CRC–TR 211
Strong-interaction matter under extreme conditions

Institute for Theoretical Physics

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Moving Towards Investigations of Multi-Charge Diffusion in Heavy Ion Collisions

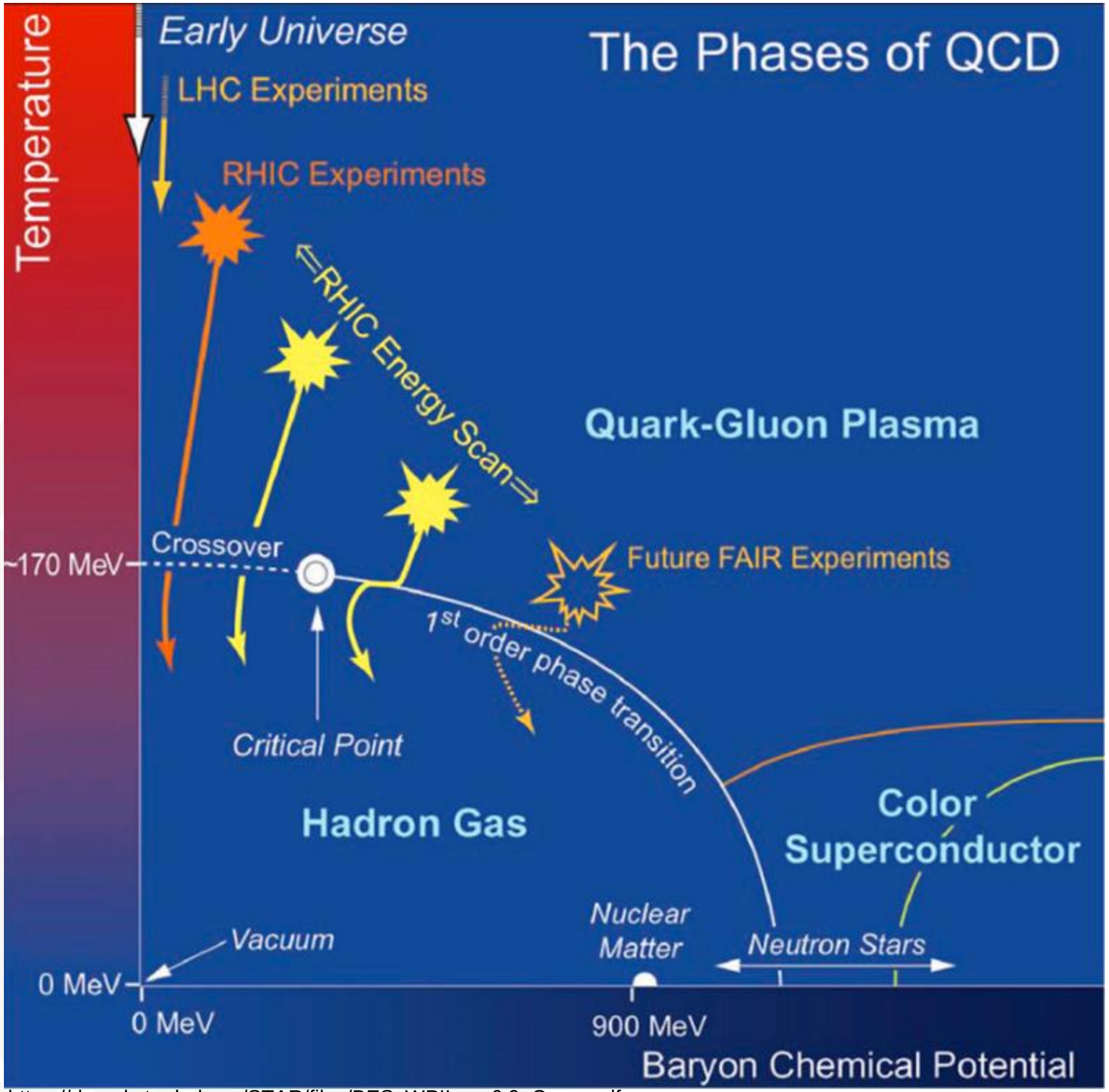
Presented by **Jan Fotakis**

Collaborators

Moritz Greif, Gabriel Denicol, Carsten Greiner and Harri Niemi

Greif, Fotakis, Denicol, Greiner, Phys. Rev. Lett. ***120****, 242301 (2018)*

Why could diffusion be important?



