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Spinodal Enhancement of Light Nuclei Yield Ratio in Relativistic Heavy-Ion Collisions

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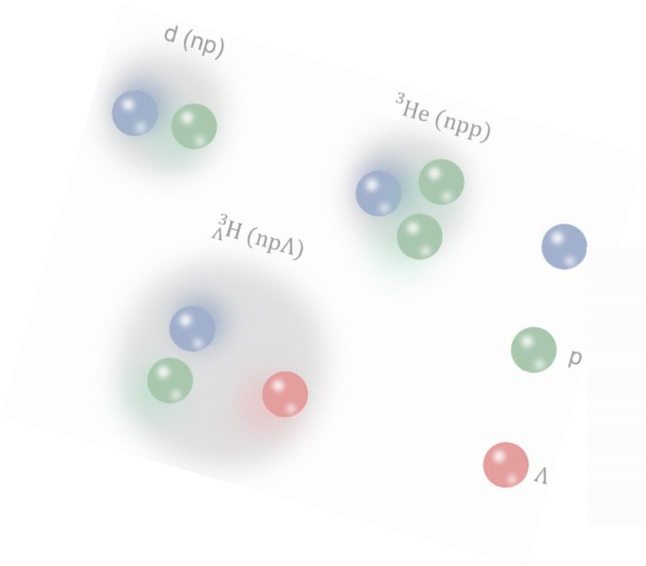
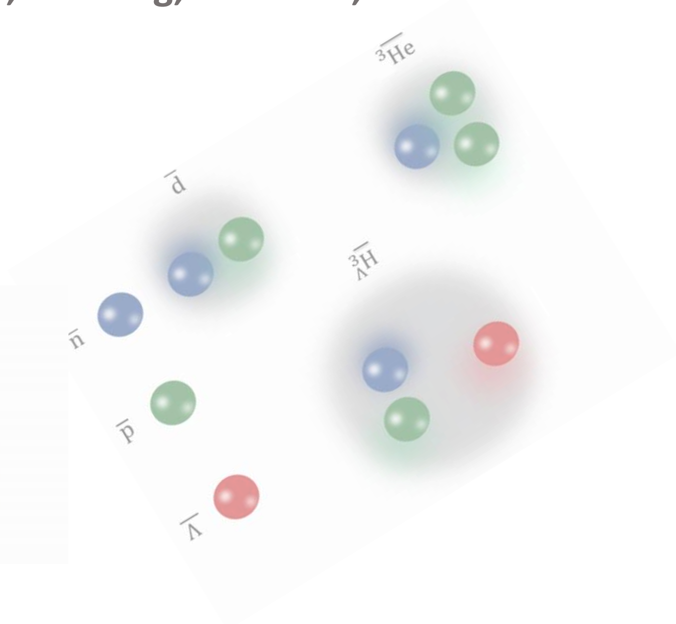
Ref.: K. J. Sun, W. H. Zhou, L. W. Chen, C. M. Ko, and F. Li, R. Wang, and J. Xu, arXiv:2205.11010(2022)





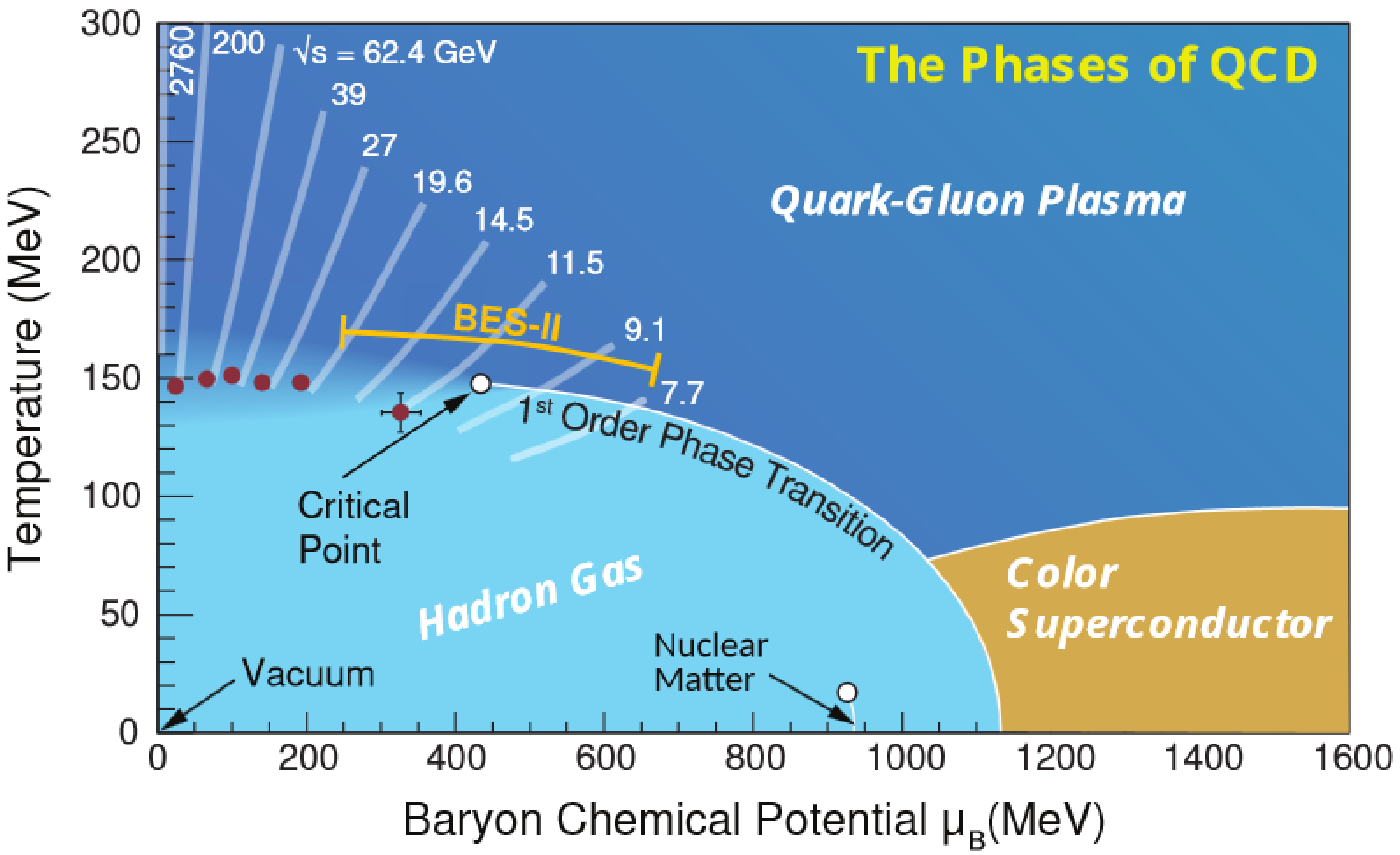
Outline

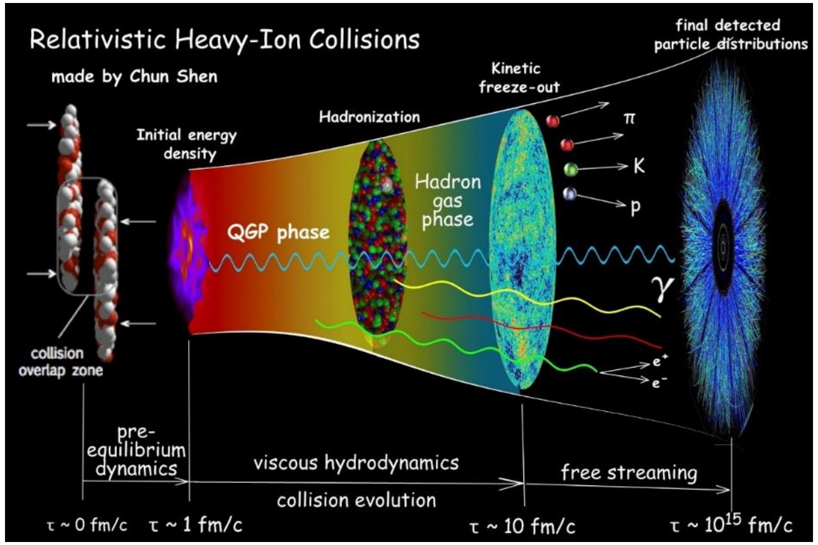
1. Motivation: Why light nuclei? Why $N_t N_p / N_d^2$ (tp/d^2)?

