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Non-equilibrium attractors of QCD Kinetic theory at zero and finite density

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CRC-TR 211
Strong-interaction matter under extreme conditions

Pre-equilibrium quark-gluon plasma

Relativistic Heavy-Ion Collisions smash nucleus and produce hot, dense quark-gluon plasma (QGP), which undergoes a non-equilibrium stage for a short time before reaching thermal equilibrium. That motives us to study how the systems thermalize towards hydrodynamics in terms of non-equilibrium attractors

Effective Kinetic Theory

We study the dynamics of non-equilibrium QGP with an effective kinetic theory based on a classical Boltzmann equation

$$\left[\frac{\partial}{\partial\tau} - \frac{p_\parallel}{\tau}\frac{\partial}{\partial p_\parallel}\right] f_a(\tau,p_T,p_\parallel) = -C_a^{2\leftrightarrow2}[f](\tau,p_T,p_\parallel) - C_a^{1\leftrightarrow2}[f](\tau,p_T,p_\parallel)$$

where collision terms are calculated with quantum chromodynamics. Evolving the Boltzmann equations for gluon and all the light quark, antiquarks provides us the real time dynamics of the QGP

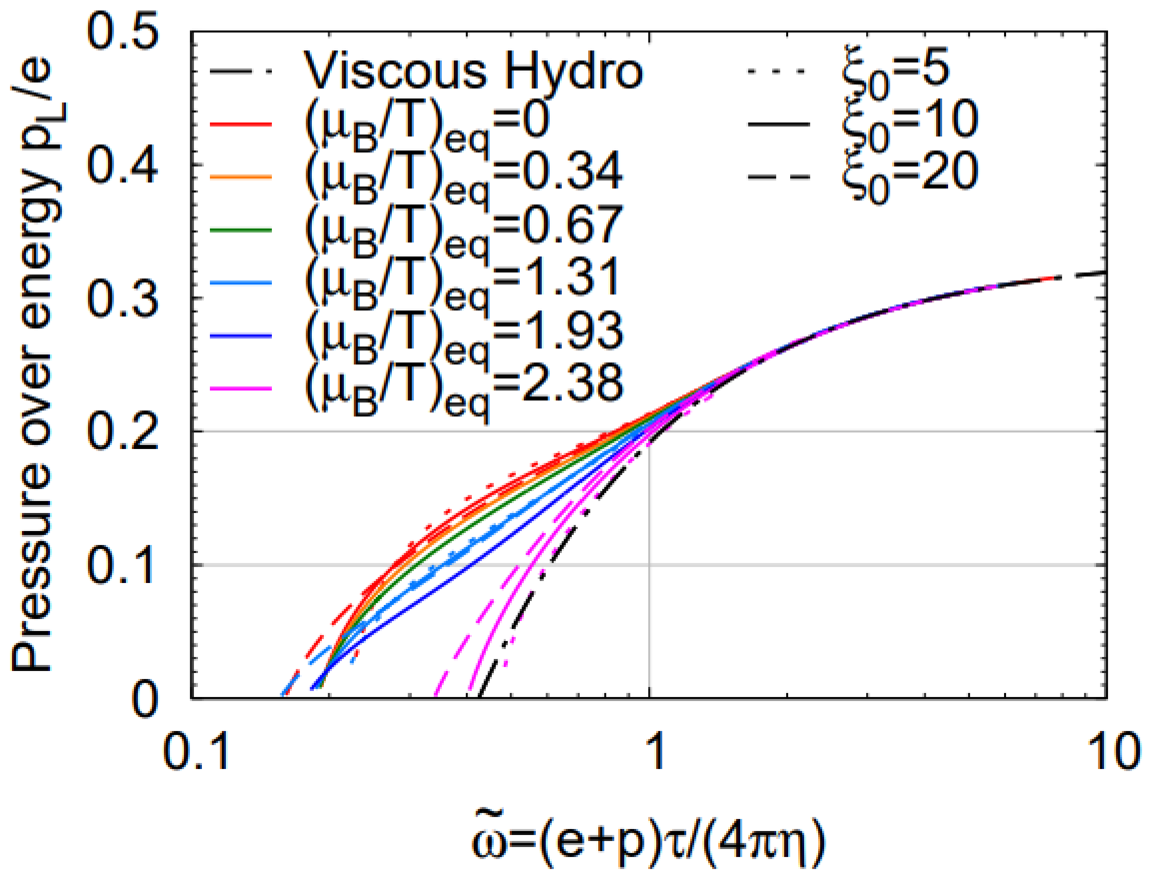
Non-equilibrium evolution

The time evolution of the system can be presented in terms of a dimensionless time scale

$$\tilde\omega = \frac{(e+p)\tau}{4\pi\eta}$$

So that the asymptotic longitudinal pressure over energy near equilibrium from 1st-order hydrodynamics can be expressed universally

$$\frac{p_L}{e} = \frac{1}{3} - \frac{4}{9\pi\tilde\omega}$$



The non-equilibrium curves provide an effective constitutive relation before hydrodynamics become applicable

