Thermal photons from a modern hydrodynamical model: status of the direct photon puzzle

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(arXiv:1509.06738)

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Photon and hadron sources in HIC

Direct photons

Prompt photons
(Nucleon-collision-like photon production)

Thermal photons

Decays photons
(subtracted to define direct photons)

Initial state
Energy Stopping
Hard Collisions

Hydrodynamic Evolution

Hadronic observables
A puzzlingly large photon $v_2$ (and spectra)

Hadrons/hadronic decay photons

Unexpectedly large direct photon $v_2$

Direct photons

Also: large direct photon spectra
Outline

- Hydrodynamical model & hadrons
- Evaluating thermal photons
- Comparison with measurements & discussion
- Status of the direct photon puzzle
Hydrodynamical model

- Event-by-event IP-Glasma ($\tau < 0.4 \text{ fm/c}$)
- Hydrodynamics - MUSIC ($\tau > 0.4 \text{ fm/c}$)

**2+1D second-order (viscous) relativistic hydrodynamics**

Shear EOM: \[
\tau_\pi \Delta^{\mu \nu}_{\alpha \beta} \pi^{\alpha \beta} + \pi^{\mu \nu} = 4\eta \sigma^{\mu \nu} - \delta_{\pi \pi} \pi^{\mu \nu} \theta - \tau_{\pi \pi} \Delta^{\mu \nu}_{\alpha \beta} \pi^{\lambda \alpha} \sigma^{\beta}_\lambda + \lambda_{\pi \Pi} \Pi^{\mu \nu} + \varphi_T \Delta^{\mu \nu}_{\alpha \beta} \pi^{\lambda \alpha} \pi^{\beta}_\lambda
\]

Bulk EOM: \[
\eta_\Pi + \Pi = -\zeta \theta - \delta_{\Pi \Pi} \Pi \theta + \lambda_{\Pi \pi} \pi^{\mu \nu} \sigma_{\mu \nu}
\]

**Shear viscosity:** $\eta/s = 0.095$ (LHC); $0.06$ (RHIC)

**Bulk viscosity:** Peak at $T = 180$ MeV

Inspired from:
- HRG: Noronha-Hostler, Noronha and Greiner. 2009
- (Lattice: Karsch, Kharzeev and Tuchin. 2008)
- (from Denicol, Kodama, Koide, Mota. 2009)
Hydrodynamical model

- Event-by-event IP-Glasma ($\tau<0.4 \text{ fm/c}$)
- Hydrodynamics - MUSIC ($\tau>0.4 \text{ fm/c}$)

2+1D second-order (viscous) relativistic hydrodynamics

\[
\begin{align*}
\tau_{\pi}\Delta_{\alpha\beta}^{\mu\nu}\pi^{\alpha\beta} + \pi^{\mu\nu} &= 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\Delta_{\alpha\beta}^{\mu\nu}\pi^{\lambda\alpha}\sigma_{\lambda}^{\beta} + \lambda_{\pi\Pi}\Pi^{\mu\nu} + \varphi_{7}\Delta_{\alpha\beta}^{\mu\nu}\pi^{\lambda\alpha}\pi^{\beta}_{\lambda} \\
\tau_{\pi}\Pi + \Pi &= -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}
\end{align*}
\]

- Afterburner UrQMD ($T<T_{sw}$)

At RHIC: $T_{sw} = 165 \text{ MeV}$

At the LHC: $T_{sw} = 145 \text{ MeV}$
LHC $\sqrt{s_{NN}} = 2760$ GeV

(Sangwook Ryu's poster)

**Multiplicity of**
$\pi^+, K^+$ & $p$

**Mean transverse momentum of** $\pi^+$, $K^+$ & $p$

**$V_{2/3/4}$ of charged hadrons**

Hydro with bulk = good description of hadrons
(not possible here without bulk)

(see Ryu et al, PRL 115, 132301)
Direct photons

How are they computed?
Photon production

**Thermal photons:**

\[ E \frac{d^3 N}{d \mathbf{k}} = \int d^4 X E \frac{d^3 \Gamma}{d \mathbf{k}} (K^\mu, \omega^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X)) \]

“Thermal” photon production rate

**Spacetime profile of medium**

Prompt photons: NLO perturbative QCD + nuclear p.d.f.'s + isospin effect, scaled by the number of binary collisions
Thermal photon emission rate

\[ E \frac{d^3 N}{d\mathbf{k}} = \int d^4 X E \frac{d^3 \Gamma}{d\mathbf{k}}(K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X)) \]

- Photon production rate

Temperature

- Less hot (hadronic D.O.F.)
- Very hot (QGP)

Effective Lagrangian

- Effective (Switch at 180 MeV)
- Perturbative expansion in \( \alpha_s \)

Texas A&M/McGill (Turbide, Rapp, Gale et al)

- Include corrections due to viscosity
- QGP LO (Arnold, Moore, Yaffe. 2002)

(Meson gas + photons from \( \rho \) spct fct + pion brem. + \( \pi-\rho-\omega \) channels)

(Compton scattering & quark-antiquark annihilation + bremsstrahlung)
Thermal photon emission rate

$$E \frac{d^3 N}{dk} = \int d^4 X E \frac{d^3 \Gamma}{dk} (K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X))$$

