Possible non-prompt photons in pp collisions and their effects in AA collisions

Akihiko Monnai (KEK, Japan)

Hard Probes 2018

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Introduction

- Relativistic nuclear colliders: a gateway to quark-gluon plasma
  - Relativistic Heavy Ion Collider (RHIC)@BNL, $\sqrt{s_{NN}}$ = 5.5-200 GeV (2000-)

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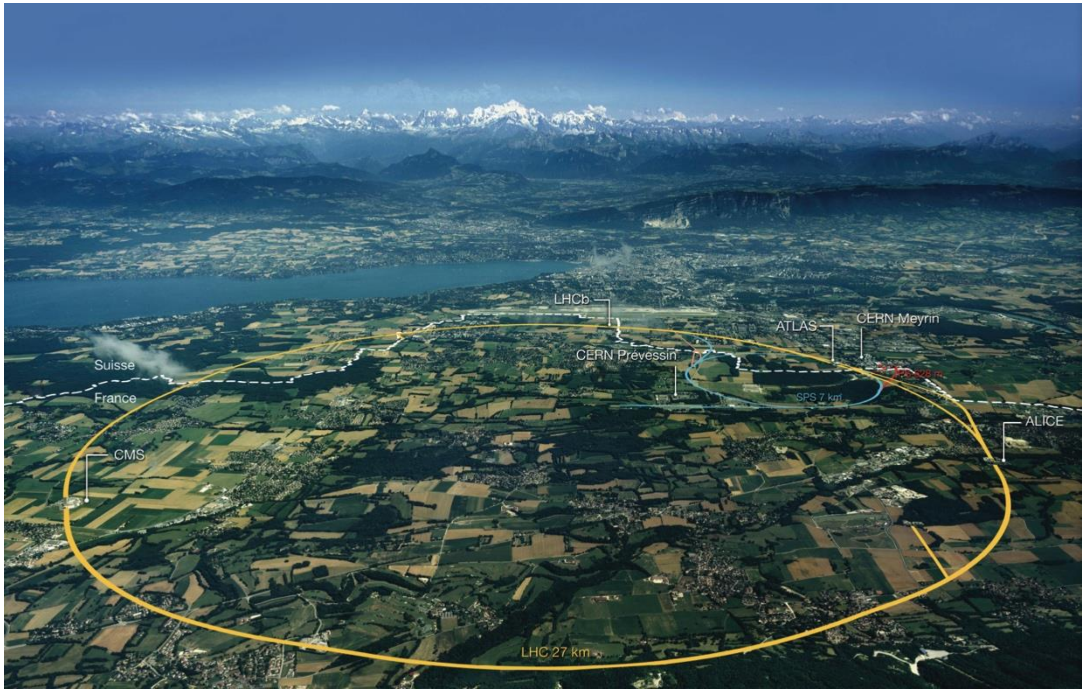

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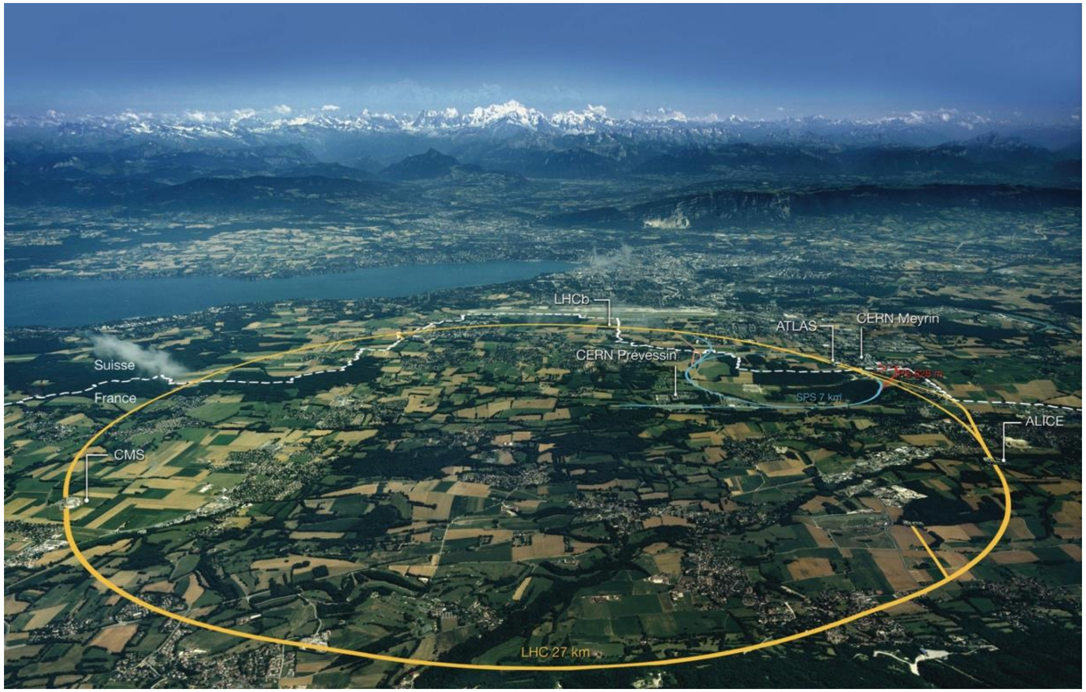
  - FAIR@GSI, NICA@JINR, SPS@CERN, J-PARC@JAEA/KEK … ?



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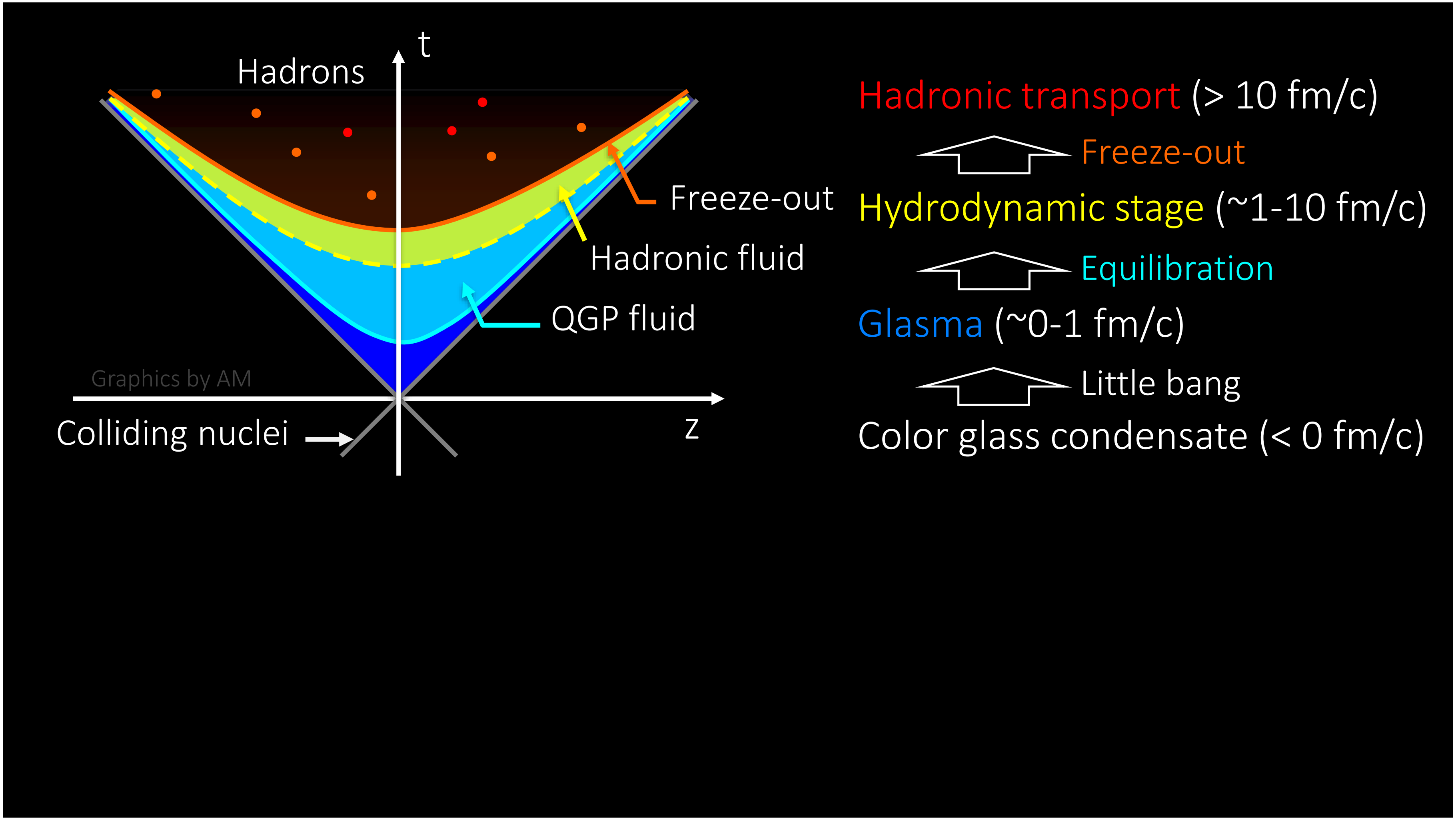

