Multi-messenger constraints on heavy-ion collision dynamics with hadrons and photons

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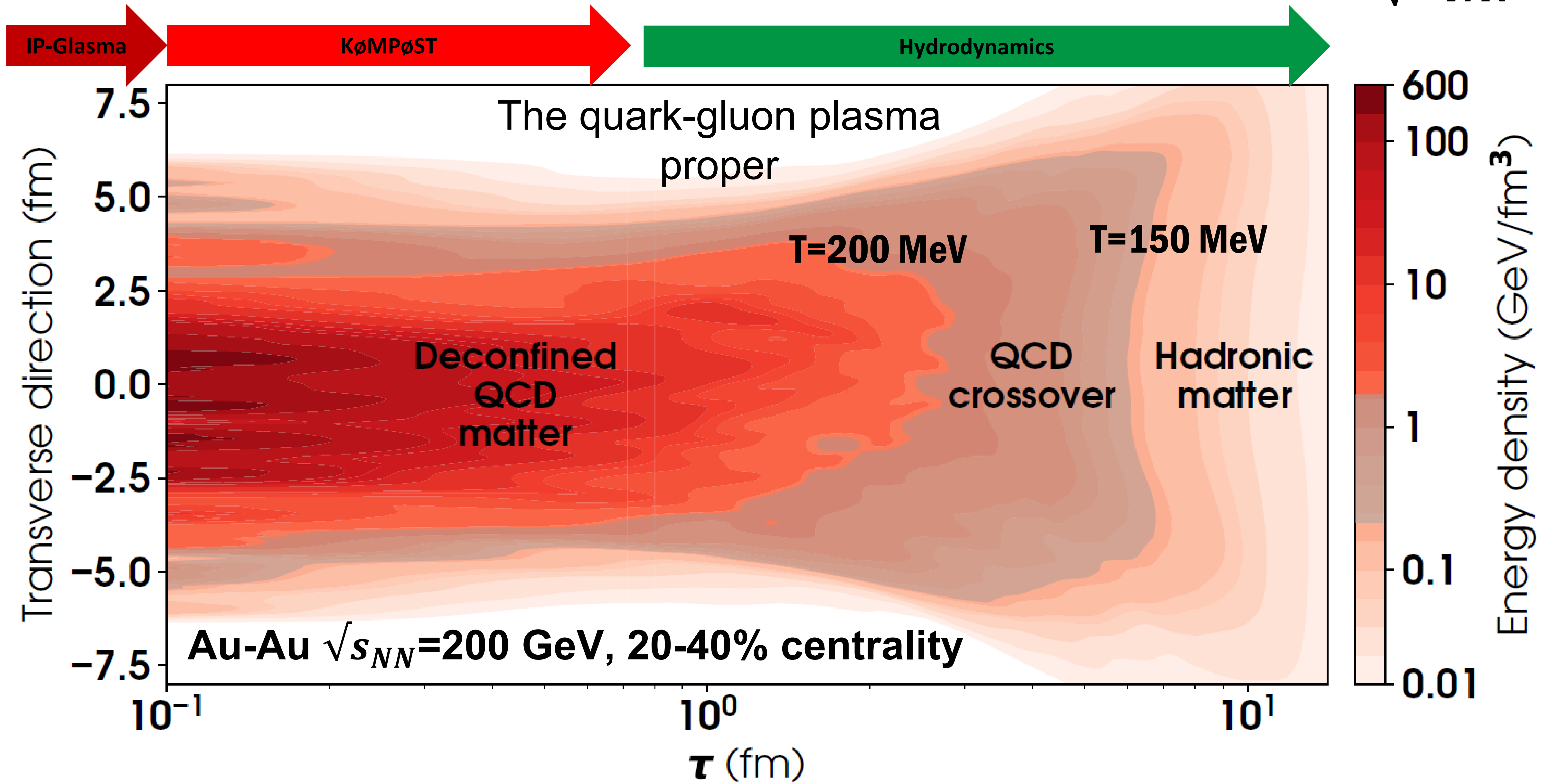
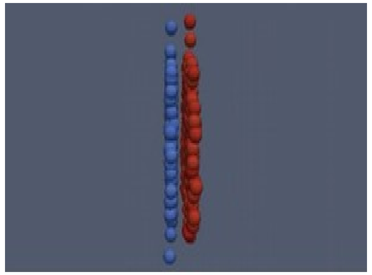
Time Evolution Stages of a Heavy Ion Collision (at high $\sqrt{s_{NN}}$)



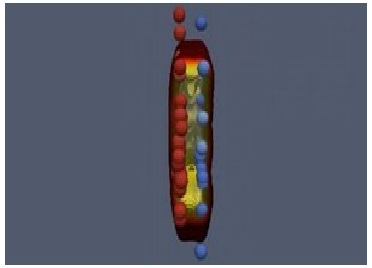
Pre-hydro phase | Hydrodynamic phase | Post-hydro phase

Multistage model of heavy ion collisions at high $\sqrt{s_{NN}}$



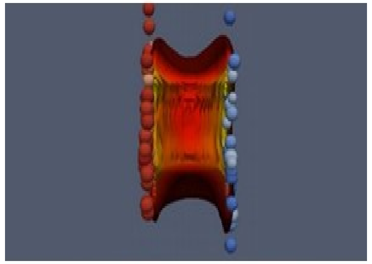
$\tau =$ "0^+": IP-Glasma   [Ref: Schenke, Tribedy, and Venugopalan, PRL (2012)]

- Incoming nuclei described using Color-Glass-Condensate effective theory
- Glasma evolution described by solving the Yang-Mills equations



$\tau = 0.1$ fm: KøMPøST   [Ref: Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, PRL (2019); PRC (2019)]

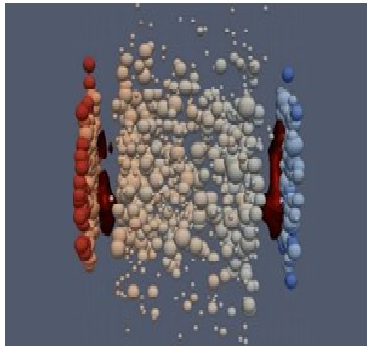
- Energy-momentum tensor divided in background and perturbations
- Background evolved w/ locally boost-invariant QCD (“AMY”) effective kinetic theory
- Perturbations evolved w/ nonequilibrium **linear** response, also in “AMY” kinetic theory



$\tau = 0.8$ fm: Beginning of “hydrodynamic phase”

- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Shear and bulk viscosity [Constant η/s=0.12; temperature-dependent ζ/s]

[MUSIC ref.: Schenke et al, PRC (2010), PRL (2011); Paquet et al, PRC (2016); EOS ref.: HotQCD Coll., PRD (2014); Bernhard (2018)]



