AM, arXiv:1403.4225 [nucl-th]

Thermal photons from chemically non-equilibrated QCD medium

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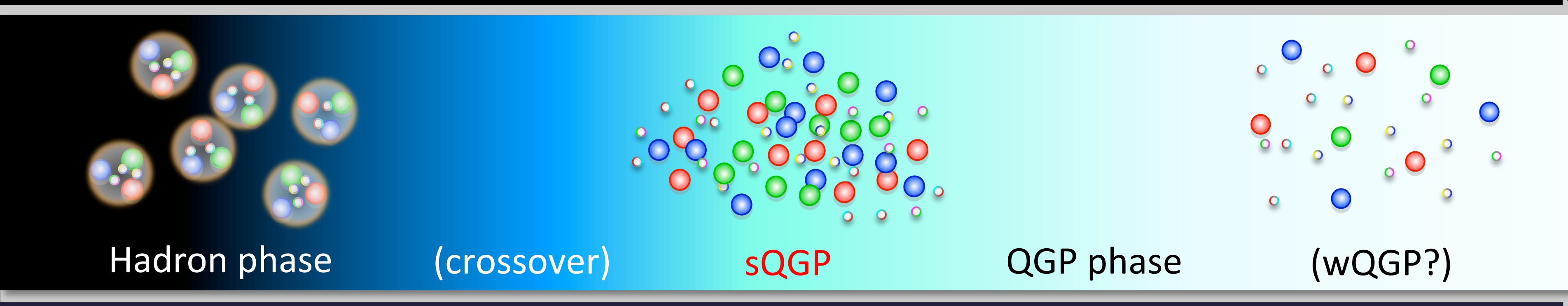
Introduction

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

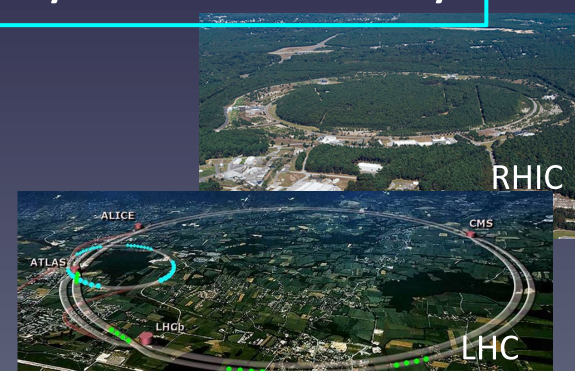
Graphics by AM



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

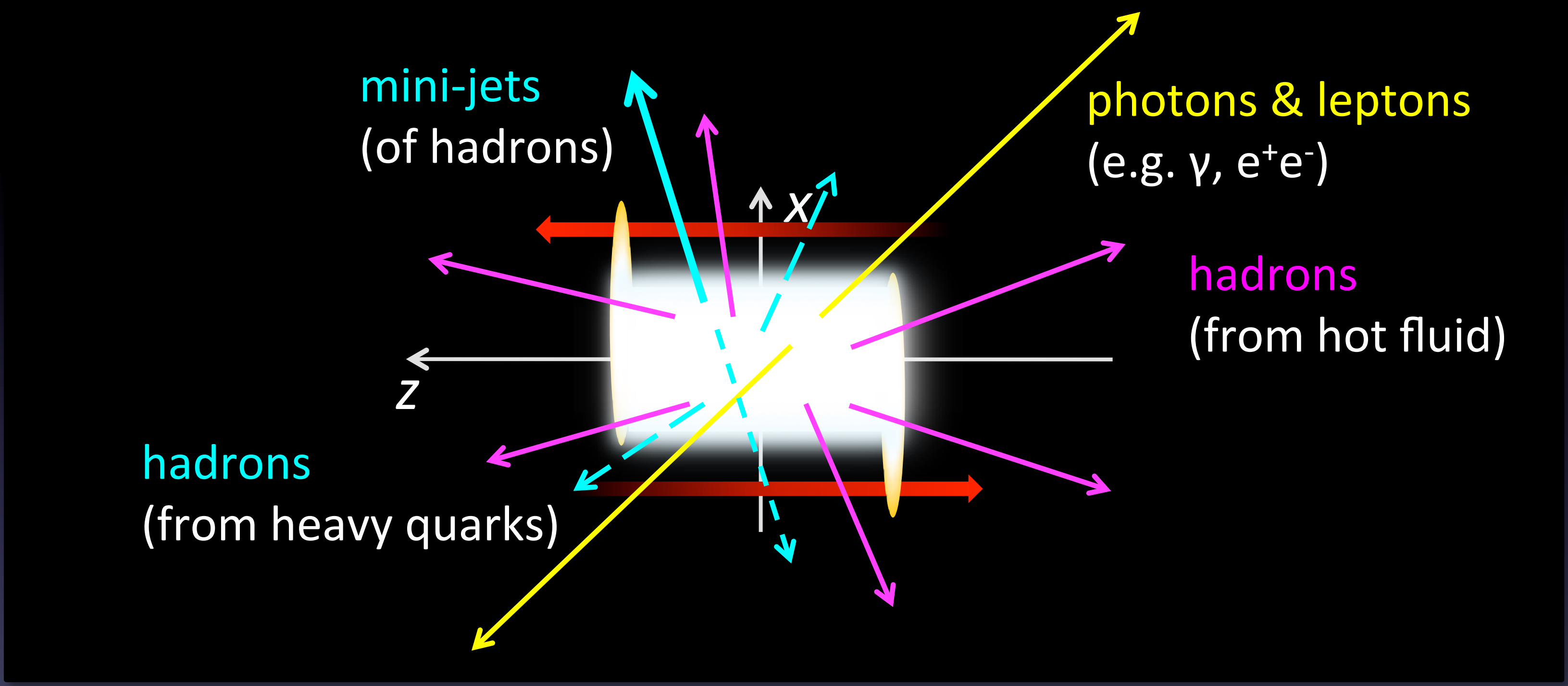
Pb-Pb (2.76 TeV) at LHC



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

Introduction

- Observables of the hot QCD matter



Electromagnetic probes: ⇨ EM transparency
Jet quenching, heavy quarks: ⇨ color opaqueness
Hydrodynamic medium: ⇨ strong coupling

