

Chemical equilibration as an effective bulk viscosity in the early QGP

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Chemical Kinetics and Evolution

Heavy-ion collisions create a quark-gluon plasma that behaves as a nearly perfect fluid. Its initial state (CGC / IP-Glasma) is almost pure glue; quarks are produced slowly through the inelastic reaction $g + g \leftrightarrow q + \bar{q}$ (~ 1 fm/c for gluons, $\gtrsim 3$ fm/c for quarks).



The particle four-currents $J_i^\mu = n_i u^\mu$ give the covariant rate equations:

$$Dn_g + n_g \Theta = -R \left(n_g - \frac{n_q^2}{n_g} \right), \quad Dn_q + n_q \Theta = +R \left(n_g - \frac{n_q^2}{n_g} \right).$$

The composition variable measures the distance from saturation:

$$Y_q \equiv \frac{n_q^2}{n_g^2} : \quad 0 \text{ (pure glue)} \rightarrow 1 \text{ (equilibrium)}.$$

It obeys a single evolution equation:

$$DY_q = 2R (1 + \sqrt{Y_q}) \sqrt{Y_q} (1 - Y_q).$$

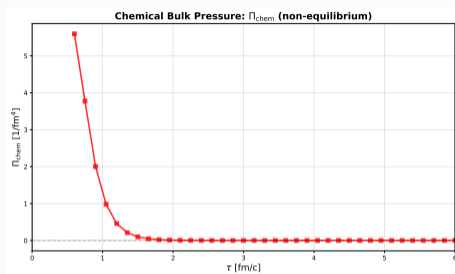
Chemical Bulk Pressure

Standard hydro starts from a **fully equilibrated** EoS, $P_{\text{QCD}}(\epsilon)$. A lagging plasma ($Y_q < 1$) has a *different* pressure and that gap is a bulk pressure:

$$\Pi \equiv P(\epsilon, Y_q) - P_{\text{QCD}}(\epsilon).$$

- As the plasma equilibrates ($Y_q \rightarrow 1$), $\Pi \rightarrow 0$.
Gavassino & Noronha: a reactive mixture relaxing this way is *exactly* an Israel–Stewart bulk-viscous fluid.
- ⇒ **The chemistry is the bulk viscosity** no fitted $\zeta(T)$, no matching of separate equations of state.

Gavassino & Noronha, PRD **109**, 096040 (2024); neutron-star application: Yang *et al.*, PRC **109**, 015805 (2024).



$\Pi_{\text{chem}}(\tau)$ spikes early, gone by ~ 2 fm/c.

Bulk Viscosity (ζ/s)

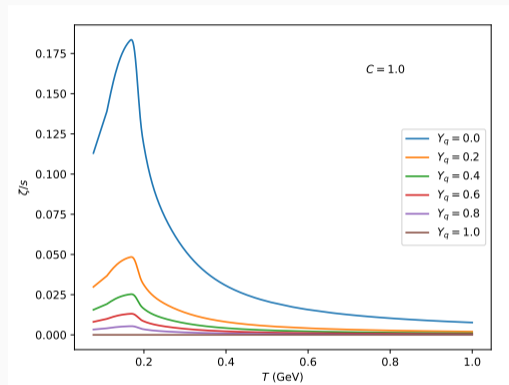
- Y_q enters via the trace anomaly $I = \epsilon - 3P$:

$$I(\epsilon, Y_q) = (1 - \sqrt{Y_q}) I_0 + \sqrt{Y_q} I_{\text{QCD}}.$$

- The lag obeys $\tau_\Pi D\Pi + \Pi = -\zeta\Theta$, with

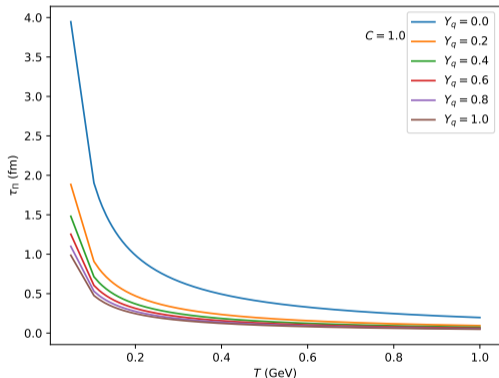
$$\frac{\zeta}{s} = \frac{1}{C(1 + \sqrt{Y_q})^2} \frac{1}{3} (1 - \sqrt{Y_q}) \frac{dI_{\text{QCD}}}{d\epsilon}.$$

- The magnitude is largest far from equilibrium ($Y_q \approx 0$) and vanishes as equilibrium is approached ($Y_q \rightarrow 1$).
- The peak near T_c is driven by the rapid change in the trace anomaly, $\partial I_{\text{QCD}}/\partial e$.



ζ/s vs. T , ordered by Y_q .

Relaxation Time (τ_π)

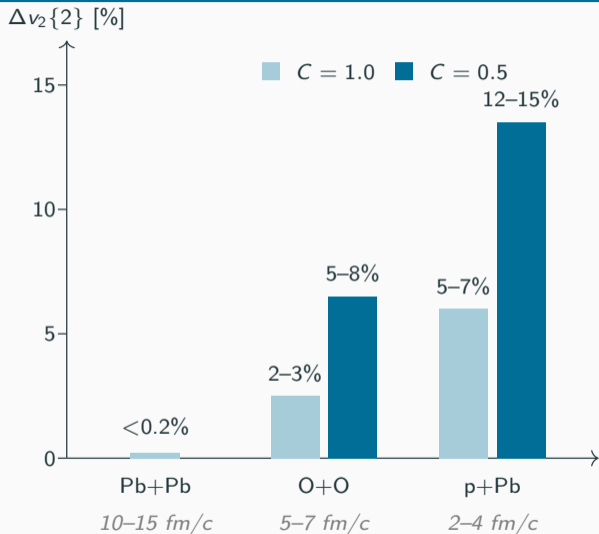


The relaxation time is given by:

$$\tau_\pi = \frac{1}{R(1 + \sqrt{Y_q})^2}$$

- The relaxation time is largest when the system is far from equilibrium ($Y_q \approx 0$).
- It decreases at higher temperatures (as $1/T$) and as the system equilibrates (as $Y_q \rightarrow 1$), reflecting faster reaction rates.

System-size scan: the effect lives only in small systems



- Π_{chem} vanishes by ~ 2 fm/c, so only short-lived systems feel it: **Pb+Pb** shrugs it off, **p+Pb** is caught in the act.
- $\langle p_T \rangle$ tracks v_2 (down 5-8% in p+Pb), and the **mass ordering** heavier hadrons hit harder is the fingerprint.

Conclusion

- Chemical non-equilibrium = a **transient effective bulk viscosity** derived, not fitted, and gone within ~ 2 fm/c.
- Because it's transient, it's a **system-size probe**: negligible in Pb+Pb, up to **12–15%** on p+Pb flow a controlled handle on the quark-production timescale, with the upcoming **O+O program** ideally placed.
- **In progress**: a **Fourier Neural Operator (FNO)** surrogate for the equilibrating QGP, conditioned on C enabling fast **Bayesian inference** of the quark-production rate from observables.
- Also ahead: electromagnetic probes (photons / dileptons) and event-by-event fluctuations.

Thank you! anar.akbarov@wayne.edu