Freezing out critical fluctuations

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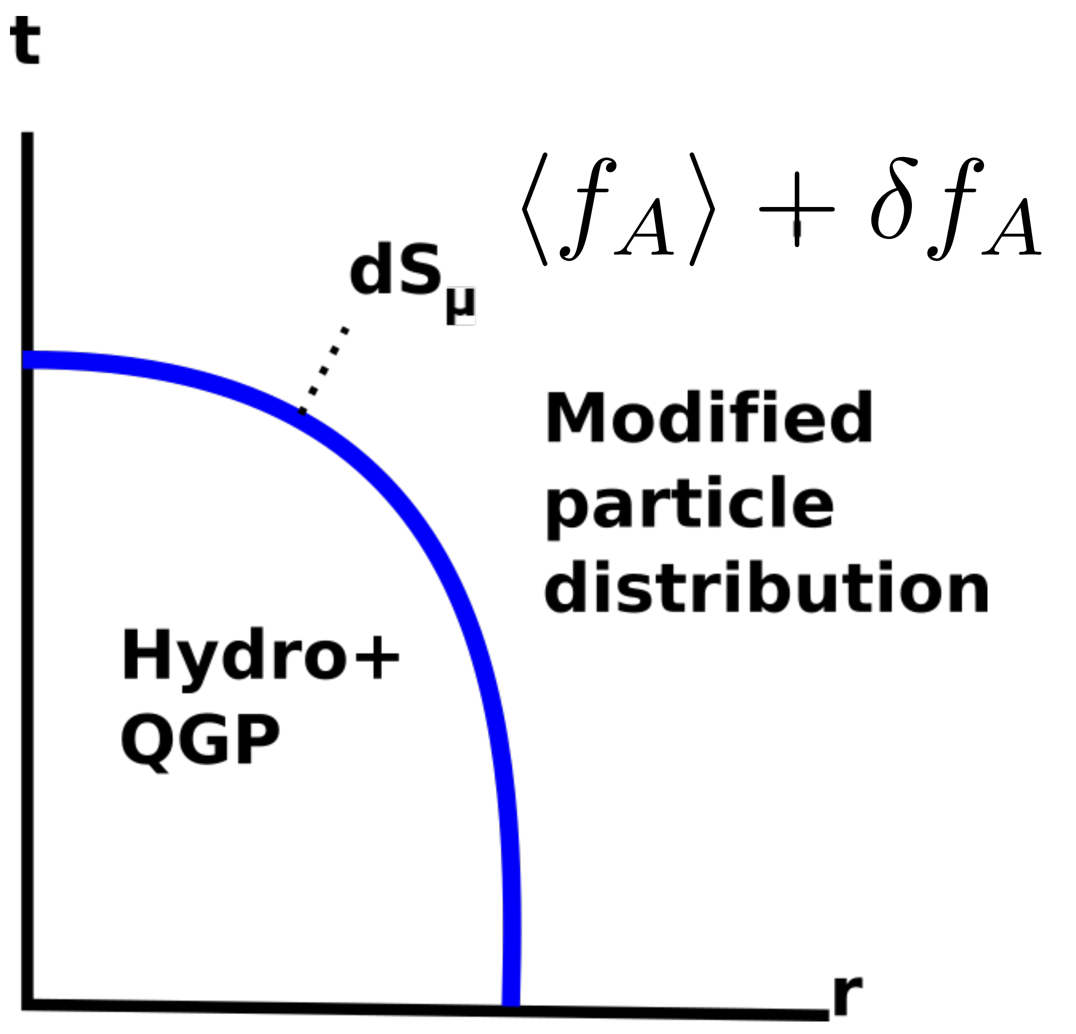
Premise :

- Particle multiplicity fluctuations are observables for QCD critical point
- The evolution of critical fluctuations of the QGP can be described by Hydro+
- Models and simulations of Hydro+ in semi-realistic backgrounds are available
- Traditional Cooper-Frye freeze-out procedure is inadequate to translate these fluctuations into cumulants of particle multiplicities

Our goal : A freeze-out procedure that turns hydrodynamics + fluctuations into observables, particle correlations and cumulants

