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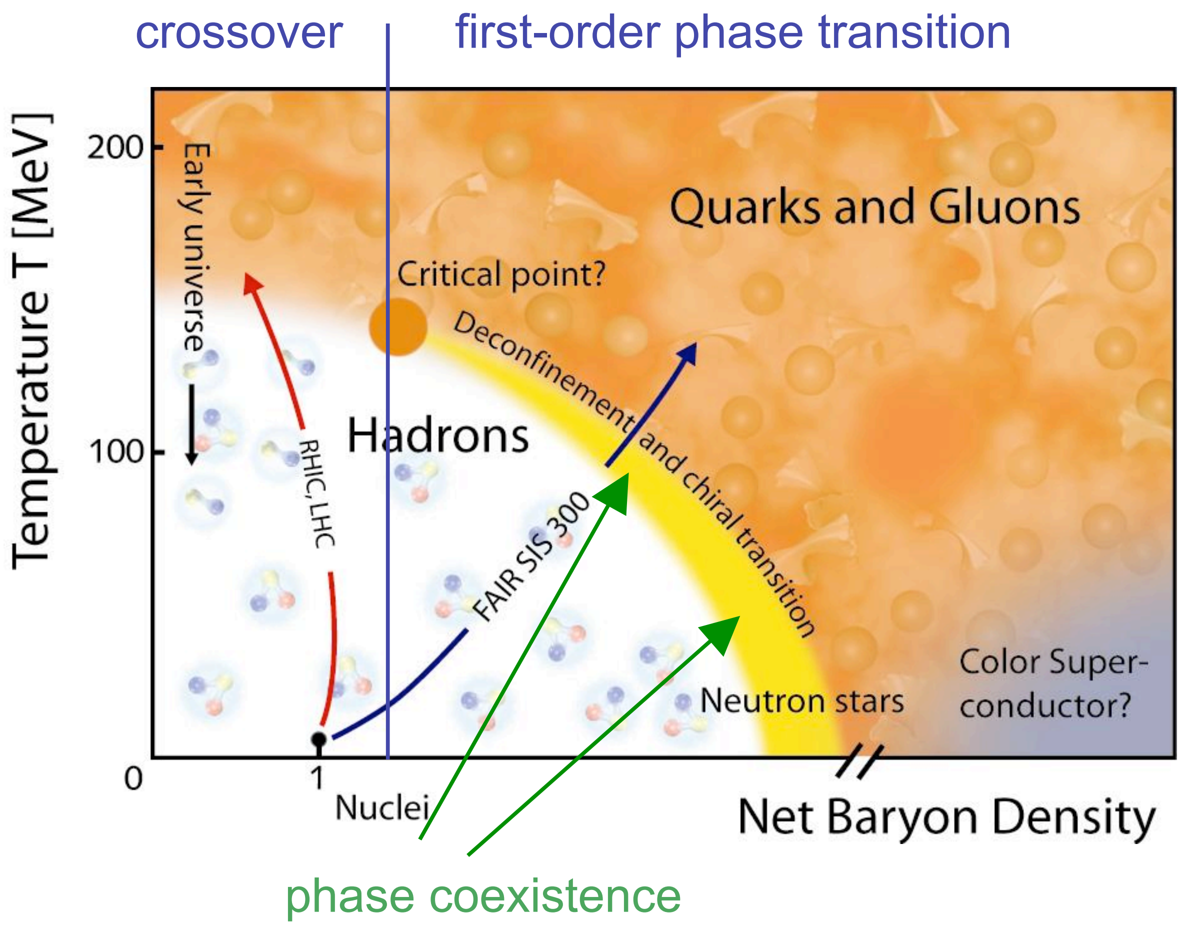
Signatures of a first-order hadronization transition?



1) What is a first-order phase transition?

2) Getting into the phase coexistence region?

3) What happens in the coexistence region?

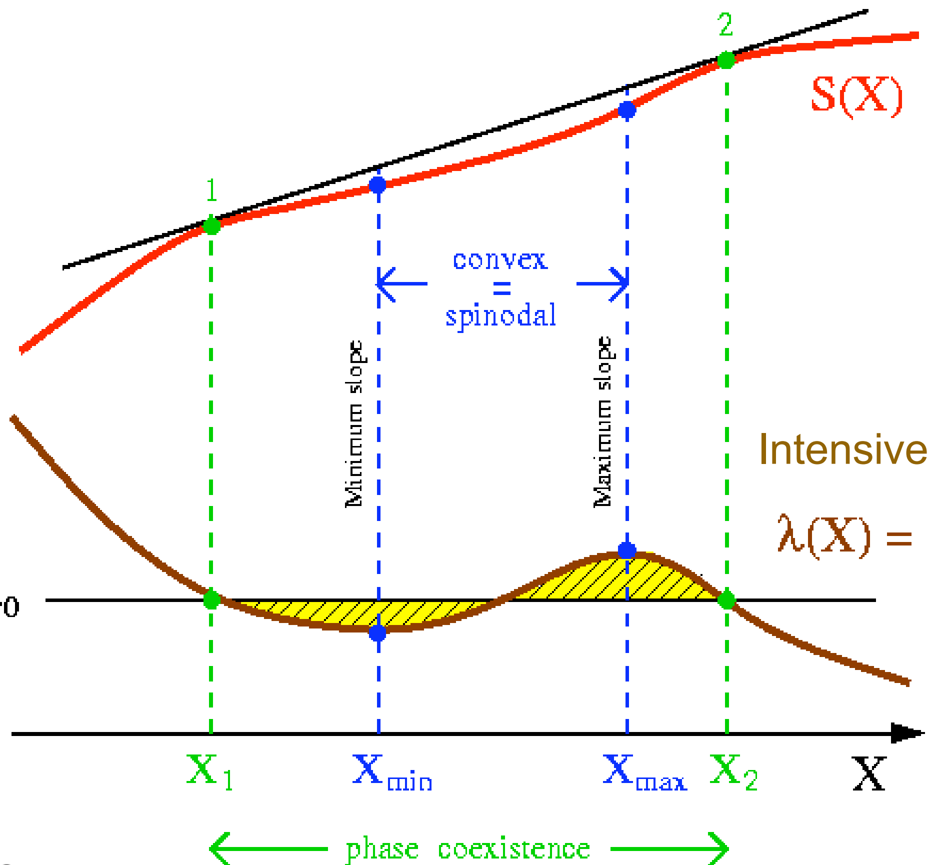
4) How can we detect it?

