Density Fluctuations as a Signal for First Order Phase Transitions

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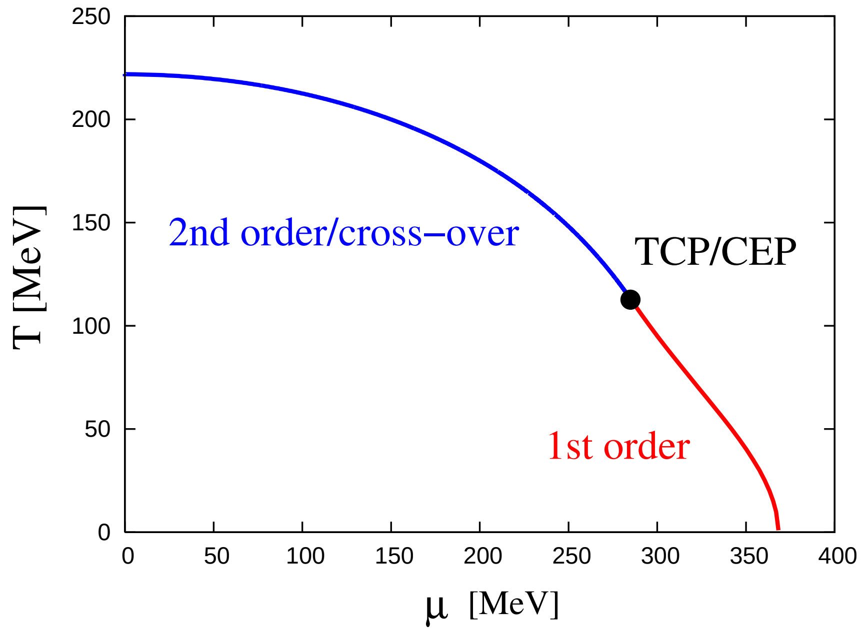
based on

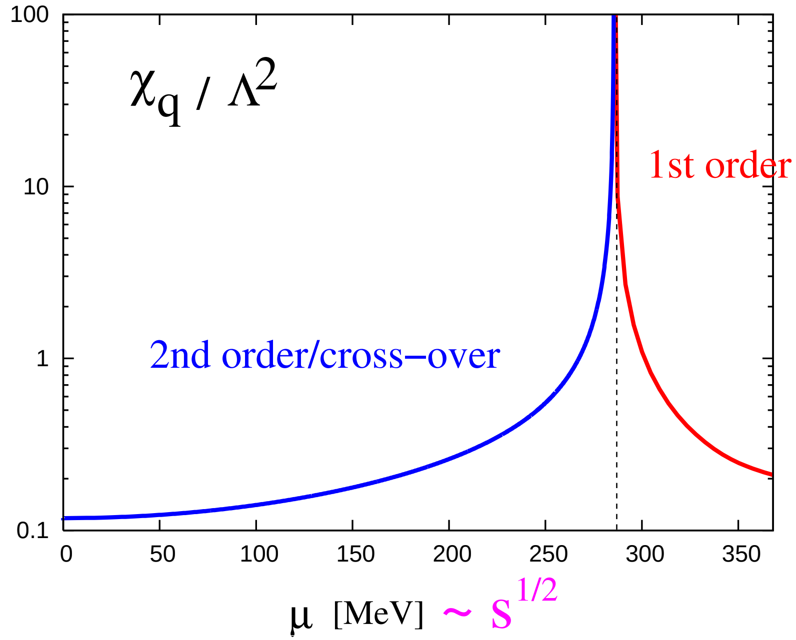
C. Sasaki, B. Friman and K. Redlich, hep-ph/0702254

QCD phase structure and fluctuations

- conserved charge fluctuations : critical behaviors
- net quark number/electric charge susceptibilities : search for the CEP

NJL model calculation : C. S., B. Friman, K. Redlich, Phys. Rev. D, 2007



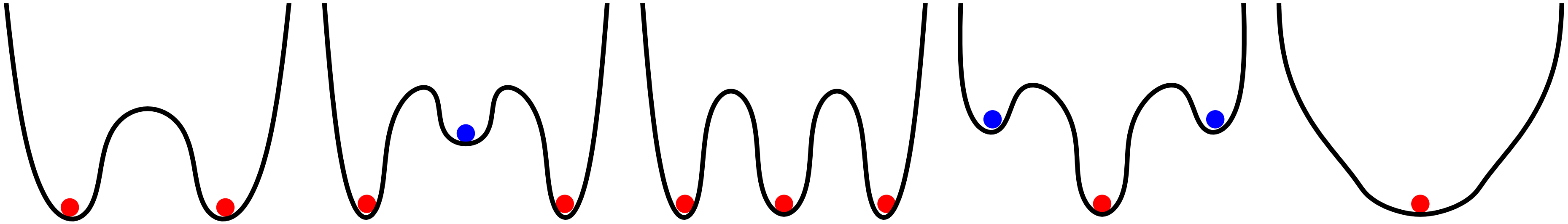


$\chi_q \to \infty$ at CEP while $\chi_q \sim$ finite for the 1st order transition in equilibrium

