



Beam Energy Scan Theory: some recent progress

Swagato Mukherjee

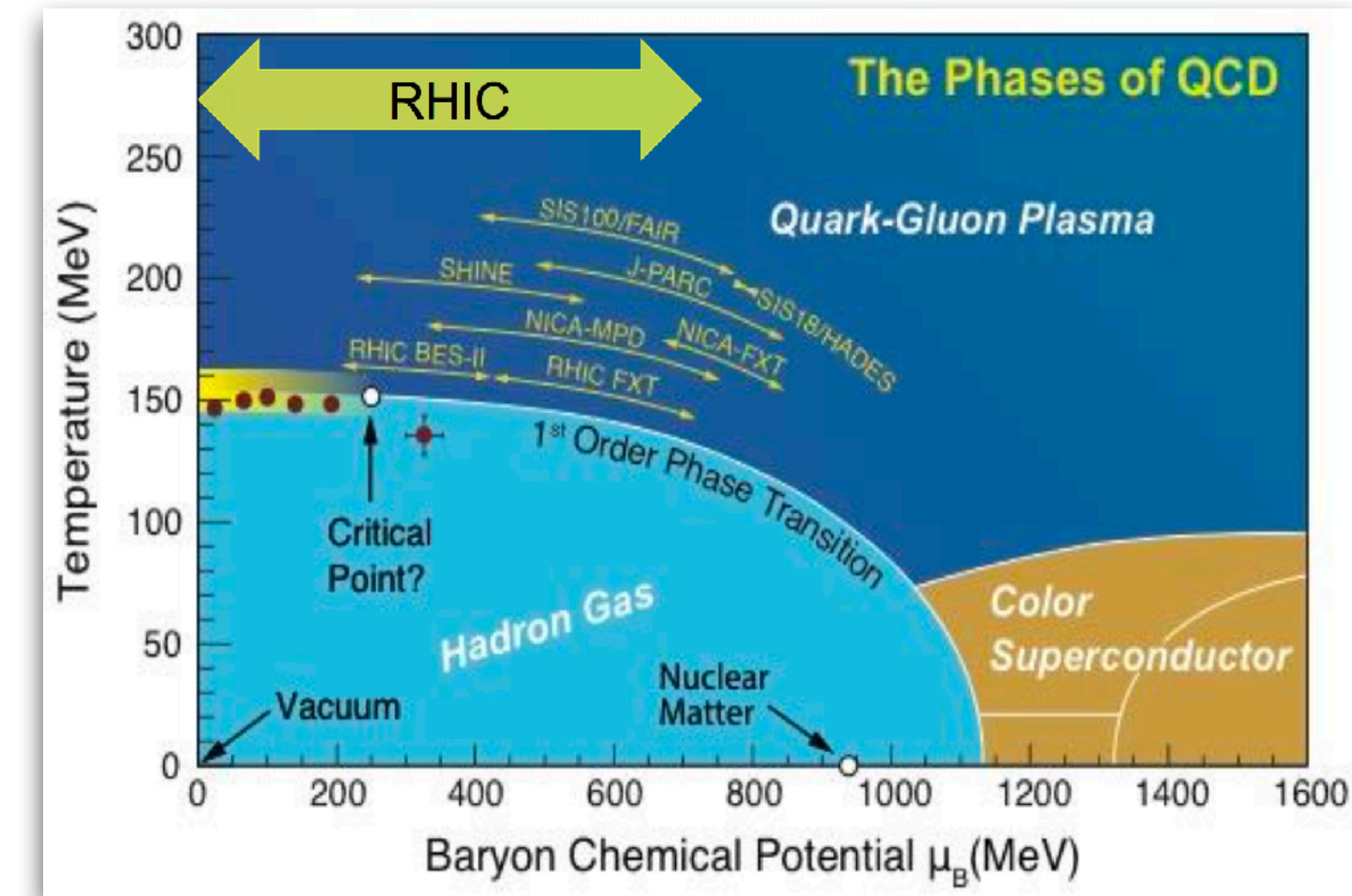


July 2017, Strange Quark Matter, Utrecht

Beam Energy Scan (BES) II @ RHIC

starting 2019

- QCD critical point & phase diagram
- properties of baryon-rich QGP
- onset of chiral symmetry restoration
- unexpected new phenomena



Beam Energy Scan Theory (BEST) Collaboration

Topical Collaboration in Nuclear Theory

develop a comprehensive theory framework for RHIC BES



funded by: U.S. Department of Energy, Office of Science, Office of Nuclear Physics

BEST COLLABORATION

initial conditions
3-d, conserved &
axial charges

EoS: LQCD
model critical EOS

chiral anomaly
& EM fields

hydrodynamic
evolution
(3+1)-d, viscous,
conserved currents

fluctuations
critical mode &
hydrodynamic

hadronic
dynamics

explore new
phenomena

global analysis
of expt data

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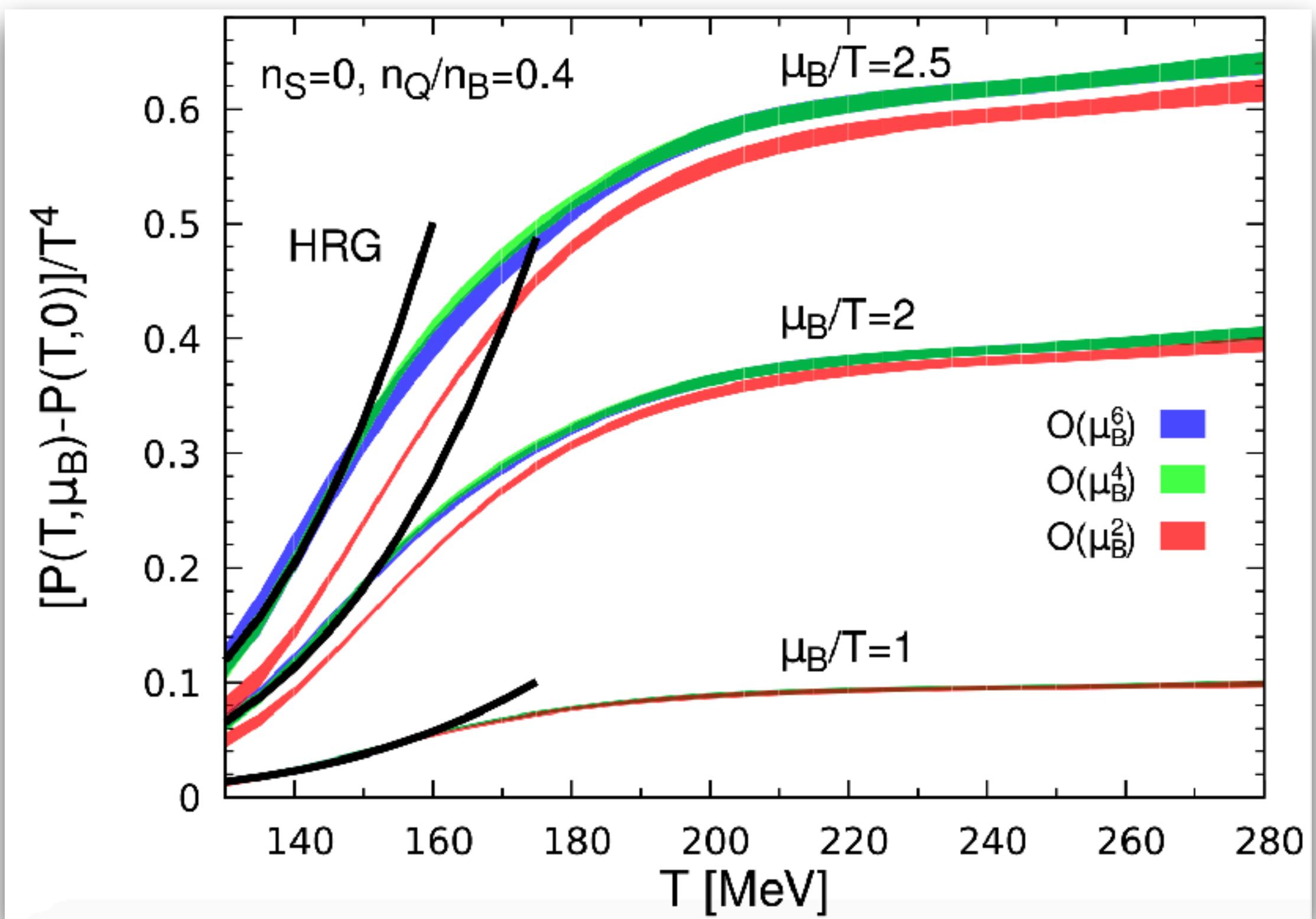
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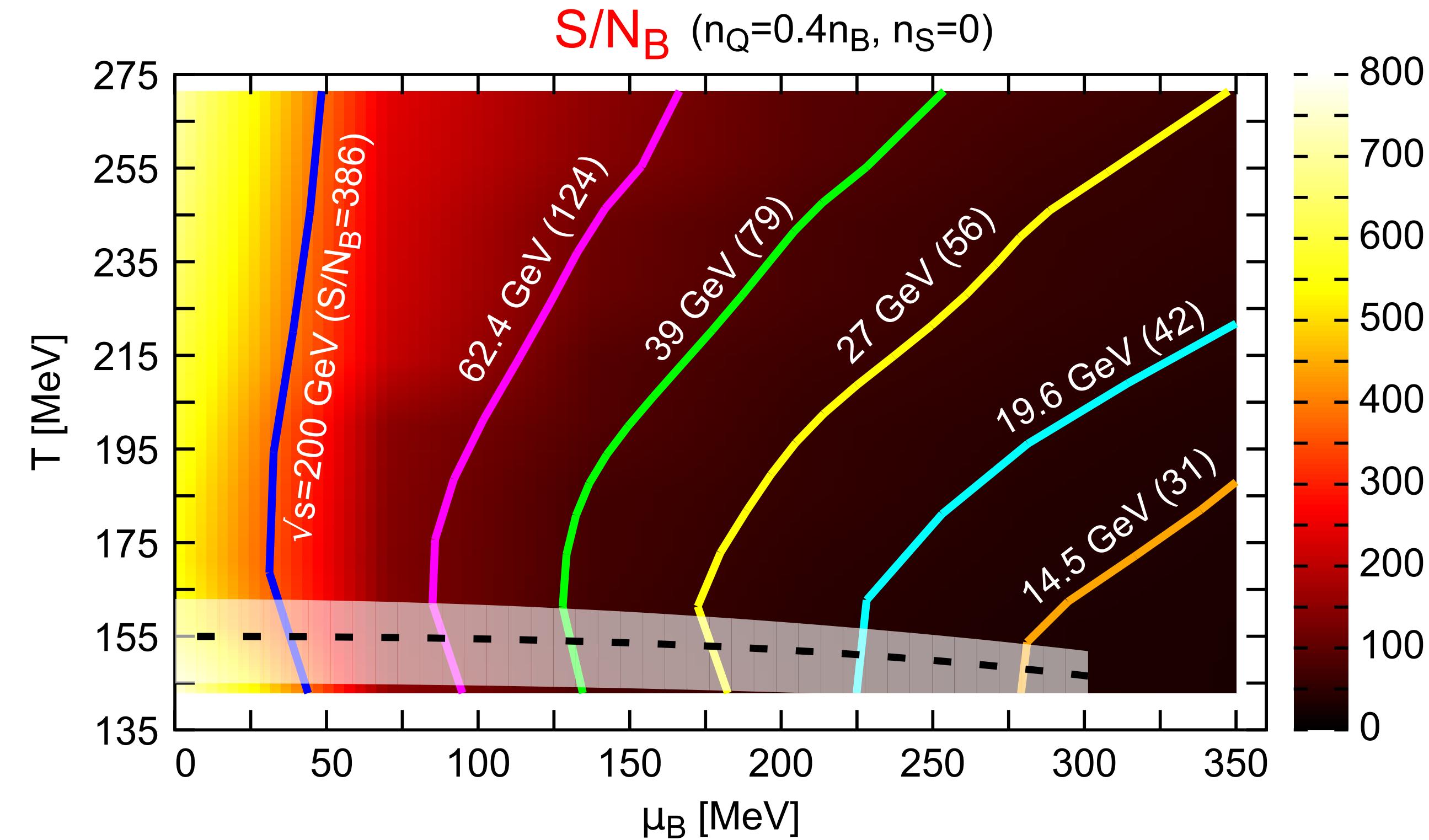
Taylor expansion up to $\mathcal{O}(\mu_B^6)$

$$\frac{P(T, \mu_B)}{T^4} = \sum_{n=0,2,4,6} \frac{1}{n!} \chi_n^B(T) \left(\frac{\mu_B}{T} \right)^n$$



LQCD EoS, present reach:

$$\mu_B/T \lesssim 2, \sqrt{s} \gtrsim 14.5 \text{ GeV}$$

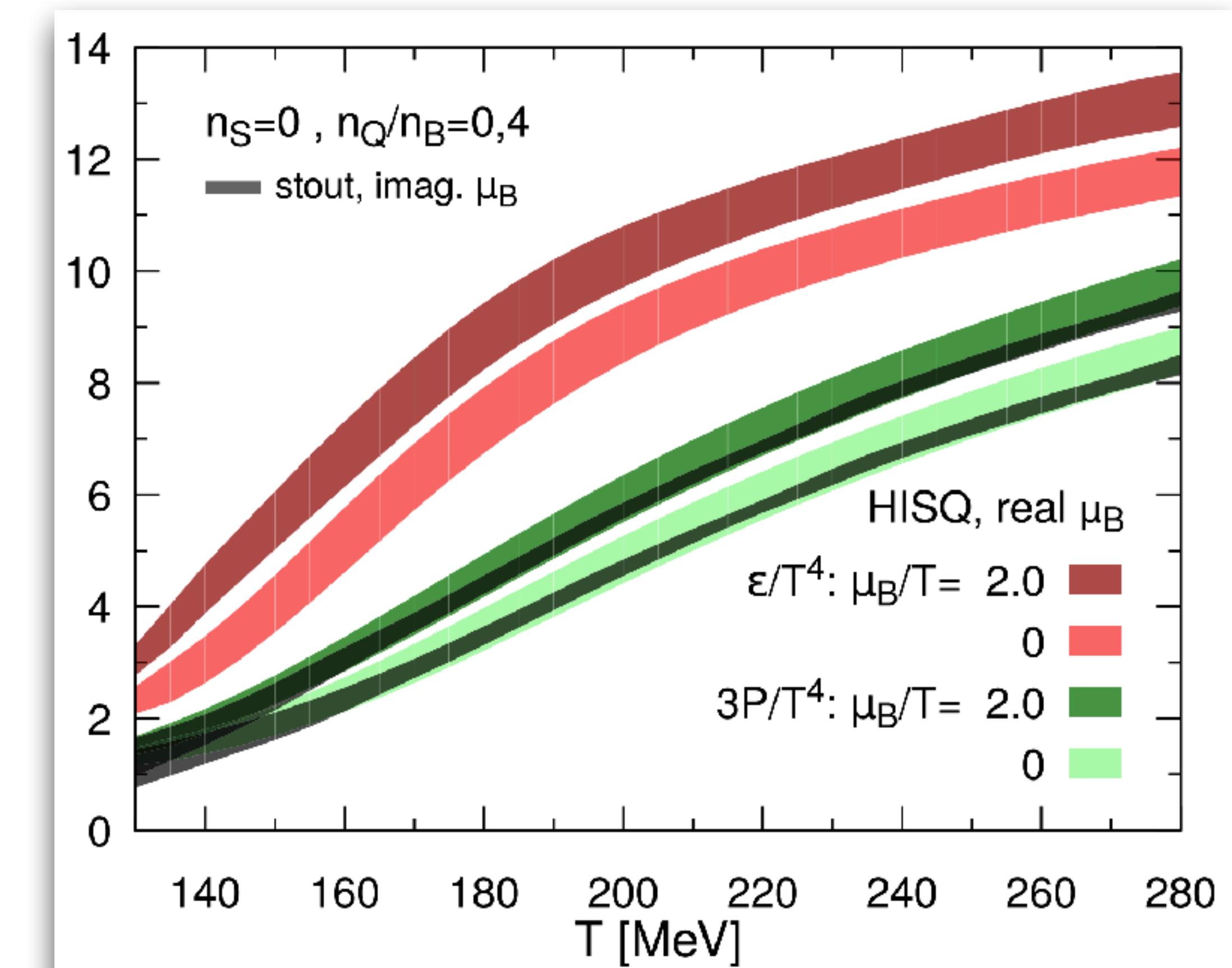
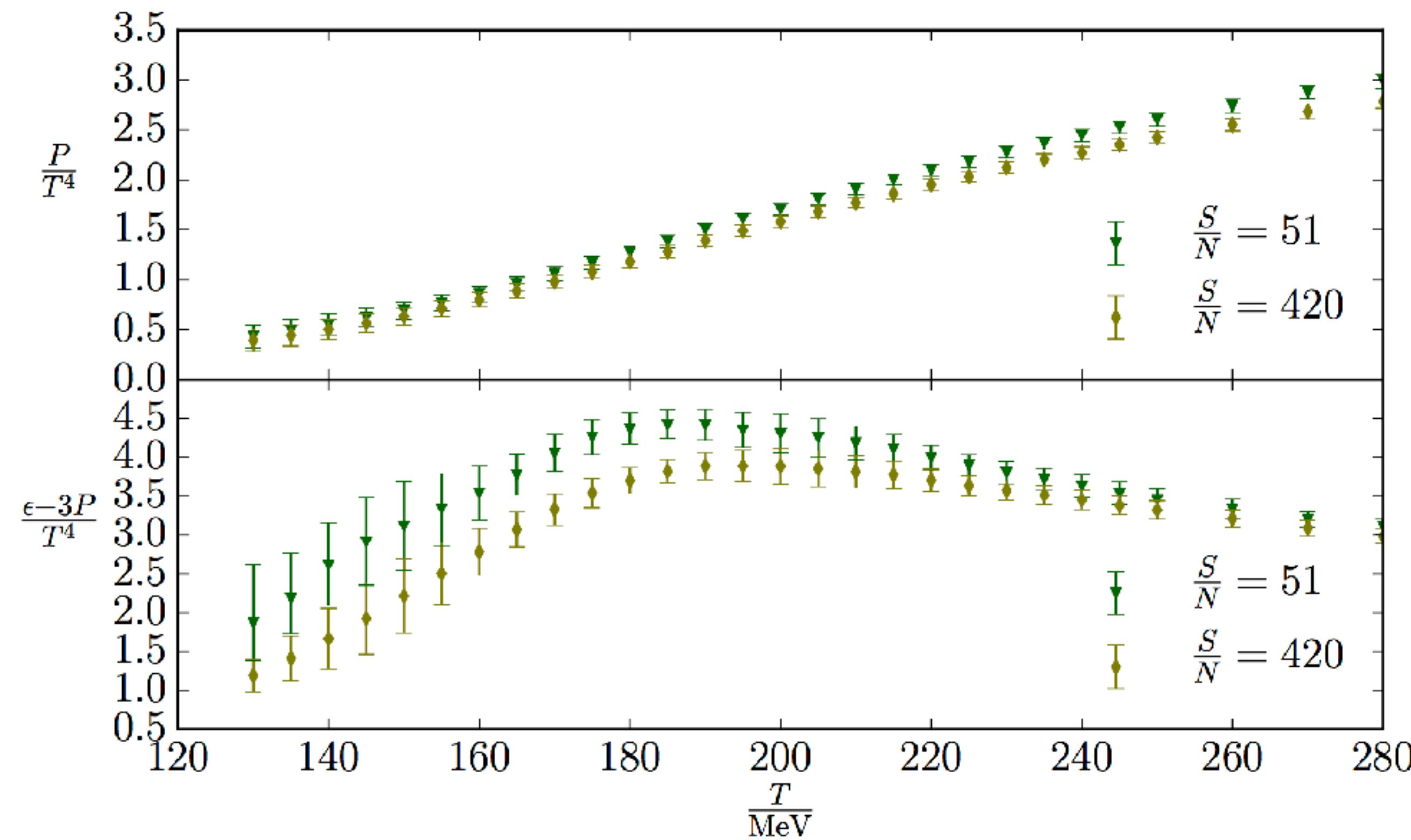


lines of const. entropy to bet-baryon number
— approx. evolution trajectories of inviscid QGP