2. Spinodal enhancement of tp/d^2 from the first-order QCD phase transition

3. Summary and Outlook

1.1 QCD phase transition & light nuclei production (1)





Neutron star merger

From Wiki.

Critical Point: long-range correlation

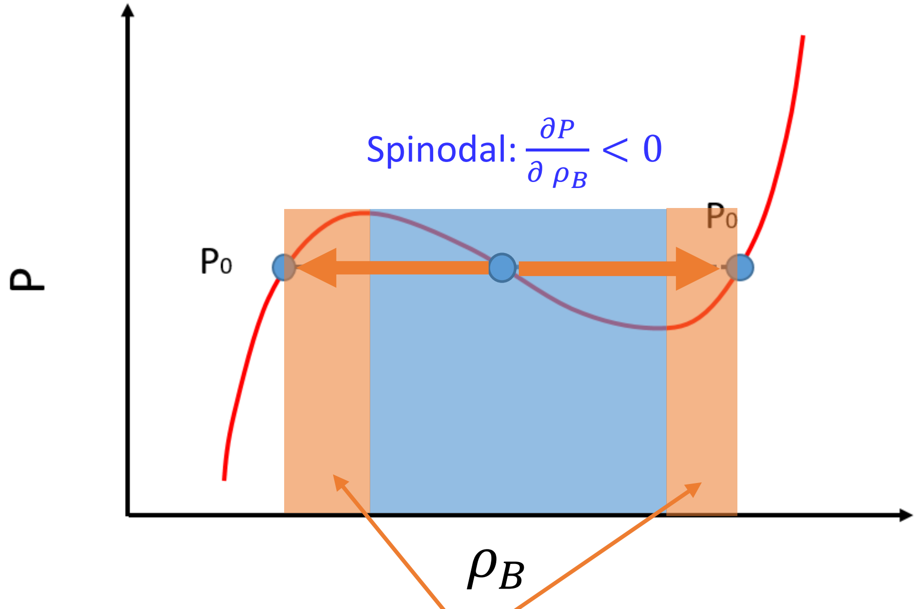
First-order Phase Transition: Spinodal instability

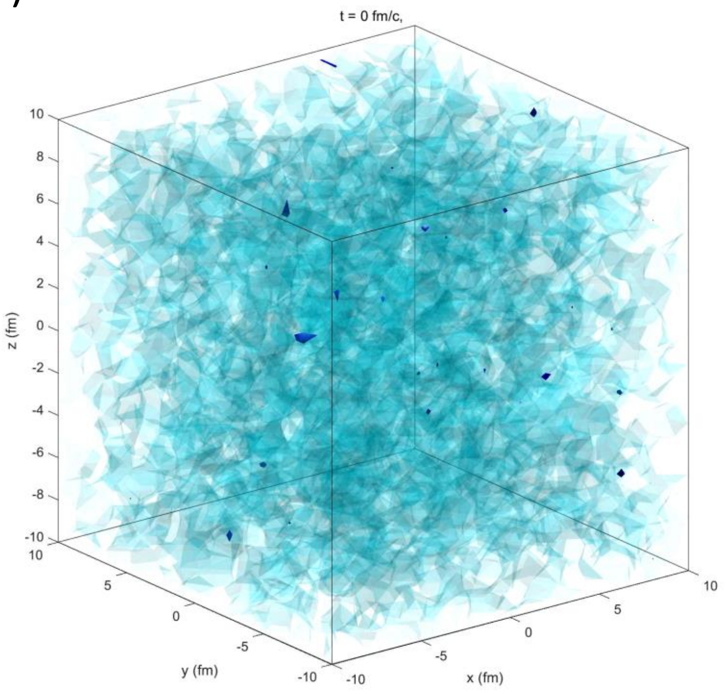
X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017) A. Bzdak et al., Phys. Rept. 853, 1 (2020);
W. J. Fu, J. M. Pawlowski, F. Renneke, Phys. Rev. D101, 054032 (2020); LIGO & VIRGO, Phys. Rev. Lett. 119, 161101 (2017)

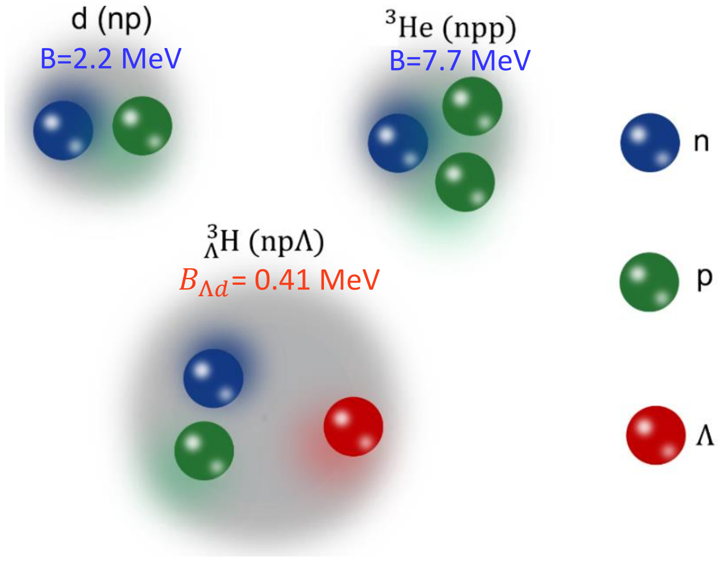
1.2 1st order QCD phase transition & light nuclei production (2)

P. Chomaz, M. Clonna, and J. Randrup, Phys. Rep. 389, 263 (2004)

Phase separation, spinodal decomposition(SD)







K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu, Phys. Lett. B 774, 103 (2017)

Density matrix formulation (coalescence)

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

$$\frac{N_t N_p}{N_d^2} \propto \Delta\rho_n \qquad \Delta\rho_n = \frac{\int \mathrm{d}\mathbf{x}(\delta\rho(\mathbf{x}))^2}{\int \mathrm{d}\mathbf{x}\rho_0^2}$$

characterizes density inhomogeneity

See [PLB 816, 136258 (2021)] for critical effects on $N_t N_p / N_d^2$

1.3 QCD phase transition & light nuclei production (3)

light nuclei production & QCD phase transition

2012 2014 2015 2016 2017 2018 2019 2020 2021 2022

Other works

First-order phase transition & composite particle production

- J. Steinheimer et al. PRC 87, 054903 (2013)
- PRL 109, 212301 (2012)(Hydrodynamics)
- JHEP 12, 122(2019)(Machine learning)

Baryon clustering near the critical point

- E. Shuryak, J.M.Torres-Rincon et al., PRC 100, 024903(2019)
- PRC 101,034914(2020)
- EPJA 56, 241(2020)
- PRC 104,024908(2021)

Background effects

- S. Wu et al.,PRC 106,034905(2022)

Our works

Probing QCD phase transition with light nuclei production

- PLB 774, 103 (2017)

K. J. Sun, L. W. Chen, C. M. Ko, and Z. Xu

$$\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}[1+\Delta\rho_n]$$

- PLB 781, 499 (2018)
- PLB 816, 136258 (2021)(criticality)

1st-order QCD phase transition

- PRD 103, 014006 (2021)
- EPJA 57, 313 (2021)(Transport)
- arxiv:2205.11010 (Transport) (First-order PT in BES)