- heavy-ion collisions : deviation from equilibrium, instabilities

The nature of first order phase transition

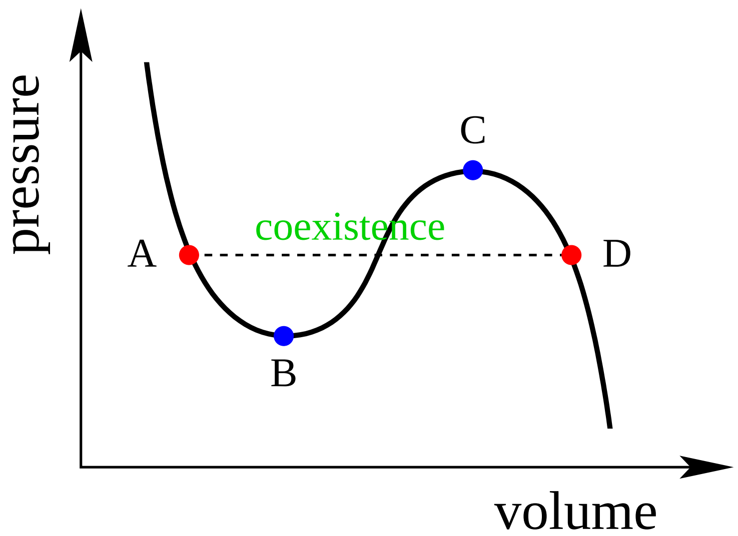
- change of thermodynamic potential from broken to symmetric phase



$T < T_1$ $T_1 < T < T_c$ $T = T_c$ $T_c < T < T_2$ $T_2 < T$

appearance of meta-stable state in $T_1 < T < T_2$

- stability of a system



$\partial P/\partial V < 0$: stable
$\partial P/\partial V > 0$: unstable
$\partial P/\partial V = 0$: spinodals

A-B : supercooling (symmetric phase)
B-C : non-equilibrium state
C-D : superheating (broken phase)

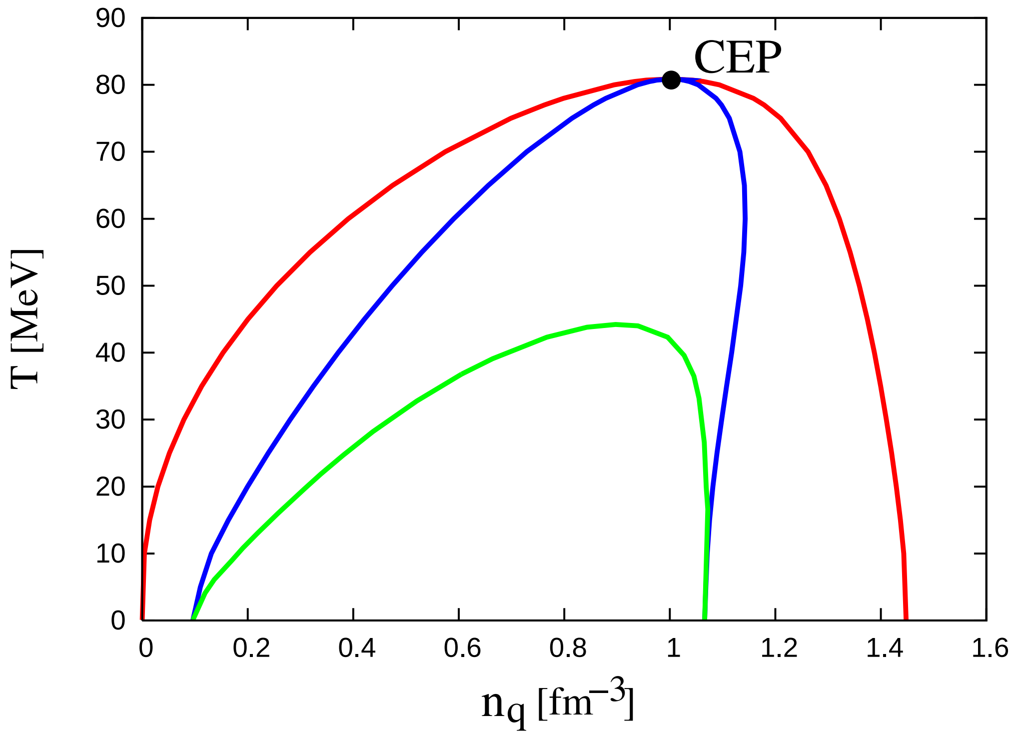
Phase diagram in the Nambu–Jona-Lasinio model