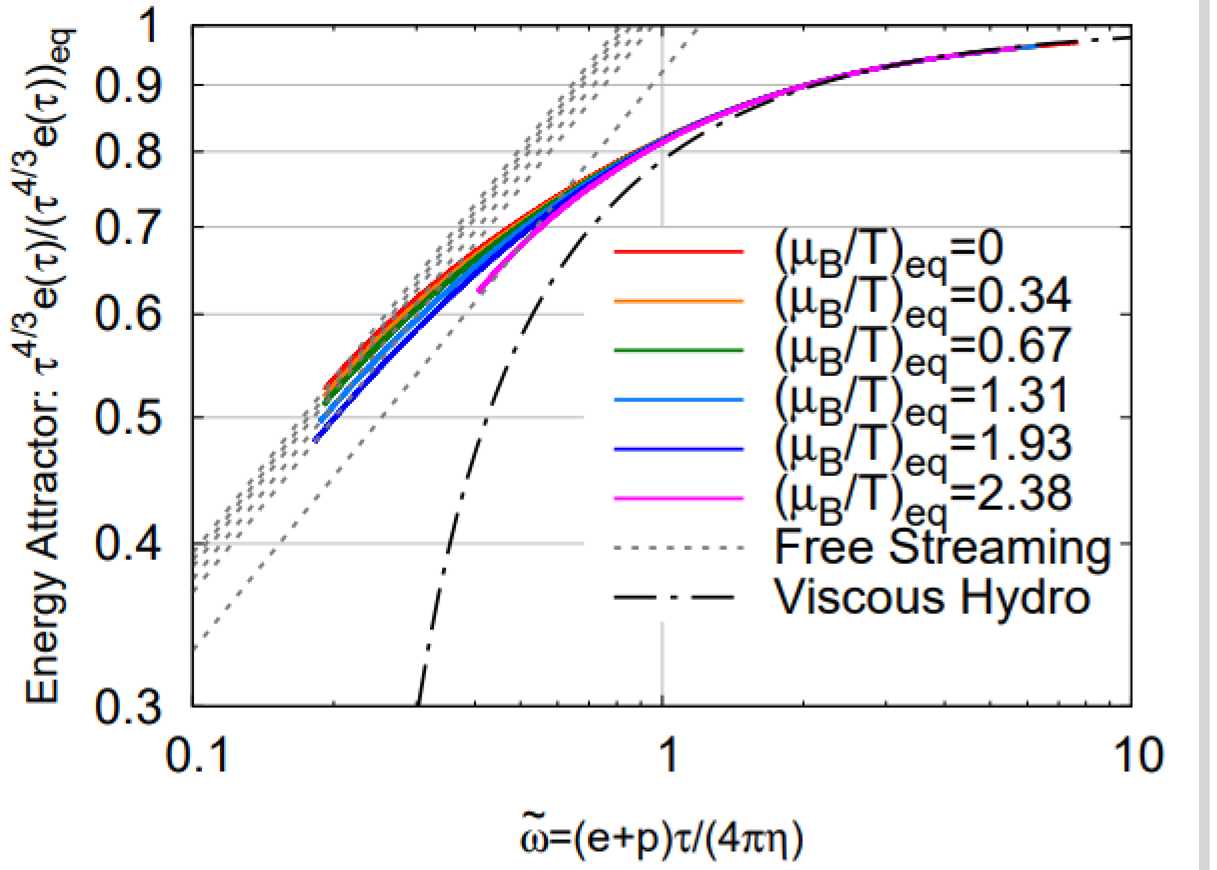
Connection to hydrodynamics

From free streaming to pre-equilibrium stage and eventually to hydrodynamics, an attractor theory in terms of conserved quantities as energy density and baryon density can be established to connect those stages.

$$\left(\tau^{\frac{4}{3}}e\right)(\tilde\omega) = \left(4\pi\frac{\eta T_{\rm eff}}{e+p}\right)^{\frac{4}{9}}\left(\frac{\pi^2\nu_{\rm eff}}{30}\right)^{\frac{1}{9}}(e\tau)_0^{\frac{8}{9}}C_\infty\mathcal{E}(\tilde\omega)$$

