AM, Phys. Rev. C 90, 021901(R) (2014)
AM, arXiv:1408.1410 [nucl-th]

Elliptic flow of thermal photons in chemically non-equilibrated QCD medium

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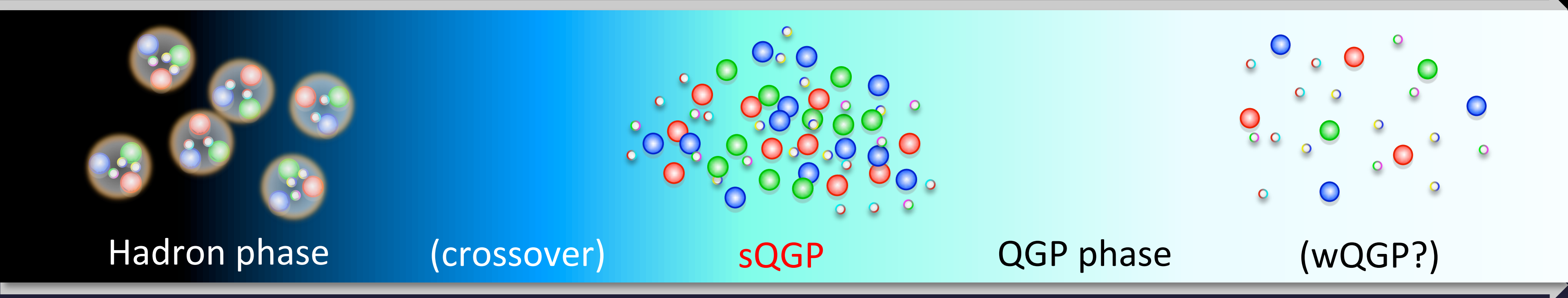
Introduction

- 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

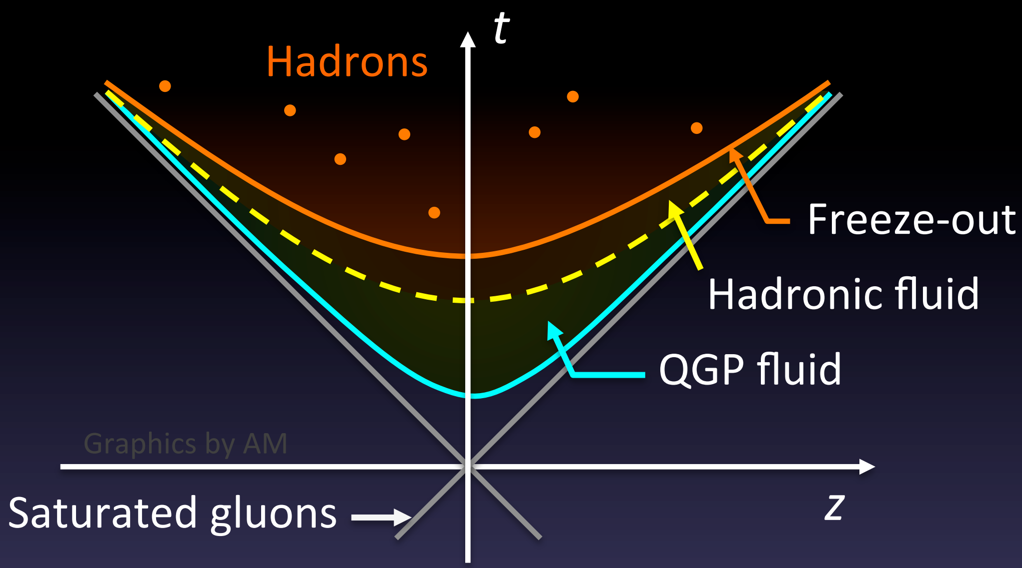
Au-Au, Au-Cu (200 GeV) and U-U (193 GeV) at RHIC

Pb-Pb (2.76 TeV) at LHC

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

Introduction

- 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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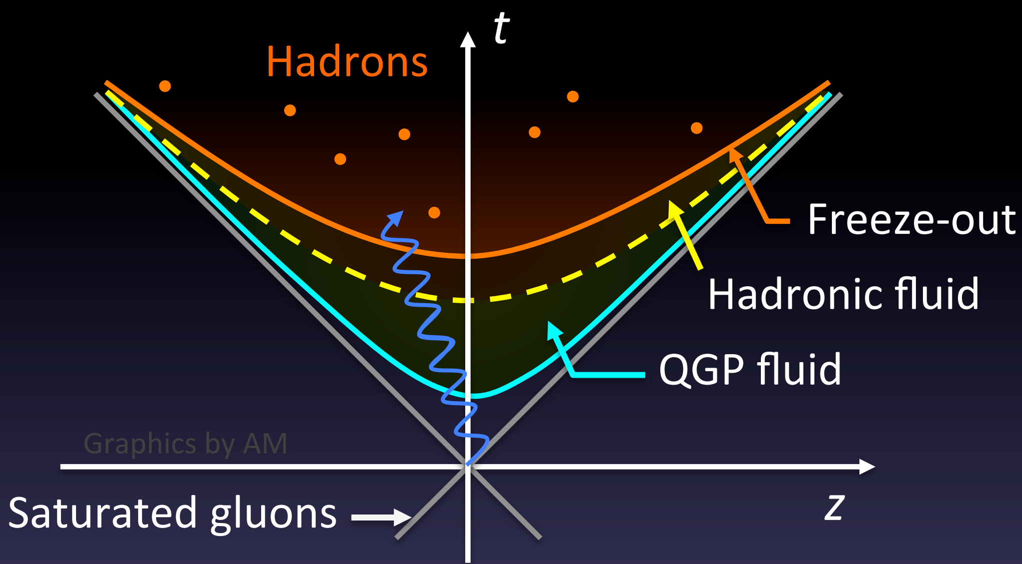

Prompt photons
- from hard processes

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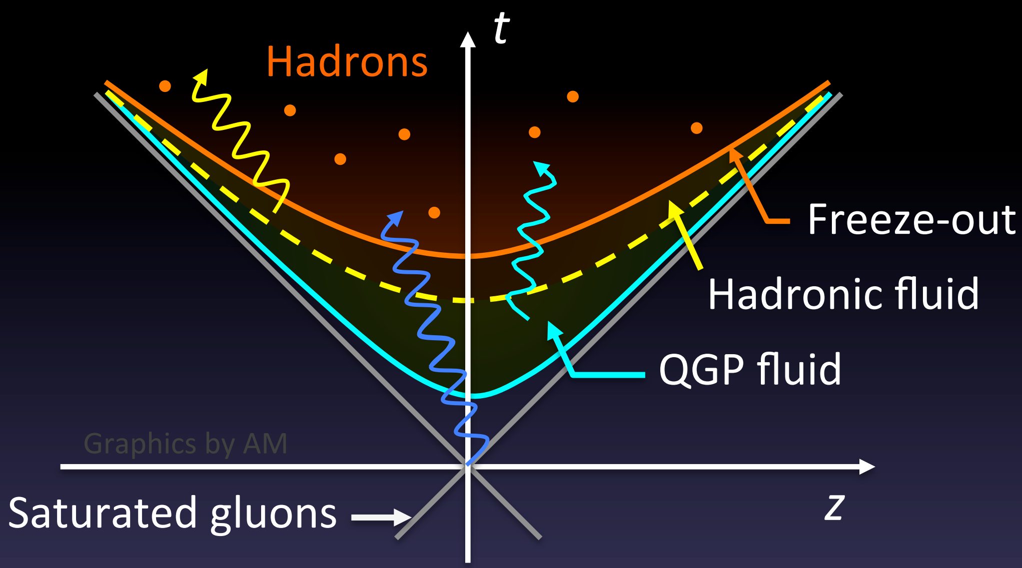

Thermal photons (hadronic)

Thermal photons (QGP)

- from black-body radiation

Prompt photons

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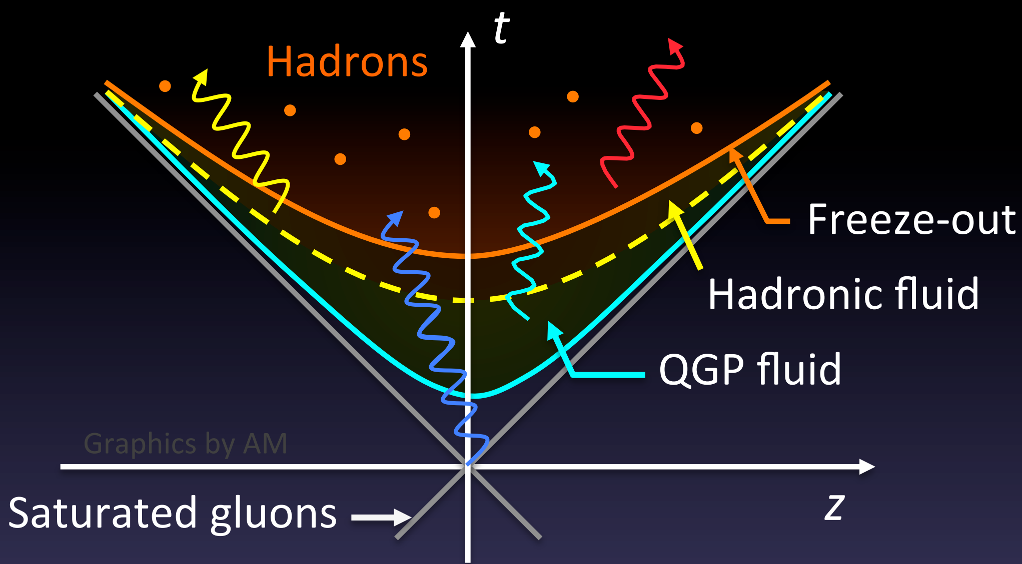