- NJL model with two flavors

$$\mathcal{L} = \bar\psi(i\partial\!\!\!/ - m)\psi + \bar\psi\mu\gamma_0\psi + G_S\left[(\bar\psi\psi)^2 + (\bar\psi i\vec\tau\gamma_5\psi)^2\right]$$

$$m = 5.6\,\text{MeV}\,,\ G_S\Lambda^2 = 2.44\,,\ \Lambda = 587.9\,\text{MeV}$$

- phase diagram



critical end point (CEP) :
$T = 81$ MeV, $\mu = 330$ MeV

spinodal lines :

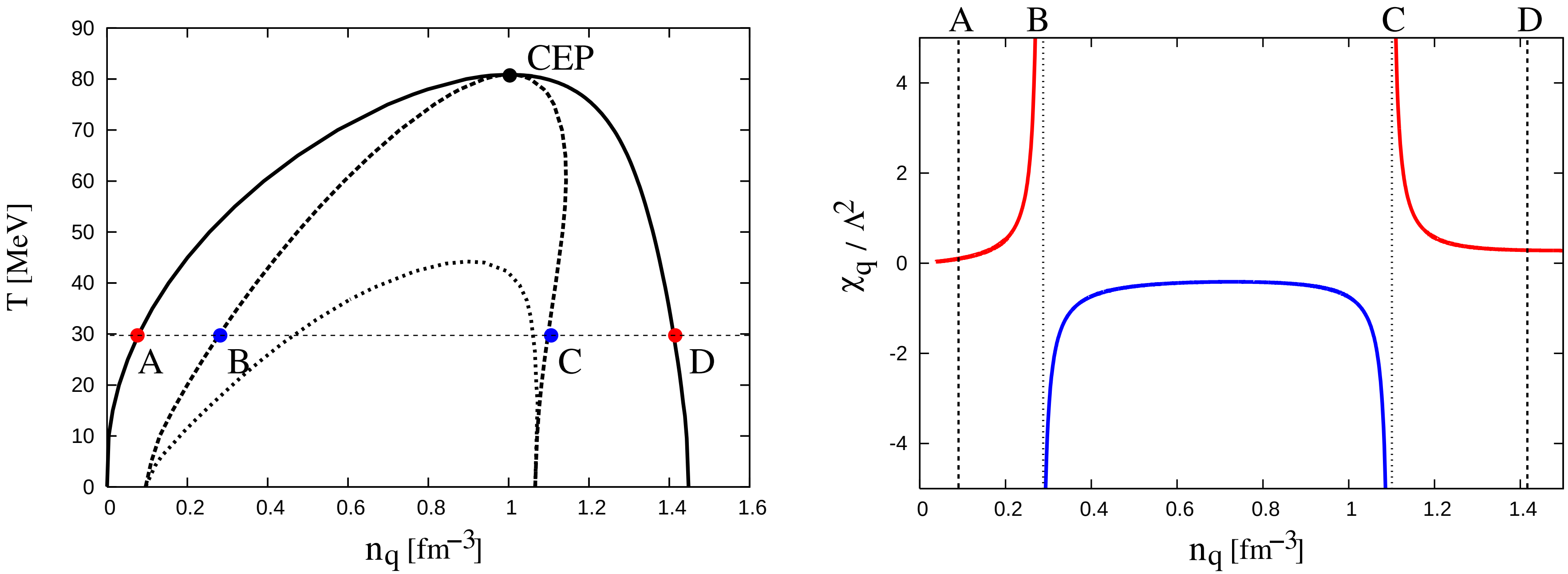
$$\left(\frac{\partial P}{\partial V}\right)_T = 0 \quad : \text{isothermal}$$

$$\left(\frac{\partial P}{\partial V}\right)_S = 0 \quad : \text{isentropic}$$

$$\left(\frac{\partial P}{\partial V}\right)_T = \left(\frac{\partial P}{\partial V}\right)_S + \frac{T}{C_V}\left[\left(\frac{\partial P}{\partial T}\right)_V\right]^2$$

