BARYON NUMBER, STRANGENESS, AND ELECTRIC CHARGE FLUCTUATIONS IN HYDRODYNAMICS AT THE LHC

DEKRAYAT ALMAALOL

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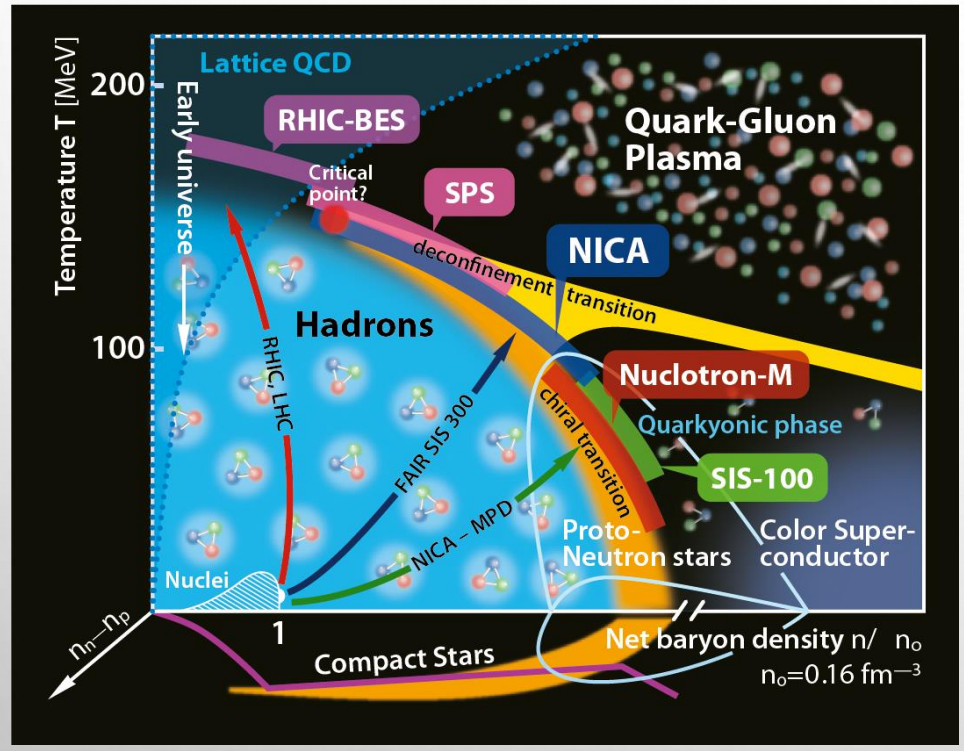
SQM2022

