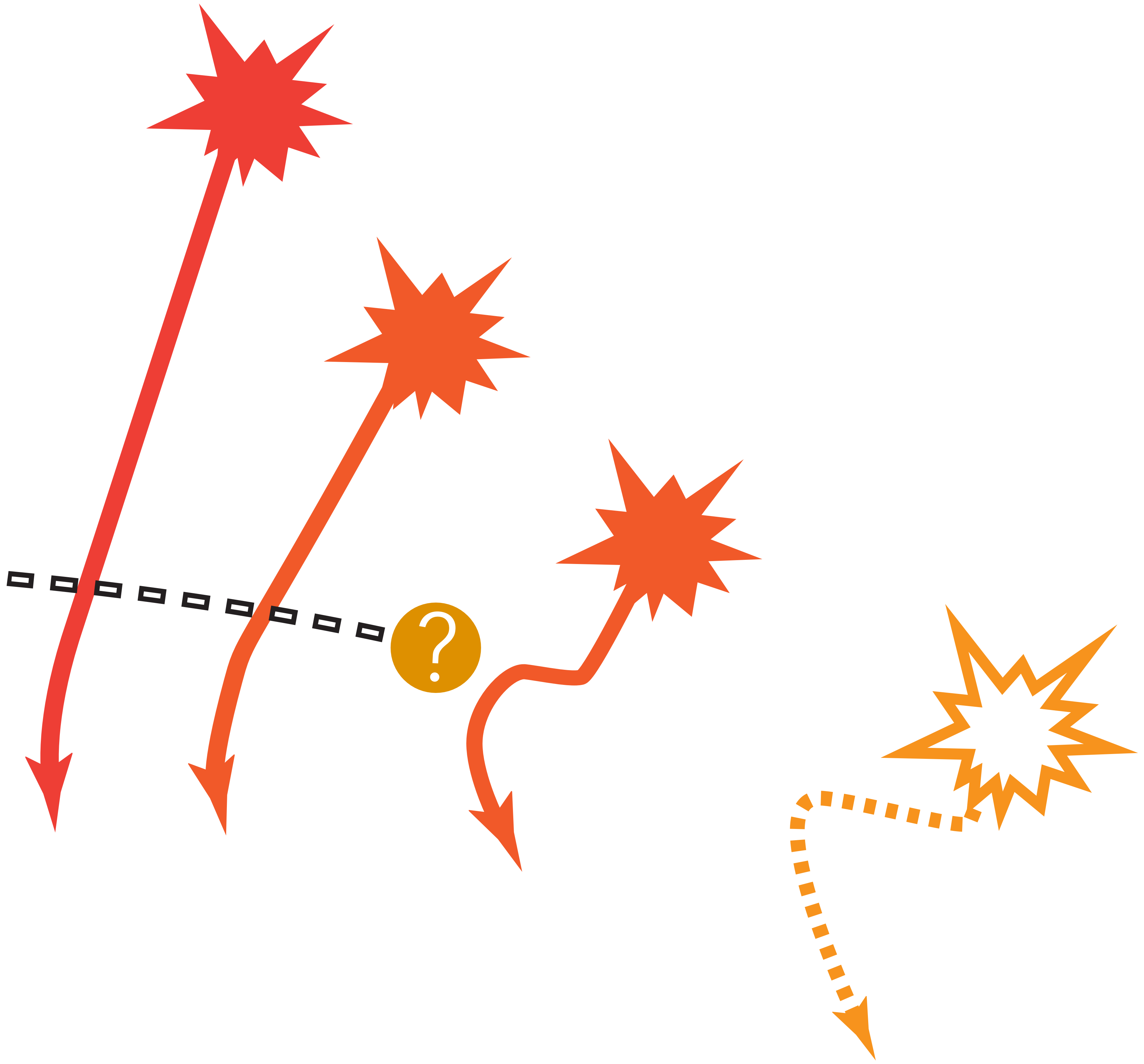
U.S. DEPARTMENT OF ENERGY | Office of Science

BEST COLLABORATION

BROOKHAVEN NATIONAL LABORATORY

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

THEORY PROGRESS RELATED TO THE RHIC BEAM ENERGY SCAN PROGRAM

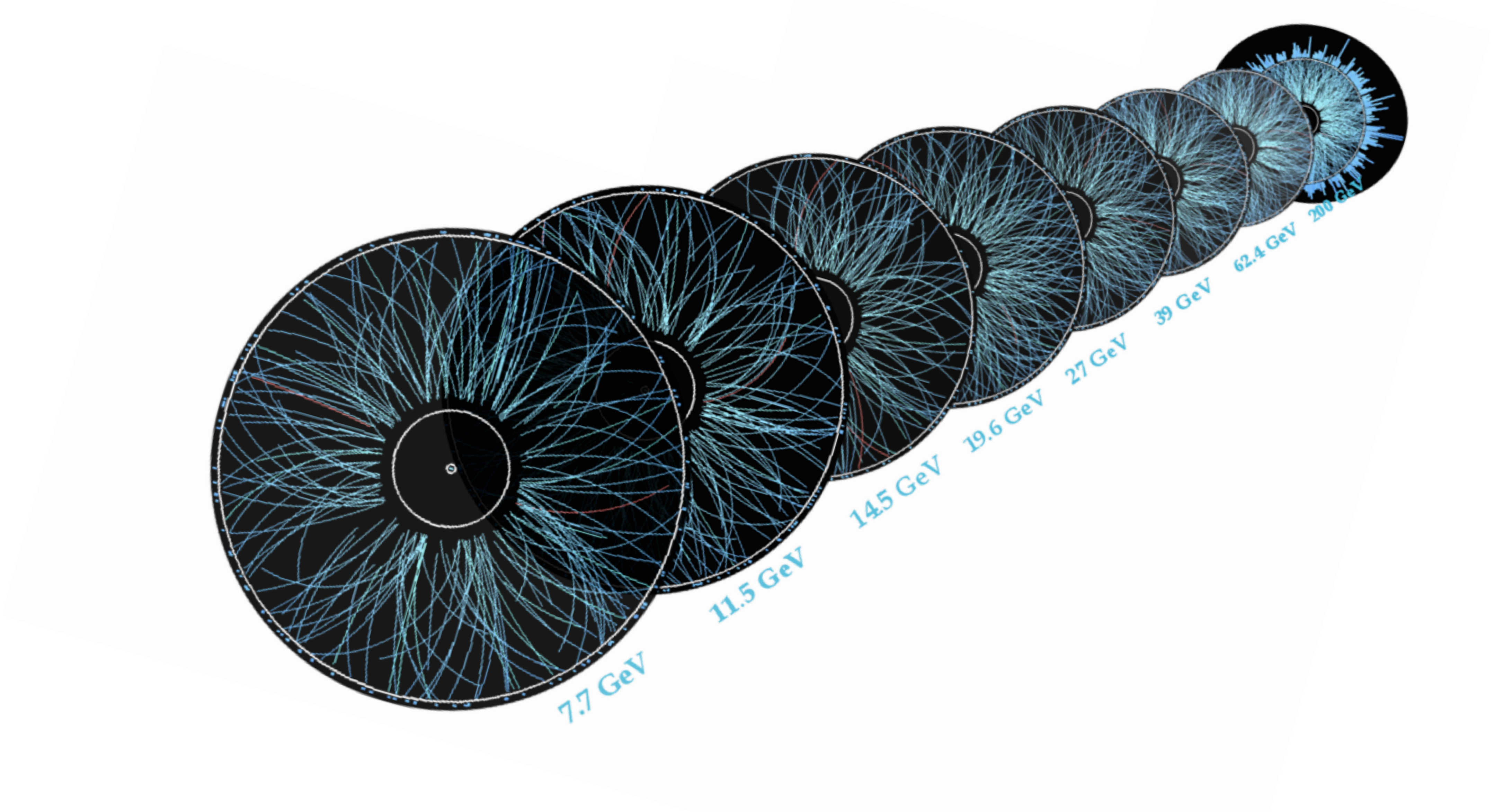


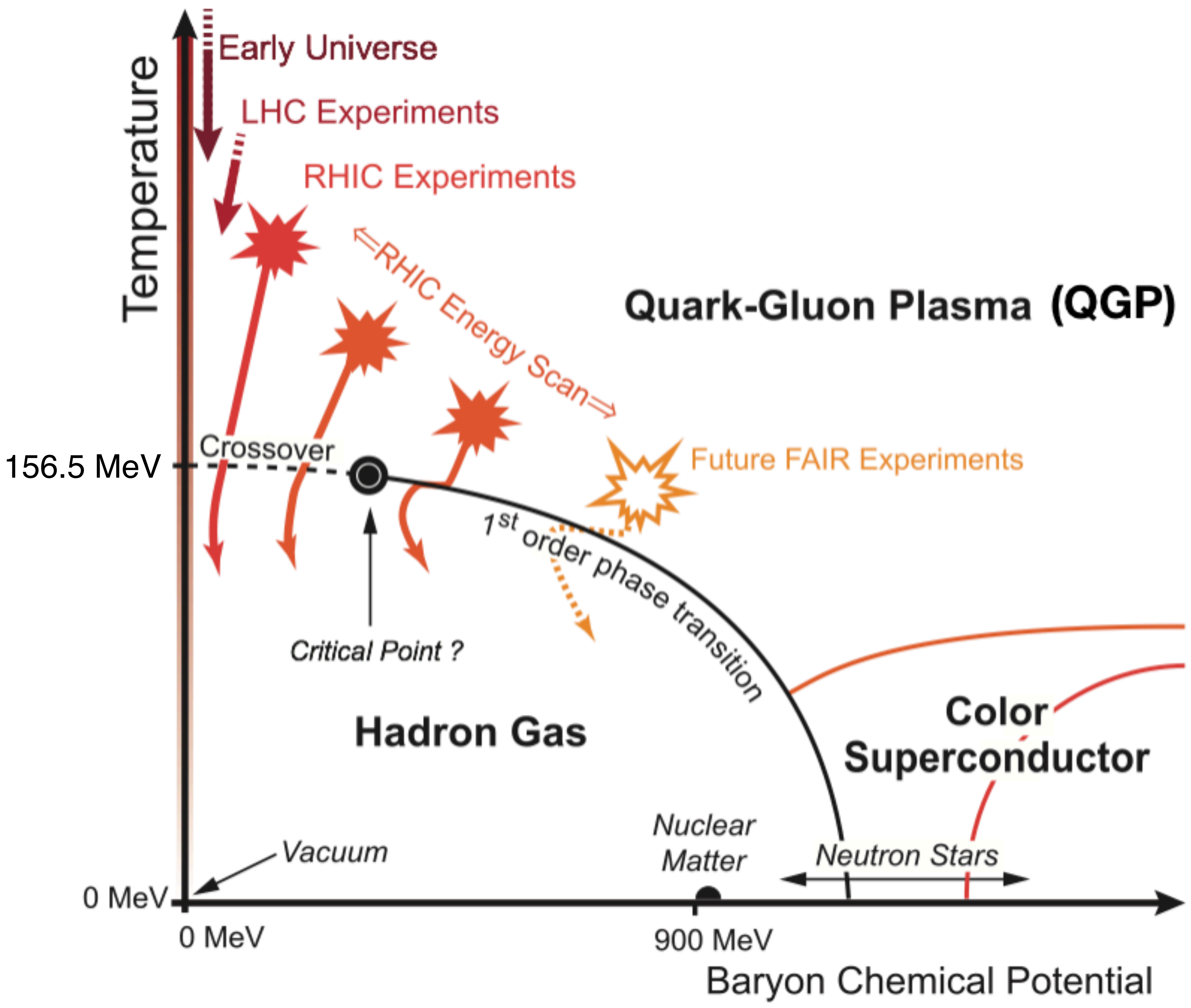
4/11/2019

2019 GHP WORKSHOP, DENVER, CO

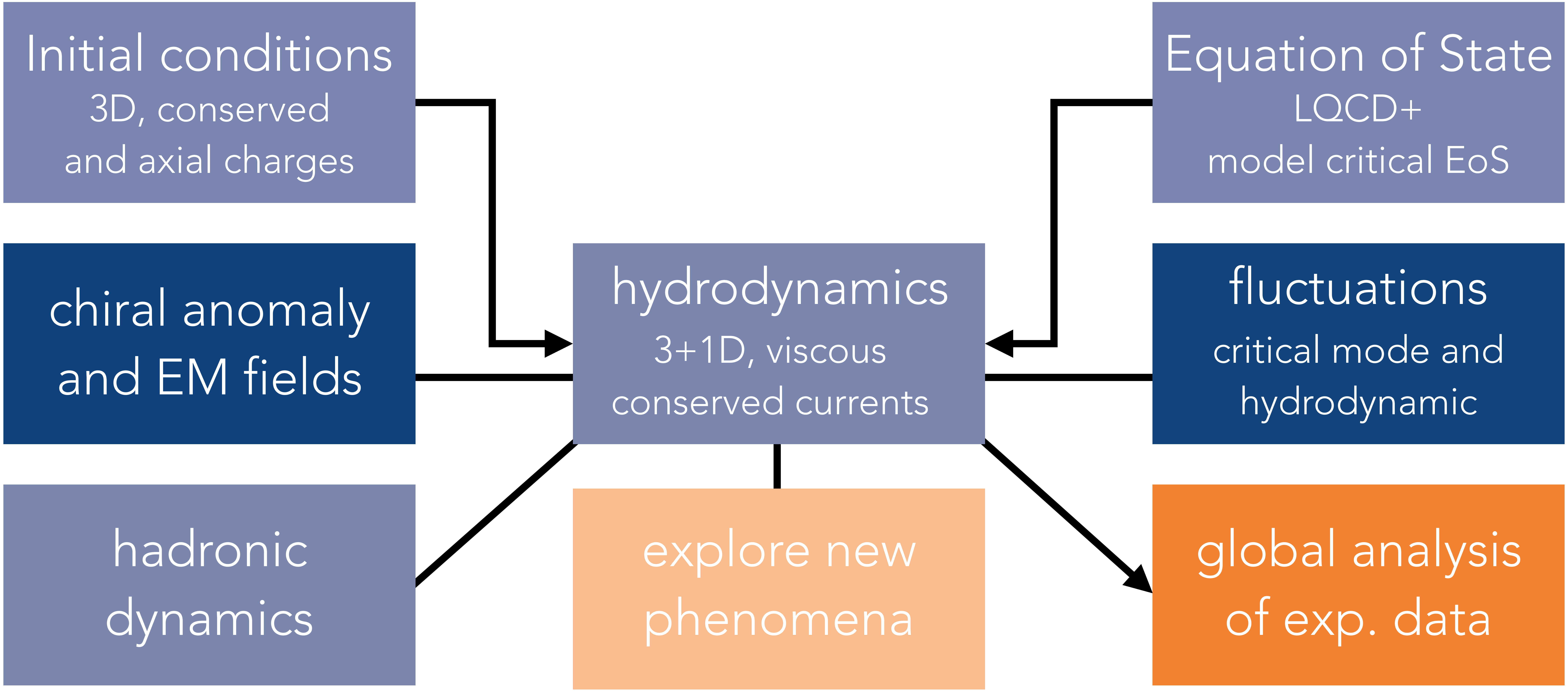
BEAM ENERGY SCAN (BES) II AT RHIC

- QCD critical point & phase diagram
- Properties of baryon-rich QGP
- Onset of chiral symmetry restoration
- Unexpected new phenomena

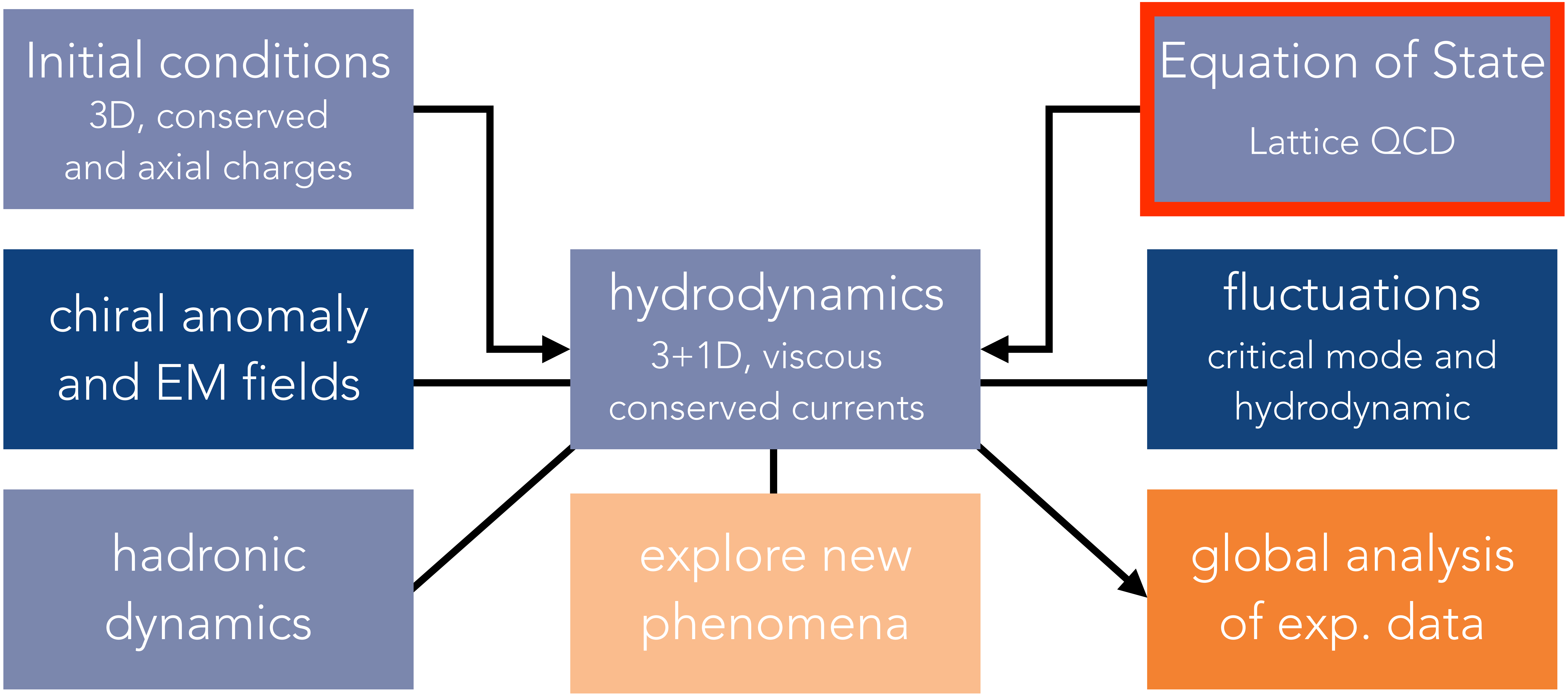




BEAM ENERGY SCAN THEORY

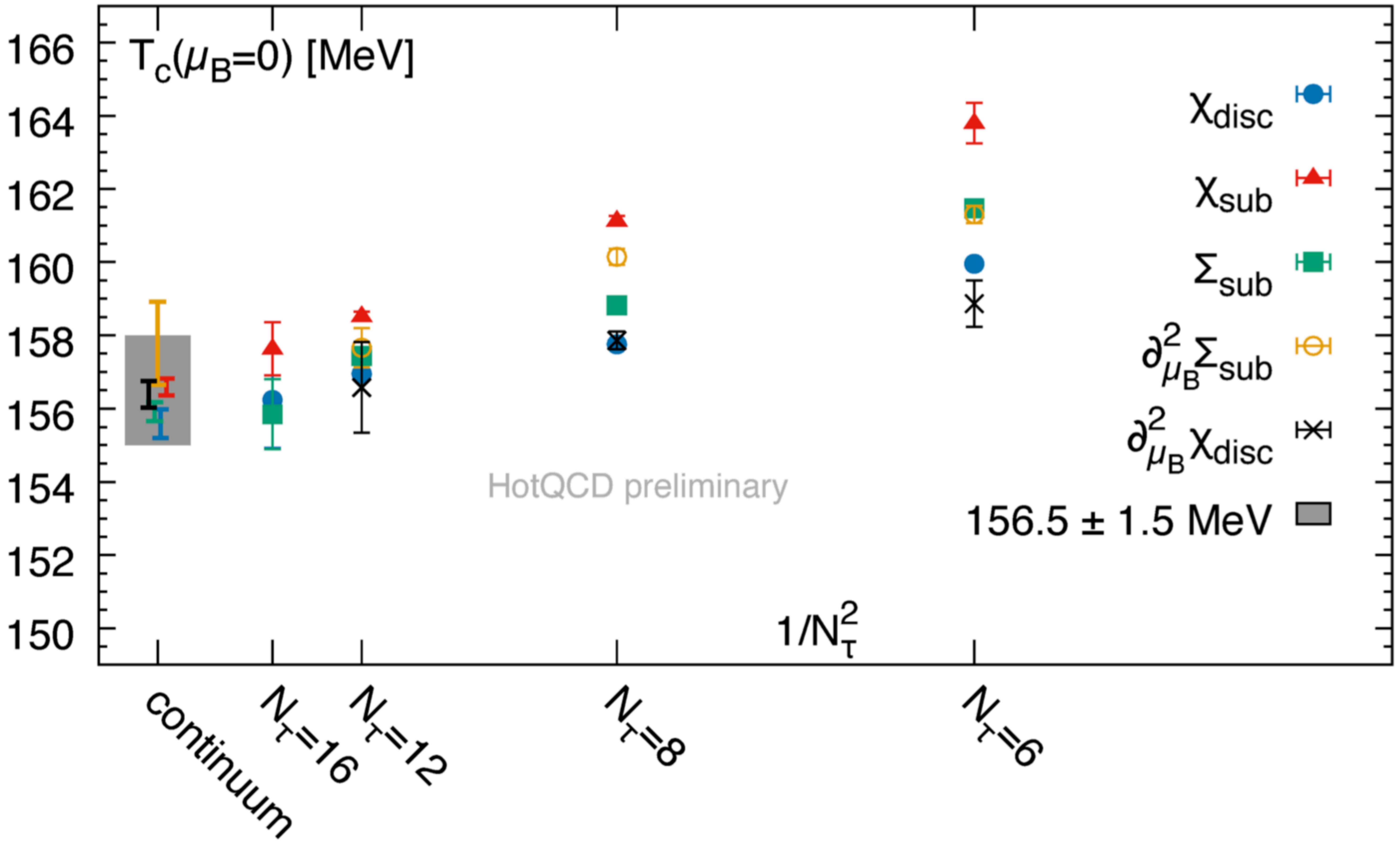


BEAM ENERGY SCAN THEORY



EQUATION OF STATE AT $\mu_B = 0$

HotQCD, Nucl.Phys. A982 (2019) 847-850



P. Steinbrecher @QM2018

Latest result for the QCD crossover temperature: Tc ≃ 156.5 ± 1.5 MeV

from the chiral condensate

EQUATION OF STATE AT $\mu_B \neq 0$

$$Z = \int \mathcal{D}U e^{-S_G[U]} \det M[\mu_B]$$

$\det M[\mu_B]$ is complex and Monte Carlo simulations are not feasible

→ sign problem

One way to cope: Taylor expansion around μ_B=0:

$$\frac{P(T,\mu_B)}{T^4} = \sum_n \frac{1}{n!} \chi_n^B(T) \left(\frac{\mu_B}{T}\right)^n$$

where $\chi_n^B = \left. \frac{\partial^n P(T,\mu_B/T)/T^4}{\partial(\mu_B/T)^n} \right|_{\mu_B=0}$

are the susceptibilities

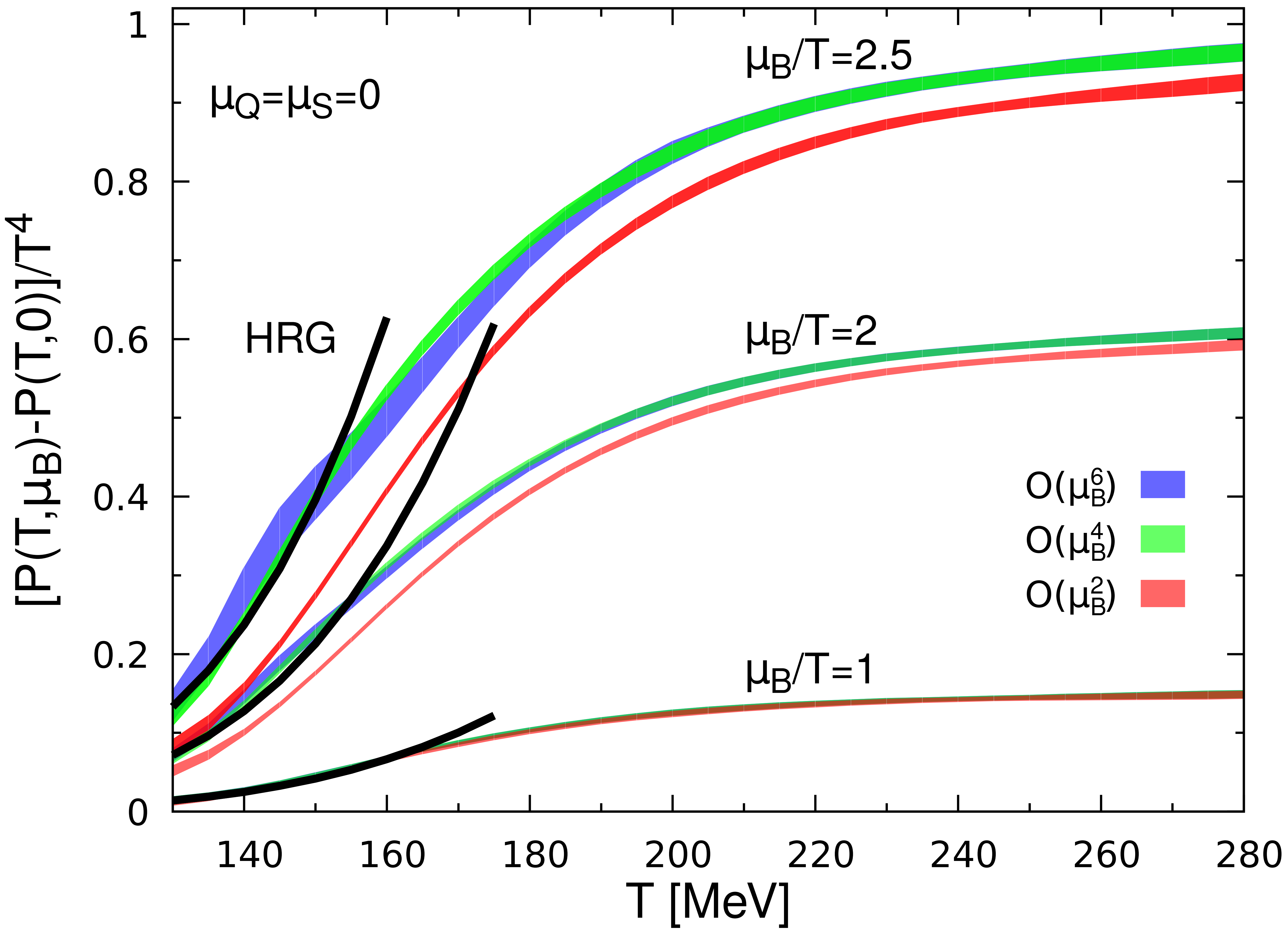
EQUATION OF STATE AT $\mu_B \neq 0$

Taylor expansion up to $\mathcal{O}(\mu_B^6)$

Present reach of the Lattice QCD EoS:

$$\mu_B/T \lesssim 2$$

HotQCD: Phys. Rev. D95, 054504 (2017)



also see: Guenther at. al.: Nucl. Phys. A967, 720-723 (2017)

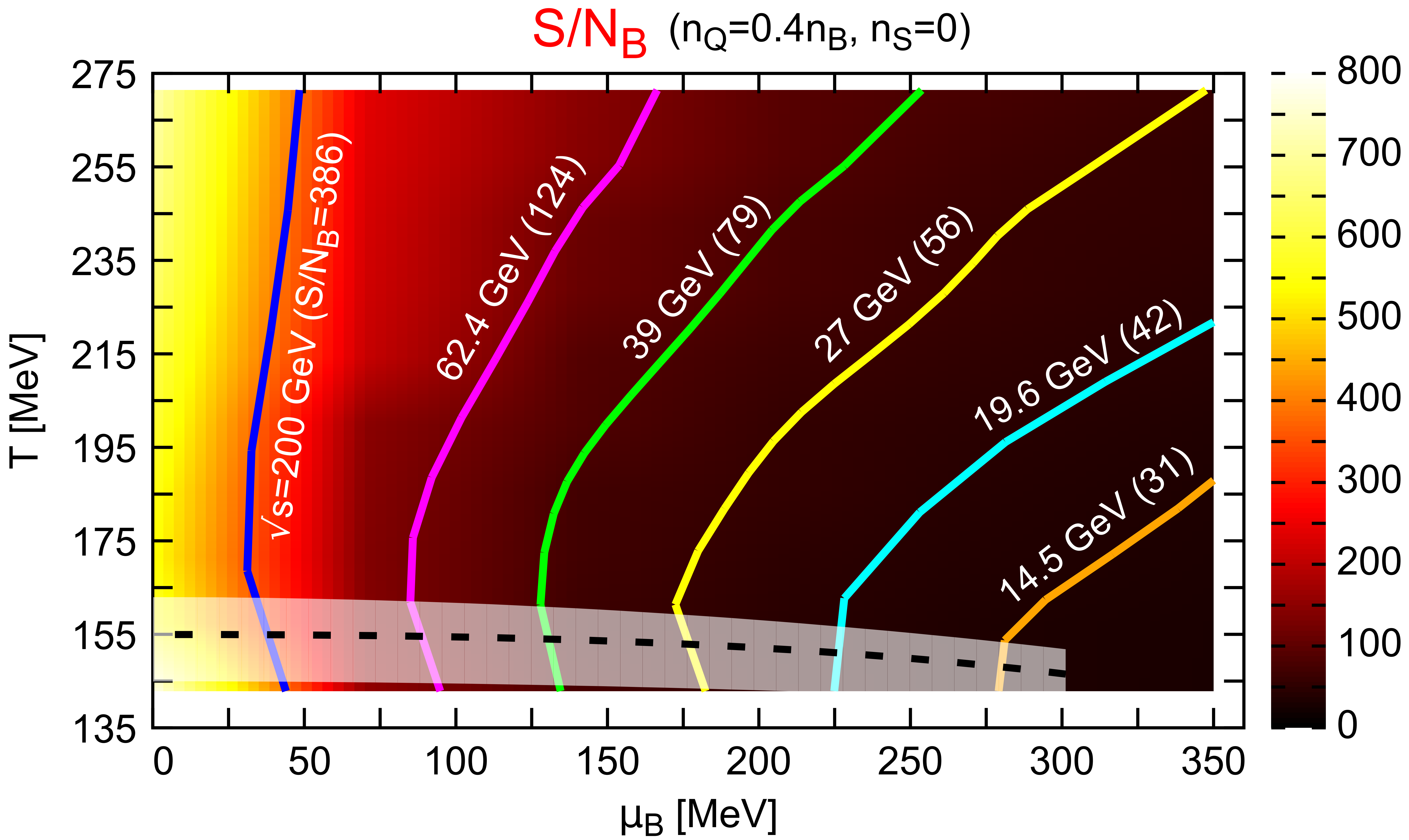
EQUATION OF STATE AT $\mu_B \neq 0$

Present reach of the Lattice QCD EoS:

$$\mu_B/T \lesssim 2$$

or

$$\sqrt{s} \gtrsim 14.5\,\mathrm{GeV}$$



Lines: Constant entropy to net-baryon number
(Approximate evolution trajectories of inviscid QGP)

THE QCD CROSSOVER LINE

MORE TODAY 5:15PM IN TALK BY PETER PETRECZKY (DIRECTOR'S ROW I)

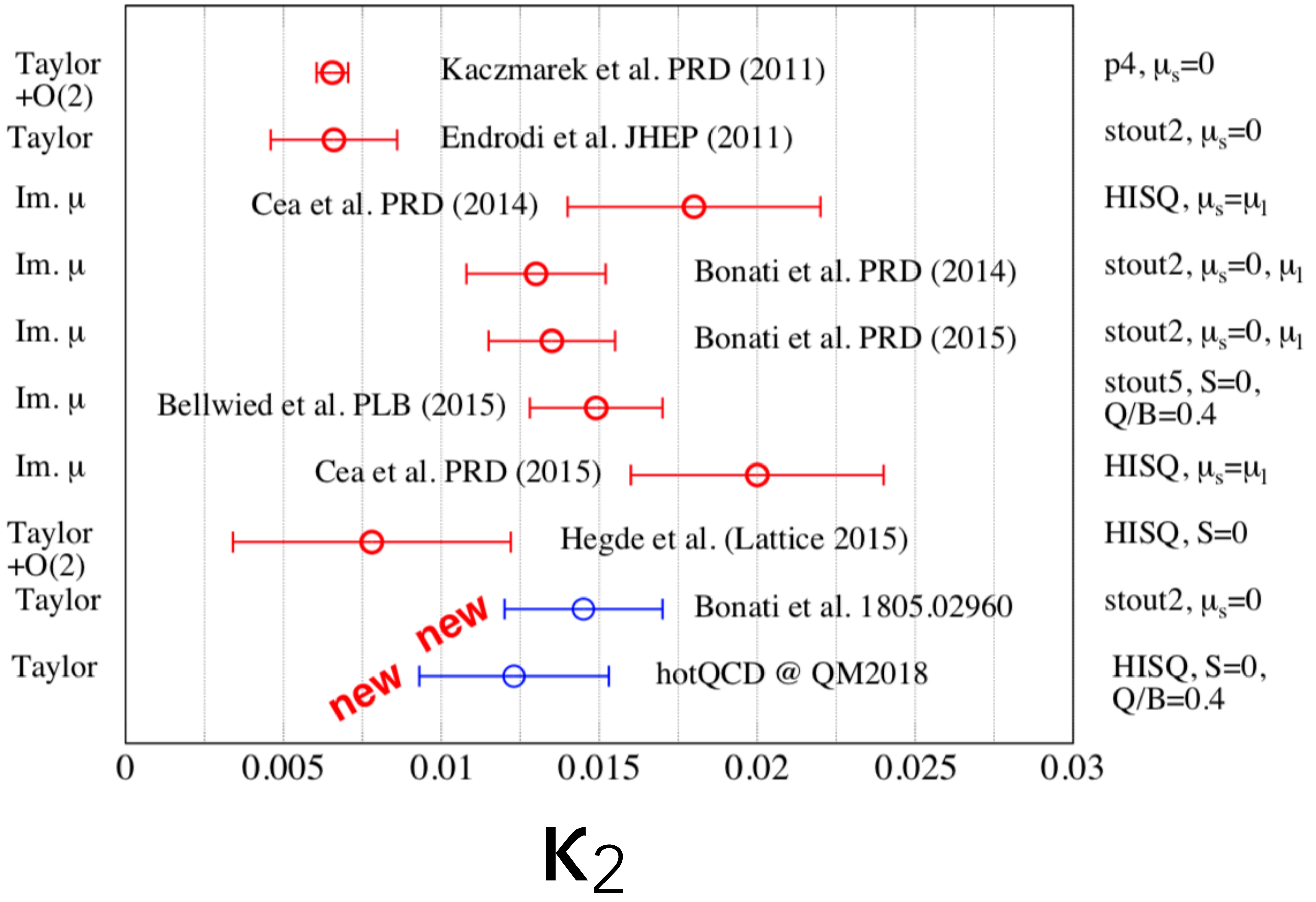
$$\frac{T_c(\mu_B)}{T_c} = 1 - \kappa_2^B \left(\frac{\mu_B}{T_c}\right)^2 - \kappa_4^B \left(\frac{\mu_B}{T_c}\right)^4 + \mathcal{O}(\mu_B^6)$$

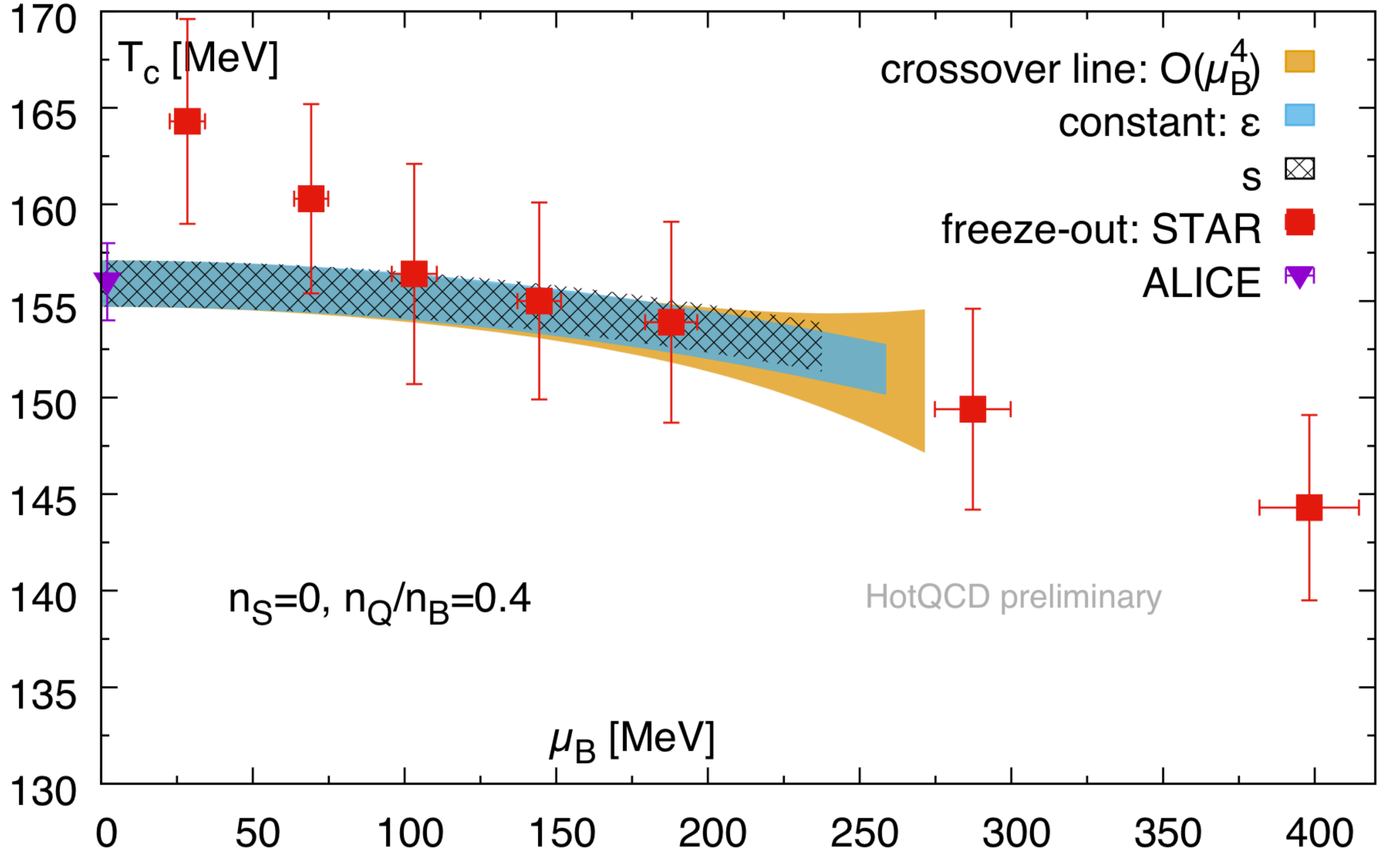
STAR: arxiv:1701.07065

ALICE: arxiv:1408.6403

Imposing strangeness neutrality → $\kappa_2 = 0.0123(30)$

$\kappa_4 = 0.000131 \pm 0.0041$





P. Steinbrecher @QM2018

HotQCD: arXiv:1812.08235

CRITICAL POINT WITHIN REACH OF LQCD?

