Hydrodynamic analyses of nuclear collisions in Landau and Eckart frames

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PANIC Lisbon Portugal 22nd edition
Particles and Nuclei International Conference

日本女子大学 JAPAN WOMEN'S UNIVERSITY

科研費 KAKENHI

JP19K14722

Abstract

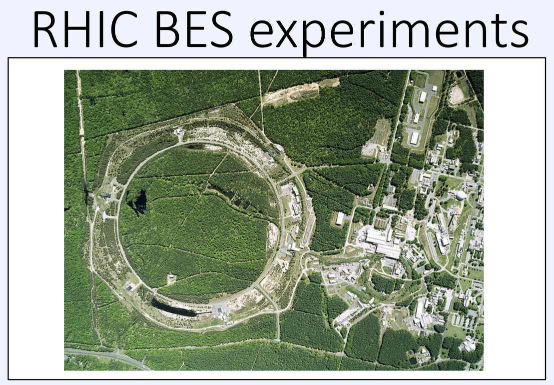
We investigate full second-order relativistic hydrodynamics in the Landau and the Eckart frames to elucidate the effect of frame choice on flow observables in nuclear collisions. The results indicate that charged particle and net baryon rapidity distributions are mostly frame independent when off-equilibrium kinetic freeze-out is considered.

1. Introduction

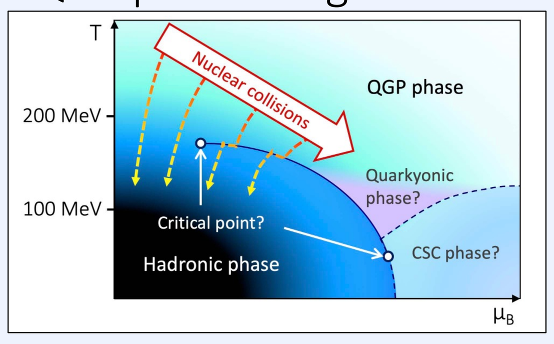
Cf: AM, Phys. Rev. C **90**, 014908 (2012); G. Denicol, C. Gale, S. Jeon, AM, B. Schenke, C. Shen, Phys. Rev. C **98**, 034916 (2018) [Editors' suggestion]

▶ Hydrodynamic model at finite density is used for interpreting the heavy-ion collisions in beam energy scan (BES) experiments

RHIC BES experiments

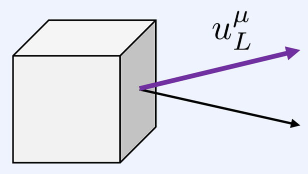


QCD phase diagram



▶ Relativistic hydrodynamics has a long-standing issue of frame fixing

Landau frame: local rest frame of energy flow



L. D. Landau and E. M. Lifshitz, Fluid Mechanics (Pergamon, New York, 1959)

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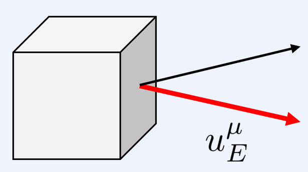
Eckart flame: local rest frame of conserved charge flow



C. Eckart, Phys. Rev. **58**, 919 (1940)

We analytically and numerically investigate the two frames and their implications on the phenomenology of heavy-ion collisions

2. Stability and causality of 2nd order hydrodynamics

▶ Equations of motion in Landau frame

Conservation laws $\partial_\mu T^{\mu\nu} = 0\,,\ \partial_\mu N^\mu = 0$

Diffusion
$$V^\mu_L = \kappa_V \nabla^\mu_L \alpha - \tau_V (\Delta_L)^\mu{}_\nu D_L V^\nu_L + \chi^a_V V^\mu_L D_L \alpha + \chi^b_V V^\mu_L D_L \beta + \chi^c_V V^\mu_L \nabla^L_\nu u^\nu_L + \chi^d_V V^\nu_L \nabla^L_\nu u^\mu_L + \chi^e_V V^\nu_L \nabla^\mu_L u^L_\mu$$

Perturbation from global equilibrium $\delta Q = \delta\bar{Q} e^{i(\omega t - kx)}$ implies that $\omega(k)$ is subject to the following conditions:

