Critical dynamics and search for QCD critical point

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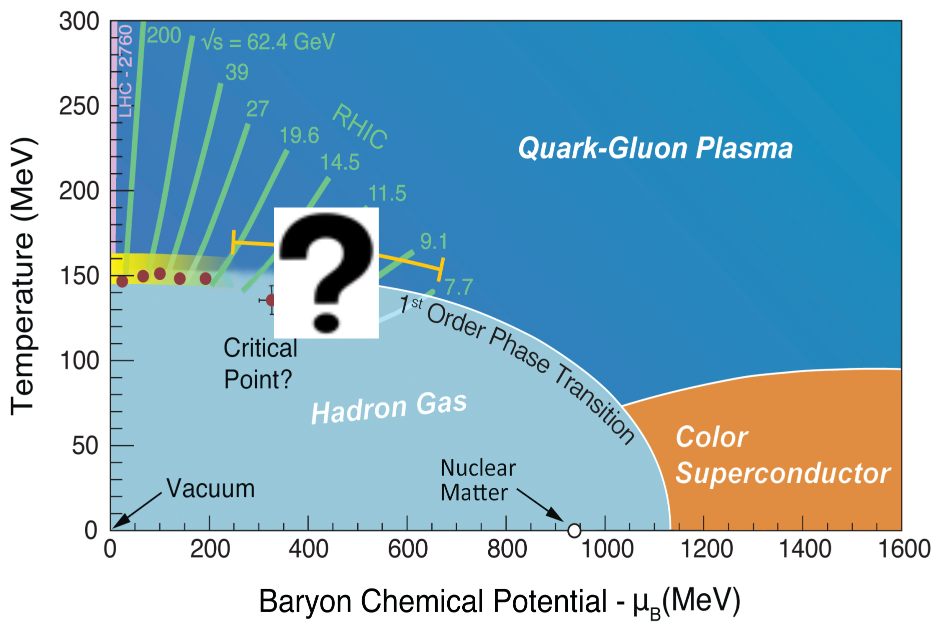

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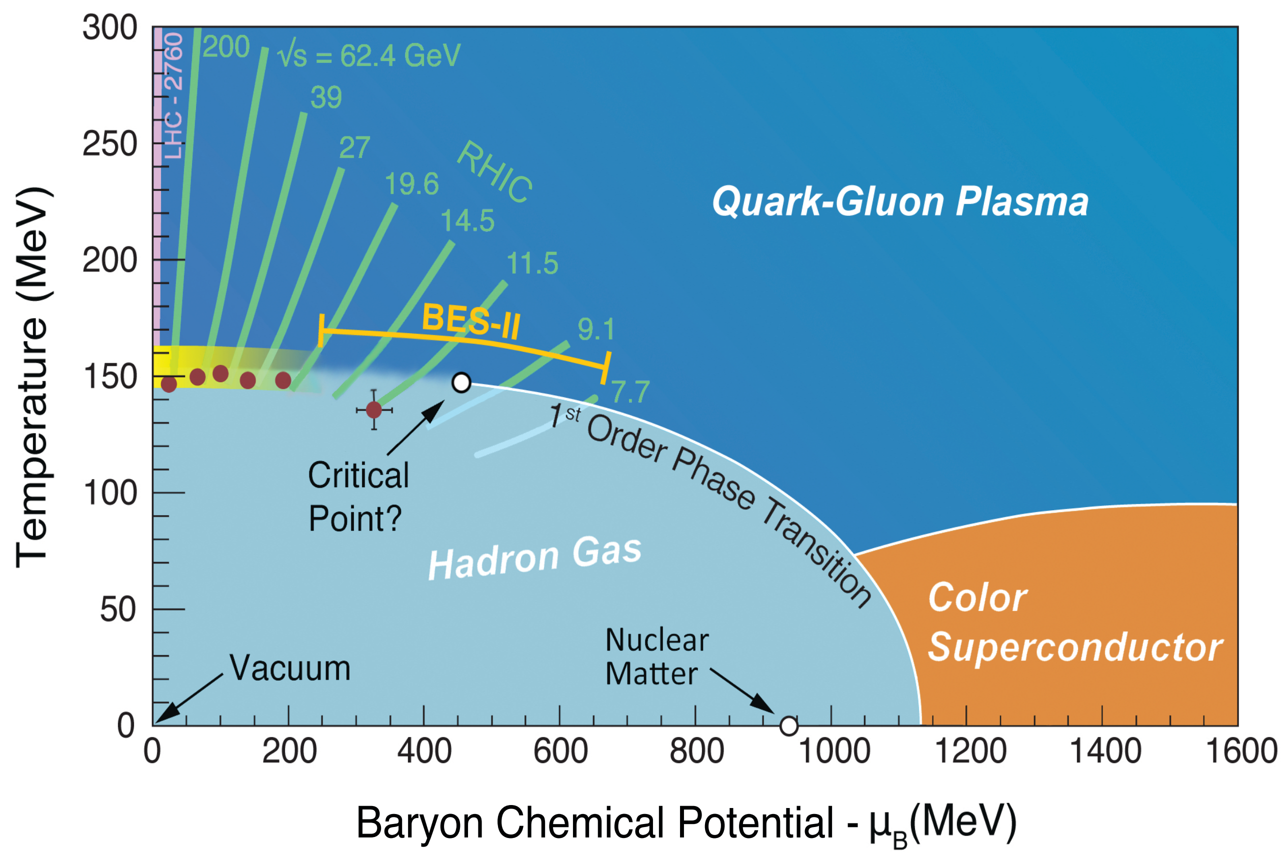
Beam energy scan and search for the QCD critical point



- A success paradigm for heavy-ion collisions: Lattice E.O.S +hydro.
- New ingredients near critical point: critical statics + critical dynamics.

Critical Fluctuations and Static Universality

- Fluctuations of critical mode σ : scale with correlation length near a critical point.

- Higher cumulants: stronger dependence on $\xi_{\rm eq}$, universal pattern in sign (Stephanov, 2009, 2011) from static universality (the same as 3d Ising model).

$$\kappa_2^{eq} \equiv \langle \delta\sigma^2 \rangle \sim \xi_{eq}^2$$

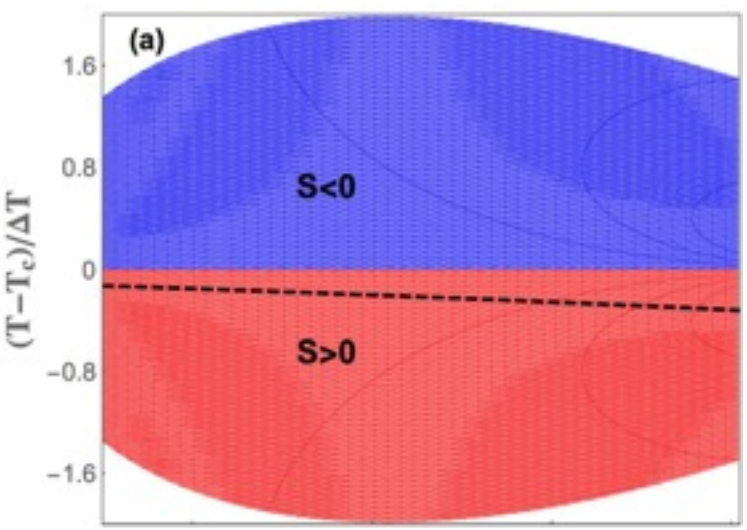
$$\kappa_3^{eq} \equiv \langle \delta\sigma^3 \rangle \sim \xi_{eq}^{4.5} \qquad \kappa_4^{eq} \equiv \langle \delta\sigma^4 \rangle - 3\left(\kappa_2^{\rm eq}\right)^2 \sim \xi_{eq}^7$$

- Static universality is not enough and non-equilibrium effects are unavoidable (z=3):

