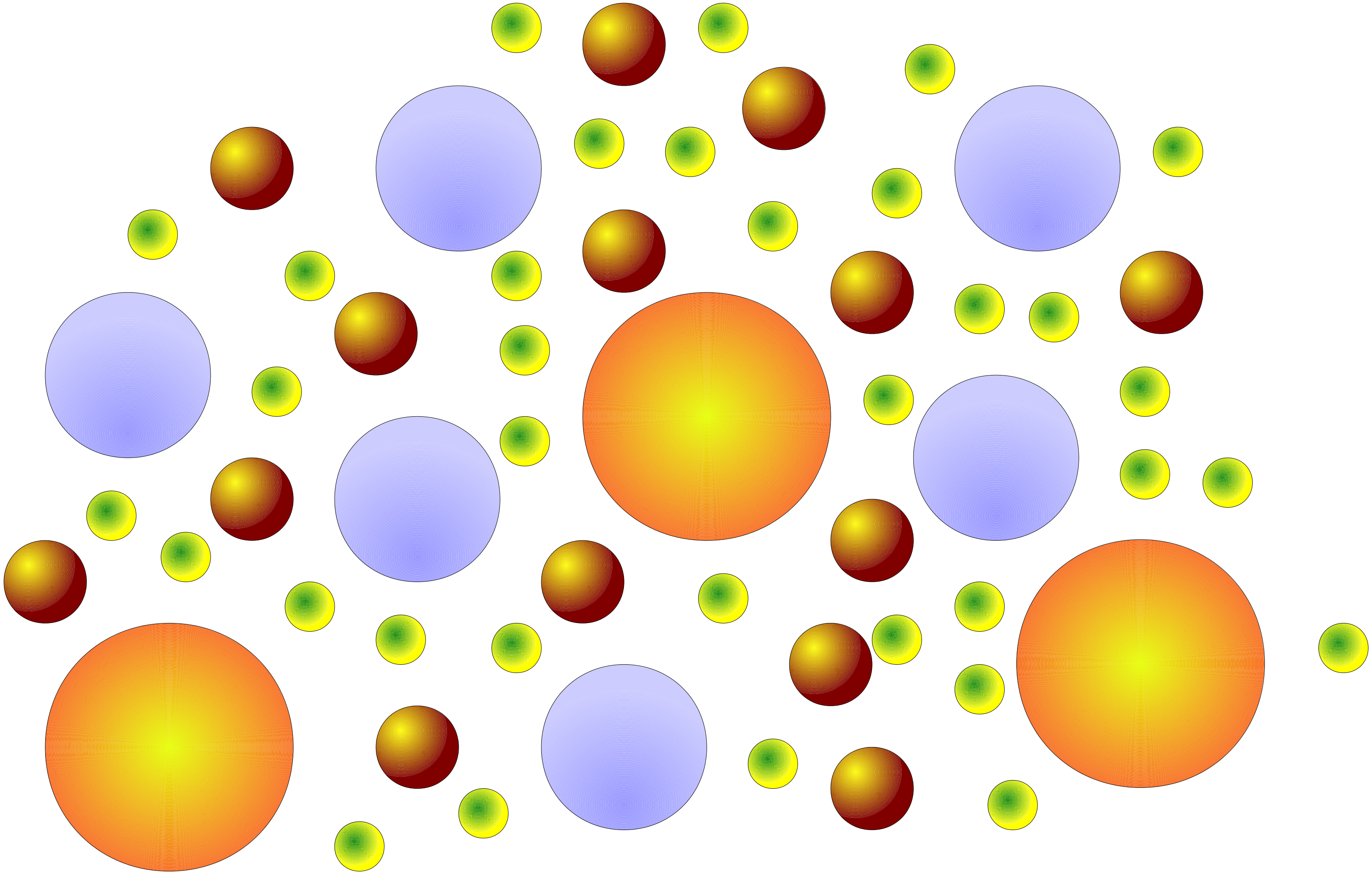


Probability of 6-quark cluster vs mass at $T = 0$ and

$$\rho = \rho_0 = 3\rho_{oB} = 0.5/\mathrm{fm}^{-3}$$

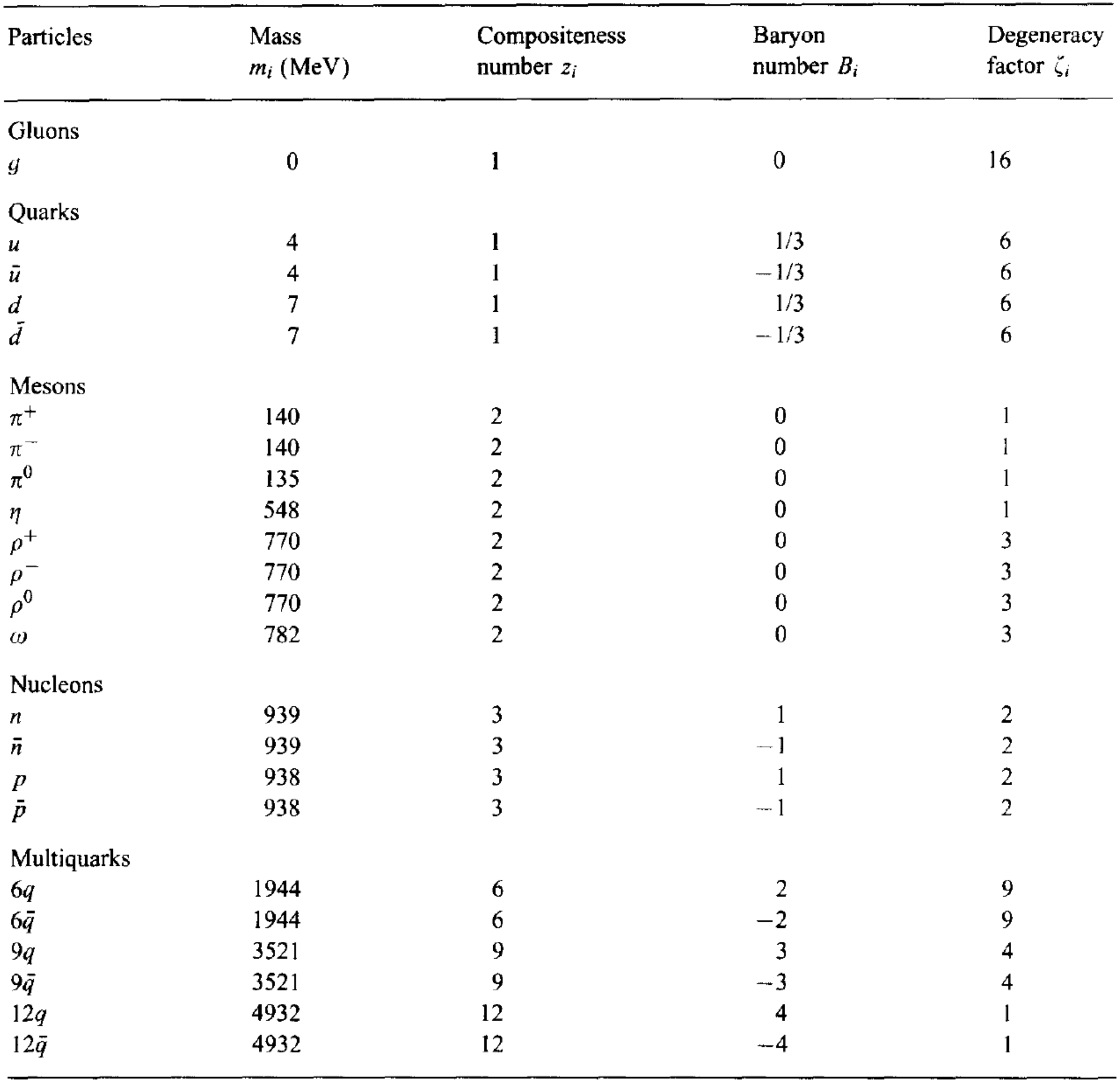
(normal quark density nuclear matter}

Multicomponent quark-hadron matter

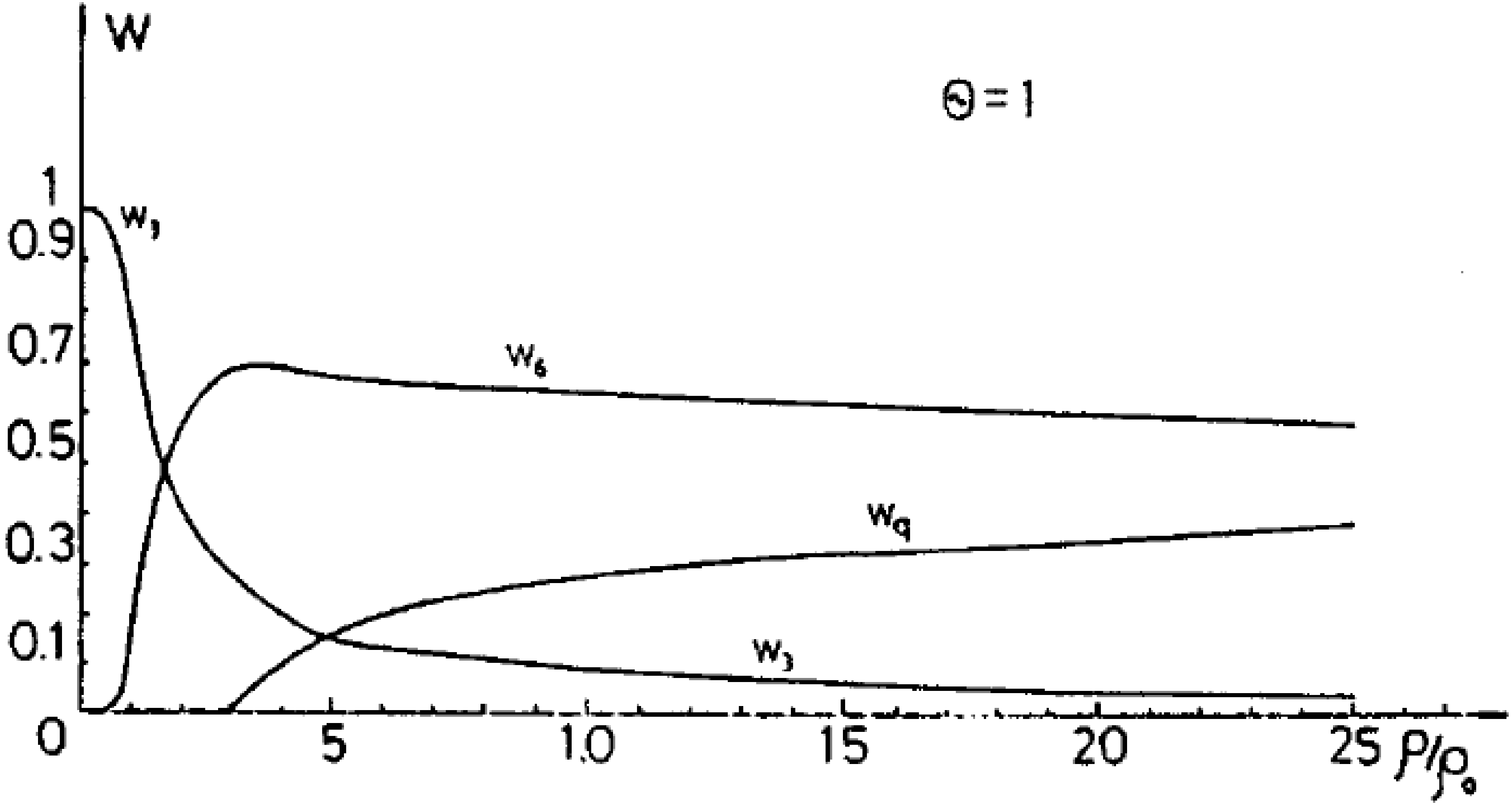


