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Off-equilibrium photon production during a rapid birth of the QGP

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Outline of the talk

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- **Introduction and Motivation**
  short overview on quark-gluon plasma and heavy-ion physics
  direct photons as electromagnetic probes / finite lifetime effects

- **Previous approaches**
  divergent vacuum contribution / unphysical UV scaling behavior
  debate how to handle these artifacts

- **Model description of finite lifetime effects**
  time-dependent occupation numbers
  achievements / aspects not under control

  arXiv:0906.1734 [hep-ph]

- **First-principle description on chiral photon production**
  Yukawa-like source term
  insertion on pair production
  asymptotic photon numbers

  Annals of Phys. 336 (2013) 331

- **Summary and Outlook**

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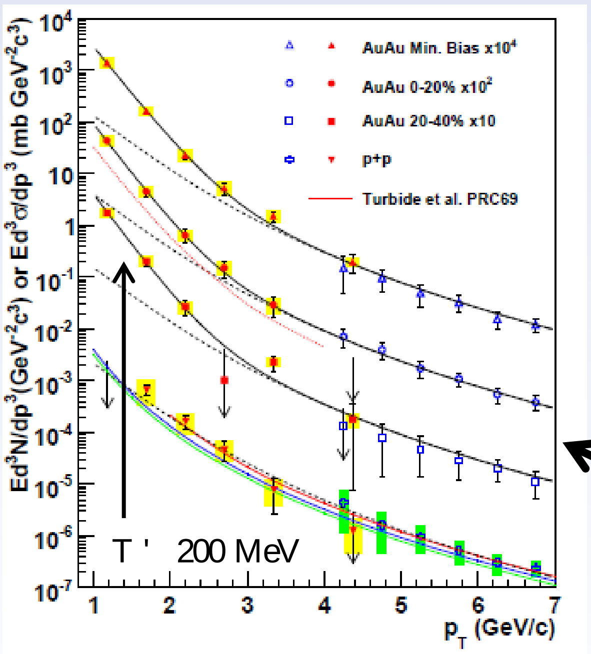
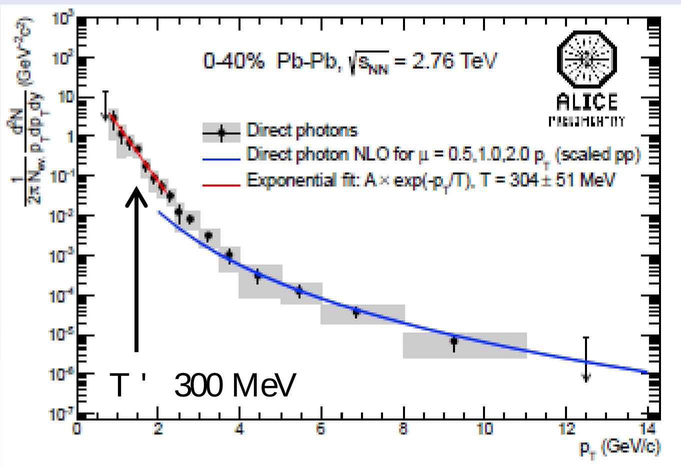
Introduction and Motivation

- **direct access to QGP not possible**

  experimental signatures needed
  direct photons as electromagnetic probes / no finial state interactions
  provide direct insight into the early stage of the collision

- **direct photon measurement by PHENIX and ALICE collaborations**





PHENIX data; Au+Au at $s^{1/2}$=200 MeV

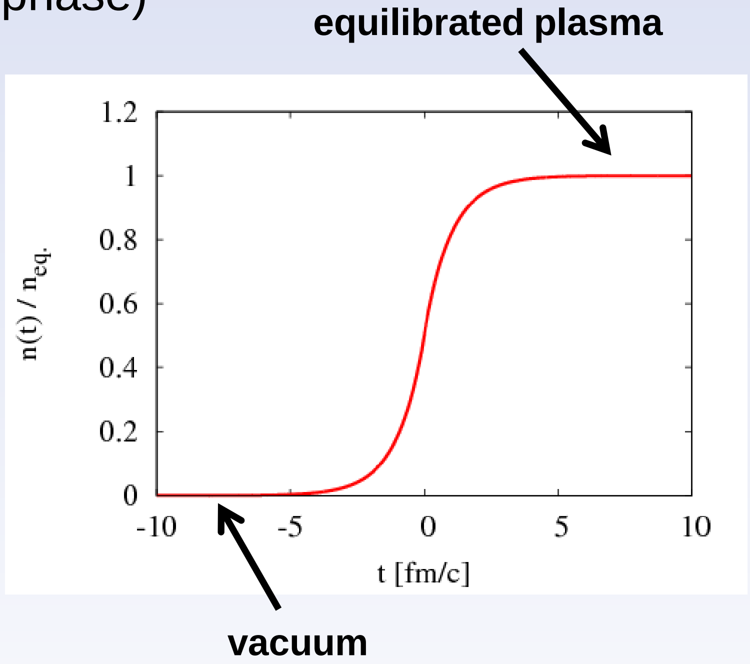
thermal fit $\sim e^{-p_T/T}$ in low-p_T region

Introduction and Motivation

- **theoretical investigations / identified photon sources**
  - prompt photons from initial nucleon-nucleon scatterings
  - photons from jet-medium interactions
  - medium photons from QGP (+hadronic phase)

- **standard treatment of QGP photons**
  - integration of thermal rates on hydrodynamic background

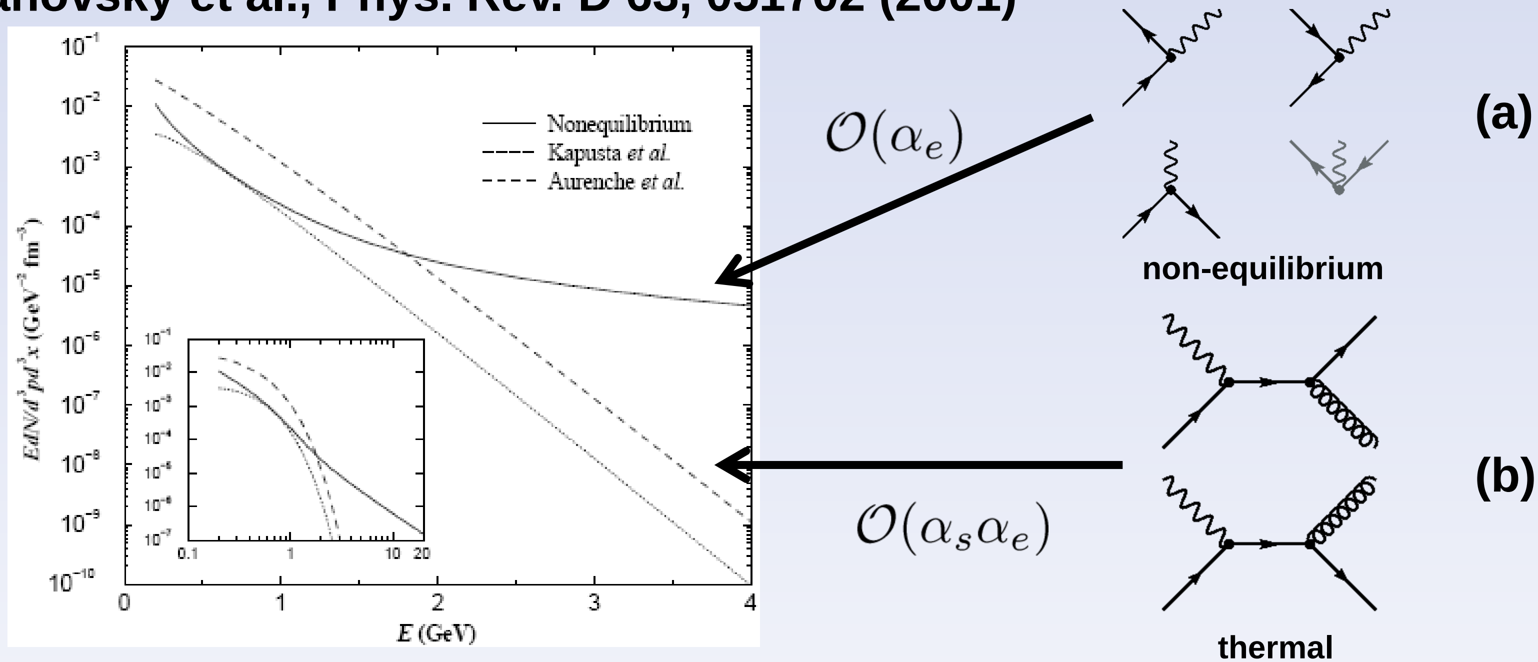
- **aspect to take into account**
  - QGP no static medium, but created over a finite timescale
  - non-equilibrium situation occurs during creation period



- **questions of interest**
  - non-equilibrium / finite lifetime effects on photon emission?
  - consistent description within real-time formalism?