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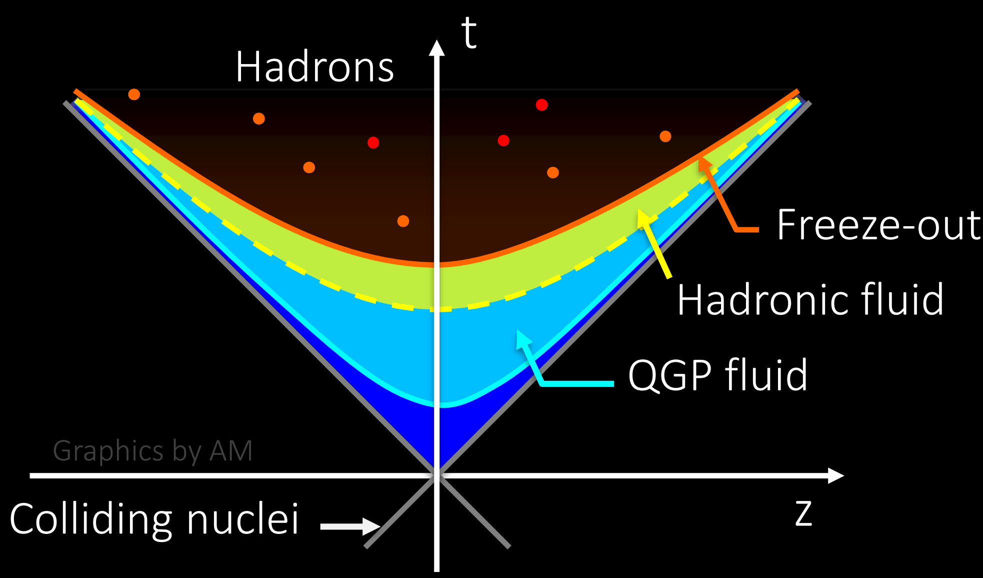


Hadronic transport (> 10 fm/c)

⇧ Freeze-out

Hydrodynamic stage (~1-10 fm/c)

⇧ Equilibration

Glasma (~0-1 fm/c)

⇧ Little bang

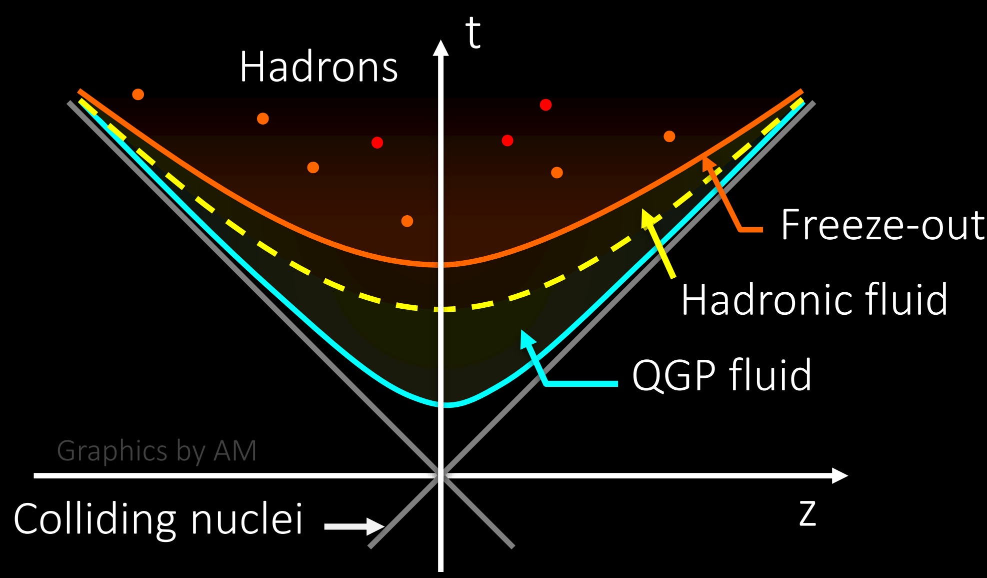
Color glass condensate (< 0 fm/c)

▶ Color opaque

Most information before freeze-out is lost in "thermal hadrons"

Introduction

- Relativistic nuclear collisions: Electroweak point of view



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Photons retain information of the space-time evolution of the system

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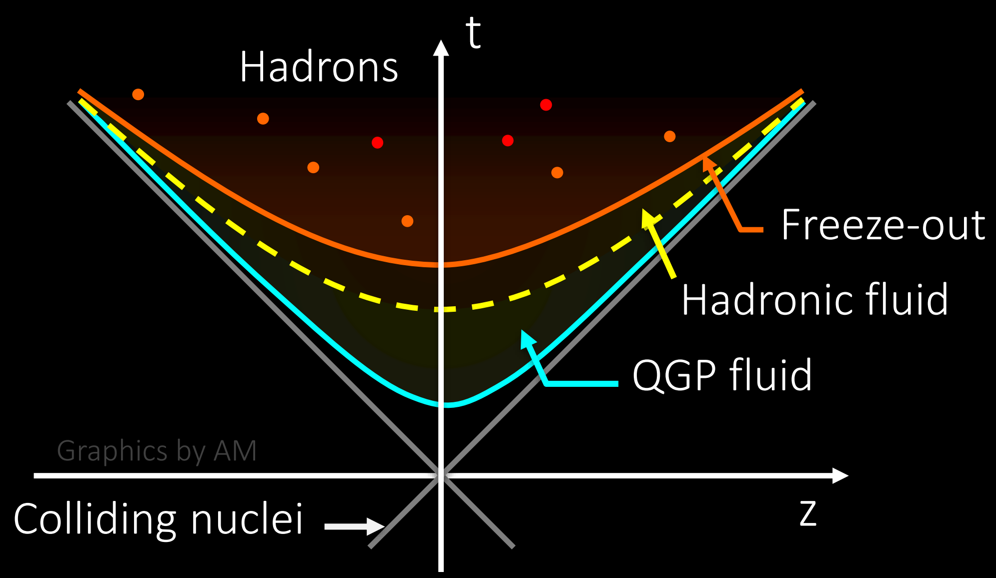

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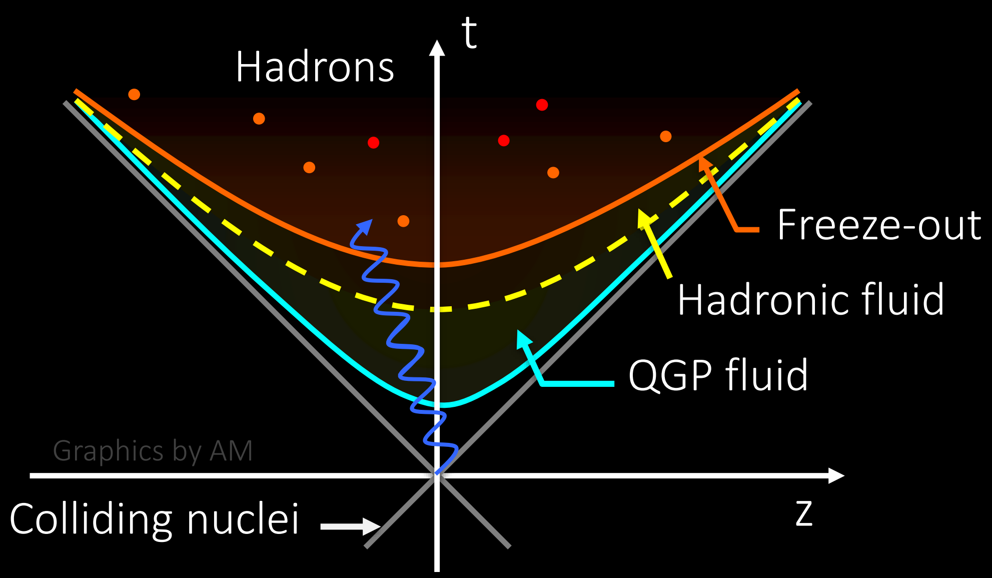

