Holographic photon and dilepton production in a thermalizing plasma

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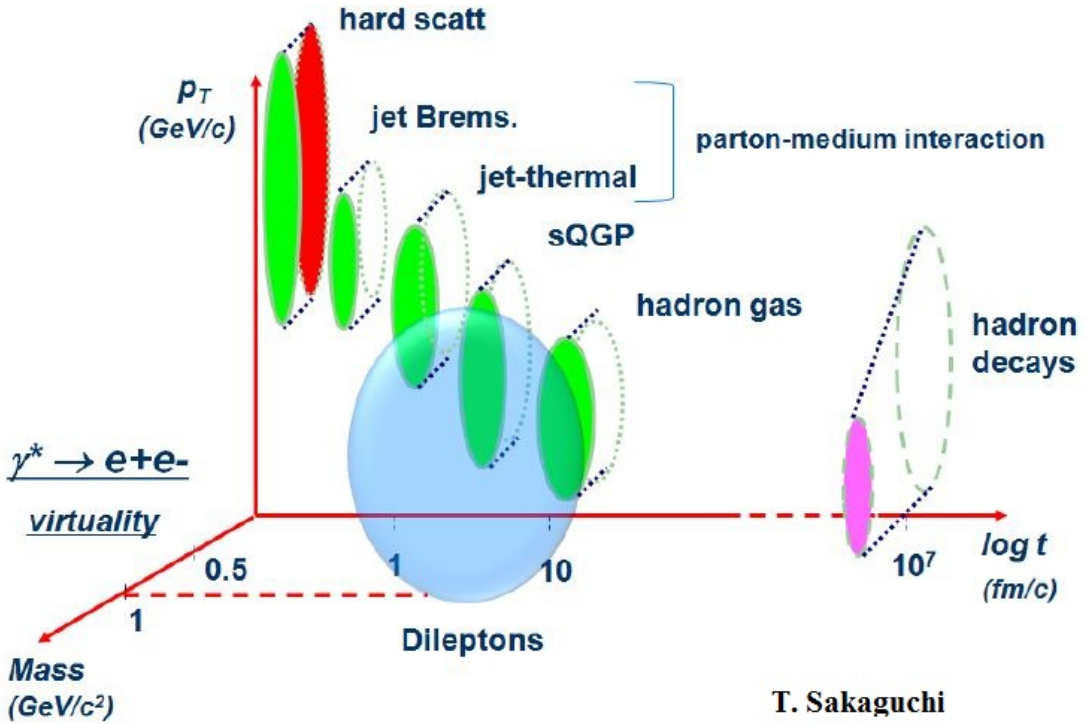
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Photon emission in heavy ion collisions



Photons emitted at all stages of a heavy ion collision

- Direct photons from initial hard scattering and thermalizing plasma
- Additional (uninteresting) emissions from charged hadron decays
- Virtual photons $\rightarrow$ Dilepton pairs

Interesting aspect: Weak coupling of EM probes to the plasma

Photon emission in heavy ion collisions

Differential photon production rate:

$$k^0 \frac{d\Gamma_\gamma}{d^3k} = \frac{1}{4\pi k}\frac{d\Gamma_\gamma}{dk_0} = \frac{\alpha}{4\pi^2}\eta^{\mu\nu}\Pi^<_{\mu\nu}(k^0 = k) \,,$$

with $\Pi^<_{\mu\nu}$ the EM current Wightman function

$$\Pi^<_{\mu\nu}(k_0, k) = \int \mathrm{d}^4x\, e^{-iK\cdot x}\langle J^{\mathrm{EM}}_\mu(0) J^{\mathrm{EM}}_\nu(x)\rangle$$

In thermal equilibrium, Fluctuation Dissipation Theorem $\Rightarrow$

$$\eta^{\mu\nu}\Pi^<_{\mu\nu}(k^0 = k) = n_B(k^0)\chi^\mu_\mu(k_0) = -2n_B(k^0)\mathrm{Im}(\Pi^{\mathrm{ret}})^\mu_\mu(k_0)$$

Problem: Extracting spectral function from lattice extremely difficult — perturbation theory complicated and convergence suboptimal (see poster by J. Ghiglieri)

