Flavor equilibration of the quark-gluon plasma

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How can we observe quark chemical equilibration in the QGP?

Equilibration in Heavy Ion Collisions

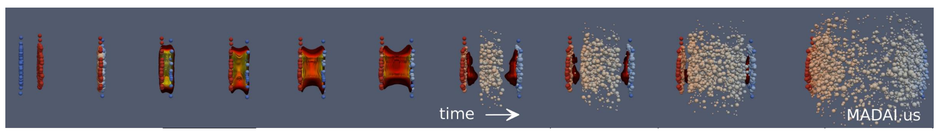
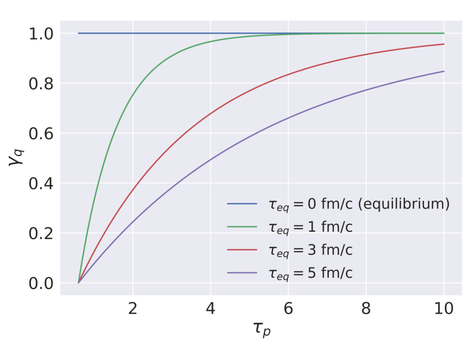


Figure: Hannah Elfner (MADAI collaboration)

- Success of gluon saturation models (e.g., IP-Glasma[1]) suggests the initial state is **gluon-dominated**
- Conventional hydrodynamic models initialize QGP in **thermal and chemical equilibrium**
- Theoretical predictions for quark chemical equilibration times vary[2]: **the QGP likely forms out of equilibrium**

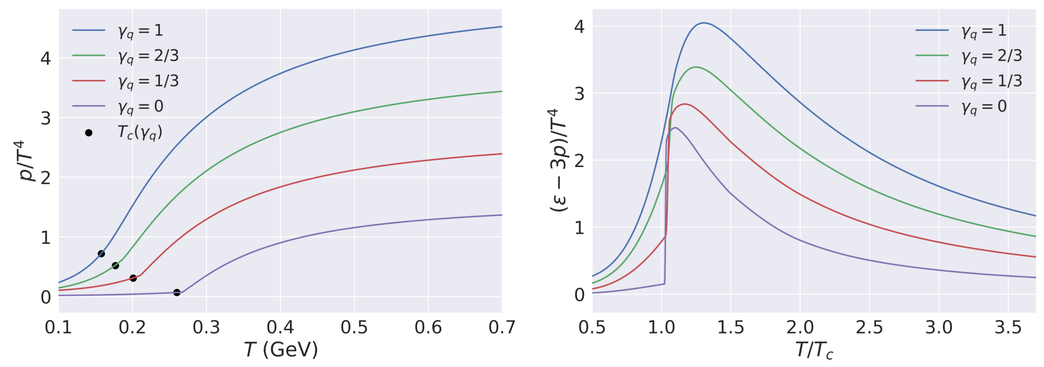
- **Our goal:** study the evolution of the QGP in a scenario where (anti)quarks are produced during hydrodynamic stage
- We model this using local quark fugacity γ_q with relaxation time τ_{eq}[3]:

$$\gamma_q(\tau_p) = 1 - \exp\left(\frac{\tau_0 - \tau_p}{\tau_{eq}}\right)$$



Model: Partial Chemical Equilibrium

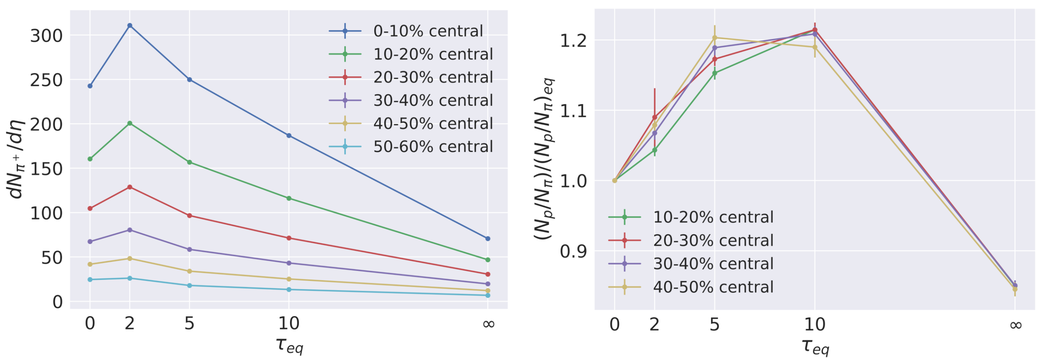
- We assume the QGP forms as fluid of thermalized gluons and zero (anti)quarks
- **Equation of state transitions from $N_f = 0$ to $N_f = 2 + 1$** with shifting critical temperature $T_c(\gamma_q)$ that increases with distance from equilibrium
  - High T: $\frac{p}{T^4}(T, \gamma_q) = \gamma_q \frac{p_{N_f=2+1}}{T^4}\left(T\frac{T_{c,N_f=2+1}}{T_c(\gamma_q)}\right) + (1-\gamma_q)\frac{p_{N_f=0}}{T^4}\left(T\frac{T_{c,N_f=0}}{T_c(\gamma_q)}\right)$
  - Low T: Hadron resonance gas with hadronic fugacities: $\lambda_{meson} = 0.85\,\gamma_q + 0.15$, $\lambda_{baryon} = \lambda_{meson}^{3/2}$



