Does the hadronic phase of relativistic nuclear collisions feature a hydrodynamic regime?

Based on: Ronald Scaria, Captain R. Singh and Raghunath Sahoo
arXiv:2208.14792 (2022)

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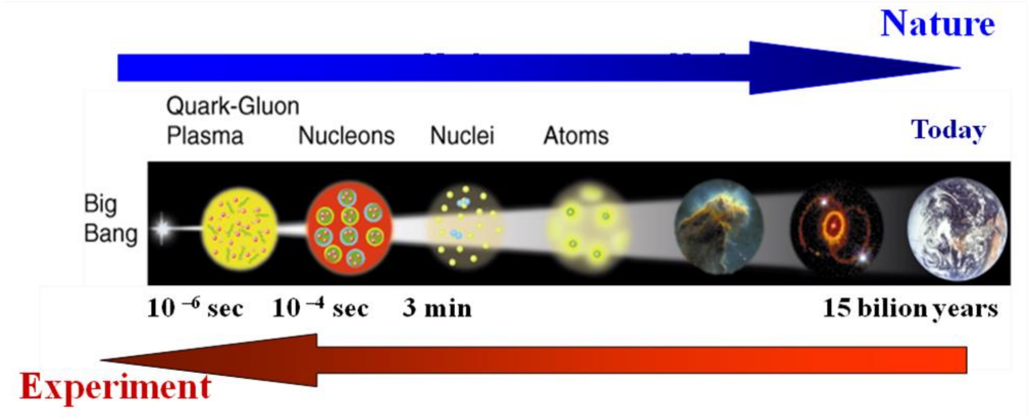
Outline

- Relativistic Heavy Ion Collisions
- Hadronic Phase and Resonances
- Hydrodynamics: The Hadronic Phase question
- Methodology
- Results
- Summary

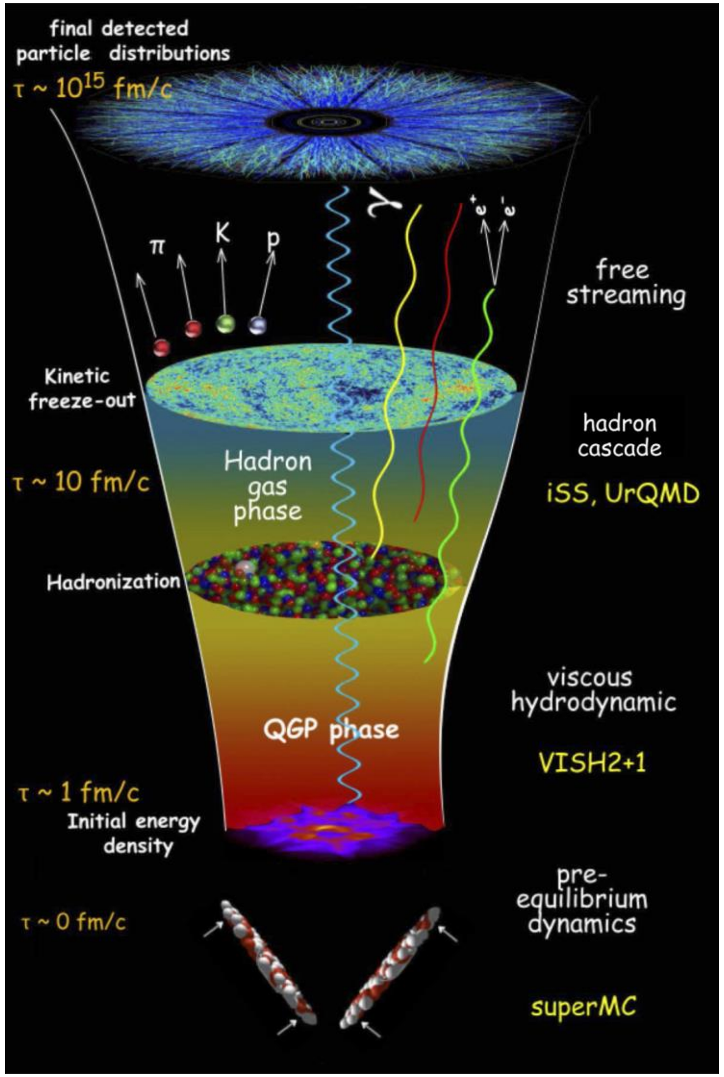
Relativistic Heavy Ion Collisions

- Pre-Equilibrium Phase
- Quark Gluon Plasma – Thermalized partons
- It is believed that QGP existed in the early universe a few microseconds after the big bang



- Chemical freeze out – Particle production stops
- Hadron Gas phase – Elastic interactions
- Kinetic freeze out – Momentum freeze out

[1] C. Shen et. al., Comput. Phys. Commun. 199, 61 (2016)
[2] R. Sahoo, and T. K. Nayak, Curr. Sci. 121, 1403 (2021)



