Coupled baryon, electric charge and strangeness fluctuations in heavy-ion collisions

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Online Strangeness in Quark Matter Conference 2021

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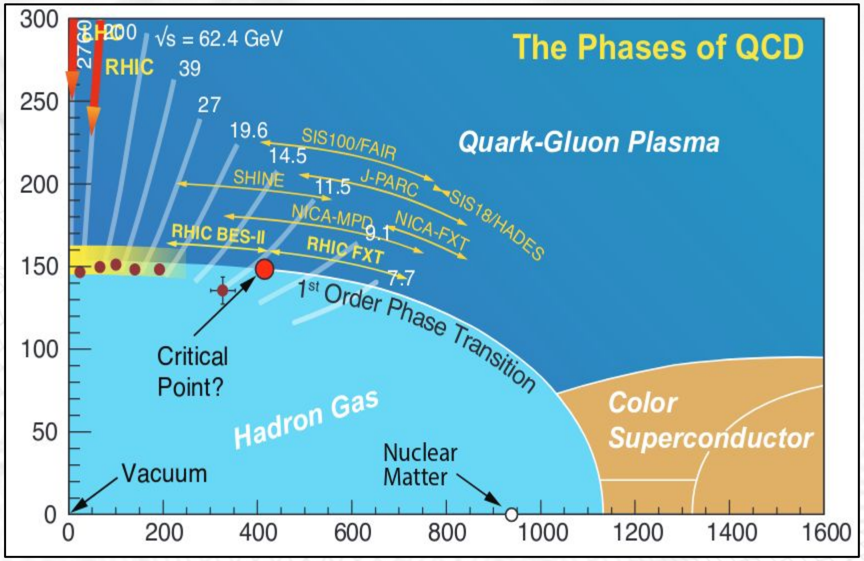
Role of fluctuation observables

- Fluctuations of conserved charges reflect change in degrees of freedom.
  Asakawa, Heinz, Müller, Phys.Rev.Lett.85 (2000)
  Jeon, Koch, Phys.Rev.Lett.85 (2000)

- Highlight phase transitions (critical point, confinement-deconfinement).
  Stephanov, Rajagopal, Shuryak, Phys.Rev.Lett.81 (1998); Karsch, Redlich, Phys.Lett.B.695 (2011)

- Connection with chemical freeze-out if close to phase transition.
  Braun-Munzinger, Stachel, Wetterich, Phys.Lett.B.596 (2004); Alba et al., Phys.Lett.B.738 (2014)



H. Caines, Quark Matter 2017.

❖ Fluctuations of conserved charges change through diffusion:

Asakawa, Kitazawa, Müller, Phys.Rev.C.101 (2020)

➢ How much do they change during a heavy-ion collision ?
➢ Which role plays the coupling between the three (B,S,Q) conserved charges ?

What is the impact of the dynamics/diffusion on the critical point physics and the determination of freeze-out conditions?

Search for the QCD critical point

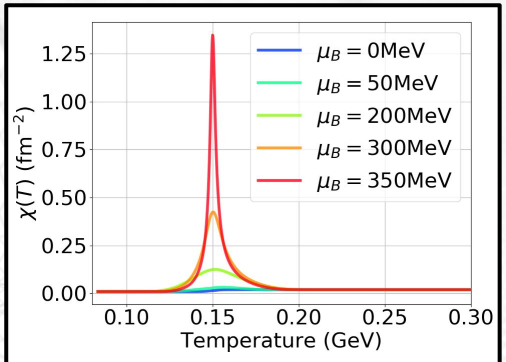
- Dynamics of **net-B** density fluctuations in a Bjorken-type expanding medium via stochastic diffusion

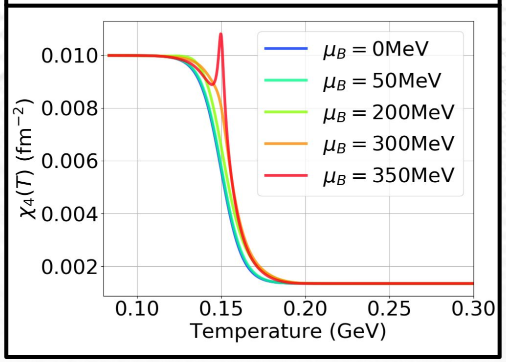
$$\partial_{\tau} n_B = D(\tau)\, \partial_y^2 \left\{ \frac{\delta F}{\delta n_B} \right\} + \partial_y \zeta$$

$$< \zeta(Y)\ \zeta(Y') > \ = 2\, D(\tau)\, \delta(Y - Y')$$

- Susceptibilities of free energy functional F :
  - ➔ Singular part : 3D Ising model
  - ➔ Regular part : connected to lattice QCD