Phase coexistence <==> Spinodal instability

Extensive variable X

Entropy function S(X)

… occur when S(X) is locally convex:



Intensive variable:

$\lambda(X) = \cdot dS/dX$

[X=E => λ=1/T]

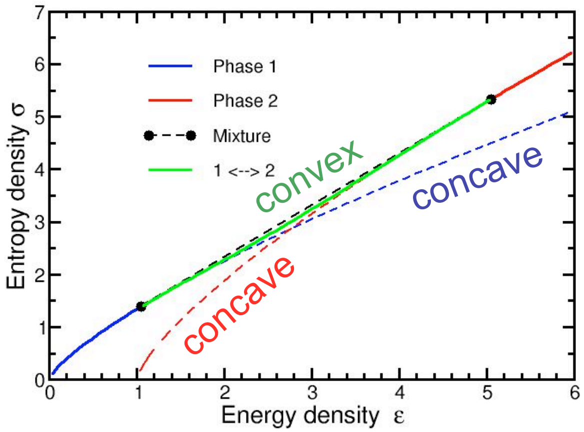
[X=V => λ= p/T]

Maxwell construction:

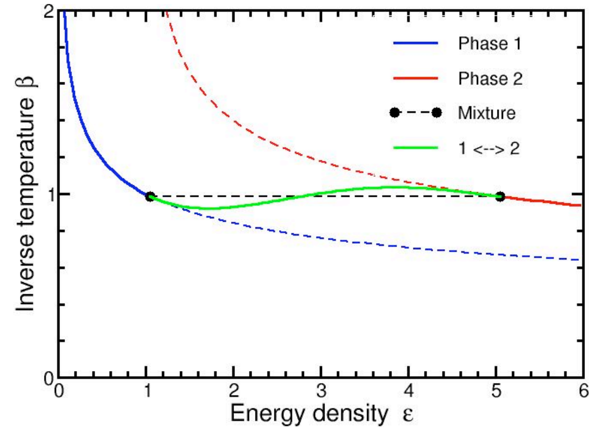
$$\int_{X_1}^{X_2} dX\,(\lambda(X) - \lambda_0) = 0$$

Example: No conserved charges

Entropy density: $\sigma(\varepsilon)$

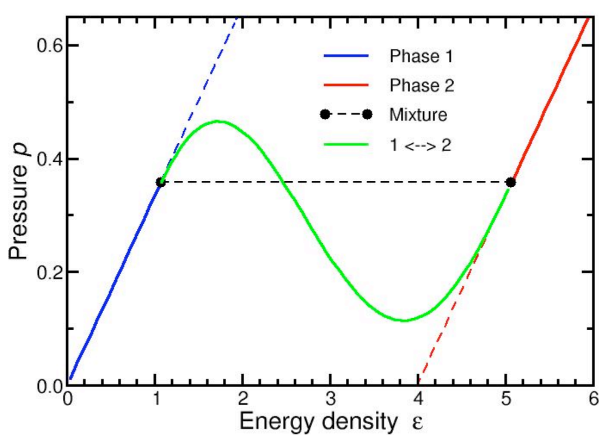


Inverse temperature: $\beta(\varepsilon) = \partial\sigma/\partial\varepsilon$

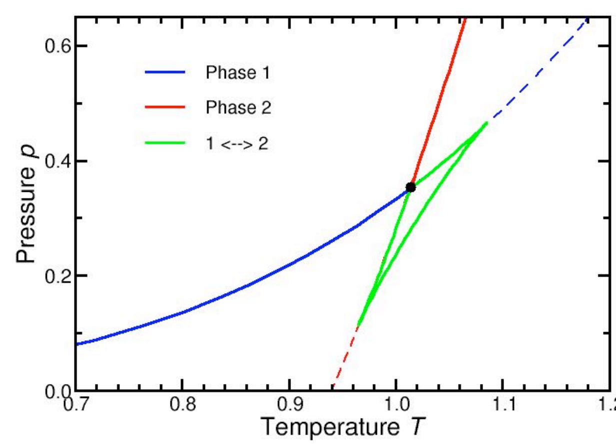


Equation of State

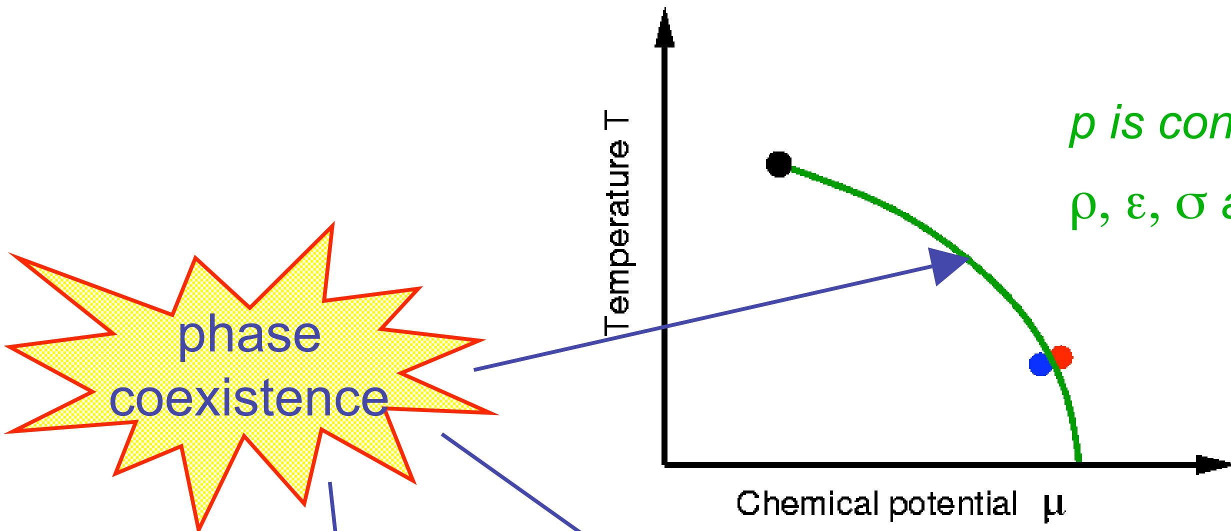
Pressure: $p(\varepsilon) = T\sigma - \varepsilon$



Pressure: $p(T)$



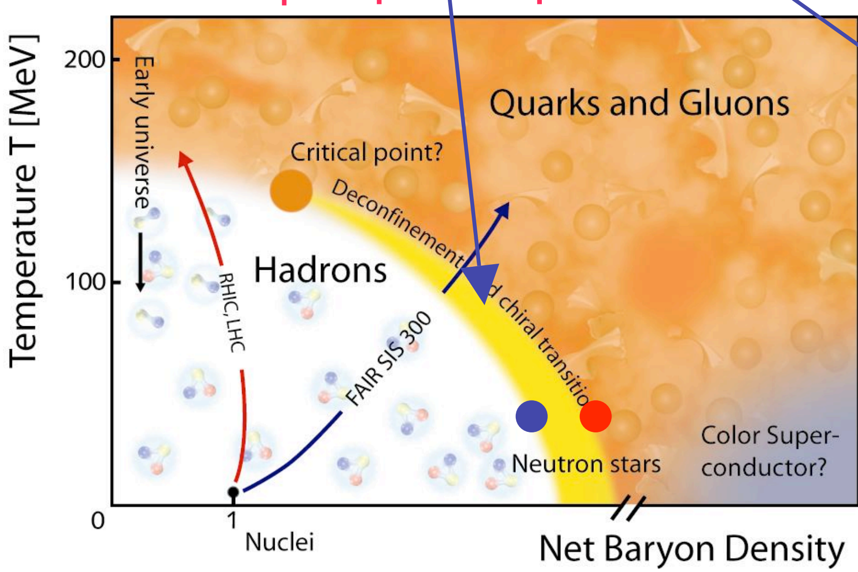
Example: One conserved charge



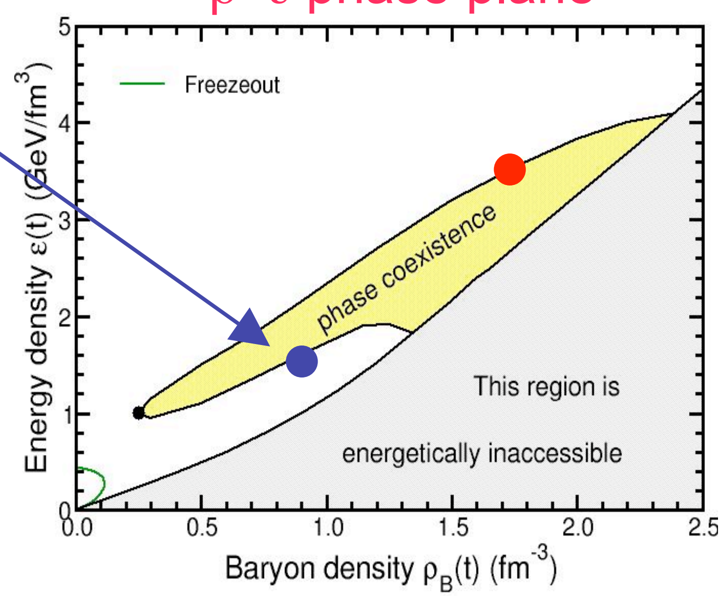
p is continuous but

ρ, ε, σ *are discontinuous!*

ρ-*T* phase plane



ρ–ε phase plane



μ, T versus ρ, ϵ

Temperature: $T = 1/\beta$

Chemical potentials: μ_B , μ_Q , μ_S

… are *not* order parameters:

$p(\mu,T)$ is multi-valued

… do *not* obey conservation laws:

can change spontaneously

… exist *only* in equilibrium

Energy density: ϵ

Charge densities: ρ_B , ρ_Q , ρ_S

… *are* order parameters:

$p(\epsilon,\rho)$ is single-valued

… *do* obey conservation laws:

$$\partial_\mu T^{\mu\nu} = 0 \ , \quad \partial_\mu j^\mu = 0$$

… *always* exist

=> are well suited for dynamics

Dynamical trajectories in the ρ - ε phase plane

Contributors (so far):

3-fluid: *Yuri Ivanov et al.*

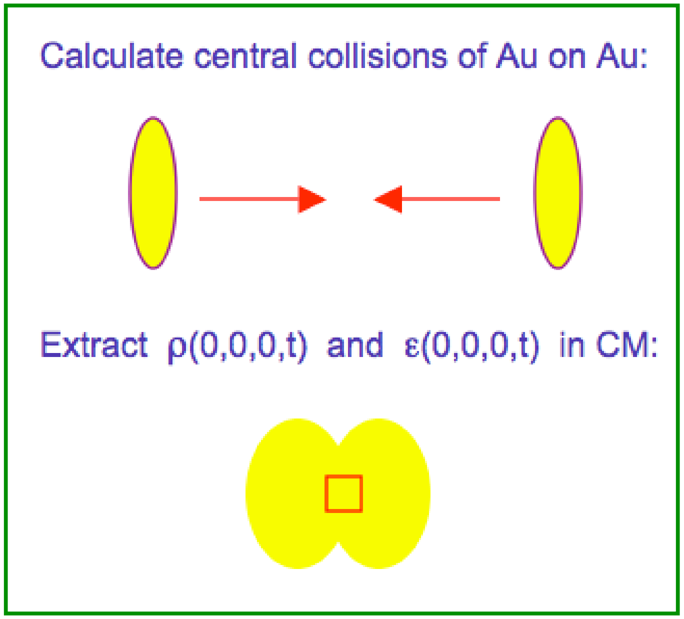
PHSD: *Wolfgang Cassing et al.*

QGSM: *Viatchelav Toneev et al.*

GiBUU: *Alexei Larionov*

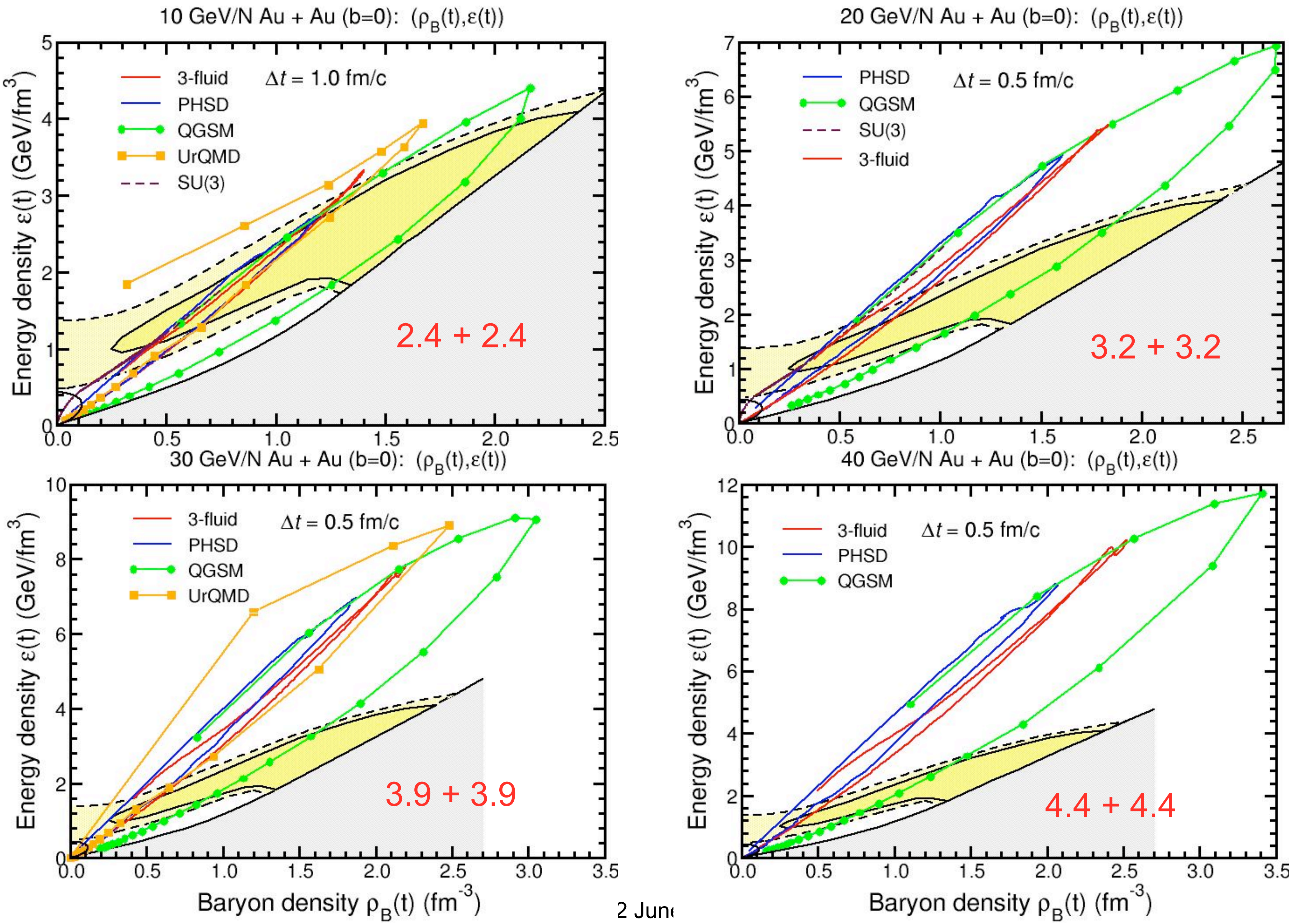
UrQMD: *Ionut Arsene & Larissa Bravina*

SU(3): *Gebhard Zeeb & Detlef Zchiesche* (adiabatic expansion)