Previous Approaches

- **Boyanovsky et al., Phys. Rev. D 63, 051702 (2001)**



contribution from first-order QED processes **(a)**
dominance over leading-order thermal contributions **(b)** in UV domain

However:

photon numbers $\propto 1/\omega_{\vec{k}}^3$ ($\omega_{\vec{k}} = |\vec{k}|$) in UV domain → unphysical
pair creation process neglected so far → results incomplete

Previous Approaches

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- **Boyanovsky et al., Phys. Rev. D 68, 065018 (2003), hep-ph/0305224**

  inclusion of pair-creation process → divergent vacuum contribution
  renormalization attempt
  unphysical UV scaling behavior remains

- **Serreau, JEHP 0405 (2004), hep-ph/0310051**

  encountered problems ↔ virtual radiation (not observable)
  consideration of correlated initial state required
  no concrete calculations

- **Dadić, Moore und Gelis, hep-ph/0311131**

  uncorrelated initial state ↔ 'switching on' of e.m. interaction at t_0

- **Fraga, Gelis and Schiff, Phys. Rev. D 71, 085015 (2005)**

  photon free initial state **??** ↔ uncorrelated initial state
  transient photon numbers **??** ↔ 'switching off' of e.m. interaction at time t
  renormalization scheme **??** → no re-derivation of photon numbers

Previous Approaches

- **Boyanovsky et al., Nucl. Phys. A 747, 564-608 (2005)**
  photon-free initial state ↔ initial value problem
  transient photon numbers → QGP has finite lifetime
  renormalization scheme → consistent definition of photon numbers

- **original problems remained unsolved**
  main motivation for our investigations

Model description

Time-dependent occupation numbers

- **find an ansatz for the photon self-energy (PSE)**
  take into time evolution of QGP properly

- **things to take into account / disregarded by Boyanovsky et al.**
  vacuum contribution to PSE → always persistent / $t_0 \to -\infty$
  medium contribution to PSE → only temporarily persistent as long as QGP is heated up

- **introduction of time-dependent occupation numbers in PSE**

$$n_{\mathrm{F}}(E) \to n_{\mathrm{F}}(E,t) = f(t) n_{\mathrm{F}}(E)$$

- **adhered to consideration of transient photon numbers**

- **achievement of ansatz**
  consistent renormalization of vacuum contribution

Model description
Time-dependent occupation numbers

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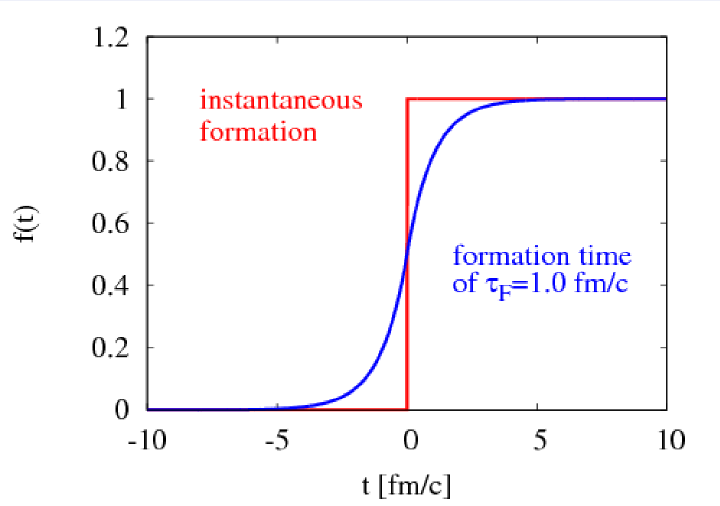
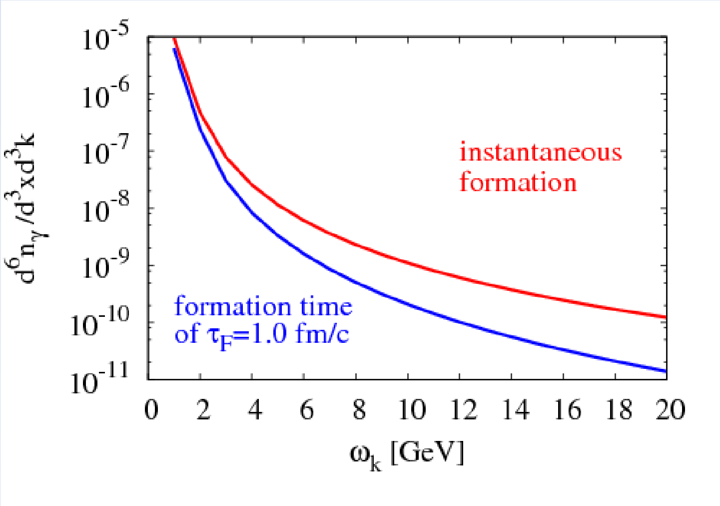
- **However:**

  UV scaling behavior of photon numbers **not** fully under control





photon numbers $\propto 1/\omega_{\vec{k}}^3$ for **instantaneous** formation

photon numbers $\propto 1/\omega_{\vec{k}}^{3.8}$ for formation over **finite time interval**

total photon number density UV convergent **but** total photon energy density still UV divergent

artifact remains for arbitrarily smooth f(t)

Chiral photon production

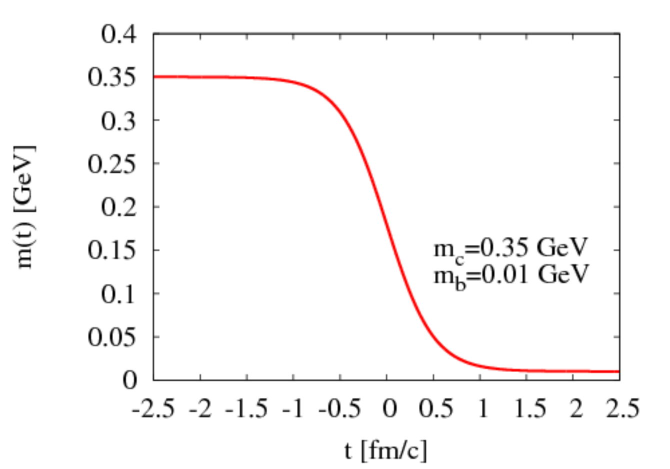
- **consider Ward Takahashi identities ↔ current conservation**

$$\mathrm{i}\Pi^{<}_{\mu\nu}(x,y) = \langle \hat{j}^{\dagger}_{\nu}(y)\hat{j}_{\mu}(x)\rangle \quad \text{with} \quad \partial^{\mu}_{x}\mathrm{i}\Pi^{<}_{\mu\nu}(x,y) = 0$$

not fulfilled by model approach (and not by Boyanovsky et al. either)
possible reason for photon spectra being not UV integrable

- **chiral photon production**

chiral symmetry temporarily restored during heavy-ion collisions
change of quark mass from constituent value m_c to bare value m_b
mass change induces pair creation
consider photon emission arising from pair-creation process



- **mass shift contributes to formation of quark-gluon plasma**

investigations relevant in the context of finite lifetime effects

Chiral photon production

Yukawa-like source term

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- **allows for first principle calculation**

- **model change in quark mass by Yukawa-like source term**

$$\hat{\mathcal{L}}(x) = \hat{\mathcal{L}}_{\text{QED}}(x) - g\phi(t)\hat{\bar{\psi}}(x)\hat{\psi}(x)$$

  source field classical and time-dependent only / time-dependent mass

$$m(t) = m_c + g\phi(t)$$

  compatible with Ward-Takahashi identities / gauge invariance

- **keep coupling to source field to all orders**
  pair creation process non-perturbative phenomenon
  construct interaction picture including full dynamics from source field

- **determine photon numbers through perturbative calculation in α_e**
  restriction to first-order QED processes
  required energy provided by coupling to source field

Chiral photon production

Yukawa-like source term

- **photon numbers expressed in terms of photon self energy**

$$2\omega_{\vec{k}} \frac{\mathrm{d}^6 n_\gamma(t)}{\mathrm{d}^3x\mathrm{d}^3k} = \frac{1}{(2\pi)^3} \int_{-\infty}^{t} \mathrm{d}t_1 \int_{-\infty}^{t} \mathrm{d}t_2 \mathrm{i}\Pi_T^{<}(\vec{k}, t_1, t_2) \mathrm{e}^{\mathrm{i}\omega_{\vec{k}}(t_1 - t_2)}$$

- **photon self-energy given by one-loop approximation**

$$\mathrm{i}\Pi_{\mu\nu}^{<}(\vec{k}, t_1, t_2) = e^2 \int \frac{\mathrm{d}^3p}{(2\pi)^3} \mathrm{Tr}\left\{\gamma_\mu S_\mathrm{F}^{<}(\vec{p} + \vec{k}, t_1, t_2)\gamma_\nu S_\mathrm{F}^{>}(\vec{p}, t_1, t_2)\right\}$$