Prompt photons
- from hard processes

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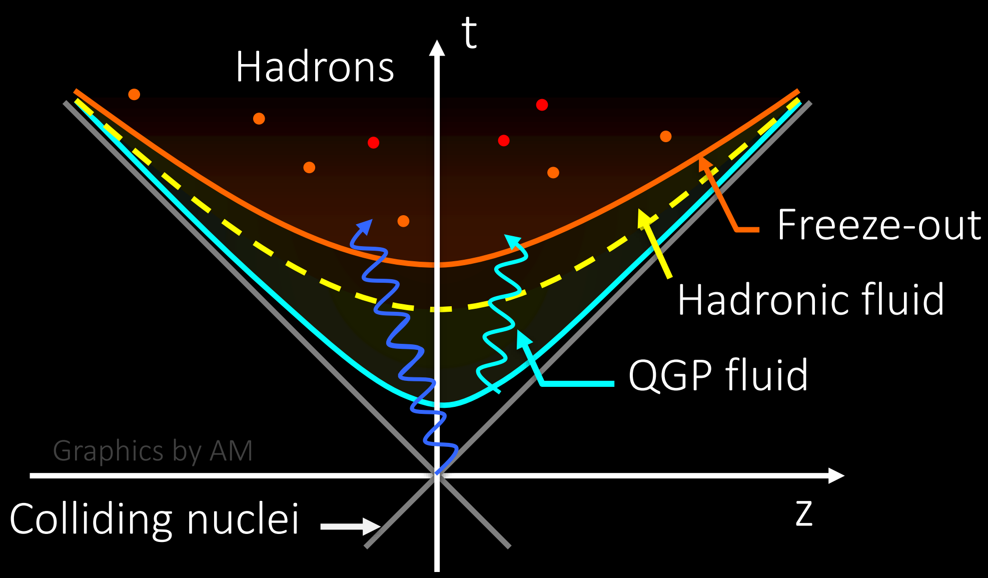

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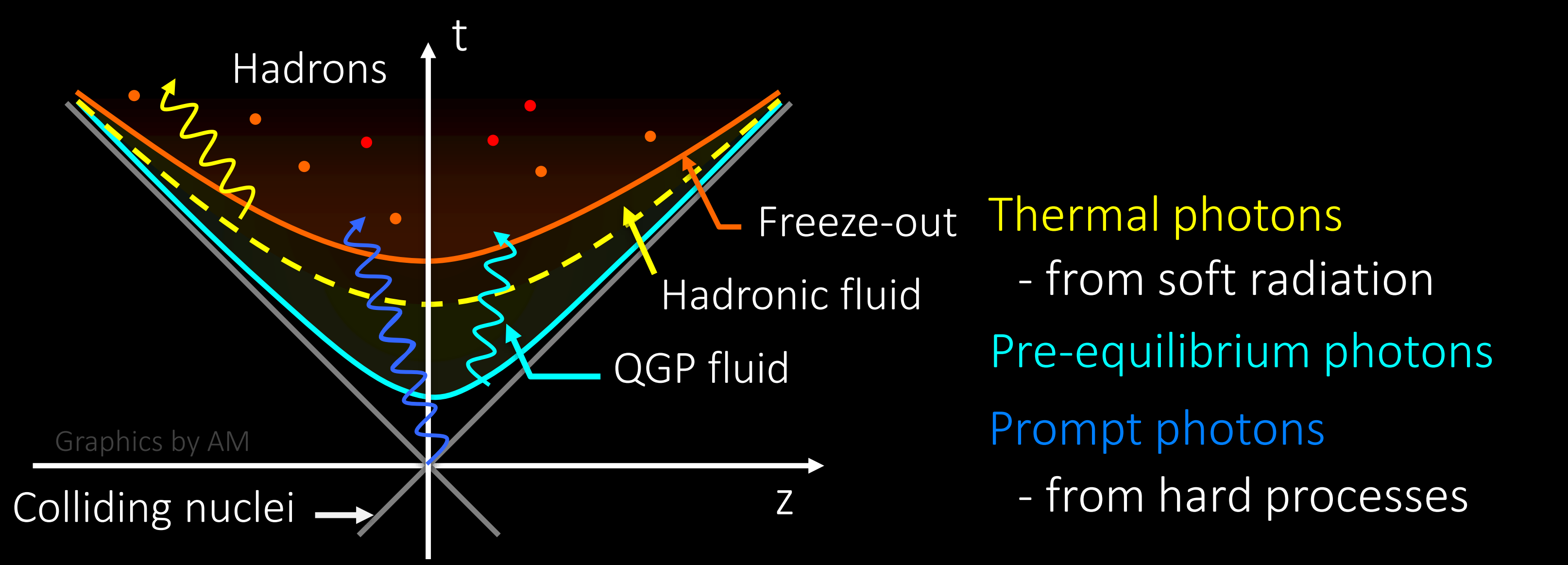

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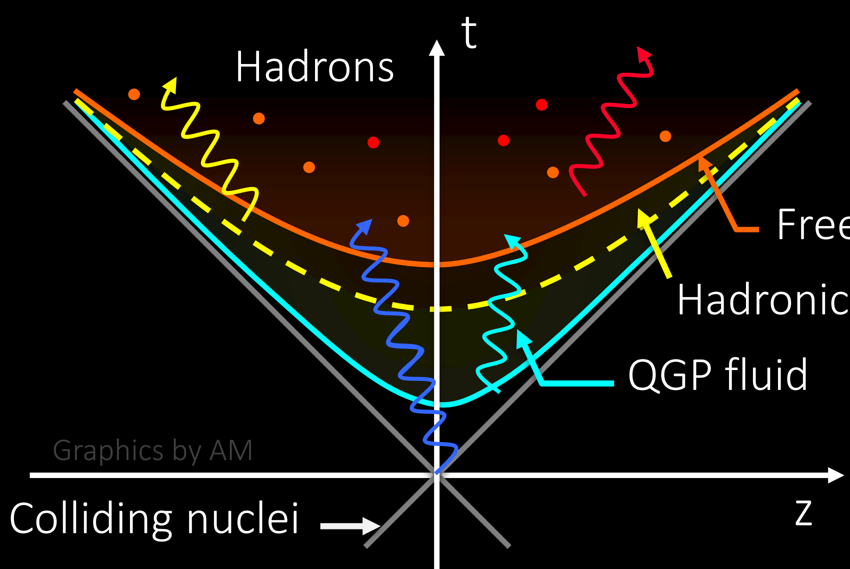

Decay photons
- from hadronic decay

Thermal photons
- from soft radiation

Pre-equilibrium photons

Prompt photons
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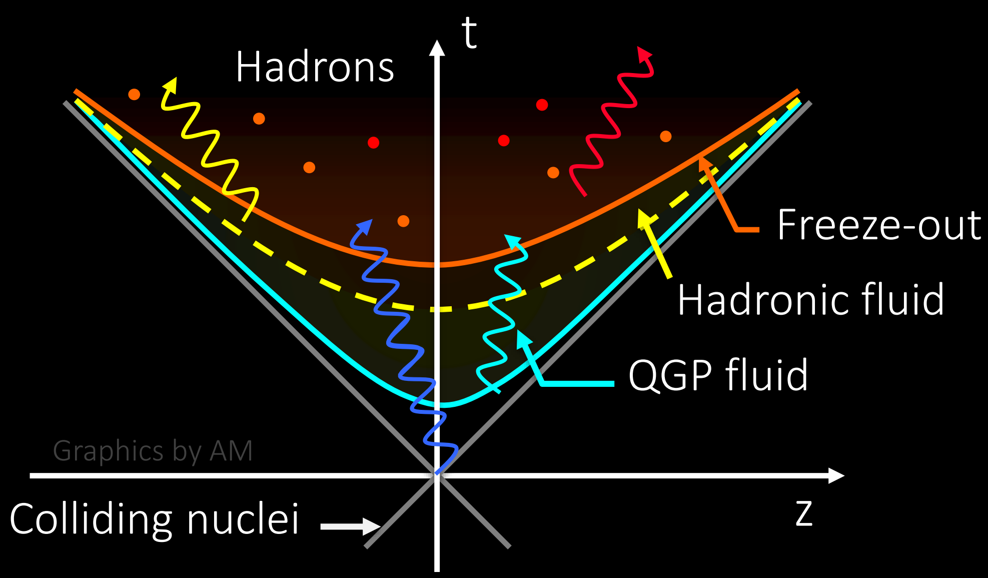