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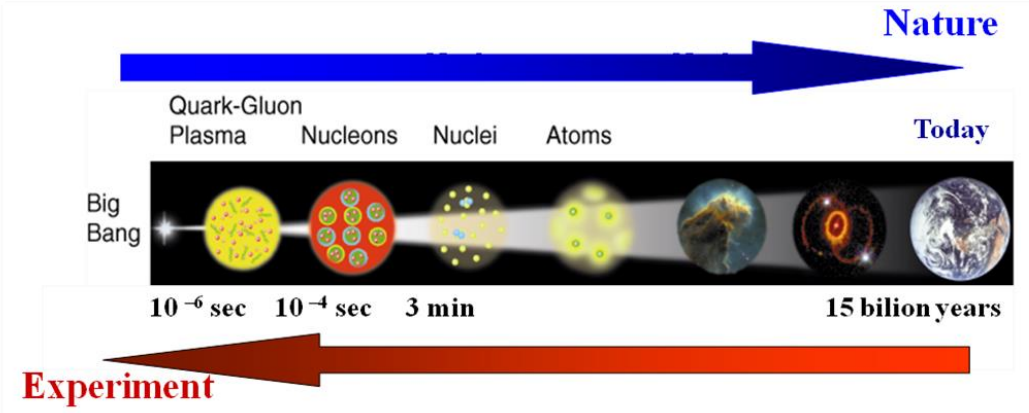

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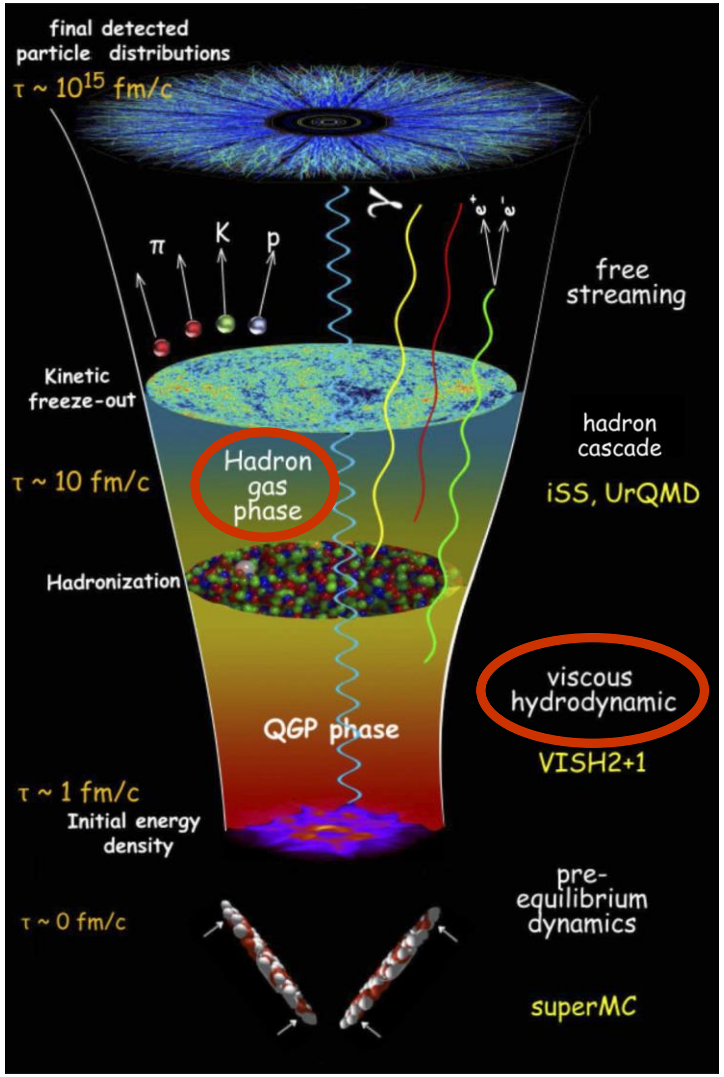