- Photon production rate

### Temperature

- less hot (hadronic D.O.F.)
- **Effective Lagrangian**
  - Texas A&M/McGill (Turbide, Rapp, Gale et al)
  - (Meson gas + photons from $\rho$ spct fct + pion brem. + $\pi-\rho-\omega$ channels)

- very hot (QGP)
  - **Perturbative expansion in $\alpha_s$**
  - QGP LO (Arnold, Moore, Yaffe. 2002)
  - (Compton scattering & quark-antiquark annihilation + bremsstrahlung)

(Switch at 180 MeV)

**Include corrections due to viscosity**
Post-hydrodynamics photons

Photons after hydro phase?

**Hadrons:** UrQMD

**Photons:** Not yet calculated from transport model

Run hydro to lower temperature (105 MeV) instead

**Coarse-grained UrQMD vs hydro:** Huovinen et al. 2002
Direct photons

Comparison with data from RHIC and the LHC
RHIC $\sqrt{s}_{\text{NN}} = 200$ GeV: spectra

**Direct photon spectra**

![Graphs showing direct photon spectra for Au-Au collisions at RHIC at 0-20% and 20-40% centrality.](image-url)
RHIC $\sqrt{s}_{\text{NN}} = 200$ GeV: $v_2$

Direct photon $v_2$

New data: Stay tuned for Richard Petti's (PHENIX) talk at 9h40
LHC $\sqrt{s}_{NN} = 2760$ GeV:
Prompt, thermal & direct

**Direct photon spectra**

**Direct photon $v_2$**

New data just published: see ALICE talk at 10h
Direct photons

Effect of bulk viscosity
Bulk: change shape of $v_2$

Medium expands for longer with a reduced transverse flow

➡️ More photons, softer photons ⬅️
Effect of viscosity on the rates

Viscous corrections to rate suppress the $v_2$ at high $p_T$

(And only part of the rates are corrected)
Direct photons

Late stage photons and hadronic rates
Late stage photons

Significant contribution of late stage photons to $v_2$

► Need afterburner calculation? ◄
Using latest hadronic rates is important
(many emission channels contribute)
Verdict: puzzle or not?

- Modern hydro + latest hadronic photon rates = reasonable agreement with measurements, mild tension at worst
- Large thermal photon $v_2$
- Late stage photons & hadronic rates are important for photon $v_2$

*Thermal photons can explain most low $p_T$ direct photon excess and $v_2$*
Where do we go from here?

- **Late stage photons:** transport model?
- **Photon emission rates:** QGP/crossover/hadronic thermal rates & effect of viscosity
- **Prompt photons:** Parton energy loss vs fragmentation photons; jet-QGP photons
- **Include other proposed sources of photons?**
Backup
Hadronic rates comparison

**Two different hadronic rates calculations:**
Texas-A&M/McGill and Stony Brook (Zahed-Dusling)

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**Graph 1:**
- **LHC 0-40%**
- Direct photons
- ALICE (prelim)
- QGP LO+Rapp HG
- QGP LO+Zahed-Dusling HG

**Graph 2:**
- Pb-Pb 0-40%
- $\sqrt{s}=2.76$ TeV
- $V_2^{SP}$
- ALICE (prelim)
- QGP LO+Rapp HG
- QGP LO+Zahed-Dusling HG

(no $\delta f$)
RHIC $\sqrt{s_{NN}} = 200$ GeV

Multiplicity of $\pi^+, K^+ \& p$

Mean transverse momentum of $\pi^+ \& K^+$

$v_2$ and $v_3$ of charged hadrons
**Dual effect of viscosity**

*Thermal photons:*

\[
E \frac{d^3 N}{d^3 k} = \int d^4 X \left[ E \frac{\Gamma^{\text{ideal}}}{d^3 k} (K^\mu, u^\mu(X), T(X)) + E \frac{\Gamma^{\text{viscous}}}{d^3 k} (K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X)) \right]
\]

- Viscosity modifies:
  - The photon emission rate
  - Spacetime profile of the temperature, flow, volume, ...
Viscosity vs spacetime profile

**Thermal photons:**

\[
E \frac{d^3 N}{d^3 k} = \int d^4 X \left[ E \Gamma^{\text{ideal}} (K^\mu, u^\mu (X), T(X)) + E \Gamma^{\text{viscous}} (K^\mu, u^\mu (X), T(X), \pi^{\mu \nu}(X), \Pi(X)) \right]
\]

- Viscosity modifies:
  - The photon emission rate
  - Spacetime profile of the temperature, flow, volume, ...

...
Bulk vs spacetime/flow profiles

**Increased spacetime**

- 50% increase

**Smaller flow velocity**

\[ u^\tau = \sqrt{1 + (u_x)^2 + (u_y)^2} \]
Bulk: change shape of $v_2$
Other thermal rates

Direct photon spectra

Direct photon $v_2$

LHC 0-40%
RHIC $\sqrt{s_{NN}} = 200$ GeV: $v_2$

Direct photon $v_2$

0-20% RHIC 20-40%