Flavor Equilibration of the Quark-Gluon Plasma

ANDREW GORDEEV

STEFFEN A. BASS, BERNDT MÜLLER, JEAN-FRANCOIS PAQUET (VANDERBILT)

HYDRODYNAMICS AND RELATED OBSERVABLES IN HEAVY-ION COLLISIONS

SUBATECH/IMT-ATLANTIQUE, OCTOBER 31, 2024

Outline

Motivation

Modeling partial chemical equilibrium

Numerical results

Summary and outlook

Outline

Motivation

Modeling partial chemical equilibrium

Numerical results

Summary and outlook

Heavy Ion Collisions: Initial Stages

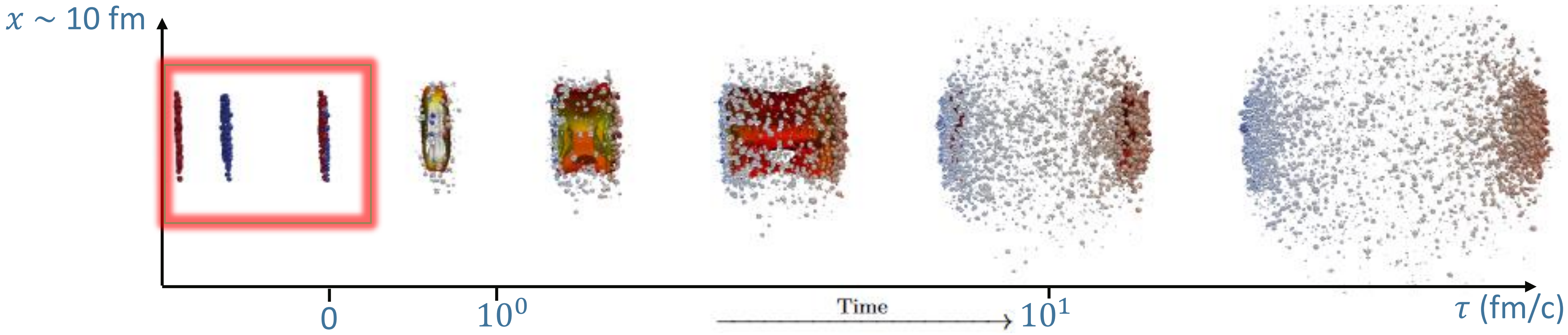


Figure by Hannah Elfner

- Quarks and gluons in participating nucleons scatter with each other
- Medium is gluon saturated and very far from equilibrium

Heavy Ion Collisions: Hydrodynamic Evolution

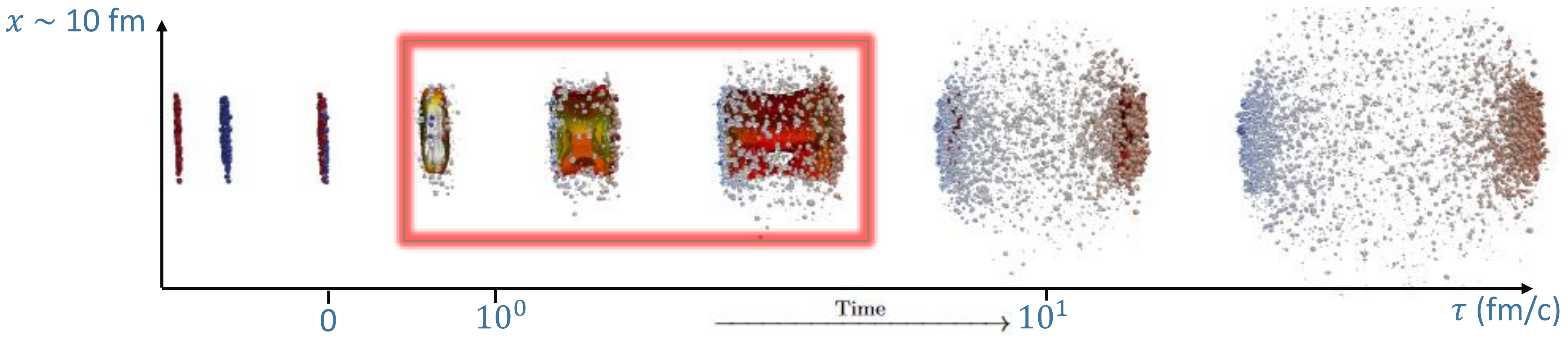


Figure by Hannah Elfner

- Quark-gluon plasma (QGP) is modeled as an expanding fluid near local thermodynamic equilibrium

Heavy Ion Collisions: Particlization

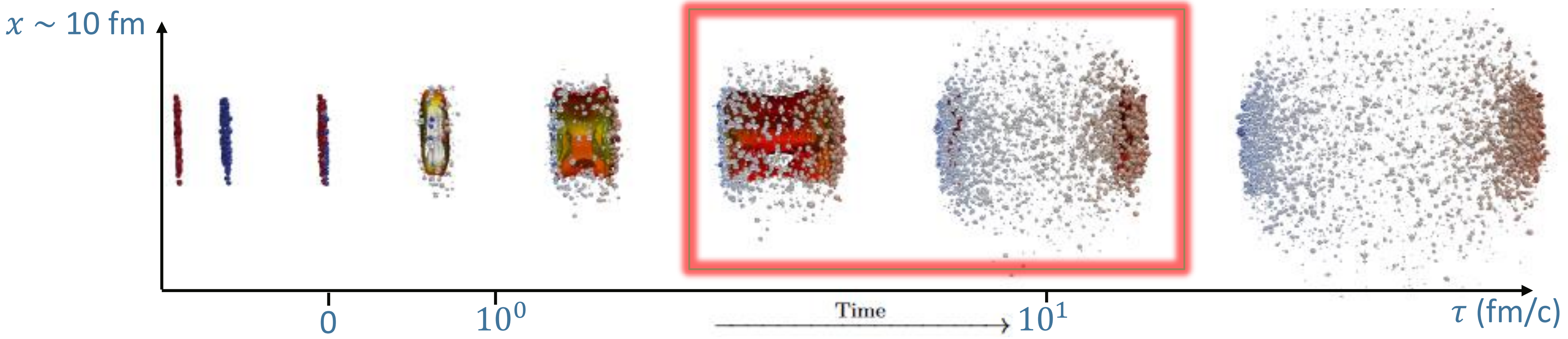


Figure by Hannah Petersen

- QGP cools to form hadron gas
- Switch from hydrodynamics to modeling particles with Boltzmann transport

Heavy Ion Collisions: Hadronic Interactions

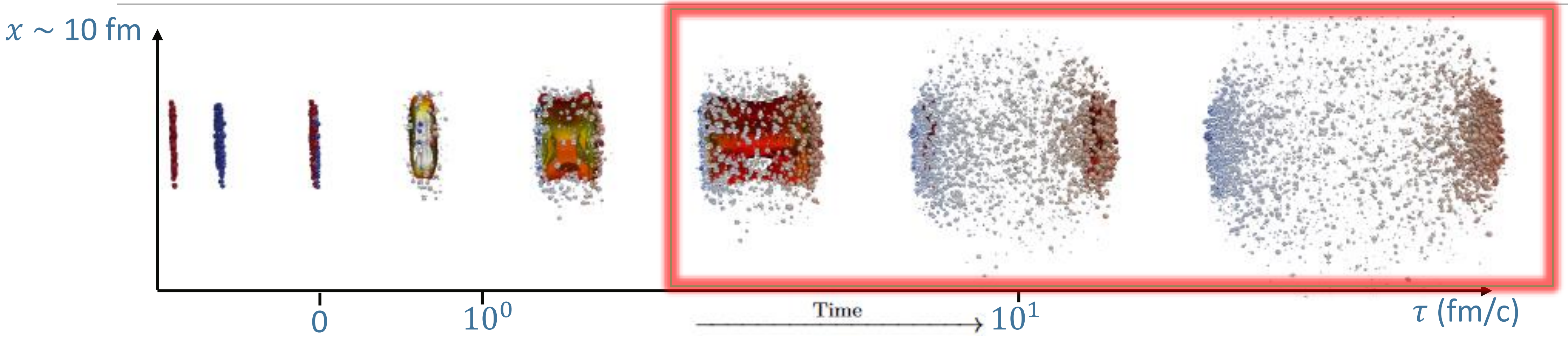


Figure by Hannah Elfner

- After decays and scattering, final particles are only experimental signature of QGP due to its short (~10 fm) lifetime

Initial State: Gluon Saturation

- Perturbative QCD: initial hard gluons produce copious soft gluons until saturation
- Basis for successful color-glass condensate and glasma models
  - E.g., IP-GLASMA[1]