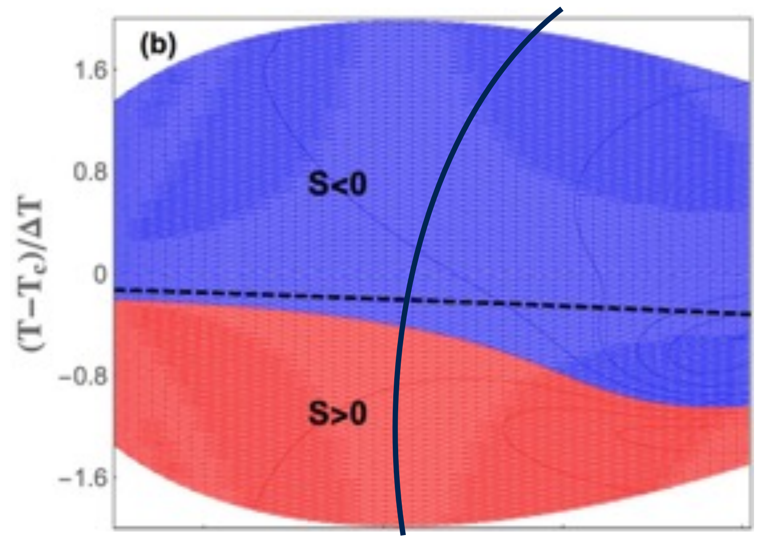
$$\tau_\sigma \sim \xi_{\rm eq}^z$$

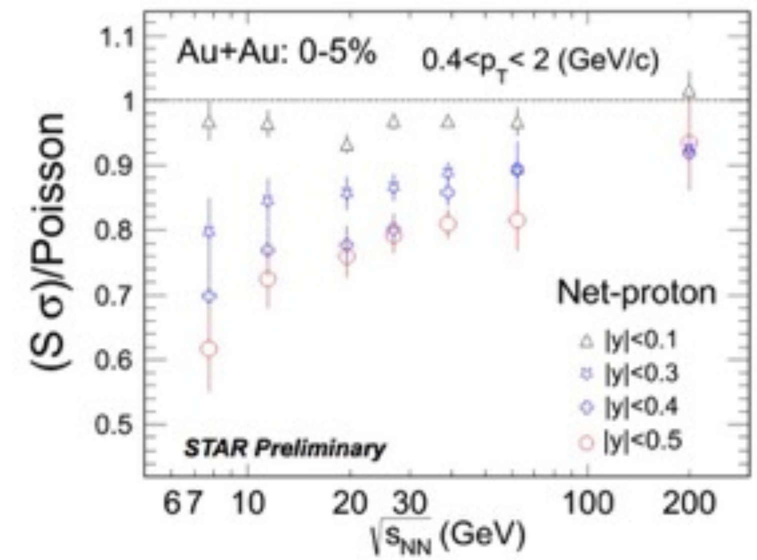
Example: non-equilibrium Skewness

Equilibrium

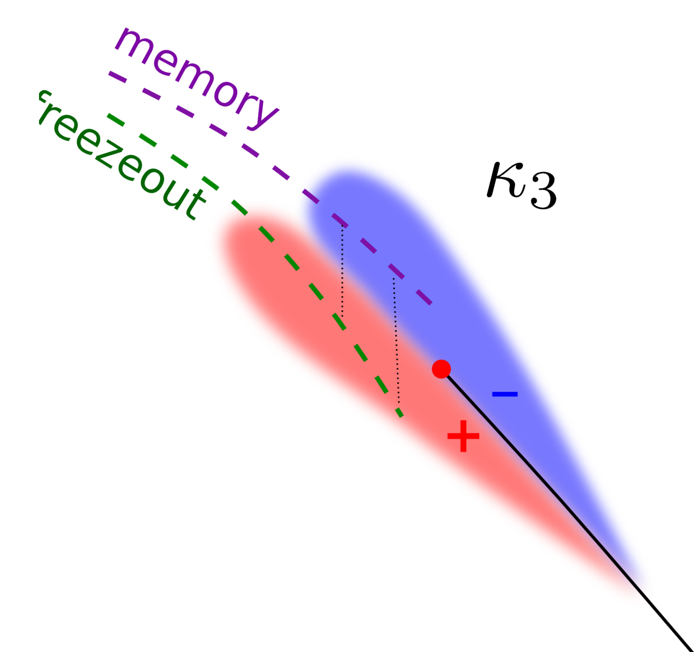


non-equilibrium





Decreasing beam energy



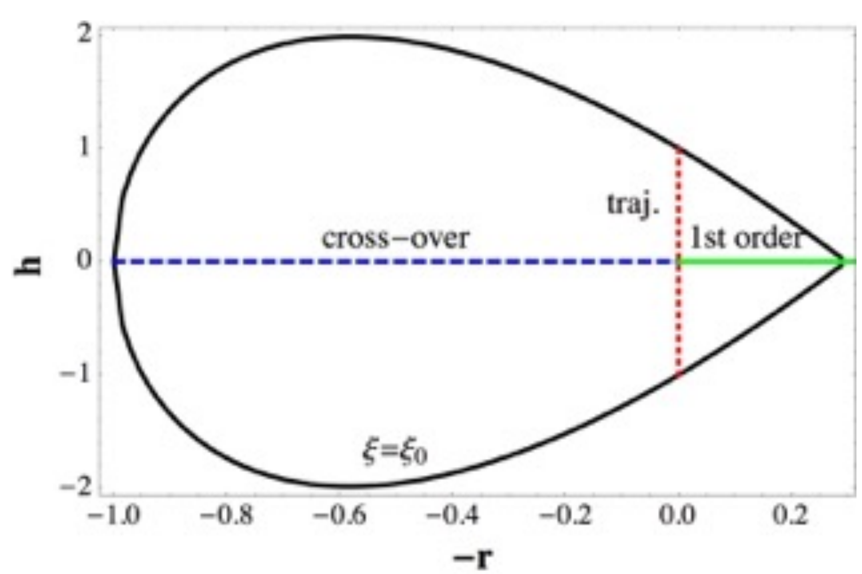
- "Sign puzzle" of skewness: "remembrance of things past" (S. Mukherjee, R. Venugopalan and YY, 1506.00645, PRC; 1512.08022, QM proceedings).

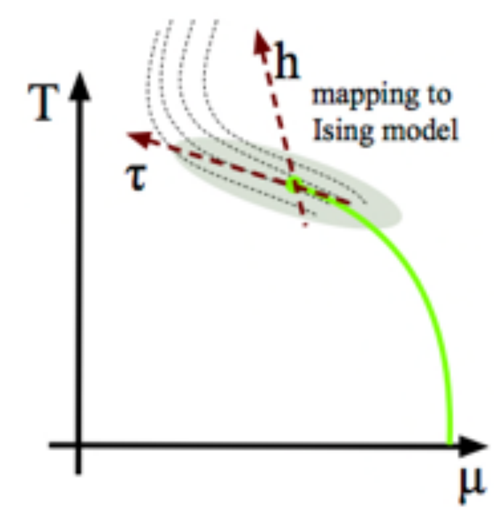
- Critical dynamics: enemy or friend?
- Naively, it is our enemy: non-equilibrium effects require detailed modeling.
- Friend: new signatures for the presence of a critical point!
- Reminder of this talk: two examples
  - Off-equilibrium universal behavior of critical cumulants (S. Mukherjee, R. Venugopalan and YY, 1605.09341).
  - Phenomenological consequences of enhanced bulk viscosity near the QCD Critical Point (A. Monnai S. Mukherjee and YY, 1606.00771).

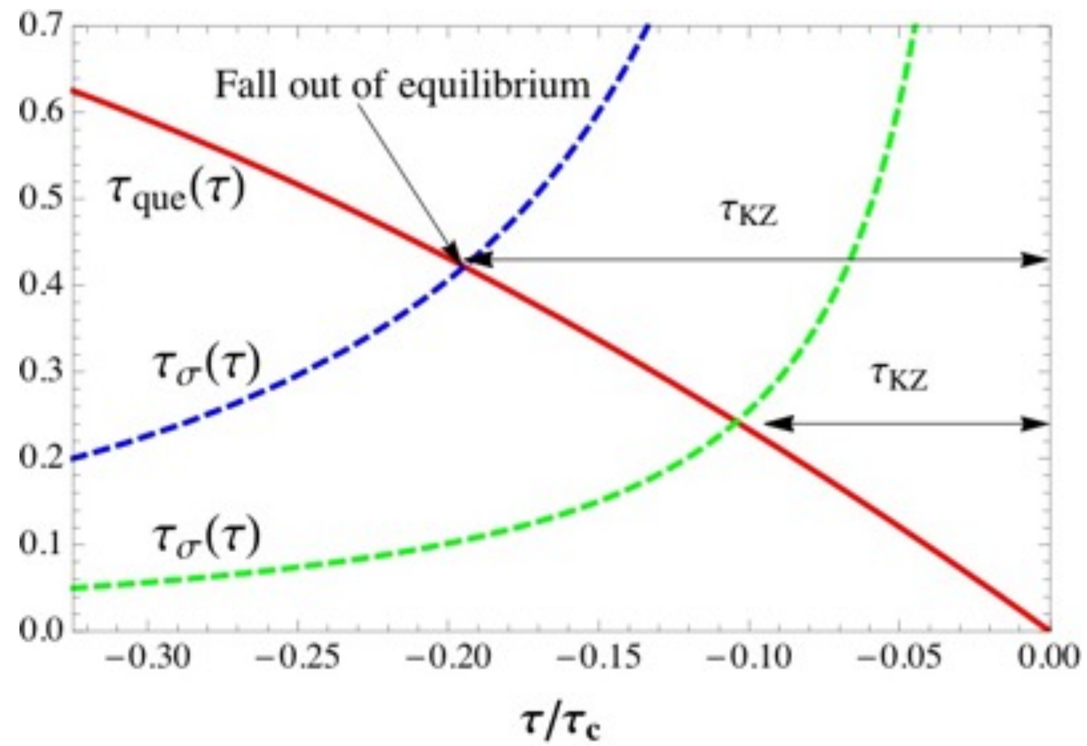
Off-equilibrium universal behavior of critical cumulants

New physics hidden in an old paper

- Consider a trajectory passing the critical point first discussed in Berdnikov-Rajagopal-1999 and study the evolution of non-equilibrium correlation length.