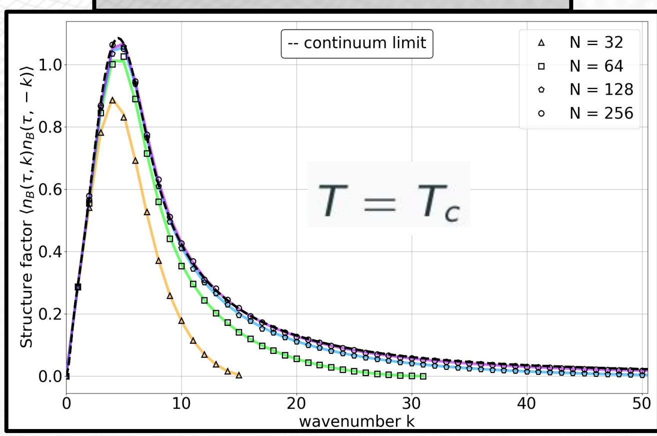
Asakawa, Heinz, Müller, Phys.Rev.Lett.85 (2000)



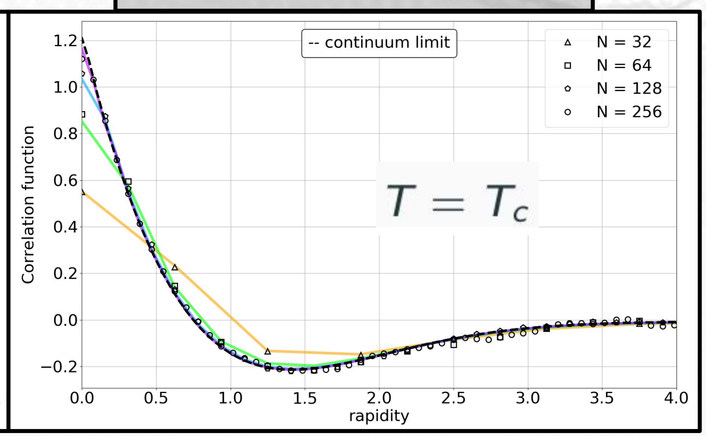


- Successful benchmark tests for Gaussian approximation.

Structure factor



Correlation function



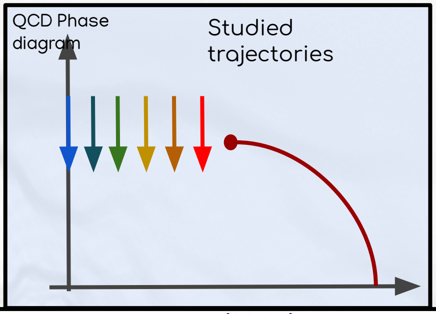
Kitazawa, GP et al, Nucl.Phys.A.1005 (2021); GP et al. in preparation

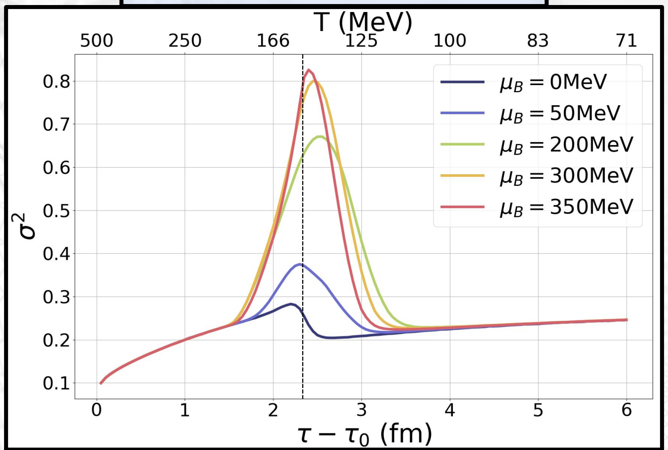
Search for the QCD critical point

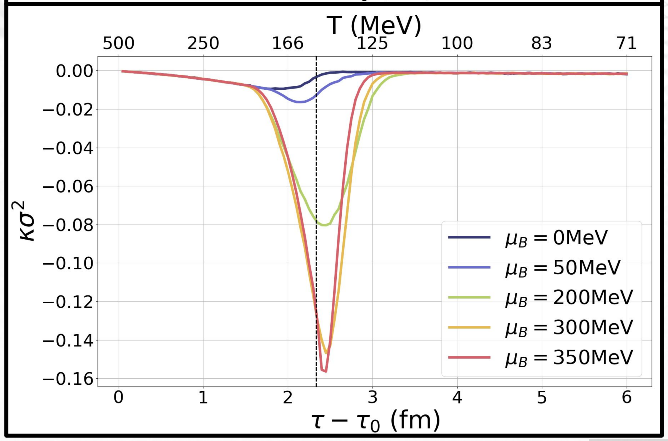
- Time evolution of local variance and kurtosis shows critical point signal for trajectories at larger μ_B.
- Signal quickly decreases for $T > T_c$.

