Effects of quark chemical equilibration on thermal photon elliptic flow

Akihiko Monnai
RIKEN BNL Research Center
Nishina Center for Accelerator-Based Science, RIKEN

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Overview

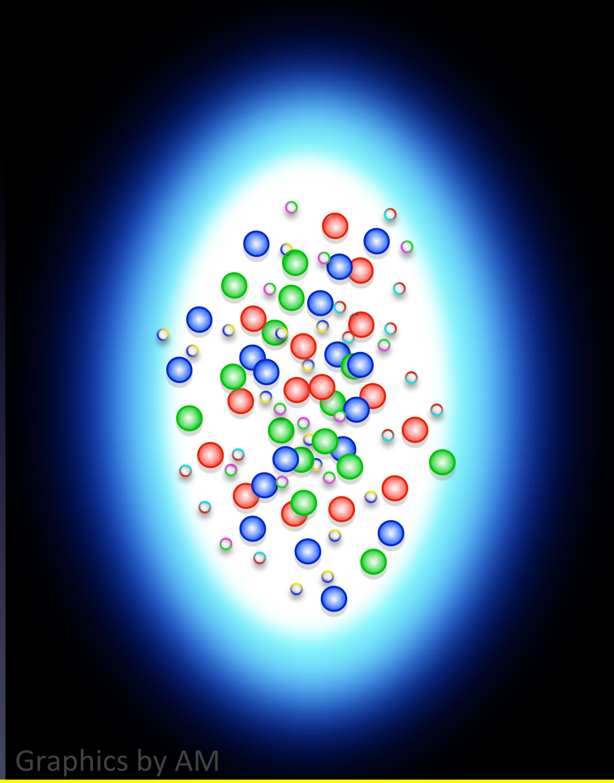
- Introduction
  - "Photon v_2 puzzle" in heavy-ion collisions
- Thermal photons from gluon-rich QGP
  - Thermal vs. chemical equilibration
  - Hydrodynamic model with rate equations for quarks and gluons
  - Numerical results: thermal photon v_2
- Summary and outlook
  - Other possible scenario: medium refraction

References:

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

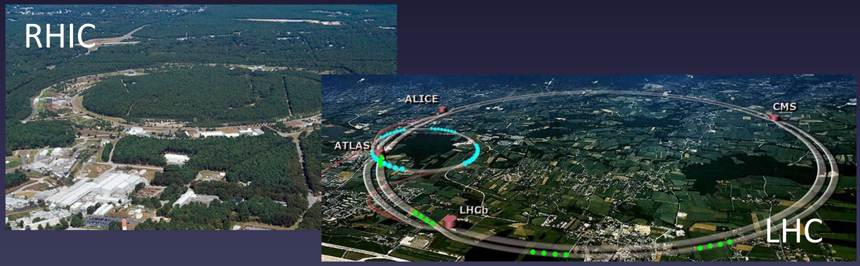
Introduction

- Quark-gluon plasma: a deconfined phase of QCD



- It can be created in high-energy heavy-ion collisions

⇨ An experimental gateway to the early Universe



- It is a QCD phenomenon; what can an electromagnetic probe tell us about its properties?

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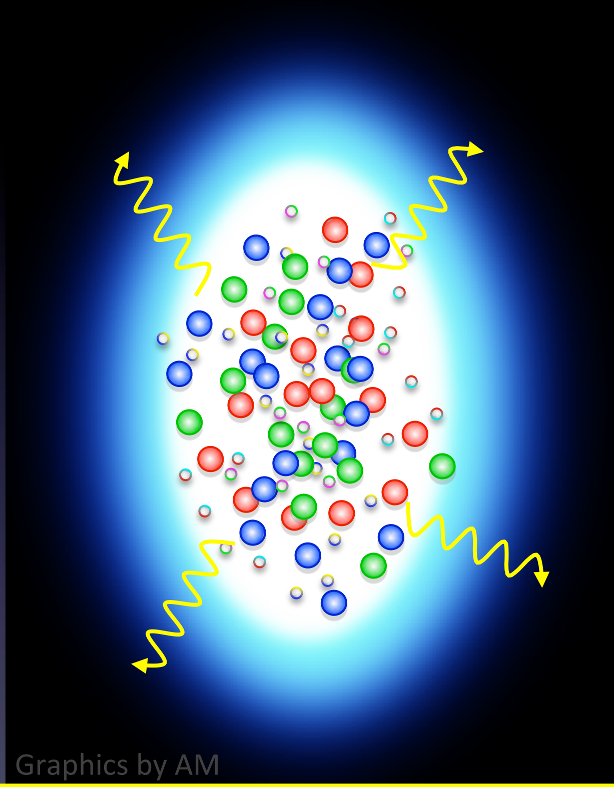