2. Spinodal enhancement of tp/d^2 from the first-order QCD phase transition

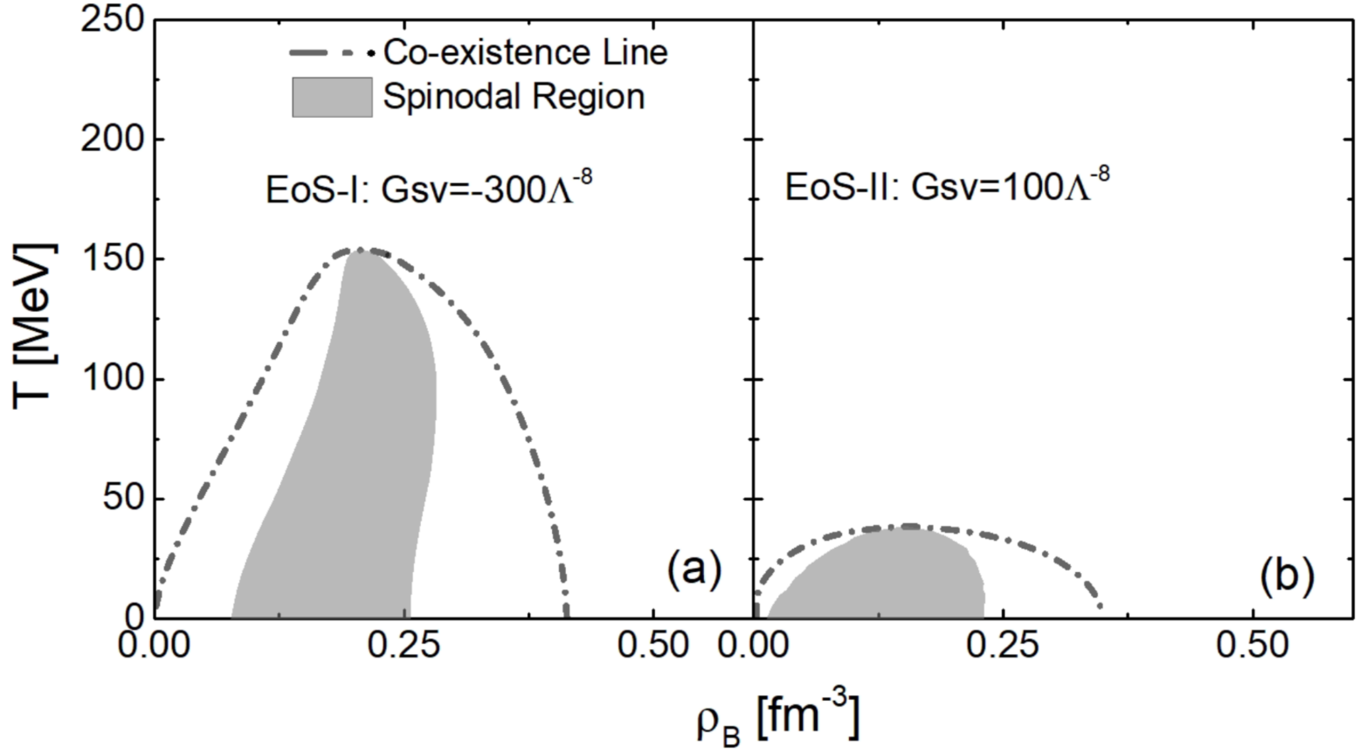
2.1 Equation of State (extended NJL model) (4)

The eNJL provides a flexible equation of state (EoS) . The critical temperature can be easily changed by varying the strength of the scalar-vector interaction without affecting the vacuum properties.

Lagrangian density for eNJL

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - \hat{m})\psi + G_S \sum_{a=0}^{8}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2] \\ &- K\{[\det[\bar{\psi}(1+\gamma_5)\psi] + \det[\bar{\psi}(1-\gamma_5)\psi]\} \\ &+ G_{SV}\left\{\sum_{a=1}^{3}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2]\right\} \\ &\times \left\{\sum_{a=1}^{3}[(\bar{\psi}\gamma^{\mu}\lambda^a\psi)^2 + (\bar{\psi}\gamma_5\gamma^{\mu}\lambda^a\psi)^2]\right\},\end{aligned}$$

Λ [MeV]	602.3	$M_{u,d}$ [MeV]	367.7
$G\Lambda^2$	1.835	M_s [MeV]	549.5
$K\Lambda^5$	12.36	$(\langle\bar{u}u\rangle)^{1/3}$ [MeV]	-241.9
$m_{u,d}$ [MeV]	5.5	$(\langle\bar{s}s\rangle)^{1/3}$ [MeV]	-257.7
m_s [MeV]	140.7		



M. Buballa, Phys. Rept. 407, 205 (2005)

K. J. Sun, C. M. Ko, S. Cao, and F. Li., Phys. Rev. D 103, 014006 (2021)

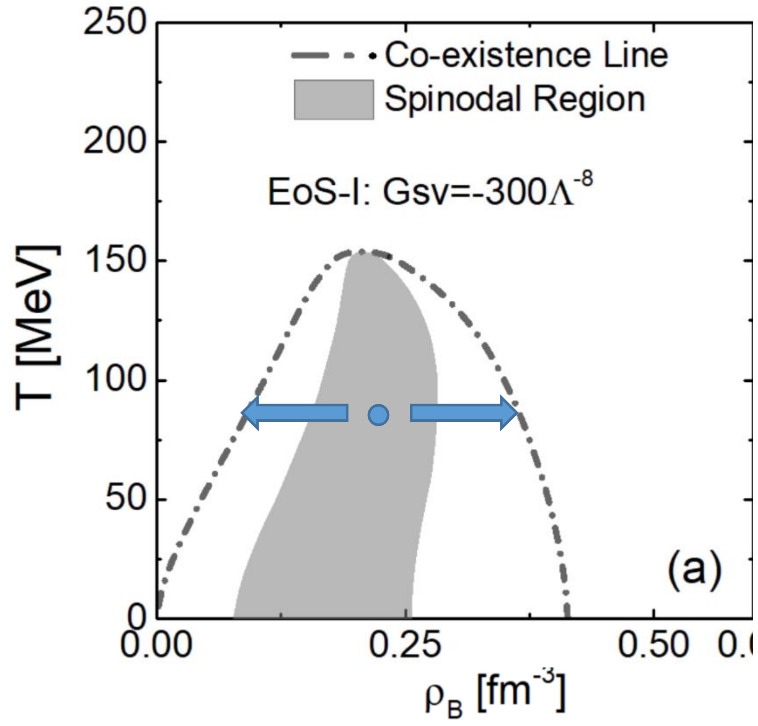
2.2 Box Simulation (5)

Effective mass:

$$M_u = m_u - 4G_S\phi_u + 2K\phi_d\phi_s - 2G_{SV}(\rho_u+\rho_d)^2(\phi_u+\phi_d),$$
$$M_d = m_d - 4G_S\phi_d + 2K\phi_u\phi_s - 2G_{SV}(\rho_u+\rho_d)^2(\phi_u+\phi_d),$$
$$M_s = m_s - 4G_S\phi_s + 2K\phi_u\phi_d$$

$$\phi_i = -2N_c\int_0^\Lambda \frac{d^3p}{(2\pi\hbar)^3}\frac{M_i}{E_i}(1-f_i-\bar{f}_i)$$

