Bayesian constraints on flavor equilibration in the quark-gluon plasma

ANDREW GORDEEV

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

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Outline

Motivation

Modeling light and strange equilibration

Bayesian calibration

Summary and outlook

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Heavy Ion Collision Timeline

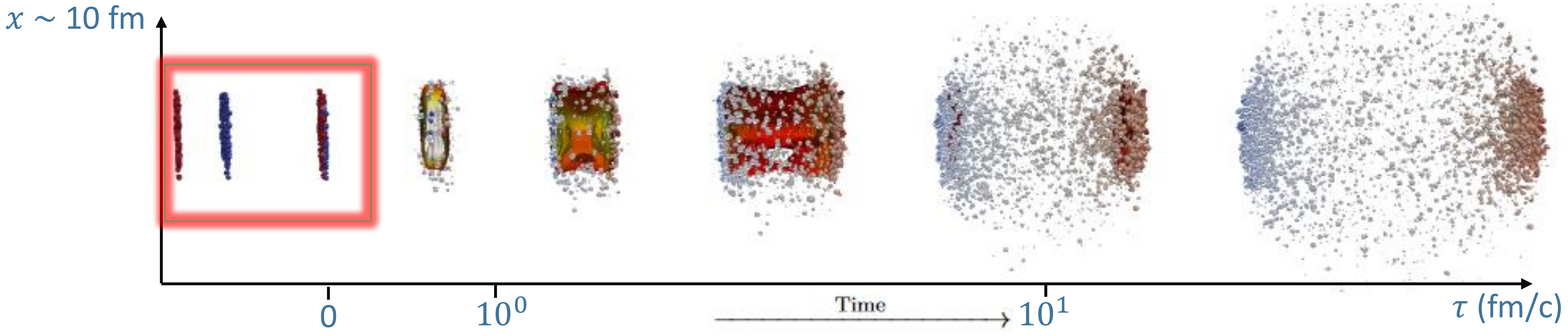

Figure by Hannah Elfner

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

Heavy Ion Collision Timeline

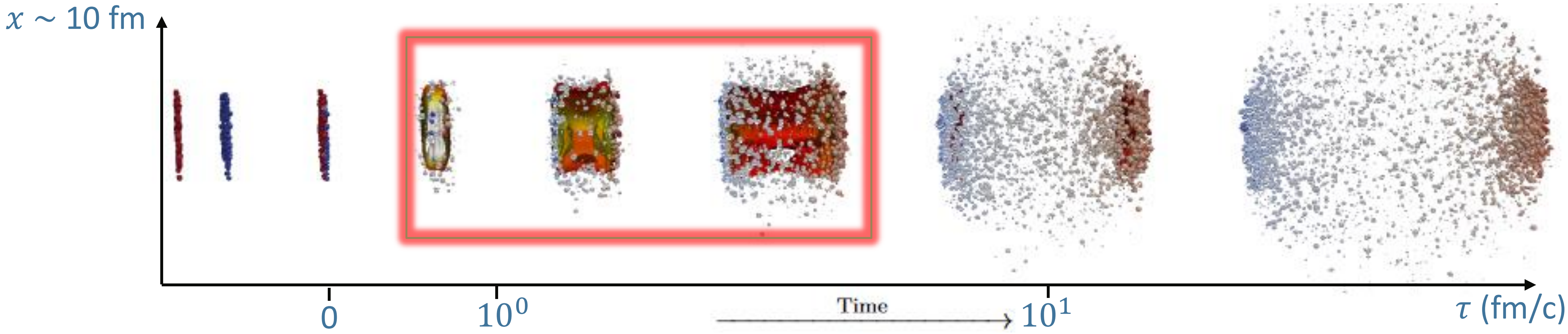

Figure by Hannah Elfner

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

Heavy Ion Collision Timeline

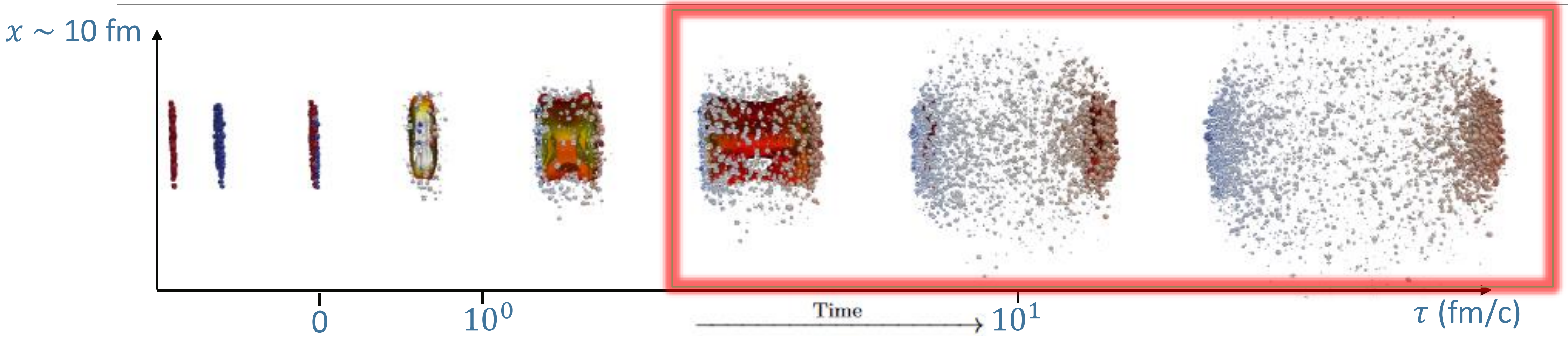

Figure by Hannah Elfner

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

Chemical Equilibration in the QGP

- The early QGP is likely gluon dominated
- Conventional hydrodynamics models assume chemical equilibrium at the onset

- Our goal: constrain the chemical equilibration timescales by modeling equilibration during hydrodynamics
    - Partial chemical equilibrium: QGP forms with thermalized gluons and suppressed (anti)quarks
    - Light and strange quarks equilibrate gradually during the hydro evolution

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Equilibrium QCD Equation of State

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

- Low T: calculated using hadron resonance gas

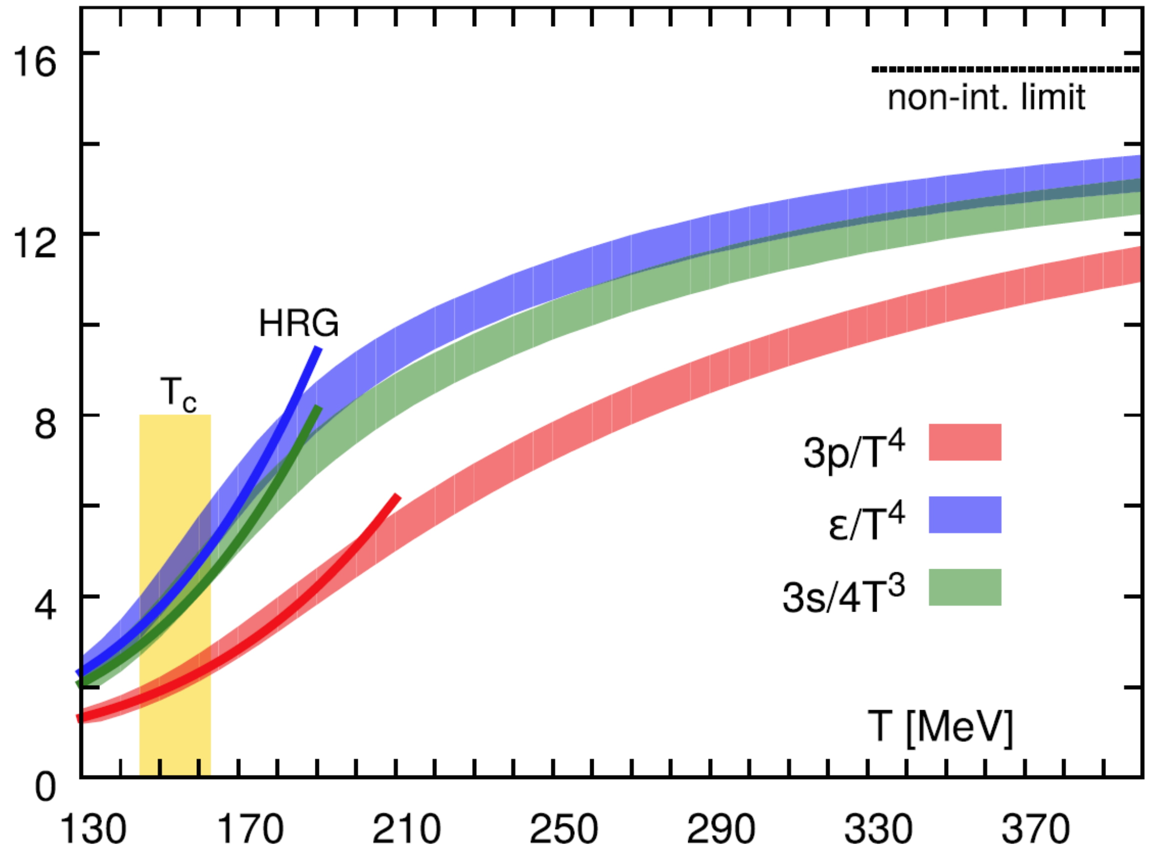
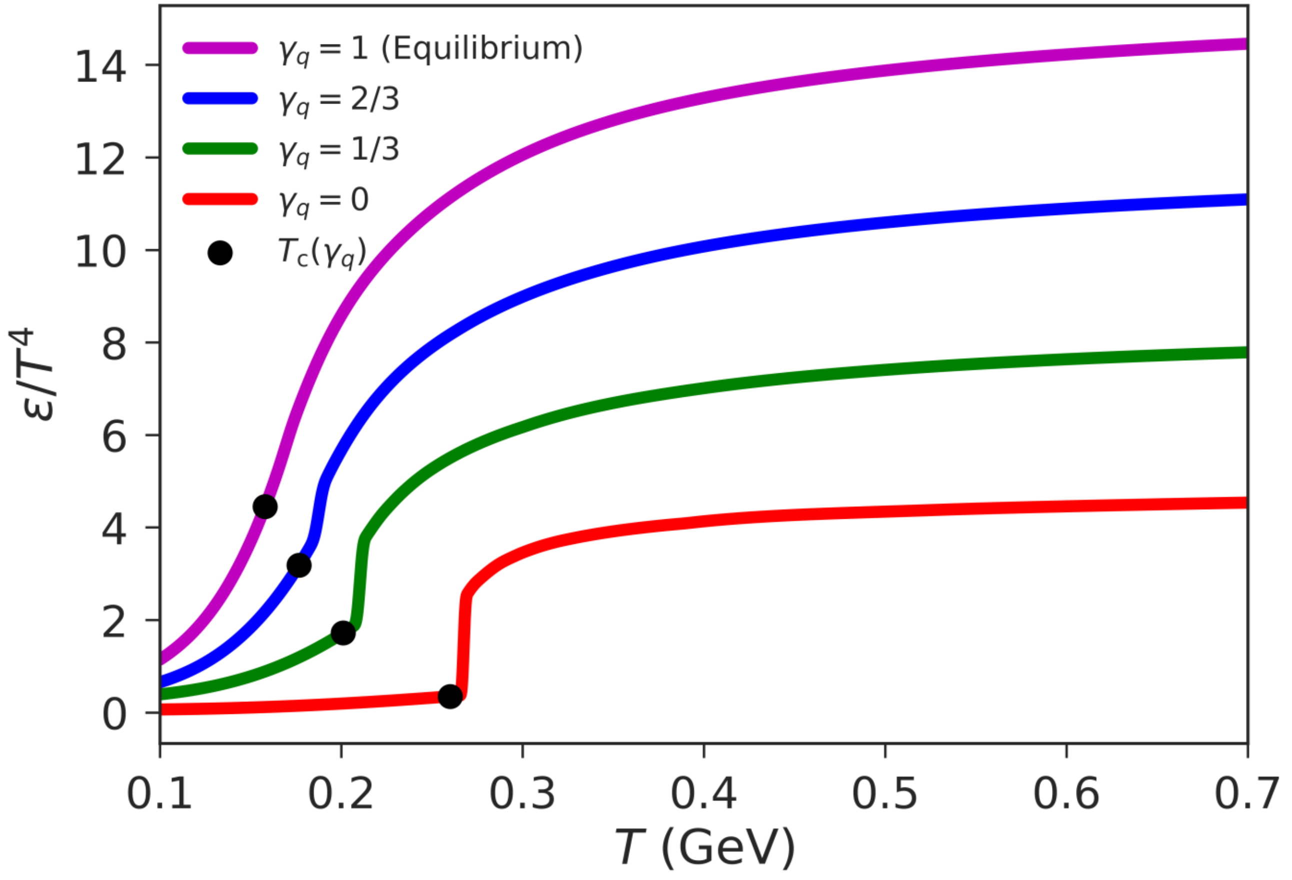


