Evolution of the Quark-Gluon Plasma in Partial Chemical Equilibrium

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HEAVY ION COLLISIONS IN THE QCD PHASE DIAGRAM

SUBATECH, NANTES

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Outline

Quark chemical equilibration in heavy ion collisions

Modeling heavy ion collisions

Implementation of the partial chemical equilibrium model

Preliminary results

Summary and outlook

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Heavy Ion Collisions: Initial Stages

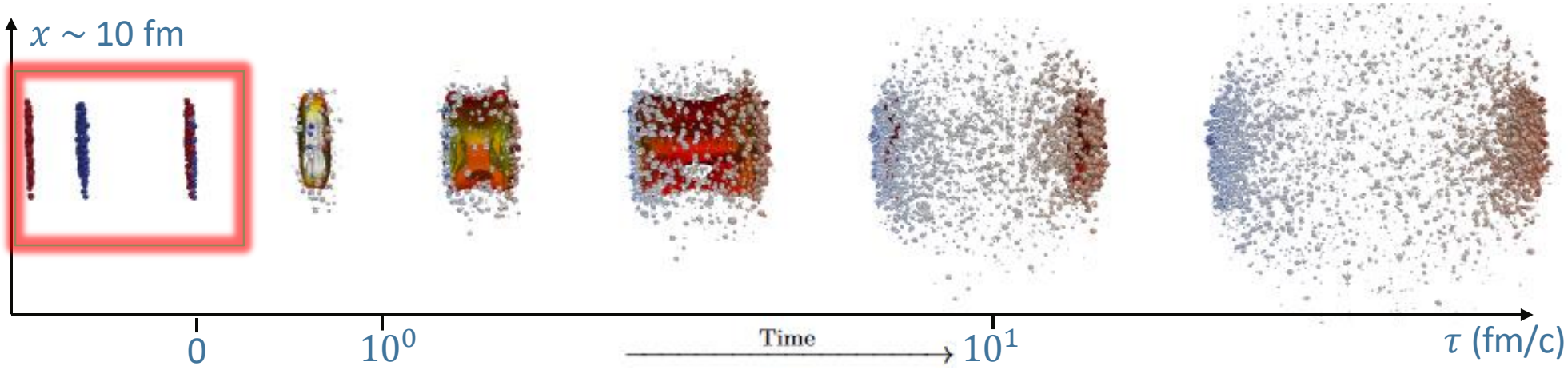

Figure by Hannah Petersen

- Quarks and gluons in participating nucleons scatter with each other
- Nearly all of the final entropy is produced
- Medium is gluon saturated and very far from equilibrium

Heavy Ion Collisions: QGP Evolution

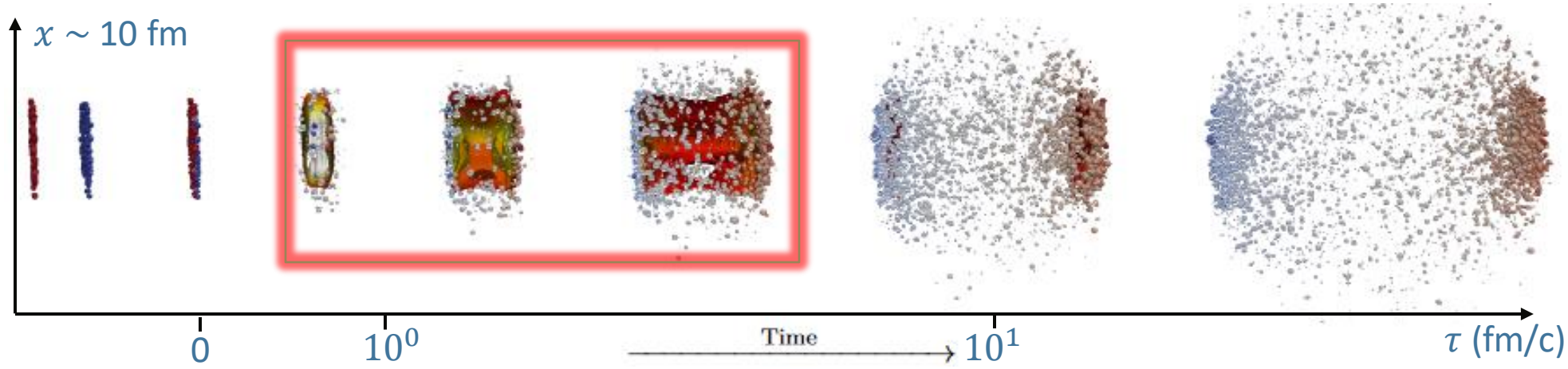

Figure by Hannah Petersen

- QGP is modeled as a fluid near local thermodynamic equilibrium
- Pressure gradients drive expansion as QGP cools
- Thermodynamic properties given by equation of state

Heavy Ion Collisions: Particlization

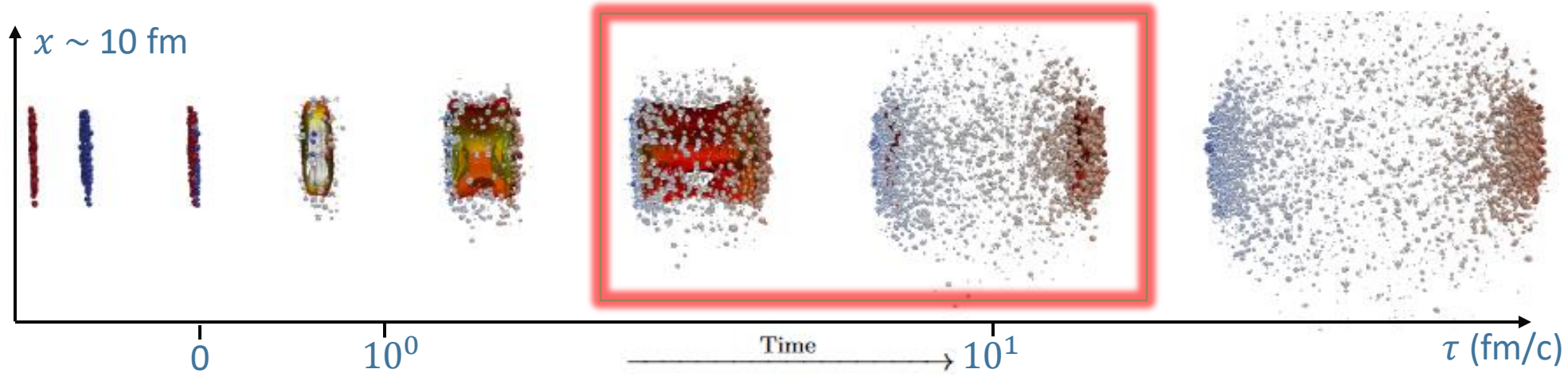

Figure by Hannah Petersen

- QGP cools to form hadron gas
- In simulations, fluid is converted to discrete hadrons at a constant temperature or energy density hypersurface

