Bottom up versus top down thermalization

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D. Steineder, SS, A. Vuorinen, arXiv:1209.0291 (accepted in PRL)
R. Baier, SS, O. Tanilla, A. Vuorinen,, Phys. Rev. D 86, 081901(R) (2012)
R. Baier, SS, O. Tanilla, A. Vuorinen, JHEP 1207 (2012) 094

Outline

Motivation

quark gluon plasma

- produced in heavy ion collisions at RHIC and LHC
- behaves as a strongly coupled liquid
- hydrodynamic simulations work surprisingly well
- apparent puzzle: fast thermalization : $\tau < 1 fm/c$

goal

- gain insight into thermalization process
- which modes thermalize first ?
- production rates of weakly interacting particles

strategy

- use photons/dileptons as probes of the QGP

Thermalization scenerios

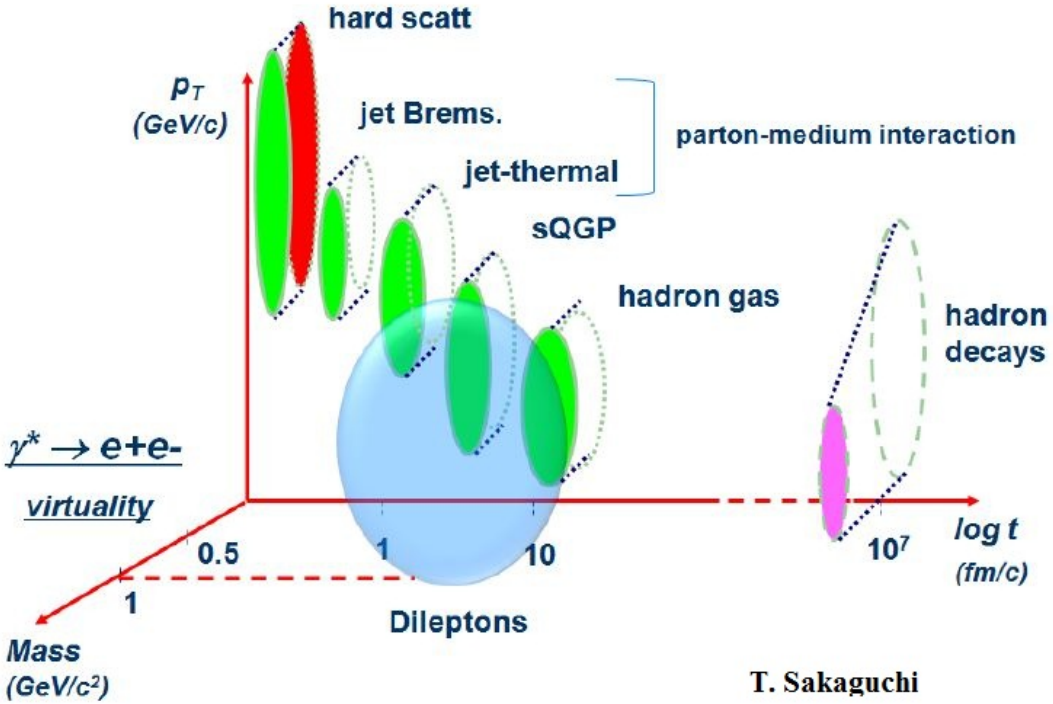
bottom up scenario

- at weak coupling
- scattering processes:
  - in the early stages many soft gluons are emitted which then thermalize the system (*Baier et al*)
- driven by instabilities
  - instabilities isotropize the momentum distribution more rapidly than scattering processes (*Kurkela, Moore*)

top down scenario

- at strong coupling
- UV modes thermalize first
- In AdS calculations at infinte coupling, follows naturally from causality

