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Energy Dependence of $N_t N_p / N_d^2$ with a First-Order QCD Phase Transition

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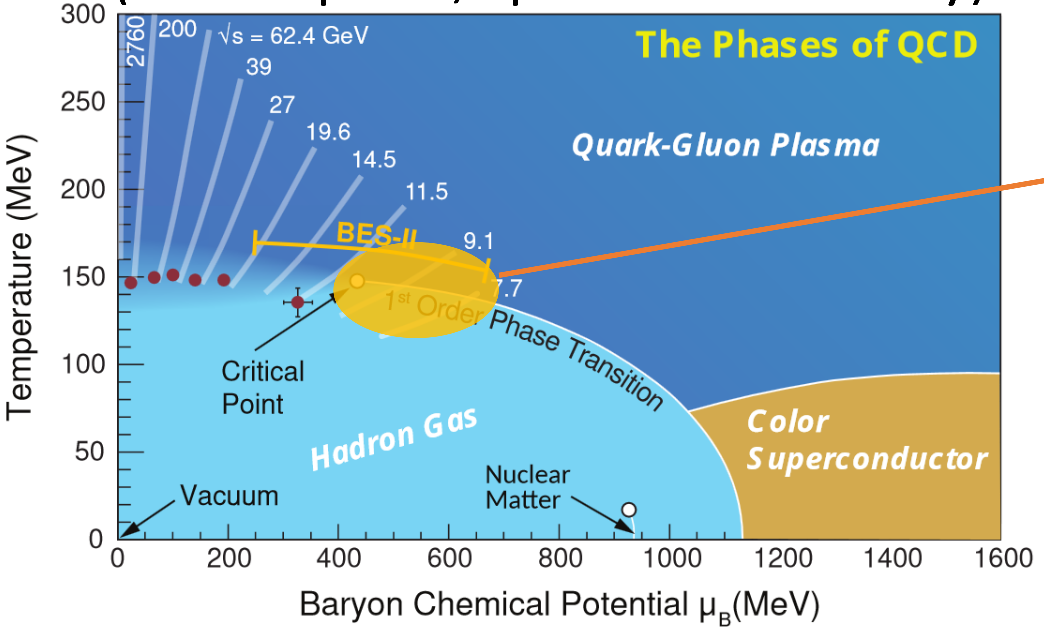
Why light nuclei? (1)

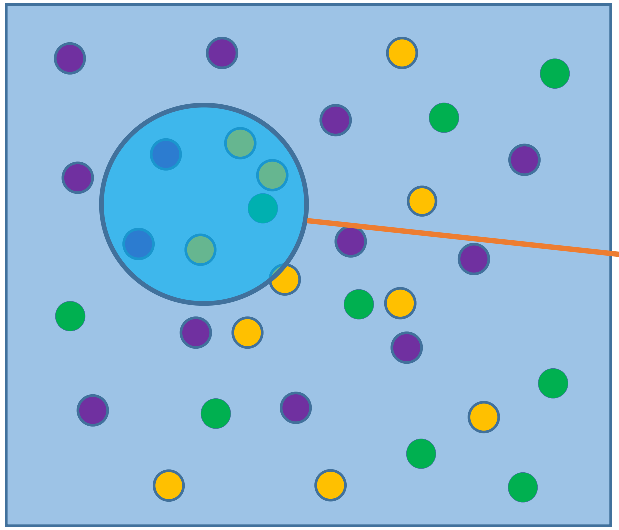
A. Bzdak et al., Phys. Rept. 853, 1 (2020)