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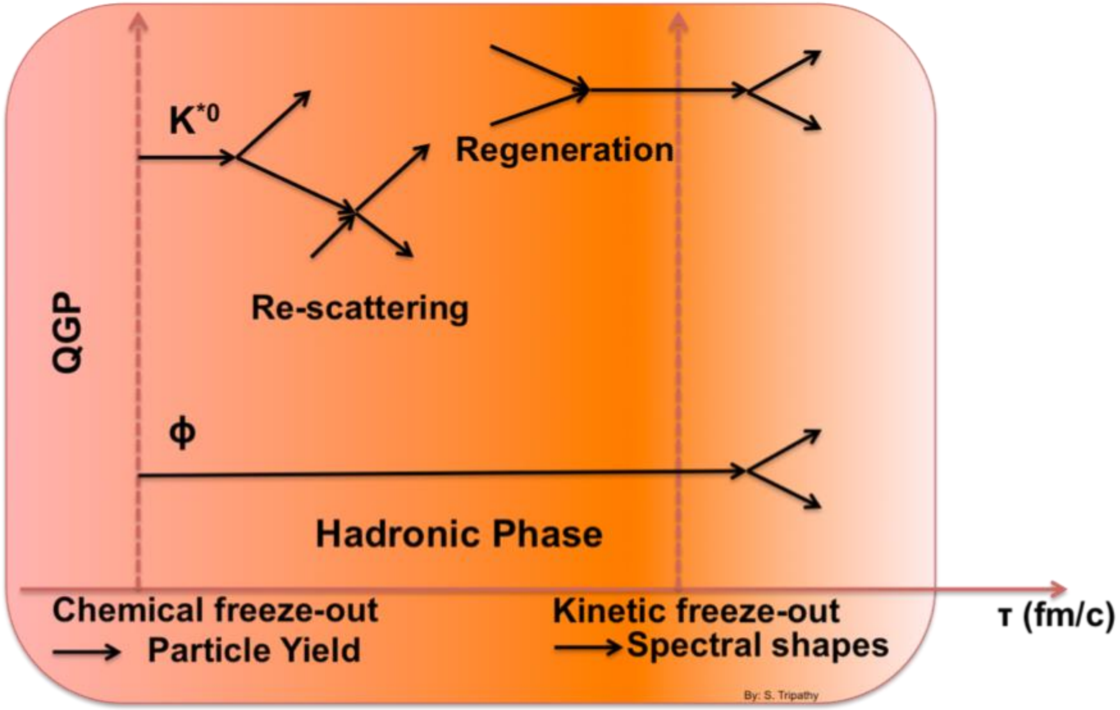
[2] R. Sahoo, and T. K. Nayak, Curr. Sci. 121, 1403 (2021)

Hadronic Phase and resonances

- Short-lived resonances are generally used to determine properties of the hadronic phase
- Resonance particles undergo re-scattering and regeneration within the hadronic phase, thus altering their initial yields
- The $\mathrm{K}^*(892)^0$ meson has a lifetime of 4.16 fm/c which is comparable with the hadronic phase lifetime
- A simple toy model may be used based on these particle yields to determine the hadronic phase lifetime

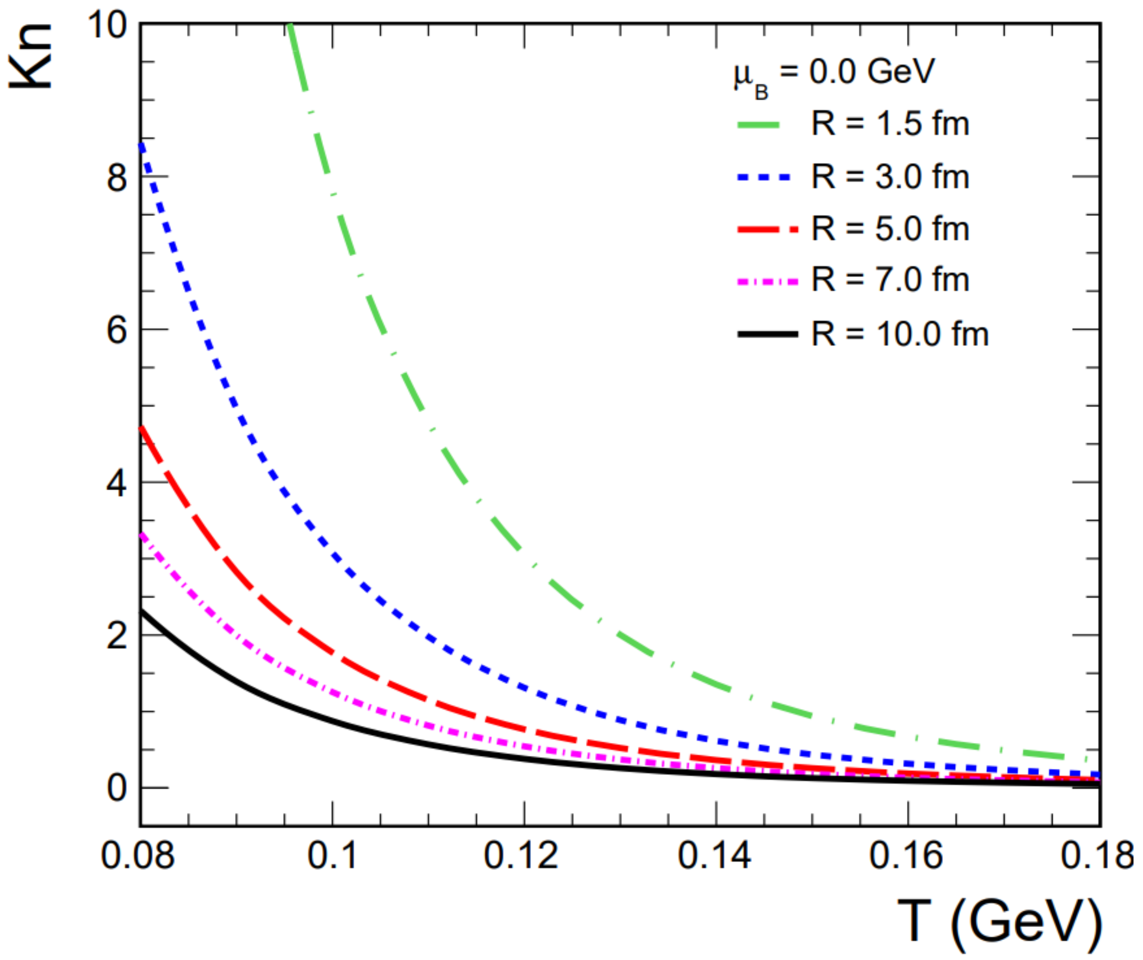
$$[K^*/K]_{kin} = [K^*/K]_{chemical}\ \exp(-\Delta\tau/\tau_l)$$