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 → Dilepton pairs

Probing the plasma

probing the plasma

- once produced photons and dileptons stream through the plasma almost unaltered
- provide observational window in thermalization process of the plasma

quantity of interest

- number of photons emitted with given momentum
- differential production rate per unit volume

$$\frac{d\Gamma_\gamma}{dk_0} = \frac{\alpha_{\mathrm{EM}}}{\pi} k_0 n_B(k^0) \chi^\mu_\mu = \frac{-2\alpha_{\mathrm{EM}}}{\pi} k_0 n_B(k^0) \mathrm{Im}(\Pi^{\mathrm{ret}})^\mu_\mu(k_0)$$

problem

- very hard to study out of equilibrium in strongly coupled regime

Our approach

use SYM theory where strongly coupled regime is accessible

gauge gravity duality

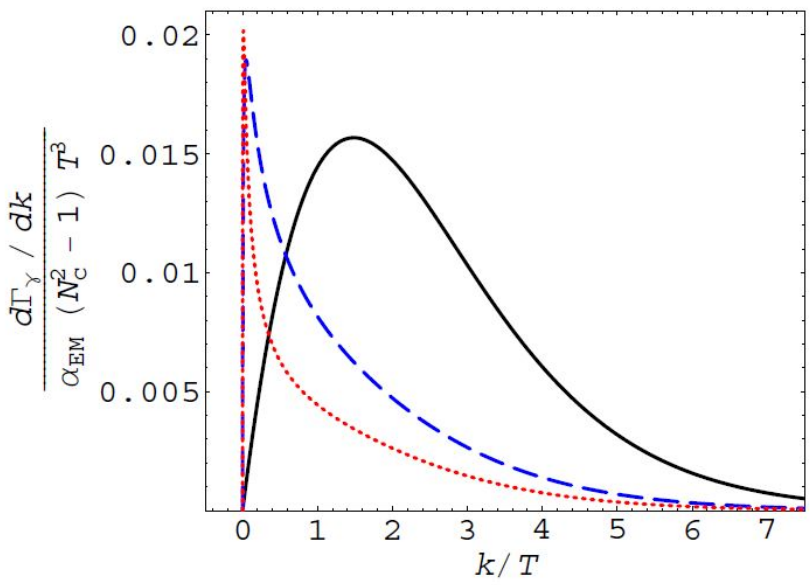
- strongly coupled large N_c, $\mathcal{N} = 4$ SYM at finite T $\Leftrightarrow$ classical gravity in AdS_5 black hole background
- temperature of the black hole can be identified with field theory temperature

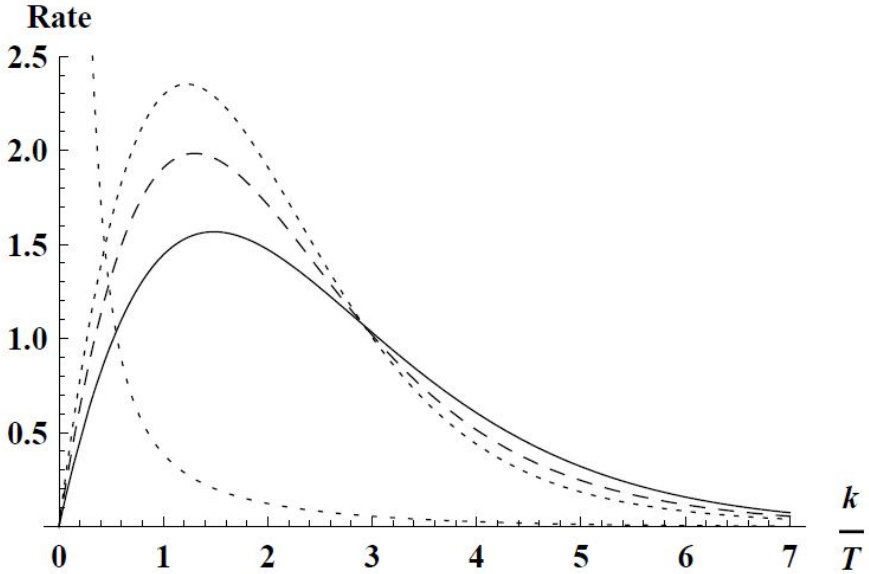
similarities to QCD at finite T

- deconfinement
- Debye screening
- SUSY and conformal symmetry broken
- finite spatial screening length