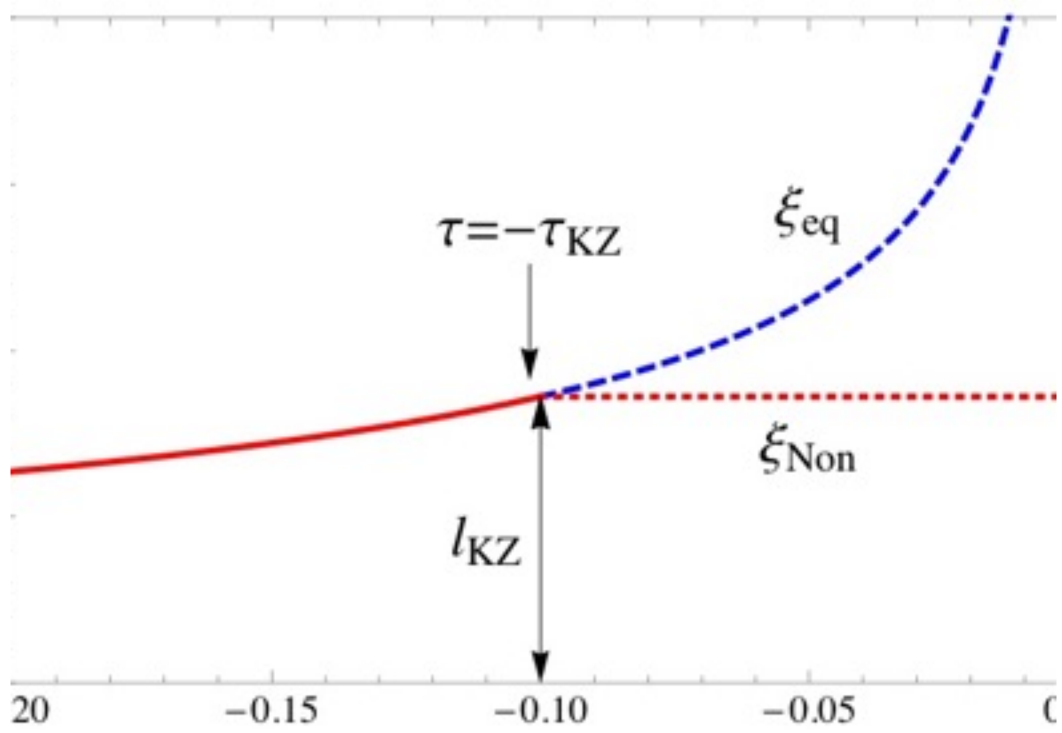
Q: when do non-equilibrium effects become important?

A: relaxation time becomes longer than the "quench" time.

$$\tau_\sigma(\tau) > \tau^{\xi}_{\rm que} \equiv |\frac{\xi_{\rm eq}}{\partial_\tau \xi_{\rm eq}}|$$

- Kibble-Zurek time (Kibble, domain growth in early universe, 1976, Zurek, Superfluid, 1993): an emergent time scale for non-equilibrium dynamics.

$$\tau_\sigma(\tau_{\rm KZ}) = \tau_{\rm que}(\tau_{\rm KZ})$$



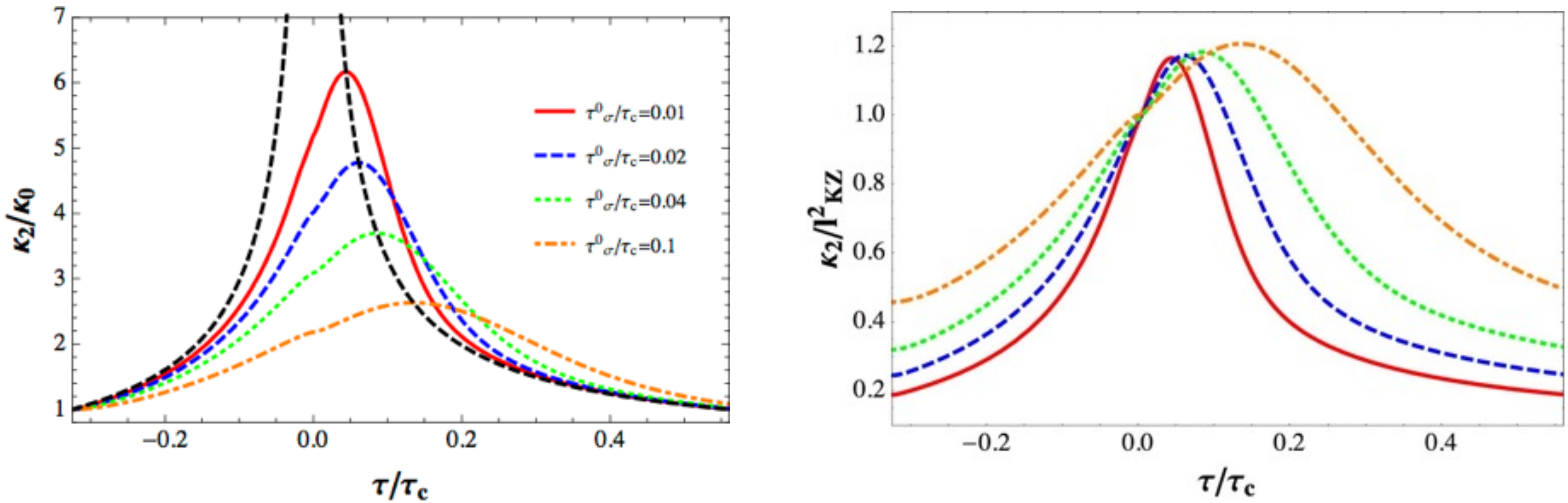
- A simple approximation: the evolution is frozen .

$$l_{KZ} = \xi_{eq}(\tau_{KZ})$$

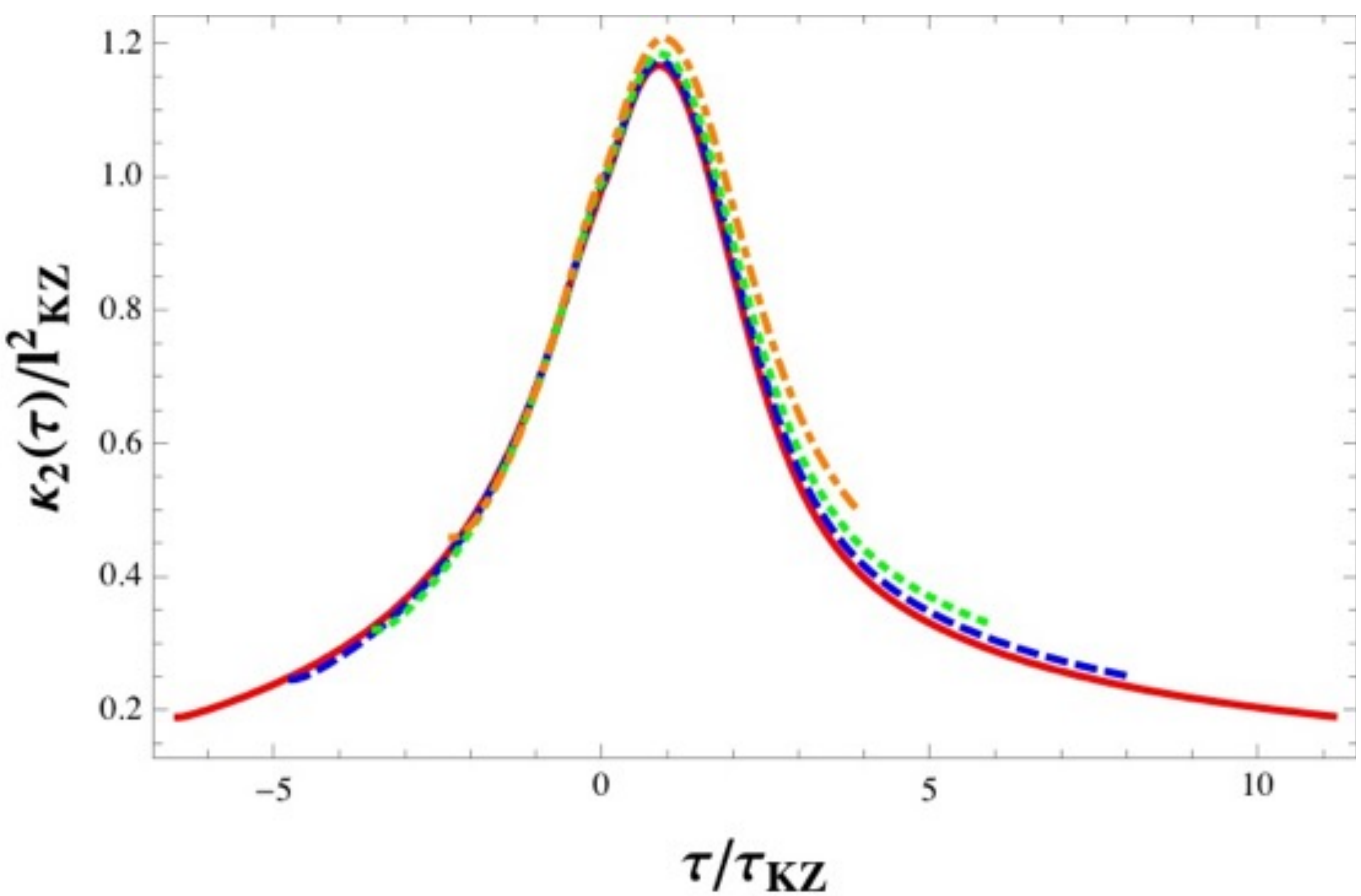
- Kibble-Zurek dynamics: l_{KZ}, τ_{KZ} determine the length and time scale of the non-equilibrium evolution.

