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AM, arXiv:1408.1410 [nucl-th]

Quark chemical equilibration for thermal photon elliptic flow

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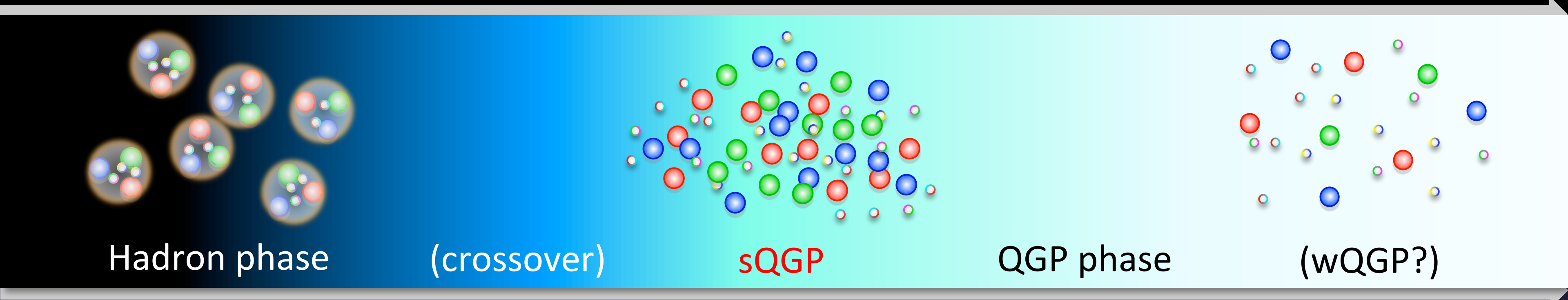
Thermal Photons and Dileptons in Heavy-Ion Collisions

21st August 2014, Brookhaven National Laboratory, NY, USA

Introduction

- Quark-gluon plasma (QGP): many-body system of deconfined quarks and gluons

Graphics by AM

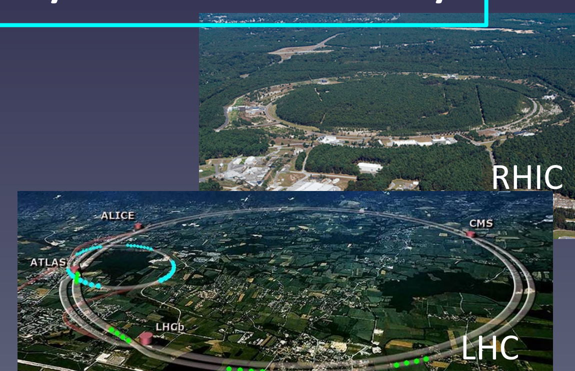


The QGP created in high-energy heavy ion collisions is quantified as a relativistic fluid with extremely small viscosity

Au-Au, Au-Cu (200 GeV) and U-U (193 GeV) at RHIC

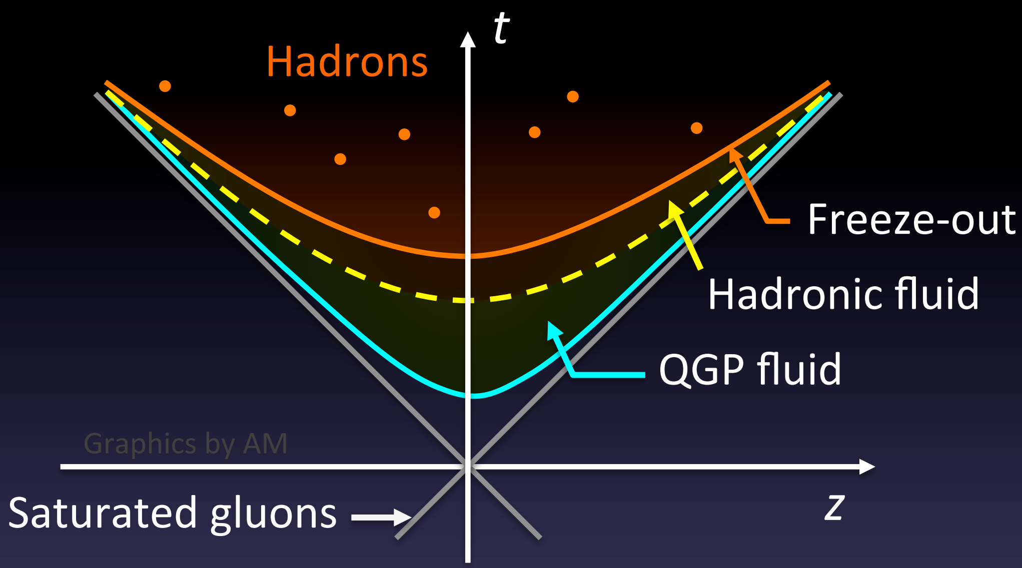
Pb-Pb (2.76 TeV) at LHC

⇨ It is a QCD phenomenon; what can an electromagnetic probe tell us?



Introduction

- Photon emission in heavy ion collisions (low p_T)



The hot medium is opaque in terms of QCD; transparent in terms of electromagnetism

Hadrons: Most of information before freeze-out is lost
Photons: Retain information during time evolution

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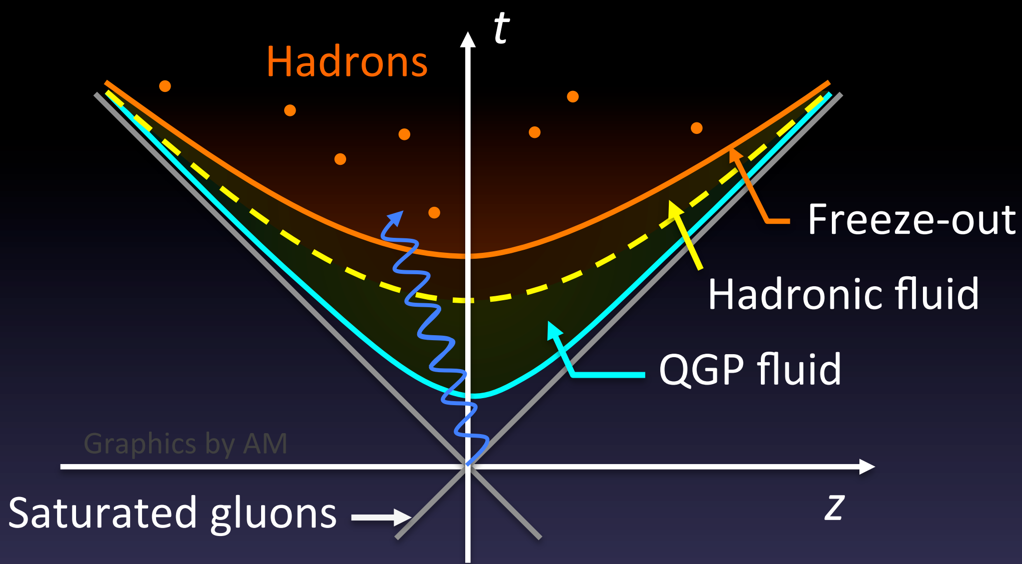