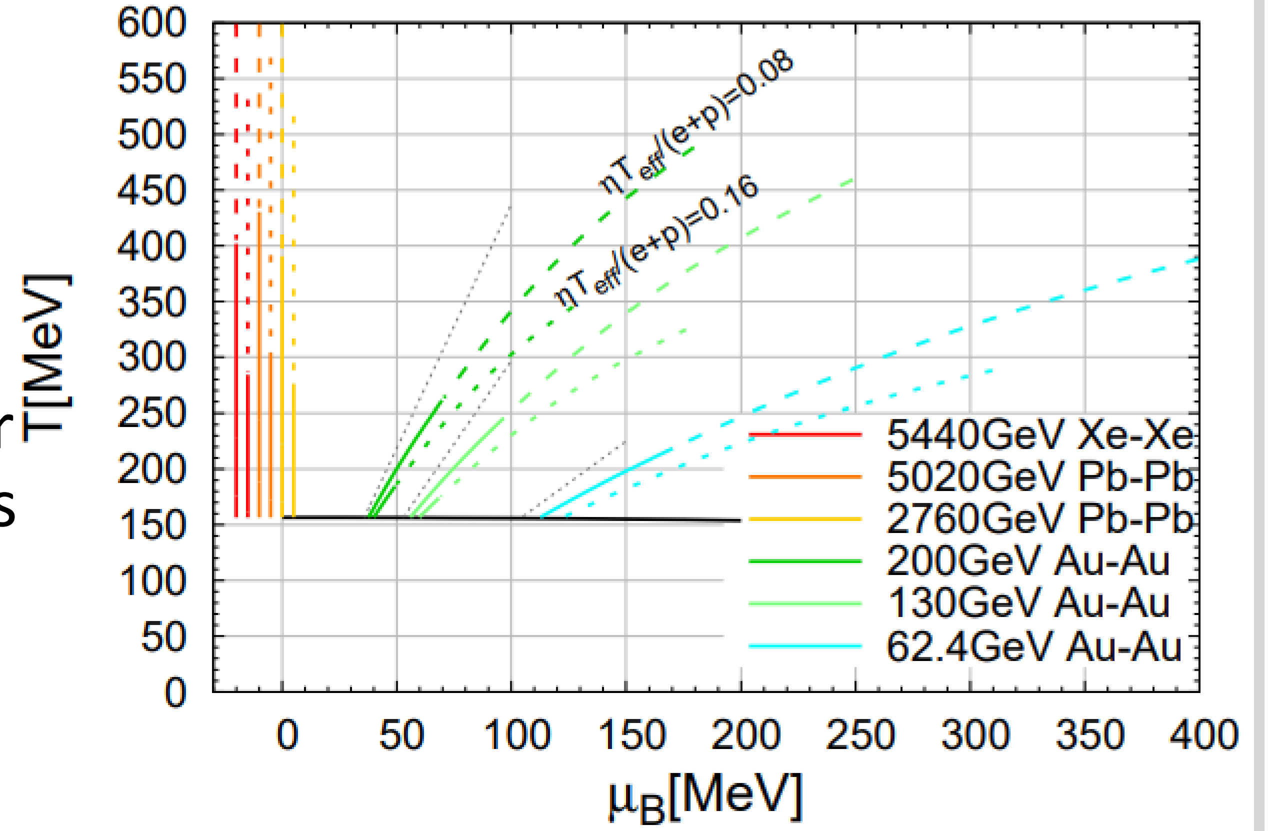
$$(\tau\Delta n_f)(\tilde\omega) = (\tau\Delta n_f)_0$$

A quick memory loss of the initial condition is observed in the non-equilibrium attractor, which universally approach the hydrodynamics.



Phenomenological consequence

Fixing the scales from charged particle multiplicity from experimental data and baryon number to entropy ratio from lattice data with entropy and baryon number calculated from kinetic theory, we are able to project the realistic energy density and baryon density from attractor theory at any time during pre-equilibrium stage. Then it is also profitable to define non-equilibrium temperature, baryon chemical potential with the help of Landau matching. Thus the trajectory of pre-equilibrium QGP evolution can be provided at various collision energies.



With the fixed scales, we conclude on an empirical form of estimating the applicable time and temperature for hydrodynamics

$$\tau \simeq 1.3\ \mathrm{fm}/c\left(\frac{4\pi\eta/s}{2}\right)^{\frac{3}{2}}\left(\frac{dN_{ch}/d\eta}{1942}\right)^{-\frac{1}{2}}\left(\frac{S_\perp}{138\mathrm{fm}^2}\right)^{\frac{1}{2}}$$

$$T \simeq 300\mathrm{MeV}\left(\frac{4\pi\eta/s}{2}\right)^{-\frac{1}{2}}\left(\frac{dN_{ch}/d\eta}{1942}\right)^{\frac{1}{2}}\left(\frac{S_\perp}{138\mathrm{fm}^2}\right)^{-\frac{1}{2}}$$

Conclusion

We study the non-equilibrium quark-gluon plasma with numerical simulations of QCD kinetic theory at zero and finite density. An attractor theory is established connecting the pre-equilibrium quark-gluon plasma to hydrodynamics.

References: X. Du, S. Schlichting, arXiv:2012.09068 (attractor, phenomenology), arXiv: 2012.09079 (QCD kinetic theory, …)