- For example: $\kappa_2 \sim l_{KZ}^2$ and $\kappa_3 \sim l_{KZ}^{9/2}$ $\kappa_4 \sim l_{KZ}^7$

Scaling with length is not enough



- Let us rescale Gaussian cumulants determined from Berdnikov-Rajagopal model by l_{KZ}^2 .
- The peak value now looks universal, but time-dependence does not.
- A step forward: let us rescale time by τ_{KZ} !



- We illustrated the existence of a scaling function:

$$\kappa_2(\tau;\Gamma) \sim l^2_{\mathrm{KZ}}(\Gamma)\ \underbrace{f_2\left(\tau/\tau_{\mathrm{KZ}}(\Gamma)\right)}_{\text{Universal}}$$ (Γ: non-universal inputs)

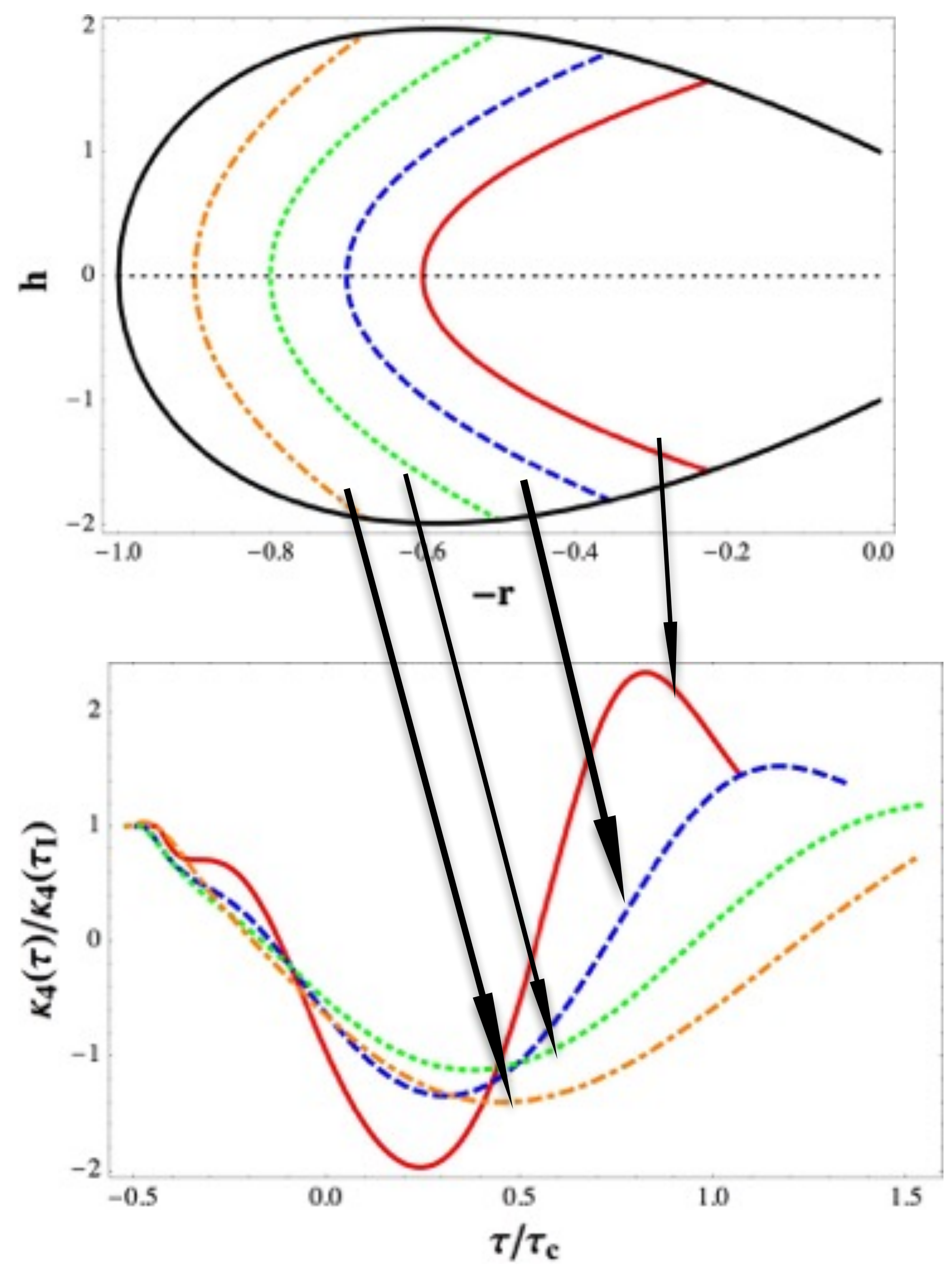
- NB: the study of non-equilibrium dynamical scaling is a new frontier in critical dynamics.

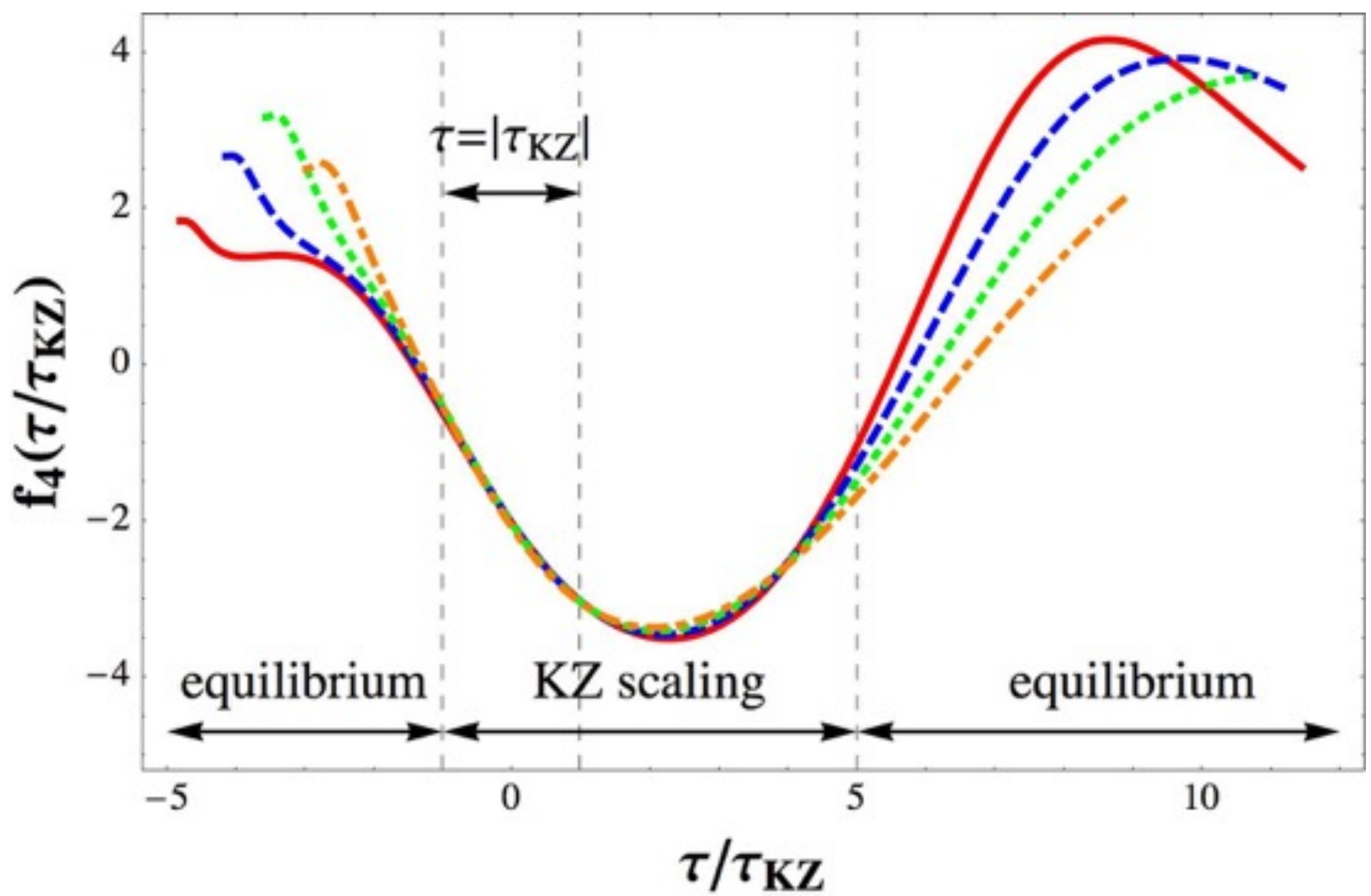
- What does Kibble-Zurek scaling imply for search for QCD critical point via Beam energy scan program?
- To-do list:
  - Formulating and testing scaling hypothesis for non-Gaussian cumulants (done!).
  - Generalizing non-equilibrium scaling for trajectories away from the critical point (done!).