https://drupal.star.bnl.gov/STAR/files/BES_WPII_ver6.9_Cover.pdf

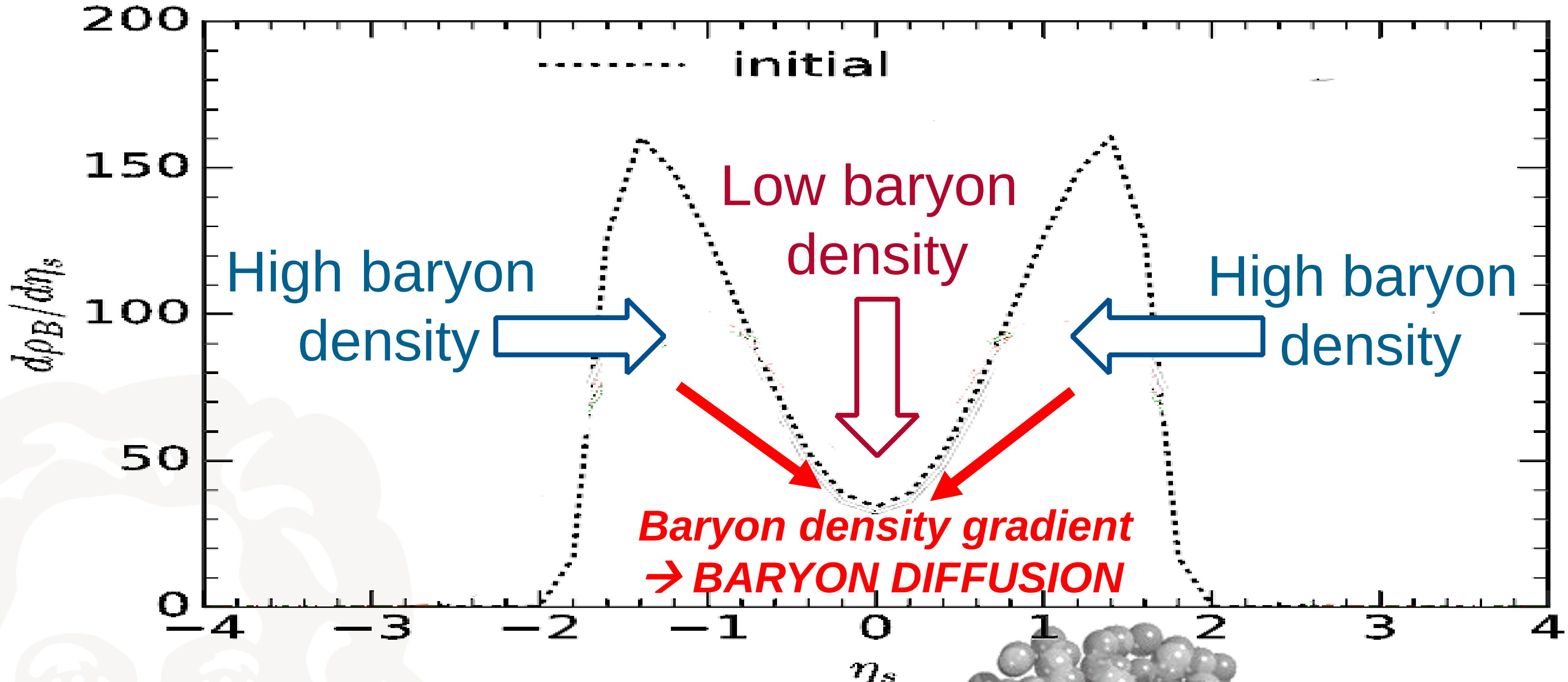
LHC: $\mu_B \approx 0\,\mathrm{MeV}$

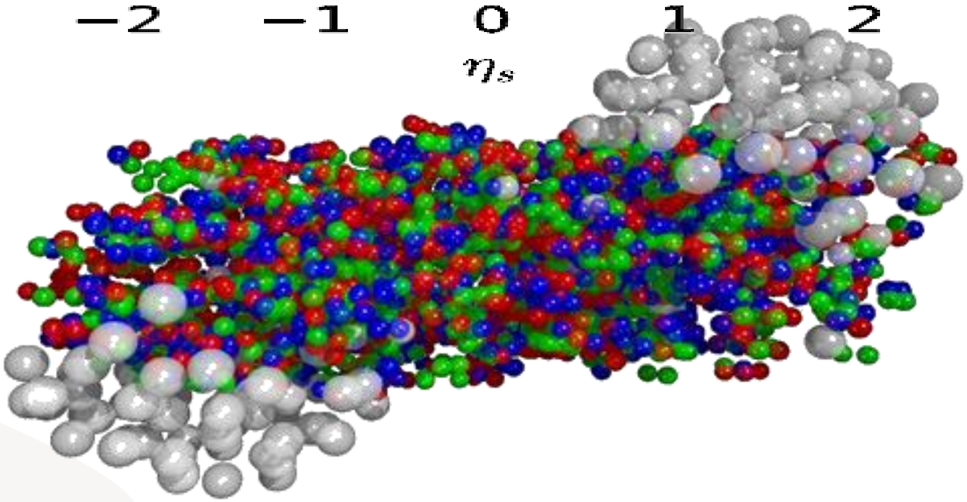
→ Vanishingly small gradients

RHIC BES: $\mu_B \sim 400\,\mathrm{MeV}$

→ Large gradients possible

Why could diffusion be important?

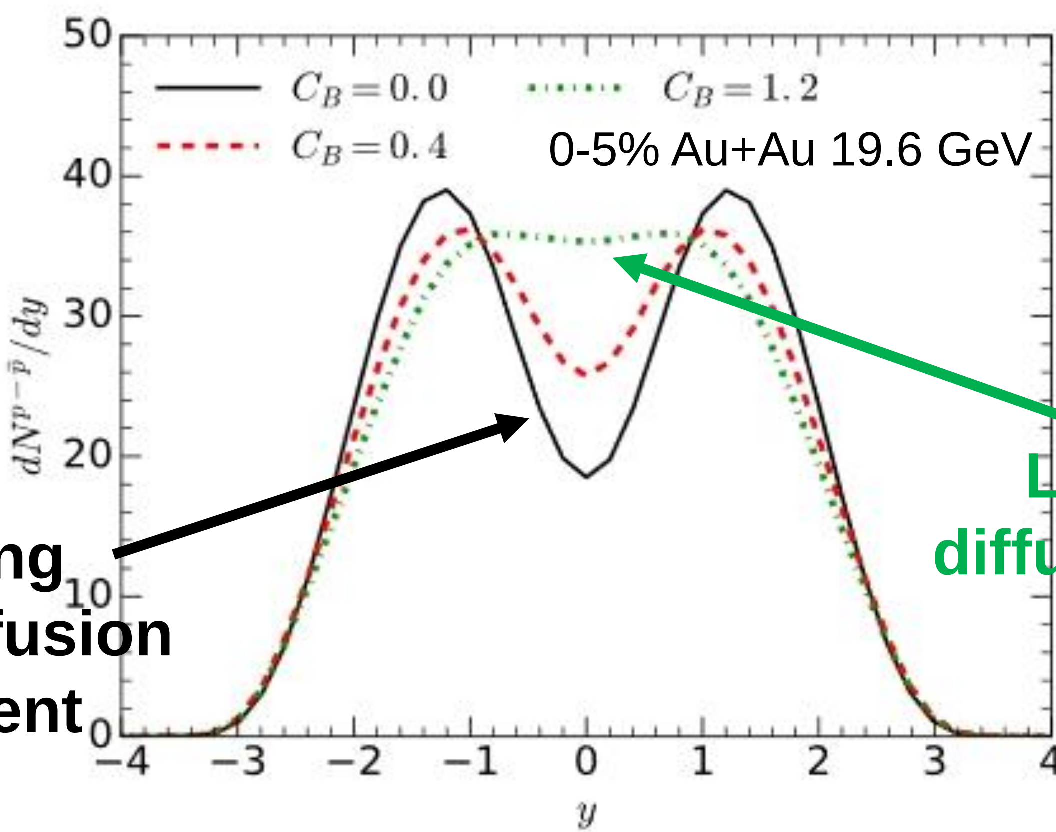




HIC

Why could diffusion be important?