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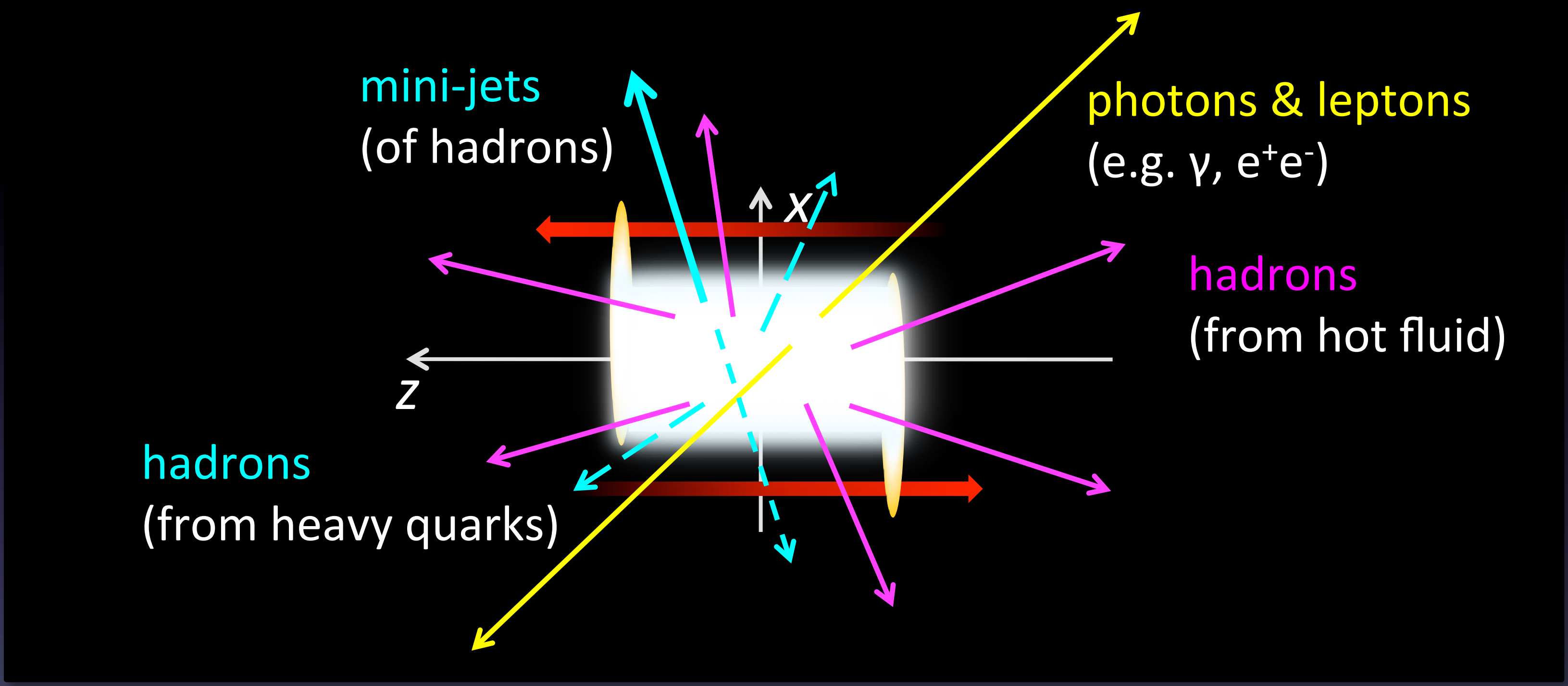

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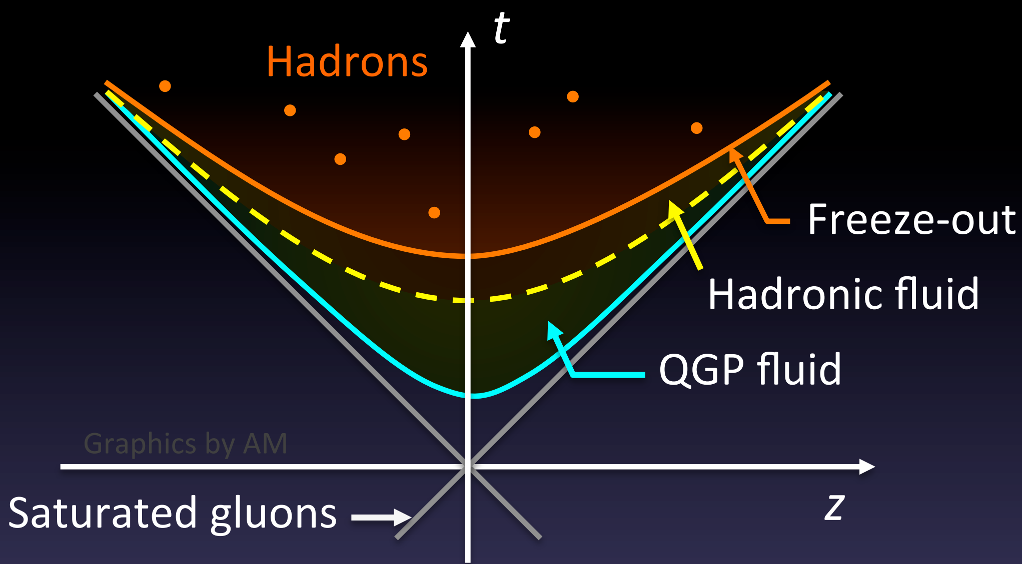
- Photon emission in heavy ion collisions (low p_T)