▶ It can be created in high-energy heavy-ion collisions

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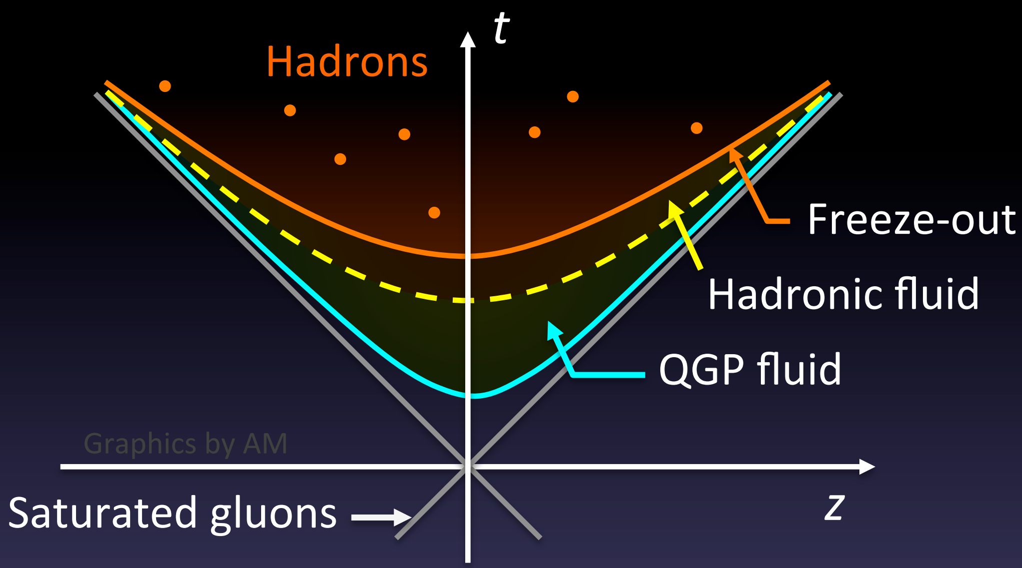
▶ It is a QCD phenomenon; what can an electromagnetic probe tell us about its properties?

Introduction

- Photon emission in heavy ion collisions (low p_T)



- Color opacity
  - ⇨ Most of information before freeze-out is lost in hadrons
- Electromagnetic transparency
  - ⇨ Photons retain information during time evolution

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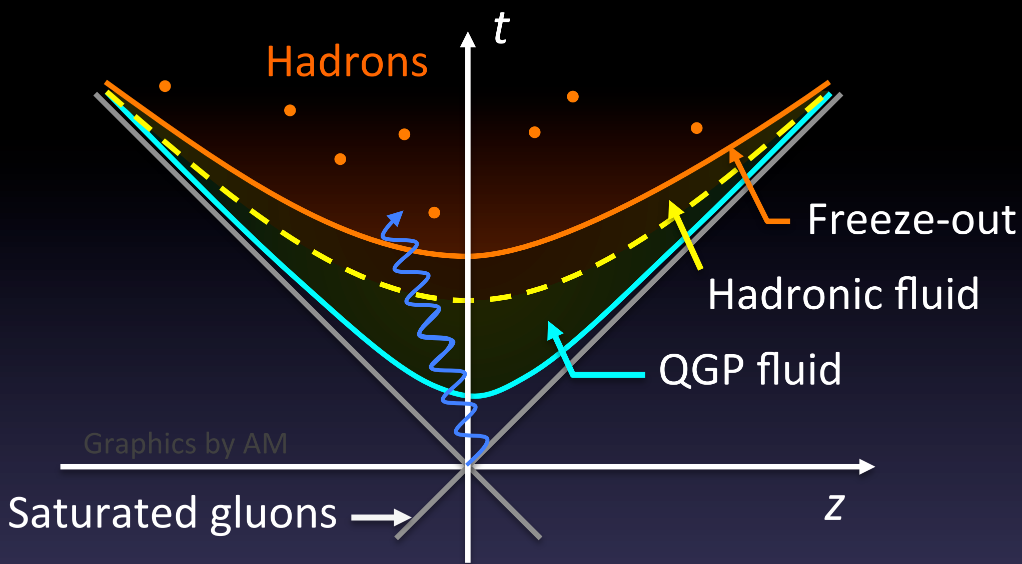
■ Photon emission in heavy ion collisions (low p_T)



