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

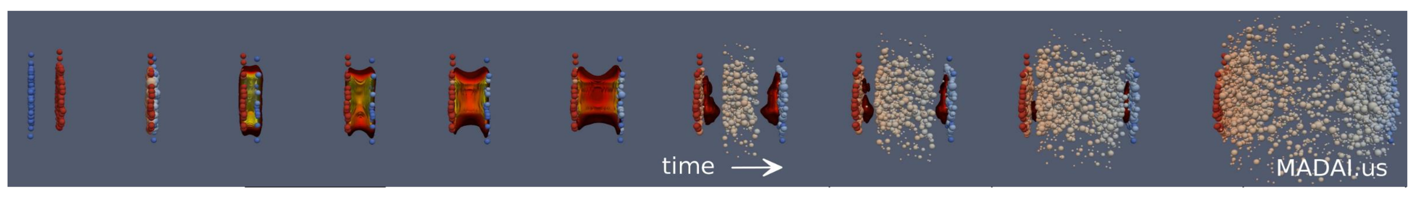


Figure: Hannah Elfner (MADAI collaboration)

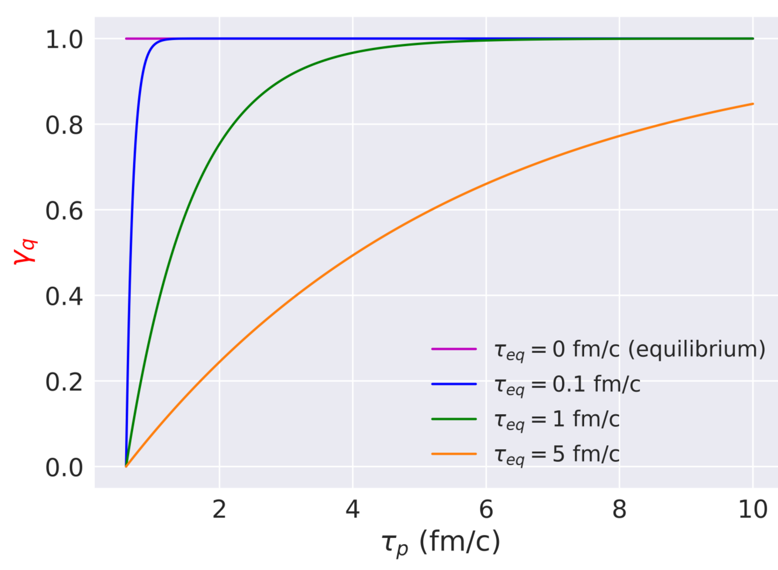
- Success of gluon saturation models suggests the initial state is **gluon-dominated**
- Conventional hydrodynamic models initialize QGP in **thermal and chemical equilibrium**
- Theoretical predictions for quark chemical equilibration times vary[1]: **the QGP likely forms out of equilibrium**

- **Our goal:** study the evolution of the QGP in a scenario where (anti)quarks are produced during hydrodynamic stage

- We introduce local quark fugacity γ_q with relaxation time τ_{eq}[2]:

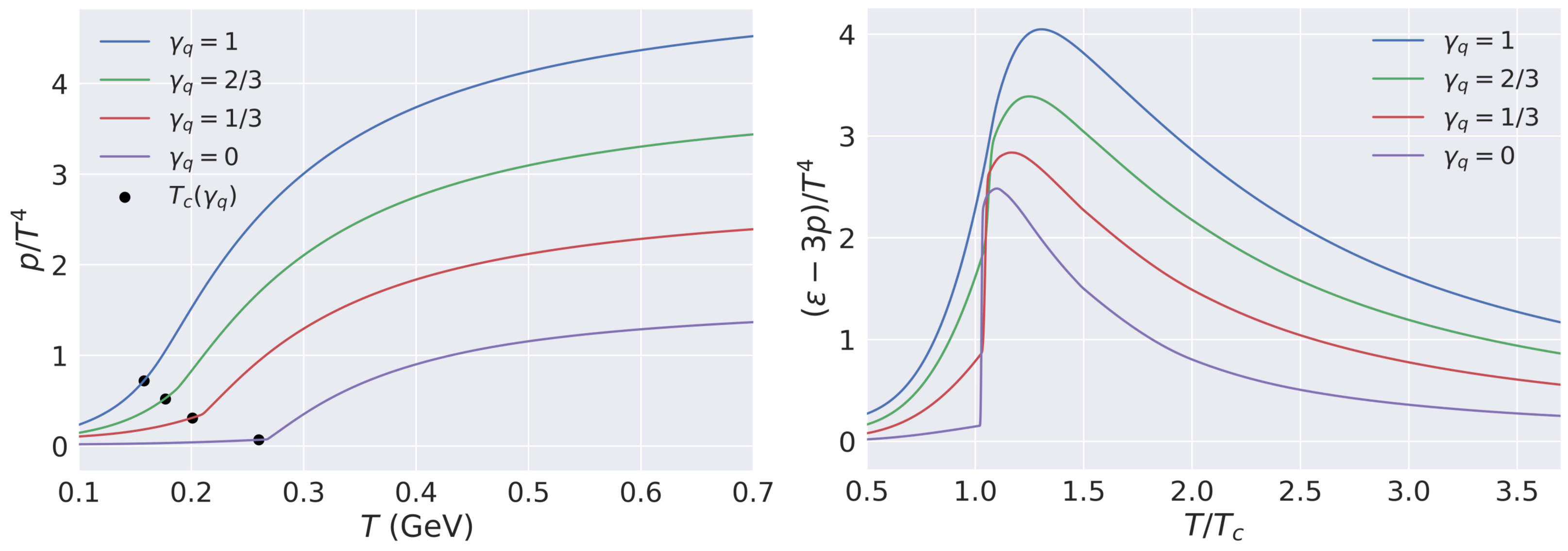
$$\gamma_q(\tau_p) = 1 - \exp\left(\frac{\tau_0 - \tau_p}{\tau_{eq}}\right)$$

- Can define independent γ_q and τ_{eq} for each flavor



Model: Partial Chemical Equilibrium

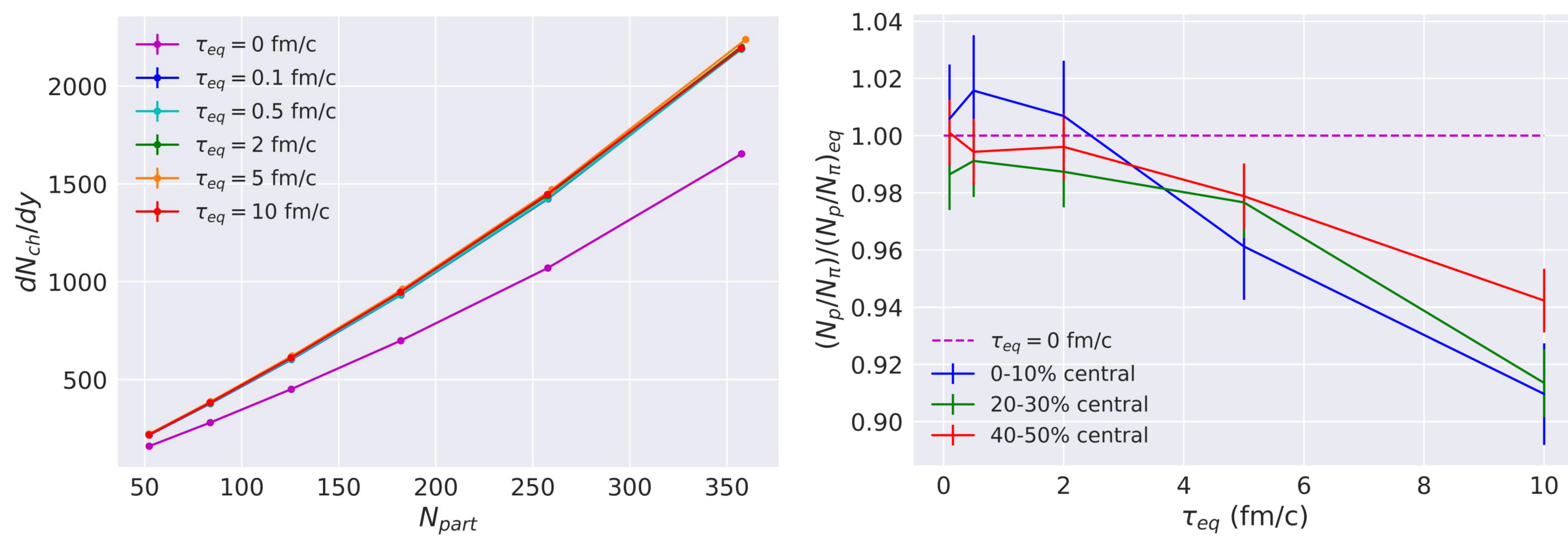
- Assume the QGP forms as fluid of thermalized gluons and zero (anti)quarks
- **Equation of state transitions from $N_f = 0$ to $N_f = 2+1$** with shifting critical temperature $T_c(\gamma_q)$ that increases with distance from equilibrium
  - High T: $\frac{p}{T^4}(T,\gamma_q) = \gamma_q \frac{p_{N_f=2+1}}{T^4}\left(T\frac{T_{c,N_f=2+1}}{T_c(\gamma_q)}\right)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