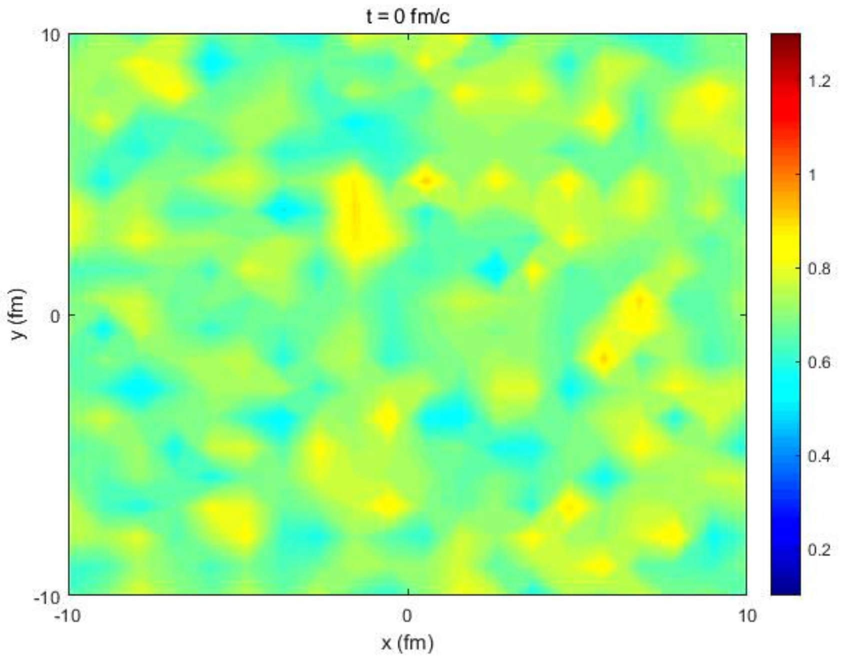
$$\rho_i = 2N_c\int_0^\Lambda \frac{d^3p}{(2\pi\hbar)^3}(f_i-\bar{f}_i)$$



Test –particle method: J. Xu, arXiv:1904.00131 (2019)

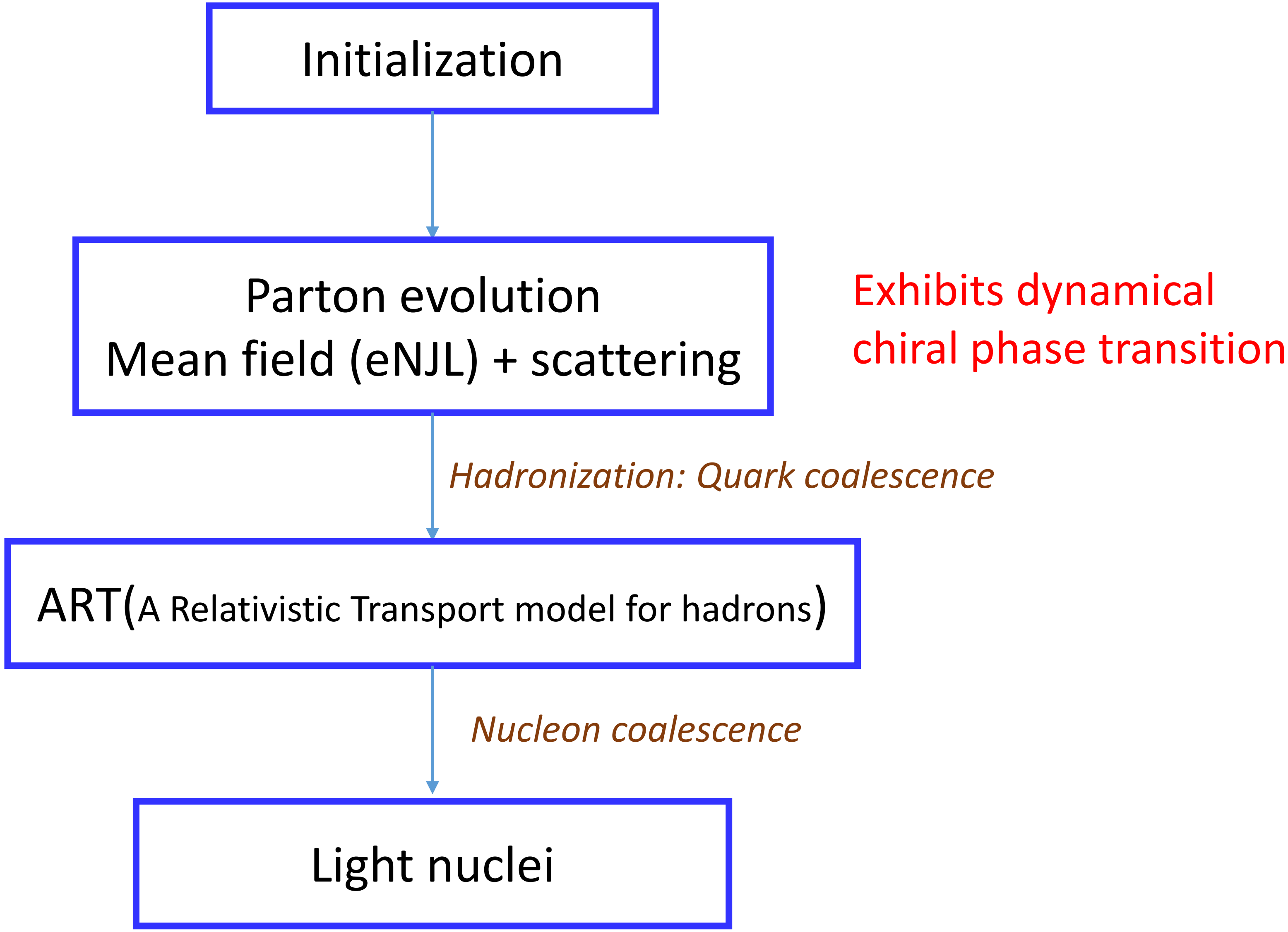
$$\frac{d\mathbf{r}}{dt} = \mathbf{v},$$
$$\frac{d\mathbf{p}}{dt} = -\frac{M}{E^*}\nabla_r M \pm \mathbf{E} \pm \mathbf{v}\times\mathbf{B}$$

Strong EM fields



M. Buballa, Phys. Rept. 407, 205 (2005)
K. J. Sun, C. M. Ko, S. Cao, and F. Li., Phys. Rev. D 103, 014006 (2021)

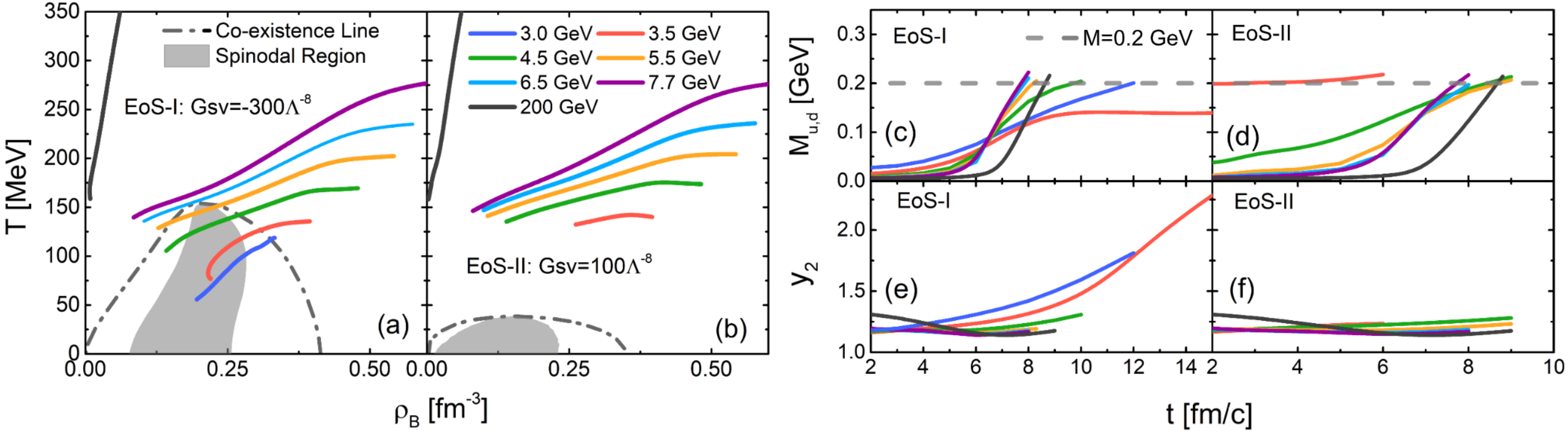
2.3 Relativistic Heavy-Ion Collisions (6)



