Direct Photons: Messengers from relativistic heavy-ion collisions

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Relativistic Heavy-ion Collisions

direct photons

prompt photons

jet in-medium bremsstrahlung

jet-plasma photons

collision overlap zone

pre-equilibrium photons

direct photons

thermal radiation

QGP phase

Hadron gas phase

colliders

decay photons

$\pi^0$

$\pi^+$

$K$

$K^-$

$p$

$\pi^-$
Thermometer and speedometer
Fitted $T_{\text{eff}}$ from Experiments

RHIC

fit: $A \exp(-p_T/T) \quad T = 304 \pm 51^{\text{stat}}_{\text{sys}}$ MeV

LHC

0 - 20%

$T = 221 \pm 19 \pm 19$ MeV

What does this T mean?
Slope of Photon Spectrum

Slicing the hydrodynamic medium
Slope of Photon Spectrum

T = 400 MeV

T (GeV)
Slope of Photon Spectrum

\[ T = 300 \text{ MeV} \]
Slope of Photon Spectrum

T = 230 MeV

The diagram shows the spatial distribution of photon spectra at a fixed temperature T = 230 MeV, with the slope of the photon spectrum plotted against q (GeV) for different values of x (fm) and τ (fm/c). The left panel presents a contour map of the photon spectrum, while the right panel shows a plot of dN/df_T (GeV^-2) against q (GeV).
Slope of Photon Spectrum

T = 160 MeV

T (GeV)

$\frac{dN^\gamma}{dy_\parallel dq_T}$ (GeV$^{-2}$)

$q$ (GeV)

$10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$

1.0 1.5 2.0 2.5 3.0 3.5 4.0

$\tau$ (fm/c)

$x$ (fm)
Slope of Photon Spectrum

T = 120 MeV

T (GeV)

\(\tau (\text{fm/c})\)

\(x (\text{fm})\)

\(dN^\gamma / (dy_{\text{pT}} d_{\text{T}}) \ (\text{GeV}^{-2})\)

\(q (\text{GeV})\)
• All photons with $T < 250$ MeV at RHIC and $< 300$ MeV at LHC carries $T_{\text{eff}}$ within the experimental fitted region

• About **50-60%** of photons are emitted from $T = 165\sim250$ MeV, they are strongly blue shifted by radial flow

$$T_{\text{eff}} = T \sqrt{\frac{1 + v}{1 - v}}$$
Slope of Photon Spectrum

\( T \text{ (GeV)} \)

\( \tau = 0.6 \text{ fm/c} \)

\( dN^\gamma / (d\eta | dq_T) \text{ (GeV}^{-2} \)
Slope of Photon Spectrum

\[ \tau = 2.5 \text{ fm/c} \]
Slope of Photon Spectrum

\( \tau = 4.5 \text{ fm/c} \)
Slope of Photon Spectrum

\[ \tau = 7.5 \text{ fm/c} \]
• About 25% of thermal photons are emitted in the first 2 fm/c
• After 2 fm/c, thermal photons are significantly blue shifted by radial flow
• Viscous corrections to the slope of photon spectra are stronger during the early part of the evolution
A large $T_{\text{eff}}$ is in favour of thermal emission with strong blue shift scenario, in which the hydrodynamic flow originates from a high temperature core.

How about the $p_T$-integrated yield?
Centrality dependence of photon yield

Paquet, Shen, Denicol, Luzum, Schenke, Jeon, and Gale, arXiv:1509.06738


• Thermal photon yield shows a stronger centrality dependence than prompt photons

\[
\frac{dN^\gamma}{dy} \propto N_{\text{part}}^{1.4} \frac{dN^\pi}{dy} \propto \frac{\langle T^4 \rangle \tau_f V}{\langle s \rangle V} \propto \langle T \rangle \tau_f
\]
Centrality dependence of photon yield

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• Thermal photon yield shows a stronger centrality dependence than prompt photons


\[
\frac{dN}{dy} \propto \frac{dN_{\text{ch}}}{dy} \propto \frac{\langle T \rangle T_f}{\langle s \rangle V} \propto \langle T \rangle \tau_f
\]