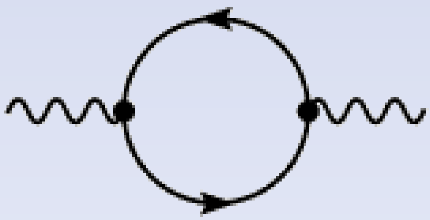
fermion propagators obey equations of motion

$$\begin{aligned}\left(\mathrm{i}\partial_{t_1} + \gamma^i p_i - m(t_1)\right) S_\mathrm{F}^{\gtrless}(\vec{p}, t_1, t_2) &= 0 \\ \left(\mathrm{i}\partial_{t_2} - \gamma^i p_i + m(t_2)\right) S_\mathrm{F}^{\gtrless}(\vec{p}, t_1, t_2) &= 0\end{aligned}$$

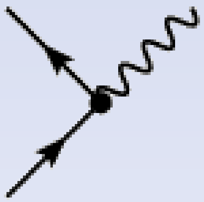
full inclusion of mass shift effects

Chiral photon production

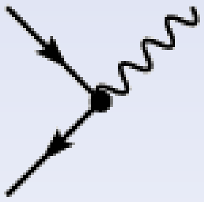
Yukawa-like source term



$\longleftrightarrow$

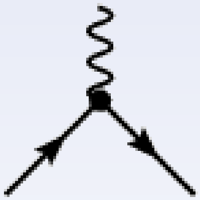


$q \to q + \gamma$



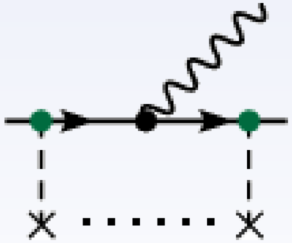
$\bar{q} \to \bar{q} + \gamma$

1-loop diagram corresponds to 1st order QED processes



$q + \bar{q} \to \gamma$

1st order QED processes possible by coupling of quarks/antiquarks to ϕ(t)



$\longleftrightarrow$

$0 \to q + \bar{q} + \gamma$

Chiral photon production

Absolute-square representation

- **photon numbers given by an absolute square**

$$2\omega_{\vec{k}}\frac{\mathrm{d}^6 n_\gamma(t)}{\mathrm{d}^3x\mathrm{d}^3k} = \frac{1}{V(2\pi)^3}\sum_{\lambda,f}\left|\int_{-\infty}^{t}\mathrm{d}u\;\langle f;\vec{k},\lambda|\hat{H}_{\mathrm{J}}(u)|0\rangle\right|^2$$

integrand ↔ 1st order QED transition amplitude

initial state: $|0> = \; |0_{q\bar{q}} > \otimes \; |0_\gamma >$

final state: $|f;\vec{k},\lambda> = \; |f > \otimes \; |\vec{k},\lambda >$

- **photon numbers positive semi definite**

unphysical negative values excluded a priori

absolute square free of vacuum contribution ↔ consideration of photon numbers for free asymptotic states

Chiral photon production

Pair production from chiral mass shift

- **diagonalize Hamiltonian via Bogolyubov transformation**

$$\hat{\tilde{b}}_{\vec{p},s}(t) = \xi_{\vec{p},s}(t)\hat{b}_{\vec{p},s} + \eta_{\vec{p},s}(t)\hat{d}^{\dagger}_{-\vec{p},s}$$

$$\hat{\tilde{d}}^{\dagger}_{-\vec{p},s}(t) = \xi^{*}_{\vec{p},s}(t)\hat{d}^{\dagger}_{-\vec{p},s} - \eta^{*}_{\vec{p},s}(t)\hat{b}_{\vec{p},s}$$

expansion of fermion-field operator in terms of instantaneous eigenstates of Hamiltonian

- **instantaneous particle / antiparticle number operators**

$$\hat{n}_{\vec{p},s}(t) = \hat{\tilde{b}}^{\dagger}_{\vec{p},s}(t)\hat{\tilde{b}}_{\vec{p},s}(t) \ , \quad \hat{\bar{n}}_{\vec{p},s}(t) = \hat{\tilde{d}}^{\dagger}_{-\vec{p},s}(t)\hat{\tilde{d}}_{-\vec{p},s}(t)$$

normal ordering of Hamiltonian with respect to instantaneous vacuum

- **definition of number of quark-antiquark pairs**

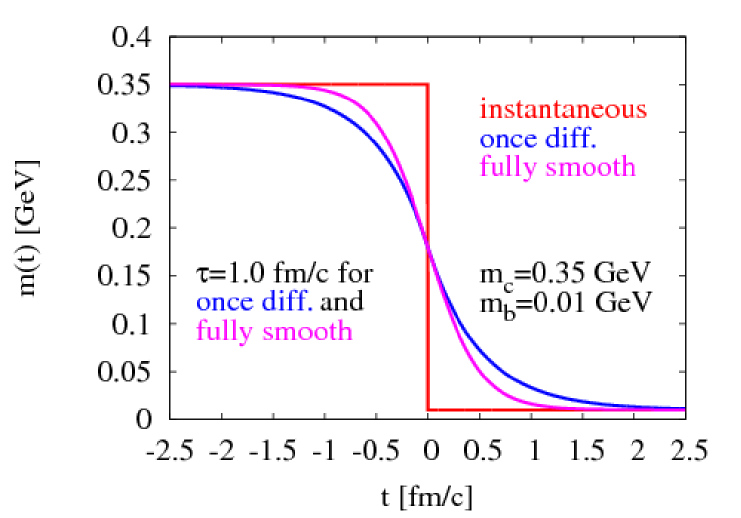
$$\frac{\mathrm{d}^6 n_{q\bar{q}}(t)}{\mathrm{d}^3x\mathrm{d}^3p} = \sum_s |\eta_{\vec{p},s}(t)|^2 \quad \longleftrightarrow$$

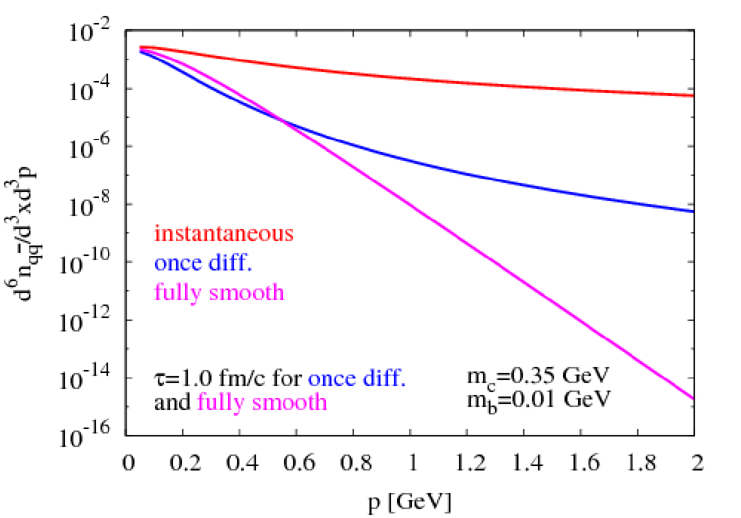
expectation value of inst. number operator w.r.t. initial vacuum state

Chiral photon production
Pair production from chiral mass shift

- **particle numbers in the asymptotic limit**

  decay behavior for large p highly sensitive to m(t)





particle numbers ∝ **$1/p^2$** for **instantaneous** mass shift

particle numbers ∝ **$1/p^6$** if mass function **once differentiable**

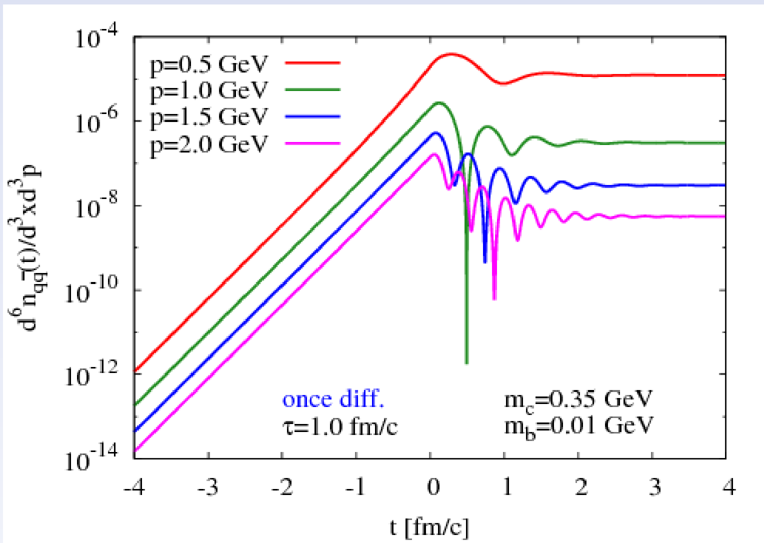
exponential suppression for **fully smooth** mass function

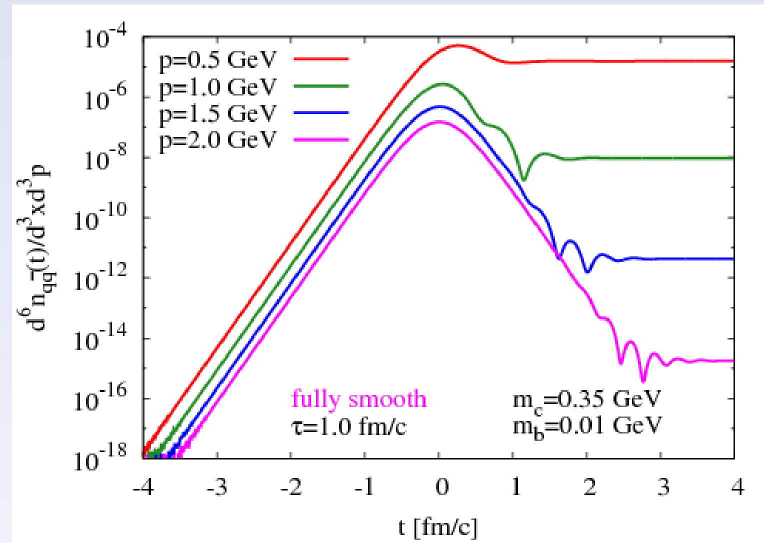
- **same dependence on mass function for $m_c \rightarrow m_b \rightarrow m_c$**

Chiral photon production
Pair production from chiral mass shift

- **particle numbers at finite times**

  strong ‘overshoot’ over asymptotic value





particularly distinctive for **fully smooth** case

particle numbers ∝ **$1/p^4$** for large p at finite times ↔ temporary logarithmic divergence in in total energy density

ambiguity of particle number definition at finite times?