Figure: A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

Partial Chemical Equilibrium Equation of State

- High T: calculated from lattice with (2+1)-flavor QCD
  - Interpolate with Nf=0 and Nf=2 equations of state
- Low T: calculated using hadron resonance gas
  - Modify each hadron species with a fugacity dependent on quark content



Partial Chemical Equilibrium: Quark Fugacity

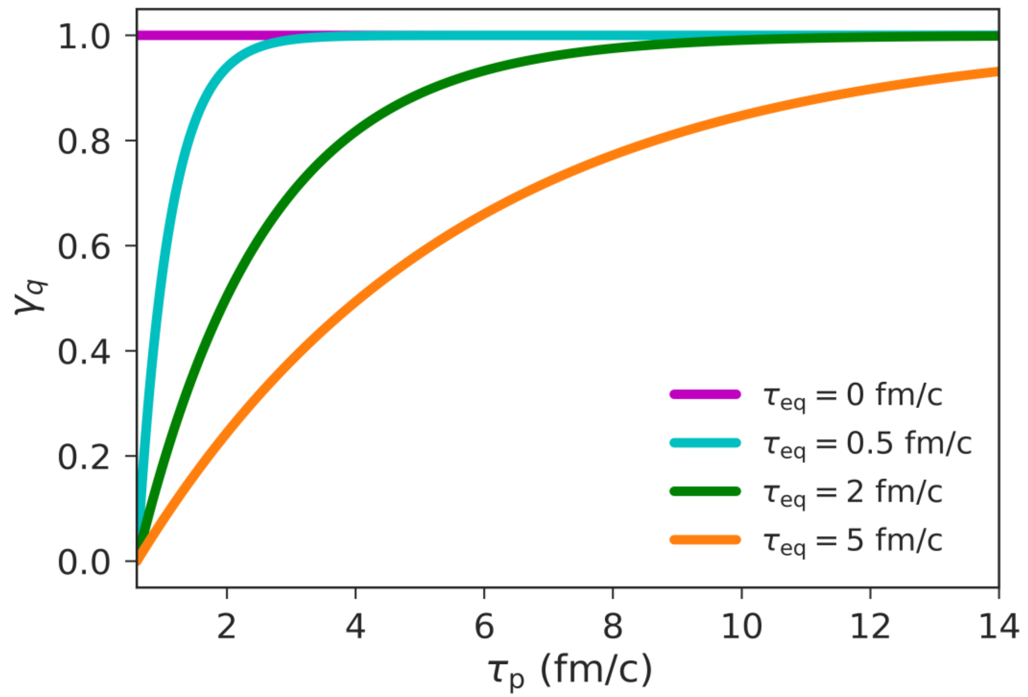
- Equation of state is now a function of time-dependent (anti)quark fugacities $\gamma_l(\tau_P)$ and $\gamma_s(\tau_P)$:

$$\gamma_{l/s}(\tau_P) = 1 - (1 - \gamma_{0,l/s})\exp\left(\frac{\tau_0 - \tau_P}{\tau_{eq,l/s}}\right)$$

  - Four independent parameters: $\gamma_{0,l/s}\,, \tau_{eq,l/s}$

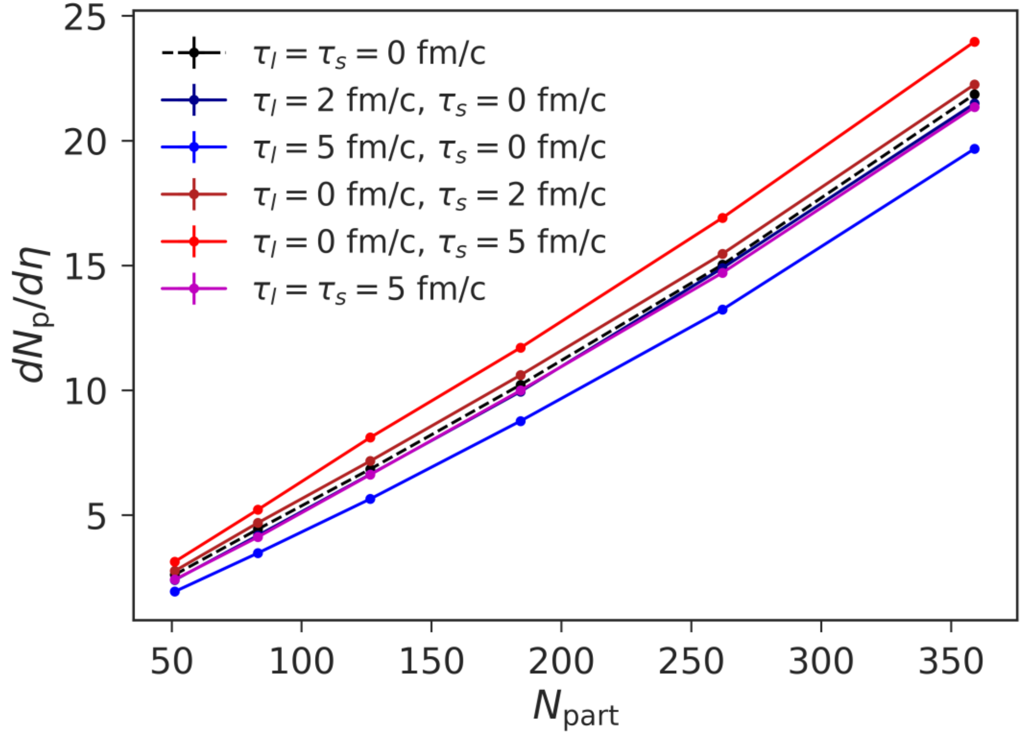
- Local proper time τ_P is solved for by