Quarks, gluons, mesons, nucleons, multiquarks

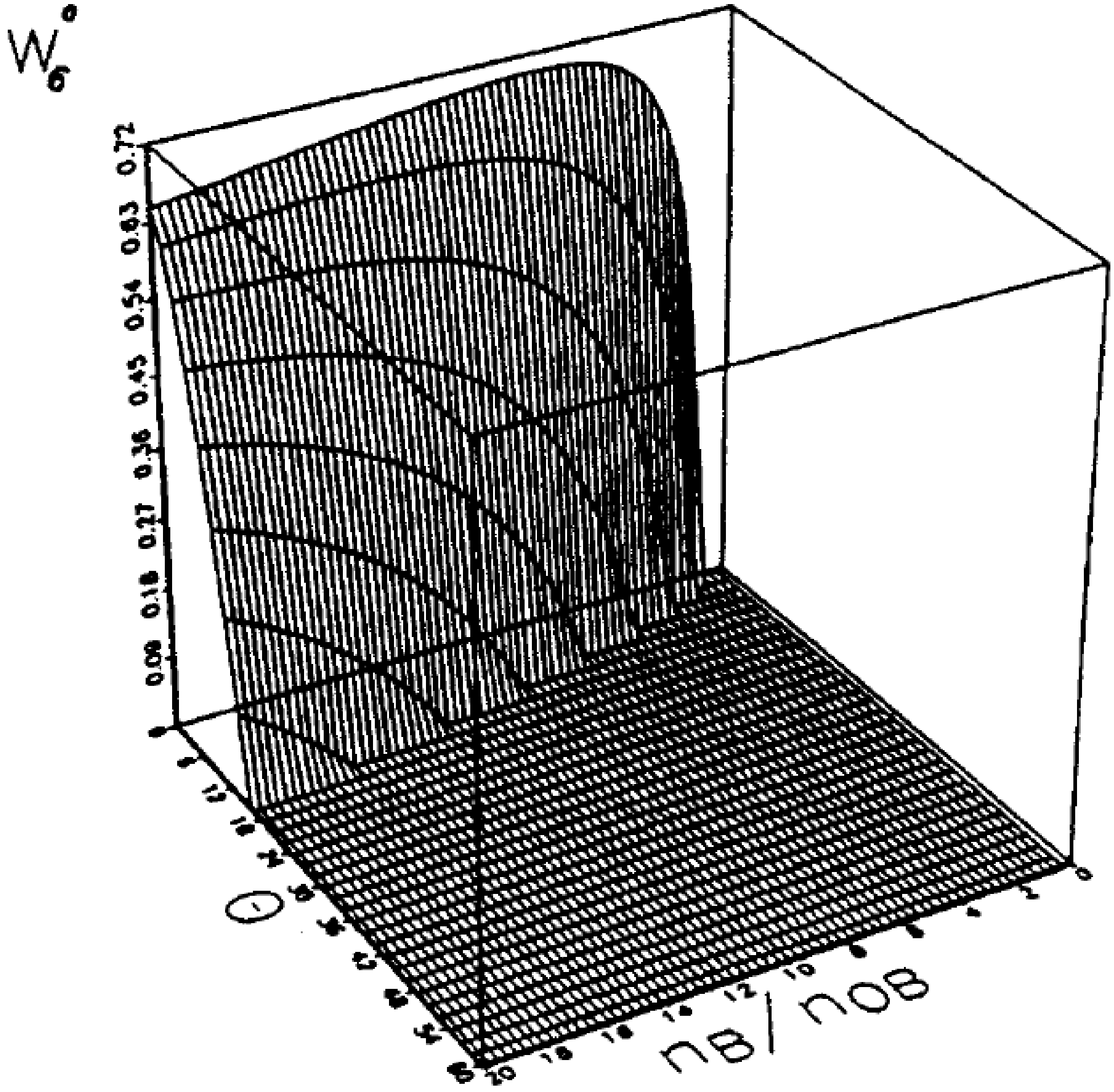
Constituents taken into account



Particles	Mass m_i (MeV)	Compositeness number z_i	Baryon number B_i	Degeneracy factor ζ_i
Gluons				
g	0	1	0	16
Quarks				
u	4	1	1/3	6
$\bar{u}$	4	1	−1/3	6
d	7	1	1/3	6
$\bar{d}$	7	1	−1/3	6
Mesons				
π^+	140	2	0	1
π^-	140	2	0	1
π^0	135	2	0	1
η	548	2	0	1
ρ^+	770	2	0	3
ρ^-	770	2	0	3
ρ^0	770	2	0	3
ω	782	2	0	3
Nucleons				
n	939	3	1	2
$\bar{n}$	939	3	−1	2
p	938	3	1	2
$\bar{p}$	938	3	−1	2
Multiquarks				
$6q$	1944	6	2	9
$6\bar{q}$	1944	6	−2	9
$9q$	3521	9	3	4
$9\bar{q}$	3521	9	−3	4
$12q$	4932	12	4	1
$12\bar{q}$	4932	12	−4	1