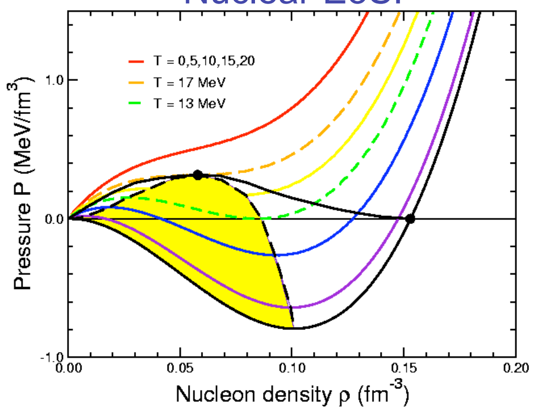
… plus in contact with others (the more the merrier)

Dynamical trajectories in the ρ - ε phase plane

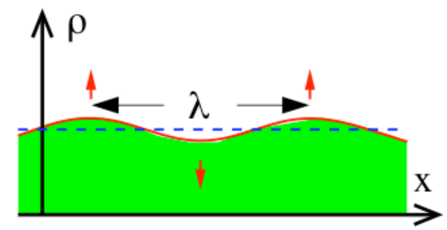


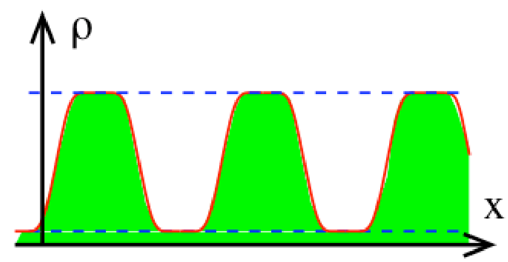
Spinodal decomposition

Nuclear EoS:



Density undulations
are amplified:



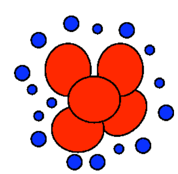


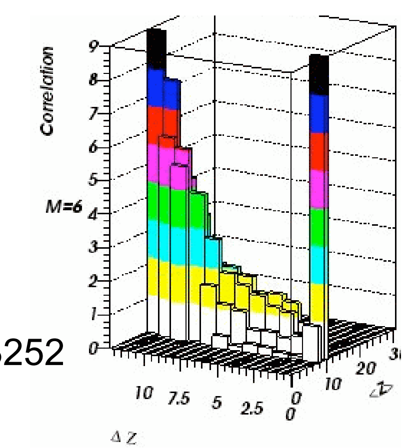
Long-wavelength distortions grow slowly
(it takes time to relocate the matter)

Short-wavelength distortions grow slowly
(they are hardly felt due to finite range)

There is an *optimal wavelength*
that grows faster than all others

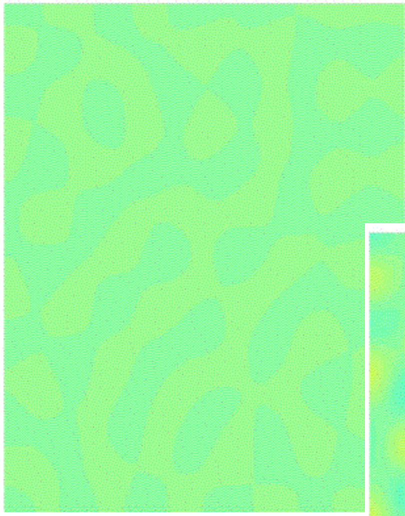
Ph Chomaz, M Colonna, J Randrup
Nuclear Spinodal Fragmentation
Physics Reports 389 (2004) 263



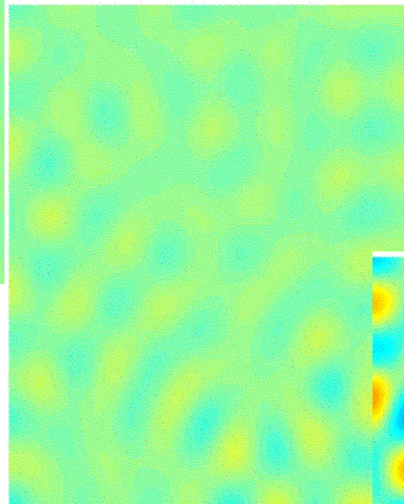


INDRA: PRL 86 (2001) 3252

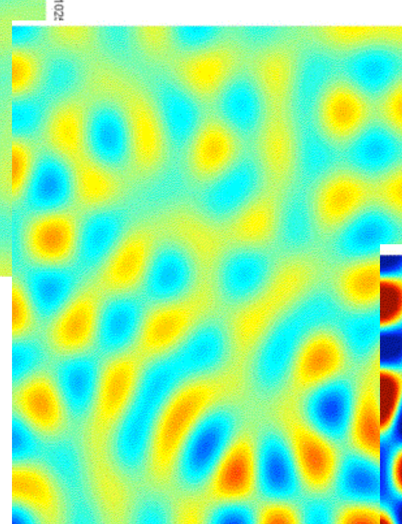
Emergence of spinodal patterns:



