Fast chemical equilibration via Hagedorn states in heavy ion collisions

Igor Shovkovy

Department of Applied Sciences & Mathematics

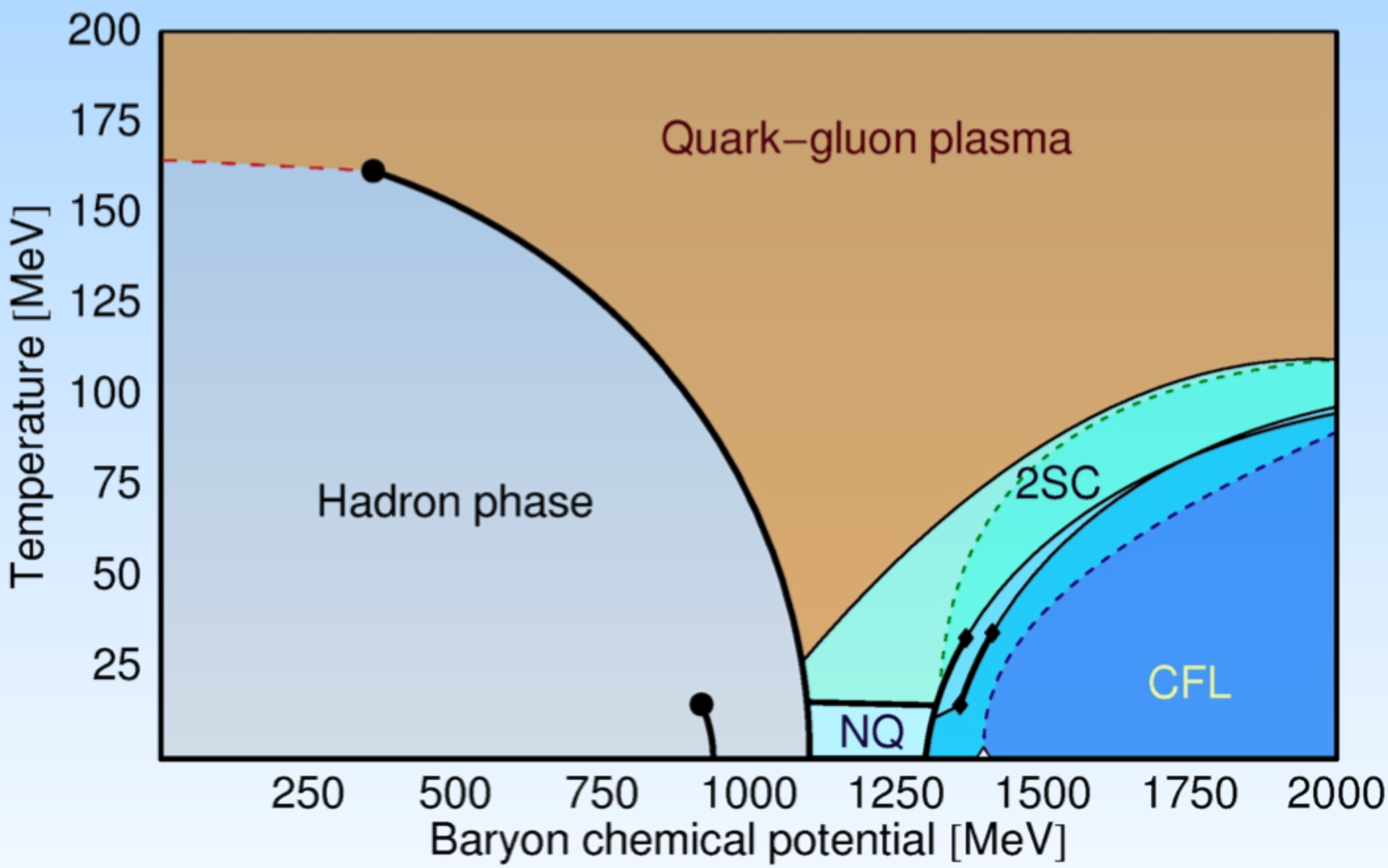
Arizona State University

ASU

Symposium on Contemporary Subatomic Physics (JoeFest)
Montreal, Canada, June 12-14, 2012

Phase diagram (1)