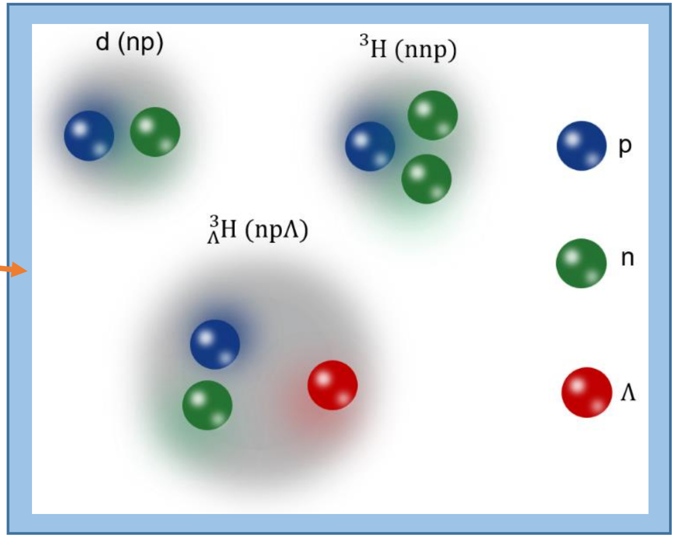
Equation of state
(critical point, spinodal instability)

Density fluctuation/correlation

Light nuclei production







J. Steinheimer et al. PRC 87, 054903 (2013)
E. Shuryak et al., PRC 100, 024903(2019)

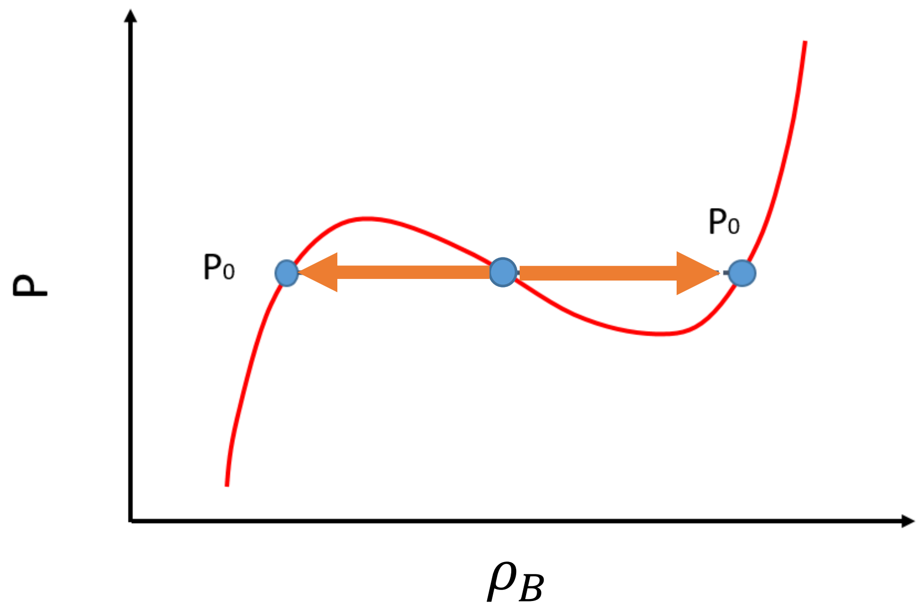
K. J. Sun et al., Phys. Lett. B 774, 103 (2017)
Phys. Lett. B 781, 499 (2018)
Phys. Lett. B 816, 136258 (2021)