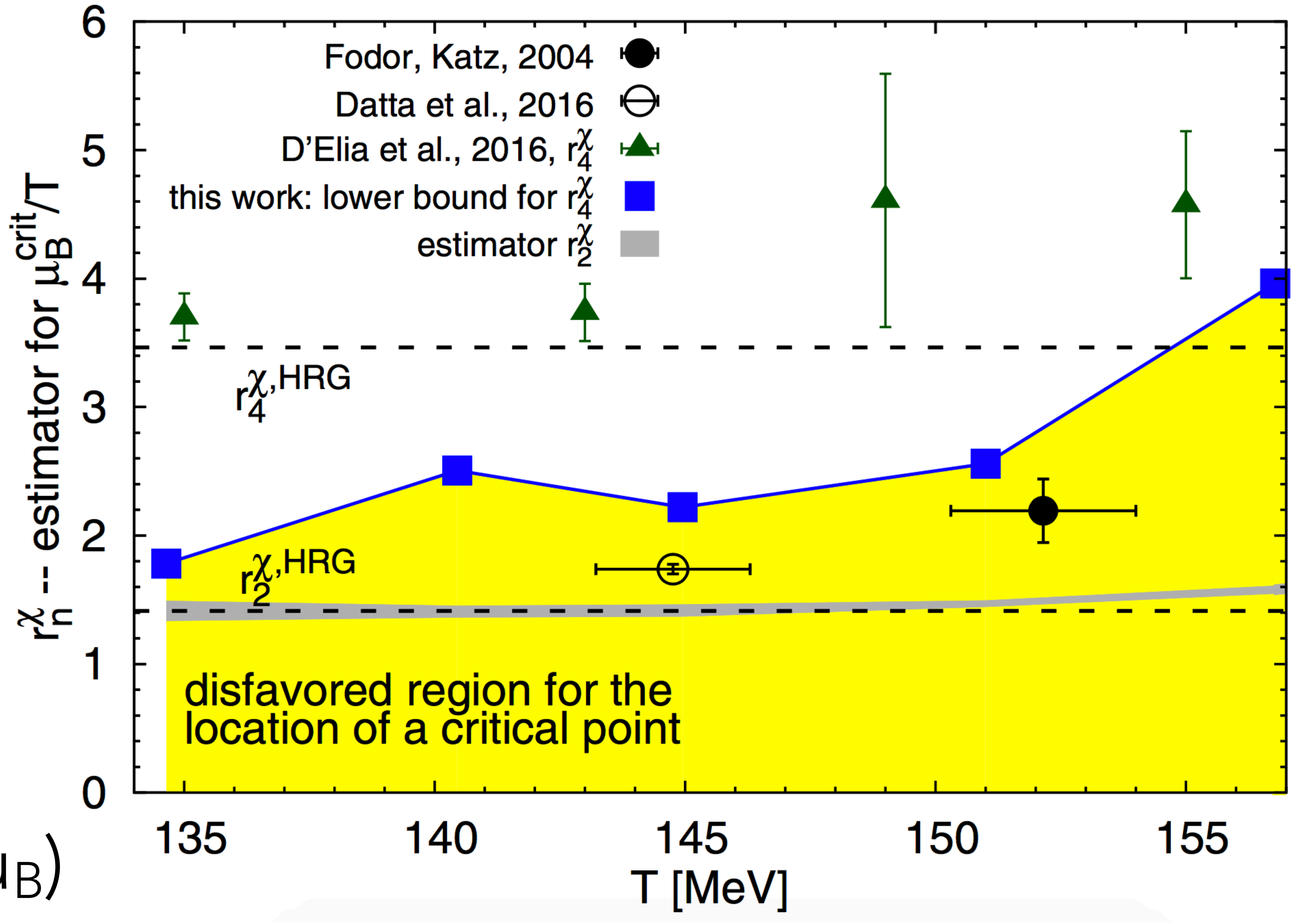
If there is a critical point close-by, we expect radius of convergence of Taylor series of pressure or susceptibility, r_c to be $< \infty$:

$$\chi_2^B(T,\mu_B) = \sum_{n=0}^{\infty} \frac{1}{(2n)!} \chi_{2n+2}^B \left(\frac{\mu_B}{T}\right)^{2n}$$

$$r_{2n}^{\chi} = \left| \frac{2n(2n-1)\chi_{2n}^B}{\chi_{2n+2}^B} \right|^{1/2}, \quad r_c = \lim_{n\to\infty} r_{2n}^{\chi}$$

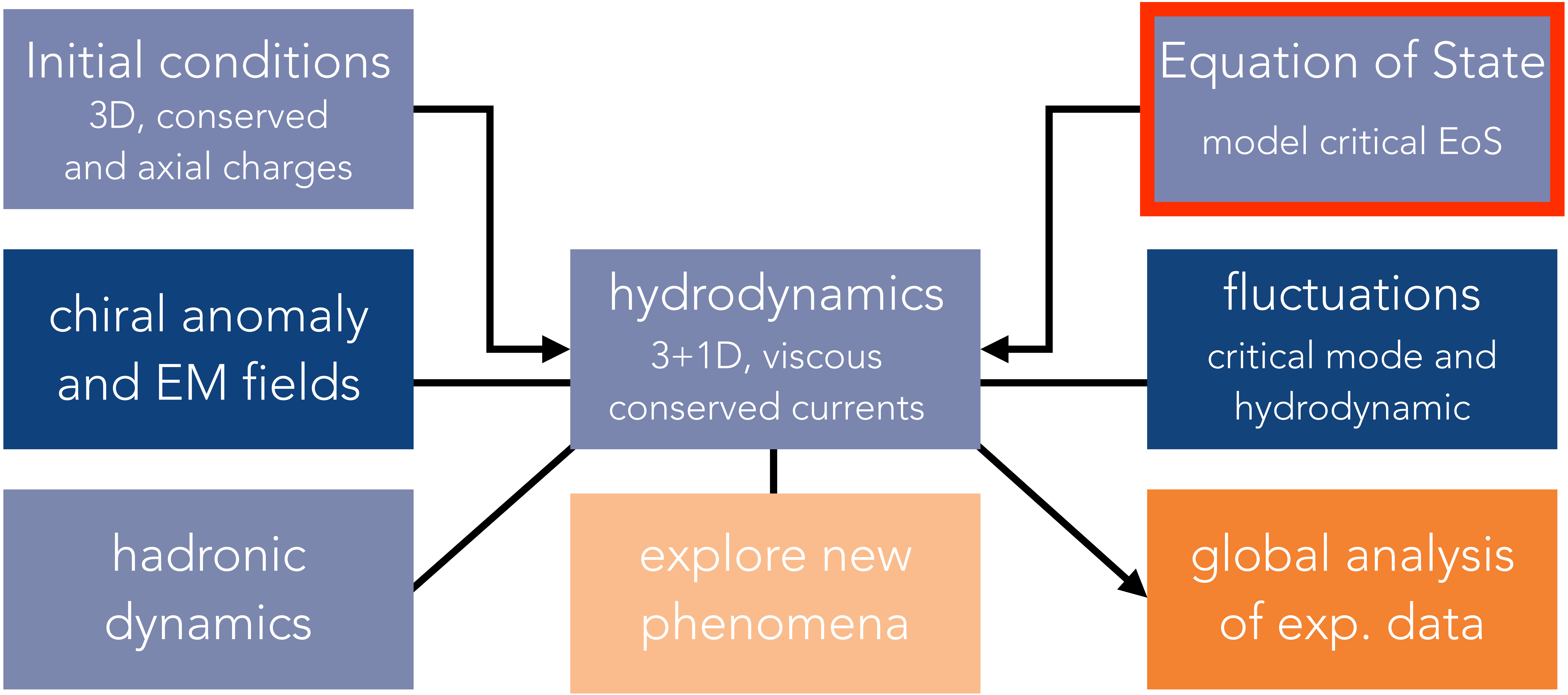
To get r_c to be $< \infty$ we need $|\chi_{n+2}^B/\chi_n^B| \sim n^2$ which does not happen up to n=4

→Identify disfavored region (T,μ_B)



HotQCD: Phys. Rev. D95, 054504 (2017)

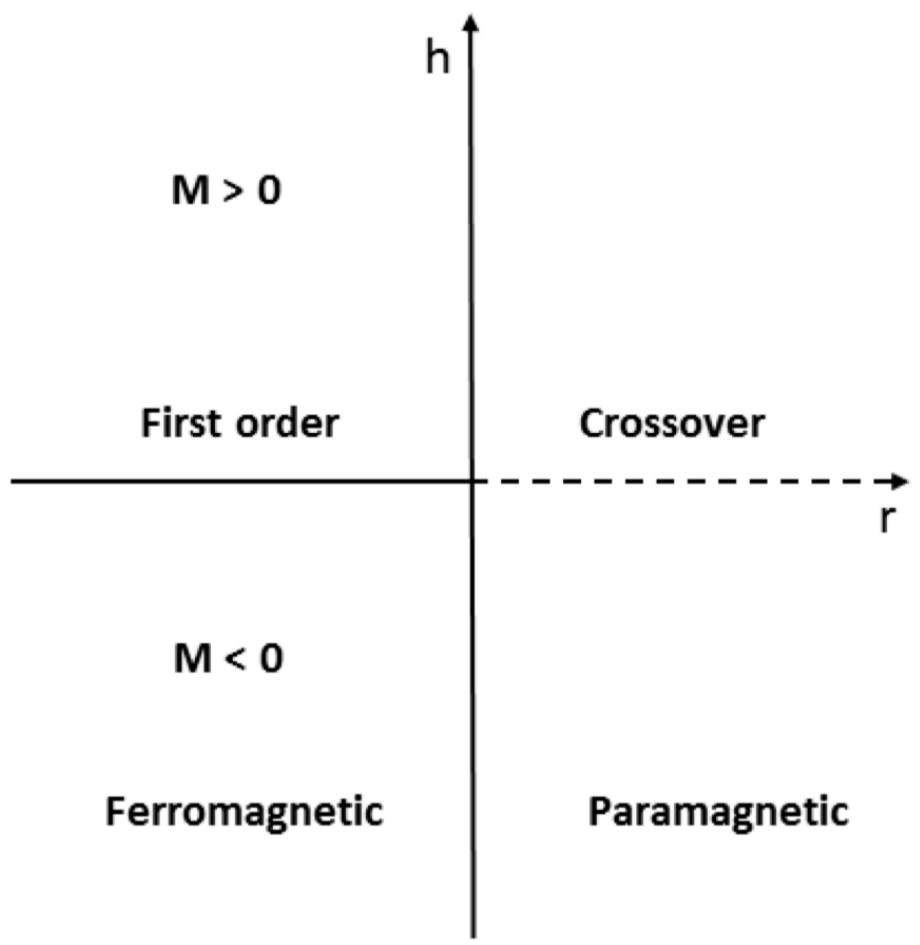
BEAM ENERGY SCAN THEORY

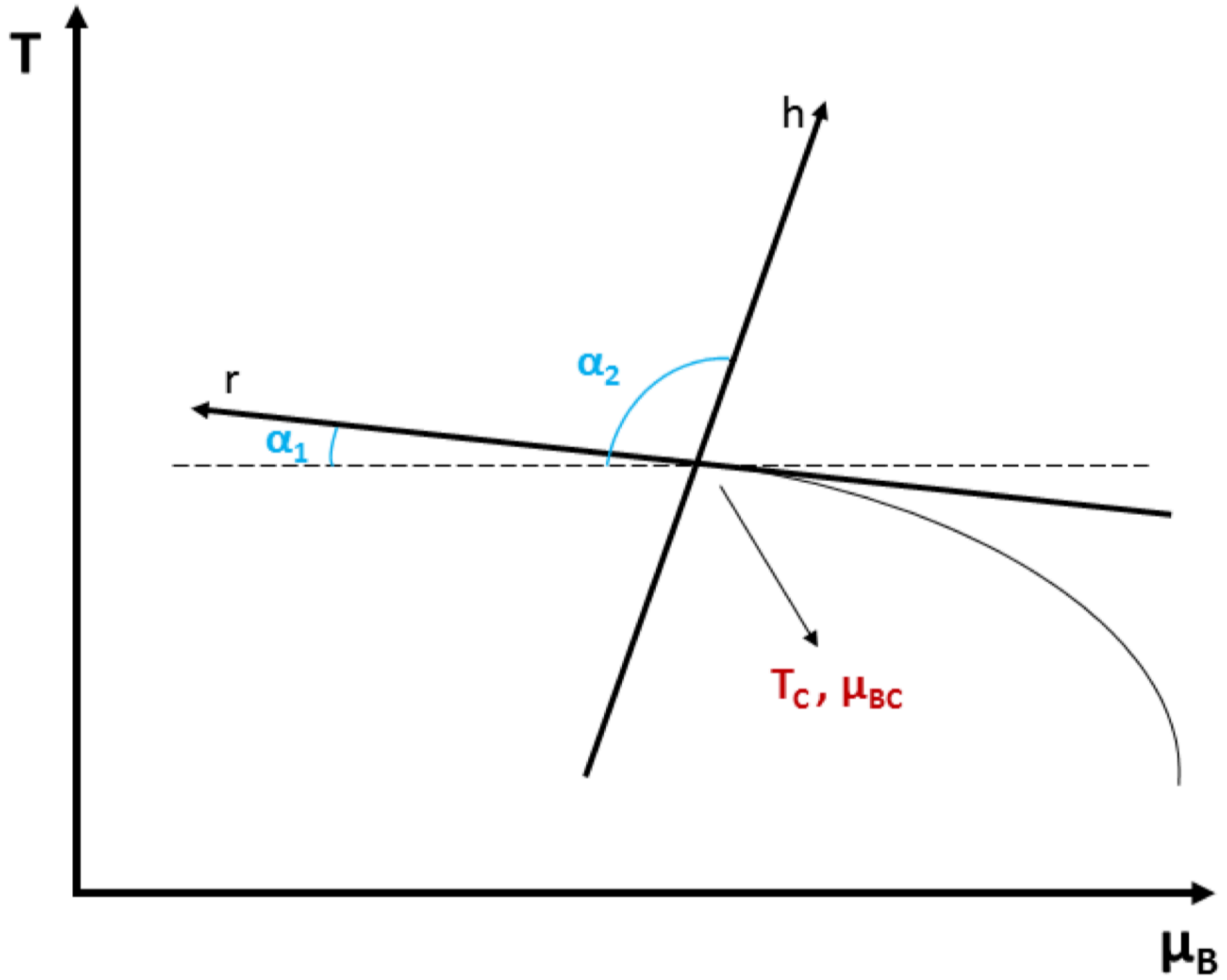


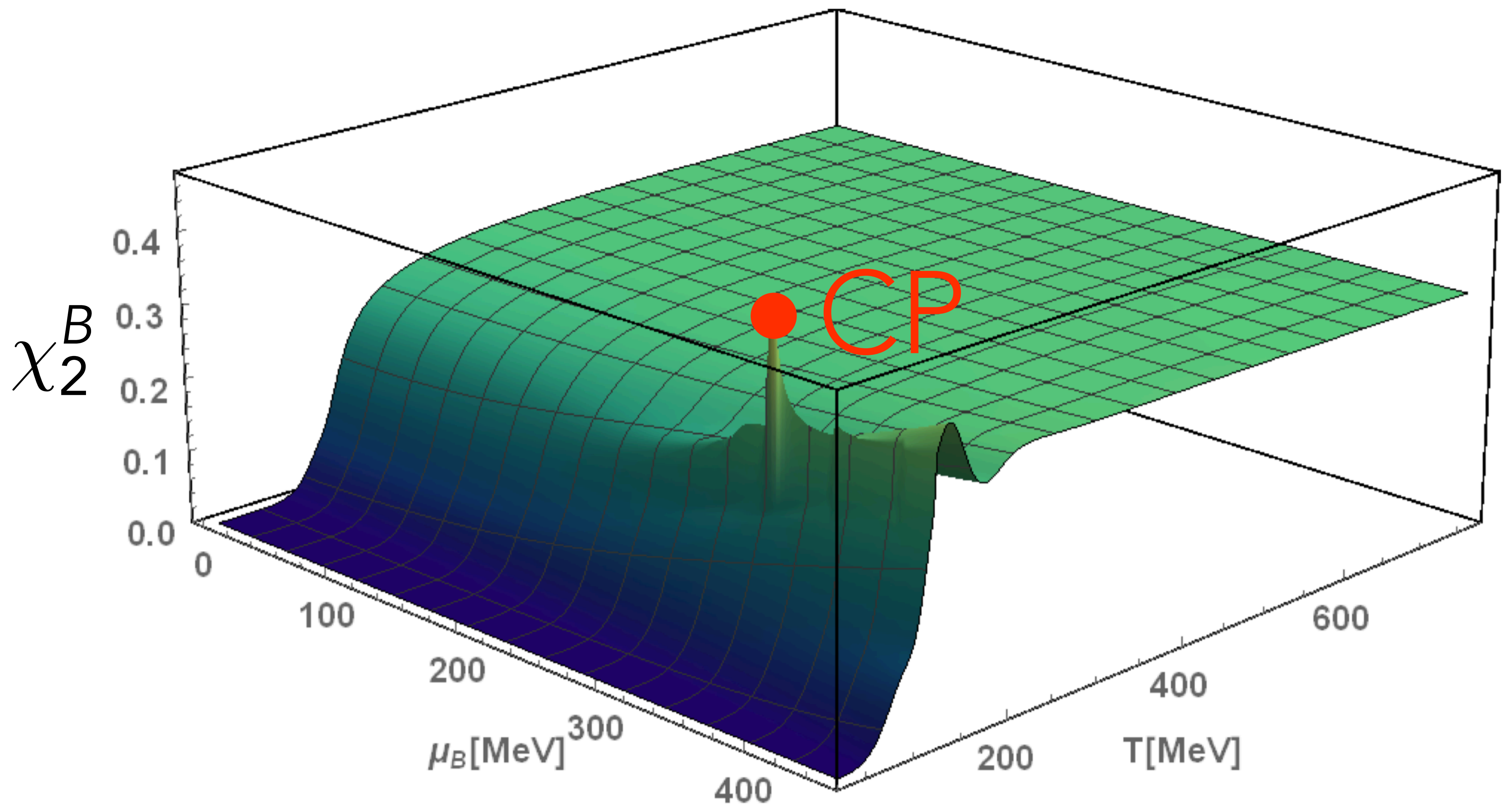
INCLUDE CRITICAL POINT IN LQCD EOS

P. Parotto et al, arXiv:1805.05249

Take LQCD EoS with Taylor expansion and place a critical point in the 3D-Ising model universality class: Add critical pressure to LQCD pressure







Map from Ising variables (r,h) to (T,μ_B) is not universal: 6 free parameters:

$$\frac{T - T_C}{T_C} = w\,(r\rho\,\sin\alpha_1 + h\,\sin\alpha_2)$$

$$\frac{\mu_B - \mu_{BC}}{T_C} = w\,(-r\rho\,\cos\alpha_1 - h\,\cos\alpha_2)$$

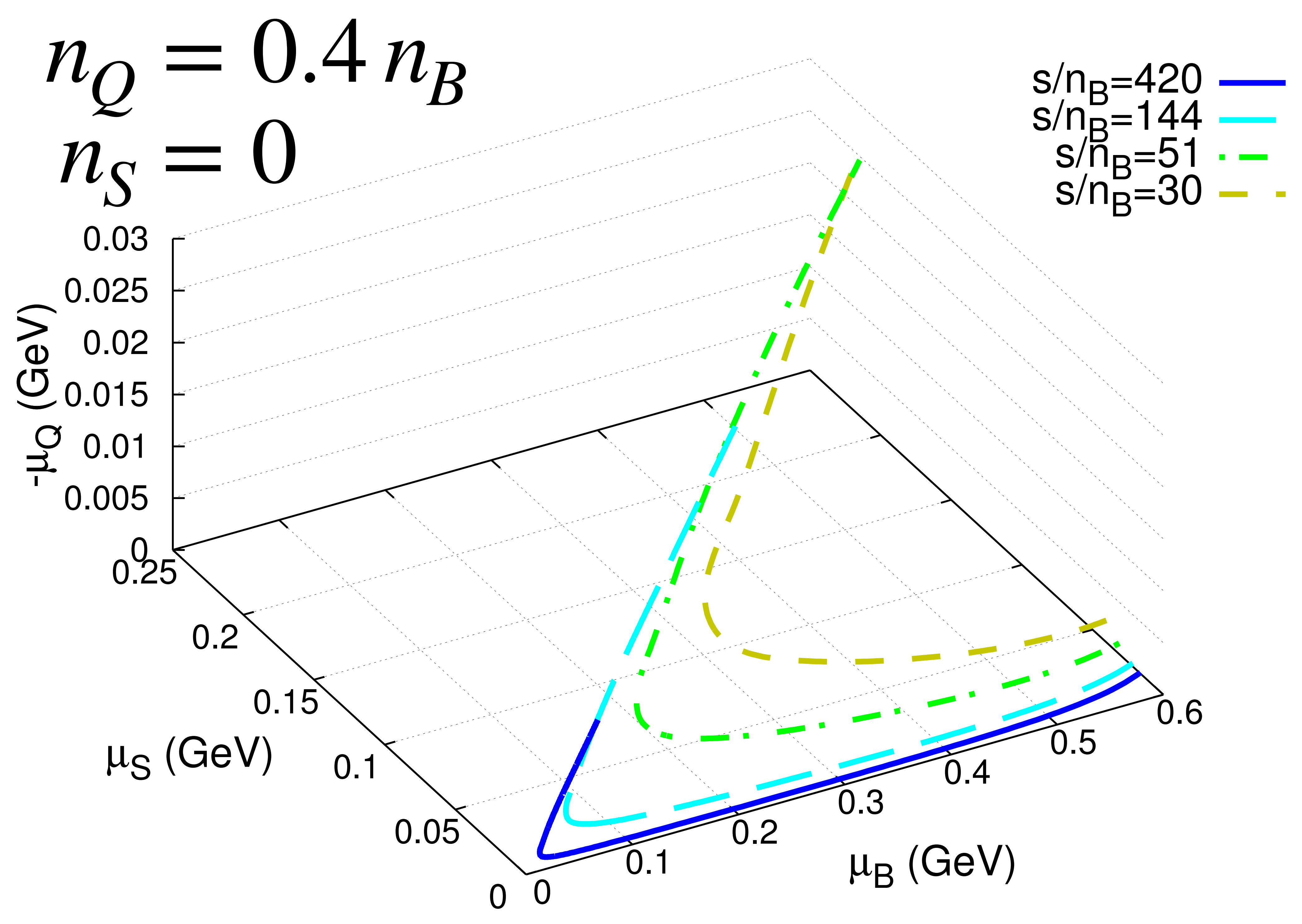
Available for download at
https://www.bnl.gov/physics/best/resources.php

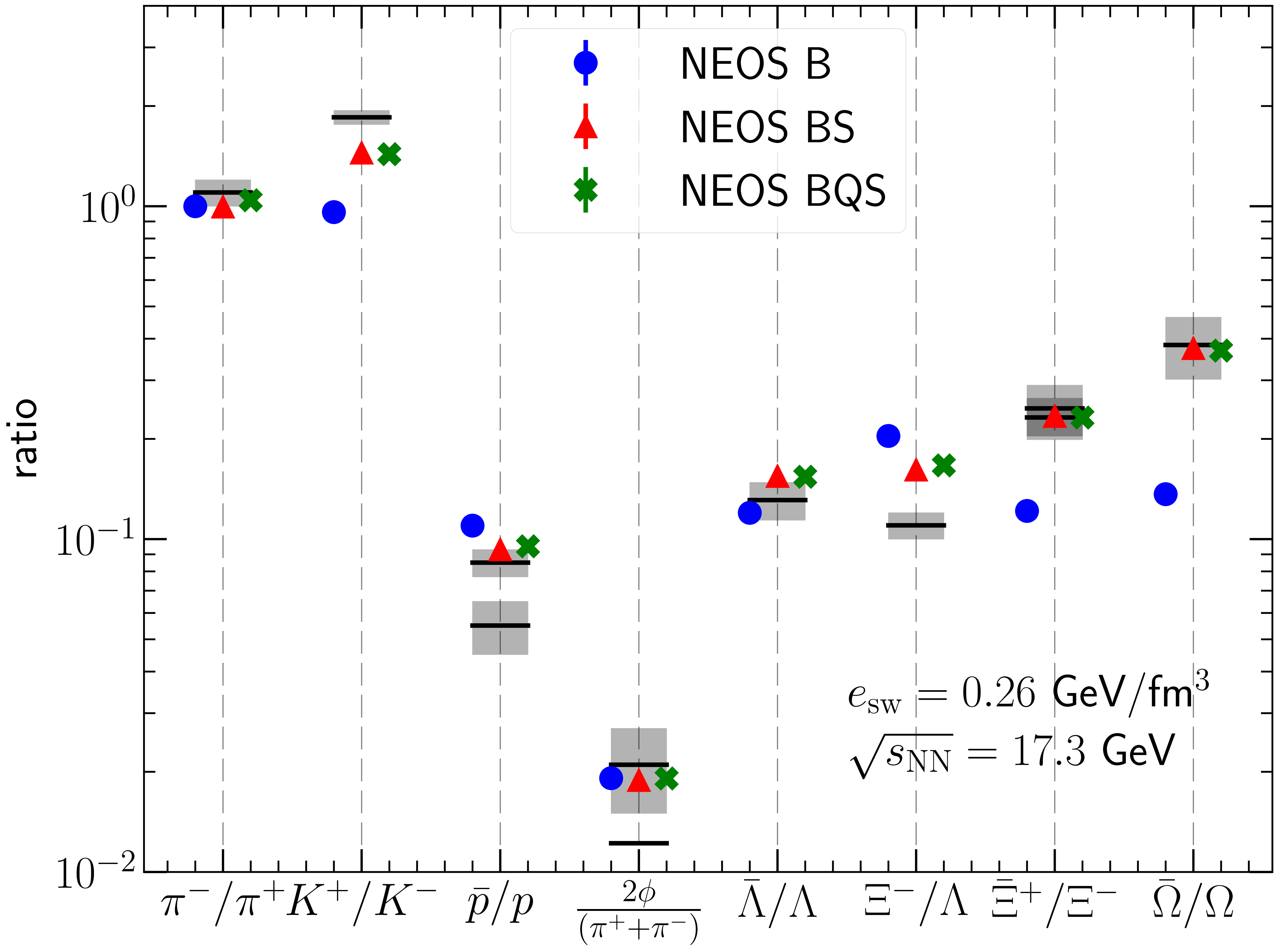
BEST COLLABORATION

EQUATION OF STATE AT FINITE DENSITIES

A. Monnai, B. Schenke and C. Shen, arXiv:1902.05095

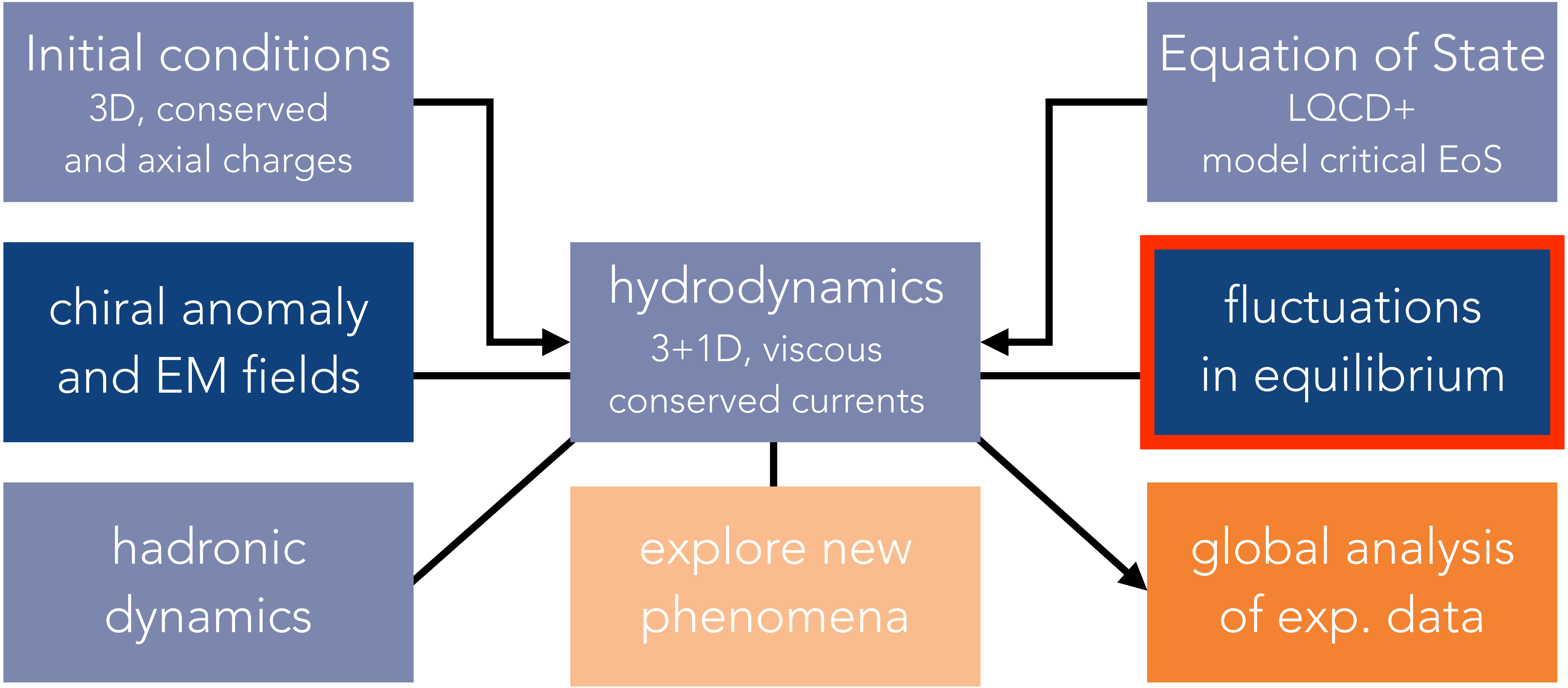
Lattice QCD EoS has been extended to non-zero net baryon, strangeness, and electric charges and implemented in hydrodynamics





see also: J. Noronha-Hostler, P. Parotto, C. Ratti and J. M. Stafford, arXiv:1902.06723

BEAM ENERGY SCAN THEORY



CUMULANTS OF NET BARYON NUMBER

- At the critical point the correlation length ξ of the order parameter diverges (for infinite volume)
- Growing correlation length means increasing fluctuations
- Order parameter for chiral critical point is chiral condensate
- Chiral condensate mixes with the baryon density
  → expect large baryon number fluctuations at the critical point
- Measure using cumulants

$$\kappa_n^B = \frac{\partial^n}{\partial(\mu_B/T)^n}\ln Z = \frac{\partial^{n-1}}{\partial(\mu_B/T)^{n-1}}\langle N_B\rangle$$

(note that $\chi_n^B = \kappa_n^B/V$)

$$\kappa_1^B = \langle N_B\rangle, \quad \kappa_2^B = \langle(N_B - \langle N_B\rangle)^2\rangle, \quad \kappa_3^B = \langle(N_B - \langle N_B\rangle)^3\rangle$$

Sensitivity to crit. point increases with n: $\kappa_2^B \sim \xi^2$, $\kappa_3^B \sim \xi^{4.5}$, $\kappa_4^B \sim \xi^7$

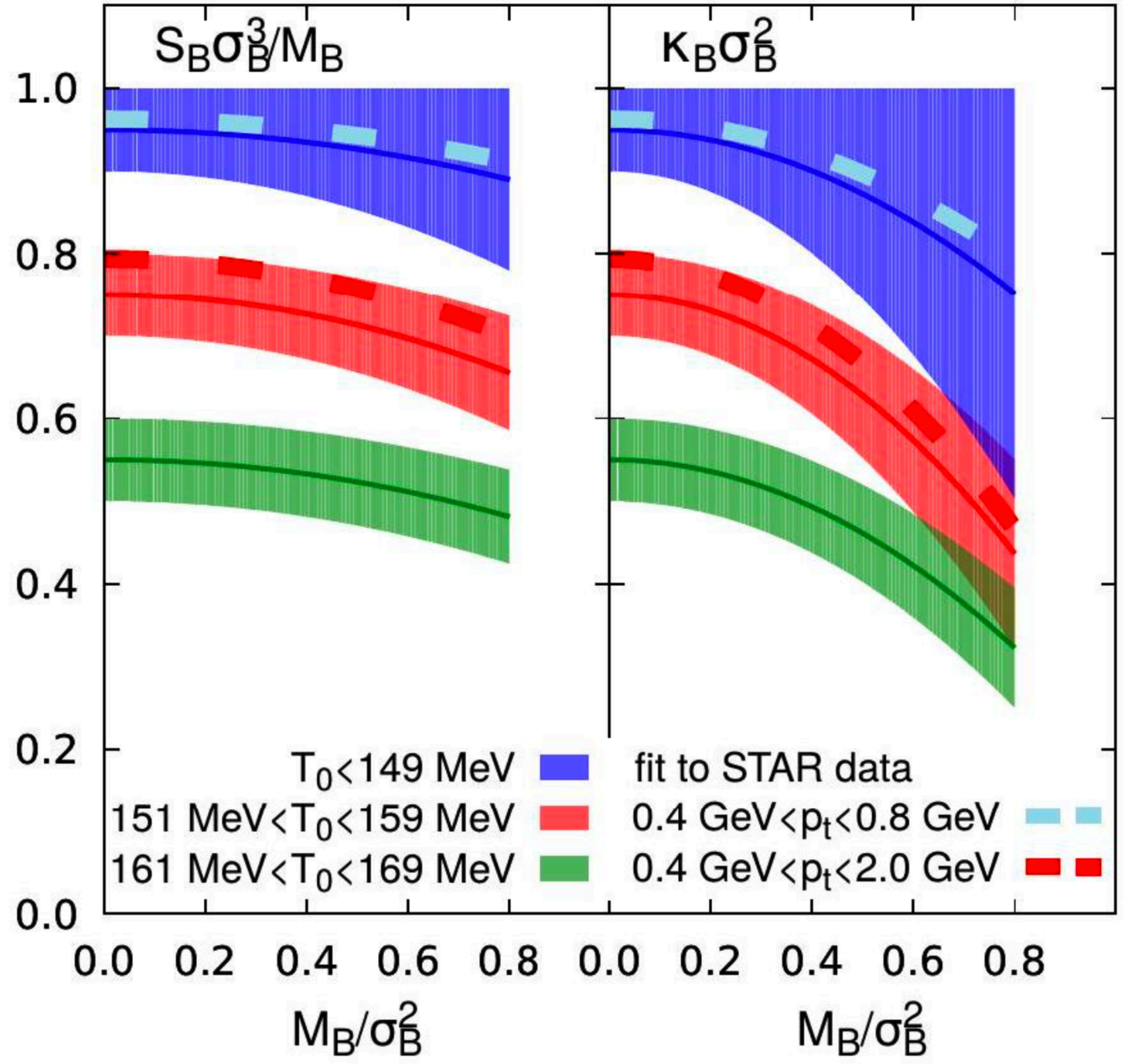
CUMULANTS OF NET BARYON NUMBER

- Cumulants scale with volume, which is not well known in HIC
- So take ratios of cumulants

$$\frac{\chi_1^B(T,\mu_B)}{\chi_2^B(T,\mu_B)} \equiv \frac{M_B}{\sigma_B^2}\,,$$
$$\frac{\chi_3^B(T,\mu_B)}{\chi_1^B(T,\mu_B)} \equiv \frac{S_B\sigma_B^3}{M_B}\,,$$
$$\frac{\chi_4^B(T,\mu_B)}{\chi_2^B(T,\mu_B)} \equiv \kappa_B\sigma_B^2\,.$$

with mean (M_B), variance (σ_B^2), skewness (S_B), kurtosis (κ_B)

Compute on the lattice:

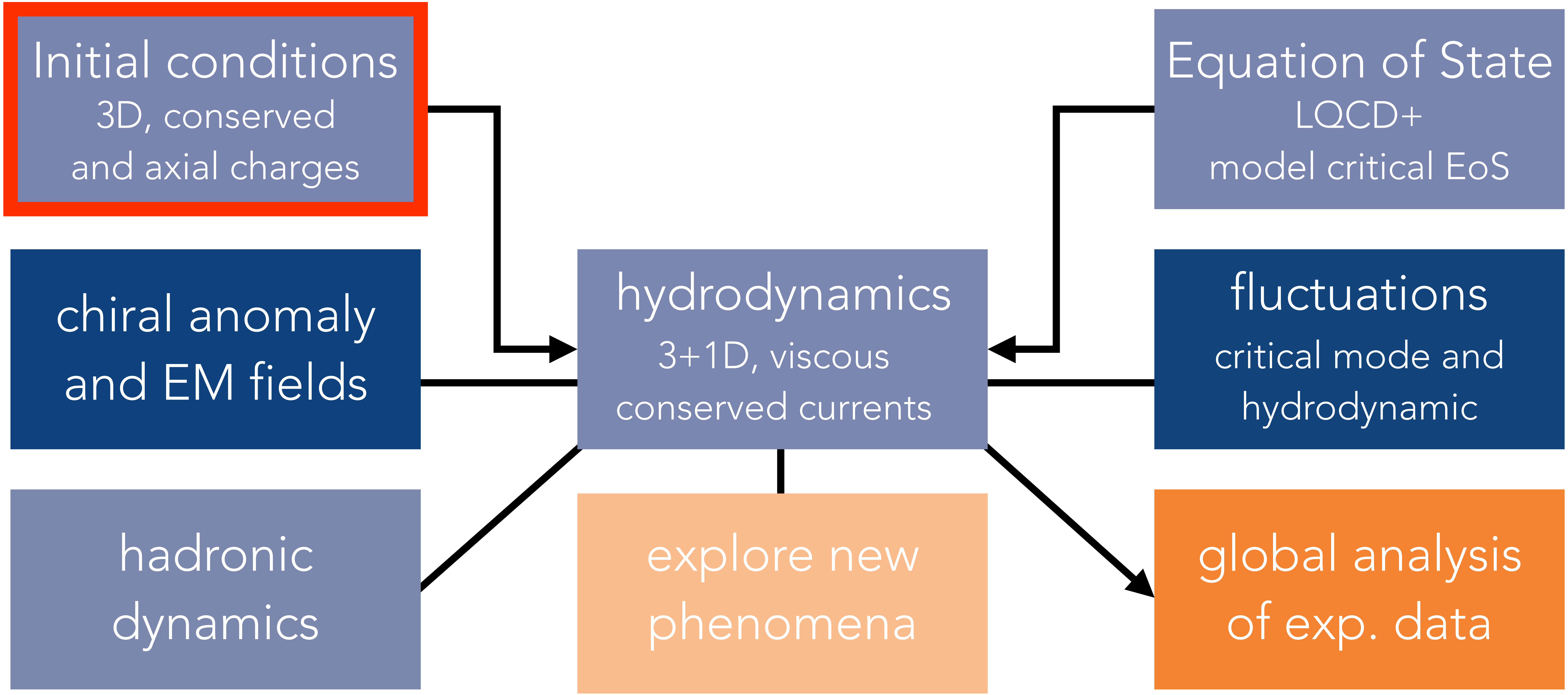


HotQCD, Phys.Rev. D96 (2017) 074510

LQCD consistent with data
but should not be compared directly

also see: Borsanyi et. al.: JHEP 1810, 205 (2018)