advantage: can calculate observables at week and strong coupling

Photon emission in equilibrium SYM plasma





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

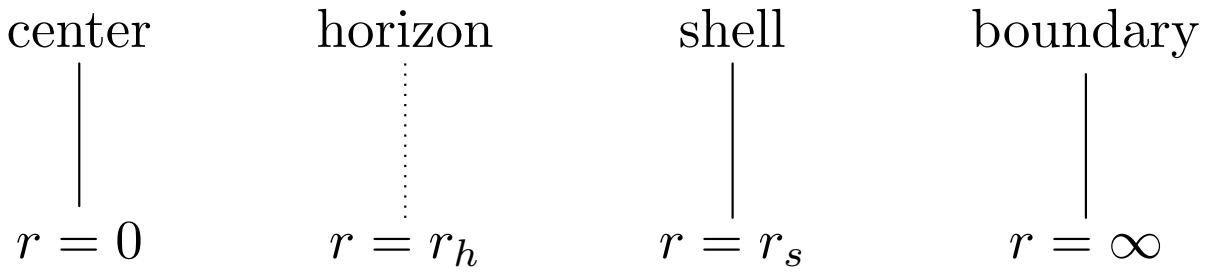
- Effect of increasing coupling in perturbative result: Slope at $k = 0$ decreases, hydro peak broadens and moves right
- Effect of decreasing coupling from $\lambda = \infty$: Peak sharpens and moves left

Out of equilibrium

- equilibrium picture in SYM fairly complete
- how does photon/dilepton emission rate get modified out of thermal equilibrium ?
- can one access thermalization at finite coupling ?