Chiral photon production

Asymptotic photon numbers

- **reflect definition of photon numbers more carefully**

- **model approach / investigations by Boyanovsky et al.**

  definition of photon number for transient times

$$2\omega_{\vec{k}} \frac{\mathrm{d}^6 n_\gamma(t)}{\mathrm{d}^3x\mathrm{d}^3k} = \sum_{\lambda=\perp} \left\langle \hat{a}^\dagger_{\mathrm{H}}(\vec{k},\lambda,t)\hat{a}_{\mathrm{H}}(\vec{k},\lambda,t) \right\rangle \quad (1)$$

  average taken with respect to initial state

  mode operators $\hat{a}_{\mathrm{H}}(\vec{k},\lambda,t)$ ↔ coefficients in plane-wave decomposition of photon operator

  however: interacting fields ↔ interpretation as single-photon operator questionable

  interpretation of (1) as photon number problematic ↔ argument by Fraga, Gelis and Schiff

- **how to obtain a consistent definition**

  possible in the limit t→∞ for free asymptotic states

Chiral photon production

Asymptotic photon numbers

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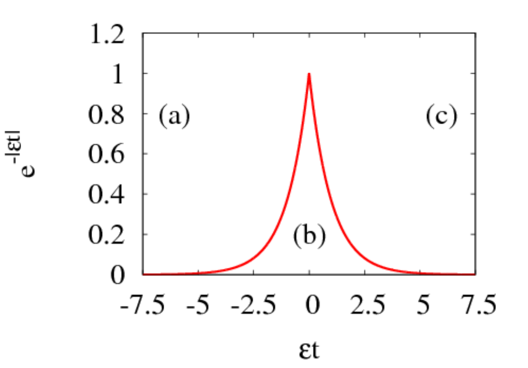
- **how to construct free asymptotic states**

  introduce adiabatic switching of electromagnetic interaction according to Gell-Mann and Low theorem

$$\hat{H}_{\rm EM} \rightarrow {\rm e}^{-\varepsilon|t|}\hat{H}_{\rm EM} \ , \hat{H}_{\rm EM} = e\int {\rm d}^3x \ \hat{\bar{\psi}}(\vec{x})\gamma_\mu\hat{\psi}(\vec{x})\hat{A}^\mu(\vec{x})$$



  specify initial state for $t_0 \rightarrow -\infty$ (a)
  interacting fields at finite t (b)
  evolution into free fields for $t \rightarrow \infty$ (c)

- **how to obtain correct asymptotic limit for the photon numbers**

  sequence of limits: first $t \rightarrow \infty$ for a consistent definition
  then $\varepsilon \rightarrow 0$ as adiabatic limit

- **exact sequence of limits crucial**

  eliminate possible unphysical contributions from vacuum polarization

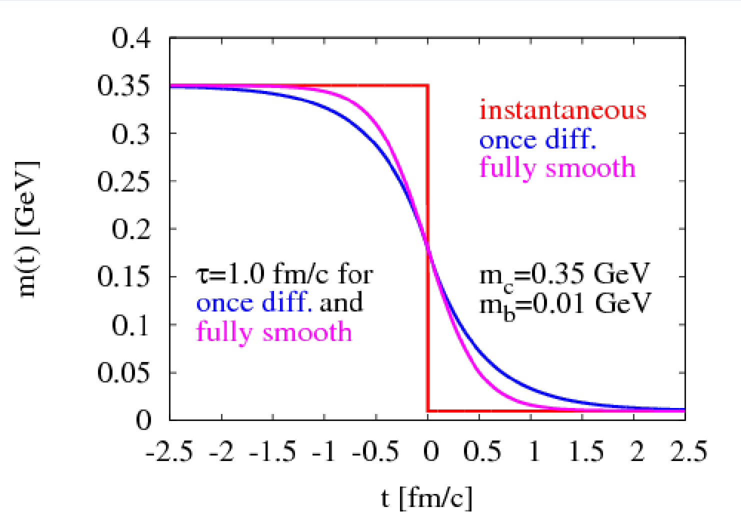
  obtain physically sensible results from mass shift effects ↔ damping out of spurious transient contributions

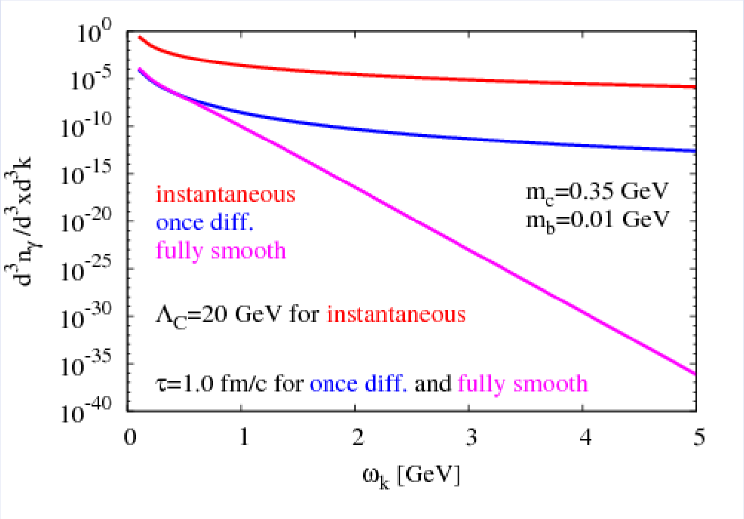
Chiral photon production

Asymptotic photon numbers

- **achievement of asymptotic description**

  photon spectra UV integrable for suitable m(t)





photon numbers $\propto 1/\omega_{\vec{k}}^3$ for **instantaneous** mass shift

photon numbers $\propto 1/\omega_{\vec{k}}^6$ if mass function **once differentiable**

exponential suppression for **fully smooth** mass function

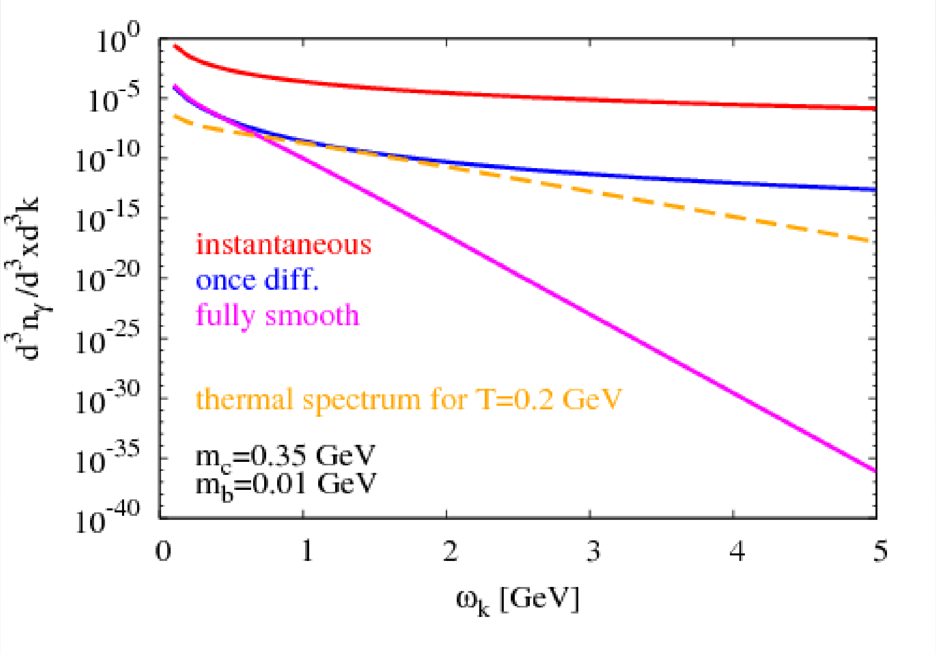
- **same dependence on mass function for $m_c \rightarrow m_b \rightarrow m_c$**