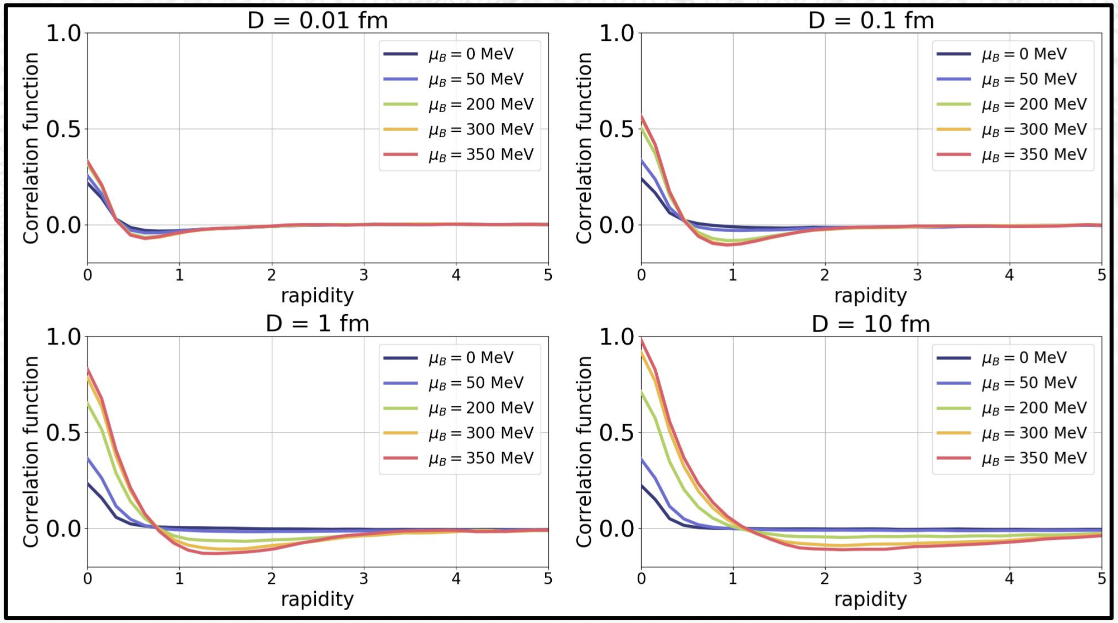
  Strong dependence on freeze-out temperature and diffusion in the late hadronic phase !

- With increasing diffusion length :
  - Diffusion wins over expansion.
  - Observables resemble equilibrium in a static system.









Kitazawa, GP et al, Nucl.Phys.A.1005 (2021); GP et al. in preparation

Coupled dynamics of fluctuations in a HIC

- Diffusion of conserved charges (B,S,Q) in QCD is coupled !
  - Mixing between different diffusive currents.
  - Charge diffusion coefficient matrix κ_{ij}.

Greif et al., Phys.Rev.Lett.120 (2018); Fotakis et al., Phys.Rev.D.101 (2020)

$$\partial_\tau n_i = \partial_y\left(\frac{\kappa_{ij}}{\tau}\partial_y\left(\frac{\mu_j}{T}\right)\right) + \partial_y \zeta_i$$

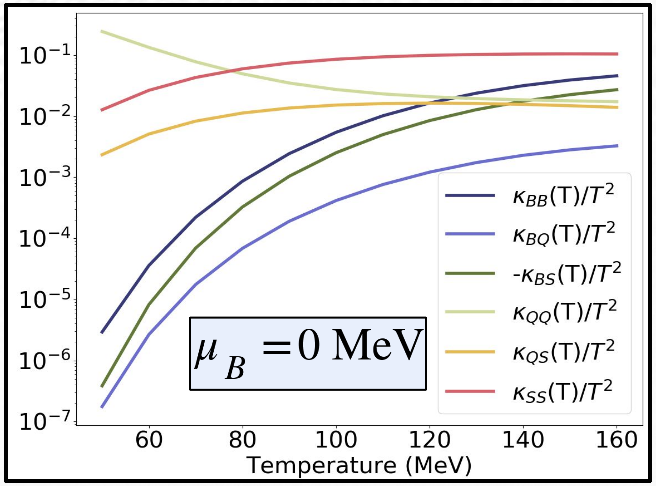
$$\left\langle \zeta_i(Y)\,\zeta_j(Y)\right\rangle = 2\frac{\kappa_{ij}}{\tau}\delta^{(2)}(Y - Y')$$

  - According to the FDT the non-vanishing off-diagonal elements of κ_{ij} introduce cross-correlations in the noise of different charges.

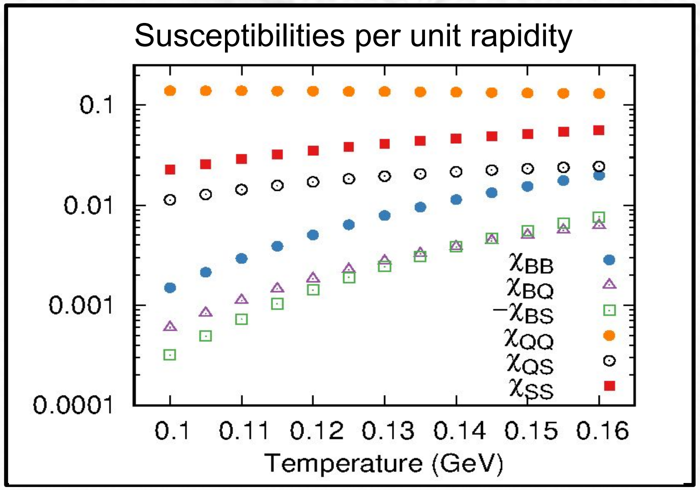
- Underlying Equation of State :

  Hadron Resonance Gas of 19 lightest species in line with kinetic theory calculation of κ_{ij}.
- Coupled diffusion affects the **deterministic** evolution of density profiles non-trivially.