Quark number susceptibility

- deviation from equilibrium, large fluctuations induced by instabilities



- at 1st order transition point (A, D) : χ_q is finite
- at isothermal spinodal point (B, C) : χ_q diverges and changes its sign
  $\frac{\partial P}{\partial V} < 0$ for stable/meta-stable state $\Rightarrow$ $\frac{\partial P}{\partial V} > 0$ for unstable state
- in unstable region (B-C) : χ_q is finite and negative

- divergence of χ_q :

$$\left(\frac{\partial P}{\partial V}\right)_T = -\frac{n_q^2}{V}\frac{1}{\chi_q} = 0 \quad \text{at any spinodal points}$$

$\Rightarrow$ χ_q diverges along the isothermal spinodal lines

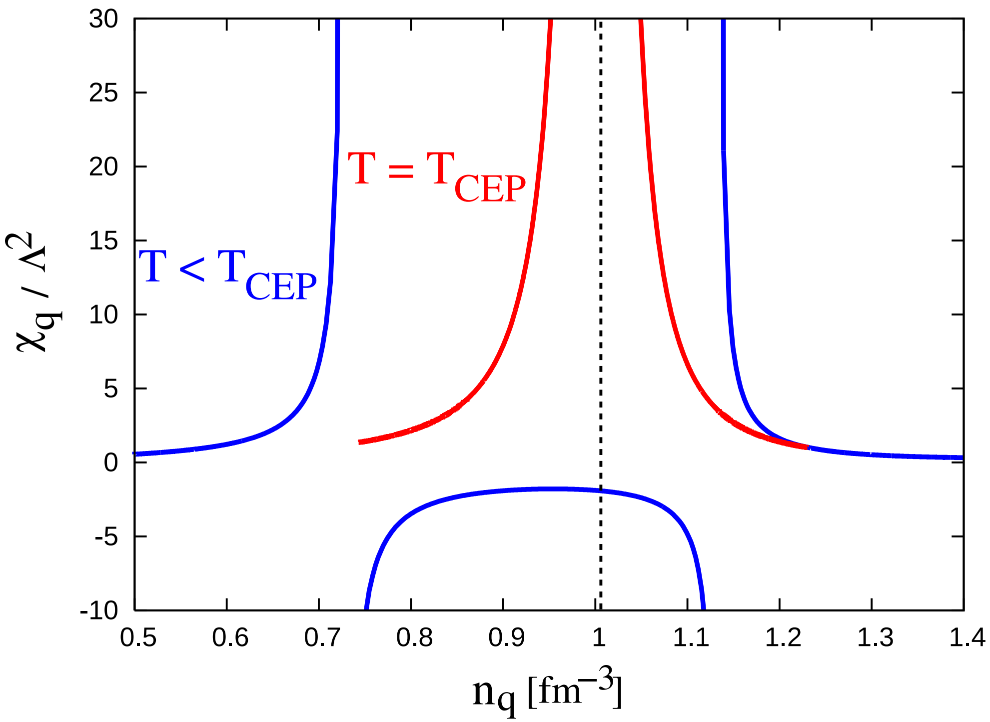
- electric charge susceptibility also diverges:

$$\chi_Q = \frac{1}{36}\chi_q + \frac{1}{4}\chi_I + \frac{1}{6}\frac{\partial^2 P}{\partial\mu_q\partial\mu_I}$$

- spinodal decomposition for the chiral/deconfinement phase transition in heavy-ion collisions :
  instabilities, enhancement of baryon and strangeness fluctuations

Heiselberg, Pethick and Ravenhall (1988);
Bower and Gavin (2001);
Chomaz, Colonna and Randrup (2004);
Koch, Majumder and Randrup (2005)

- toward the critical end point



– two positive branches are approaching

– instability region shrinks

– strength of divergence remains the same because of the same critical exponents :