Prompt photons
- from hard processes

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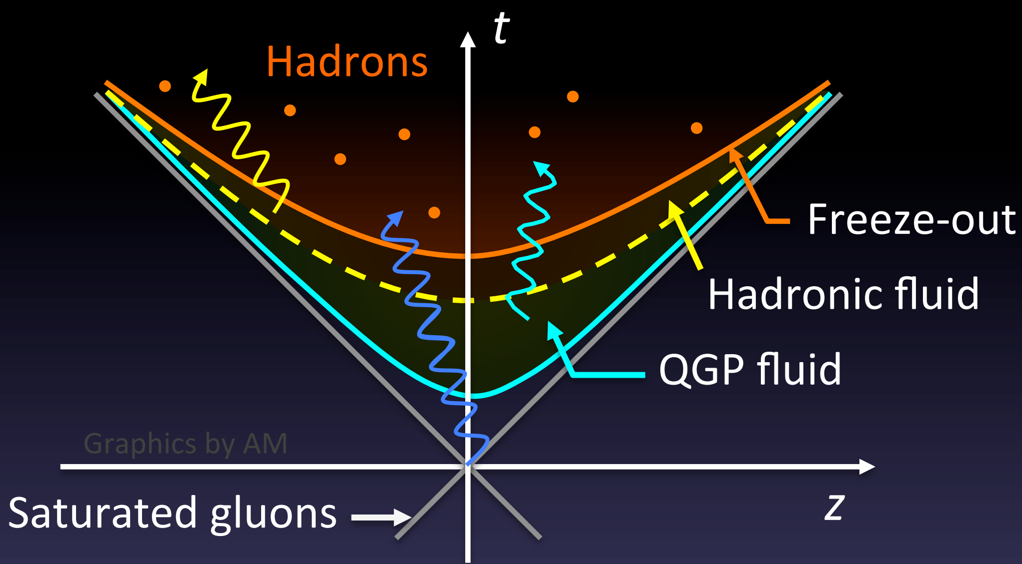

Thermal photons (hadronic)
Thermal photons (QGP)
- from black-body radiation

Prompt photons
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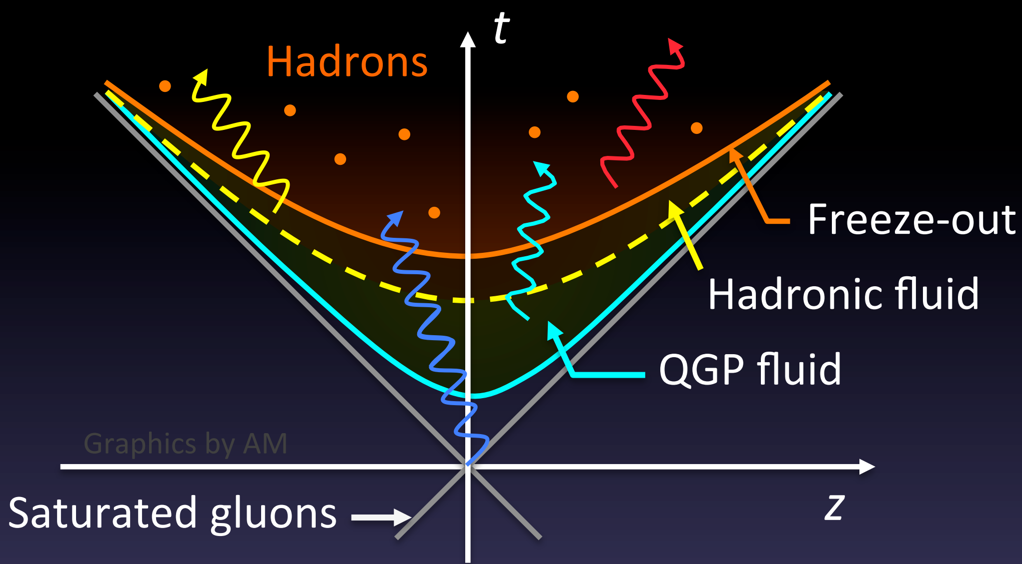

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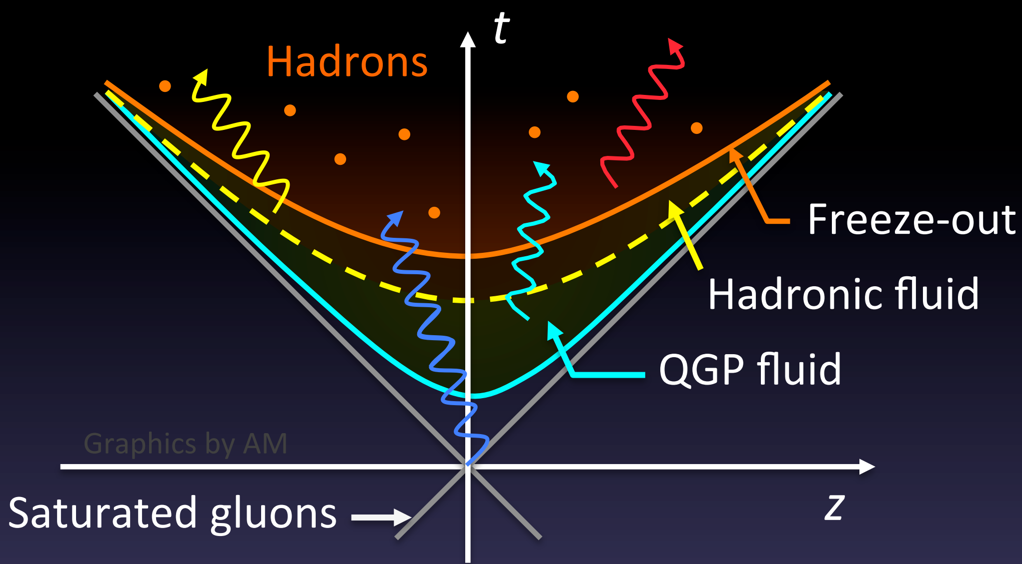