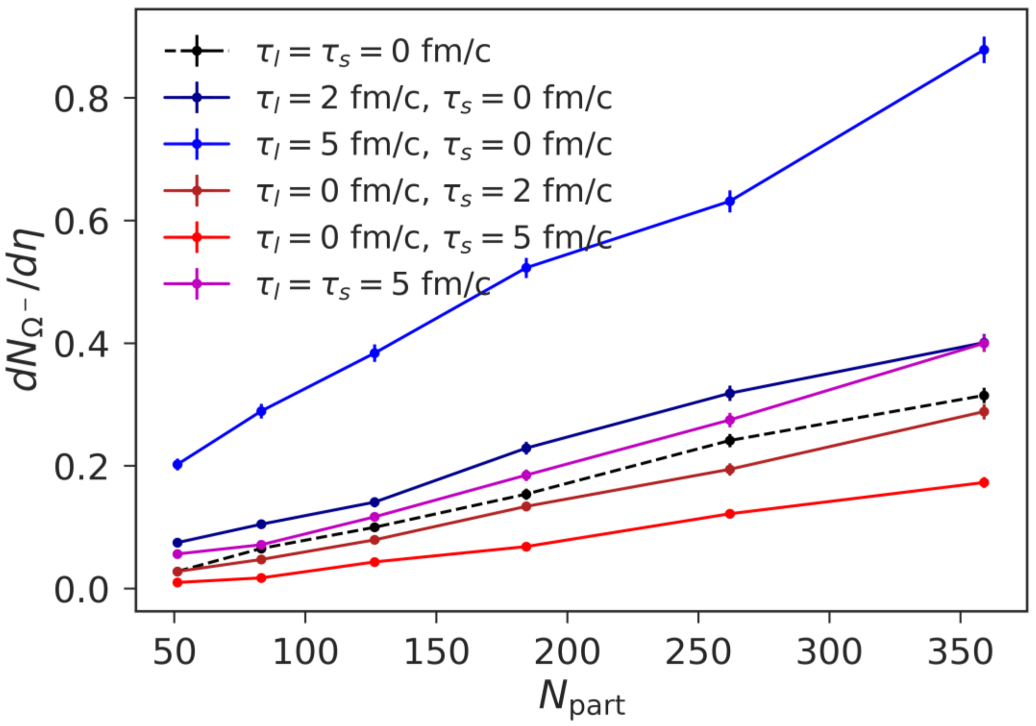
$$u^\mu \partial_\mu \tau_P = 1$$



Hadron Production

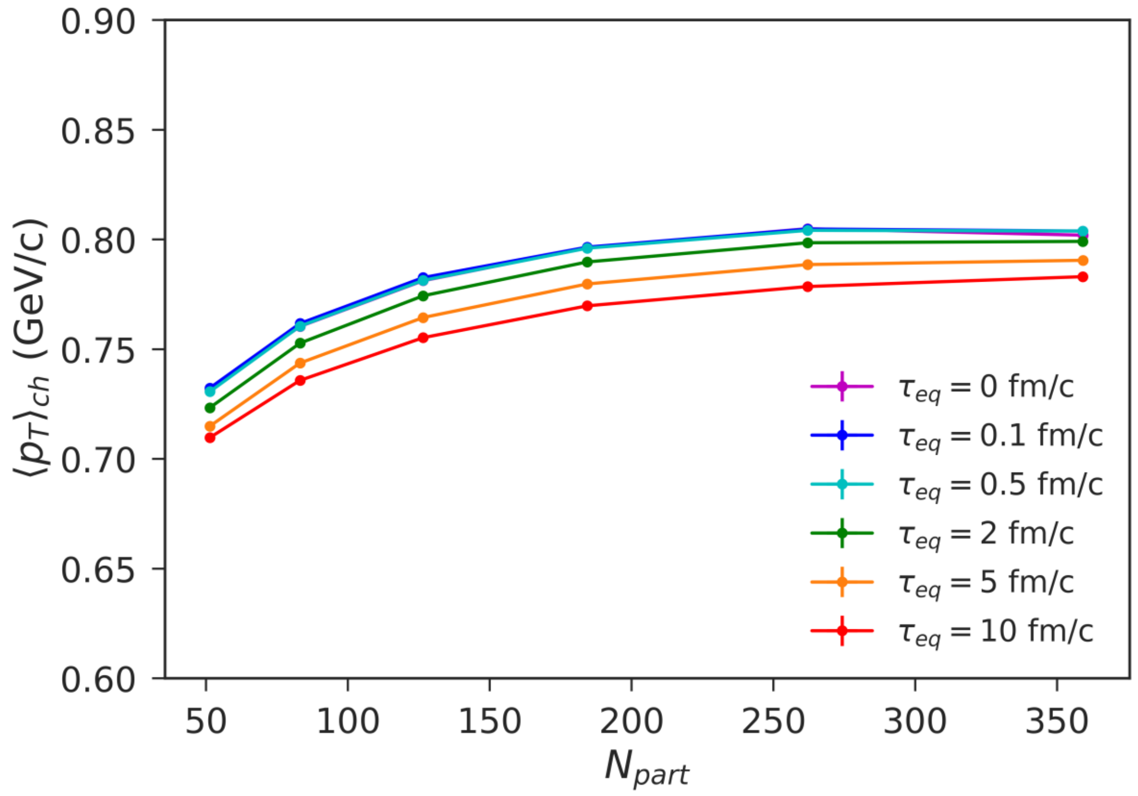
- Lower γ_s suppresses strange hadron yields but enhances light hadron yields
  - Vice versa for γ_l

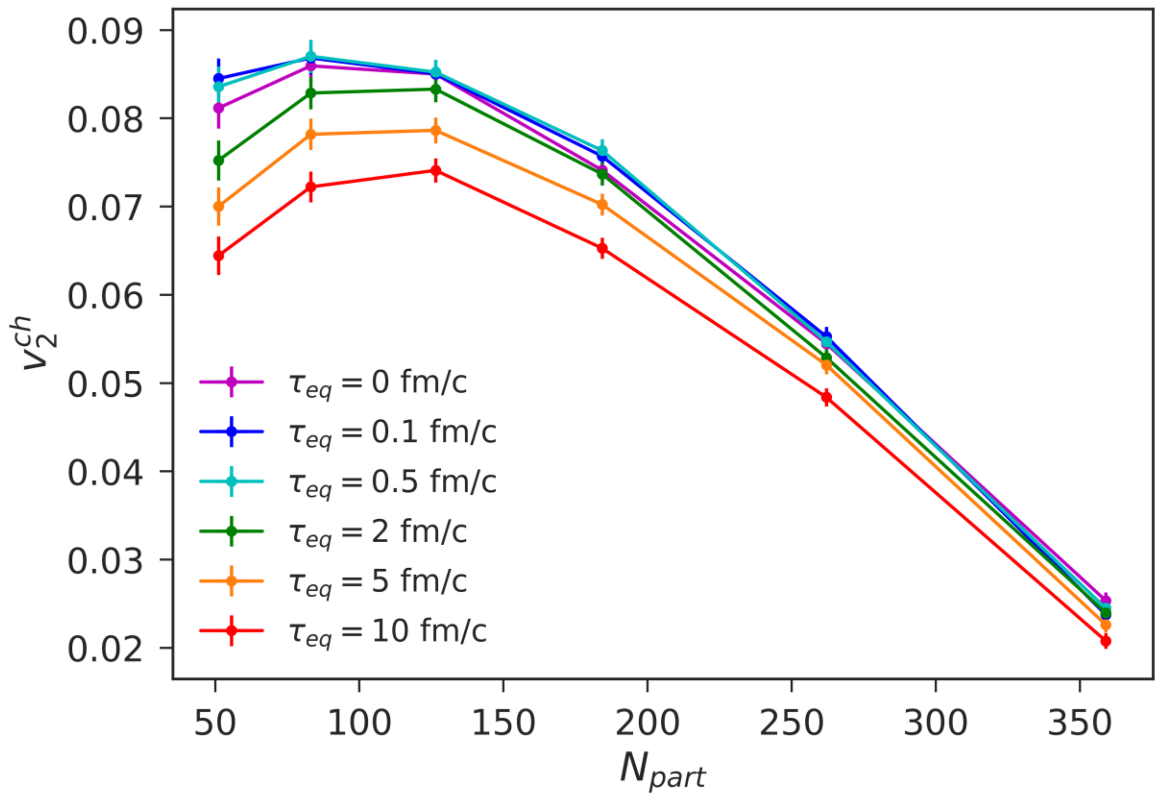




Transverse Flow

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





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Bayesian Analysis Framework

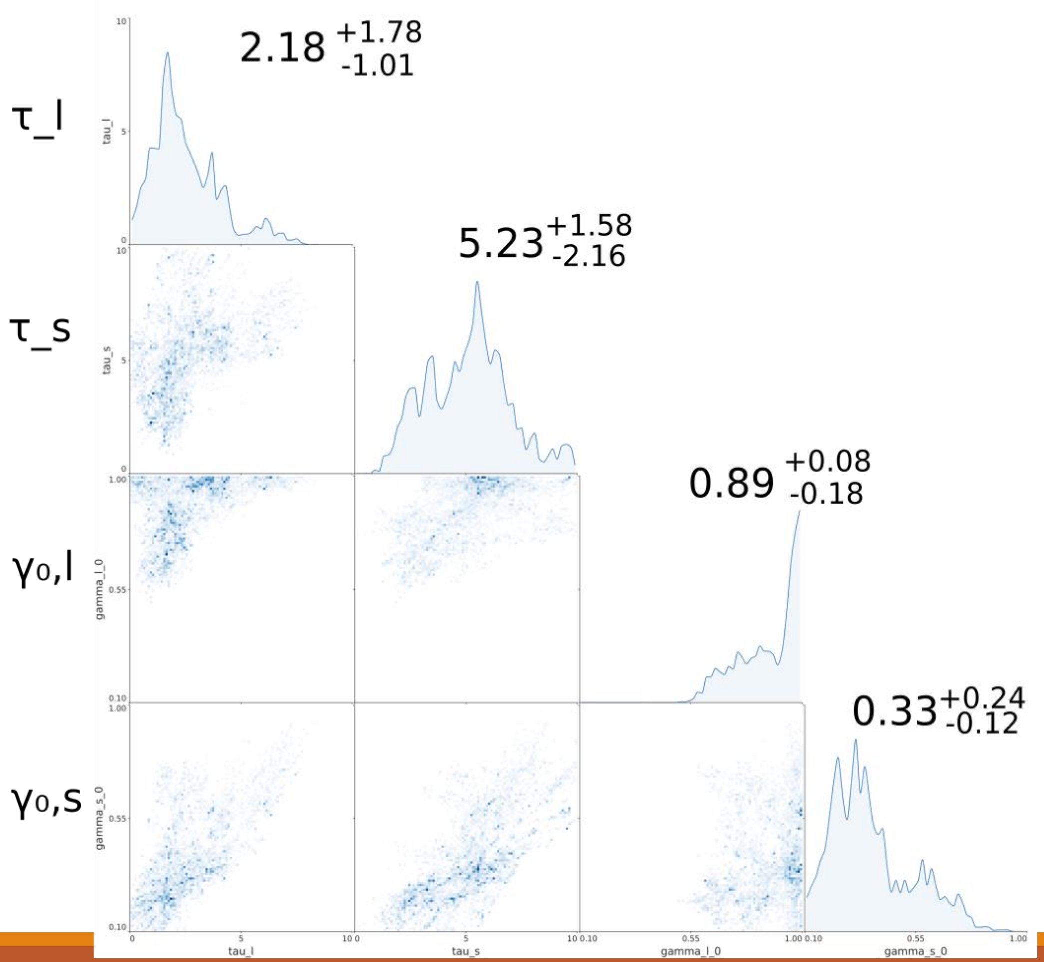
- Bayesian inference: infer model parameter distributions from experimental data
- Model chain: TRENTo → MUSIC → iS3D → SMASH
- Parameters:
  - Equilibration timescales: $\tau_{eq,l}$ and $\tau_{eq,s}$ (prior: [0,10 fm/c])
  - Initial fugacities: $\gamma_{0,l}$ and $\gamma_{0,s}$ (prior: [0.1,1])
  - Additional bulk and initial condition parameters

Experimental Observables

- Preliminary analysis with a reduced set of observables
- System
  - Au-Au (200 GeV) from STAR
- Observables:
  - Hadron yields: π, K, p, Ω
  - Mean p_T: π, K, p
  - Transverse energy $dE_T/d\eta$