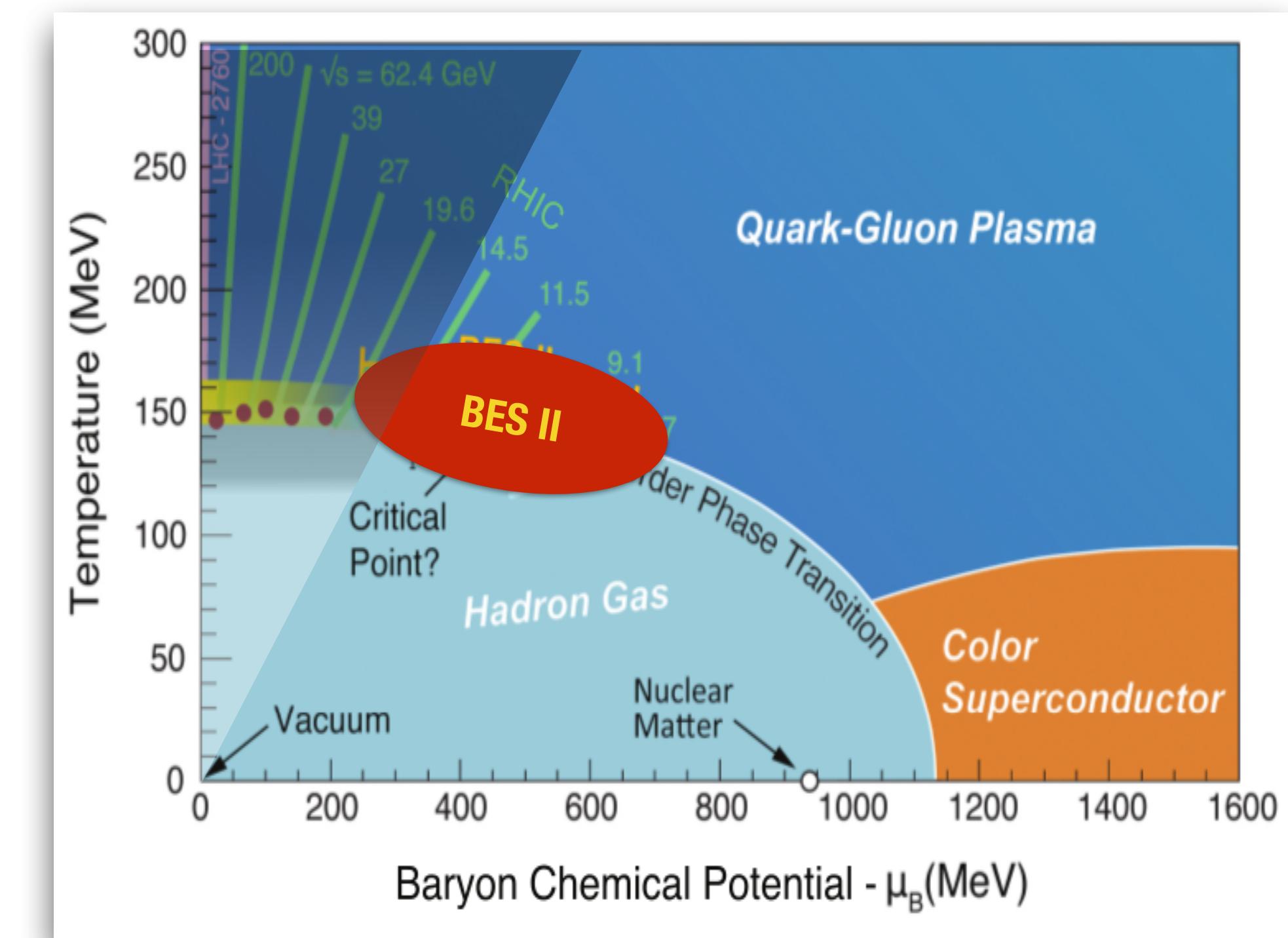
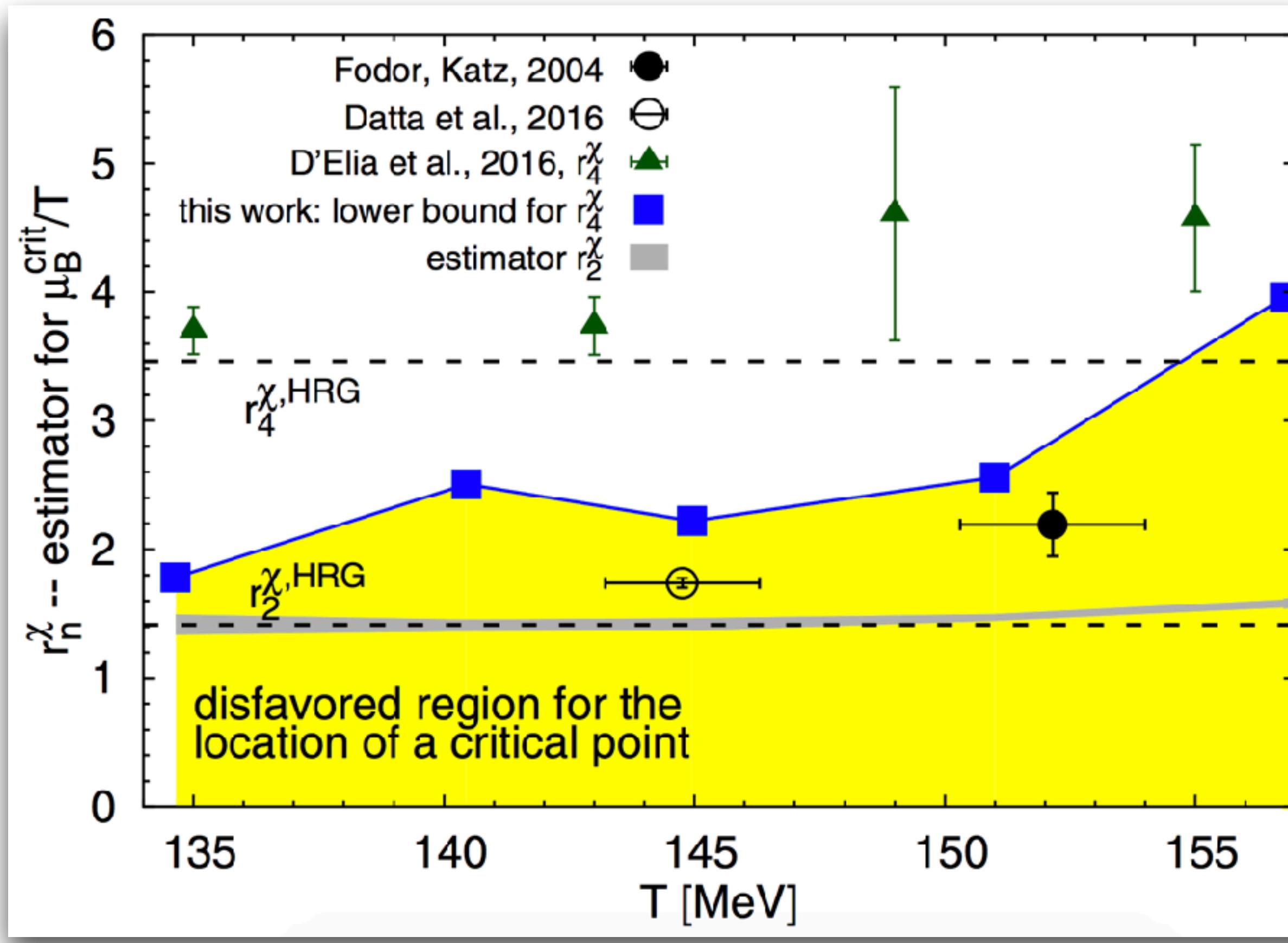
analytic continuations from imaginary chemical potentials

Wuppertal-Budapest-Houston: EPJ Web Conf. 137, 07008 (2017)

consistent results: 2 independent
calculations, 2 methods

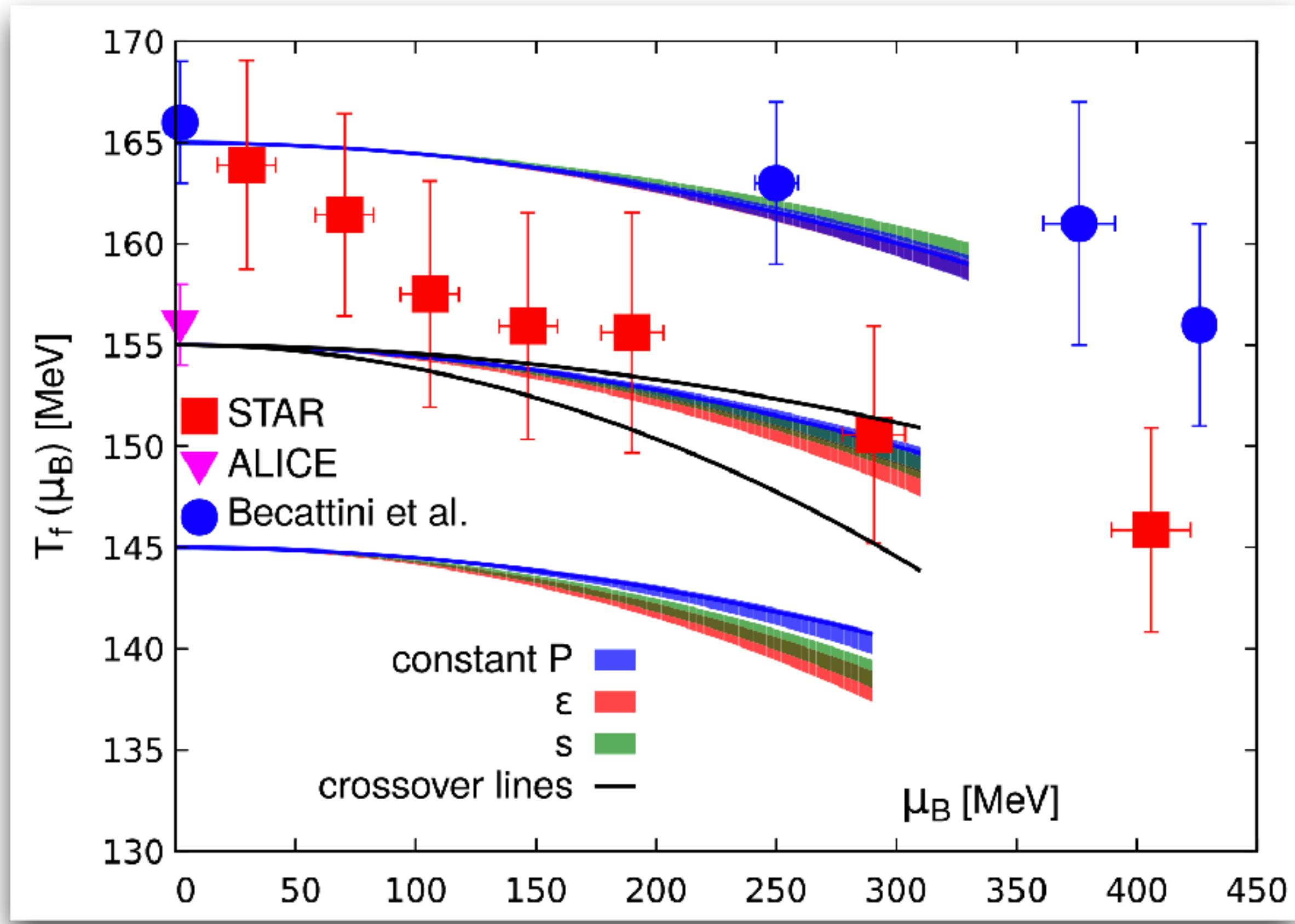


location of critical point: $\mu_B/T \lesssim 2$ presently disfavored

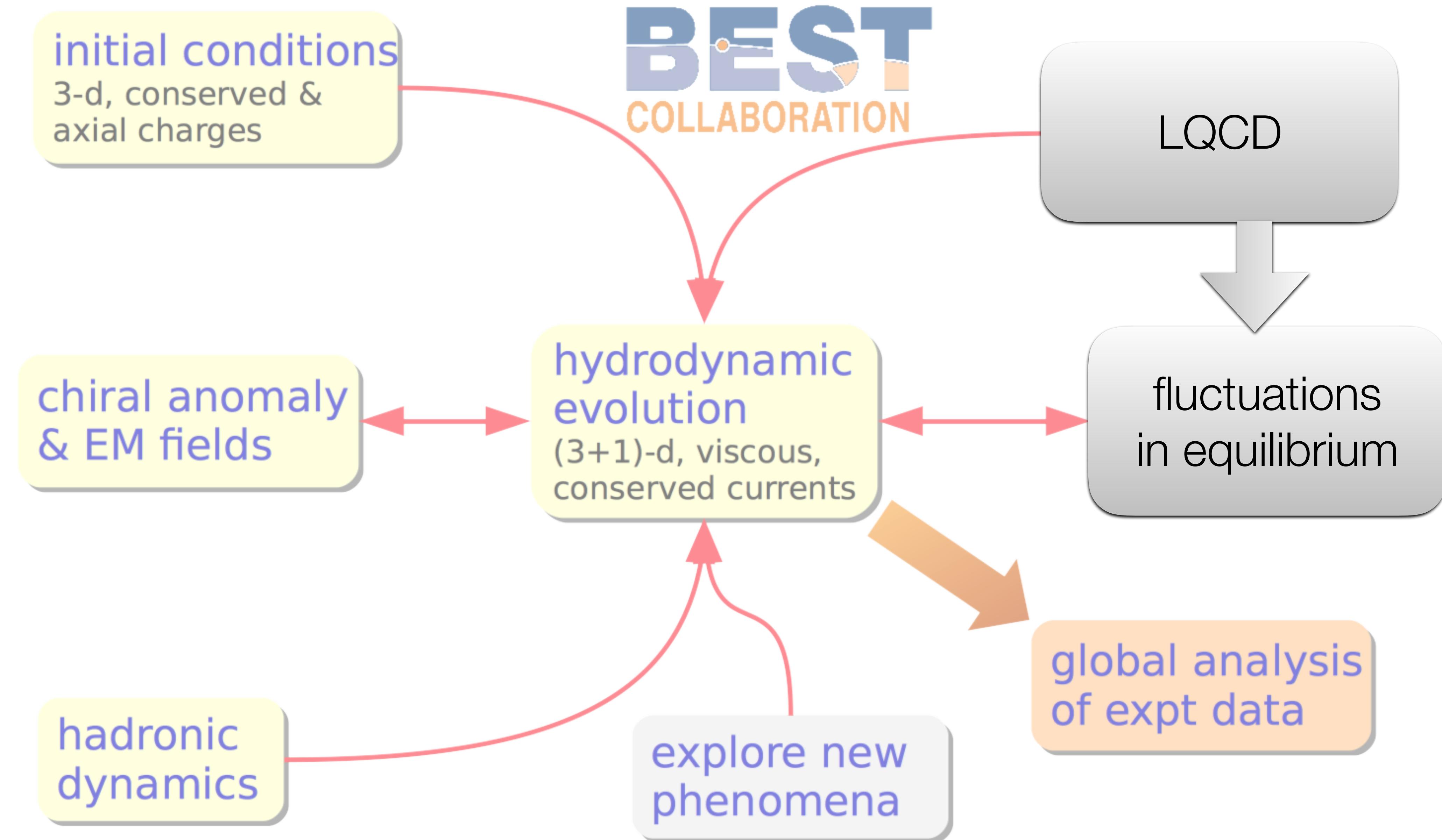


analyzing radius of convergence of Taylor expansion:

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



QCD transition in $T - \mu_B$ happens @ constant physics ?



static universality:

$$n^{\text{th}} \text{ cumulant} \sim \xi_{eq}^{\frac{1}{2} + \frac{5}{2}(n-1)}$$

specific signs

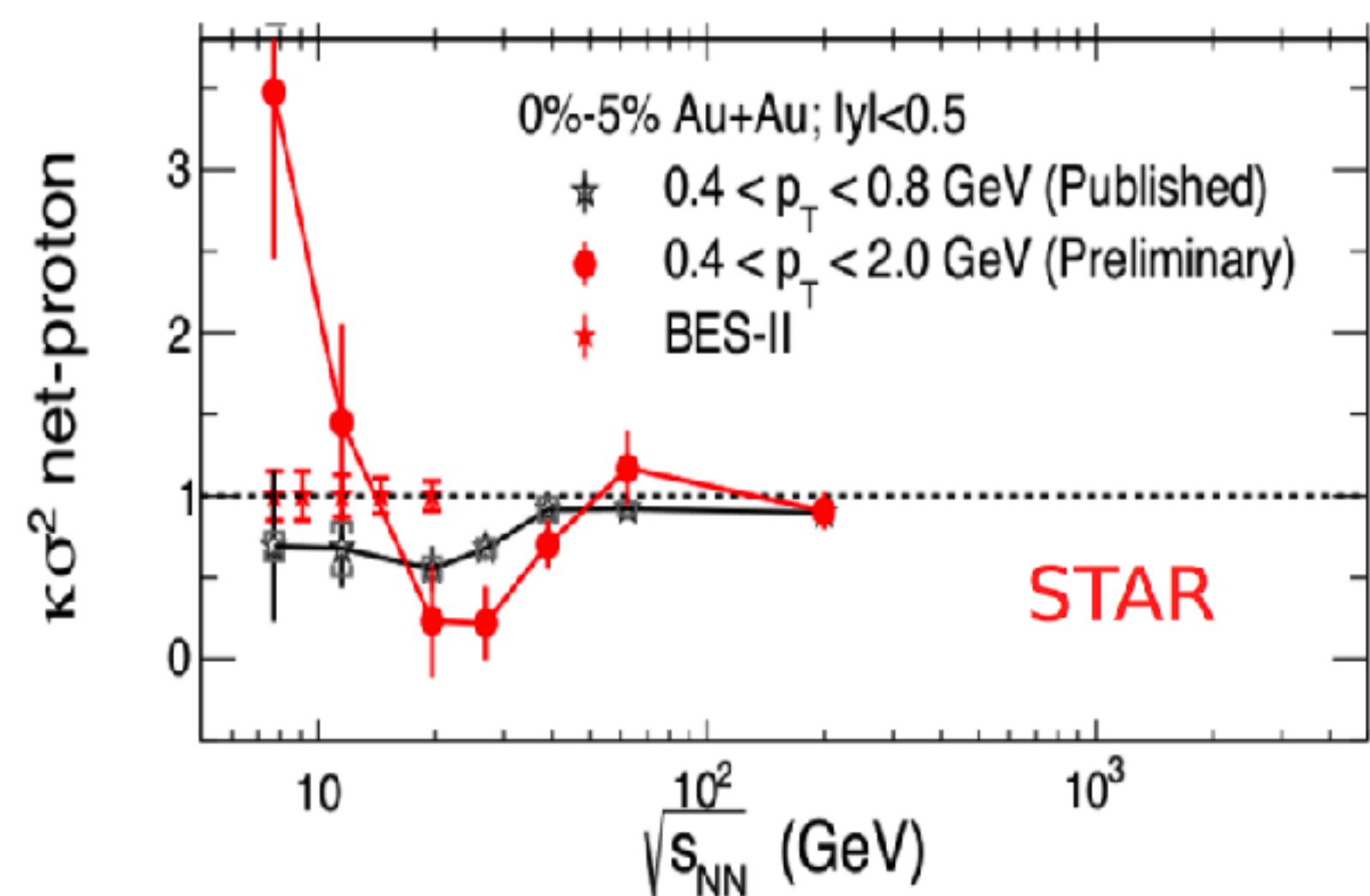
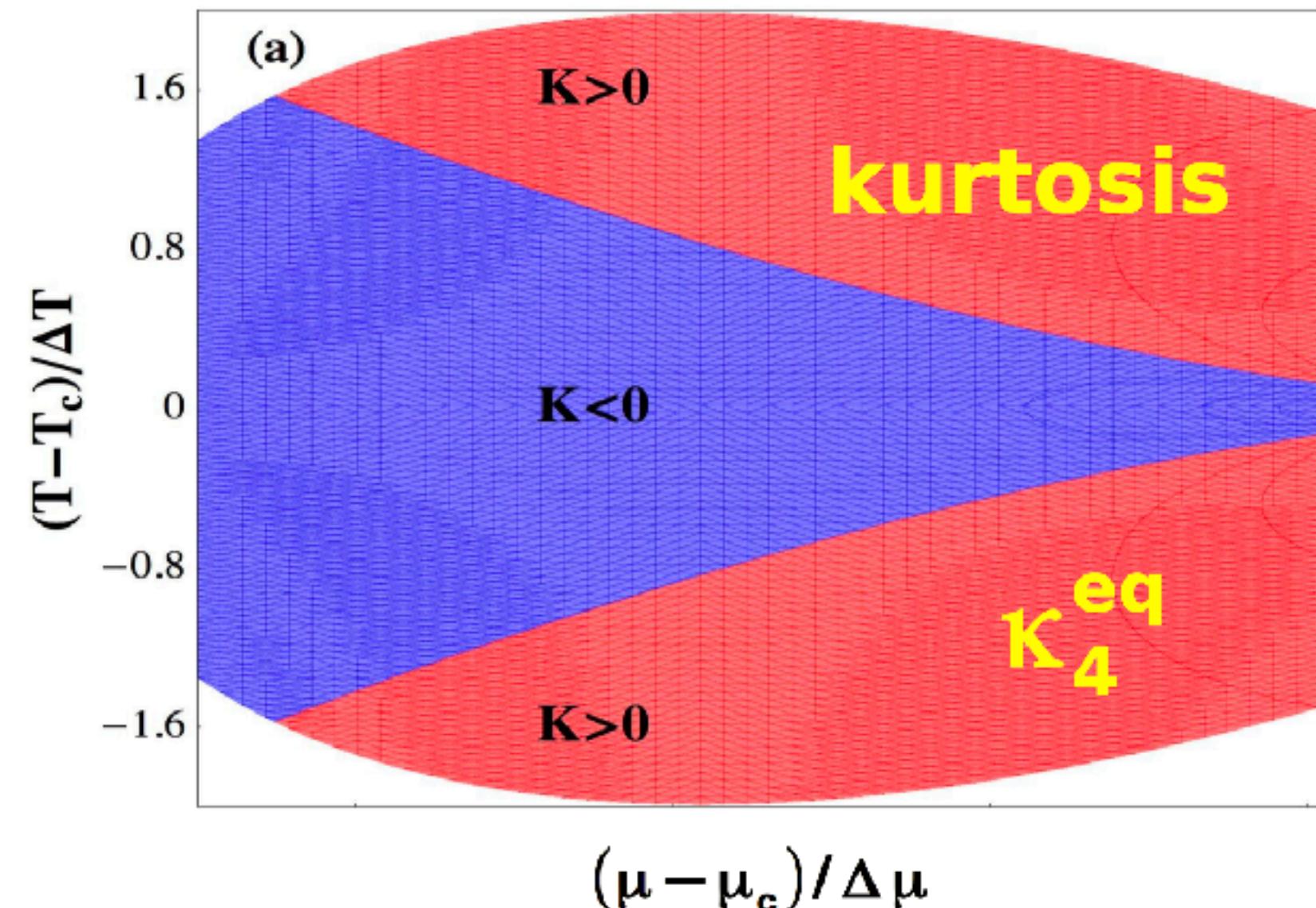
- QCD critical point \longleftrightarrow 3-d Ising
- coupling of critical mode to baryon & proton

Stephanov: Phys. Rev. Lett. 107, 052301 (2011)

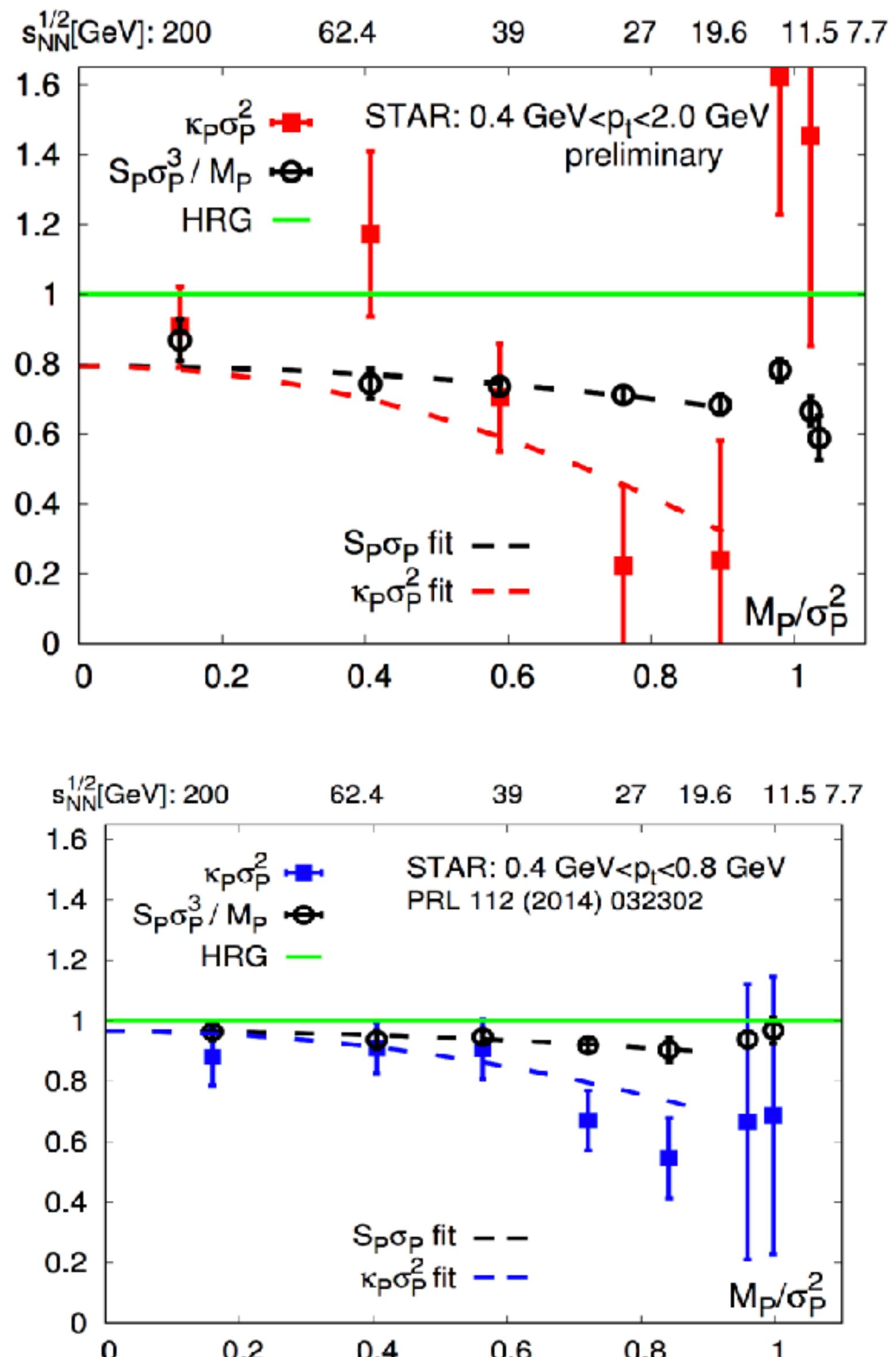
Stephanov: Phys. Rev. Lett. 102, 032301 (2009)