The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

MOTIVATION AND GOALS

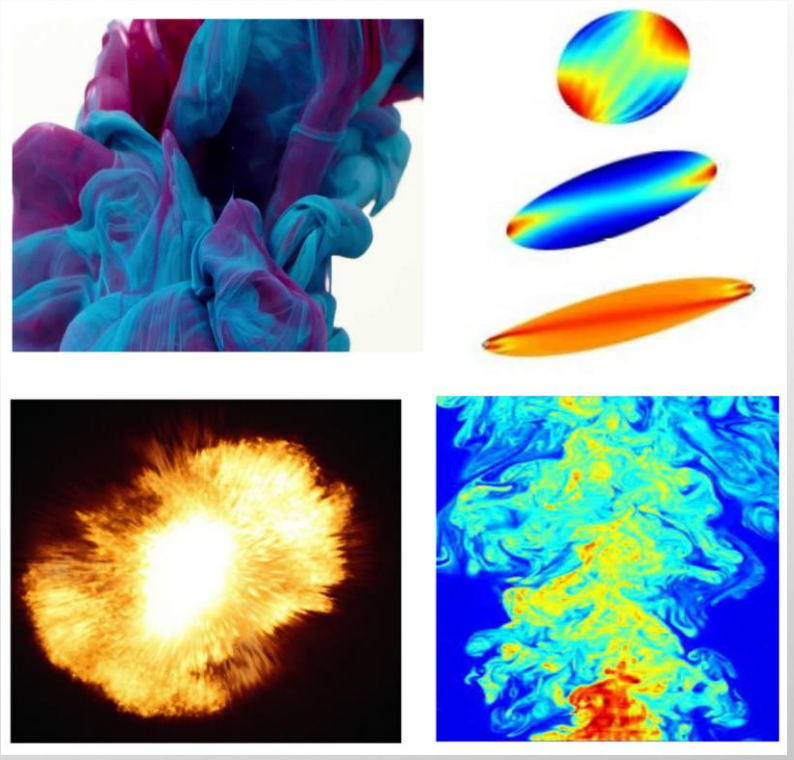
Thermodynamics of QCD

- the structure of the QCD phase diagram



Non-equilibrium dynamics

- Transport properties at finite densities



OUTLINE

- A fluid dynamical theory for multiple conserved charges
- stability analysis and numerical benchmarks
- An ideal simulation of BSQ hydrodynamic

TRANSIENT HYDRODYNAMICS WITH MULTIPLE CONSERVED CHARGES

The state of the system is described by $(\varphi_i) = (u^\mu, \varepsilon, \sum_{q=BSQ} \rho_q, \Pi, \pi^{\mu\nu}, \sum_{q=BSQ} n_q^\mu)$

u^μ = Flow four velocity
ρ_q = Charge density
n_q = Charge current
Π = Bulk viscosity
$\pi^{\mu\nu}$ = Shear stress

Conservation laws

$$D_\mu T^{\mu\nu} = 0$$
$$D_\mu N_q^\mu = 0$$

Constitutive relations

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$
$$N_q^\mu = \rho_q u^\mu + n_q^\mu$$

BSQ Israel-Stewart fluid dynamics

$$S^\mu = s u^\mu - \sum_q^{B,S,Q} \alpha_q n_q^\mu - \frac{1}{2} u^\mu \left(\beta_\Pi \Pi^2 + \beta_\pi \pi^{\mu\nu}\pi_{\mu\nu} + \sum_q^{B,S,Q} \beta_n^{qq'} n_q^\mu n_\mu^{q'} \right) - \sum_q^{B,S,Q} \left(\gamma_{n\Pi}^q n_q^\mu \Pi + \gamma_{n\pi}^q n_q^\nu \pi_\nu^\mu \right) - \frac{1}{2}(u^\nu \beta_{\Pi\pi} \Pi \pi_{\mu\nu})$$

Relaxation-type equations

$$\tau_\Pi \dot{\Pi} + \Pi = -(\zeta + \tau_\Pi \Pi)\theta - \frac{\tau_\Pi}{2\beta_\Pi}\dot{\beta}_\Pi \Pi + \text{dif coupling terms}$$
$$\tau_\pi \dot{\pi}^{\mu\nu} + \pi^{\mu\nu} = (2\eta\sigma^{\mu\nu} + \tau_\pi \pi^{\mu\nu})\theta - \frac{\tau_\pi}{2\beta_\pi}\dot{\beta}_\pi \pi^{\mu\nu} + \text{dif coupling terms}$$
$$\tau_{qq'} \dot{n}_{q'}^\mu + n_q^\mu = -(\kappa_{qq'} \nabla^\mu \alpha_{q'} + \tau_{qq'} n_{q'}^\mu)\theta - \frac{\tau_{qq'}}{2\beta_{qq'}}\dot{\beta}_{qq'} n_{qq'}^\mu + \text{dif coupling terms}$$

2nd order Transport coefficients

$\beta_\Pi, \beta_\pi, \gamma_{n\Pi}, \gamma_{n\pi}, \beta_{qq'}$

Fotakis et al, 2203.11549 [nucl-th]

$p = (T, \mu_q) \Rightarrow$ 4D EOS(lattice QCD),10 new thermodynamic derivatives

Jaki Noronha-Hostler, Paolo Parotto, Claudia Ratti, Jamie Stafford Phys.Rev.C 100 (2019) 6, 064910