Chiral photon production

Asymptotic photon numbers

- **comparison to thermal photon spectra**

  thermal photon production ~$\alpha_e \alpha_s$ / chiral photon production ~α_e



no general dominance of chiral photon production

consider **fully smooth** case / most physical scenario

chiral photon production subdominant in UV domain

Summary

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- **photon emission from a quark-gluon plasma**
  role of finite lifetime effects
  consistent description in real-time formalism

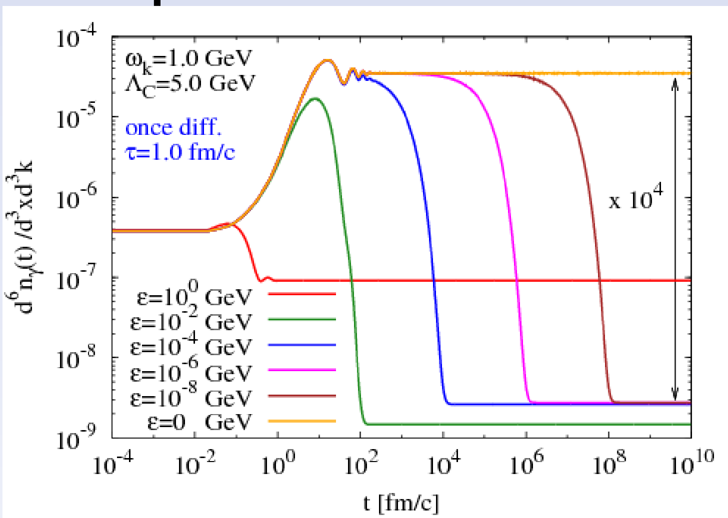
- **model description**
  time-dependent occupation numbers
  ‘photon numbers’ at **finite times**
  renormalization of vacuum contribution
  photon spectra still not UV integrable
  artifact from violation of Ward-Takahashi identities

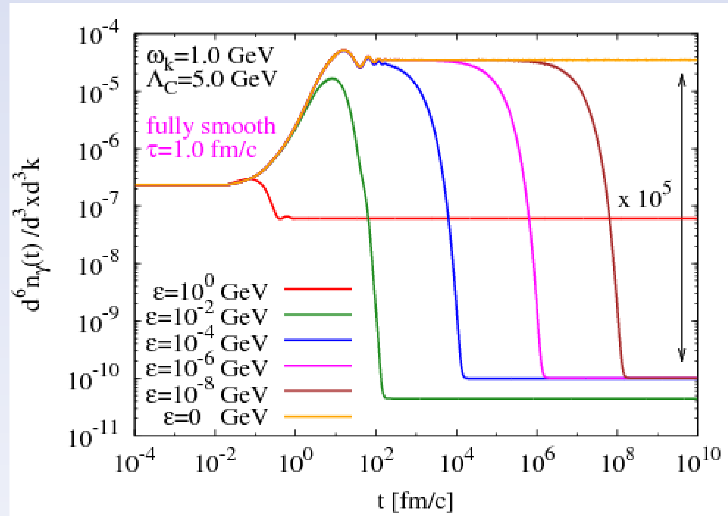
- **first-principle description**
  chiral photon production
  Ward Takahashi identities fulfilled
  photon numbers for **free asymptotic states**
  no unphysical vacuum contribution
  photon spectra UV integrable

Chiral photon production

Photon numbers at finite times?

- **consider pure mass-shift contribution for different values of ε**





excess over asymptotic value by several orders of magnitude
transient photon numbers ill defined

no free asymptotic states **or** artificial 'switching off' of e.m. interaction
↔ violation of Ward-Takahashi identities

- **interchange of limits forbidden**

corresponds to consideration of transient value for small ε

Revised model description

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- **relevance of results for earlier model approach**
  unphysical UV scaling behavior ↔ ill defined photon numbers?
  artifact removed for free asymptotic states?

- **accordant revision of model description**
  keep ansatz for photon self-energy (PSE) to describe time-evolution of QGP

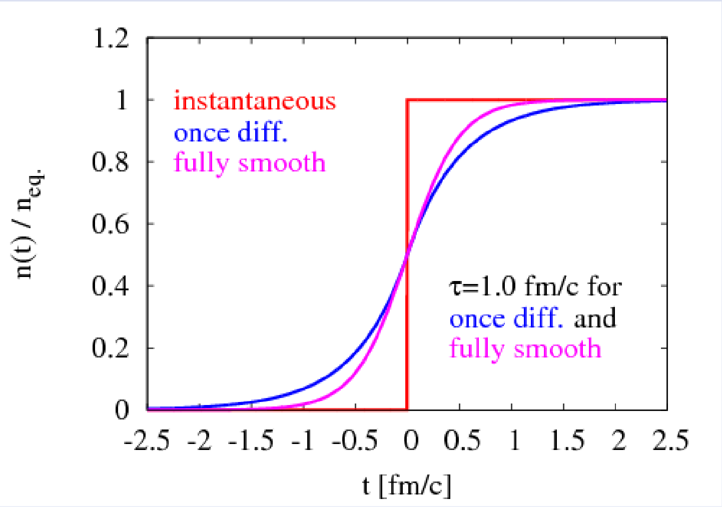
$$n_{\mathrm{F}}(E) \rightarrow n_{\mathrm{F}}(E,t) = f(t)n_{\mathrm{F}}(E)$$

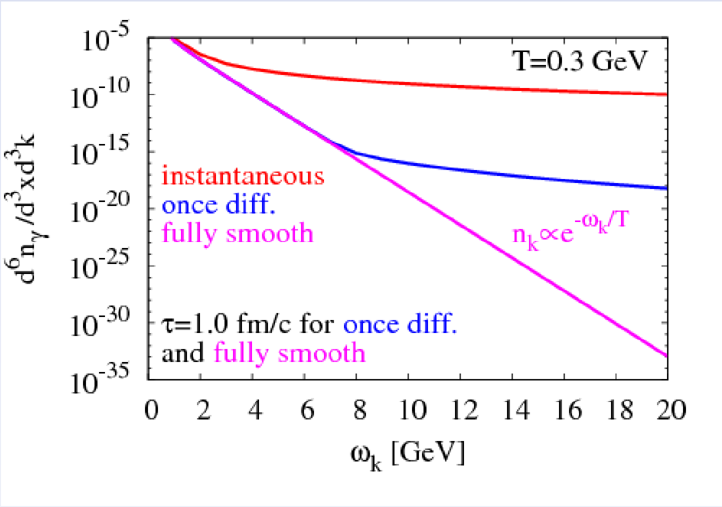
  but: consider photon numbers for free asymptotic states
  again restriction to first-order QED processes

- **achievements of revised model approach**
  possible unphysical contribution from vacuum polarization again **eliminated**
  photon spectra moreover **UV integrable** for suitable f(t)

Revised model description

- **consider photon spectra for different f(t)**





photon numbers $\propto 1/\omega_{\vec{k}}^3$ for **instantaneous** formation

photon numbers $\propto 1/\omega_{\vec{k}}^7$ for f(t) **once differentiable**

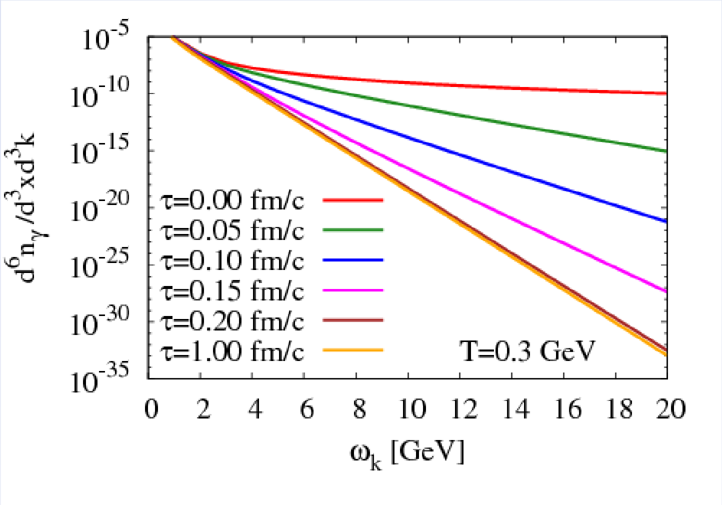
exponential suppression **fully smooth** f(t) / slope coincides with inverse temperature

thermal-looking photon spectrum at large τ for **fully smooth** case?