2.4 Trajectories in the phase diagram (7)

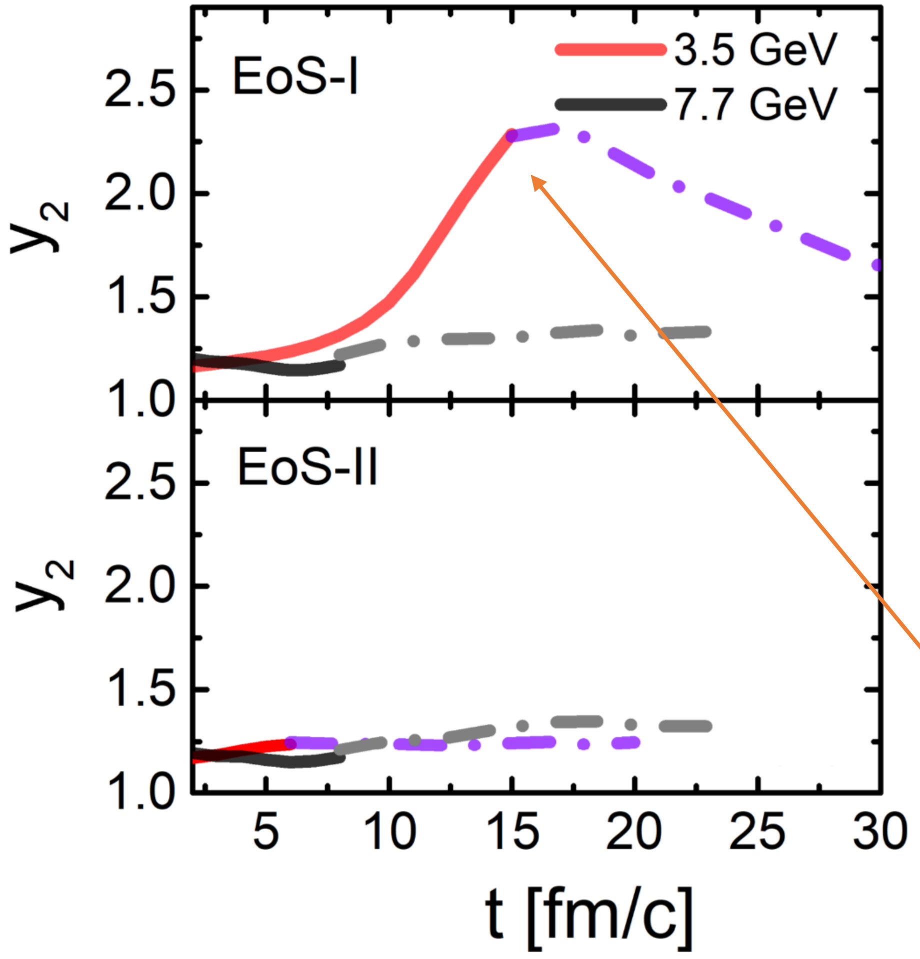
Phase trajectories of central cells in the phase diagram

$$\overline{\rho^N} = \frac{\int d\mathbf{x}\rho^{(N+1)}(\mathbf{x})}{\int d\mathbf{x}\rho(\mathbf{x})} \qquad y_2 = \frac{[\int d\mathbf{x}\rho(\mathbf{x})][\int d\mathbf{x}\rho^3(\mathbf{x})]}{[\int d\mathbf{x}\rho^2(\mathbf{x})]^2}$$



2.5 Survival of density fluctuation in an expanding fireball (8)

Off-equilibrium effects



Density moment:

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

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

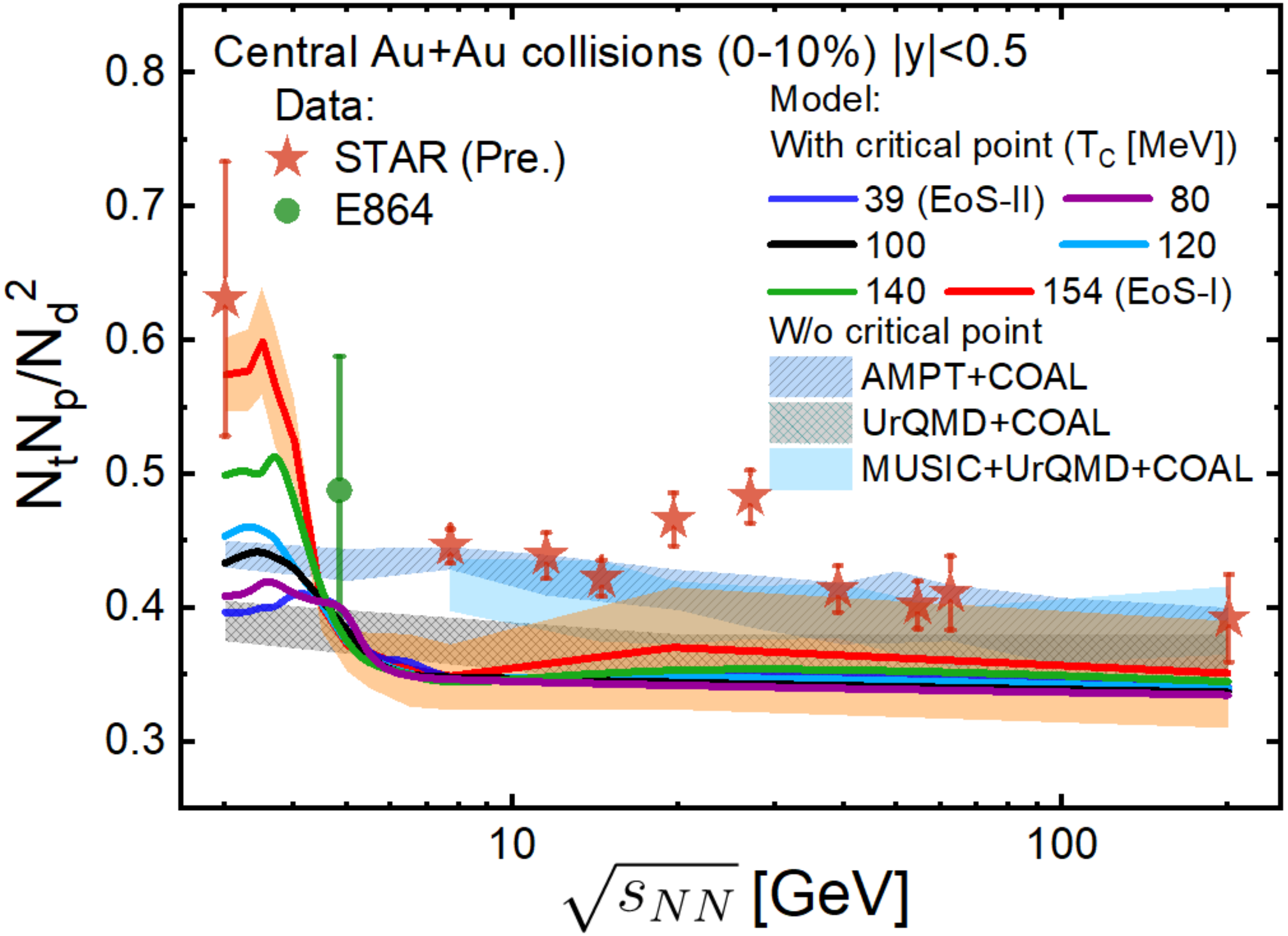
If the expansion is self-similar or scale invariant