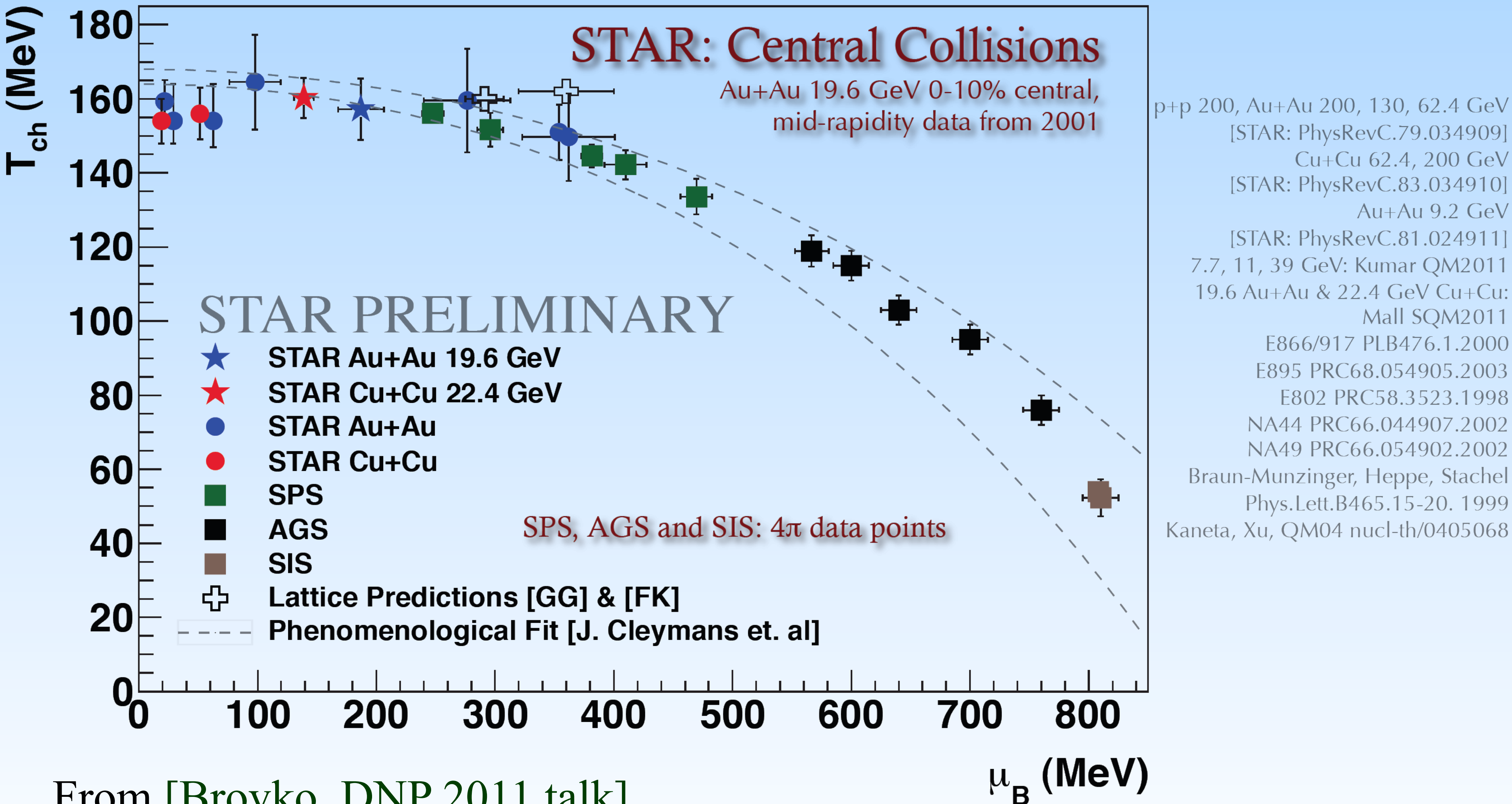
as theoreticians imagine it…



Adapted from [Rüster et al., Phys. Rev. D 72, 034004 (2005)]

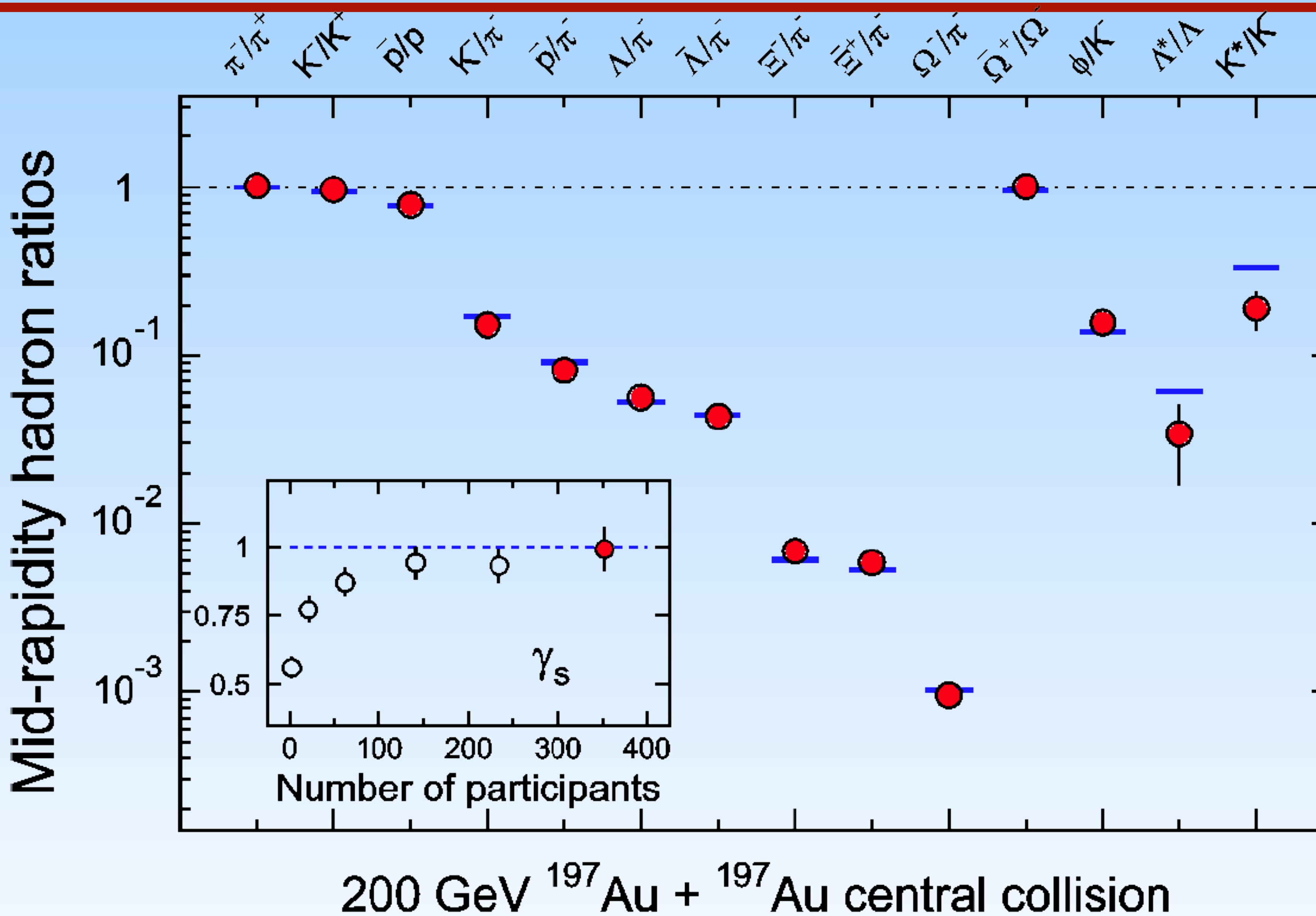
Phase diagram (2)

as RHIC physicists get to know it…



From [Brovko, DNP 2011 talk]

Simple observation



From [STAR Collaboration, Nucl. Phys. **A 757**, 102 (2005)]

Big puzzle

- What is the mechanism of chemical equilibration in heavy ion collisions?
- Rates of hadronic processes are too slow…
- The problem is further amplified for strangeness
- Some suggestions
  - "born into equilibrium" (?)
  - unknown "collective effects" (?)
  - multi-particle interactions (?)
  - or a new incarnation of an old idea…

Hadron gas?

- Two-body reactions $\left(\text{e.g., } \pi\pi \leftrightarrow B\overline{B}\right)$ are not sufficient

  [Koch, Muller, Rafelski, Phys. Rev. **142**, 167 (1986)]

- Multi-particle reactions $\left(\text{e.g., } \pi\pi\pi K\overline{K} \leftrightarrow B\overline{B}\right)$ become important

  [Rapp and Shuryak, Phys. Rev. Lett. 86, 2980 (2001)]

  [Greiner and Leupold, J. Phys. G 27, L95 (2001)]

yielding equilibration times ~ 1-3 fm/c at SPS

$$\sigma \approx 50 \text{ mb}, \quad n_B^{eq} \approx \rho_0 \quad \Rightarrow \quad \tau \approx 1-3 \text{ fm/c}$$

How about RHIC?