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Direct photons

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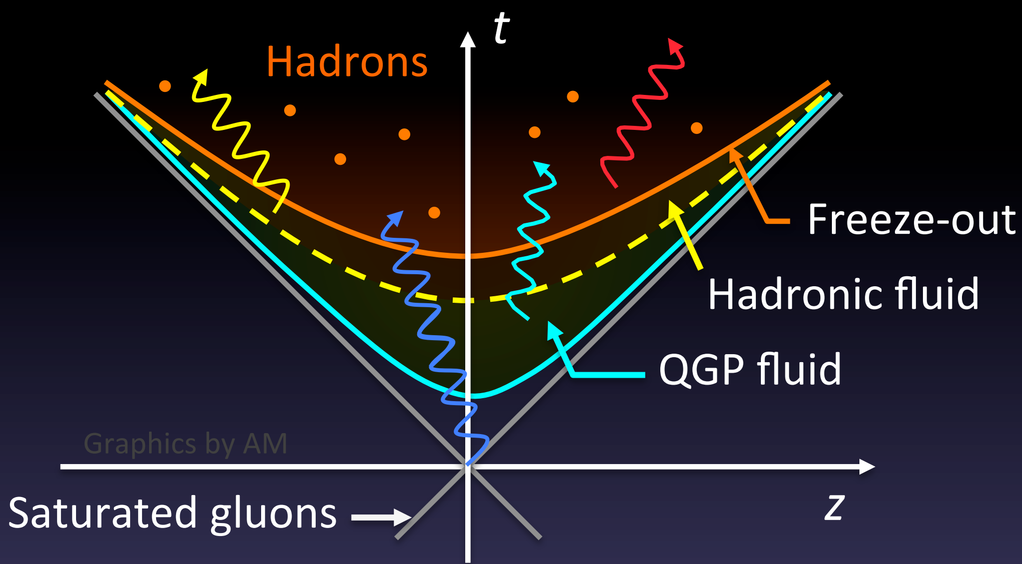

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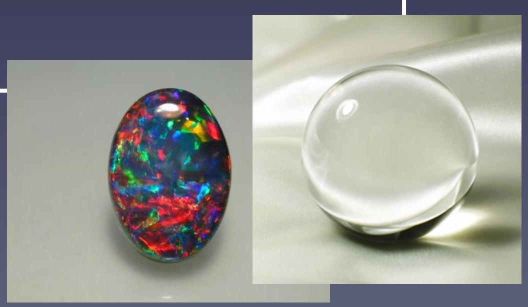


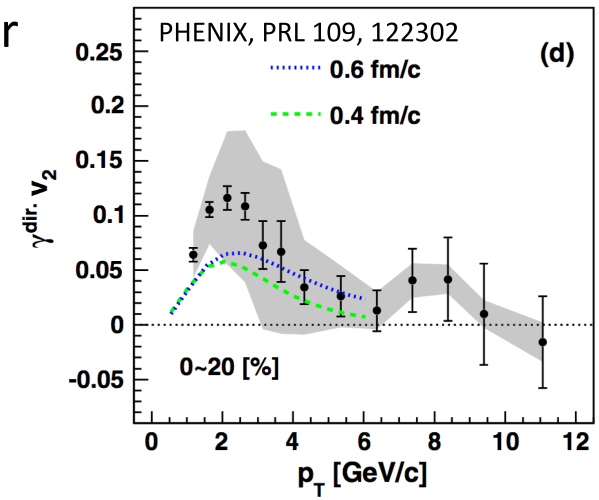
Motivation

- Experiments have posed "photon v_2 puzzle"

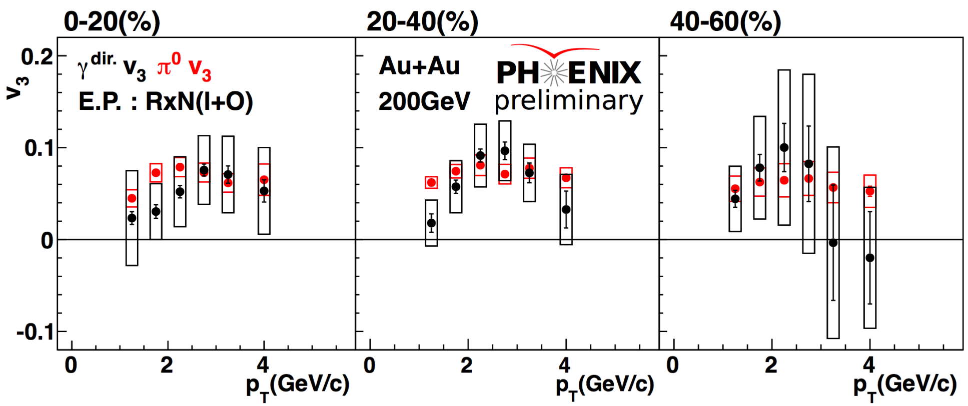
  - Direct photon v_2 is large; no definite answer so far

    - Hydrodynamic models predict small flow harmonics because of the contribution from earlier stages with little elliptic flow

    - Viscosity? Magnetic field? Pre-equilibrium flow? Modified photon emission rate?



  - Direct photon v_3 is also LARGE



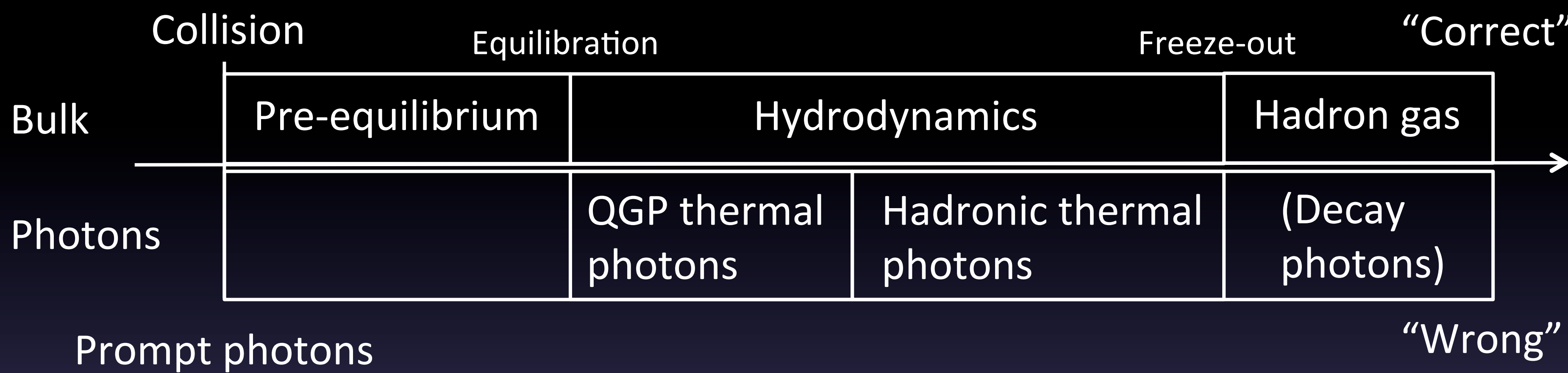
Talk by S. Mizuno (PHENIX) at QM14

No centrality dependence

The enhancement is at least partially due to the properties of the hot medium itself