- During low-energy HIC (e.g. RHIC BES, *FAIR*): *diffusion could have great impact* on dynamic evolution



Vanishing baryon diffusion coefficient

Large baryon diffusion coefficient

Chun Shen et al., Nucl. Phys. A ***967****, 796-799 (2017)*
Gabriel Denicol et al., Phys. Rev. C ***98****, 034916 (2018)*

Description of Diffusion

- Dynamic evolution of HIC modeled in relativistic dissipative fluid dynamics
- In Navier-Stokes theory for one conserved charge (q):

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Net charge 4-current:

$$N_q^\mu = n_q u^\mu + \kappa_q \nabla^\mu \left(\mu_q / T\right)$$

u^μ : flow velocity
n_q : net charge density

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$\nabla^\mu \left(\mu_q / T\right)$: Gradient in thermal potential ~ Gradient in net charge density

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κ_q: Net charge diffusion coefficient

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Description of Diffusion

- In multi-component system with multiple conserved charges: particles can have any combination of charges
  (e.g. proton: electric and baryon charge)

- Net charge diffusion currents effect each other

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$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \cdot \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$

Off-diagonal coefficients: gradients of given charge can effect diffusion currents of other charges

Are the off-diagonal coefficients important?

Description of Diffusion

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STAY SIMPLE

- Net-charge … ents effect each other

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… diag… coeffici…ts important?

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Particle	Mass	B	S	Degeneracy
Gluon	0	0	0	16
Up	0	+1/3	0	6
Anti-Up	0	-1/3	0	6
Down	0	+1/3	0	6
Anti-Down	0	-1/3	0	6
Strange	0	+1/3	-1	6
Anti-Strange	0	-1/3	+1	6

The System (Equation of State)

Consider massless, conformal QGP $(u, \bar{u}, d, \bar{d}, s, \bar{s}, g\ )$
with conserved baryon (B) and strangeness (S) charge only

$$\epsilon_0 = 3P_0 = 3n_{\rm tot}T$$

$$n_{\rm B} \sim T^3 \left(2\sinh\left(\frac{1}{3}\frac{\mu_B}{T}\right) + \sinh\left(\frac{1}{3}\frac{\mu_B}{T} - \frac{\mu_S}{T}\right)\right)$$

$$n_{\rm S} \sim -T^3 \sinh\left(\frac{1}{3}\frac{\mu_B}{T} - \frac{\mu_S}{T}\right)$$

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Local **Total** Number Density

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Local **Net** Charge Densities

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Light Quarks (Baryon Only)

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Light Quarks (Baryon Only)

Strange Quark (Baryon + Strangeness) → Correlation

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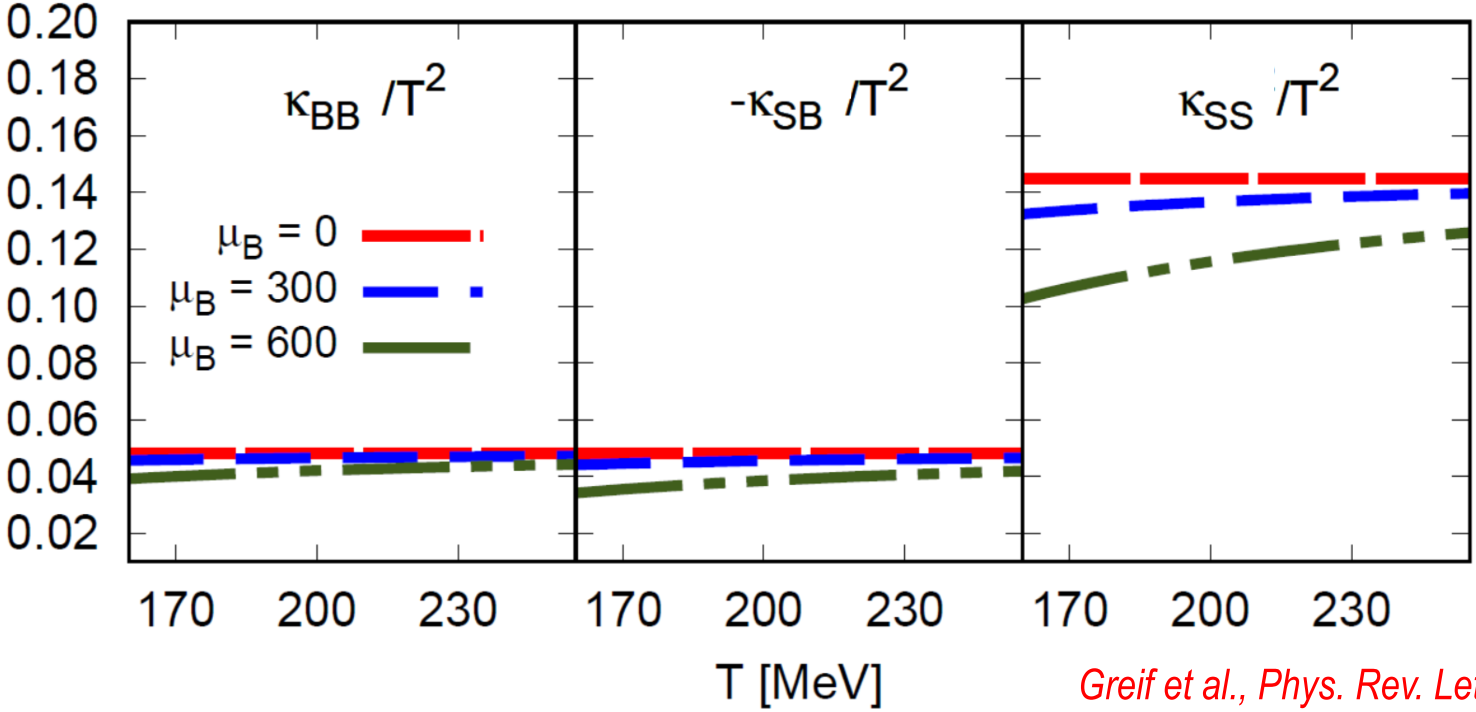