[1] D.Sahu et. al., Phys. Rev. C 101, 014902 (2020)

Hydrodynamics: The Hadronic Phase question

- Knudsen number can be used as a measure of the degree of thermalization in a medium over different system sizes
- Kn<<1: The system is thermalized, and hydrodynamics is applicable
- Kn = λ/L; λ is mean free path
- Kn decreases - the system becomes more thermalized
- Increase in number density decreases λ, which is reflected in Kn



[1] R. Scaria et.al, arXiv:2201.08096 (2022)

Temperature Evolution

- Initial yields of all hadrons with mass < 2.25 GeV is determined from the EVHRG model at critical temperature, $T_c = 0.156$ GeV
- **Massless case:**

$$\frac{dT}{d\tau} = -\frac{T}{3\tau} + \frac{\phi}{12aT^3\tau}$$

$$\frac{d\phi}{d\tau} = -\sigma b T^3 \phi - \frac{1}{2}\left(\frac{1}{\tau} - 5\frac{1}{T}\frac{dT}{d\tau}\right) + \frac{8aT^4}{9\tau}$$

$\phi = 0$ Perfect fluid (PF)

$\phi = \frac{4}{3}\frac{\eta}{\tau}$ First order (FO)

$\frac{d\phi}{d\tau} = -\frac{\phi}{\tau_\phi} - \frac{\phi}{2}\left[\frac{1}{\tau} + \frac{1}{\beta_2} T \frac{d}{d\tau}\left(\frac{\beta_2}{T}\right)\right] + \frac{2}{3}\frac{1}{\beta_2 \tau}$ Second order (SO)