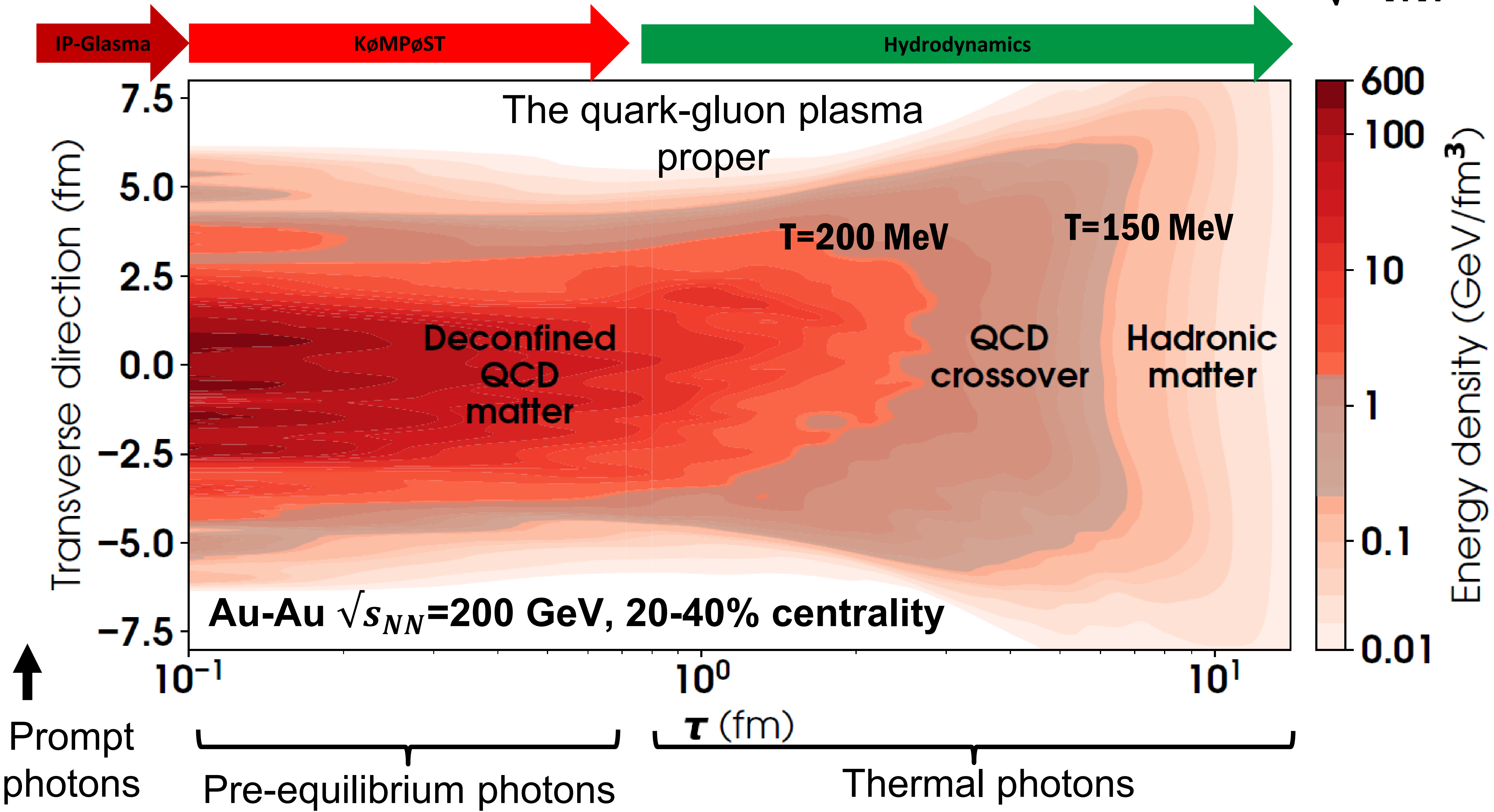
$\tau \sim 10$ fm: End of “hydrodynamic phase”

- Fluid converted to hadrons; hadronic interactions with UrQMD hadronic transport

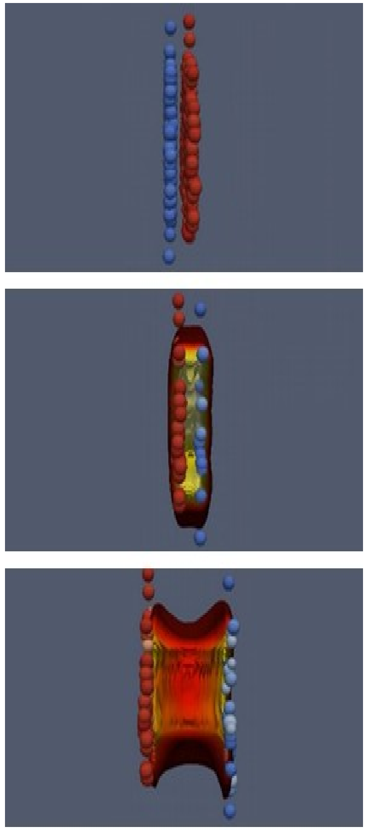
  [UrQMD ref.: Bass et al PPNP (1998), Bleicher et al, JPG (1999), Petersen et al, PRC (2008)]
- Photon emission NOT calculated from UrQMD; instead, estimated from hydrodynamics

  ➥ However, see Oscar Garcia-Montero's poster, Session 2 T13 (today)

Time Evolution Stages of a Heavy Ion Collision at high $\sqrt{s_{NN}}$



Photons: contribution of different sources



$\boldsymbol{\tau = \text{"}0^+\text{"}}$:

- Prompt photons: $$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \frac{N_{binary}}{\sigma_{pp}^{inel}} \overbrace{f_{a/A} \otimes f_{b/B} \otimes \mathrm{d}\hat{\sigma}_{ab\to\gamma/c+d}[\otimes D_{\gamma/c}]}^{\text{NLO pQCD [INCNLO] [Could also use fit to p+p data]}}$$

$\boldsymbol{\tau = 0.1}$ **fm: KøMPøST**

- Pre-equilibrium photons:
  - Energy-momentum tensor evolved with "KøMPøST"
  - "Effective temperature" extracted from the energy density, with QCD equation of state
  - Photon production estimated as if thermal photons (including viscous corrections)

$\boldsymbol{\tau = 0.8}$ **fm: Hydrodynamics**

- "Thermal" photons

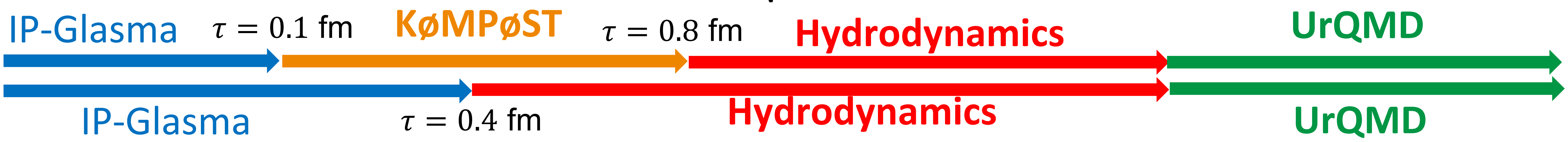
$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(\mathrm{p}, \underbrace{T(X), u^\mu(X), \ldots}_{\text{Spacetime profile of plasma from hydrodynamic simulation}})$$

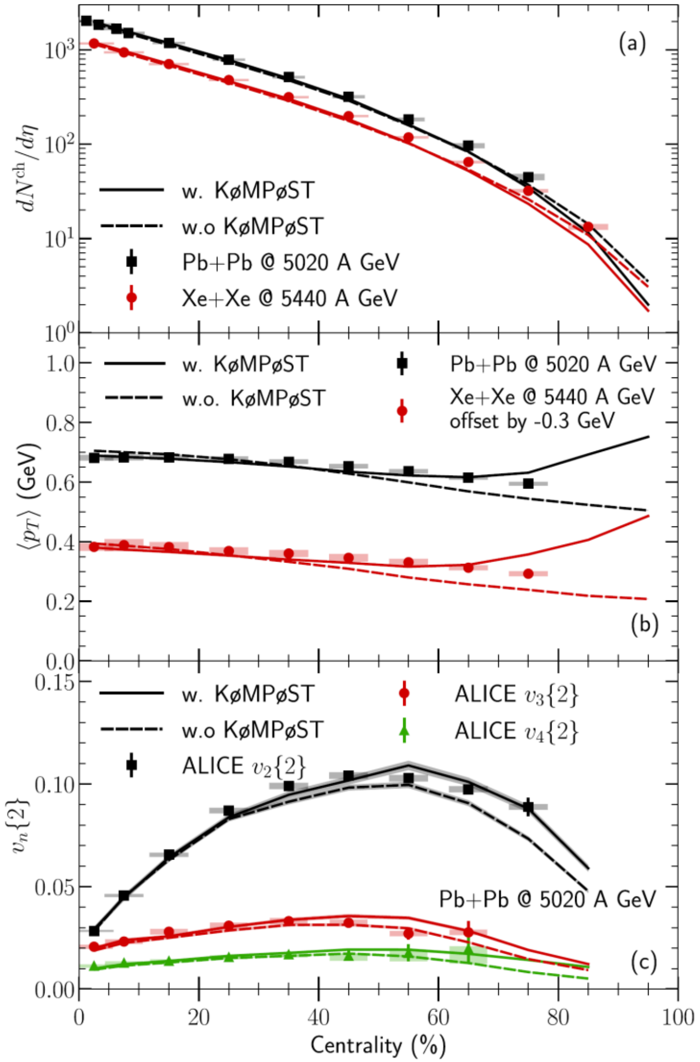
Photon emission rate (per volume) for hot QCD plasma