Decay photons
- from hadronic decay

Thermal photons
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Pre-equilibrium photons

Prompt photons
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Direct photons

▶ Color opaque

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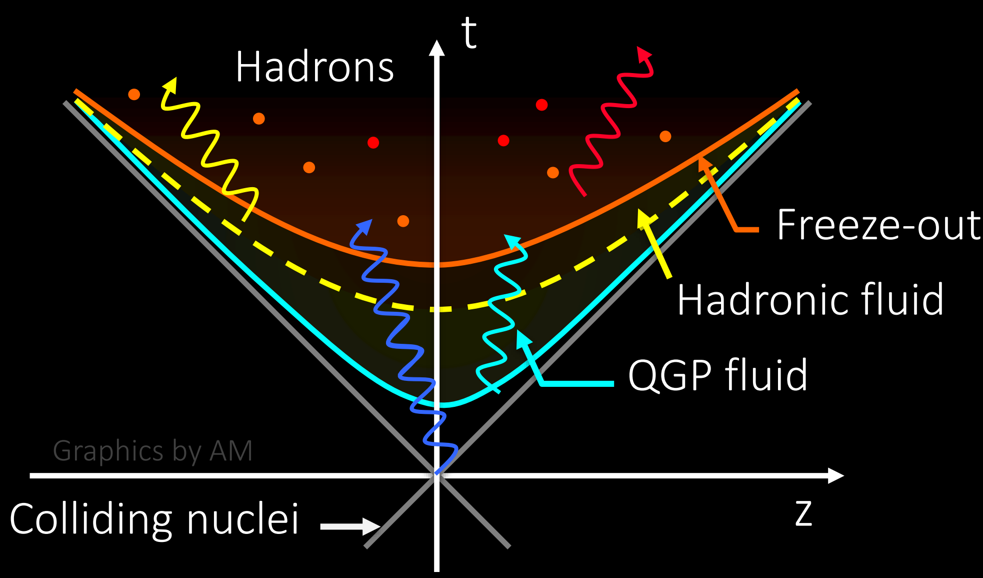

Decay photons
- from hadronic decay

Thermal photons
- from soft radiation

Pre-equilibrium photons

Prompt photons
- from hard processes

(Jet photons, etc)

Direct photons

▶ **Color opaque**

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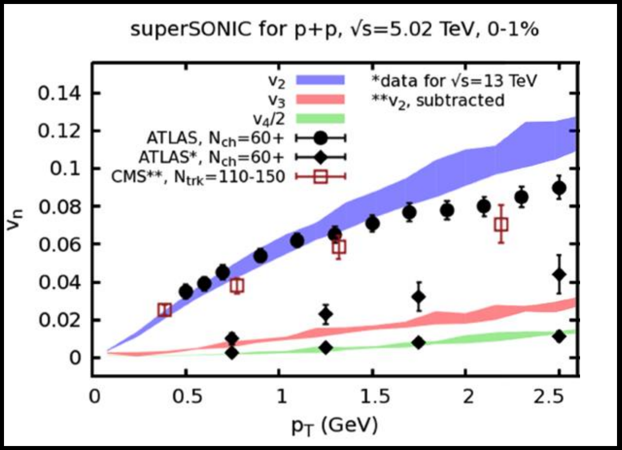
Photons retain information of the space-time evolution of the system

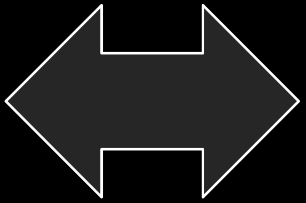
Introduction

- "Collectivity" in small systems

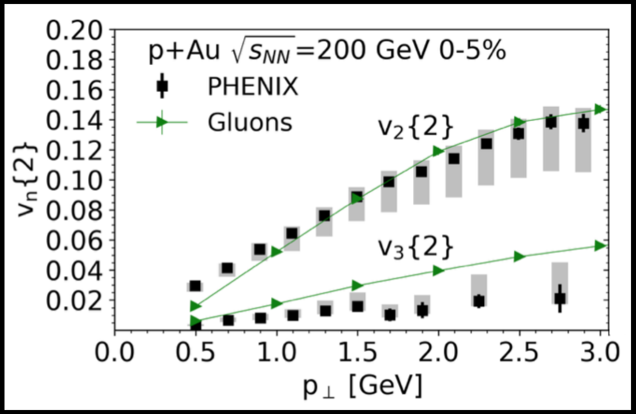
  - Hydrodynamic and non-hydrodynamic models both work

Weller and Romatschke, PLB 774,351 (2017)





Mace et. al., PRL 121, 052301 (2018)

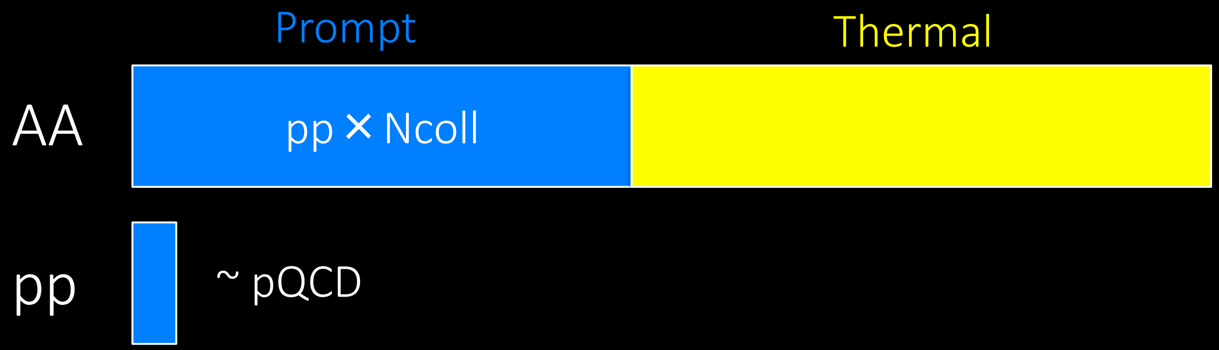


  - Thermalized QGP in pp is still controversial; but there is a possibility in most central collisions

Introduction

- Direct photon ingredients

- AA collisions vs. pp collisions



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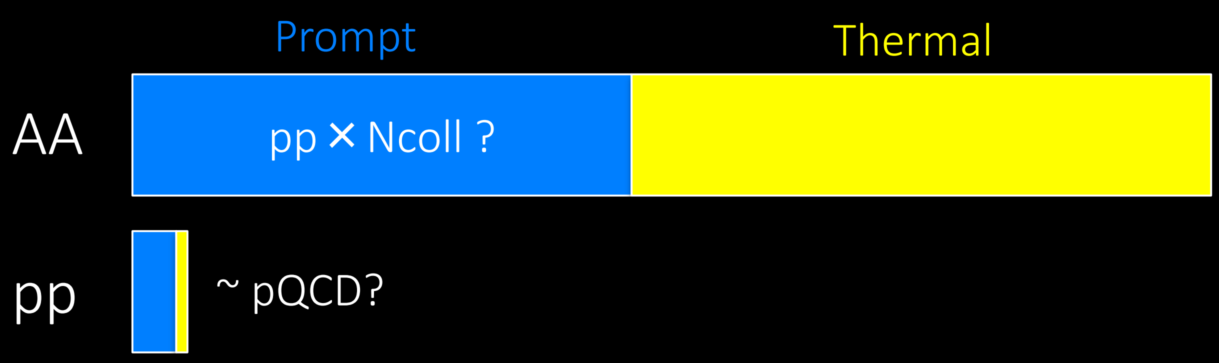
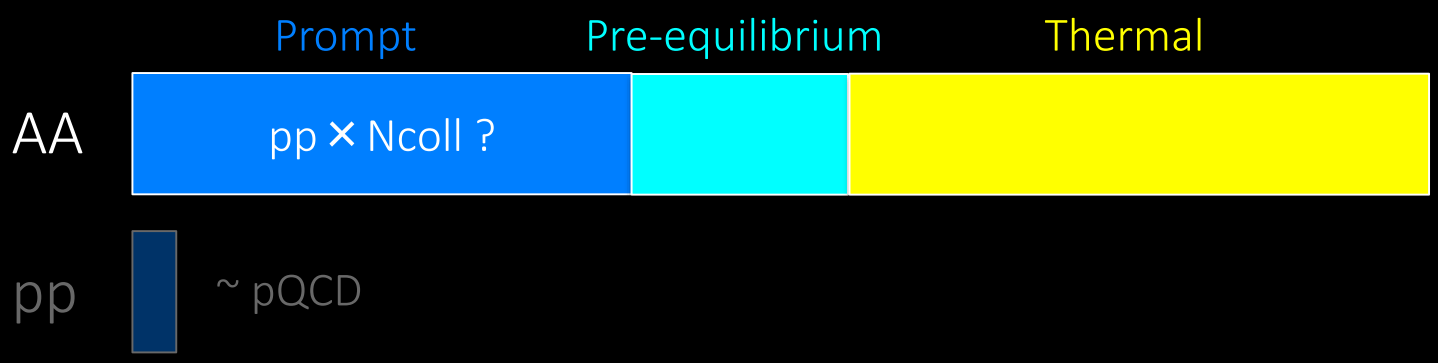