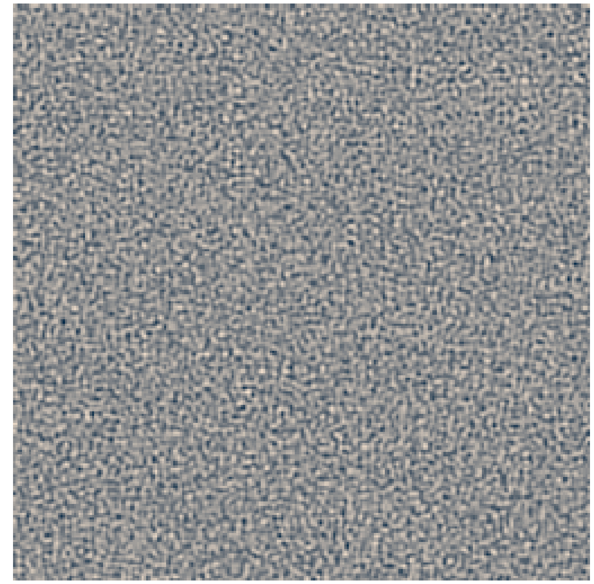
t = 0



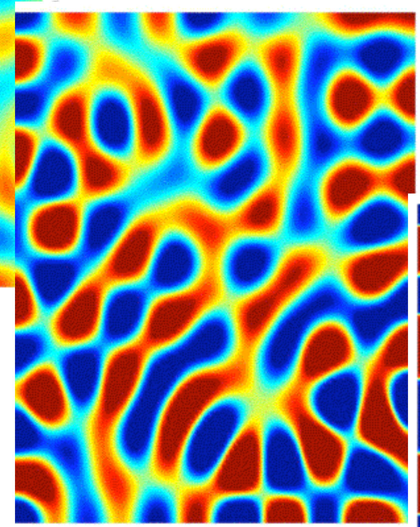
t = 1



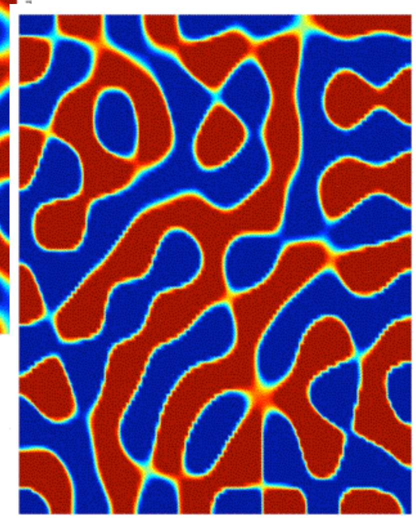
t = 2

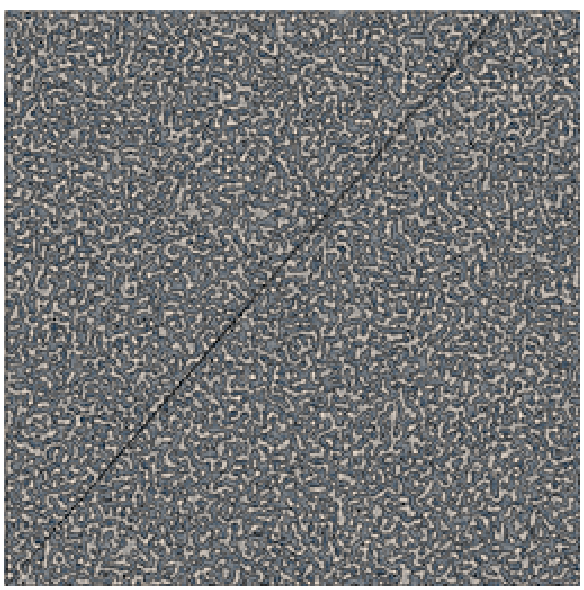


t = 3



t = 4





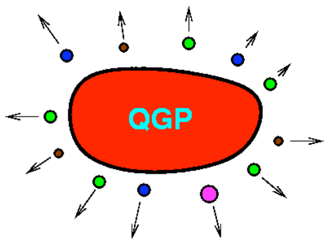
Does spinodal hadronization occur in high-energy nuclear collisions?

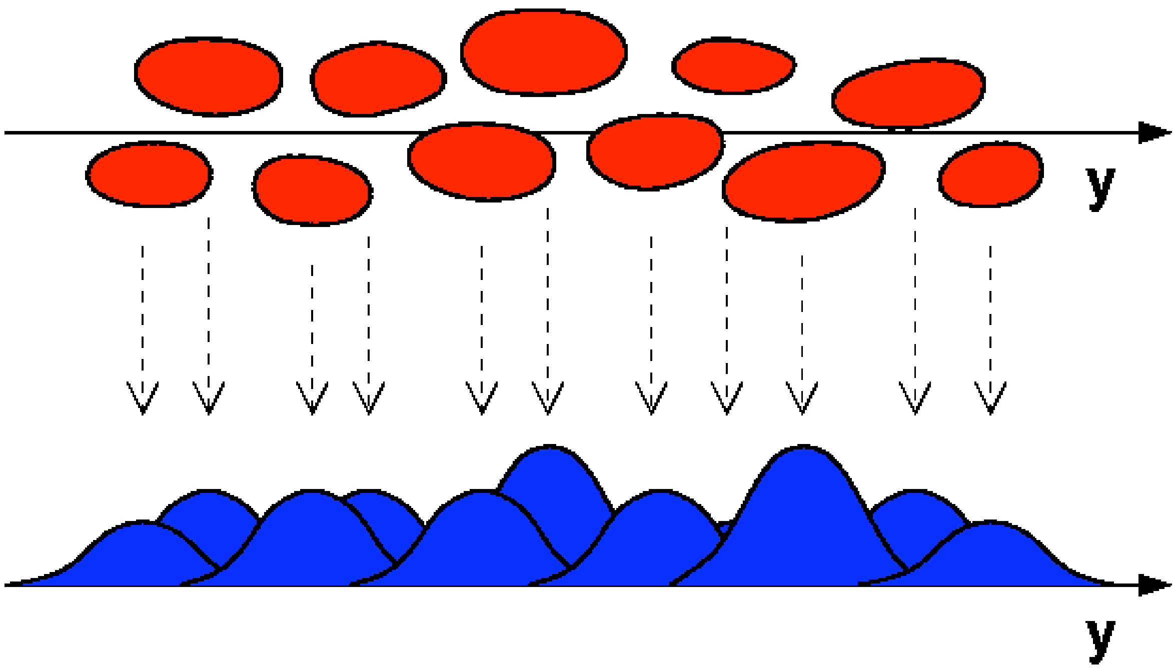
There is yet no reliable dynamical model
(especially in the phase-transition region):
Accurate predictions are hard to make!

Nevertheless, it is possible to look for
the phenomenon experimentally.

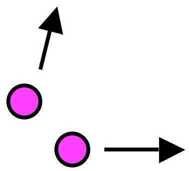
What might be suitable observables
to signal spinodal hadronization?

The expanding system decomposes into plasma blobs which hadronize thermally:

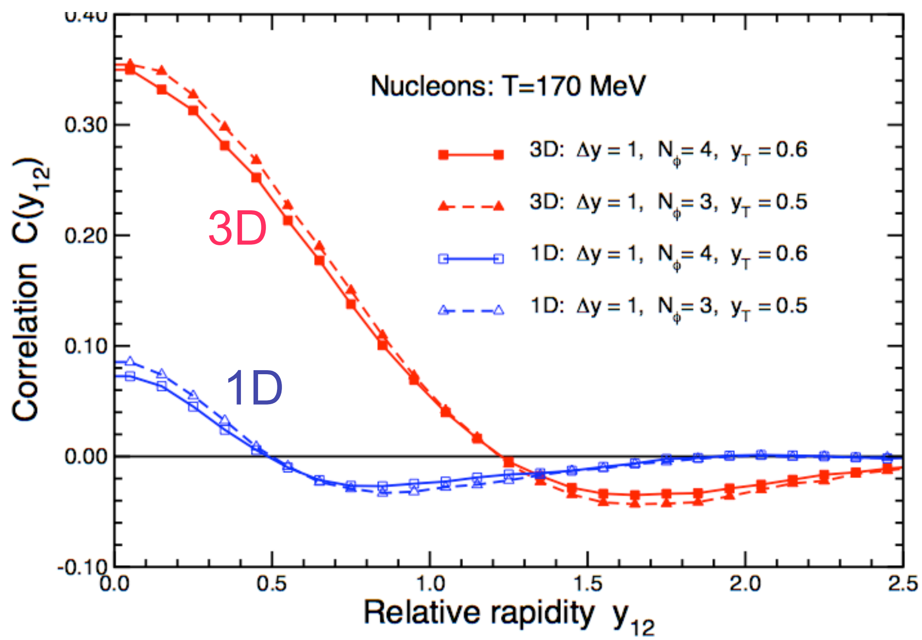




Relative rapidity correlations

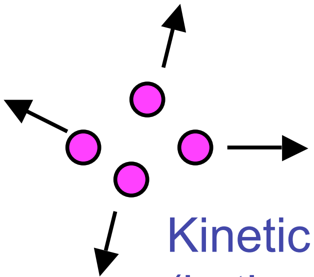


$$m_1 m_2 \gamma_{12} = p_1 \cdot p_2 = E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2 \quad \Rightarrow \quad y_{12}$$



[J. Randrup, J. Heavy Ion Physics 22 (2005) 69]

Kinematic clumping =>



Invariant-mass correlations

Total four-momentum:

$$P\{\boldsymbol{p}_n\} = \sum_n (E_n, \boldsymbol{p}_n)$$

Kinetic energy per particle (in the N-body CM frame):

$$\kappa_N\{\boldsymbol{p}_n\} = \frac{1}{N}\left[[P\{\boldsymbol{p}_n\}\cdot P\{\boldsymbol{p}_n\}]^{\frac{1}{2}} - \sum_n m_n \right]$$

Distribution of κ:

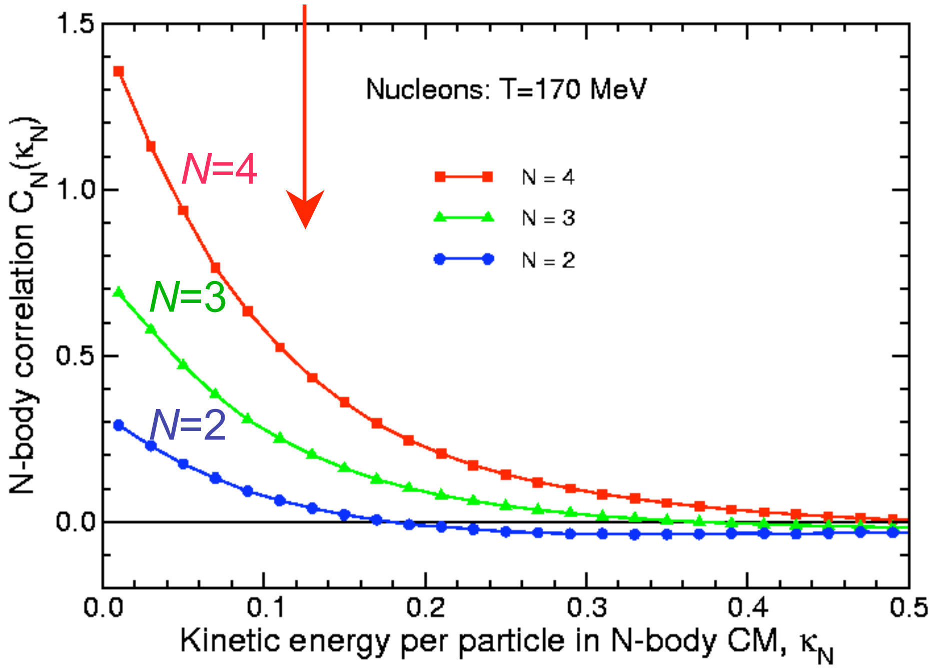
$$P_N(\kappa) \equiv \prec \delta(\kappa - \kappa_N\{\boldsymbol{p}_n\}) \succ$$

Correlation function:

$$C_N(\kappa) \equiv P_N(\kappa) \,/\, P_N^0(\kappa) - 1$$

Same event / *Mixed* events

- is *enhanced* at $\kappa \approx T$



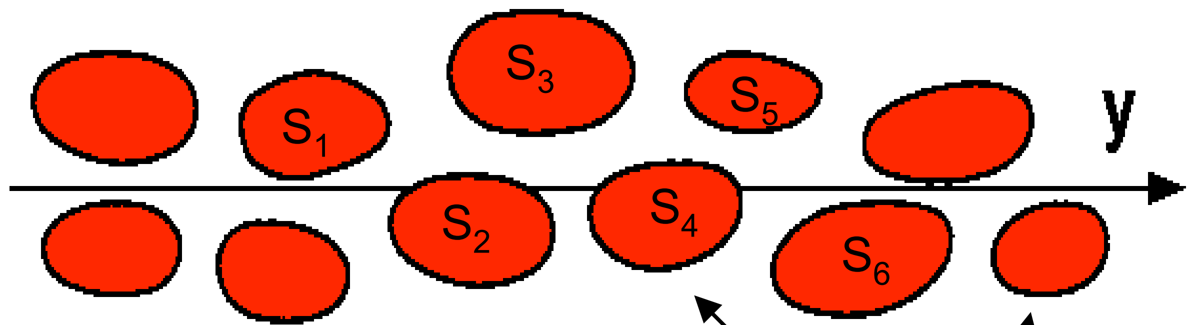
Higher-order correlations stand out more clearly!

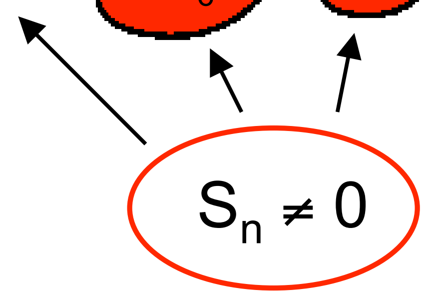
(but require larger samples)

[J. Randrup, J. Heavy Ion Physics 22 (2005) 69]

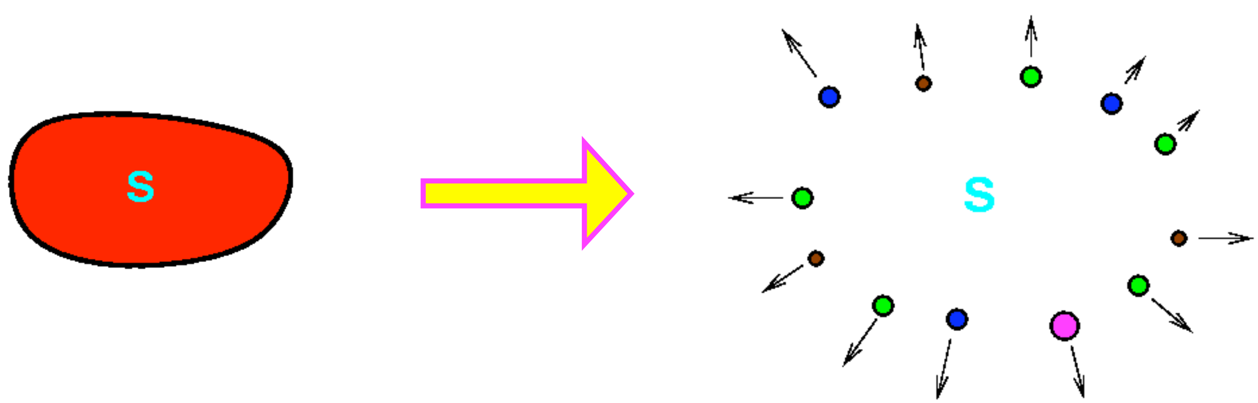
Strangeness correlations

The expanding system decomposes into plasma blobs which each contain a certain amount of strangeness:





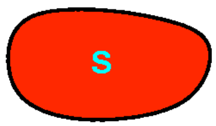
The hadronization of each isolated blob *conserves* strangeness:



[V. Koch, A. Majumder, J. Randrup, Phys. Rev. C72, 064903 (2005)]

Spinodal model: Plasma blobs form, expand & hadronize

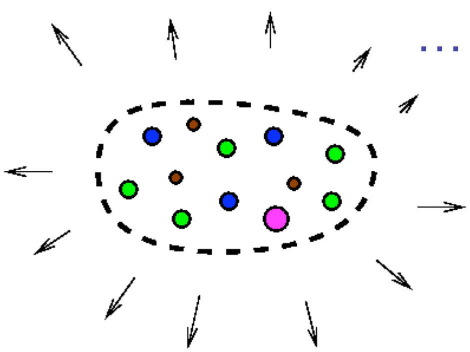
The plasma blob contains strange quarks and antiquarks:



$$\langle \nu \rangle = \langle \bar{\nu} \rangle \approx \zeta_s = \frac{3}{\pi^2} V_q T_q^3 \left(\frac{m_s}{T_q} \right)^2 K_2\left(\frac{m_s}{T_q}\right)$$

Its total strangeness, $S_0 = \nu_{\bar{s}} - \nu_s$, is conserved.