(S. Mukherjee, R. Venugopalan and YY, 1605.09341).

Demonstration: off-equilibrium scaling for kurtosis.

$$\kappa_n(\tau;\Gamma) \sim l^{\#}_{\mathrm{KZ}}(\Gamma)\, f_n(\tilde{t}, \theta_{\mathrm{KZ}})$$





- Connecting to experimental observables in progress !

Our vision: "observables sensitive to critical dynamics in heavy-ion collisions should be expressible as universal scaling functions, thereby providing powerful model independent guidance in searches for the QCD critical point" (S. Mukherjee, R. Venugopalan and YY, 1605.09341).

Bulk viscous effect near the QCD critical point

Hydrodynamics near a critical point

- If QCD critical point is probed by a heavy-ion collision, can we identify other signals in addition to fluctuation measures?

- Specifically, how would critical behavior of transport coefficient affect bulk evolution and produced particle spectrum.

$$\text{(Baryon) conductivity}\, \sigma \sim \xi_{\mathrm{eq}}\,,$$
$$\text{diffusive constant}\, D \sim \xi_{\mathrm{eq}}^{-1}\,,$$
$$\text{shear viscosity}\, \eta \sim \xi_{\mathrm{eq}}^{\mathcal{O}(\epsilon)}$$

- In particular, bulk viscosity strongly depends correlation length: $\zeta \sim \xi_{\mathrm{eq}}^{3}$.

Bulk viscous effect

- Considering second order viscous hydro. (Israel-Stewart theory) with finite baryon density.

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + (p - \Pi)\,\Delta^{\mu\nu} + \text{shear viscous term}$$

$$\begin{aligned} \partial_\mu T^{\mu\nu} &= 0\,, \\ \partial_\mu J^\mu &= 0\,, \\ u^\mu \partial_\mu \Pi &= \frac{1}{\tau_\Pi}\left[\Pi_\zeta - \Pi\right]. \end{aligned}$$

$\Pi_\zeta \equiv \zeta \partial_\mu u^\mu$ (Navier-Stokes limit)

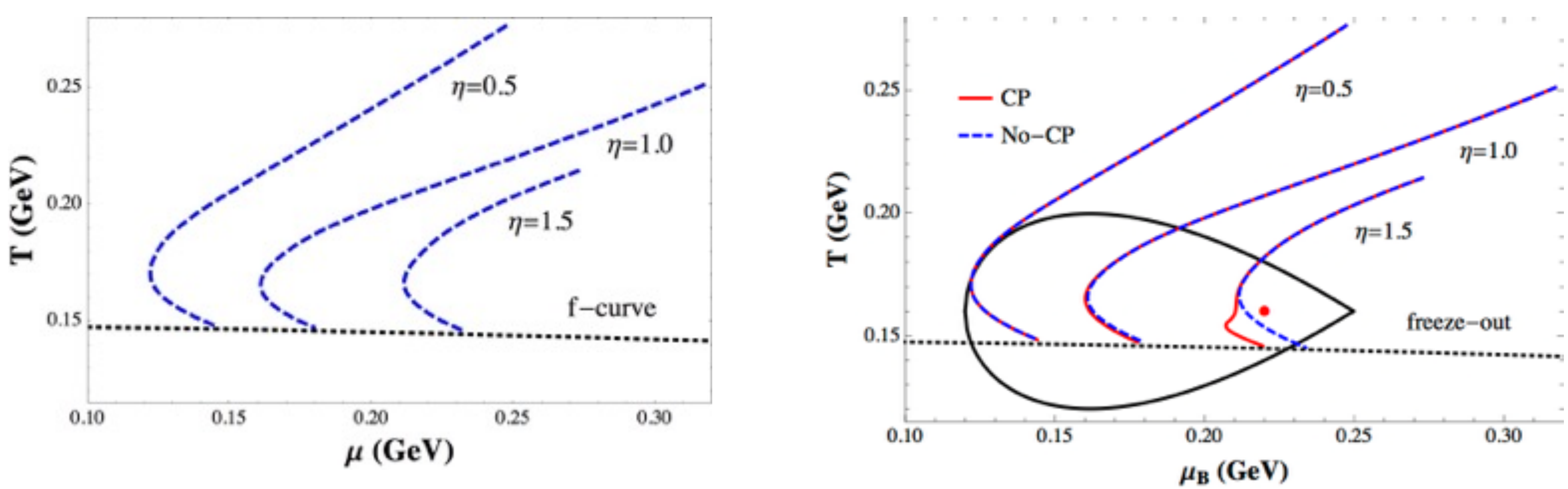
- Bulk viscous pressure will grow. The growth of bulk pressure is limited by finite time effects (c.f. Song-Heinz, 2009).

- The behavior of τ_Π near a critical point is unknown in literature. We argue (A. Monnai, S. Mukherjee and YY, 1606.00771):