Stability $\mathrm{Im}(\omega) \geq 0$

Causality $\left|\dfrac{\partial \mathrm{Re}(\omega)}{\partial k}\right| \leq 1$

⇔ Stable and causal Landau frame if

$$\kappa_V \geq 0\ ,\ \tau_V \geq 0 \quad (\,k \to 0\,)$$

Defs. u^μ : flow $\alpha = \mu/T$: fugacity $\beta = 1/T$: inverse temperature
κ : conductivity τ : relaxation time χ : 2nd order transport coefficients
$D = u^\mu \partial_\mu$: time-like derivative $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$: space-like derivative

▶ Equations of motion in Eckart frame

Conservation laws $\partial_\mu T^{\mu\nu} = 0\,,\ \partial_\mu N^\mu = 0$

Dissipation
$$W^\mu_E = -\kappa_W (\nabla^\mu_E \beta + \beta D_E u^\mu_E) - \tau_W (\Delta_E)^\mu{}_\nu D_E W^\nu_E + \chi^a_W W^\mu_E D_E \alpha + \chi^b_W W^\mu_E D_E \beta + \chi^c_W W^\mu_E \nabla^E_\nu u^\nu_E + \chi^d_W W^\nu_E \nabla^E_\nu u^\mu_E + \chi^e_W W^\nu_E \nabla^\mu_E u^E_\nu$$

$\mathrm{Im}(\omega) \geq 0$, $\left|\dfrac{\partial \mathrm{Re}(\omega)}{\partial k}\right| \leq 1$ ⇔ Stable and causal Eckart frame if

$$\kappa_W \geq 0\ ,\ \tau_W - \frac{\kappa_W}{(e+P)T} \geq 0 \quad (\,k \to 0\,)$$

▶ Identification of the entropy production yields

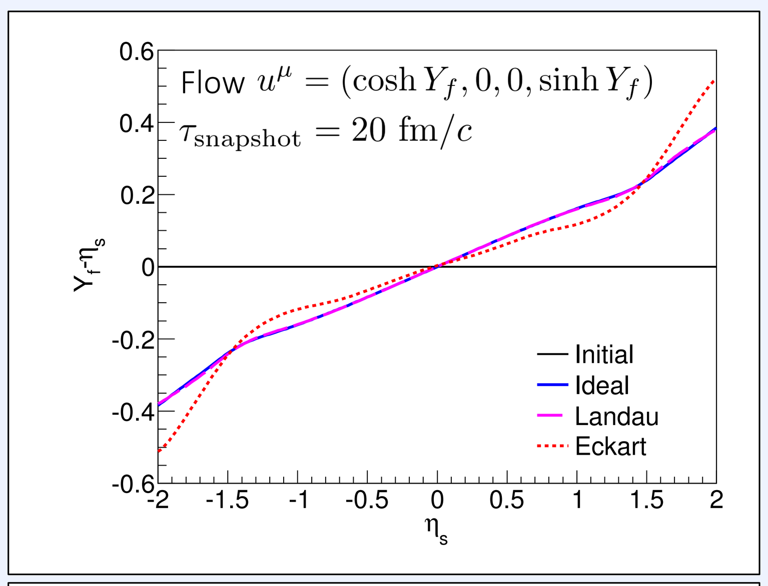
$$\kappa_V = \kappa_W \left(\frac{n}{e+P}\right)^2,\quad \tau_V = \tau_W - \frac{\kappa_W}{(e+P)T}\,,\quad \chi^a_V = \chi^a_W - \frac{\tau_W n T}{e+P}$$
$$\chi^b_V = \chi^b_W + \tau_W T - \frac{\kappa_W}{e+P}\,,\quad \chi^{c,d}_V = \chi^{c,d}_W + \frac{\kappa_W}{(e+P)T}\,,\quad \chi^e_V = \chi^e_W$$

1. Stability and causality conditions of the two frames are equivalent
2. Full 2nd order terms are needed for stability and causality analyses