Photon/dilepton emission in SYM plasma

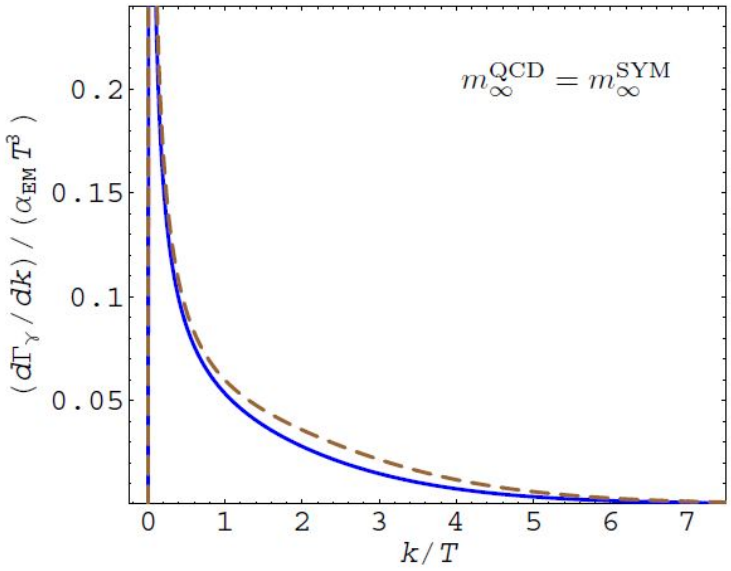
Clearly, a case calling for holographic methods: Photon and dilepton production at strong coupling

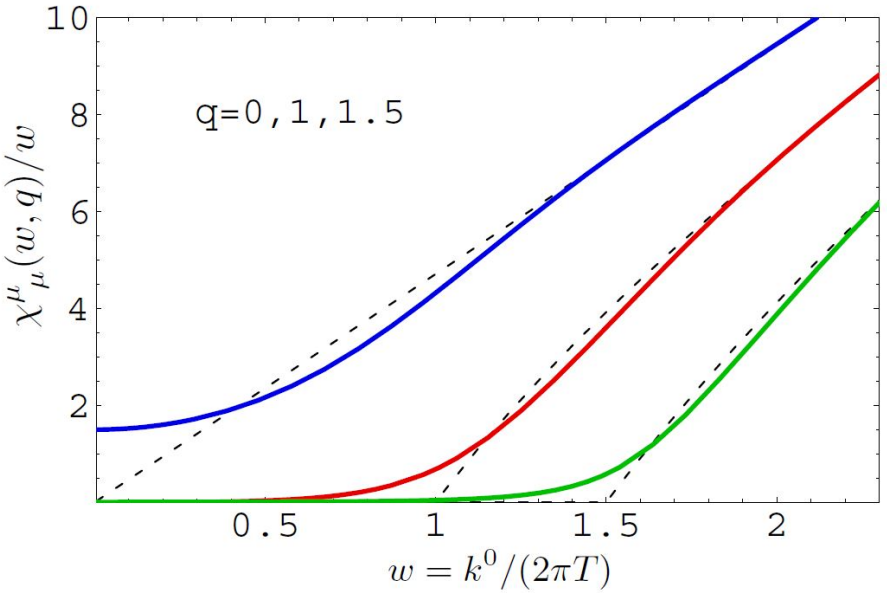
Cleanest holographic setup: Strongly coupled, large-N_c $\mathcal{N} = 4$ SYM theory at finite $T \Leftrightarrow$ Classical gravity in AdS_5 black hole background

- Duality well established
- Not too far from QGP: Deconfined non-Abelian plasma with SUSY and conformal invariance broken by finite T
- Weakly coupled limit of SYM accessible as easily as that of QCD

EM interactions: Add to the theory a U(1) gauge field coupled to a conserved current corresponding to $U(1) \subset SU(4)_R$, such that $\mathcal{N} = 4$ fermions and scalars have equal charges