Extended Cooper-Frye freeze-out procedure

Hydro+->Particles



As in Cooper-Frye freeze-out [2],

$$N_A = \int dS_\mu \int Dp\, p^\mu\, f_A(x,p)$$

But now also [1],

$$\langle \delta N_A^2 \rangle = \langle N_A \rangle + \langle \delta N_A^2 \rangle_\sigma$$

- We incorporate the effects of critical fluctuations via the modification of particle masses due to their interaction with a **critical sigma field**
- The particle distribution thus gets modified as, $\delta m_A \approx g_A \sigma$

$$f_A = \langle f_A \rangle + g_A \frac{\partial \langle f_A \rangle}{\partial m_A} \sigma$$

- The two point correlation function of sigma field is **matched** to the slowest mode, the two point correlation function of s/n obtained from Hydro+ simulation

$$\langle \sigma \rangle = 0, \quad \langle \sigma(x_+)\sigma(x_-) \rangle \equiv Z\tilde{\phi}(x,\Delta x) = Z \left\langle \delta\frac{s}{n}(x_+)\delta\frac{s}{n}(x_-) \right\rangle$$

$$\langle \delta N_A^2 \rangle_\sigma = g_A^2 \int dS_\mu J_A^\mu(x_+) \int dS_\nu J_A^\nu(x_-)\, Z(x)\tilde{\phi}(x,\Delta\tilde{x})$$

$$J_A^\mu = d_A \int Dp\, p^\mu \frac{\partial \langle f_A \rangle}{\partial m_A}$$

Dynamics of critical fluctuations in an azimuthally symmetric boost invariant background [3]

- The Wigner transform of the slowest mode, the two point function of $\hat{s} \equiv s/n$

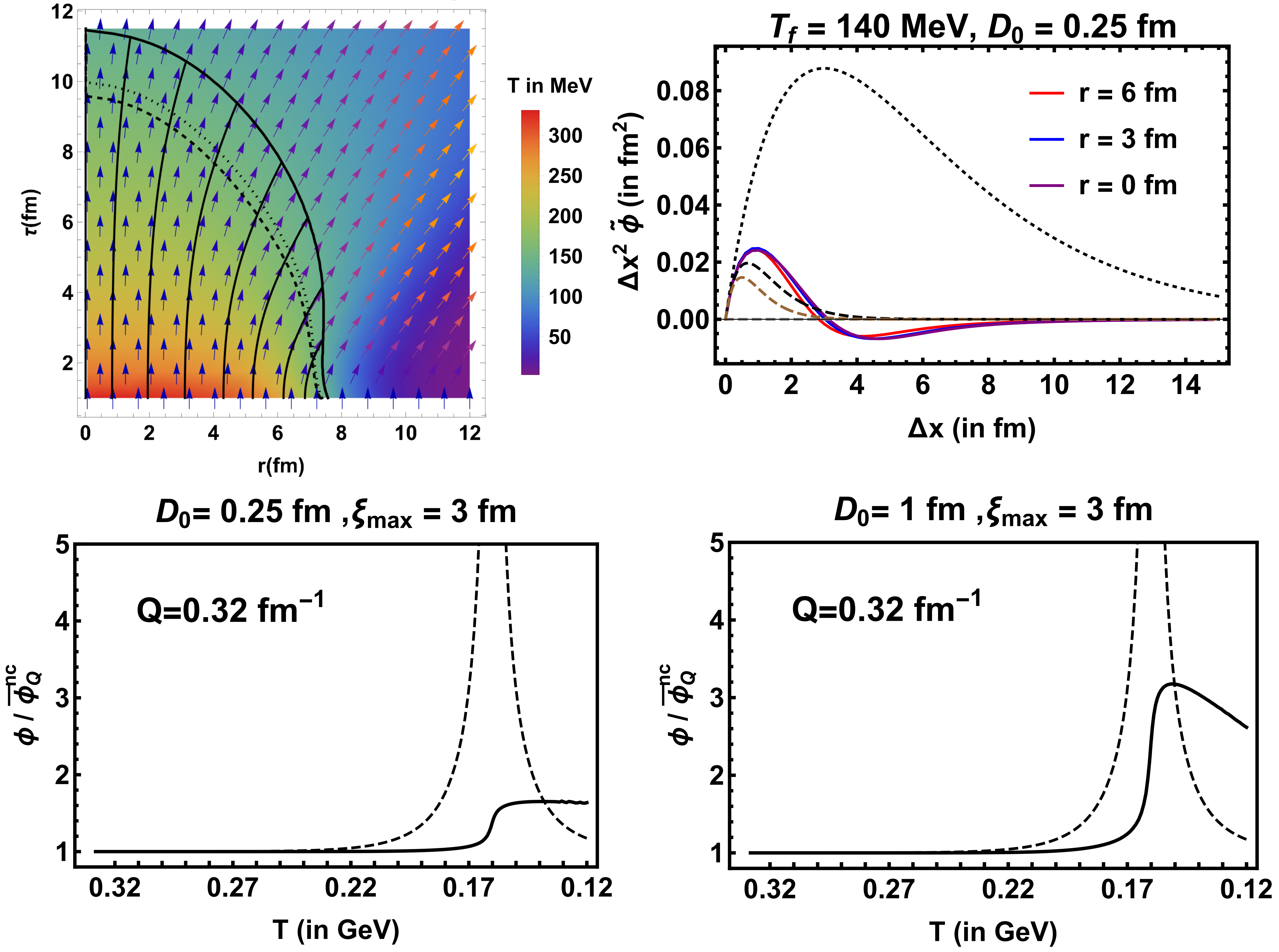
$$\tilde{\phi}(x, \Delta x) \equiv \left\langle \delta\hat{s}(x_+)\, \delta\hat{s}(x_-) \right\rangle = \int_{\mathbf{Q}} e^{i\,\mathbf{Q}\cdot\mathbf{\Delta x}}\, \phi_{\mathbf{Q}}(x)$$