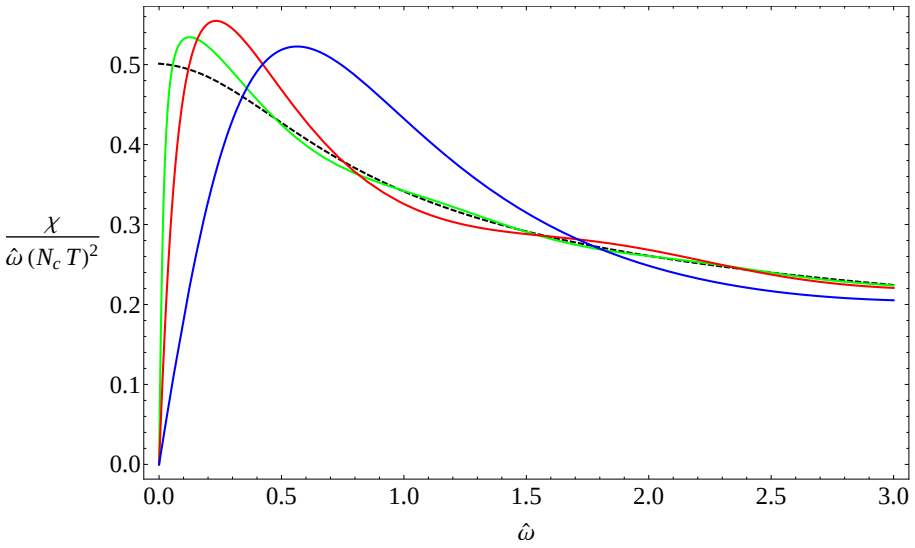
AdS/CFT duality: Thermalizing system

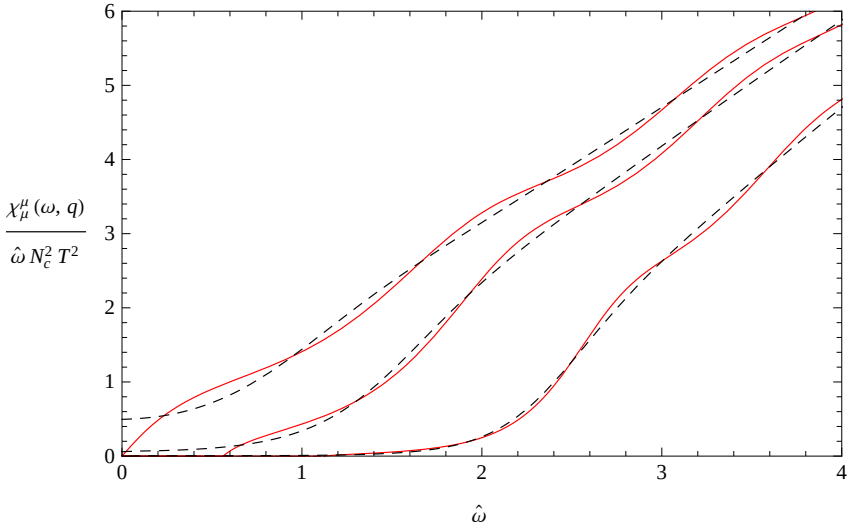
- Simplest way to take system out of equilibrium: Begin with a thin massive shell at $r = r_s > r_h$ and let it collapse towards $r_s = r_h$ (Danielsson, Keski-Vakkuri, Kruczenski (1999))



- 2-point functions 'see' the location of the shell through modified boundary conditions $\Rightarrow$ Out-of-equilibrium effects
- **quasistatic approximation**: static shell; $\omega \gg 1/\tau_s$; energy scale of interest $\gg$ characteristic time scale of shells motion

Photon and dilepton spectral density





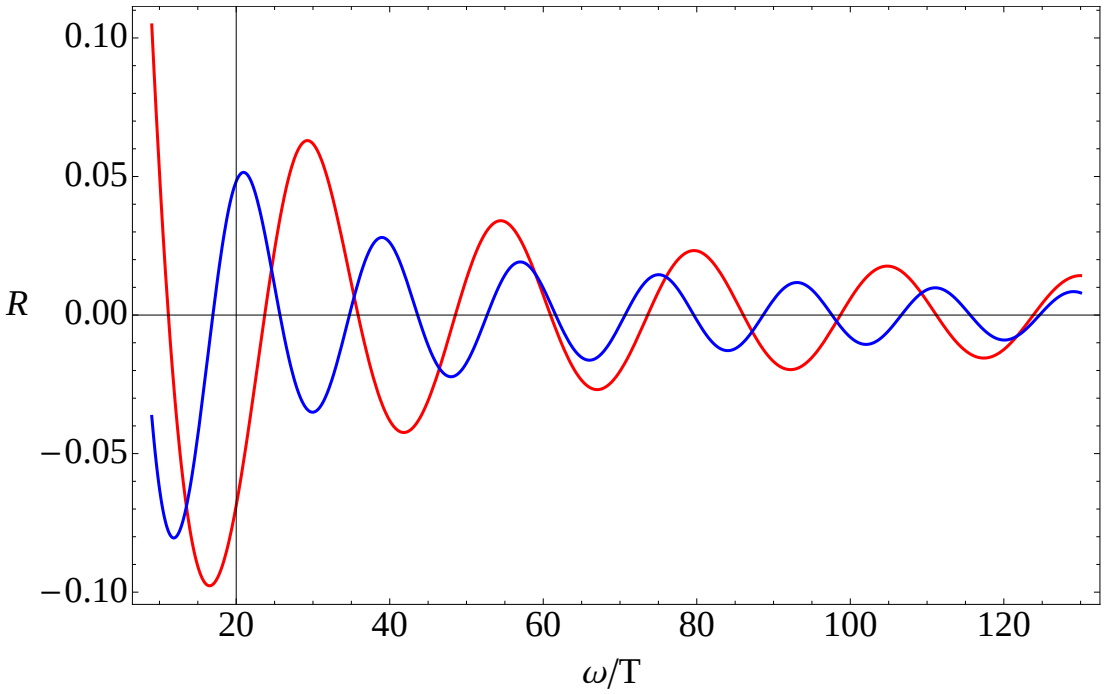
left: photon sepctral density $\chi_\gamma(\omega = k = 2\pi T\hat{\omega}, r_s/r_h)$ for $r_s/r_h = 1.001,\ 1.01,\ 1.1$. right: dilepton spectral density for $q = 0,\ 1,\ 2$.