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

Hadrons: Most of information before freeze-out is lost (*thermal* hadrons)
Photons: Retain information during the medium time evolution

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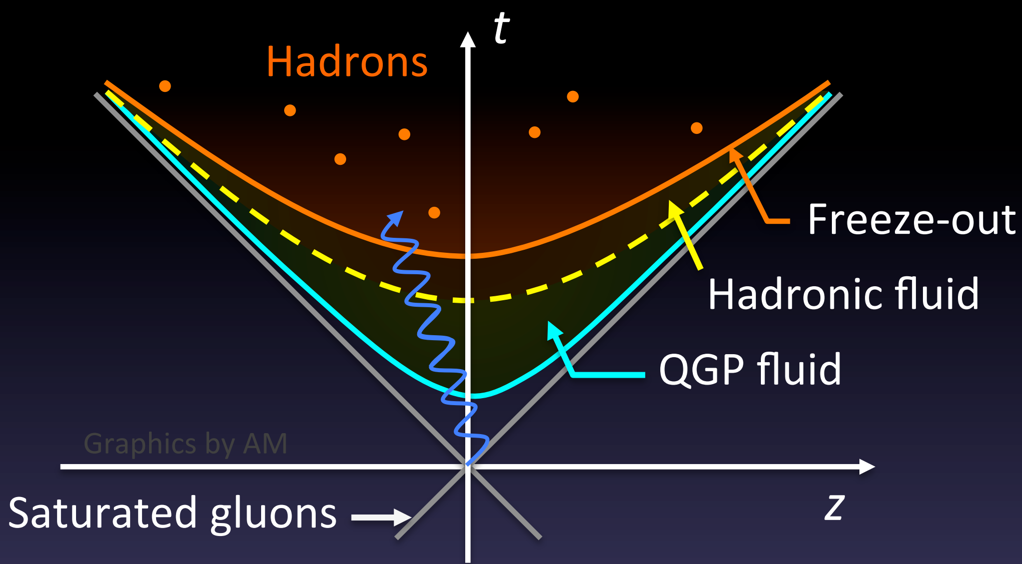

Prompt photons
- from hard processes

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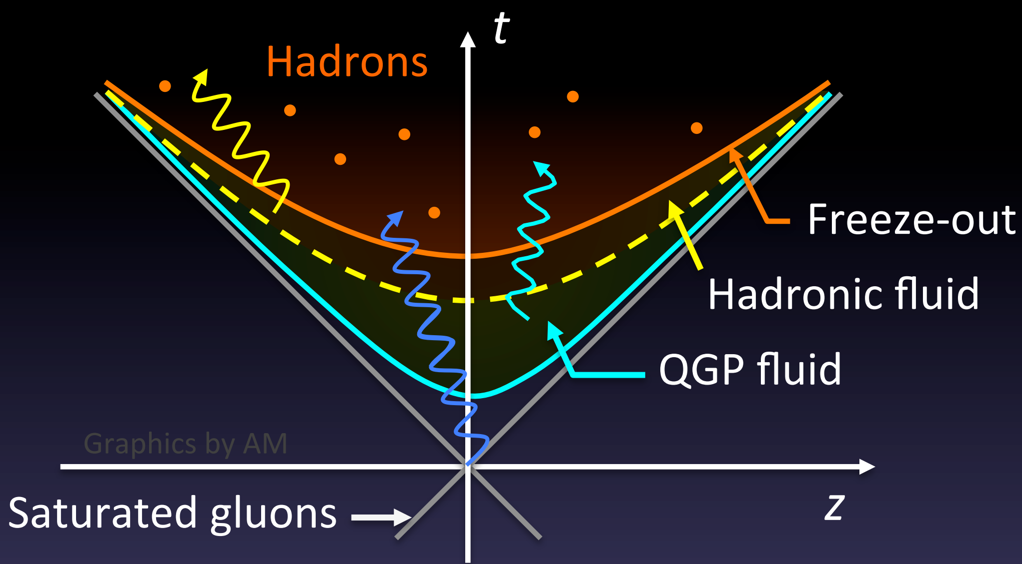