Heavy Ion Collisions: Hadronic Interactions

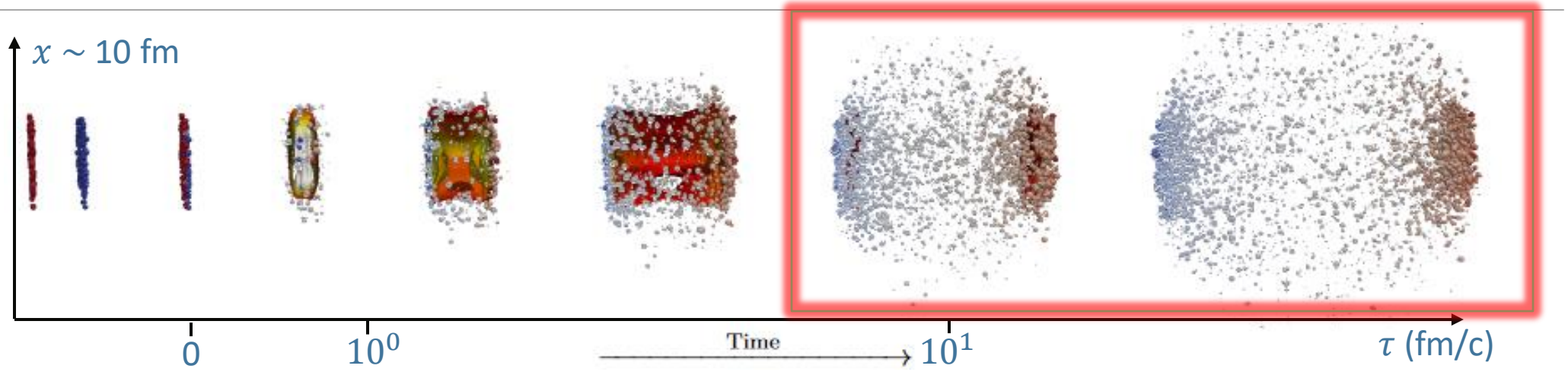

Figure by Hannah Petersen

- Hadrons decay and cool until freeze-out
- Microscopic dynamics drive Boltzmann transport
- Final detected 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 through splitting
  - Saturation: Splitting is balanced by recombination

- Basis for successful color-glass condensate and glasma models
  - E.g., IP-GLASMA[1]

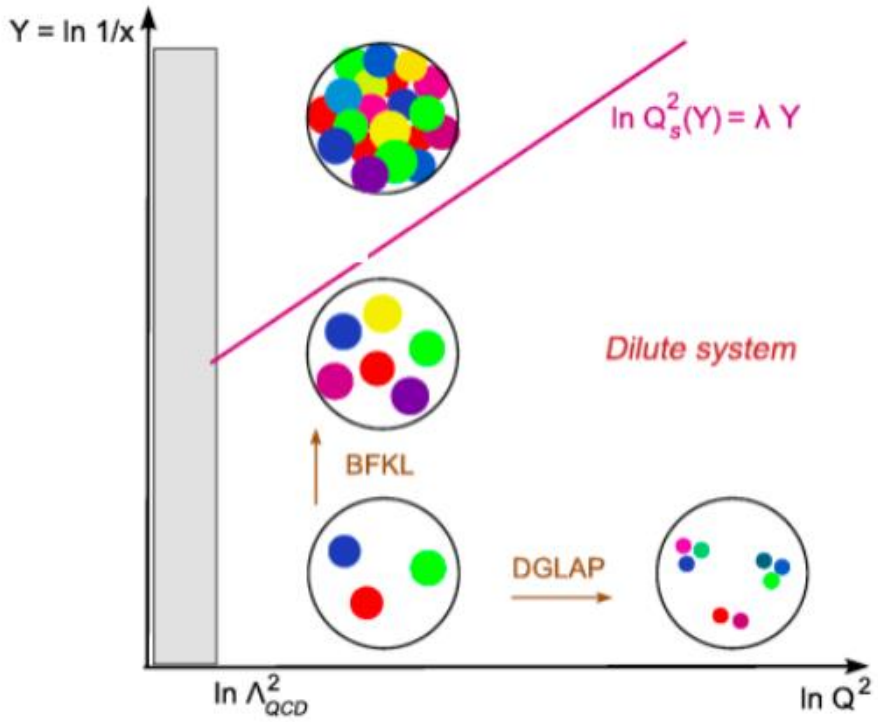

Figure: E. Iancu, CERN-2014-003, pp. 197-266 (2011)

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

Kinetic and Chemical Equilibration of the QGP

- **Bottom-up thermalization:** soft gluons scatter to form a thermal bath
  - At saturation scale Q_s, gluons thermalize over timescale $\tau_{th} \sim \alpha_s^{-13/5} Q_s^{-1}$
  - At colliders: $Q_s \sim$ 1-3 GeV, $\tau_{th} \lesssim 1$ fm/c

- **Quark chemical equilibration:** quarks and antiquarks are initially suppressed, and reach their equilibrium densities on a longer timescale
  - Potentially[2] $\tau_{eq} \gtrsim 3$ fm/c
  - Evolution of quark densities is defined by rate equations

2. Z. Xu and C. Greiner, Phys. Rev. C 71, 064901 (2005)

Partial Chemical Equilibrium

- The issue: conventional hydrodynamics models assume the QGP is chemically equilibrated at the onset, but the initial state is believed to be gluon saturated and it is uncertain how long chemical equilibration takes

- Our goal: to 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 with time during the hydro evolution

Signatures of Quark Chemical Equilibration

- From prior studies of pure glue initial state[3]:
  - Entropy production after hydrodynamization
  - Photon and dilepton suppression

- We're looking for signatures in hadron yields and flow anisotropy

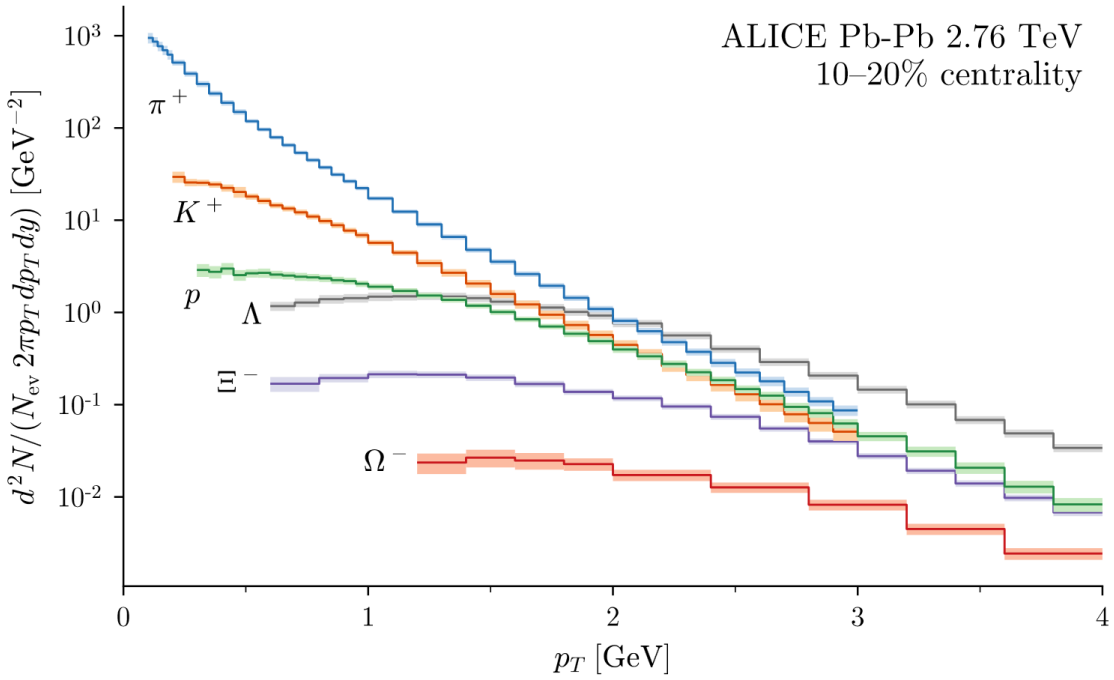

Figure: J. Bernhard, PhD thesis (2018)