  Fotakis et al., Nucl.Phys.A.1005 (2021)



Diffusion coefficients



Equilibrium HRG

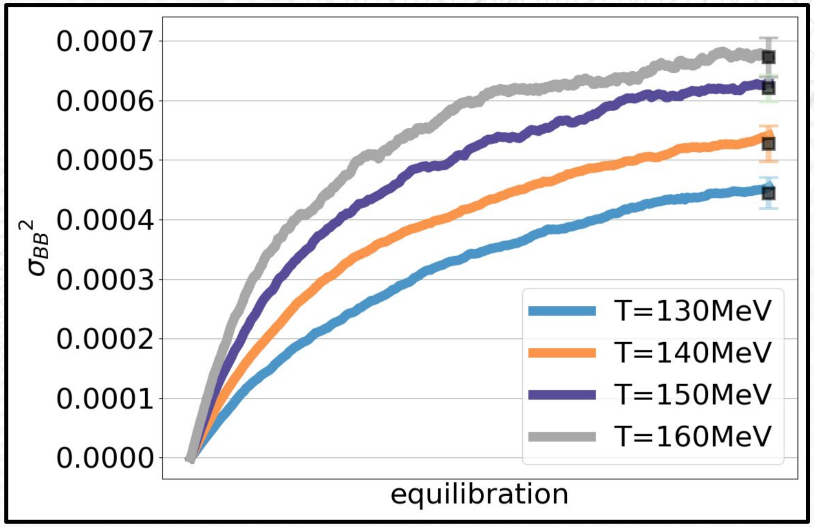
Baryon fluctuations in uncoupled diffusion

- Study **uncoupled baryon diffusion** with realistic diffusion coefficient in the expanding medium:
  - Average net-B density zero.
  - Hubble-like temperature evolution:

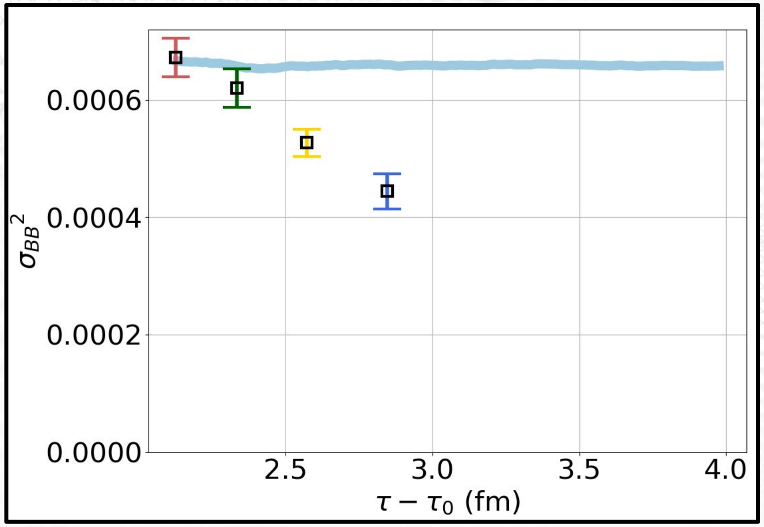
$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{dc_s^2}$$

- Variance of n_B fluctuations:

Equilibration:



Dynamical expansion and cooling:



- Reasonable equilibration is reached for uncoupled n_B diffusion.
- During expansion and cooling fluctuations are driven out of equilibrium (in line with decreasing kappa at lower T).

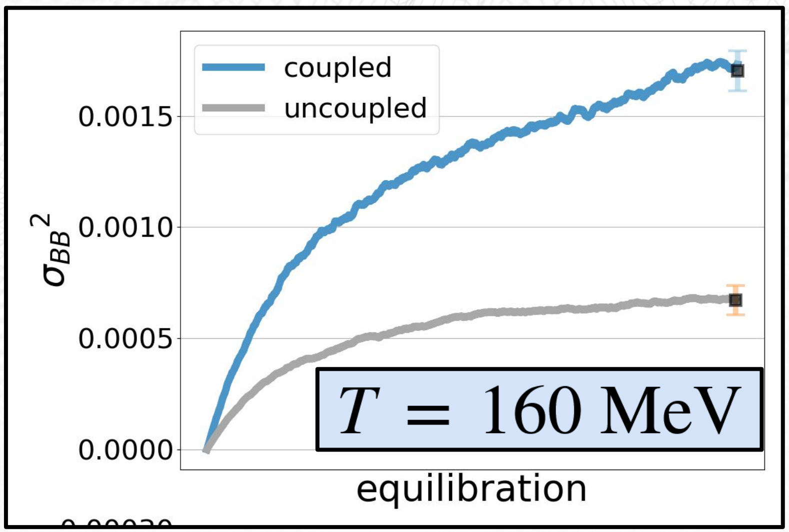
BSQ fluctuations in coupled diffusion

- Study **coupled BSQ diffusion** with realistic diffusion coefficients in the expanding medium:
  - Average net-densities zero.
  - Hubble-like temperature evolution.