- There can be thermal photons in pp

Cf. C. Shen, J.-F. Paquet, G. S. Denicol, S. Jeon and C. Gale, PRC 95, 014906 (2017)

Introduction

- Direct photon ingredients
  - AA collisions vs. pp collisions



  - Pre-equilibrium photons can be important

Cf. Early hydro vs. glasma: J. Berges et. Al., PRC 95, 054904 (2017),
mBU-Glasma: V. Khachatryan et. al., NPA 978, 123 (2018)

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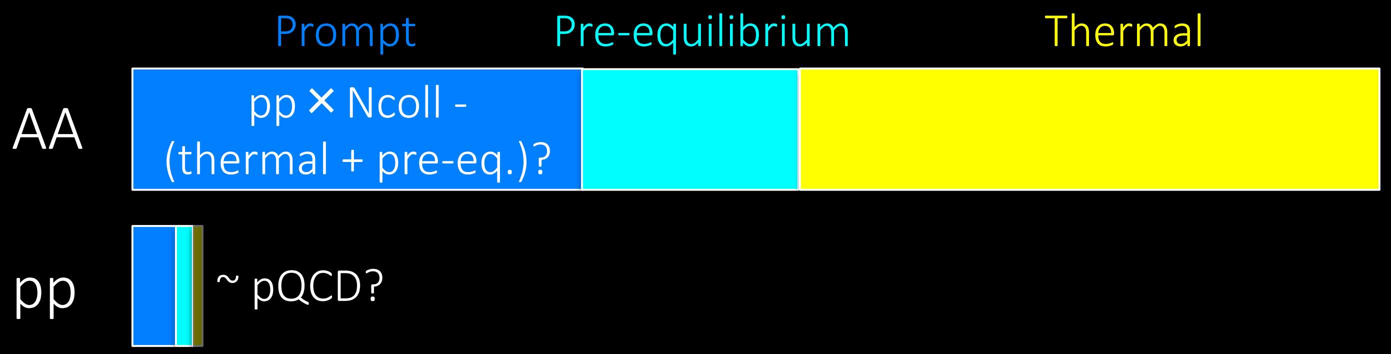
■ Direct photon ingredients

- AA collisions vs. pp collisions



- Aim of this study: Non-prompt photons in both AA and pp
  (glasma production more likely at LHC)

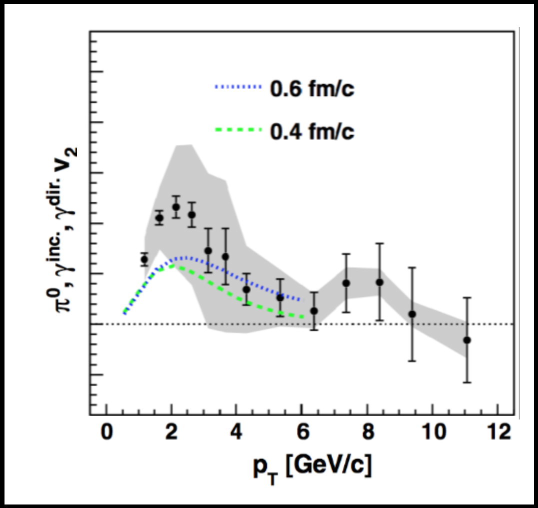
  - It may pose limit to the amount of QGP in pp collisions
  - Pre-eq. photons may affect the analyses of AA collisions

Introduction

- Photon puzzle

  - Observed azimuthal momentum anisotropy (v_2) is large

PHENIX, PRL 109, 122302 (2012)



Systematic tension not removed yet;
clarification from experiments is essential

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▶ Observed azimuthal momentum anisotropy (v_2) is large

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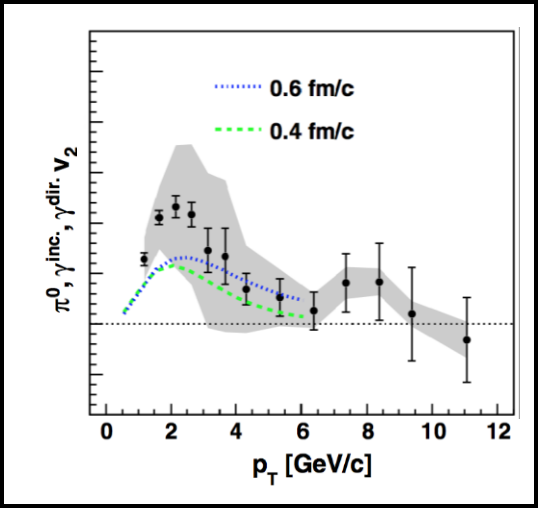

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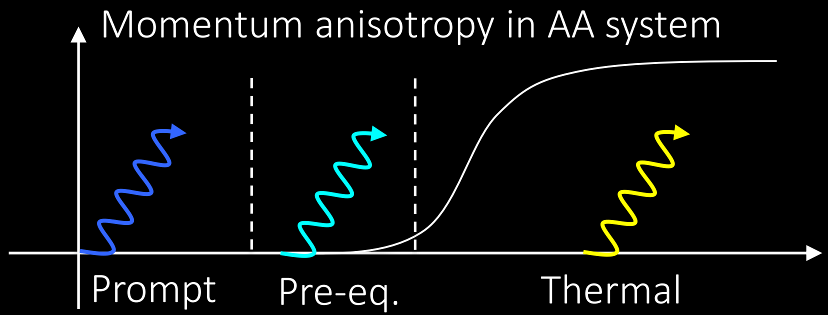
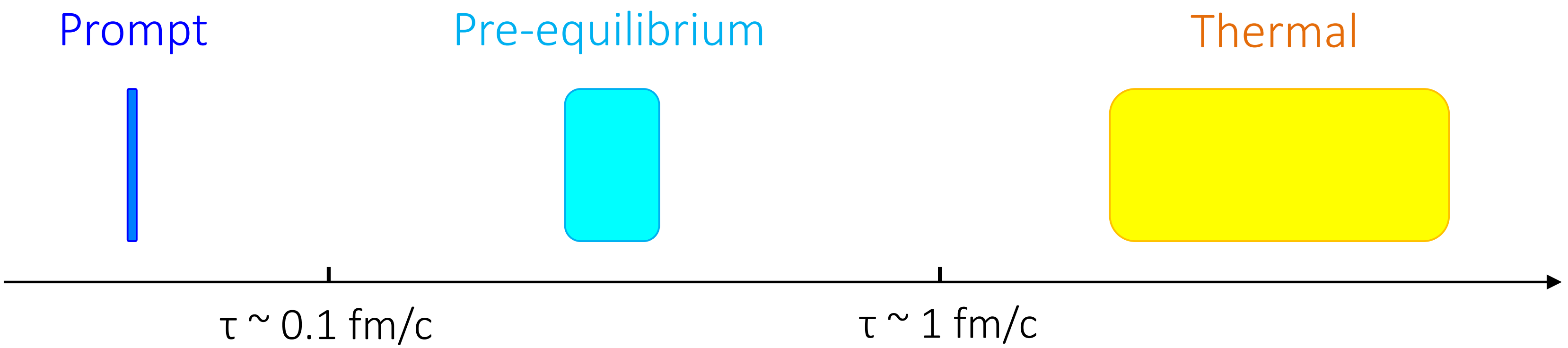