Thermal photons (hadronic)
Thermal photons (QGP)
- from black-body radiation

Prompt photons
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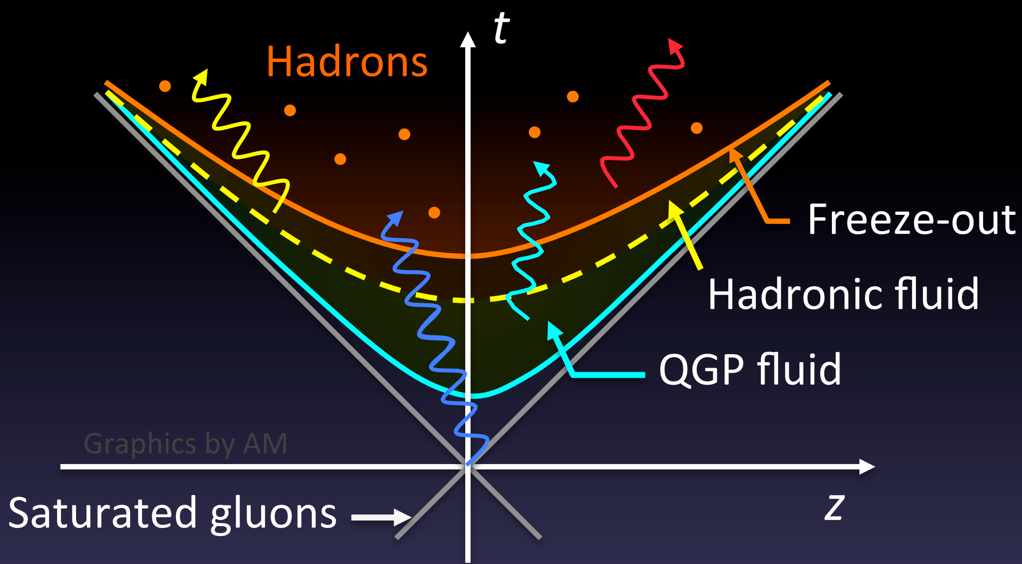

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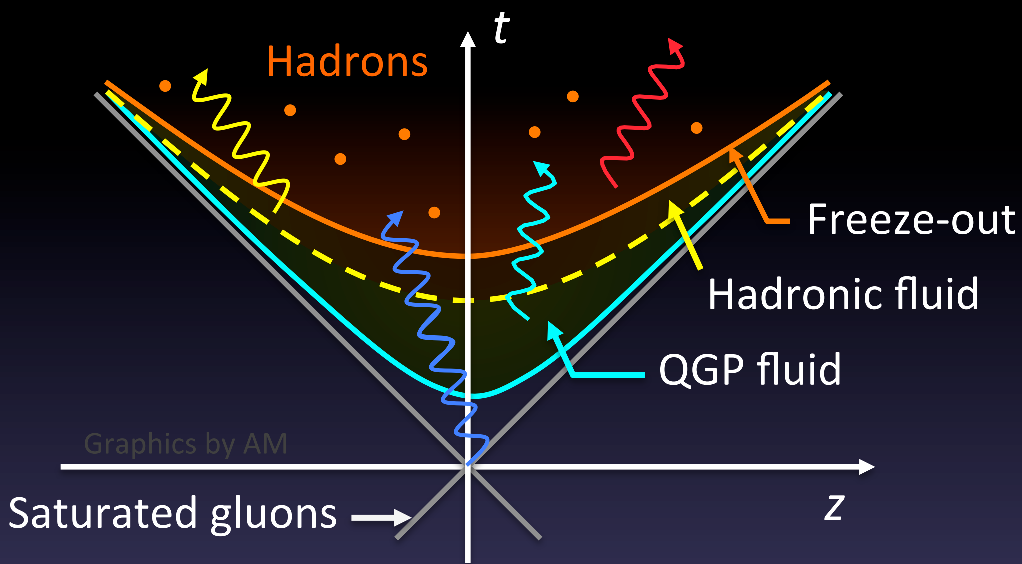

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Direct photons

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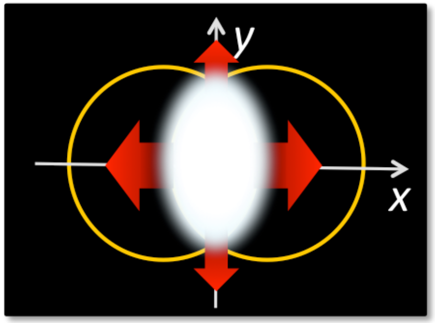
Introduction

■ Elliptic flow v_2

- Azimuthal momentum anisotropy

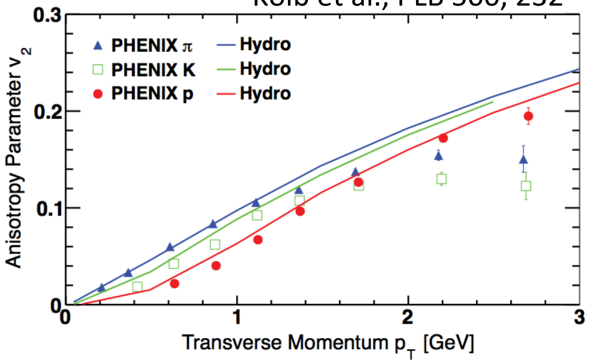
$$v_2(p_T, y) = \frac{\int_0^{2\pi} d\phi_p \cos(2\phi_p - \Psi_2) \frac{dN}{d\phi_p p_T dp_T dy}}{\int_0^{2\pi} d\phi_p \frac{dN}{d\phi_p p_T dp_T dy}}$$



Large v_2 imply strong-medium interaction because spatial anisotropy has to be converted

⇨ Hadronic v_2 is well quantified by nearly ideal hydrodynamic models; strongly-coupled QGP

Kolb et al., PLB 500, 232



- Photons are weakly-coupled and do not intrinsically have v_2

⇨ Direct photon v_2 can be finite because of the contribution from thermal photons which are emitted from an anisotropic medium