Son, Stephanov: Phys. Rev. D70 (2004) 056001 (2004)

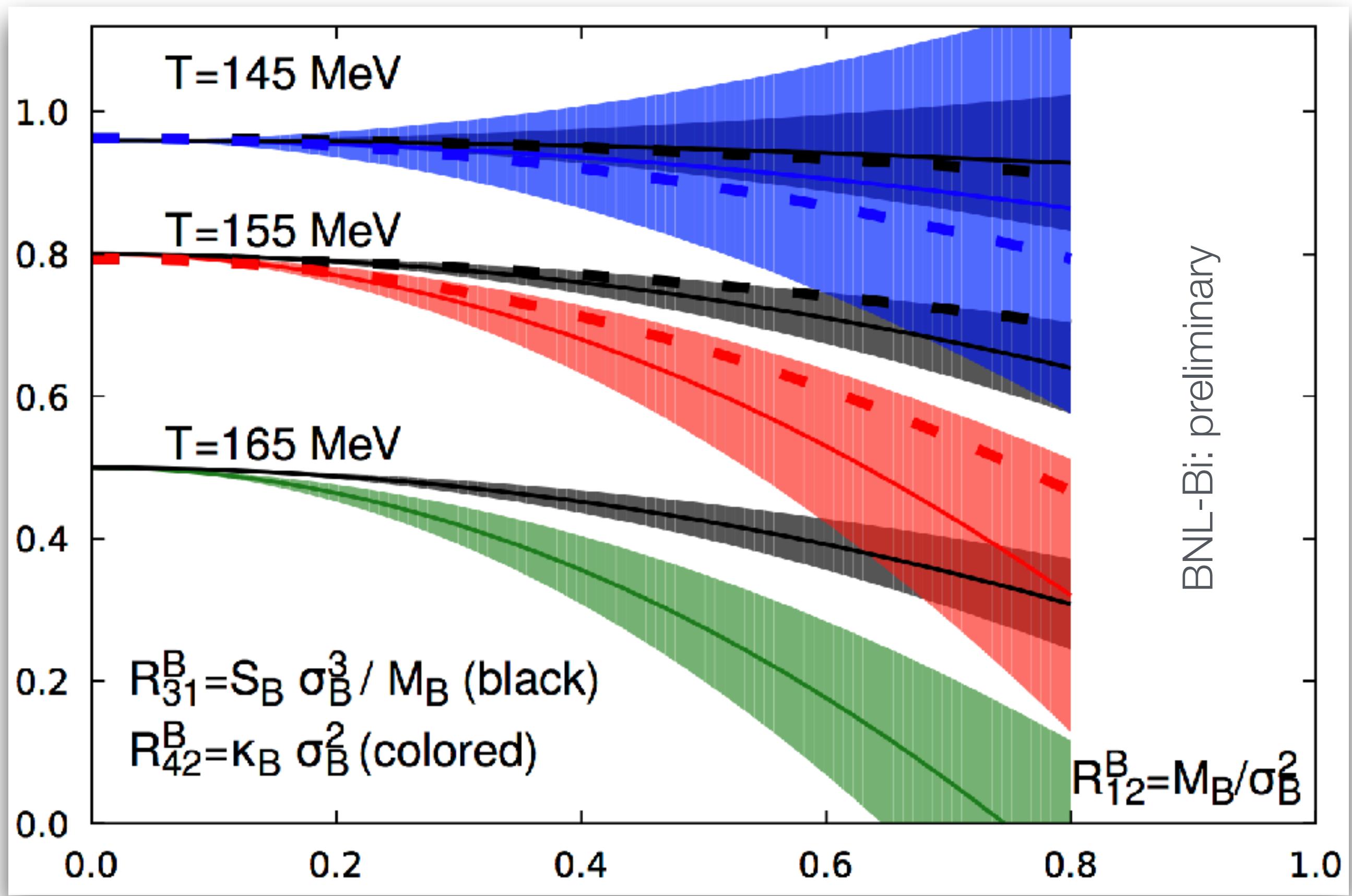
Hatta, Stephanov: Phys. Rev. Lett. 91, 102003 (2003)



STAR: cumulants of net-p fluctuations



LQCD: cumulants of net-baryon fluctuations



$\sqrt{s} \gtrsim 27 \text{ GeV}$: cumulants of net-p fluctuations are consistent with equilibrium QCD

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dynamics of
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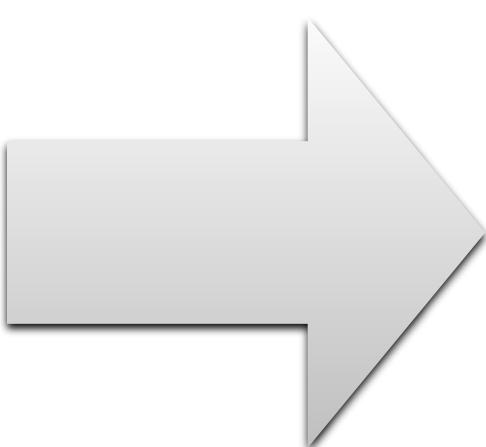
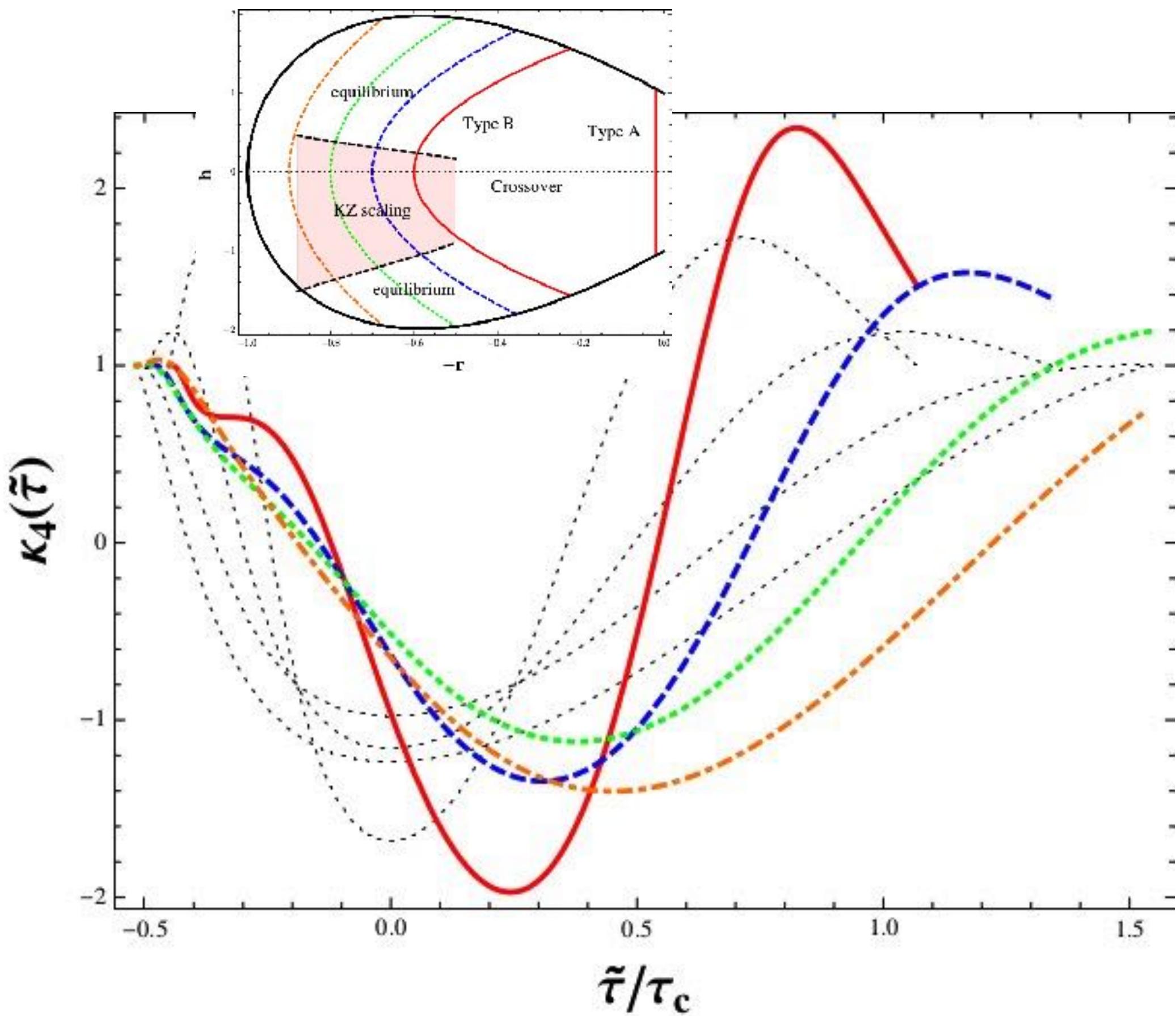
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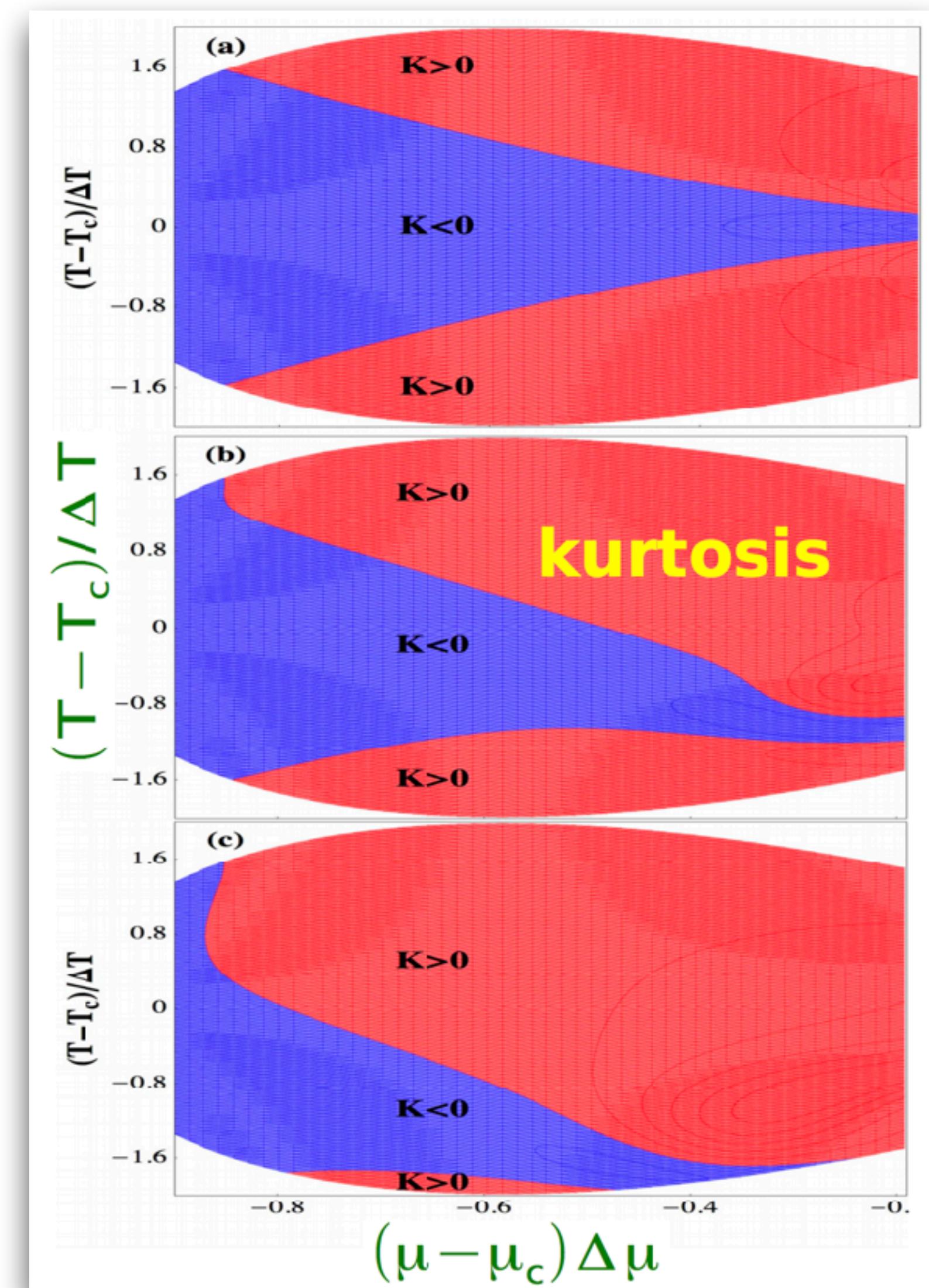
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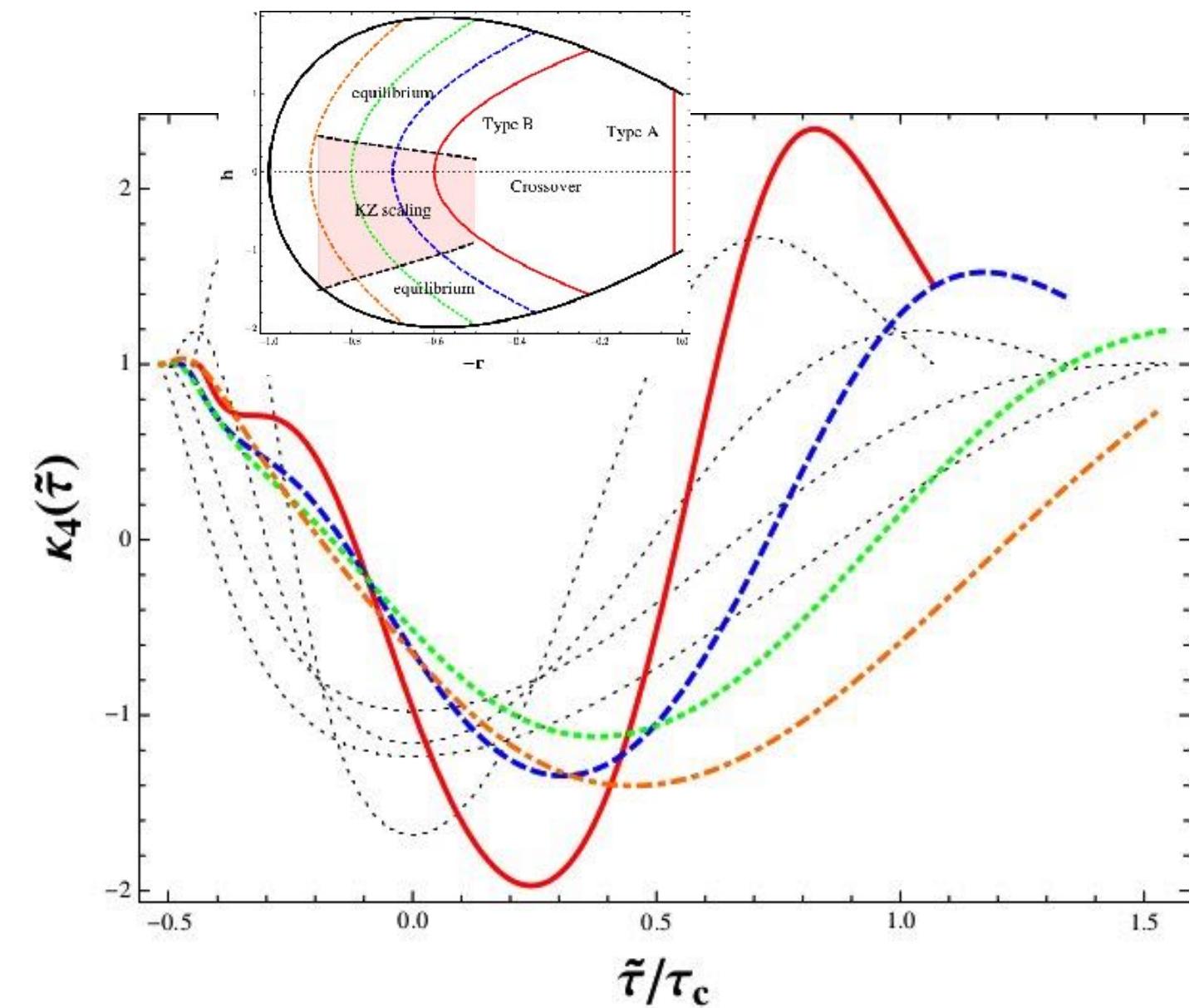
time evolution of non-Gaussian fluctuations
 – based on generalized Fokker-Planck evolution

Mukherjee, Venugopalan, Yin: Phys. Rev. C92, no.3, 034912 (2015)

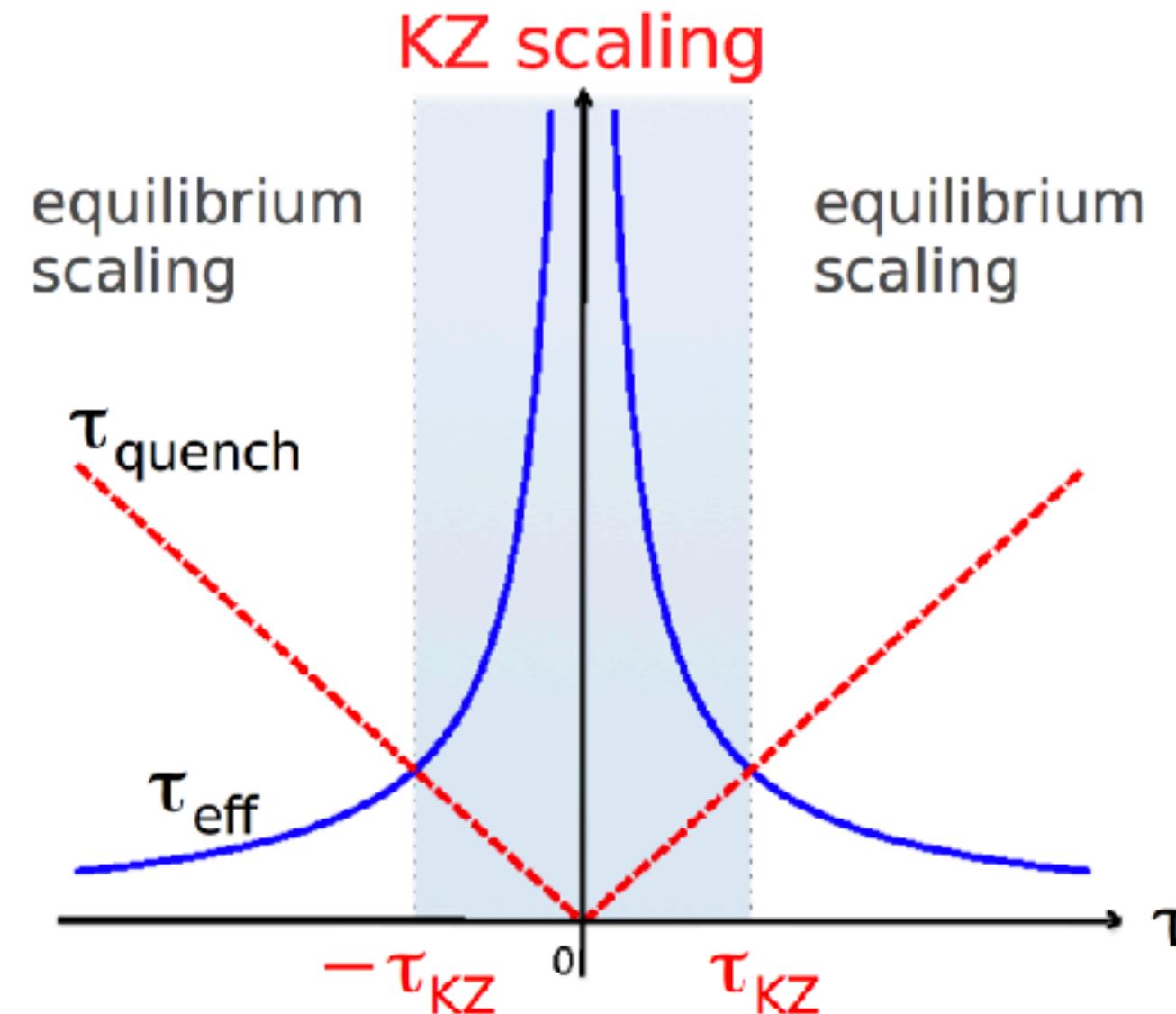


signs can be different from equilibrium
 – universality lost





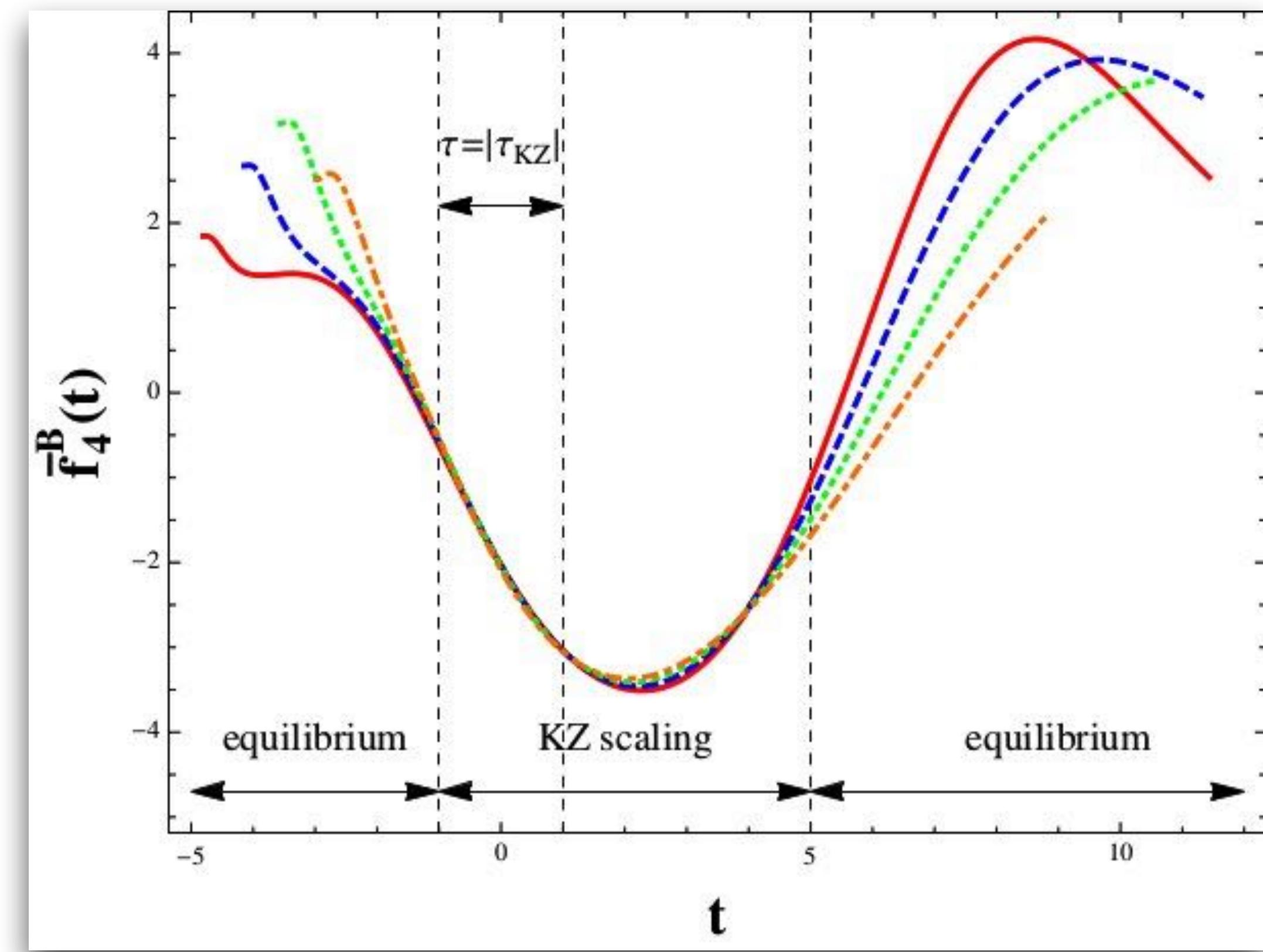
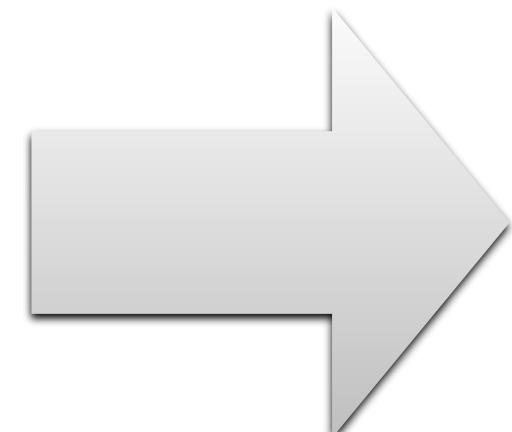
emergent time scale: $\tau_{KZ} = \tau_{eff}(\tau^*) = \tau_{quench}(\tau^*)$