- Two-particle annihilation rate

$$\Gamma \approx \langle \sigma v \rangle n_{\bar{B}}$$

Naively, one has

$$\sigma \approx 30 \text{ mb}, \;\; n_B^{eq} = n_{\bar{B}}^{eq} \approx 0.04 \text{ fm}^{-3} \;\; \Rightarrow \tau_\Omega \geq 10 \text{ fm/c}$$

which is about 10 fm/c at RIHC

How about multi-particle processes?

Equilibration times with Joe

- Baryon production rates, e.g.,
  [Kapusta & Shovkovy, PRC **68**, 014901 (2003)]

$$r(n\bar{p}) = 2r_+(m_N, m_N) + 2r_-(m_N, m_N)$$

$$r(p\bar{p}) = 2r_+(m_N, m_N) + \frac{82}{81} r_-(m_N, m_N)$$

$$r(\Lambda\bar{p}) = 3r_+(m_\Lambda, m_N) + \frac{25}{27} r_-(m_\Lambda, m_N)$$

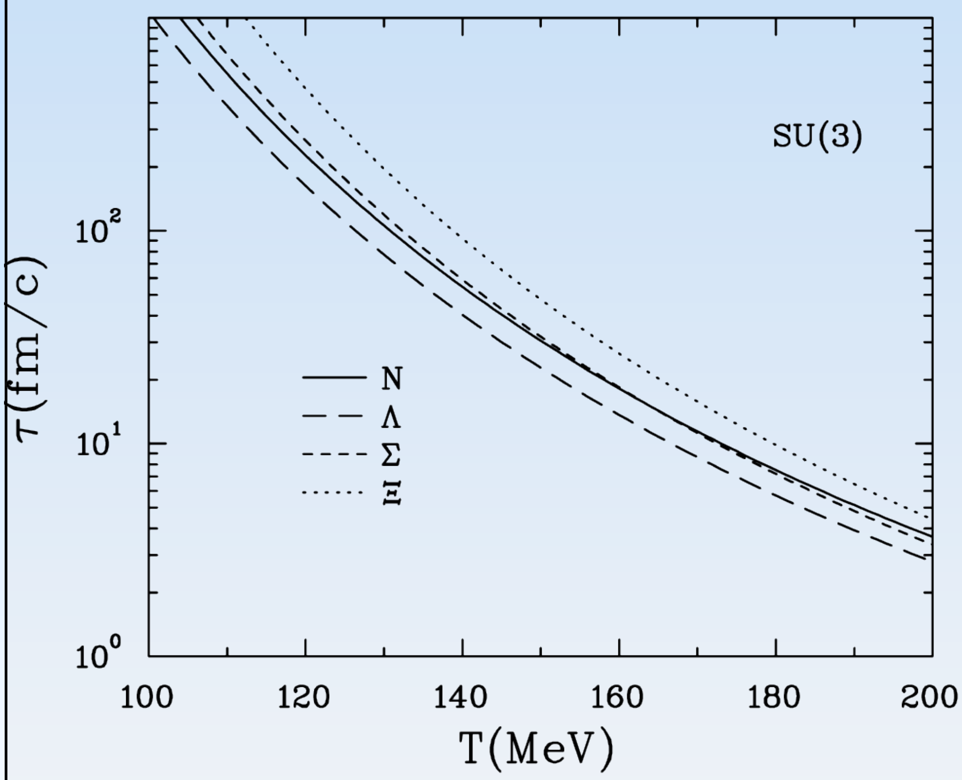
$$r(\Xi\bar{\Lambda}) = 3r_+(m_\Lambda, m\Xi) + \frac{1}{27} r_-(m_\Lambda, m_\Xi)$$

$$r_\pm(m_1, m_2) = \frac{2}{(4\pi)^7} \frac{F^2_{\mathrm{ANN}}(s)}{e^{\beta(E_1+E_2)} - 1} \frac{2s^2 - (m_1^2 + m_2^2)s - (m_1^2 - m_2^2)^2 \pm 6m_1 m_2 s}{f_\pi^4} \left(1 + \frac{\alpha_s}{\pi}\right)$$

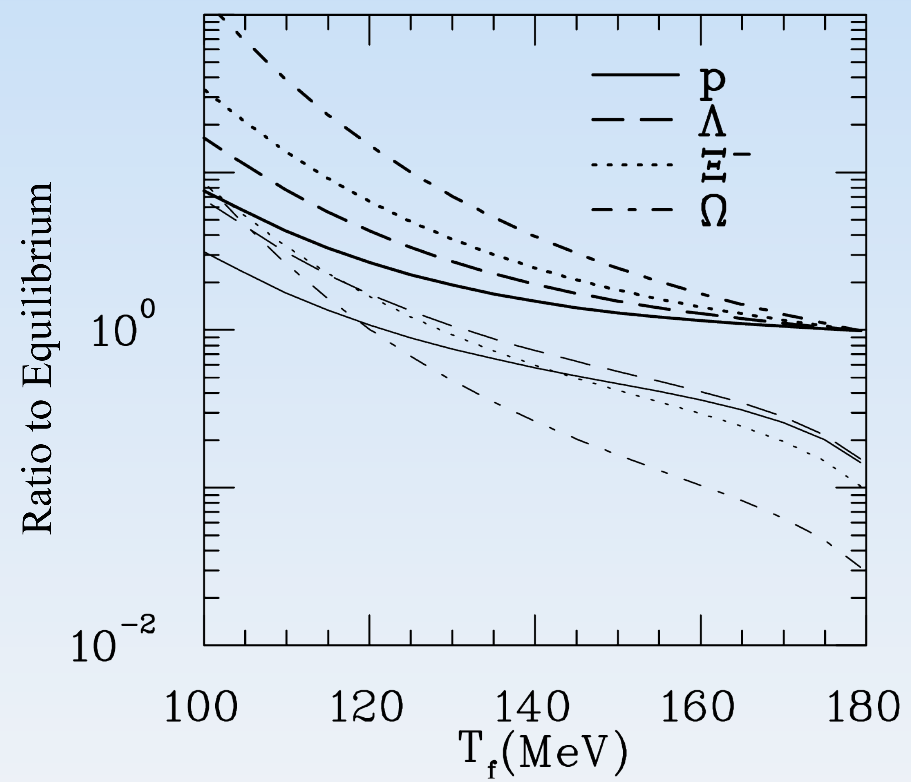
Results

- Using fluctuation-dissipation theorem, obtain rates of baryon production

Kapusta & Shovkovy, Phys. Rev. C **68**, 014901 (2003)