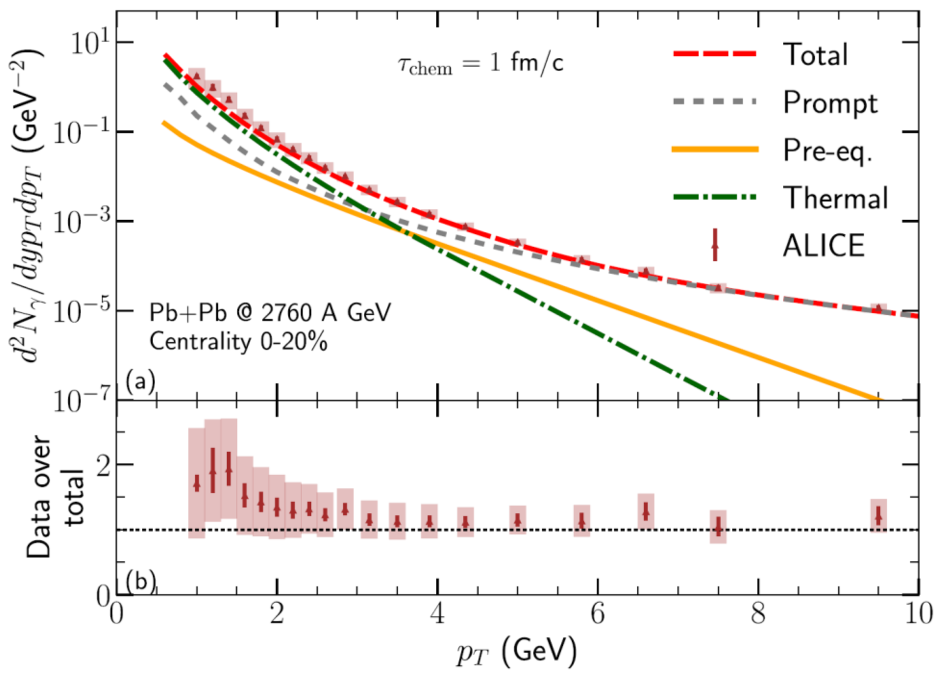
Viscous corrections included in photon emission rate where available

Hadrons and photons at high $\sqrt{s_{NN}}$

Gale, Paquet, Schenke, Shen, PRC (2022)





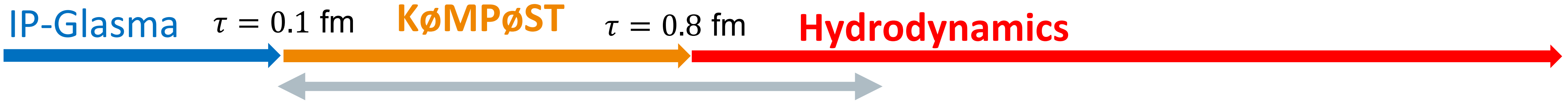


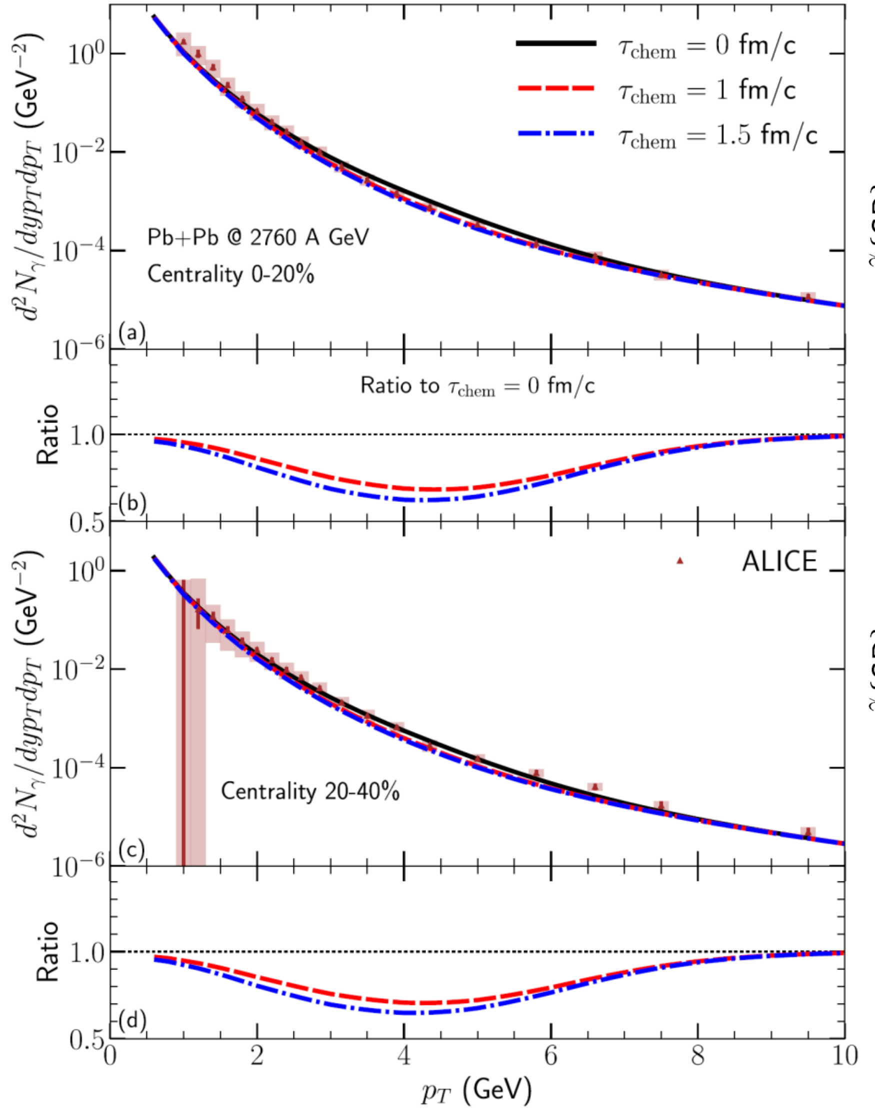
$\underline{\boldsymbol{\tau = \text{"}0^+\text{"}}}$: Prompt photons

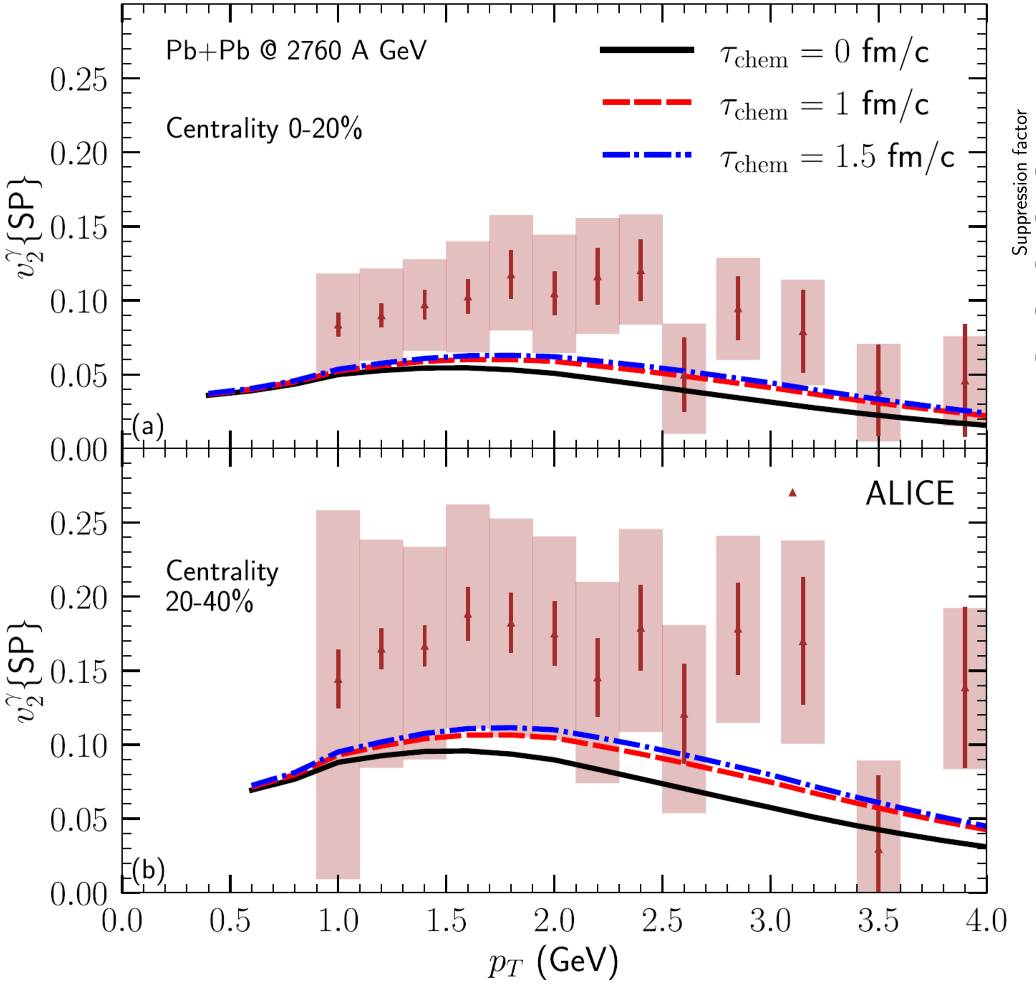
$\underline{\mathbf{0.1 < \boldsymbol{\tau} < 0.8}}$ **fm: KøMPøST** [Pre-equilibrium photons]