▶ Non-prompt photons in pp may improve the situation; pre-equilibrium photons in AA collisions may do the opposite

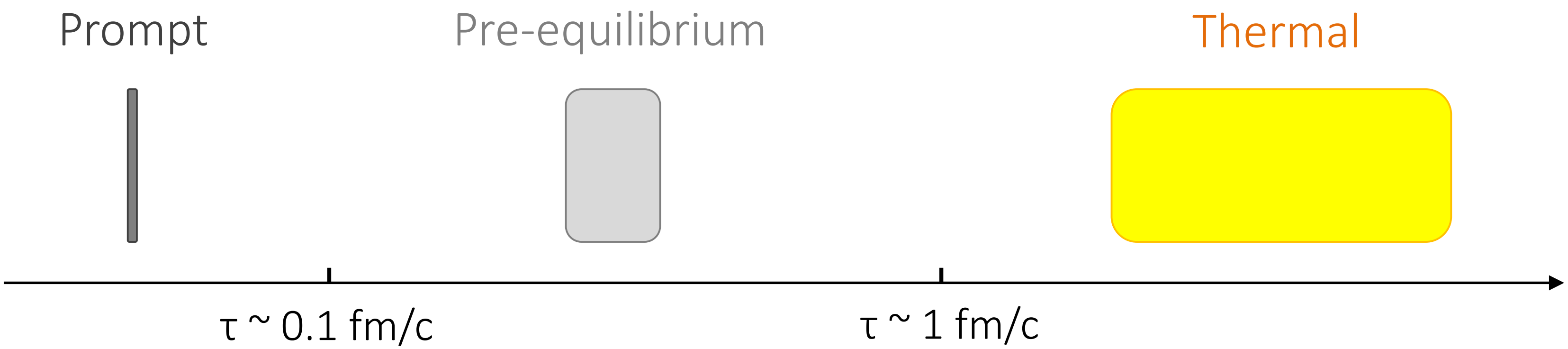
Timeline

- Photons from different stages of HIC



Timeline

- Thermal photons



▶ Estimated using a (2+1)-D hydrodynamic model

Collision energy: 2.76 TeV

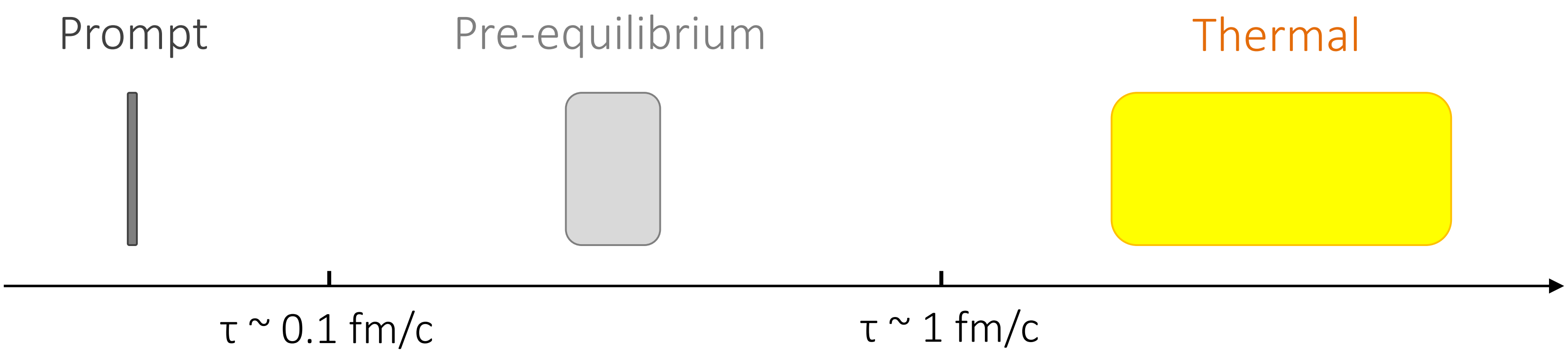
Equation of state: lattice QCD

Initial condition: Glauber model (event-averaged)

τ_{th}: tuned to 1 fm/c

Timeline

- Thermal photons



- Thermal photon emission rate

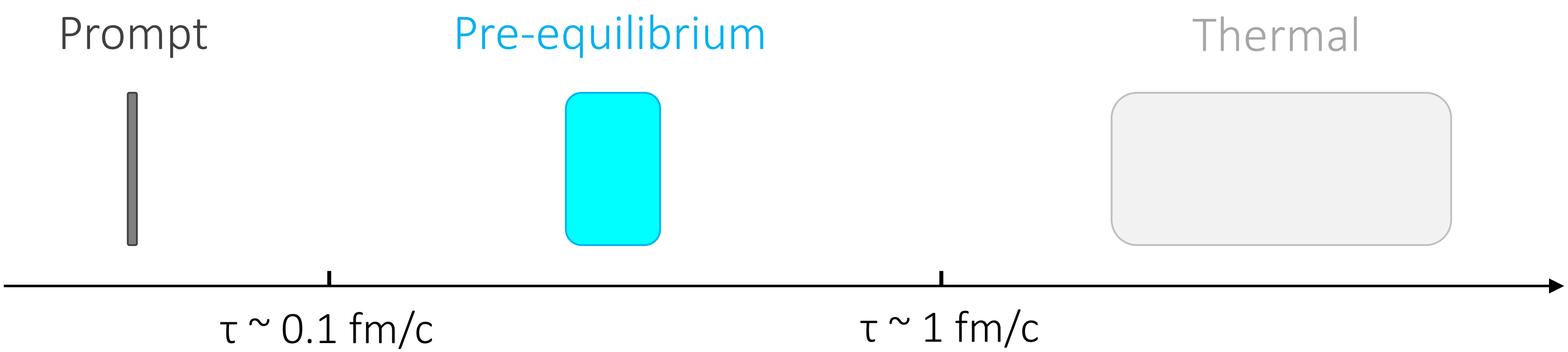
$$E\frac{dR^\gamma}{d^3p} = \frac{1}{2}\left(1 - \tanh\frac{T-T_c}{\Delta T}\right)E\frac{dR^\gamma_{\mathrm{hadron}}}{d^3p} + \frac{1}{2}\left(1 + \tanh\frac{T-T_c}{\Delta T}\right)E\frac{dR^\gamma_{\mathrm{QGP}}}{d^3p}$$

Turbide, Rapp and Gale, PRC 69, 014903   Arnold, Moore and Yaffe, JHEP 0112, 009

where $T_c = 0.17$ GeV and $\Delta T = 0.017$ GeV

Timeline

- Pre-equilibrium photons



- Bottom-up / turbulent thermalization approach to glasma

R. Baier, A. H. Mueller, D. Schiff, and D. T. Son, PLB 502, 51 (2001)
J. Berges et. al., PRC 95, 054904 (2017)

(i) $$c_0 Q_s^{-1} \ll \tau \ll c_1 Q_s^{-1} \alpha_s^{-3/2}$$

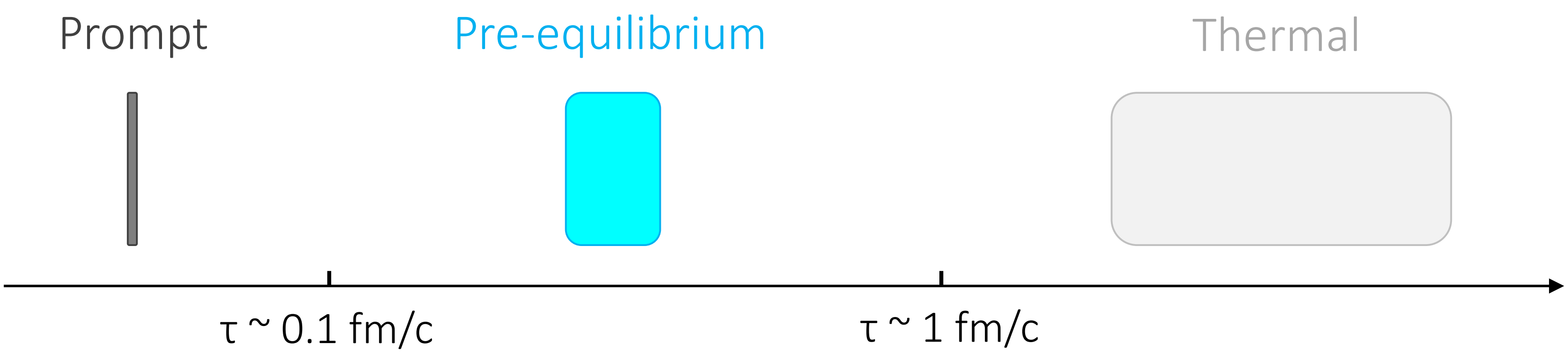
(ii) $$c_1 Q_s^{-1} \alpha_s^{-3/2} \ll \tau \ll c_2 Q_s^{-1} \alpha_s^{-5/2}$$