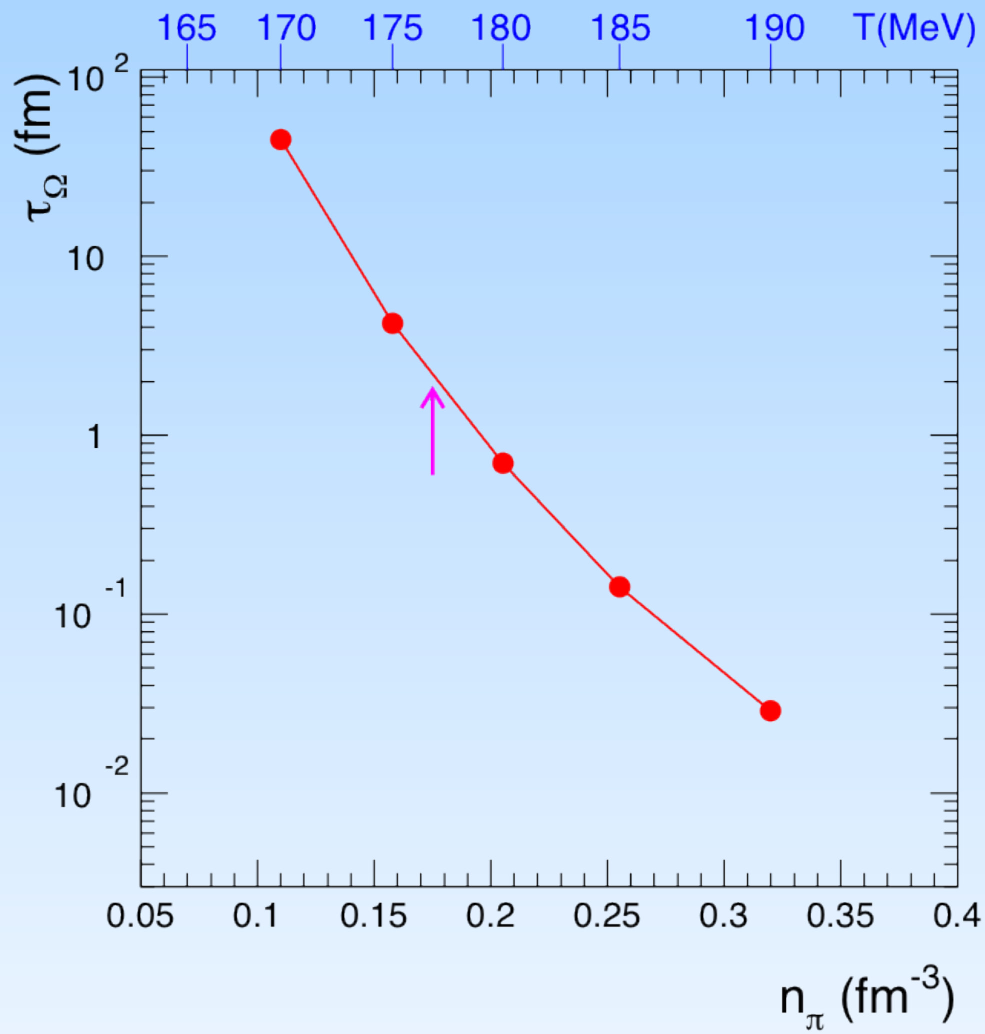


Huovinen & Kapusta, Phys. Rev. C **69**, 014902 (2004)



Multi-particle collisions

- Intuition based argument:
  [Braun-Munzinger, Stachel, Wetterich, Phys. Lett. **B 596**, 61 (2004)]
  - Large energy density near T_c
  - Overpopulation of pions/kaons
  - Multi-particle rates overwhelm
  - Equilibration is reached



…, but there is a one LITTLE problem:

one is left with an overpopulation of (anti-)baryons

What if …

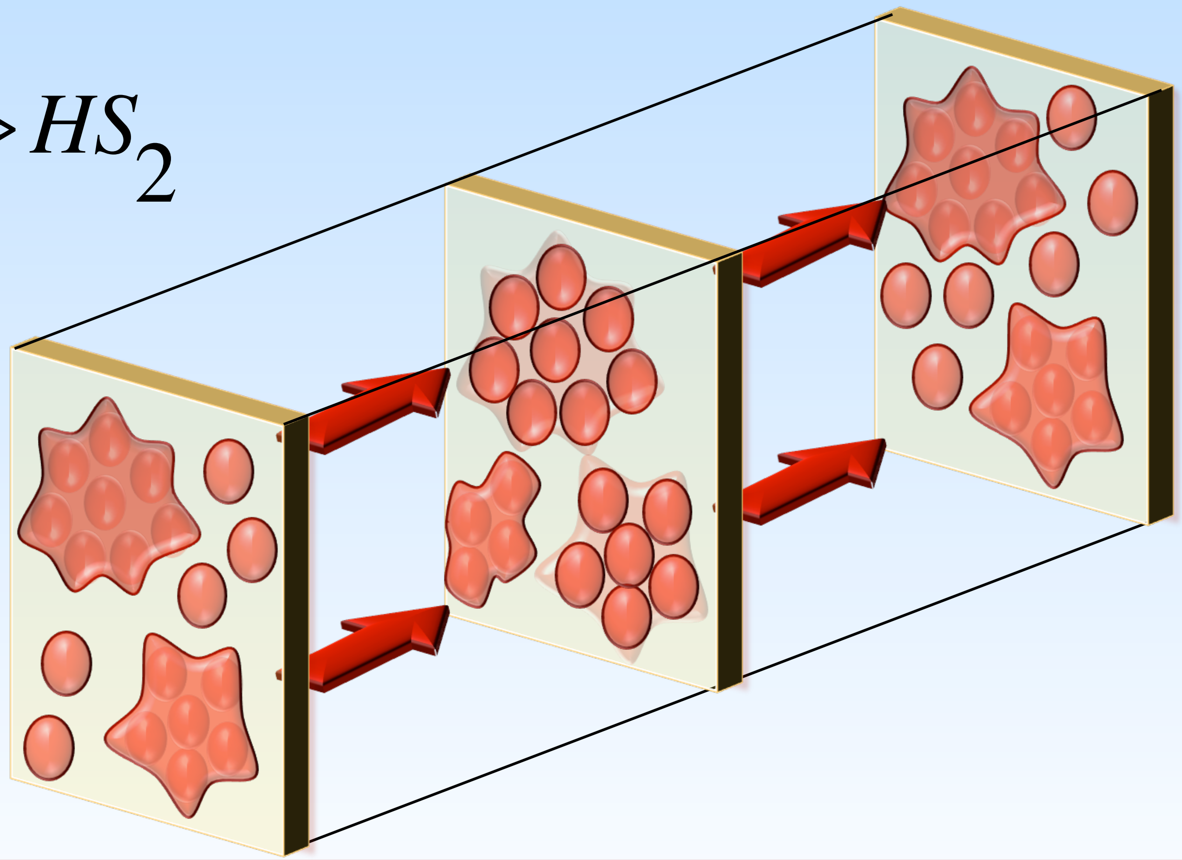
there were Hagedorn states in the spectrum?