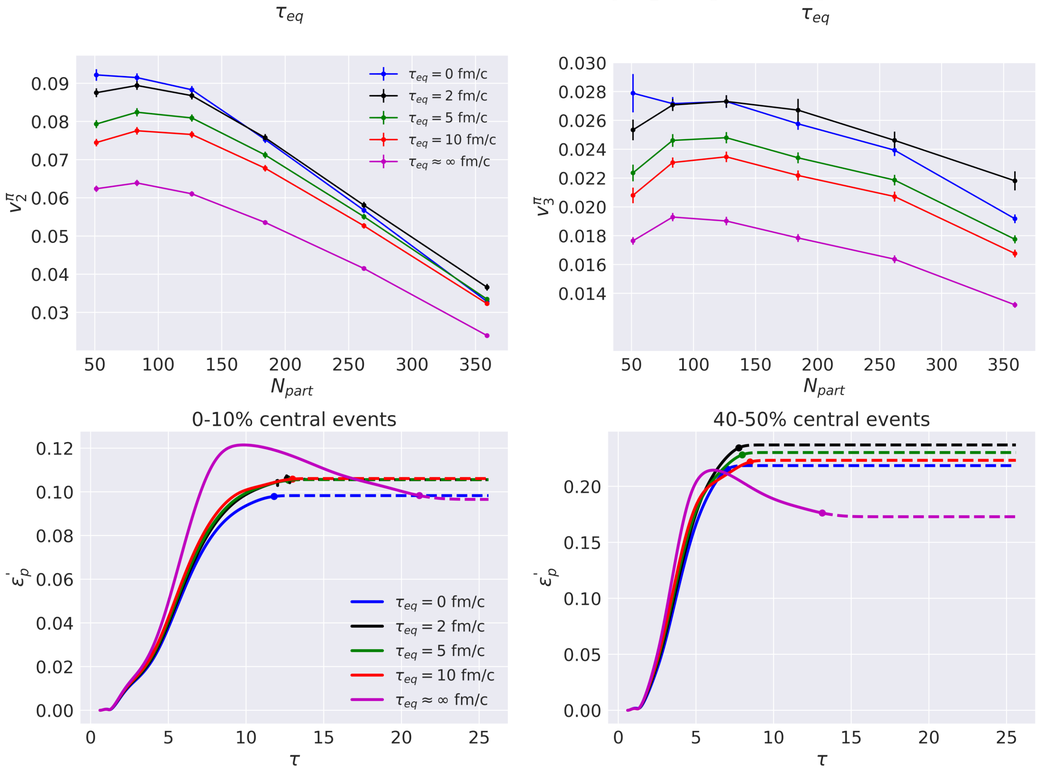
- Specific shear and bulk viscosities (η/s and ζ/s respectively) are functions of (T,γ_q)
- Particlization occurs at $T_c(\gamma_q)$ using Cooper-Frye prescription with **γ_q-dependent corrections to hadron distribution functions and viscous corrections**
- Implemented in: MUSIC[4] (hydrodynamics) and iS3D[5] (particlization)
- Initial conditions: 2.76 TeV Pb-Pb events generated by T$_R$ENTo[6]

Exploratory Results

- Higher hadronization temperature out of equilibrium **increases** production of more massive and energetic hadrons
- Non-unity γ_q **suppresses** baryon production at hadronization



- Anisotropic flow is sensitive to:
  - Initial pressure gradients with gluon-dominated equation of state
  - Rate of quark production during hydrodynamic evolution



Future Studies

- Separate **light and strange** flavor equilibration
- Model **shorter-lived** collision systems that equilibrate less
- Integrate a **hadronic afterburner** to model post-particlization dynamics
- Study **photon production** with the same model
- Bayesian parameter estimation will be essential to **constrain equilibration timescales** alongside their effect on QGP transport properties

Hadron production and anisotropic flow are sensitive to the quark chemical equilibration timescale.

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