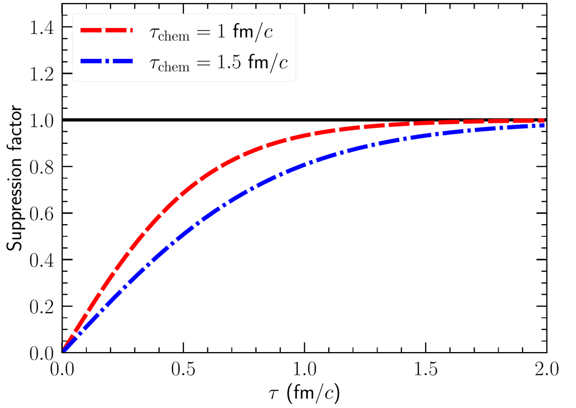
$\underline{\boldsymbol{\tau > 0.8}}$ **fm: Hydrodynamics** ["Thermal" photons]

Photons at high $\sqrt{s_{NN}}$: sensitivity to chemical equilibration

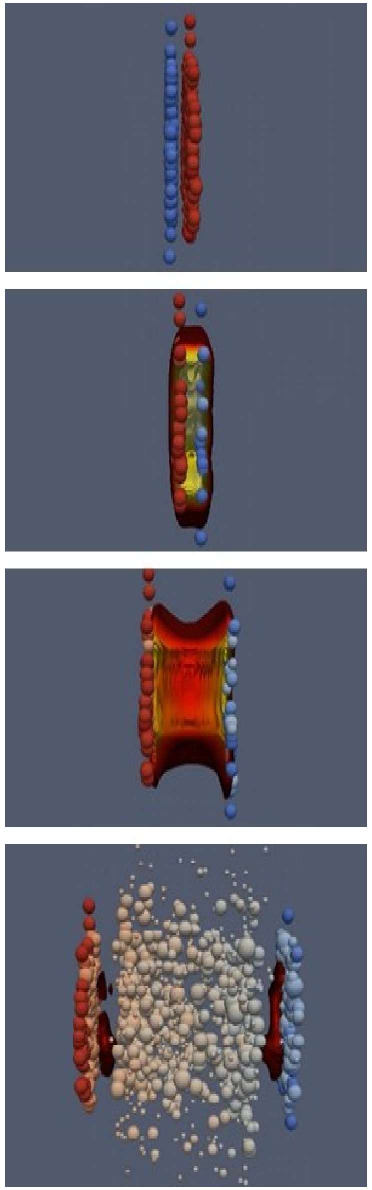






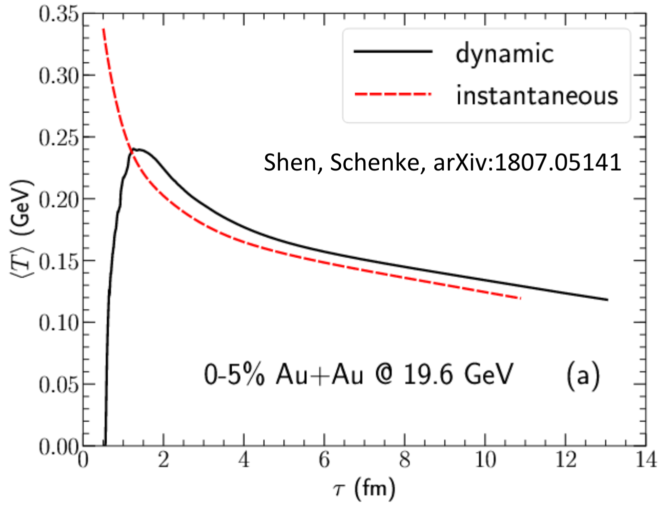


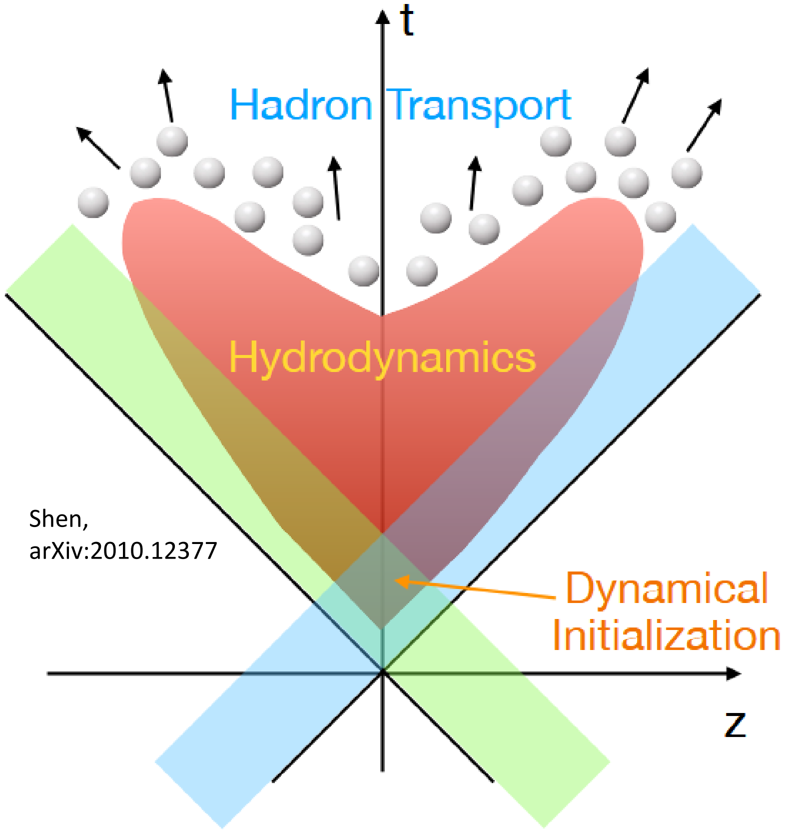
Multistage model of heavy ion collisions at low $\sqrt{s_{NN}}$



$\tau > 0$: Dynamical initialization with 3D MC Glauber [Shen&Schenke, arXiv:2203.04685]

- Energy-momentum source terms dynamically added to hydrodynamics





$\tau > 0$ fm: Beginning of "hydrodynamic phase"

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- Shear viscosity [Constant η/s=0.12]

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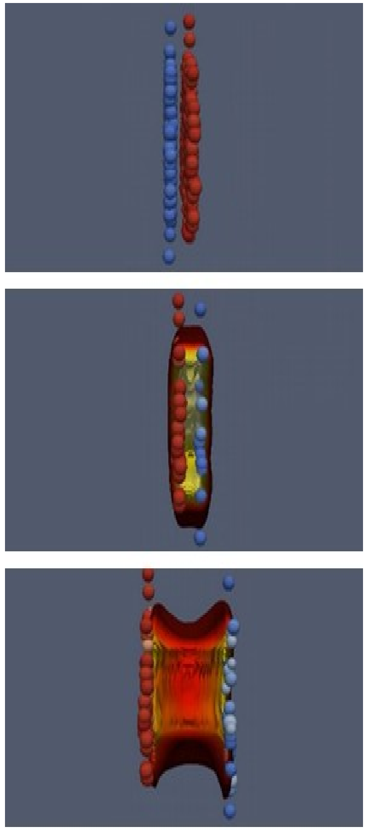