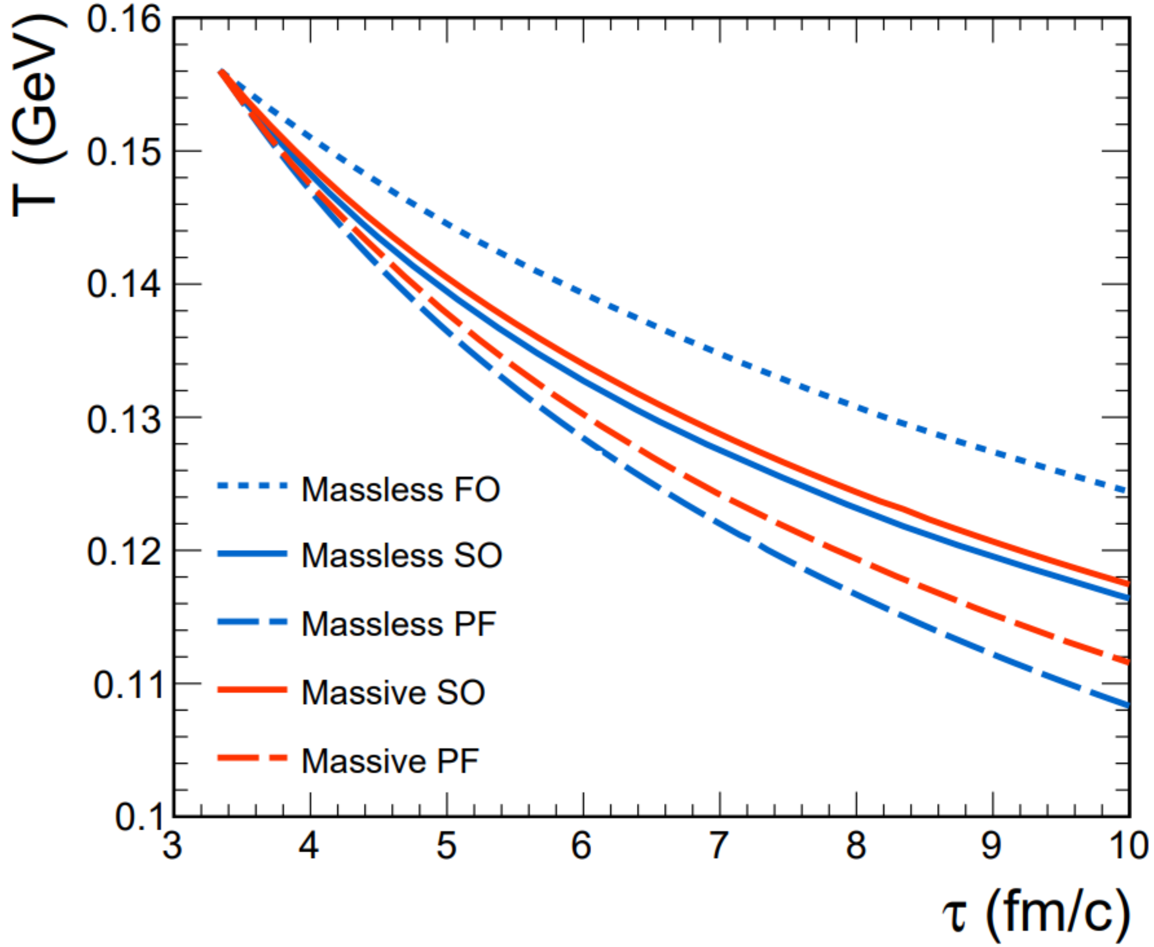
- **Massive case:**

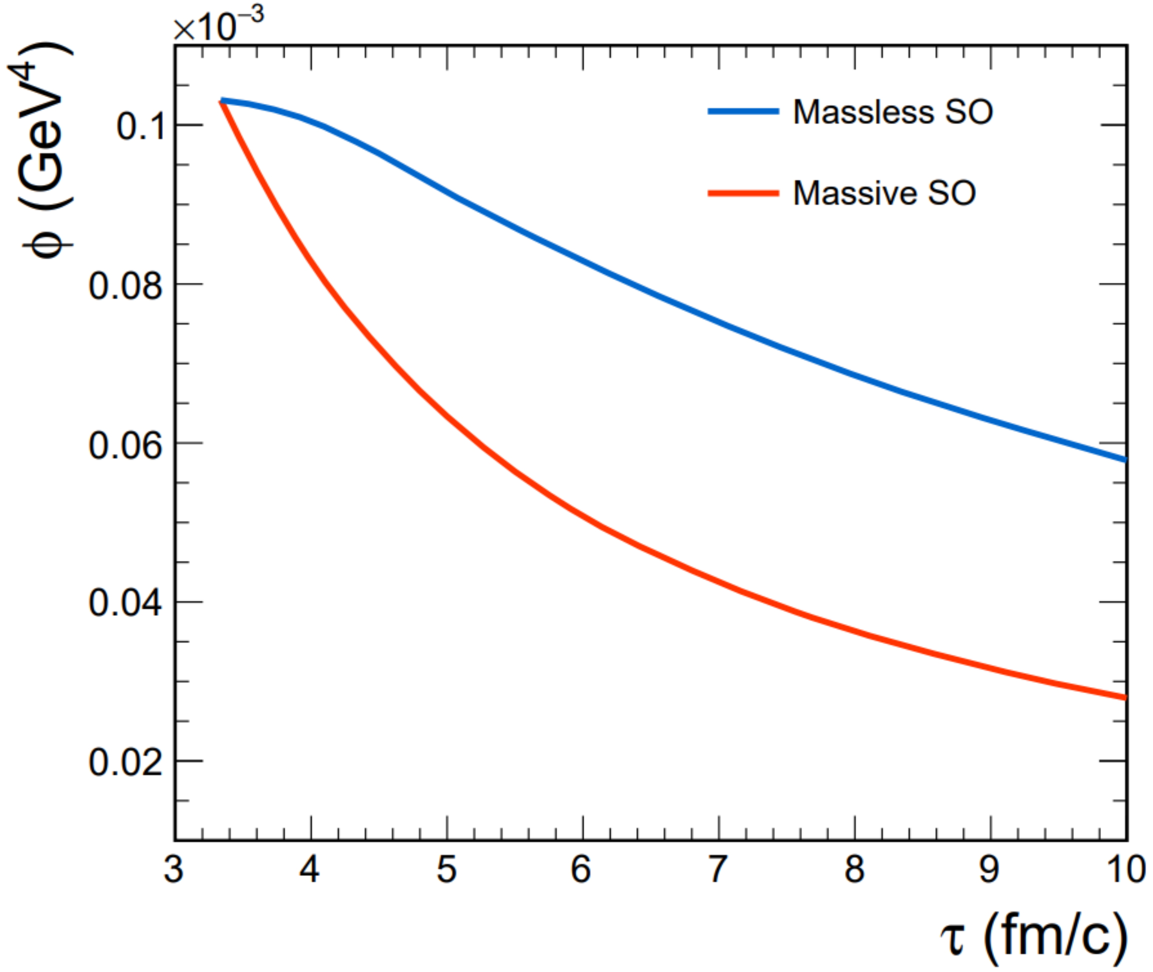
$$\frac{dT}{d\tau} = -\frac{c_s^2 T}{\tau} + \frac{\phi c_s^4}{n\tau(c_s^2+1)}$$