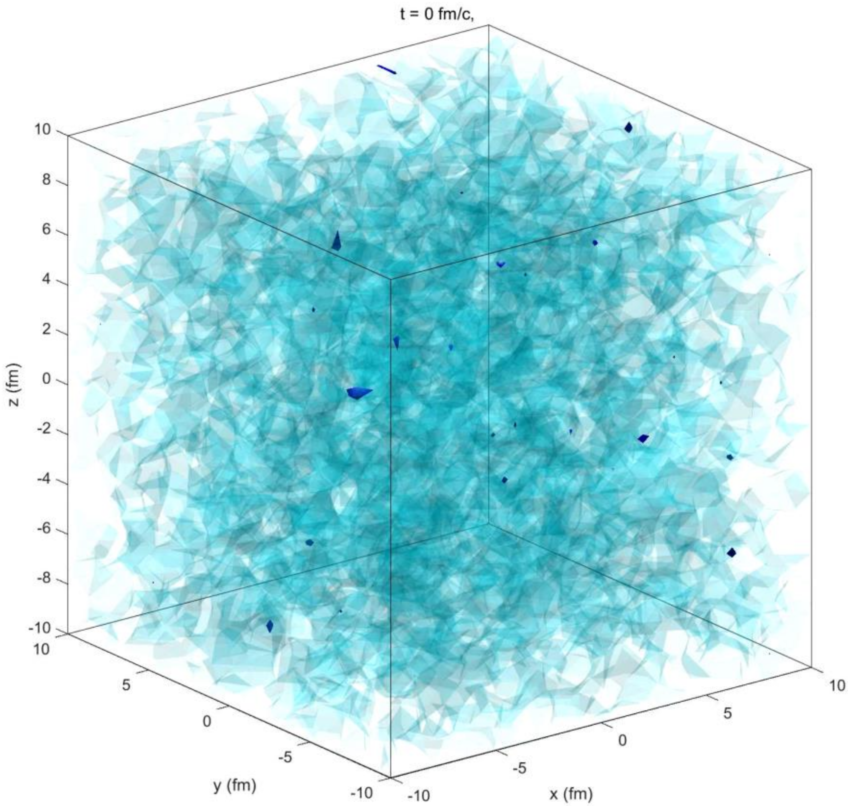
Critical Point: Long-range correlation
First-order Phase Transition: Spinodal instability

Due to their composite structure:
Deuteron probes 2-body correlation function
Triton probes 2- and 3-body correlation function

Density fluctuation from the spinodal instability (2)

Phase separation, spinodal decomposition(SD)





Small irregularities will grow exponentially and soon the evolution becomes ’chaotic’.