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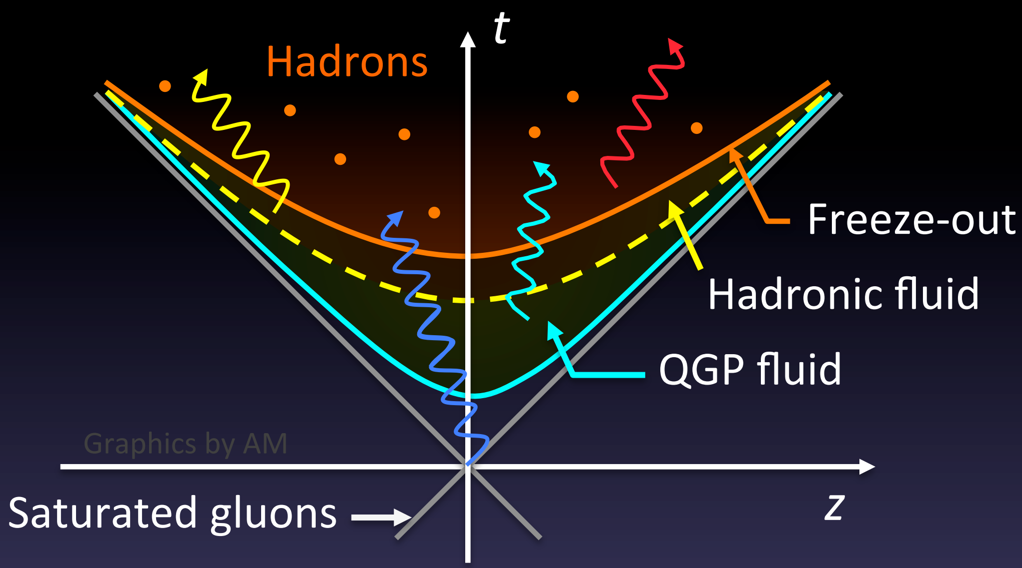

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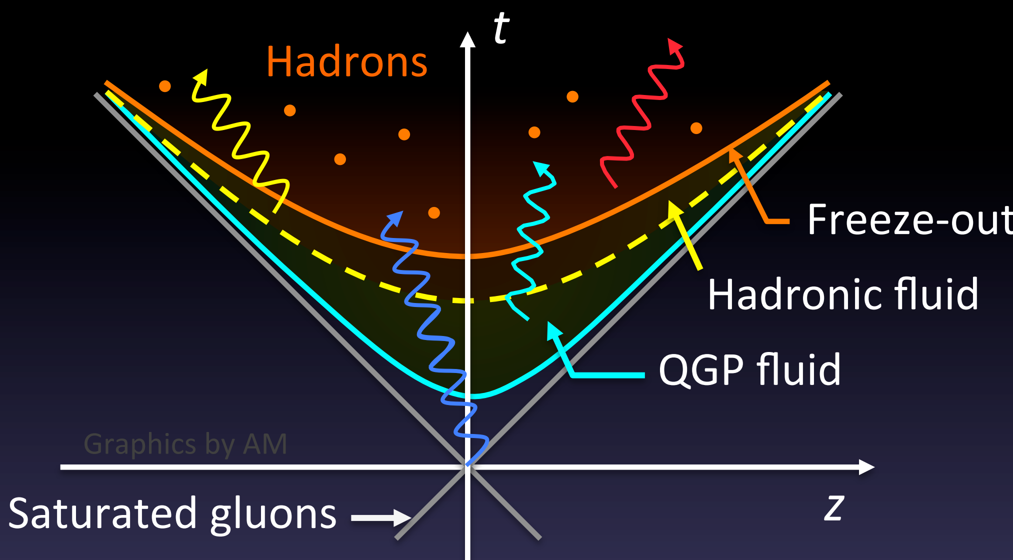

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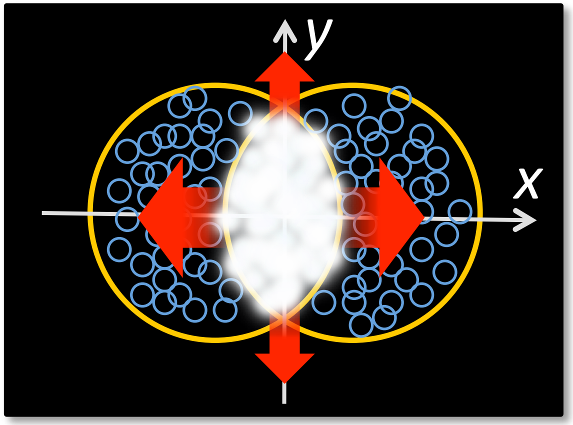
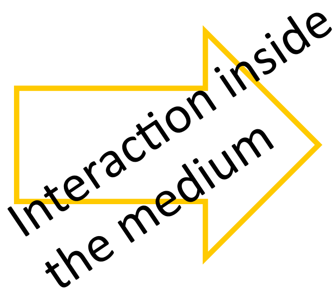
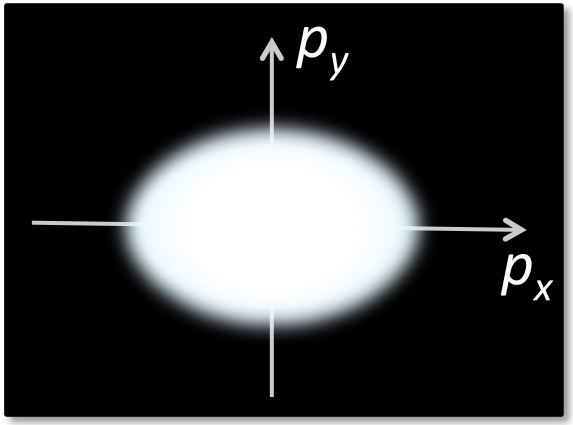
Introduction

- Heavy-ion observable: Elliptic flow (v_2)

- $$\frac{dN}{d\phi} = \frac{N}{2\pi}[1 + 2v_1\cos(\phi - \Psi_1) + 2v_2\cos(2\phi - 2\Psi_2) + 2v_3\cos(3\phi - 3\Psi_3) + ...]$$







Azimuthal anisotropy in **coordinate** space

Azimuthal anisotropy in **momentum** space

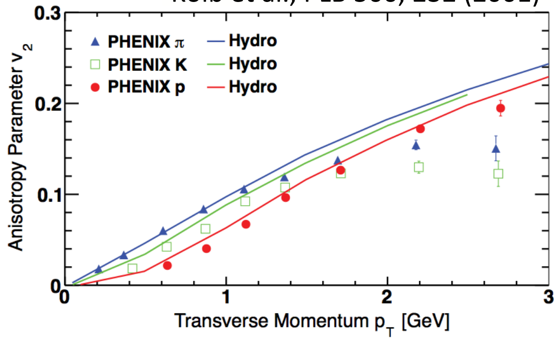
- If the system is strongly interacting (= hydro-like), v_2 is **large**
  If the system is weakly interacting (= gas-like), v_2 is *small*

Motivation

■ Experimental results of flow anisotropy

- Hadronic v_2 is found to be large at RHIC & LHC
  - Nearly-ideal hydrodynamic models work well
  - An evidence for strongly-coupled QGP fluid; early equilibration ($\tau < 1$ fm/c) is suggested

Kolb et al., PLB 500, 232 (2001)



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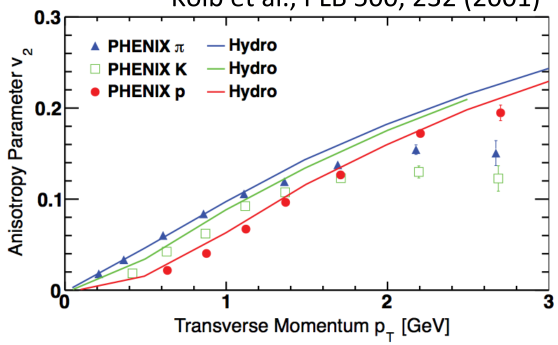
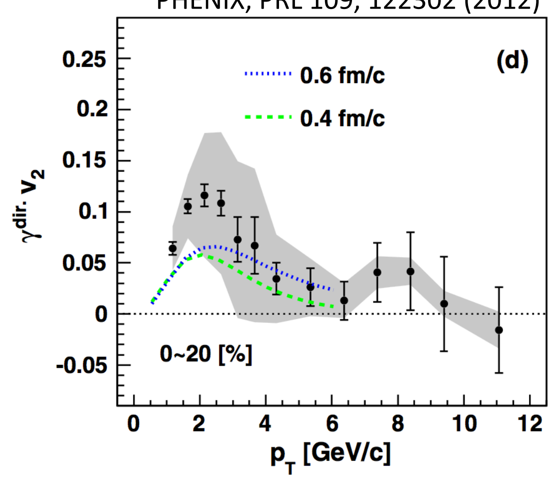


- Direct photon v_2 is found to be large at RHIC & LHC
  - Hydro models predict small v_2 because of the contribution from earlier stages with little anisotropy (*Note: QGP is EM transparent*)
  - No definite answer so far; recognized as "photon v_2 puzzle"

PHENIX, PRL 109, 122302 (2012)



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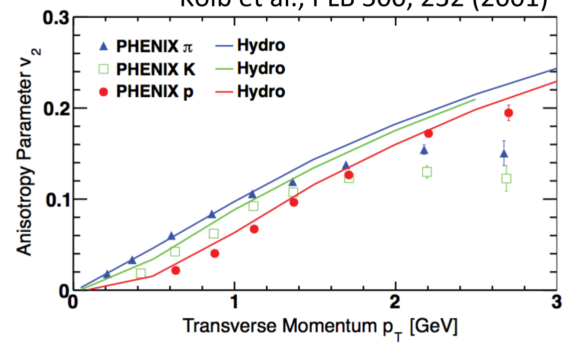