Photon/dilepton emission in SYM plasma

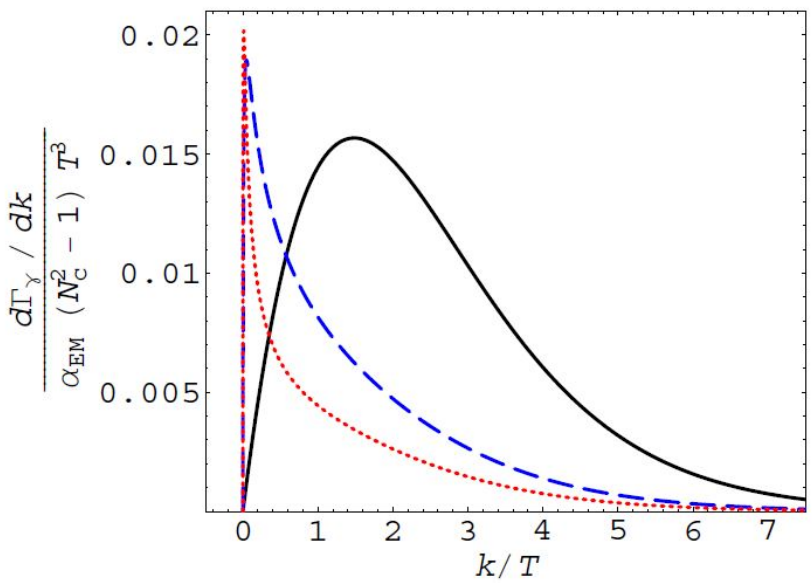


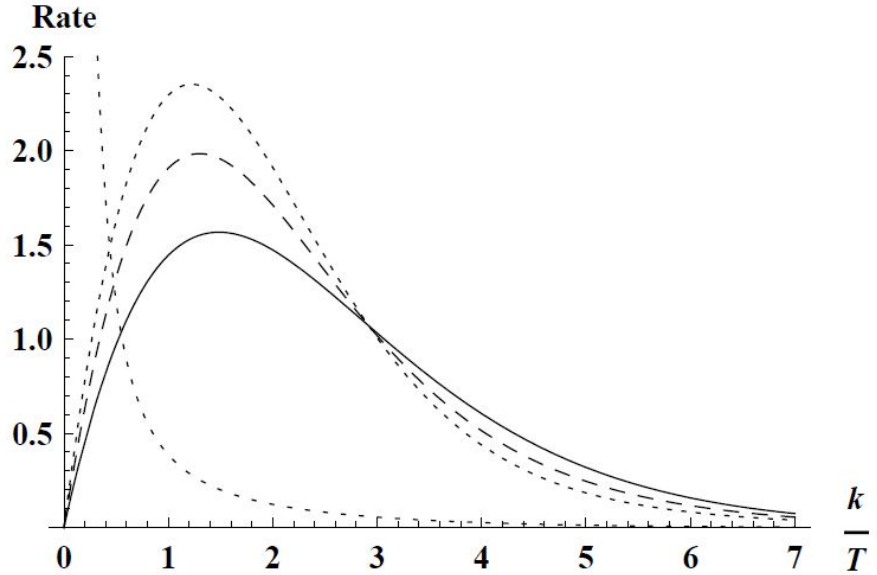


Caron-Huot *et al.* (2006):

- Weakly coupled limits of QCD and $\mathcal{N} = 4$ SYM very similar (almost identical for fixed fermionic thermal masses)
- Strong coupling results for both photon and dileption spectral densities determined

Photon/dilepton emission in SYM plasma





Caron-Huot *et al.* (2006) & Hassanain *et al.* (2011):

- Effect of increasing coupling in perturbative result: Slope at $k = 0$ decreases, hydro peak broadens and moves right
- Effect of decreasing coupling from $\lambda = \infty$: Peak sharpens and moves left

Out of equilibrium

Equilibrium picture in SYM theory fairly complete. Natural next question: How about photon/dilepton emission out of equilibrium?

Extremely challenging question for traditional QFT methods, (slightly) less so on the gravity side.