Revised model description

Dependence on switching time

- **indeed: convergence of slope against inverse temperature at large τ**



however: photon numbers seem to saturate for τ→∞ / **unphysical**

- **Where does the apparent saturation come from?**
  consider individual processes separately

Revised model description

Dependence on switching time

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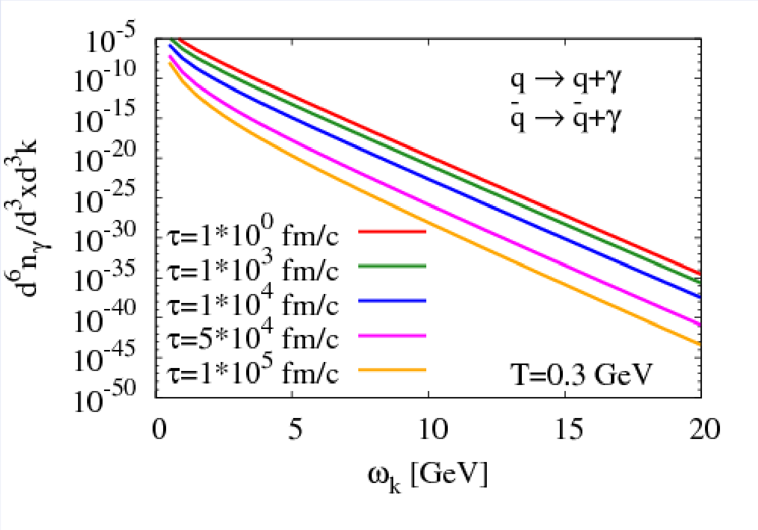
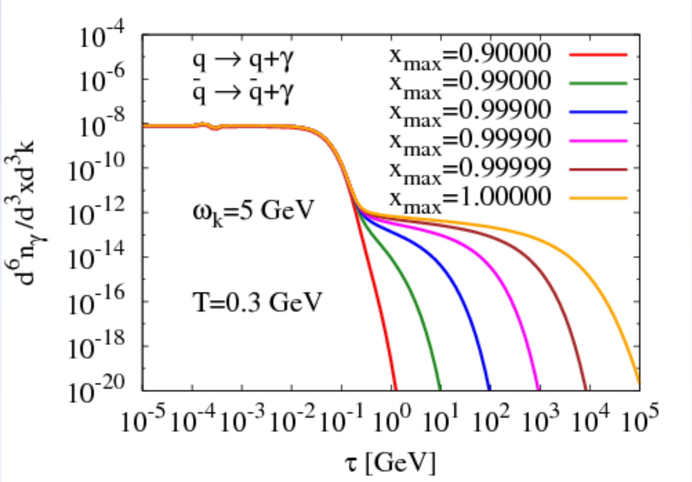
- **exclude collinear modes for** $q(\bar{q}) \rightarrow q(\bar{q}) + \gamma$

  consider only modes with $-1 < x < x_{max}$ / x ↔ cosine of angle between fermion and photon momentum





significantly faster decrease for x_{max}=0.9

decrease delayed for x_{max}→1.0 / collinear modes reincluded

Revised model description

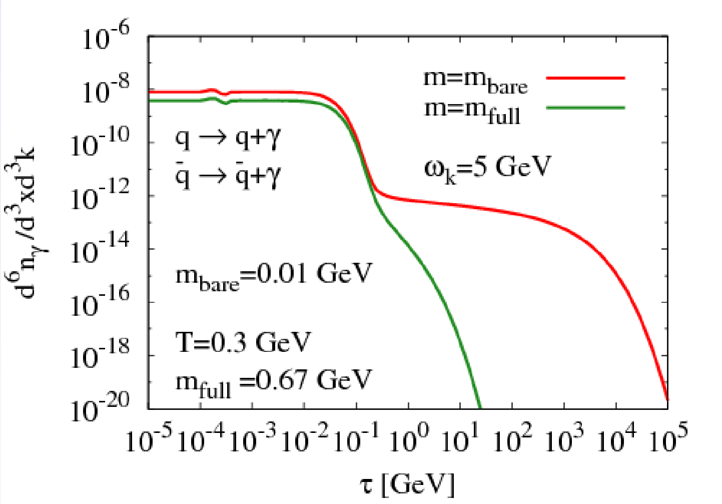
Thermal masses

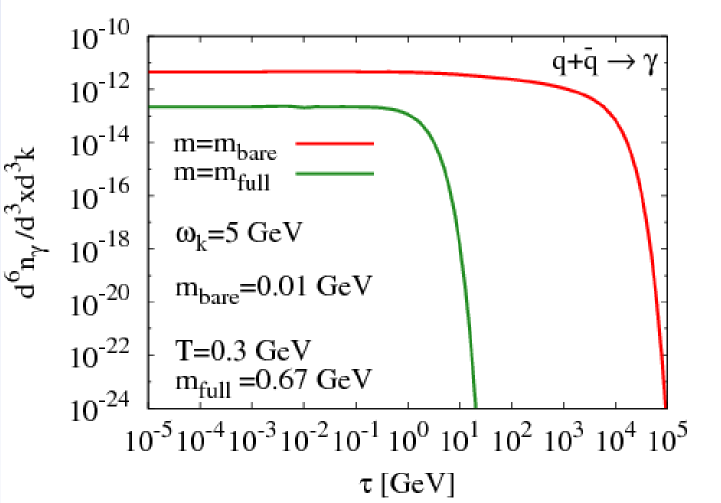
- **modes with large formation times require HTL-resummation**

  effective provided assigning quarks/antiquarks a thermal mass

$$m^2(T) = \frac{4\pi\alpha_s}{3}\left(N_c + \frac{N_f}{2}\right)T^2 \gg m_{\rm bare}^2$$

formation times decrease by several orders of magnitude





significantly faster decrease in τ

Revised model description

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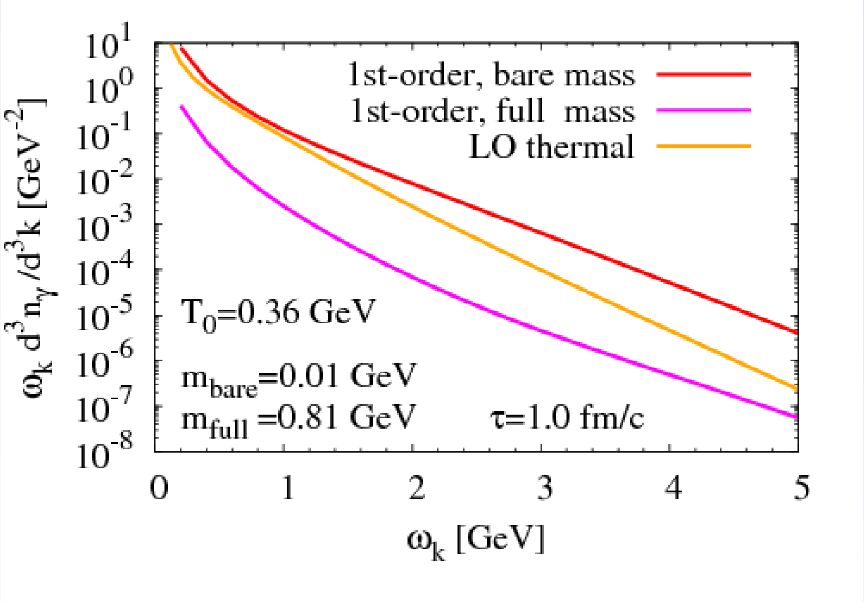
- **comparison to thermal photon spectra**

  thermal photon production ~$\alpha_e \alpha_s$ / non-equilbrium photon production ~α_e



non-equilibrium photon production subdominant for $\omega_{\vec{k}} = 1 - 5$ GeV

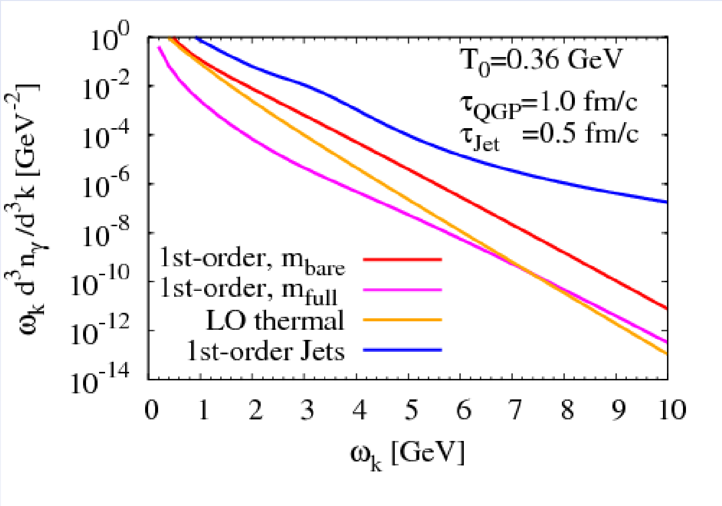
for full thermal mass / reversion for $\omega_{\vec{k}} \gtrsim 5$ GeV

- **non-equilibrium quantum field theory remains challenging**

Revised model description

- **demonstration of last aspect**

  replace thermal distributions function by jet distribution function in photon self-energy → model for photon emission from jets



