Constraining early time dynamics in ultrarelativistic Heavy Ion Collisions

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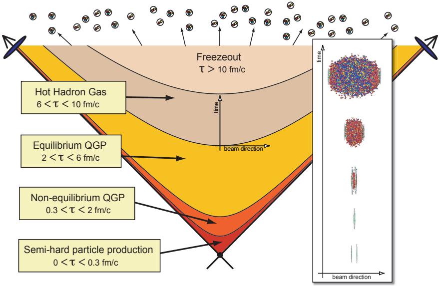
with S. Kamata, M. Martinez and M. Spaliński, arXiv:2012.02184 [nucl-th]

A far-from-equilibrium attractor is a property of the system where the memory of initial conditions is rapidly swept away and a universal behaviour sets in. Early is $\tau \sim 0.5$ fm/c

Connects the initial state with the start of the hydro expansion

Observed in hydrodynamics, kinetic theory and holography

- What mechanism drives the system towards the attractor?
- Can it have experimental imprints?
- How much can we constrain initial times?



Bjorken flow

At ultrarelativistic energies

$$T_{\mu\nu} = \mathrm{diag}\{\epsilon(\tau), P_L(\tau), P_T(\tau), P_T(\tau)\}$$

where $\nabla_\mu T^{\mu\nu} = 0$ and $T^\mu_\mu = 0$ imply

$$P_L(\tau) = \frac{\epsilon}{3}\left(1 - \frac{2}{3}\mathcal{A}\right) \qquad P_T(\tau) = \frac{\epsilon}{3}\left(1 + \frac{1}{3}\mathcal{A}\right)$$

where $\mathcal{A}$ is the pressure anisotropy

Local effective temperature and dimensionless time variable

$$\epsilon(\tau) = \gamma T(\tau)^4 \qquad w = \tau T(\tau) = \frac{\lambda_{\mathrm{macro}}}{\lambda_{\mathrm{micro}}} = \frac{1}{\mathrm{Kn}}$$

J. D. Bjorken, Phys. Rev. D 27, 140 (1983)

W. Florkowski,*et al.* Rept. Prog. Phys. 81, no. 4, 046001 (2018)

Pressure anisotropy determines the conservation equation

$$\nabla_\mu T^{\mu\nu} = 0 \iff \tau \partial_\tau \log \epsilon = -\frac{4}{3} + \frac{2}{9}\mathcal{A}(w)$$

or in dimensionless variables

$$\frac{d \log T}{d \log w} = \frac{\mathcal{A}(w) - 6}{\mathcal{A}(w) + 12}$$

with a solution

$$T(w) = T(w_0) \exp\left(\int_{w_0}^{w} \frac{dx}{x} \frac{\mathcal{A}(x) - 6}{\mathcal{A}(x) + 12} \right)$$

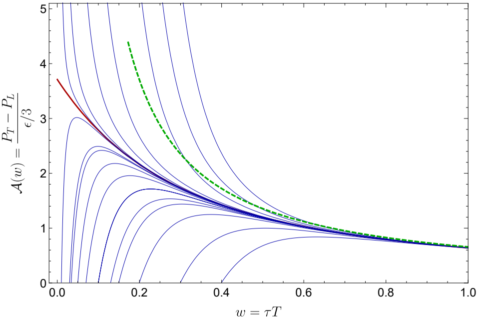
Function $\mathcal{A}(w)$ comes from a microscopic model and encodes remaining initial conditions of the system

Mueller-Israel-Stewart (MIS) theory

For the Bjorken flow equations read

$$C_{\tau\Pi}\left(1+\frac{\mathcal{A}}{12}\right)\mathcal{A}'+\left(\frac{C_{\tau\Pi}}{3w}+\frac{C_\lambda}{8C_\eta}\right)\mathcal{A}^2=\frac{3}{2}\left(\frac{8C_\eta}{w}-\mathcal{A}\right)$$

The attractor is the unique regular solution $\mathcal{A}_*(w=0)=6\sqrt{\frac{C_\eta}{C_{\tau\Pi}}}$

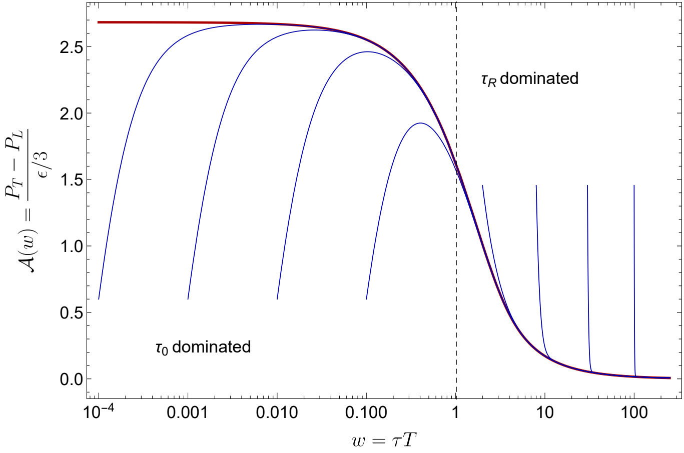


M. P. Heller M. Spalinski, Phys. Rev. Lett. **115**, no.7, 072501 (2015)

W. Florkowski,*et al.* Rept. Prog. Phys. 81, no. 4, 046001 (2018)

What attracts to attractors?