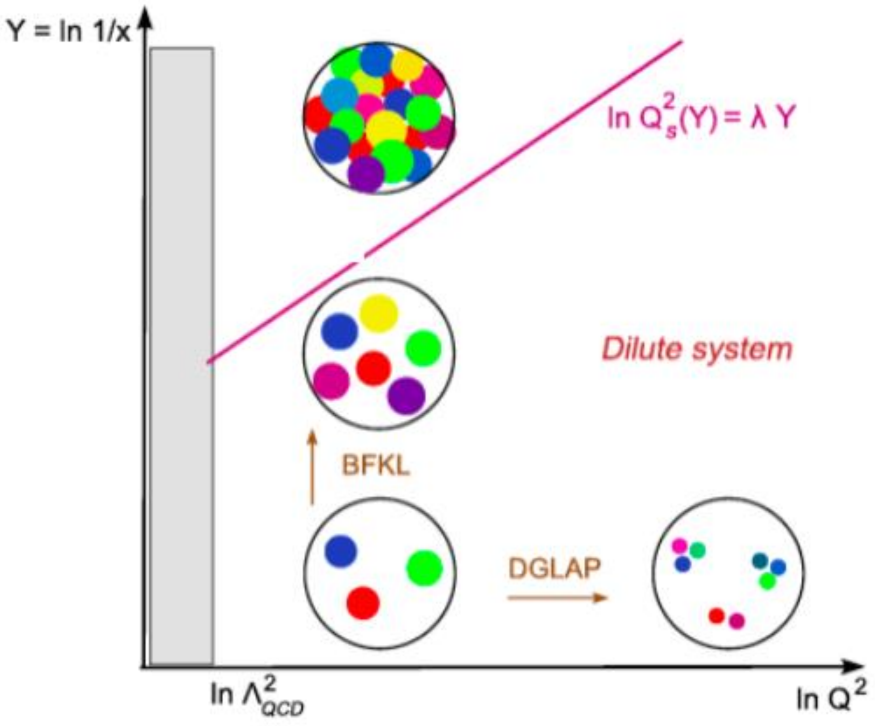


Figure: E. Iancu, CERN-2014-003, pp. 197-266 (2011)

1. B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. 108, 252301 (2012)

Partial Chemical Equilibrium

- The initial state is gluon saturated, and it is uncertain how long chemical equilibration takes
- Conventional hydrodynamics models assume the QGP is chemically equilibrated at the onset

- Our goal: model chemical equilibration during hydrodynamics using an equation of state in partial chemical equilibrium:
  - QGP forms with thermalized gluons and zero (anti)quarks
  - Quark concentrations gradually increase over time during the hydro evolution

Outline

Motivation

Modeling partial chemical equilibrium

Numerical results

Summary and outlook

Hydrodynamics

- Conservation of energy-momentum: $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = \varepsilon u^\mu u^\nu - (P + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

- Chemistry is encoded in the equation of state $P(\varepsilon)$
- Israel-Stewart-type second-order viscous hydrodynamics adds equations of motion for $\pi^{\mu\nu}, \Pi$

Hydrodynamics: Simplifying Assumptions

- (2+1)-D hydrodynamics using MUSIC[2]
- Single (anti)quark flavor with $\mu_B = 0$
- Neglect chemical dependence of $\pi^{\mu\nu}, \Pi$

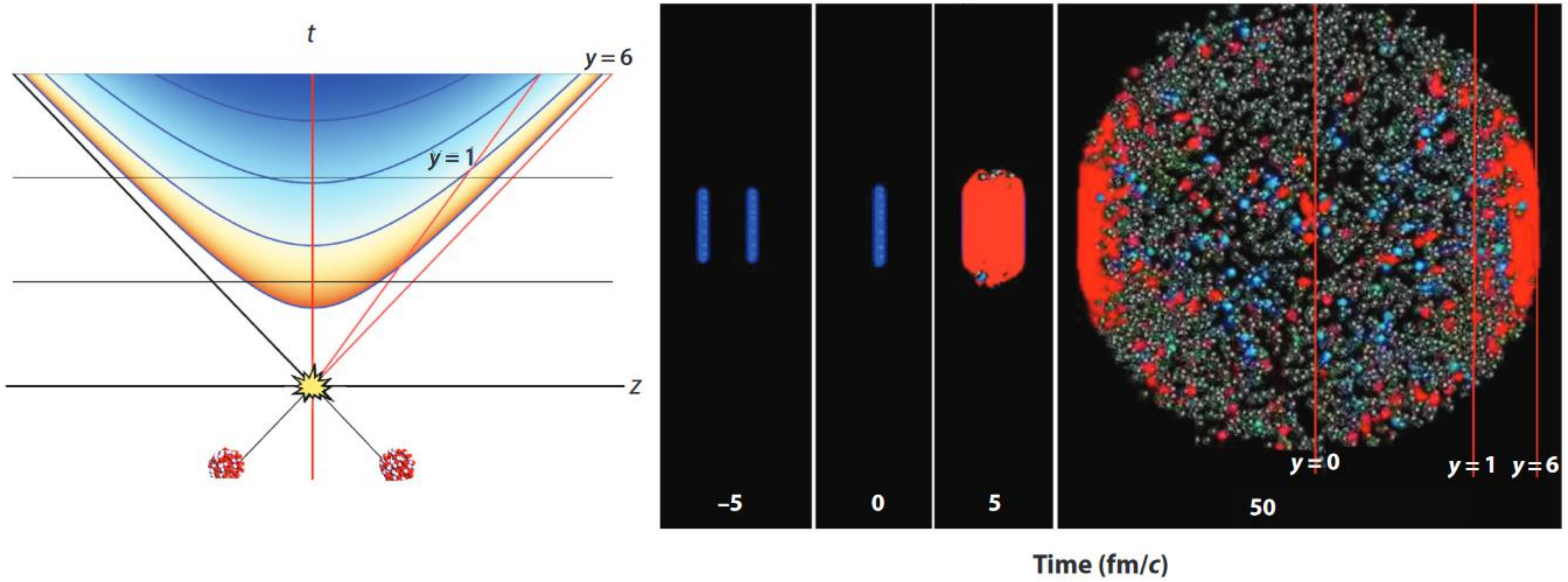


Figure: W. Busza, K. Rajagopal, and W. van der Schee, Annu. Rev. Nucl. Part. Sci., 68:339-76 (2018)