3. V. Vovchenko et al., Phys. Rev. C 94, 024906 (2016)

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Hydrodynamics

- Short distance particle interactions are averaged out; only bulk properties matter
- Based on local conservation of energy-momentum: $\partial_\mu T^{\mu\nu} = 0$

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

- We use MUSIC: a (3+1)-dimensional viscous hydrodynamics solver[4]
  - Israel-Stewart-like second-order viscous hydrodynamics used to solve equations of motion for $\pi^{\mu\nu}, \Pi$

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

Second-Order Viscous Hydrodynamics

- Equations of motion (DNMR[5]):

$$\tau_\pi \dot{\pi}^{<\mu\nu>} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + 2\tau_\pi \pi_\alpha^{<\mu}\omega^{\nu>\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \phi_7 \pi_\alpha^{<\mu}\pi^{\nu>\alpha} - \tau_{\pi\pi}\pi_\alpha^{<\mu}\sigma^{\nu>\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \phi_6\Pi\pi^{\mu\nu}$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \phi_1\Pi^2 + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} + \phi_3\pi^{\mu\nu}\pi_{\mu\nu}$$

- Transport coefficients:

$$\tau_\pi = \frac{5\eta}{\epsilon + P} \qquad \tau_\Pi = \frac{\zeta}{15\left(\frac{1}{3} - c_s^2\right)^2(\epsilon + P)}$$

$$\phi_1 = \phi_3 = \phi_6 = 0 \qquad \lambda_{\pi\Pi} = \frac{6}{5} \qquad \delta_{\pi\pi} = \frac{4}{3}\tau_\pi$$

$$\phi_7 = \frac{9}{70P} \qquad \tau_{\pi\pi} = \frac{10}{7}\tau_\pi \qquad \lambda_{\Pi\pi} = \frac{8}{5}\left(\frac{1}{3} - c_s^2\right)\tau_\Pi \qquad \delta_{\Pi\Pi} = \frac{2}{3}\tau_\Pi$$

5. G. S. Denicol, H. Niemi, E. Molnar, and D. H. Rischke, Phys. Rev. D 85, 114047 (2012)

Hydrodynamics: Simplifying Assumptions

- Ideal hydrodynamics: neglect $\pi^{\mu\nu}, \Pi$ terms
- Zero baryon number chemical potential
- Boost-invariant flow: $v_z = z/t$, solve (2+1)-D hydro and look at midrapidity observables

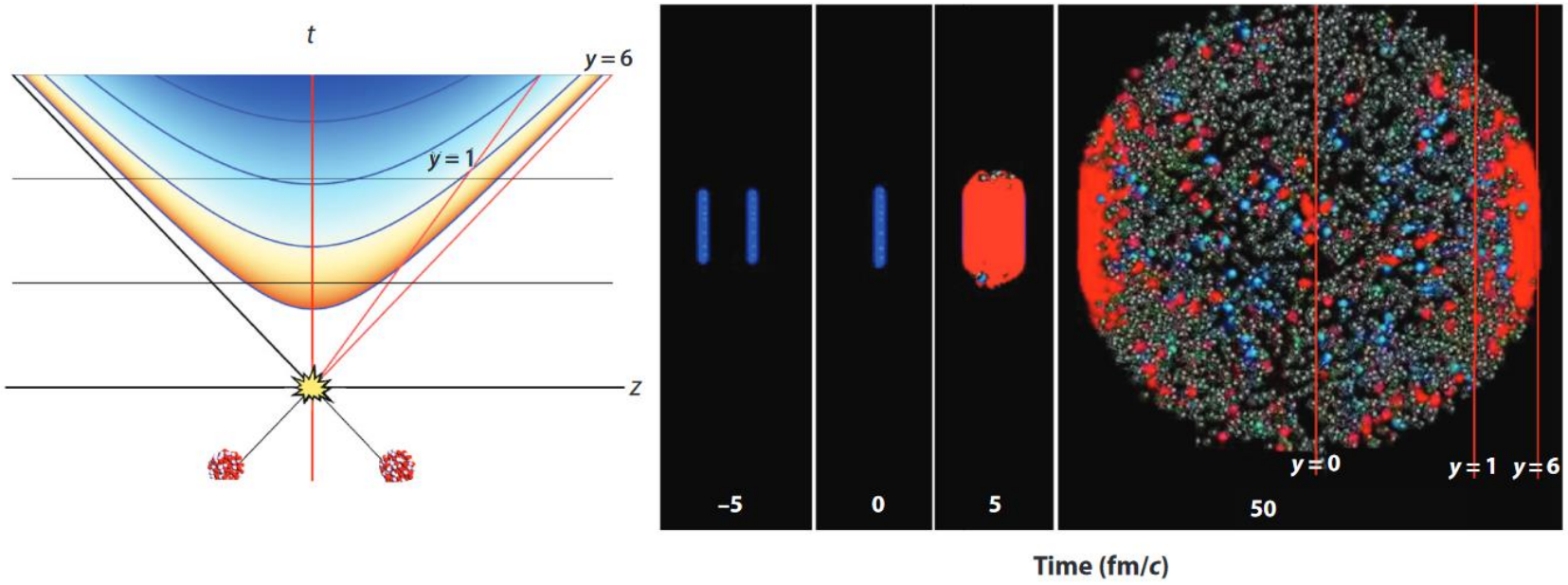

Figure: W. Busza, K. Rajagopal, and W. van der Schee, Annu. Rev. Nucl. Part. Sci., 68:339-76 (2018)

Equilibrium QCD Equation of State

- We account for chemical equilibration by generalizing the equation of state
- High T: calculated from lattice with (2+1)-flavor QCD
- Low T: calculated using hadron resonance gas