Prompt photons
- from hard processes

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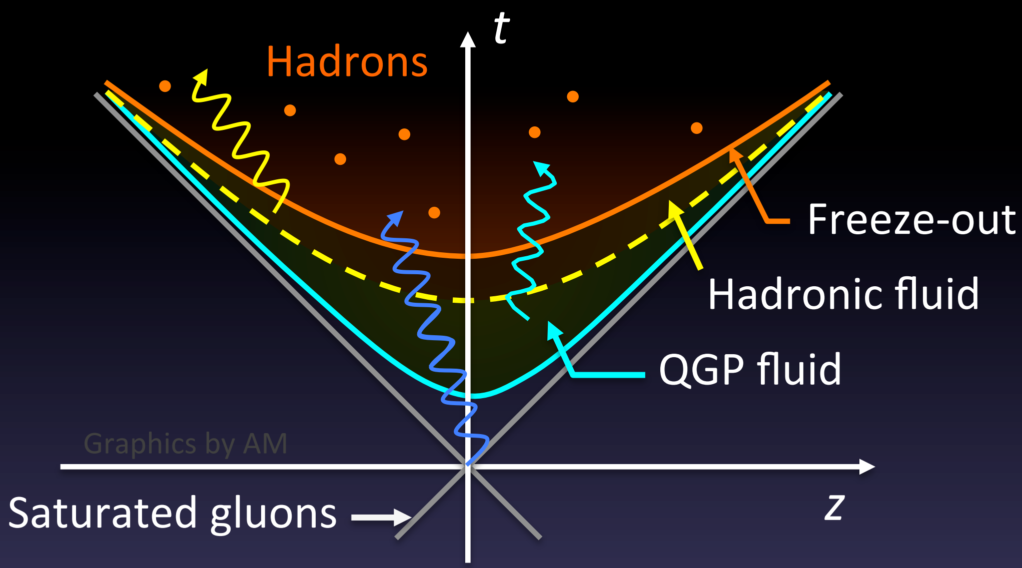

Thermal photons (hadronic)

Thermal photons (QGP)

- from bulk medium

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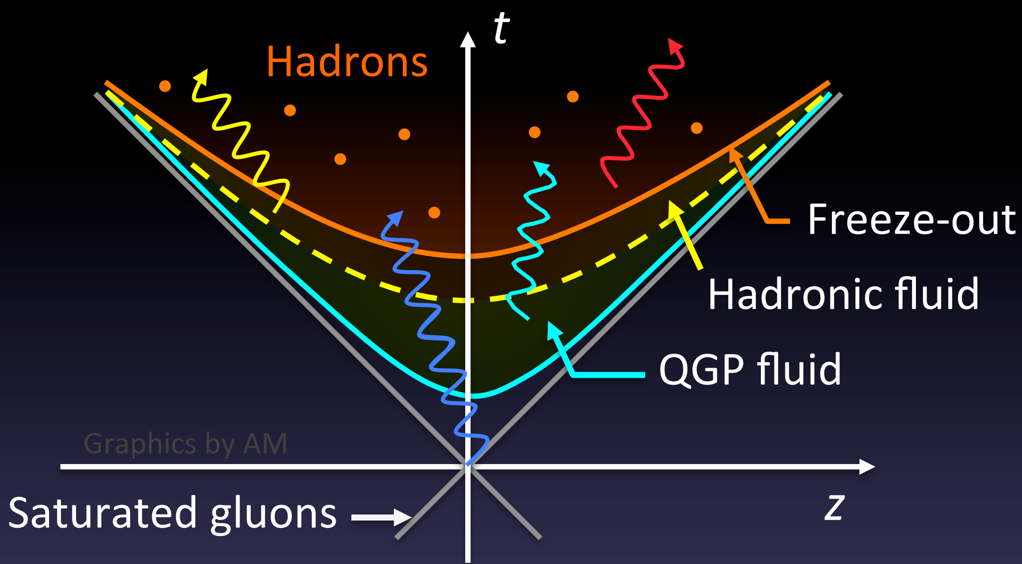