2. B. Schenke, S. Jeon, and C. Gale, Phys. Rev. C 82, 014903 (2010)

Equilibrium QCD Equation of State

- High T: calculated from lattice with (2+1)-flavor QCD

- Low T: calculated using hadron resonance gas

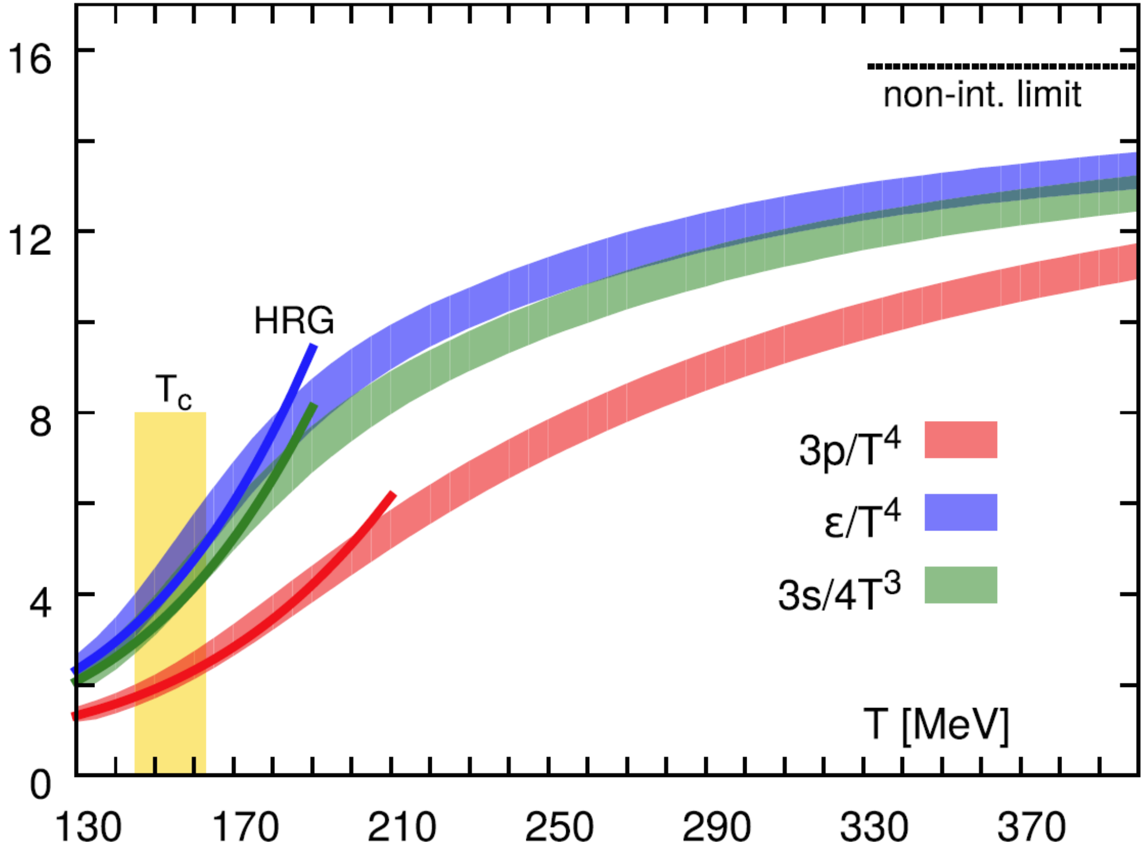
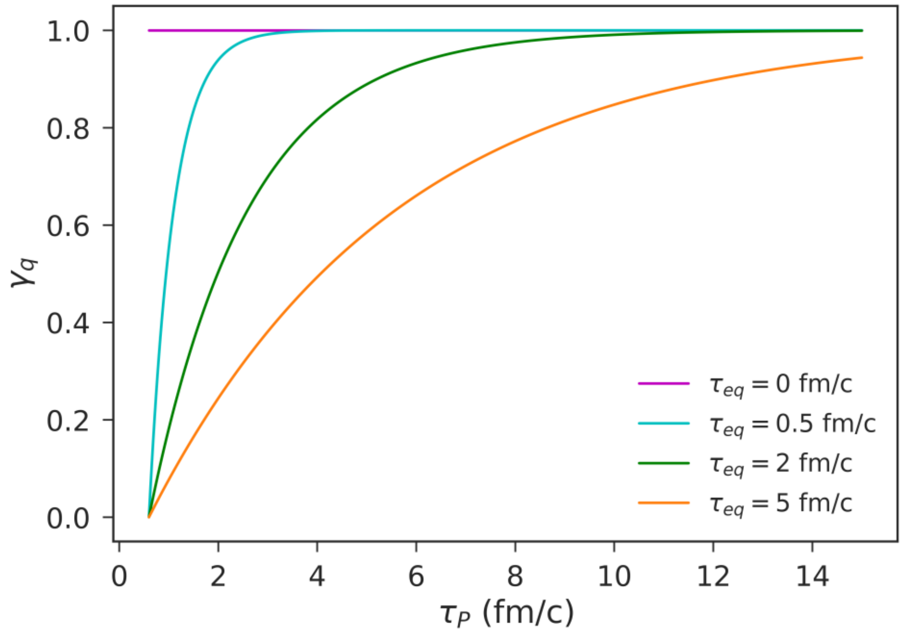


Figure: A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

Partial Chemical Equilibrium: Quark Fugacity

- Lattice calculation of far-from-equilibrium equation of state is impractical due to sign problem
- We instead interpolate $N_f = 3$ and $N_f = 0$ lattice equations of state using a time-dependent (anti)quark fugacity $\gamma_q(\tau_P)$:

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



- Local proper time τ_P is solved for by

$$u^\mu \partial_\mu \tau_P = 1$$

Partial Chemical Equilibrium: High T

- Linear interpolation of lattice equations:

$$\frac{P(T,\gamma_q)}{T^4} = \gamma_q \frac{P_{N_f=3}}{T^4}(T_3^*) + (1-\gamma_q)\frac{P_{N_f=0}}{T^4}(T_0^*)$$

$$\frac{\varepsilon(T,\gamma_q)}{T^4} = \gamma_q \frac{\varepsilon_{N_f=3}}{T^4}(T_3^*) + (1-\gamma_q)\frac{\varepsilon_{N_f=0}}{T^4}(T_0^*)$$

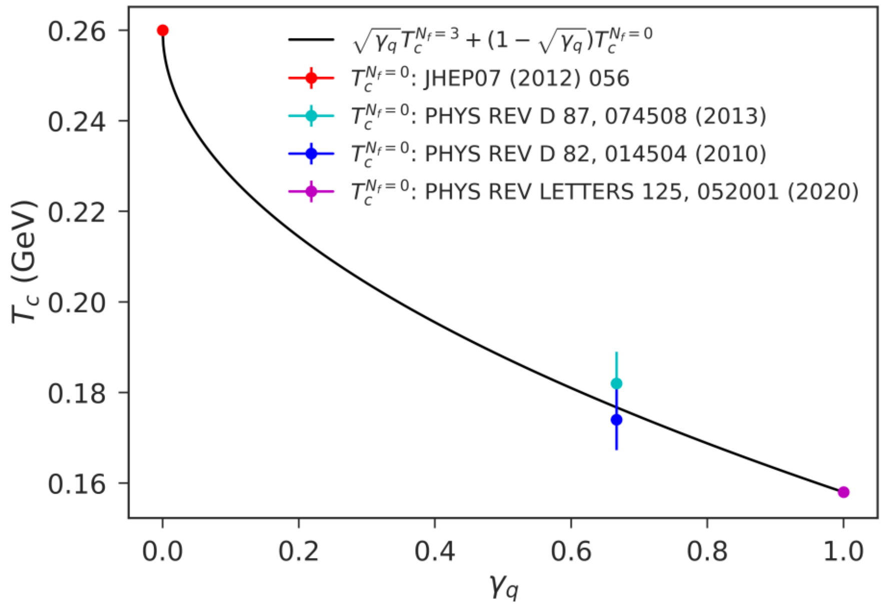
Partial Chemical Equilibrium: High T

- Linear interpolation of lattice equations:

$$\frac{P(T,\gamma_q)}{T^4} = \gamma_q \frac{P_{N_f=3}}{T^4}\left(T\frac{T_c^{N_f=3}}{T_c(\gamma_q)}\right) + (1-\gamma_q)\frac{P_{N_f=0}}{T^4}\left(T\frac{T_c^{N_f=0}}{T_c(\gamma_q)}\right)$$

- Rescaling of critical temperature T_c:

$$T_c(\gamma_q) = \sqrt{\gamma_q}\,T_c^{N_f=3} + \left(1-\sqrt{\gamma_q}\right)T_c^{N_f=0}$$



Partial Chemical Equilibrium: Low T

- Hadron resonance gas equation of state:

$$\varepsilon = \sum_i g_i \int \frac{d^3p}{(2\pi)^3} E_p f_i(p) \qquad P = \sum_i g_i \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{3E_p} f_i(p)$$

- Each hadron species is modified by a species-specific fugacity λ_i:

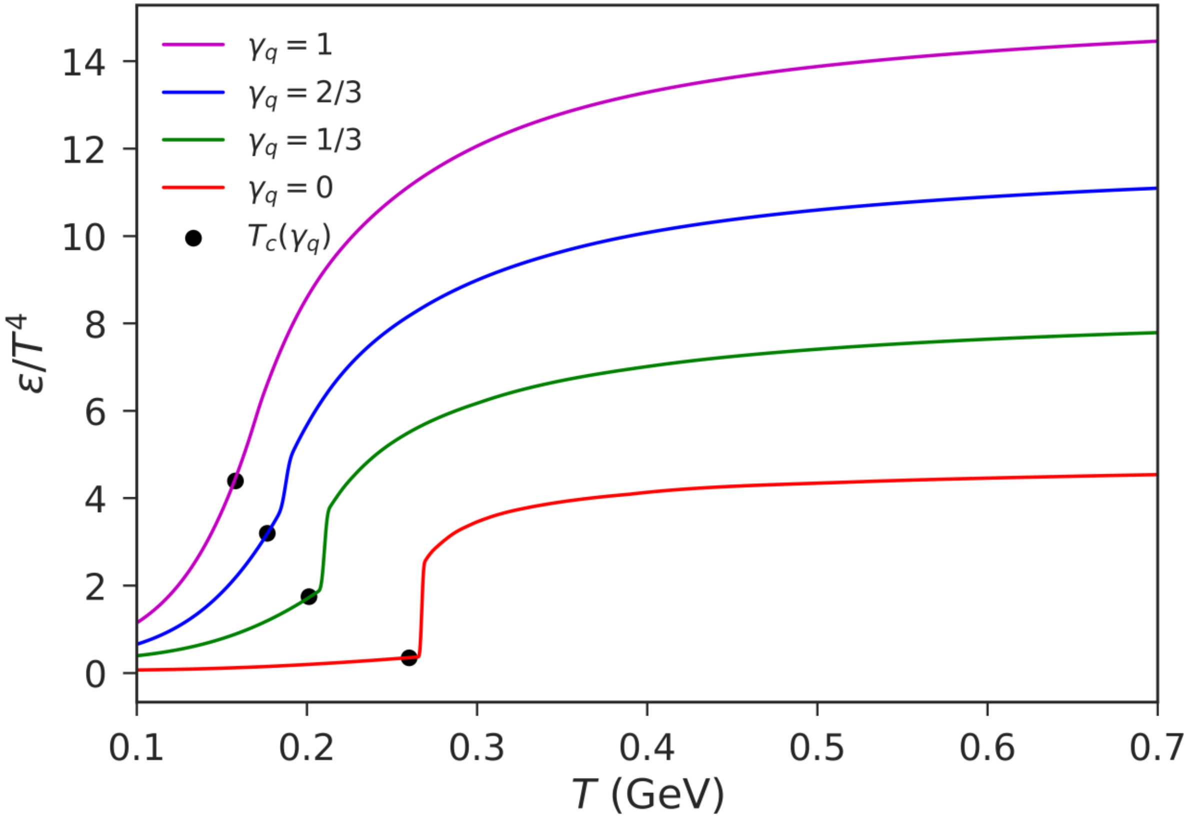
$$f_i(p) = \frac{1}{\lambda_i^{-1}\, e^{E_p/T} \pm 1}$$