Mukherjee, Venugopalan, Yin: Phys. Rev. Lett. 117, no.22, 222301 (2016)
(editor's suggestion)

novel off-equilibrium Kibble-Zurek scaling

- universality regained



insensitive to the initial conditions

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

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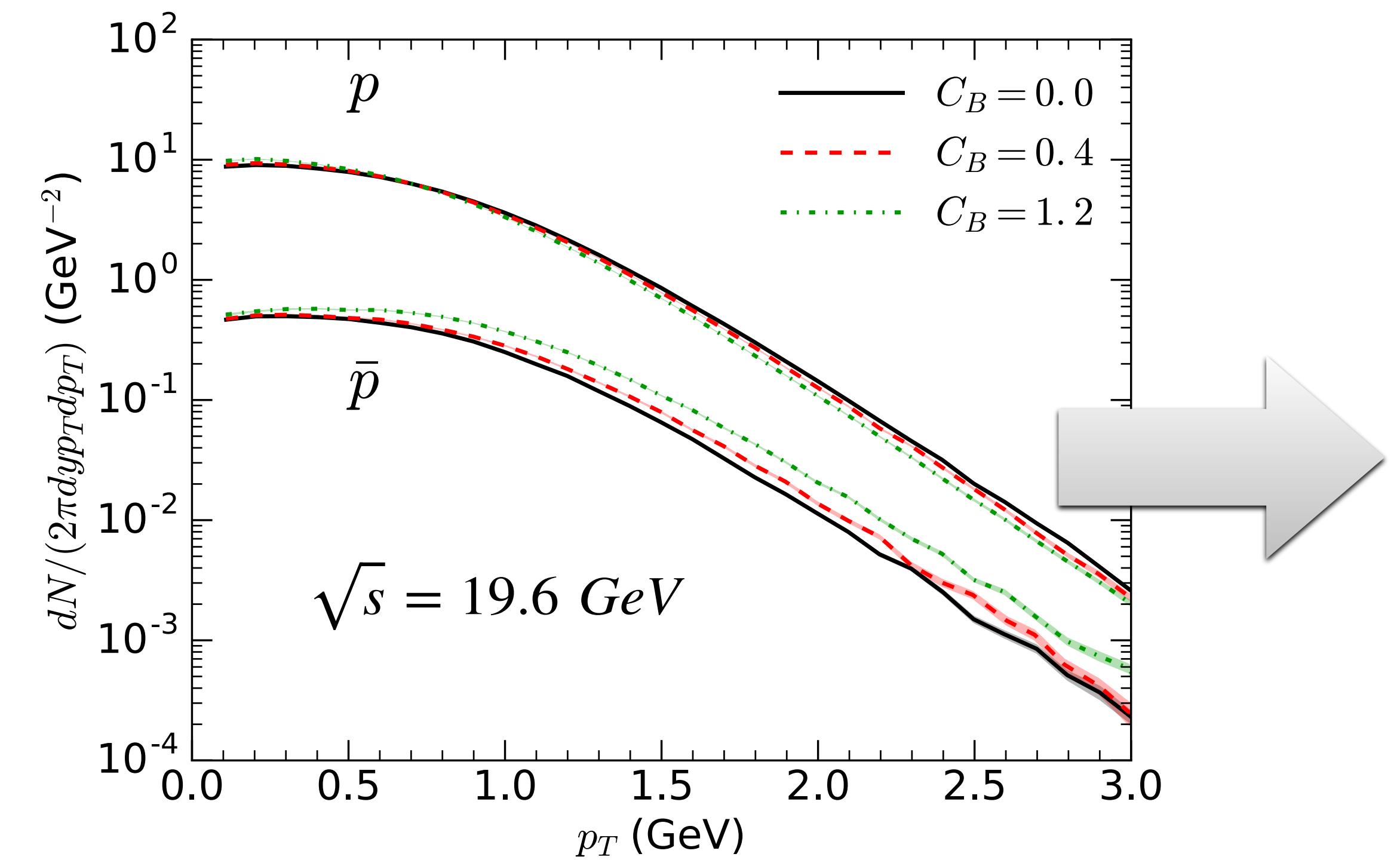
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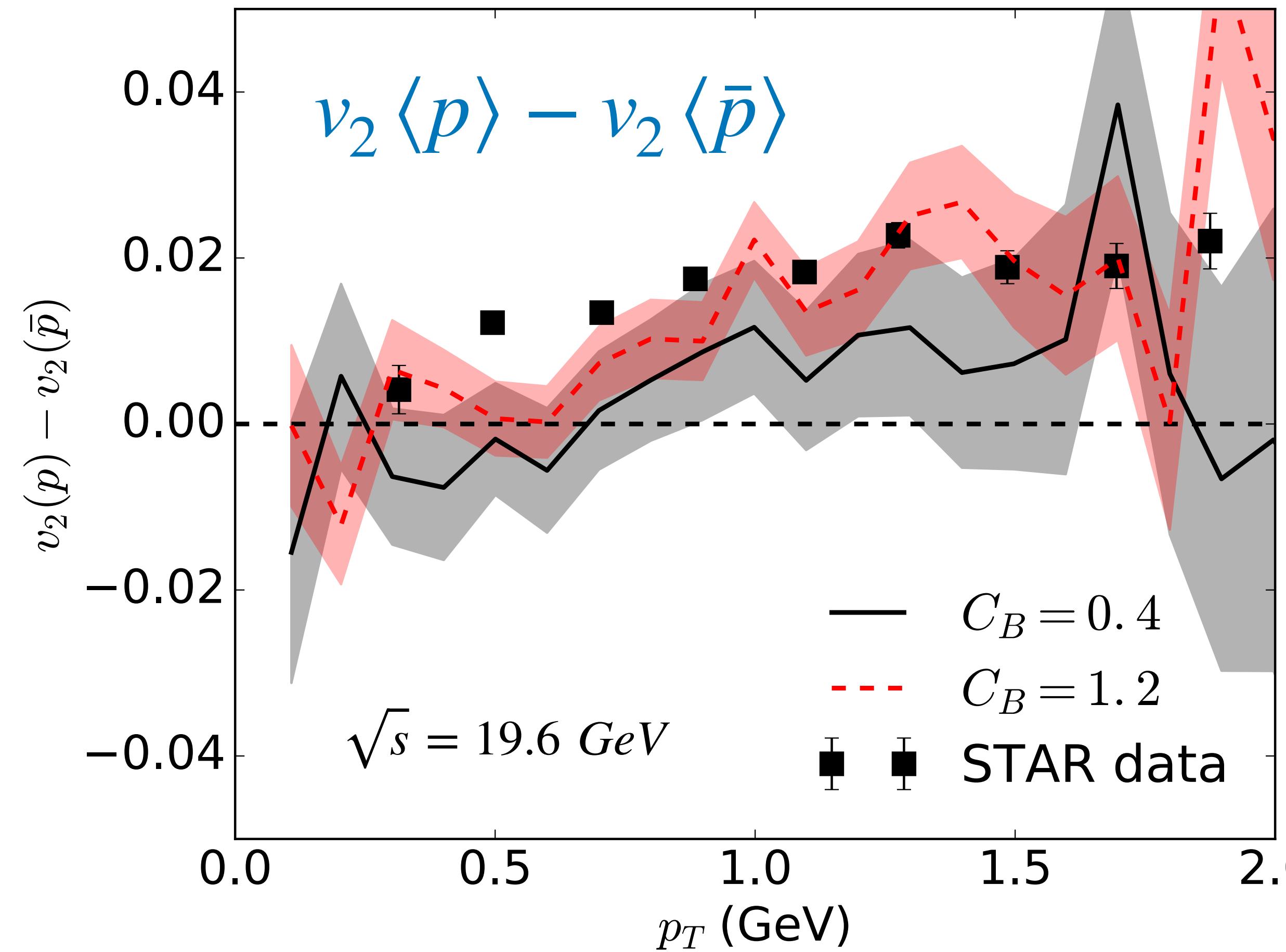
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sensitivity to baryon diffusion contant (C_B)

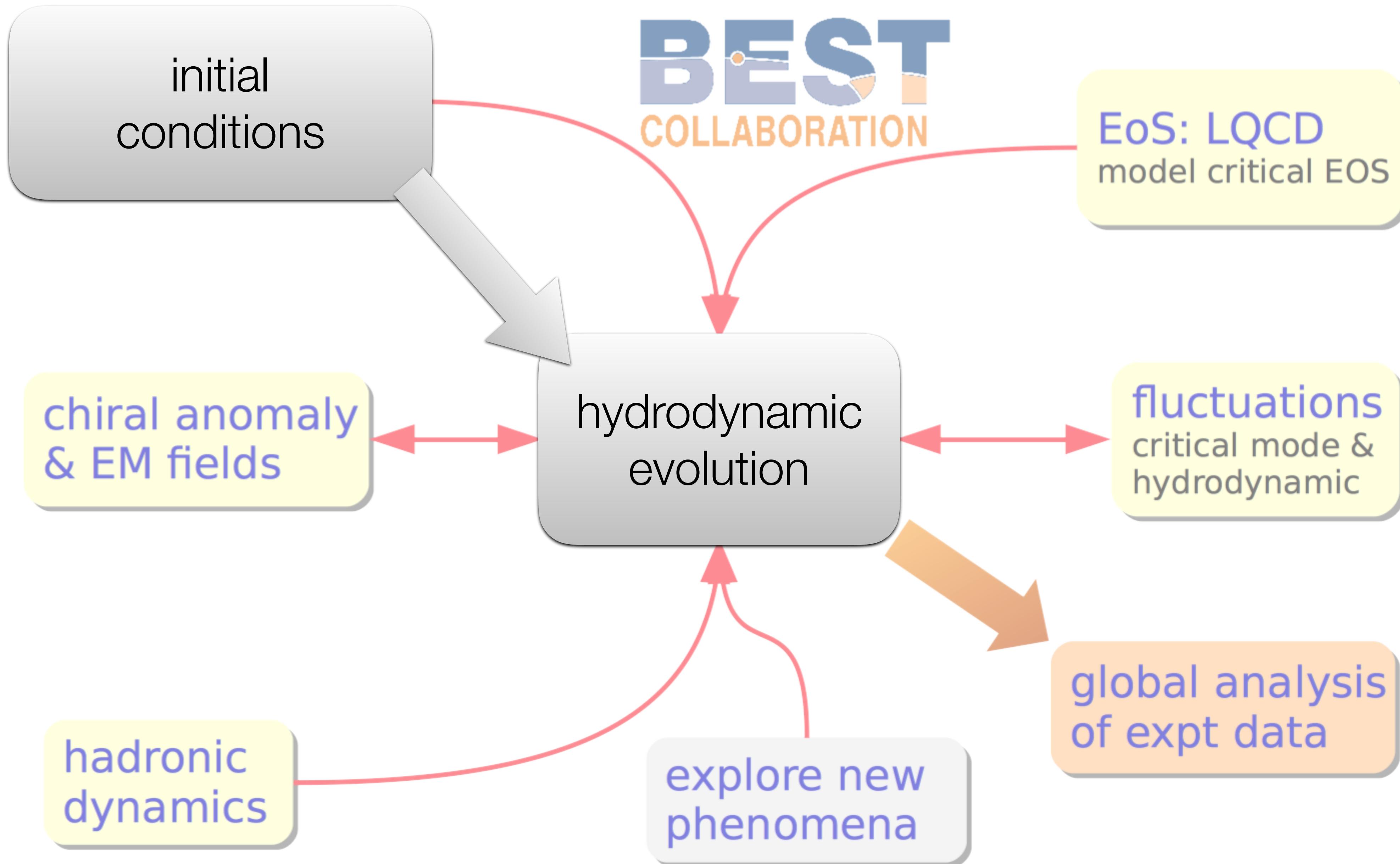


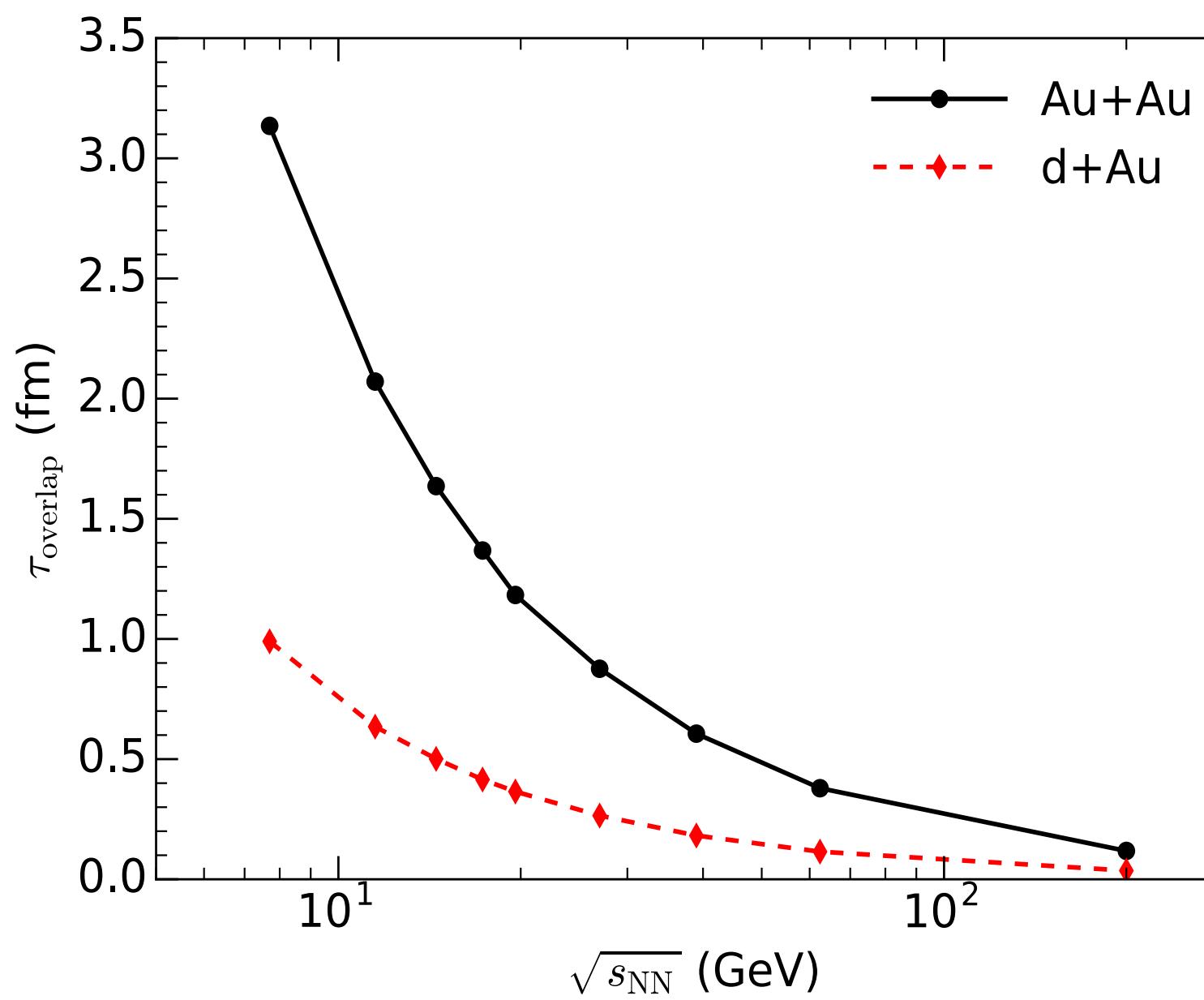
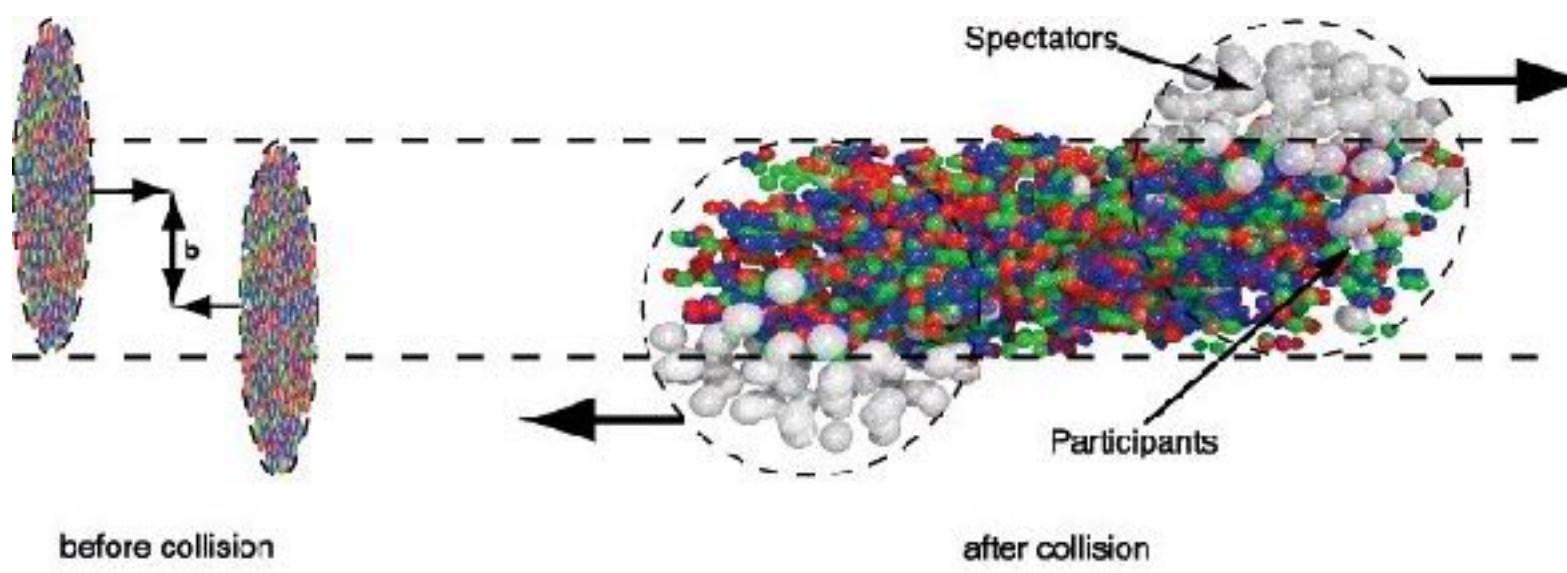
	$C_B = 0.0$	$C_B = 0.4$	$C_B = 1.2$
$\langle p_\perp \rangle^{\bar{p}} - \langle p_\perp \rangle^p$ (GeV)	0.046	0.091	0.158

sensitivity to baryon diffusion contant (C_B)