BEAM ENERGY SCAN THEORY

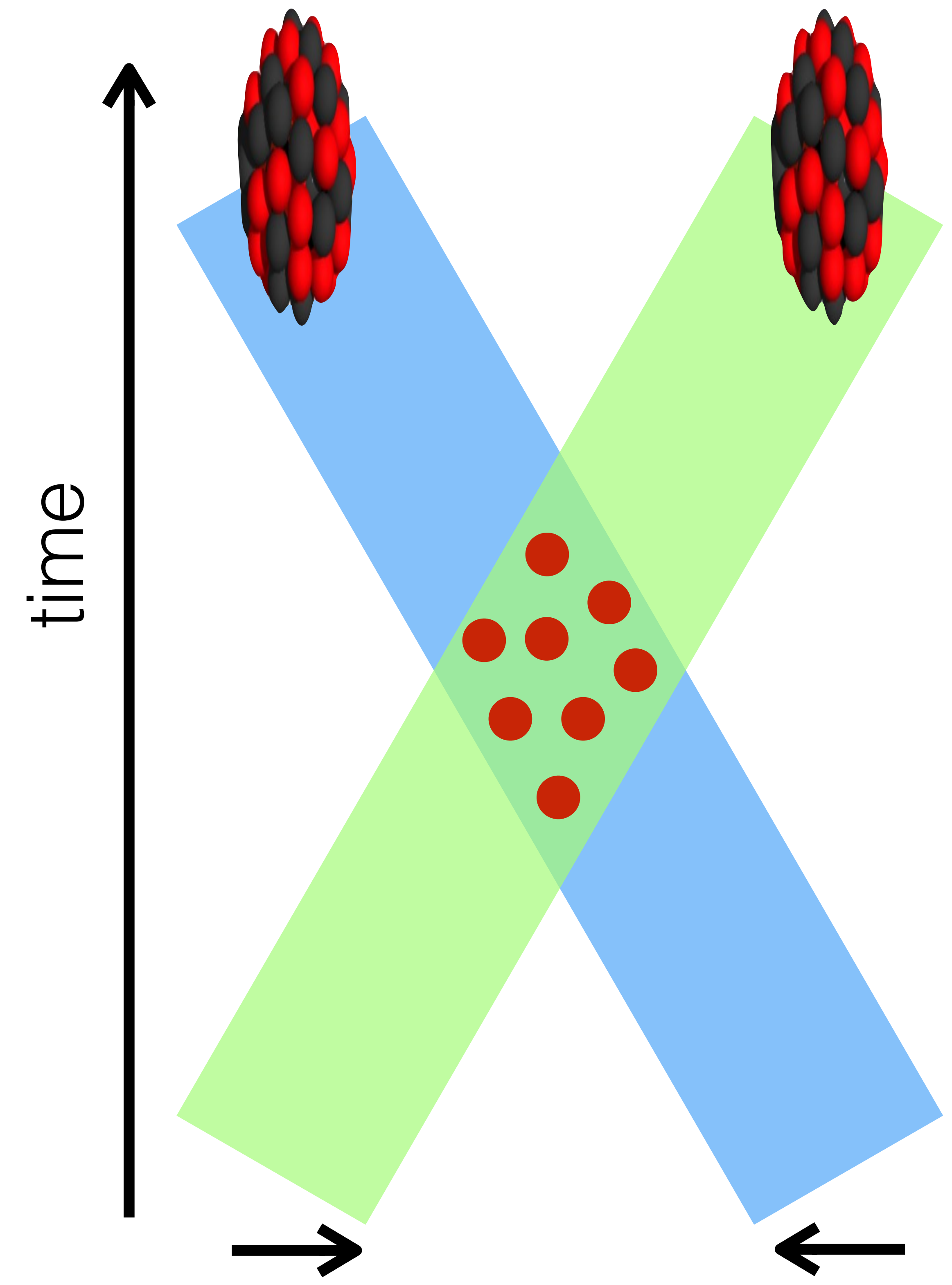


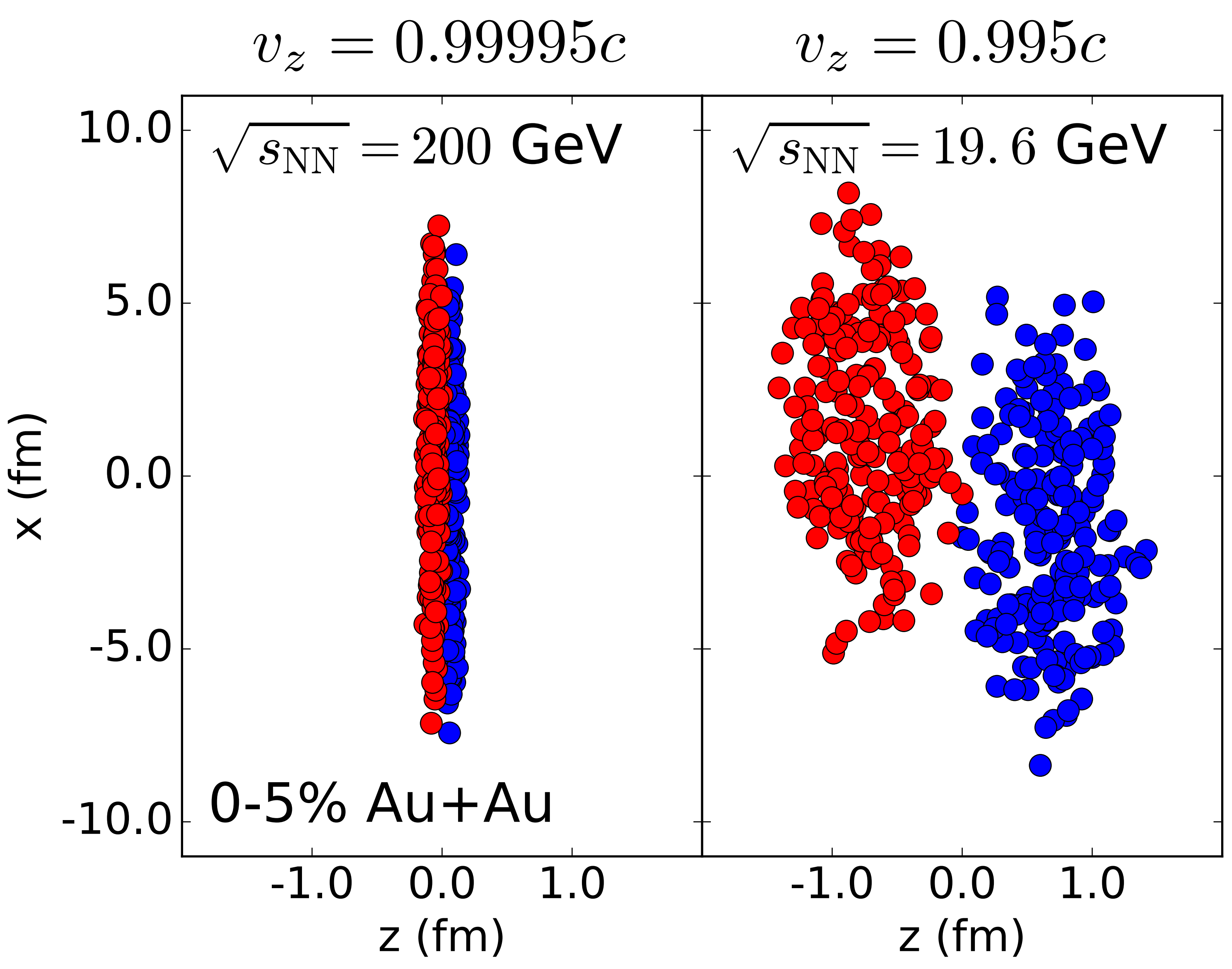
DYNAMICAL INITIAL STATE FOR 3D HYDRO

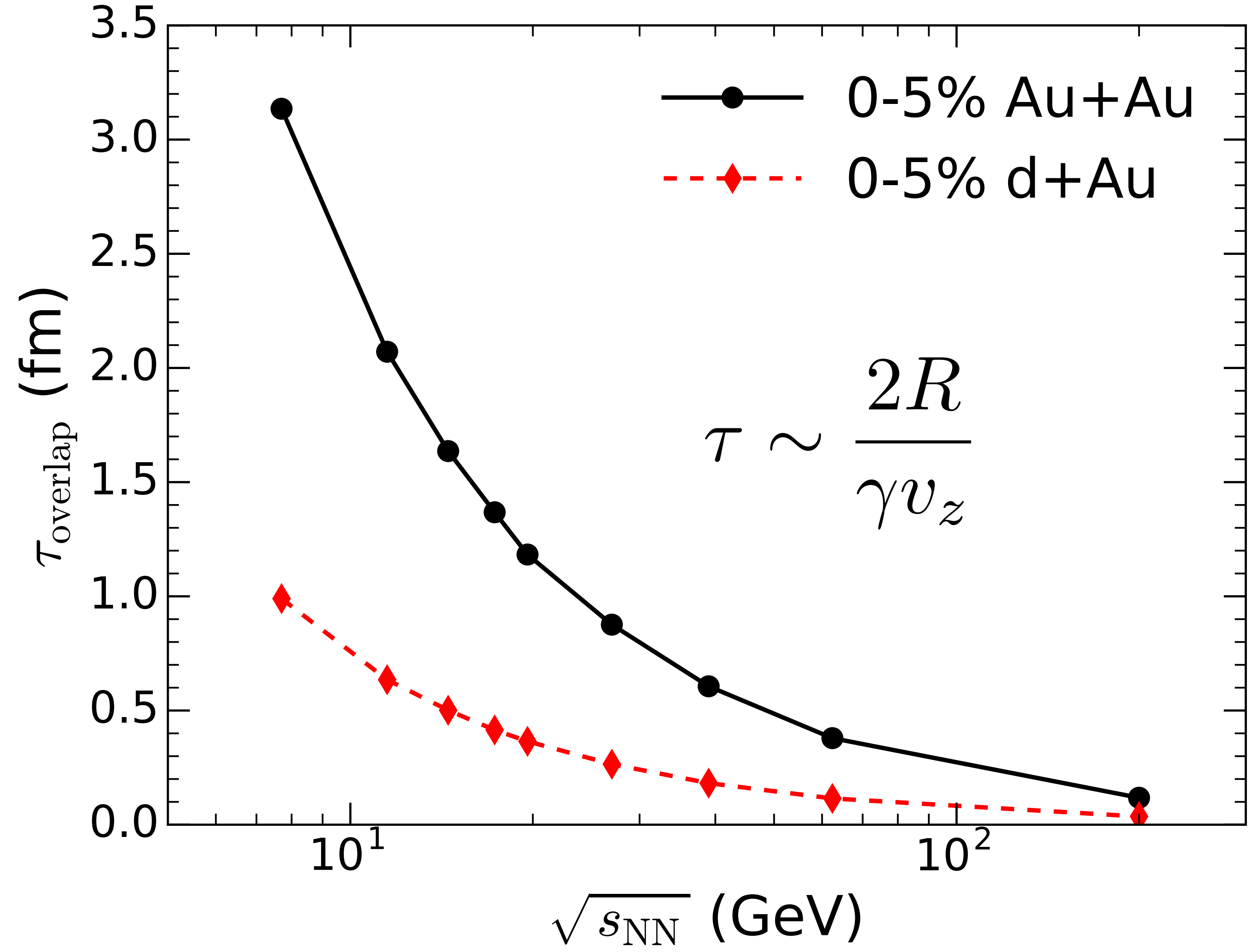
C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

MORE TODAY 4PM IN TALK BY CHUN SHEN (DIRECTOR'S ROW I)

Nuclear overlap time becomes large at lower energies:





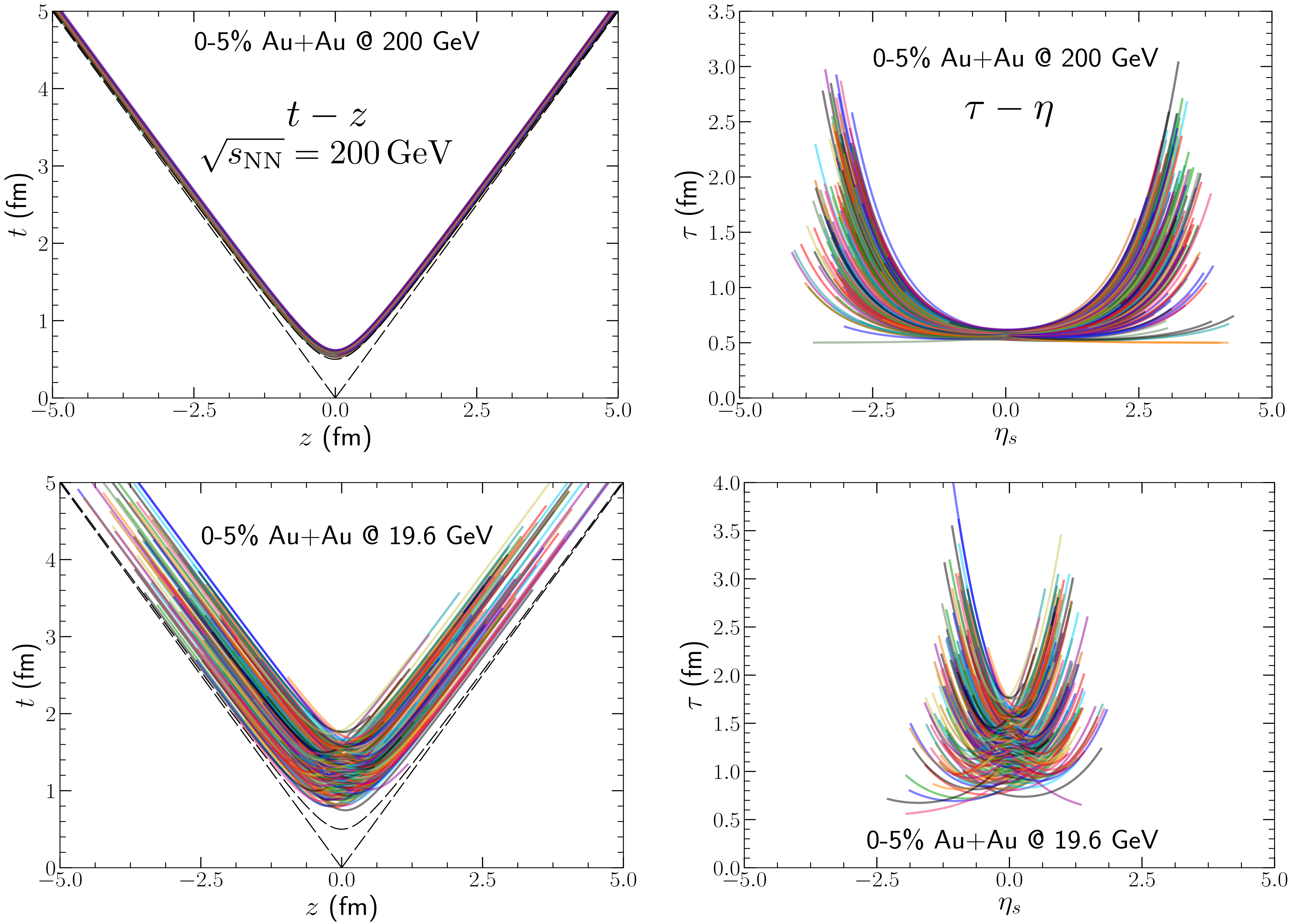


- The interaction zone is not point like
- Colliding nucleons are decelerated with a classical string model

  A. Bialas, A. Bzdak and V. Koch, arXiv:1608.07041
- The lost energy and momentum of the decelerated nucleons are fed into hydrodynamics as source terms

ENERGY DEPOSITION IN SPACE-TIME

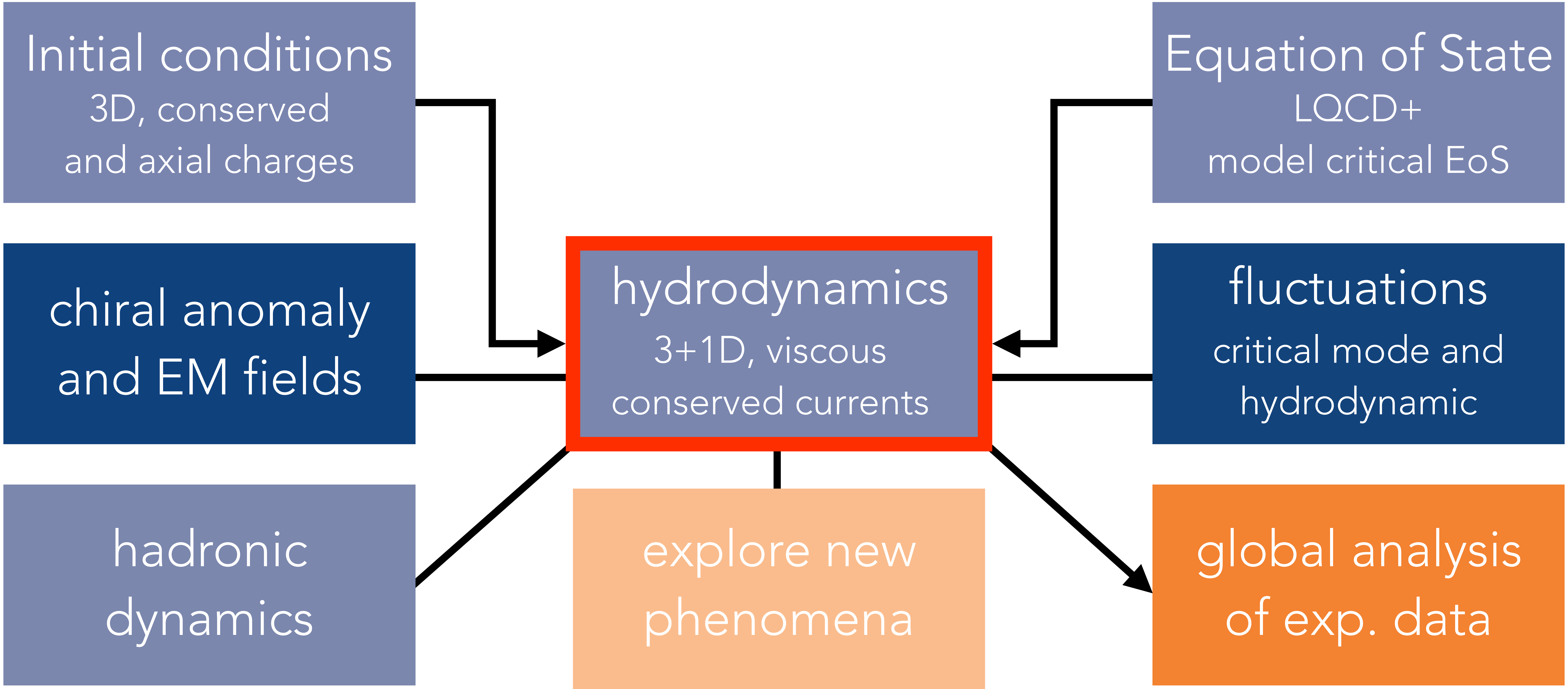
C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907



$\sqrt{s} = 200\,\mathrm{GeV}$

$\sqrt{s} = 19.6\,\mathrm{GeV}$

BEAM ENERGY SCAN THEORY

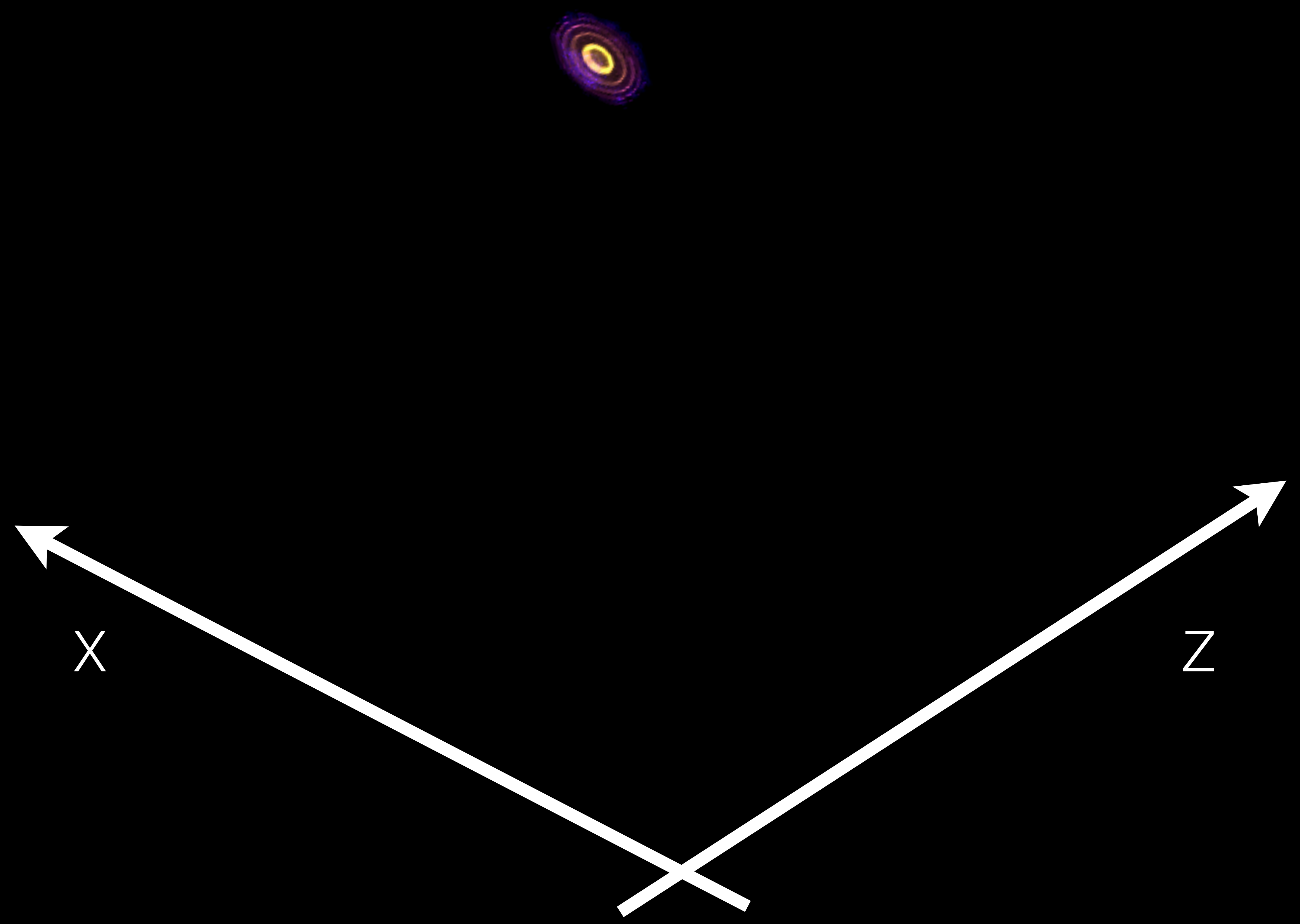


HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

t=0.5 fm/c

energy density
contours

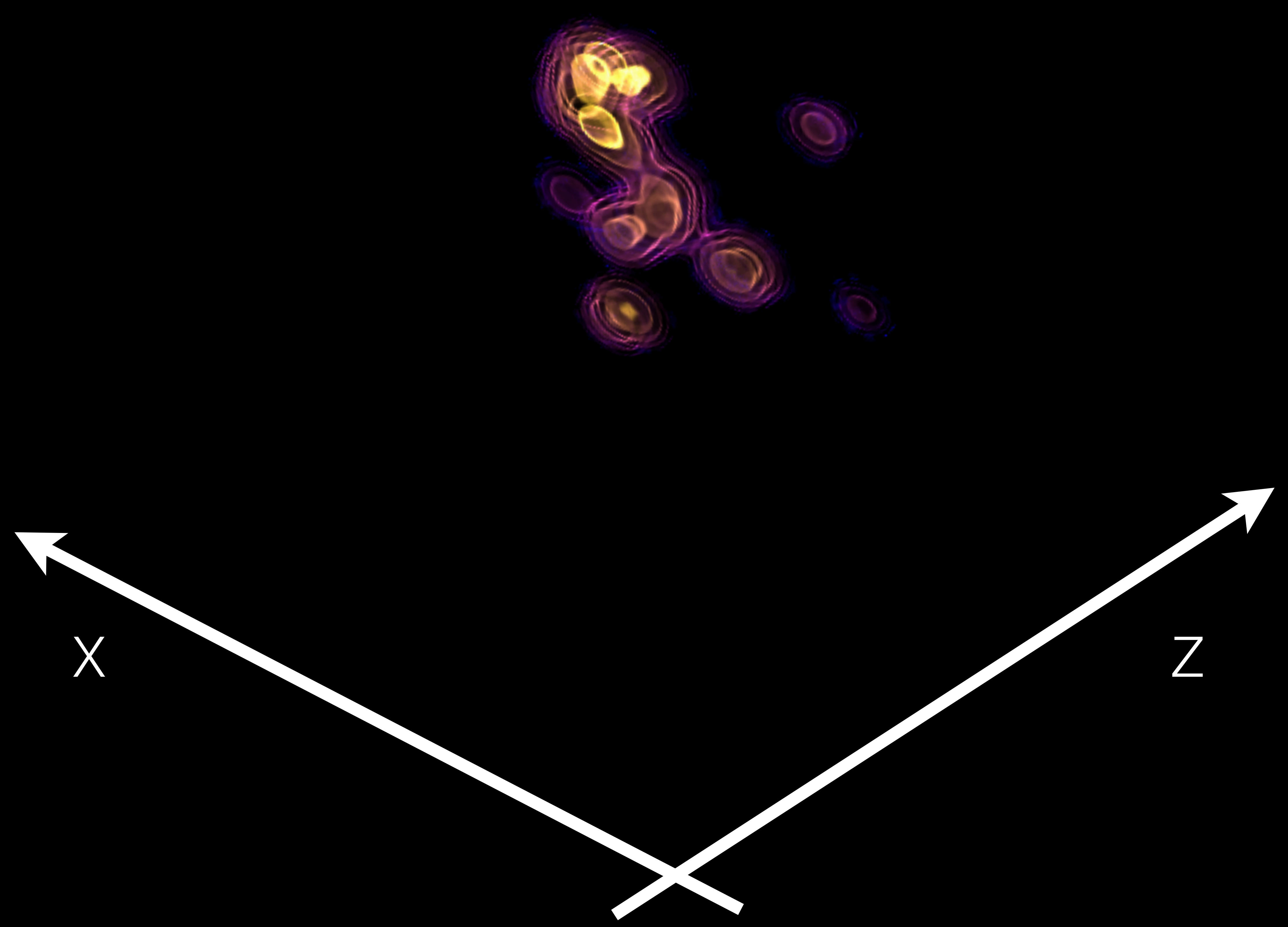


$$\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

t=0.8 fm/c

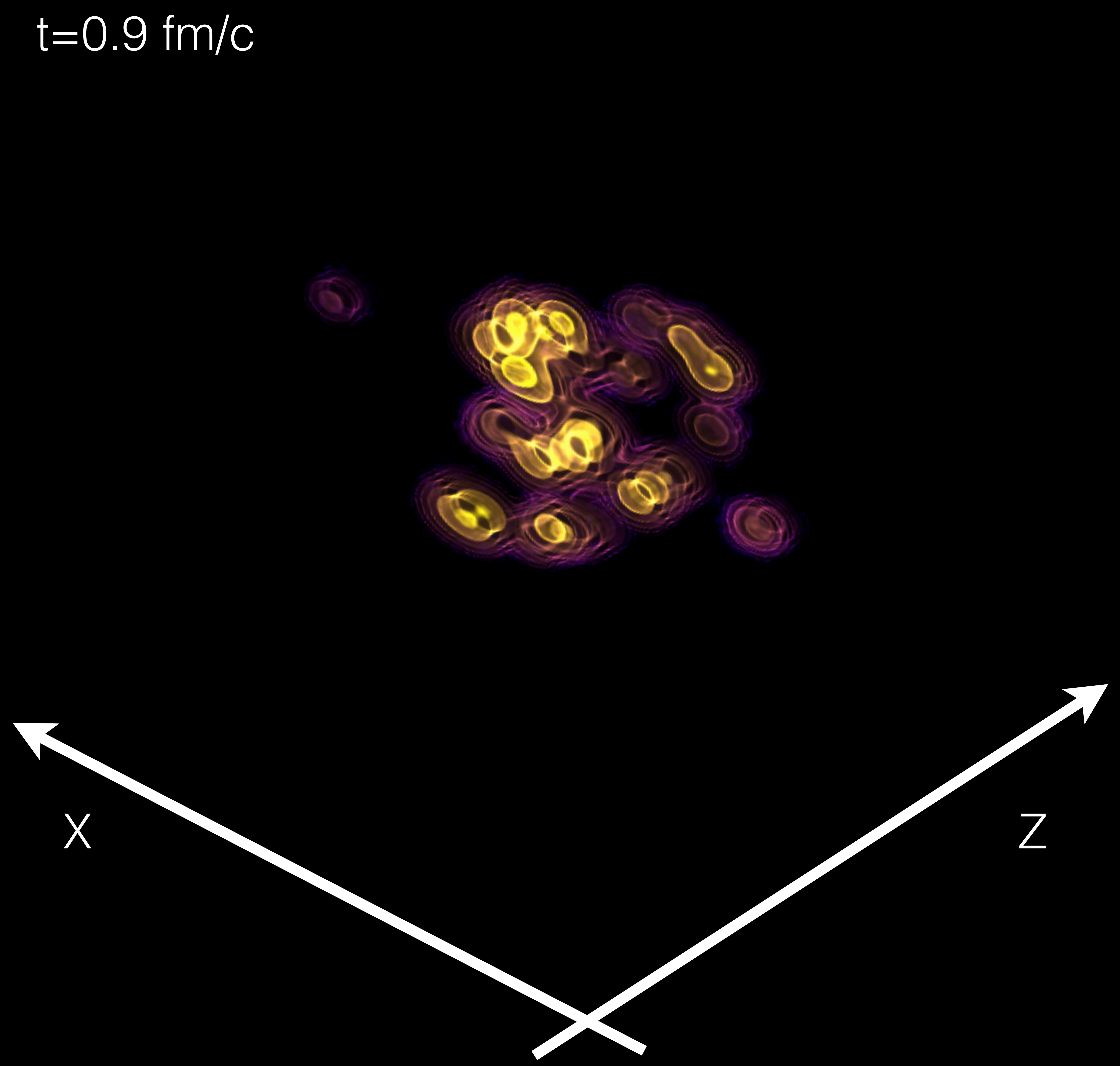


energy density
contours

$$\sqrt{s_{NN}} = 19.6\,\text{GeV}$$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907



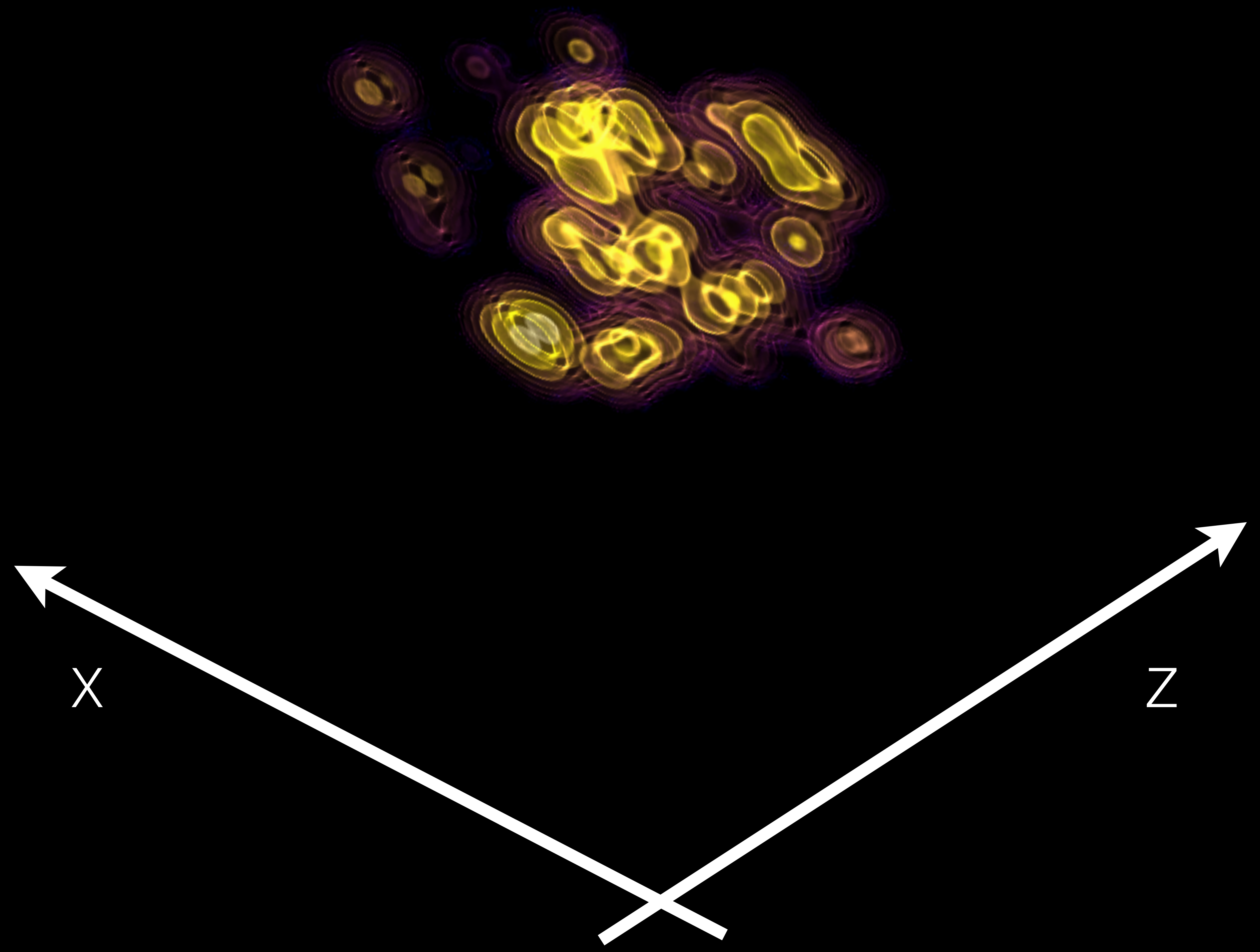
energy density contours

$\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

t=1.0 fm/c

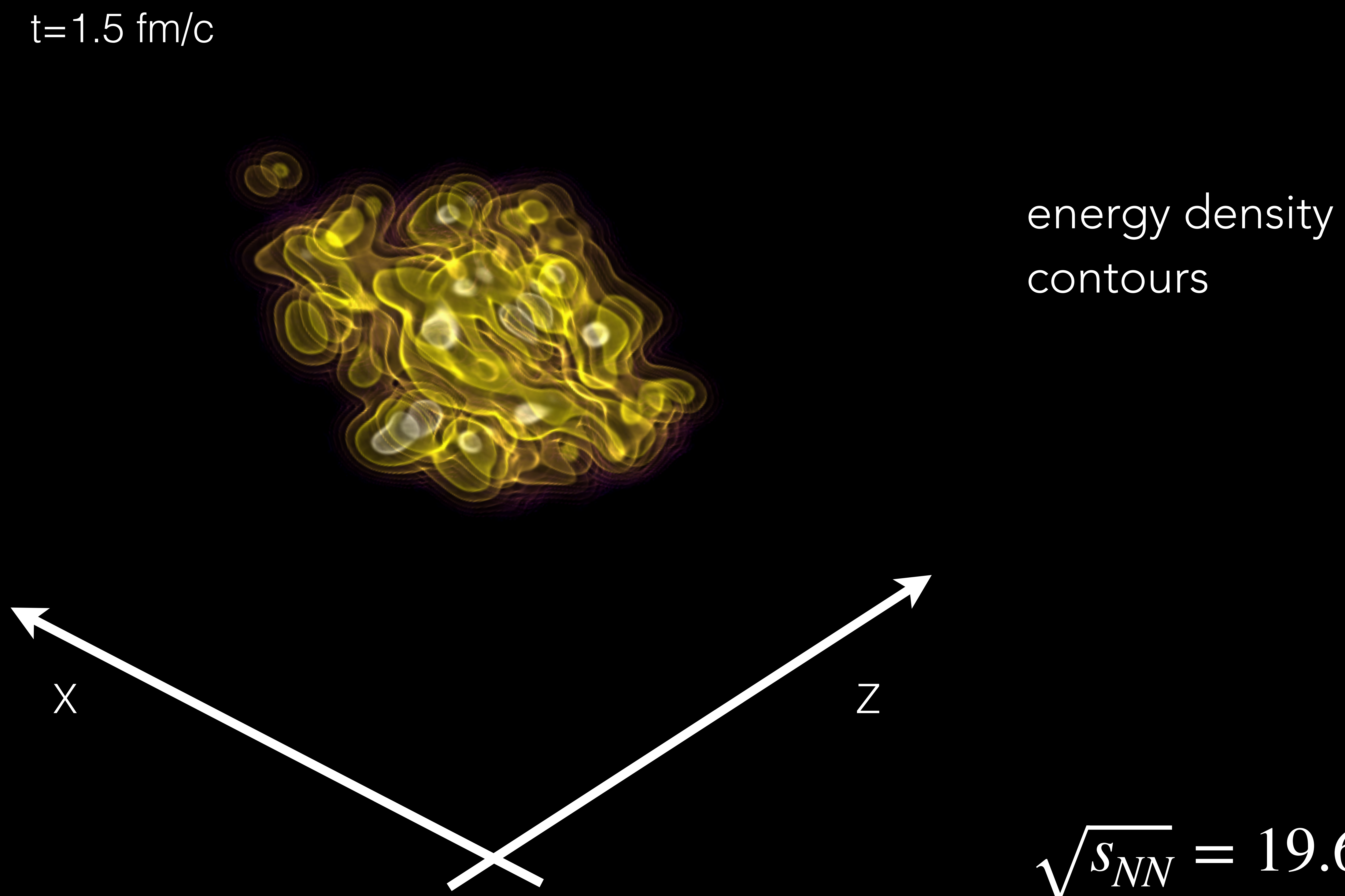


energy density
contours

$$\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

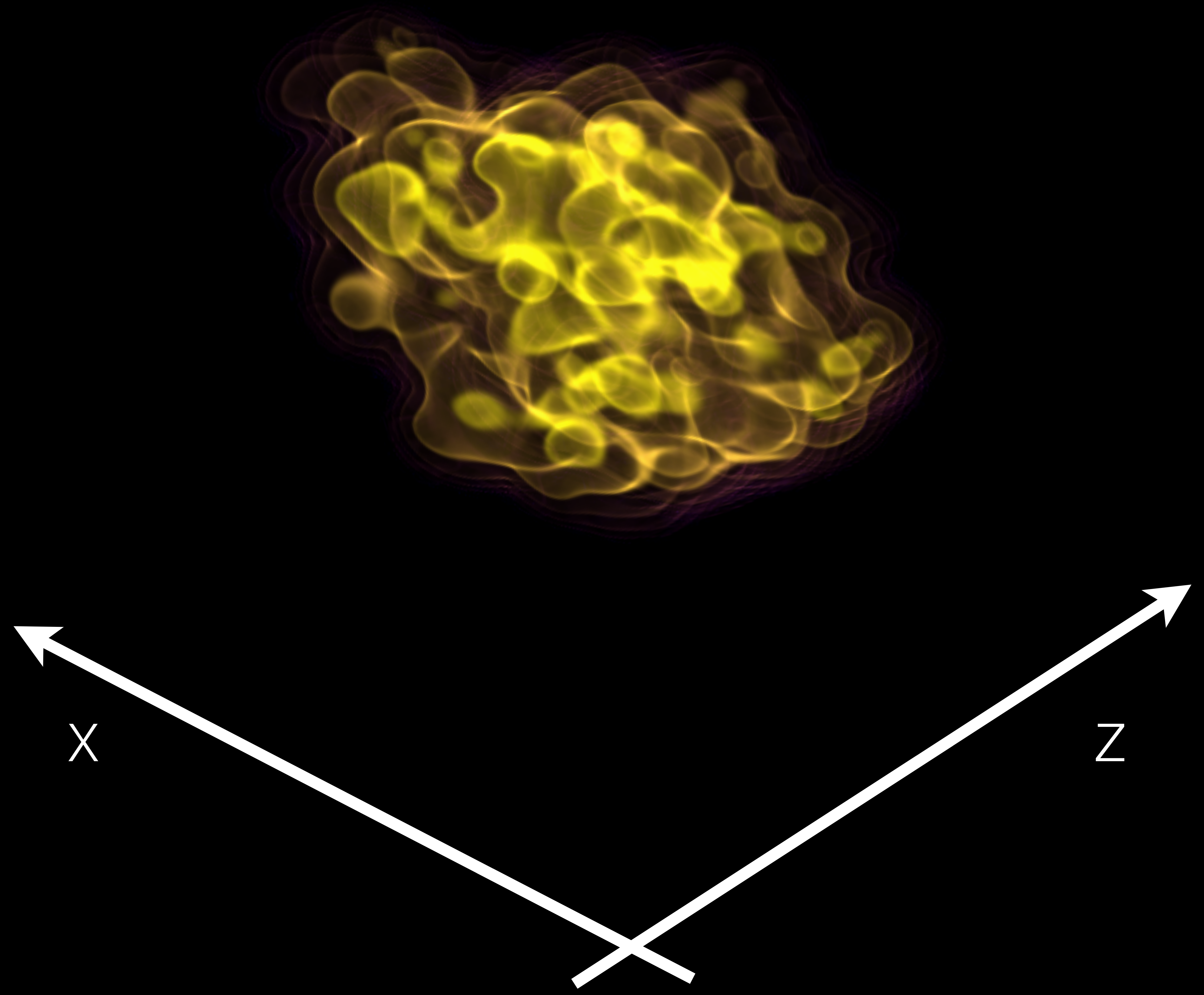


$\sqrt{s_{NN}} = 19.6\,\text{GeV}$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