See also: Monnai Nucl.Phys.A 847 (2010) 283-314

STABILITY ANALYSIS

- **Lyapunov functional** Stability analysis for BSQ Israel Stewart

  See also: Gavassino Class.Quant.Grav. 38 (2021) 21, 21LT02 for single charge analysis in Ekart frame

$$D_\mu T^{\mu\nu} = 0\,; D_\mu N_q^\mu = 0$$

$$D_\mu S^\mu \geq 0$$

Conditions on Thermo

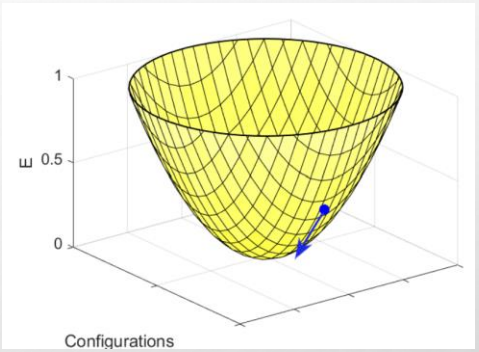
$$C_{\mathcal{P},u^\mu,n_B^\mu} = \frac{1}{\varepsilon + p}\frac{\partial \varepsilon}{\partial p}|_s > 0$$

$$C_{s,u^\mu,n_B^\mu} = \frac{1}{\varepsilon + \mathcal{P}}\frac{\partial \varepsilon}{\partial s}|_p \frac{\partial p}{\partial s}|_{\theta_B} > 0$$

Conditions on transport

$$C_{\Pi,n_B^\mu,u^\mu} = \beta_\Pi > 0$$

$$C_{\pi,n_B^\mu,u^\mu} = \beta_\pi > 0$$



Conditions connecting Thermo+Transport

$$C_{n_B^\mu,s,\pi,\Pi} = \frac{\kappa_n^{BB}}{2\lambda^2} - \frac{(\gamma_{n\Pi}^B)^2}{\beta_\Pi} - \frac{(\gamma_{n\pi}^B)^2}{\beta_\pi} > (\varepsilon + p)\left(T^2 \frac{\partial s}{\partial \varepsilon}|_p \frac{\partial s}{\partial p}|_{\theta_B}\left(\frac{\partial \theta_B}{\partial s}|_p\right)^2 - \frac{1}{4}\frac{\partial p}{\partial \mathcal{E}}|_s\left(\frac{\partial \theta_B}{\partial p}|_s\right)^2\right)$$

$$+ \text{Many more terms!}$$

- **Numerical benchmark**: The code passes Gubser test of ideal BSQ charges Denicol et al, Phys.Rev.C 98 (2018) 3, 034916

INITIAL STATE FLUCTUATIONS WITH FINITE CHARGE DENSITIES

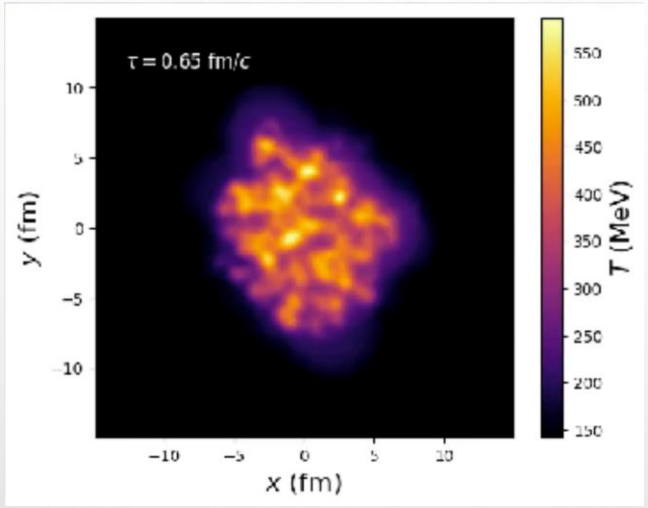
- Including quark production from gluon splittings in the initial state of hydrodynamics

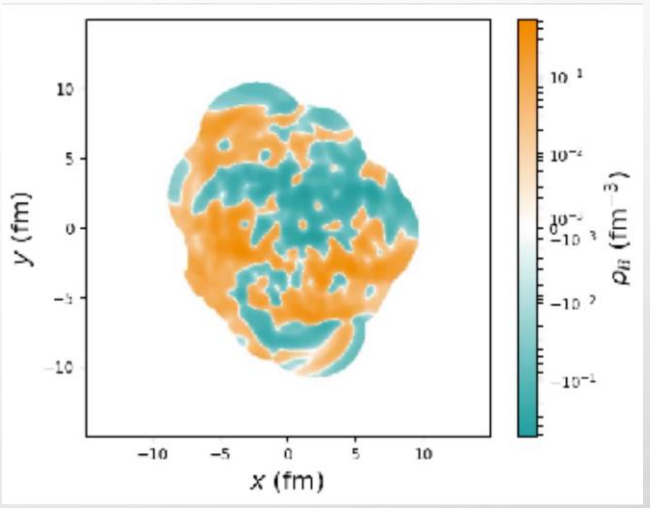
Carzon et al, Phys.Rev.C 105 (2022) 3, 034908