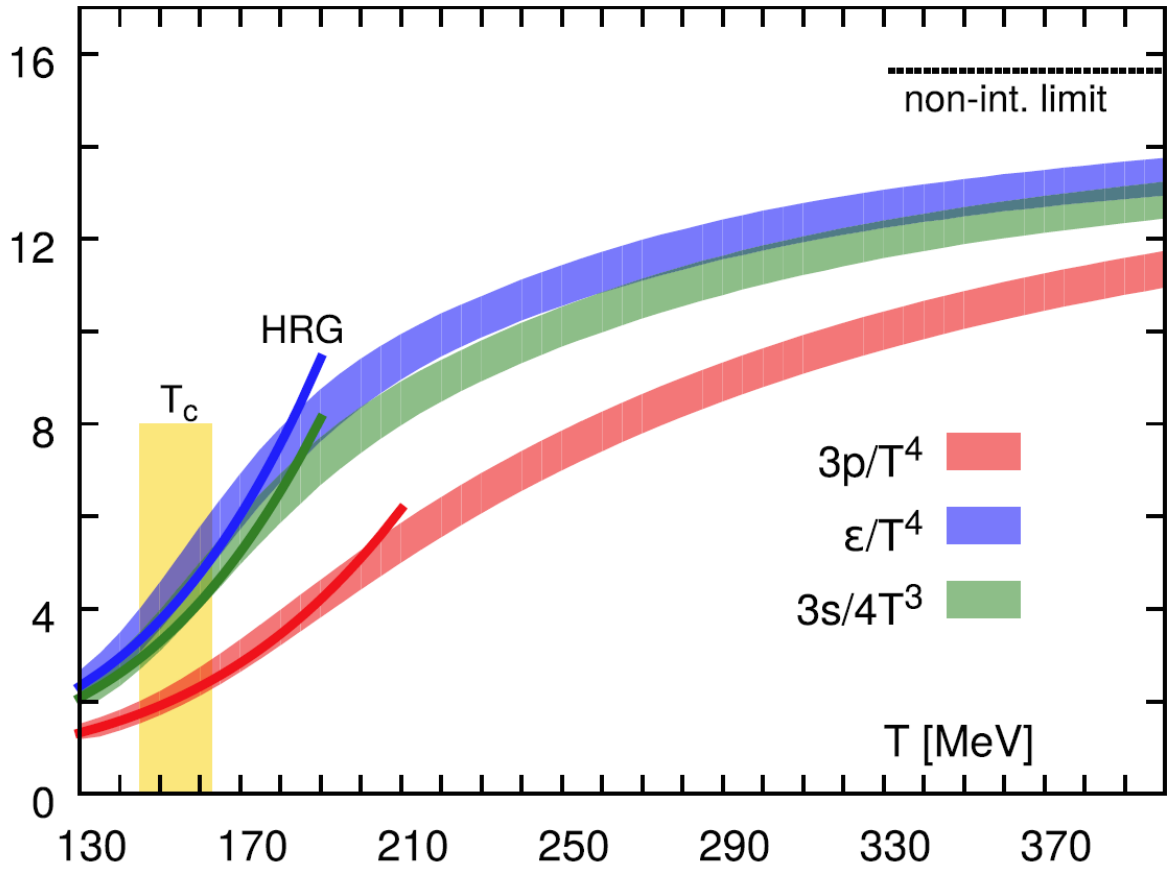

Figure: A. Bazavov et al., Phys. Rev. D 90, 094503 (2014)

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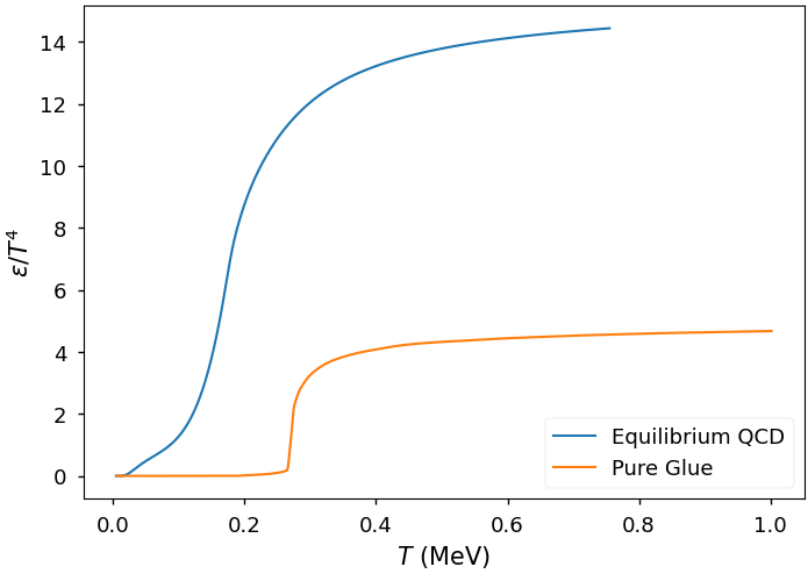
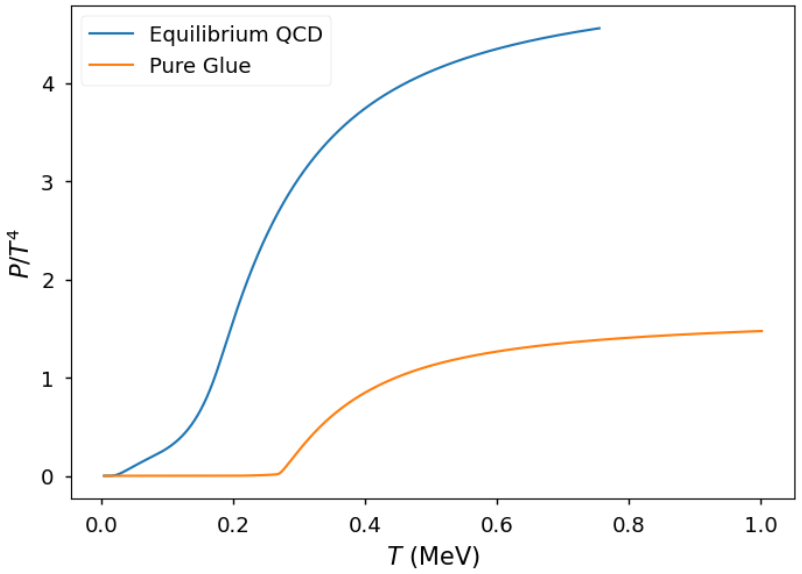
Pure Glue Equation of State

- Lattice calculation from SU(3) gauge theory with no (anti)quarks
- First order phase transition to glueball gas at T_c ~ 270 MeV
- Not quite accurate for initial stages due to different coupling α_s



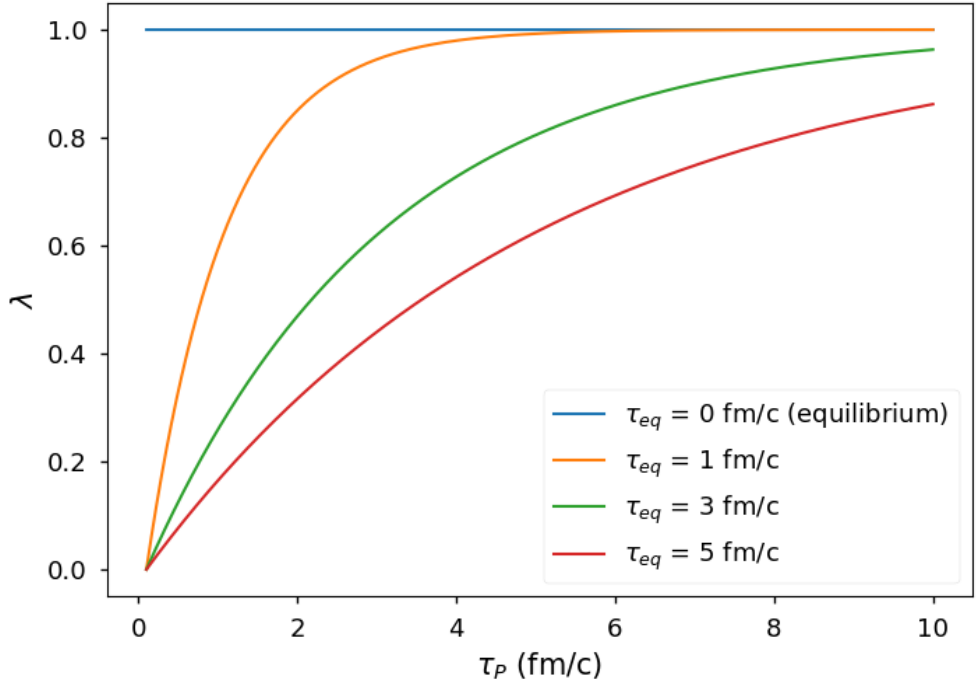


Partial Chemical Equilibrium: High T

- Lattice calculation of far-from-equilibrium equation of state is impractical
- We instead interpolate two equilibrium lattice equations of state using a local proper time-dependent (anti)quark fugacity $\gamma_q(\tau_p)$:

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

- This fugacity can be parameterized as a function of the local proper time of each fluid cell, solved for by $u^\mu \partial_\mu \tau_p = 1$