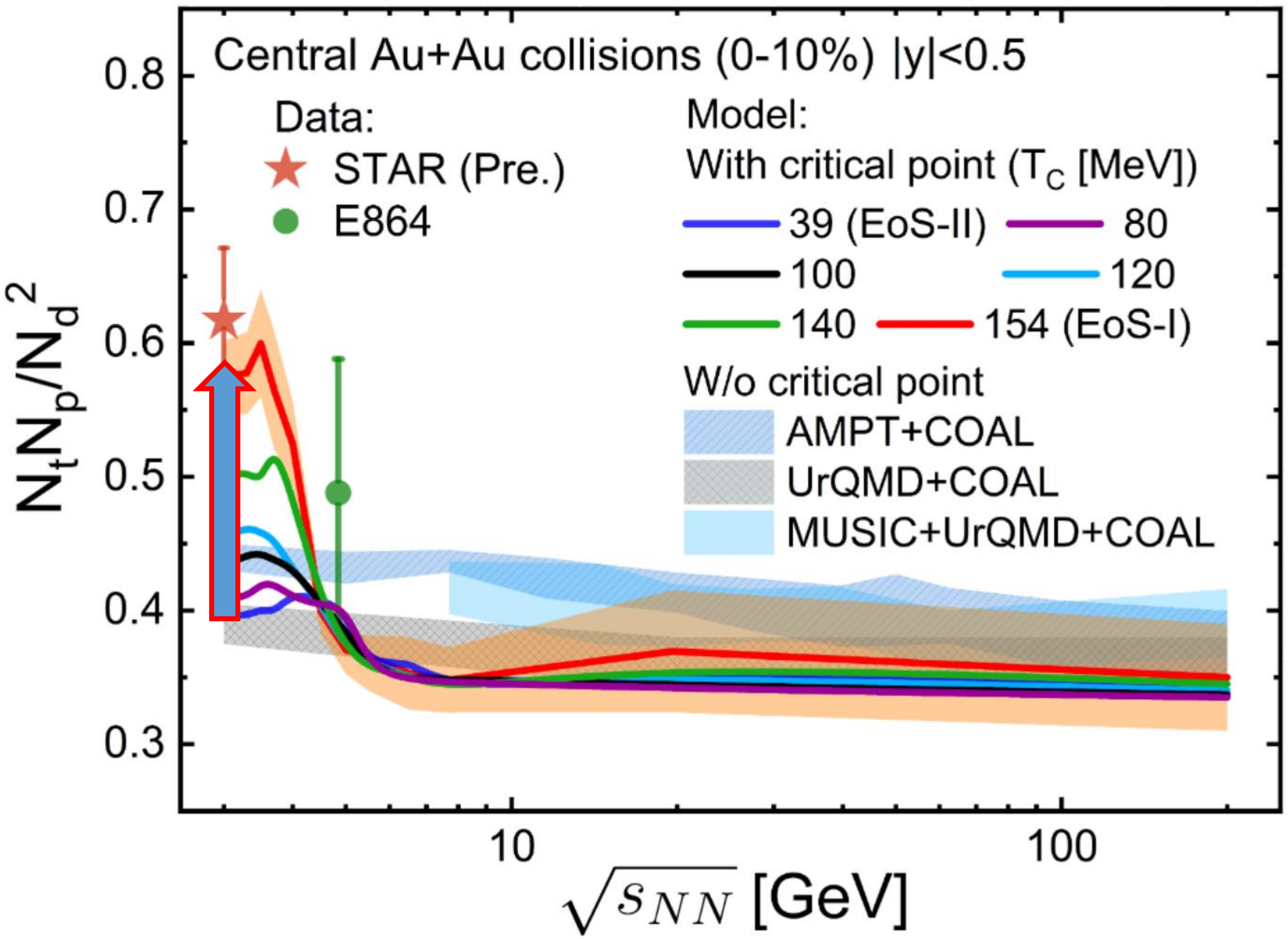
In low-energy nuclear reactions, SD could lead to nuclear multifragmentation (P. Chomaz, M. Clonna, and J. Randrup, Phys. Rep. 389, 263 (2004)).

What is the consequence for heavy ion collisions?

Hydro: J. Steinheimer and J. Randrup, PRL. 109, 212301 (2012); PRC79, 054911 (2009); K. Paech, A. Dumitru, PLB623, 200 (2005)
Chiral Fluid Dynamics: C. Herold, M. Nahrgang, I. Mishustin, and M. Bleicher, NPA 925, 14 (2014)
Transport: F. Li and C. M. Ko, PRC95, 055203 (2017); K. J. Sun et al., arXiv:2006.08929(2020)

Collision energy dependence of $N_t N_p / N_d^2$ (3)

K. J. Sun, W. H. Zhou, L. W. Chen, C. M. Ko, and F. Li, R. Wang, and J. Xu, arXiv:2205.11010(2022); Eur. Phys. J. A 57 (2021) 11, 313