(iii) $$c_2 Q_s^{-1} \alpha_s^{-5/2} \ll \tau \ll c_3 Q_s^{-1} \alpha_s^{-13/5}$$

$c_{0,1,2,3}$ are introduced to "squeeze" the processes into the pre-hydro phase

Timeline

- Pre-equilibrium photons



- Emission rate: Berges-Reygers-Tanji-Venugopalan model

J. Berges et. al., PRC 95, 054904 (2017); N. Tanji and R. Venugopalan PRD 95, 094009 (2017)

Stages (i), (ii)

$$E\frac{dR^\gamma}{d^3p} = \frac{20}{9\pi^2}\alpha\alpha_s \ln\left(1+\frac{2.919}{g^2}\right) f_q(p) \int \frac{d^3p'}{(2\pi)^3}\frac{1}{p'}[f_g(p')+f_q(p')]$$

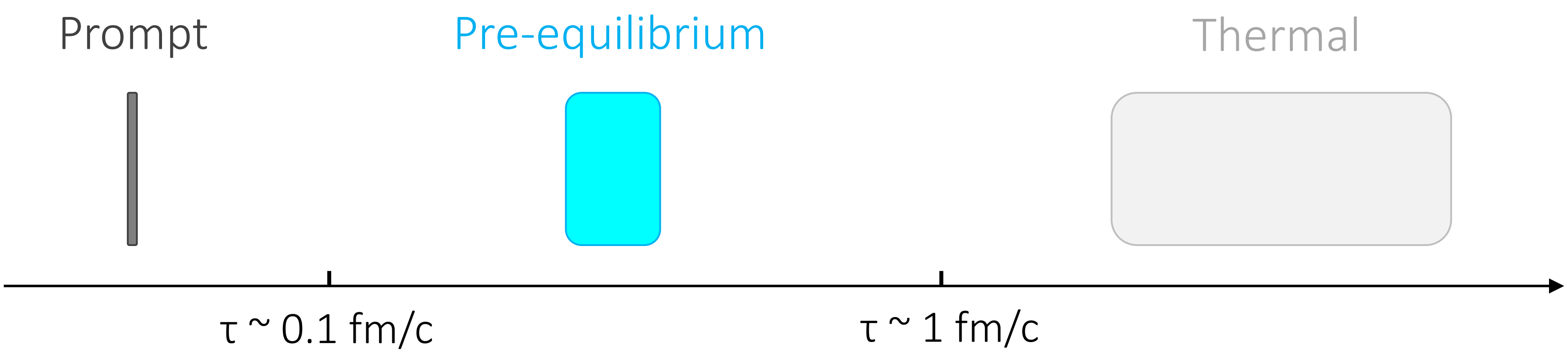
$$f_q = (Q_s\tau)^{-2/3} f_s(p_T, (Q_s\tau)^{1/3}p_z)$$

$$f_s(p_T, p_z) = A p_T^{-1} \exp(-p_z^2/\sigma_z^2)$$

: Self-similar scaling distribution (Exponentially cut off for p_T > Qs; normalized as $n_q = n_q^{th}$ at τ^{th})

Timeline

- Pre-equilibrium photons



- Emission rate: Berges-Reygers-Tanji-Venugopalan model

J. Berges et. al., PRC 95, 054904 (2017); N. Tanji and R. Venugopalan PRD 95, 094009 (2017)

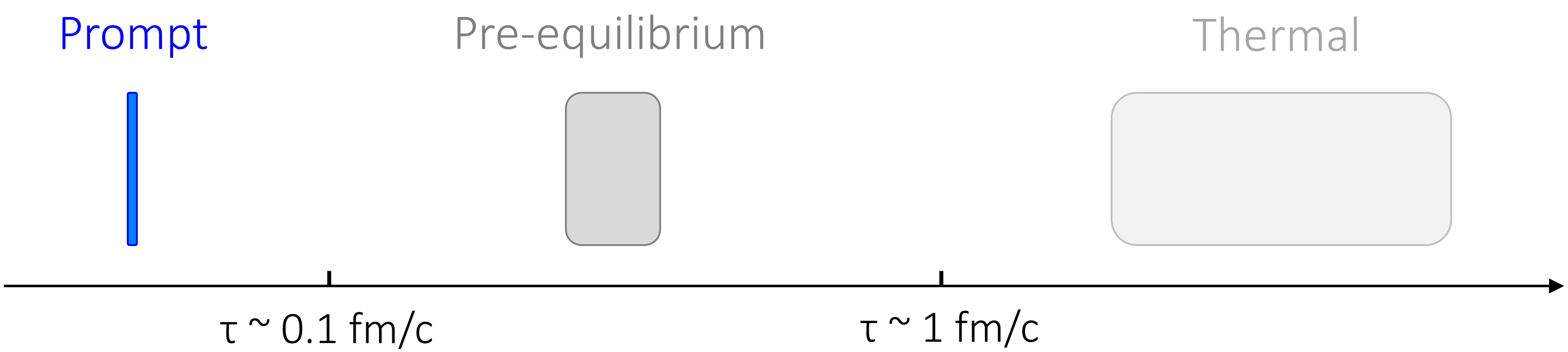
<u>Stage (iii)</u>

$$E\frac{dR^\gamma}{d^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}T^2 e^{-E/T}\ln\left(1+\frac{2.919}{g^2}\right)$$ with effective $T = T_{\rm th}\tau/\tau_{\rm th}$

Note: The model is parametrically extended to fit into the pre-hydro time; quantitative discussion should be made carefully

Timeline

- Prompt photons



- pp direct photons - (other photons) scaled by N_{coll}

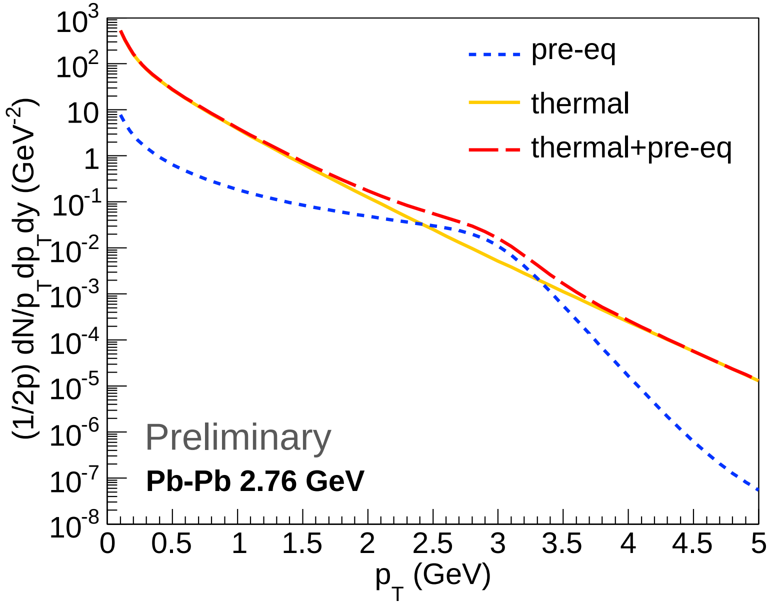
$$E\frac{dN^{\gamma}_{\mathrm{dir}}}{d^3p} = 6745\frac{\sqrt{s}}{(p_T)^5}\frac{N_{\mathrm{coll}}}{\sigma^{\mathrm{in}}_{pp}[\mathrm{pb}]}$$

Turbide, Rapp and Gale, PRC 69, 014903

Alternatively one may perform pQCD analyses; it should be noted that yet other sources of photons can be hidden

Photons in AA collisions

- Pb-Pb 2.76 TeV, Glauber, 0-5%, Qs = 3 GeV



Pre-equilibrium photons

- Semi-hard reflecting the saturation momentum scale Qs
- Absolute value is dependent on parametrization; they could be comparable to thermal photons