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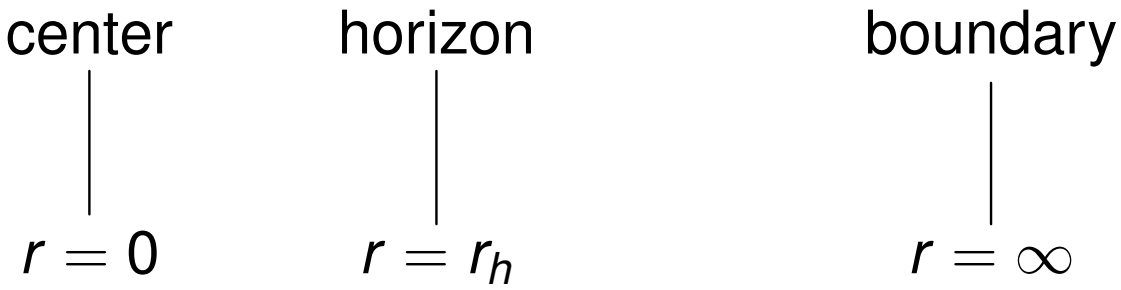
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AdS/CFT duality: Finite T

- Classical gravity in AdS_5 space with a black hole of radius $r_h \Leftrightarrow$ Strongly coupled large-N_c $\mathcal{N} = 4$ Super Yang-Mills theory at finite temperature $T = r_h/\pi$

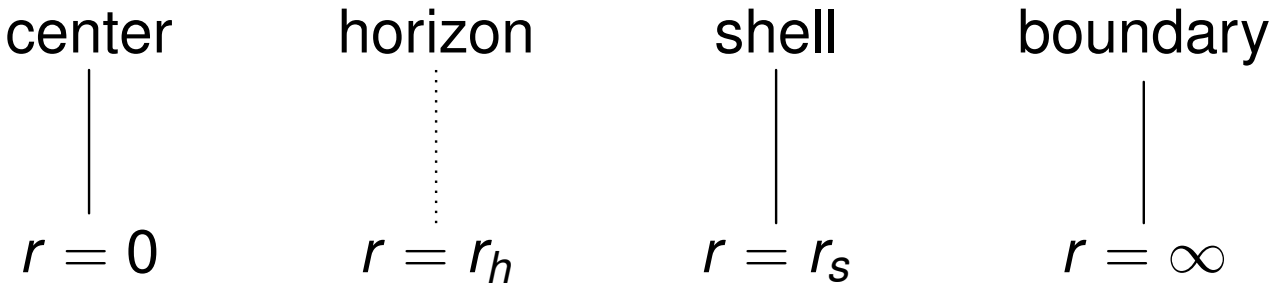


- Metric of the setup:

$$ds^2 = -(1 - \frac{m^2}{r^2} + r^2)dt^2 + \frac{dr^2}{1 - \frac{m^2}{r^2} + r^2} + r^2 d\mathbf{x}^2$$

AdS/CFT duality: Thermalizing system

- Simplest way to take system out of equilibrium: Begin with a thin massive shell at $r = r_s > r_h$ and let it collapse towards $r_s = r_h$



- On the boundary the metric looks like a black hole solution $\Rightarrow$ 1-point functions look thermal
- 2-point functions 'see' the position of the shell through modified boundary conditions $\Rightarrow$ non-equilibrium results
- Model proposed by Danielsson *et al.* (1999), analyzed in more detail by Lin, Shuryak (2008)

The falling shell system

Some generic remarks:

- The shell fills all of the Minkowski 3-space $\Rightarrow$ System fully symmetric both rotationally and translationally symmetric
- Matter content and initial condition of the shell can be chosen at will; after this, time dependence of the system obtainable by solving the shell's EoM
- So far, nearly all work within the setup (including ours) in the *quasistatic approximation*, i.e. considering the shell static when solving for field theory correlators
  - Holds as long as $\omega \gg 1/\tau_s$, where ω energy scale of interest and τ_s characteristic time scale of shell's motion
  - Not *dynamic thermalization* in the sense of previous talks of this morning

Photon and dilepton emission with $r_s > r_h$

Goal: Repeat calculation of Caron Huot *et al.* in the collapsing shell background and try to find *qualitative characteristics* of photon and dilepton emission spectra out of thermal equilibrium. Specialize to dileptons at rest ($k = 0$).