Photon v_n puzzle

- Possible (not *all*) reasons: an overview



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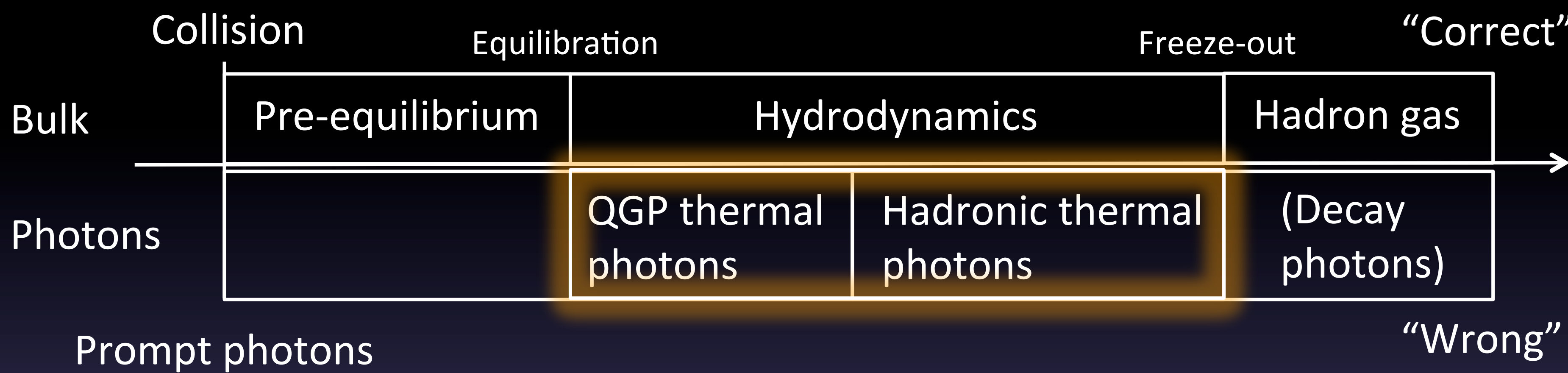

- Thermal photon emission/v_n estimate needs modification

Photon v_n puzzle

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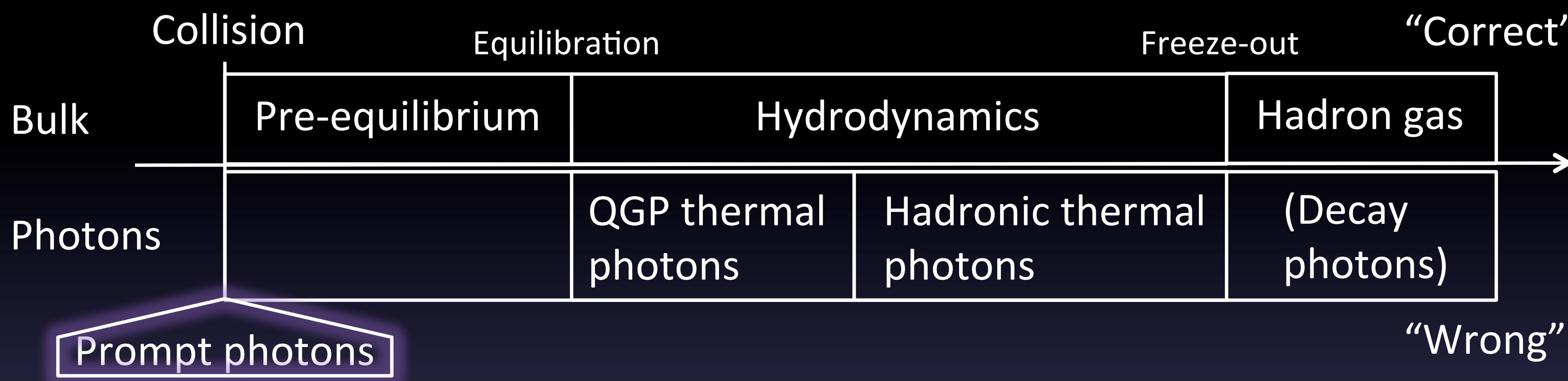

- Thermal photon emission/v_n estimate needs modification
- Prompt photon emission/v_n estimate needs modification

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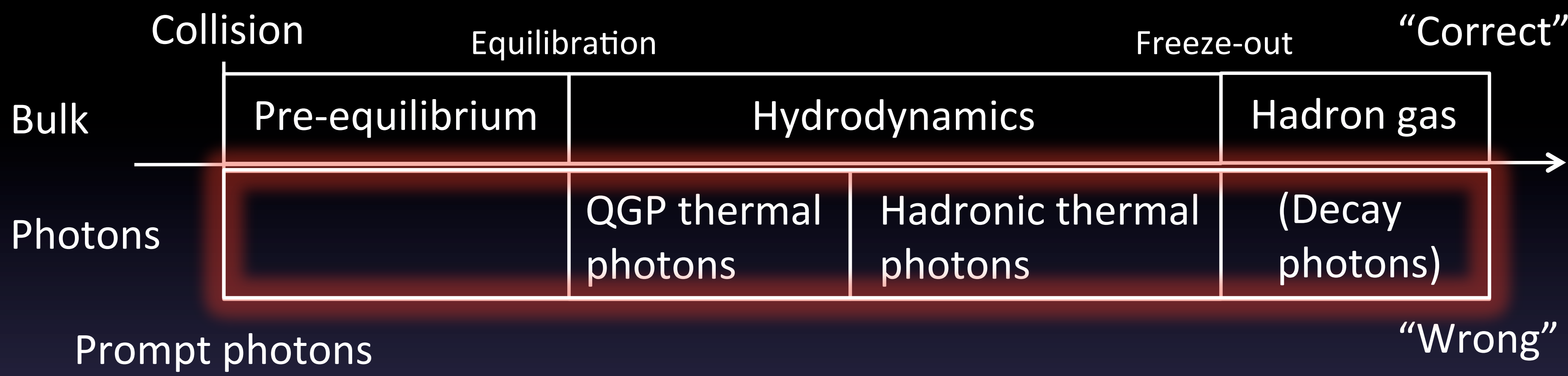

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- Prompt photon emission/v_n estimate needs modification
- Other sources of photons are not considered

Photon v_n puzzle

- Possible (not *all*) reasons: an overview

Collision — Equilibration — Freeze-out — "Correct"

Bulk	Pre-equilibrium	Hydrodynamics		Hadron gas
Photons		QGP thermal photons	Hadronic thermal photons	(Decay photons)

Prompt photons — "Wrong"

- Thermal photon emission/v_n estimate needs modification
- Prompt photon emission/v_n estimate needs modification
- Other sources of photons are not considered
- Other effects which work on photons are missing