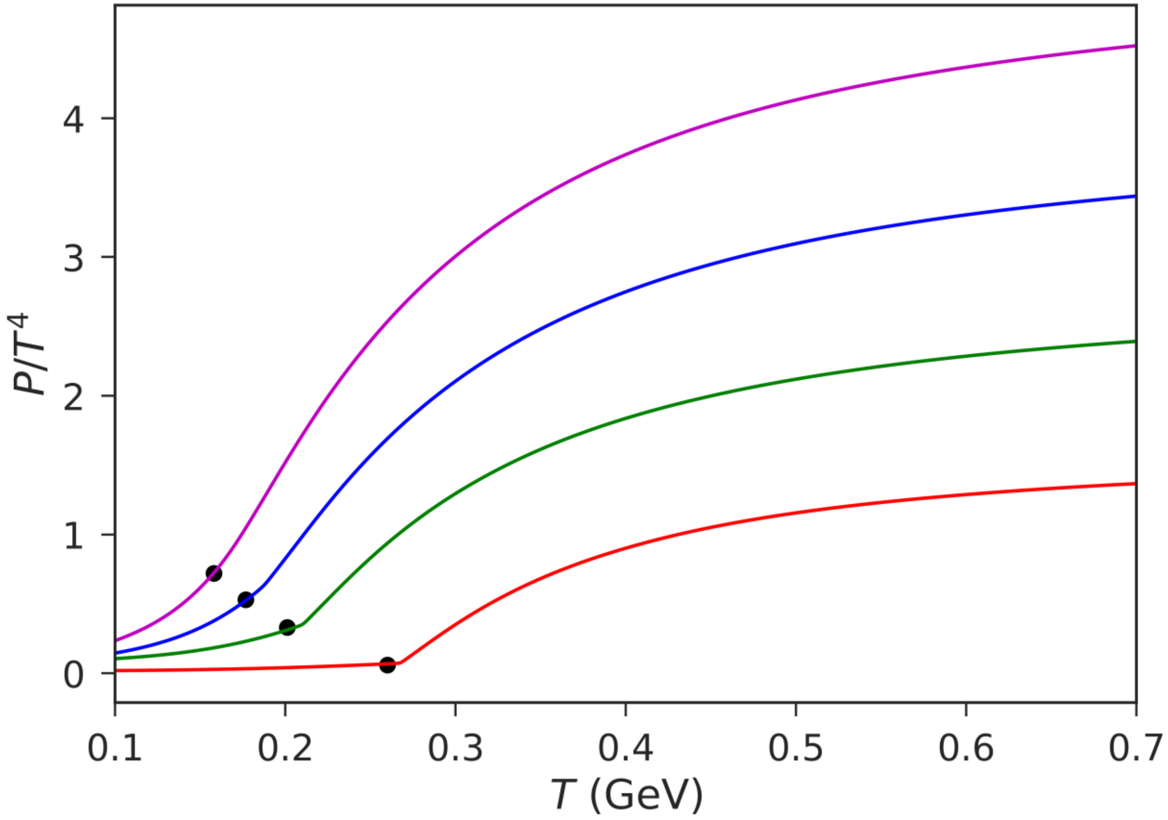
- Fitting for smooth EoS:

$$\lambda_{i,meson} = 0.85\,\gamma_q + 0.15$$
$$\lambda_{i,baryon} = \lambda_{i,meson}^{3/2}$$

Partial Chemical Equilibrium Equation of State

- The two regimes are matched by interpolating over the region near $T_c(\gamma_q)$:





Particlization

- Particlization on $T_c(\gamma_q)$ hypersurface using Cooper-Frye:

$$E\frac{d^3N_i}{dp^3} = g_i \int_\Sigma d\Sigma_\mu p^\mu f_i(p)$$

- Same modified distributions as HRG:

$$f_i(p) = \frac{1}{\lambda_i^{-1}\, e^{E_p/T} \pm 1}$$

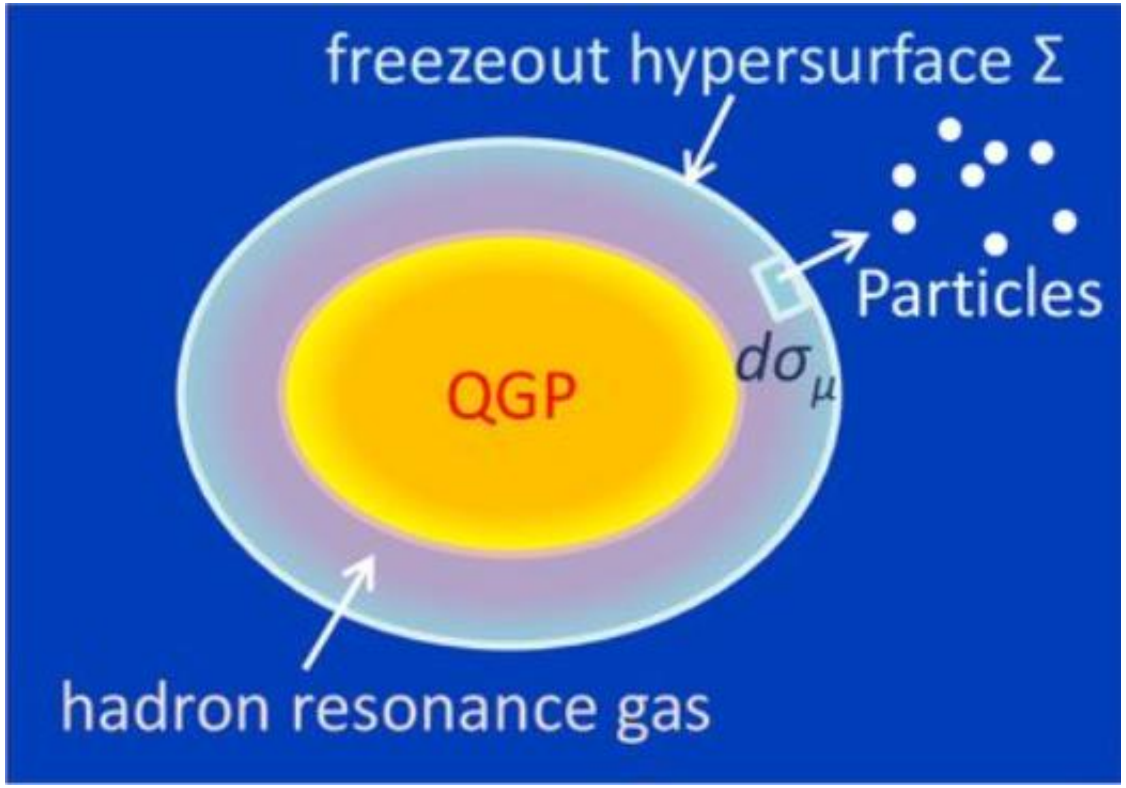


Figure by Akihiko Monnai

Outline

Motivation

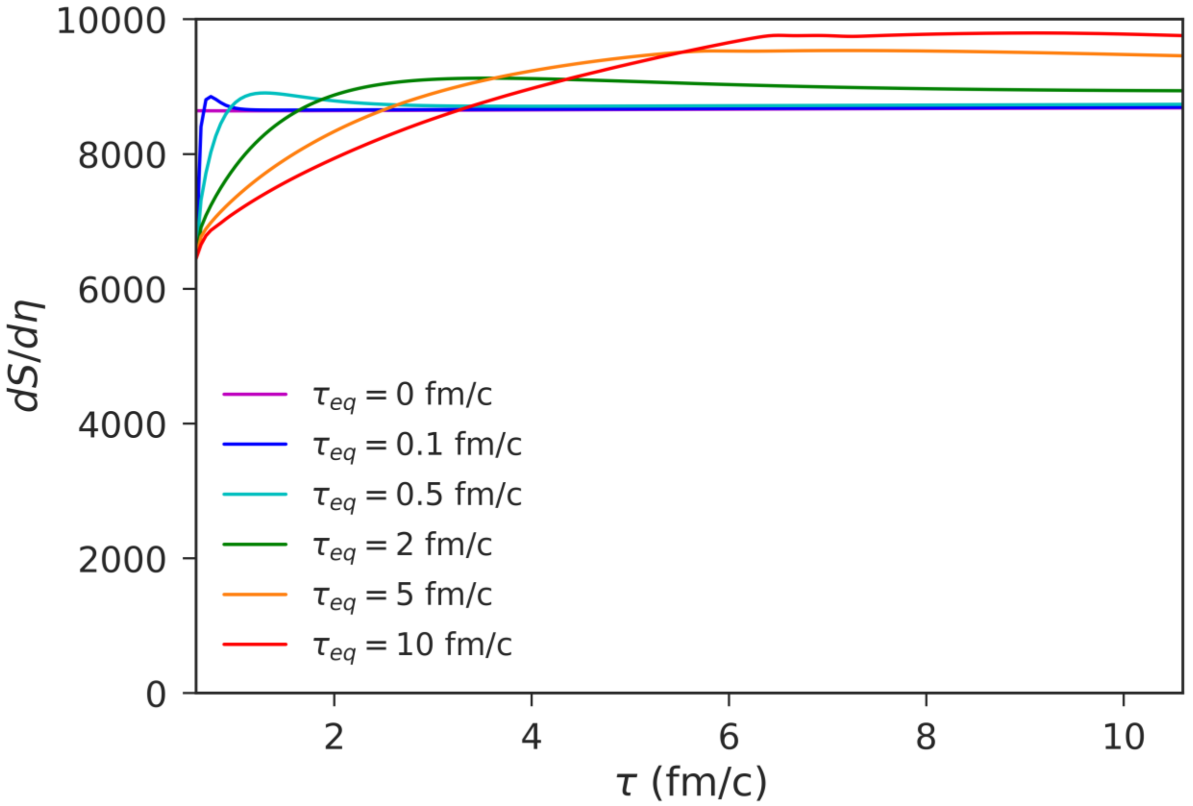
Modeling partial chemical equilibrium

Numerical results

Summary and outlook

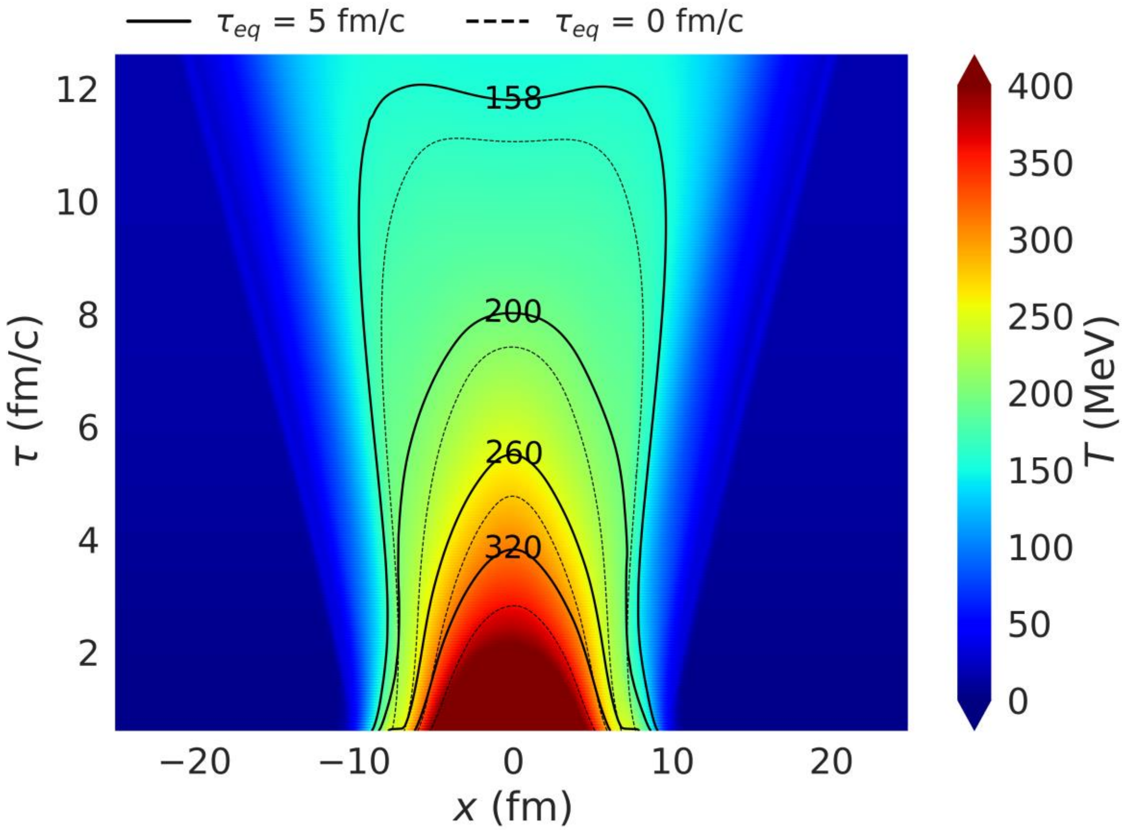
Entropy Production

- Even with ideal hydro, entropy is produced through chemical equilibration:



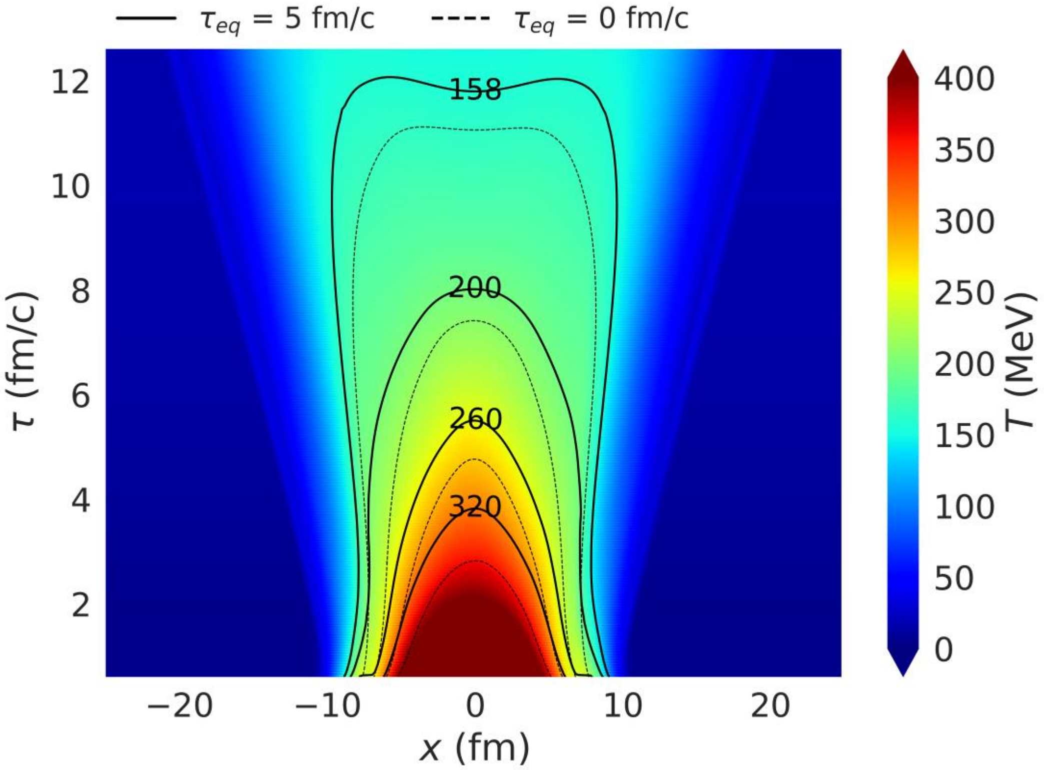
Temperature Evolution

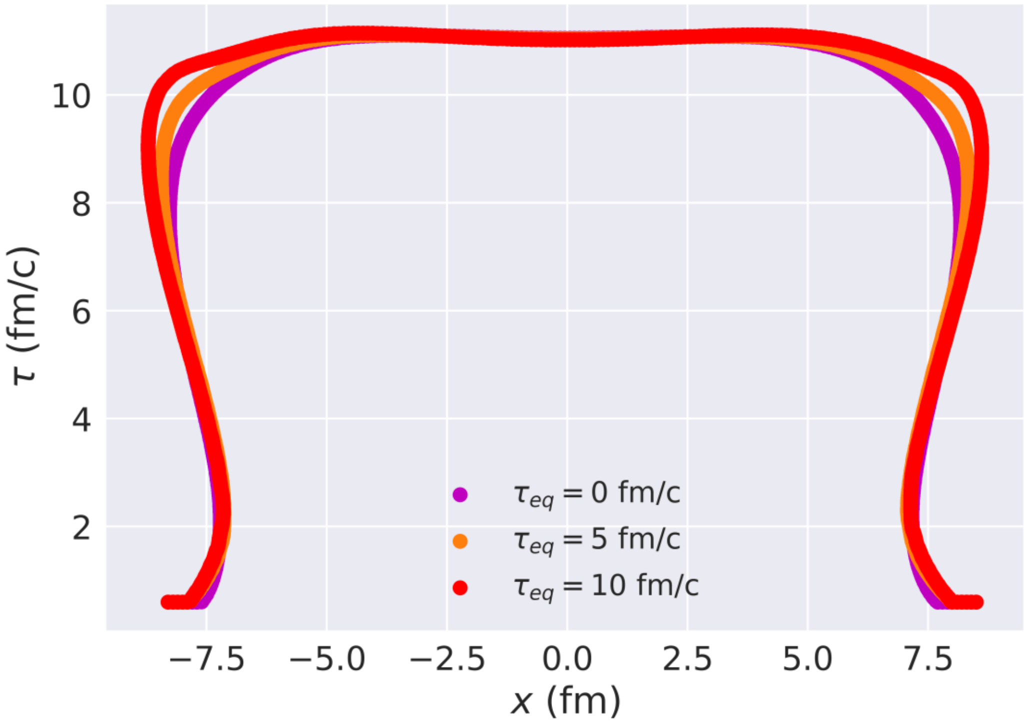
- Higher τ_{eq} (fewer quark degrees of freedom) corresponds to a hotter medium:



Temperature Evolution: Particlization

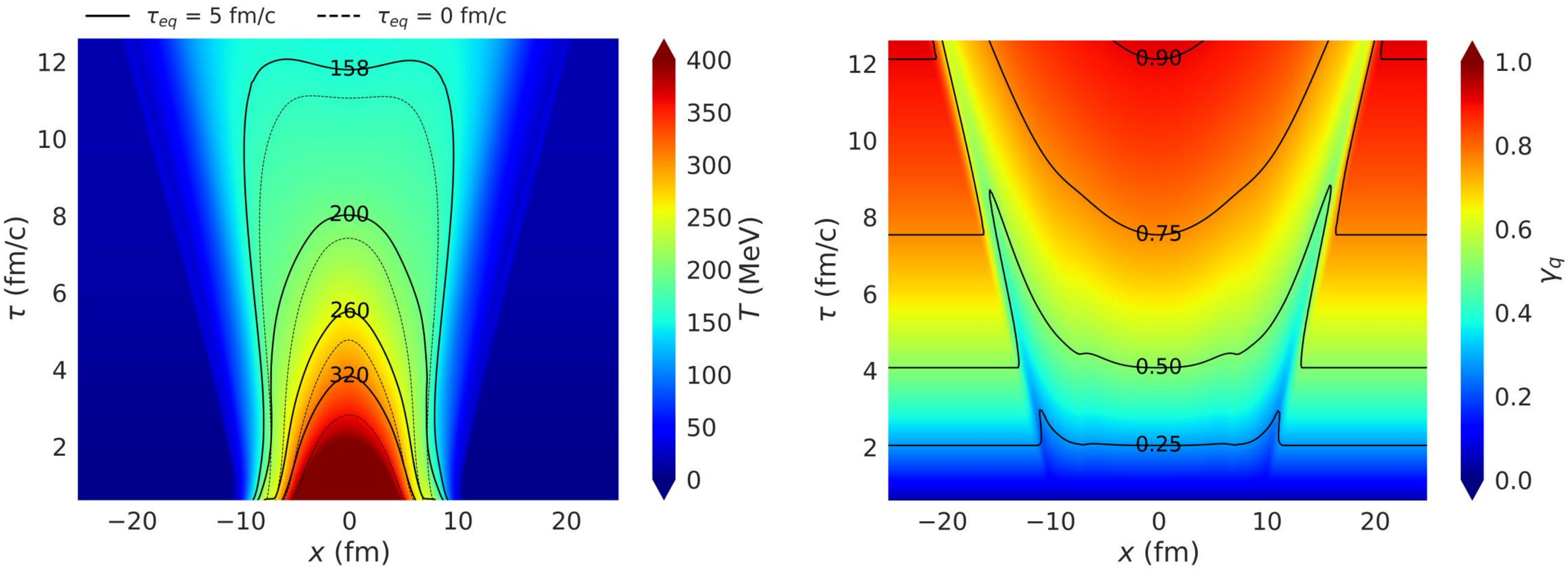
- However, the shape of the $T_c(\gamma_q)$ surface changes only slightly:





Fugacity Evolution

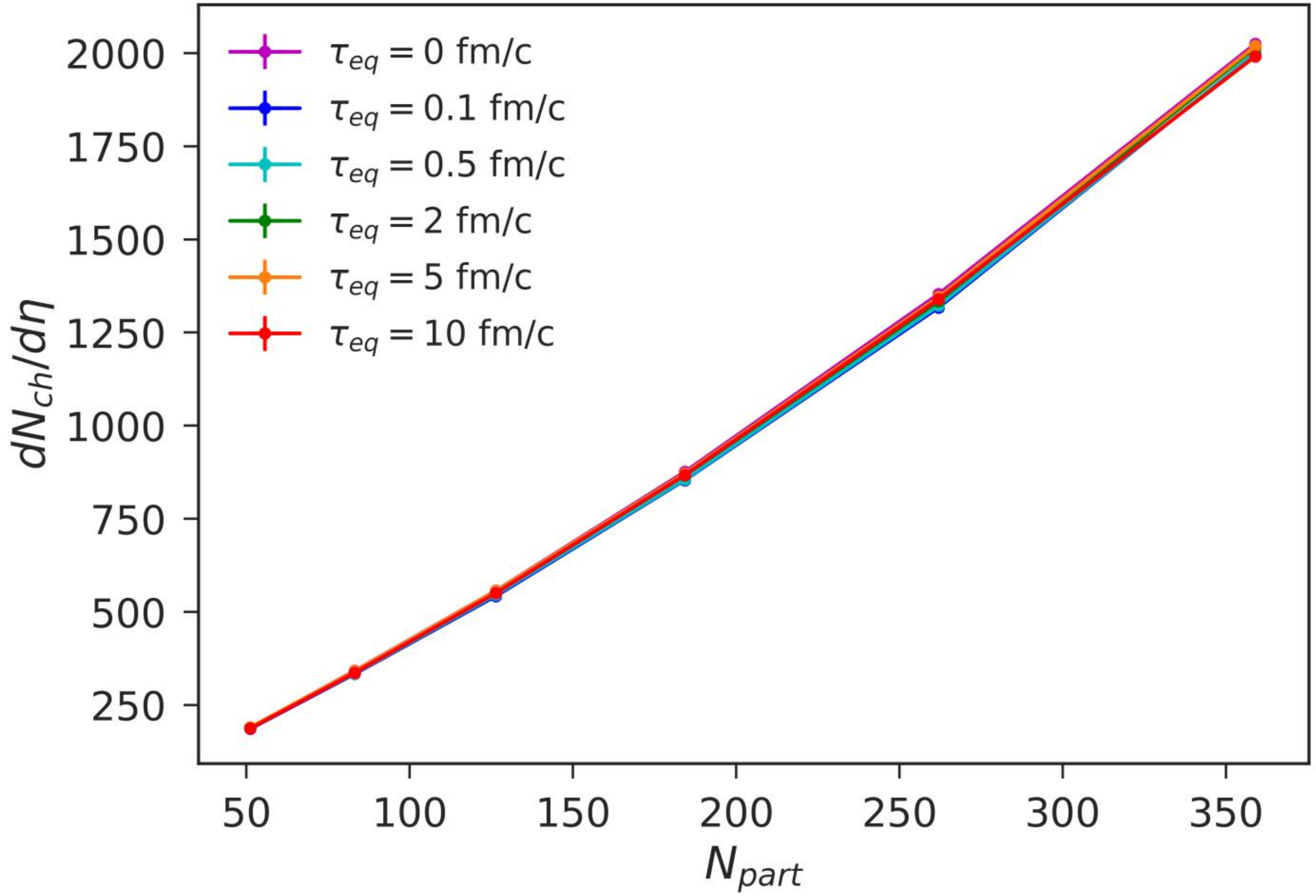
- For larger equilibration timescales, most cells are far from equilibrium:



Hadron Production

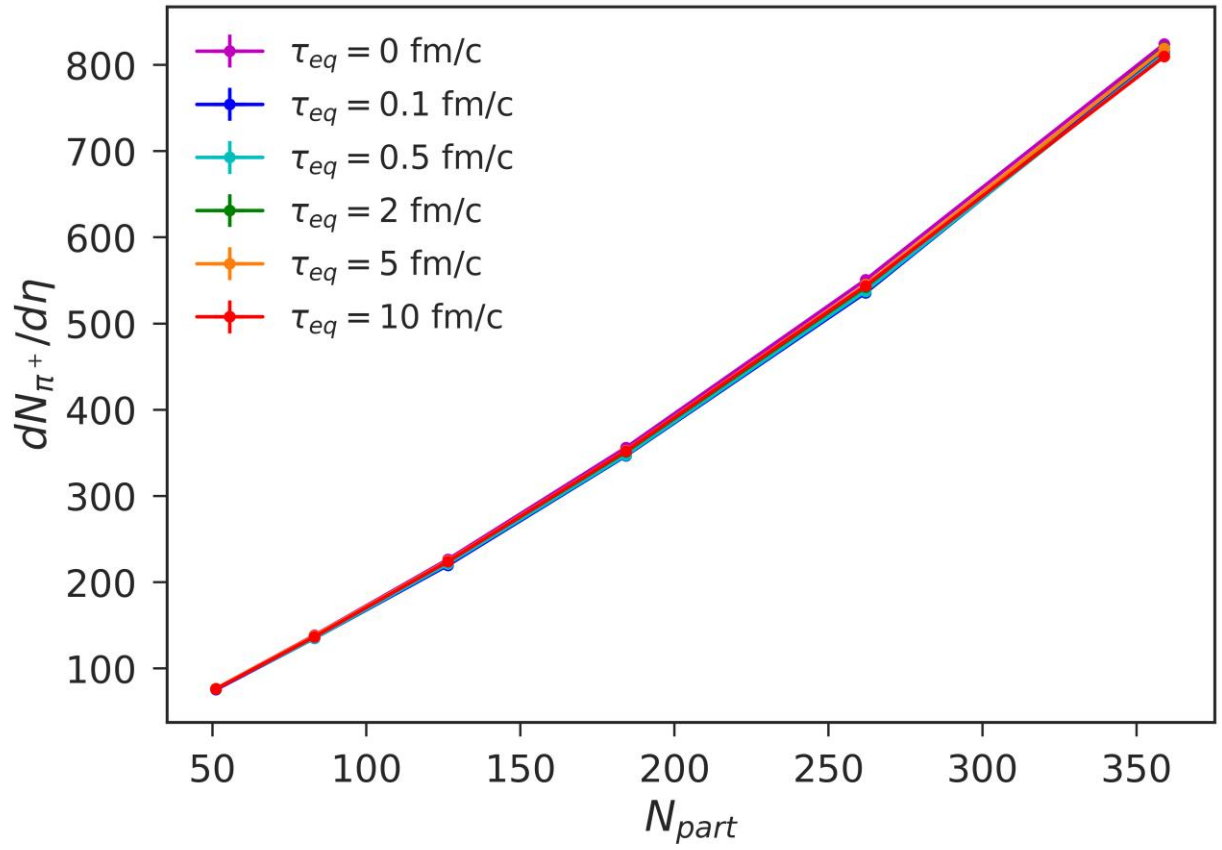
- We evolve an ensemble of Pb+Pb events with fixed initial conditions and varying τ_{eq}

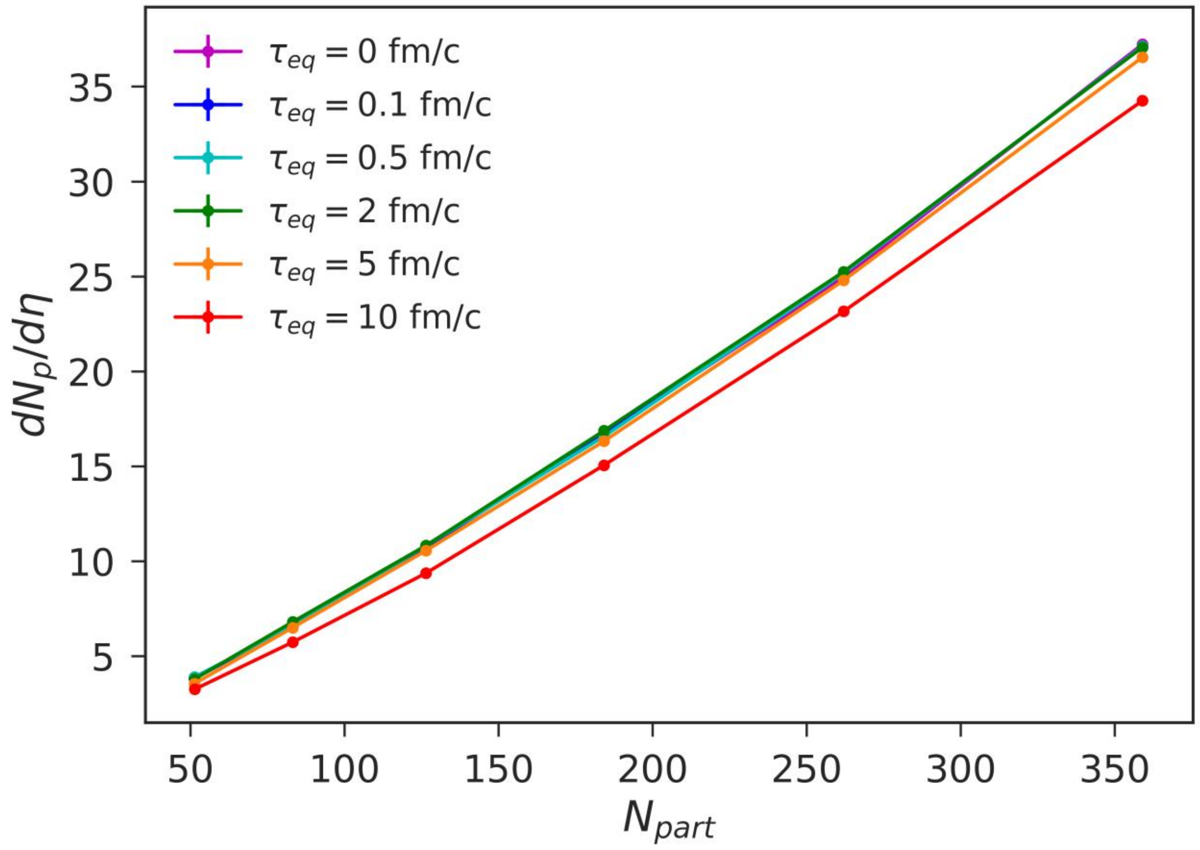
- Farther from equilibrium:
  - Higher particlization temperature increases hadron yields
  - Lower γ_q suppresses hadron yields