MCGBl Au+Au @ RHIC

\(1 < p_T < 3 \text{ GeV}\)
Viscometer
Framework of modelling direct photons

Initial Condition Generators

Hydrodynamic Evolution

Hadrons spectra & $v_n$

Thermal Photon Emission Rates

$E \frac{dN^\gamma}{d^3p} = \int d^4x q \frac{dR}{d^3q}$

Thermal Photon Interface

Photon spectrum & $v_n$
Framework of modelling direct photons

Initial Condition Generators

Hydrodynamic Evolution

Thermal Photon Emission Rates

Thermal Photon Interface

\[ E \frac{dN^\gamma}{d^3p} = \int d^4x q \frac{dR}{d^3q} \]

\[ q \frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} q_\mu q_\nu}{2(e+p)} a_{\alpha\beta} \Gamma^{\alpha\beta} \]

Hadrons spectra & \( v_n \)

Photon spectrum & \( v_n \)
Photon emission rate

**QGP**

LO: AMY JHEP 0112, 009, (2001)


NLO: J. Ghiglieri et al., JHEP 1305, 010 (2013)

**Hadron Gas**


Photon emission rate

QGP

Hadron Gas

\[ f = f_{eq} + \delta f \]

NLO: J. Ghiglieri et al., JHEP 1305, 010 (2013)


Shear viscous effects on photon elliptic flow

- Shear viscous suppression of photon $v_2$ is dominated by the viscous corrections to the photon emission rate
- Photon elliptic flow is sensitive to the larger shear stress tensor at early times
Shear viscous effects on photon elliptic flow

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- Photon elliptic flow is sensitive to the larger shear stress tensor at early times.
New developments in hydrodynamics


IP-Glasma + MUSIC + UrQMD

\[
\tau_{\pi} \Delta_{\alpha\beta}^{\mu\nu} \pi^{\alpha\beta} + \pi^{\mu\nu} = 2\eta \phi^{\mu\nu} + \lambda_{\pi\Pi} \Pi \sigma^{\mu\nu} \\
-\delta_{\pi\pi} \pi^{\mu\nu} \theta - \tau_{\pi\pi} \Delta_{\alpha\beta}^{\mu\nu} \pi^{\alpha\lambda} \sigma_{\lambda}^{\beta} + \phi \Delta_{\alpha\beta}^{\mu\nu} \pi^{\alpha\lambda} \pi^{\lambda}^{\beta} \\
\tau_{\Pi} \dot{\Pi} + \Pi = -\zeta^{\mu\nu} - \delta_{\Pi\Pi} \Pi \theta + \lambda_{\Pi\pi} \pi^{\mu\nu} \sigma_{\mu\nu}
\]

\[\eta/s = 0.095\]
New developments in hydrodynamics

IP-Glasma + MUSIC + UrQMD


\[ \frac{\eta}{s} = 0.095 \]

\[ \frac{\zeta}{s(T)} \]

- Excellent agreement with global hadronic observables
- Bulk viscosity is **essential**
Bulk viscous effects on space-time evolution

\[ P_{\text{eff}} = P_{\text{eq}} - \zeta \partial \cdot u \]

- Bulk viscosity reduces **radial flow** by \(~10\%\)
- Bulk viscosity increases **space-time volume** by \(~50\%\) in the hadronic phase

**More space-time volume in late stage evolution**
The soften of direct photon spectrum is due to the reduction of hydrodynamic radial flow and more hadronic emission.

The peak of direct photon $v_2$ shifted towards low $p_T$. 
Towards resolving the direct photon flow puzzle?

Paquet, Shen, Denicol, Luzum, Schenke, Jeon, and Gale, arXiv:1509.06738

• Latest calculations show much reduced tension between theory and experiment
Towards resolving the direct photon flow puzzle?

Paquet, Shen, Denicol, Luzum, Schenke, Jeon, and Gale, arXiv:1509.06738

- Latest calculations show much reduced tension between theory and experiment.
- Theory still underestimates the direct photons yield from additional sources?

![Graphs showing direct photon flow at RHIC and LHC](attachment:image.png)
Jet in-medium bremsstrahlung is comparable with the prompt photons from Pythia showers.

