Non-equilibrium Attractors of QCD Kinetic Theory at Zero and Finite Density

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Based on X. D, S. Schlichting

arXiv: 2012.09068 (attractor, phenomenology)
arXiv: 2012.09079 (QCD kinetic theory)

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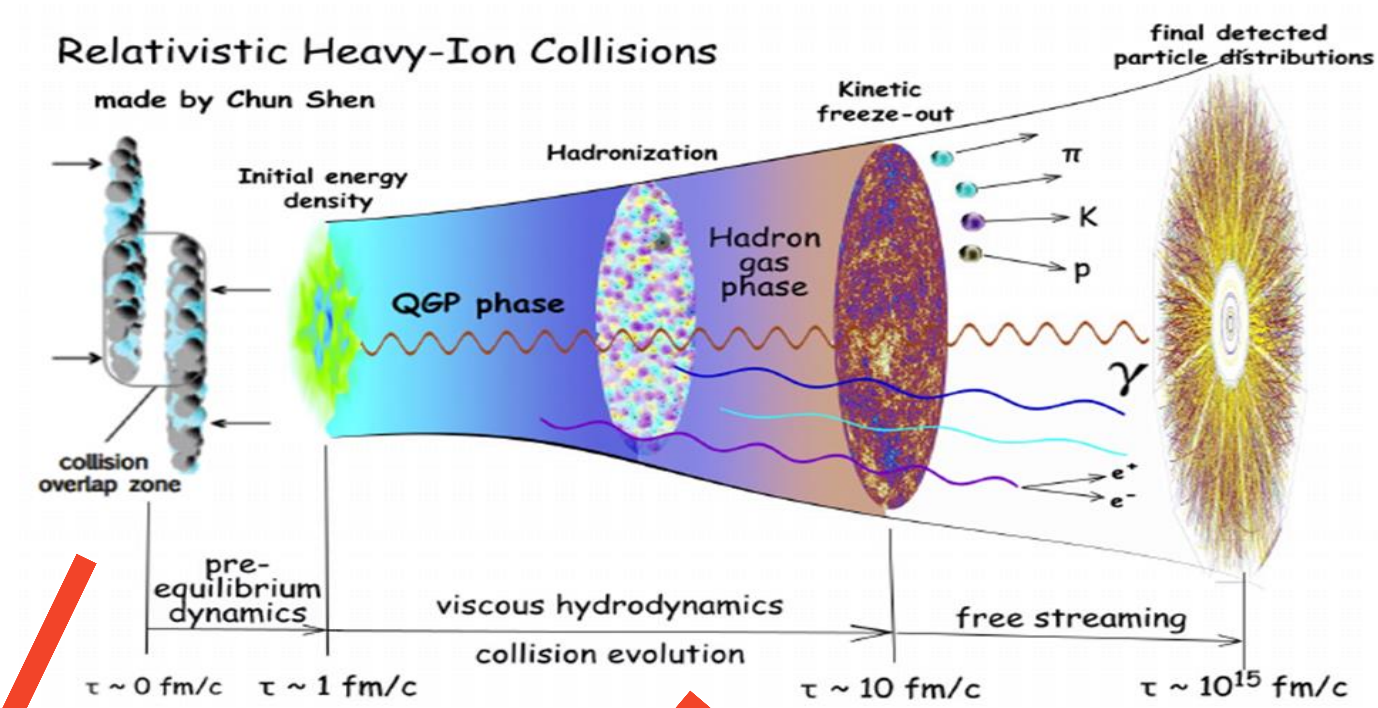
CRC-TR 211
Strong-interaction matter under extreme conditions

Pre-Equilibration Quark-Gluon Plasma



- Initial Collision
- Off-Thermal
- Gluon Saturation

- Pre-Equilibrium QGP
- Thermalization
- Chemical Equilibration

- Hydrodynamic
- Thermal
- Gluon/Quarks

QCD Effective Kinetic Theory

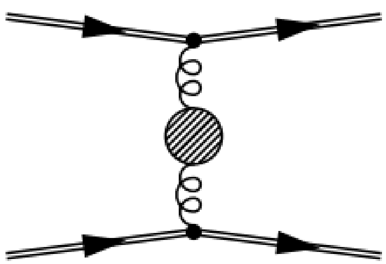
Effective Kinetic Theory (Arnold, Moore, Yaffe) at LO