is **evolved** according to Hydro+ equation [4]

$$u \cdot \partial \phi_{\mathbf{Q}} = -\Gamma\left(|\vec{\mathbf{Q}}|\,\xi\right)\left(\phi_{\mathbf{Q}} - \bar{\phi}_{\mathbf{Q}}\right)$$

- The Wigner transform relaxes into its equilibrium form

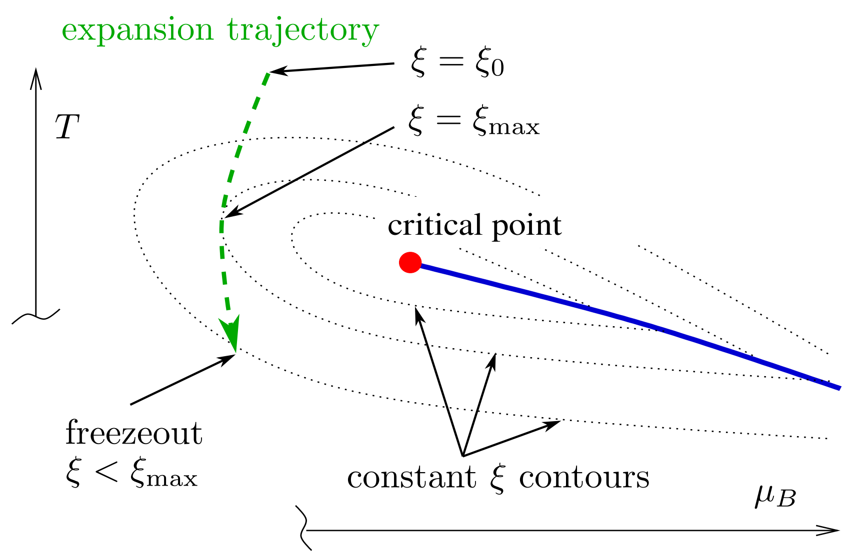
$$\bar{\phi}_{\mathbf{Q}} = \frac{c_p/n^2}{1 + (\mathbf{Q}\xi)^2}$$