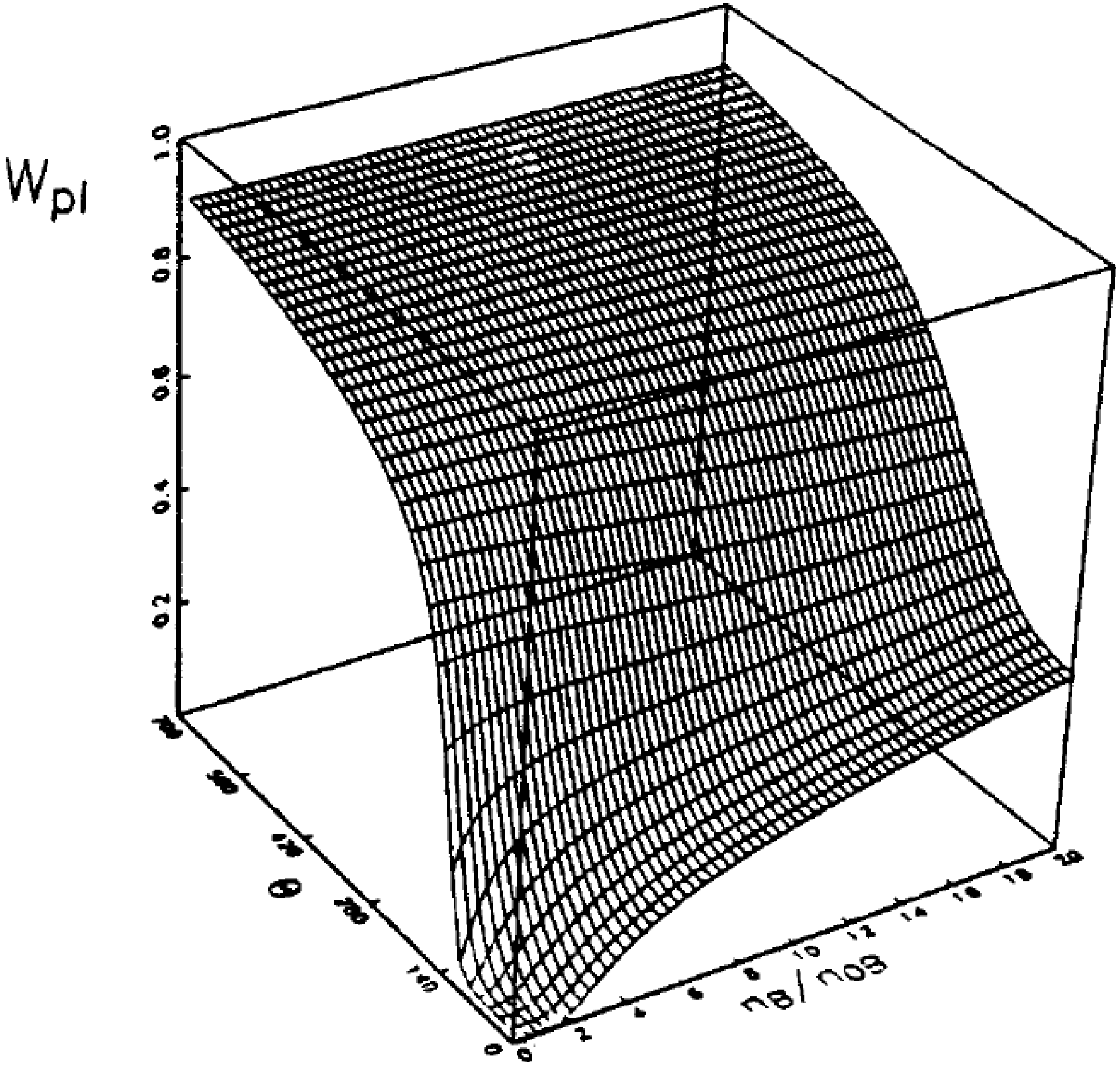
Nucleon, 6-quark cluster, and quark probabilities as functions of the relative density at $T = 0$



Probability of Bose-condensed 6-quark clusters as a function of temperature and reduced density.

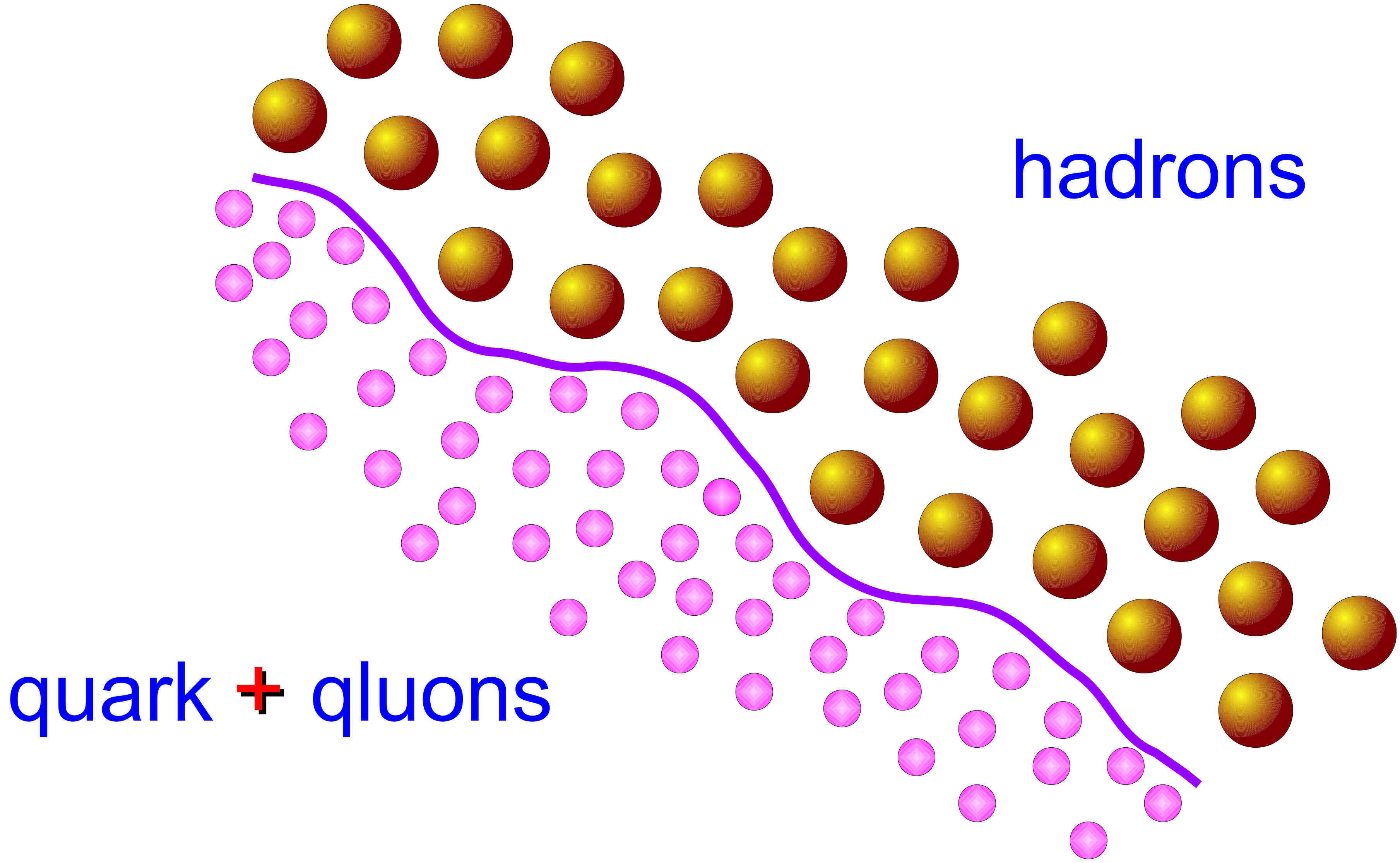
Quark-gluon probability

$$w_{qg} = \frac{1}{\rho}\left(\rho_g + \rho_u + \rho_d + \bar{\rho}_u + \bar{\rho}_d \right)$$