$n_S = 0$

Greif et al., Phys. Rev. Lett. ***120****, 242301 (2018)*

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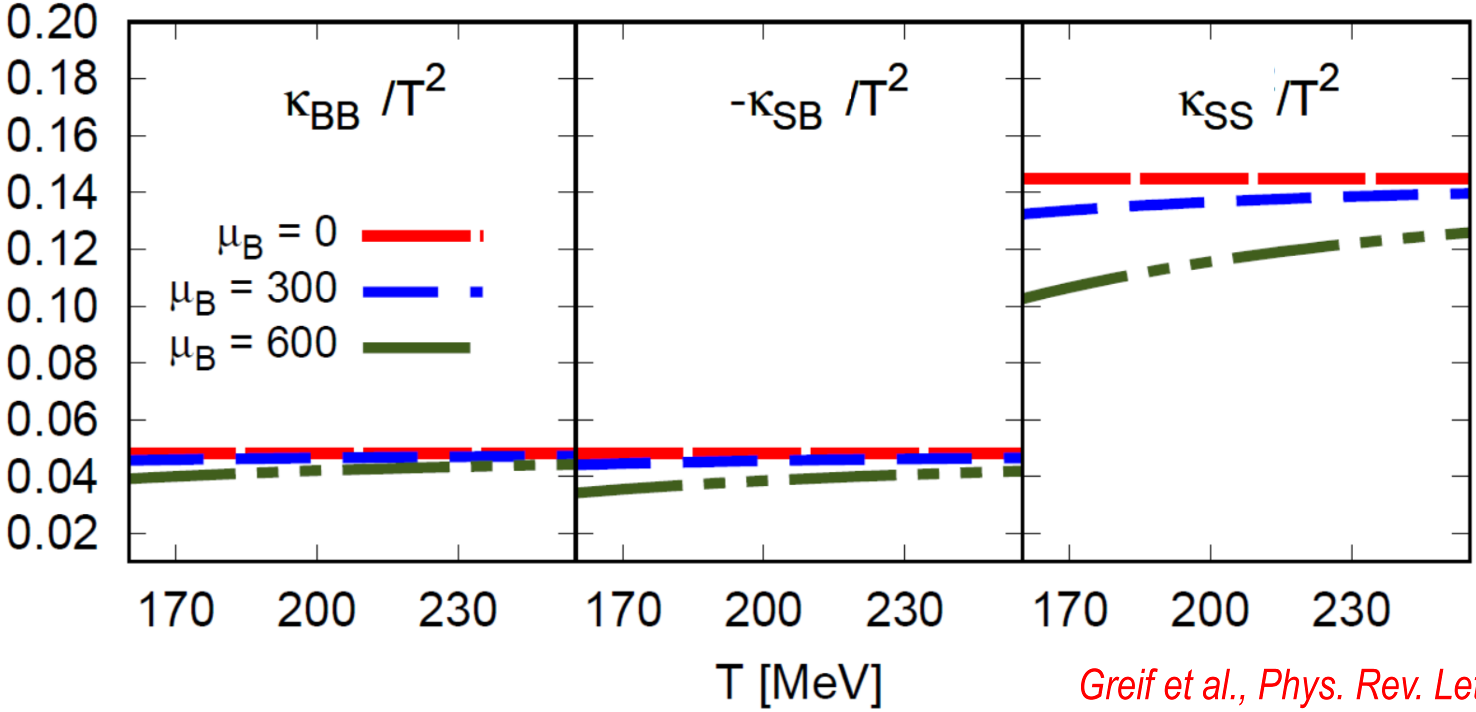

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Assume diffusion coefficients to scale with temperature:

$$\frac{\kappa_{BB}}{T^2} \approx 0.05, \quad \frac{\kappa_{SS}}{T^2} \approx 0.1, \quad \frac{\kappa_{SB}}{T^2} \approx -0.05$$

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Strangeness and Baryon Diffusion Currents = Anti-Correlated

Is there Baryon-Strangeness (Anti-)Correlation in a dynamic setting? → *Use Fluid Dynamics!*

Greif et al., Phys. Rev. Lett. ***120****, 242301 (2018)*

The Hydrodynamic Equations

Assume system to be close to local equilibrium with multiple conserved charges
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$$\partial_\mu T^{\mu\nu} = 0, \qquad \partial_\mu N_q^\mu = 0$$

Conservation of **Energy** and **Momentum**

Conservation of **Charge (q)**

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with

$$T^{\mu\nu} = \epsilon_0 u^\mu u^\nu - P_0 \left(g^{\mu\nu} - u^\mu u^\nu\right)$$ **Energy-Momentum** Tensor

$$N_q^\mu = n_q u^\mu + j_q^\mu$$ **Net Charge** Flow

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Net Charge Diffusion Current

Here: We do not consider any viscous corrections!

The Hydrodynamic Equations

- Conservation of Energy-Momentum and Charge **= exact**!
- Extract dissipative currents from Boltzmann equation

Denicol et al., Phys.Rev. ***D85*** *(2012) 114047, Erratum: Phys.Rev.* ***D91*** *(2015) no.3, 039902*

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Source term of dissipative currents ~
Expansion in **Knudsen Number** and **inverse Reynolds Number**

$$\mathrm{Kn} \sim \frac{\text{microscopic scale}}{\text{macroscopic scale}} \quad , \quad \mathrm{Rn}^{-1} \sim \frac{\text{dissipative field}}{\text{equilibrium field}}$$