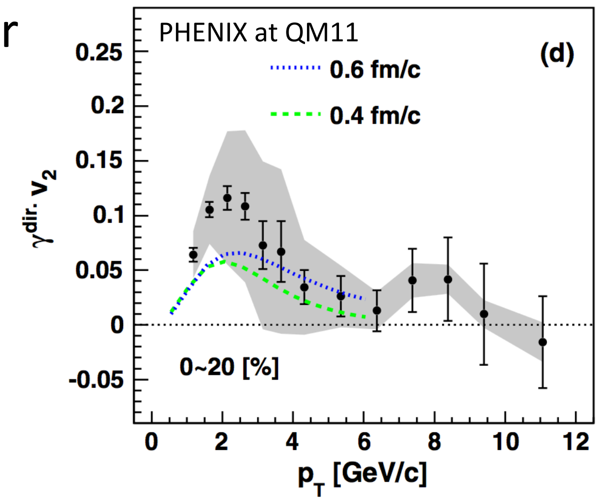
Motivation

- Experiments have posed "photon v_2 puzzle"

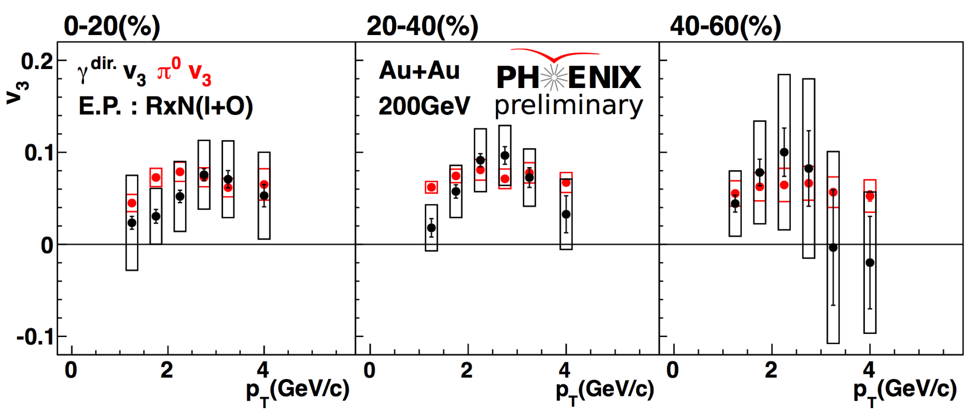
▶ Direct photon v_2 is large; no definite answer so far

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

- Viscosity? Magnetic field? Pre-equilibrium flow?



▶ Direct photon v_3 is also LARGE



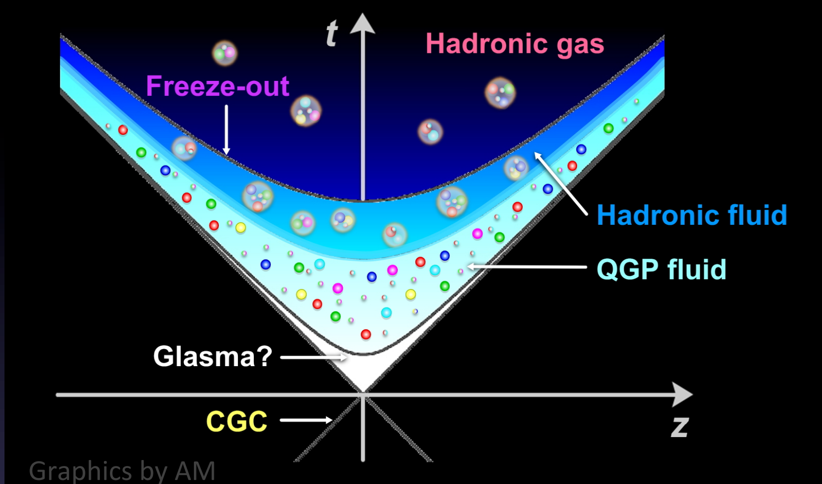
Talk by S. Mizuno (PHENIX) at QM14

No centrality dependence

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

Properties of bulk medium

- Time-evolution: quark-hadron view



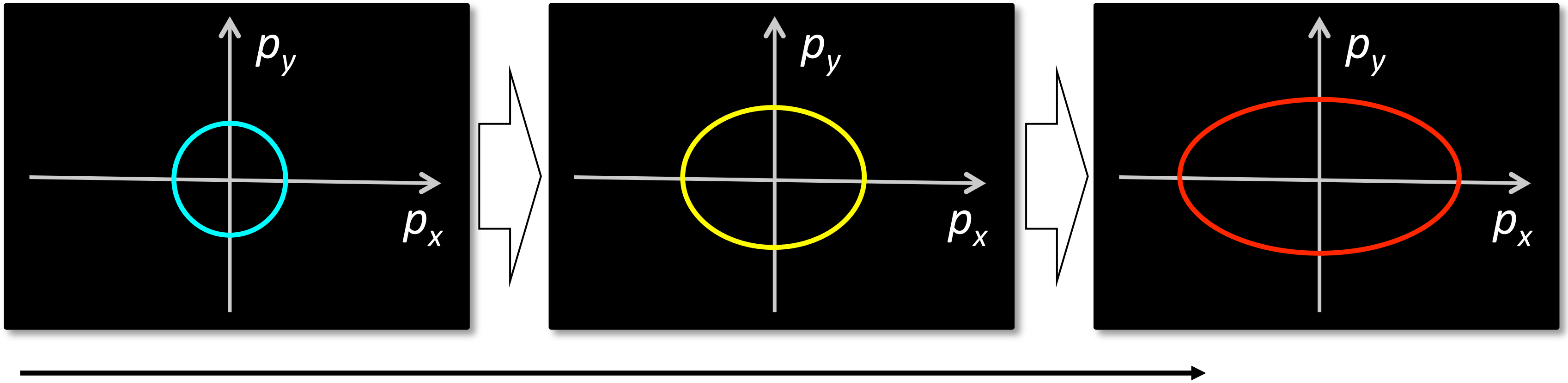
- τ > 10 fm/c: Hadronic gas
  - ⇧ Freeze-out
- τ ~ 1-10 fm/c: QGP/hadronic fluid
  - ⇧ Equilibration
- τ ~ 0-1 fm/c: Glasma
  - ⇧ "Little bang"
- τ < 0 fm/c: Color glass condensate