$$\frac{d\phi}{d\tau} = -\frac{\phi}{\tau_\phi} - \frac{\phi}{2}\left[\frac{1}{\tau} - \frac{T(c_s^2+1)}{m^2+6(c_s^2+1)T^2}\left\{12 + \frac{6}{c_s^2} + \frac{m^2}{T^2(c_s^2+1)}\left(4 + \frac{1}{c_s^2}\right)\right\}\frac{dT}{d\tau}\right] + \frac{4}{3\tau}\frac{T^3(c_s^2+1)^2 n}{m^2+6(c_s^2+1)T^2}$$

[1] A. Muronga, Phys. Rev. C 69, 034903 (2004)
[2] W. Israel, Ann. Phys. (N.Y.) 100, 310 (1976)

Temperature Evolution





Resonance Yield Estimation

- Rescattering and Regeneration effects are included by using a modified kinetic formation model

$$N_f(\tau_f) = \varepsilon(\tau_f)\lambda_D(\tau_f)[\mathrm{N_i}(\tau_i) + \mathrm{N_\pi N_K} \times \int_{\tau_i}^{\tau_f} \Gamma_F[V(\tau)\varepsilon(\tau)\lambda_D(\tau)]^{-1} d\tau]$$

- $\lambda_D(\tau) = \exp(-\frac{\tau-\tau_i}{\tau_l})$ gives the natural decay contribution

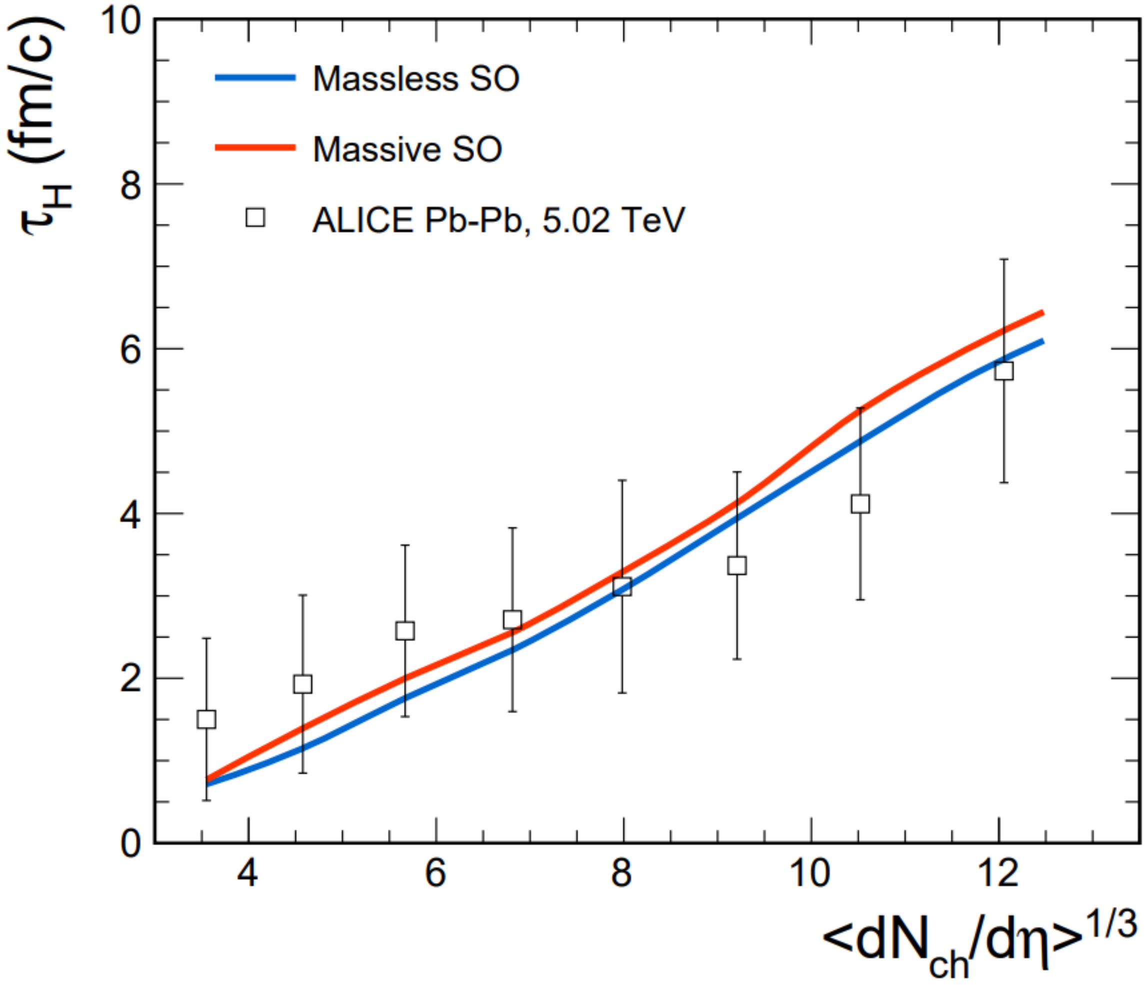
- $\varepsilon(\tau) = \exp(-\int_{\tau_i}^{\tau} \Gamma_D N_{co} V(\tau)^{-1} d\tau\ )$ gives re-scattering due to co-moving hadrons