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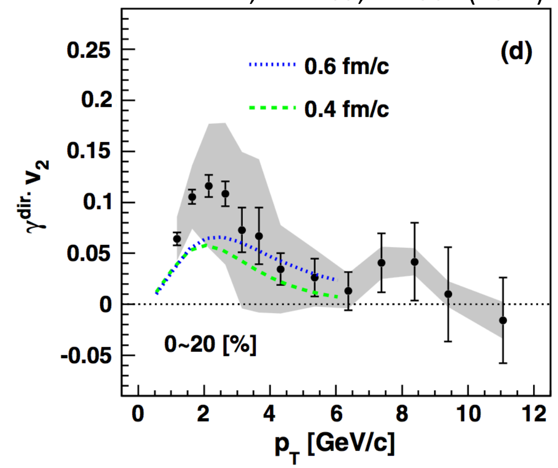
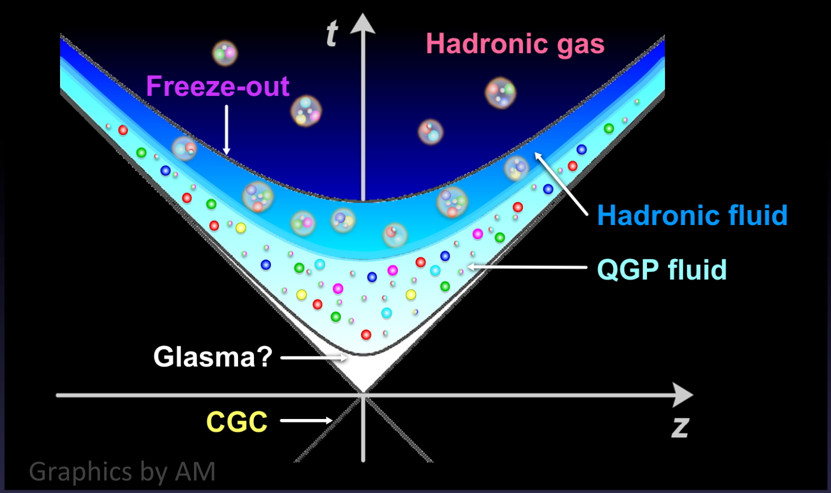


- Now direct photon v_3 is found to be large (2014)
  - The enhancement can be due to the properties of the medium

Approach of this work

- Properties of the medium



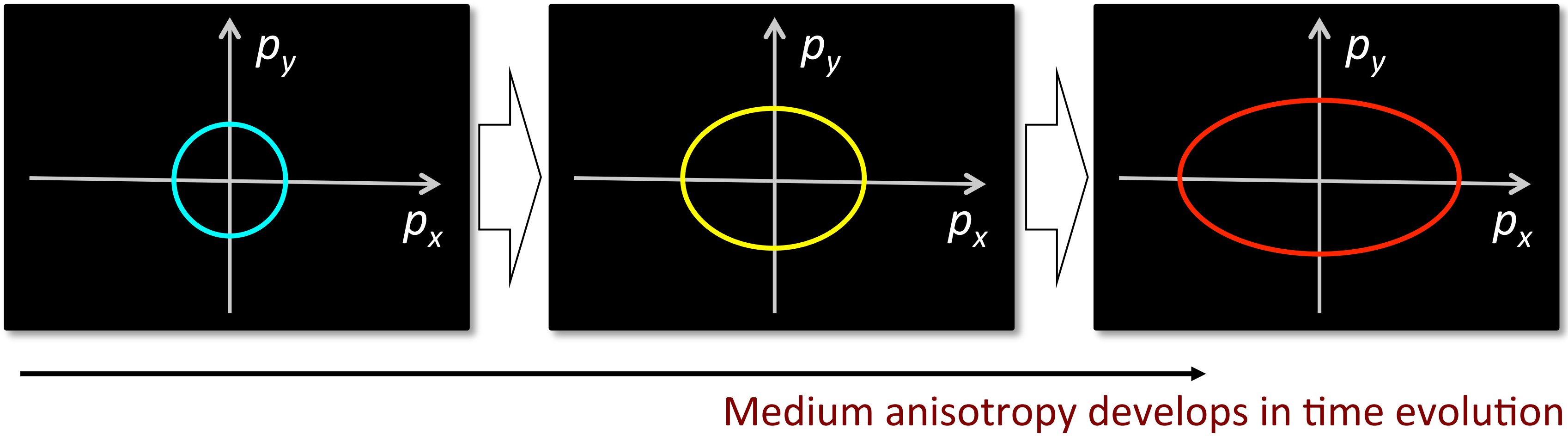
- $\tau > 10$ fm/c: Hadronic gas
  - ⇧ Freeze-out
- $\tau \sim 1\text{-}10$ fm/c: QGP/hadronic fluid
  - ⇧ Equilibration
- $\tau \sim 0\text{-}1$ fm/c: Glasma
  - ⇧ "Little bang"
- $\tau < 0$ fm/c: Color glass condensate

- 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



Equilibrated QGP (small v_2)

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

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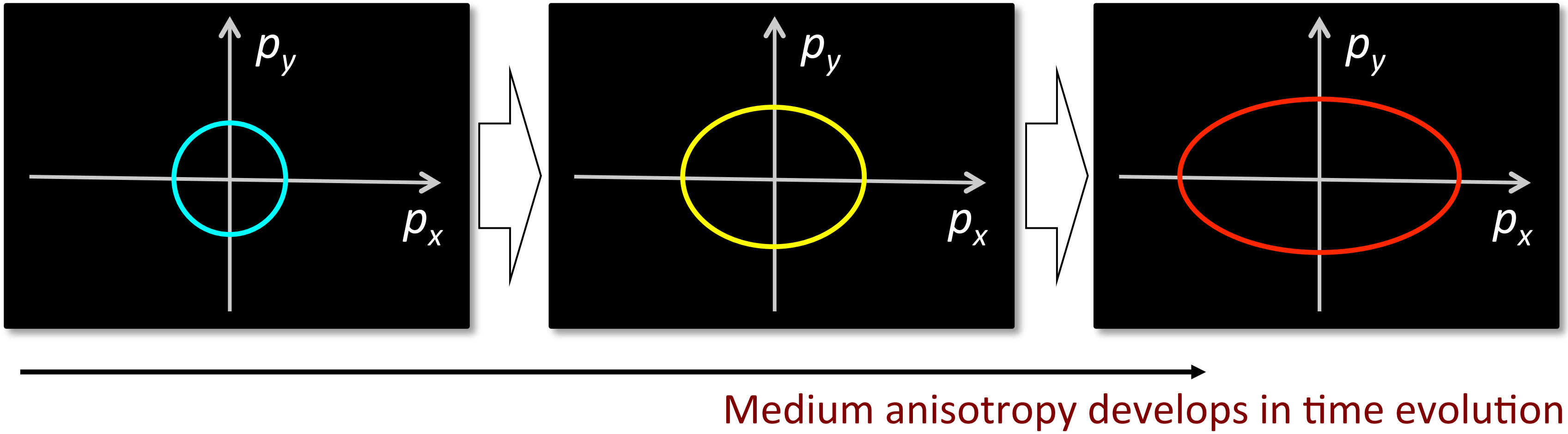

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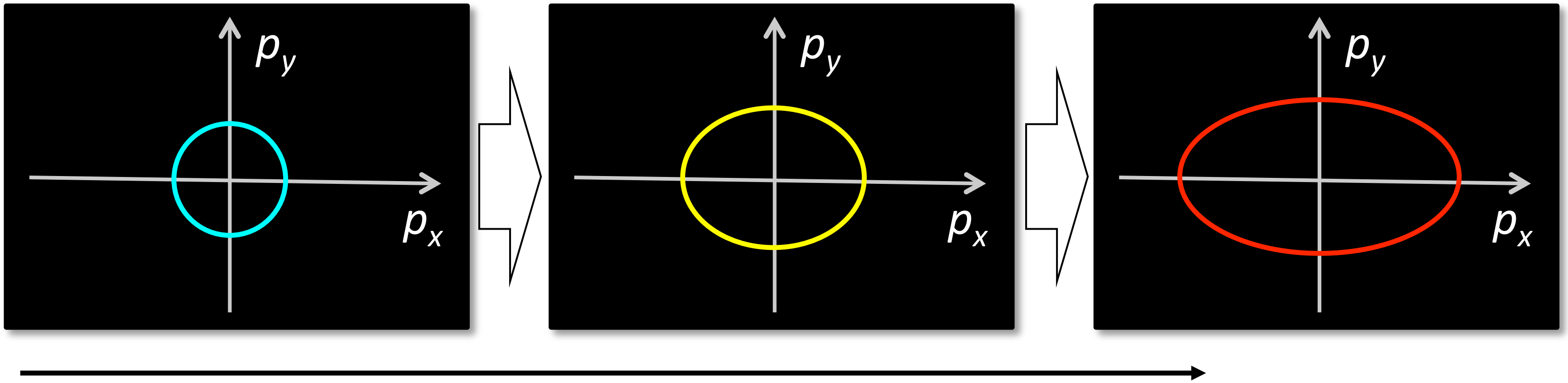

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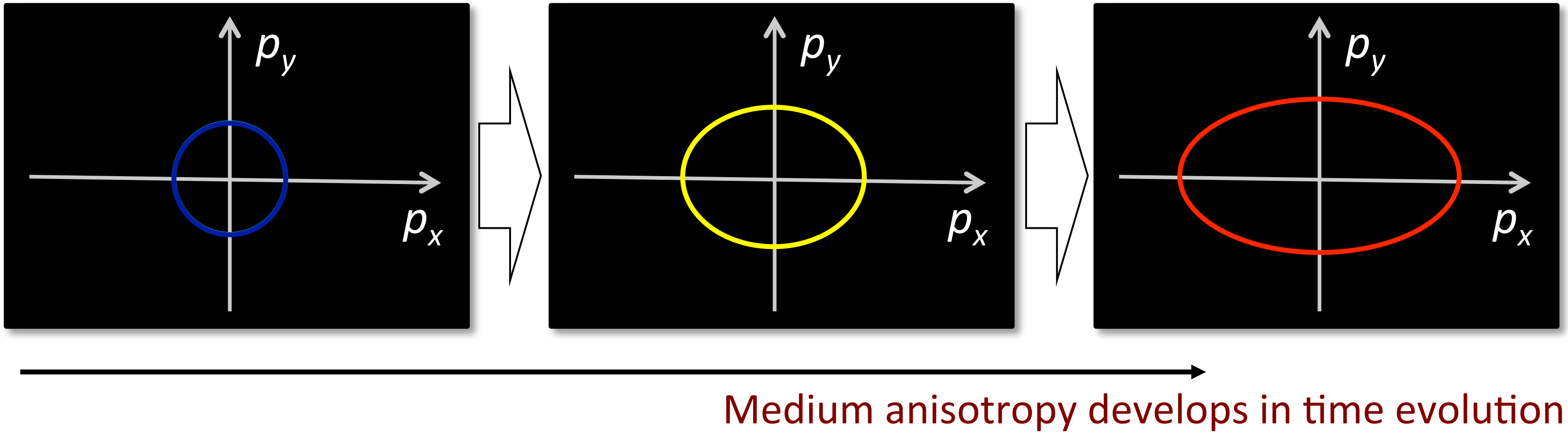