t=2.5 fm/c

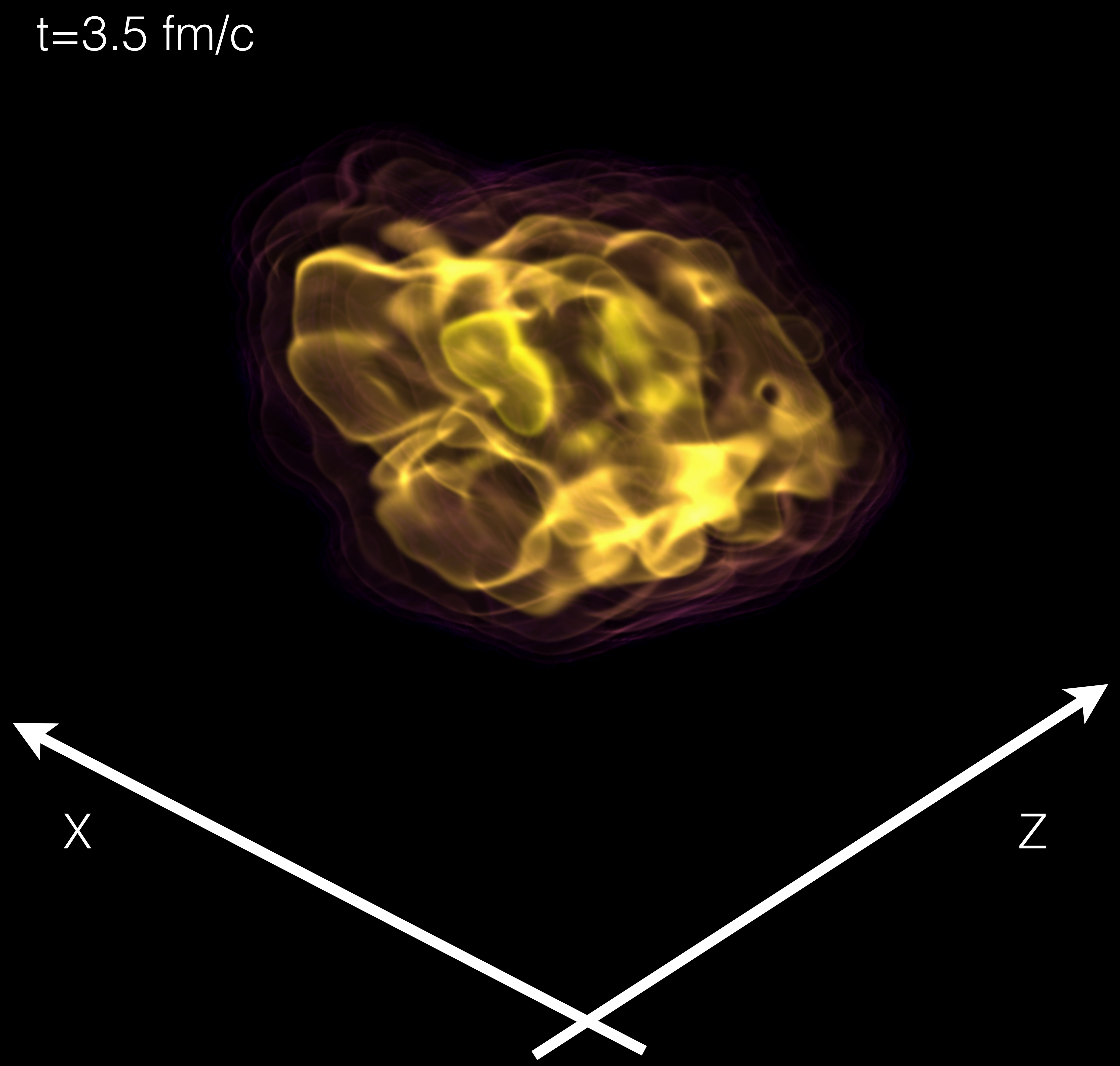


energy density contours

$$\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907



energy density contours

$\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$

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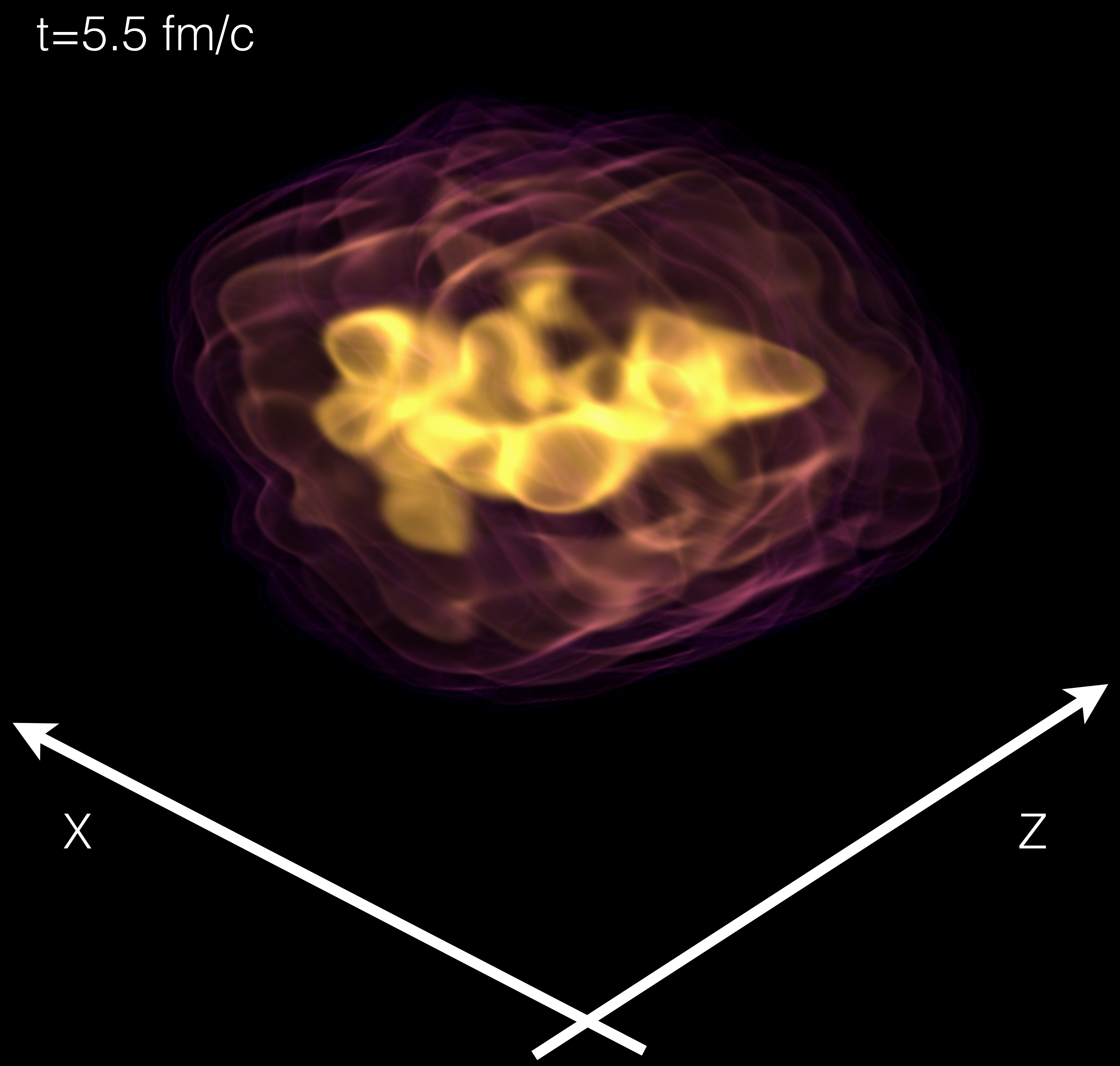
C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907



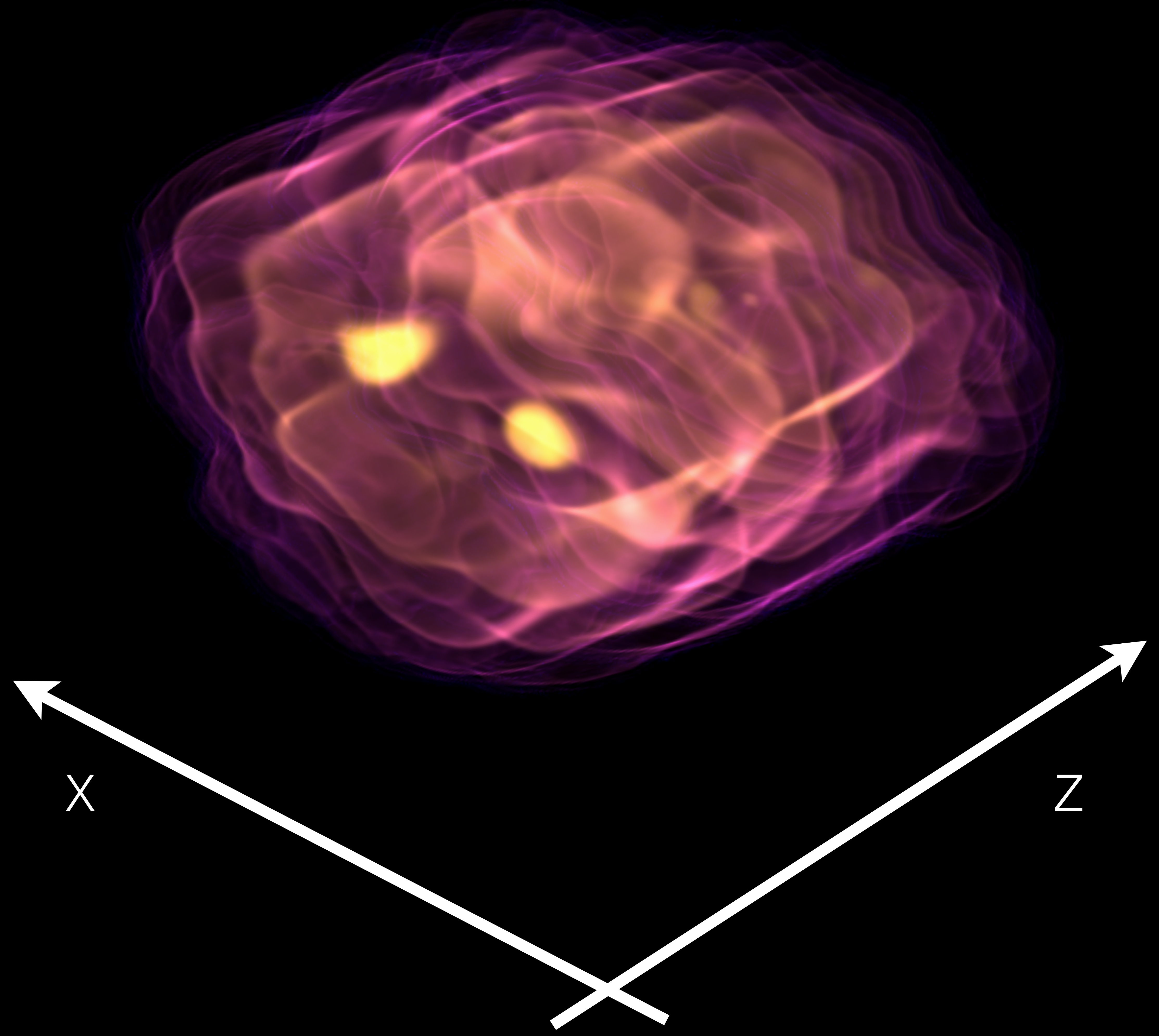
energy density contours

$$\sqrt{s_{NN}} = 19.6\,\text{GeV}$$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

t=6.5 fm/c

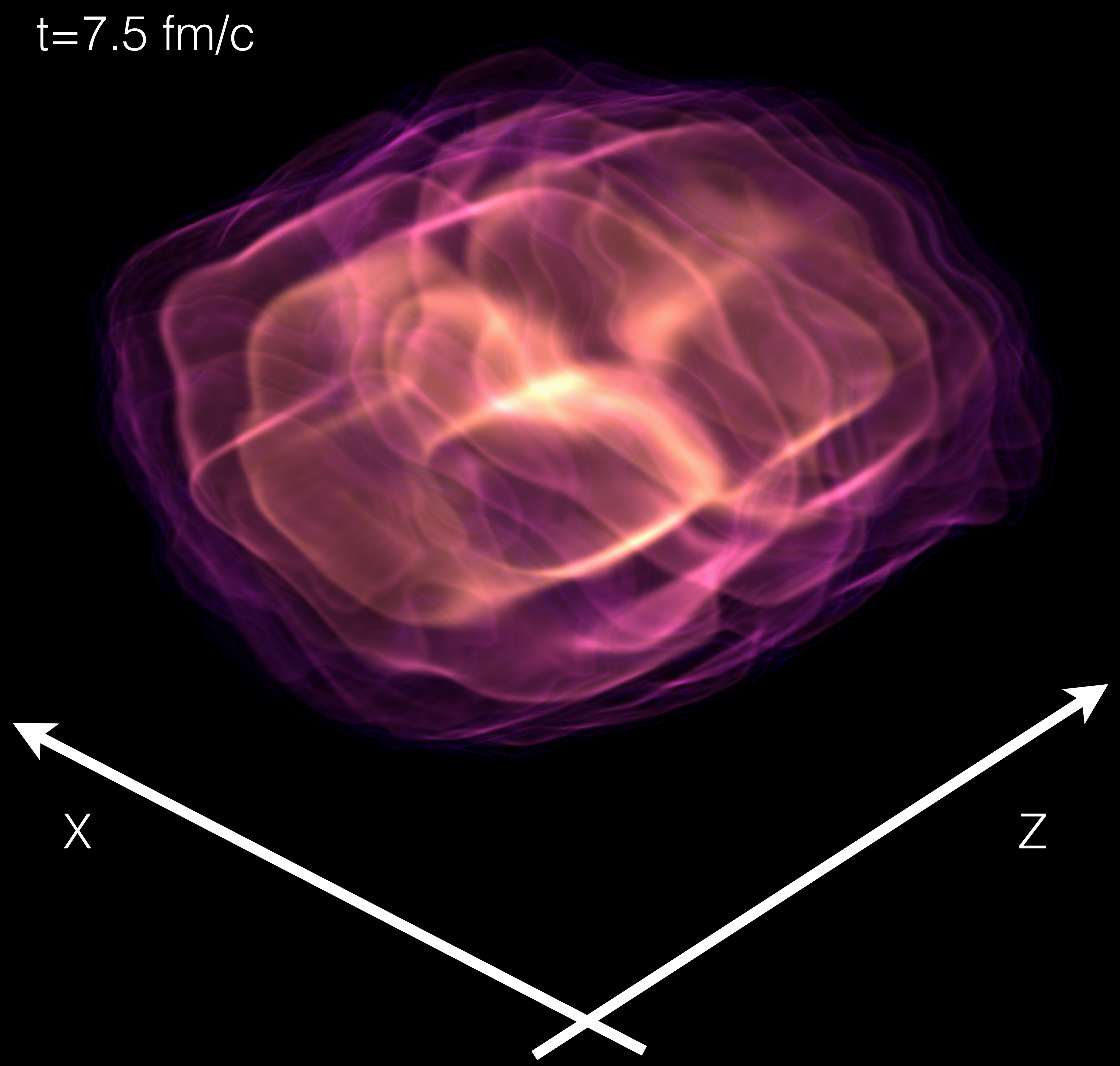


energy density contours

$$\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$$

HYDRODYNAMIC EVOLUTION WITH SOURCES

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907



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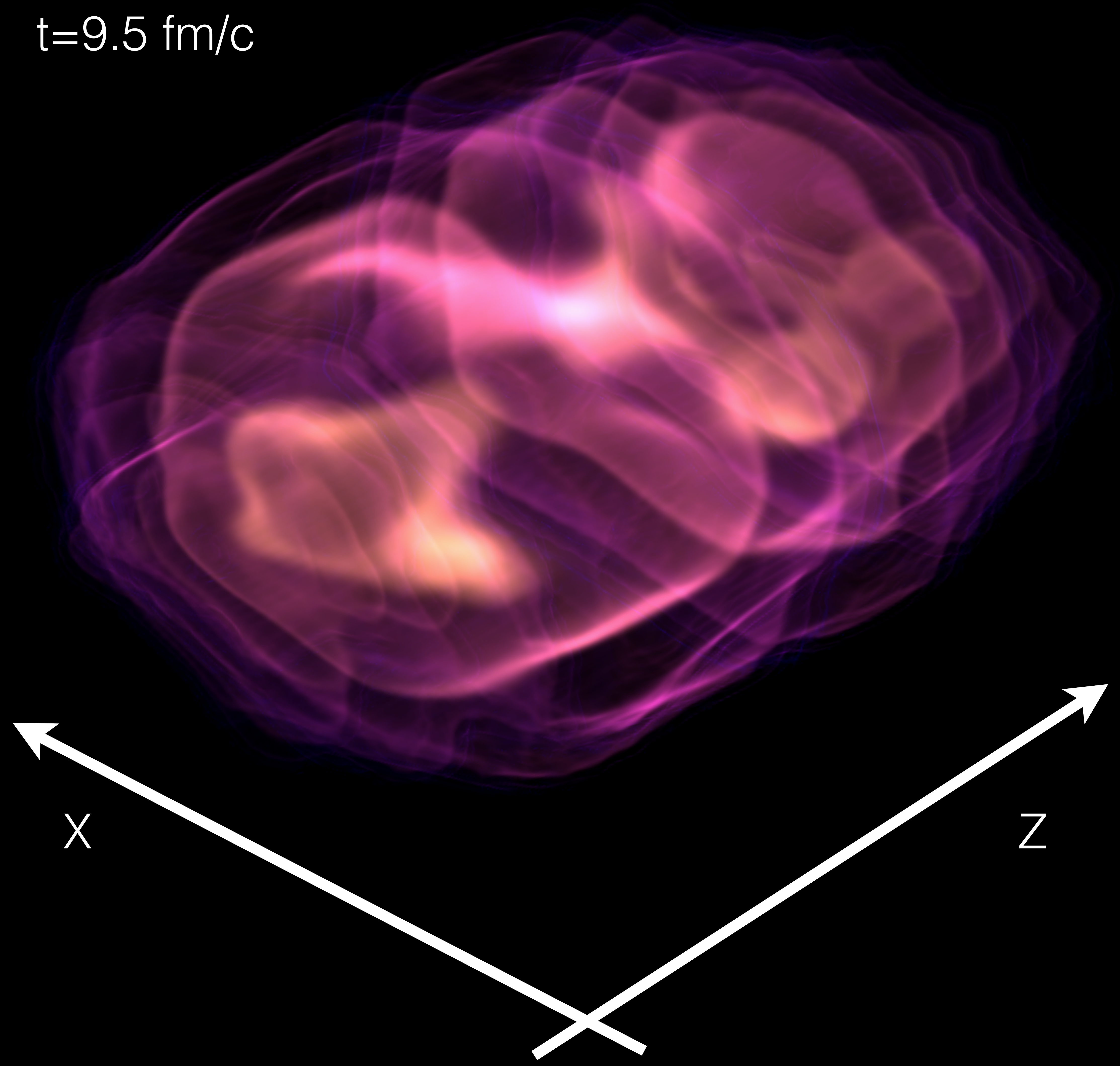

energy density contours

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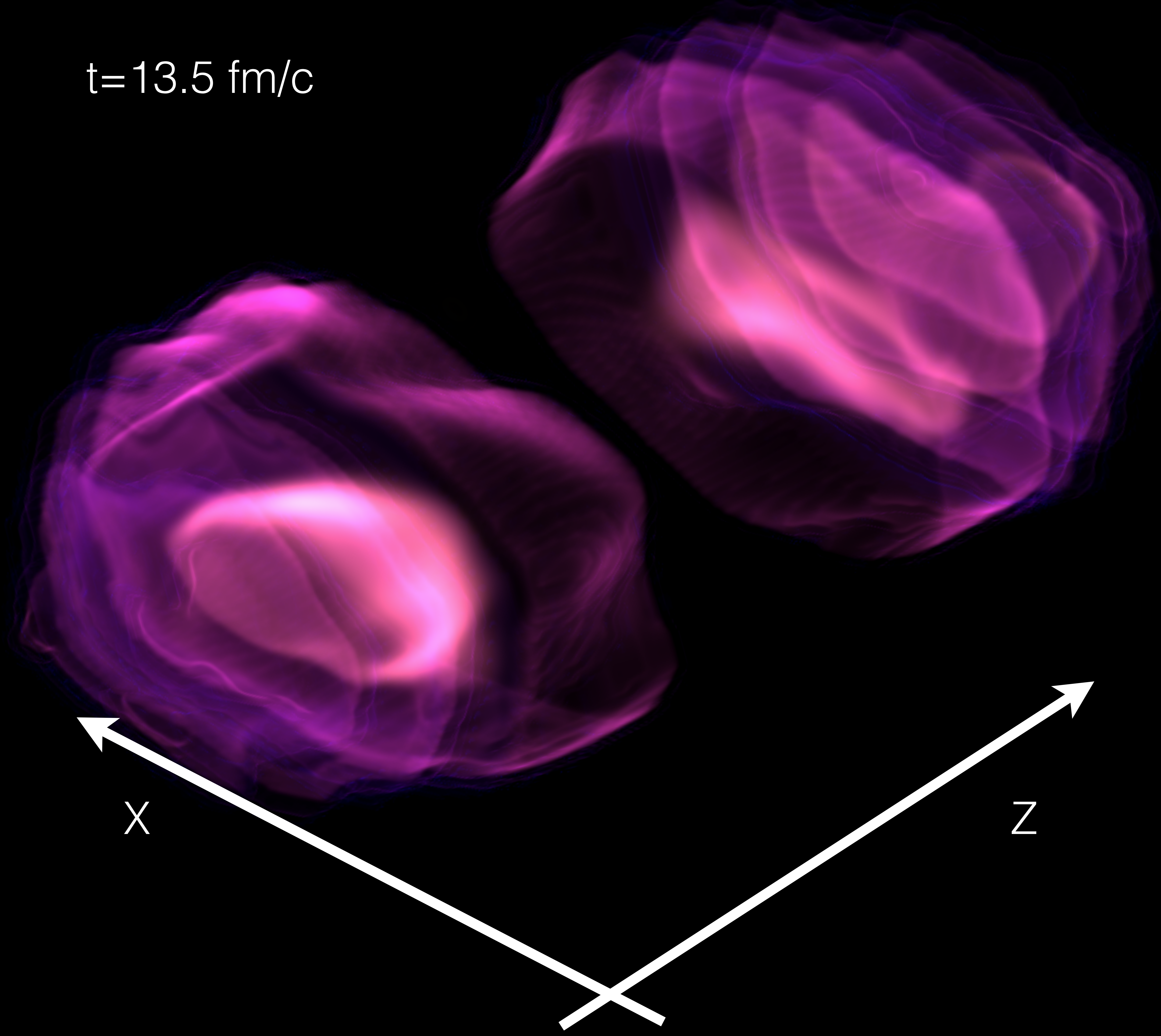
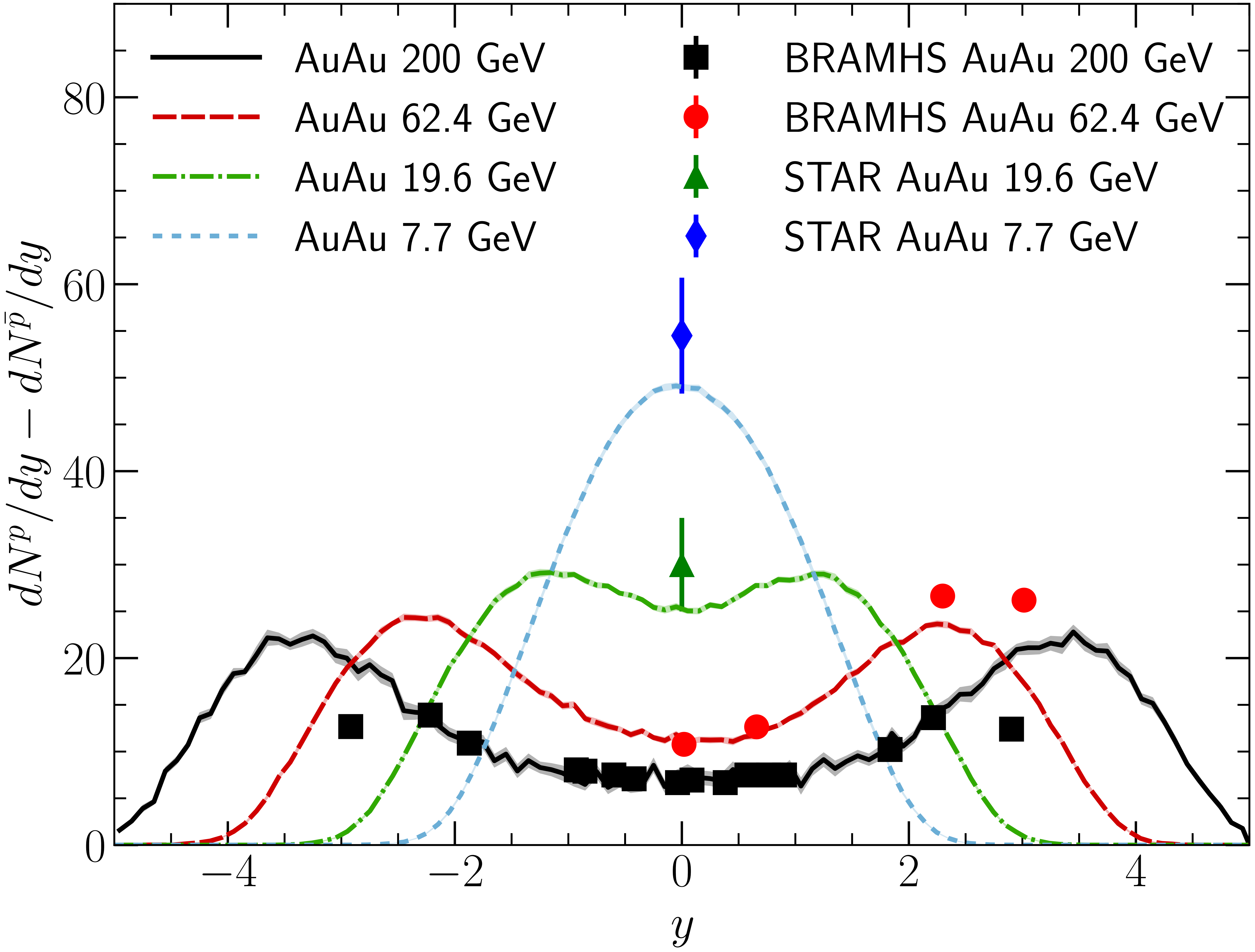


$$\sqrt{s_{NN}} = 19.6\,\mathrm{GeV}$$

NET PROTON RAPIDITY DISTRIBUTIONS

C. Shen, B. Schenke, in preparation

MORE TODAY 4PM IN TALK BY CHUN SHEN (DIRECTOR'S ROW I)



Model baryon stopping

Baryon number can fluctuate along the string: one parameter for all energies

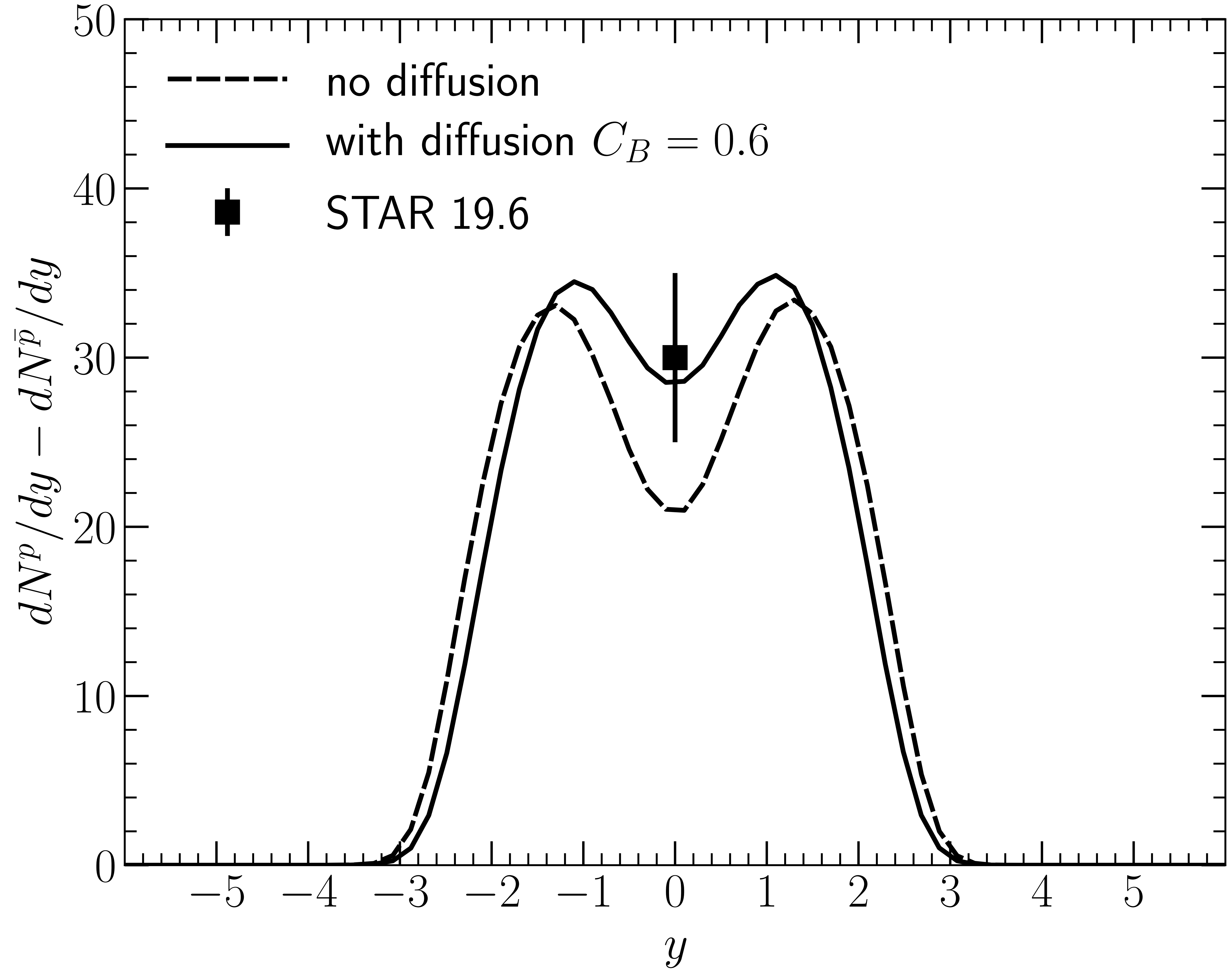
Here no baryon diffusion

BARYON DIFFUSION

MORE TODAY 4PM IN TALK BY CHUN SHEN (DIRECTOR'S ROW I)

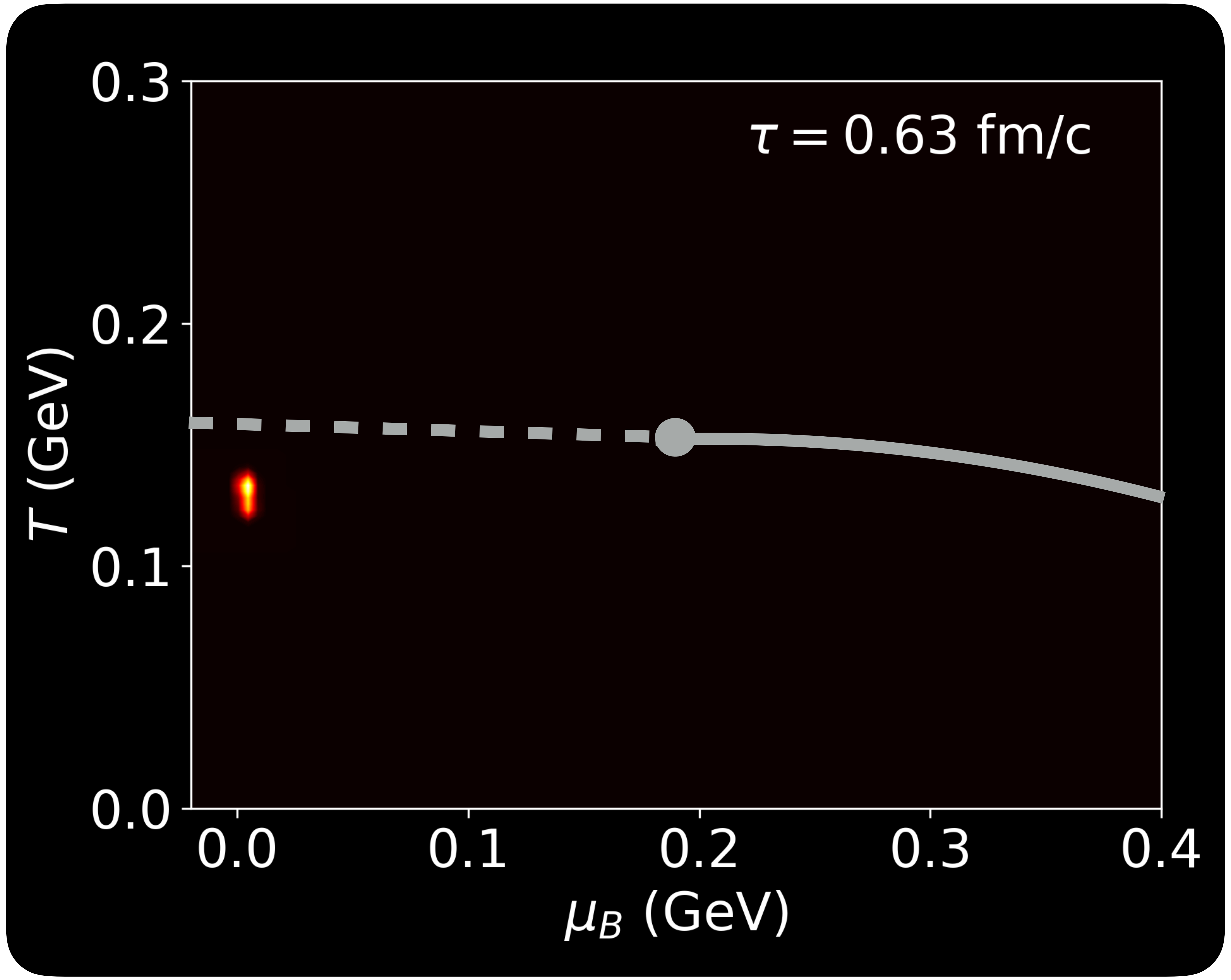
G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C 98, 034916 (2018), arXiv:1804.10557

- Extended MUSIC 3+1D hydro to include baryon diffusion



EVOLUTION IN THE T-μ_B PLANE

- dynamic initial state + 3+1D hydrodynamic evolution



C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

0-5% AuAu@19.6 GeV

EVOLUTION IN THE T-μ_B PLANE

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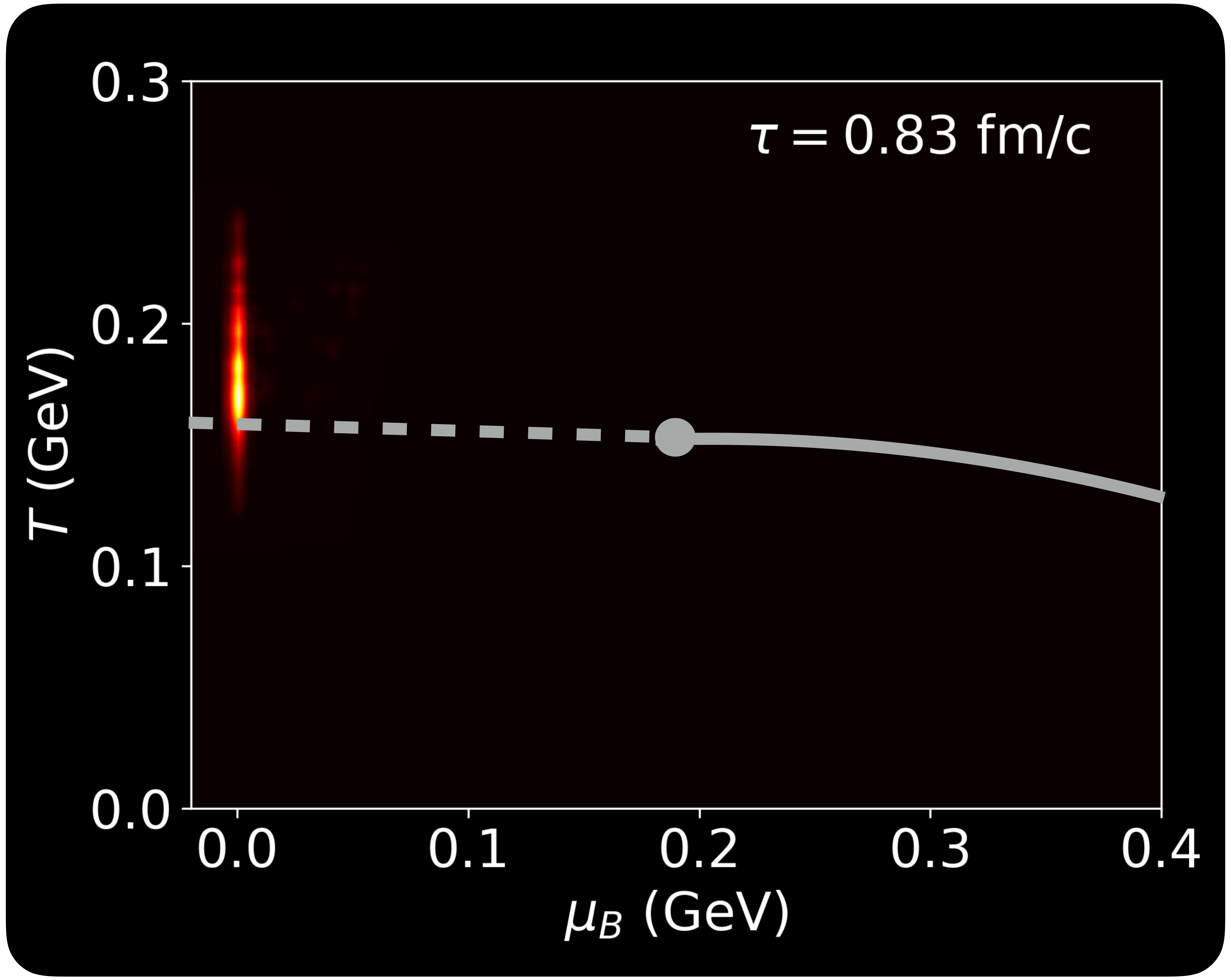