AMY,JHEP01 (2003) 030
AMY,JHEP0206(2002)030
Kurkela, Mazeliauskas,PRD99 (2019) 054018

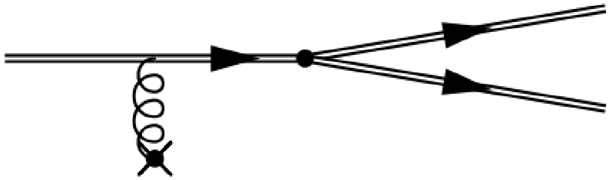
$$\left[\frac{\partial}{\partial\tau} - \frac{p_\parallel}{\tau}\frac{\partial}{\partial p_\parallel}\right] f_a(\tau, p_T, p_\parallel) = -C_a^{2\leftrightarrow2}[f](\tau, p_T, p_\parallel) - C_a^{1\leftrightarrow2}[f](\tau, p_T, p_\parallel)$$

Boltzmann equation for massless gluon and 3 light quarks/anti-quarks $a = g, u, \bar{u}, d, \bar{d}, s, \bar{s}$

Including $2 \leftrightarrow 2$ elastic processes and $1 \leftrightarrow 2$ inelastic processes



$2 \leftrightarrow 2$: Color screening by Debye mass fit to HTL calculation



$1 \leftrightarrow 2$: Collinear radiation including LPM effect via effective vertex resummation

Non-equilibrium evolution

System initially highly anisotropic with CGC inspired gluon dist. & finite baryon/charge density

Universal scaling variable:

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

1st-order hydrodynamics near equilibrium

$$\frac{p_L}{e} = \frac{1}{3} - \frac{4}{9\pi}\left(\frac{\eta T_{\rm eff}}{e+p}\right)\frac{4\pi}{\tau T_{\rm eff}} \Rightarrow \frac{p_L}{e} = \frac{1}{3} - \frac{4}{9\pi\tilde{\omega}}$$

const.

Larger μ_B: slower isotropization:

Ineffectiveness of quark interaction

Spin degeneracy

Quantum statistics

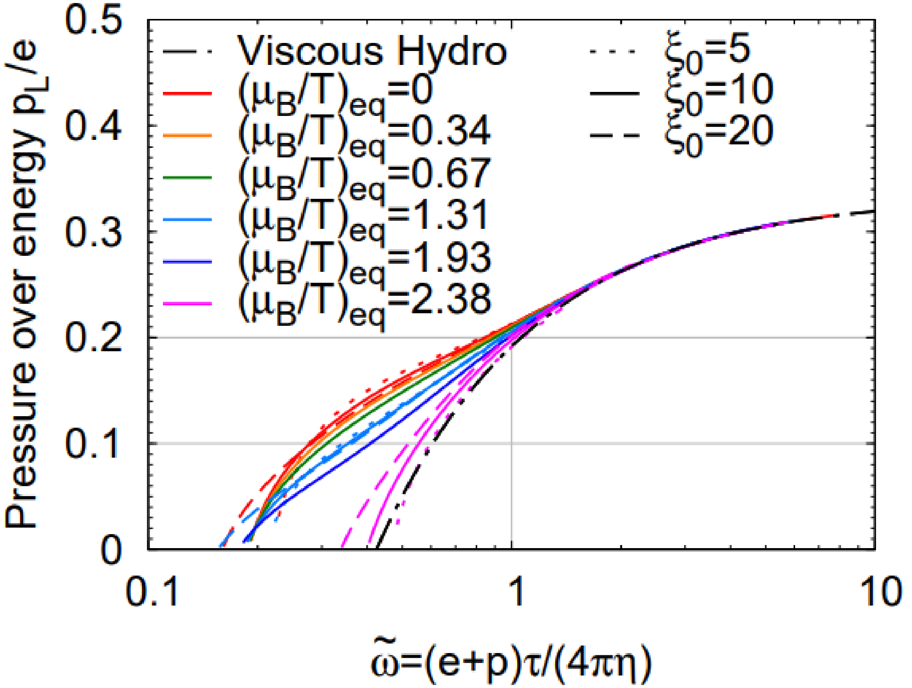
Non-equilibrium attractors from kinetic theory:

Effective constitutive relations

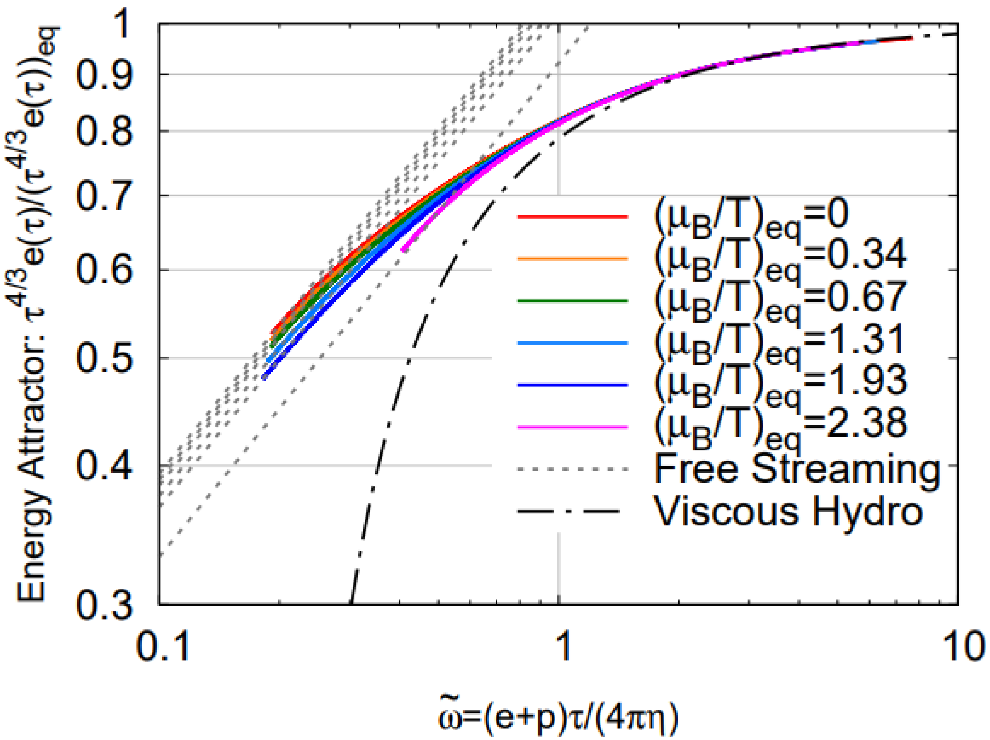
(far-from equilibrium)

$$\frac{p_L}{e} = f(\tilde{\omega})$$

Isotropization later than hydrodynamization



Connection to Hydrodynamics



Non-equilibrium attractor

$$\mathcal{E}\left(\tilde{\omega} = \left(\frac{e+p}{\eta T_{\rm eff}}\right)\frac{\tau T_{\rm eff}}{4\pi}\right) = \frac{\tau^{\frac{4}{3}}e}{\left(\tau^{\frac{4}{3}}e\right)_{\rm eq}}$$

Asymptotes:

$$\mathcal{E}(\tilde{\omega} \gg 1) \simeq 1 - \frac{2}{3\pi\tilde{\omega}}$$ Hydrodynamics

$$\mathcal{E}(\tilde{\omega} \ll 1) \simeq C_\infty^{-1}\tilde{\omega}^{\frac{4}{9}}$$ Free streaming

Pre-equilibrium description connects initial state to hydrodynamics

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

$$(\tau\Delta n_f)_{\tilde{\omega}} = \boxed{(\tau\Delta n_f)_0}$$

Input to hydrodynamics through pre-equilibrium evolution

Giacalone, Mazeliauskas, Schlichting PRL123(2019)26

Phenomenological Consequence

In equilibrium:

Entropy:
$$(s\tau)_{\text{eq}} = \frac{\left(e+p-\sum_f \mu_f \Delta n_f\right)\tau}{T}$$

Net Baryon Number:
$$\Delta n_B = \frac{1}{3}\Delta n_u + \frac{1}{3}\Delta n_d$$