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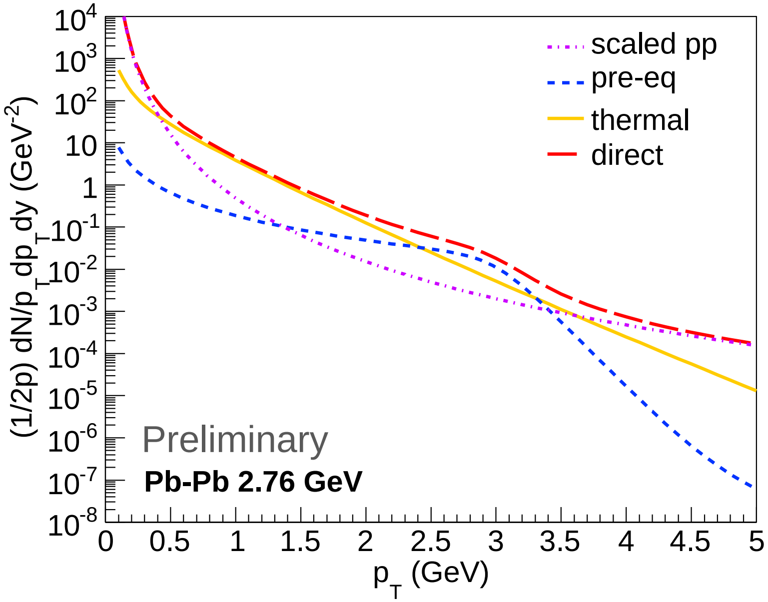

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N_{coll} scaled pp

- Prompt photons if pp is not modified by thermal or pre-eq. photons

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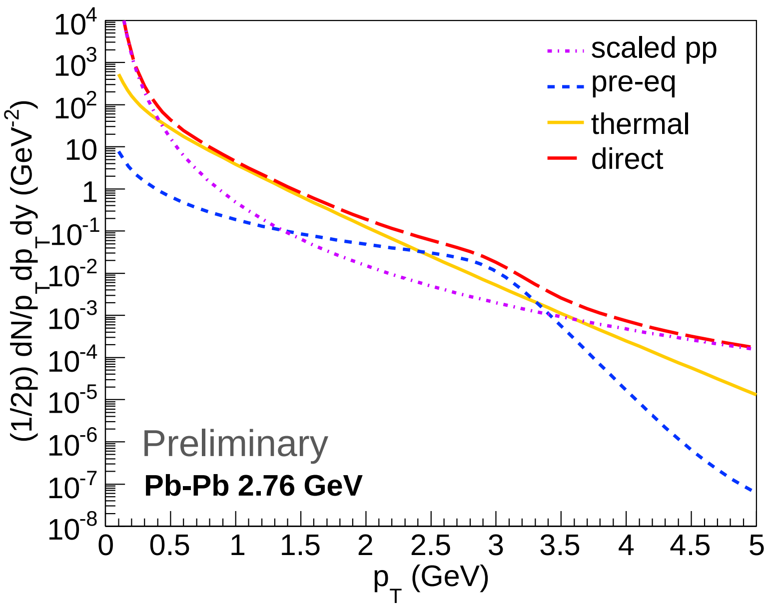

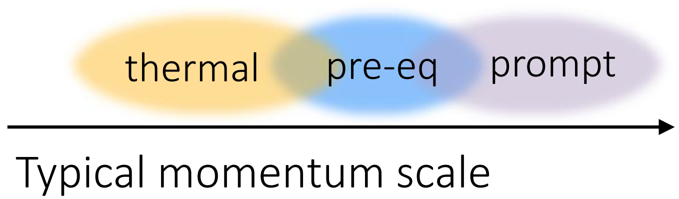

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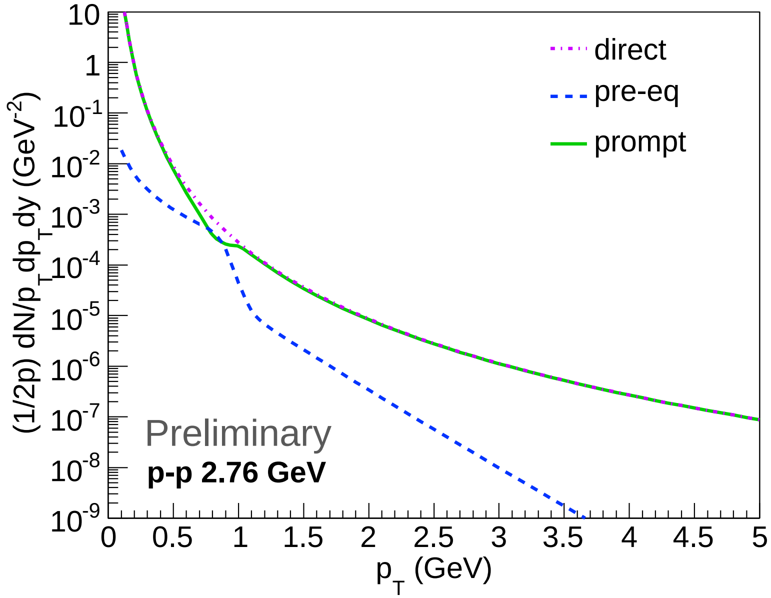
Photons in pp collisions

- p-p 2.76 TeV, Glauber, Qs = 0.9 GeV



Thermal photons

Cf: C. Shen, Hard Probes '16

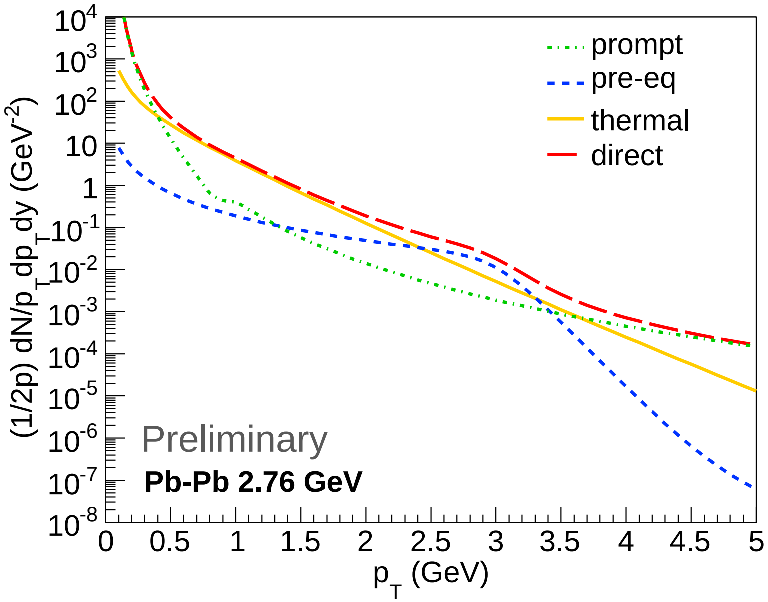
- They can be com-parable to direct photons in most central events
- No thermal QGP is assumed for the moment to be "conservative"

Pre-equilibrium photons

- They can be comparable to direct photon near Qs
- Modified prompt background?

Photons in AA collisions

- Pb-Pb 2.76 TeV, Glauber, 0-5%, Qs = 3 GeV



Prompt & pre-eq photons

- Reduced at pT ~ $Qs^{(p)}$ and enhanced at pT ~ $Qs^{(Pb)}$
- Modified prompt photons do not have much effect on spectra as thermal photons are dominant at pT ~ 1 GeV
- Results are dependent on the value of Qs; v_2 may be affected more

Summary and outlook

- We have studied non-prompt photons in PbPb and pp collisions
  - Pre-equilibrium photons can provide visible semi-hard contribution to pT spectra
  - pp direct photons may not be pure prompt photons; the baseline for AA analyses may well be modified by glasma creation
  - One may probe and constrain the pre-equilibrium physics (Qs etc.) through direct photon analyses

Summary and outlook

- We have studied non-prompt photons in PbPb and pp collisions
  - Pre-equilibrium photons can provide visible semi-hard contribution to pT spectra
  - pp direct photons may not be pure prompt photons; the baseline for AA analyses may well be modified by glasma creation
  - One may probe and constrain the pre-equilibrium physics (Qs etc.) through direct photon analyses
- Future prospects include:
  - Analyses of the effects on elliptic flow v_2
  - Full pp thermal photon analyses can be used to test if the QGP is produced in pp collisions
  - Implementation of chemically equilibrating QGP in hydrodynamic models

Cf: AM, PRC 90, 021901(R) (2014)

Fin

- Merci de votre attention!