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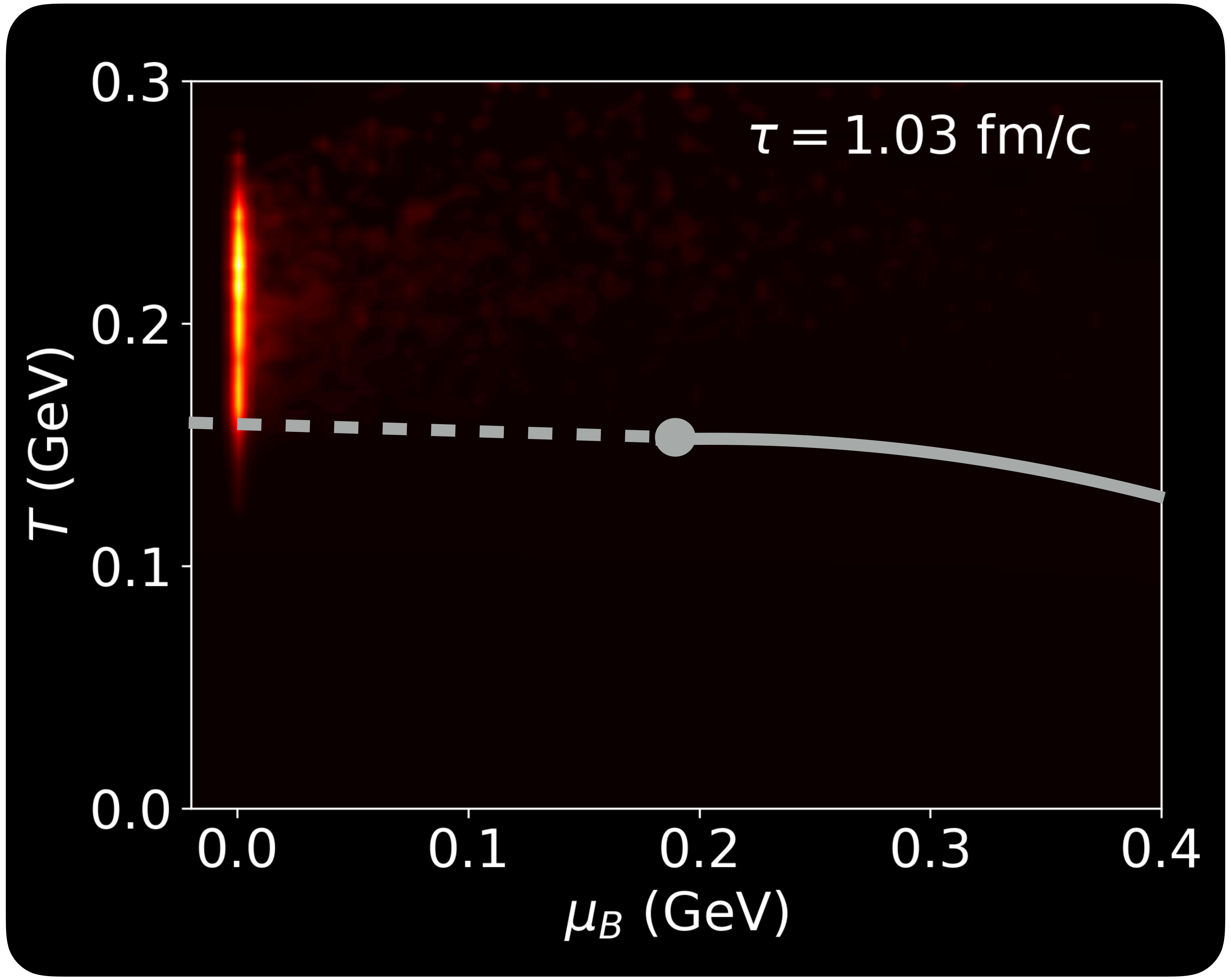

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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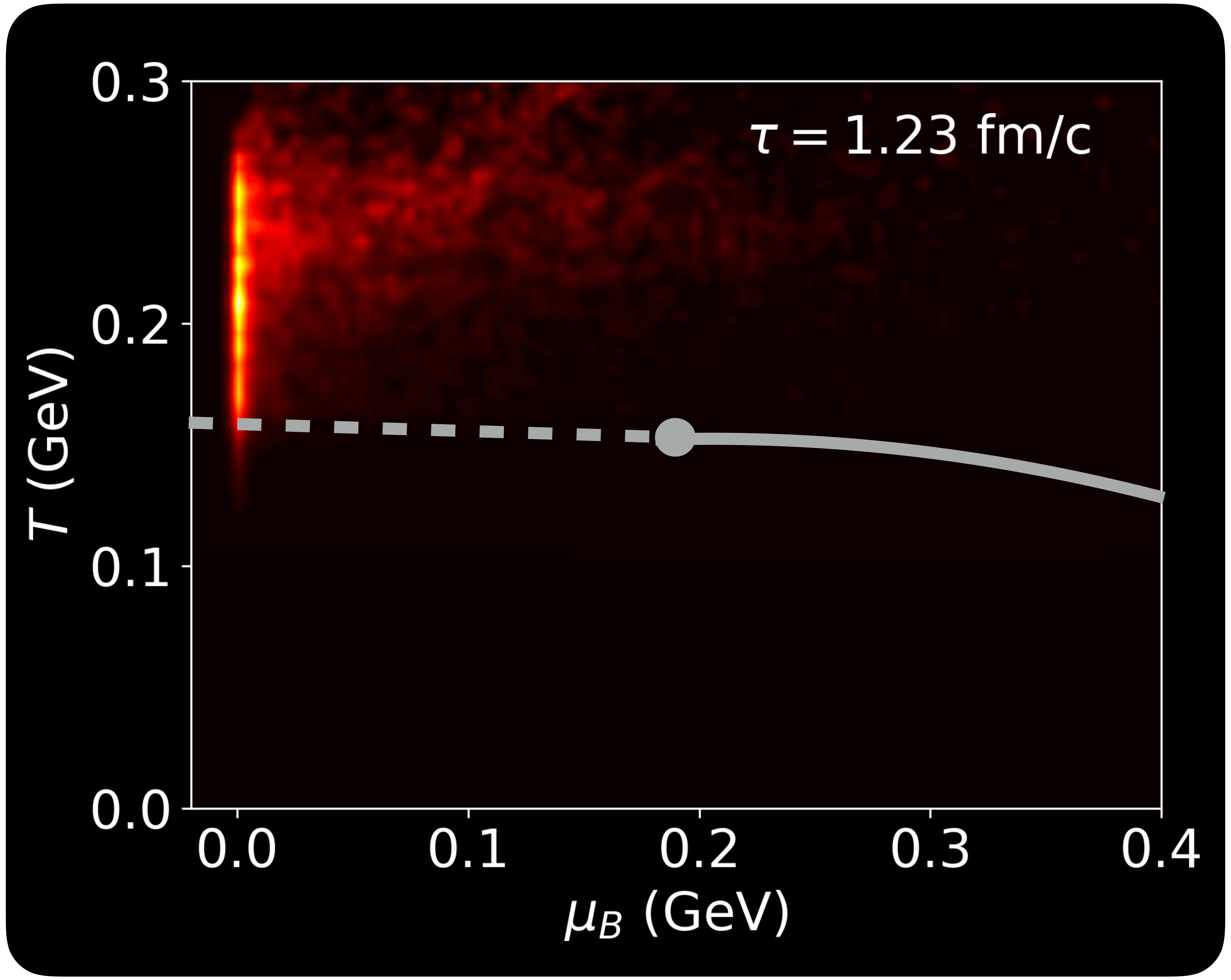

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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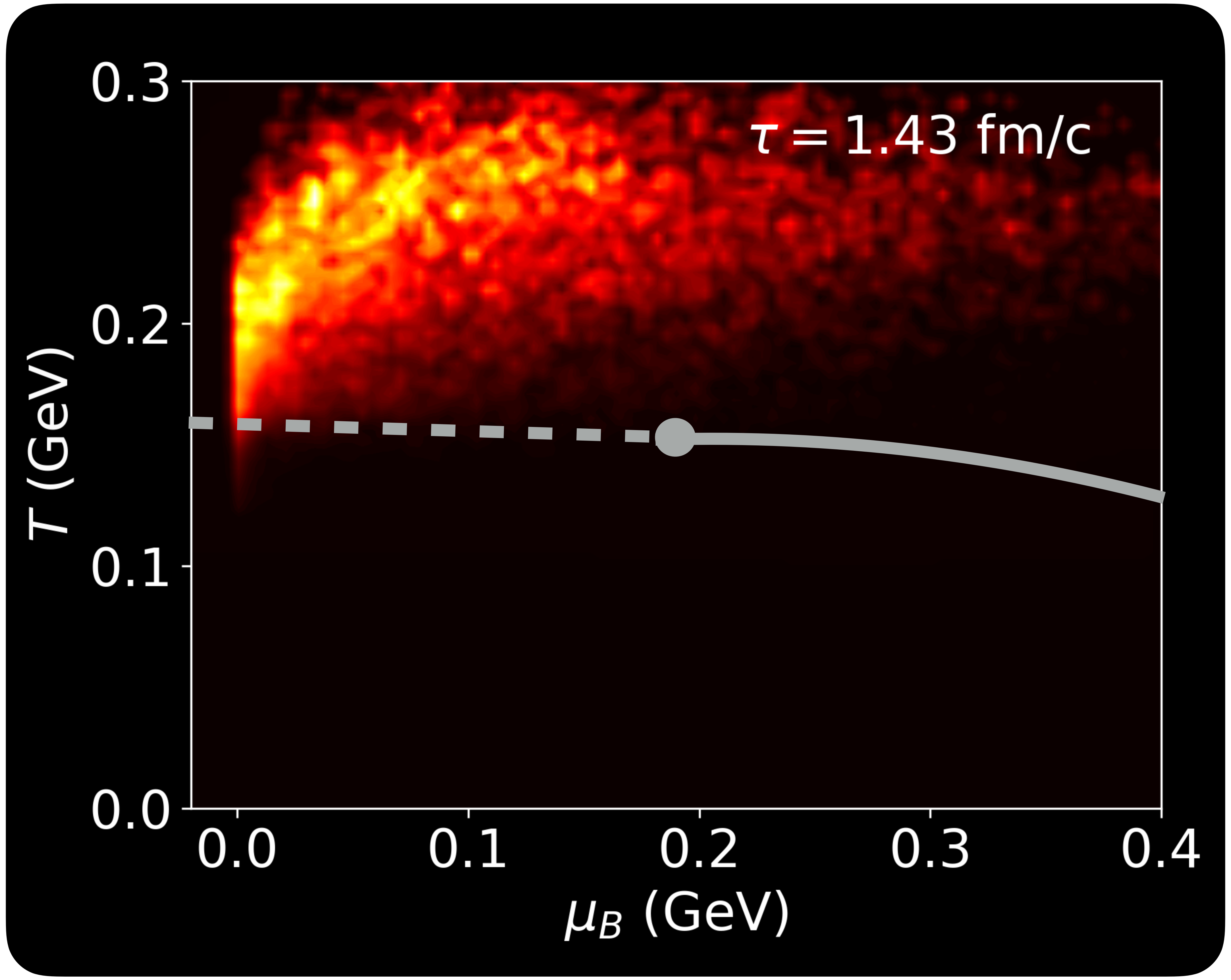

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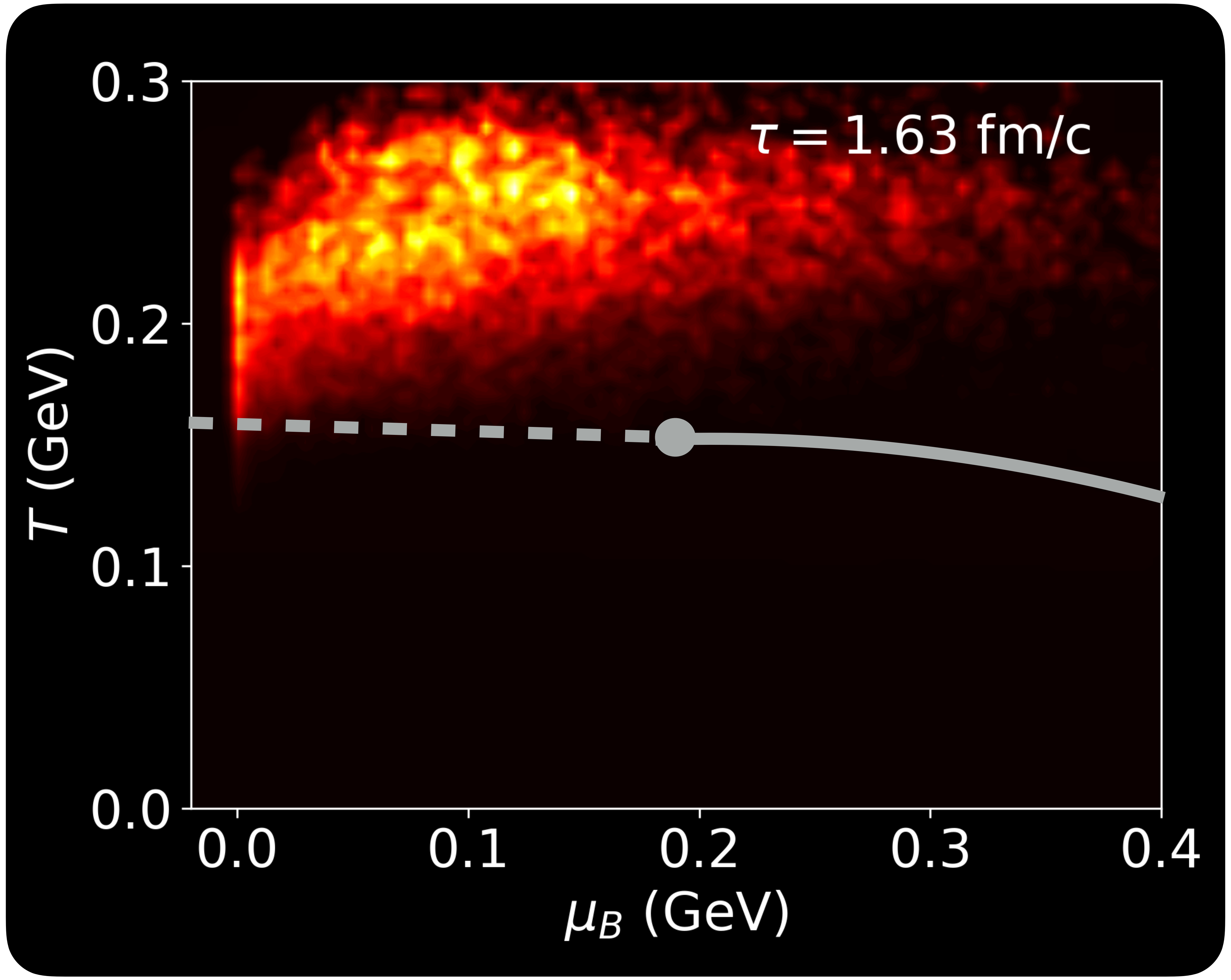
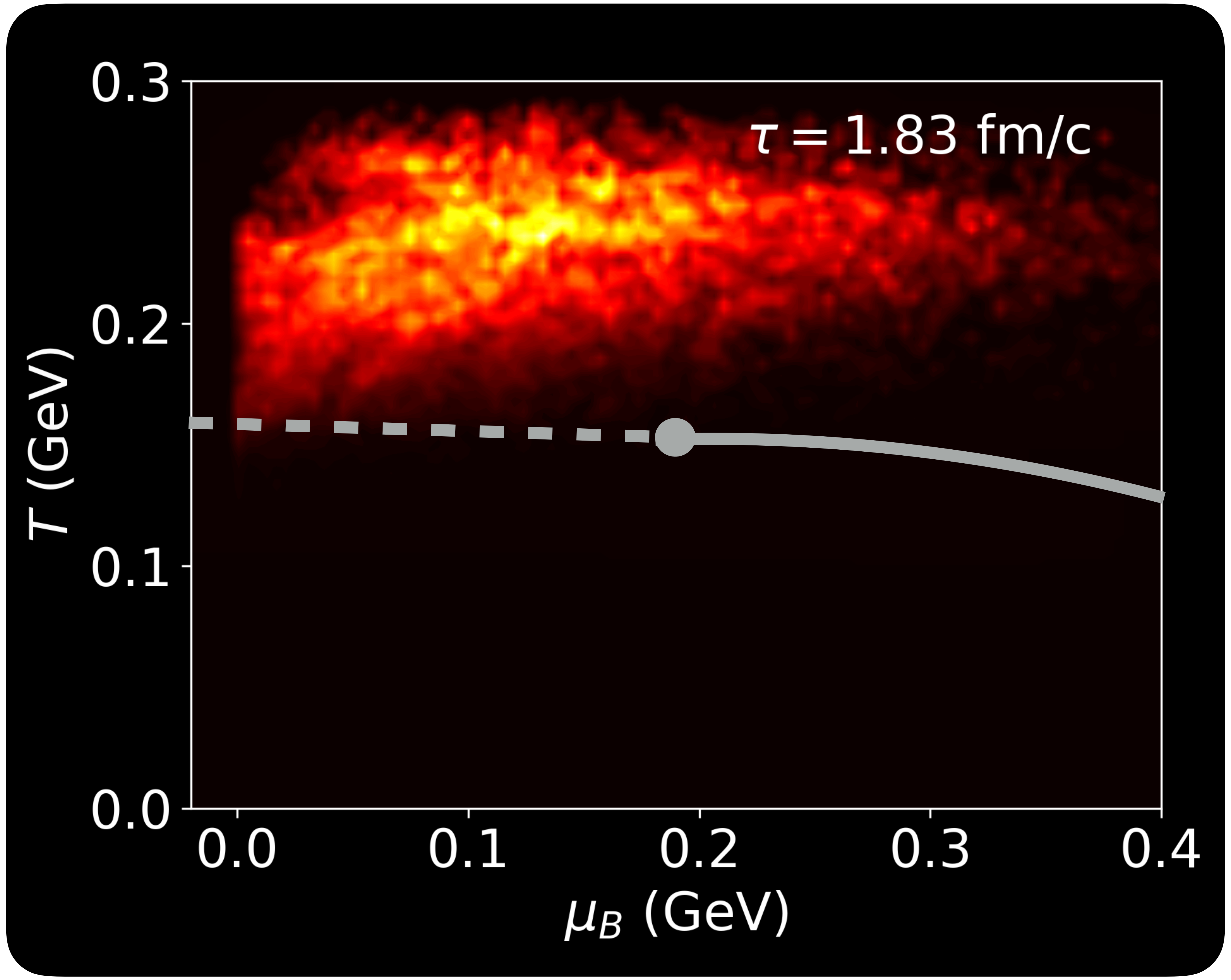


C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

0-5% AuAu@19.6 GeV

EVOLUTION IN THE T-μ_B PLANE

- dynamic initial state + 3+1D hydrodynamic evolution



C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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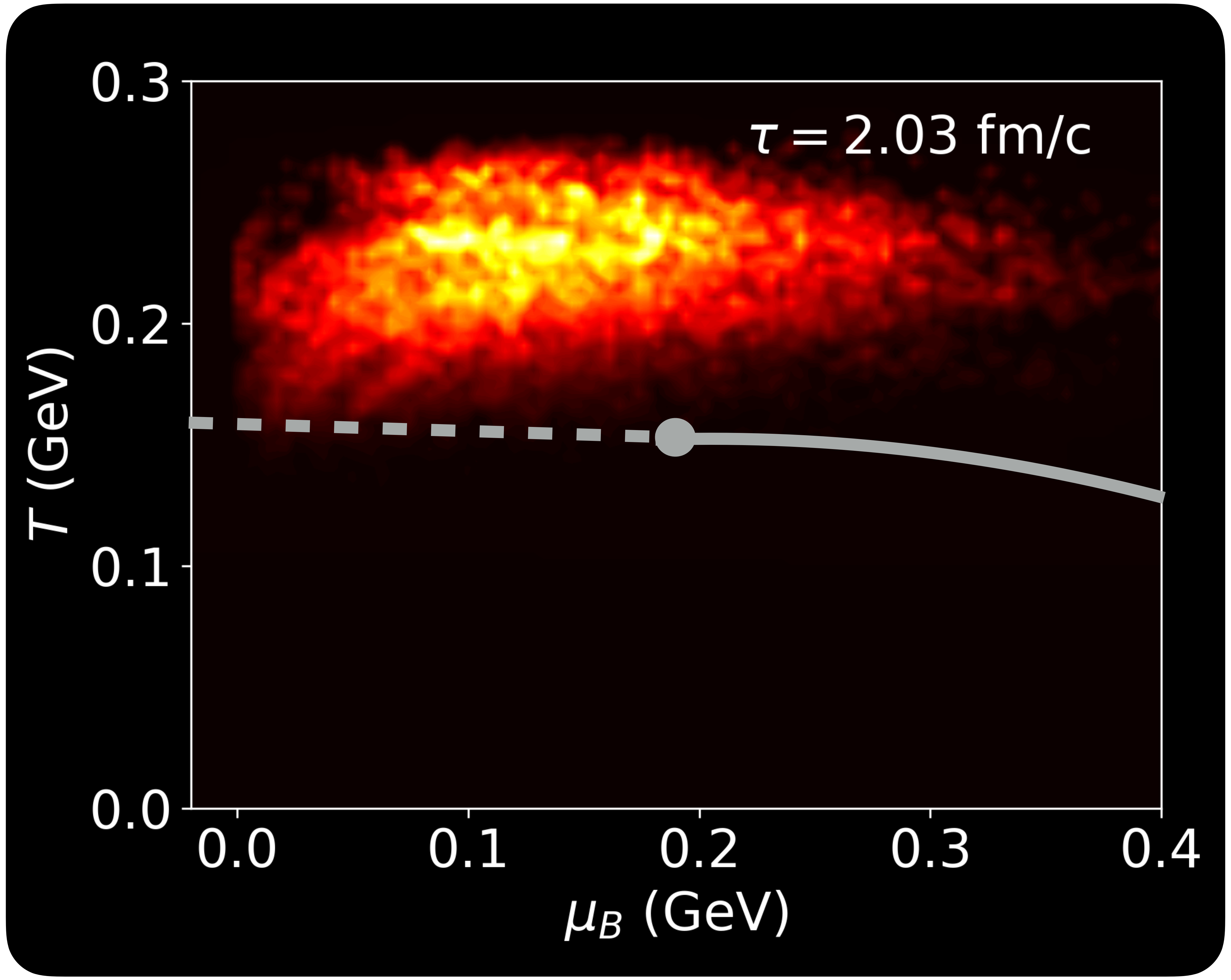

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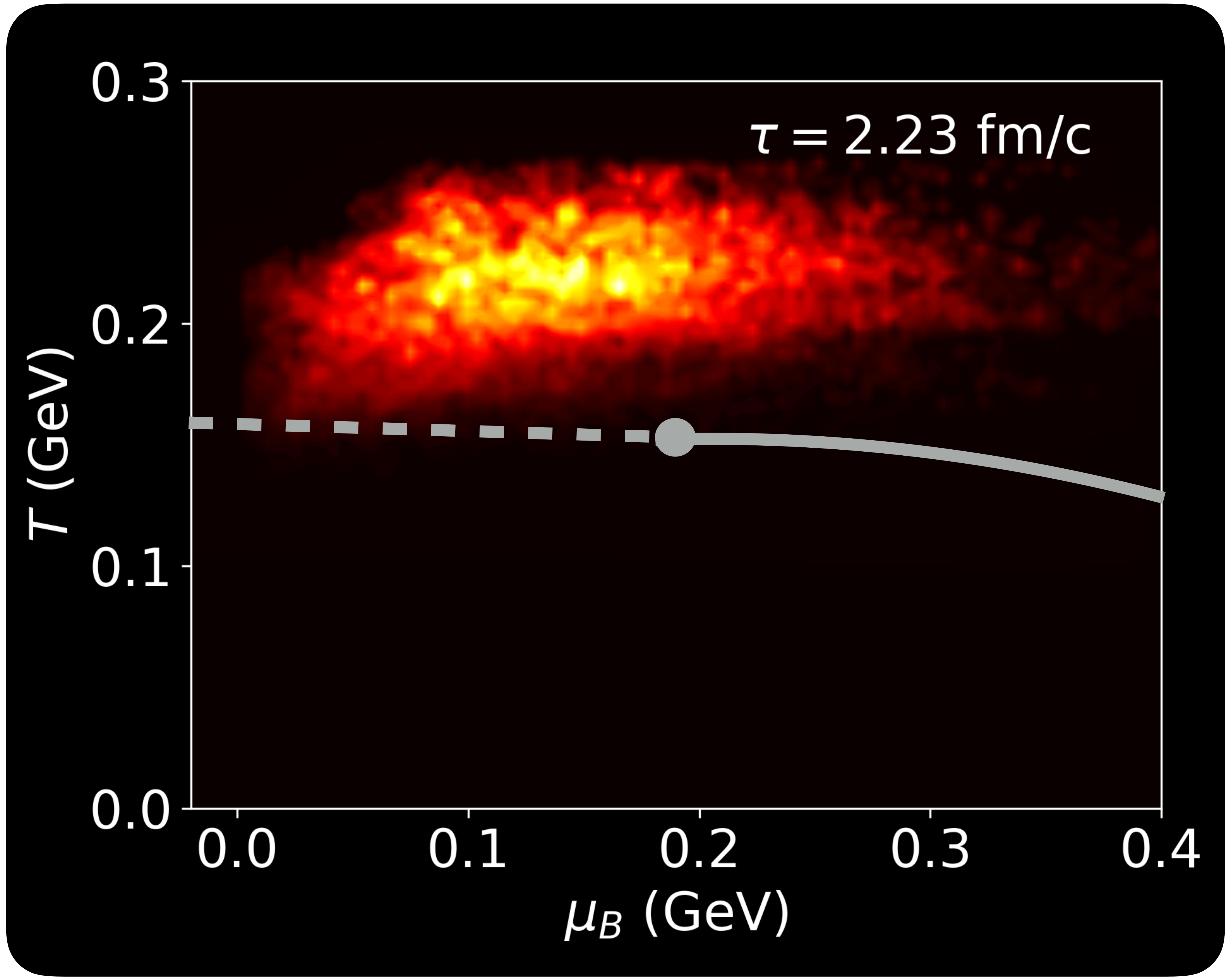

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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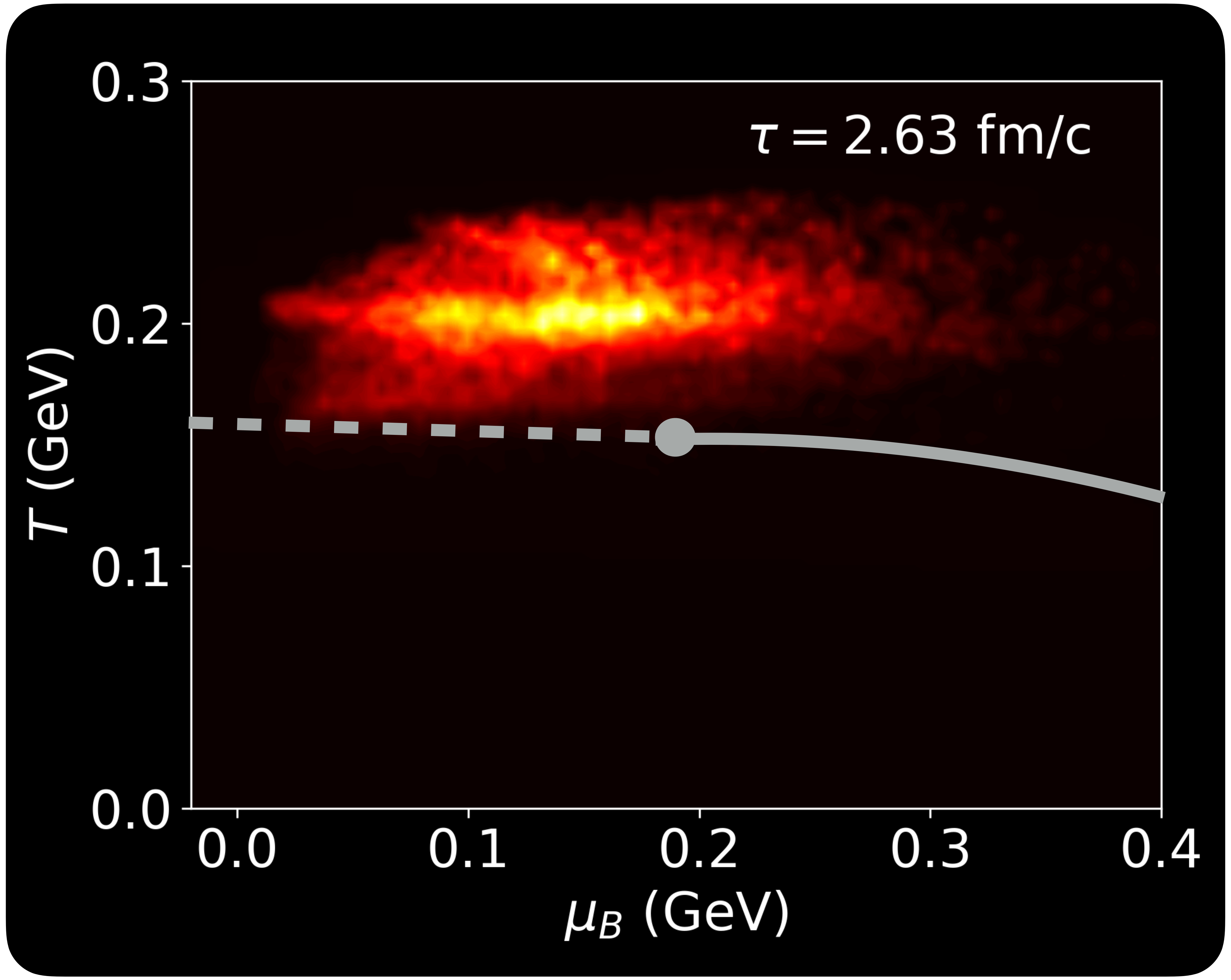

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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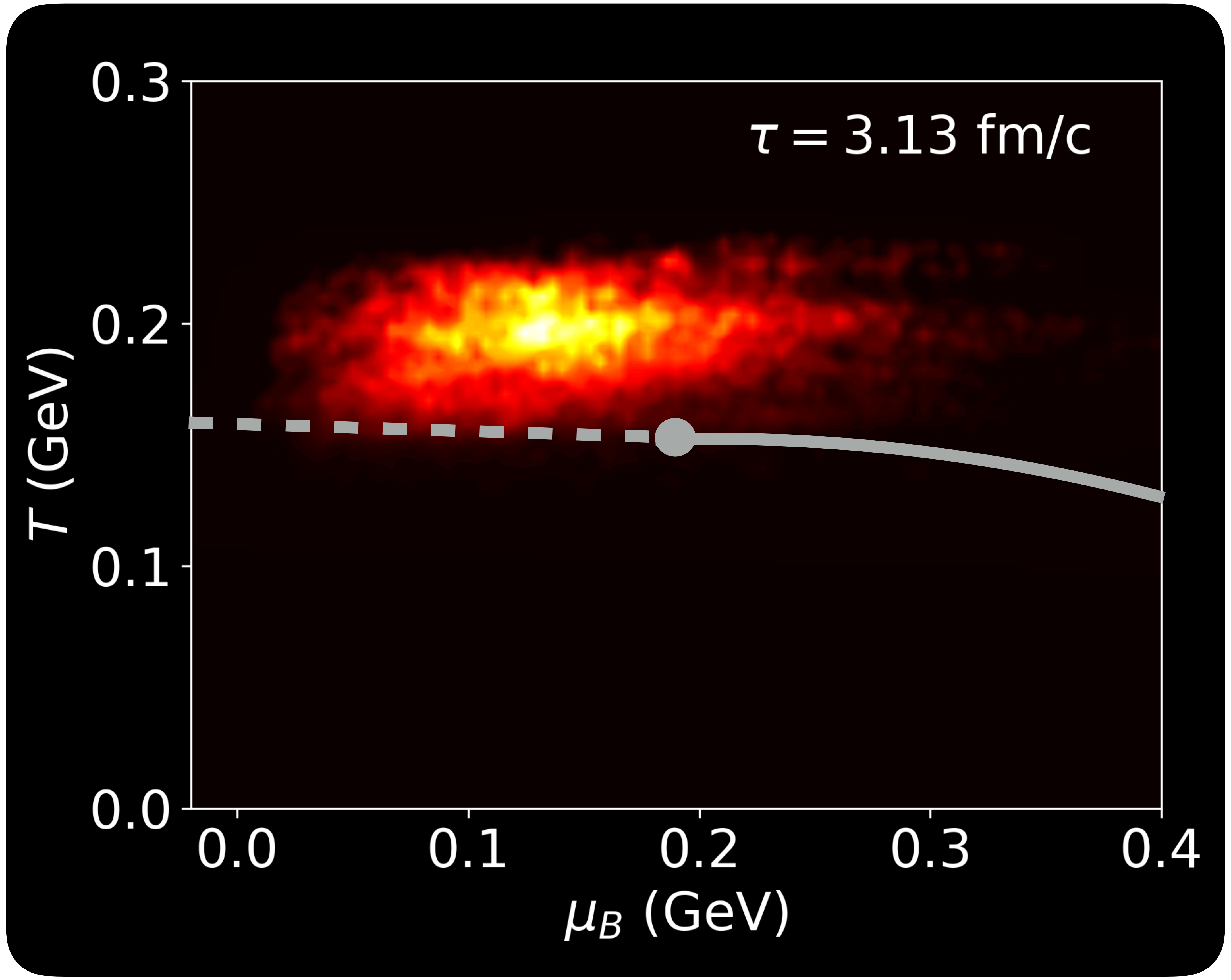

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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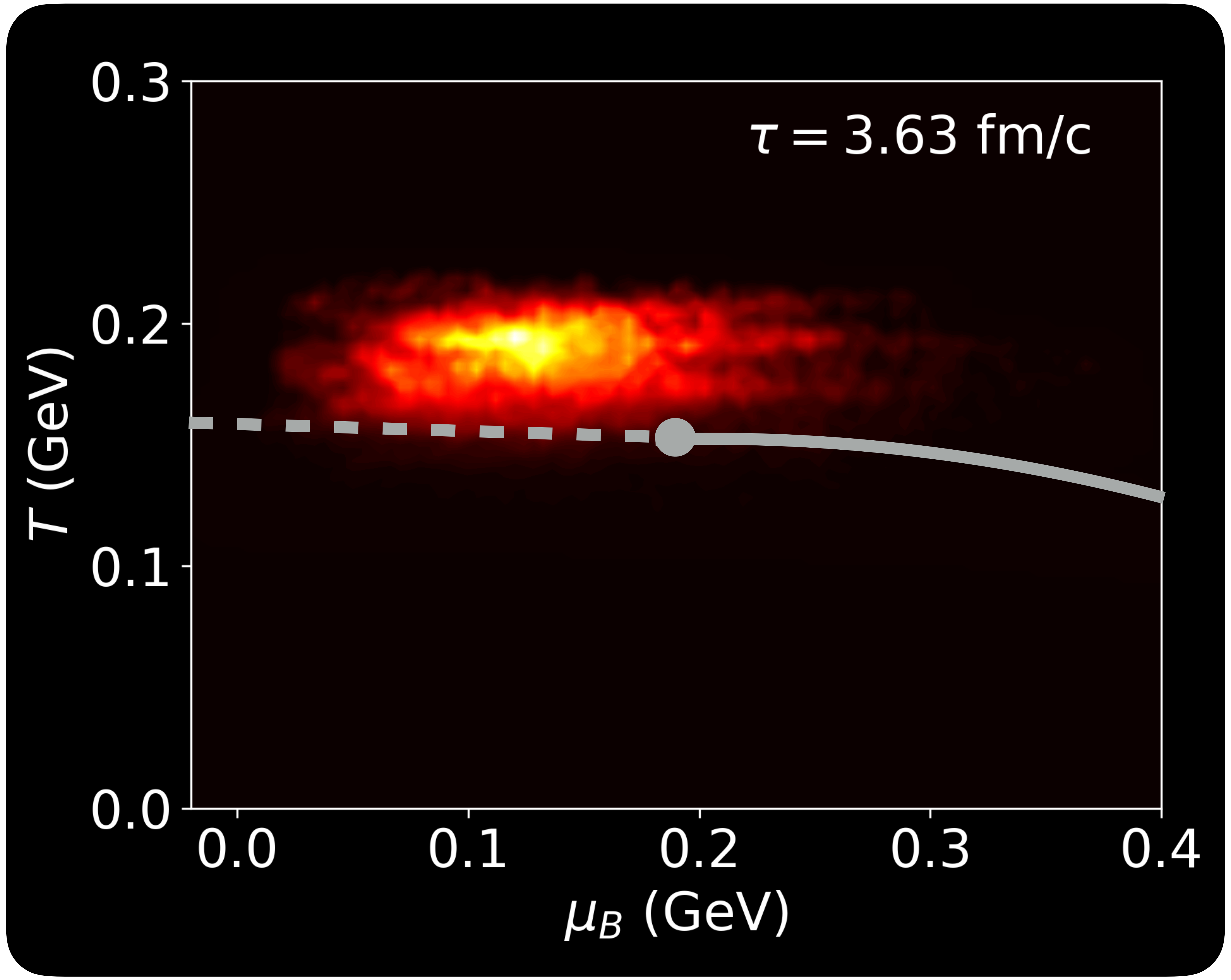

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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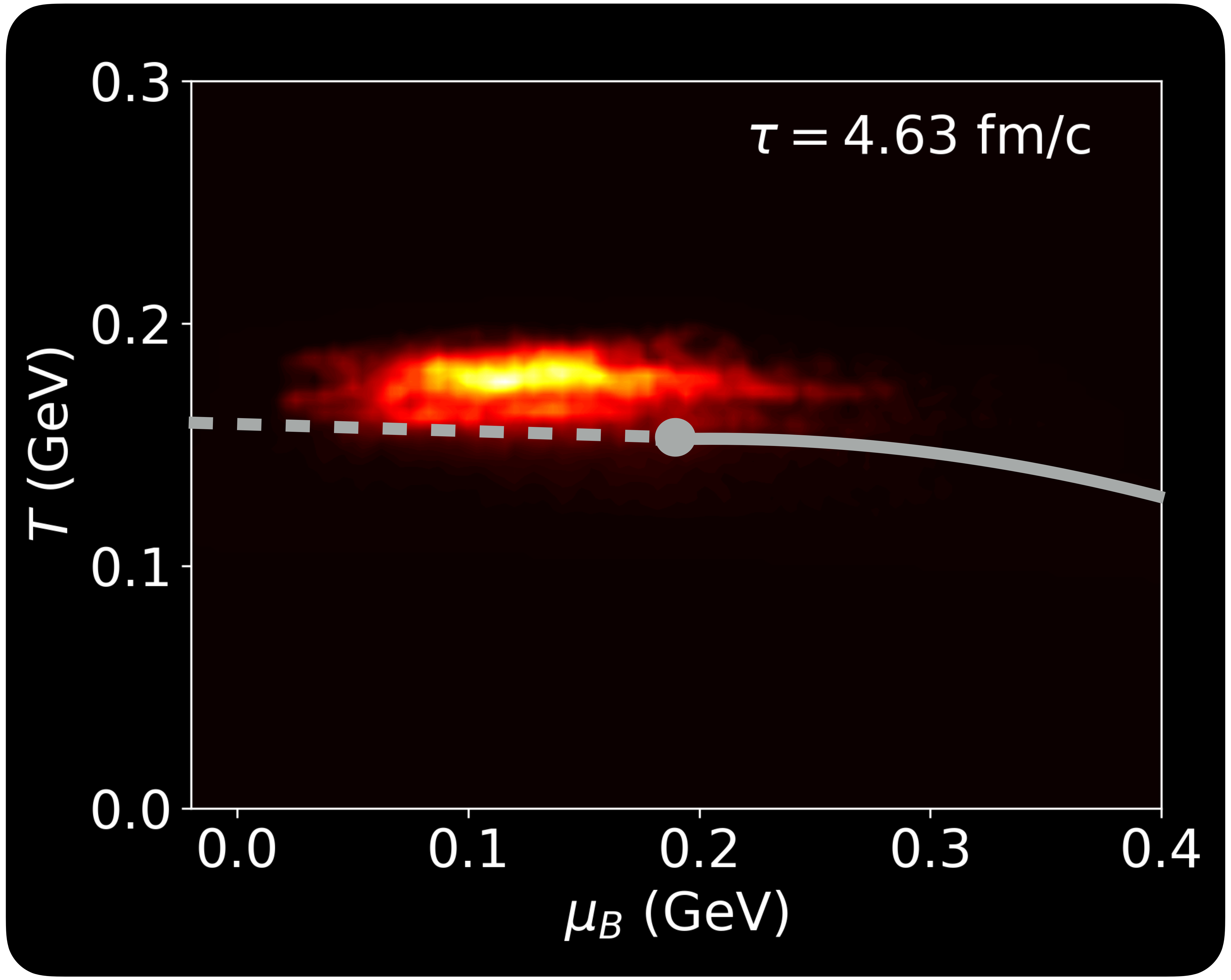