Its anisotropy and fragmentation photons are under investigation.
Tomography
By cutting hydro medium both in $T$ and $\tau$, we observe a **two-wave** structure in thermal photon emission:

- **early time production** — high rates at **high temperatures**
- **near transition region** — **growth of space-time volume**

Thermal photon tomography

MCGlab, $\eta/s = 0.08$
0-20% Au+Au @ 200 A GeV
1 < $p_T$ < 4 GeV
Thermal photon tomography
Thermal photon tomography

$1 \leq p_T \leq 4\text{GeV}$

- By cutting hydro medium both in $T$ and $\tau$, we observe a **two-wave** structure in thermal photon emission.
- Thermal photon $v_2$ is mostly coming from the transition region, $T = 150\sim200\text{ MeV}$, $\tau = 3 \sim 8\text{ fm}$ @ RHIC.
A microscope for the QCD matter
Collective behavior are observed in high multiplicity p+Pb and d+Au collisions at the RHIC and LHC.

Within hydrodynamic framework, we find central p+Pb collisions can reach high temperature and the estimated Knudsen number is small.

\[ K_\theta = \frac{5\eta}{(e + P) \partial_\mu u^\mu} \]
(2+1)-d hydro can give a reasonable description of the hadronic data
In minimum bias \(p+Pb\) collisions, thermal photons are small compared to prompt photons.

There is sizeable direct photon anisotropic in \(p+Pb\) collisions.

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### Summary

- In minimum bias \(p+Pb\) collisions, thermal photons are small compared to prompt photons.
- There is sizeable direct photon anisotropic in \(p+Pb\) collisions.
In 0-20% p+Pb collisions, thermal photons become comparable to prompt photons.

There is sizeable direct photon anisotropic in central p+Pb collisions.
• In 0-1% p+Pb collisions, thermal photon can out-shine prompt photons

• **Sizeable** direct photon anisotropy in central p+Pb collisions!
Thermal emission in small systems


- Thermal photon radiation can leave visible imprint in the minimum bias $R_{pA}$

$$R_{pA} = \frac{(\frac{dN^\gamma}{dy_{pT}dp_T})_{pA}}{\langle N_{coll}\rangle (\frac{dN^\gamma}{dy_{pT}dp_T})_{pp}}$$
Thermal emission in small systems


- Thermal photon radiation can leave visible imprint in the minimum bias $R_{pA}$ signature of hot medium.
Jet in-medium Bremsstrahlung in pA

- Jet energy loss is smaller in pA compared to AA owing to the small size of the system
- Jet in-medium bremsstrahlung is smaller compare to the prompt photons from Pythia showers
Conclusion

• Electromagnetic probes are very sensitive to:
  • initial conditions/pre-equilibrium flow
  • non-equilibrium properties/transport coefficients
  • dynamics over all stages of heavy-ion collisions

• Simulating photons is an art of combining precision modelling of the dynamics of heavy-ion collisions with the state-of-the-art calculations of the emission rates

• Recent theory improvements released some tension with the direct photon measurements at the RHIC and the LHC

• Photons can serve as a diagnostic tool of small collision systems
Back up
• In 0-1% p+Pb collisions, thermal photons can shine over prompt photons
• There is sizeable direct photon anisotropic in central p+Pb collisions
viscous correction in pA

MCGlb. 0-1% p+Pb @ 5.02 TeV
1 < p_T < 1.5 GeV
viscous correction in pA

0-1% p+Pb @ 5.02 TeV

\( \frac{dN}{(2\pi dydp_T dp_T)} \) (GeV\(^{-2}\))

- **total**
- **thermal**
- **thermal** \(|\delta f| < f_{eq}\)
- **thermal no \(\delta f\)**
- **prompt**

\( p_T \) (GeV)
viscous correction in pA

0-1% p+Pb @ 5.02 TeV

$v_2$ full
$v_2$ no $\delta f$
$v_2 |\delta f| < f_{eq}$

thermal photons

$p_T$ (GeV)
viscous correction in pA

\[ v_2 \text{ full} \quad 0-1\% p+Pb @ 5.02 \text{ TeV} \quad \text{(b)} \]

\text{thermal + prompt photons}

\[ v_2 \text{ no } \delta f \]

\[ |\delta f| < f_{eq} \]