- 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 number of quarks at the onset of QGP fluid



Equilibrated QGP (small v_2)

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

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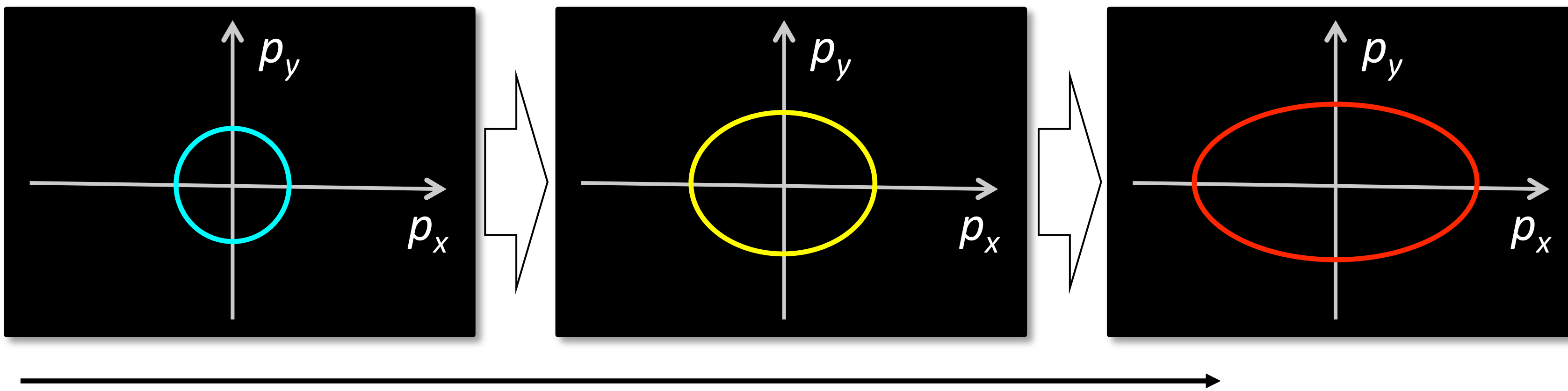

Flow anisotropy develops (medium v_2)

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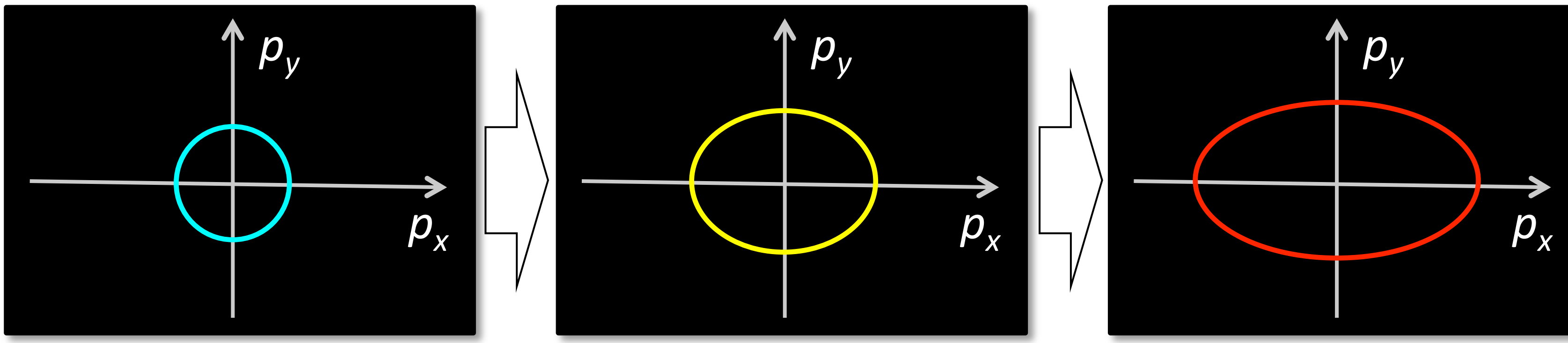

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⇒ Contribution of later stage becomes large as thermal photons are emitted in the presence of quarks; photon v_2 can be enhanced

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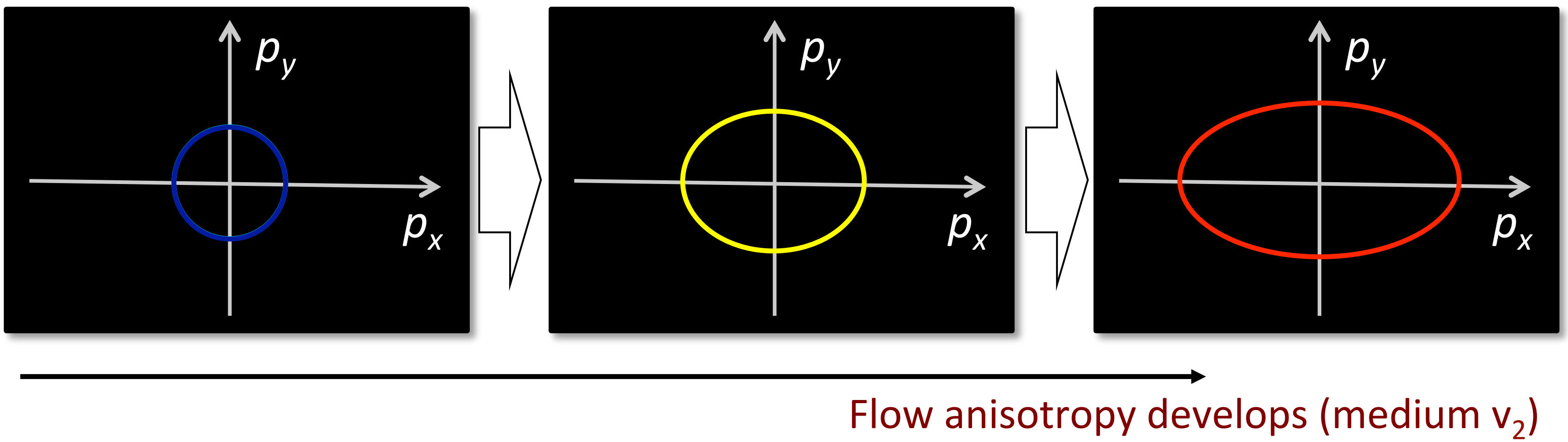