1. Without a critical point:
   The energy dependence of tp/d^2 is almost flat.

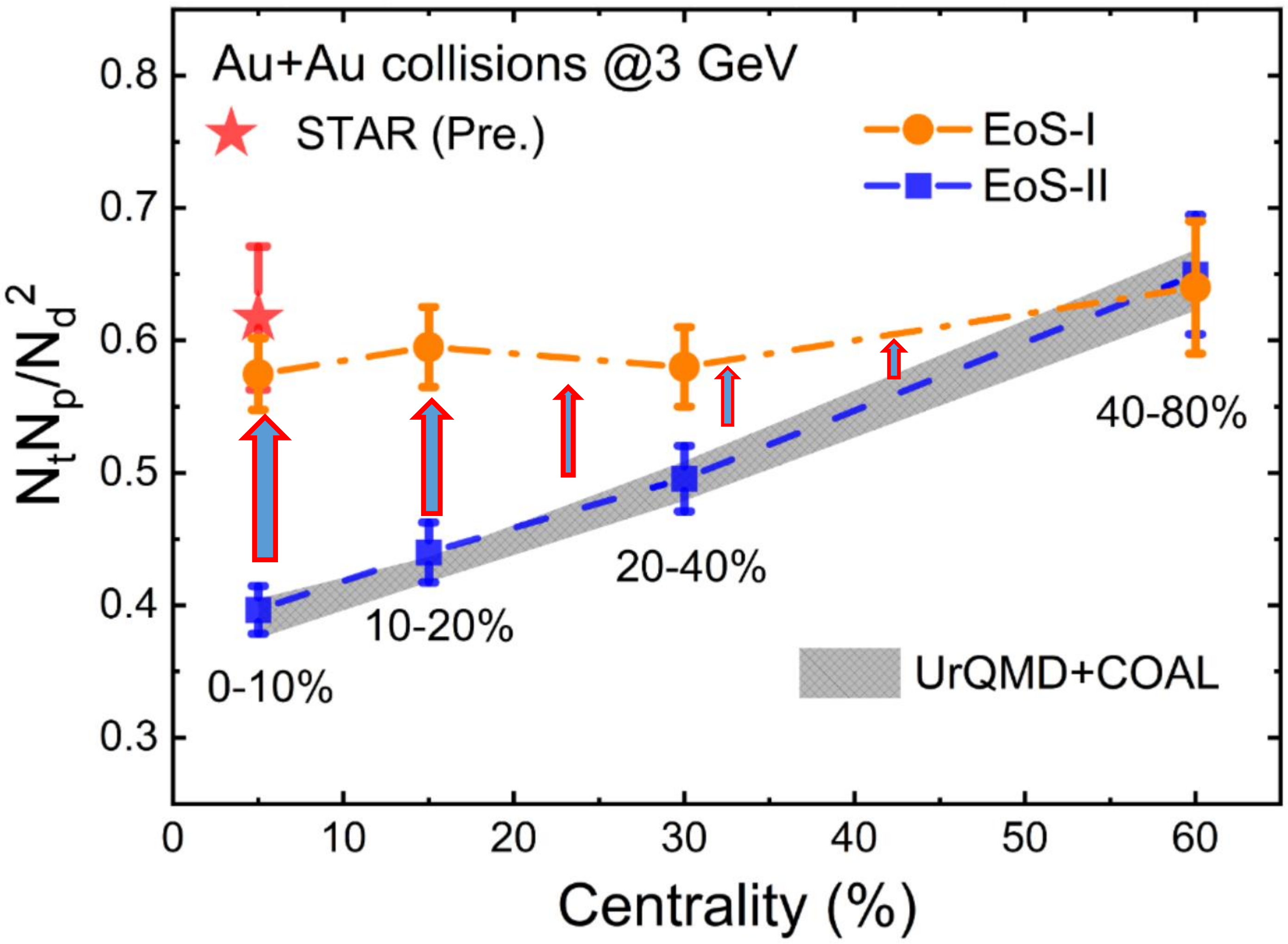
2. With a first-order phase transition:
   The spinodal instability induced enhancement of tp/d^2 during the first-order phase transition increases as increasing the critical temperature.

Hui Liu (STAR), QM2022

T. A. Armstrong et al. (E864), Phys. Rev. C 61, 064908 (2000).

Centrality dependence of $N_t N_p / N_d^2$ (4)

arXiv:2205.11010(2022)