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Fluid Dynamics: close local equilibrium
+ mean free path smaller fluid cell

$$\Rightarrow \quad \mathrm{Kn},\ \mathrm{Rn}^{-1} \ll 1$$

The Hydrodynamic Equations

Impose transient equation of first order in Knudsen number for diffusion currents (neglect higher orders)

$$\begin{pmatrix} \tau_{\mathrm{B}} \frac{\mathrm{d}}{\mathrm{d}\tau} j_{\mathrm{B}}^{\langle\mu\rangle} + j_{\mathrm{B}}^{\mu} \\ \\ \tau_{\mathrm{S}} \frac{\mathrm{d}}{\mathrm{d}\tau} j_{\mathrm{S}}^{\langle\mu\rangle} + j_{\mathrm{S}}^{\mu} \end{pmatrix} = \begin{pmatrix} \kappa_{\mathrm{BB}} & \kappa_{\mathrm{SB}} \\ \\ \kappa_{\mathrm{SB}} & \kappa_{\mathrm{SS}} \end{pmatrix} \begin{pmatrix} \nabla^{\mu} \alpha_{\mathrm{B}} \\ \\ \nabla^{\mu} \alpha_{\mathrm{S}} \end{pmatrix} + \mathcal{O}(\mathrm{Kn}^2)$$

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Navier-Stokes term

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Use vSHASTA solver to solve fluid dynamics numerically

Molnar, Niemi, Rischke, Eur. Phys. J. ***C65****, 615-635 (2010)*

The Setup

- (1+1)-hydrodynamic evolution in longitudinal setup

- In hyperbolic coordinates
  (proper time $\tau \equiv \sqrt{t^2 - z^2}$ and
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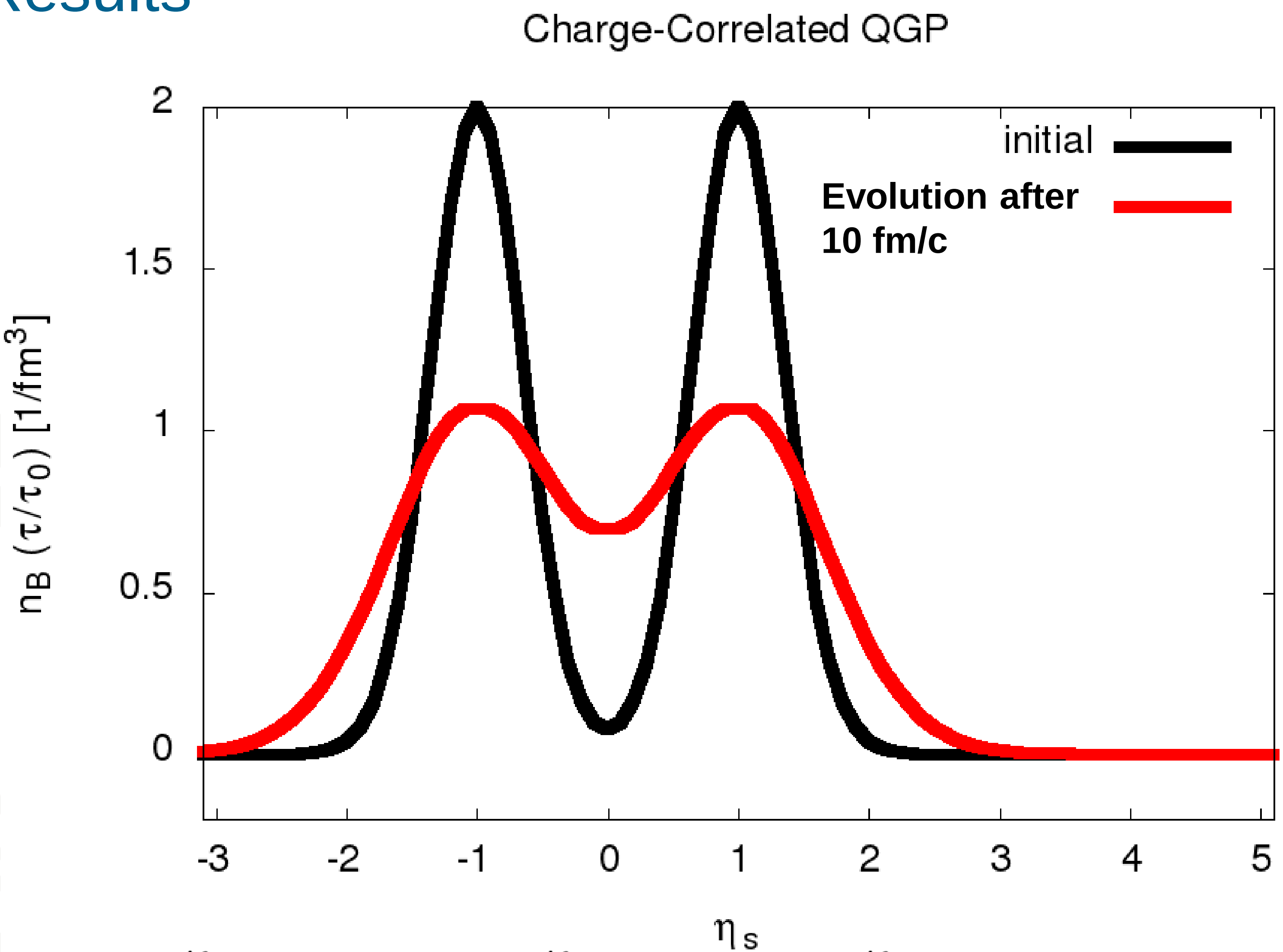
→ Fluid velocity is always zero during the evolution