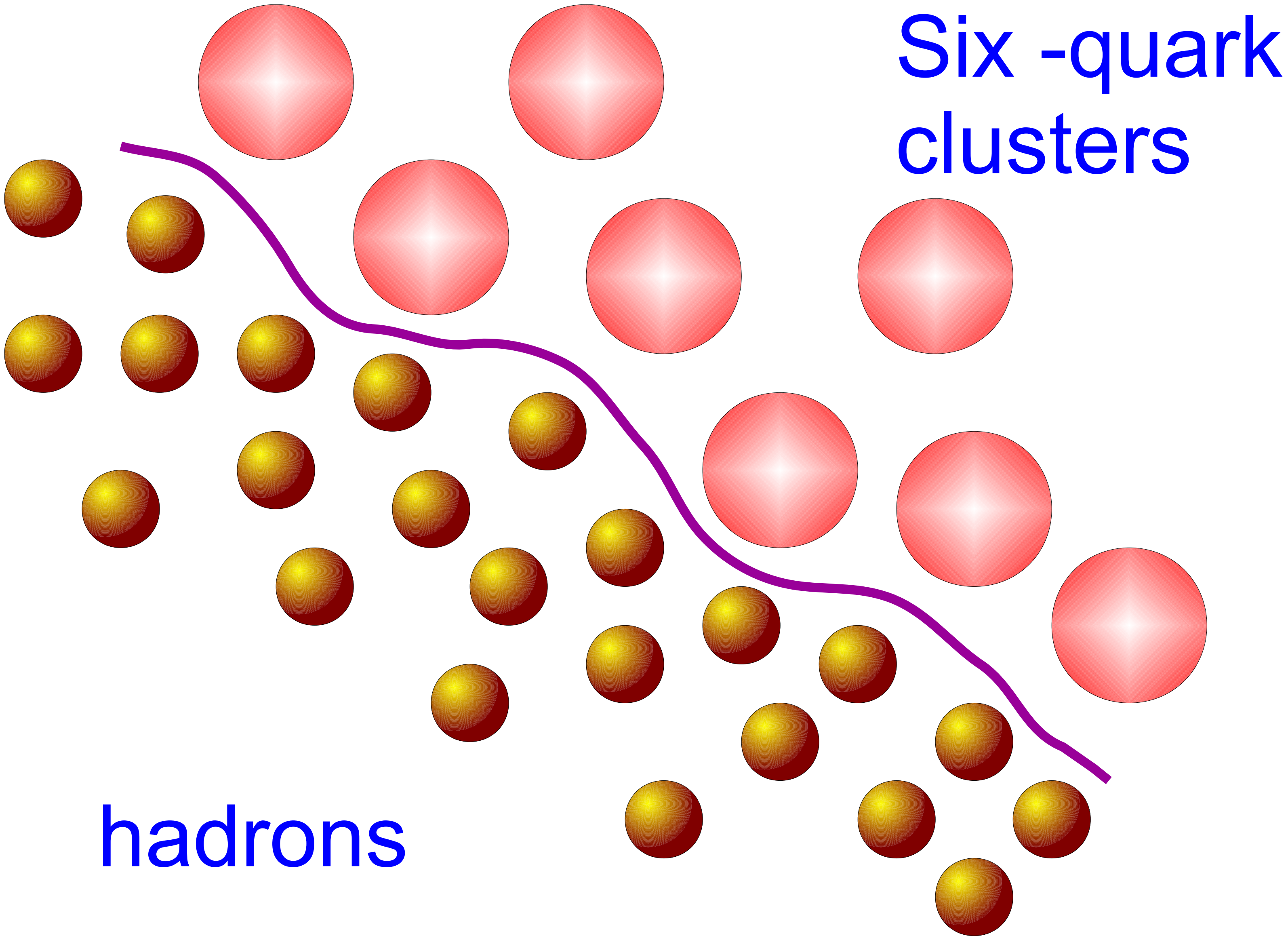
Deconfinement-gradual
crossover

Stratified quark-hadron mixture

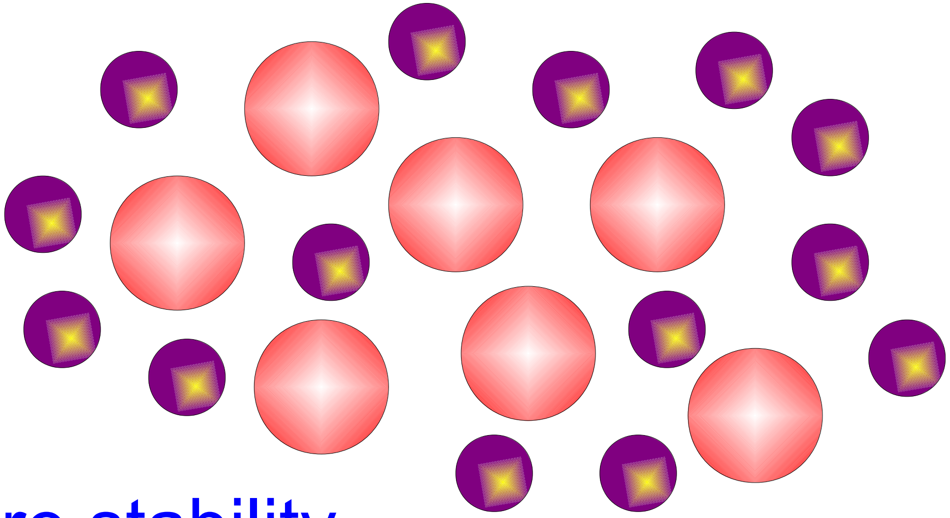


First – order phase transition

Stratified hadron-hadron mixture



Mixture of different clusters



Condition of mixture stability