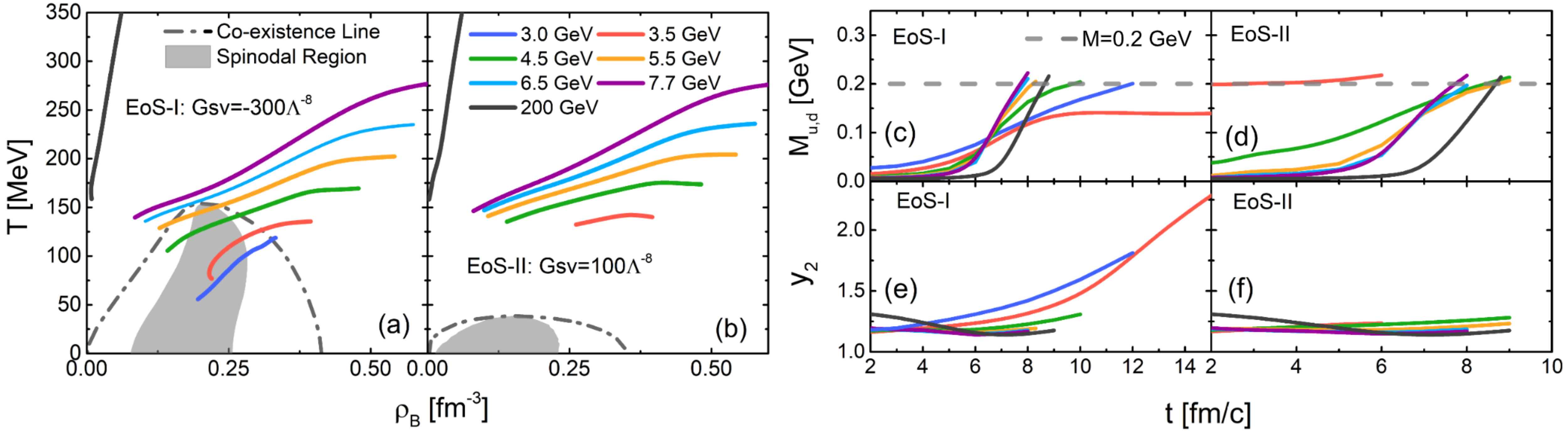


The spinodal enhancement of tp/d^2 subsides with increasing collision centrality because of smaller fireball lifetime in more peripheral collisions.

The slope with EoS-I is 5 times smaller

Backup

Trajectories in the phase diagram



$$\overline{\rho^N} = \frac{\int d\mathbf{x}\rho^{(N+1)}(\mathbf{x})}{\int d\mathbf{x}\rho(\mathbf{x})}$$

$$y_2 = \frac{[\int d\mathbf{x}\rho(\mathbf{x})][\int \mathrm{d}\mathbf{x}\rho^{\mathbf{3}}(\mathbf{x})]}{[\int \mathrm{d}\mathbf{x}\rho^{\mathbf{2}}(\mathbf{x})]^{\mathbf{2}}}$$

Why $N_t N_p / N_d^2 (tp/d^2)$? (6)

Density matrix formulation

Phys. Lett. B 774, 103 (2017)
Phys. Lett. B 781, 499 (2018)
Phys. Lett. B 816, 136258 (2021)

$$N_d \propto Tr[\hat{\rho}_s \hat{\rho}_d]$$

Encodes many-body density fluctuation/correlation

Phase-space representation:

$$N_d = \frac{3}{4} \int d\Gamma\, f_{pn}(\vec{p}_1, \vec{r}_1, \vec{p}_2, \vec{r}_2) \times W_d(\vec{r}, \vec{p})$$

$$W_d(\vec{r}, \vec{p}) = \frac{1}{\pi\hbar} \int d\vec{r}' \psi_d^* (\vec{r} + \vec{r}') \psi_d(\vec{r} - \vec{r}') e^{2i\vec{p}\cdot\vec{r}'}$$