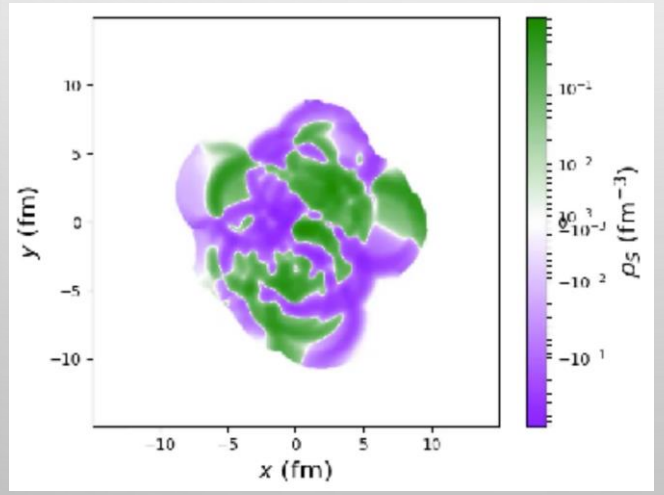
- 4D Initial input $[\varepsilon_0(\tau_0), \rho_0^q(\tau_0)]$

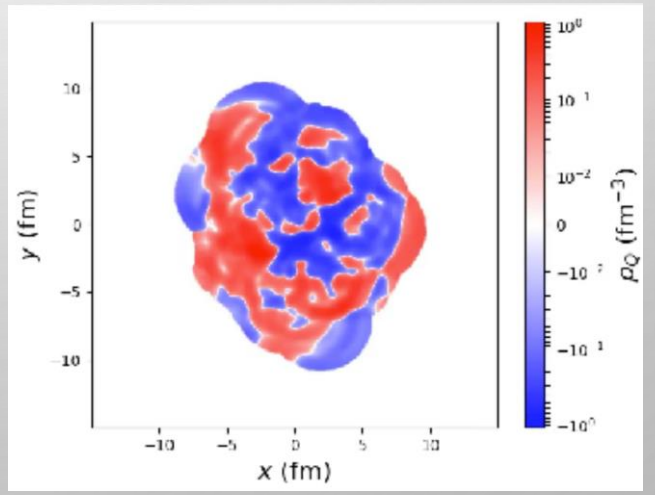
- A pre-equilibrium evolution for the charge densities