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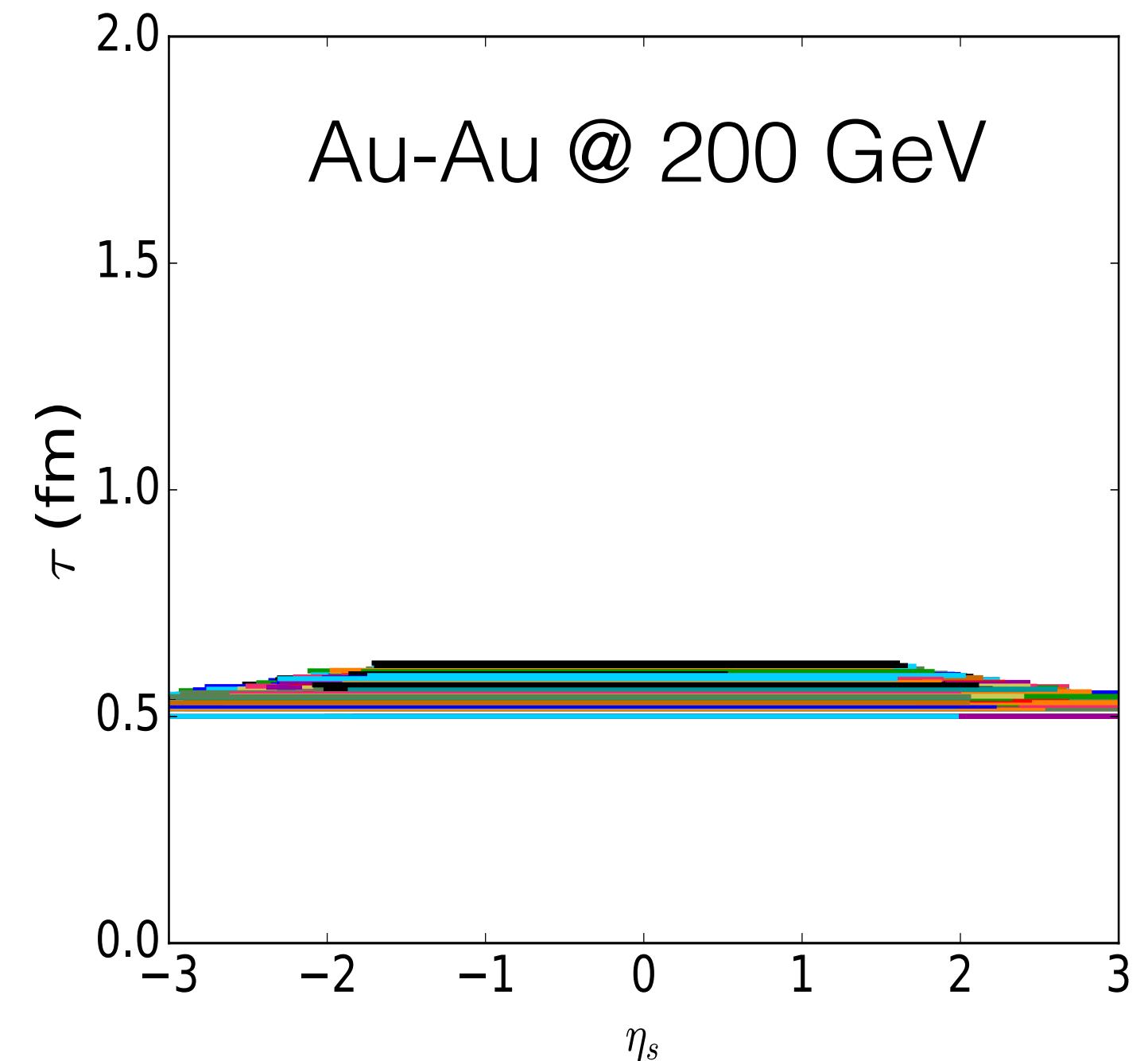


nuclei overlap time: $\tau \sim 2R/\gamma v_z$

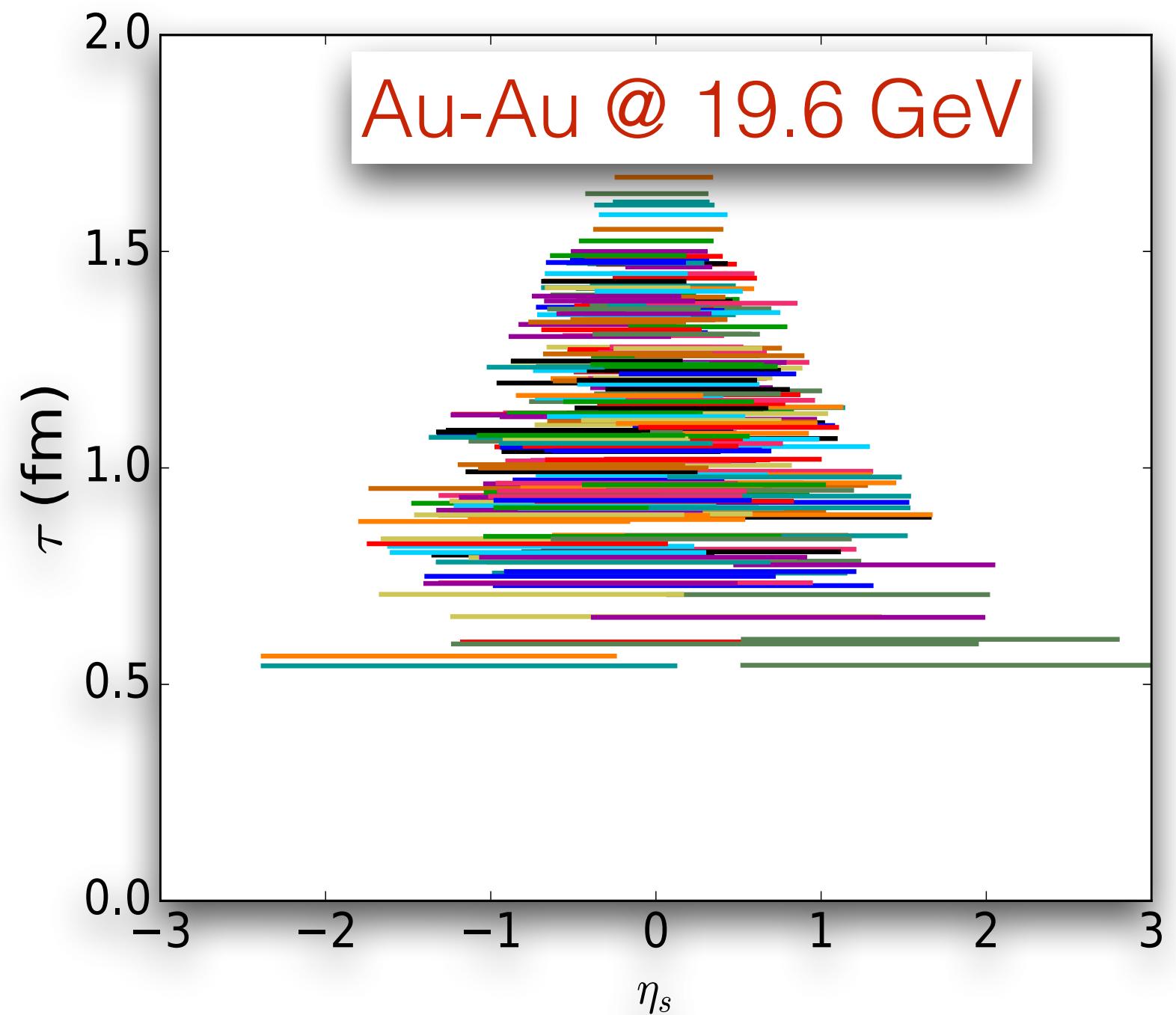
- large at lower collisional energy
- pre-equilibrium dynamics important

3-d MC Glauber-LEXUS model ...

Shen, Schenke: in preparation



Au-Au @ 200 GeV



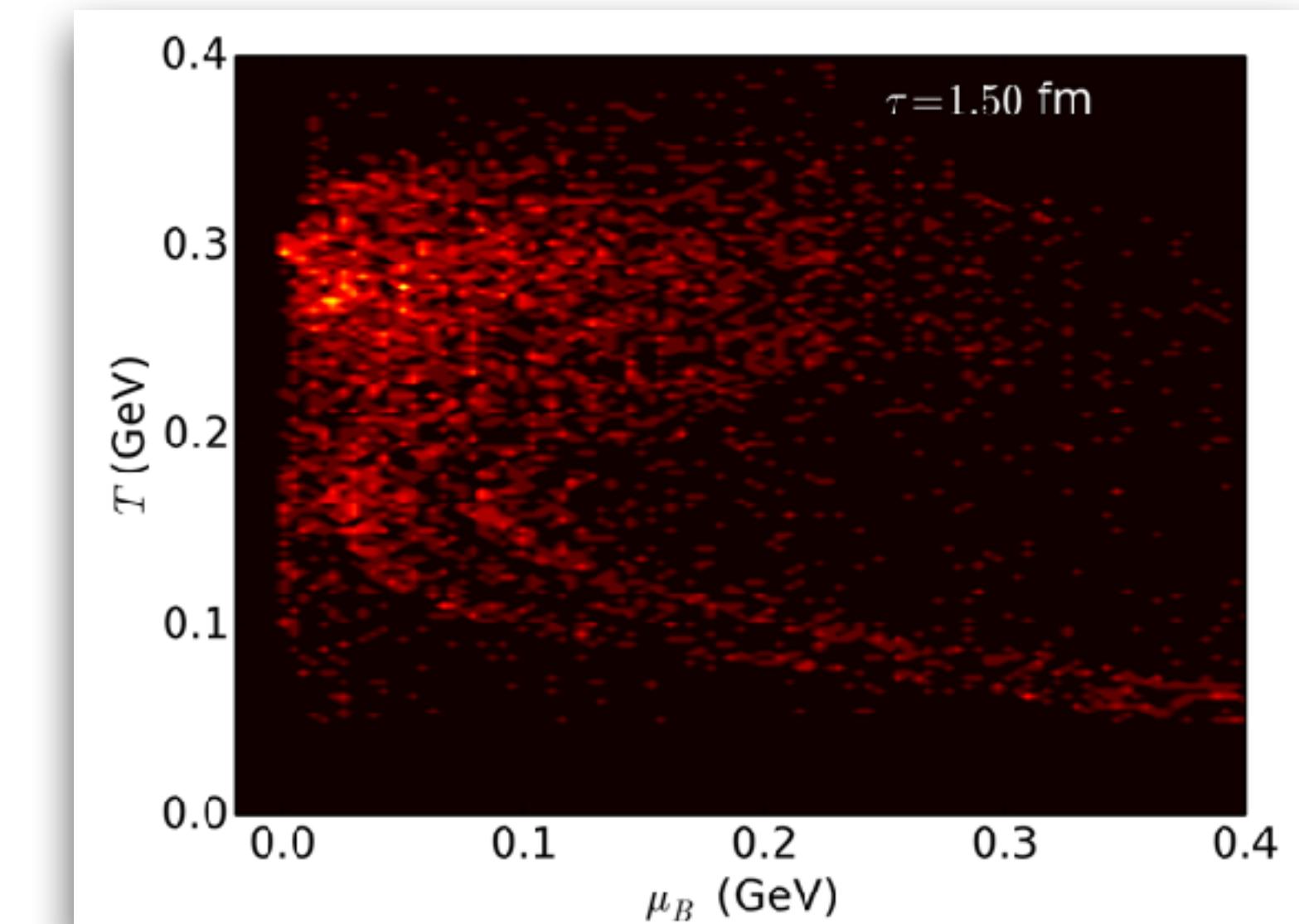
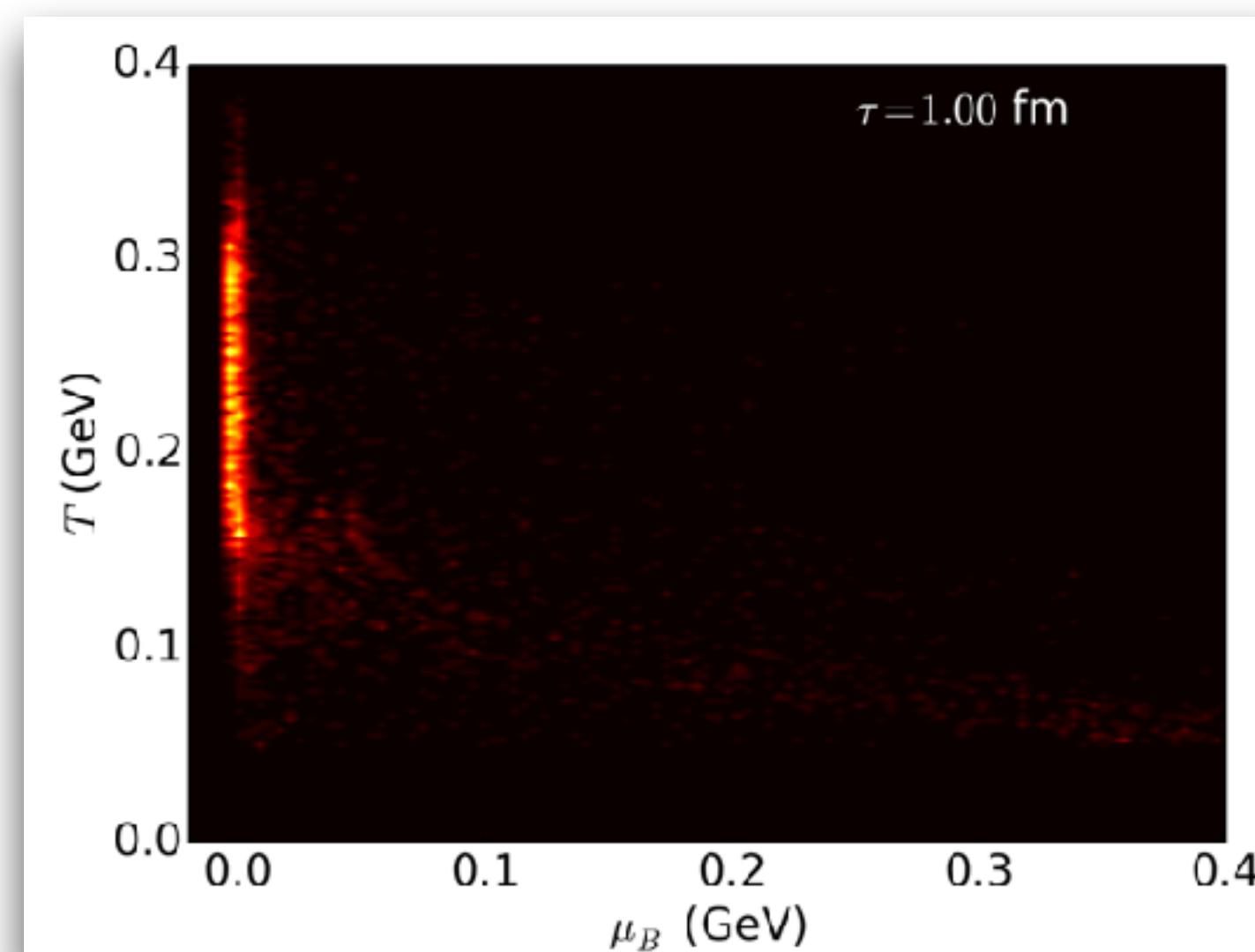
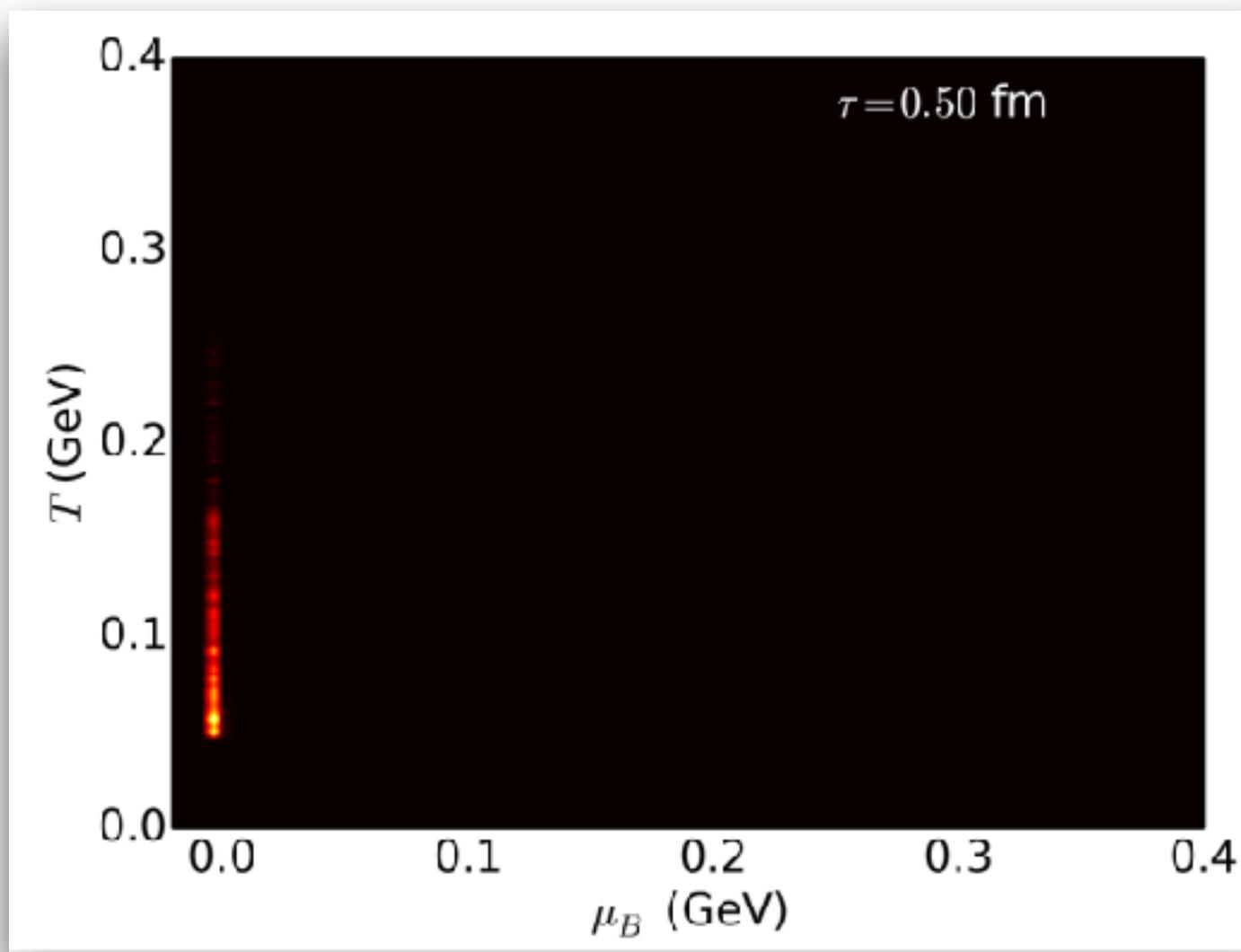
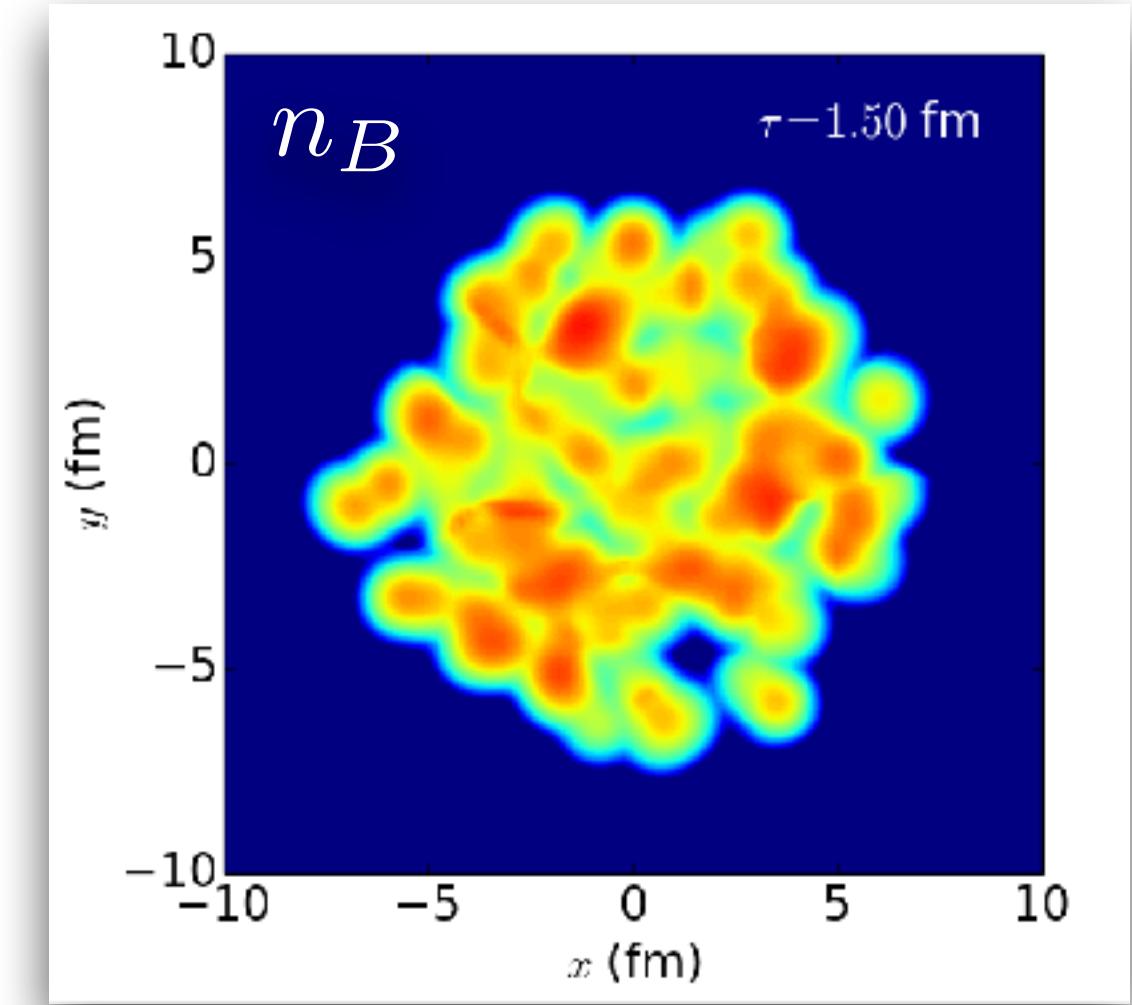
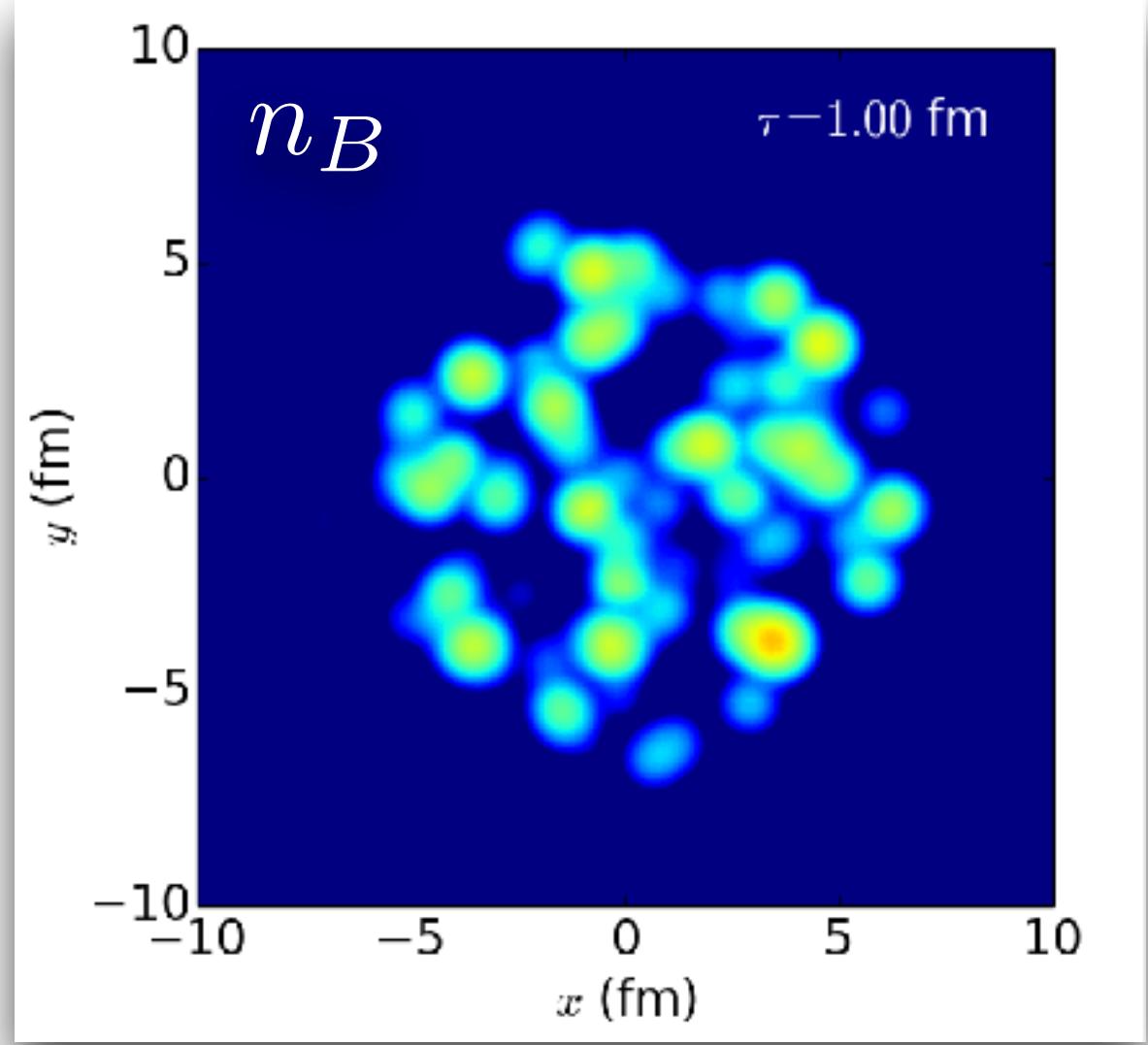
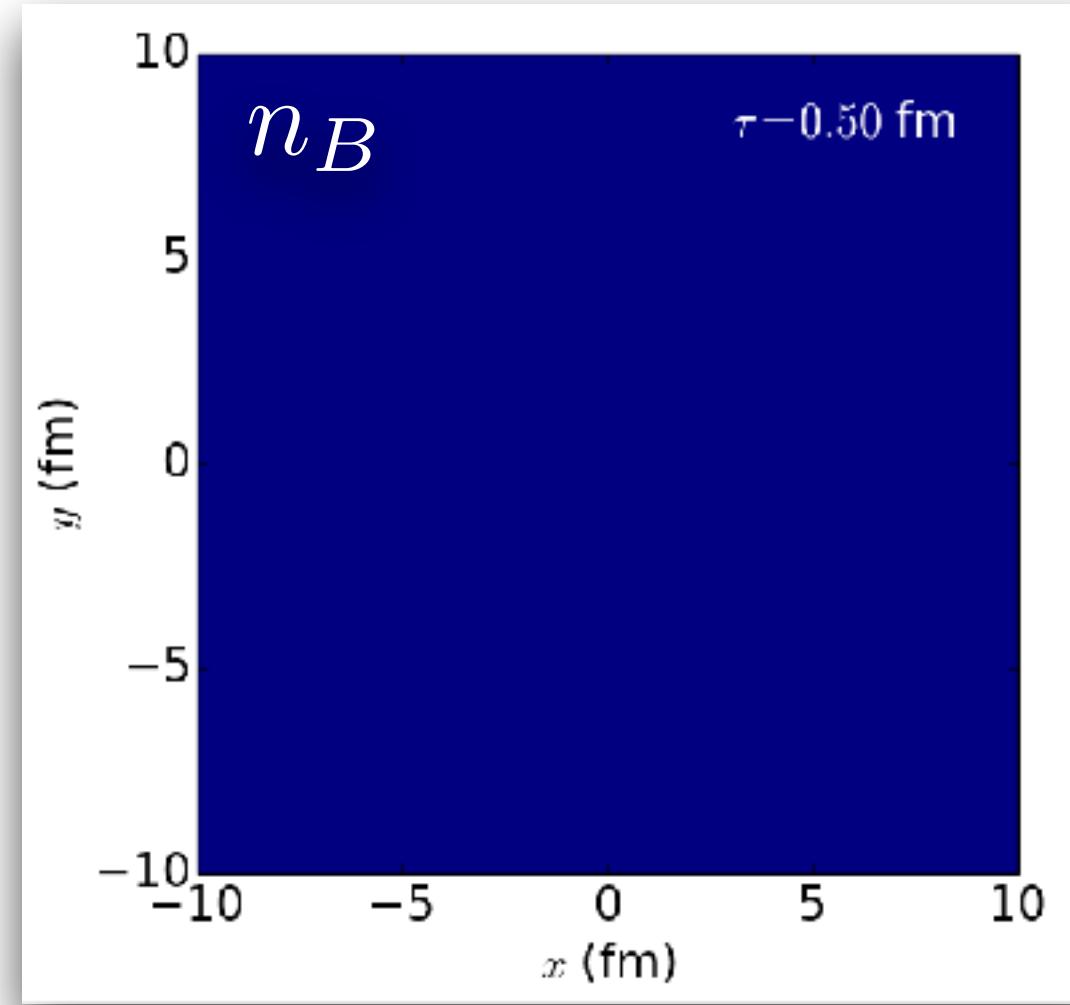
Au-Au @ 19.6 GeV