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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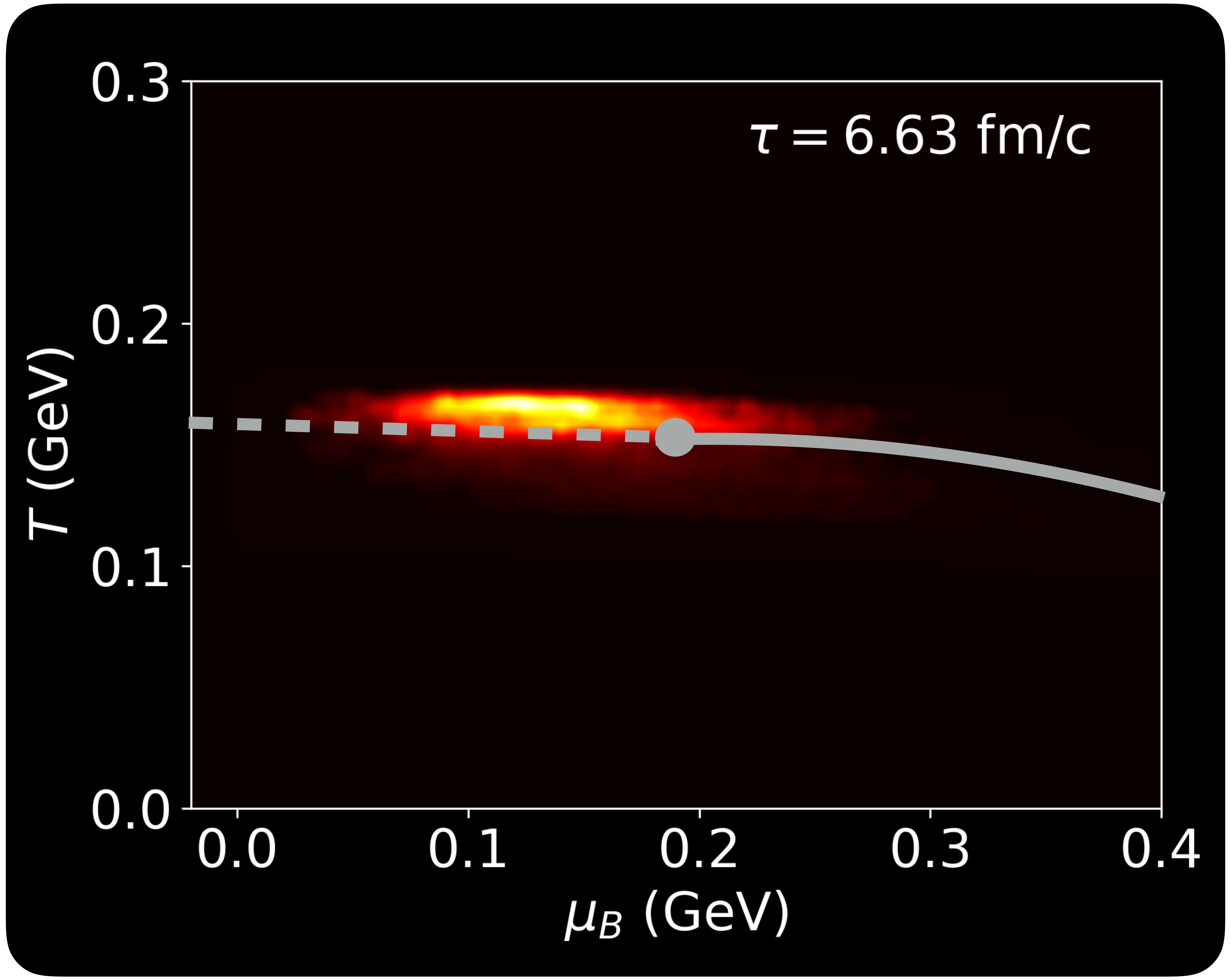

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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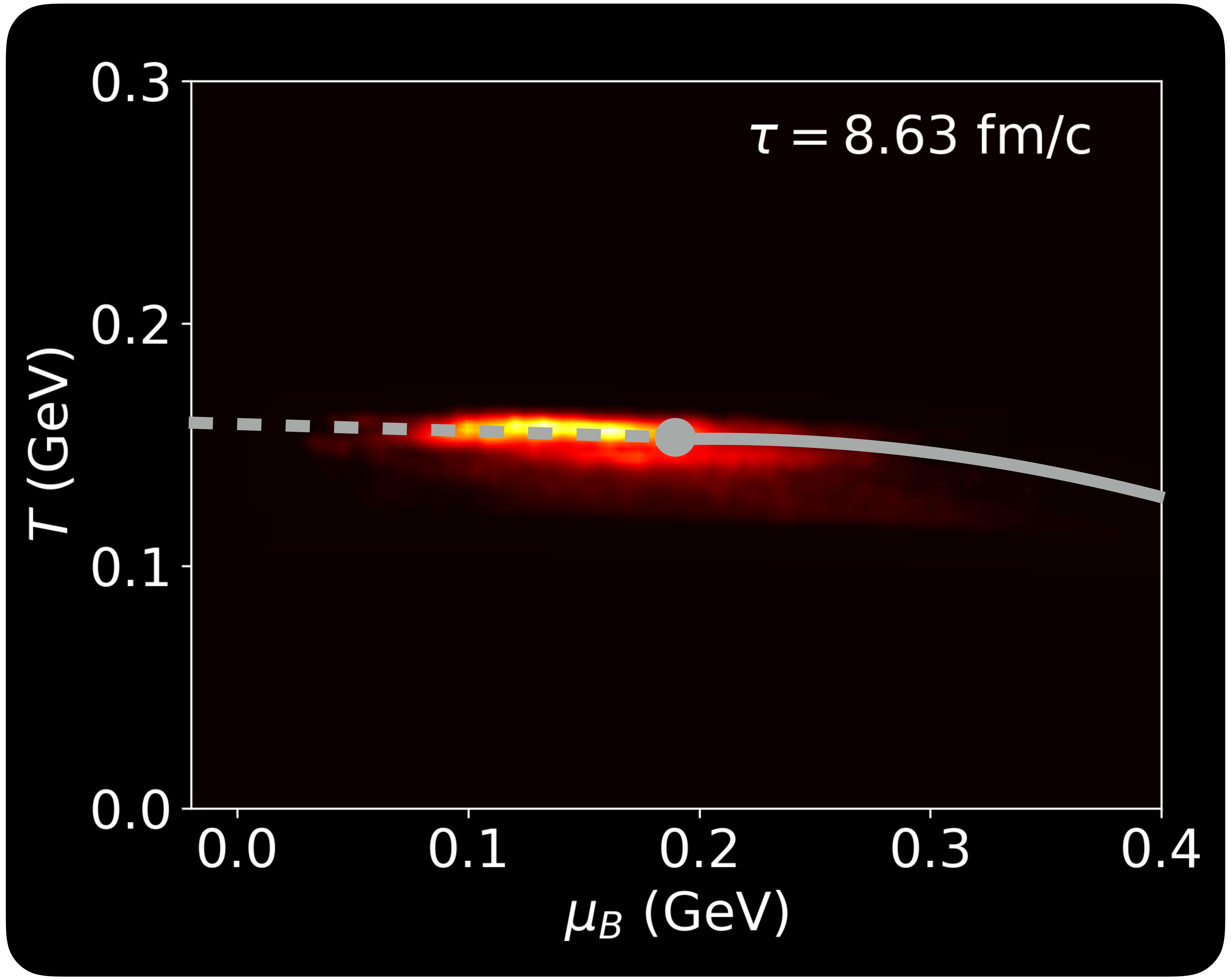

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

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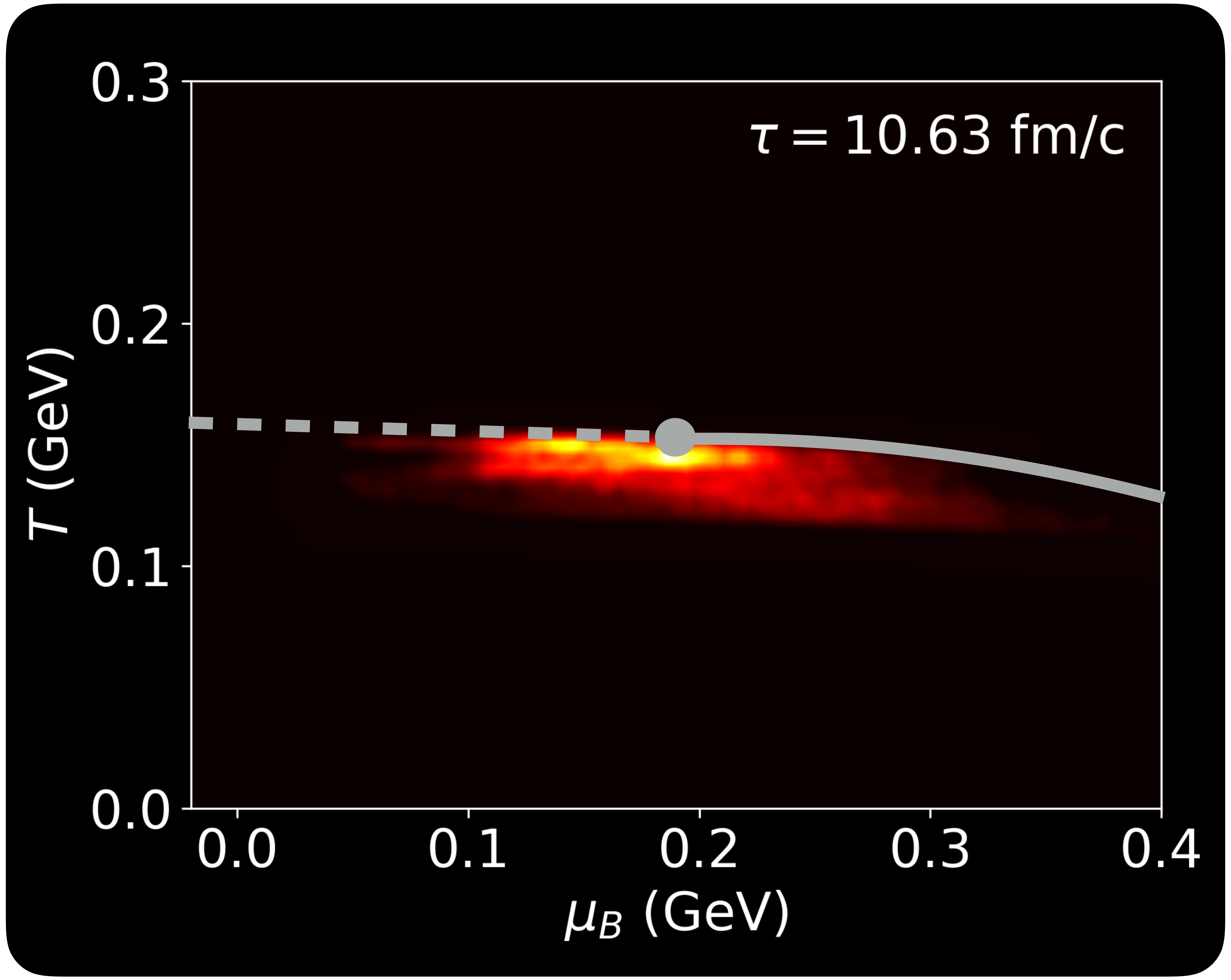

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

0-5% AuAu@19.6 GeV

EVOLUTION IN THE T-μ_B PLANE

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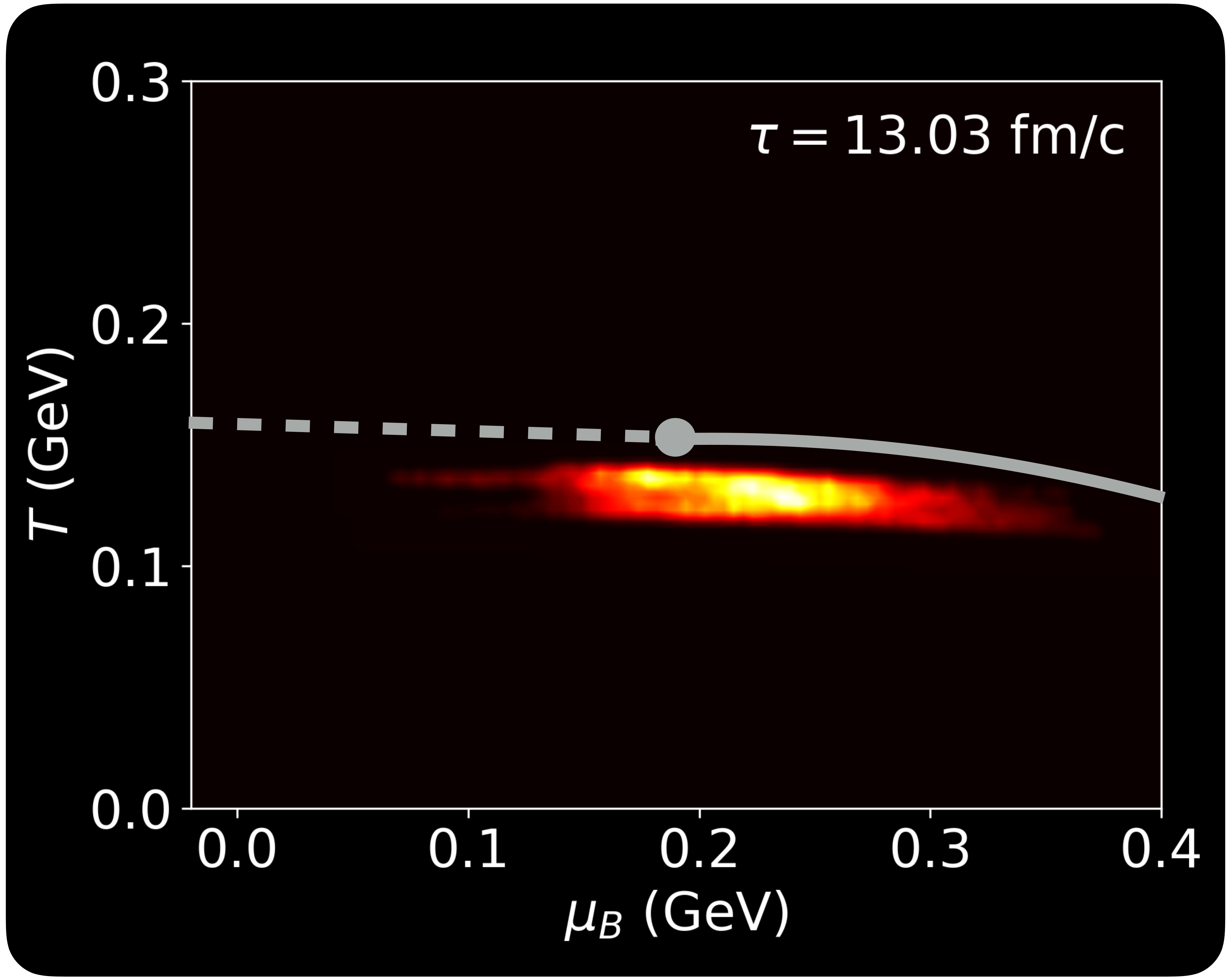
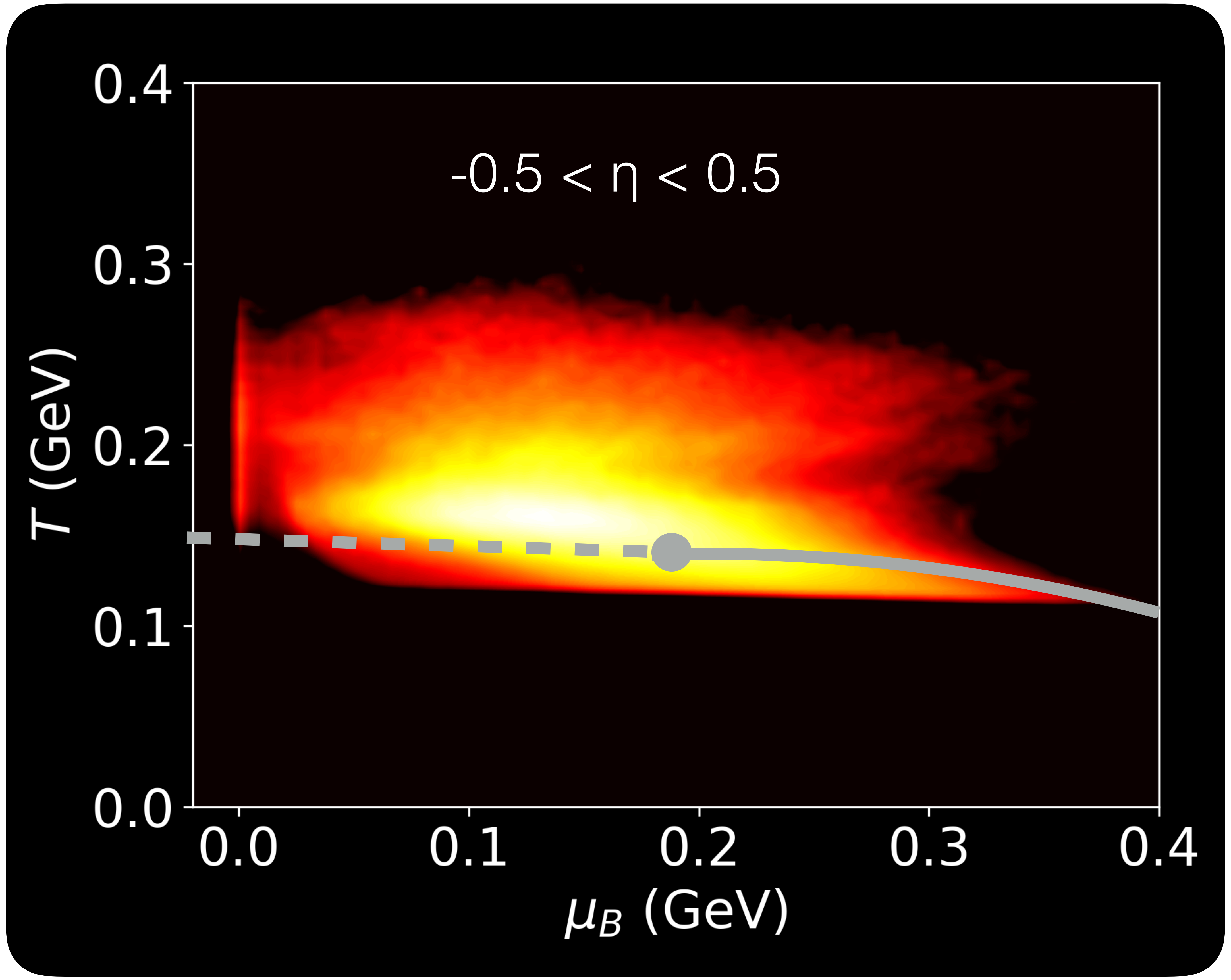


C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

0-5% AuAu@19.6 GeV

EVOLUTION IN THE T-μ_B PLANE

- Fireball trajectory in the T-μ_B is a wide distribution



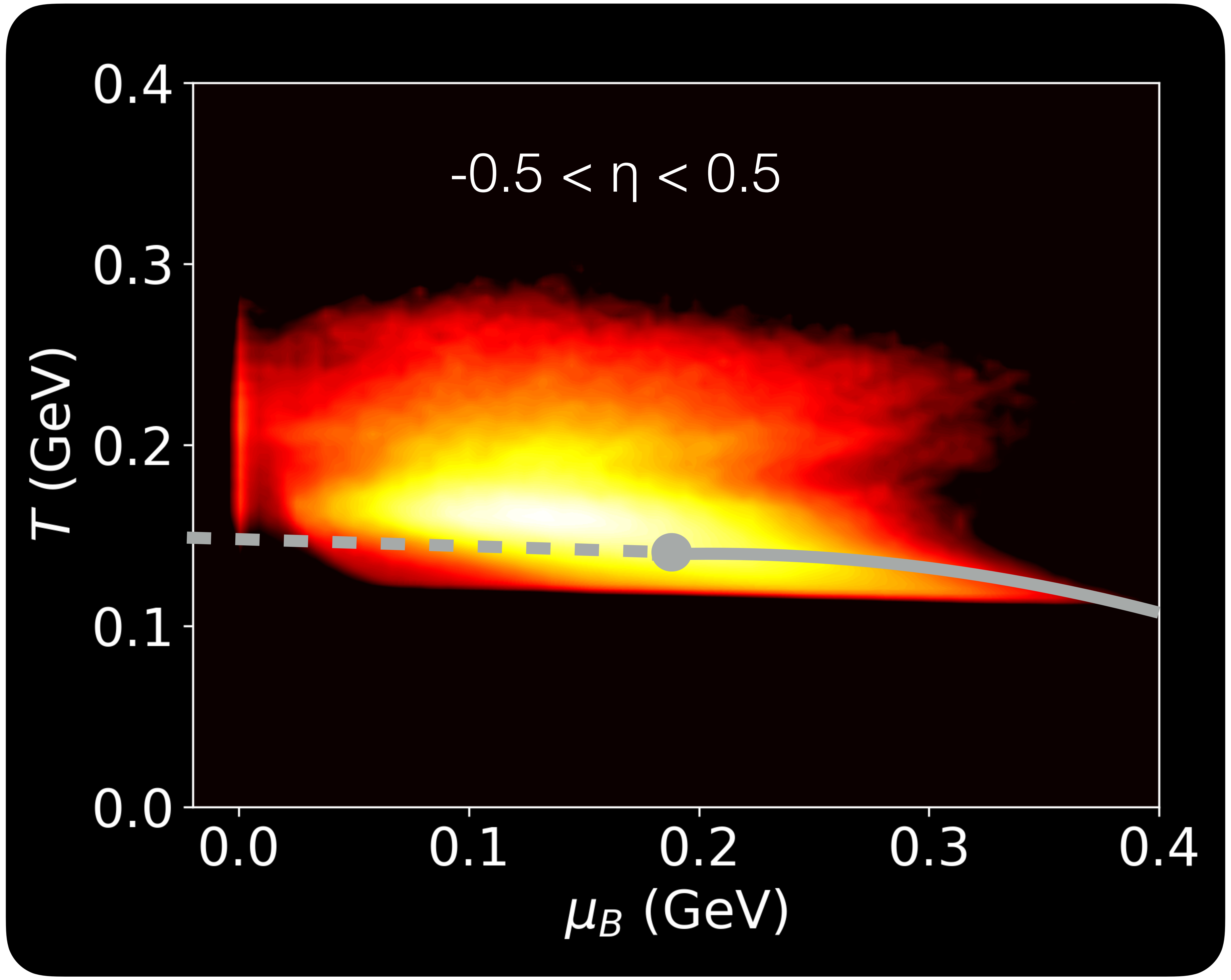
C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

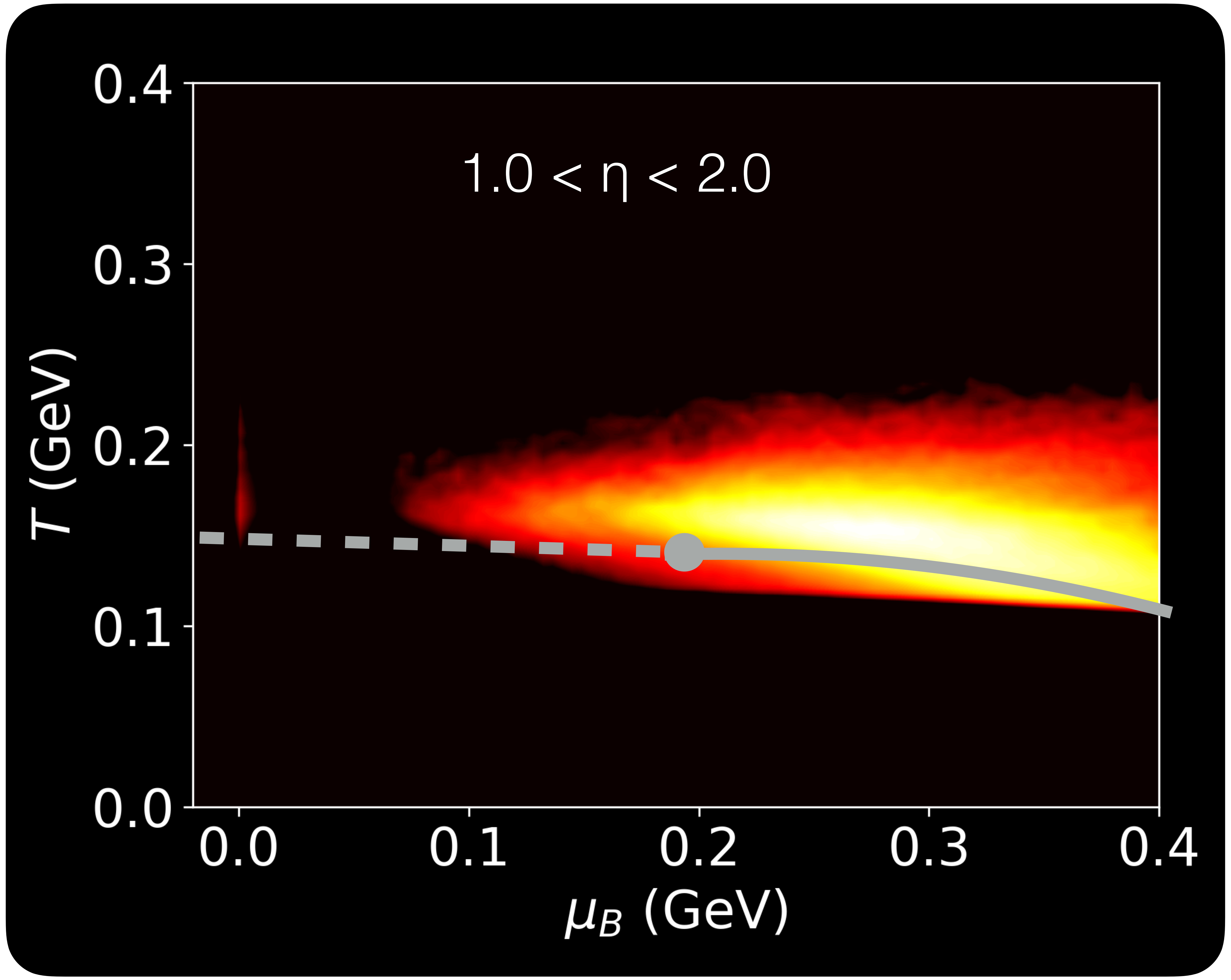
time and space integrated

0-5% AuAu@19.6 GeV

EVOLUTION IN THE T-μ_B PLANE

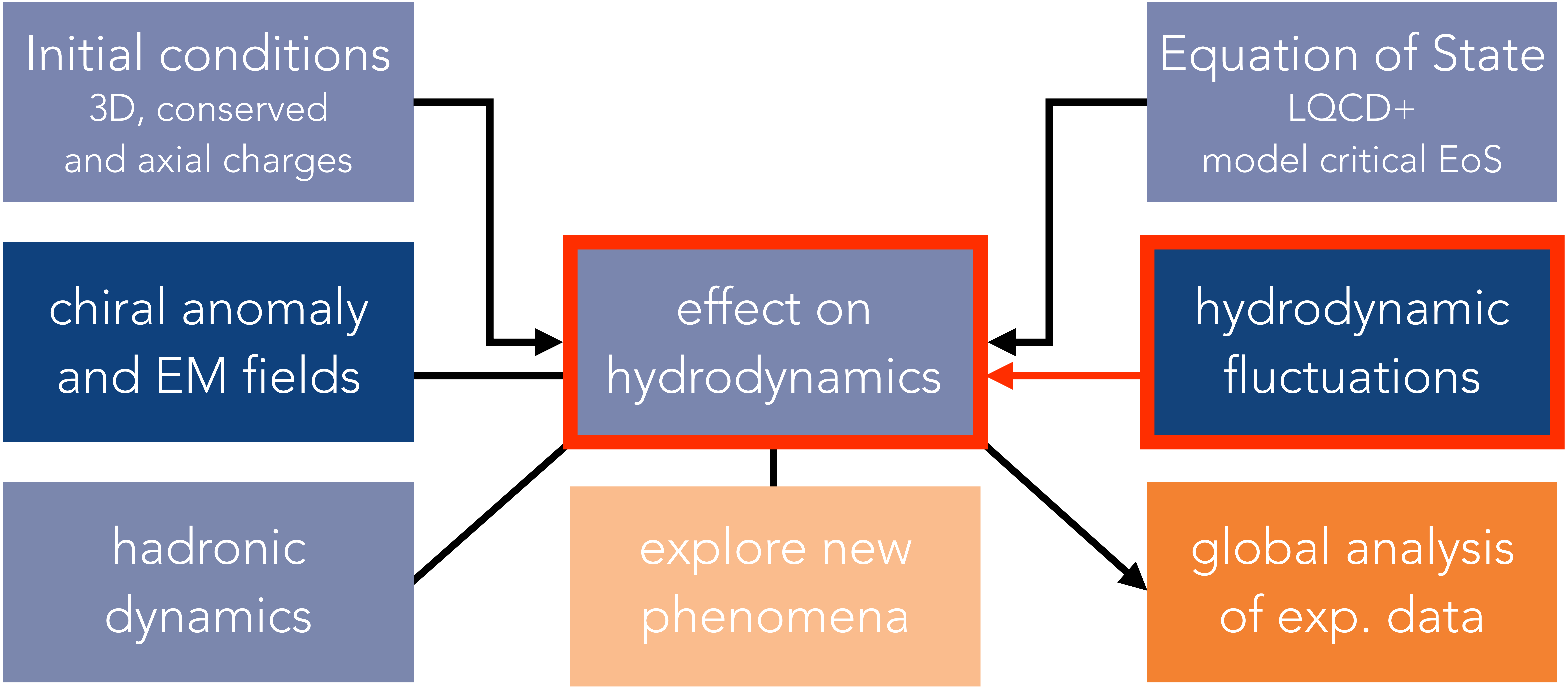
- Trajectory changes significantly with rapidity





C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

BEAM ENERGY SCAN THEORY

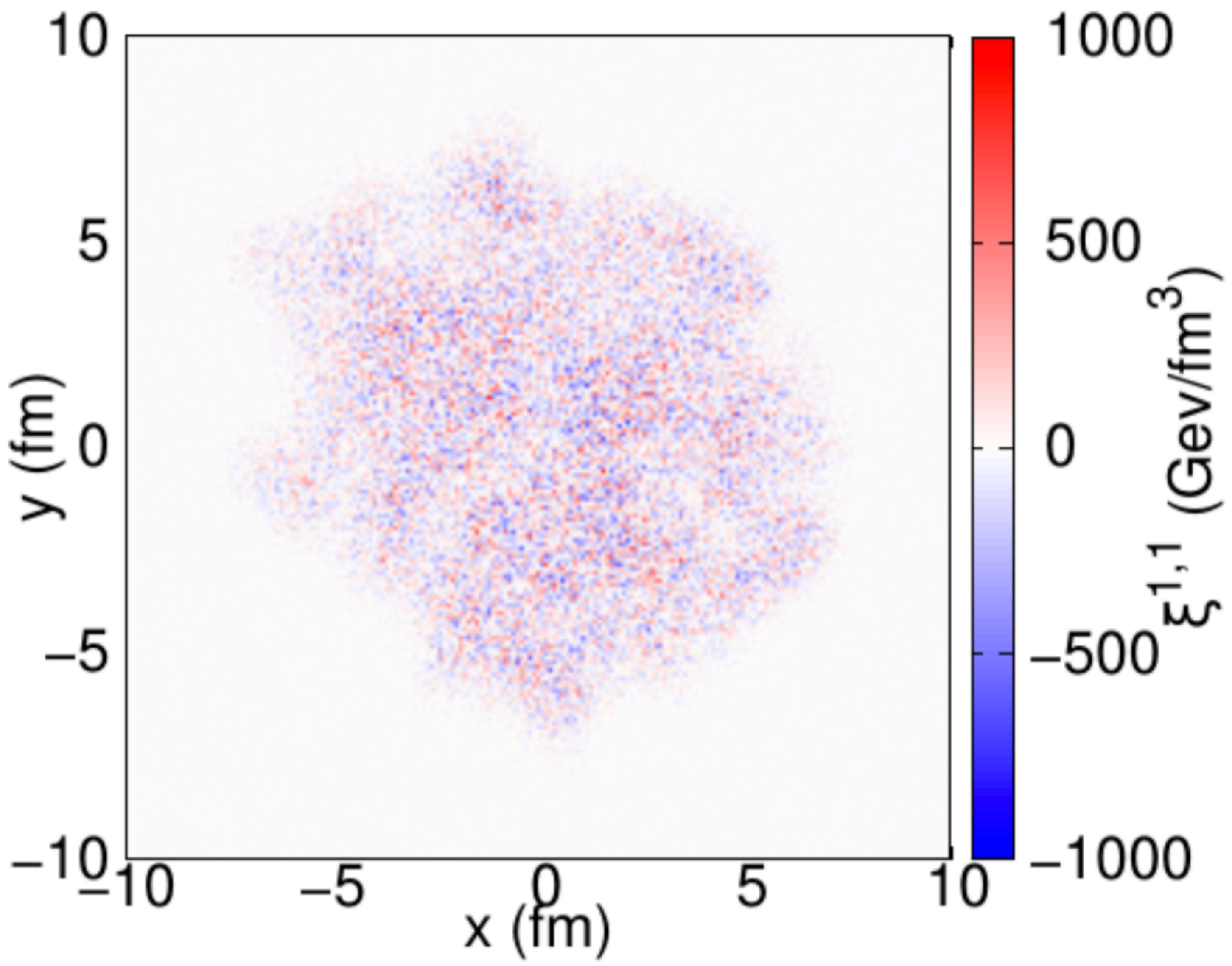


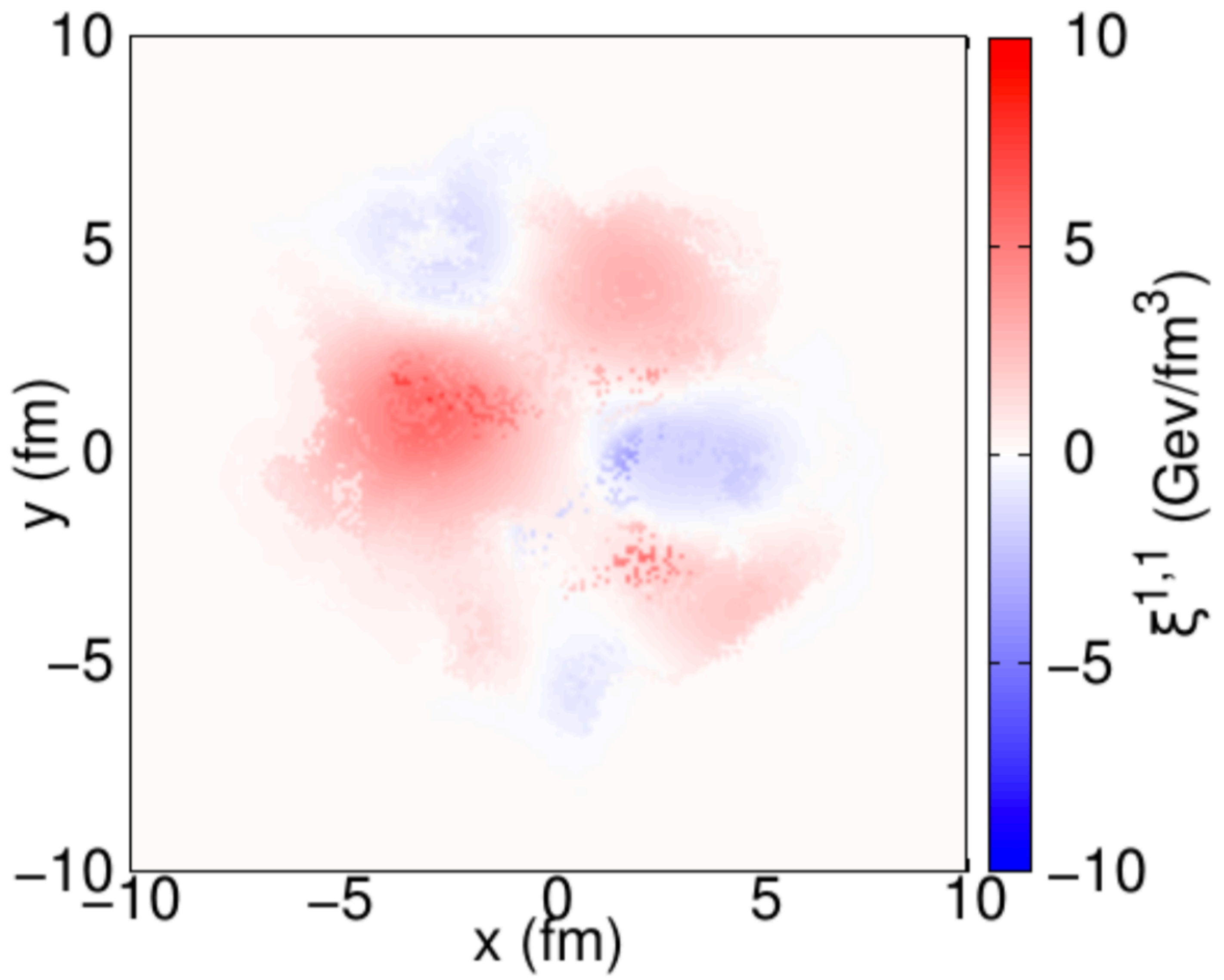
FLUCTUATING HYDRODYNAMICS

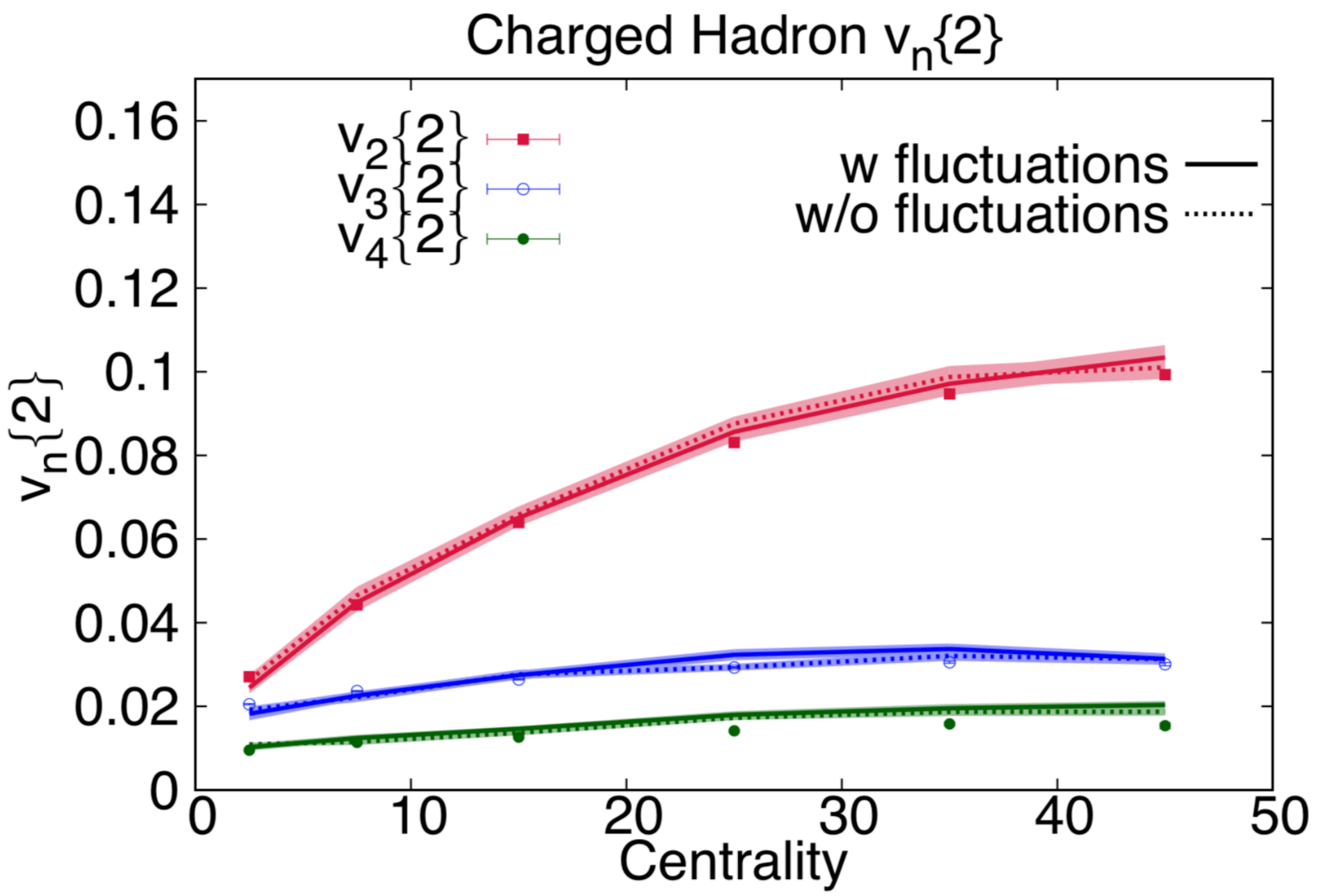
Dissipation (as in viscous hydrodynamics) requires (thermal) fluctuations

$$\partial_\mu (T^{\mu\nu}_{ideal} + \pi^{\mu\nu} + \Pi\Delta^{\mu\nu} + S^{\mu\nu}) = 0$$

$S^{\mu\nu}$ is the noise term







Main issue – “infinite noise” – leads to cutoff (cell-size) dependence.
Addressed by noise mode filtering with FFT

M. Singh, C. Shen, S. McDonald, S. Jeon and C. Gale, Nucl. Phys. A982, 319 (2019)

CONVERSION TO PARTICLES

Comparison to experiment requires event-by-event particle distributions

Hydro → Sample particles → Hadronic transport → Data comp.