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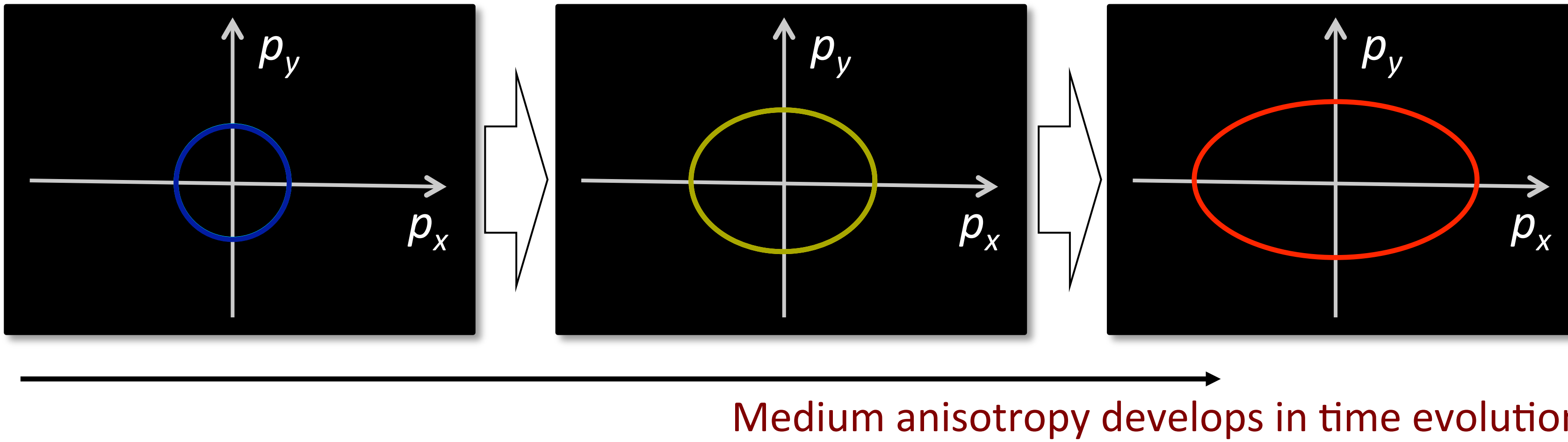

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The model

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

Energy-momentum conservation

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

Quark and gluon number changing processes

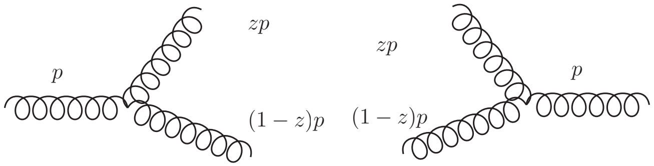
$$\partial_\mu N_q^\mu = 2r_b n_g - 2r_b \frac{n_g^{\mathrm{eq}}}{(n_q^{\mathrm{eq}})^2} n_q^2$$

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

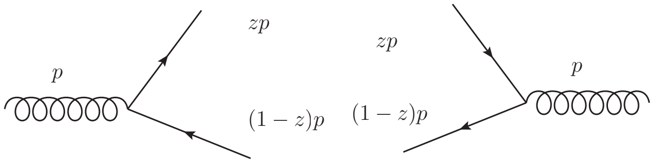
r_a, r_b, r_c : reaction rates

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

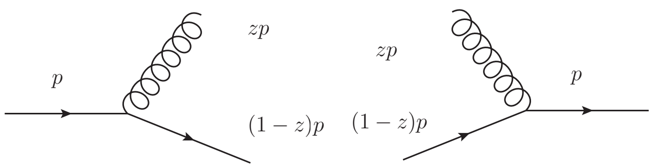
(a) gluon splitting



(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 (mass below 2 GeV) + Parton gas (N_f = 2)
  - Chemical reaction rates: $r_i = c_i T$ where c_i ranges are
    $0.2 \leq c_b \leq 2$ ($\tau_b \sim 0.5\text{–}5$ fm/c) and $0 \leq c_{a,c} \leq 3$ ($\tau_{a,c} \sim 0.3\text{–}\infty$ fm/c)

- Photon emission rate

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

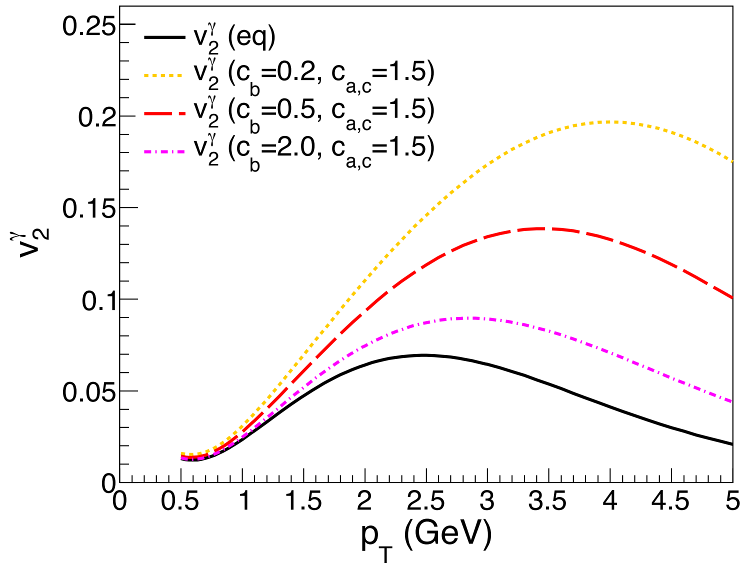
Turbide, Rapp and Gale, PRC 69, 014903 — Traxler and Thoma, PRC 53, 1348

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

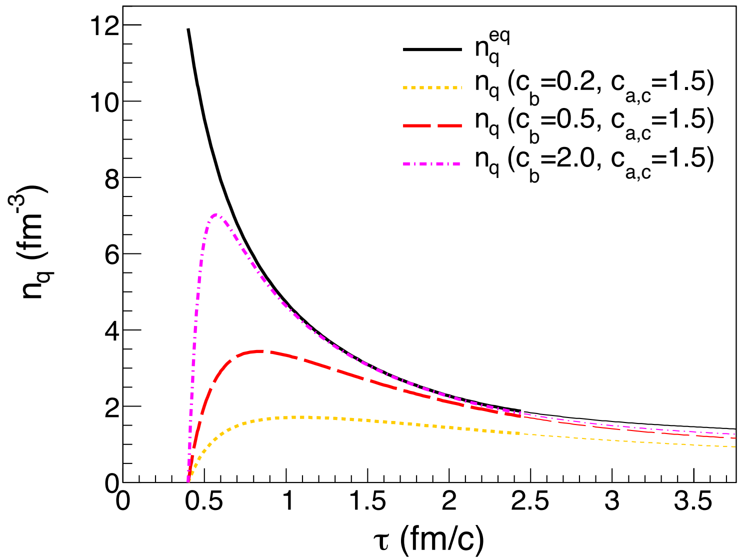
Results

- Elliptic flow of thermal photons – c_b dependence

Thermal photon v2



Quark number density

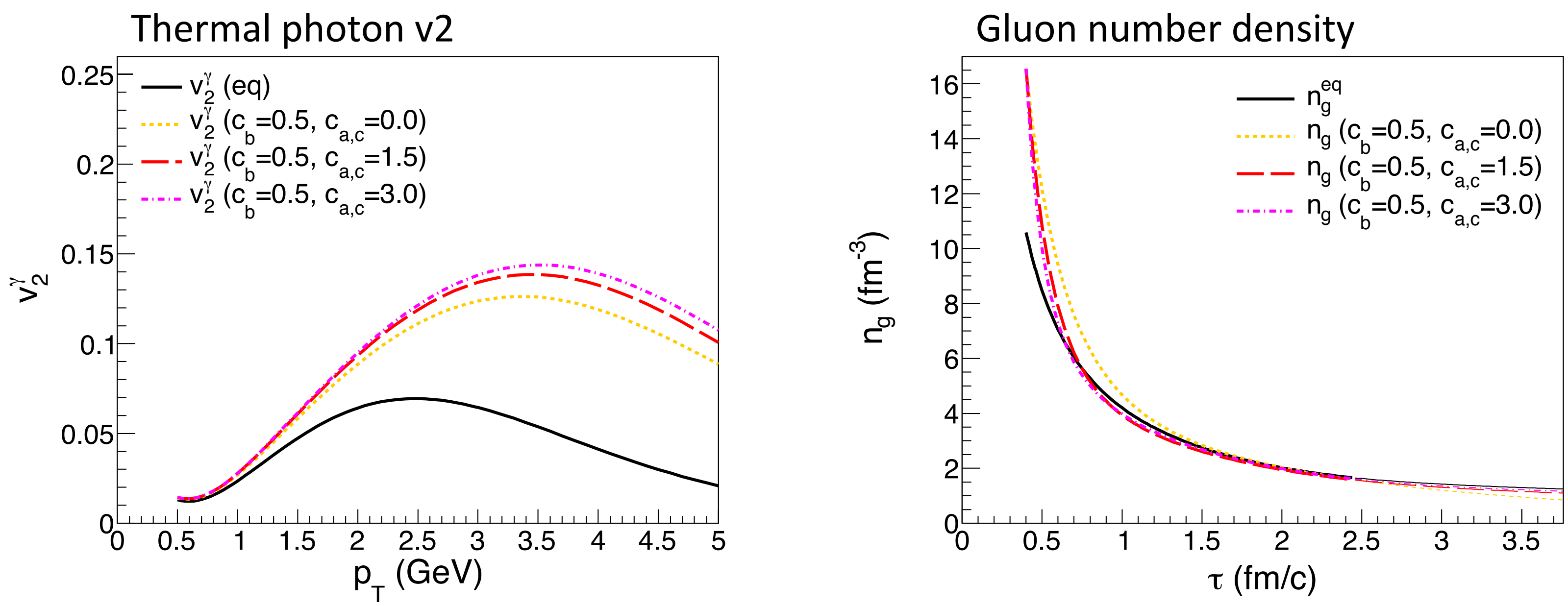


Late quark chemical equilibration ($\tau_{\rm chem} \sim 1/c_b T$) leads to enhancement of thermal photon v_2

