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 $\sqrt{s_{NN}}$)

The quark-gluon plasma proper

Hydrodynamic phase

Pre-hydro phase

Post-hydro phase

Au-Au $\sqrt{s_{NN}}$=200 GeV, 20-40% centrality

Energy density (GeV/fm$^3$)

$\tau$ (fm)
Multistage model of heavy ion collisions at high $\sqrt{s_{NN}}$

$\tau = "0^+": \text{IP-Glasma}$  [Ref: Schenke, Triedy, and Venugopalan, PRL (2012)]
- Incoming nuclei described using Color-Glass-Condensate effective theory
- Glasma evolution described by solving the Yang-Mills equations

$\tau = 0.1 \, \text{fm}$: $\text{KøMPøST}$  [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

$\tau = 0.8 \, \text{fm}: \text{Beginning of "hydrodynamic phase"}$
- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Shear and bulk viscosity [Constant $\eta/s=0.12$; temperature-dependent $\zeta/s$]
[MUSIC ref.: Schenke et al, PRC (2010), PRL (2011); Paquet et al, PRC (2016); EOS ref.: HotQCD Coll., PRD (2014); Bernhard (2018)]

$\tau \sim 10 \, \text{fm}: \text{End of "hydrodynamic phase"}$
- Fluid converted to hadrons; hadronic interactions with UrQMD hadronic transport
- 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 $\sqrt{s_{NN}}$

The quark-gluon plasma proper

$T=150$ MeV
$T=200$ MeV

Deconfined QCD matter
QCD crossover
Hadronic matter

Au-Au $\sqrt{s_{NN}}=200$ GeV, 20-40% centrality

Prompt photons
Pre-equilibrium photons
$\tau$ (fm)
Thermal photons
Photons: contribution of different sources

\( \tau = "0^+" : \)
- **Prompt photons:**
  \[
  \frac{dN_\gamma}{d^3p} = \frac{N_{binary} \sigma_{inel}^{pp}}{\sigma_{pp}} f_{a/A} \otimes f_{b/B} \otimes d\hat{\sigma}_{ab\rightarrow\gamma/c+d} \otimes D_{\gamma/c}
  \]

\( \tau = 0.1 \text{ fm: } \text{KøMPøST} \)
- **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)

\( \tau = 0.8 \text{ fm: Hydrodynamics} \)
- **“Thermal” photons**
  \[
  \frac{dN_\gamma}{d^3p} = \int d^4X \frac{d\Gamma_\gamma}{d^3p} (p, T(X), u^\mu(X), \ldots)
  \]

Viscous corrections included in photon emission rate where available

NLO pQCD [INCNLO] [Could also use fit to p+p data]
Hadrons and photons at high $\sqrt{S_{NN}}$

**IP-Glasma** $\tau = 0.1$ fm

**KøMPøST** $\tau = 0.8$ fm

**Hydrodynamics** $\tau = 0.4$ fm

**UrQMD**

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$x_\tau$ = $\tau$ = 0.4 fm

$x_\tau$ = 0.1 fm

$x_\tau$ = 0.8 fm

$x_\tau$ = $0^+$: Prompt photons

0.1 < $\tau$ < 0.8 fm: KøMPøST [Pre-equilibrium photons]

$\tau$ > 0.8 fm: Hydrodynamics [“Thermal” photons]
Photons at high $\sqrt{s_{NN}}$: sensitivity to chemical equilibration

**IP-Glasma** $\tau = 0.1$ fm **KøMPøST** $\tau = 0.8$ fm **Hydrodynamics**

**Figure 1:**
- **Panel (a)**: $\frac{d^2N}{dydp_T}$ for Pb+Pb @ 2760 A GeV, Centrality 0-20%.
- **Panel (b)**: Ratio to $\tau_{\text{chem}} = 0$ fm/c.
- **Panel (c)**: $\frac{d^2N}{dydp_T}$ for Centrality 20-40%.
- **Panel (d)**: Ratio to $\tau_{\text{chem}} = 0$ fm/c.

**Figure 2:**
- **Panel (a)**: $\tau_{\text{chem}}$ dependence of $v_2(SP)$ for Centrality 0-20%.
- **Panel (b)**: $\tau_{\text{chem}}$ dependence of $v_2(SP)$ for Centrality 20-40%.

Ref.: Chun Shen
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”**
- 3+1D relativistic viscous hydrodynamics [MUSIC]
- Shear viscosity [Constant $\eta/s=0.12$]

$\tau \sim 10$ fm: **End of “hydrodynamic phase”**
- Fluid converted to hadrons; hadronic interactions with UrQMD
- Photon emission NOT calculated from UrQMD; instead, estimated from hydrodynamics
Photons: contribution of different sources

$\tau = "0^+":$

- **Prompt photons:** $\frac{dN_\gamma}{d^3p} = \frac{N_{\text{binary}}}{\sigma_{pp}^{\text{inel}}} \int f_a/A \otimes f_b/B \otimes d\hat{\sigma}_{ab \rightarrow \gamma/c + d} \otimes dD_{\gamma/c}$

$\tau > 0$ fm: **Hydrodynamics**

- "Thermal" photons

$$\frac{dN_\gamma}{d^3p} = \int d^4X \left( \frac{d\Gamma_\gamma}{d^3p} (p, T(X), u^\mu(X), \mu_B) \right)$$

Photon emission rate (per volume) for hot QCD plasma

Spacetime profile of plasma from hydrodynamic simulation

- **QGP rates:** Compton scattering, $q\bar{q}$ annihilation & bremsstrahlung (with LPM) at finite $\mu_B$
  Refs.: Traxler, Vija, Thoma (1995); Gervais, Jeon (2012); This work

- **Hadronic rates:** meson interaction, baryon interaction (at finite $\mu_B$)
  Refs.: Turbide, Rapp, Gale (2004); Heffernan, Hohler, Rapp (2014); Holt, Hohler, Rapp (2016)

Viscous corrections included in photon emission rate where available.
Photons at low $\sqrt{S_{NN}}$

3D MC Glauber → Hydrodynamics → UrQMD

Large effect from dynamical initialization

Jean-François Paquet (Duke), w/ C. Gale, A. Noble, B. Schenke & C. Shen
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: promising probe with more precise data

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

- 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 KoMPoST 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

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20 pages
e-Print: 2203.04685 [nucl-th]
3D MC-Glauber model with string deceleration

- 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 \( \sigma \), \[ dp^z/dt = -\sigma \]

Baryon density are deposited at the string ends or string junctions


Pair rest frame

Imposed conservation for energy, momentum, and net baryon density