$$\rho(\lambda(t)x, t) = \alpha(t)\rho(x, t_h)$$

then $y_2(t) = y_2(t_h)$, i.e., remains a constant

'Memory effects': Large density inhomogeneity survives to kinetic freezeout

2.7 Collision energy dependence (9)

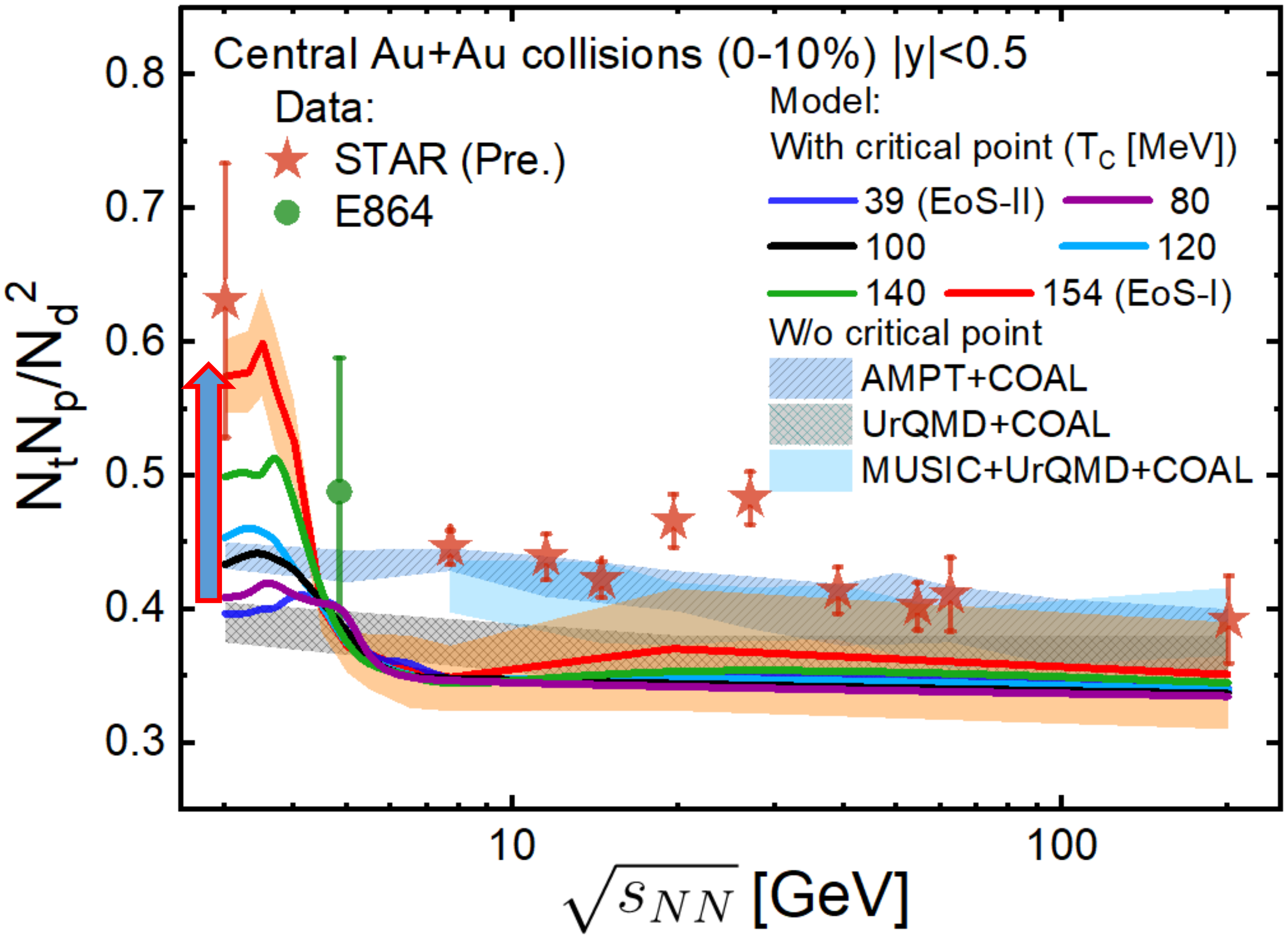


1. Without a critical point:
   The energy dependence of tp/d^2 is almost flat.