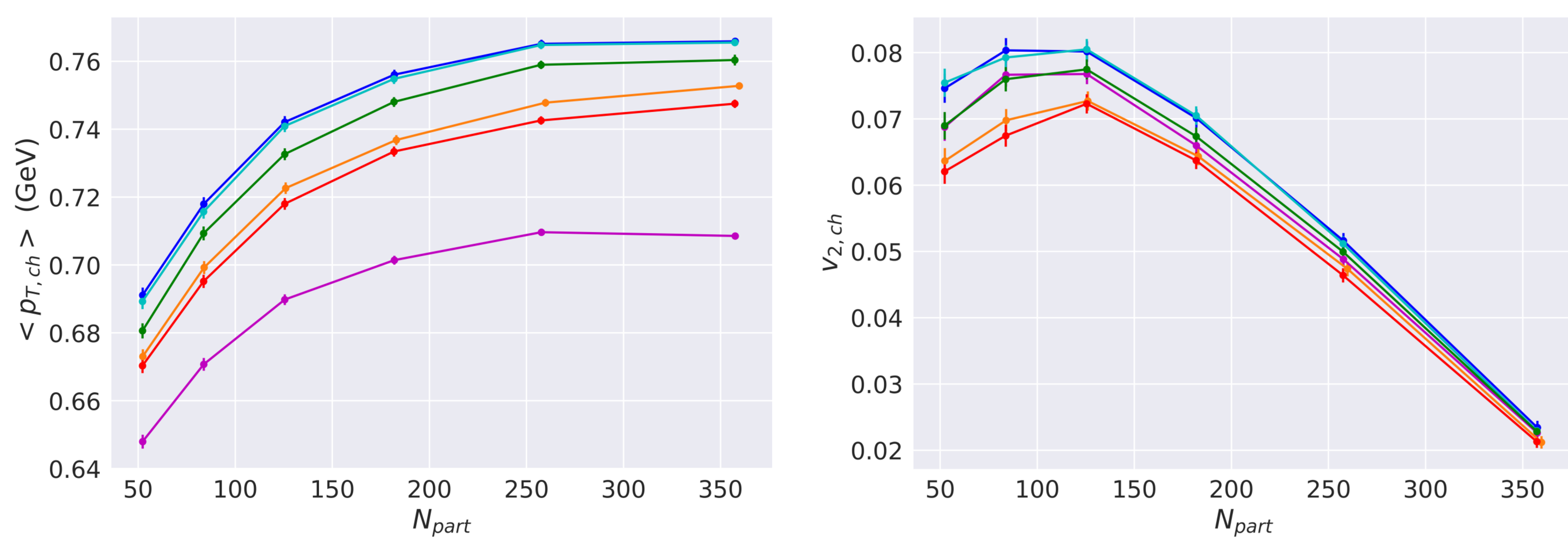
- Specific shear and bulk viscosities are functions of (T,γ_q)
- Particlization occurs at $T_c(\gamma_q)$ using Cooper-Frye prescription with **γ_q-dependent corrections to hadron distribution functions and viscous corrections**
- Implemented in: MUSIC[3] (hydrodynamics), iS3D[4] (particlization)
- T_RENTo[5] used to generate 2.76 TeV Pb-Pb events as initial conditions
- SMASH[6] used as hadronic afterburner