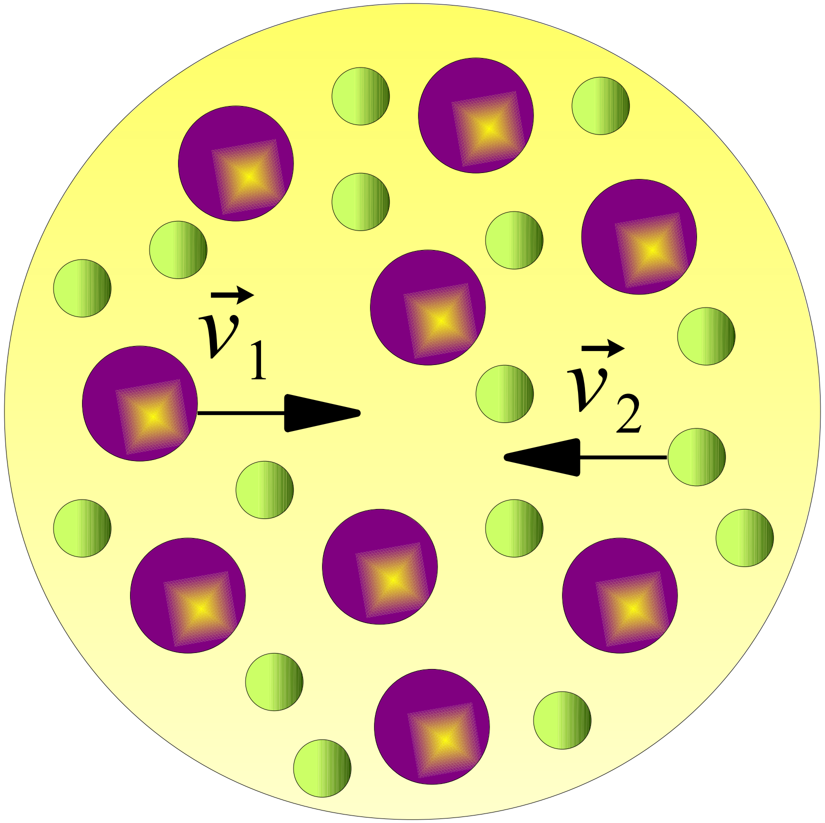
$$\Phi_{ij} - \sqrt{\Phi_{ii}\Phi_{jj}} < -\frac{2T}{\rho}\sum_i n_i \ln n_i$$

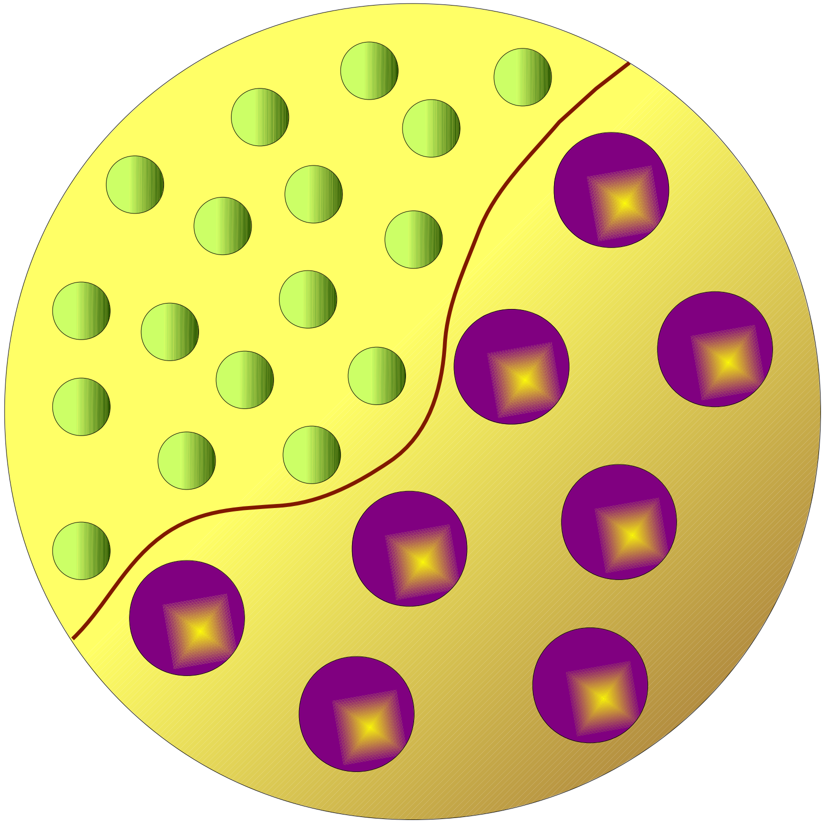
Cluster fraction

$$n_i = \frac{N_i}{N}$$

No stratification!

Counterflow instability





Relative velocity:

$$\vec{v} = \vec{v}_1 - \vec{v}_2$$

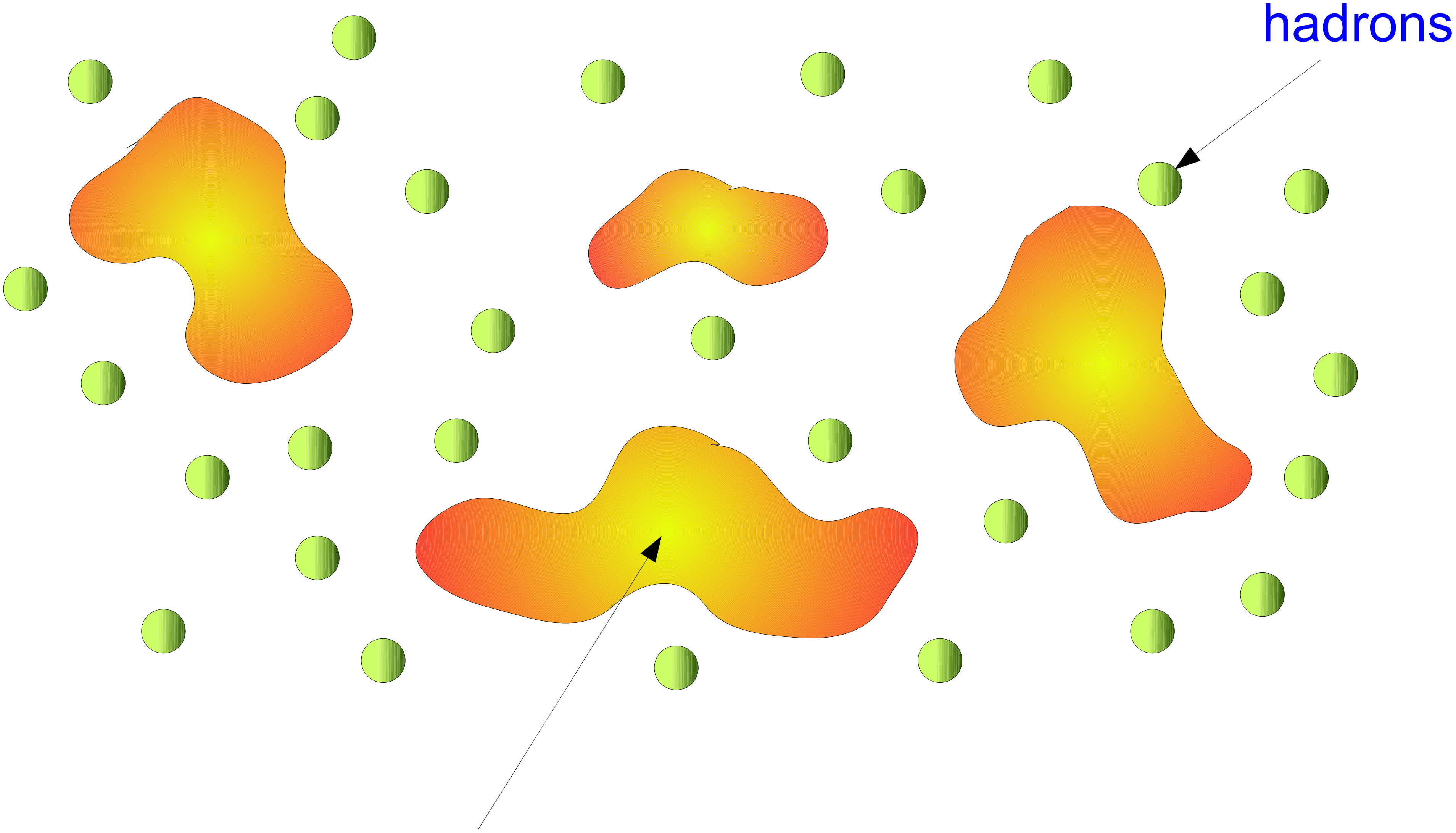
Stability conditions

$$\Phi_{12}^{2} < \left(\Phi_{11} - \frac{m_1}{\rho_1} v_1^2 \right) \left(\Phi_{2} - \frac{m_2}{\rho_2} v_2^2 \right)$$

Mixture is not stratified!

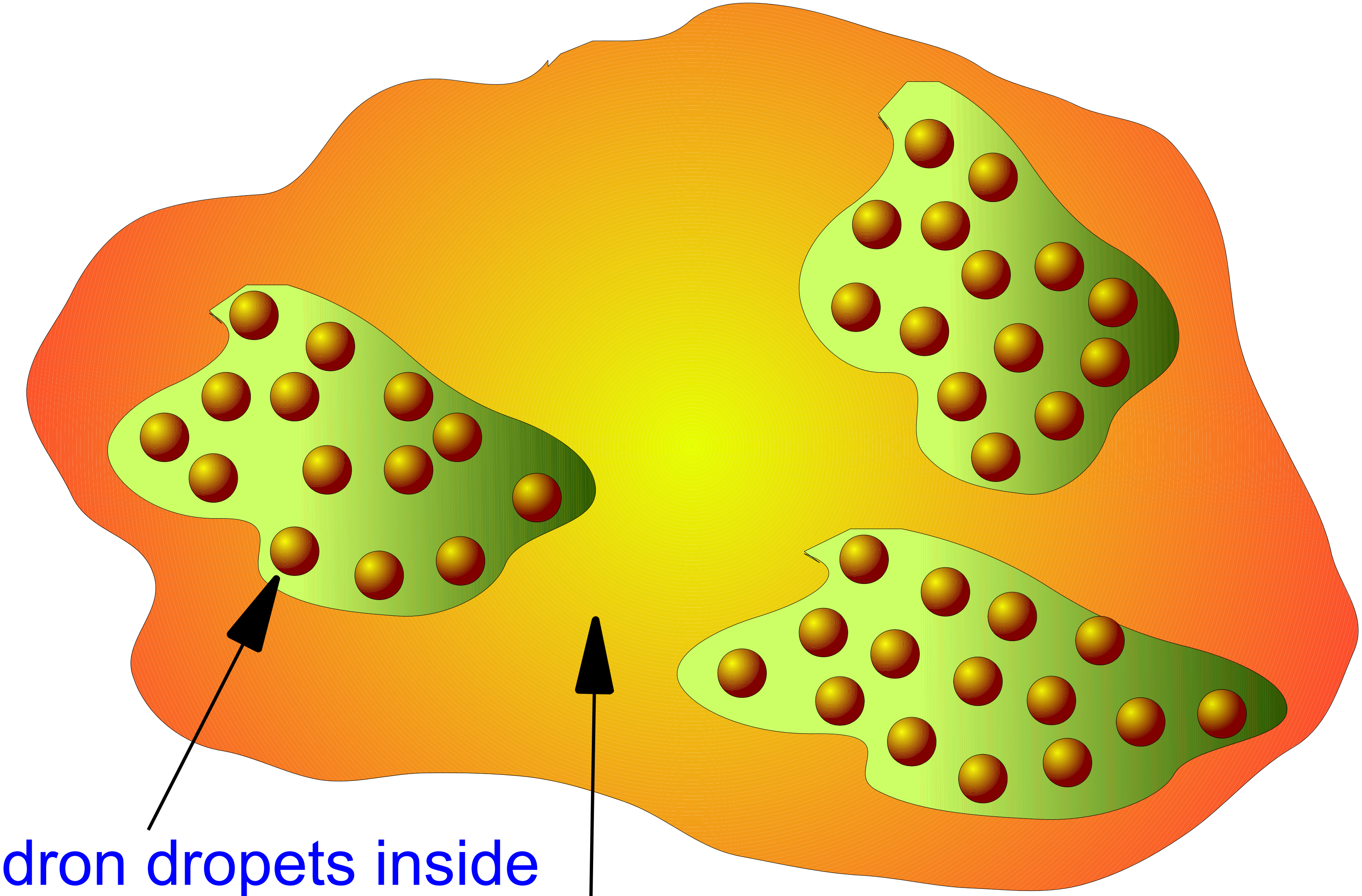
$$\Phi_{ij} = 2\pi\hbar^2 \frac{a_{ij}}{m_{ij}}$$