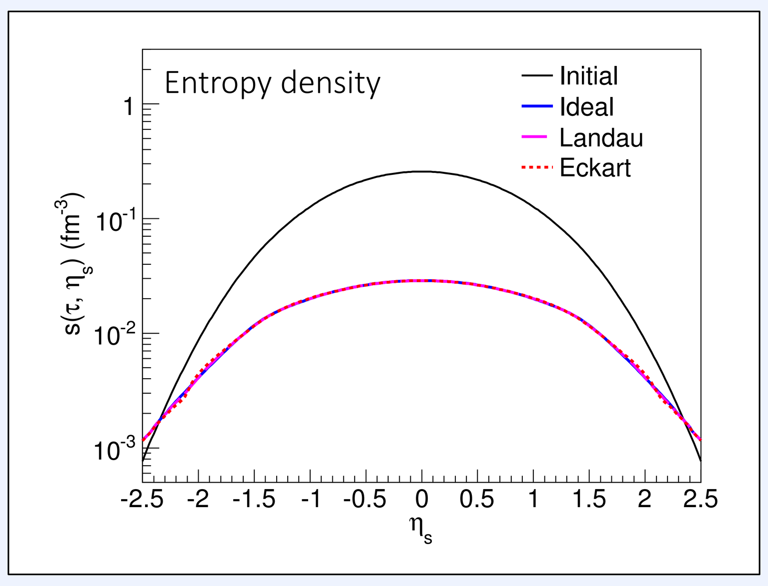
3. Numerical simulation of heavy-ion collisions

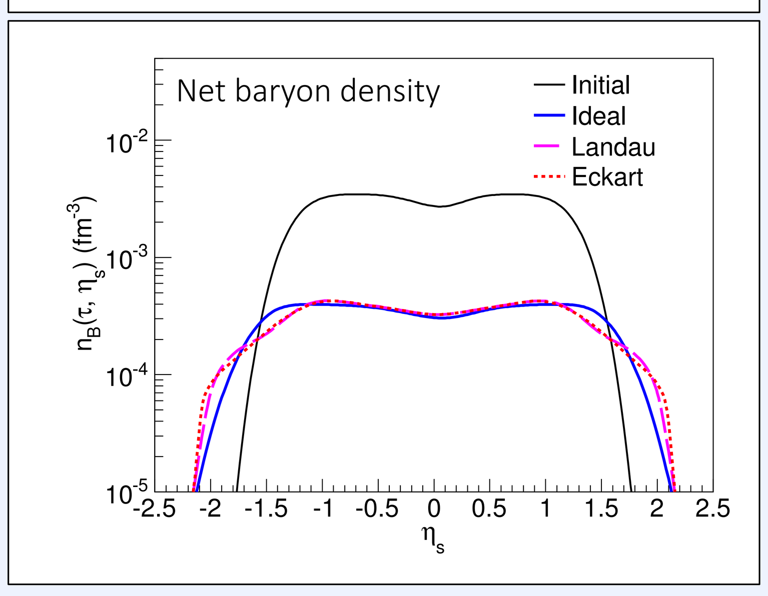
▶ (1+1)D hydrodynamic model for SPS 17.3 GeV Pb+Pb collisions

Equation of motion: NEOS B
Lattice QCD + resonance gas
AM, B. Schenke, C. Shen, Phys. Rev. C **100**, 024907 (2019)
Transport coefficients: $\chi_W = 0$
$\tau_W = 2\kappa_W/(e+P)T\,,\ \kappa_W = 10(e+P)$