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

Results

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

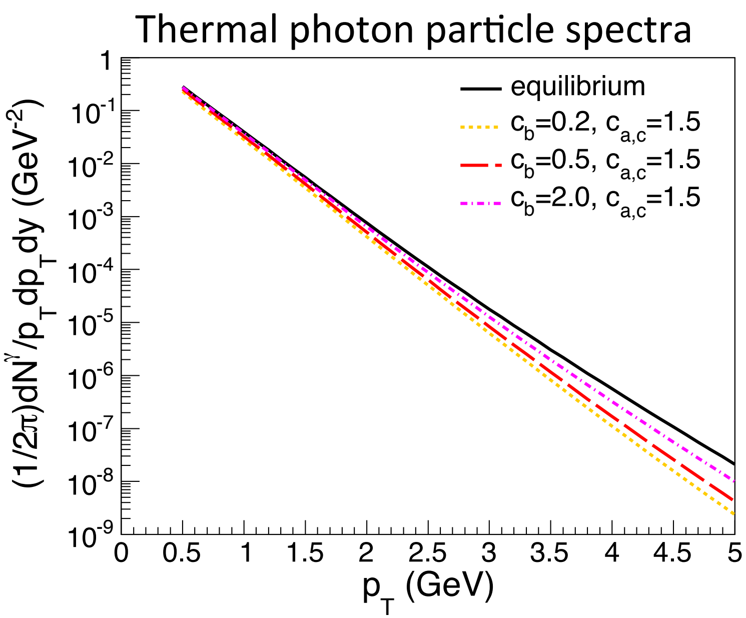


Thermal photon v_2 is slightly enhanced for faster gluon-involved equilibration processes

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

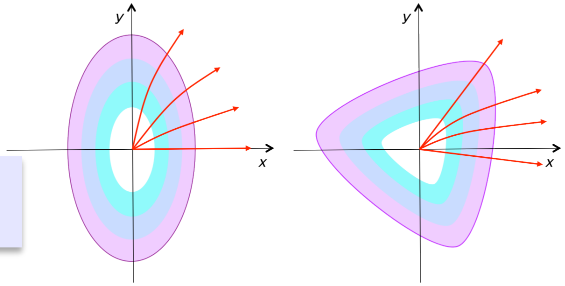
Prompt photon v_n

- 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

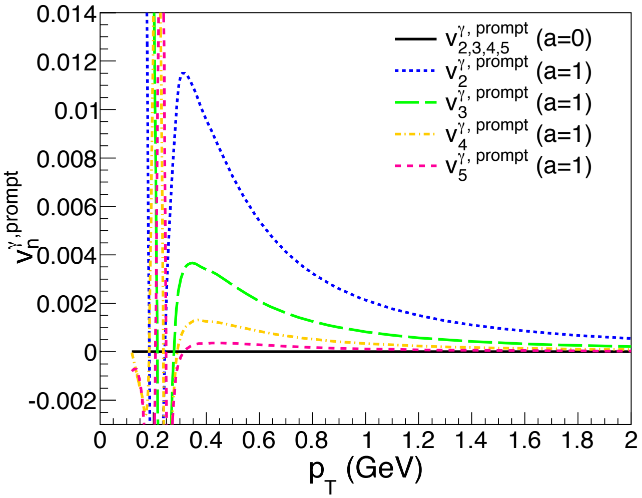


⇨ Geometrical anisotropy (ε_2, ε_3, …) is directly mapped onto thermal and prompt photon flow harmonics (v_2, v_3, …)

- 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)?

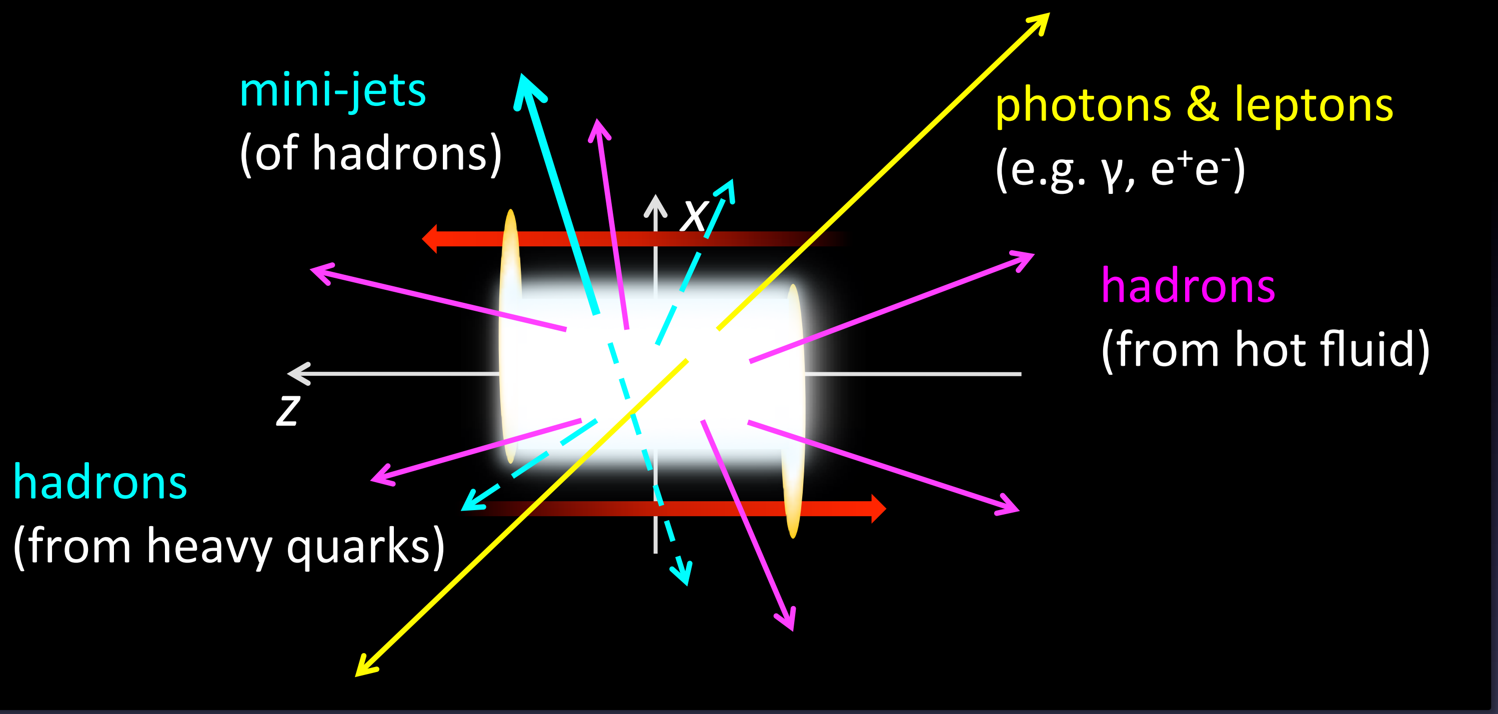


The end

- Vielen Dank für Ihre Aufmerksamkeit!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/

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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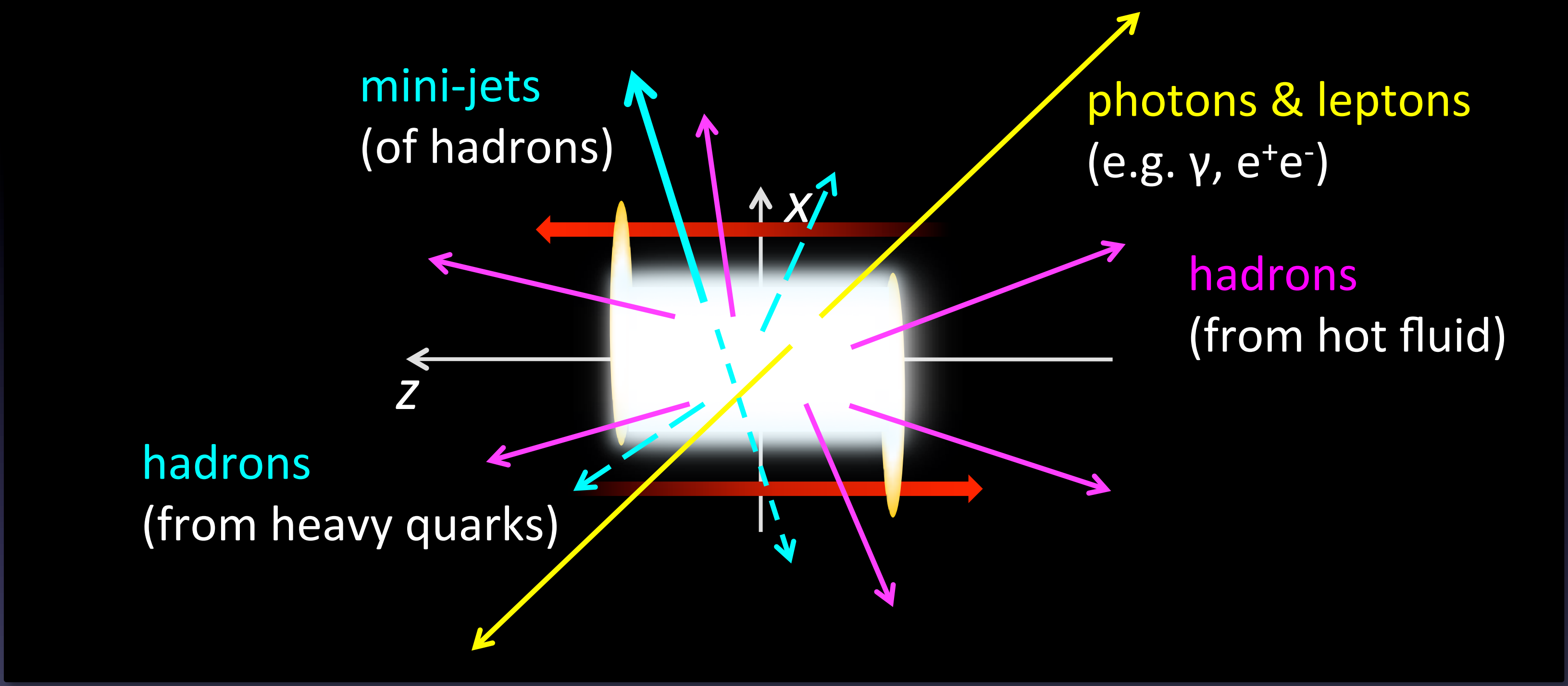