NB: Relating Wightman function to the easily computable retarded correlator via Fluctuation Dissipation Theorem non-trivial out of equilibrium (cf. talk of D. Teaney); can be shown to hold in the quasistatic limit of the falling shell setup following Herzog, Son (2002).

Quick recap of the calculation

1. Write down and solve EoM for appropriate electric field E inside and outside the shell (for dileptons $K = (\omega, 0)$, photons $K = (\omega, \omega)$)
2. Match the two solutions at the shell (here important simplification due to quasistatic approximation)
   - Note: With $r_s > r_h$, outside solution has also an outgoing component
3. Expand solution at the boundary and evaluate $\chi(\omega, r_s/r_h)$ using conventional methods (Son, Starinets)
   - r_s/r_h parametrizes thermalization; time dependence (if wanted) from shell EoM

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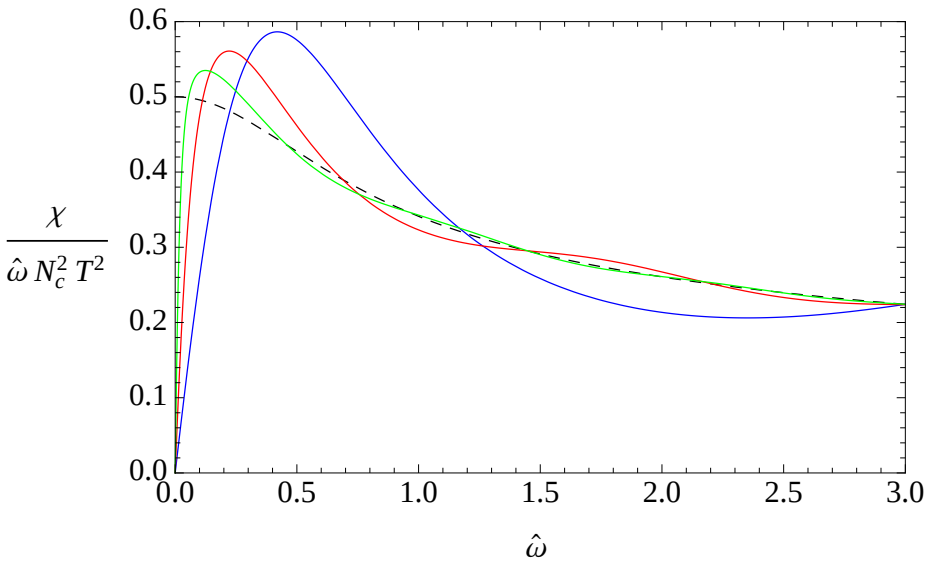
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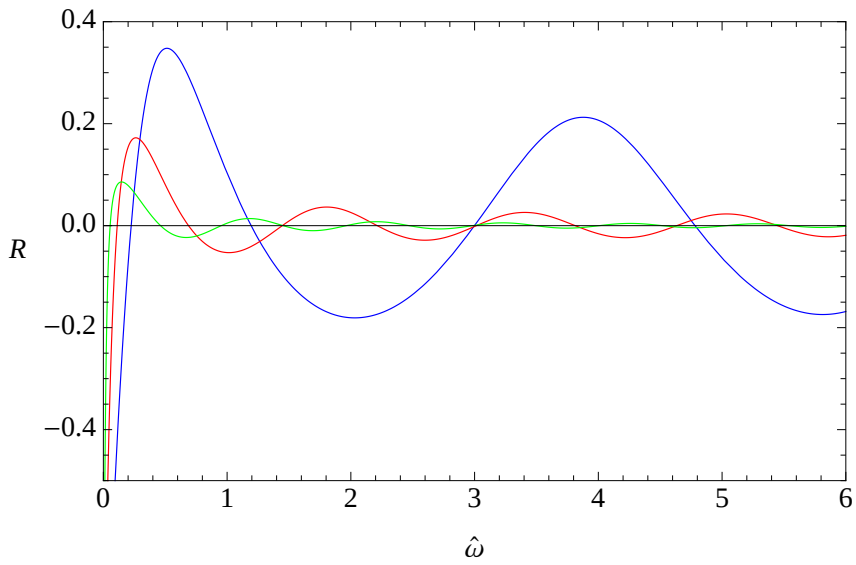
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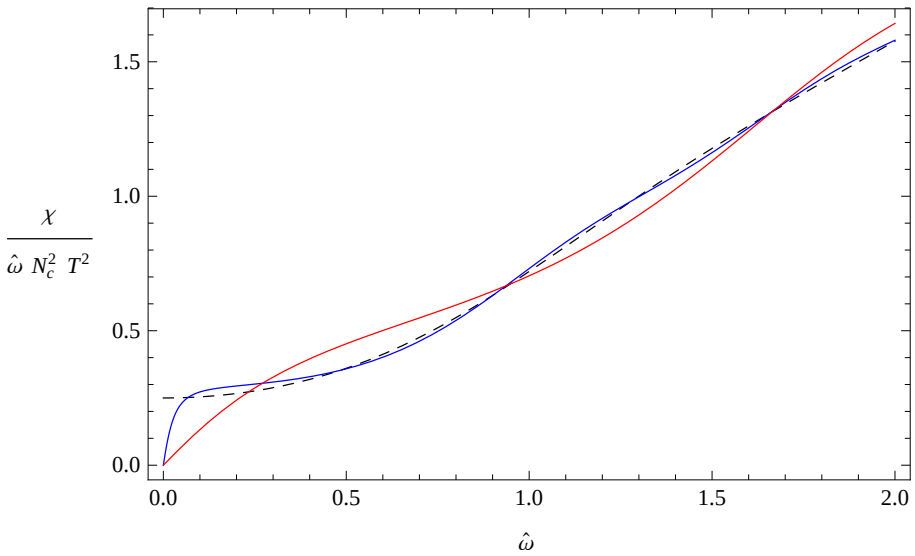
Photon spectral density