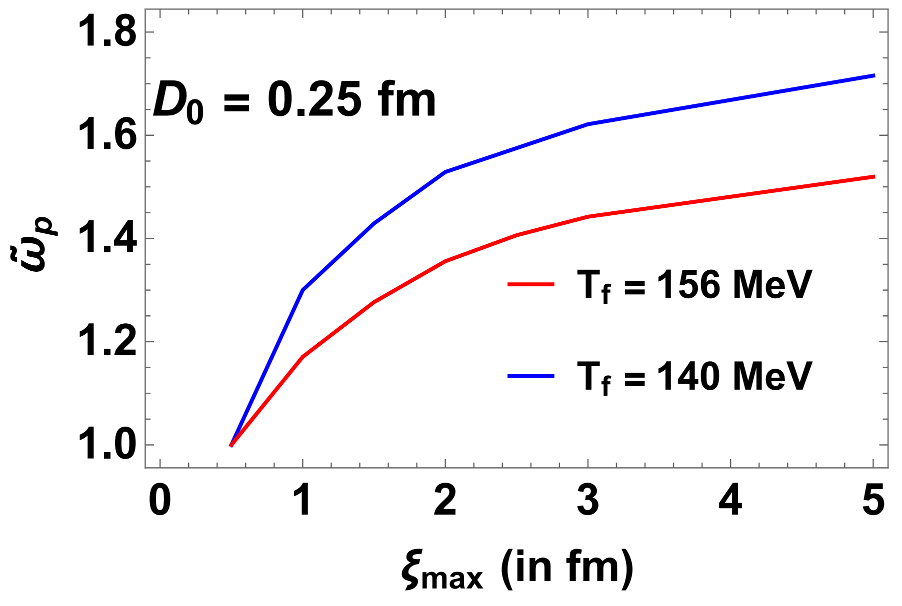


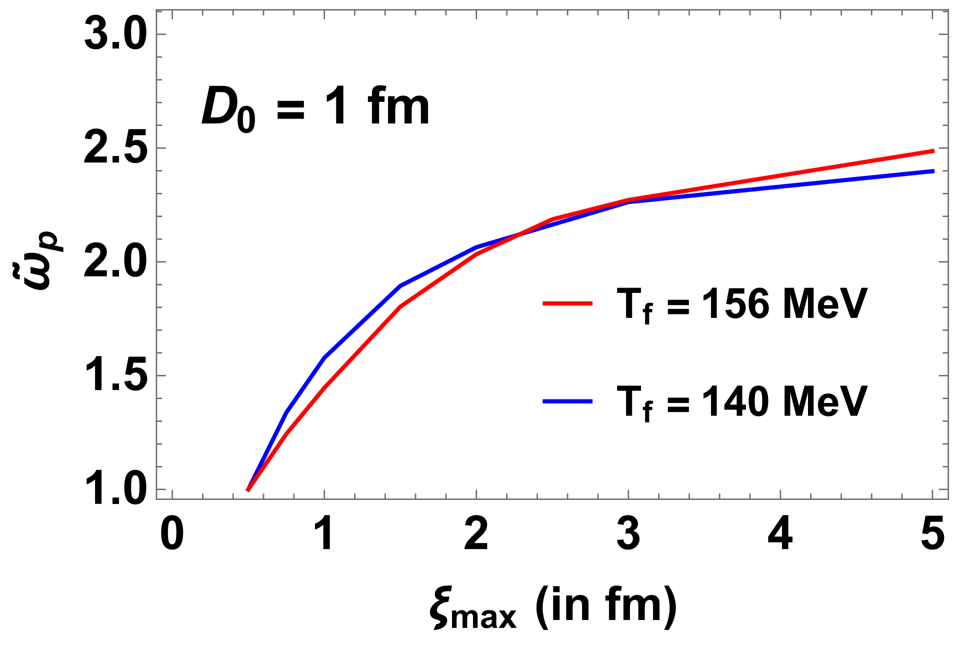
with a relaxation rate consistent with **Model H dynamics**, relevant for fluctuations of conserved quantities