- collision time & 3-d spatial positions determined for every binary collision
- rapidity loss is determined using the LEXUS model
[Jeon, Kapusta: PRC 56, 468 (1997)]
- QCD strings are free-streaming by 0.5 fm before thermalized to medium

... & hydrodynamics with sources

Shen, Schenke: in preparation

energy-momentum & net-baryon density are fed into hydro evolution as sources



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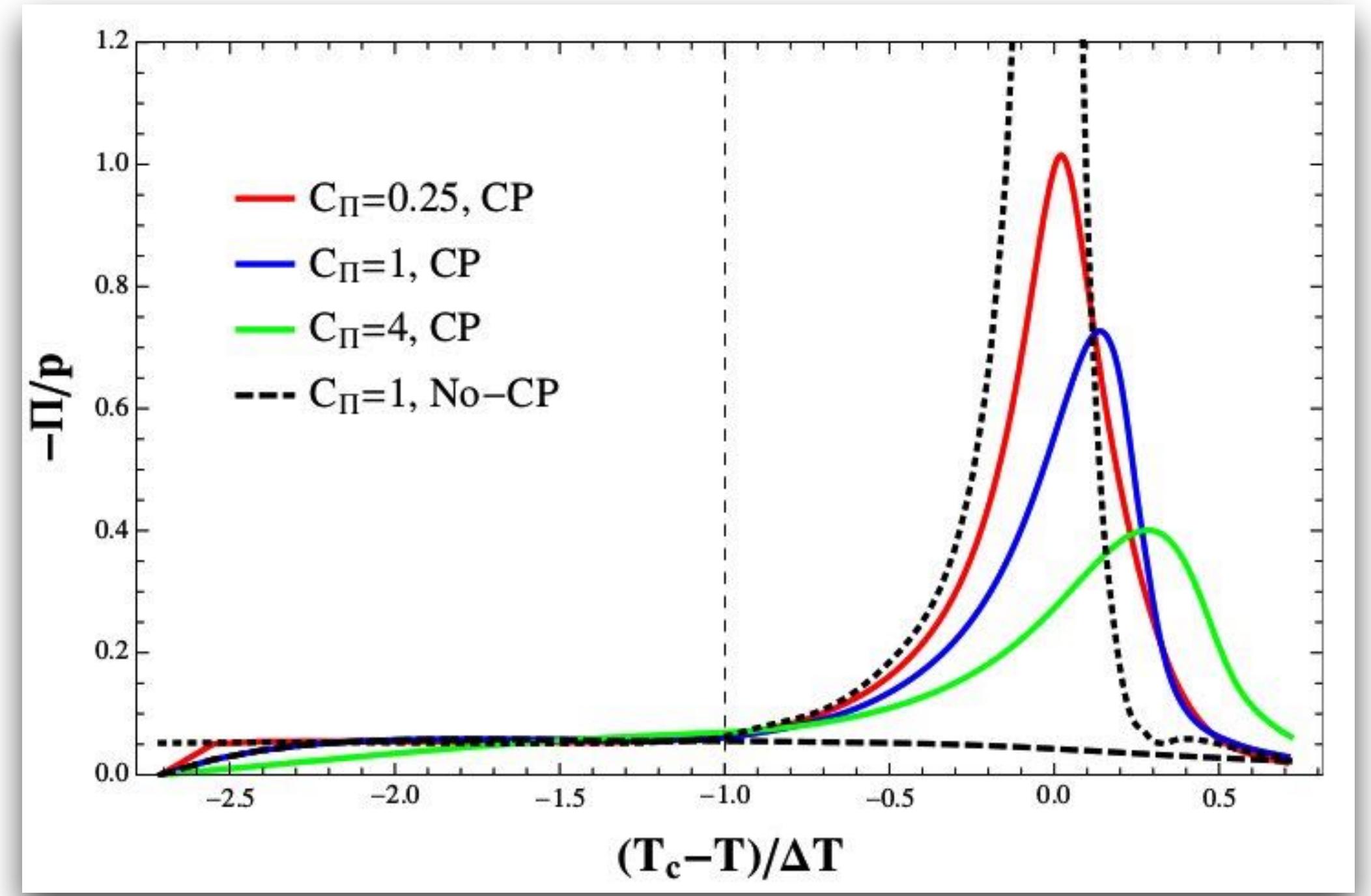
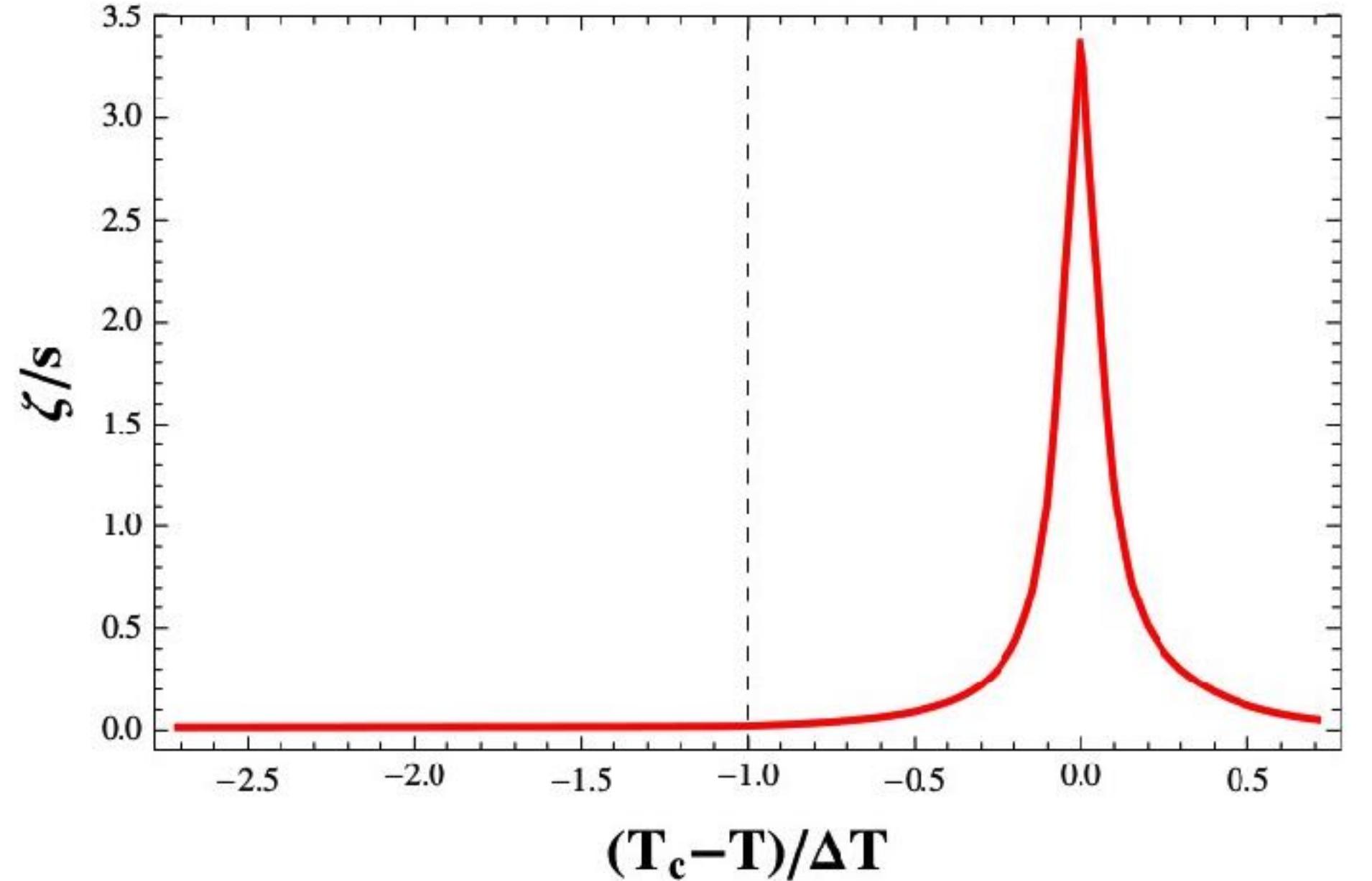
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diverging bulk viscosity at QCD critical point

Monnai, Mukherjee, Yin: Phys. Rev. C95 no.3, 034902 (2017)

$$\zeta \sim \tau_\Pi \sim \tau_\sigma \sim \xi^3$$



bulk viscous pressure

(1+1)D, Israel-Stewart hydro

critical fluctuations leads to break down of ordinary hydrodynamics for: $k \sim \xi^{-3}$

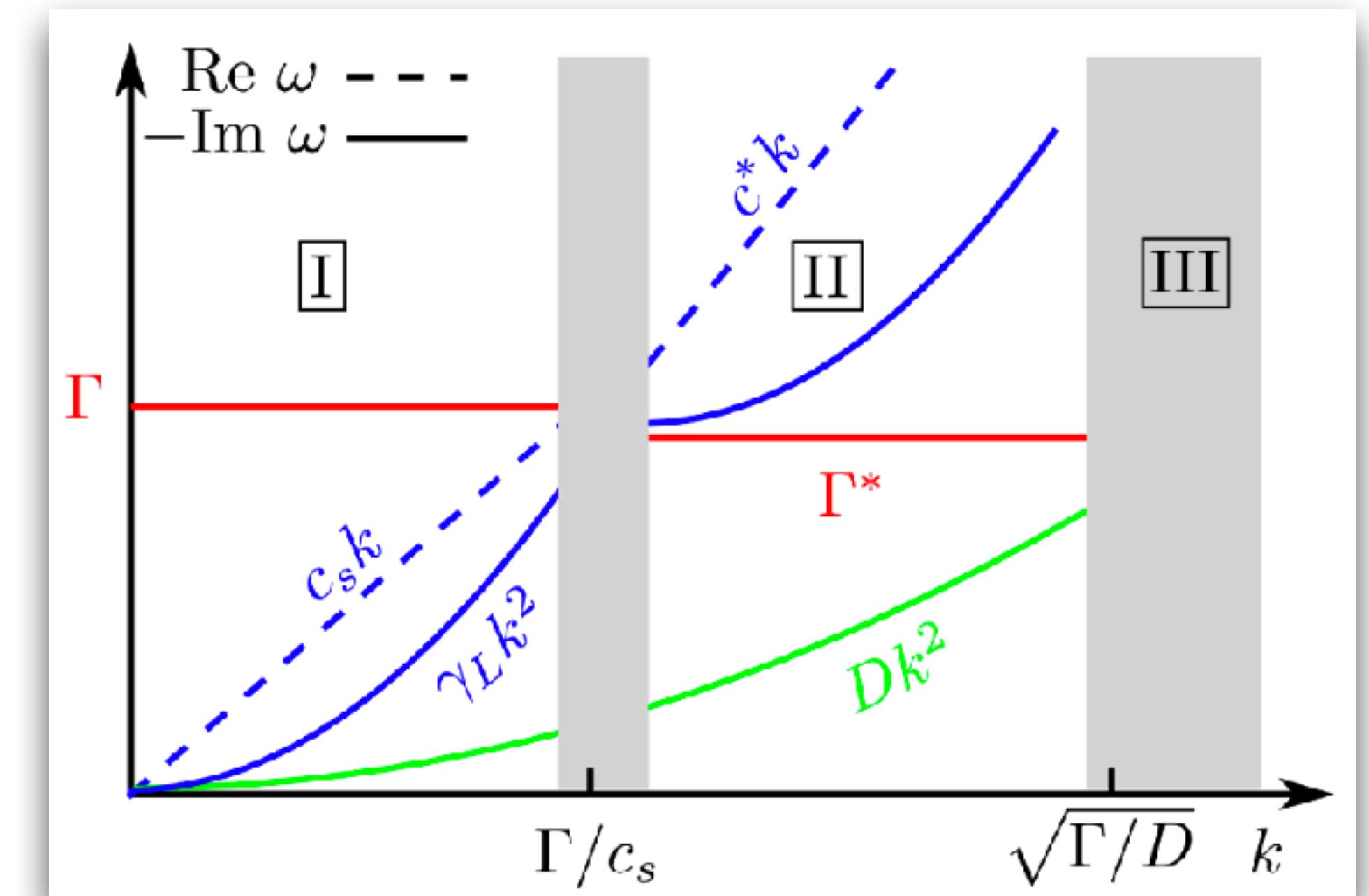
extends the validity of hydro down to scales: $k \sim \xi^{-1}$ (from $k \sim \xi^{-3}$)

- non-equilibrium / quasi-static entropy: $s^*(\varepsilon, n, \phi)$

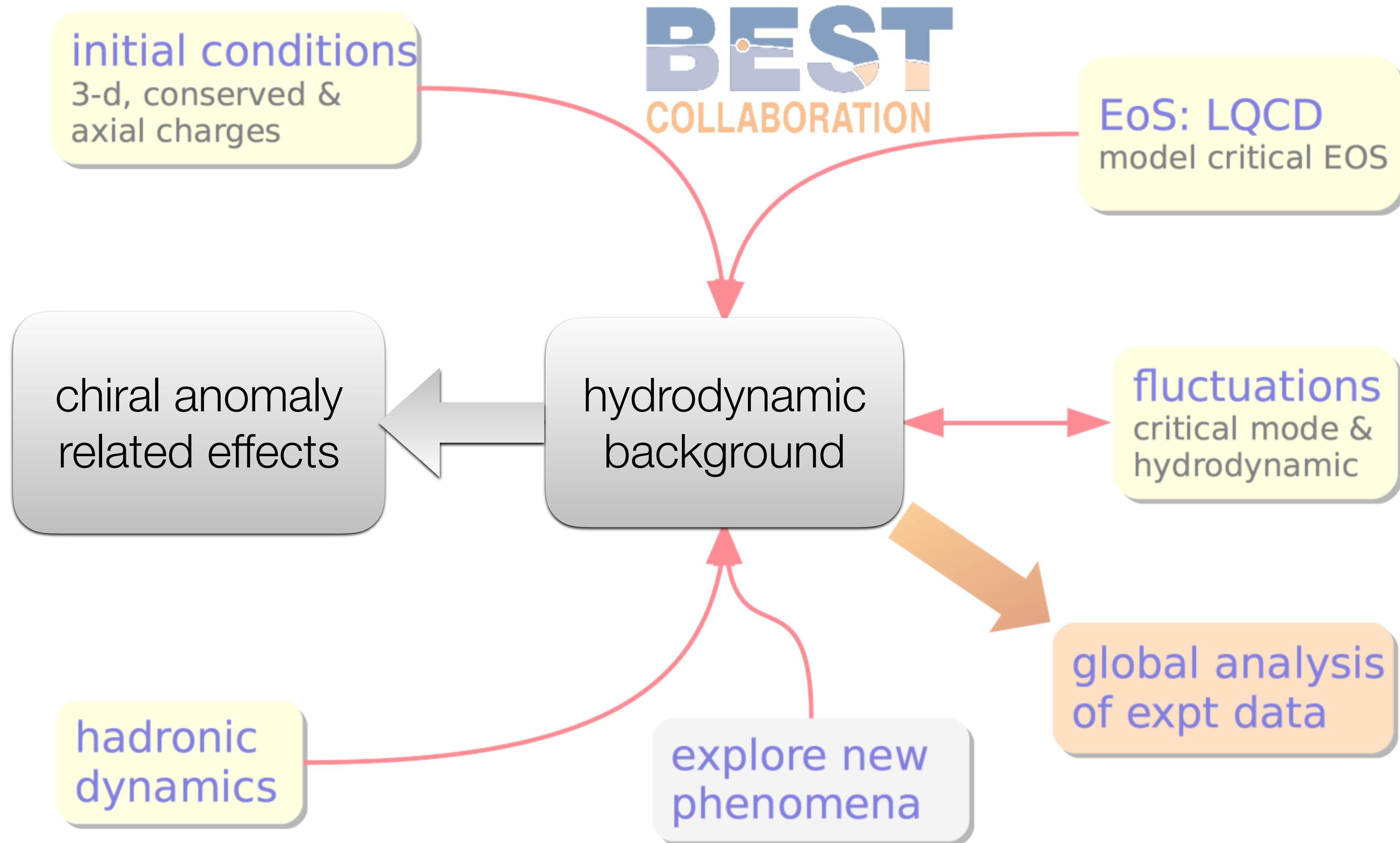
- 6th equation (constrained by 2nd law):

$$(u \cdot \partial)\phi = -\gamma_\phi \pi - G_\phi(\partial \cdot u), \quad \text{where } \pi = \frac{\partial s^*}{\partial \phi}$$