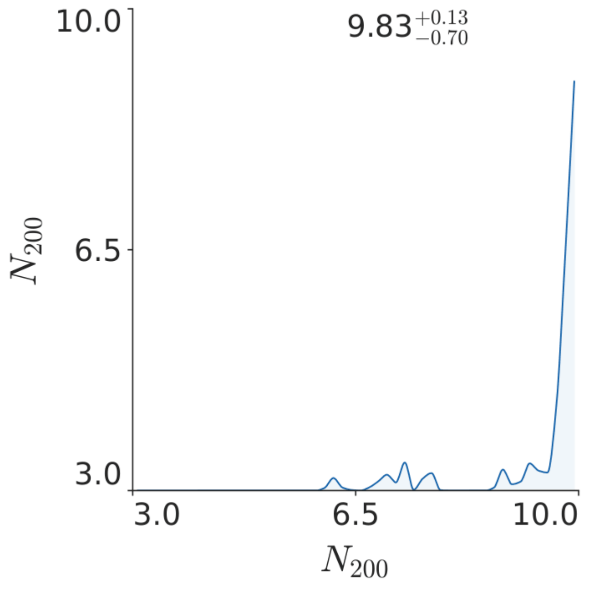
Preliminary Results

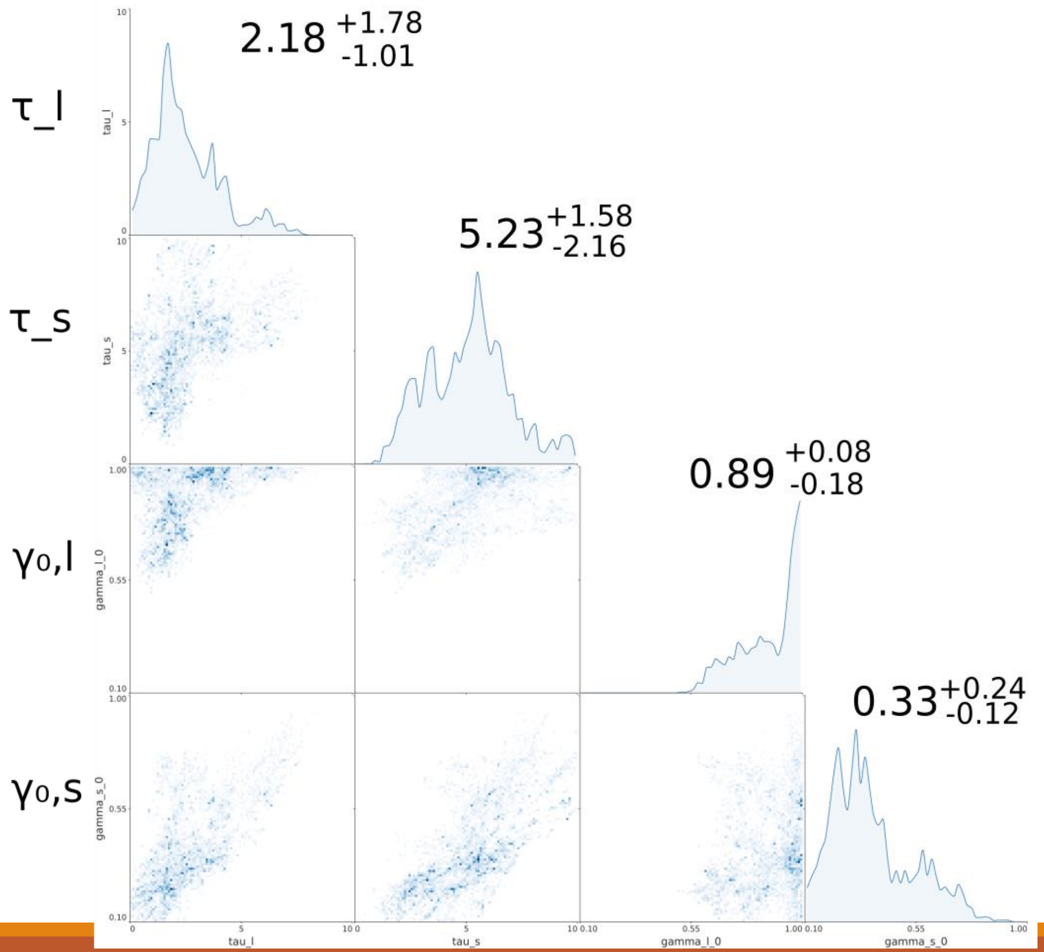
- Posterior distributions for $\gamma_{0,l/s}$, $\tau_{eq,l/s}$ show signs of earlier light, later strange equilibration…



Preliminary Results

- Posterior distributions for $\gamma_{0,l/s}$, $\tau_{eq,l/s}$ show signs of earlier light, later strange equilibration…
  ...but the prior has issues!





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Summary

- Hydrodynamic models need to account for suppressed quark densities in the QGP at early times
- We do so by incorporating chemical equilibration into the equation of state
- Bayesian calibration enables direct constraints on how quickly quarks are produced in the QGP

- Ongoing work: combined analysis of Pb-Pb, Au-Au, and O-O data with improved statistics

Backup

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 $\pi^{\mu\nu}, \Pi$

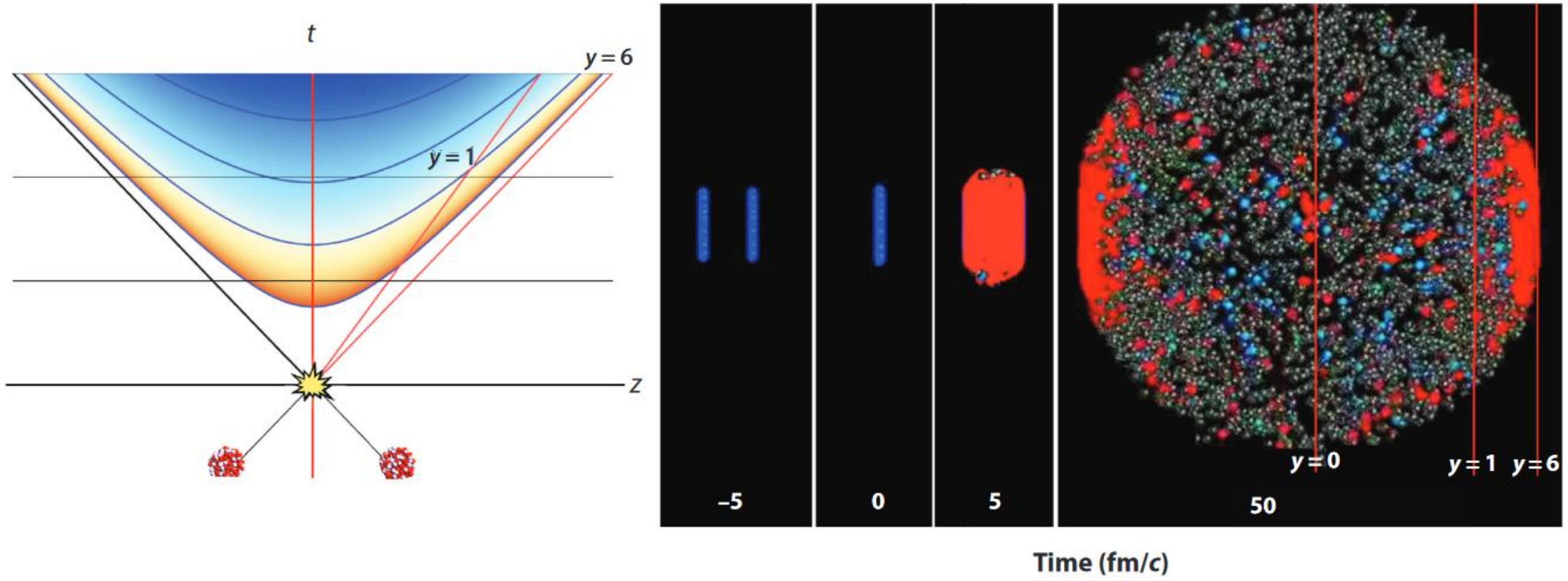


Figure: W. Busza, K. Rajagopal, and W. van der Schee, Annu. Rev. Nucl. Part. Sci., 68:339-76 (2018)

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

Partial Chemical Equilibrium: High T

- Linear interpolation of lattice equations:

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

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

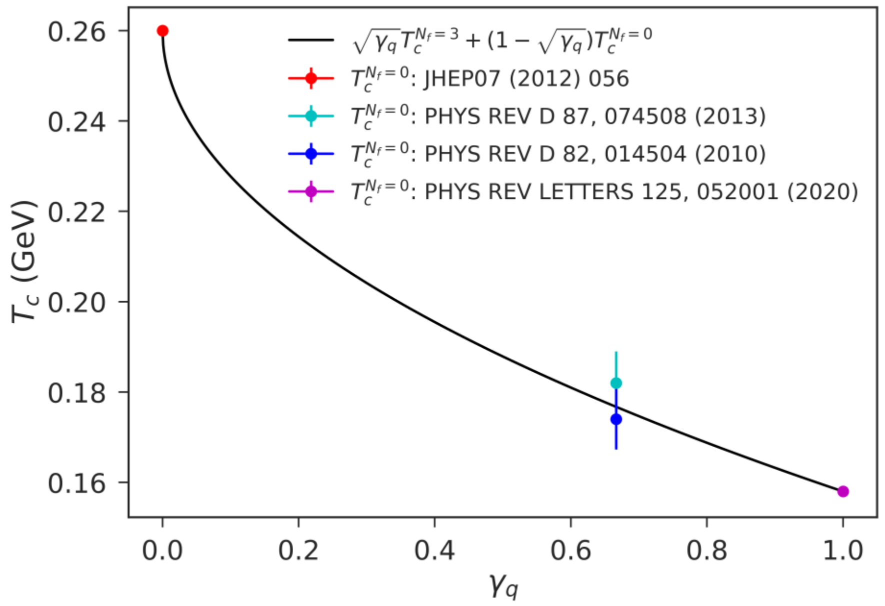
Partial Chemical Equilibrium: High T

- 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:

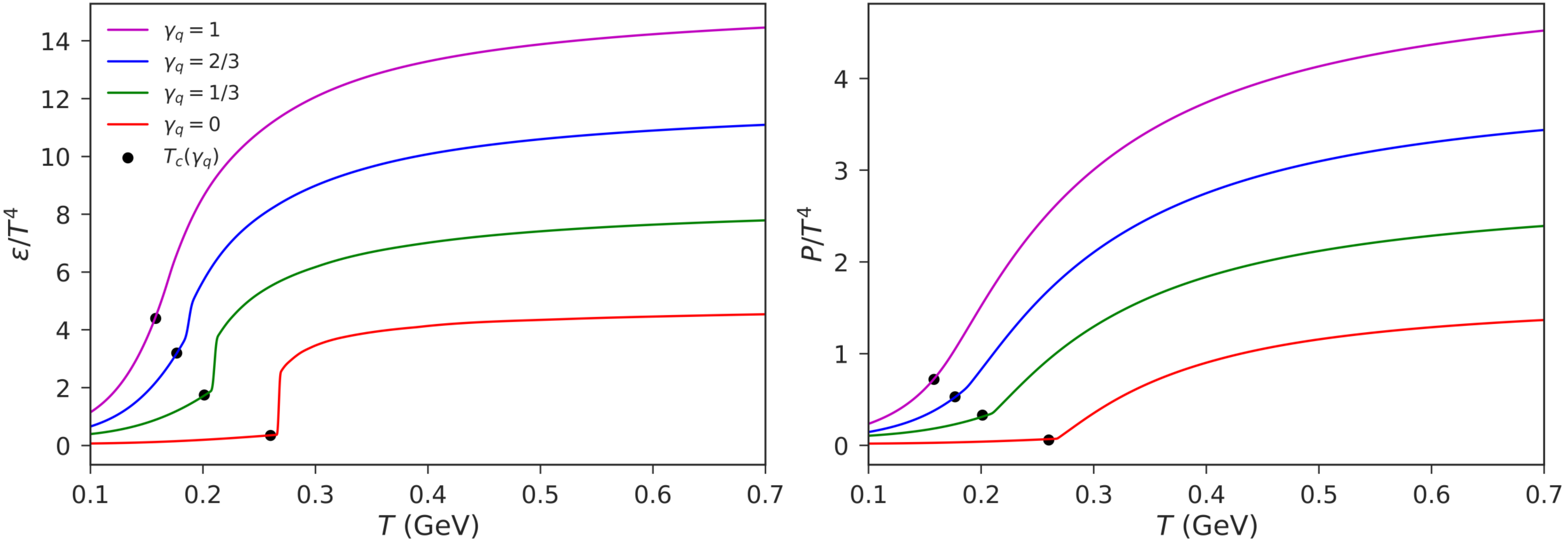
$$f_i(p) = \frac{1}{\lambda_i^{-1}\, e^{E_p/T} \pm 1}$$