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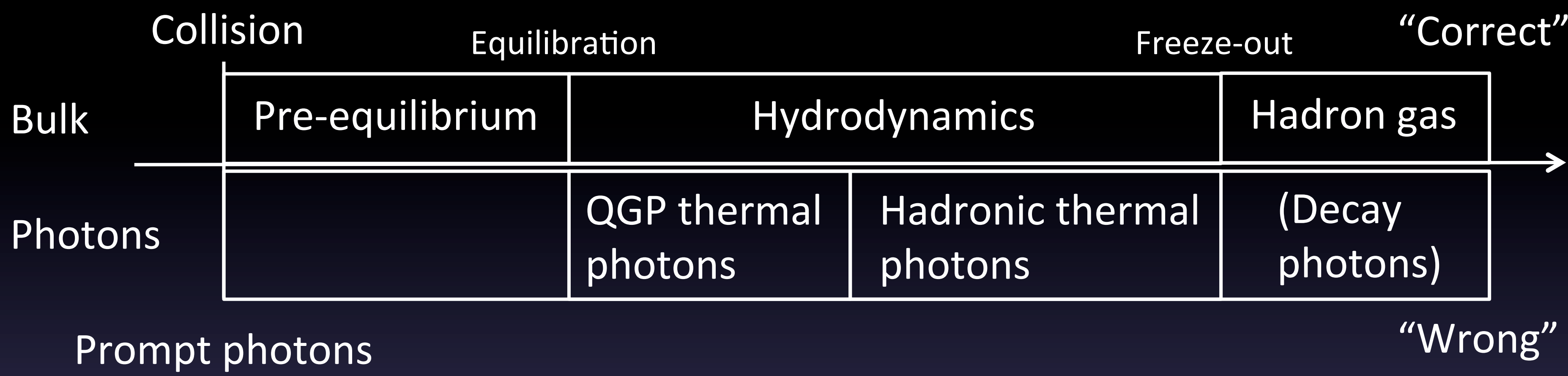
Photon v_n puzzle

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



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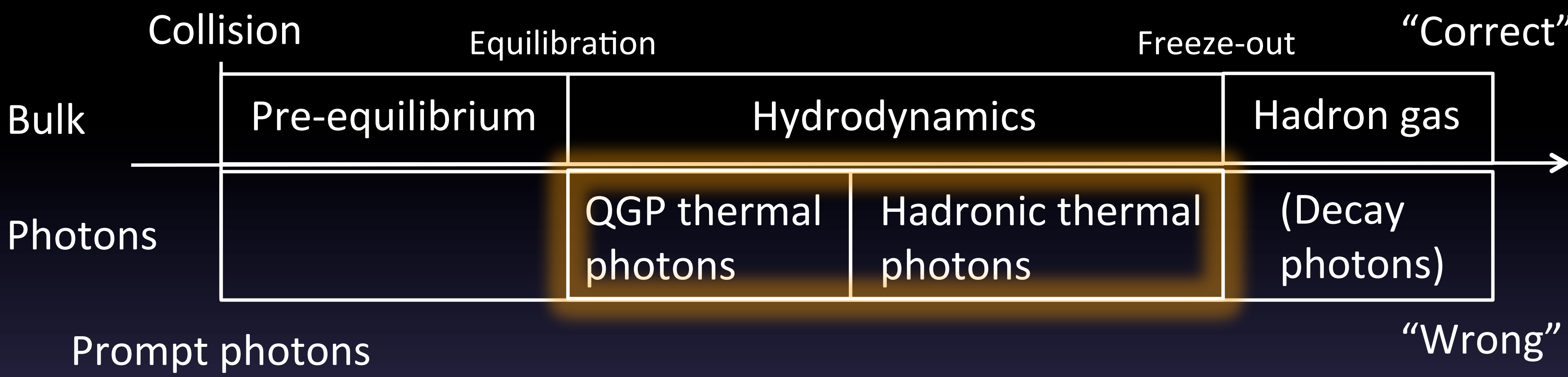

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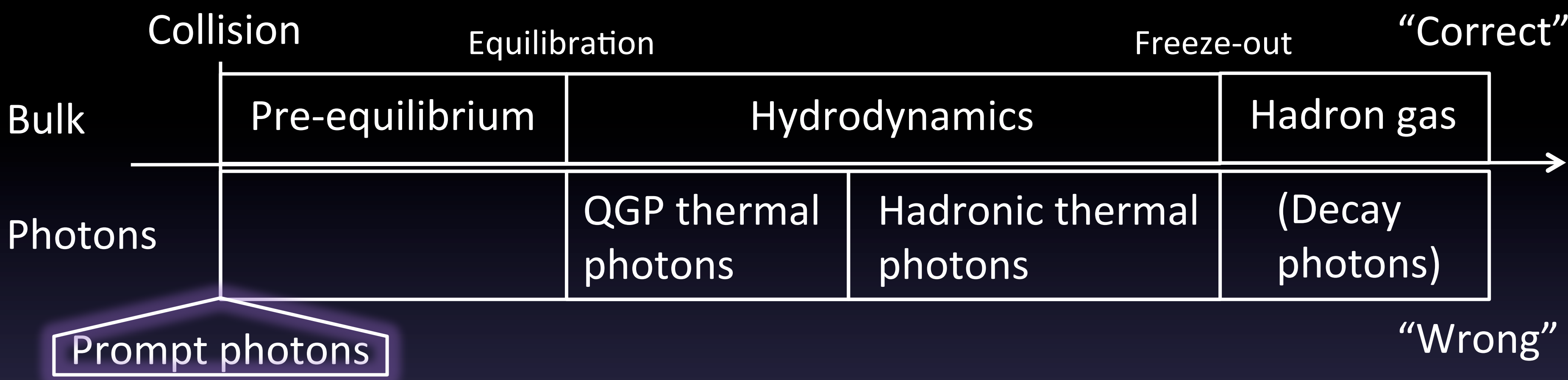

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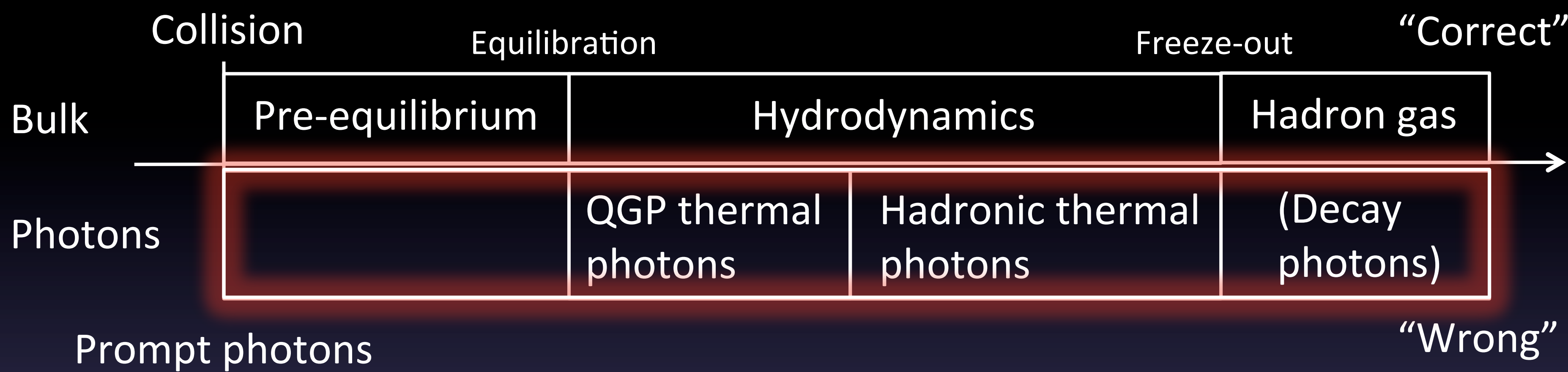

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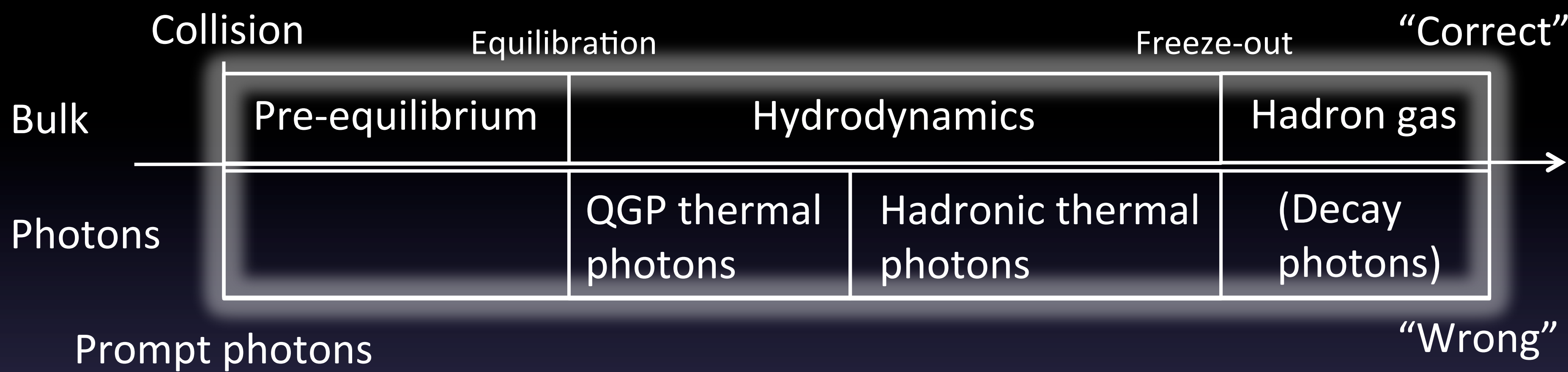