- Γ_D and Γ_F denotes the rate of co-mover induced decay and regeneration interactions, respectively:

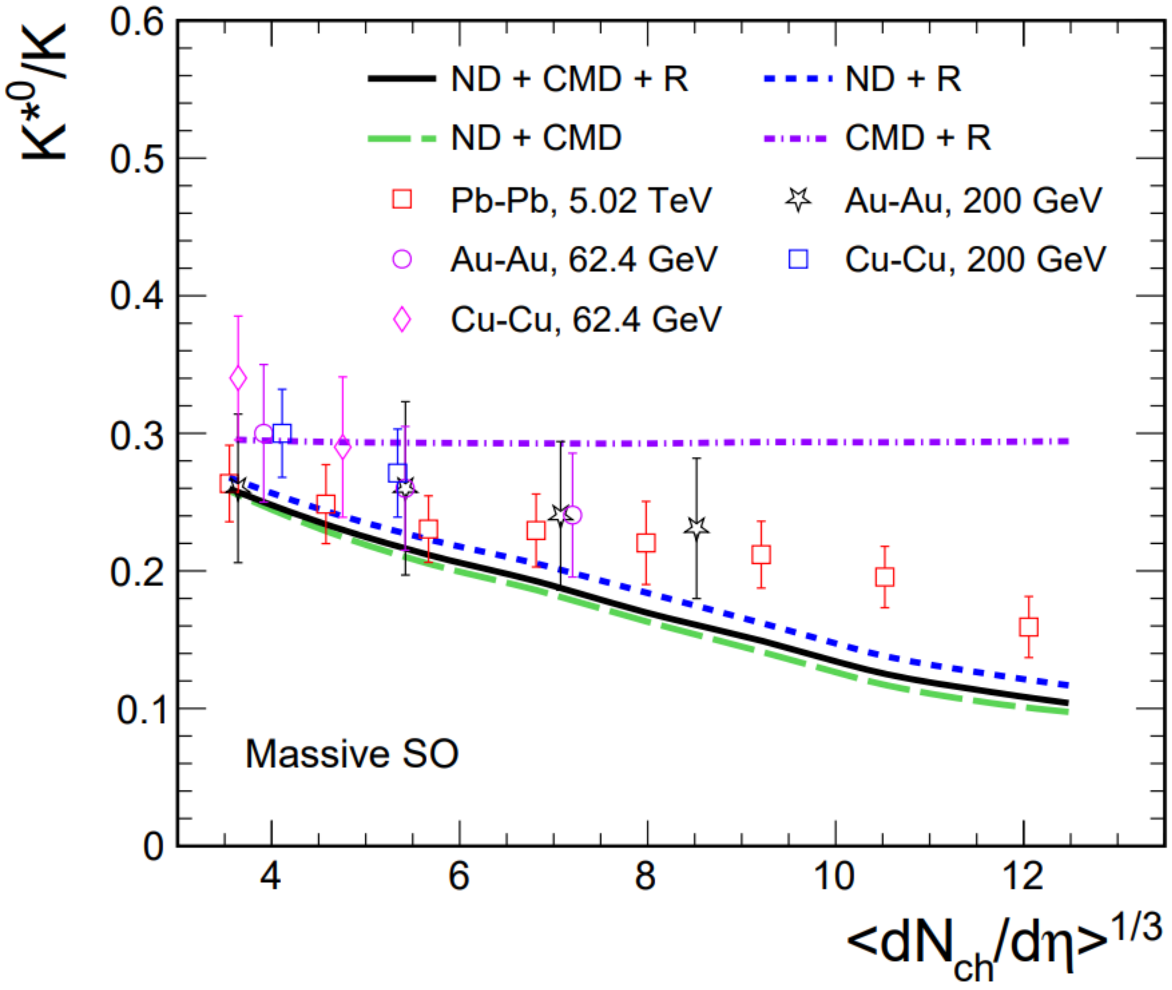
$$\Gamma_D = <\sigma_{co} v_{rel}>_{K^*,co} \qquad \Gamma_F = <\sigma_{reg} v_{rel}>_{K,\pi}$$

[1] R. L. Thews, Nucl. Phys. A 702, 341 (2002)

Results



τ_H (fm/c)
Massless SO
Massive SO
ALICE Pb-Pb, 5.02 TeV
0
2
4
6
8
10
4
6
8
10
12
<dN_ch/dη>^1/3



K*0/K
ND + CMD + R
ND + R
ND + CMD
CMD + R
Pb-Pb, 5.02 TeV
Au-Au, 200 GeV
Au-Au, 62.4 GeV
Cu-Cu, 200 GeV
Cu-Cu, 62.4 GeV
Massive SO
0
0.1
0.2
0.3
0.4
0.5
0.6
4
6
8
10
12
<dN_ch/dη>^1/3

Summary

- A hydrodynamical model with both massive and massless particles has been applied for the evolution of the hadronic phase.