$\boldsymbol{\tau = "0^+":}$

NLO pQCD [INCNLO] [Could also use fit to p+p data]

- Prompt photons: $\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \frac{N_{binary}}{\sigma_{pp}^{inel}} \overbrace{f_{a/A} \otimes f_{b/B} \otimes \mathrm{d}\hat{\sigma}_{ab\to\gamma/c+d} [\otimes D_{\gamma/c}]}^{\text{NLO pQCD [INCNLO] [Could also use fit to p+p data]}}$

$\boldsymbol{\tau > 0}$ **fm: Hydrodynamics**

- "Thermal" photons

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p} (\mathrm{p}, \underbrace{T(X), u^\mu(X), \boldsymbol{\mu_B}}_{})$$

Photon emission rate (per volume) for hot QCD plasma

Spacetime profile of plasma from hydrodynamic simulation

Viscous corrections included in photon emission rate where available

QGP rates: Compton scattering, $q\bar{q}$ annihilation & bremsstrahlung (with LPM) at finite μ_B

Refs.: Traxler, Vija, Thoma (1995); Gervais, Jeon (2012); This work

Hadronic rates: meson interaction, baryon interaction (at finite μ_B)

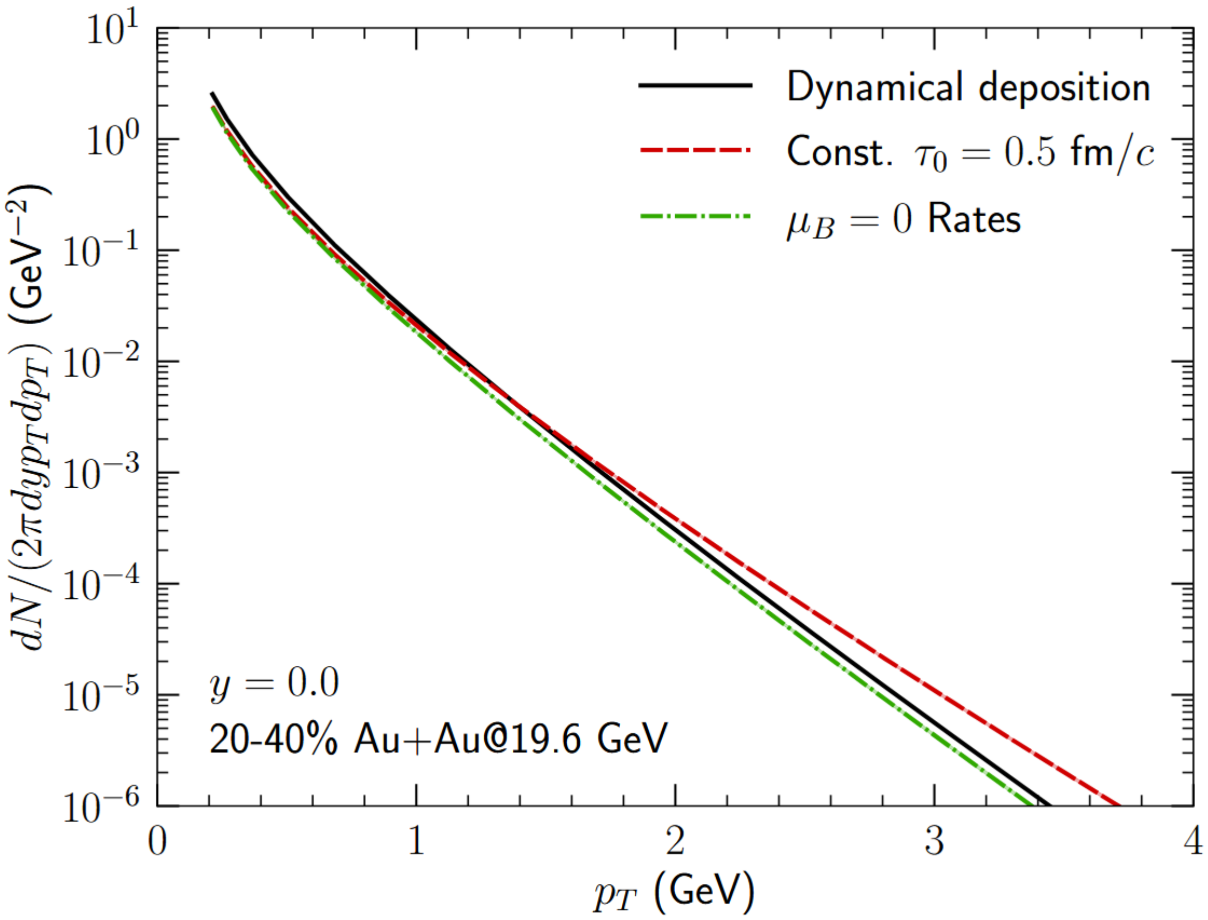
Refs.: Turbide, Rapp, Gale (2004); Heffernan, Hohler, Rapp (2014); Holt, Hohler, Rapp (2016)