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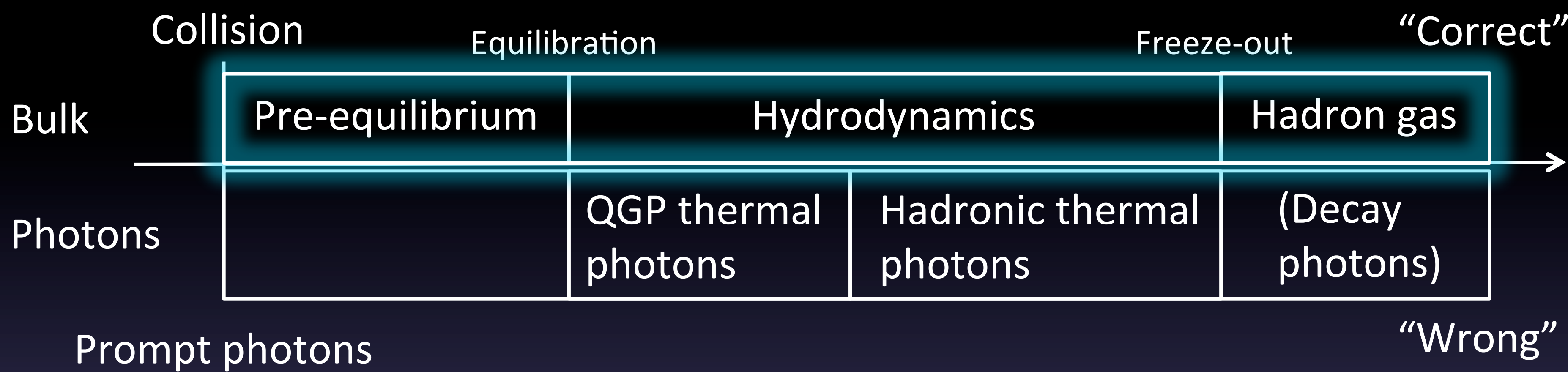

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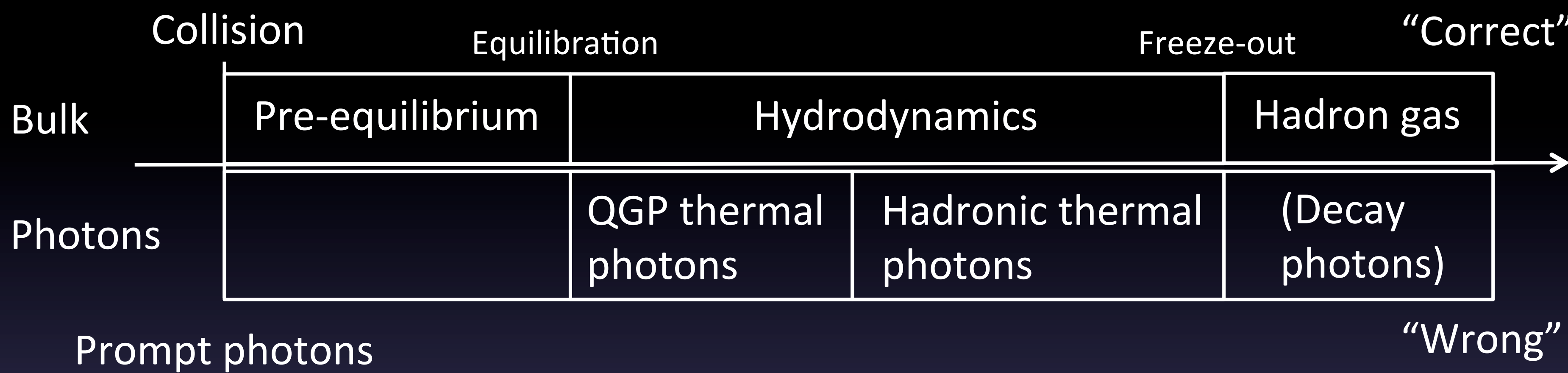

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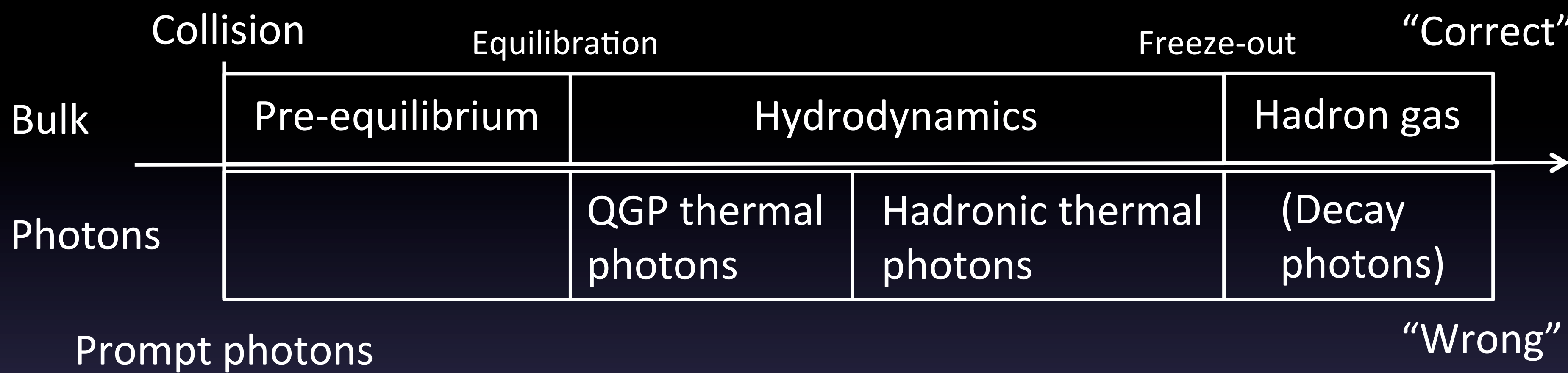
- Experimental data needs more statistics

Photon v_n puzzle

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



- 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
- Bulk evolution needs modification
- Experimental data needs more statistics

This talk (arrows pointing to the first and fifth items)

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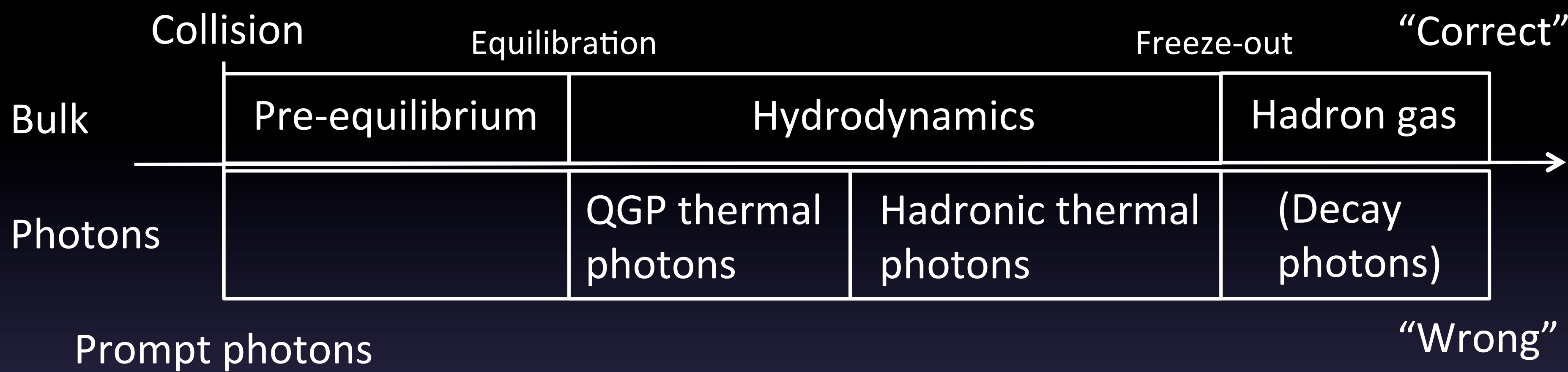

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This talk

+ preview

Introduction

- Direct photons are informative

  - Transverse momentum spectra

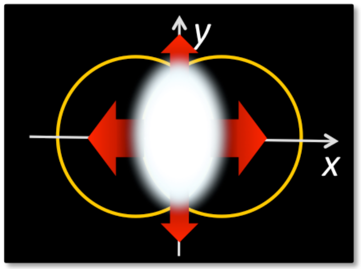
    Thermal photon slope $T = 221 \pm 38$ MeV

    ⇨ T_{init} = 300-600 MeV implied from hydrodynamic estimation

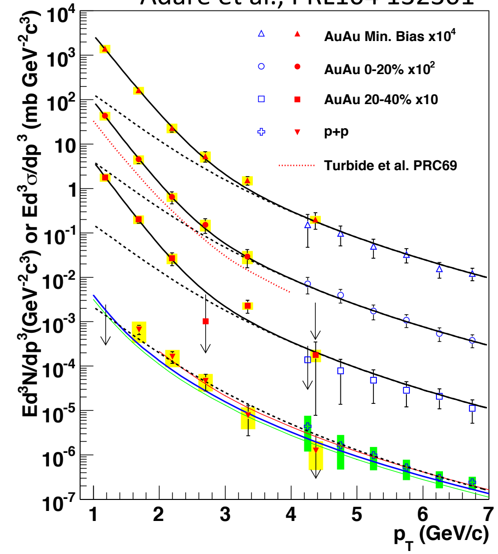
  - Elliptic flow v_2 – azimuthal momentum anisotropy