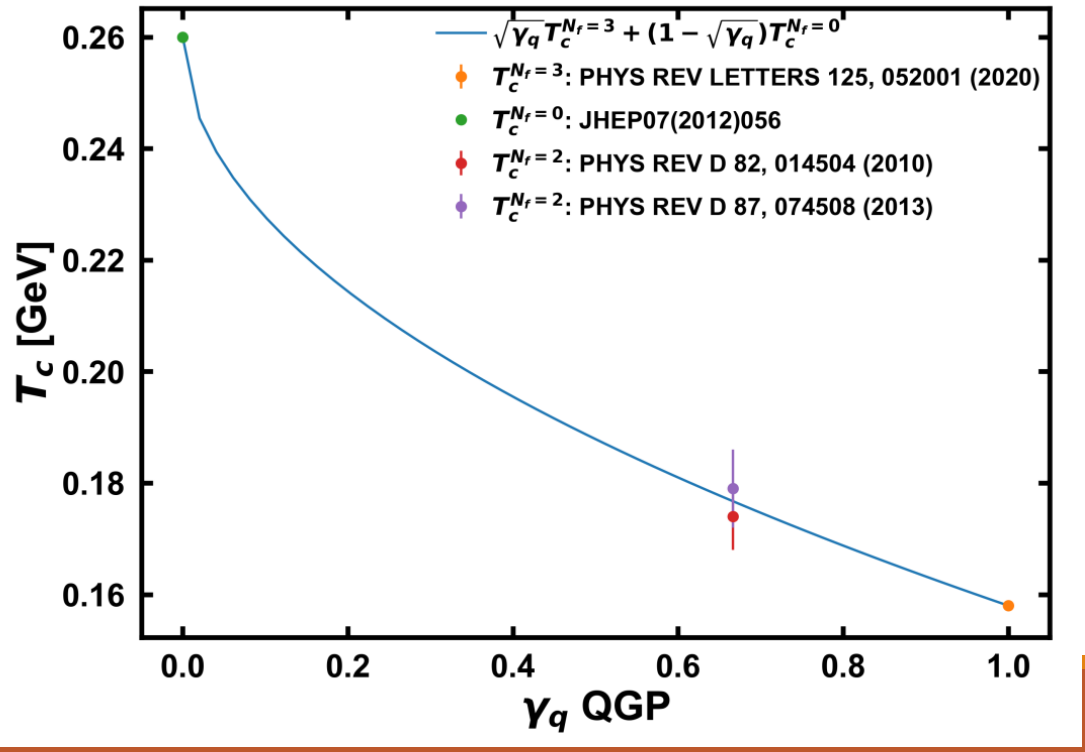
Partial Chemical Equilibrium: High T

- 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:

$$T_c(\gamma_q) = \sqrt{\gamma_q}T_{c,N_f=3} + (1-\sqrt{\gamma_q})T_{c,N_f=0}$$



Partial Chemical Equilibrium: Low T

- We modify the hadron resonance gas equation of state:

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

- Out of equilibrium, each hadron species is modified by a species-specific fugacity λ_i:

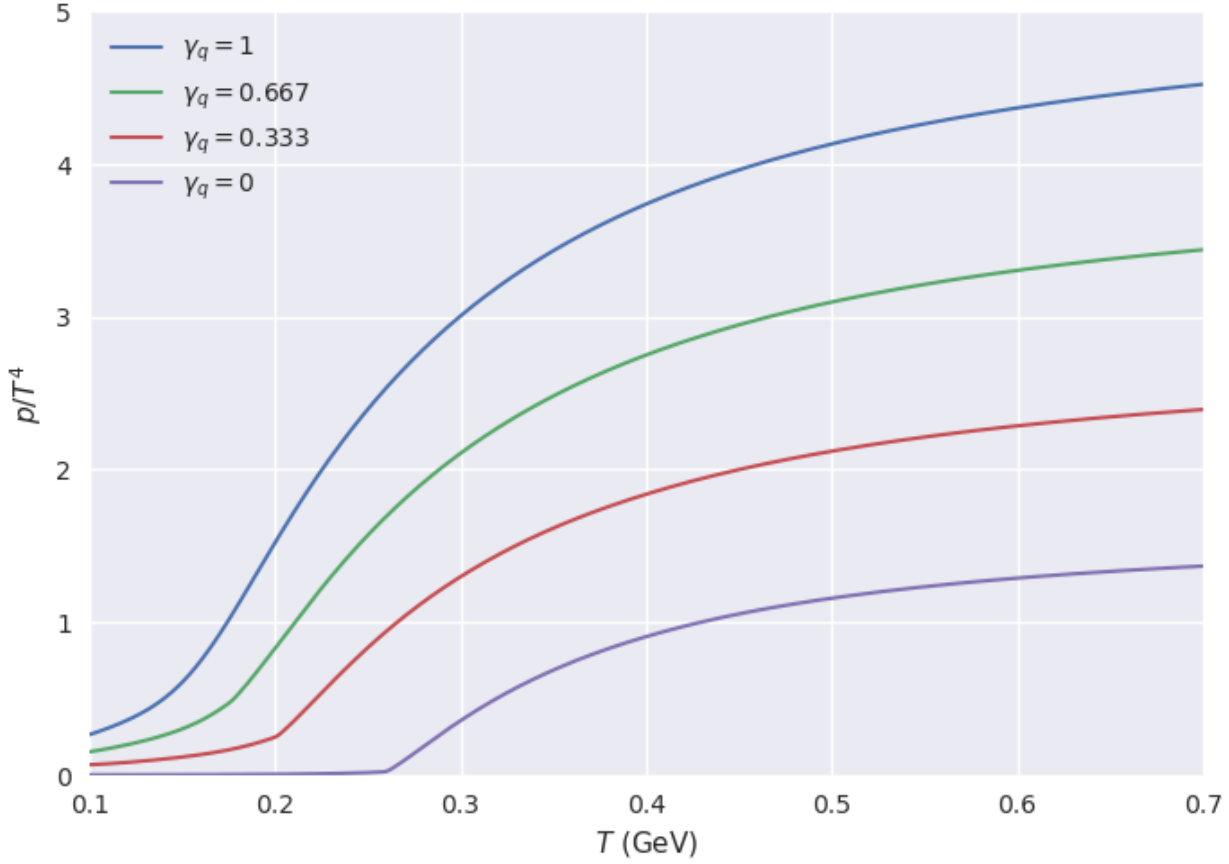
$$f_i = \frac{1}{\lambda_i^{-1} e^{Ep/T} \pm 1}$$