Hadron Production: Baryon Suppression

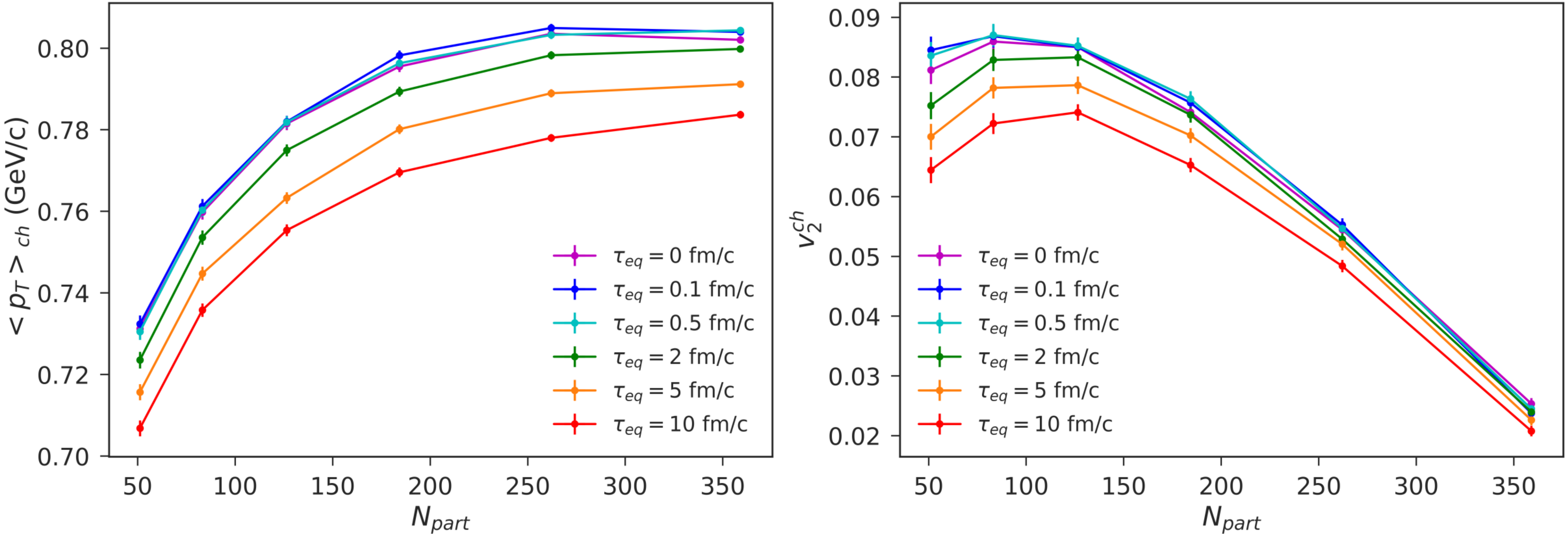
- We observe baryon suppression out of equilibrium, but only weakly:





Transverse Flow

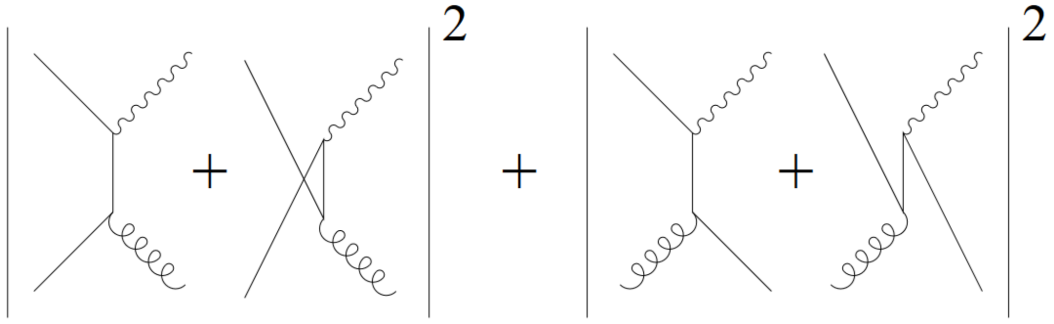
- Lower pressure when evolving out of equilibrium suppresses transverse flow:



Thermal Photon Production

- Thermal photon producing processes scale differently with γ_q:

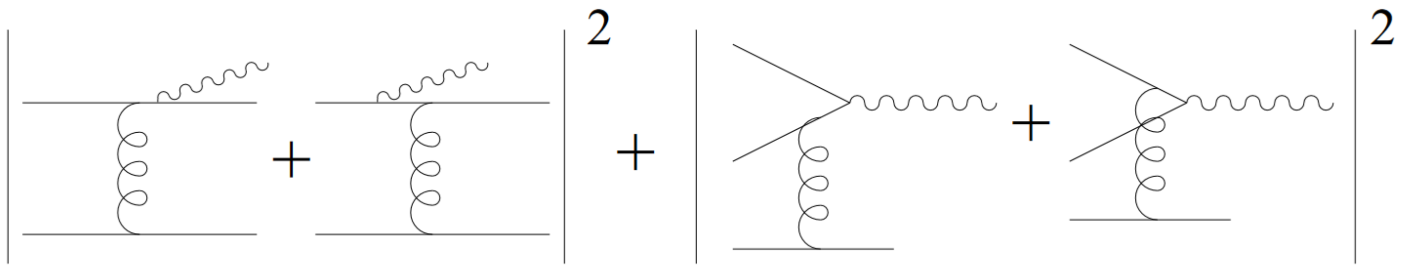
$$\Gamma(k,T,\gamma_q) = \gamma_q \Gamma_{Compton}(k,T) + \gamma_q^2 \Gamma_{annihilation}(k,T) + \gamma_q^? \Gamma_{inelastic}(k,T)$$



Elastic pair annihilation

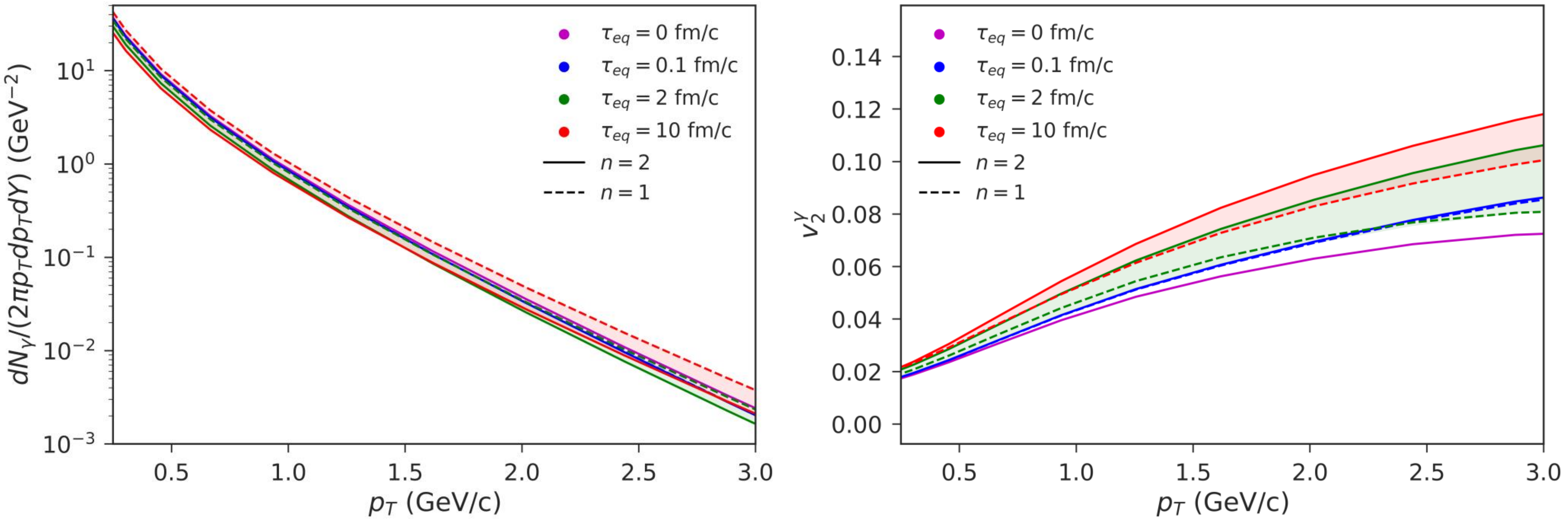
Compton scattering

Inelastic (bremsstrahlung + inelastic pair annihilation)



Thermal Photon Production

- Thermal photon producing processes scale differently with γ_q:
  $\Gamma(k,T,\gamma_q) = \gamma_q \Gamma_{Compton}(k,T) + \gamma_q^2 \Gamma_{annihilation}(k,T) + \gamma_q^n \Gamma_{inelastic}(k,T)$
- Considerable theoretical uncertainty due to choice of n



Outline

Motivation

Modeling partial chemical equilibrium

Numerical results

Summary and outlook

Summary and Outlook

- Hydrodynamic models of the QGP need to account for the limited quark densities in the early stages of a collision that initial stage models predict
- We do so by incorporating gluon saturation into the choice of equation of state
- Quark chemical equilibration has noticeable effects on transverse flow and photon production
- Future plans:
  - We are generalizing this model to study independent light and strange flavor equilibration: $\gamma_q = \frac{2\gamma_l}{3} + \frac{\gamma_s}{3}$
  - Bayesian analysis will constrain the flavor equilibration timescales with experimental data