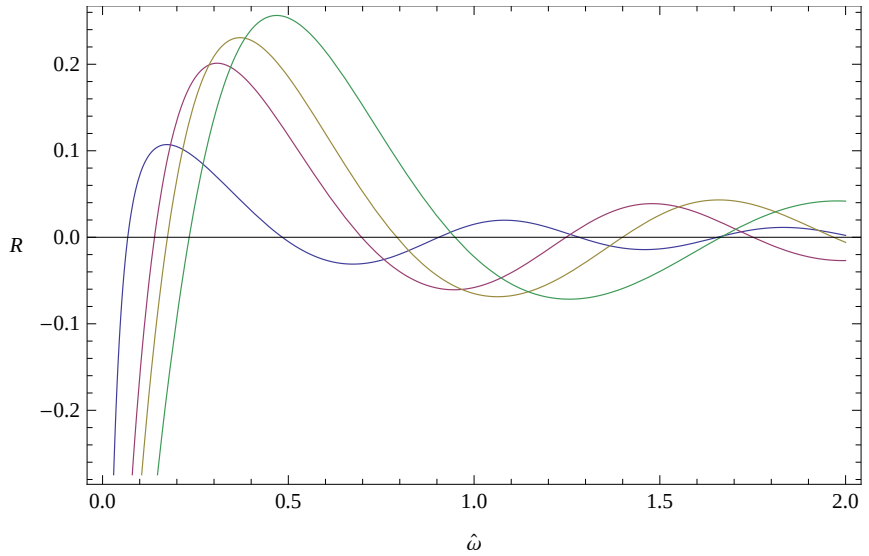




$\chi_{\text{photon}}(\omega = k = 2\pi T\hat{\omega}, r_s/r_h)$ and relative deviation
$R \equiv (\chi - \chi_{\text{therm}})/\chi_{\text{therm}}$, with r_s/r_h increasing from 1.001 to 1.1