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.

STAR, arXiv:2209.08058(2022)
Hui Liu (STAR), QM2022
T. A. Armstrong et al. (E864), Phys. Rev. C 61, 064908 (2000).

2.7 Collision energy dependence (9)



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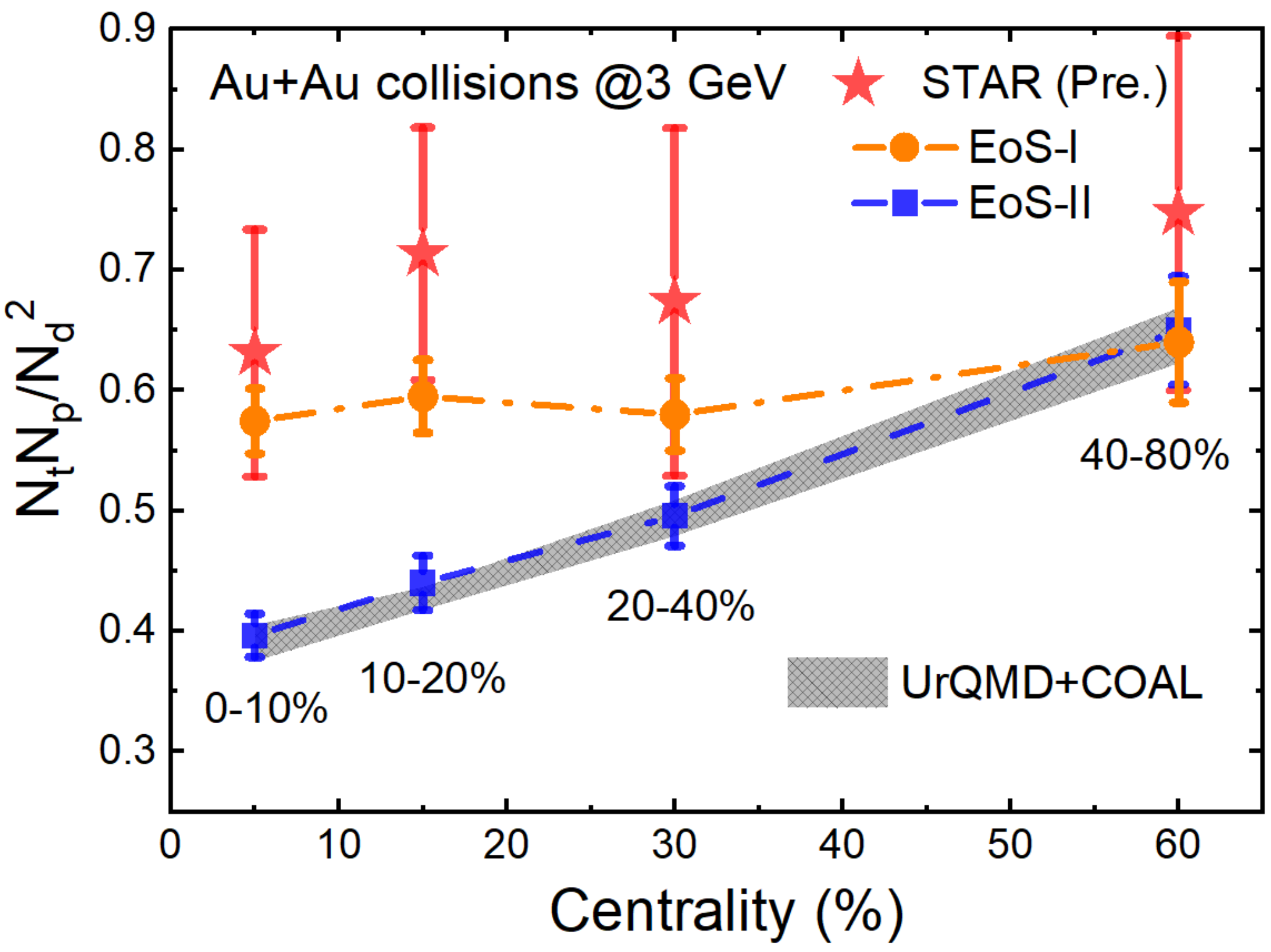
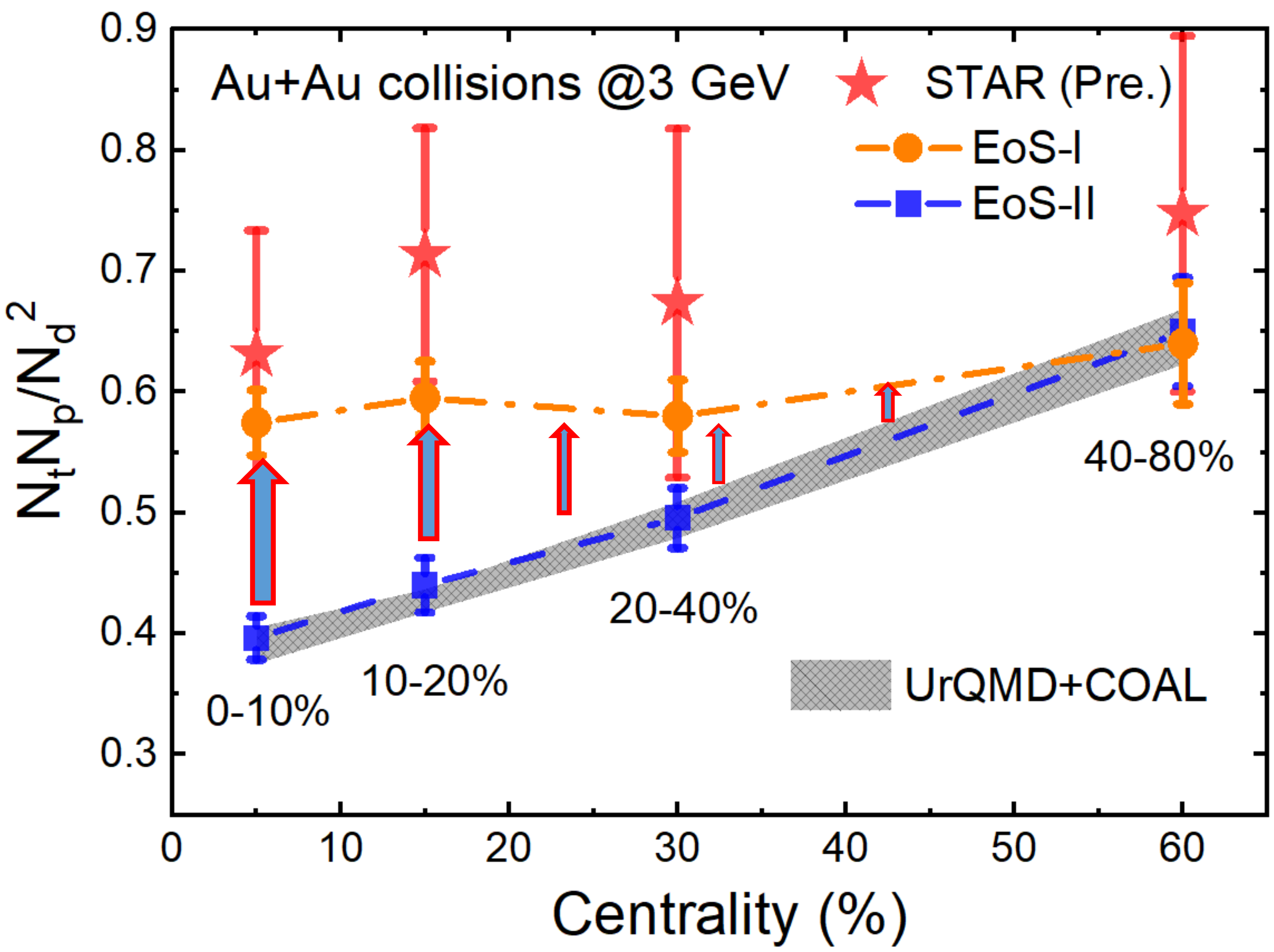
2.8 Centrality dependence