… expands …



… and hadronizes (at fixed S_0):

Freeze-out volume: $V_h = \chi\, V_q$

Freeze-out temperature: T_h

$$\zeta_k = \frac{g_k}{2\pi^2} V_h T_h^3 \left(\frac{m_k}{T_h} \right)^2 K_2\left(\frac{m_k}{T_h}\right) \mathrm{e}^{(\mu'_B B_k + \mu'_Q Q_k)/T_h}$$

$$\mathcal{Z}_{S_0} = \prod_k \left[\sum_{n_k \geq 0} \frac{\zeta_k^{n_k}}{n_k!} \right] \delta\left(\sum_k S_k n_k - S_0\right)$$

Canonical partition function

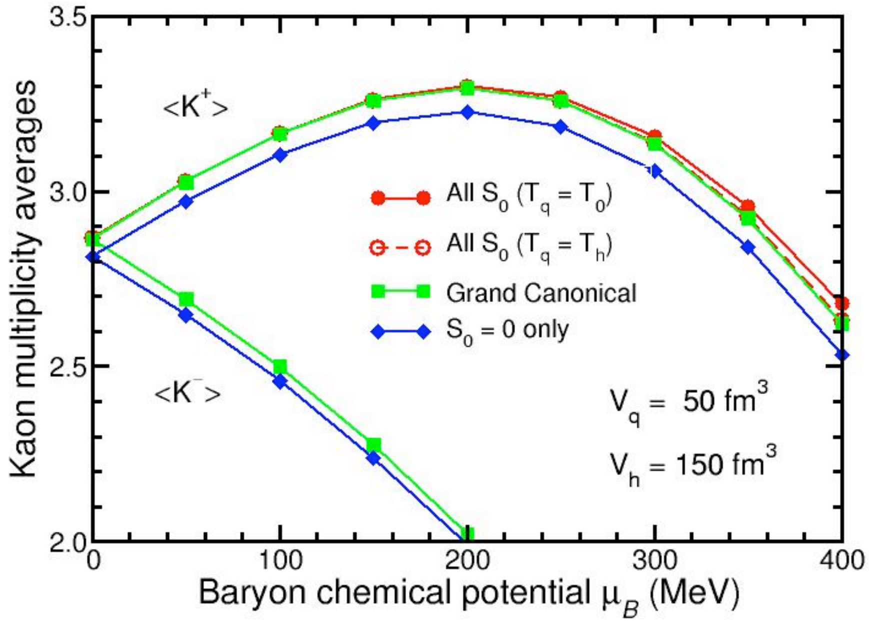
Kaon multiplicity distribution

1) Grand-canonical equilibrium in the hadron blob (V_h = 150 fm^3): $\langle S_0 \rangle = 0$

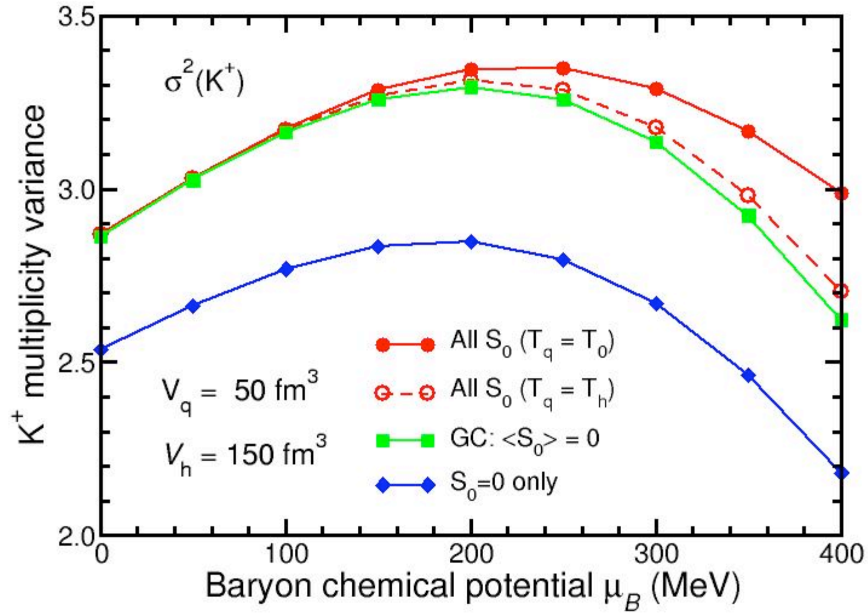
2) Canonical equilibrium in V_h demanding *zero* net strangeness: $S_0 = 0$

3) Canonical equilibrium in V_h with S_0 selected in the plasma (V_q = 50 fm^3)