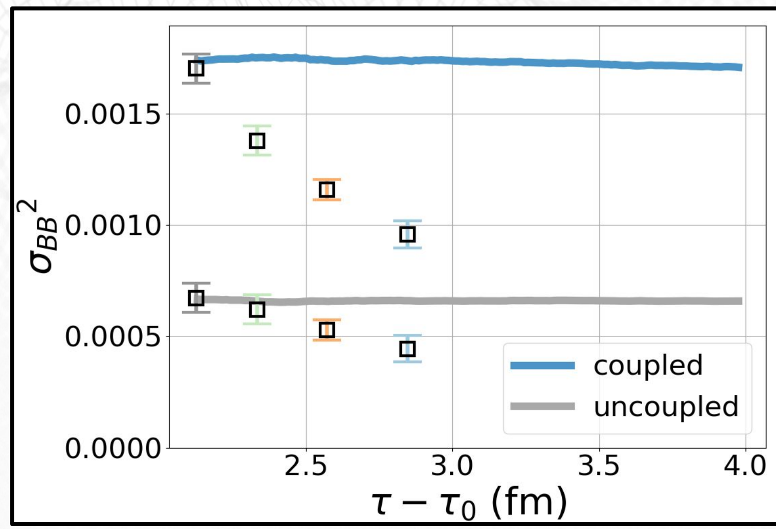
$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{dc_s^2}$$

- Variance of n_B fluctuations:

Equilibration:



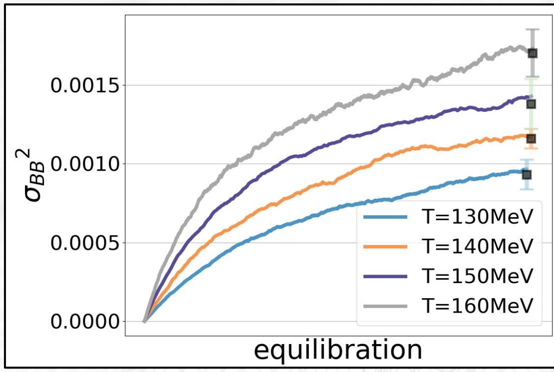
Dynamical expansion and cooling:

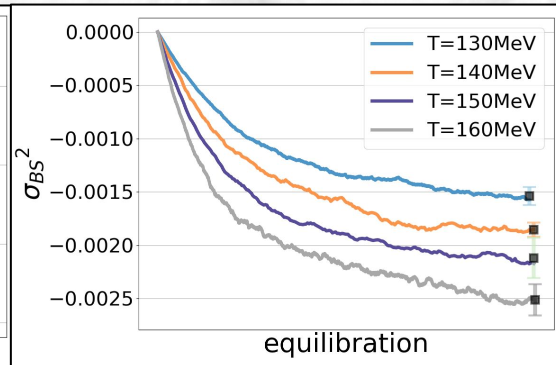


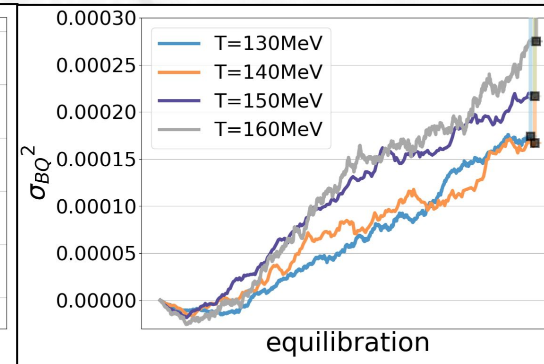
- Coupling to S, Q increases net-B fluctuations !
- During expansion and cooling fluctuations are driven out of equilibrium, but diffusion still has an impact.

Equilibration of the coupled BSQ diffusion

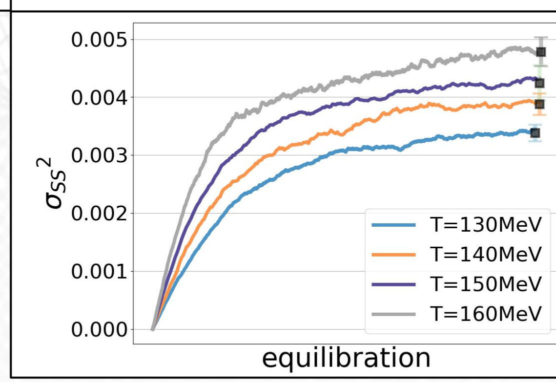
- Equilibration of the coupled fluctuations of all conserved charges, expressed via the (co)variances.

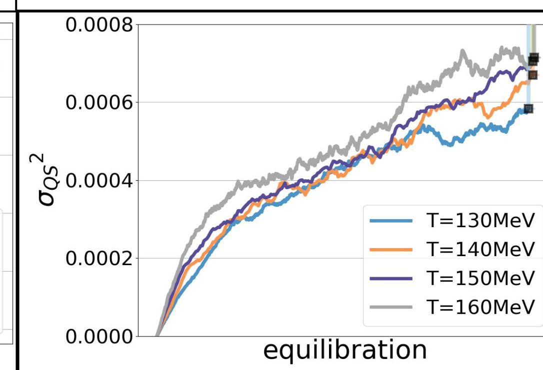




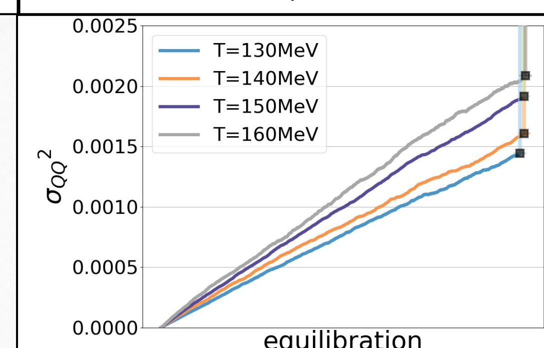


- Fluctuations in n_B and n_S equilibrate faster than those related to Q.