[Greiner et al., J. Phys. **G 31**, S725 (2005)]

[Noronha-Hostler et al., Phys. Rev. Lett. **100**, 252301 (2008)]

[Noronha-Hostler et al., Phys. Rev. C **81**, 054909 (2010)]

$$HS_1 \Rightarrow n\pi + B\overline{B} \Rightarrow HS_2$$



Rough estimate…

$$M_{HS} = 3 - 6 \text{ GeV}$$

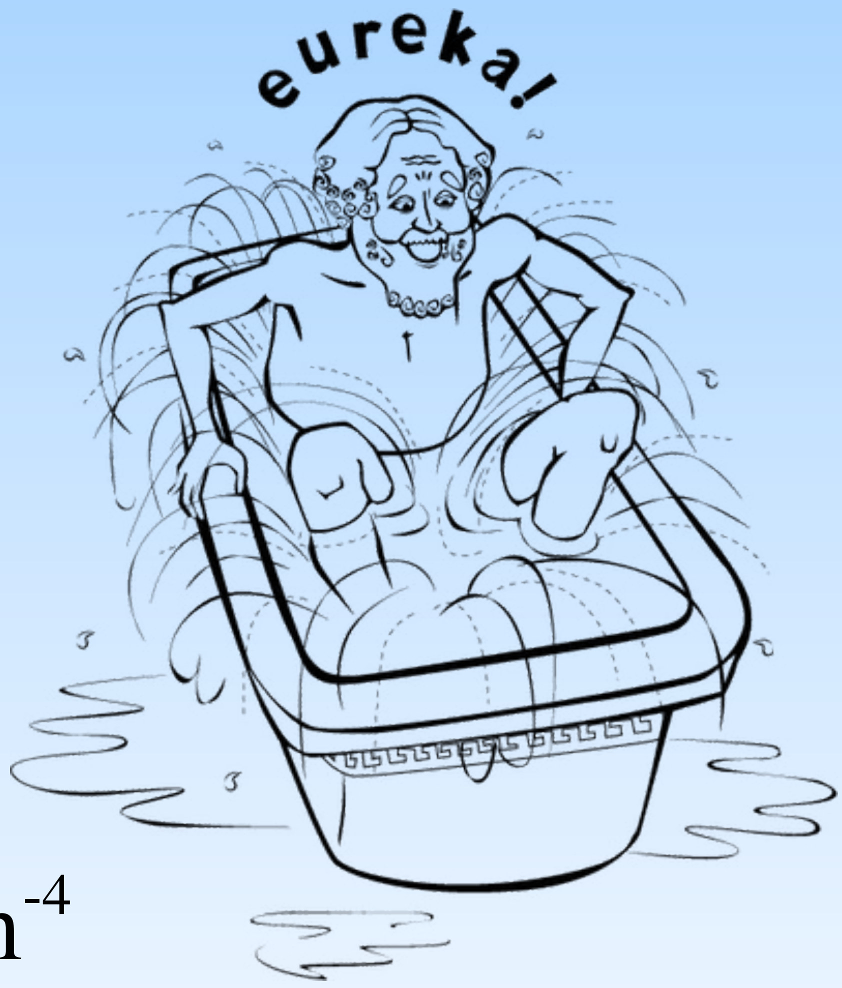
$$n_{HS} = 0.05 - 0.15 \text{ fm}^{-3}$$

$$\Gamma_{HS}^{tot} \approx 0.5 - 1 \text{ GeV}$$

$$\Gamma_{B\bar{B}X} \approx 100 - 300 \text{ MeV}$$

$$\Gamma_{B\bar{B}}^{prod} \approx n_{HS}\Gamma_{\bar{B}BX} \approx 0.05 \text{ fm}^{-4}$$

$$\tau_{B\bar{B}} \approx 1 \text{ fm/c}$$



Detailed model

- Hagedorn mass spectrum:

$$\rho = \int_{M_0}^{M} F(m) e^{\frac{m}{T_H}} \mathrm{dm}, \quad \text{where} \quad F(m) = \frac{A}{\left(m^2 + m_r^2\right)^{5/4}}$$

$m_r = 0.5$ GeV

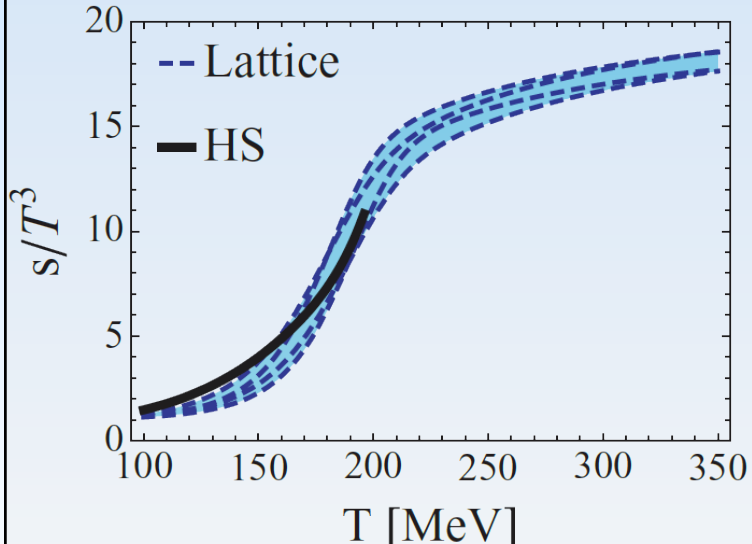
$M_0 = 2$ GeV

$M = 12$ GeV

Cf. lattice [RBC-Bielefeld]

$T_H = 196$ MeV

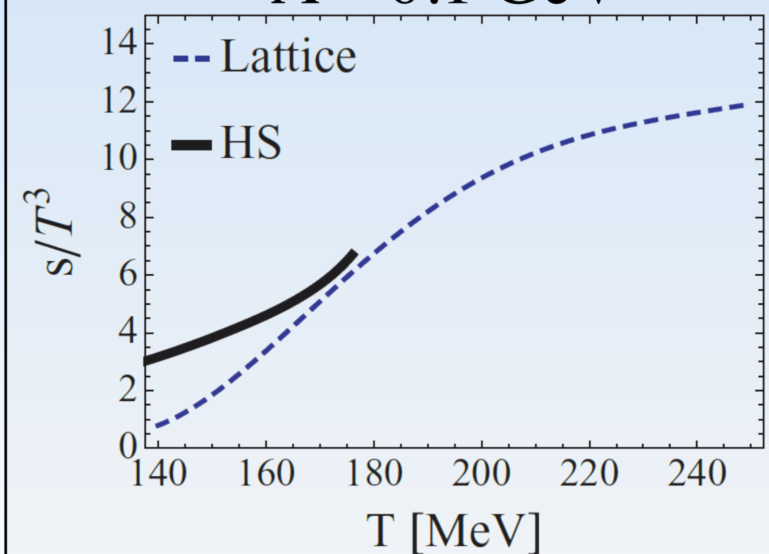
$A = 0.5 \text{ GeV}^{3/2}$



Cf. lattice [Aoki et al.]