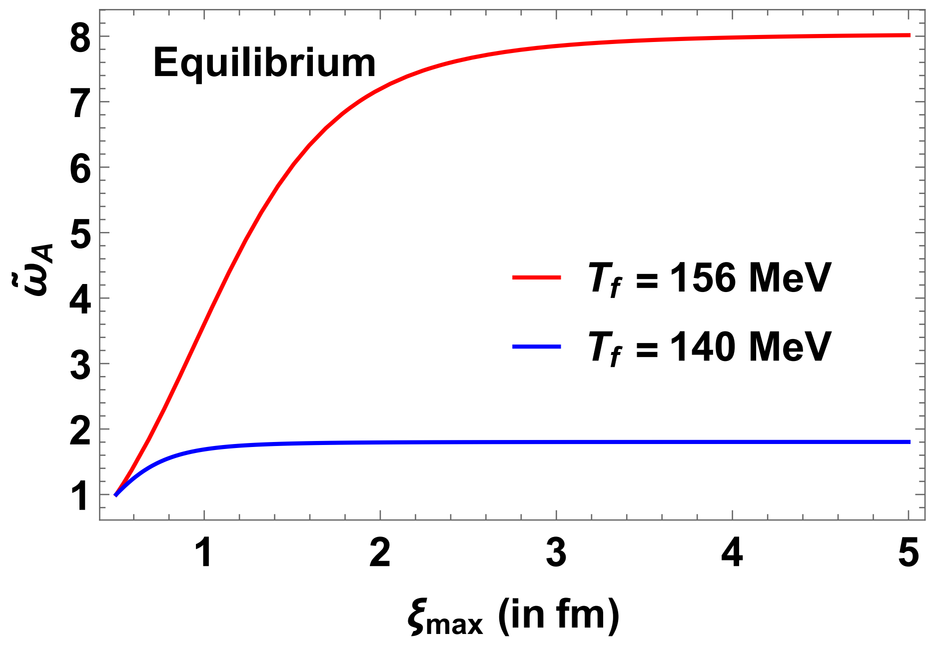
$$\Gamma(x) = \frac{D_0 \xi_0}{\xi^3} K(x),\; K(x) \sim x^2 \textbf{ for } x \ll 1$$

A semi-realistic estimate of the critical contribution to the second cumulant of proton multiplicity









$T_c = 160$ MeV (T when $\xi = \xi_{max}$)

$$\omega_A(y_{max}) \equiv \frac{\left\langle \delta N_A^2(y_{max}) \right\rangle_\sigma}{\left\langle N_A(y_{max}) \right\rangle}$$

$$\tilde{\omega}_A \equiv \frac{\omega_A}{\omega_A^{nc}}$$

$$\tilde{\omega}_A^{eq} = \frac{\xi^2(T_f)}{\xi_0^2}$$

ω_A^{nc} is a non-critical estimate

* The normalized fluctuation measure is independent of g_A, Z and less sensitive to acceptance windows
* The fluctuations are **reduced relative to equilibrium value** (conservation laws)
* Fluctuations increase with D_0 (faster diffusion)
* Compared to the equilibrium scenario, the fluctuations are **less sensitive to freeze-out temperature**

Summary and Outlook

Summary

* We have generalized the Cooper-Frye freeze-out procedure so that not only the averages, but also the fluctuations of the conserved densities are matched on the freeze-out hyper surface
* We have demonstrated the freeze-out in a semi realistic scenario and estimated the dynamical effects for the critical contribution to the Gaussian cumulants of proton multiplicity
* The fluctuations are less sensitive to the freeze-out temperature in an out-of-equilibrium scenario unlike in an equilibrium case

Outlook

* The freeze-out procedure developed here can already be integrated into the full numerical simulation of heavy ion collisions relevant for BES program
* Freeze-out of higher point fluctuations needs to be implemented and analyzed
* There is scope of improving the procedure by adding less singular contributions and modes which are not critical
* The coupling constants gAs need to be determined from the EoS

References

1. Pradeep et al., arXiv: 2204.00639
2. Cooper and Frye, Phys.Rev.D 10 (1974) 186
3. Rajagopal et al., Phys.Rev.D 102 (2020) 9, 094025
4. Stephanov and Yin, Phys.Rev.D 98 (2018) 3, 036006