- out of equilibrium effect: oscillations around thermal value
- as the shell approaches the horizon, equilibrium is reached

Thermalization at infinite coupling: photons

- relative deviation from thermal equilibrium

$$R(\hat{\omega}) = \frac{\chi(\hat{\omega}) - \chi_{th}(\hat{\omega})}{\chi_{th}(\hat{\omega})}$$



Relative deviation R_γ for $r_s/r_h = 1.01, 1.1$ and $\lambda = \infty$.

- top down thermalization: highly energetic modes are closer to their equilibrium value

$$\chi(\hat{\omega}) \approx \hat{\omega}^{\frac{2}{3}} \left(1 + \frac{f_1(u_s)}{\hat{\omega}}\right)$$

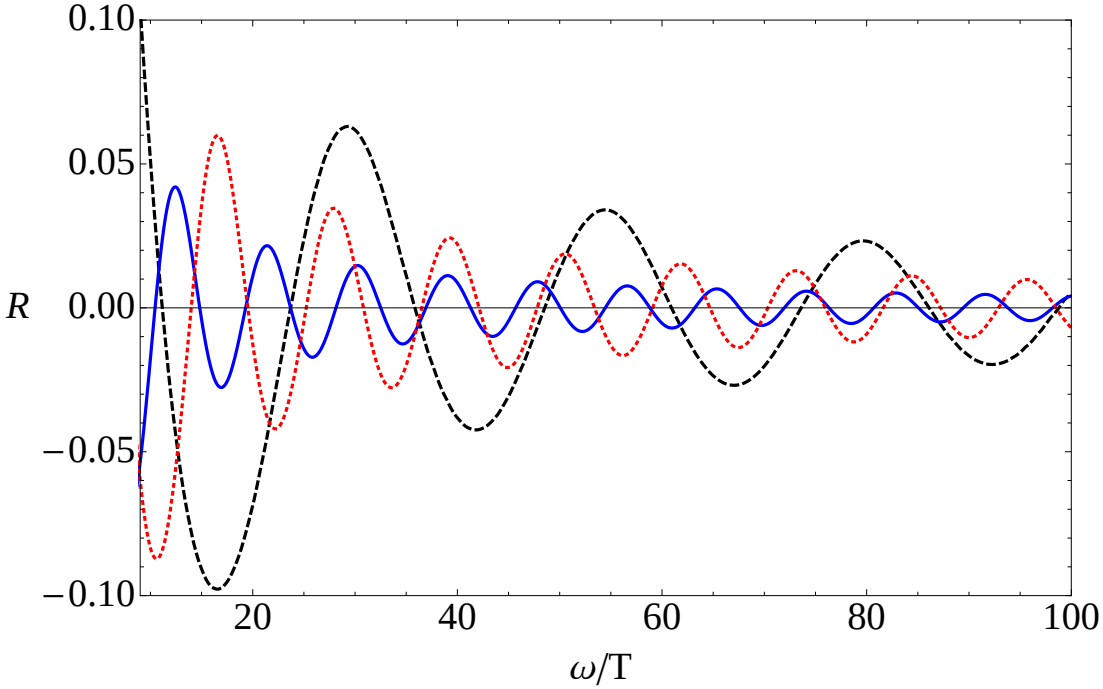
Thermalization depending on the virtuality