Wigner function(Gaussian):

$$W_d(r, k) = 8 \exp\left(-\frac{r^2}{\sigma_d^2} - \sigma_d^2 p^2\right) \qquad \sigma_d \approx 2.26 \text{ fm}$$

with density fluctuation and correlation:

$$f_{np}(x_1, p_1; x_2, p_2) = \rho_{np}(x_1, x_2)(2\pi mT)^{-3} e^{-\frac{p_1^2 + p_2^2}{2mT}}$$

$$\rho_{np}(x_1, x_2) = \rho_n(x_1)\rho_p(x_2) + C_2(x_1, x_2)$$

$$\rho_n(x) = <\rho_n> + \delta\rho_n(x) \qquad \rho_p(x) = <\rho_p> + \delta\rho_p(x)$$

$\delta\rho(x)$ denotes density fluctuation over space or inhomogeneity,

$$C_{np} = \langle \delta\rho_n(x)\delta\rho_p(x) \rangle / (\langle \rho_n \rangle \langle \rho_p \rangle)$$
$$\Delta\rho_n = \langle \delta\rho_n(x)^2 \rangle / \langle \rho_n \rangle^2$$

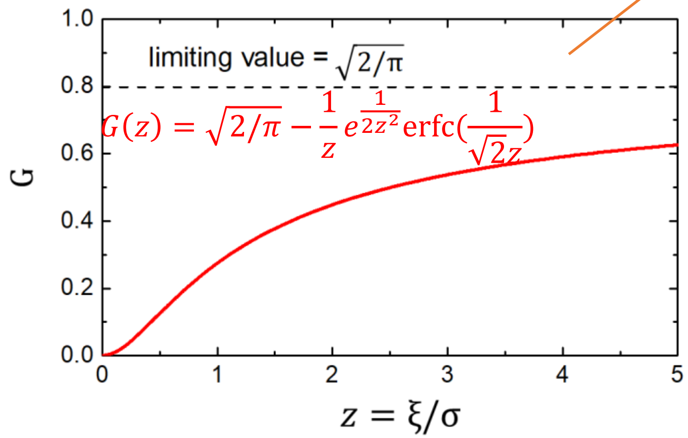
$$< \cdots > \equiv \frac{1}{V} \int dx$$

$$C_2(x_1 - x_2) \approx \lambda \langle \rho_n \rangle \langle \rho_p \rangle \frac{e^{-|x_1 - x_2|/\xi}}{|x_1 - x_2|^{1+\eta}} \quad (singular\ part\ only)$$

with ξ being the density − density correlation length

$$0 < \langle \delta N^2 \rangle \sim \int dx C_2(x) \sim \lambda \xi^2 \to \lambda > 0$$

$$\Rightarrow N_d \approx \frac{3}{\sqrt{2}} \left(\frac{2\pi}{mT}\right)^{\frac{3}{2}} N_p \langle \rho_n \rangle [1 + C_{np} + \frac{\lambda}{\sigma_d} G(\frac{\xi}{\sigma_d})]$$



Why $N_t N_p / N_d^2 (tp/d^2)$? (7)

$$N_d = \frac{3}{\sqrt{2}}\left(\frac{2\pi}{mT}\right)^{\frac{3}{2}} N_p \langle \rho_n \rangle \left[1 + C_{np} + \frac{\lambda}{\sigma_d} G\left(\frac{\xi}{\sigma_d}\right)\right]$$

$$N_t = \frac{3^{3/2}}{4}\left(\frac{2\pi}{mT}\right)^{3} N_p \langle \rho_n \rangle^2 \left[1 + 2C_{np} + \Delta\rho_n + \frac{3\lambda}{\sigma_t} G\left(\frac{\xi}{\sigma_t}\right) + O(G^2)\right]$$

Pre-factors are thermal yields w/o density fluc./corr.

Ratio: $\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}\left[1 + \Delta\rho_n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right)\right]$, $\frac{3\ pairs}{2\ pairs} \sim 1\ pair$, $\sigma \approx 2$ fm

Density fluctuation/correlation leads to enhancement of tp/d^2

We focus on the effects of density fluctuation generated from the first-order phase transition

K. J. Sun, C. M. Ko, and F. Li, Phys. Lett. B 816, 136258 (2021)