▶ Flows are different; thermo-dynamic variables are identical

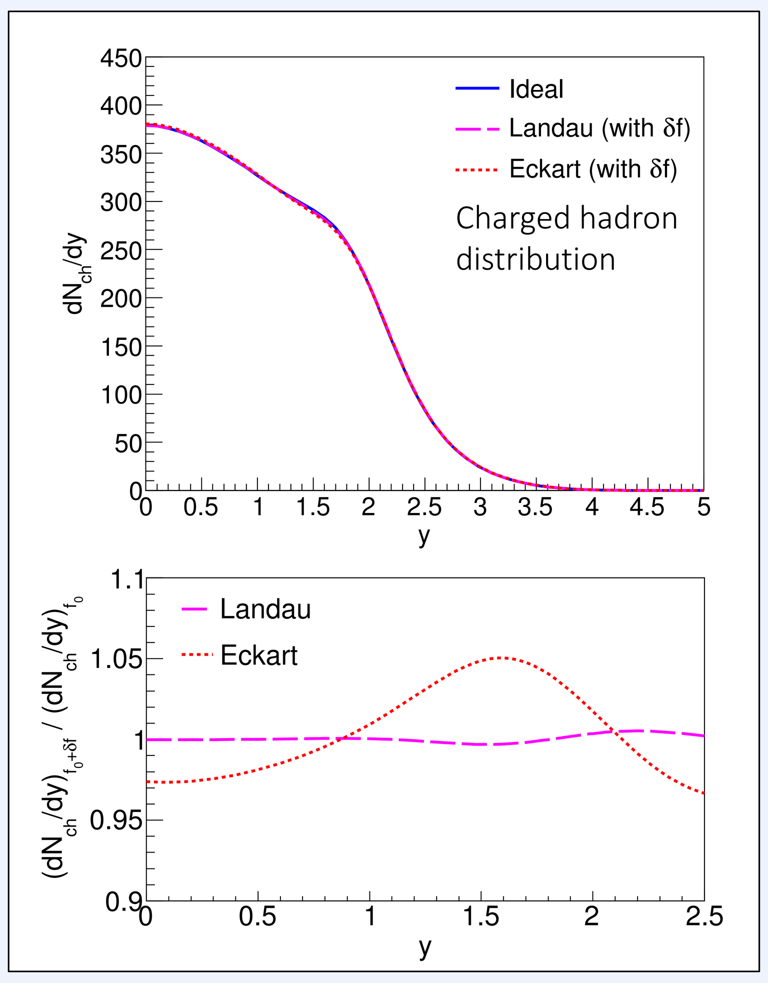


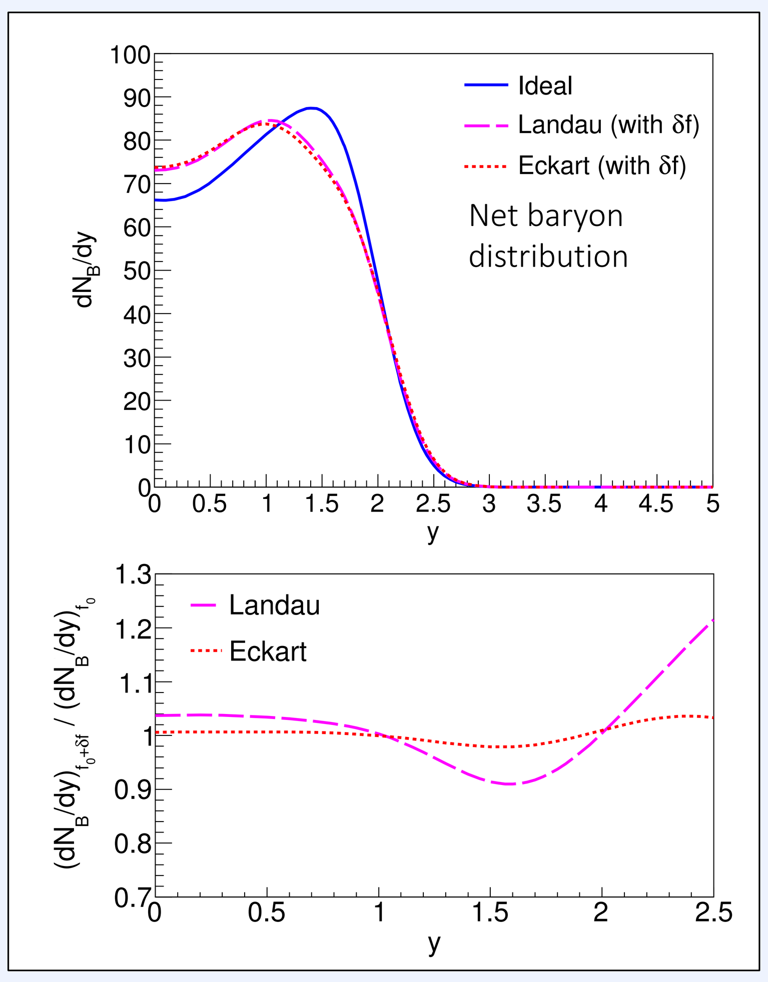


▶ Charged hadron and net baryon distributions are estimated
→ The latter is affected more by the diffusion/dissipation process

▶ Off-equilibrium corrections δf at freeze-out is essential

$$E_i \frac{dN^i}{d^3p} = \frac{g_i}{(2\pi)^3} \int_\Sigma p^\mu_i d\sigma_\mu (f^0_i + \delta f_i)$$





4. Summary and outlook

▶ Stability and causality conditions of the full 2nd order relativistic hydrodynamics are investigated in Landau and Eckart frames

▶ Numerical analyses for heavy-ion collisions imply that a frame choice has visible effects on the flow but not on particle distributions

▶ Future prospects include analyses of boosted systems, interplay with shear and bulk viscosities and (3+1)D hydrodynamic evolution

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Reference: AM, Phys. Rev. C 100, 014901 (2019)