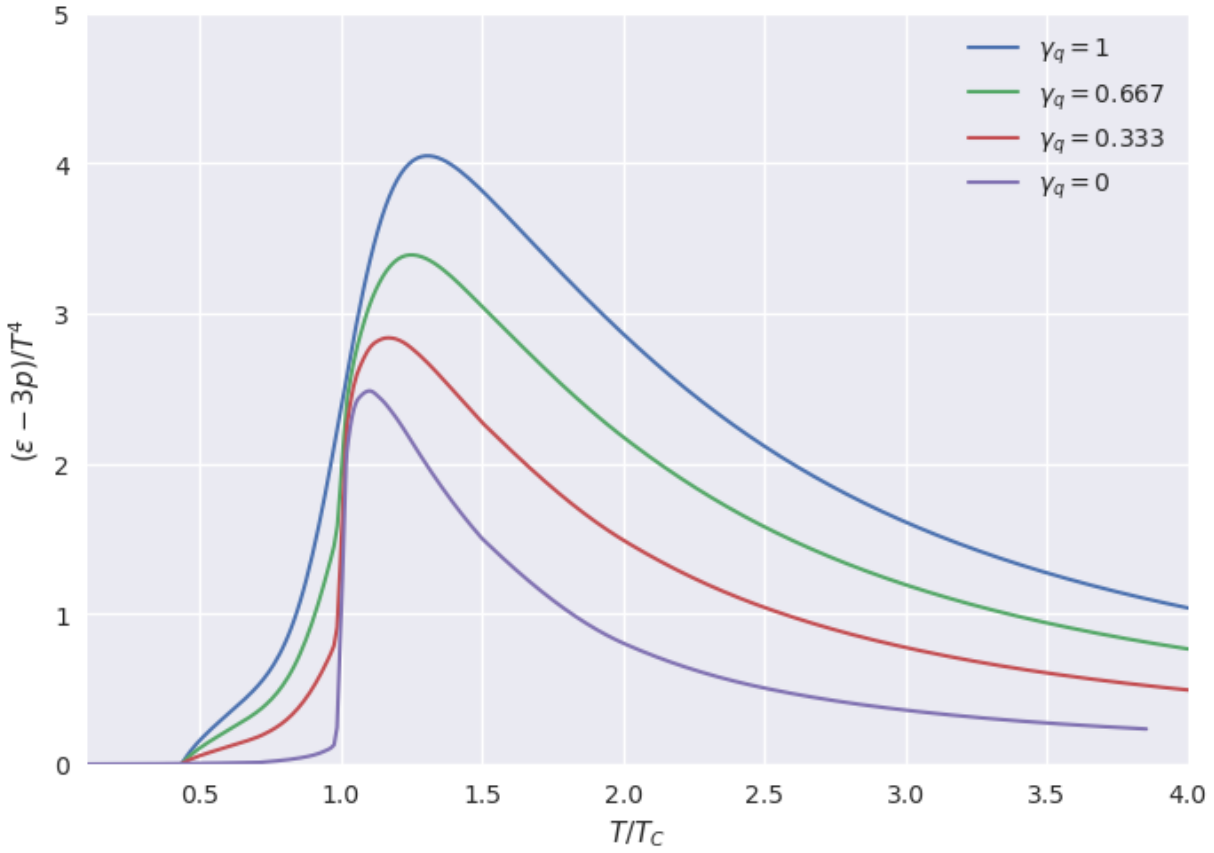
- Assuming all flavors equilibrate simultaneously, we find the best HRG-lattice matching with:

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

Partial Chemical Equilibrium Equation of State

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





Particlization

- Energy conserved at the particlization hypersurface by the Cooper-Frye formula:

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

- Same modified distributions as HRG:

$$f_i = \frac{1}{\lambda_i^{-1} e^{Ep/T} \pm 1}$$

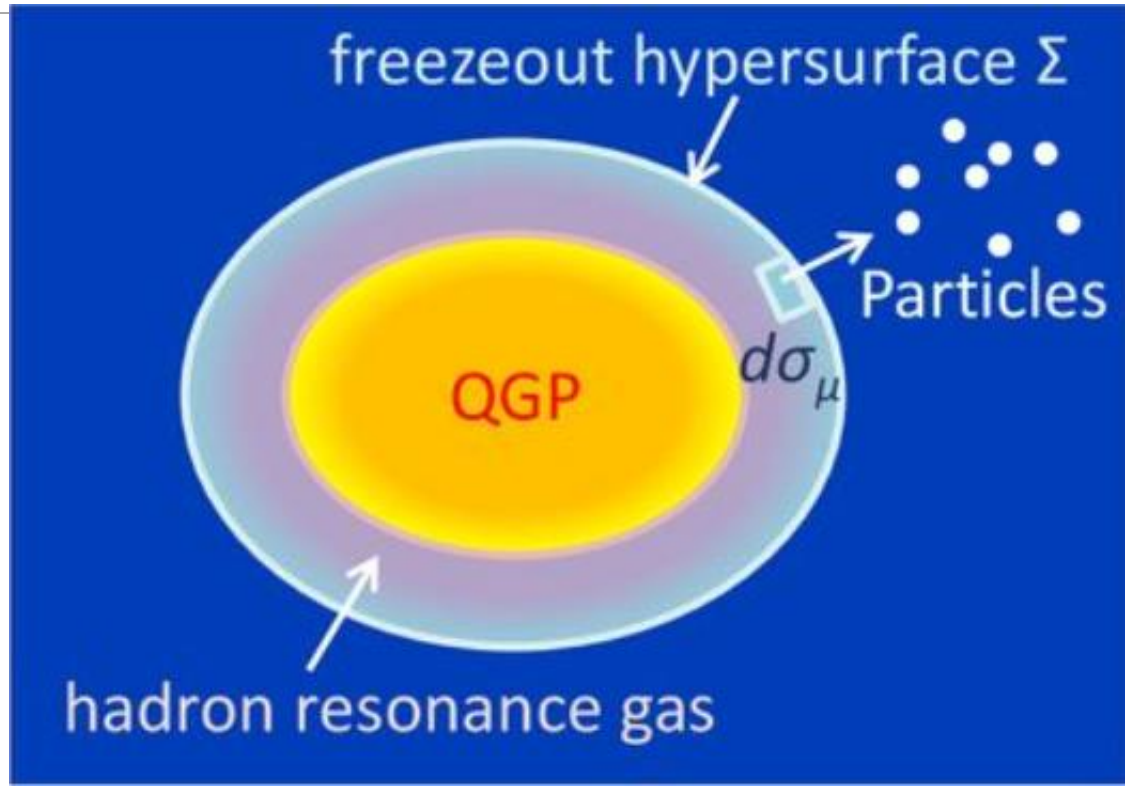


Figure by Akihiko Monnai

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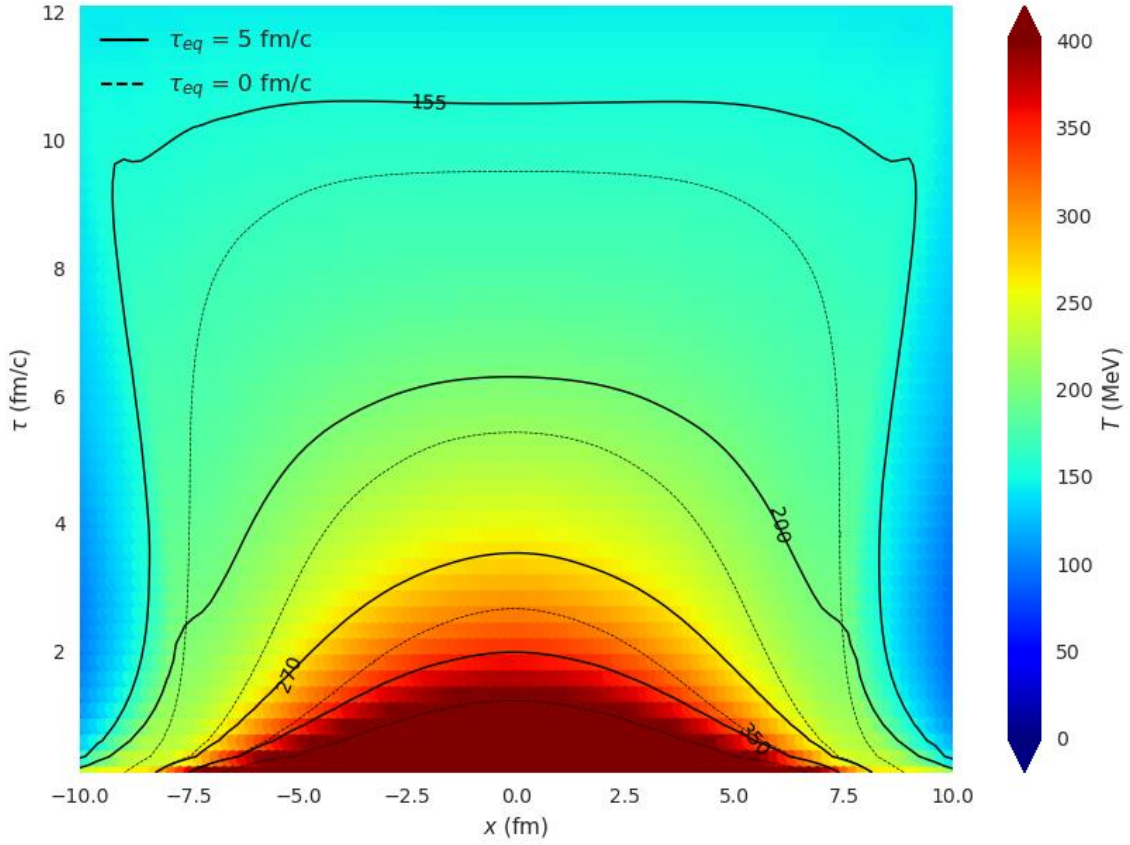
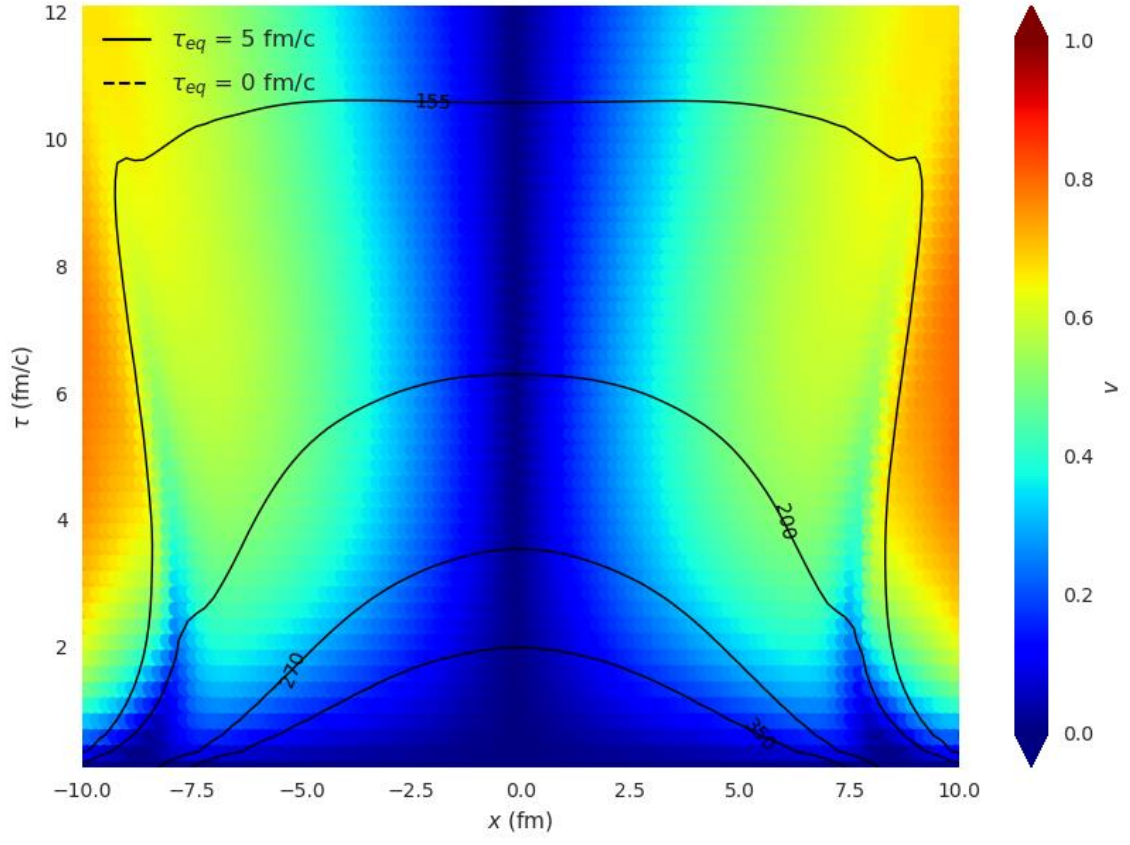
Preliminary Results: Temperature and Velocity

- Averaged 0-20% central 2.76 TeV Pb+Pb events :