$T_H = 176$ MeV

$A = 0.1 \text{ GeV}^{3/2}$



Master equations

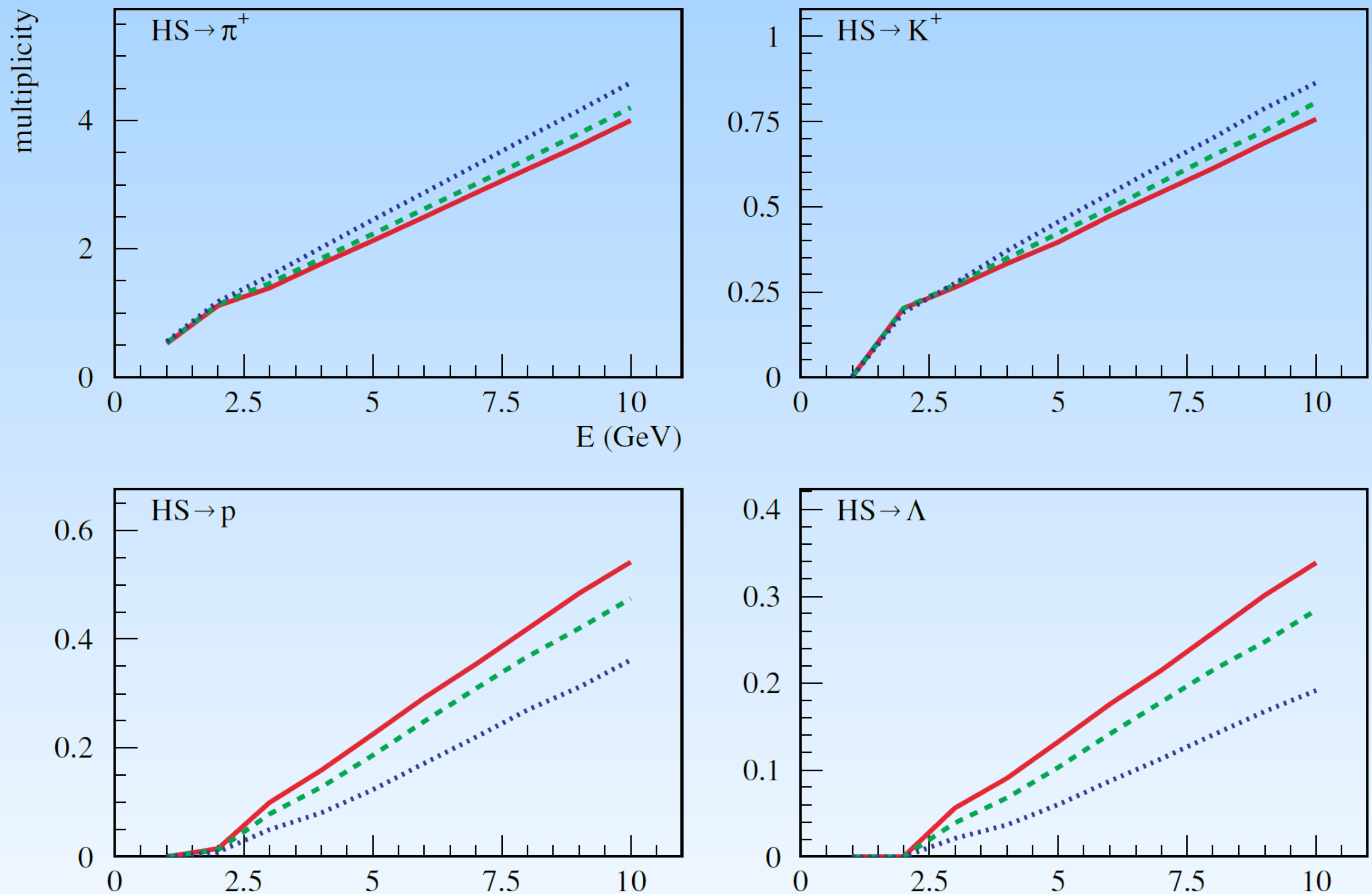
- Processes $n\pi \leftrightarrow HS \leftrightarrow n'\pi + X\,\overline{X}$
- Schematically $\frac{dN}{dt} = -"loss" + "gain"$

$$\frac{dN_{R(i)}}{dt} = -\Gamma_i N_{R(i)} + \sum_n \Gamma_{i,\pi} N_{R(i)}^{eq} \left(\frac{N_\pi}{N_\pi^{eq}}\right)^n B_{i\to n\pi} + \Gamma_{i,B\overline{B}} \frac{N_{R(i)}^{eq}}{\left(N_{B\overline{B}}^{eq}\right)^2} \left(\frac{N_\pi}{N_\pi^{eq}}\right)^{\langle n\rangle} \left(N_{B\overline{B}}\right)^2$$

$$\frac{dN_\pi}{dt} = \sum_i \sum_n \Gamma_{i,\pi} n B_{i\to n\pi} \left(N_{R(i)} - N_{R(i)}^{eq} \left(\frac{N_\pi}{N_\pi^{eq}}\right)^n \right) + \sum_i \Gamma_{i,B\overline{B}} \langle n\rangle \left(N_{R(i)} - \frac{N_{R(i)}^{eq}}{\left(N_{B\overline{B}}^{eq}\right)^2} \left(\frac{N_\pi}{N_\pi^{eq}}\right)^{\langle n\rangle} \left(N_{B\overline{B}}\right)^2 \right)$$

$$\frac{dN_{B\overline{B}}}{dt} = \sum_i \Gamma_{i,B\overline{B}} \langle n\rangle \left(\frac{N_{R(i)}^{eq}}{\left(N_{B\overline{B}}^{eq}\right)^2} \left(\frac{N_\pi}{N_\pi^{eq}}\right)^{\langle n\rangle} \left(N_{B\overline{B}}\right)^2 - N_{R(i)} \right)$$

Microcanonical decays of HS



Calculation of Fuming Liu [Greiner et al., J. Phys. **G 31**, S725 (2005)]

Model parameters (1)