Photon v_n puzzle

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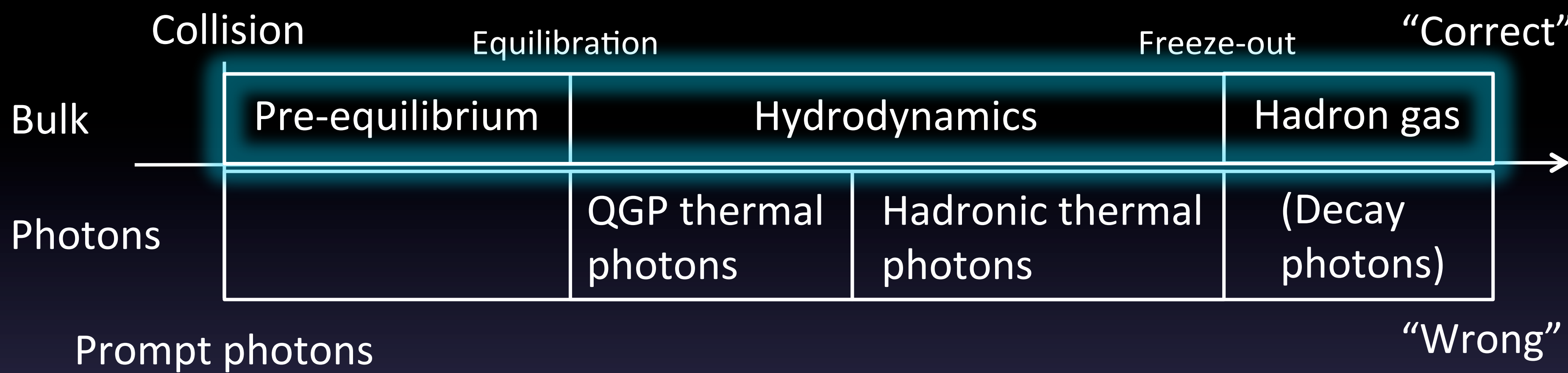

- Thermal photon emission/v_n estimate needs modification
- Prompt photon emission/v_n estimate needs modification
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- Bulk evolution needs modification

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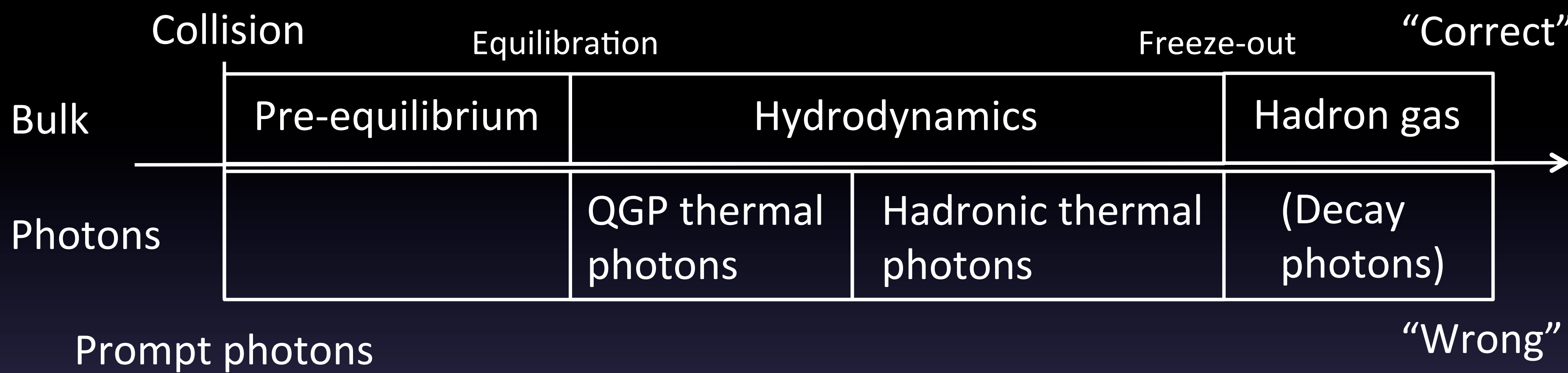

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- Experimental data needs more statistics

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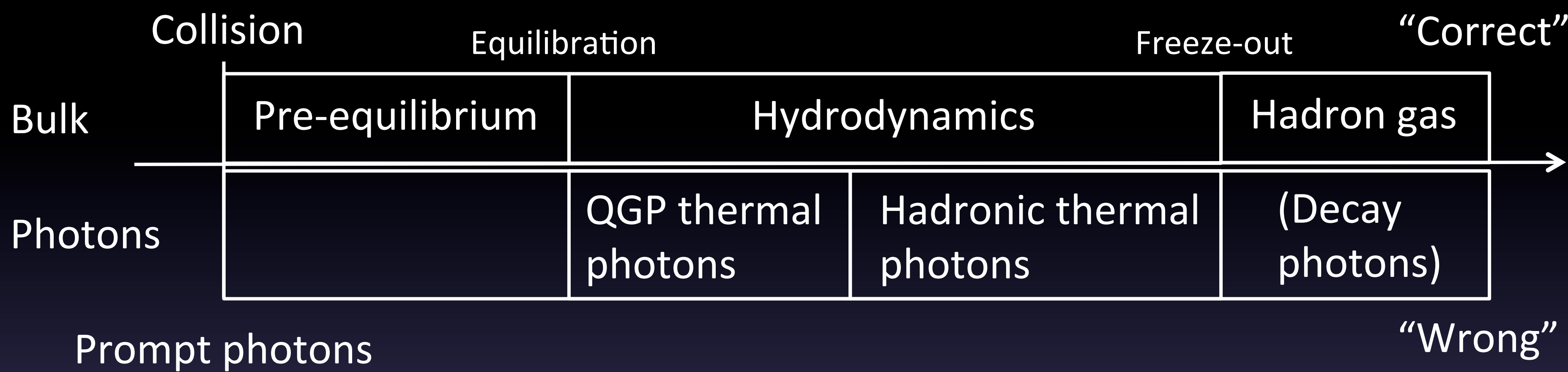

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This talk

Photon v_n puzzle

- Possible (not *all*) reasons: an overview

	Collision	Equilibration		Freeze-out	"Correct"
Bulk	Pre-equilibrium	Hydrodynamics		Hadron gas	
Photons		QGP thermal photons	Hadronic thermal photons	(Decay photons)	
	Prompt photons				"Wrong"