- sound velocities are different in Regime I & II



dispersion relations for Hydro+



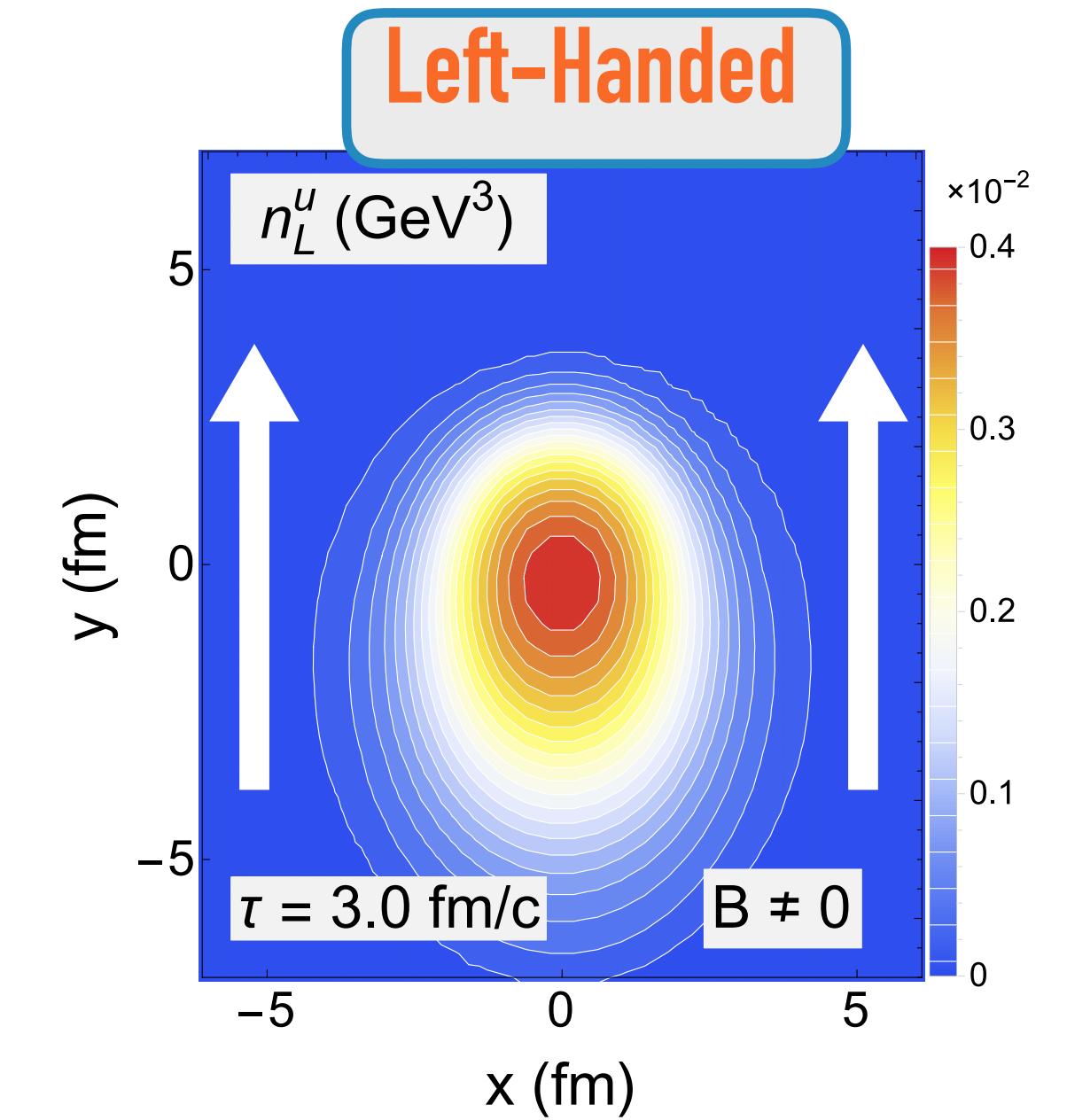
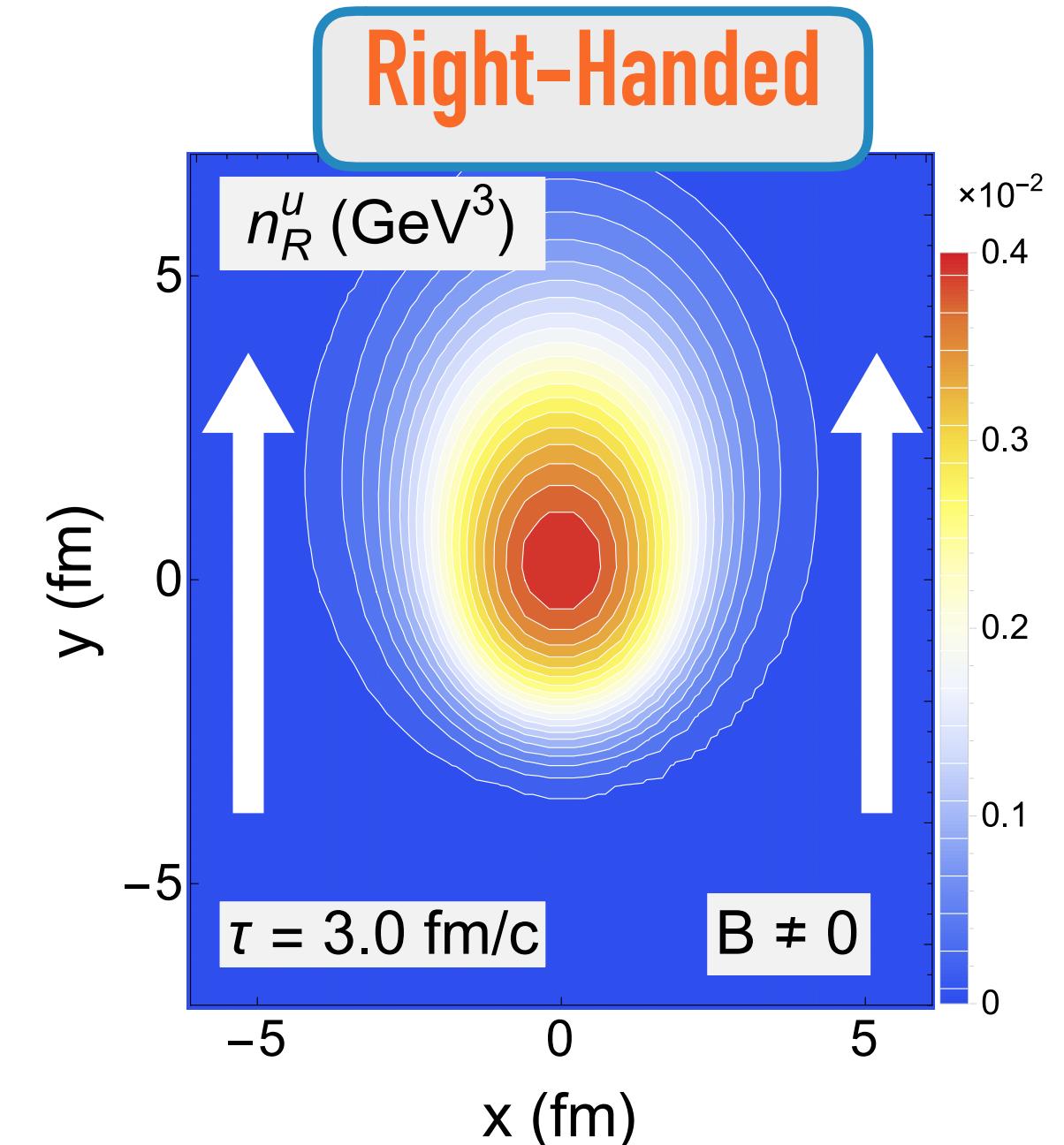
Anomalous-viscous fluid dynamics

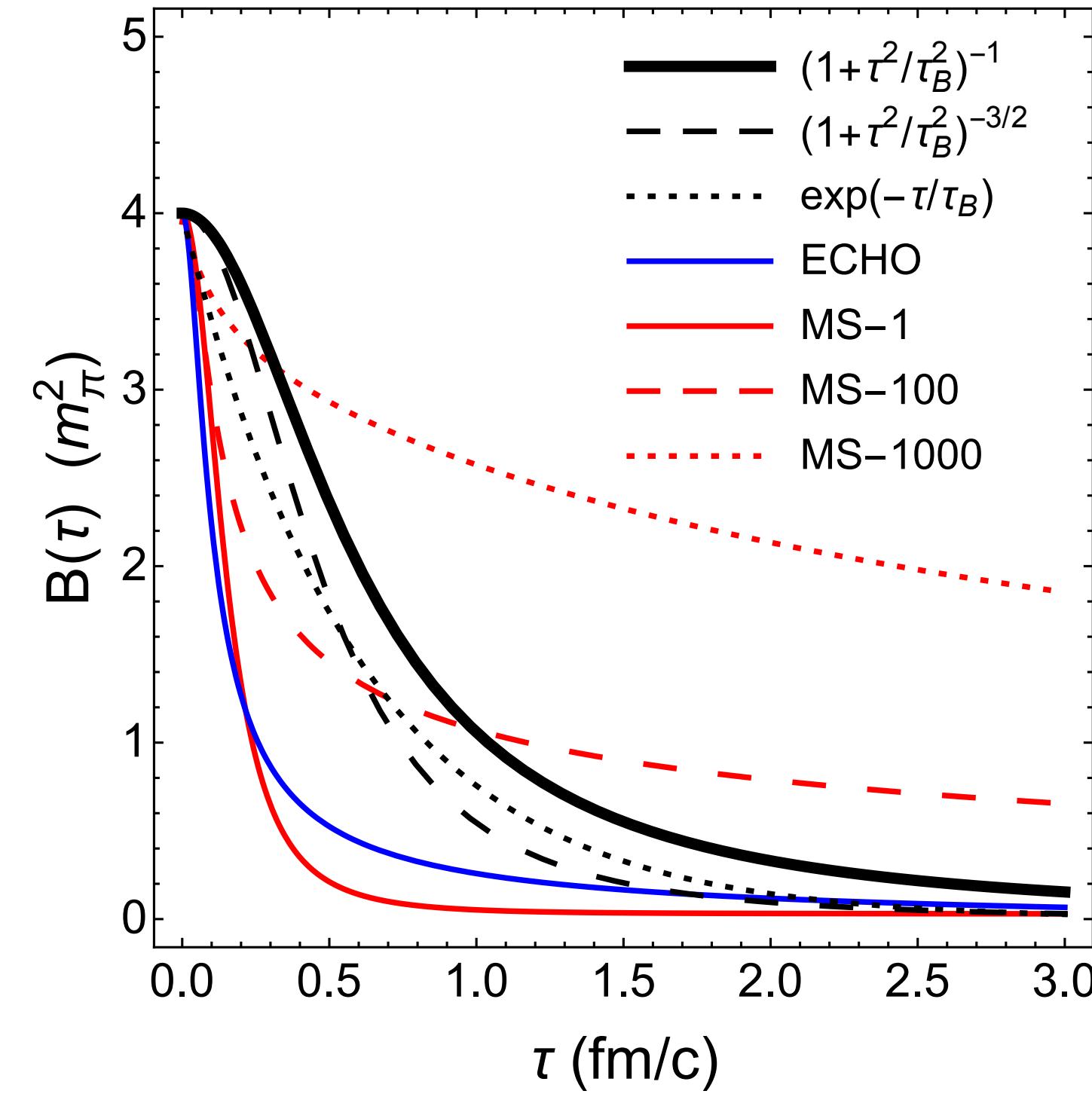
Shi, Liao et. al: arXiv:1611.04586, arXiv:1704.05531, in preparation

chiral anomalous current on hydro + EM background

$$D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \quad D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$
$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{\sigma}{2} E^\mu + \boxed{\frac{N_c q}{4\pi^2} \mu_R B^\mu}$$
$$J_L^\mu = n_L u^\mu + \nu_L^\mu + \frac{\sigma}{2} E^\mu - \boxed{\frac{N_c q}{4\pi^2} \mu_L B^\mu} \text{CME}$$
$$d\nu_{R,L}^\mu = (\nu_{NS}^\mu - \nu_{R,L}^\mu) / \tau_{rlx}$$

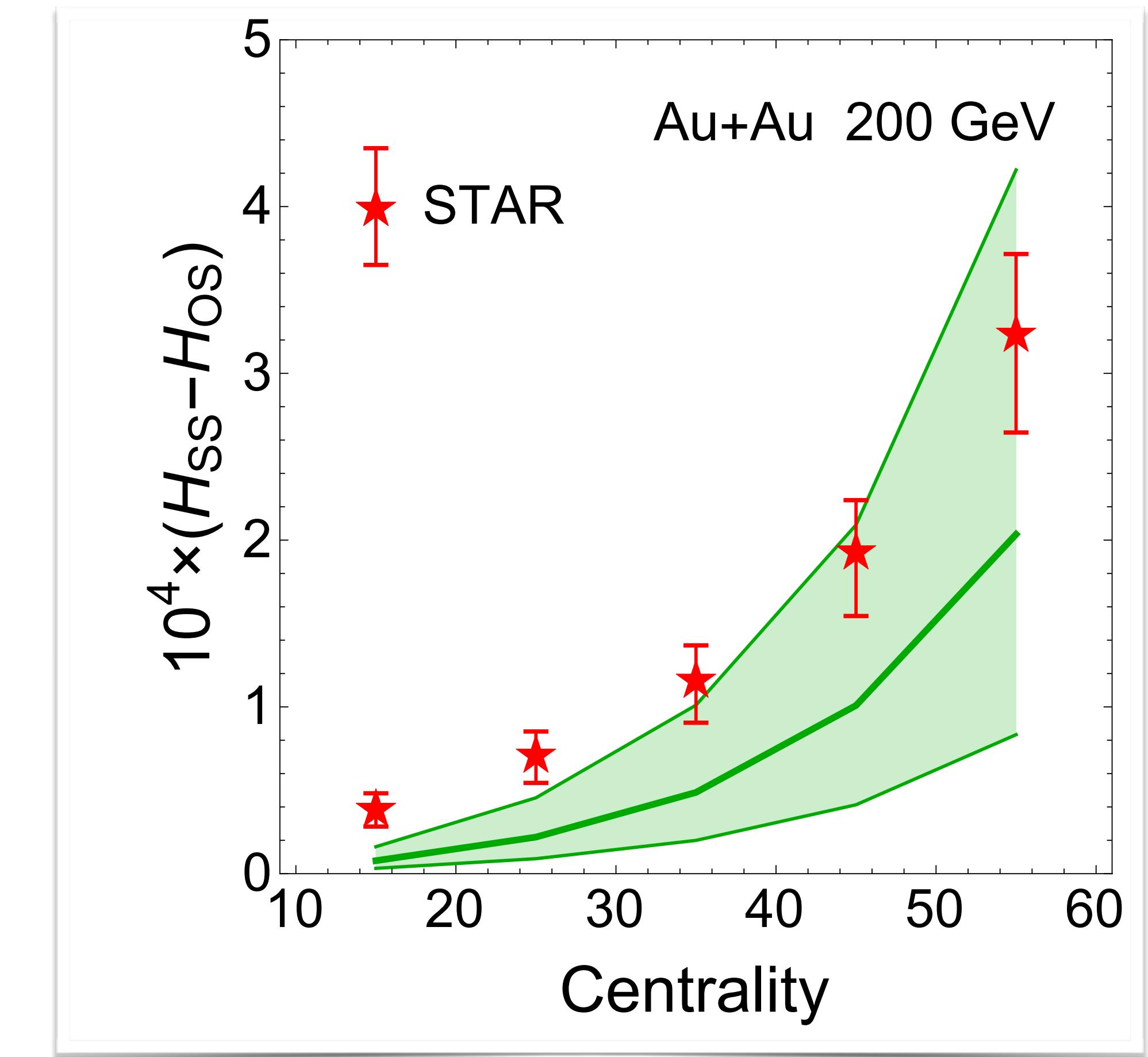
hydro background: (2+1)-d viscous VISHNU (Heinz et. al.)



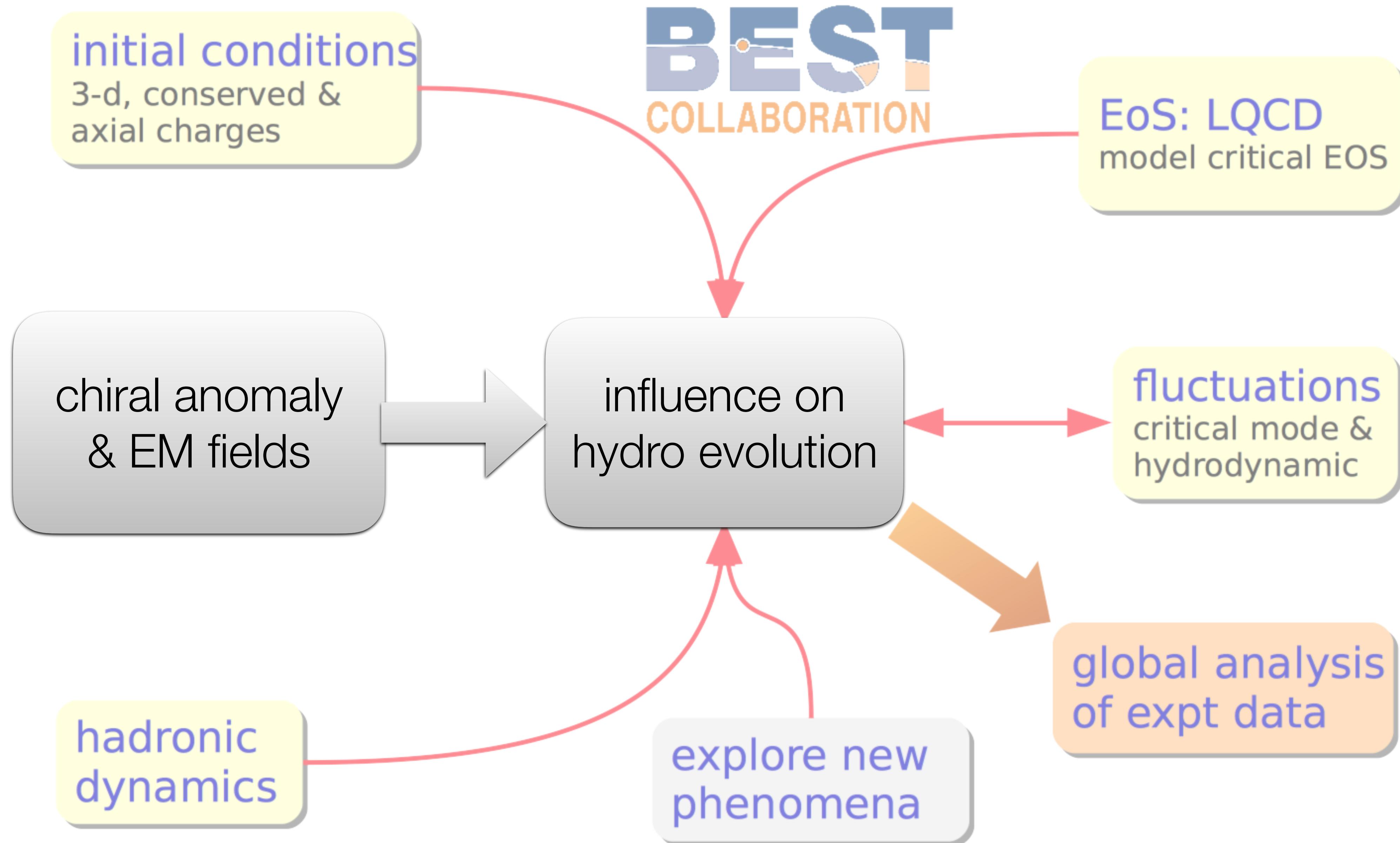


$$B = \frac{B_0}{1+(\tau/\tau_B)^2} \quad \tau_B = 0.6 \text{ fm/c}$$

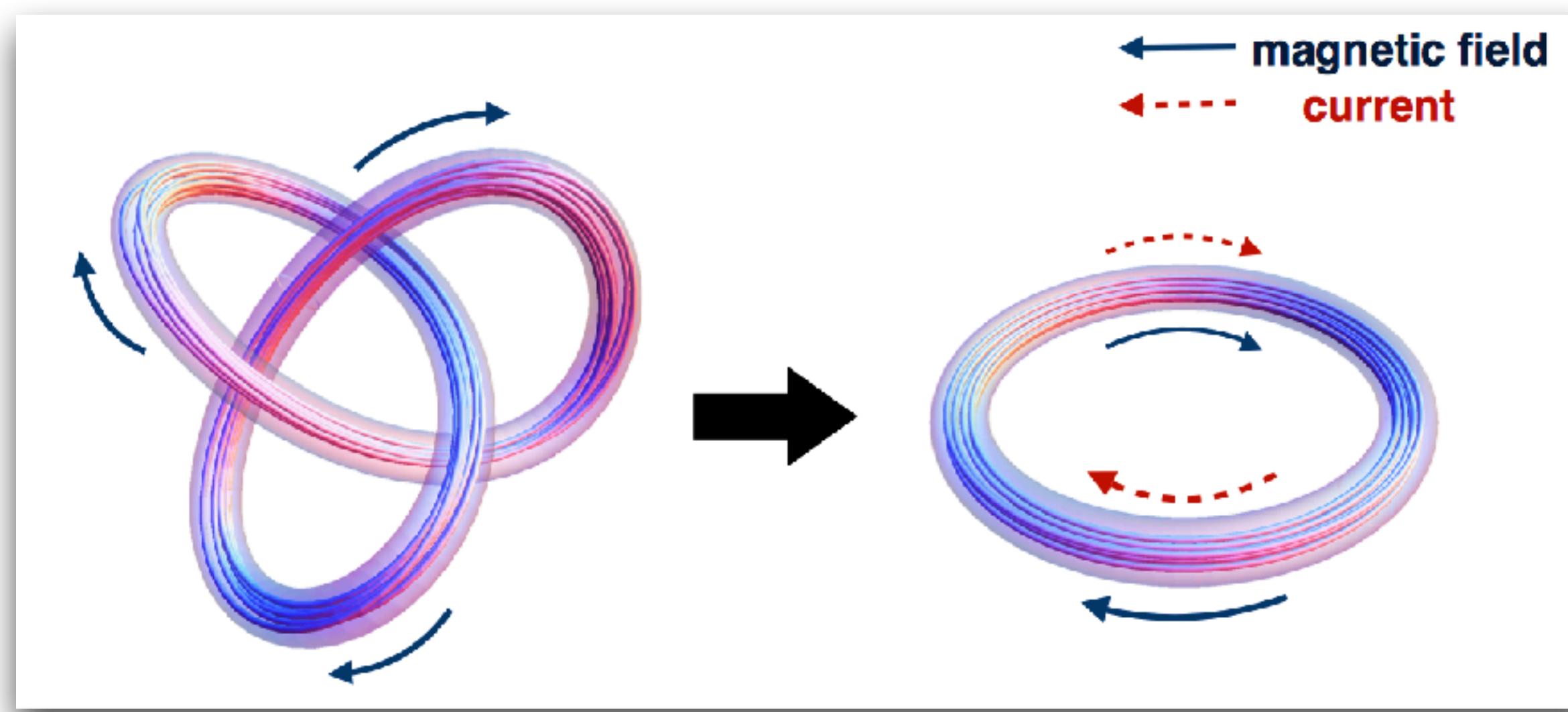
$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4 (\pi \rho_{\text{tube}}^2 \tau_0) \sqrt{N_{\text{coll}}}}{16\pi^2 A_{\text{overlap}}}$$