Carzon et al, soon to appear





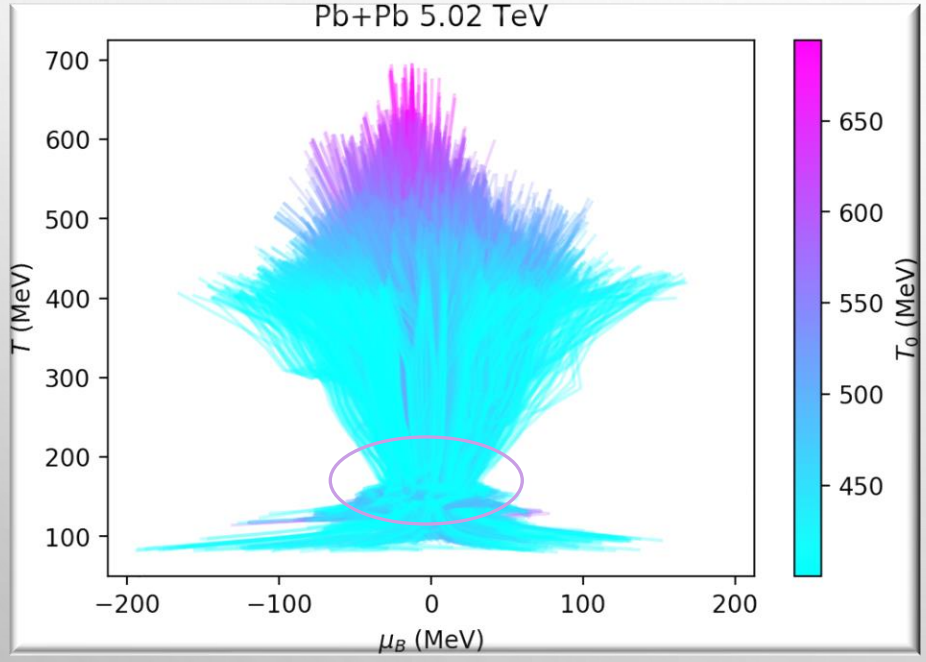


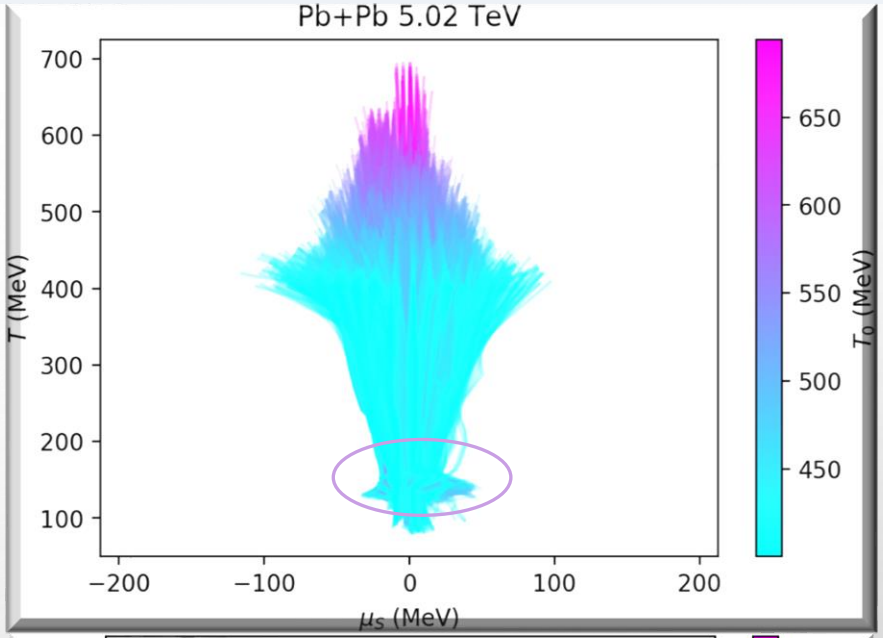


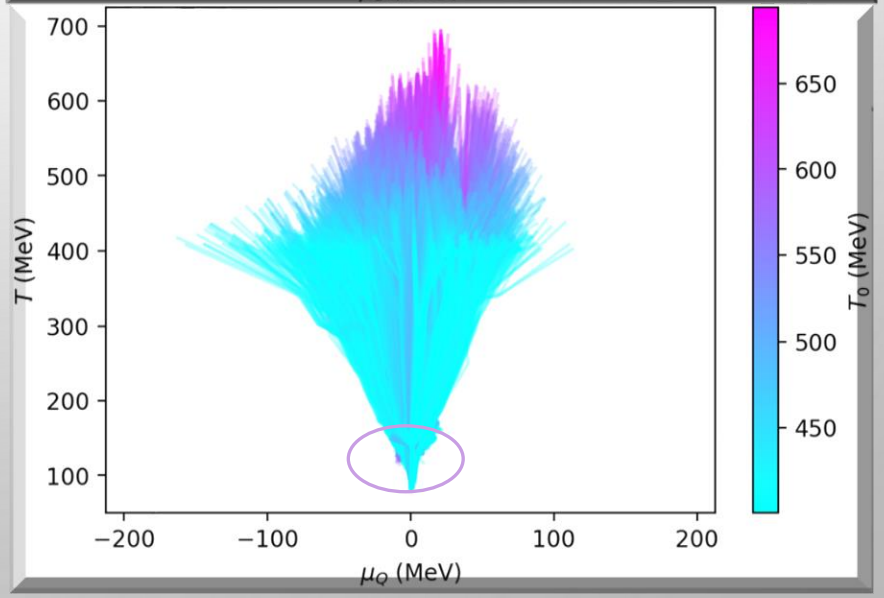
FLUCTUATIONS OF BSQ CHARGES PRESERVED UNTIL FREEZE-OUT AT LHC

- Simulation of dissipative hydrodynamics of multiple conserved charges with an ideal BSQ evolution

net-B=0, local baryon number fluctuations large







- An opportunity to access additional information form the initial state and flow variables as well as dynamical properties