- Mass range of Hagedorn states: 2 - 12 GeV
- Branching ratios
  - Gaussian distribution: $B_{i\to n\pi} \approx \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(n-\langle n\rangle)^2}{(2\sigma)^2}}$

$$\sigma_i = 0.5\frac{m_i}{m_p} \approx 0.9 - 22,$$

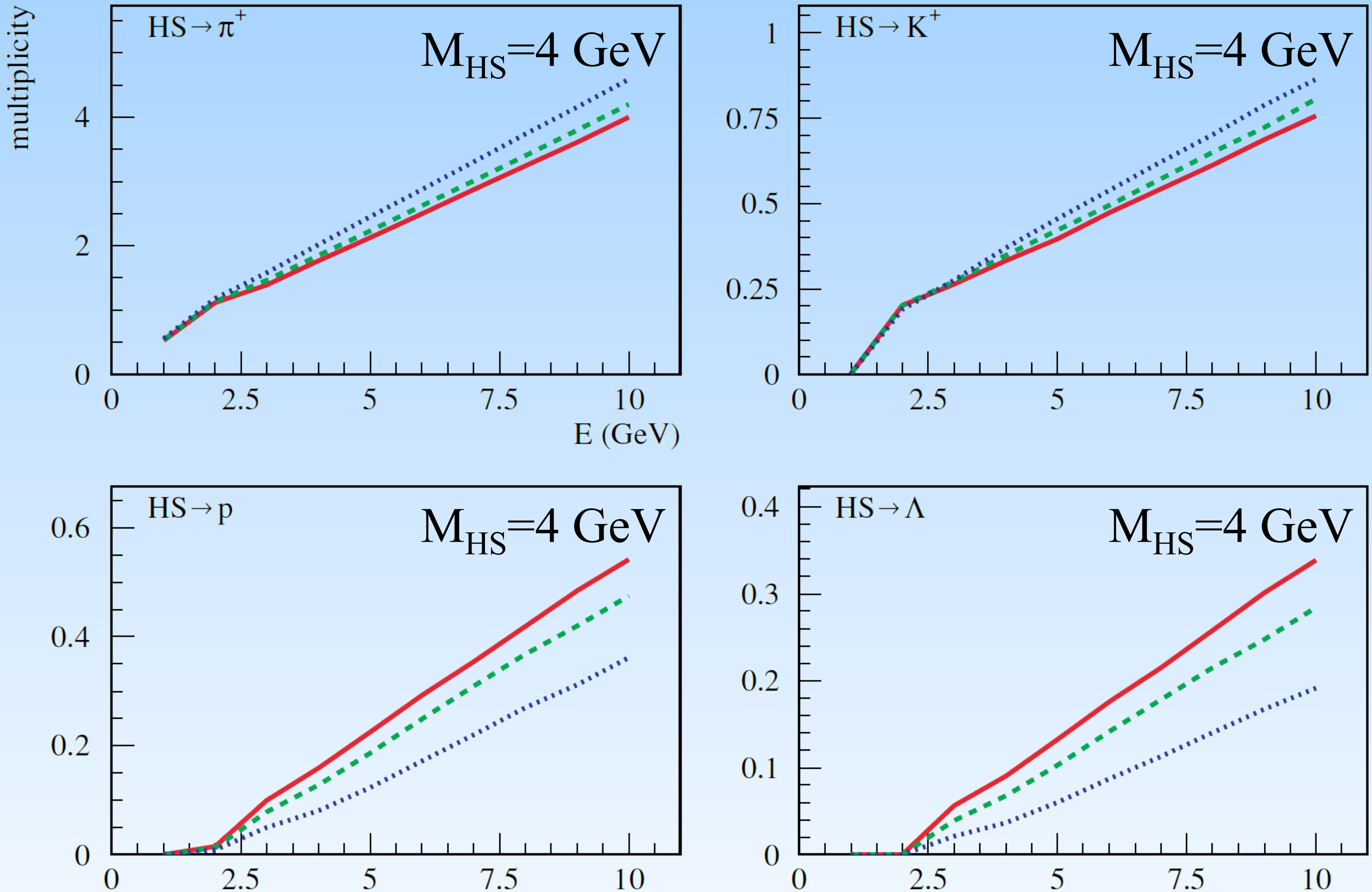
$$HS \leftrightarrow n\pi : \qquad \langle n_i\rangle = 0.9 + 1.2\frac{m_i}{m_p} \approx 3 - 34$$

$$\mathrm{HS} \leftrightarrow n\pi + X\overline{X} : \ \langle n_{i,x}\rangle = \frac{2.7}{1.9}\left(0.9 + 0.37\frac{m_i}{m_p}\right) \approx 2 - 7$$

- Decay widths

$$\Gamma_i = \Gamma_{i,\pi} + \Gamma_{i,X\overline{X}} = 0.15\, m_i - 27\ \mathrm{MeV} \approx 250 - 1800\ \mathrm{MeV}$$

Microcanonical decays of HS



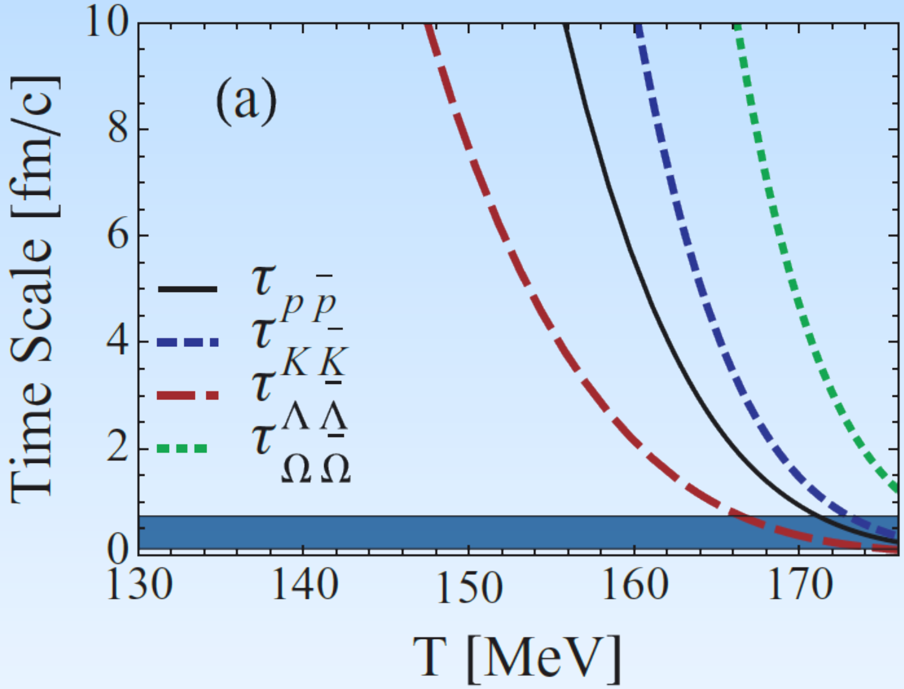
Calculation of Fuming Liu [Greiner et al., J. Phys. **G 31**, S725 (2005)]