- 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 $T_c(\gamma_q)$:



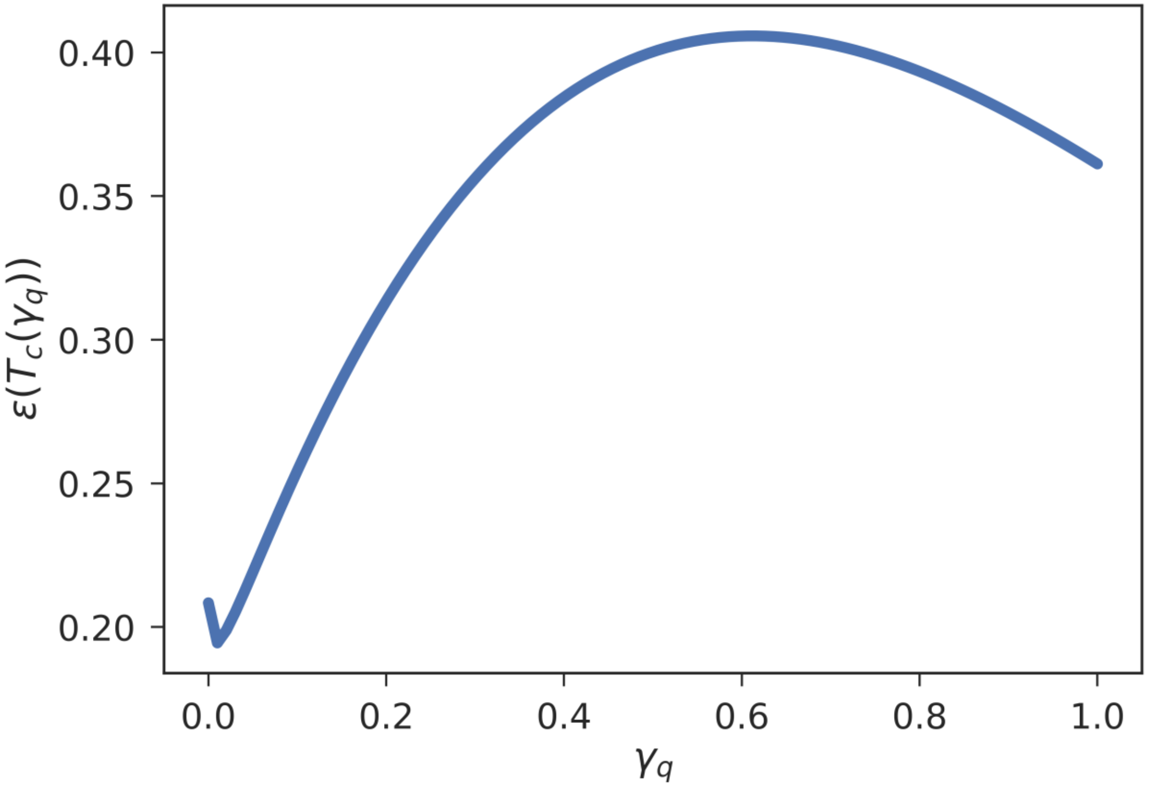
Particlization

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

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

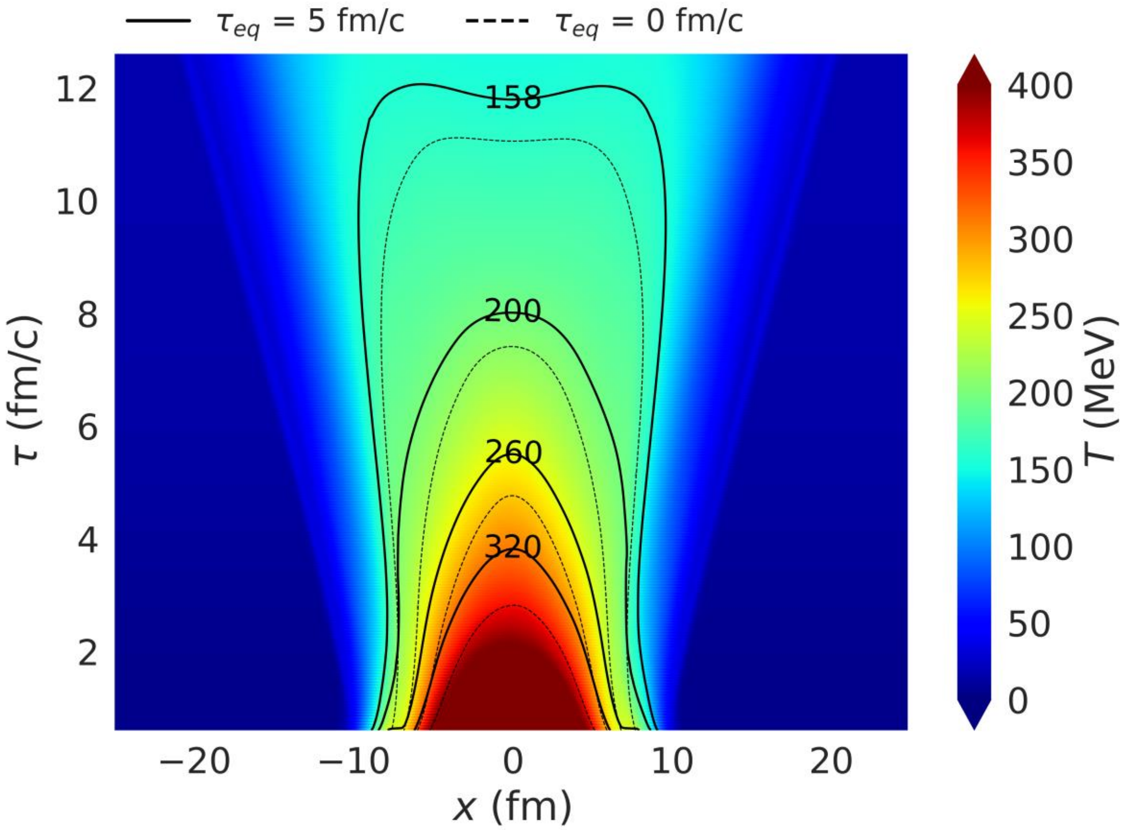
- Same modified distributions as HRG:

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



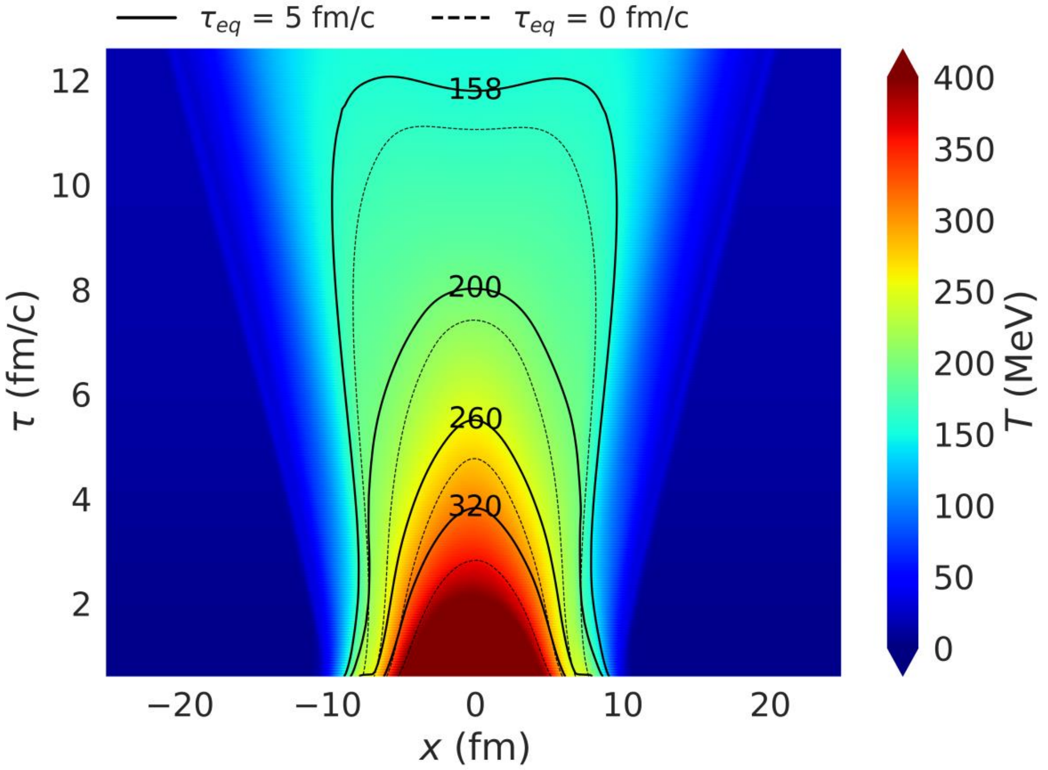
Temperature Evolution

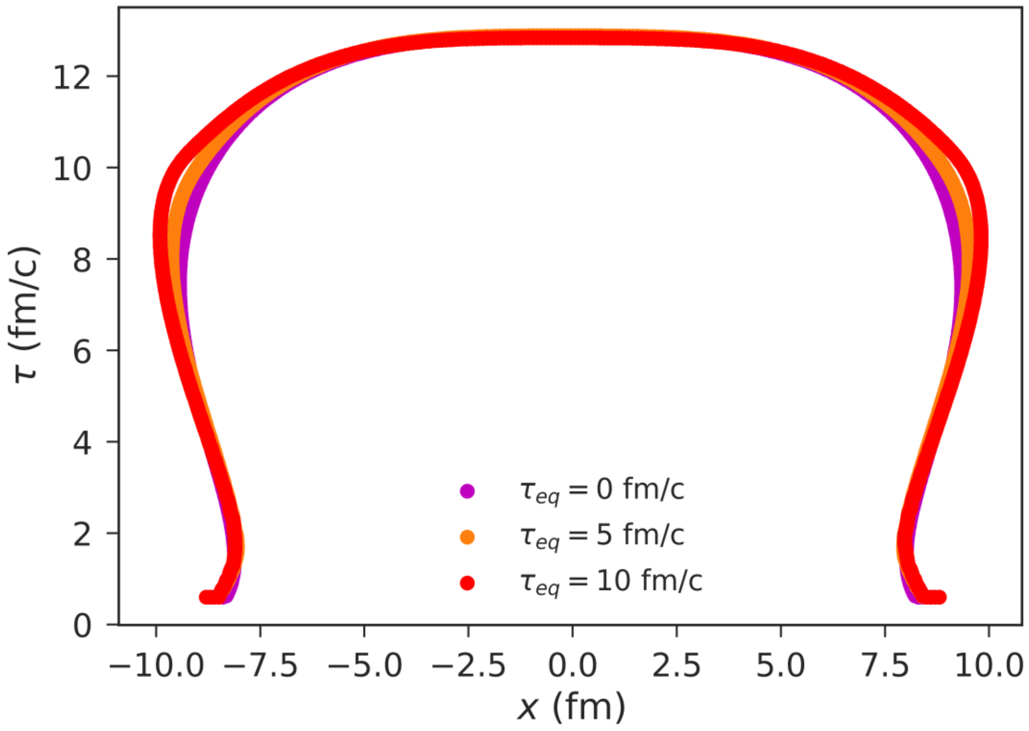
- Higher τ_{eq} (fewer quark degrees of freedom) corresponds to a hotter medium:



Temperature Evolution: Particlization

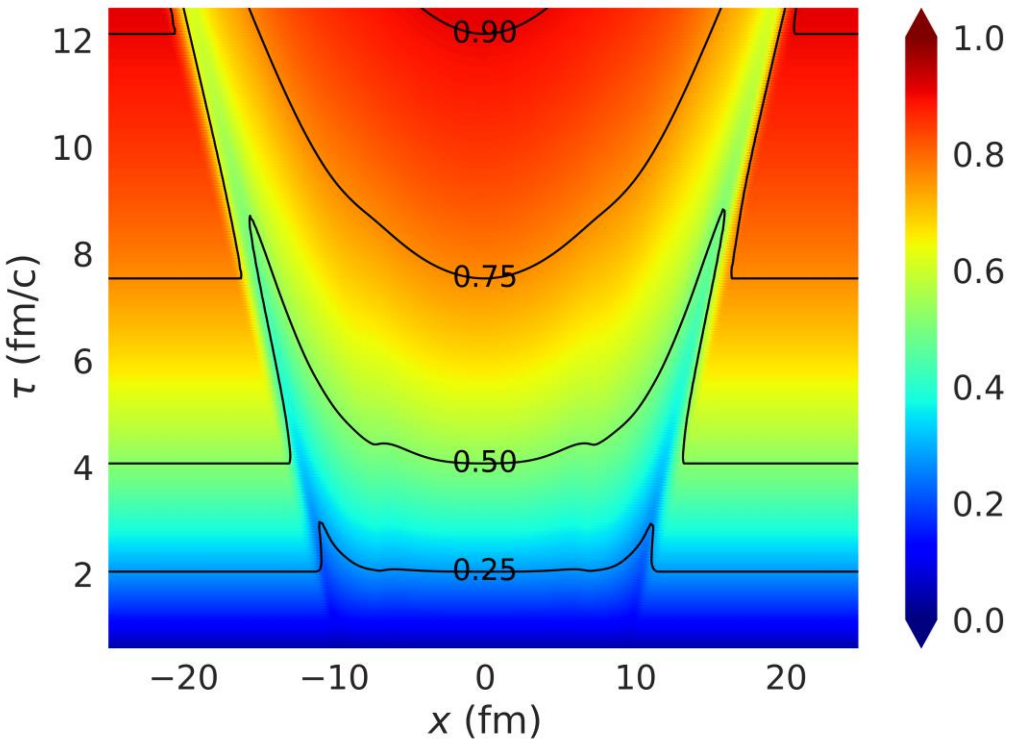
- However, the shape of the $T_c(\gamma_q)$ surface changes only slightly:

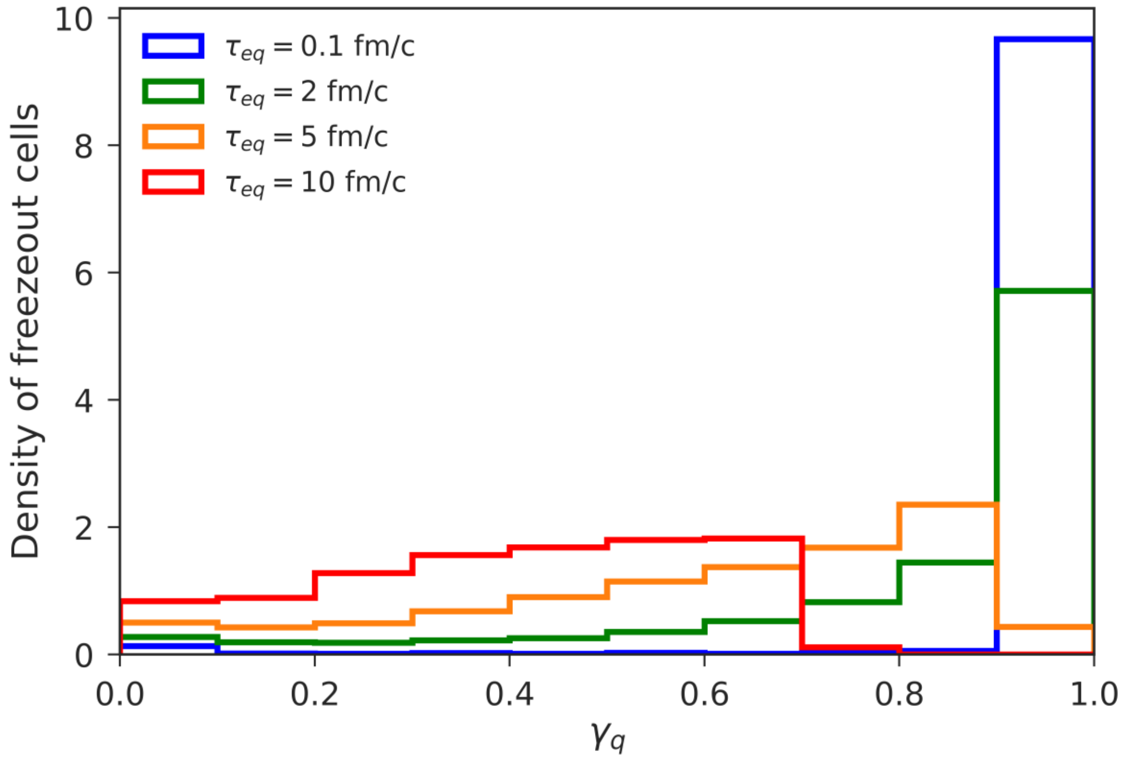




Fugacity Evolution

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

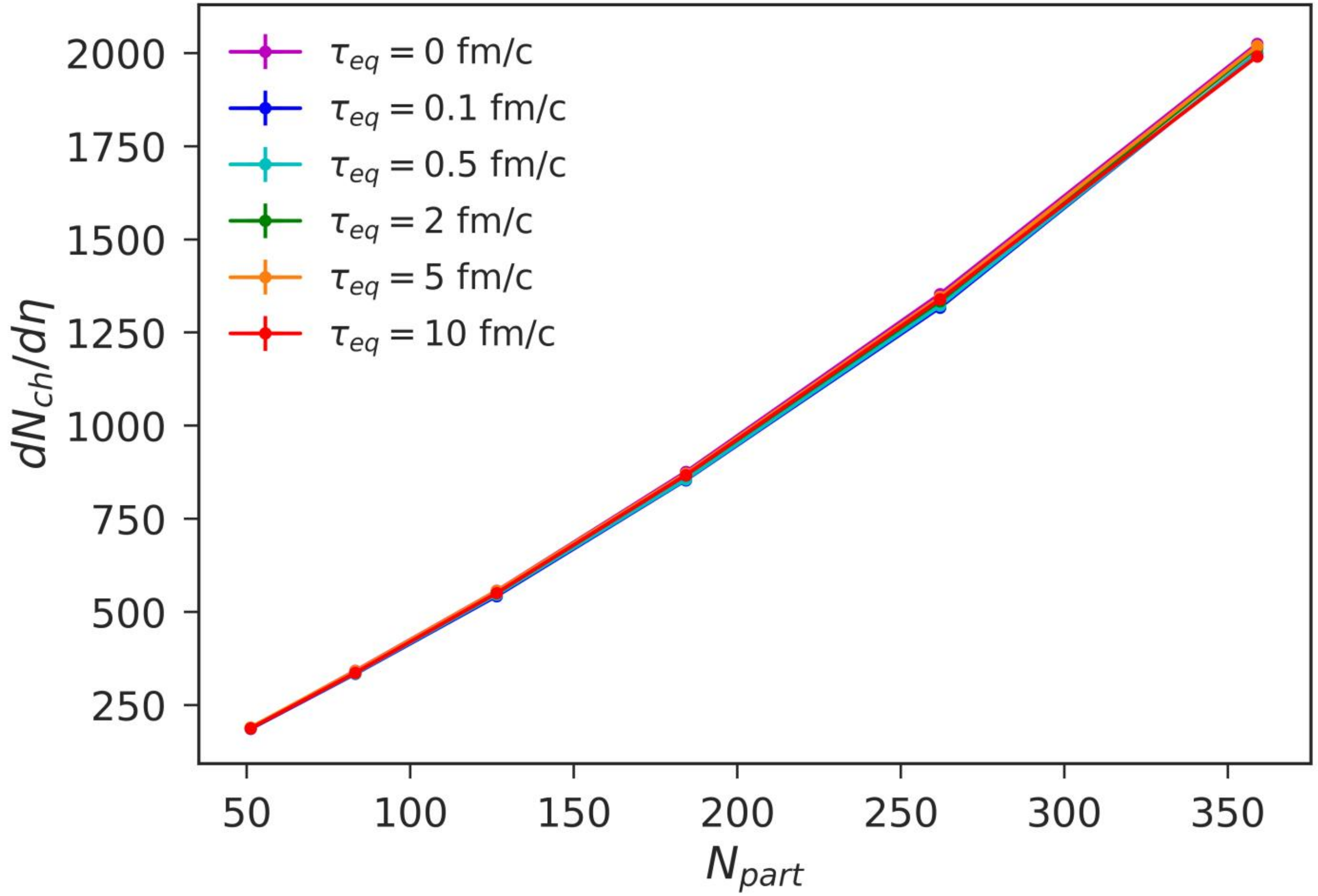




Hadron Production

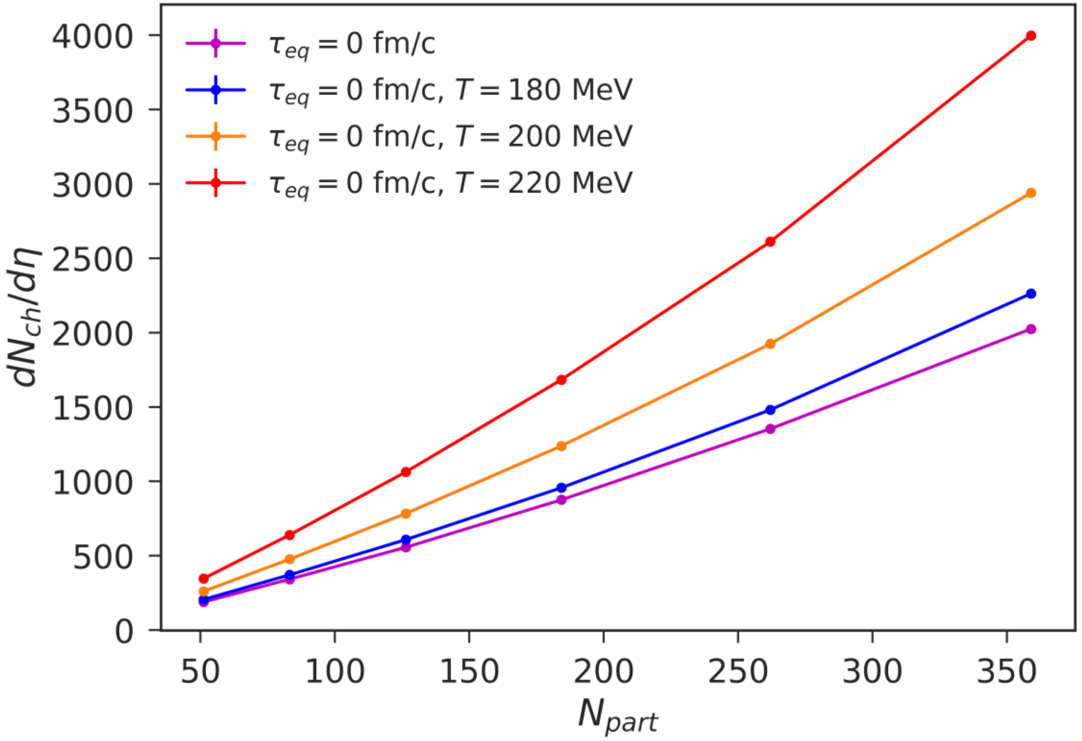
- We evolve an ensemble of Pb+Pb events with fixed initial conditions and varying τ_{eq}

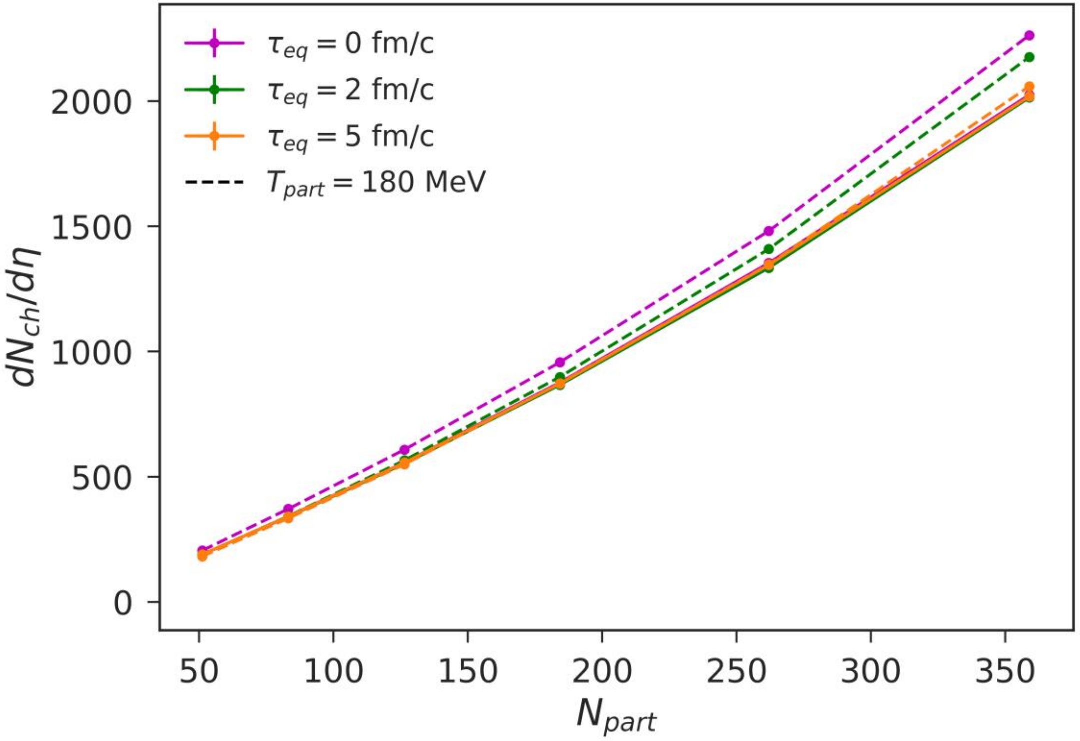
- Farther from equilibrium:
  - Higher particlization temperature increases hadron yields
  - Lower γ_q suppresses hadron yields



Hadron Production

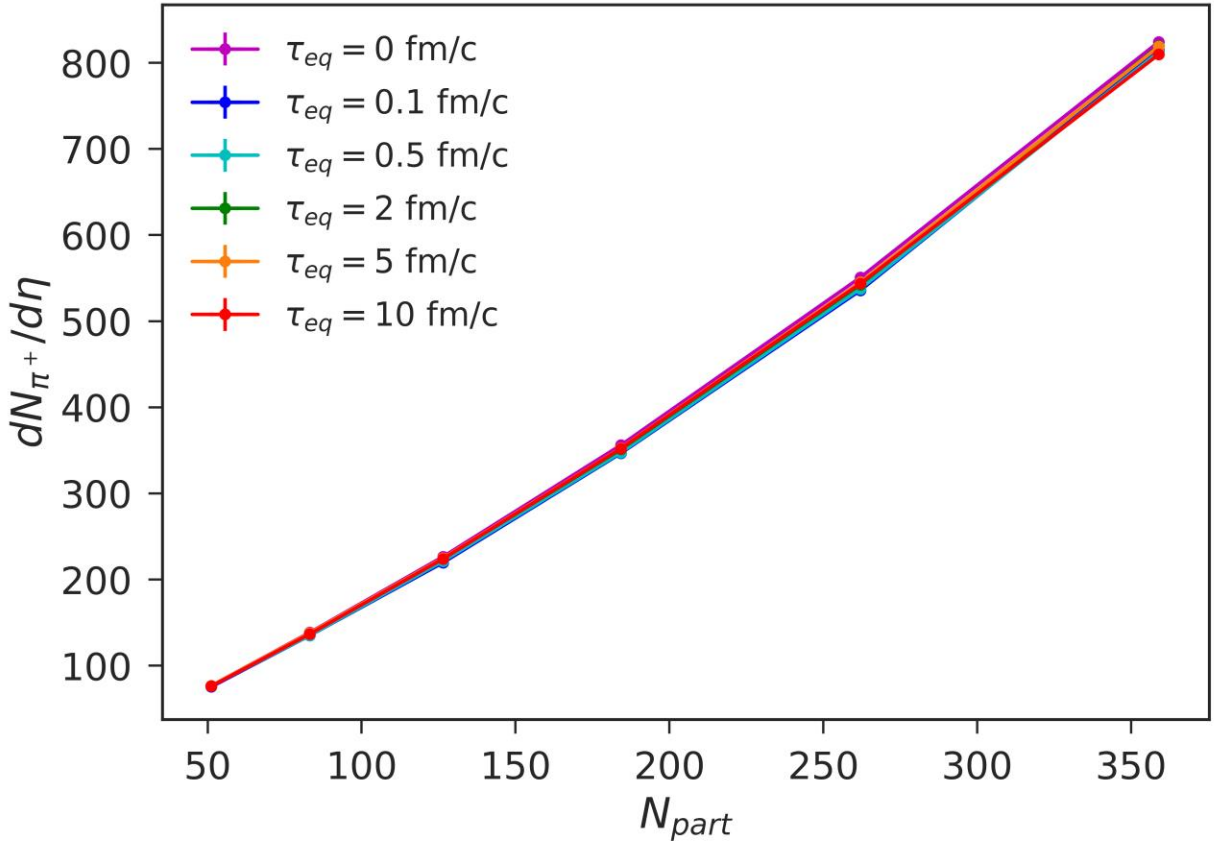
- Increase with particlization temperature (left) vs decrease with equilibration timescale (right):