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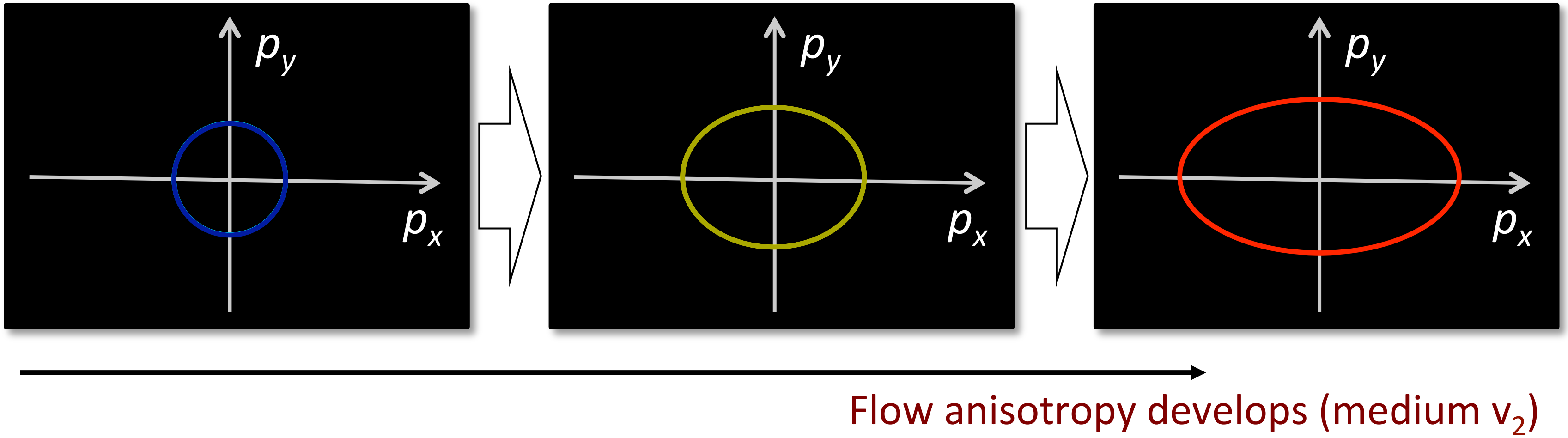

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The model

- (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

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

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

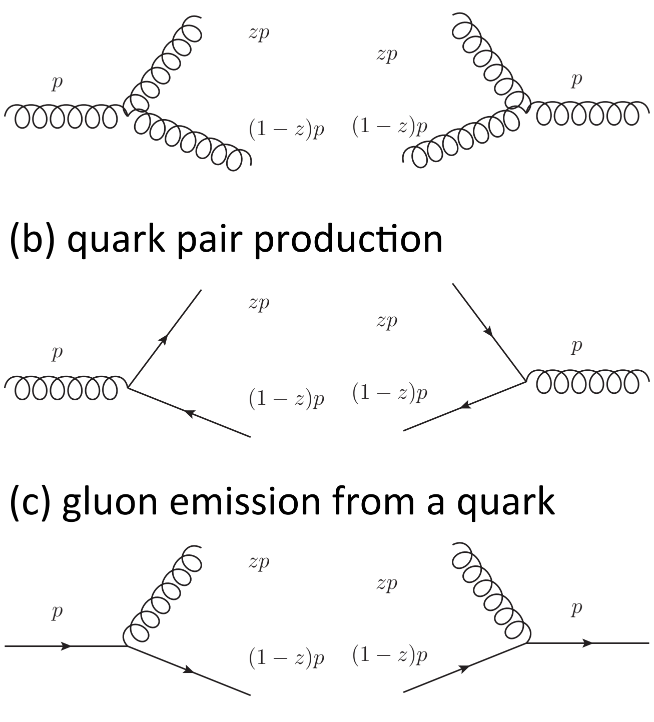
r_a, r_b, r_c : reaction rates

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

(a) gluon splitting

(b) quark pair production

(c) gluon emission from a quark



⇨ 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 (m < 2 GeV) + Parton gas
  - 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