$$\tau_\Pi \sim \tau_\sigma \sim \xi_{\rm eq}^3$$

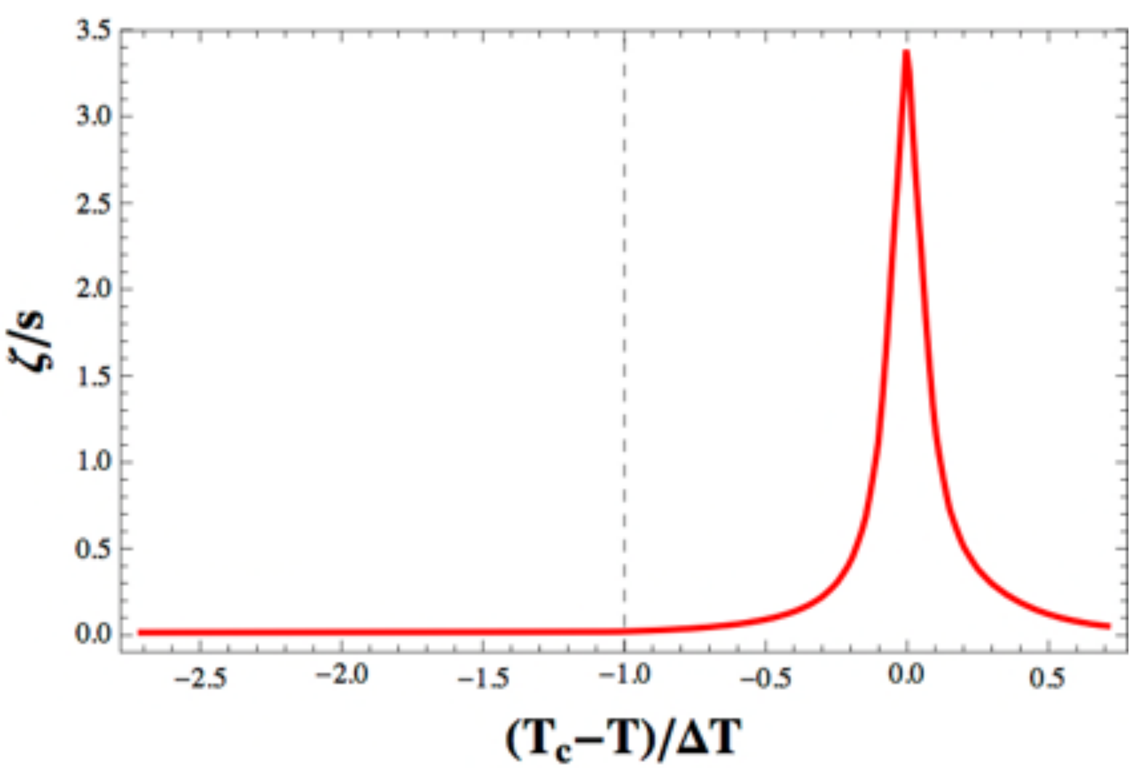
Hydro. Set-up

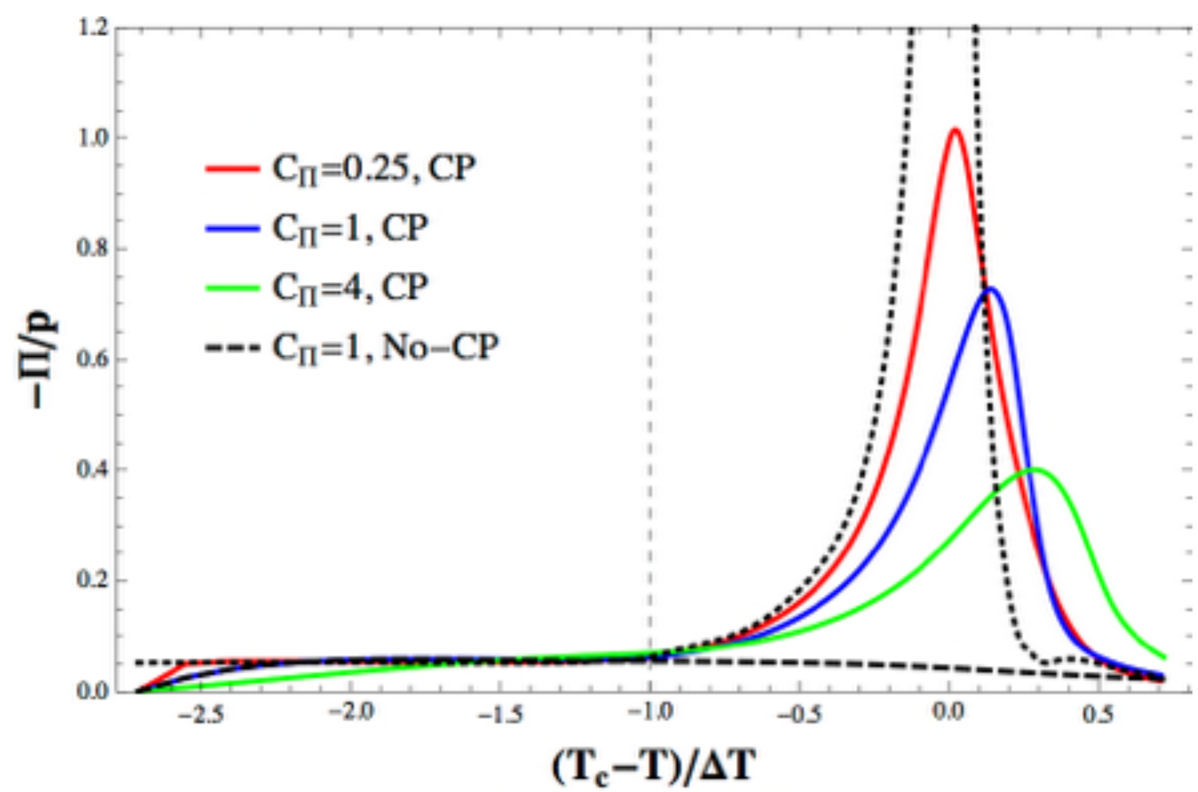
- We solved 1+1 (non-boost invariant longitudinal) hydro. with bulk viscous term only.
  - E.O.S: lattice QCD with Taylor expansion.
  - Initial condition: CGC (energy density) + Valence quark dist. (baryon density).
  - Implementing critical behavior: $\zeta = \zeta_0 \left(\frac{\xi_{eq}}{\xi_0} \right)^3 \qquad \tau_\Pi = \tau_{\Pi,0} \left(\frac{\xi_{eq}}{\xi_0} \right)^3$
- We compare evolution with and without critical point at fixed beam energy (17 GeV).



Growth of bulk viscous pressure

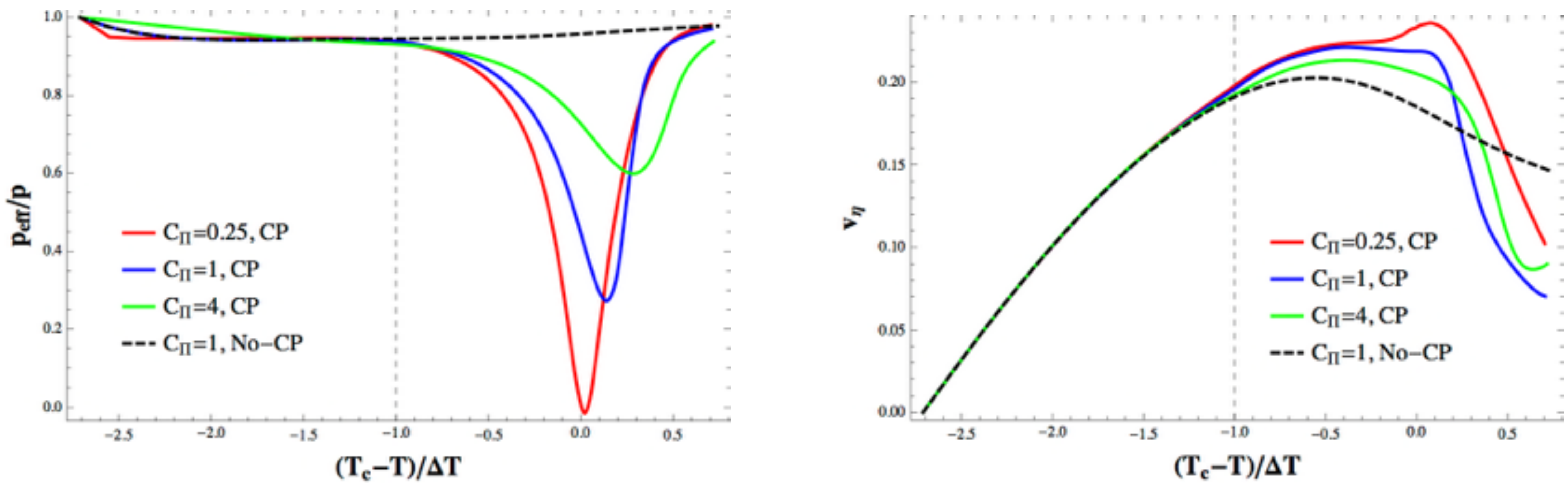
- Tracking evolution along a trajectory with fixed spatial rapidity :$\eta = 1.5$





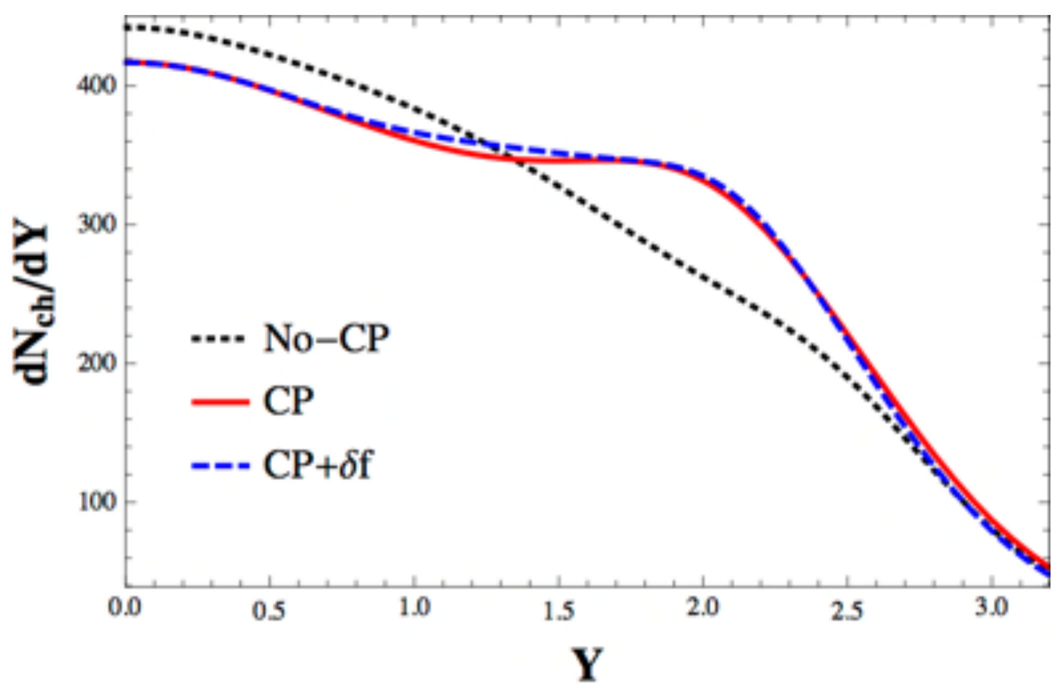
$$\tau_\Pi^0 = C_\Pi \frac{18 - (9\ln 3 - \sqrt{3}\pi)}{24\pi T}$$

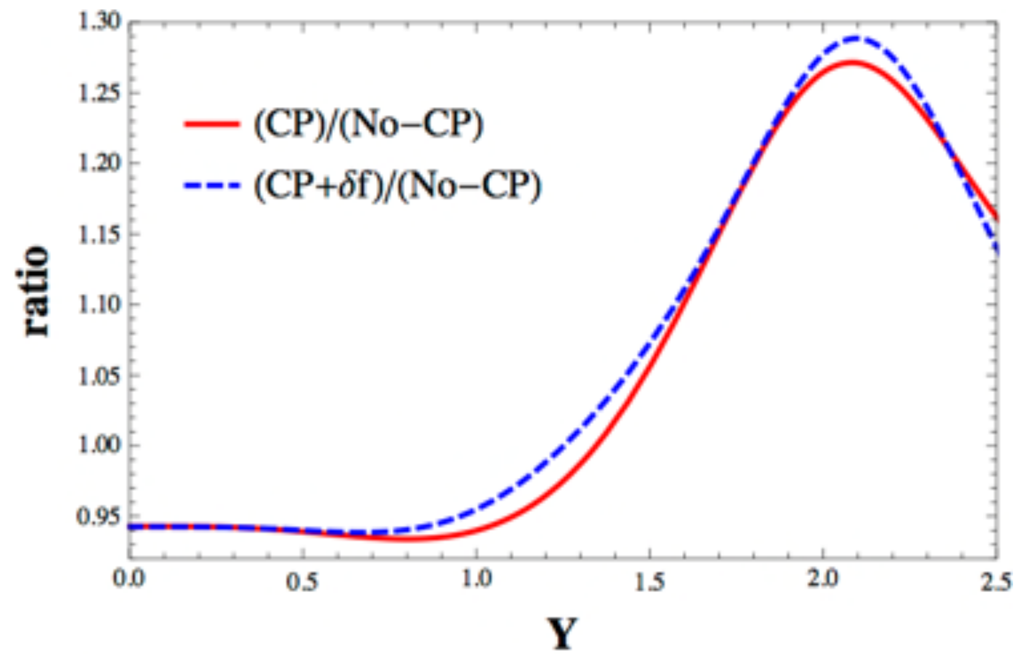
Suppression of effective pressure (softening)