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

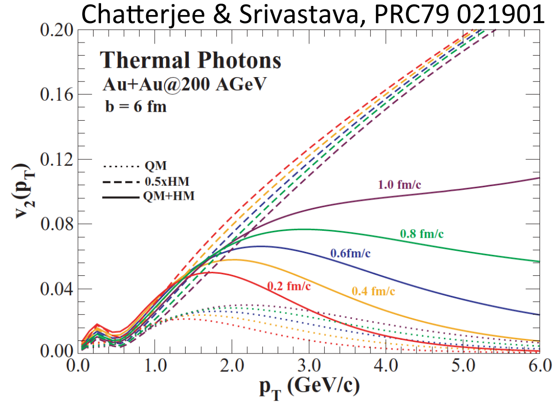
⇨ Initial time, viscosity, etc …



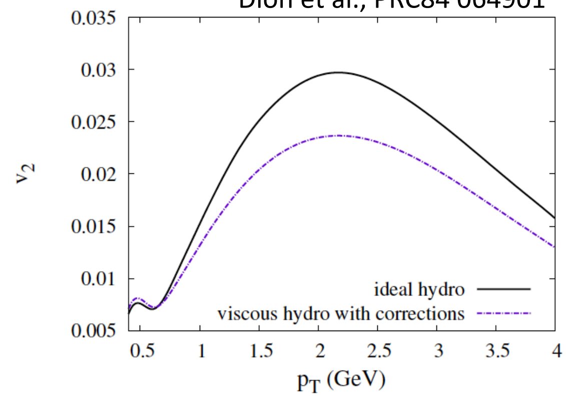
Adare et al., PRL104 132301



Chatterjee & Srivastava, PRC79 021901



Dion et al., PRC84 064901



Properties of bulk medium

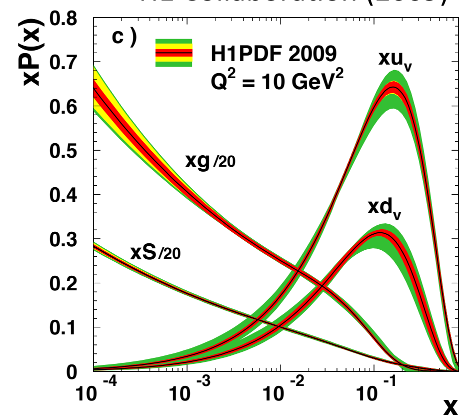
- The system transits from CGC to QGP

Color glass condensate (CGC) (τ < 0 fm/c)

- Gluons emitted from gluons emit gluons in a fast-travelling nucleon
  - They start to overlap and saturated
  - QCD matter at the initial stage of heavy ion collisions is dominated by gluons

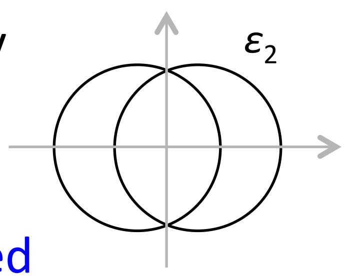
gluon gluon gluon gluon

H1 Collaboration (2009)

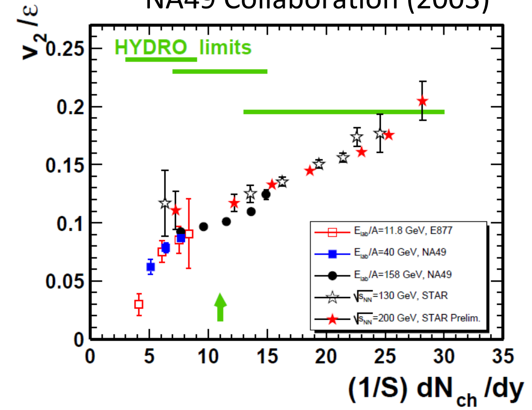


QGP/hadornic fluid (τ ~ 1-10 fm/c)

- Azimuthal momentum anisotropy v_2 is large compared with spatial one ε_2
  - QCD matter is locally equilibrated at some point and behaves as a fluid



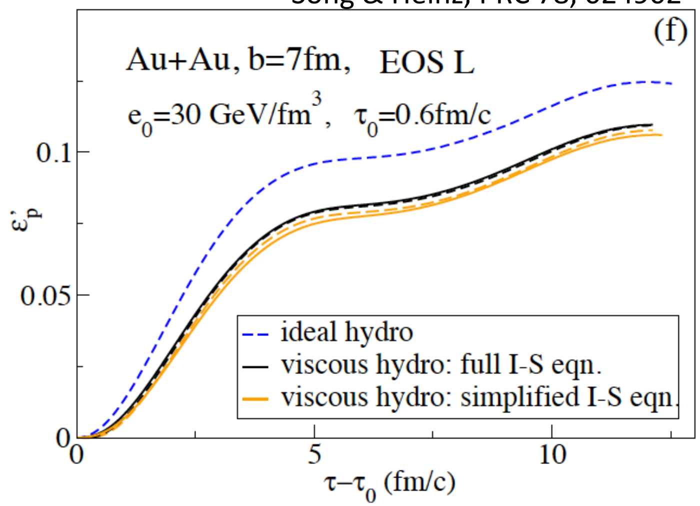
NA49 Collaboration (2003)



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

On equation of state

- Doesn't decreased degree of freedom in the EoS leads to higher initial T for the same entropy density?

A. Yes.

However, separation of the quark and the gluon contributions for an arbitrary EoS is not trivial
(e.g. crossover at $N_f = 2+1$, 1st order transition at $N_f = 0$).

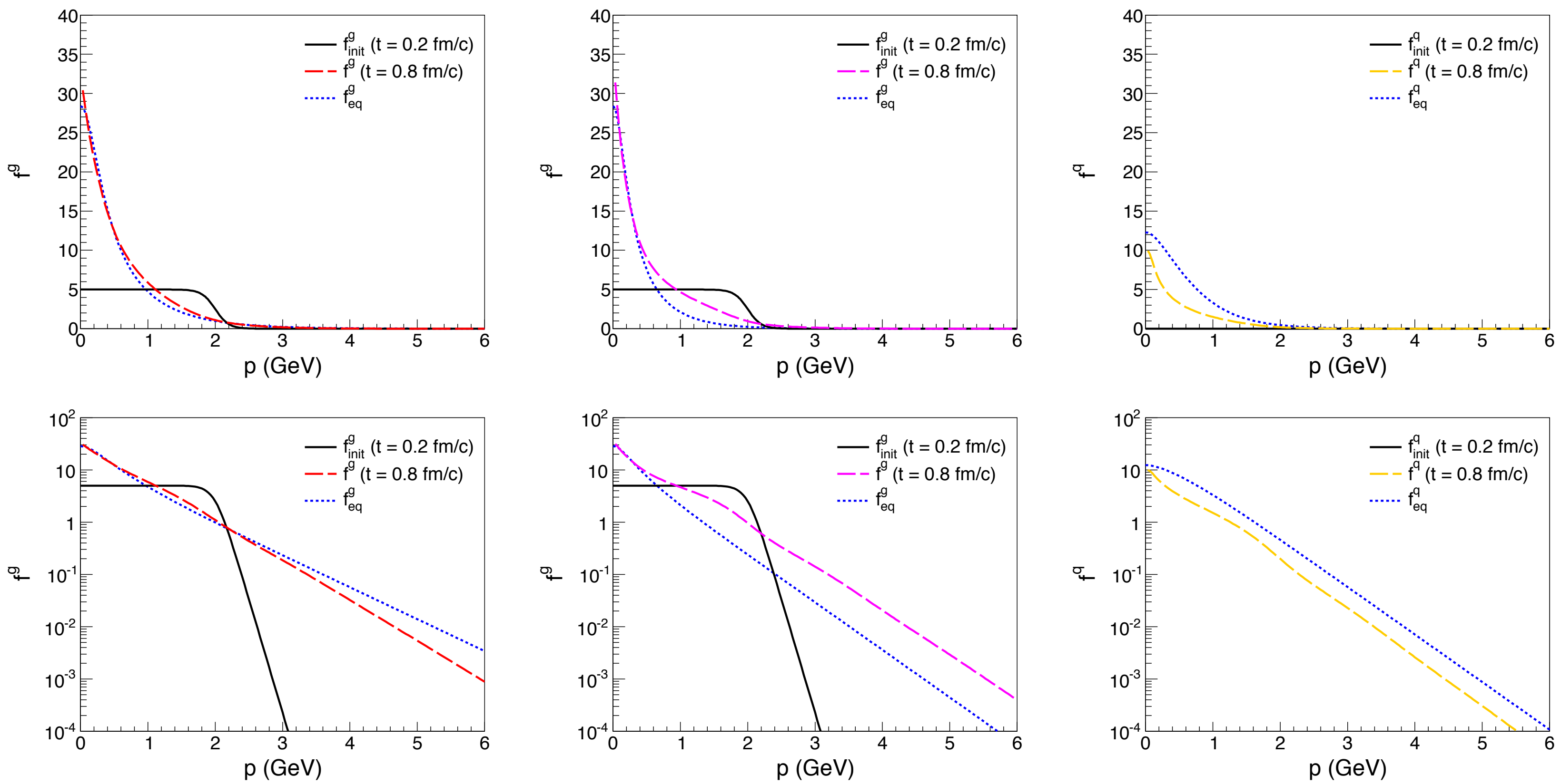
Also gluon overpopulation may increase the effective DoF.

	d_q	d_g	d_{total} (eq)	d_{total} (init)
Nf = 0	0	16	16	(16)
Nf = 1	12	16	26.5	25
Nf = 2	24	16	37	25

Thermal vs. chemical equilibration

- Collinear parton splitting picture

AM and B. Mueller, arXiv:1403.7310 [nucl-th]



- Comparison of f_g (pure gauge), f_g (N_f = 3) and f_q (N_f = 3)