flow-subtracted CME signal

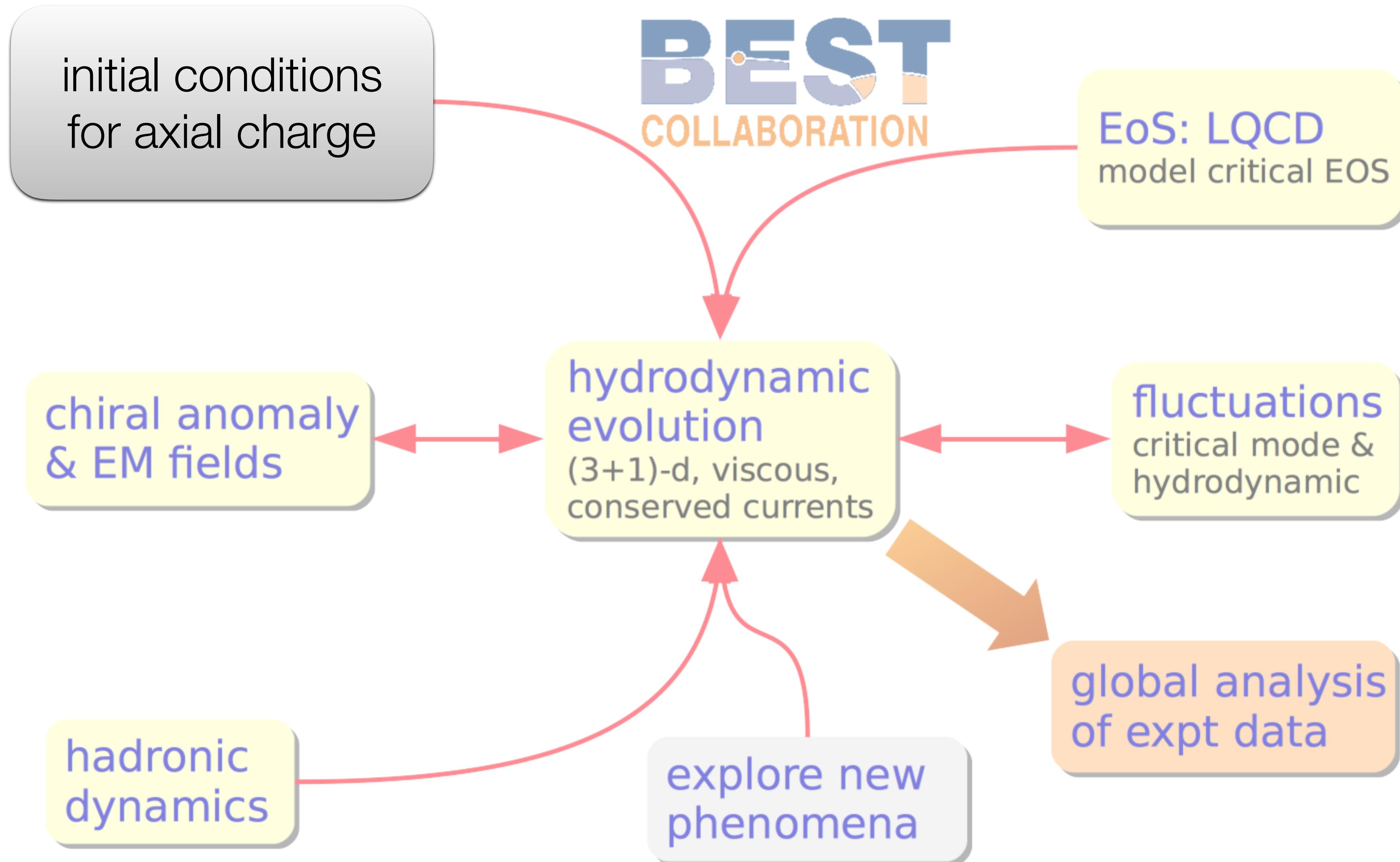


generation of quantized CME current from topology change of magnetic fields



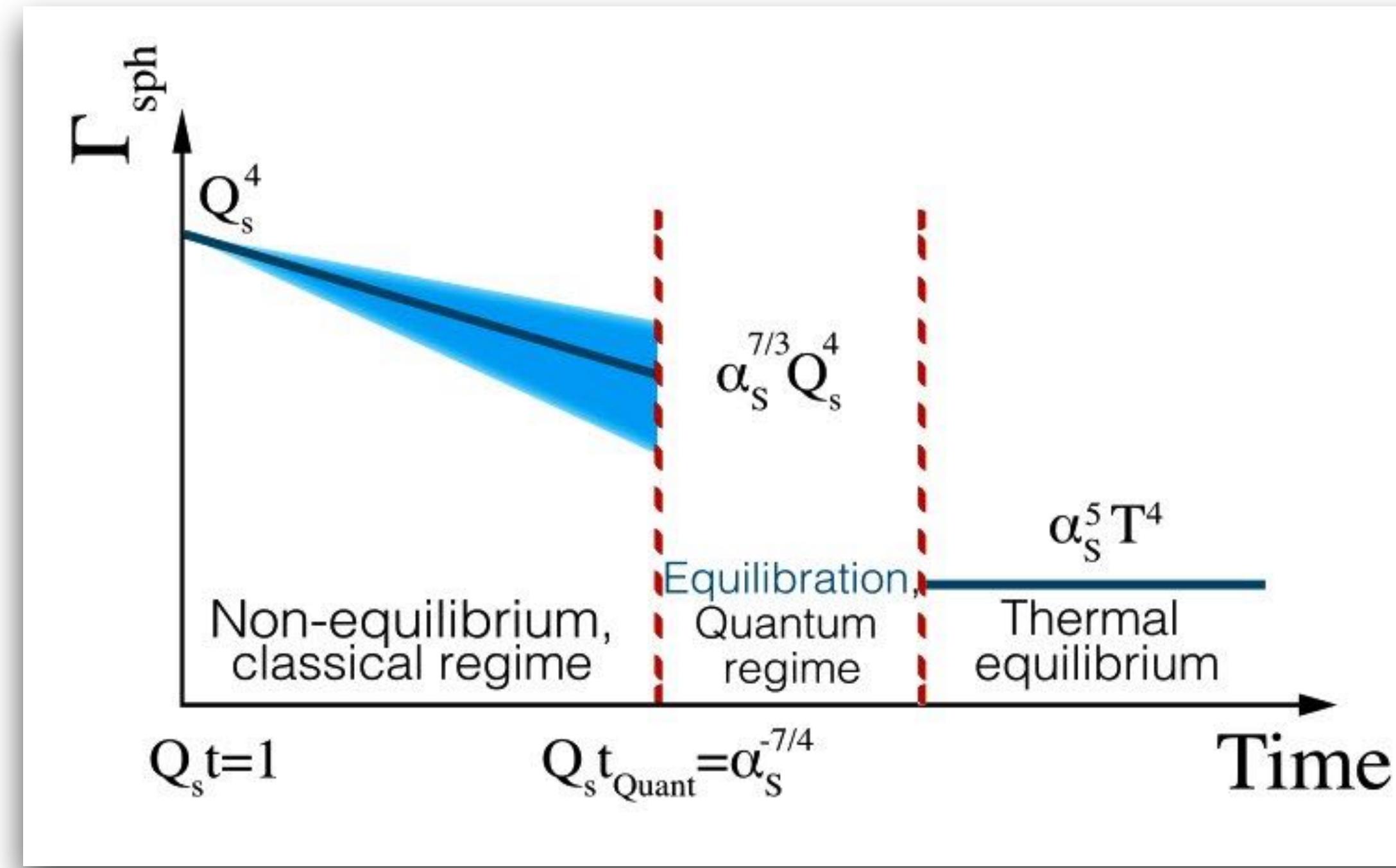
does not require an initial chirality imbalance

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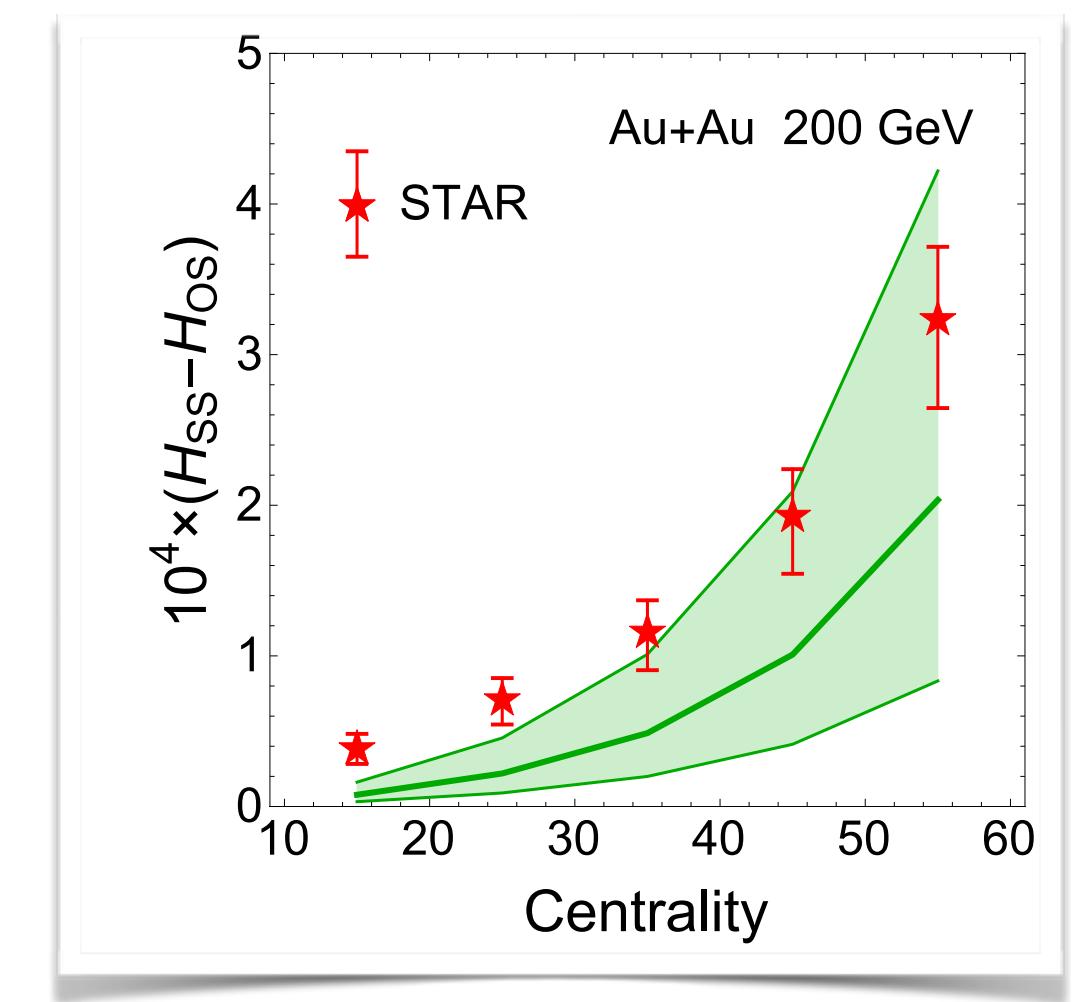
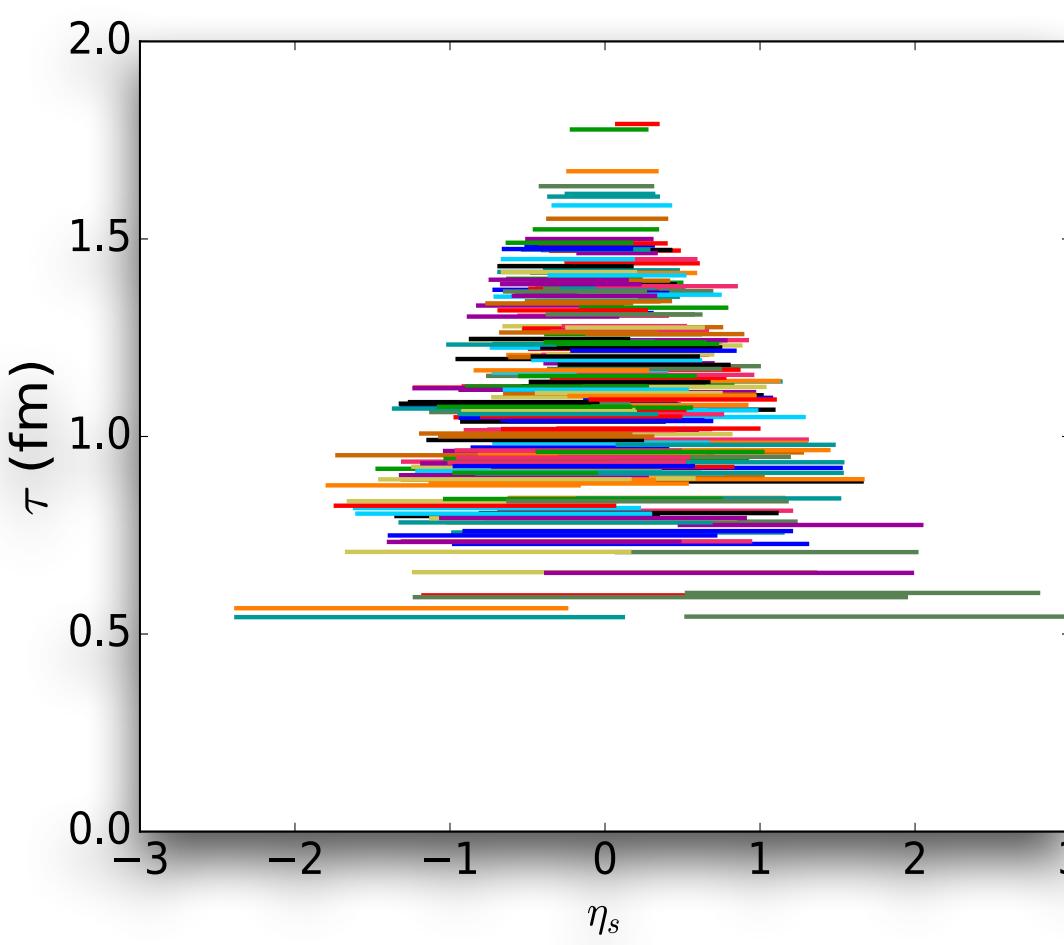
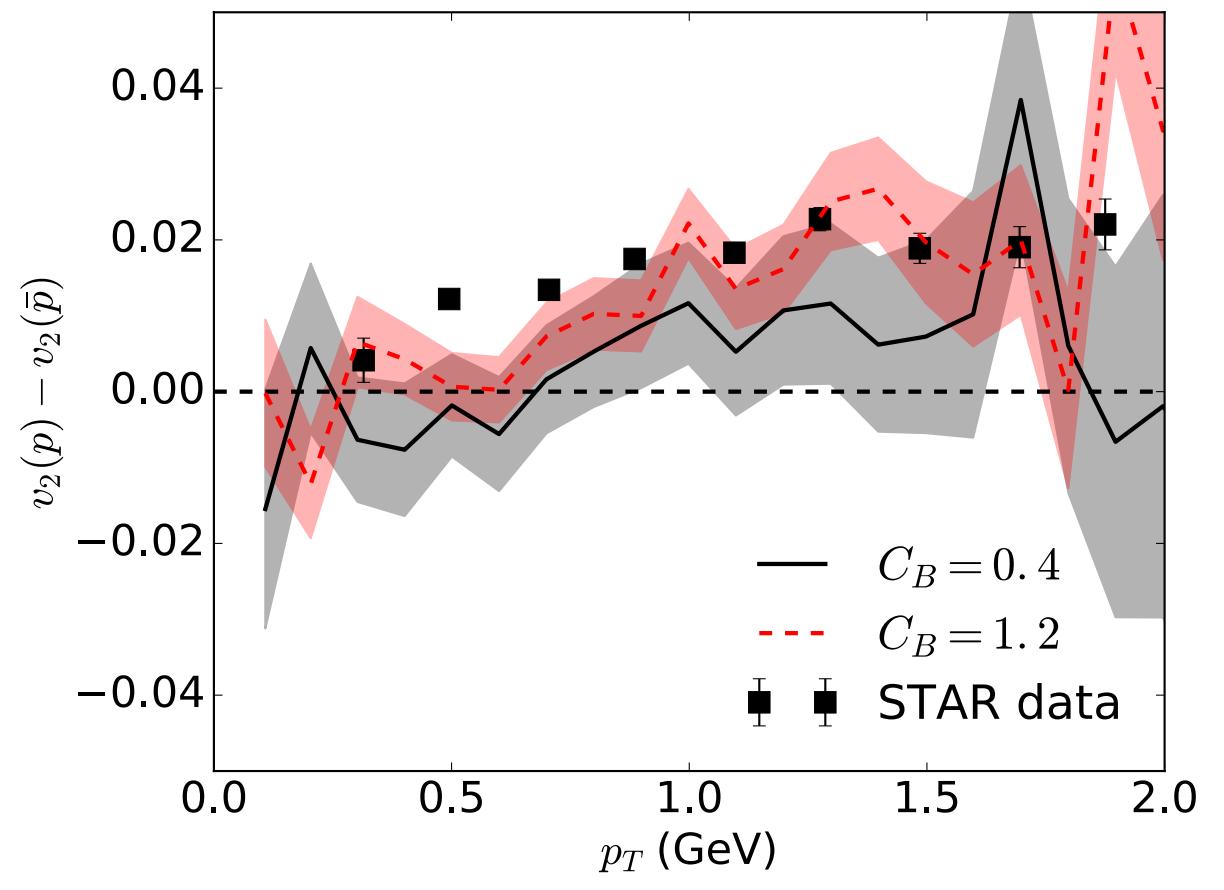
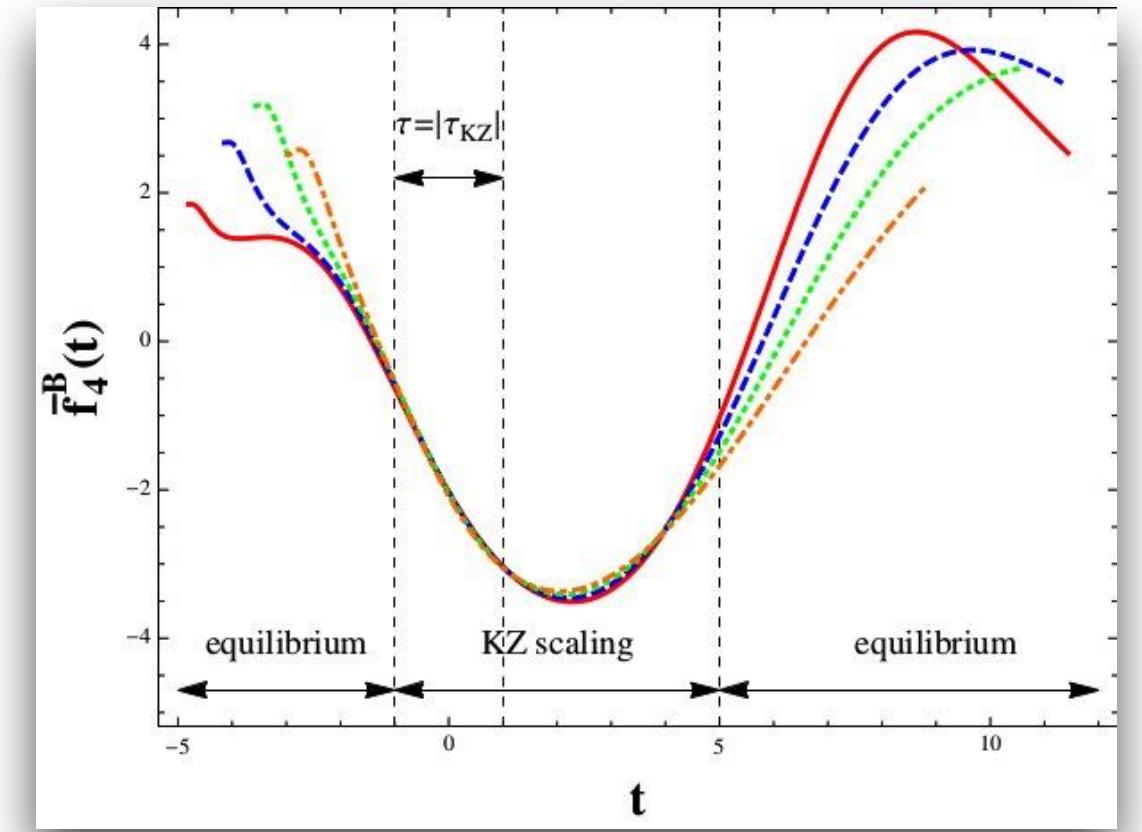
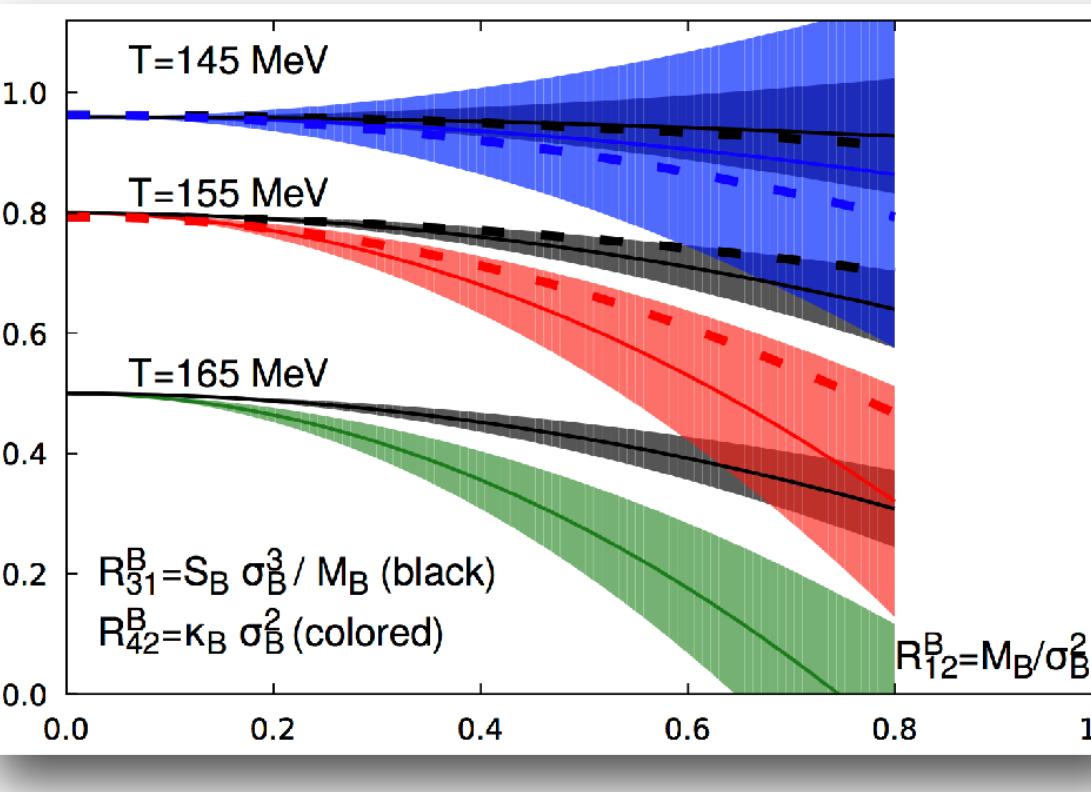
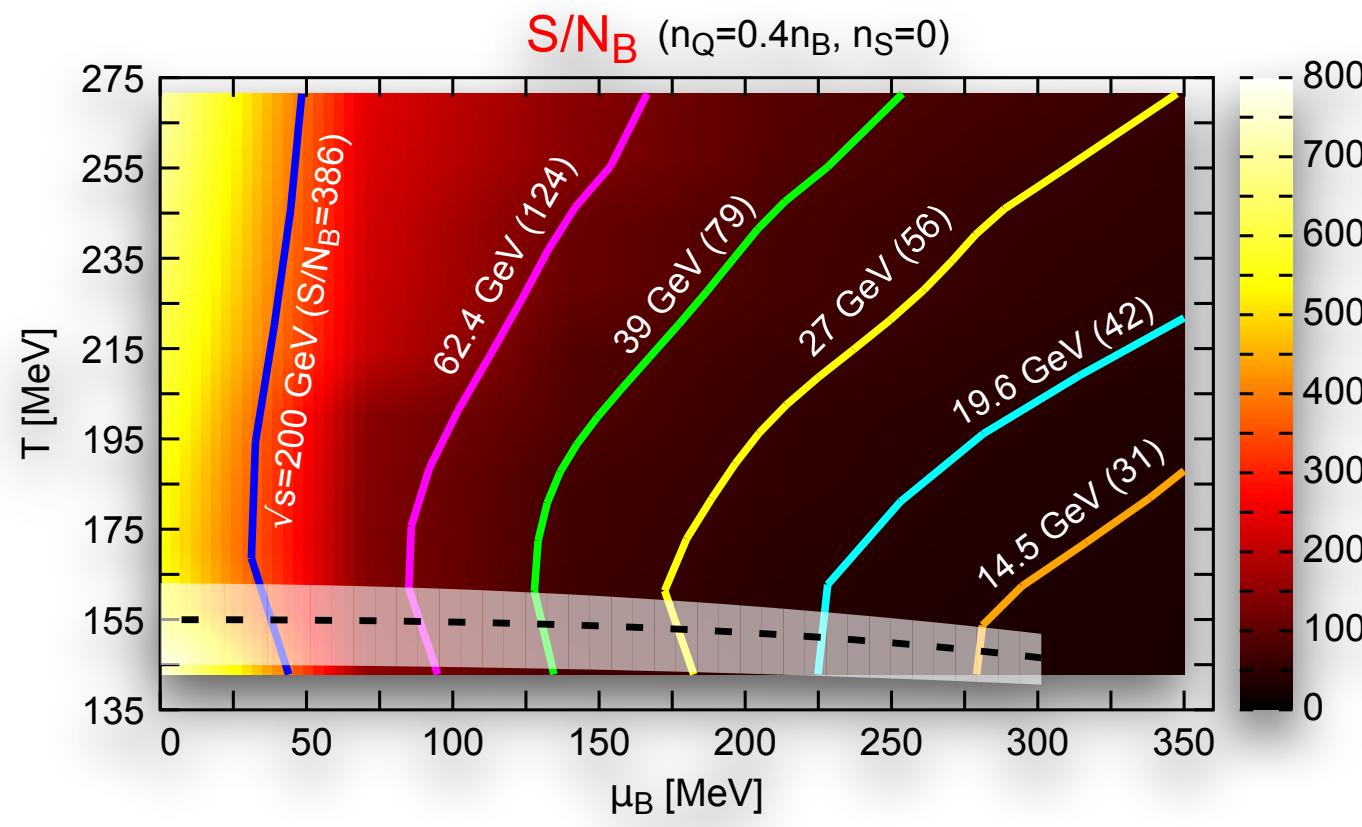
non-equilibrium sphaleron transition rate

Mace, Schlichting, Venugopalan: Phys. Rev. D93, no.7, 074036 (2016)



real-time simulations of over-occupied, classical gluons

a lot progress within just a year ...



... many more to come soon