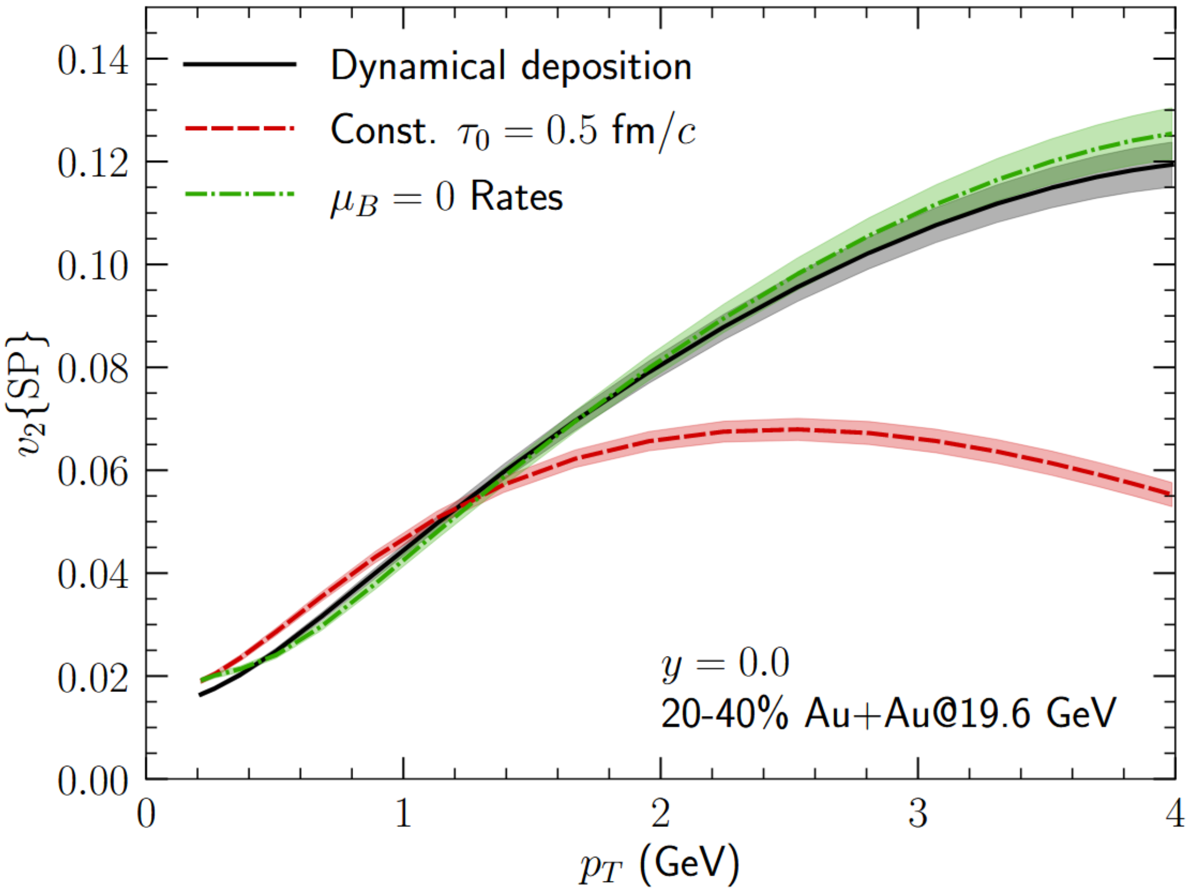
Photons at low $\sqrt{s_{NN}}$

3D MC Glauber

Hydrodynamics

UrQMD



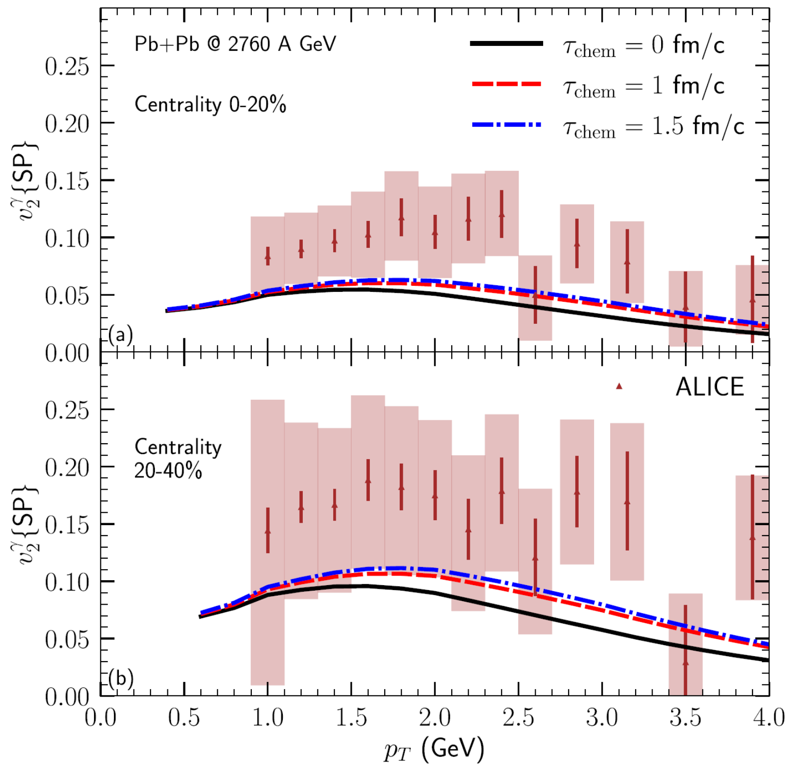


Large effect from dynamical initialization

Summary

High $\sqrt{s_{NN}}$ collisions (LHC/top RHIC)

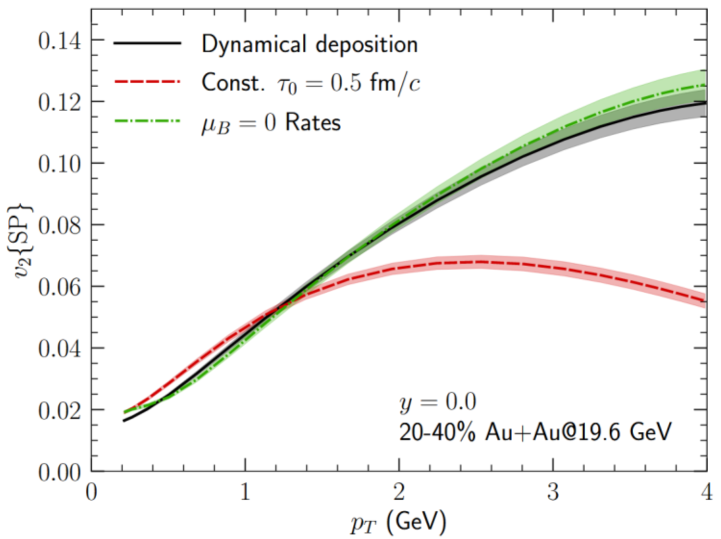
- Hadronic observables:
  ➥ pre-equilibrium phase demands modifications of transport coefficients



- Pre-eq. photons:
  ➥ Are sensitive to chemical equilibration: <u>promising probe with more precise data</u>

Low $\sqrt{s_{NN}}$ collisions (RHIC BES)

➥ Large sensitivity of photons to early stage of the collision



Backup

Future directions

- There are different sources of pre-equilibrium photons:
  - ➥ We studied pre-eq. photons from soft bath
  - ➥ Photons can be produced during formation of soft bath: need future studies

  [Monnai, arXiv:1907.09266; Garcia-Montero, arXiv:1909.12294]

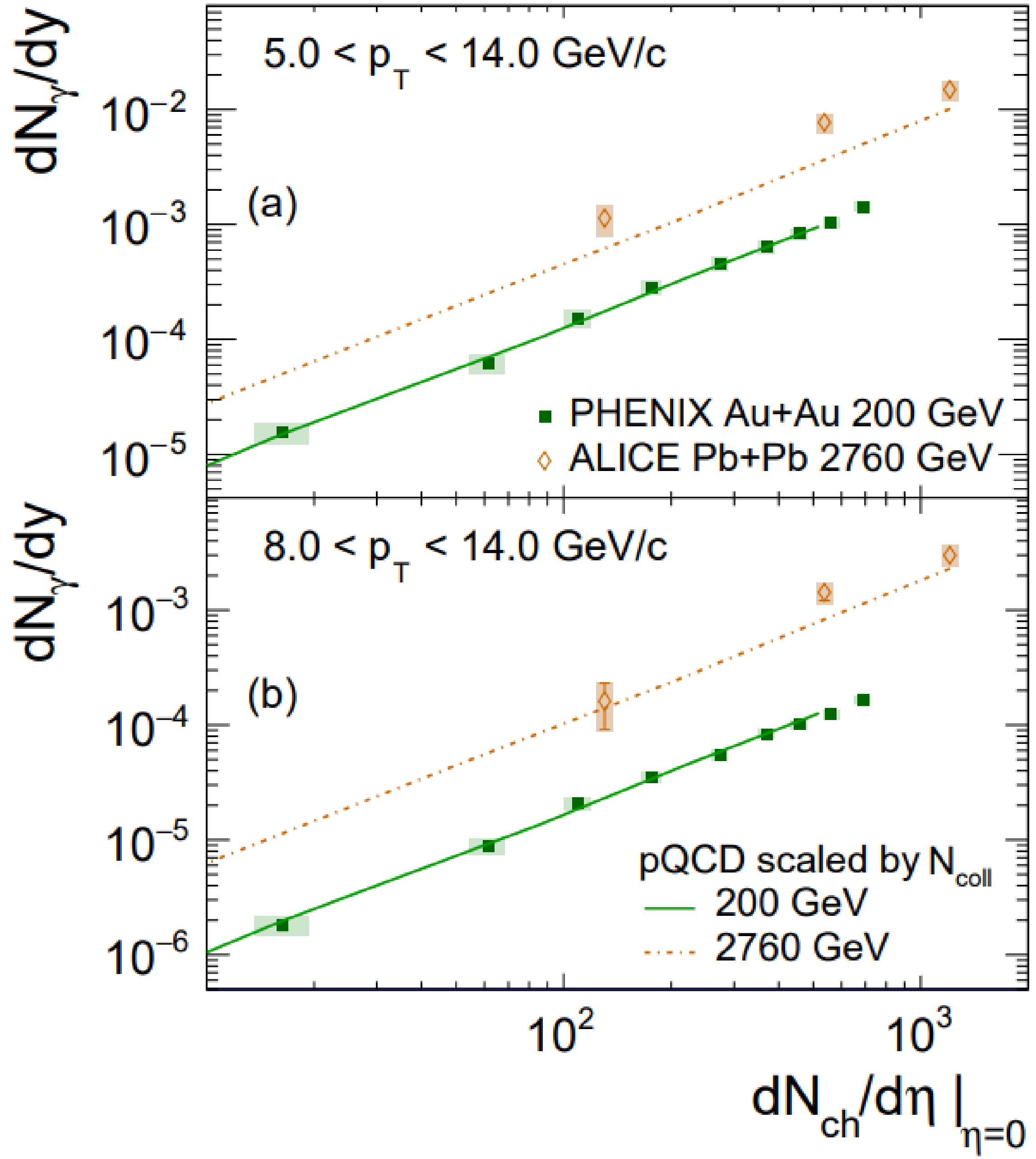
- Dynamical chemical equilibration in pre-equilibrium phase will be a major step forward