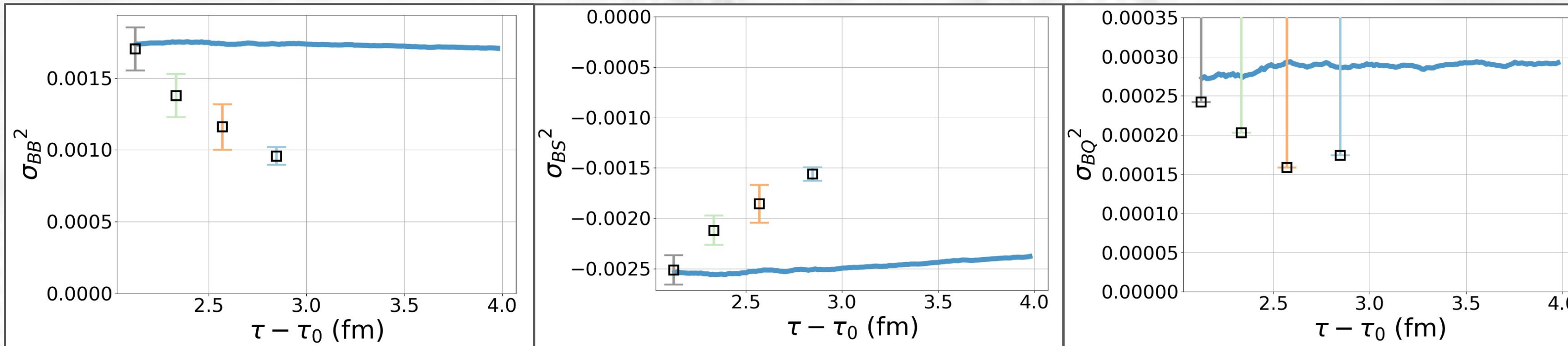


- For observables related to Q longer equilibration time needed to draw final conclusions!

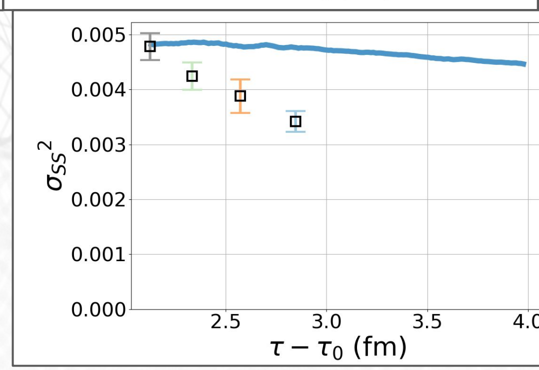


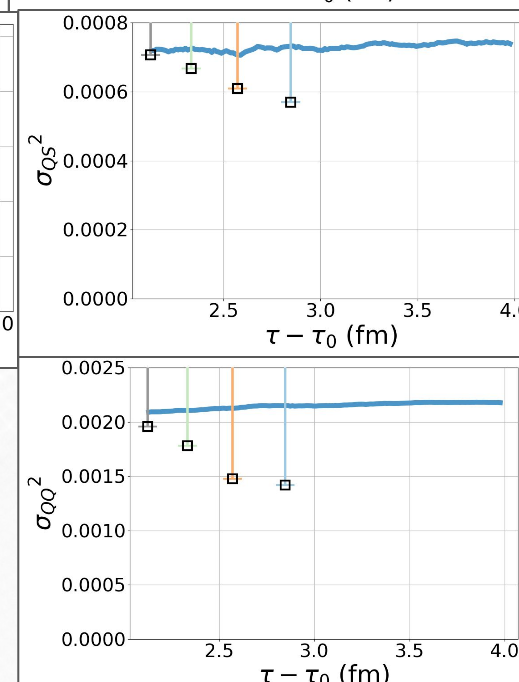
Coupled BSQ diffusion: from chemical to kinetic freeze-out

- Cooling and expansion from 160 MeV to 100 MeV:



- Fluctuations to Q probably not fully equilibrated yet.
- Fluctuations in S tend to follow the equilibrium values (largest kappa in relevant T range).
- Fluctuations in B cannot relax to equilibrium.





- System driven out of equilibrium in the late hadronic phase (expansion wins).

Consequences for chemical FO determination….