Temperature

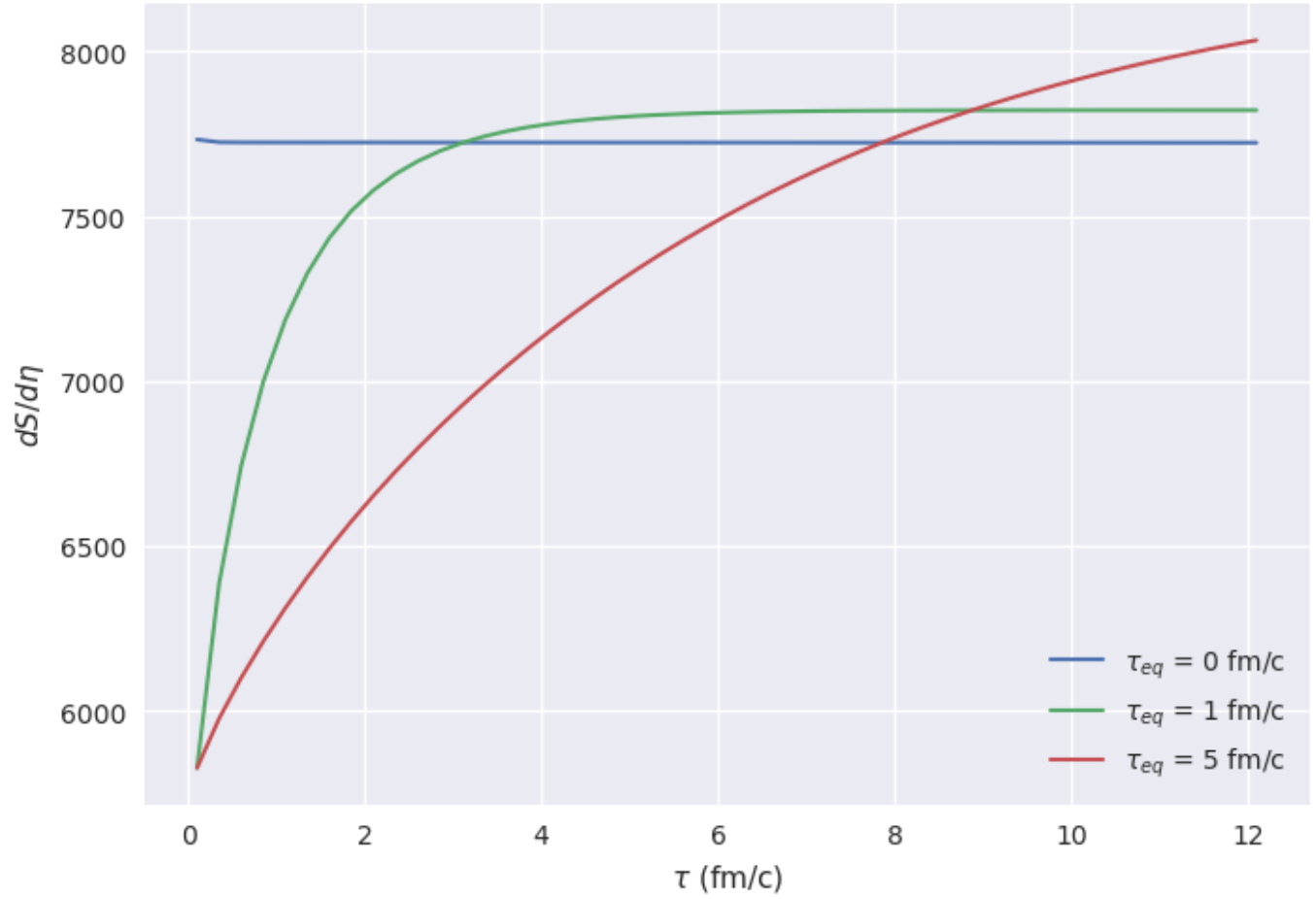


Velocity

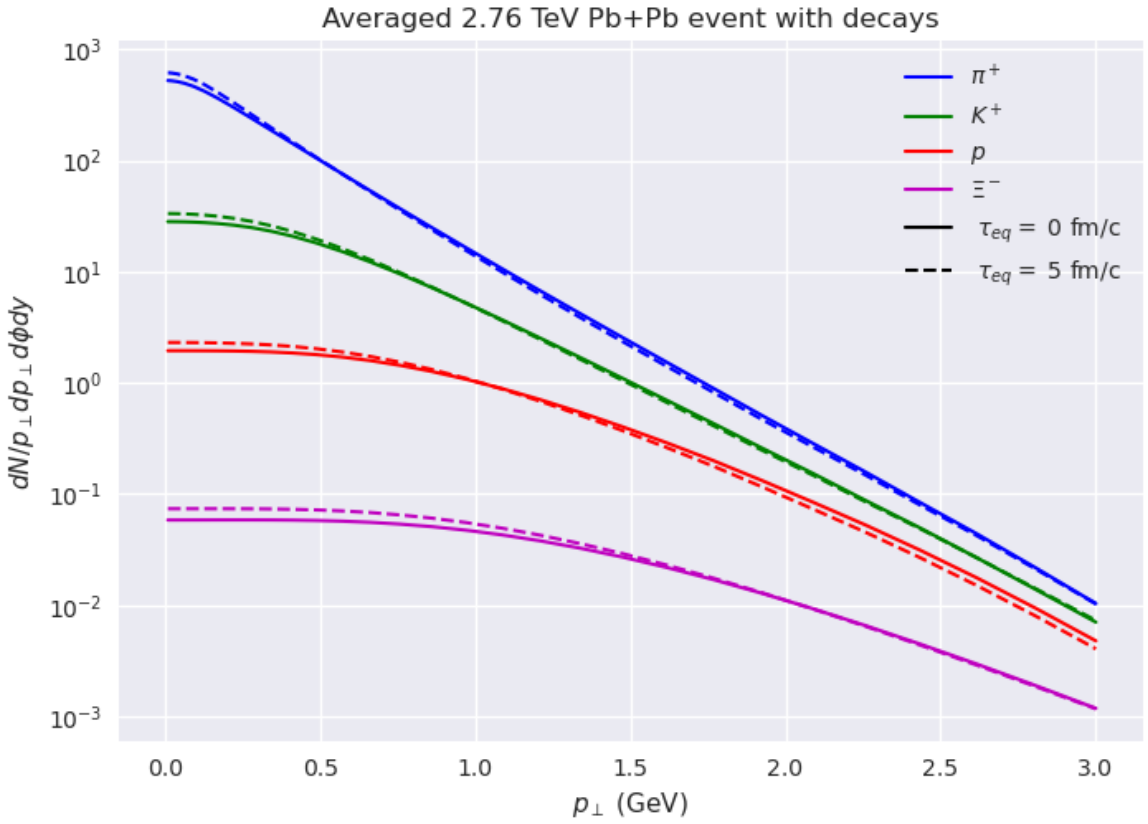


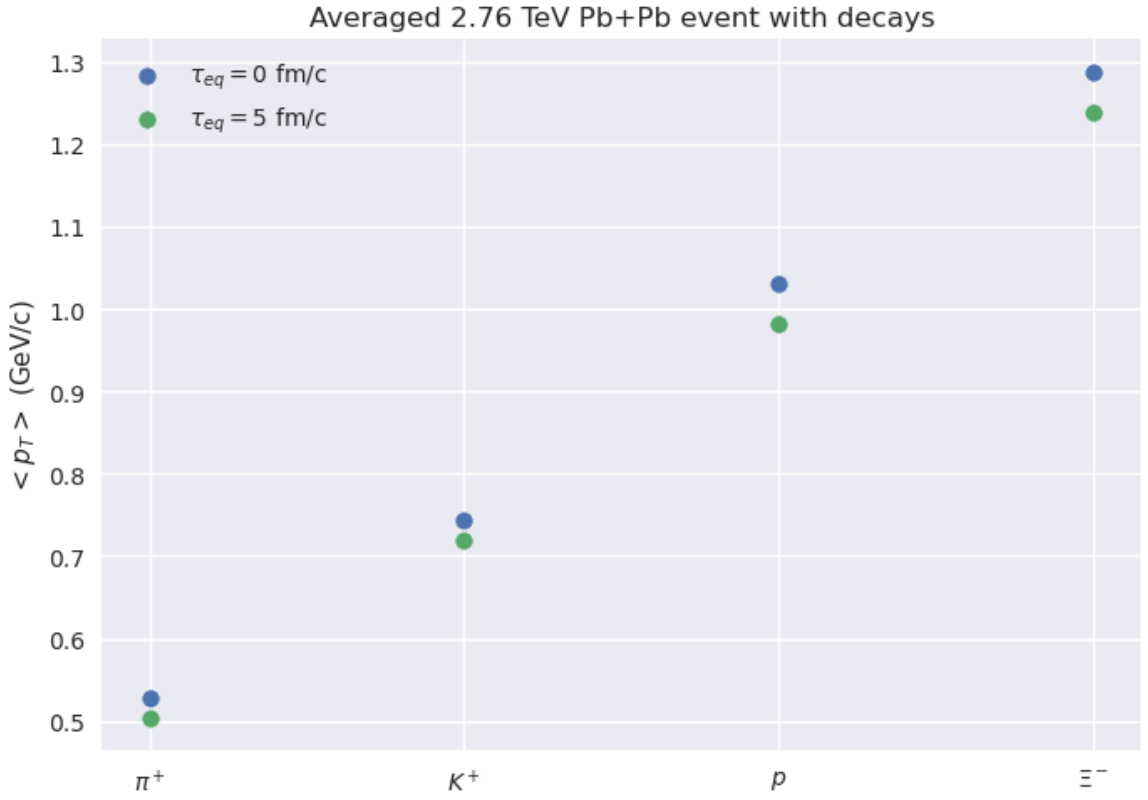
Preliminary Results: Entropy Production

- Averaged 0-20% central 2.76 TeV Pb+Pb events :



Preliminary Results: Hadron p_T Spectra





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Summary

- Hydrodynamic models need to somehow account for non-equilibrium effects of the initial stages of a collision
- We model quark chemical equilibration in the QGP phase by incorporating gluon saturation into the choice of equation of state
- This model is consistent with prior studies of equilibration and shows a modest effect on hadronic observables

Future Directions

- Short term:
  - Study of flavor equilibration: separate light and strange quark equilibration by rewriting $\gamma_q = 2\gamma_l/3 + \gamma_s/3$ with different light/strange equilibration times
  - Study of 200 GeV Au-Au collisions - less time to equilibrate!

- Long term:
  - Model effects of equilibration on viscosity
  - With a complete event generator, apply Bayesian analysis to constrain equilibration times with experimental data