Fixed from experimental/lattice data

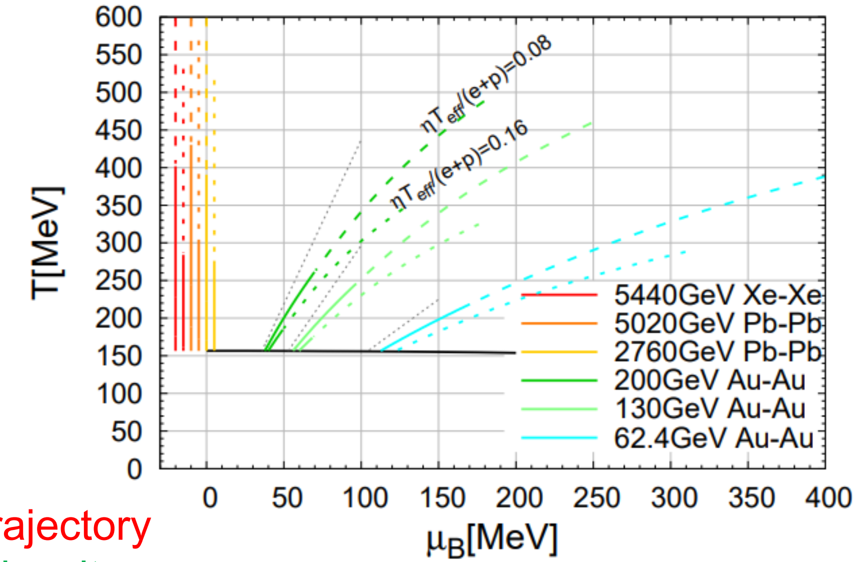
Charged particle multiplicity:
$$\frac{dN_{ch}}{d\eta} \simeq \frac{N_{ch}}{JS}(\tau s)_{\text{eq}} S_T \simeq 0.12(\tau s)_{\text{eq}} S_T$$

Entropy per baryon:
$$\frac{S}{N_B} = \left(\frac{\tau s}{\tau \Delta n_B}\right)_{\text{eq}}$$

From non-equilibrium attractor:
$$\left(\tau^{\frac{4}{3}} e\right)_{\tilde{\omega}} = \left(4\pi\frac{\eta T_{\text{eff}}}{e+p}\right)^{\frac{4}{9}}\left(\frac{\pi^2 \nu_{\text{eff}}}{30}\right)^{\frac{1}{9}}(e\tau)_0^{\frac{8}{9}} C_\infty \mathcal{E}(\tilde{\omega})$$
$$(\tau \Delta n_f)_{\tilde{\omega}} = (\tau \Delta n_f)_0$$

From Landau matching:
Time-dependent T and μ

Non-equilibrium trajectory
to higher baryon density



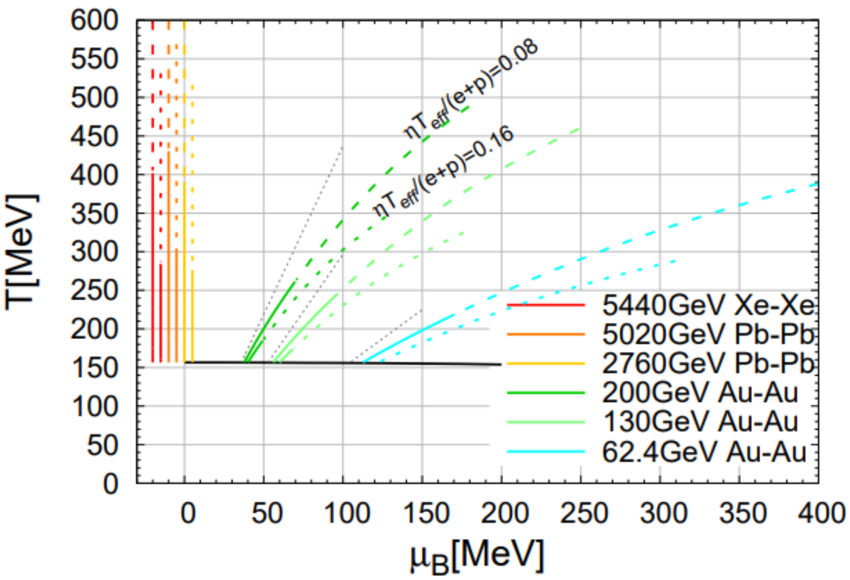
Conclusion and Outlook

⇒Theoretical and phenomenological consequence:

- Non-equilibrium effective constitutive relation from QCD kinetic theory
  - Before hydrodynamic regime
- Trajectory of pre-equilibrium QGP in T-μ diagram
  - Before hydrodynamic regime
- Applicable time and temperature for hydrodynamics
  - By fixing scales from experiments/lQCD

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

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



⇒ Application:

- pre-equilibrium di-lepton production
  - See talks by Maurice Coquet on Tuesday