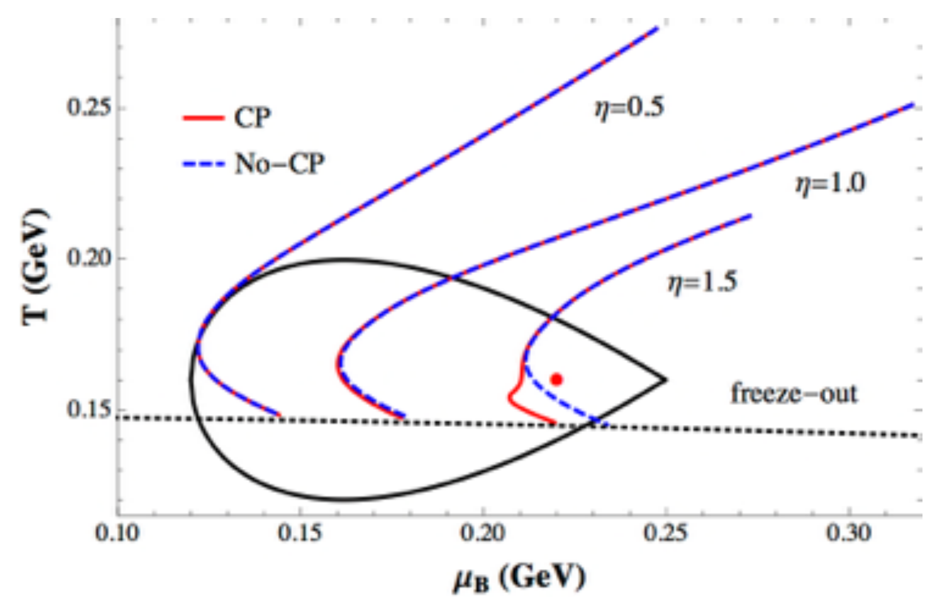
- Effective pressure in the critical regime is reduced.
- Bulk viscous effects influence flow observables. $\partial_t \vec{v} \propto \nabla p_{eff}$

Charged particle number distribution

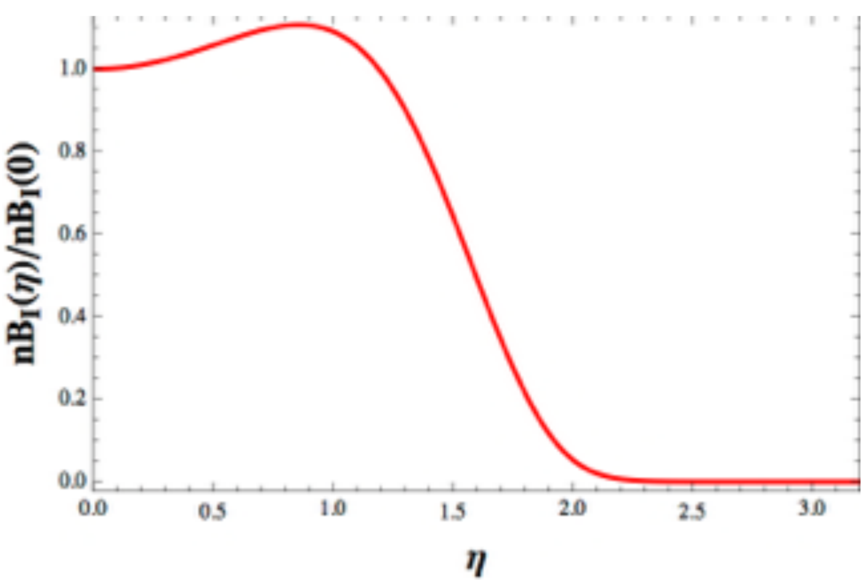




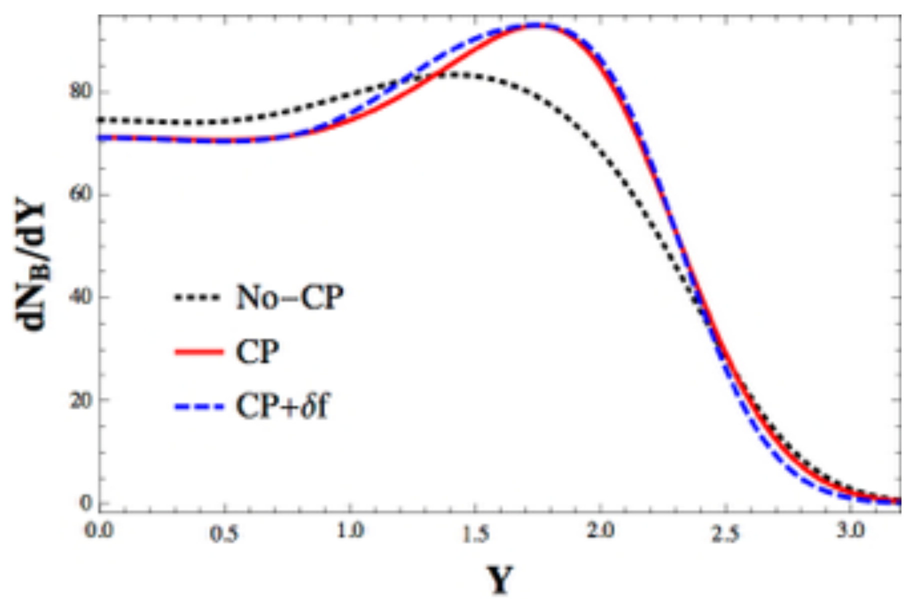
- Evolution with a critical point exhibits sizable difference.
- Difference is sensitive to the rapidity window.