Results



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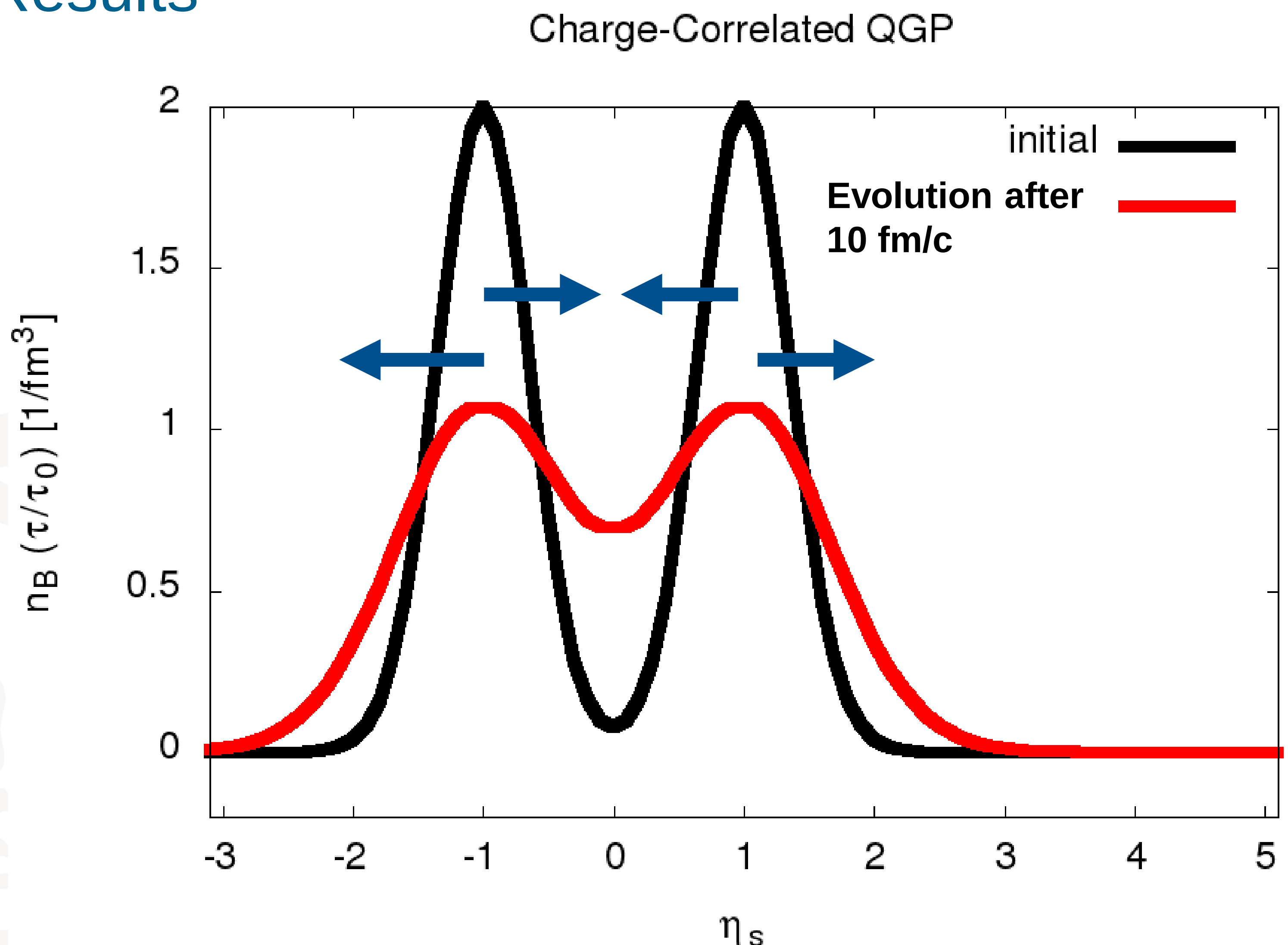
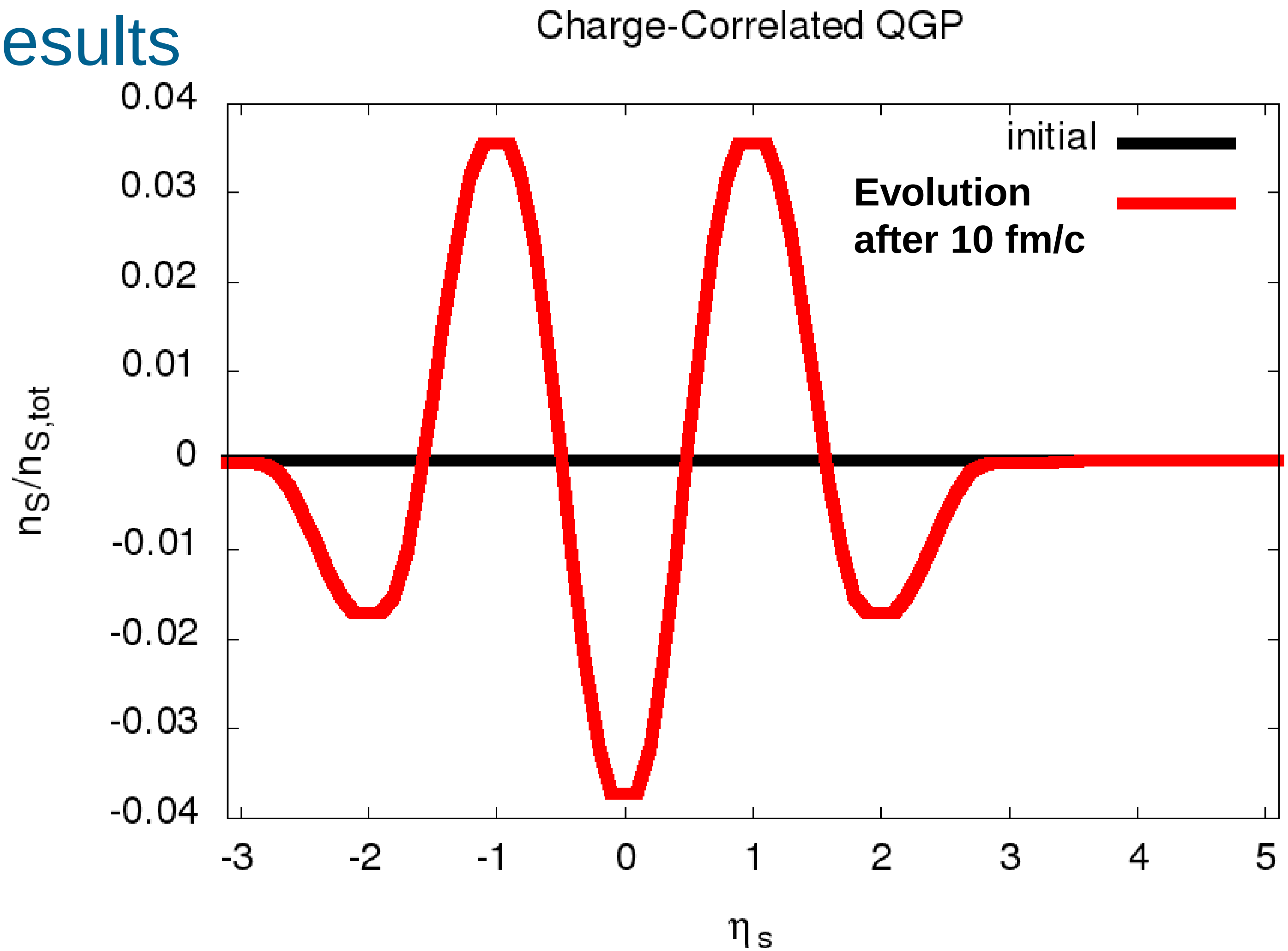