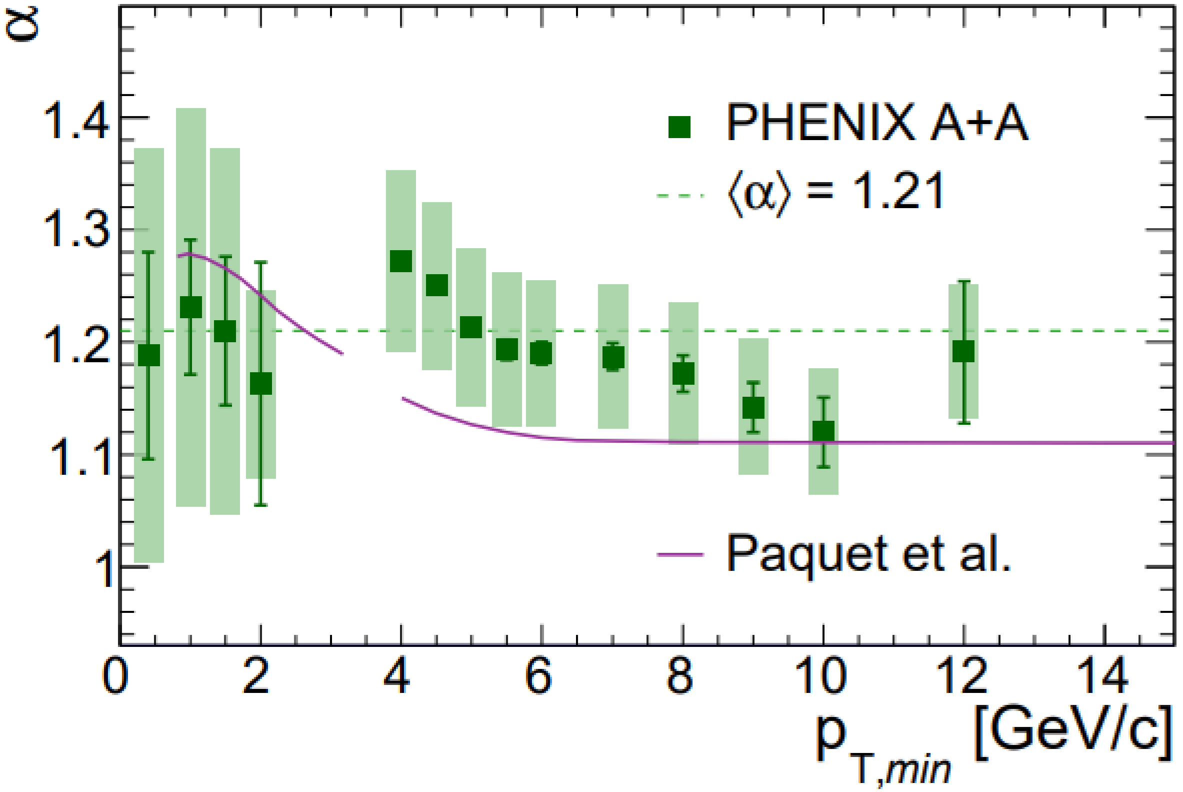
  [See e.g. Oliva et al, PRC (2017); Kurkela & Mazeliauskas PRD (2019)]

- Other aspects of photon production still need to be investigated:
  - ➥ Photon production with hadronic transport [Schäfer et al, arXiv:2111.13603; Garcia-Montero, Poster Session 2 T13]
  - ➥ Photon emission rates near confinement [Bala, Poster Session 2 T03; Nonaka, Parallel T13]
  - ➥ Consider energy loss effects on prompt photons [Modarresi-Yazdi, Parallel T13]
  - ➥ Include effect of viscosity on all thermal emission rates
  - ➥ Finite baryon chemical potential effects
  - ➥ Prompt photons at low center-of-mass energy

Centrality dependence of direct photons

PHENIX Collaboration - Low-p_T direct-photon production in Au+Au collisions at $\sqrt{s_{NN}}$=39 and 62.4 GeV
[arXiv:2203.12354]





Bulk viscosity

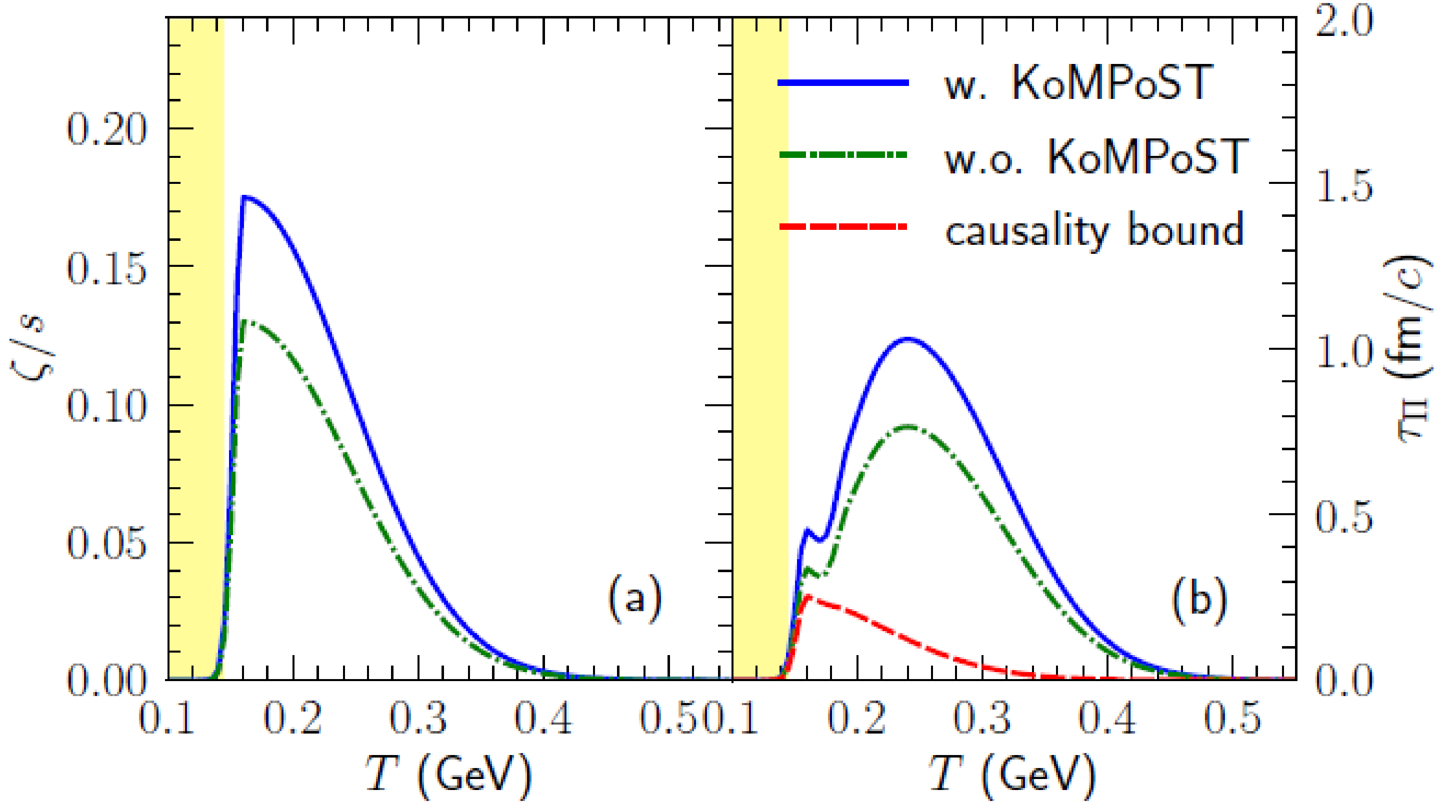


FIG. 1. (a) The bulk viscosity temperature profile consistent with heavy-ion data at RHIC and at the LHC, with and without the KøMPøST phase. Panel (b) shows the corresponding bulk relaxation times and their minimum value required by causality in the linear regime around equilibrium [23].