- virtuality

$$v = \frac{\hat{\omega}^2 - \hat{q}^2}{\hat{\omega}^2}$$

- parametrize

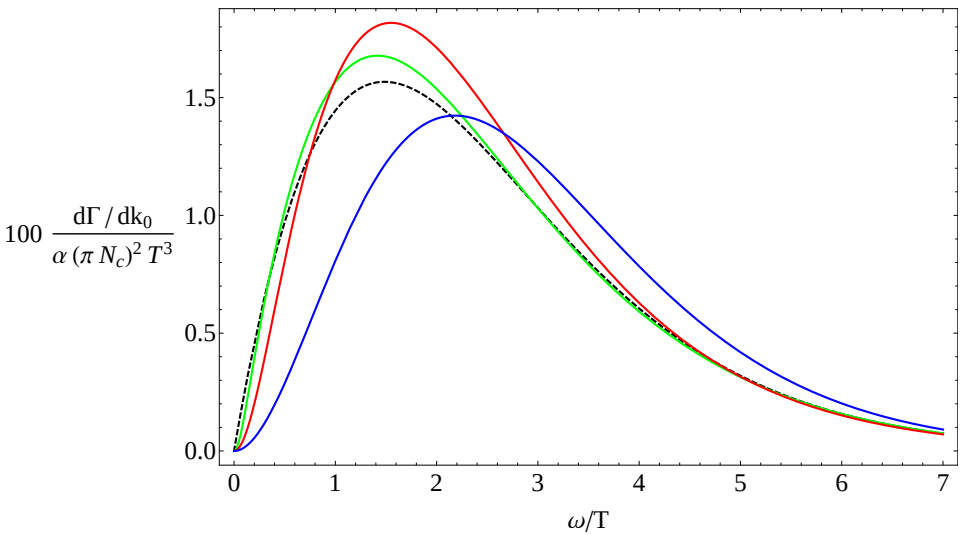
$$q = c\,\hat{\omega}$$

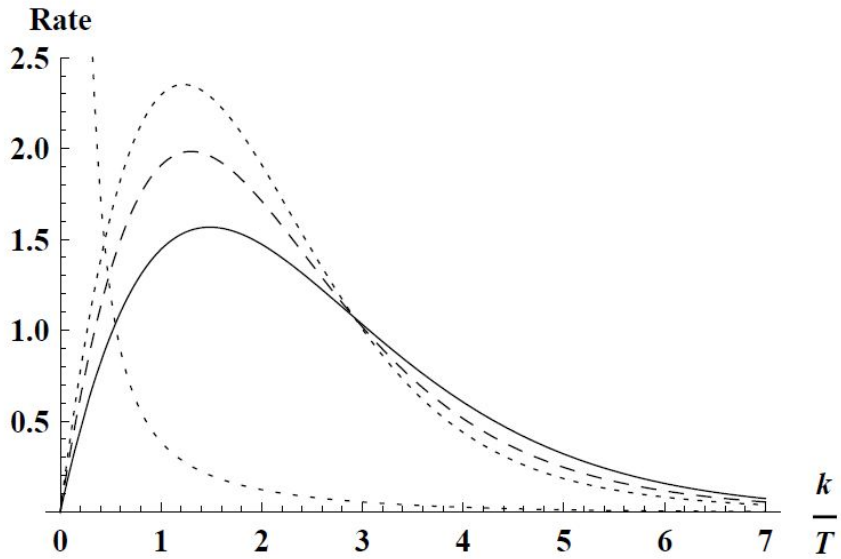


Relative deviation R_γ for $r_s/r_h = 1.1$ and $c = 1, 0.7, 0$.

- thermalization depends on the virtuality
- photons are last to thermalize
- same conclusion was reached in other models of holographic thermalization
  Arnold et al., Chesler and Teaney