Strong baryon diffusion to mid and outward spacetime rapidities

Results



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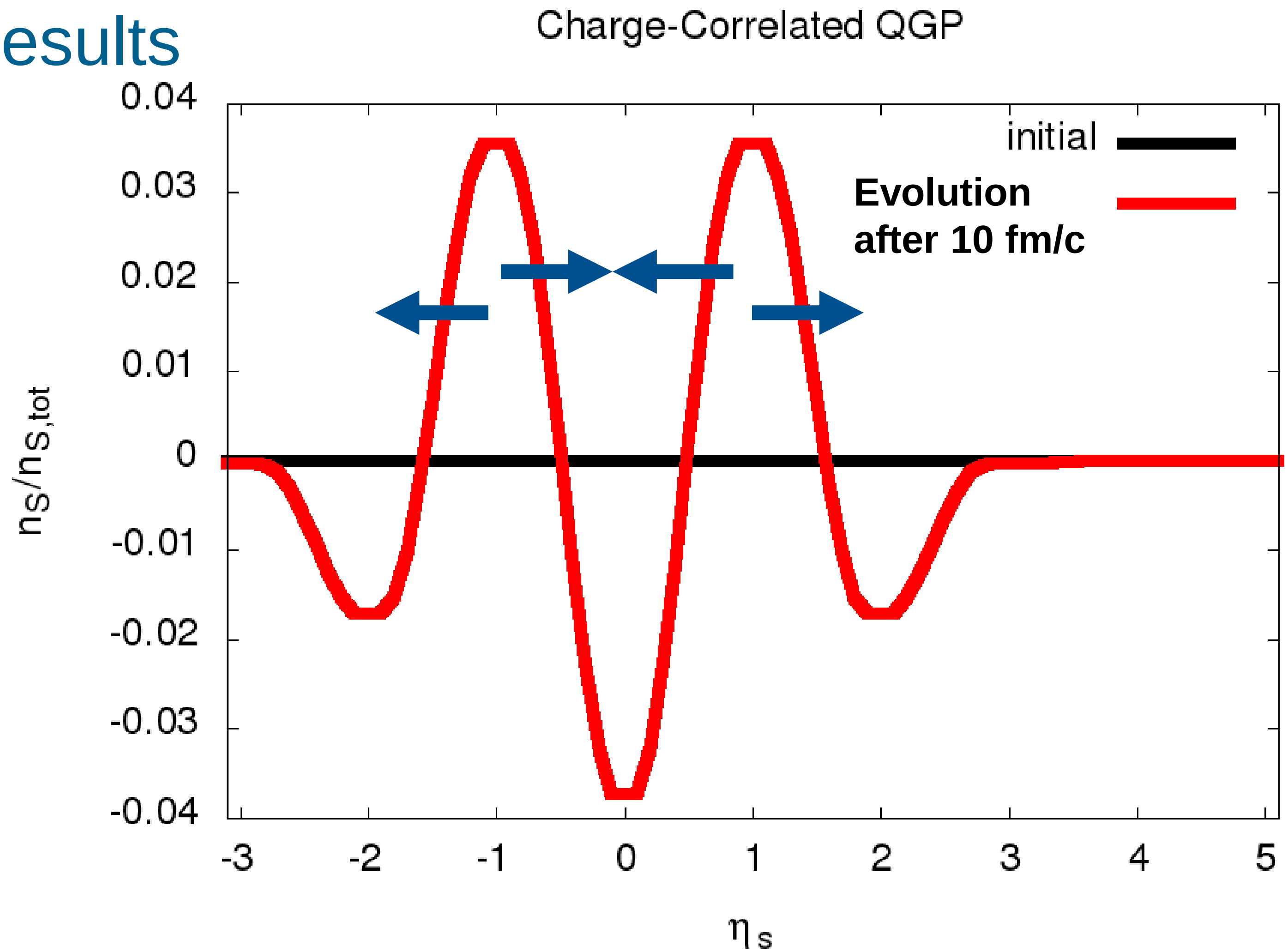
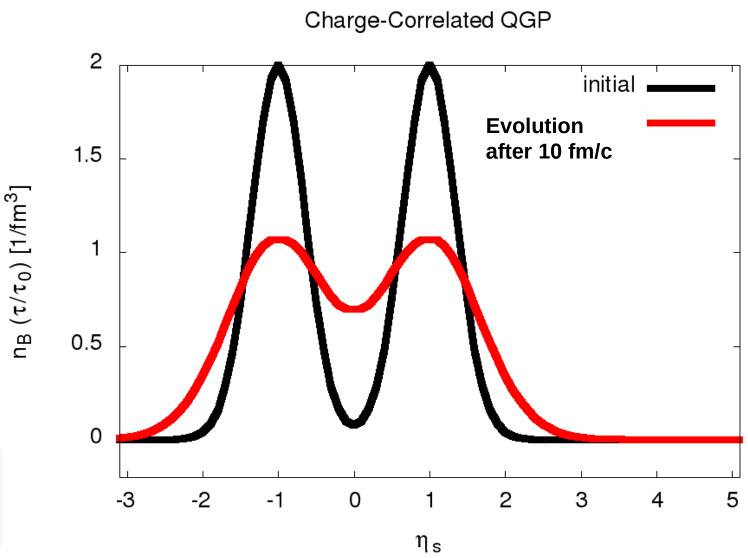


There is induced strangeness separation through Baryon-Strangeness anti-correlation!?!