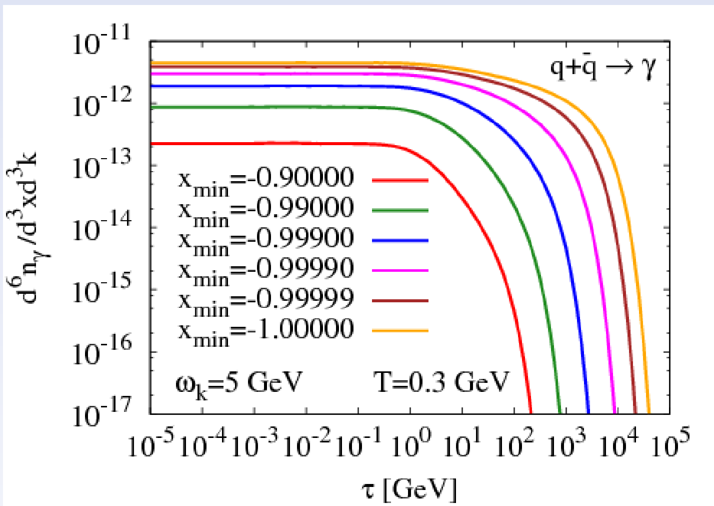
non-equilibrium photons from QGP phase dominate over thermal photons from this phase

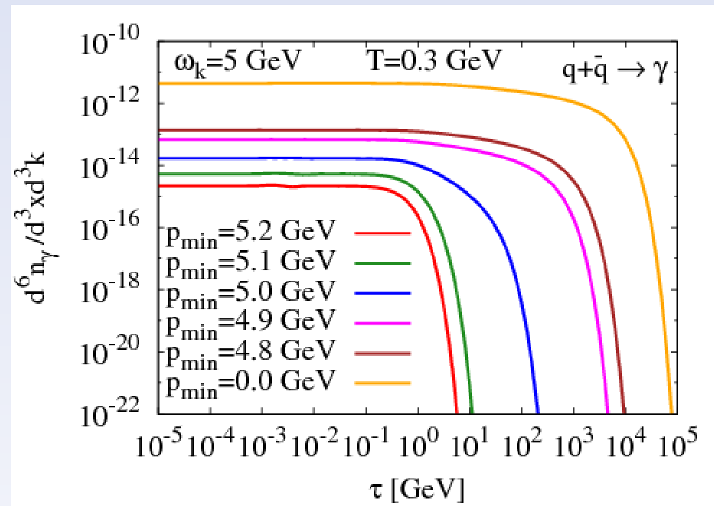
however: total photon emission from QGP phase (thermal + non-equilibrium) in turn dominated by jet photons

Revised model description
Depedendence on switching time

- **exclude anticollinear modes / modes with $p \leq \omega_{\vec{k}}$ for $q + \bar{q} \to \gamma$**

  restrict either or $x_{min} < x < 1$ or $p_{min} < p < \infty$





significantly faster decrease for x_{min}=-0.9

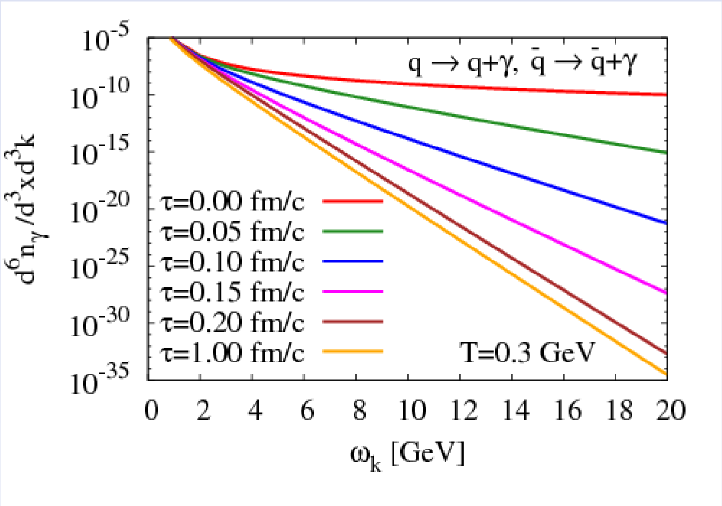
significantly faster decrease for $p_{min} > \omega_{\vec{k}}$

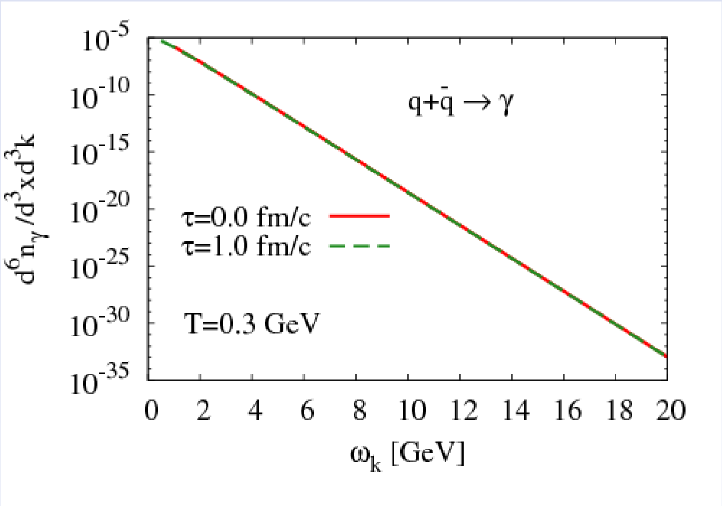
decrease delayed both for $x_{min} \to$ -1.0 and $p_{min} \to 0$ / reinclusion of anticollinear modes in domain $p \leq \omega_{\vec{k}}$

Revised model description

Dependence on switching time

- **consider first** $q(\bar{q}) \to q(\bar{q}) + \gamma$ **and** $q + \bar{q} \to \gamma$





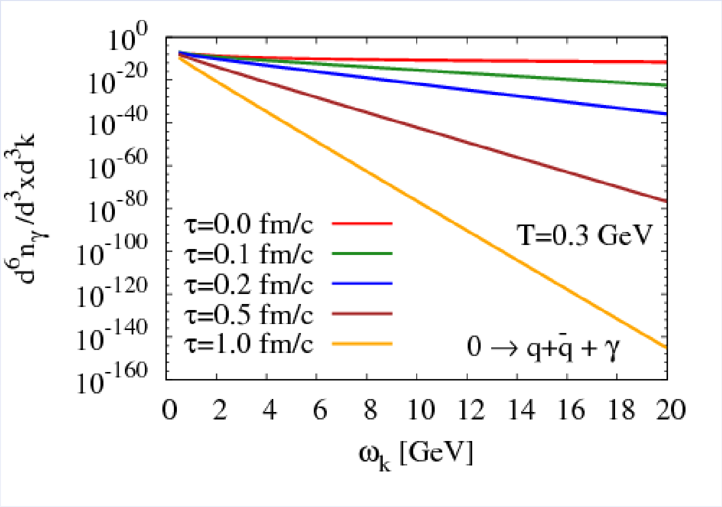
apparent saturation for $q(\bar{q}) \to q(\bar{q}) + \gamma$

apparent independence from τ for $q + \bar{q} \to \gamma$

slope given by inverse temperature for $\tau \to \infty$ in both cases

Revised model description
Dependence on switching time

- **different observation for** $0 \to q + \bar{q} + \gamma$



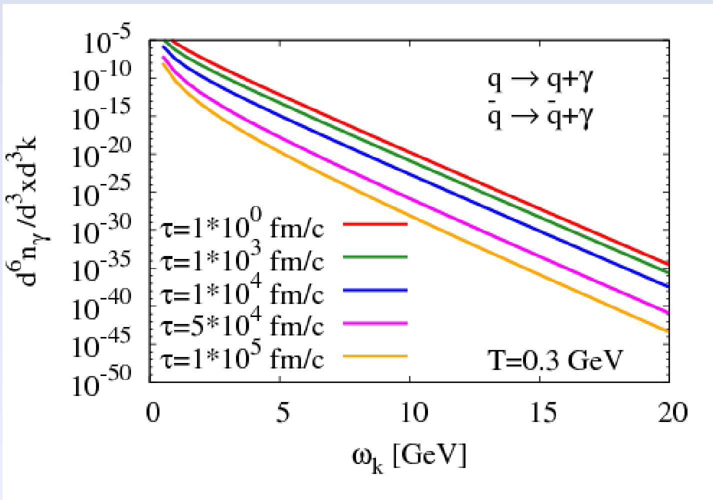
intuitive behavior / suppression w.r.t. instantaneous case
the stronger the larger τ is chosen

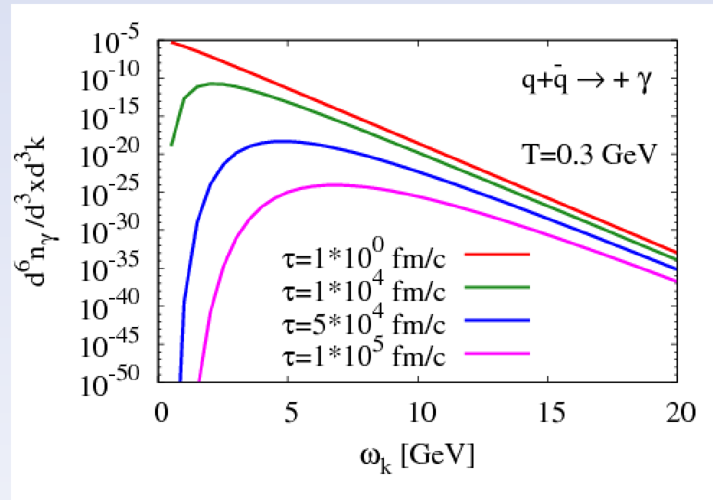
- **apparent saturation arises from** $q(\bar{q}) \to q(\bar{q}) + \gamma$ **and** $q + \bar{q} \to \gamma$