- Early time: expansion dominated, power-law, sym. determined
- Late times: decay of the non-hydro mode, generic



A. Kurkela, *et.al.* Phys. Rev. Lett. **124**, no.10, 102301 (2020)
M. P. Heller, *et al.* Phys. Rev. Lett. **125**, no.13, 132301 (2020)

J. P. Blaizot, L. Yan, Phys. Lett. B **780**, 283-286 (2018)

Connecting early and late times

If an attractor exists $\quad T(w) \sim T(w_0) \exp\left(\int_{w_0}^{w} \frac{dx}{x} \frac{\mathcal{A}_*(x)-6}{\mathcal{A}_*(x)+12} \right)$

At late times $\quad \epsilon(\tau) \sim \frac{\Lambda^4}{(\Lambda\tau)^{\frac{4}{3}}} \qquad \tau s \sim \Lambda^2$

At early times $\quad \epsilon(\tau) \sim \frac{\mu^4}{(\mu\tau)^{\beta}} \iff \mathcal{A}_*(w) \sim 6\left(1 - \frac{3}{4}\beta\right)$

$$\epsilon(\tau_0, x_\perp)^{\frac{2}{4-\beta}} \Longrightarrow (\tau s)_{\mathrm{hydro}} \Longrightarrow (\tau s)_{\mathrm{freeze-out}} \approx (\tau s)_{\mathrm{hydro}}$$

Entropy production $\tau \sim 0 \Longrightarrow$ hydro $\Longrightarrow$ freeze-out

$$\left\langle \frac{dN}{dy} \right\rangle \sim (\tau s)_{\mathrm{hydro}}$$

By now the assumption was free-streaming $\beta = 1$

J. J., S. Kamata, M. Martinez and M. Spaliński, arXiv:2012.02184 [nucl-th]

Connecting early and late times

- Due to the attractor assumption we can connect particle production with initial energy deposition

$$\frac{dN}{dy} = h(\beta) \int d^2 x_\perp \epsilon(\tau_0, x_\perp)^{\frac{2}{4-\beta}}$$

- Ratio cancels the unknown factors

$$Q(c, c') = \frac{\langle dN/dy \rangle_c}{\langle dN/dy \rangle_{c'}}$$

- Adopting various models of initial energy deposition we get predictions for β by fitting to $\sqrt{s} = 2.76$ TeV ALICE data

J. J., S. Kamata, M. Martinez and M. Spaliński, arXiv:2012.02184 [nucl-th]

Initial state models

- Dilute-dense

$$\epsilon^{(I)}(\tau_0, x_\perp) = C T^<(x_\perp)\sqrt{T^>(x_\perp)}$$

with $T^<(x_\perp) = \min(T(x_\perp + b/2), T(x_\perp - b/2))$

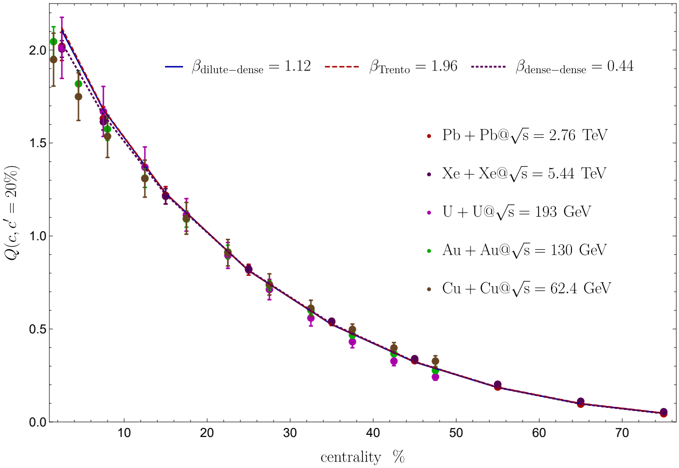
- Trento $p = -1$

$$\epsilon^{(II)}(\tau_0, x_\perp) = C \frac{T(x_\perp + b/2)T(x_\perp - b/2)}{T(x_\perp + b/2) + T(x_\perp - b/2)}$$

- Dense-dense

$$\epsilon^{(III)}(\tau_0, x_\perp) = C T(x_\perp + b/2)T(x_\perp - b/2)$$

Connecting early and late times



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Connecting early and late times

- The three adopted models of initial energy deposition predict

$$\beta^{\mathrm{dilute-dense}} = 1.12 \quad \beta^{\mathrm{Trento}} = 1.96 \quad \beta^{\mathrm{dense-dense}} = 0.44$$

- Pre-hydrodynamic flow is tightly connected to the initial state model, and determines initial pressure anisotropy

$$\mathcal{A}_{\mathrm{dilute-dense}} = 0.96 \quad \mathcal{A}_{\mathrm{Trento}} = -2.82 \quad \mathcal{A}_{\mathrm{dense-dense}} = 4.02$$

- In contrast free-streaming, ubiquitous in kinetic theory, implies

$$\beta_{\mathrm{fs}} = 1 \qquad \mathcal{A}_{\mathrm{fs}} = \frac{3}{2}$$

not necessarily consistent with a generic initial energy deposition model

J. J., S. Kamata, M. Martinez and M. Spaliński, arXiv:2012.02184 [nucl-th]

Conclusions

- The attractor provides a simple conceptual link between early and late times
- Free-streaming is not necessarily compatible with a generic initial state model
- Pre hydro flow needs to matched with a specific initial state model
- Generalize our approach by relaxing symmetry assumptions and enlarge the functional space of the Bayesian analysis