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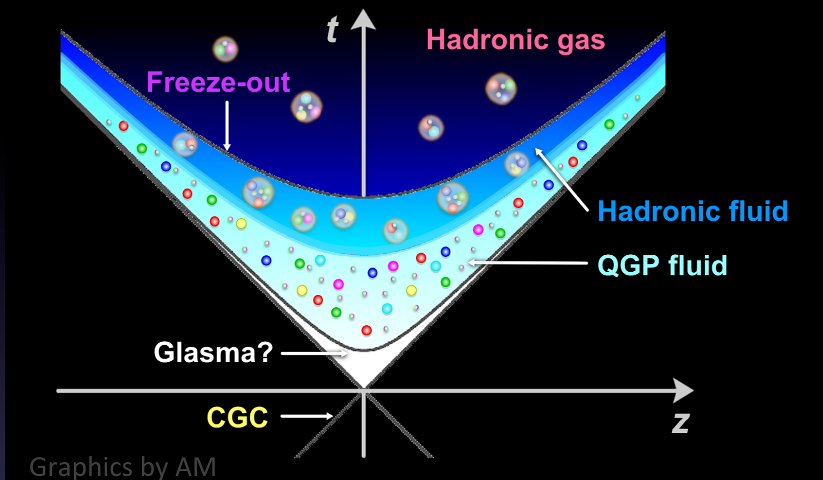
This talk

+ preview

Approach of this work

- Bulk evolution



- $\tau > 10$ fm/c: Hadronic gas

Freeze-out

- $\tau \sim 1\text{-}10$ fm/c: QGP/hadronic fluid

Equilibration

- $\tau \sim 0\text{-}1$ fm/c: Glasma

"Little bang"

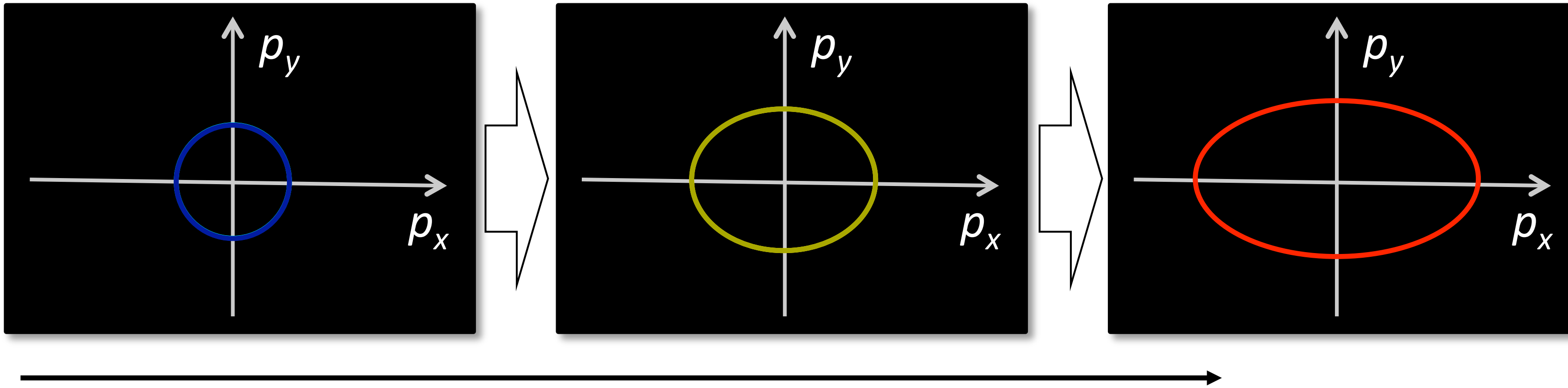
- $\tau < 0$ fm/c: Color glass condensate

- Color glass condensate (CGC): Colliding nuclei are saturated gluons
- QGP/hadronic fluid: Equilibrated quark-gluon plasma

⇒ Chemical equilibration does not necessary coincides with thermalization (cf: AM and B. Müller, arXiv: 1403.7310)

Approach of this work

- Fewer quarks + more gluons at the onset of QGP fluid



Flow anisotropy develops (medium v_2)

Equilibrated QGP (small v_2)

Quark-gluon plasma Quark-gluon plasma Quark-gluon plasma

We consider: Non-equilibrated QGP

quark-GLUON plasma quark-gluon plasma Quark-gluon plasma

Contribution of later stage becomes large as thermal photons are emitted in the presence of quarks; photon v_2 can be enhanced

The model

- (2+1)-dimensional ideal hydrodynamic model + rate equations

- The energy-momentum conservation

$$\partial_\mu T_g^{\mu\nu} + \partial_\mu T_q^{\mu\nu} = 0$$

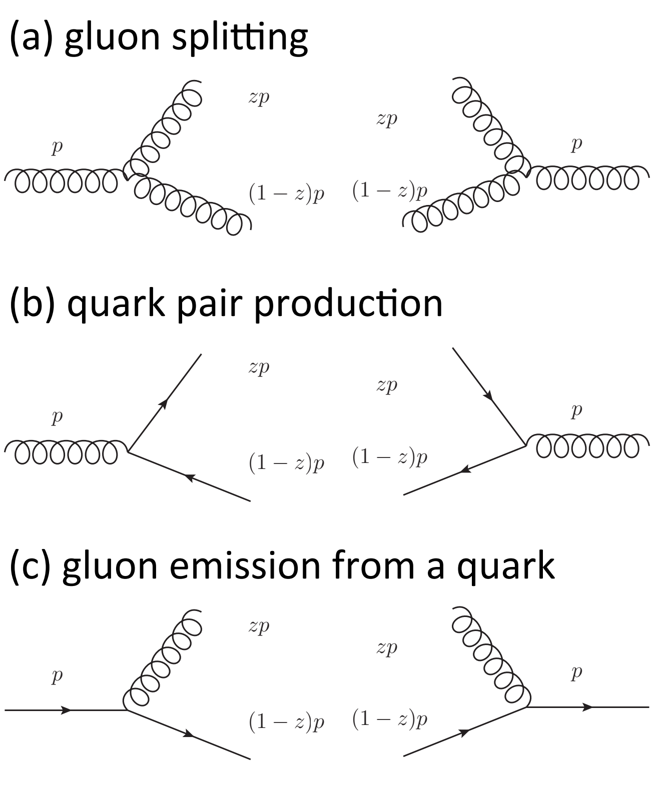
- Quark and gluon number changing processes

$$\partial_\mu N_q^\mu = 2r_b n_g - 2r_b \frac{n_g^{\mathrm{eq}}}{(n_q^{\mathrm{eq}})^2} n_q^2$$

$$\partial_\mu N_g^\mu = (r_a - r_b) n_g - r_a \frac{1}{n_g^{\mathrm{eq}}} n_g^2 + r_b \frac{n_g^{\mathrm{eq}}}{(n_q^{\mathrm{eq}})^2} n_q^2 + r_c n_q - r_c \frac{1}{n_g^{\mathrm{eq}}} n_q n_g$$

r_a, r_b, r_c : reaction rates

$n_q^{(\mathrm{eq})}, n_g^{(\mathrm{eq})}$: parton densities (in equilibrium)



⇨ Late quark chemical equilibration implies $r_b < r_a, r_c$ as the chemical equilibration times are $\tau_i \sim 1/r_i$

Input for numerical analyses

Hydrodynamic parameters (Initial conditions + fluid properties)