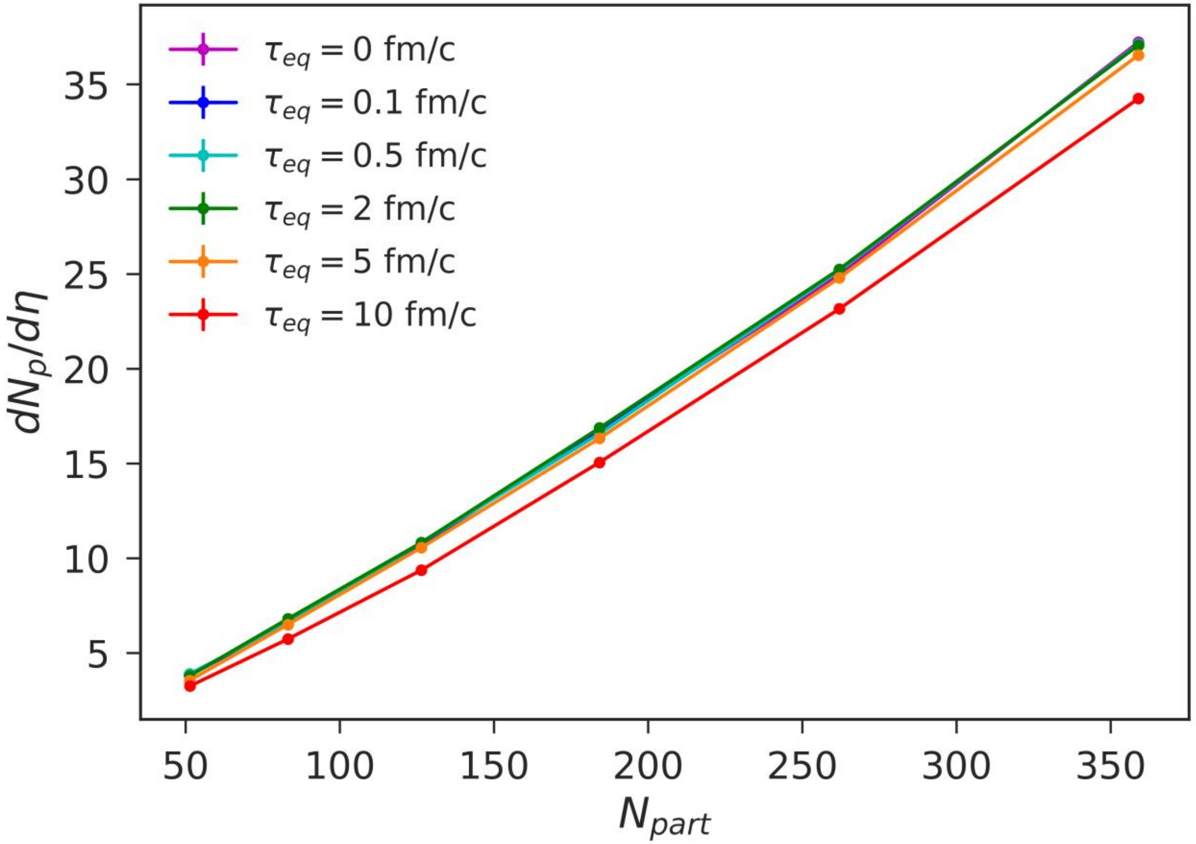




Hadron Production: Baryon Suppression

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





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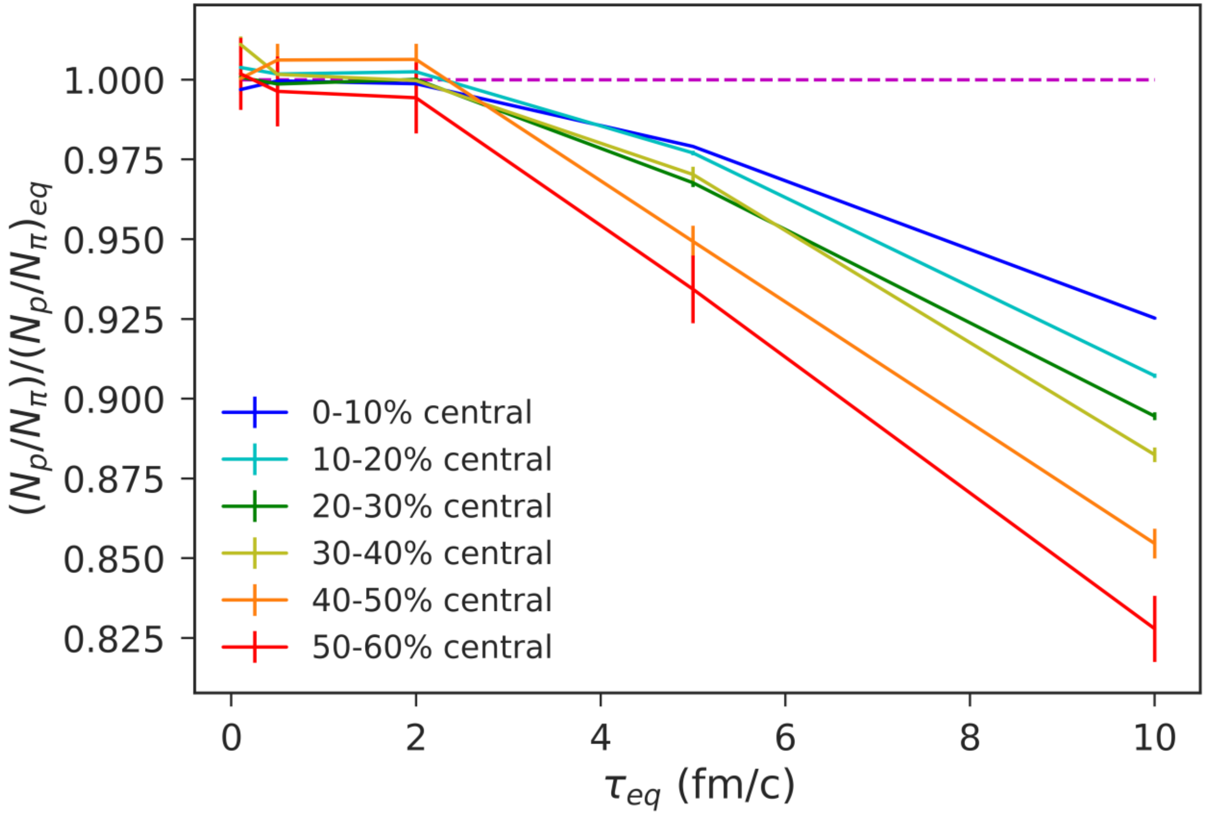

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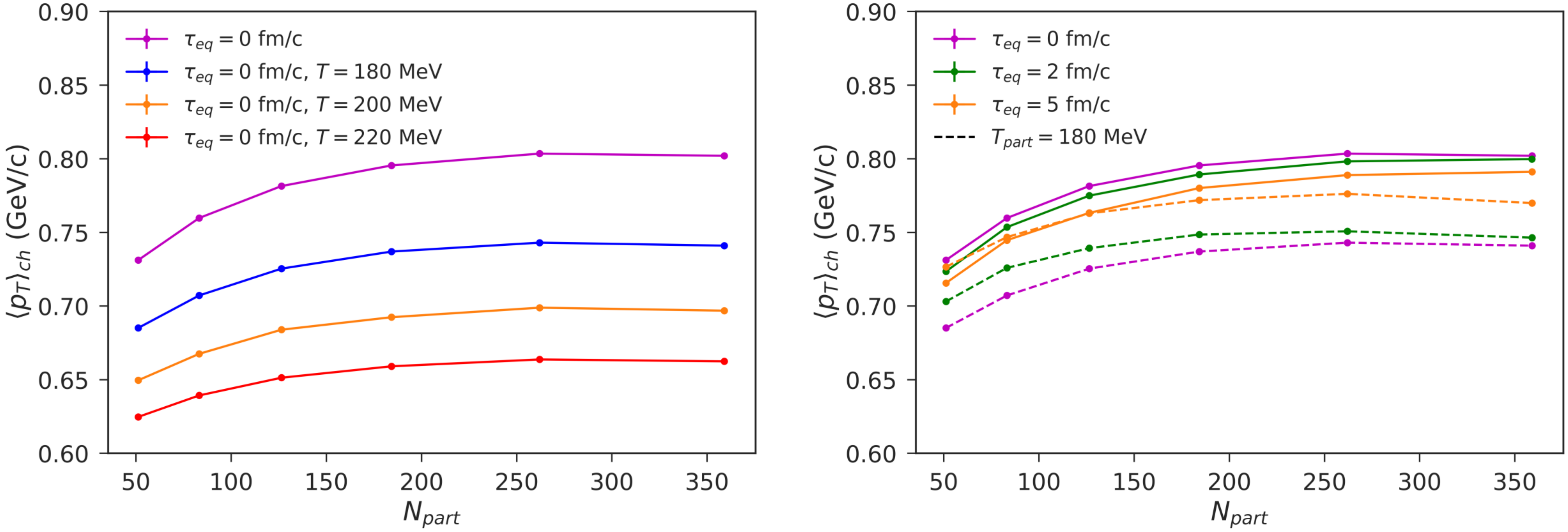
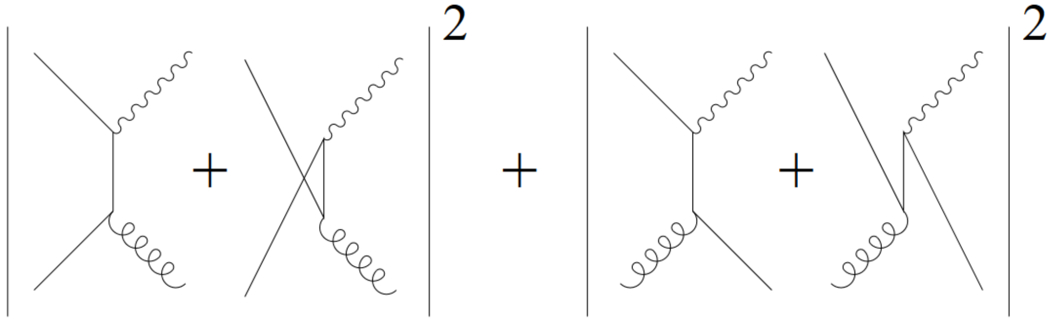
- Lower pressure when evolving out of equilibrium suppresses transverse flow:



Thermal Photon Production

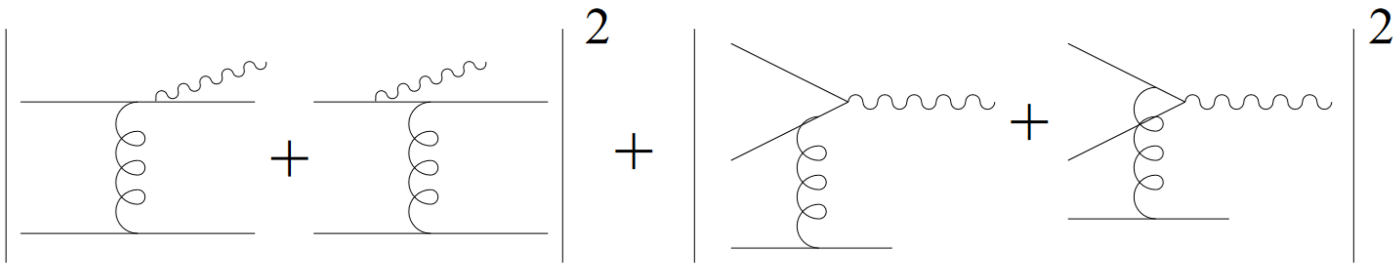
- Thermal photon producing processes scale differently with γ_q:

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



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