Results



Initial vanishing strangeness density:

$$0 \approx n_S \sim \sinh\left(\frac{1}{3}\alpha_B - \alpha_S\right) \quad \Leftrightarrow \alpha_S \approx \frac{1}{3}\alpha_B$$

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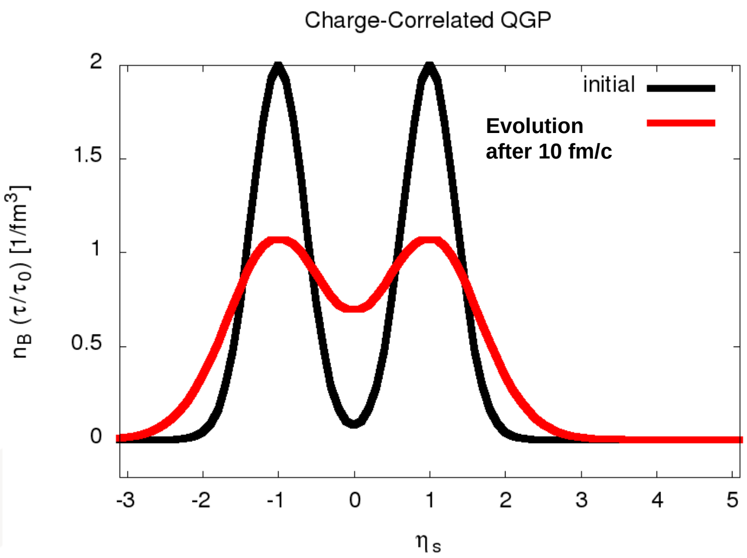

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$$\begin{pmatrix} j^\mu_\mathrm{B} \\ j^\mu_\mathrm{S} \end{pmatrix} \sim \begin{pmatrix} \kappa_\mathrm{BB}\nabla^\mu\alpha_\mathrm{B} + \kappa_\mathrm{SB}\nabla^\mu\alpha_\mathrm{S} \\ \kappa_\mathrm{SS}\nabla^\mu\alpha_\mathrm{S} + \kappa_\mathrm{SB}\nabla^\mu\alpha_\mathrm{B} \end{pmatrix}$$

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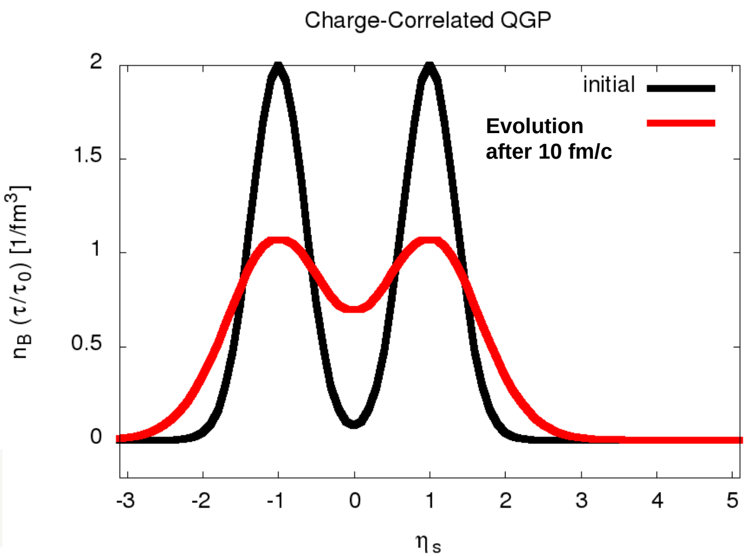

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Positive

Res

Initial vanishing strangeness density:

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$$0.1, \quad \frac{\kappa_{SB}}{T^2} \approx -0.05$$

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What charge is diffusing?!

Results

- Initially vanishing net strangeness density → as many s-quarks as anti-s-quarks everywhere!

- Current of light quarks carrying baryon charge towards mid rapidities and outwards

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- Initially vanishing net strangeness density → as many s-quarks as anti-s-quarks everywhere!

- Current of light quarks carrying baryon charge towards mid rapidities and outwards

- Microscopically: qq- and $q\bar{q}$-vertices equal → **no reason** orientated *current of light quarks* should **carry away more s-quarks than anti-s-quarks**

Results

- Initially vanishing net strangeness density → as many s-quarks as anti-s-quarks everywhere!

- Current of light quarks carrying baryon charge towards mid rapidities and outwards

- Microscopically: qq- and $q\bar{q}$-vertices equal → **no reason** orientated *current of light quarks* should **carry away more s-quarks than anti-s-quarks**

  → Expectation: no induced strangeness separation in this case!

My View on the Problem

$$\mathrm{Kn} \sim \frac{\text{microscopic scale}}{\text{macroscopic scale}}$$

$$\mathrm{Rn}^{-1} \sim \frac{\text{dissipative field}}{\text{equilibrium field}}$$

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→ For $n_q = 0$ → j_q^μ needs to be corrected to 0!

→ e.g. no strangeness separation in our case!

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However several problems:

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However several problems:

1. The choice of Reynolds number is ambiguous $\mathrm{Rn}^{-1} \sim \frac{j_q^{\mu}}{n_{q,\mathrm{tot}}}$??
2. No natural way of limiting the diffusion current!

→ Is hydro the appropriate model to use to do the investigations in the case of HIC (low density regions in strangeness)?!?

Conclusion

- First investigations of the (fluid) dynamic effects of the diffusion matrix
- Diffusive evolution of a massless, conformal QGP with conserved baryon number and strangeness and constant diffusion coefficients was examined in a dissipative fluid dynamic framework without viscous corrections

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- First investigations of the (fluid) dynamic effects of the diffusion matrix
- Diffusive evolution of a massless, conformal QGP with conserved baryon number and strangeness and constant diffusion coefficients was examined in a dissipative fluid dynamic framework without viscous corrections

- We found signals of strong baryon diffusion and separation of strangeness
- Baryon diffusion could be important in describing the evolution of heavy ion collisions at low collisional energies
- More realistic investigations are needed
- However: **hydro does seems to lead to misleading results**

Outlook

- Compare to kinetic models: SMASH? BAMPS?

- Improve investigations with dissipative hydro:
  - Use more realistic initial state with fluctuating strangeness
  - Allow viscous corrections in evolution
  - Include higher-order terms in source term in diffusion equations
  - Use more realistic equation of state (lQCD+HRG)
  - Include freeze-out stage in order to compare to experiments

- Extend investigations to (3+1)-fluid dynamics
  - Initial state correlations (flow harmonics?)