- Gluon energy distribution: Kolb, Sollfrank and Heinz, PRC 62, 054909 (2000)
- Quark energy distribution: 0 GeV/fm^3
- Initial time: 0.4 fm/*c*
- Equation of state: Hadron resonance gas (mass below 2 GeV) + Parton gas (N_f = 2)
- Chemical reaction rates: $r_i = c_i T$ where c_i ranges are

$0.2 \leq c_b \leq 2$ ($\tau_b \sim 0.5\text{–}5 \text{ fm}/c$) and $0 \leq c_{a,c} \leq 3$ ($\tau_{a,c} \sim 0.3\text{–}\infty \text{ fm}/c$)

Photon emission rate

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

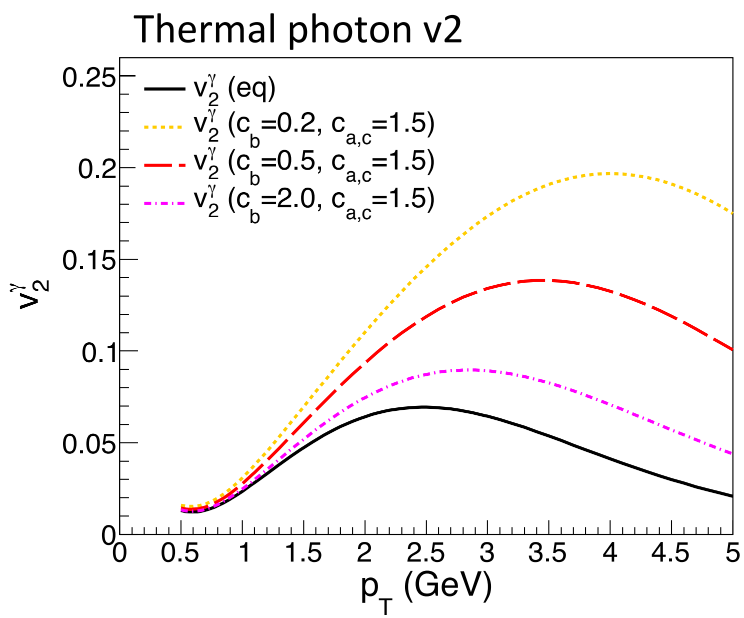
Turbide, Rapp and Gale, PRC 69, 014903

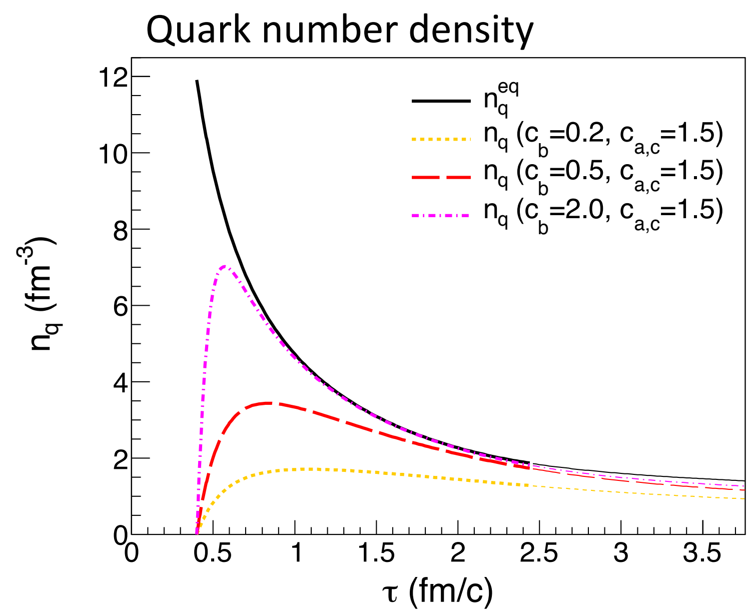
Traxler and Thoma, PRC 53, 1348

where $T_c = 0.17 \text{ GeV}$ and $\Delta T = 0.017 \text{ GeV}$

Results

- Elliptic flow of thermal photons – c_b dependence





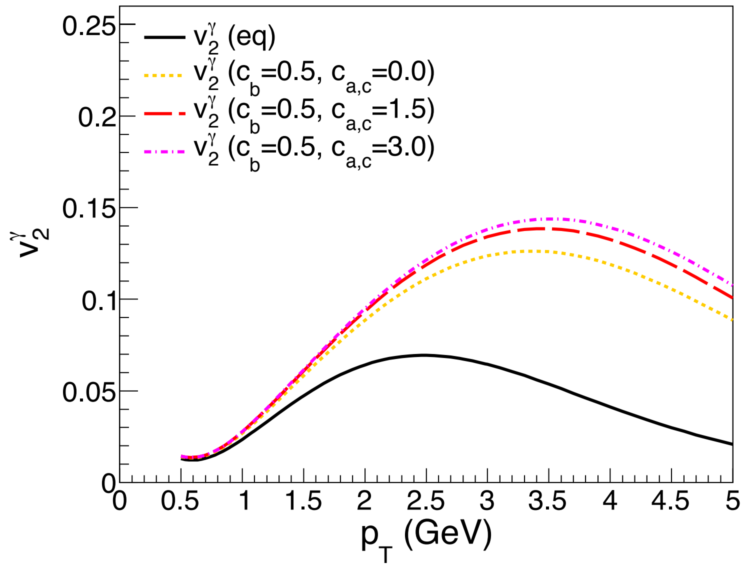
Late quark chemical equilibration ($\tau_{\mathrm{chem}} \sim 1/c_b T$) leads to enhancement of thermal photon v_2

$\tau_{\mathrm{chem}} \sim 2\ \mathrm{fm}/c$ is motivated in an early equilibration model
(AM and B. Müller, arXiv: 1403.7310) $\Leftrightarrow$ $c_b = 0.5$ for $T \sim 0.2\ \mathrm{GeV}$