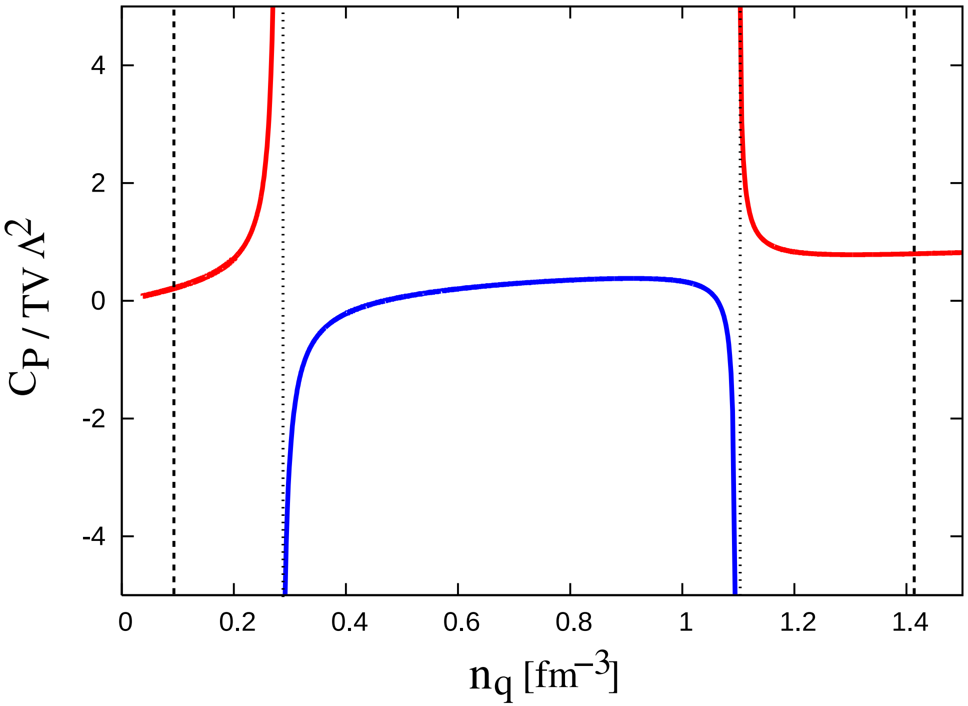
$$\chi_q \sim (\mu - \mu_c)^{-\gamma},$$
$$\gamma = 1/2 \ \ (m_q = 0)$$
$$\gamma = 2/3 \ \ (m_q \neq 0)$$

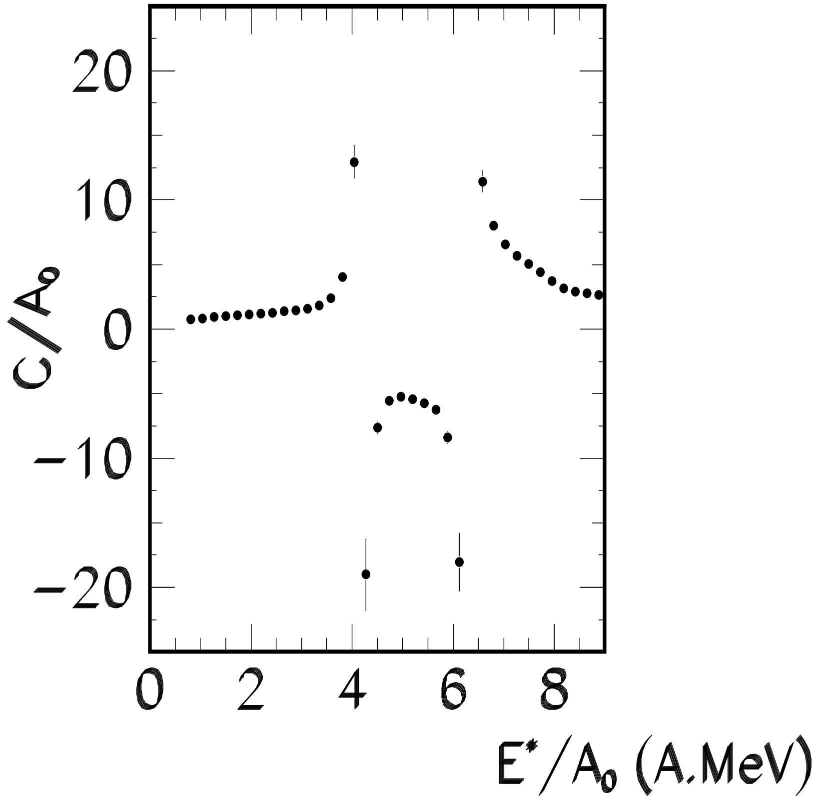
- specific heat for constant pressure

$$C_P = T\left(\frac{\partial S}{\partial T}\right)_P = TV\left[\chi_{TT} - \frac{2s}{n_q}\chi_{\mu T} + \left(\frac{s}{n_q}\right)^2 \chi_q\right]$$

Experimental evidence

- low-energy nuclear collisions





M. D'Agostino *et al.*, Phys. Lett. B **473**, 219 (2000)

negative heat capacity : anomalously large fluctuations

$\Rightarrow$ an evidence of the 1st order liquid-gas phase transition

Summary and conclusions

- The quark number susceptibility diverges if spinodal phase separation occurs.
  cf. finite in the equilibrium transition

- a signal not only for the CEP but also for the 1st order phase transitions
  $\Rightarrow$ large fluctuations will be seen in a wider range of the phase diagram.

- CBM energy $\sim$ the 1st order phase transition
  large fluctuations of baryon number, electric charge, proton number will be expected.