- A model has been introduced within the hydrodynamic framework to incorporate the re-scattering and regeneration effects of resonances.

- The effect of natural decay, co-mover-induced decay and regeneration are explored individually.

- The model results show a good agreement with experimental results.

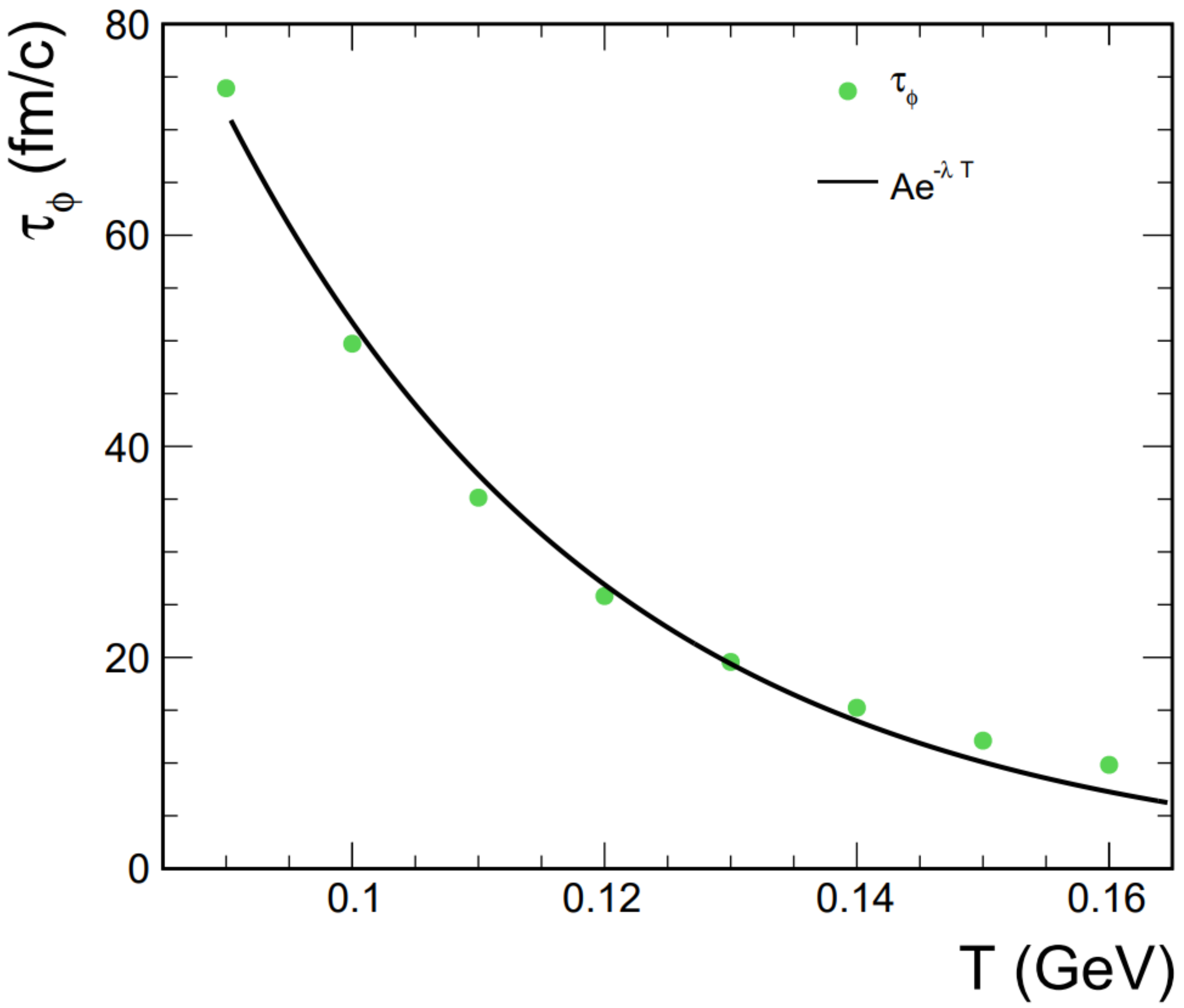
- Although natural decay is the main driver determining the yield of the hadronic phase, the effect of co-mover induced decay and regeneration might be non-trivial at high multiplicities.

Thank You

For the attention

Backup Slides

Backup: Relaxation Time



Backup: η/s of hadron gas