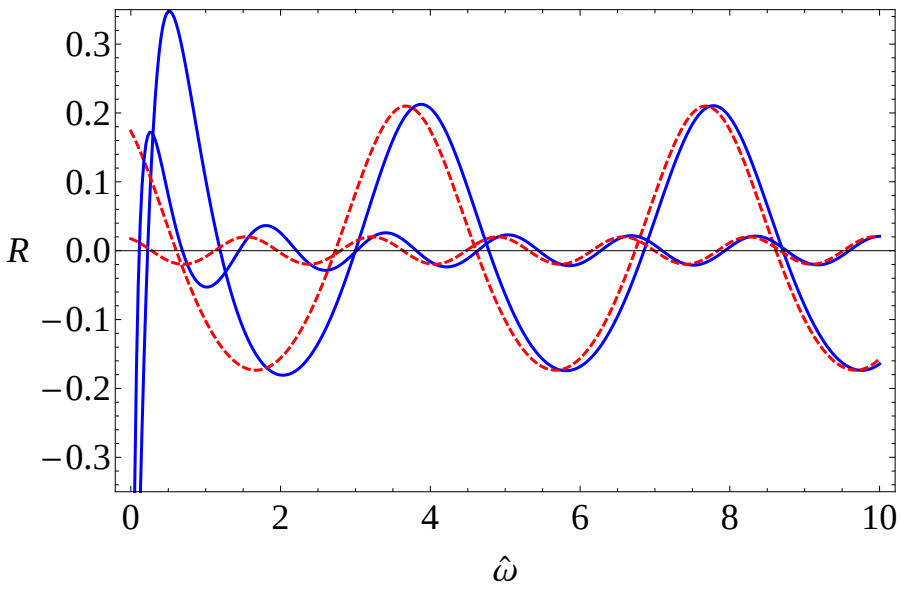
Dilepton spectral density

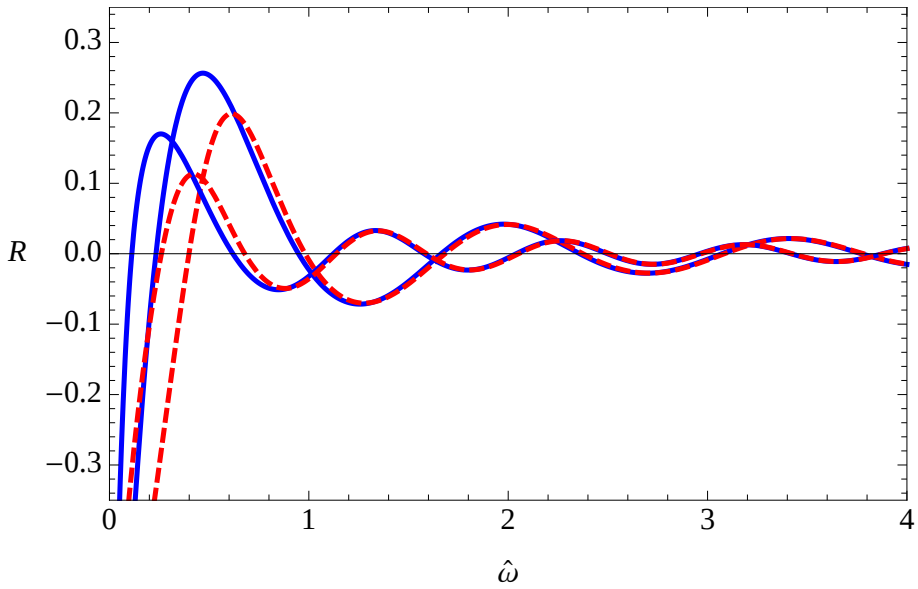




$\chi_{\text{dilepton}}(\omega = 2\pi T\hat{\omega}, k = 0, r_s/r_h)$ and relative deviation
$R \equiv (\chi - \chi_{\text{therm}})/\chi_{\text{therm}}$, with r_s/r_h increasing from 1.002 to 1.1