Modelling chemical equilibration

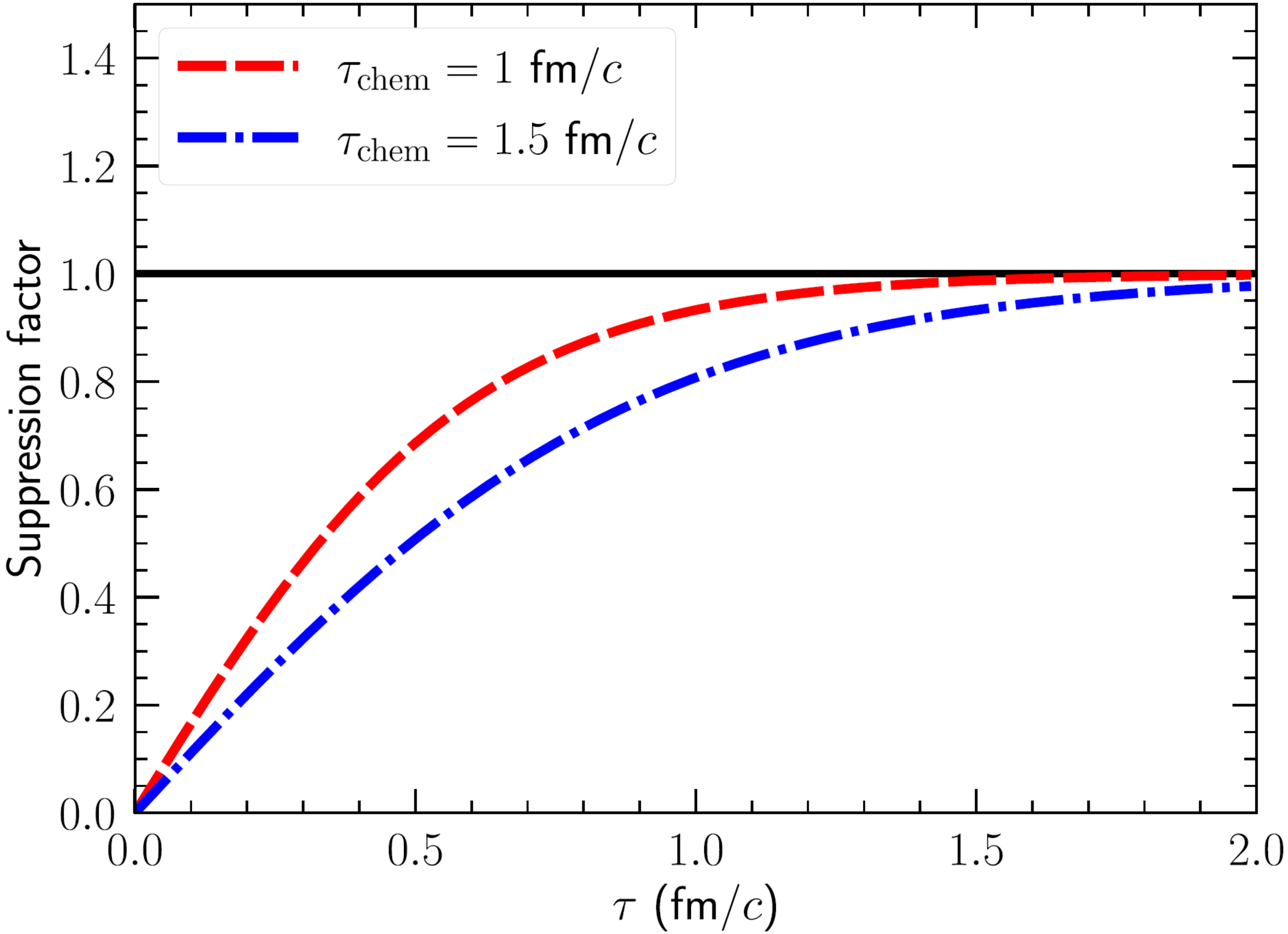


FIG. 5. The suppression factor applied to the thermal photon emission rates as a function of proper time, used to simulate the out-of-chemical equilibrium conditions. The two curves model the effect of a chemical equilibration time of 1 and 1.5 fm$/c$, respectively.

Longitudinal dynamics and particle production in relativistic nuclear collisions

Chun Shen (Wayne State U. and RIKEN BNL), Björn Schenke (Brookhaven)

Mar 9, 2022

20 pages

e-Print: 2203.04685 [nucl-th]

3D MC-Glauber model with string deceleration

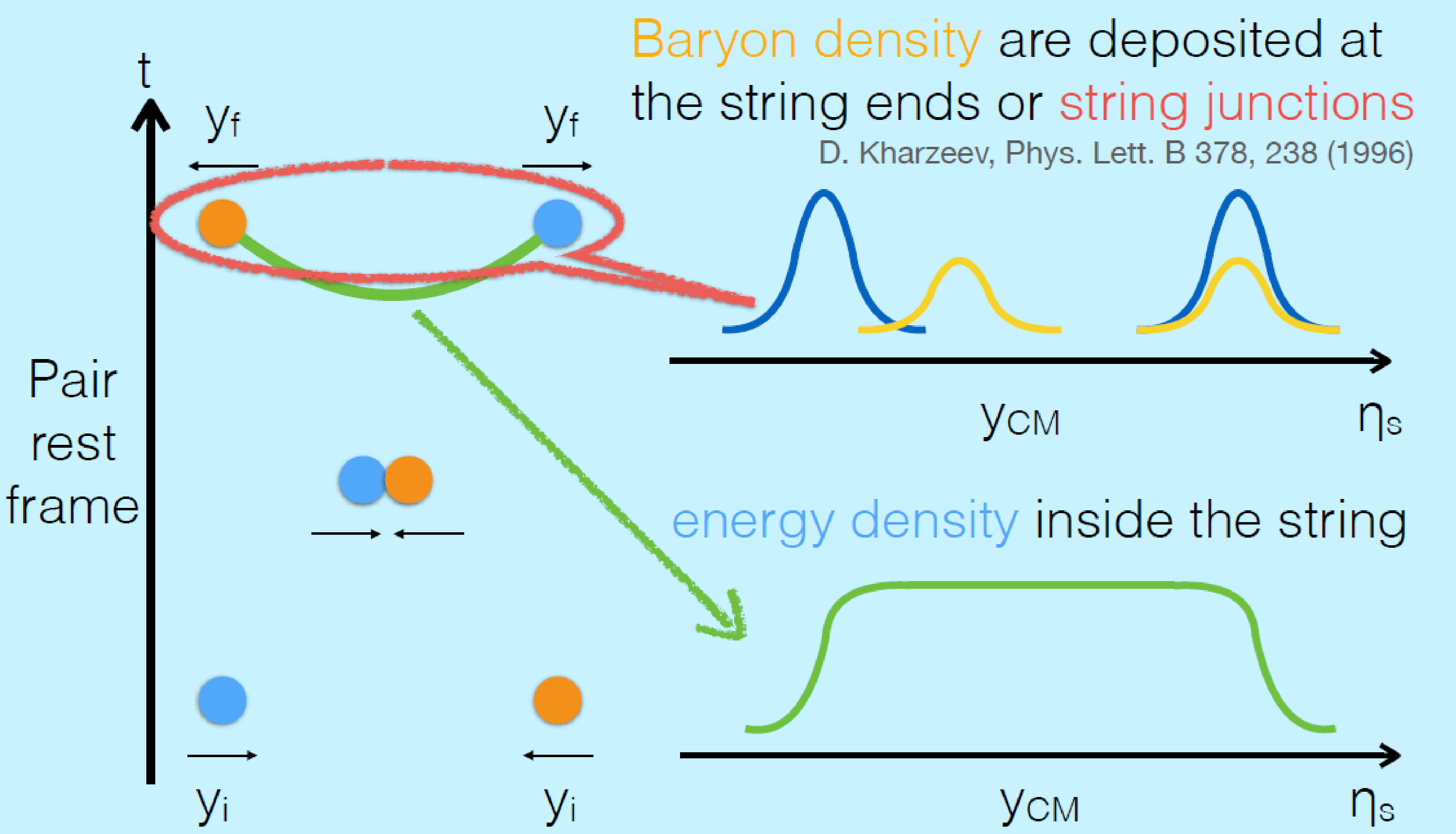
C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907 + arXiv:2203.04685 [nucl-th]

- Transverse collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF with

$$\sum_i x_i \leq 1$$

- Incoming quarks are decelerated with a string tension σ,

$$dp^z/dt = -\sigma$$



Imposed conservation for energy, momentum, and net baryon density