Revised model description

Dependence on switching time

- **however**: $q(\bar{q}) \rightarrow q(\bar{q}) + \gamma$ **and** $q + \bar{q} \rightarrow \gamma$ **also vanish for $\tau \rightarrow \infty$**





only evident for $\tau >> \tau_F \approx 1.0$ fm/c (expected formation time of QGP)

- **Why such slow decrease?**

large formation times of collinear modes for $q(\bar{q}) \rightarrow q(\bar{q}) + \gamma$

large formation times of anticollinear modes at $p \leq \omega_{\vec{k}}$ for $q + \bar{q} \rightarrow \gamma$

τ needs to be significantly larger than formation times of all contributing modes

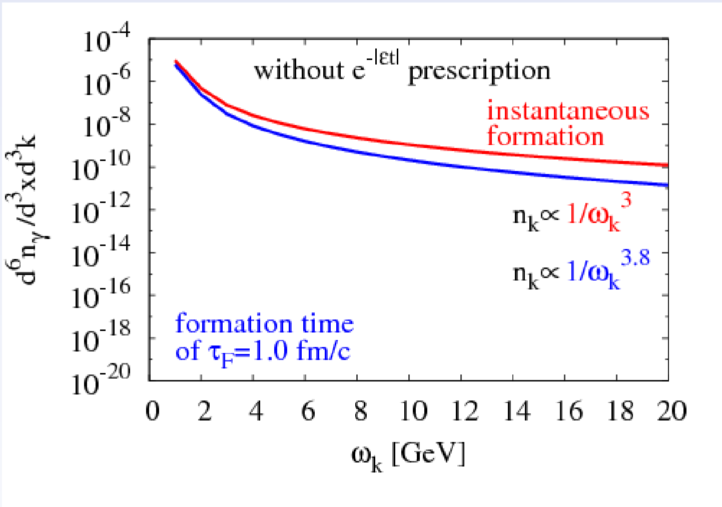
Outlook

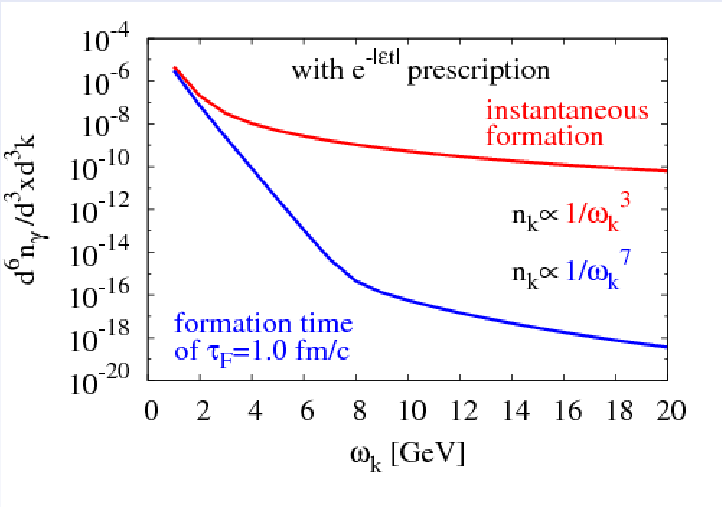
- **relevance of results for earlier model approach**

  unphysical UV scaling behavior ↔ ill defined photon numbers?
  artifact removed for free asymptotic states?

- **revisit model approach accordingly**

  photon spectra indeed UV integrable for suitable f(t)





photon numbers $\propto 1/\omega_{\vec{k}}^3$ for **instantaneous** formation

photon numbers $\propto 1/\omega_{\vec{k}}^7$ for formation over **finite time interval**

Outlook

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- **role of Ward-Takahashi identities?**

  violated for photon self-energy within model description **but** asymptotic photon spectra UV integrable

  original conjecture disapproved?

- **but keep in mind:**

  Ward-Takahashi identities can be violated in two ways

  direct violation by ansatz for photon self-energy **or** indirect violation when considering 'photon numbers' at finite times

  Does only the indirect violation lead to artificial results?

- **so far only asymptotic description / extension to finite times**

  physically sensible definition of transient photon numbers possible?

  identify possible alternative quantities

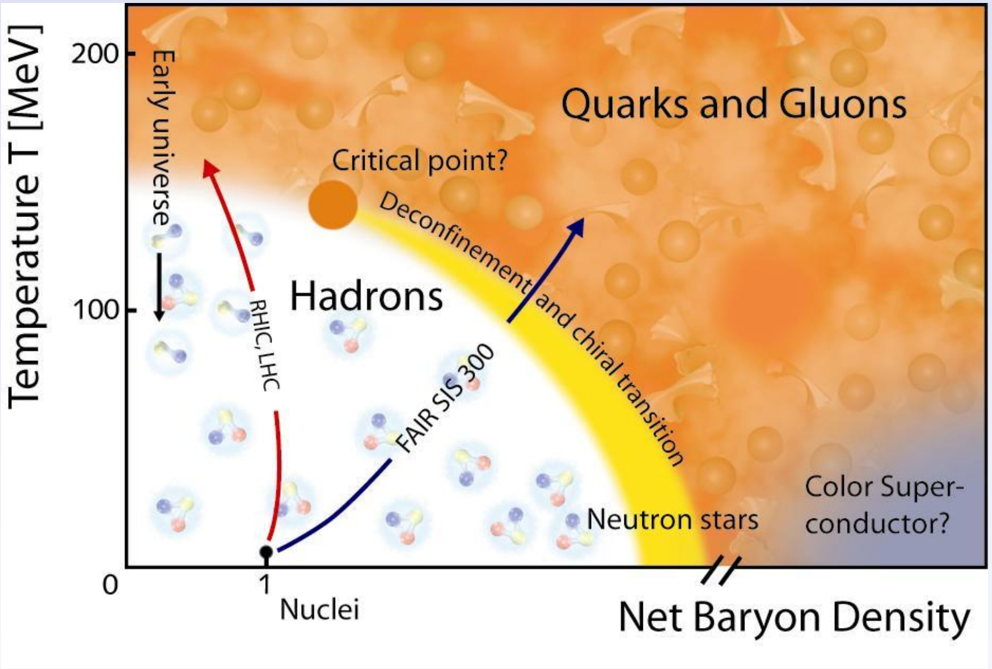
- **non-equilibrium quantum field theory remains challenging**

Introduction and Motivation

- **What is the quark-gluon plasma?**

  state of matter of deconfined quarks-and gluons

  predicted by **Q**uantum **C**hromo**D**ynamics (QCD) for large T and/or n



- **How to access the quark-gluon plasma in a laboratory?**

  Ultrarelativistic heavy-ion collisions

Introduction and Motivation

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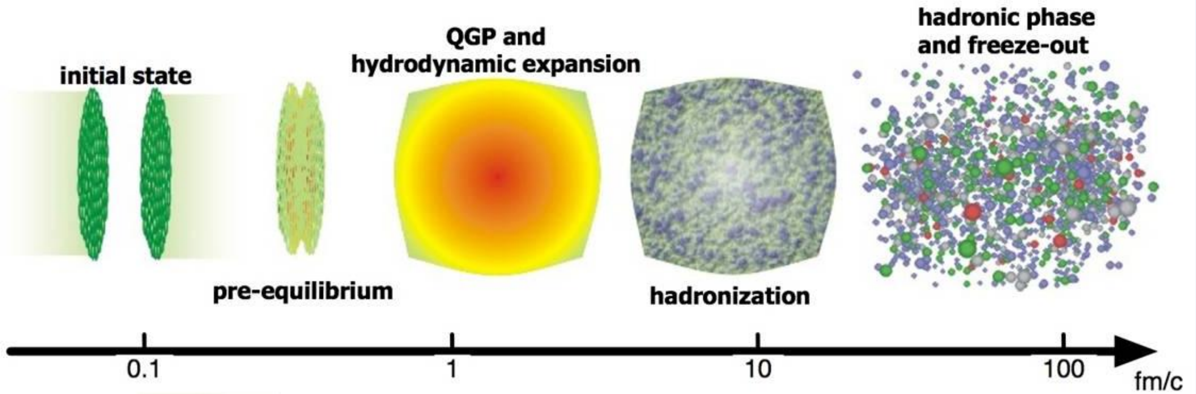
- **What are heavy-ion collisions?**

  nuclei of heavy elements (Au,Pb) are taken to collision at almost the speed of light

  required energy obtained using special accelerator facilities such as RHIC, LHC and future FAIR

- **Time-evolution of heavy-ion collision**



  Quark-gluon plasma appears during early stage

- **Major obstacle for investigating properties of QGP**

  extremely short lifetime of up to 10 fm/c ≈ 10^{-22} s !!