Photon vs. dilepton spectral density at high ω

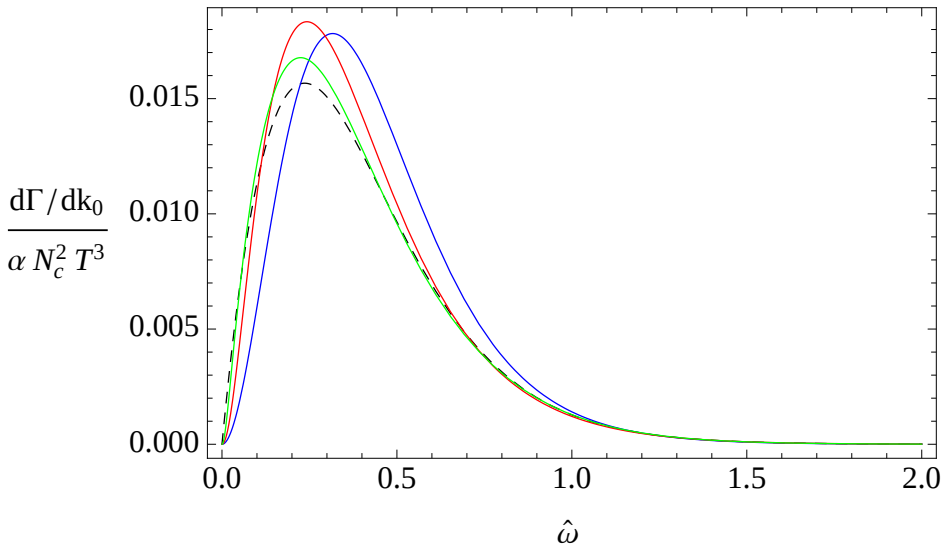


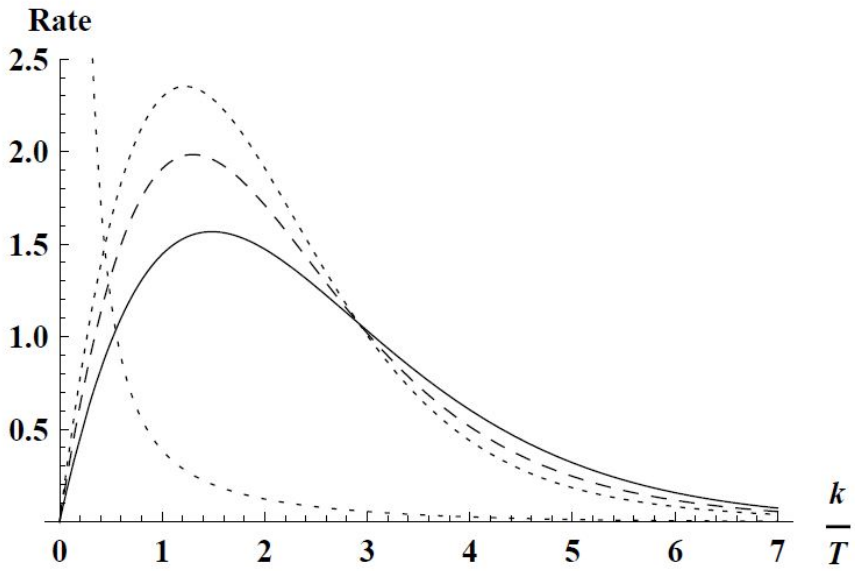


Relative deviations for $r_s/r_h = 1.01$ and 1.1 together with their analytic large-ω limits.

Interesting detail: Amplitude of fluctuations constant for photons, suppressed at large ω for dileptons. Connection to virtuality of produced photons?

Photon emission rates





Curious similarity between off-equilibrium and finite coupling modifications to $\lambda \to \infty$ limit of equilibrium photon emission rate

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Conclusions and outlook

- Dilepton and photon emission rates computed in thermalizing $\mathcal{N} = 4$ SYM plasma
- Thermalization through quasistatic limit of falling shell setup
  - Not dynamical thermalization, yet interesting starting point for more careful analysis
- Qualitative finding: Oscillations in out-of-equilibrium photon and dilepton spectral densities, which behave differently at large ω
  - Curiosity of shell model or something more universal?
- Challenges for the future:
  - Go beyond quasistatic approximation (Keski-Vakkuri *et al.*)
  - $1/\lambda$ corrections also out of equilibrium (Steineder, Stricker)
  - Falling shell from scalar field dynamics? (Bin Wu)