Local event by event charge conservation requires new sampling method

Standard procedure:
Cooper-Frye + grand-canonical sampling in each surface cell

→

- For fluct. hydro fluctuations and correlations are already part of hydro ensemble
- additional (Poisson) fluctuations from Cooper-Frye freeze out add extra (un-physical) fluctuations
- Particlization needs to conserve charges locally and event by event

Solution: Micro-canonical sampling

Dmytro Oliinychenko, Volker Koch, arXiv:1902.09775

CONVERSION TO PARTICLES

Comparison to experiment requires event-by-event particle distributions

Hydro → Sample particles → Hadronic transport → Data comp.

Micro-canonical sampling

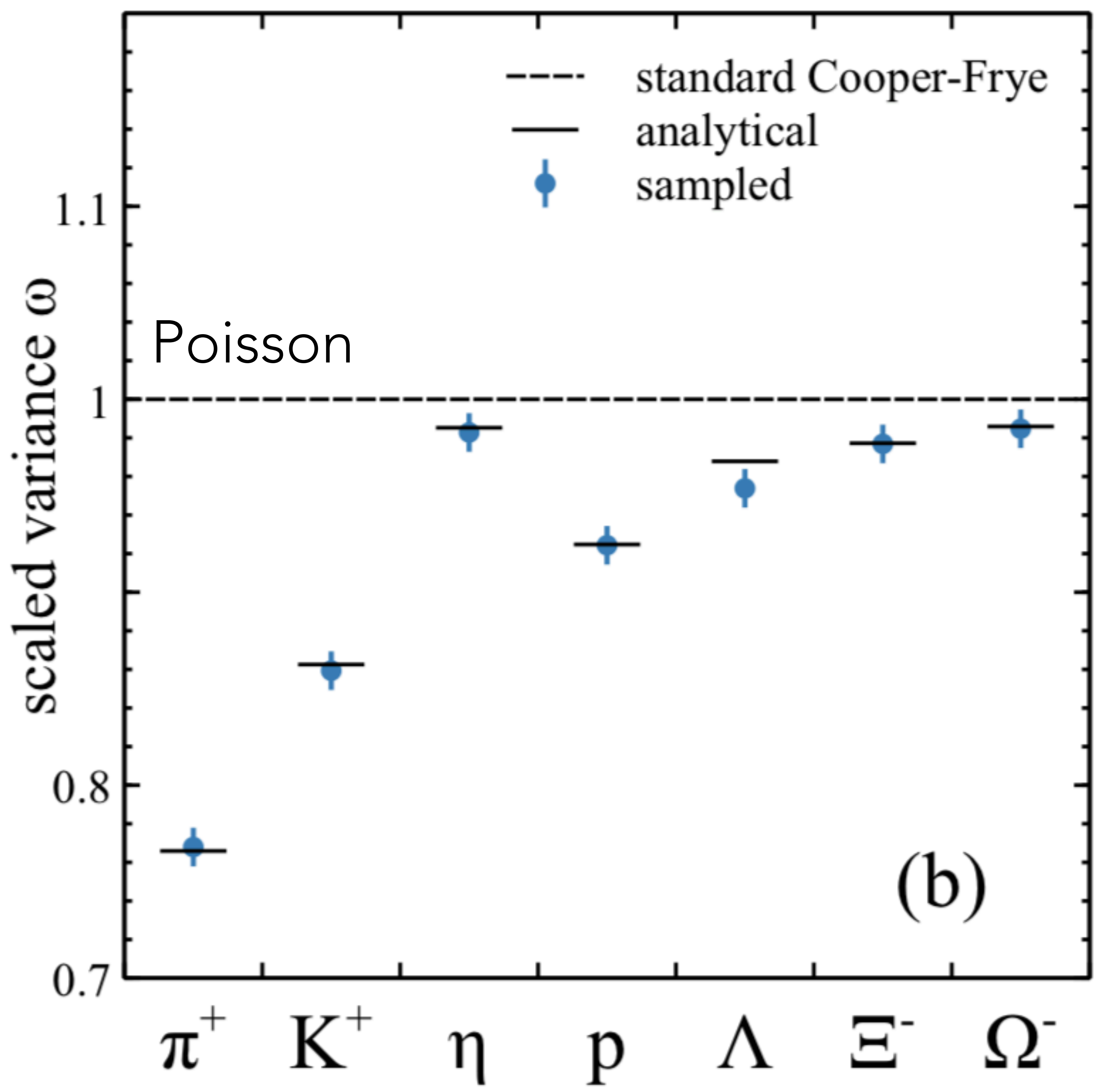
Dmytro Oliinychenko, Volker Koch, arXiv:1902.09775

Technical problem: Number of particles per cell N<1

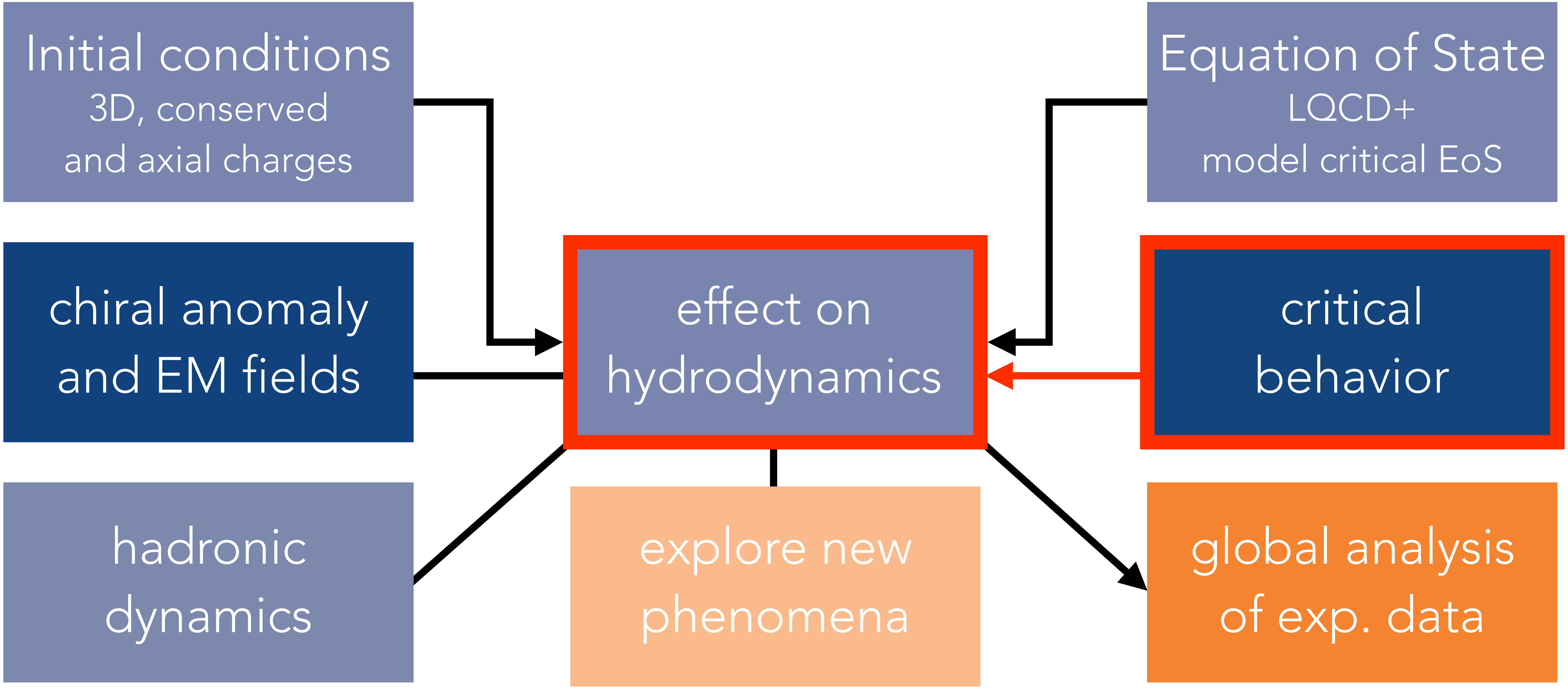
Solution: Collect hyper surface cells into patches with N>1 and impose conservation laws on patch and preserve local mean densities

Done using Metropolis algorithm

Scaled variance



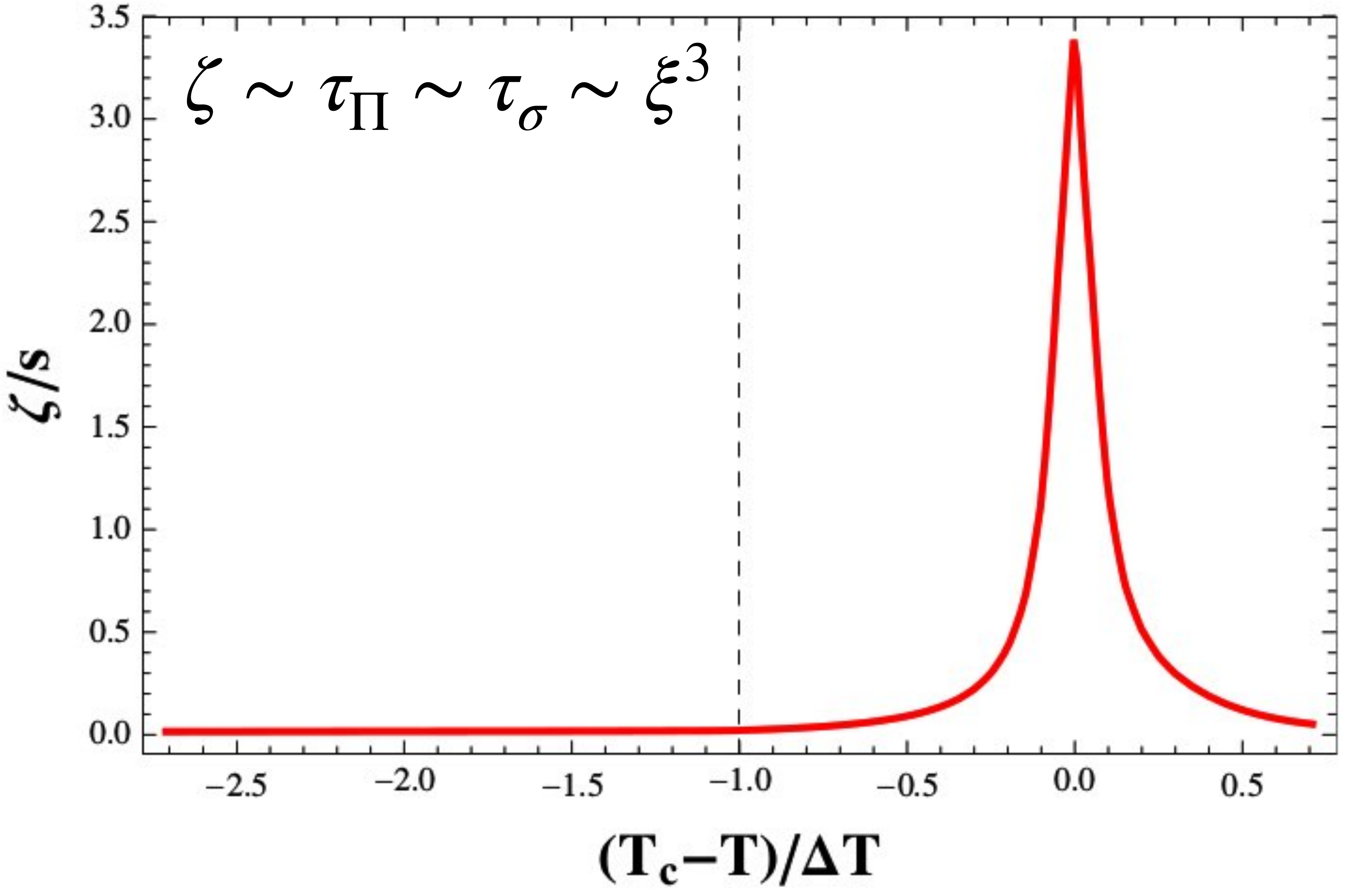
BEAM ENERGY SCAN THEORY



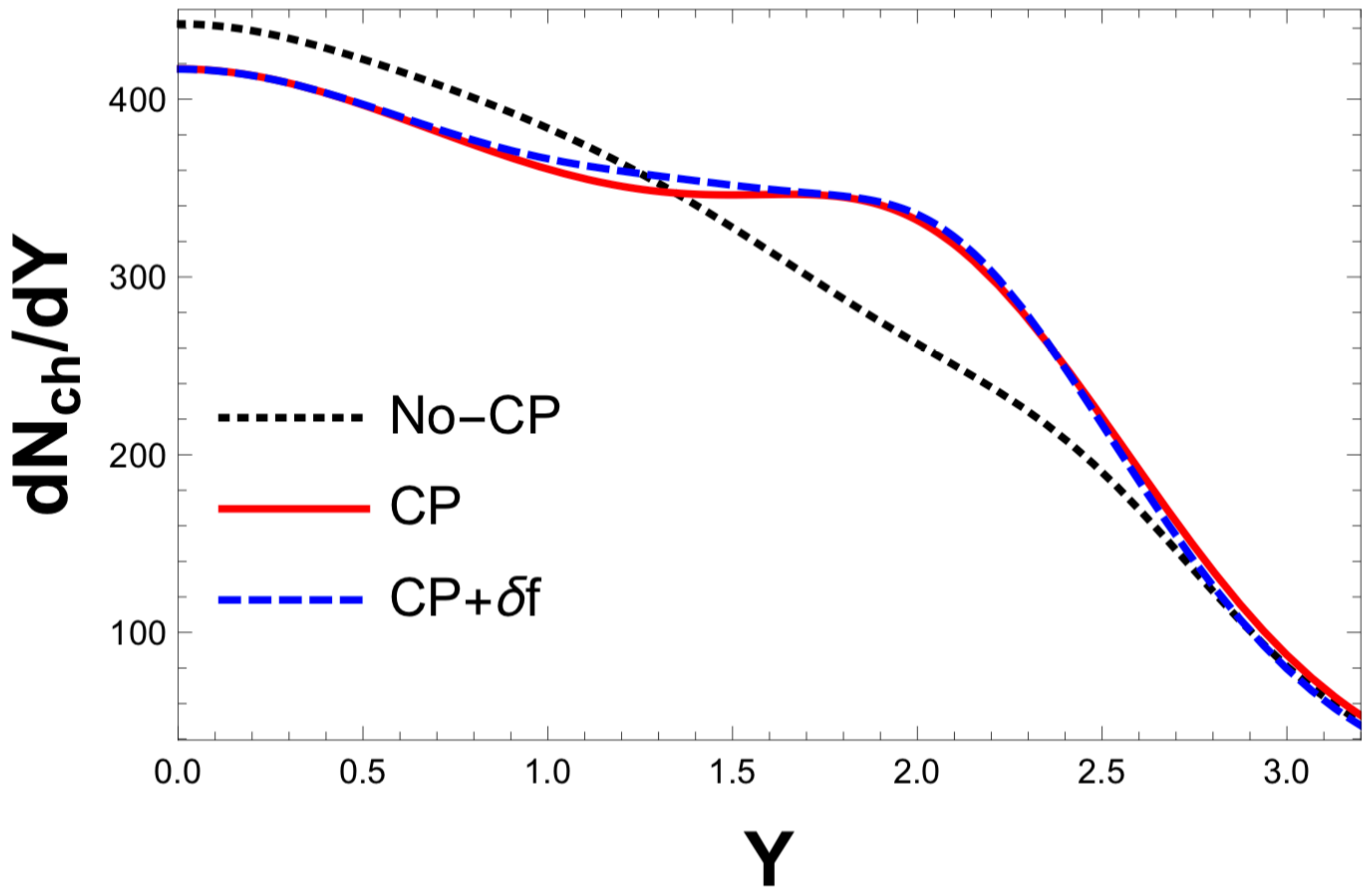
DIVERGING BULK VISCOSITY AT CRITICAL POINT

Monnai, Mukherjee, Yin: Phys. Rev. C95, 034902 (2017)

Critical behavior of bulk viscosity: $\zeta \sim \xi^3$ (**see A. Onuki, Phys. Rev. E 55, 403 (1997)**)



Bulk viscosity vs. temperature



Rapidity spectra with and without critical behavior

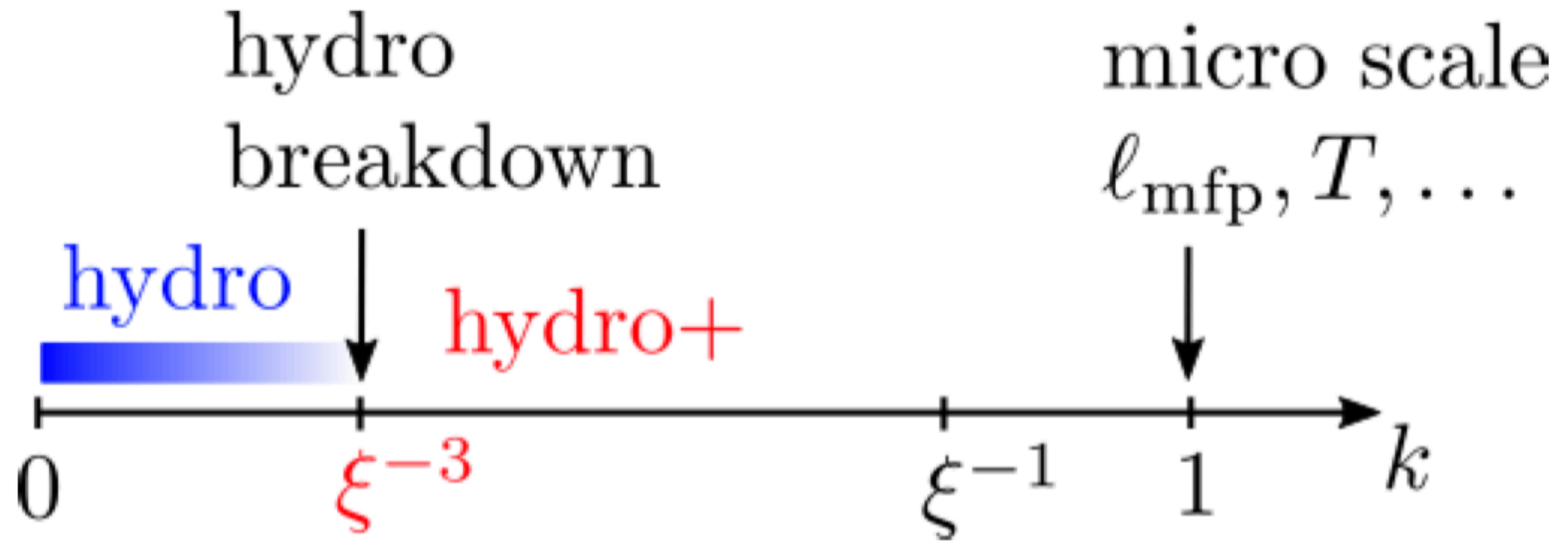
HYDRO+ COUPLING TO CRITICAL MODE

M. Stephanov, Y. Yin, arXiv:1704.07396, arXiv:1712.10305

MORE TODAY 4:25PM IN TALK BY YI YIN (DIRECTOR'S ROW I)

$\zeta \sim \tau_\Pi \sim \tau_\sigma \sim \xi^3$ Hydro breaks down because of large relaxation time

Treating the slow mode **Φ** with **$\tau_\Phi \sim \xi^3$** separately (relaxation equation) will increase range of validity:

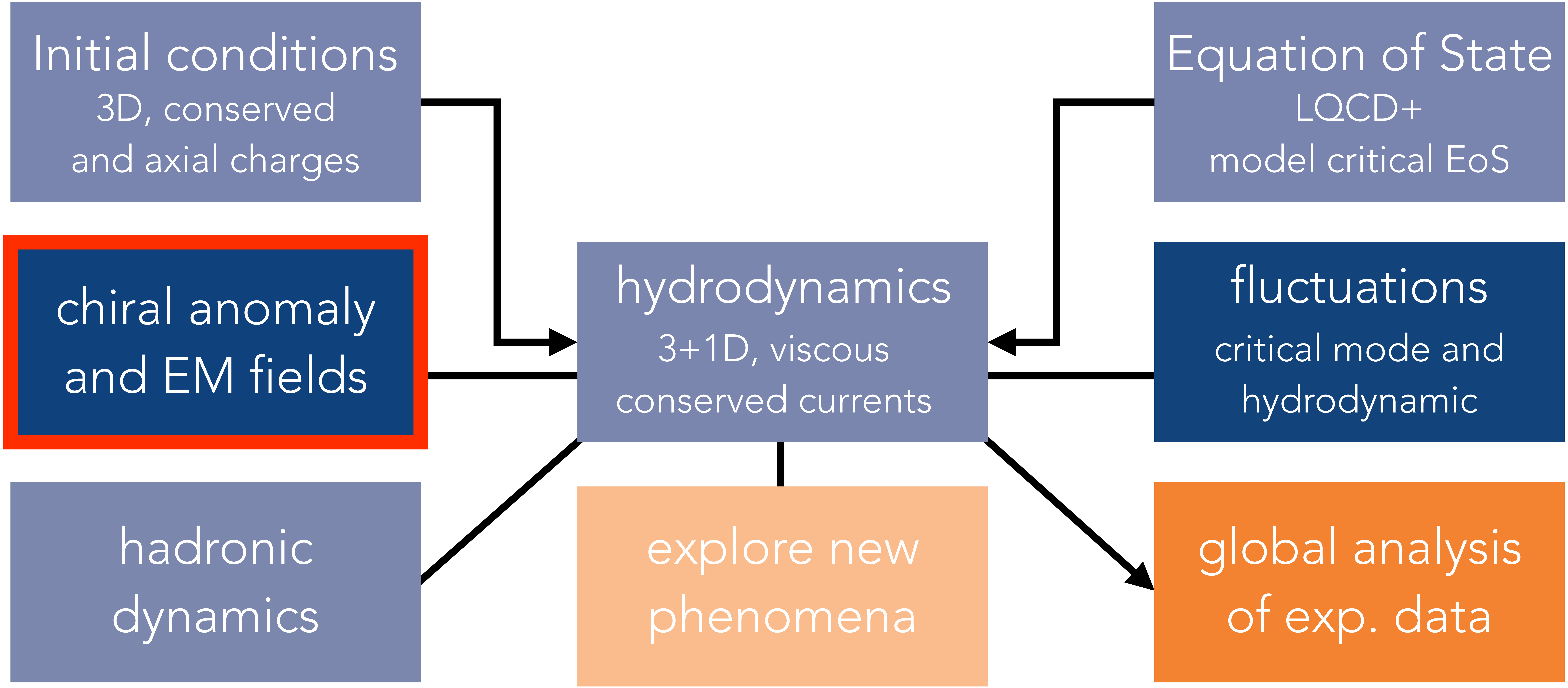


Major effects of critical fluctuations on the evolution:

- Strong frequency dependence of the anomalously large bulk viscosity
- Stiffening of the EoS with increasing frequency

Explicit implementation and simulation ongoing

BEAM ENERGY SCAN THEORY



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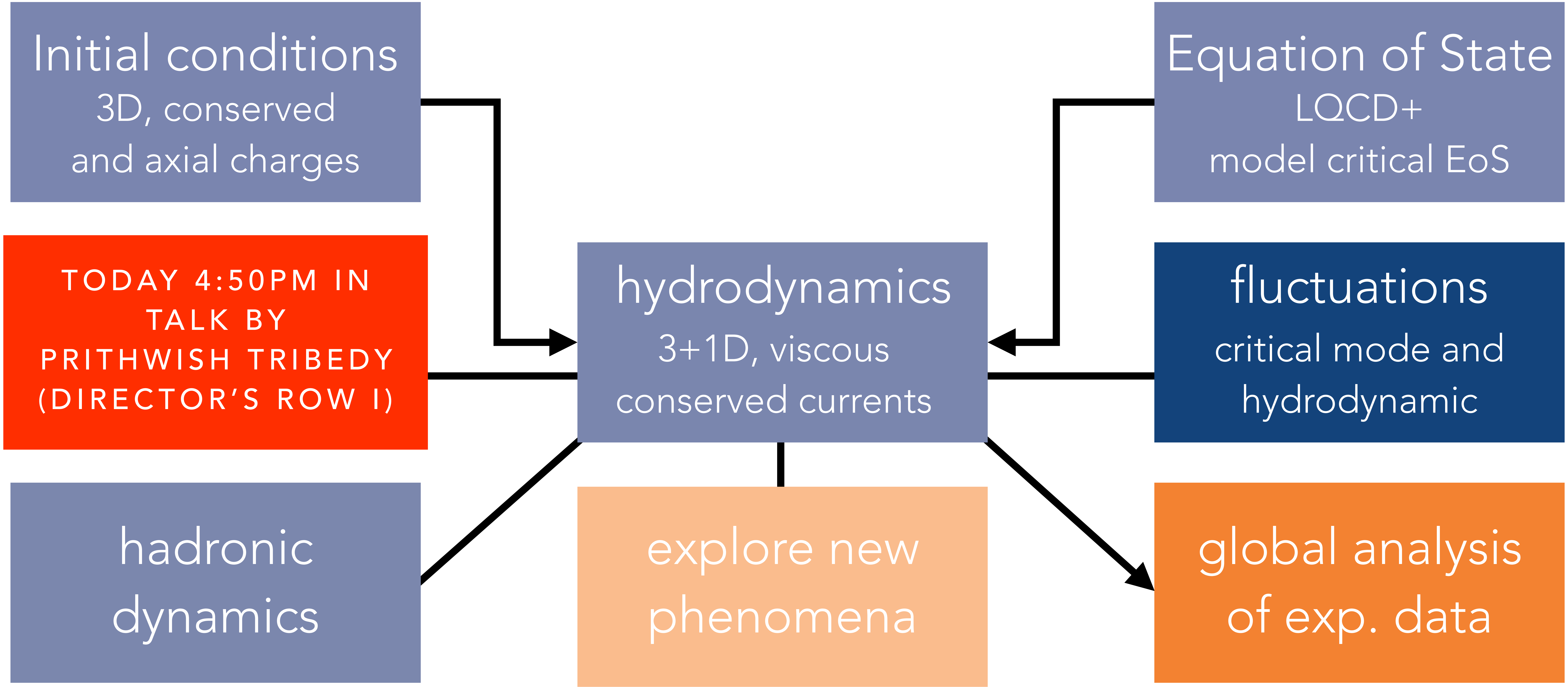


SUMMARY AND OUTLOOK

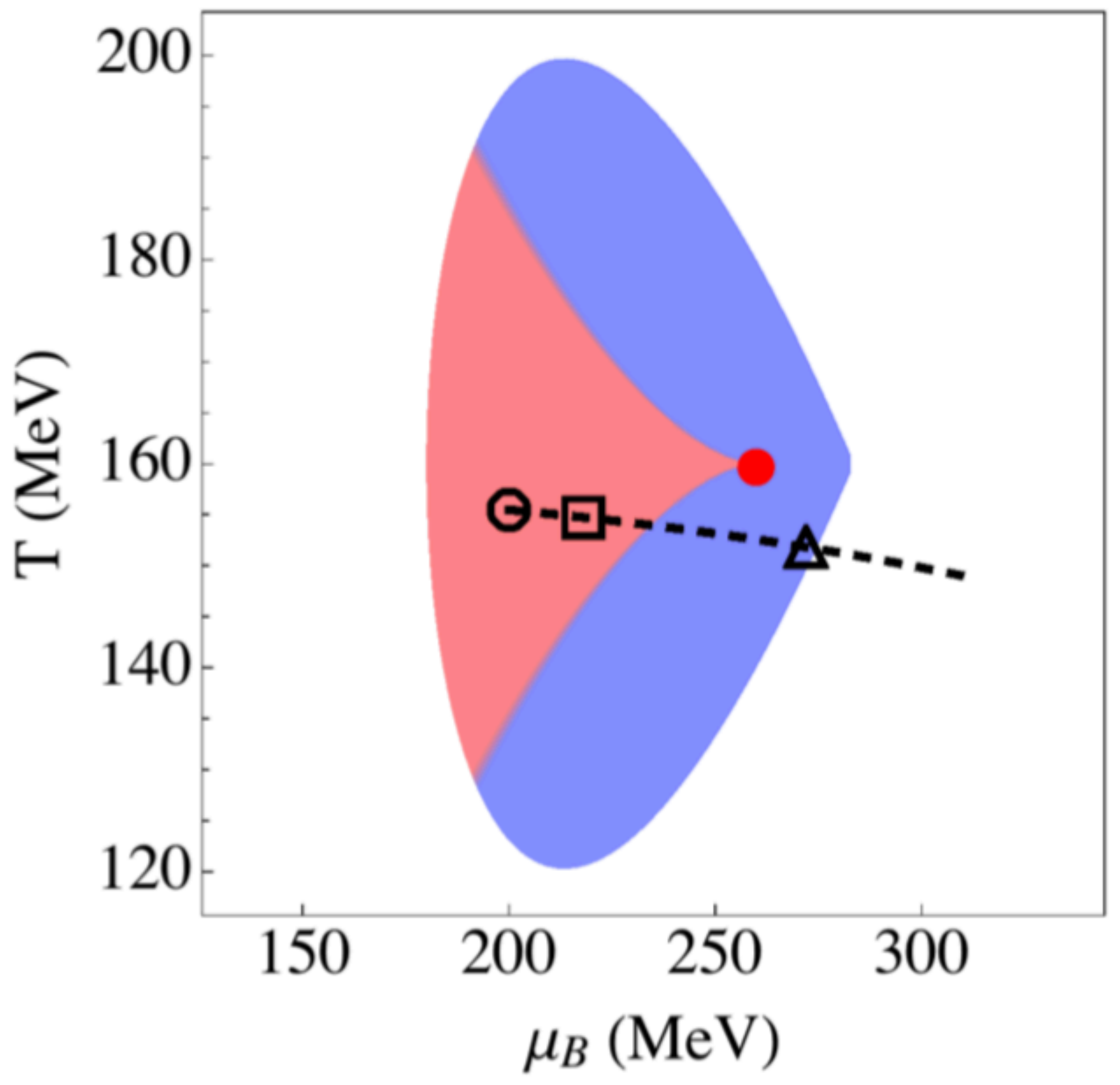
- Going away from very high energies makes life more complicated:
  - No boost-invariance, finite chemical potentials, …
- Significant progress on many aspects:
  Equation of state, initial conditions, 3+1D viscous fluid dynamics, (critical and hydrodynamic) fluctuations, conversion to particles, anomalous fluid dynamics, …
- Comprehensive theoretical framework is being developed to support BES II
- To be addressed:
  - Numerical implementation of Hydro+
  - Full implementation of event-by-event conservation of conserved charges in statistical freeze-out
  - How to match critical correlations to hadronic transport model
  - Early-time dynamics of chiral anomaly

BACKUP

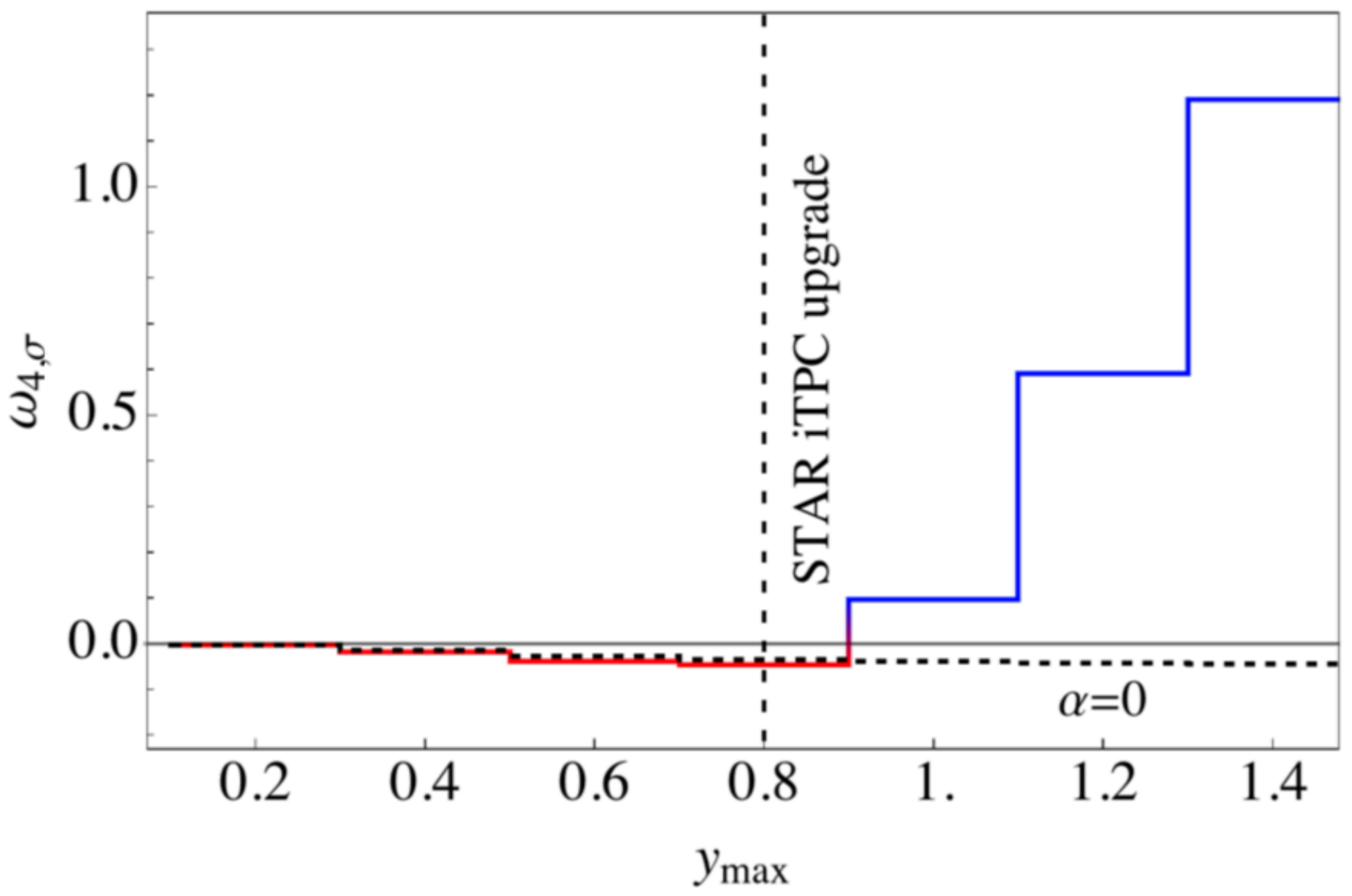
REFINING THE SEARCH: BINNING IN RAPIDITY