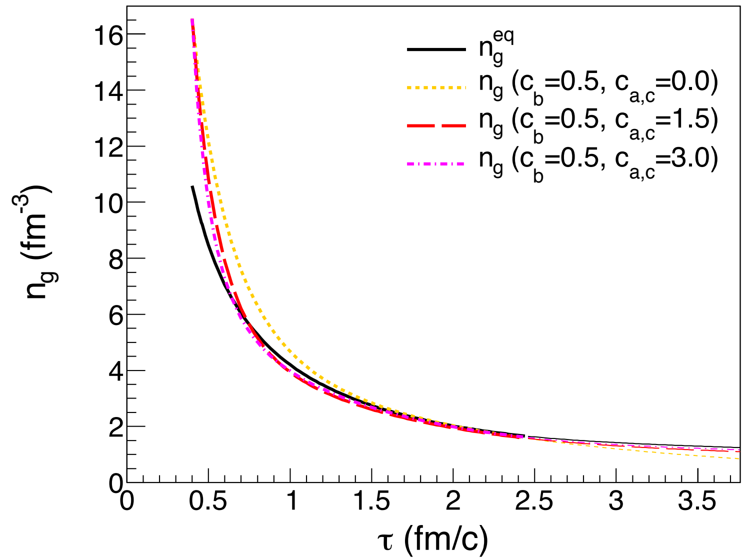
Results

- Elliptic flow of thermal photons – $c_{a,c}$ dependence

Thermal photon v2



Gluon number density

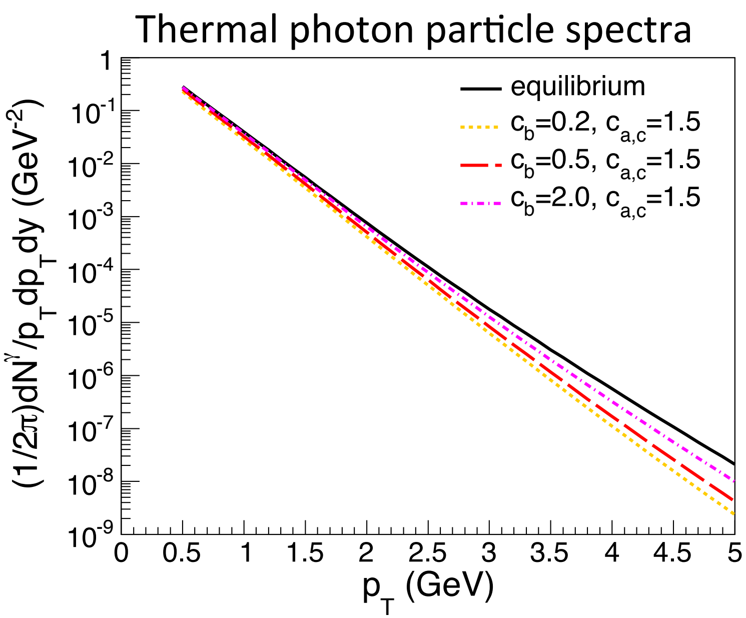


Thermal photon v_2 is moderately enhanced for faster gluon-involved equilibration processes

because quark production in early stages is suppressed due to quicker dampening of gluon overpopulation due to recombination

Results

- Transverse momentum spectra of thermal photons



p_T spectra is reduced by late quark chemical equilibration

Effect is limited for the chosen input; *however* more sophisticated photon emission rate and equation of state would be important

(Cf. Gelis et al., JPG 30, S1031)

Summary and outlook

- Thermal photon v_2 from chemically non-equilibrated QGP is investigated
  - Late quark production leads to visible enhancement of v_2, contributing positively to resolution of "photon v_2 puzzle"
    - ⇨ Evolution of bulk medium from CGC to QGP is a key
  - Late gluon equilibration slightly reduces v_2
  - Net yield of thermal photons is reduced
- Future prospects include:
  - Introduction of dynamical equation of state, more realistic initial conditions, shear and bulk viscosities etc.
  - Estimation of the contribution from prompt photons
  - Other effects in non-equilibrated QGP, e.g., heavy quarks

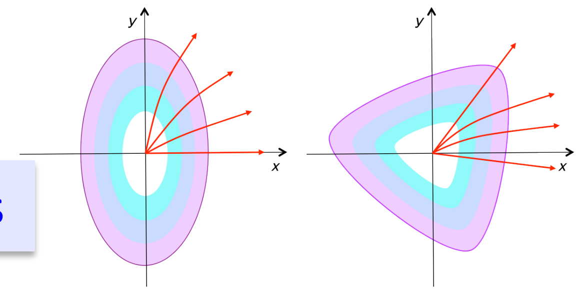
Prompt photon v_n

■ Optical effects in QGP medium

AM, arXiv:1408.1410 [nucl-th]

- Transparent medium has a non-unity refractive index

A hot QCD medium works as a 4D lens



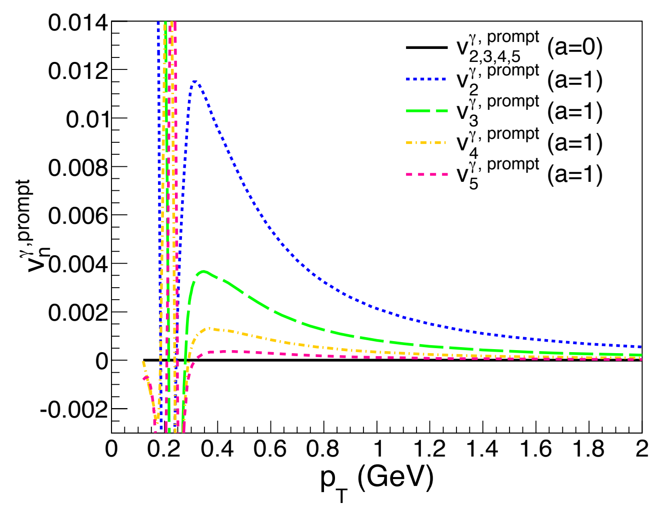
⇨ Geometrical anisotropy (ε_2, ε_3, …) is directly mapped onto thermal and prompt photon flow harmonics (v_2, v_3, …)

- Numerical analyses – prompt photon v_n

⇨ Positive flow harmonics; not large enough w/ the model index $n^2 = 1 - a^2T^2/\omega^2$ based on HTL

- Critical opalescence near T_c?

- Semi-transparency at ultra-low momentum (determining plasma frequency of QGP)?



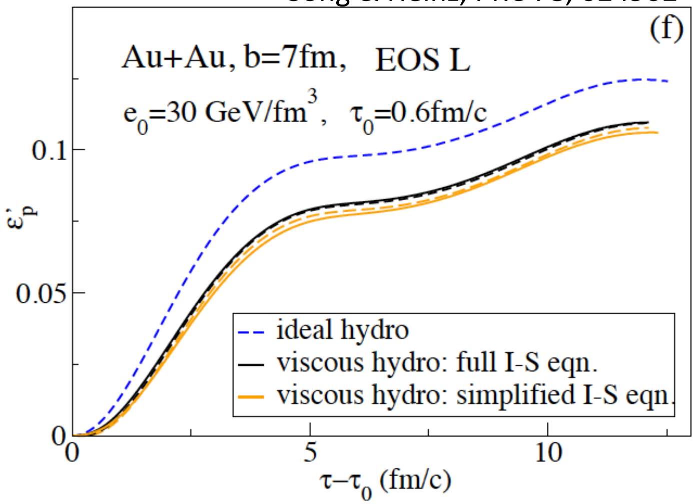
The end

- Thank you for your attention!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/

Momentum anisotropy

- Time evolution of medium “elliptic flow”

Song & Heinz, PRC 78, 024902



Elliptic flow is quickly developed

Effects of initial absence of quarks would be large