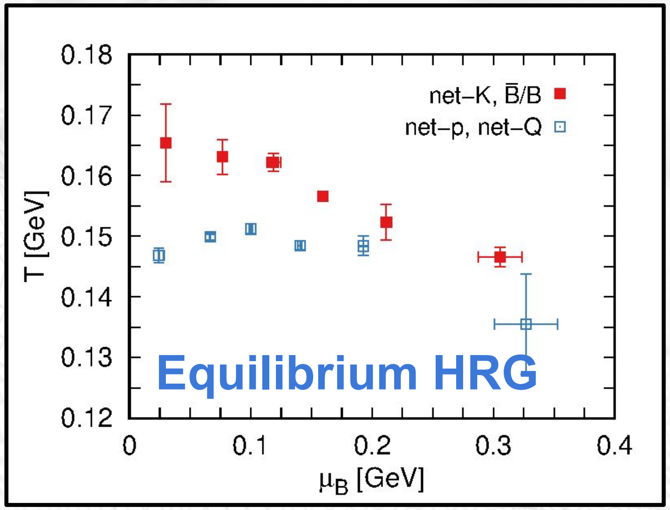
Impact on HIC phenomenology

- Can the freeze-out conditions be reliably determined from fluctuation observables?

  - Study of (net-p, net-Q) fluctuations and of (net-K fluctuations, Bbar/B yield ratios)

    ➔ High sensitivity of fluctuations vs. yields on FO conditions.

  - Separation of strange FO and light FO at highest beam energies.



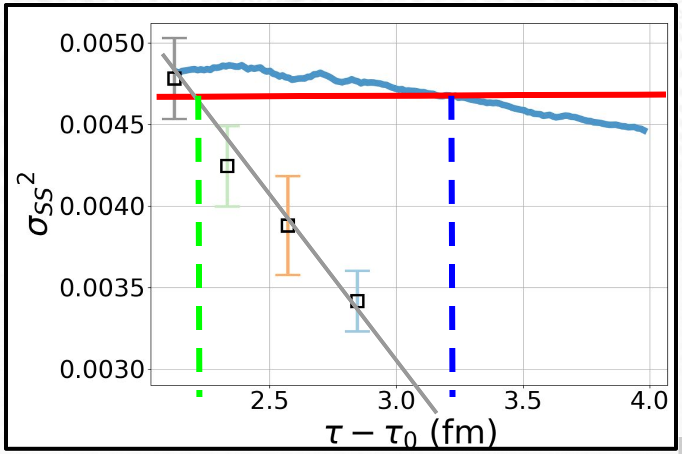
Bluhm, Nahrgang, Eur.Phys.J.C.79 (2019)

see also: Bellwied et al., Phys.Rev.C.99 (2019)

- Coupled dynamics of fluctuations shows:

  - If the prior QGP evolution/hadronization leads to equilibrium at T≈160MeV: Final fluctuations portray equilibrium at chemical freeze-out in the B channels.

  - In the S channel: FO temperatures obtained from the comparison of equilibrium HRG vs. experiment are **over-estimated** compared to dynamically expanding systems.



stochastic HRG diffusion

Conclusions

➔ Stochastic diffusion of coupled charges (B, Q, S) in the hadronic phase of heavy-ion collisions has important consequences.

➔ The fluctuations of net-baryon charge are increased by coupling to the fluctuations of electric charge and strangeness.

potentially interesting consequences on critical point signals !

➔ Impact on the determination of freeze-out conditions:

equilibrium HRG overestimates the FO temperatures in the S channel compared to a more realistic stochastic/dynamical HRG diffusion !

<u>Outlook</u> :

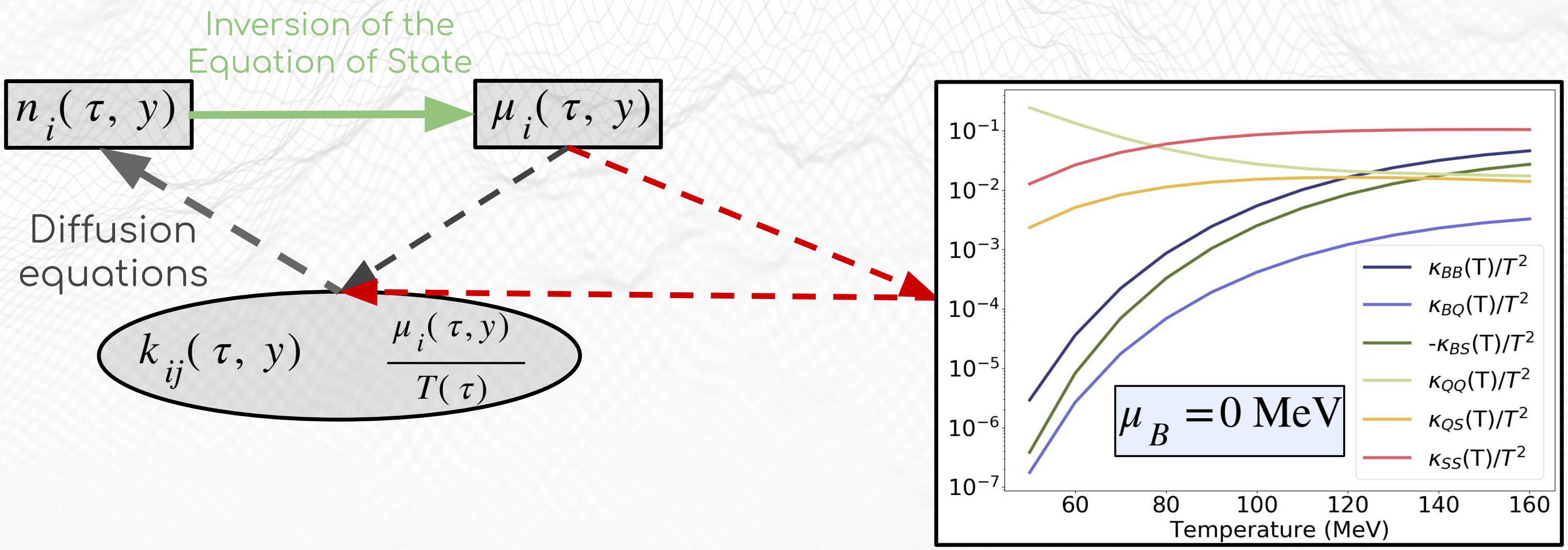
- Include full QGP evolution and EoS with a critical point.