Average

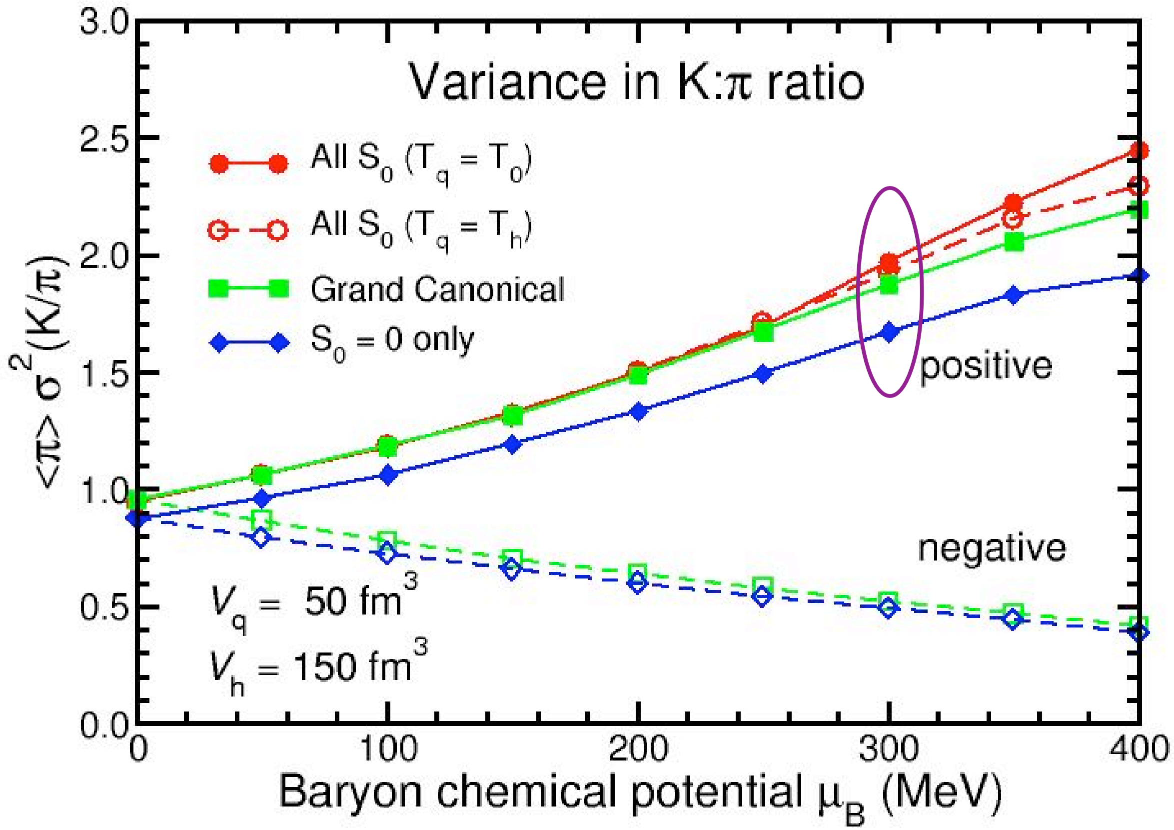


Variance

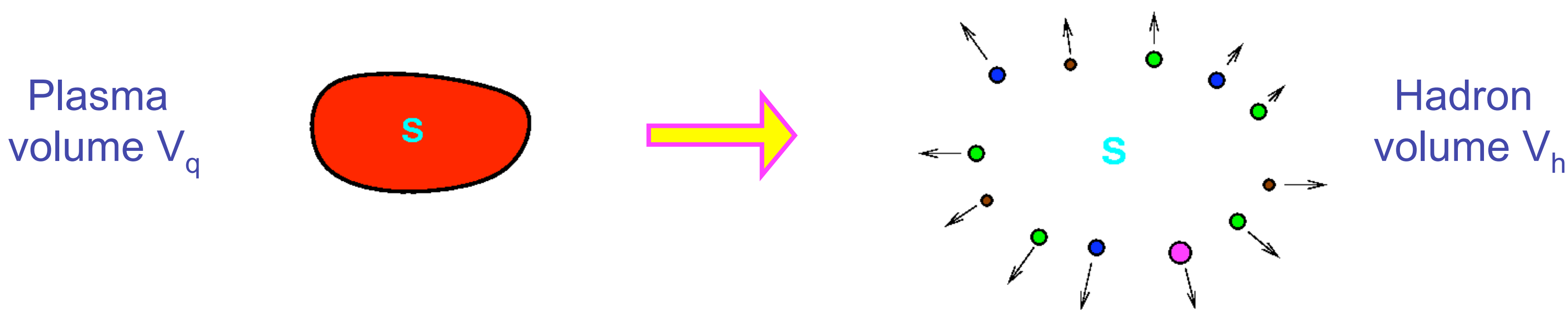


Distribution of the *K*-to-π ratio

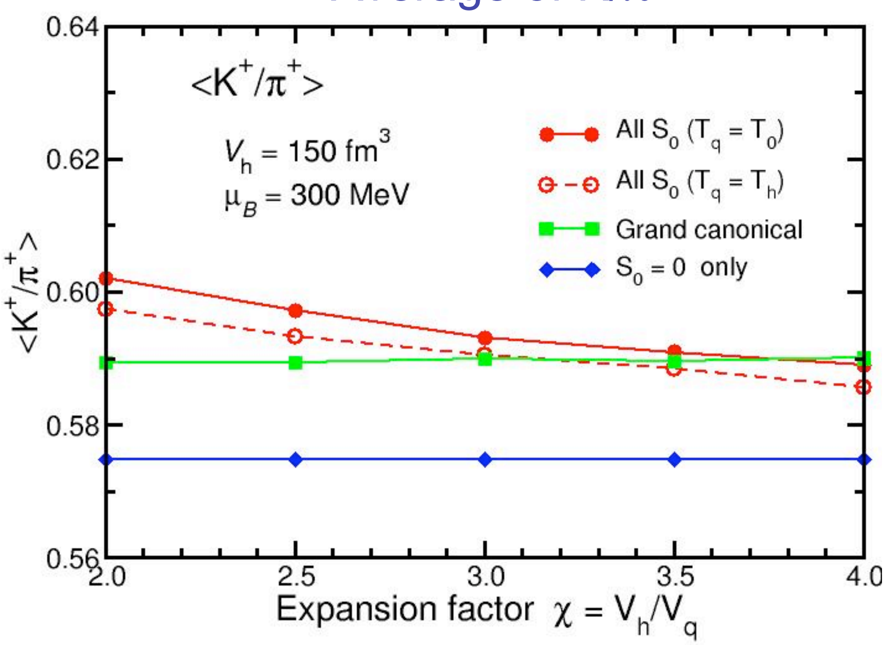
Variance in (N_K / N_π) × Normalized by the average N_π



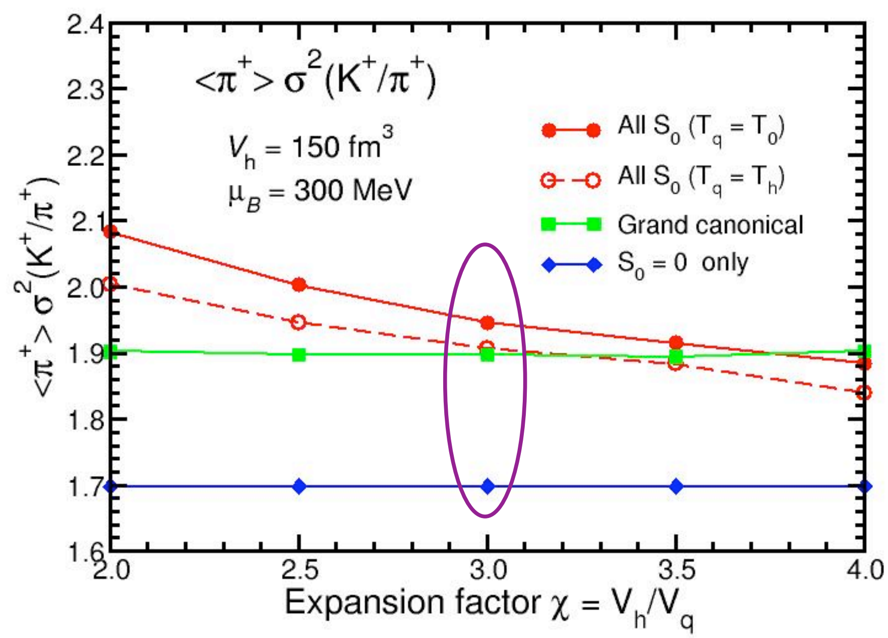
Dependence on the expansion factor χ



Average of K/π



Variance of K/π



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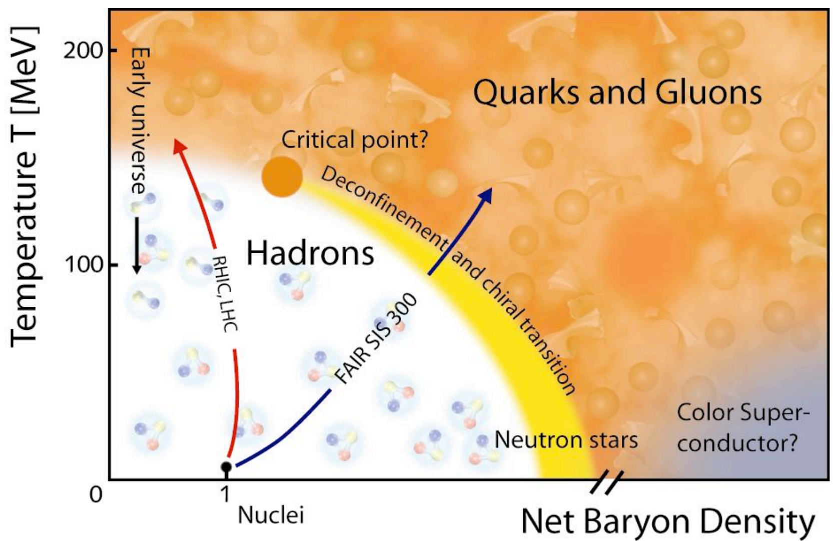

SUMMARY:

How to access the coexistence region? The exploration of the region of phase coexistence with FAIR requires beam energies of 5 - 10 GeV/N

What happens in the coexistence region? Bulk matter within the spinodal region seeks to phase separate by clumping

Dynamics needed!

Are there any observable signals? Clumping is reflected in kinematic correlation observables

Clumping enhances the fluctuations in the K:π ratio