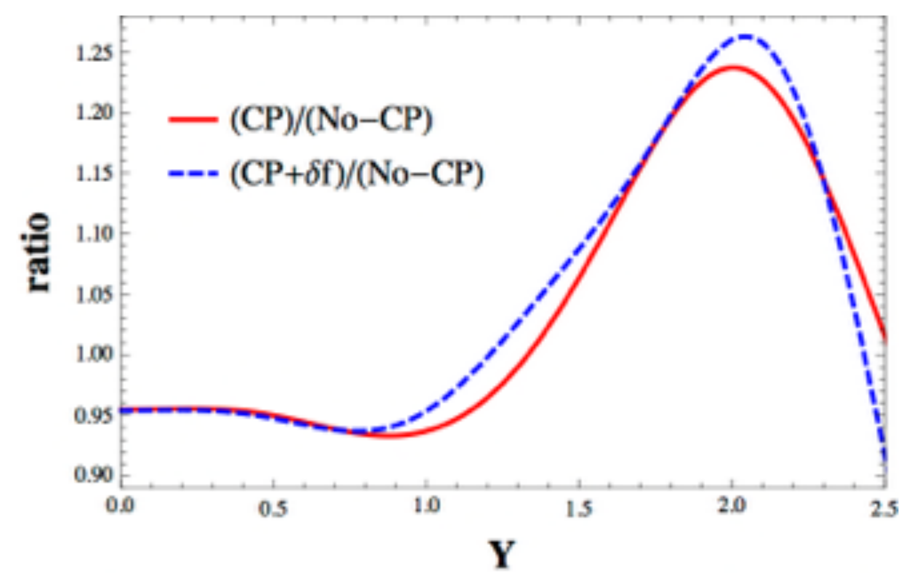


Baryon number distribution: similar



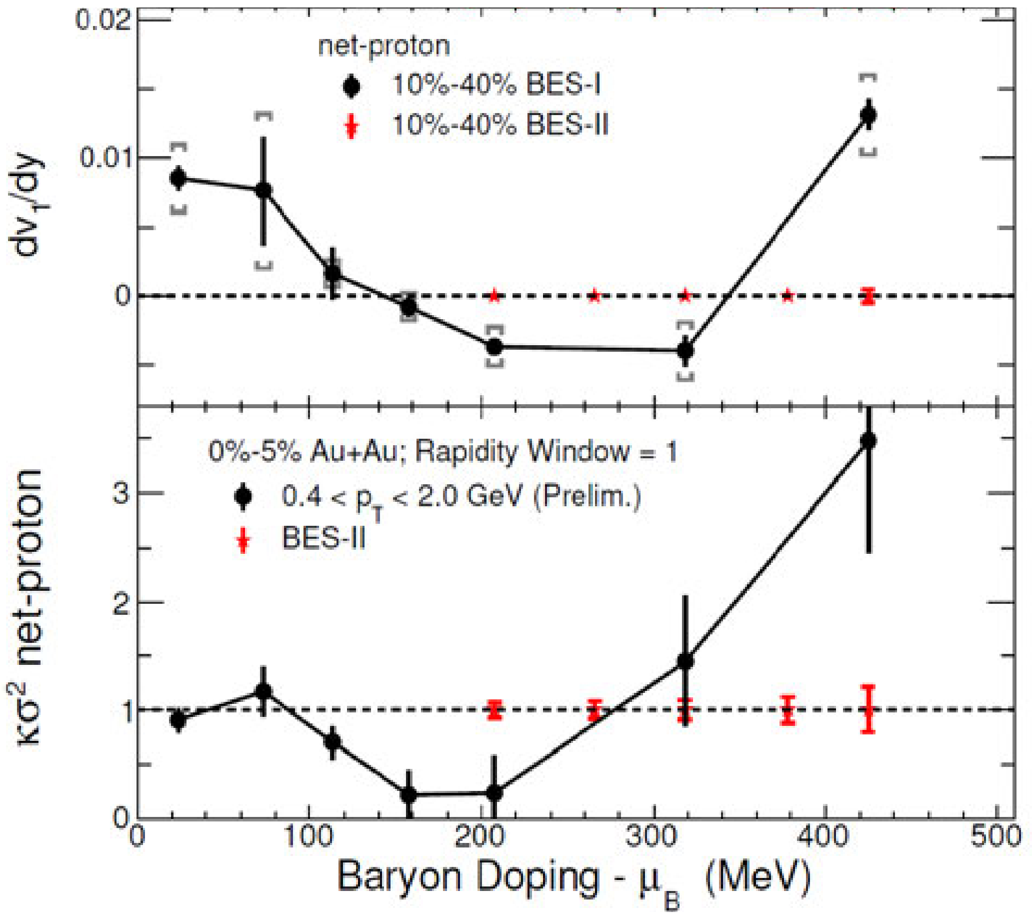
(Initial condition)

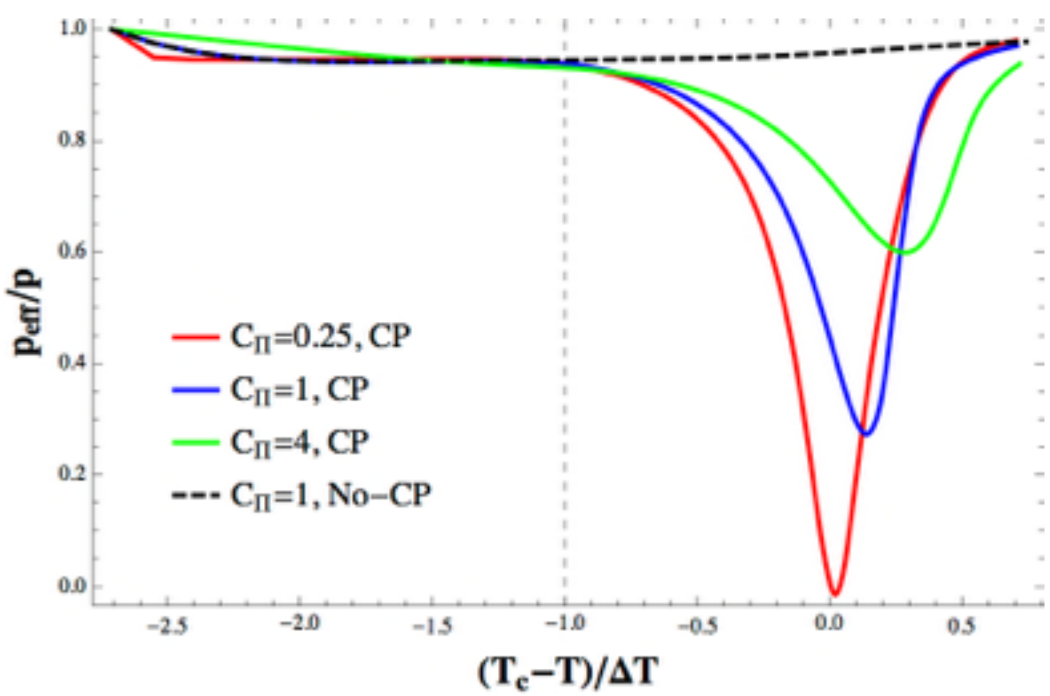




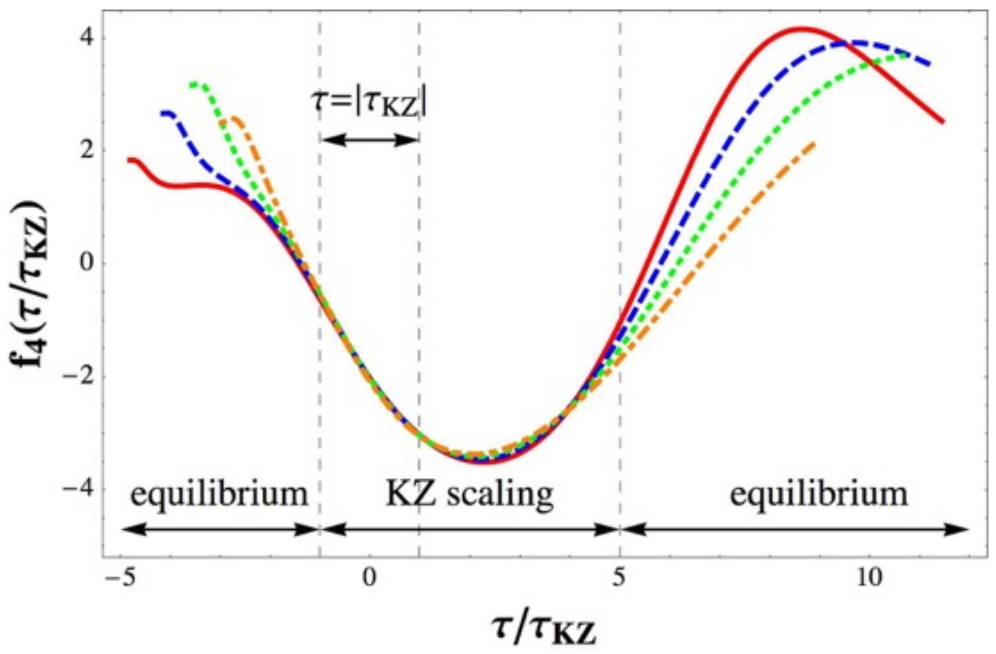
Implications

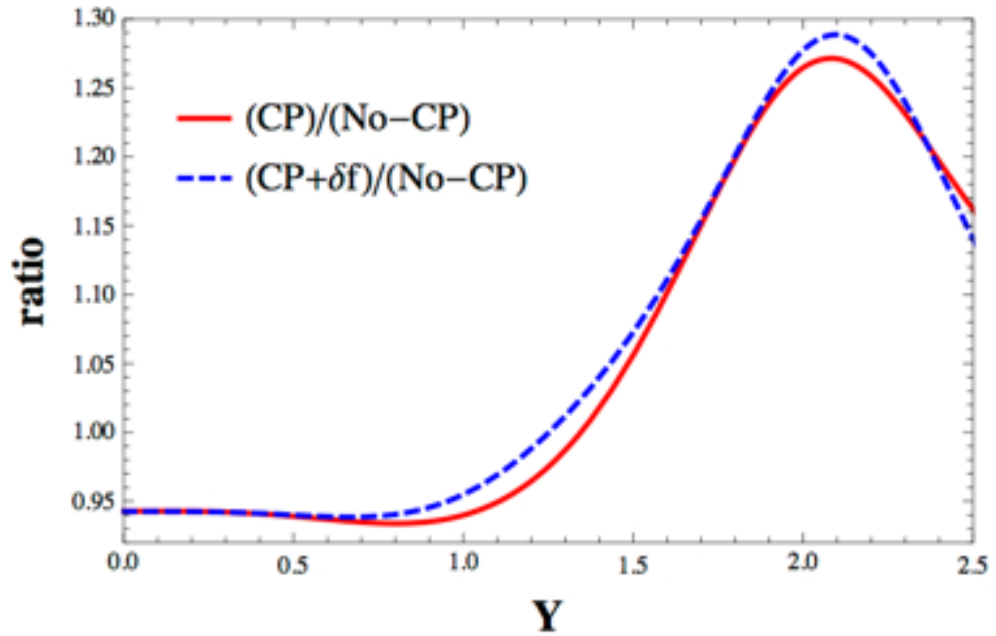
- Flow observables: complementary and correlated to fluctuation measures.
- Enhanced bulk viscous effect effectively softens the pressure. ("anomalous pressure" in data?)





Summary





- Critical dynamics: one of the least explored regime, many interesting questions awaiting us.