Photon production rate

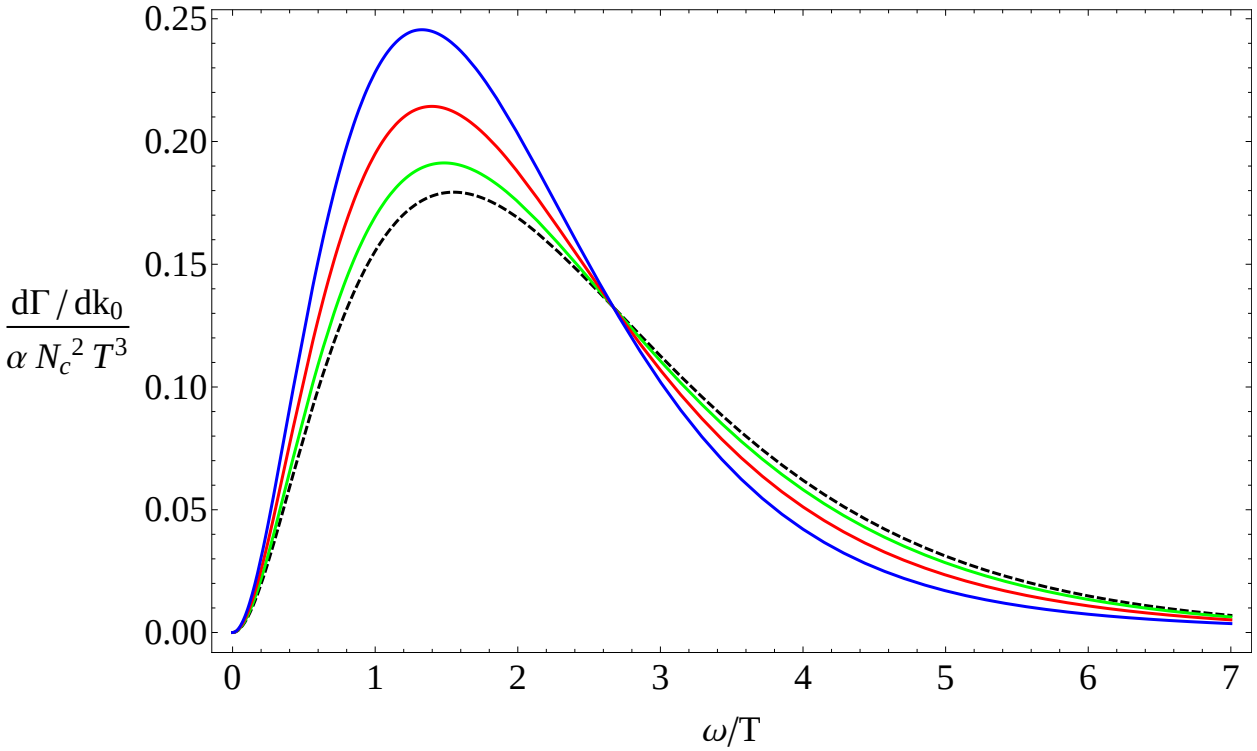




left:Photon production rate for $r_s/r_h = 1.001,\ 1.01,\ 1.1$. right: Photon production rate in equilibrium for $\lambda = \infty, 75, 50$.

- enhancement of production rate
- hydro peak broadens and moves right
- Can one combine the two calculations to study thermalization at finite coupling?