Results

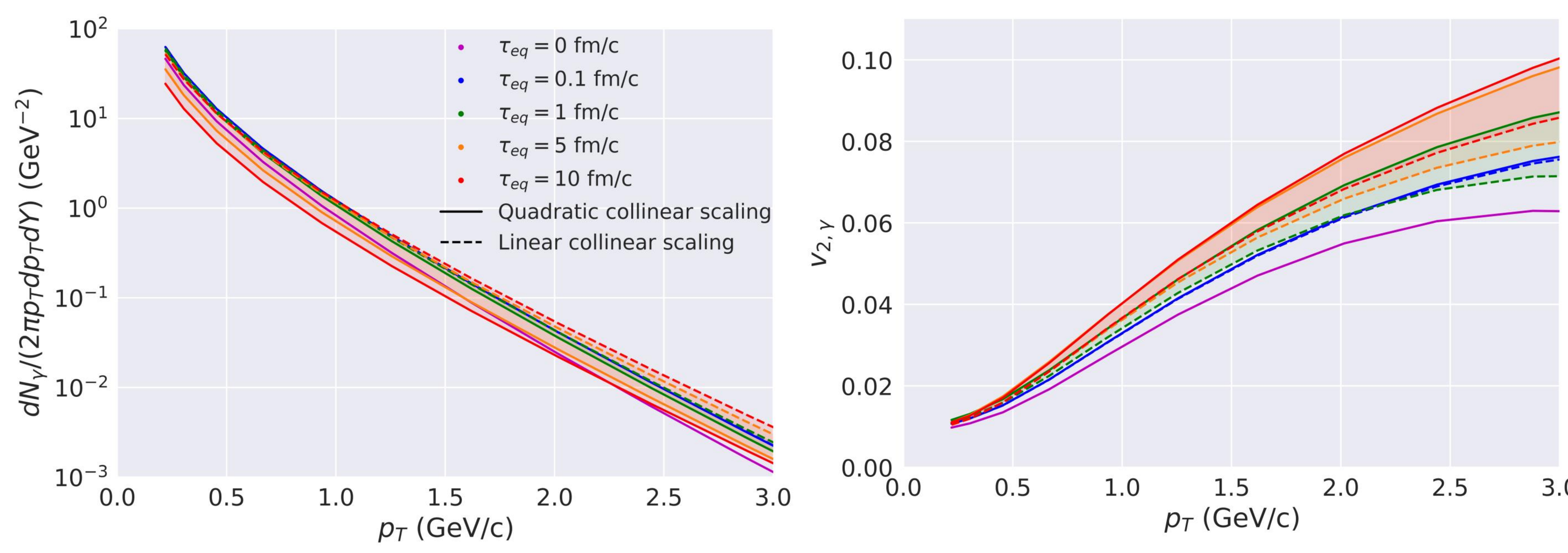
- Higher hadronization temperature **increases production** of more massive and energetic hadrons
- Non-unity γ_q **suppresses production**, especially of baryons



- Flow is sensitive to:
  - Difference in pressure gradients at initialization
  - Rate of quark production during hydrodynamic evolution



- **Photon production is affected,** consistent with prior studies[2]
  - Theoretical uncertainty dominates, preventing experimental disambiguation



Future Studies

- Study independent equilibration of **strange** and **charm** quarks
  - Strange hadrons are particularly good probes of QGP equilibration
- Model **shorter-lived** collision systems that equilibrate less
- Ultimately: Bayesian parameter estimation 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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