Appendix

Numerical scheme

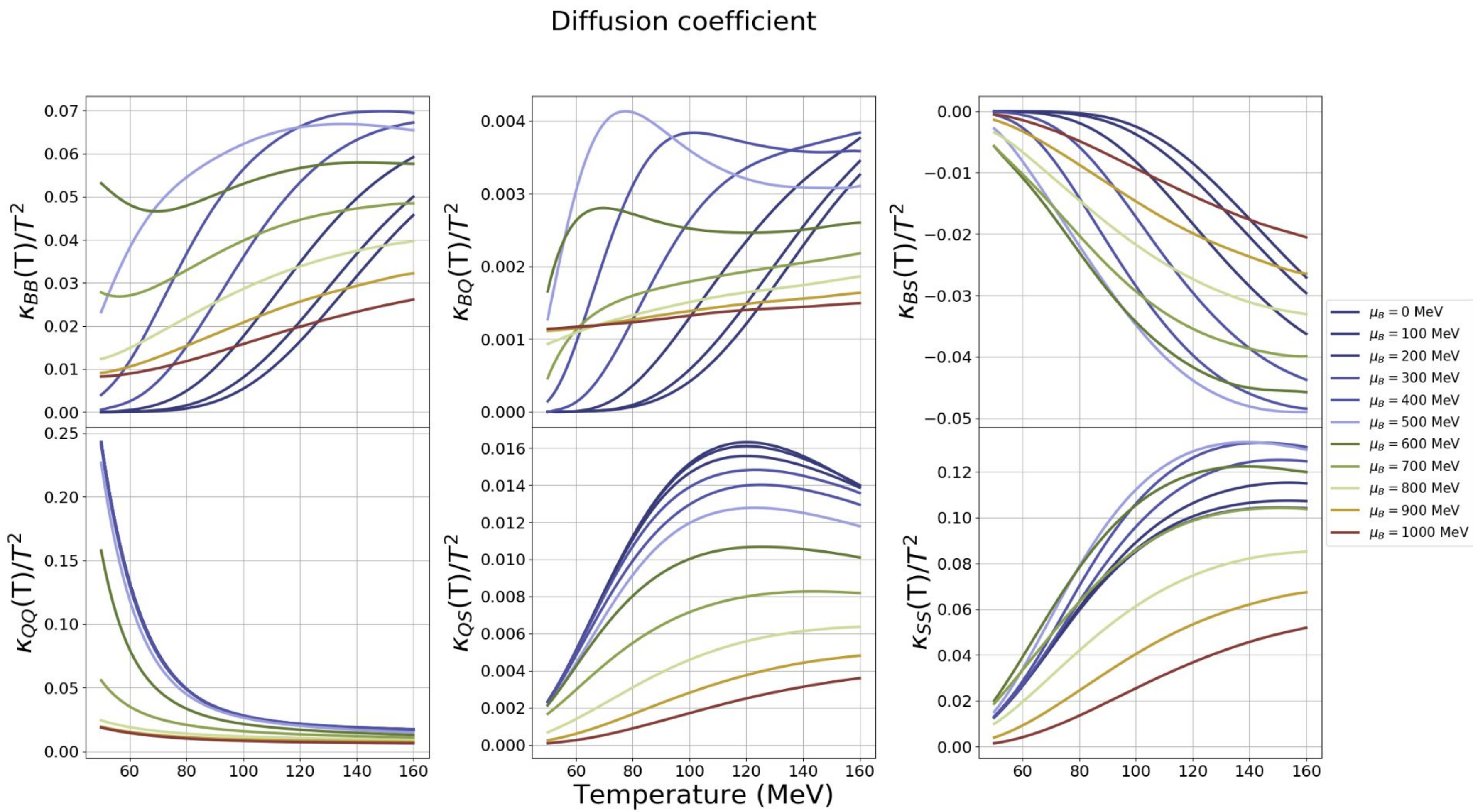
- Diffusion equations solved numerically within Euler differencing scheme.
- Noise cross-correlations established via Cholesky decomposition.

- Proper inversion of the EoS (as part of the coupling) is essentiel !



Diffusion coefficients

- Full dependence on baryon chemical potential important for fluctuations. (So far, only at nS=0 and muQ=0)



Greif et al., Phys.Rev.Lett.120 (2018); Fotakis et al., Phys.Rev.D.101 (2020)