Heterophase quark – hadron matter



hadrons

droplets of quark-gluon plasma inside hadron sea



Hadron dropets inside

quark- gluon plasma

Mesoscopic size of heterophase droplets

Mean interparticle distance	a
Typical size of a droplet	l
Fireball radius	R

$$a \ll l \ll R$$

Mesoscopic lifetime of heterophase droplets

Local equilibration time t_{loc}

Lifetime of a heterophase droplet t_{het}

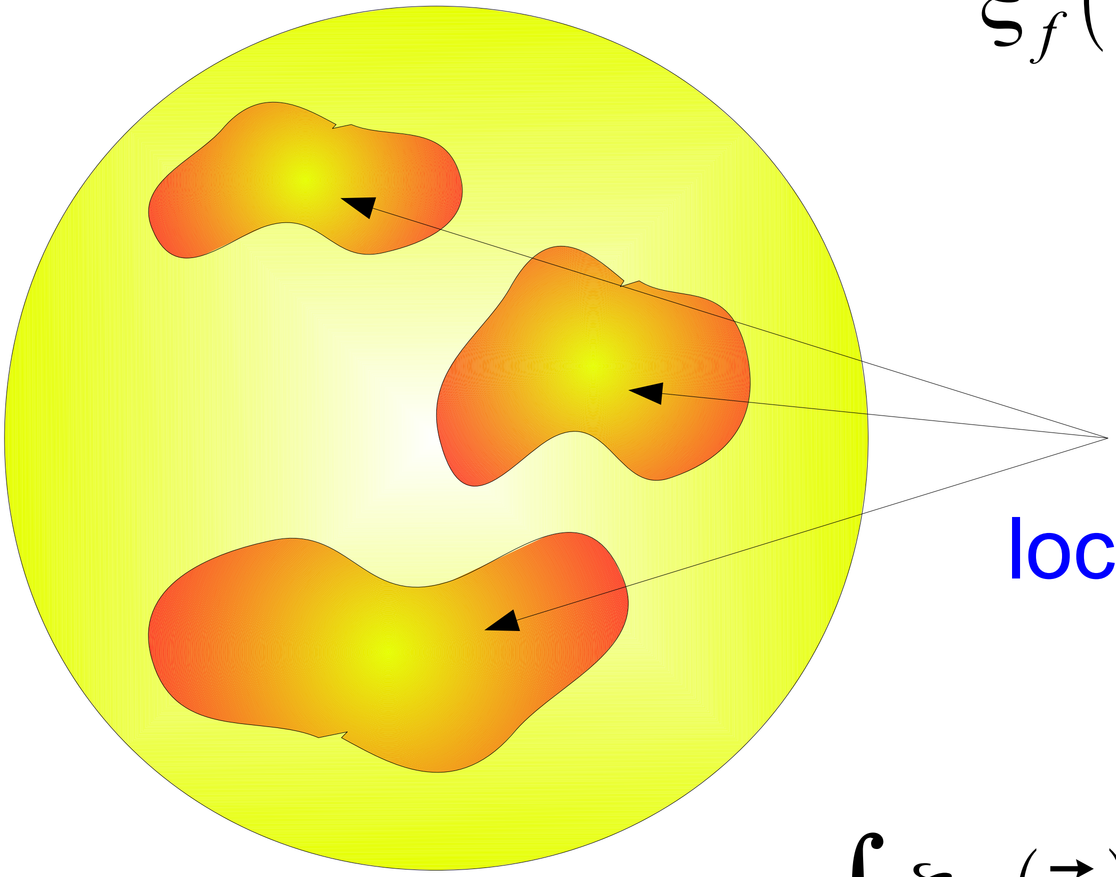
Lifetime of a fireball $t_{\exp}$

$$t_{loc} \ll t_{het} \ll t_{\exp}$$

Phase probability

Manifold indicator function

$$\xi_f(\vec{r}) = \begin{cases} 1\,, & \vec{r} \in V_f \\ 0\,, & r \notin V_f \end{cases}$$



V_f

location of f - th phase

$$w_f \;=\; \int \xi_f(\vec{r})\; D\xi$$

Averaging over phase configurations

Hamiltonian $H(\xi)$

Partition function

$$Z = \mathrm{Tr} \int \exp\{-\beta H(\xi)\}\, D\xi$$

Effective Hamiltonian $\widetilde{H}$

$$\exp(-\beta \widetilde{H}) = \int \exp\{-\beta H(\xi)\} D\xi$$

$$Z = \mathrm{Tr}\, e^{-\beta \widetilde{H}}, \qquad \Omega = -T \ln Z$$

$$\min_{\{w_f\}} \Omega \longrightarrow w_f$$

Conclusion: Life is not easy

- Experimentally measured signals can be essentially different for different states.
- Nuclear matter can form principally different mixed phases, including quark-hadron matter.
- The most stable of the states is the most probable.

Thank you for attention!

V.I. Yukalov and E.P. Yukalova, Phys. Part. Nucl. 54 (2023) 1-68. *Models of mixed matter.*