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

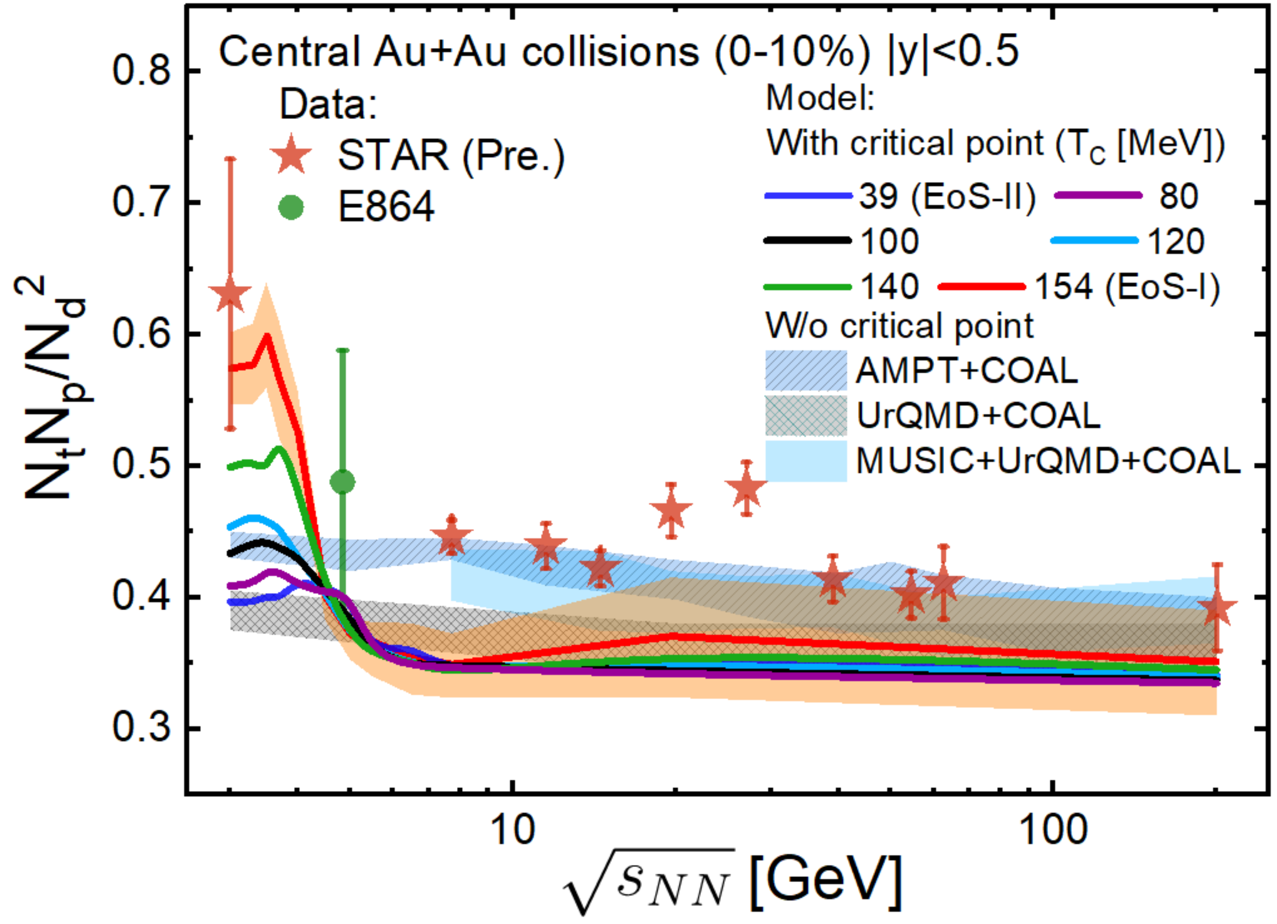
2.8 Centrality dependence



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

2.9 Possible critical effects

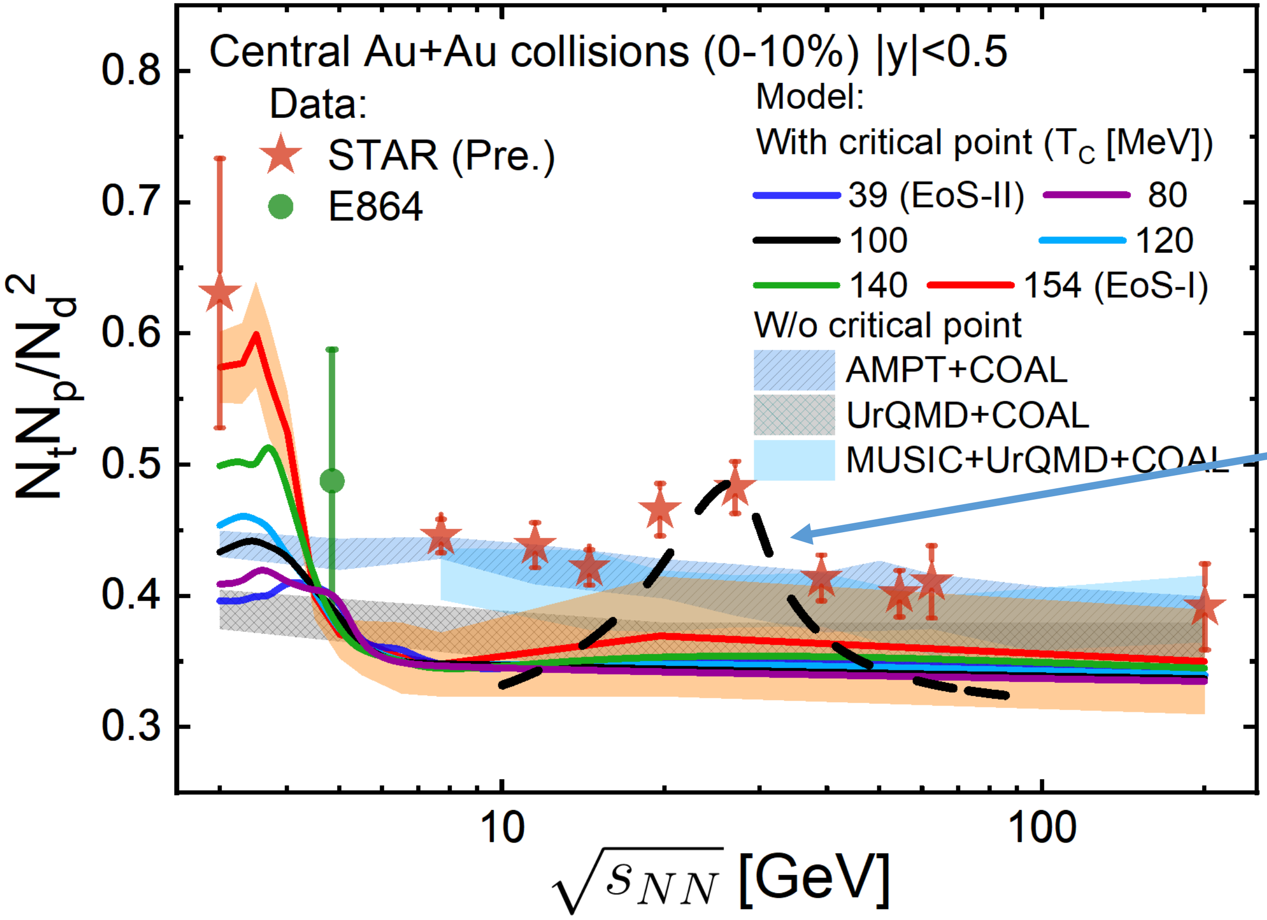


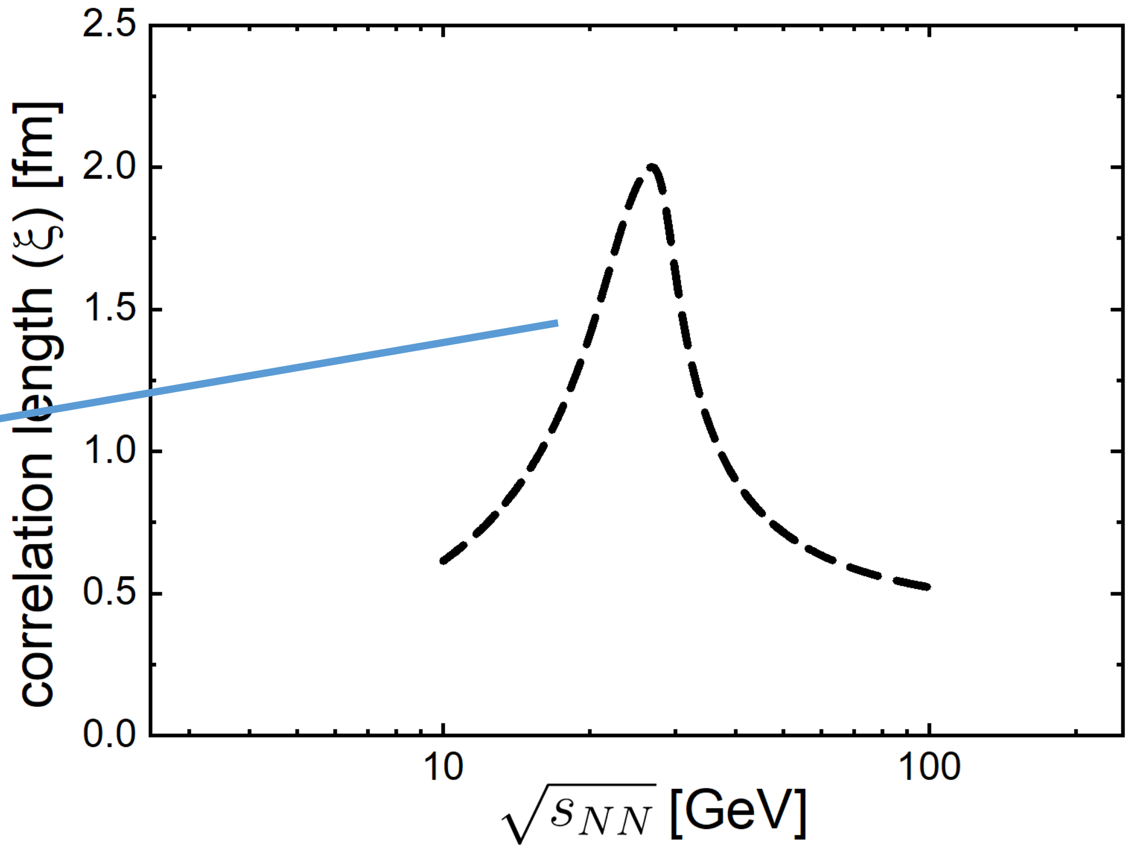
2.9 Possible critical effects (11)

With long-range correlation: $$\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}[1 + \Delta\rho_n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right)]$$

$$G(z) = \sqrt{\frac{2}{\pi}} - \frac{1}{z} e^{\frac{1}{2z^2}} \mathrm{erfc}(\frac{1}{\sqrt{2}z})$$

PLB 816, 136258 (2021)





C. Athanasion, K. Rajagopal, and M. Stephanov, Phys. Rev. D82, 074008 (2010)

further investigations are needed

3. Summary and Outlook (12)

Main findings:

1. With scans of the collision energy and centrality as well as the equation of state using a novel transport model, we find that large density inhomogeneities generated by the spinodal instability during the first-order QCD phase transition can survive the fast expansion of the subsequent hadronic matter and lead to an enhanced tp/d^2 in central Au+Au collisions at $\sqrt{s_{NN}}$ =3 – 5 GeV for $T_c \geq 80$ MeV, which is in accordance with the STAR measurements.

2. We also find that the spinodal enhancement of tp/d^2 subsides with increasing collision centrality because of the shortening of fireball lifetime, and this effect results an almost flat centrality dependence of tp/d^2 at $\sqrt{s_{NN}}$ =3 GeV, which can also be used as a signal for the occurrence of a first-order phase transition.

Future developments:

1. Incorporation of Polyakov loop
2. Inclusion of long-range correlation