Photon emission spectrum with γ corrections

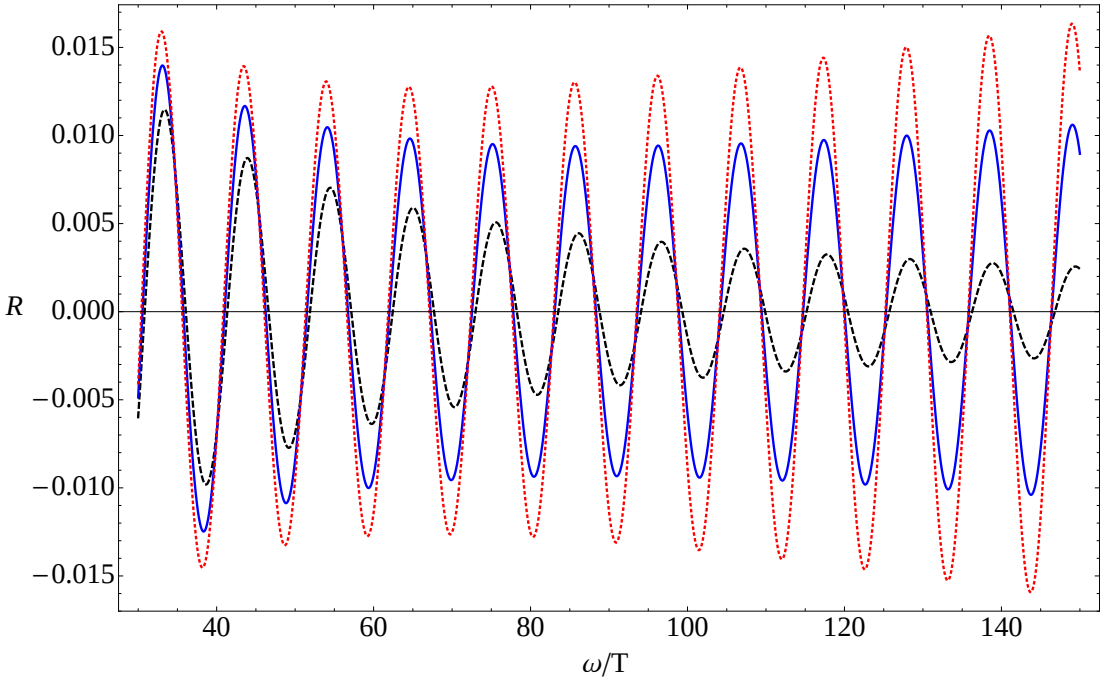


photon emission rate for $r_s/r_h = 1.01$ and $\lambda = \infty$, 150, 75, 50.

- behavior very similar to thermal limit.

Thermalization at finite coupling

- relative deviation from thermal equilibrium

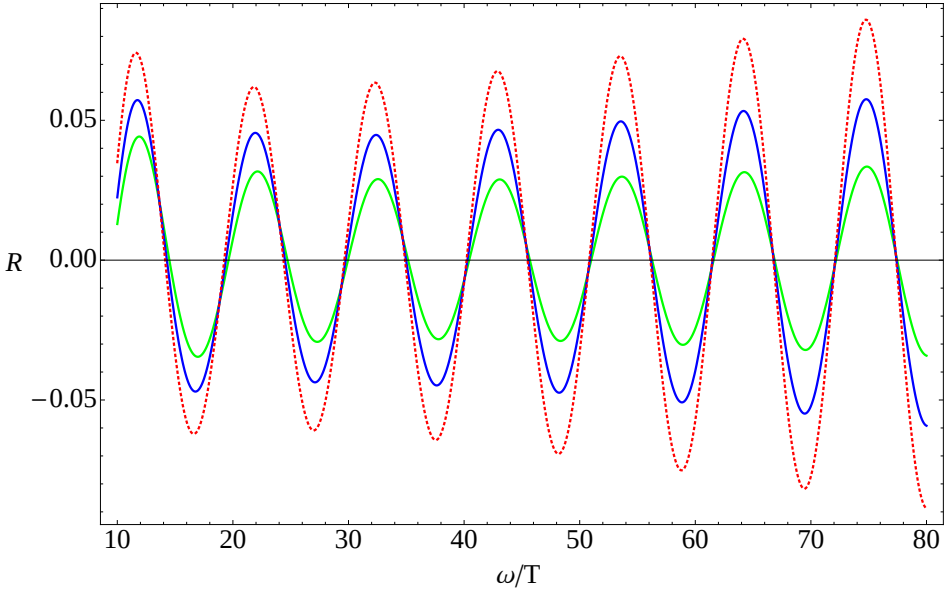


Relative deviation R_γ for $r_s/r_h = 1.01$ and $\lambda = \infty$, 500, 300, .

- behavior of relative deviation changes at large frequencies

Thermalization at finite coupling

- relative deviation from thermal equilibrium



Relative deviation R_γ for $r_s/r_h = 1.01$ and $\lambda = 150, 100, 75$.

$$\chi(\hat{\omega}) \approx \hat{\omega}^{\frac{2}{3}} \left(1 + \frac{f_1(u_s)}{\hat{\omega}} + \frac{f_2(u_s)\hat{\omega}}{\lambda^{\frac{3}{2}}}\right)$$

- might indicate a change of the thermalization pattern from top-down towards bottom up.

Conclusions

thermalization at infinite coupling

- enhancement of production rate
- observe top down thermalization

thermalization at finite coupling

- thermalization scenario depends on the coupling
- bottom up thermalization also possible at strong coupling ?

future directions

- go beyond the quasistatic approximation
- look at plasma constituents itself (components of the stress energy tensor)