J. Brewer, S. Mukherjee, K. Rajagopal, Y. Yin, arXiv:1804.10215

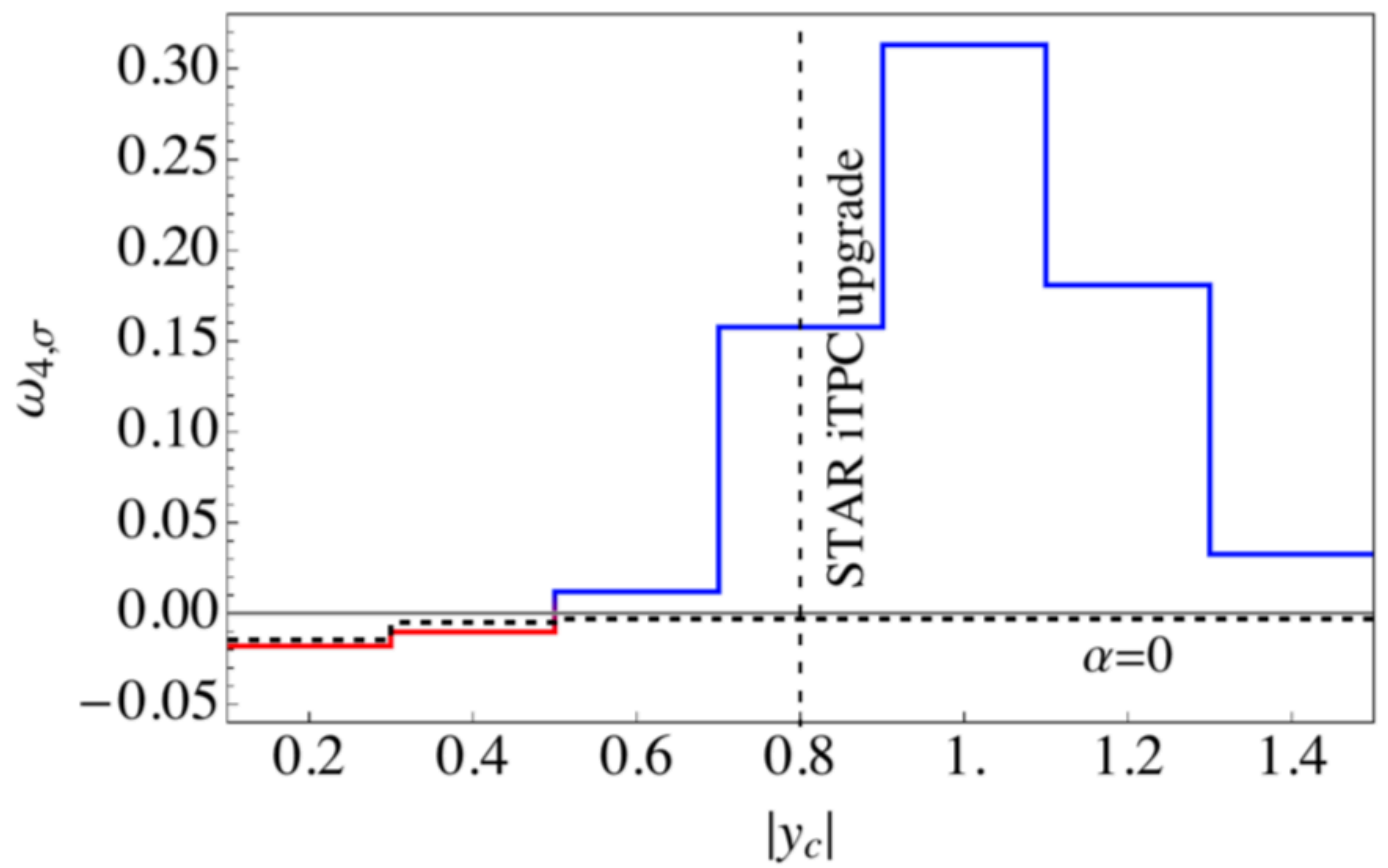
color: sign of kurtosis



Varying y_{max}



Binning in y

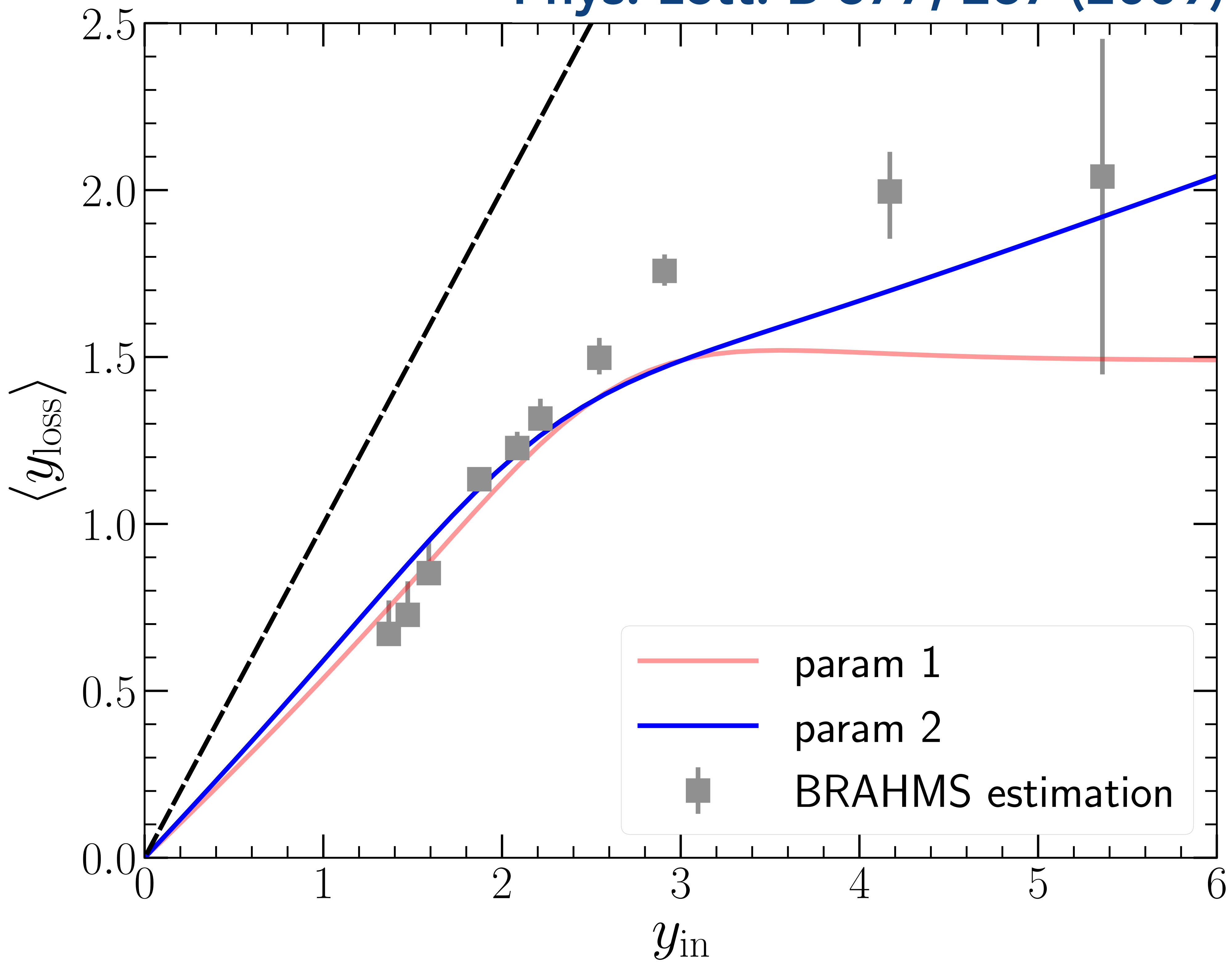


Critical signatures easier to detect at lower rapidity

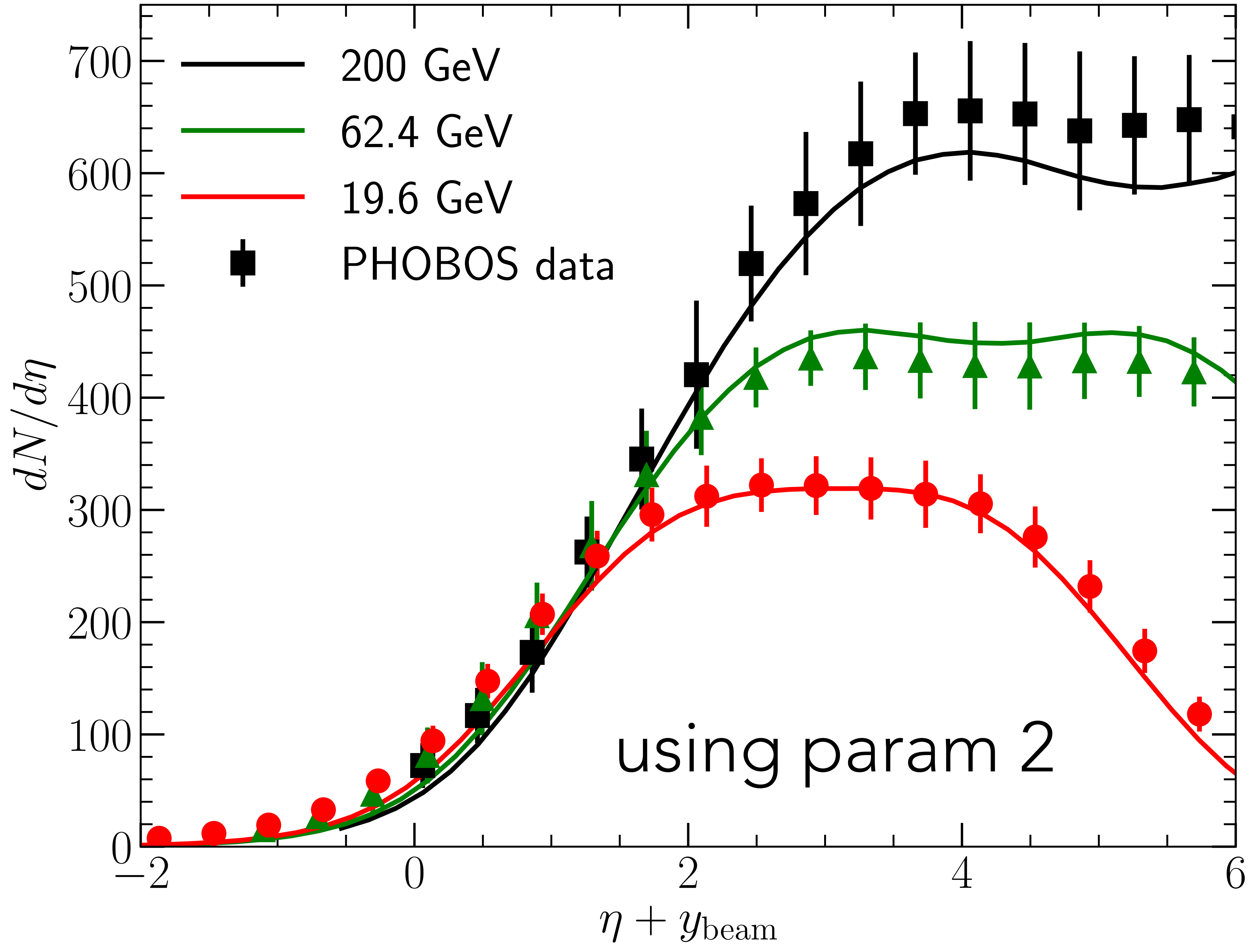
DESCRIBING RAPIDITY SPECTRA

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

Phys. Lett. B 677, 267 (2009)

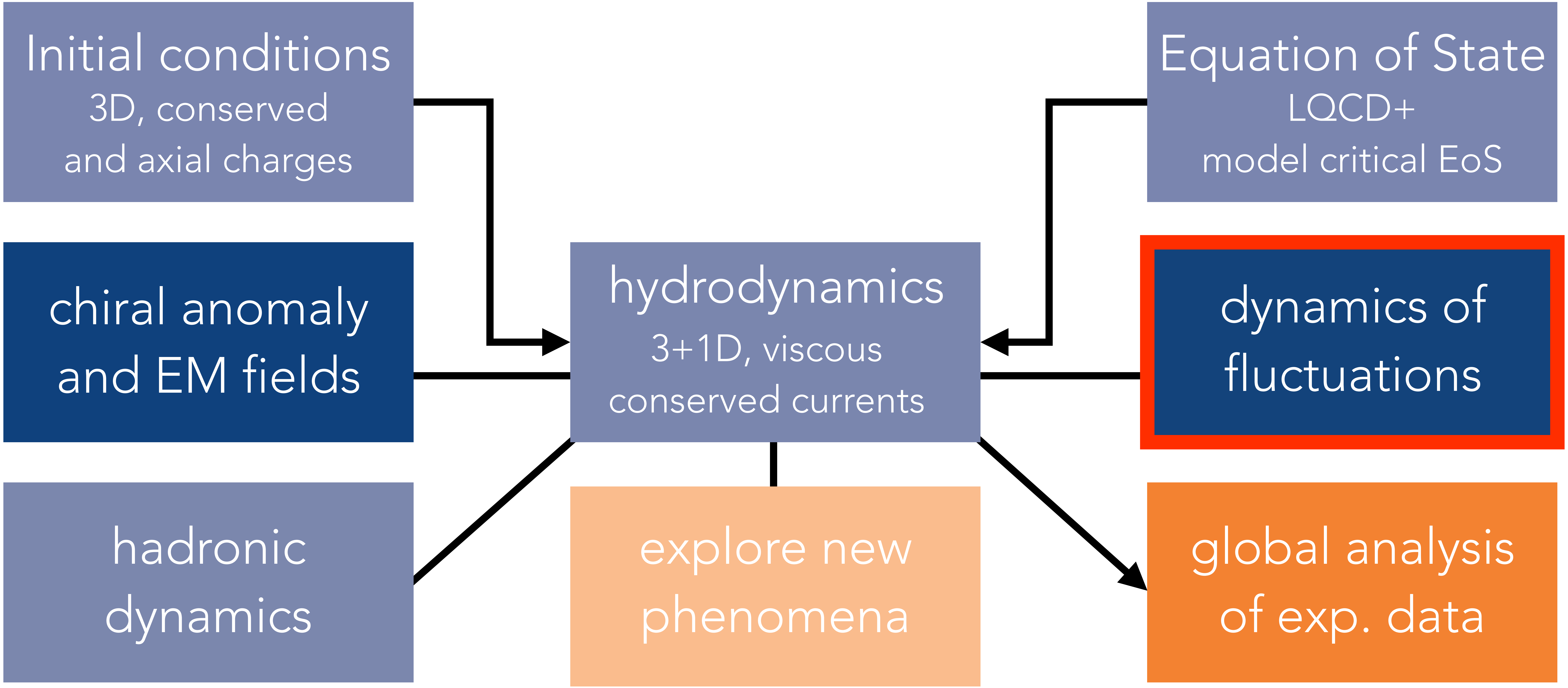


Dynamic initial state + hydro



Model baryon stopping - adjust string tension to get right amount of rapidity loss

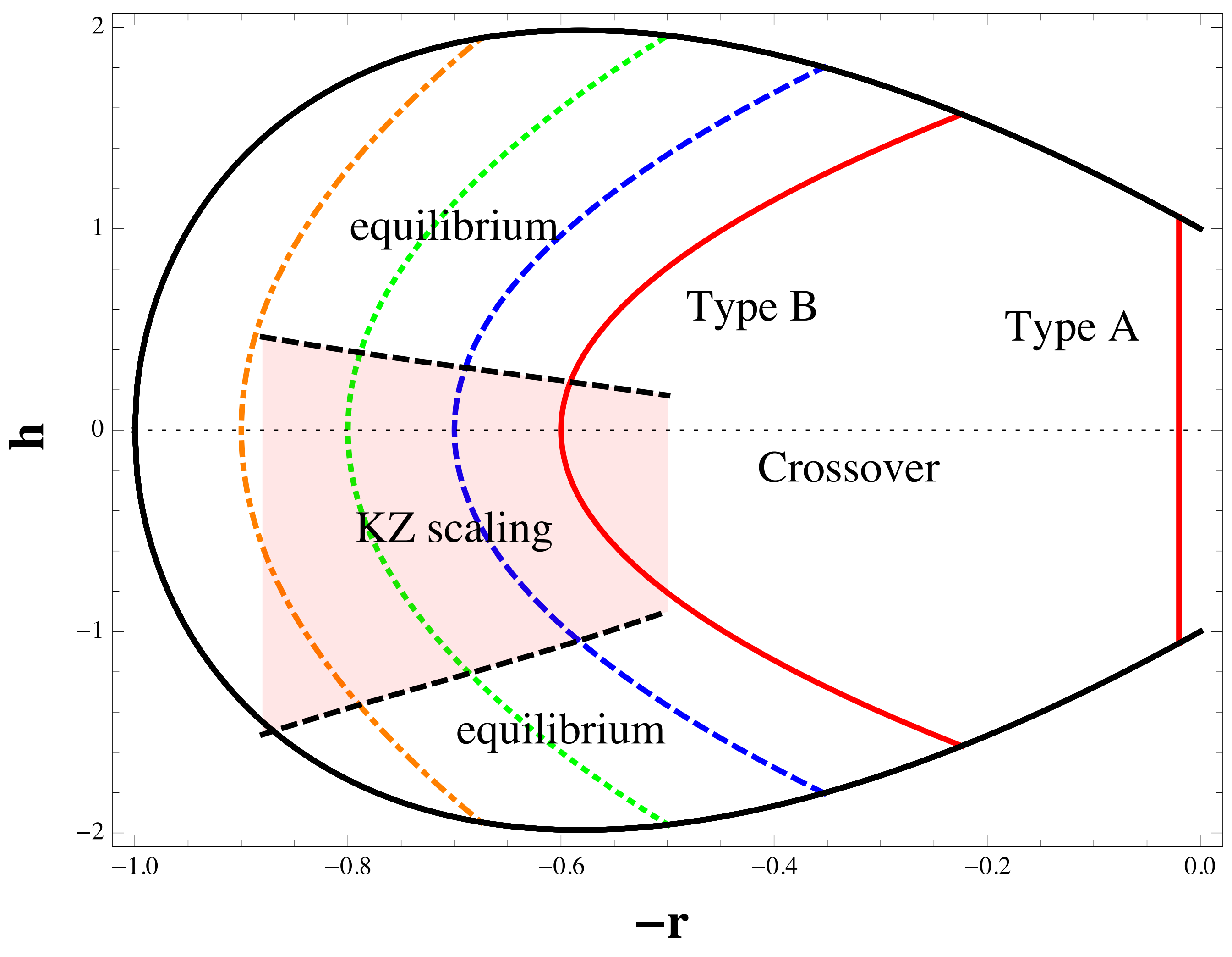
THE BEAM ENERGY SCAN THEORY

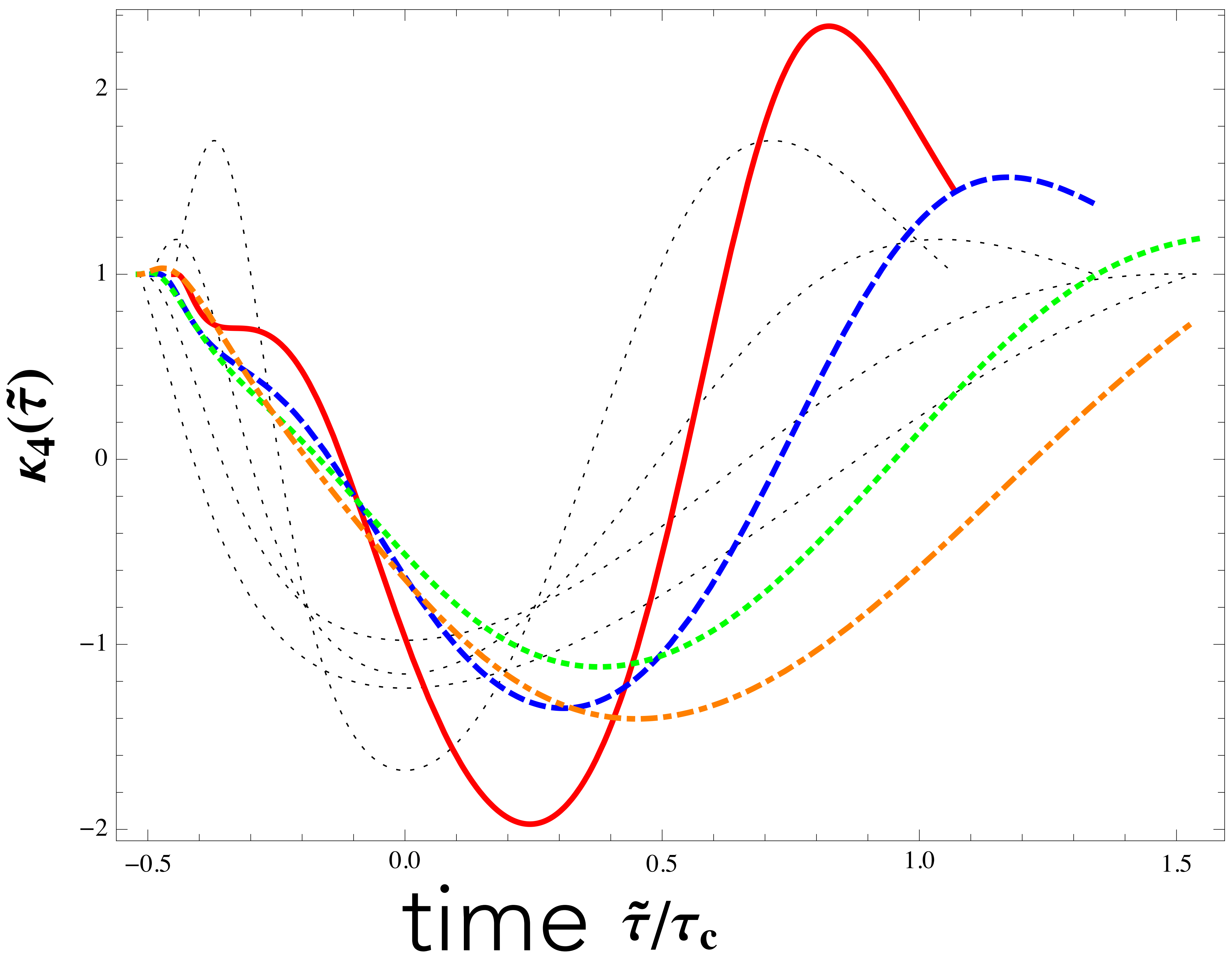


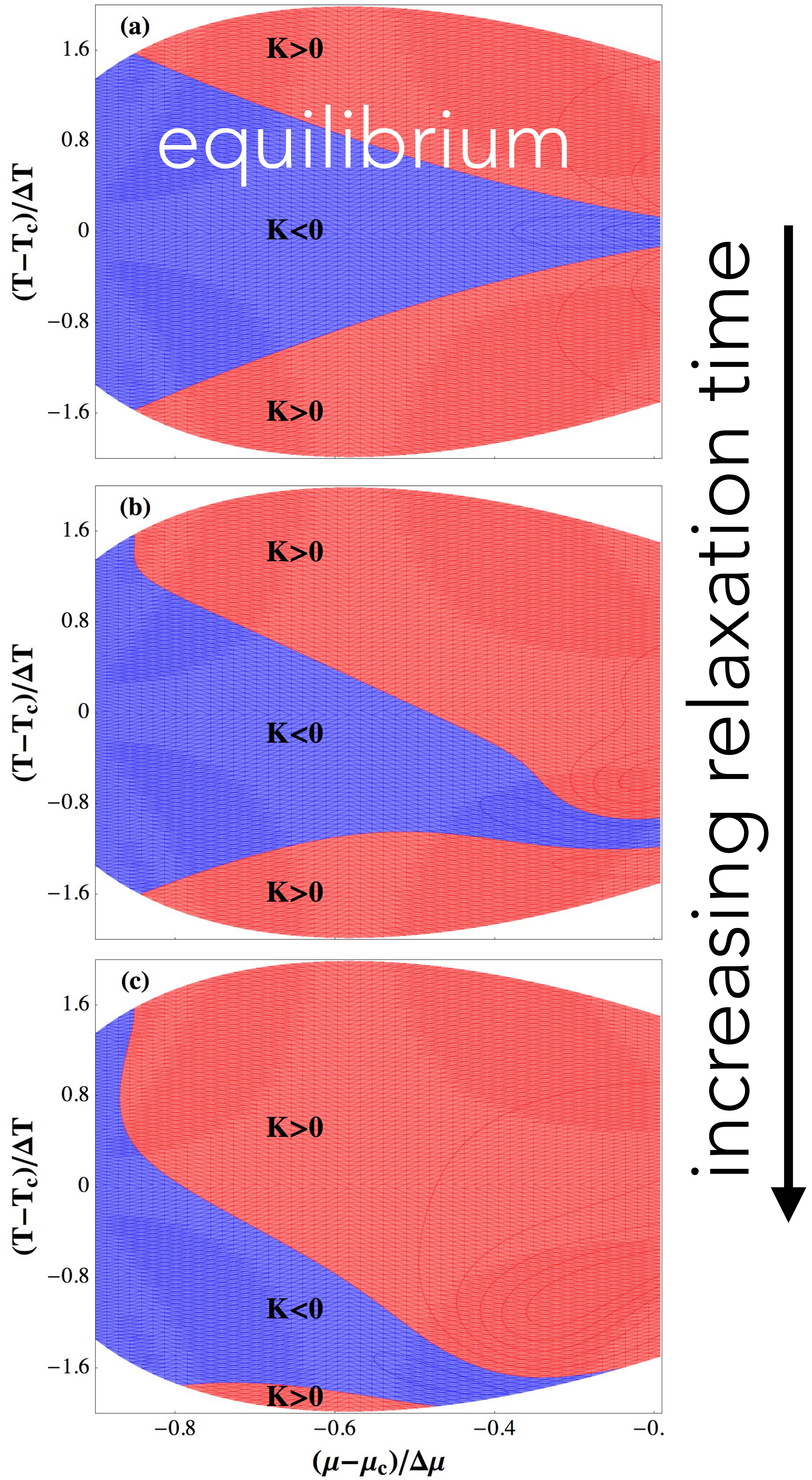
NON-EQUILIBRIUM EVOLUTION OF CRITICAL FLUCTUATIONS

Mukherjee, Venugopalan, Yin, Phys. Rev. C92, 034912 (2015)

Derive Fokker-Planck equations for the cumulants and study time evolution. Here we show kurtosis:

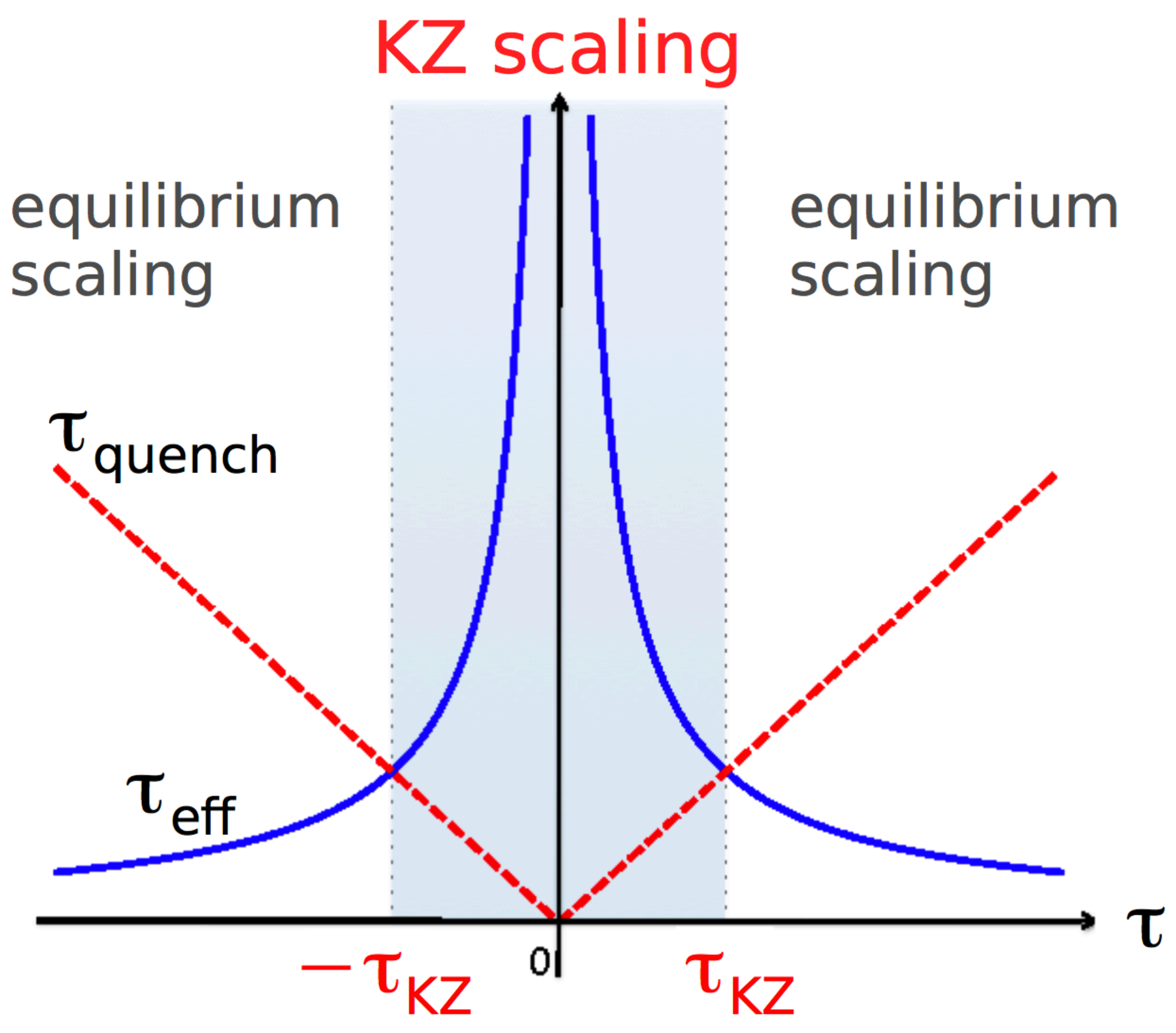






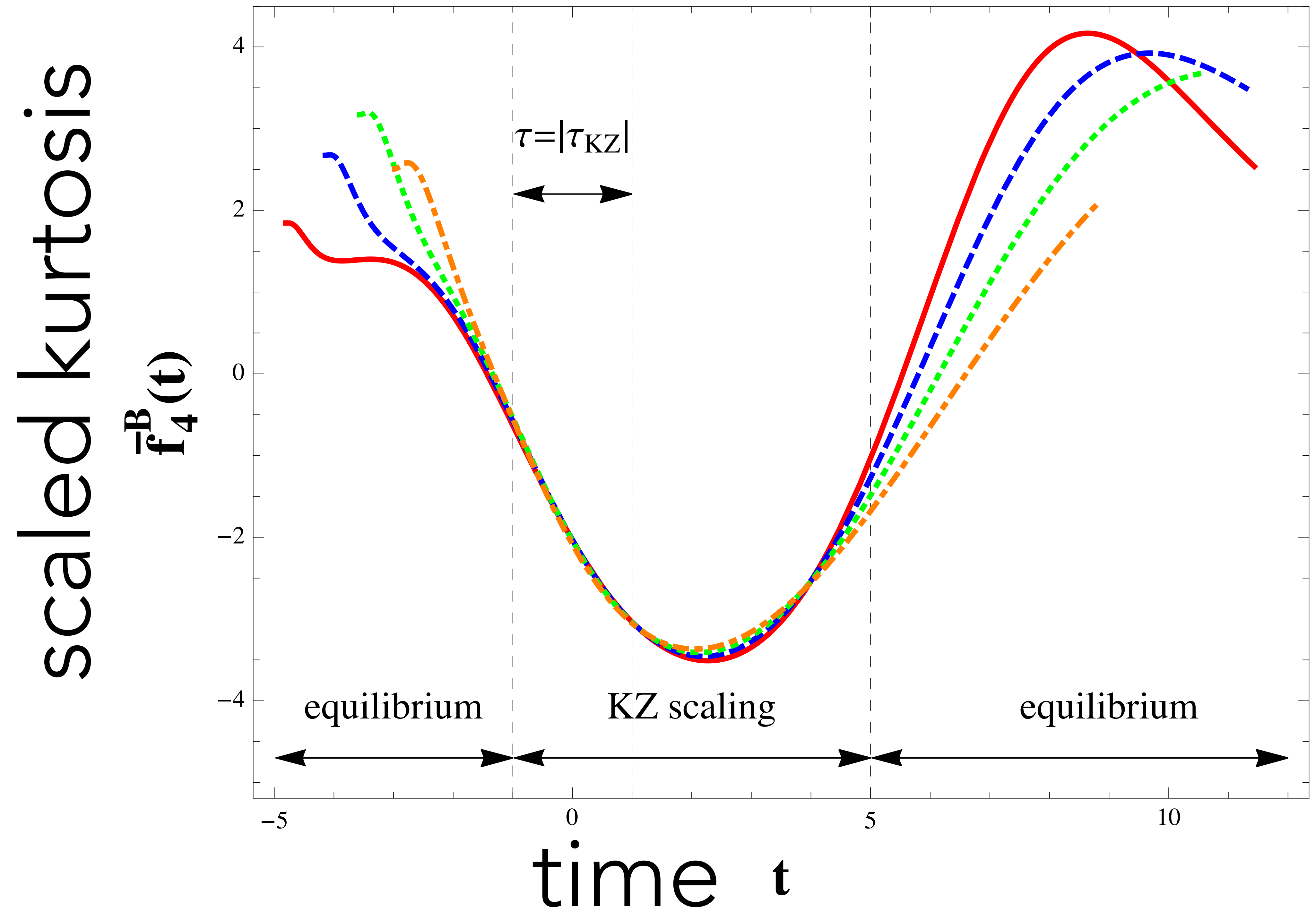
KIBBLE-ZUREK SCALING

Mukherjee, Venugopalan, Yin, Phys. Rev. Lett. 117, 222301 (2016)



Close to CP, relaxation time $\tau_{eff} \sim \xi^z$ gets larger than time in which system tries to change ξ, (τ_{quench})

Then relevant scales are $\tau_{KZ} = \tau_{eff}(\tau^*) = \tau_{quench}(\tau^*)$ and $l_{KZ} = \xi_{eq}(\tau^*)$



Cumulants show a certain scaling with ξ_{eq} in equilibrium. Using the same scaling form with the constant l_{KZ} and τ_{KZ} restores scaling in non-equilibrium

Universality is restored

$$\tilde{\tau} = \tau - \tau_c\,, \quad t = \tilde{\tau}/\tau_{KZ}$$

ANOMALOUS VISCOUS FLUID DYNAMICS

S. Shi, Y. Jiang, E. Lilleskov, J. Liao, Annals Phys. 394 (2018) 50-72

MORE TODAY 4:50PM IN TALK BY PRITHWISH TRIBEDY (DIRECTOR'S ROW I)

Framework for linearized evolution of fermion currents in the QGP, on top of neutral background described by hydrodynamic simulations

$$\hat{D}_\mu J^\mu_{f,R} = +\frac{N_c Q_f^2}{4\pi^2} E_\mu B^\mu$$

$$\hat{D}_\mu J^\mu_{f,L} = -\frac{N_c Q_f^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{N_c q}{4\pi^2} \mu_R B^\mu$$

$$J_L^\mu = n_L u^\mu + \nu_L^\mu - \frac{N_c q}{4\pi^2} \mu_L B^\mu$$

chiral magnetic effect

viscous effect

$$\Delta^\mu{}_\nu d \nu_{R,L}{}^\nu = -\frac{1}{\tau_{rlx}} (\nu_{R,L}{}^\mu - \nu_{NS}{}^\mu)$$

$$\nu_{NS}{}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q E^\mu$$

also see:

Chiral transport equations from Wigner function formalism

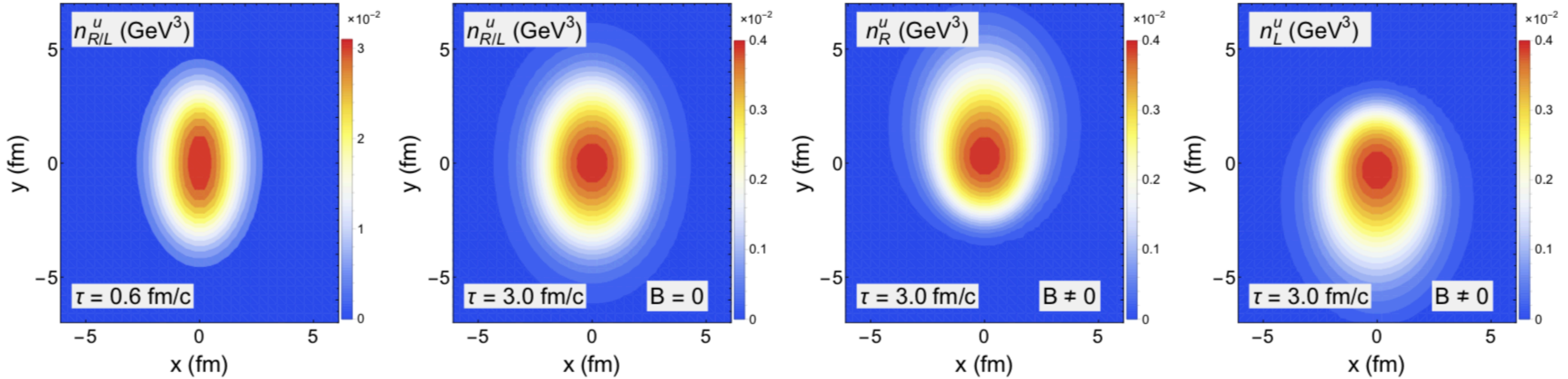
A. Huang, S. Shi, Y. Jiang, J. Liao, P. Zhuang, arXiv:1801.03640

ANOMALOUS VISCOUS FLUID DYNAMICS

S. Shi, Y. Jiang, E. Lilleskov, J. Liao, Annals Phys. 394 (2018) 50-72

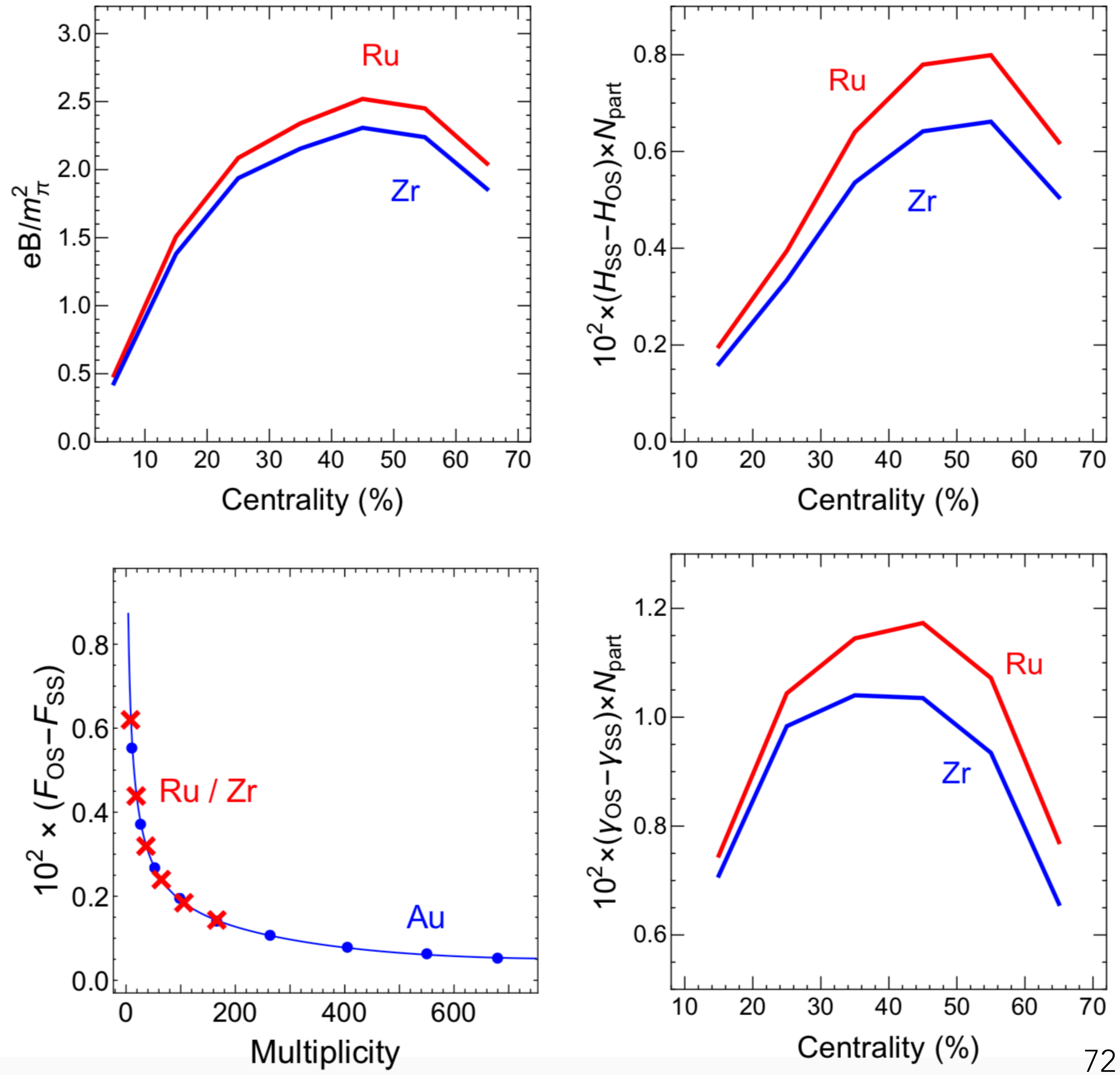
u-flavor densities:

initial | B_y=0 | B_y>0 right-handed | B_y>0 left-handed



PREDICTIONS FOR THE ISOBAR RUN

S. Shi, Y. Jiang, E. Lilleskov, J. Liao, Annals Phys. 394 (2018) 50-72



$$\gamma_{\alpha\beta} \equiv \langle \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle_{\alpha\beta}$$

α, β = +,-   SS=++,-- OS=+-

H is pure CME contribution to γ correlator

F is pure background, here estimated from Au+Au data

~15% difference between the two systems

PREDICTIONS FOR THE ISOBAR RUN

B. Schenke, C. Shen, P. Tribedy, arXiv:1901.04378, in press in PRC

Realistic pure background estimate:
< 10% difference between Ru and Zr

$$\gamma_{\alpha\beta} \equiv \langle \cos(\phi_i + \phi_j - 2\Psi_{RP}) \rangle_{\alpha\beta}$$

α, β = +,-   SS=++,-- OS=+-