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

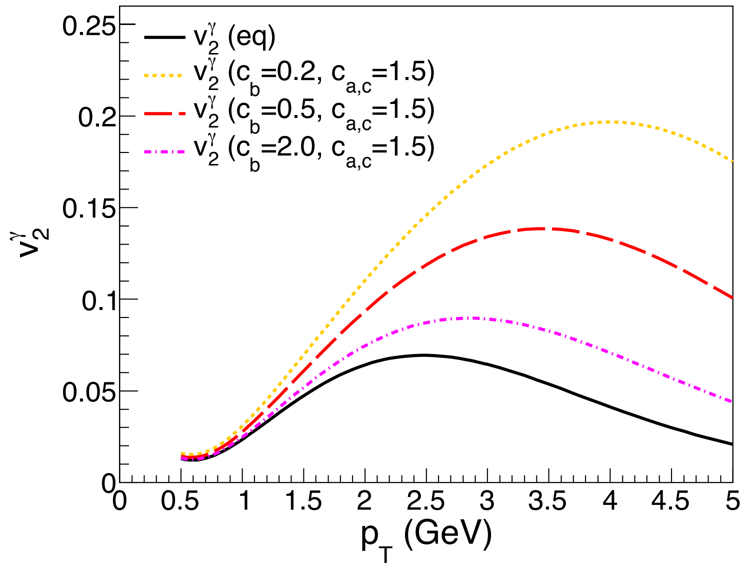
Turbide, Rapp and Gale, PRC 69, 014903 — Traxler and Thoma, PRC 53, 1348

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

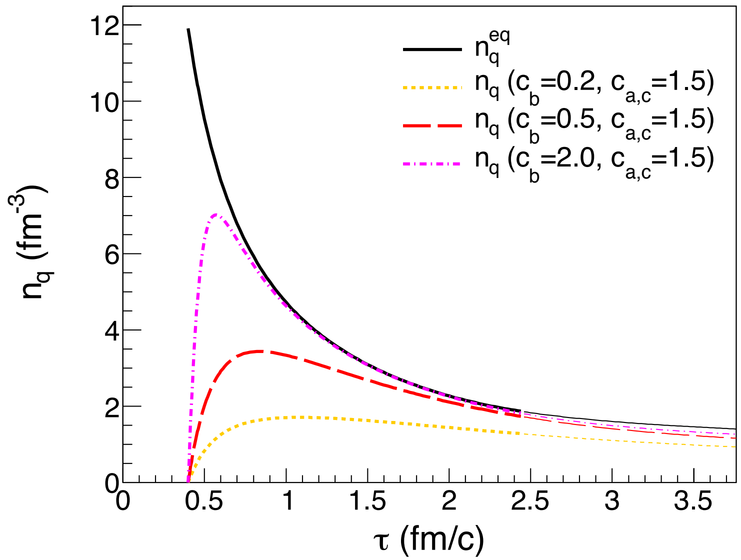
Results

- Elliptic flow of thermal photons – c_b dependence

Thermal photon v2



Quark number density



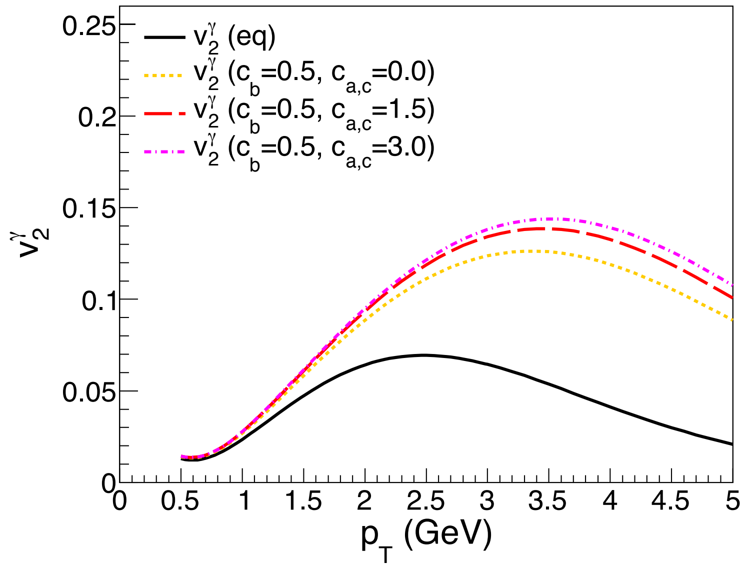
Late quark chemical equilibration ($\tau_{\rm chem} \sim 1/c_b T$) leads to enhancement of thermal photon v_2

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

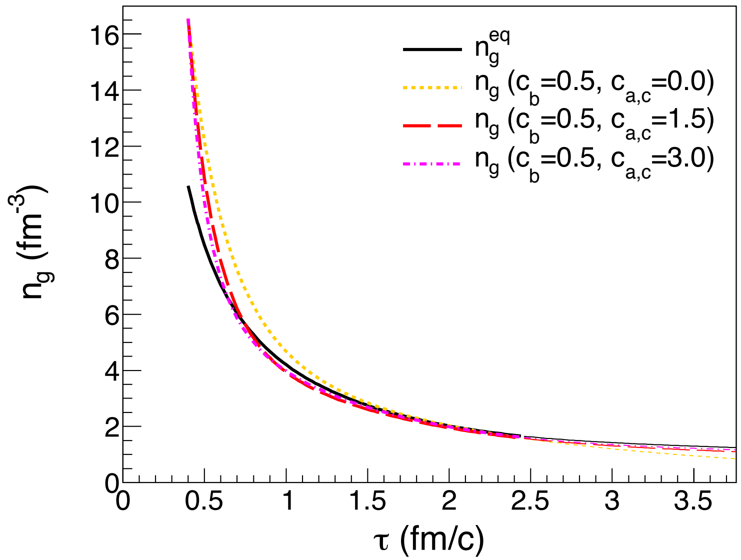
Results

- 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

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 problem”
    - ⇨ 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
  - Estimation of the contribution from prompt photons
  - Other effects of chemical non-equilibrium, e.g., heavy quarks

Fin

- Merci de votre attention!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/