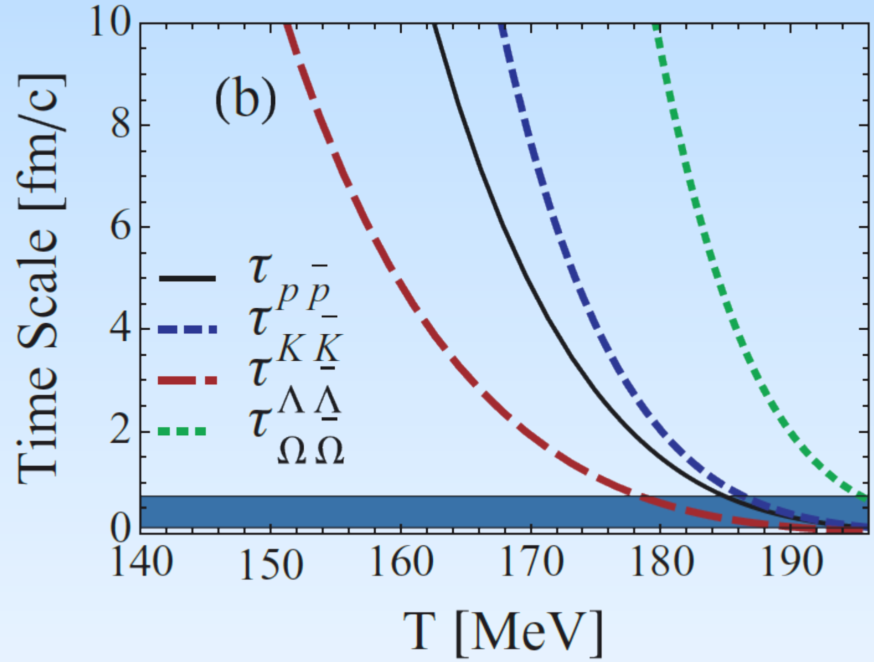
Model parameters (2)

- Protons $\Gamma_{i,p\bar{p}} = 3 - 1000\ \text{MeV}$
- Kaons $\Gamma_{i,K\bar{K}} = 50 - 1700\ \text{MeV}$
- Lambdas $\Gamma_{i,\Lambda\bar{\Lambda}} = 3 - 250\ \text{MeV}$
- Omegas $\Gamma_{i,\Omega\bar{\Omega}} = 0.01 - 4\ \text{MeV}$

Chemical equilibration time

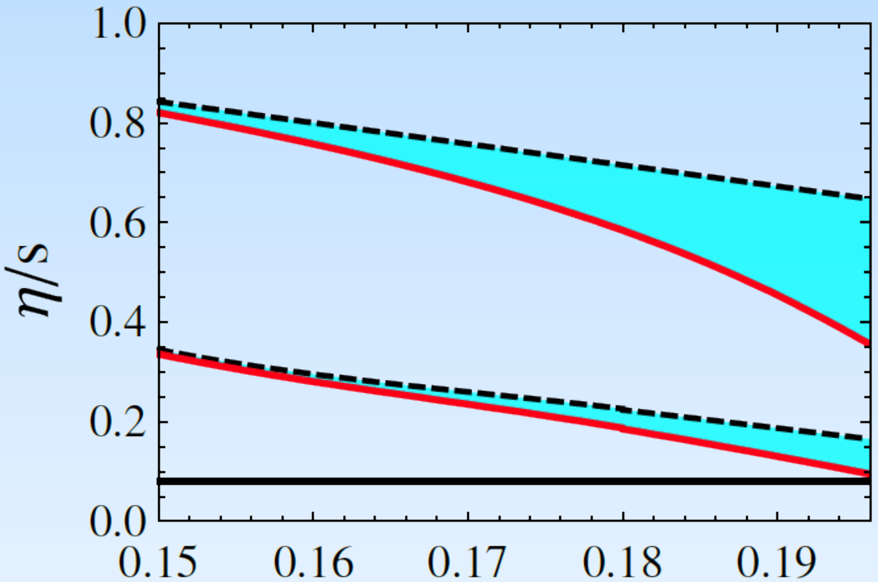
- T_H=176 MeV
- T_H=196 MeV

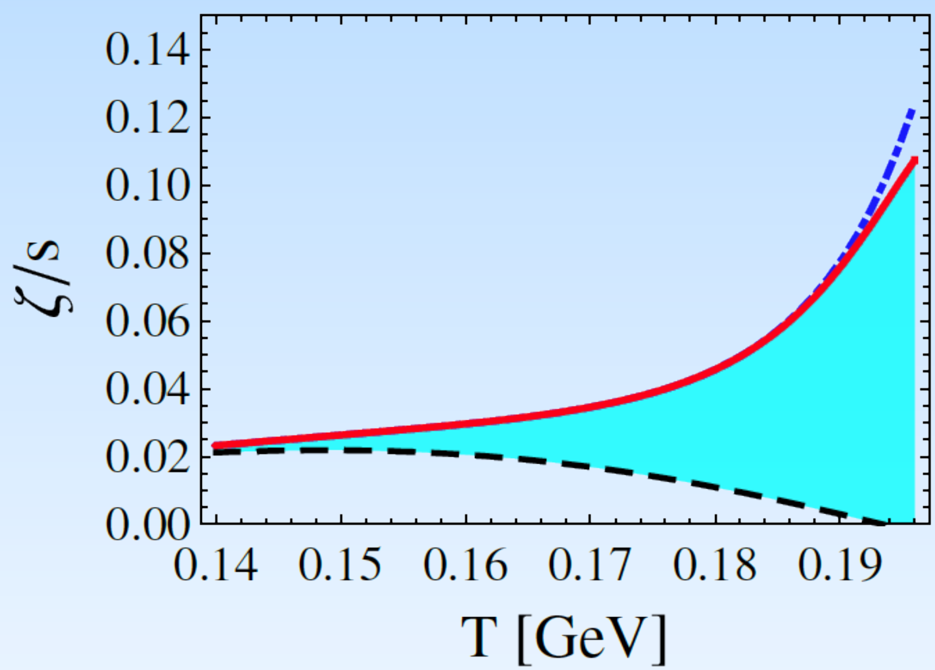




Extra bonus

- Hagedorn states also affect viscosity





[Noronha-Hostler, Noronha, Greiner, Phys. Rev. Lett. **103**, 172302 (2009)]

Summary

- Collective behavior near critical temperature is important
- Chemical equilibration via Hagedorn states is a feasible mechanism
- Perhaps, there is no need for artificial "born in equilibrium" scenario
- Hagedorn states can drive viscosity low too
- Other implications (?)