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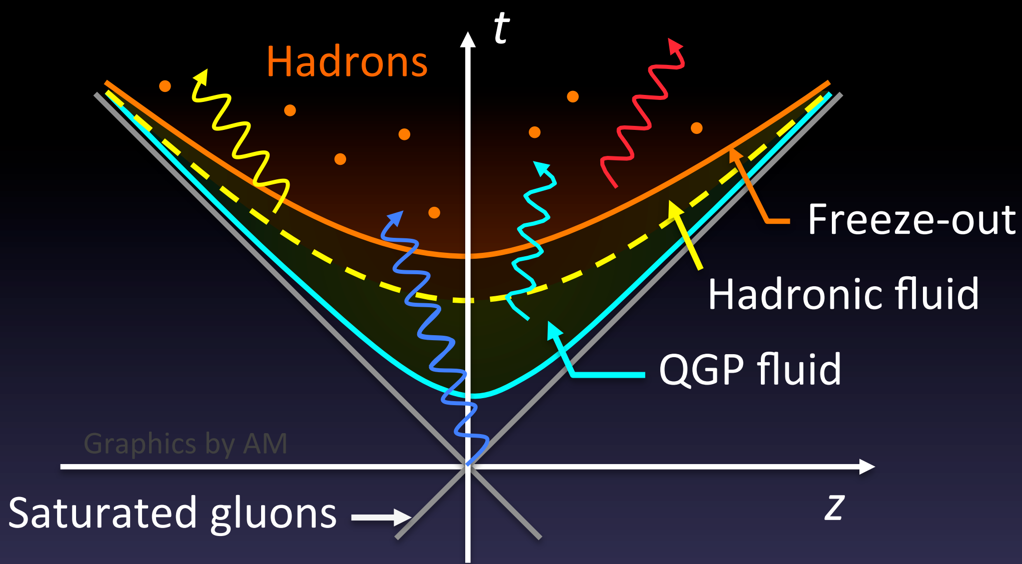

Decay photons
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Direct photons

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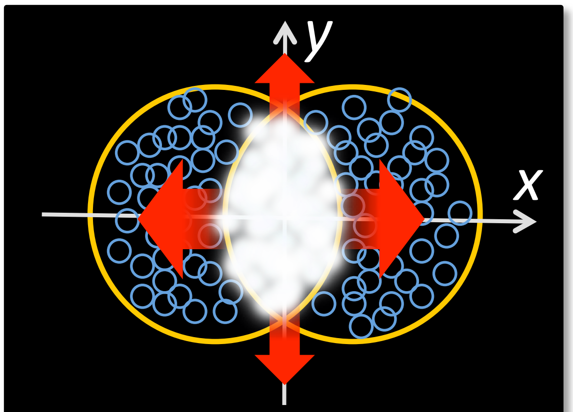
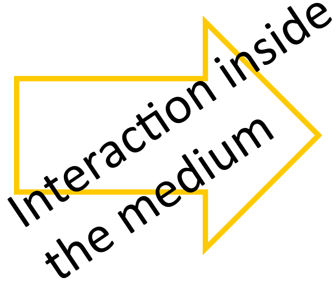
Introduction

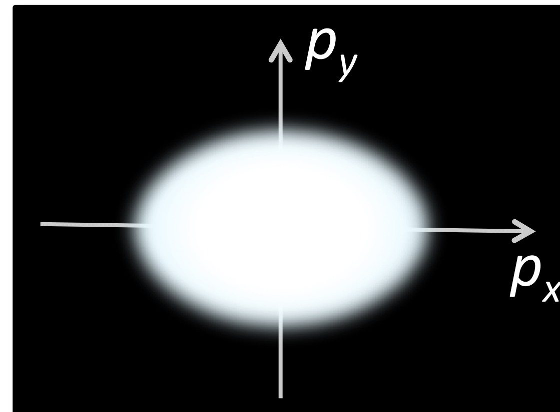
- Heavy-ion observable: Elliptic flow (v_2)

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



Spatial anisotropy

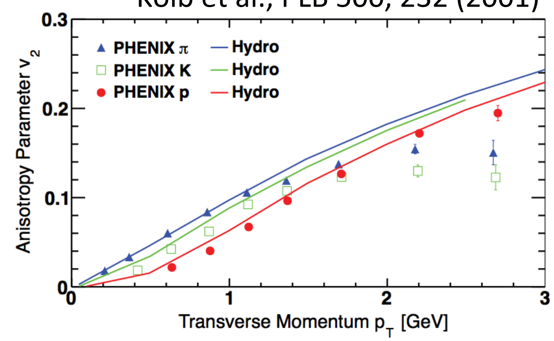




Momentum anisotropy

- Hadron v_2 is found to be large
  - It follows hydrodynamic description
  - An "evidence" for strongly-coupled QGP; early equilibration of bulk medium (τ < 1 fm/c)?

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

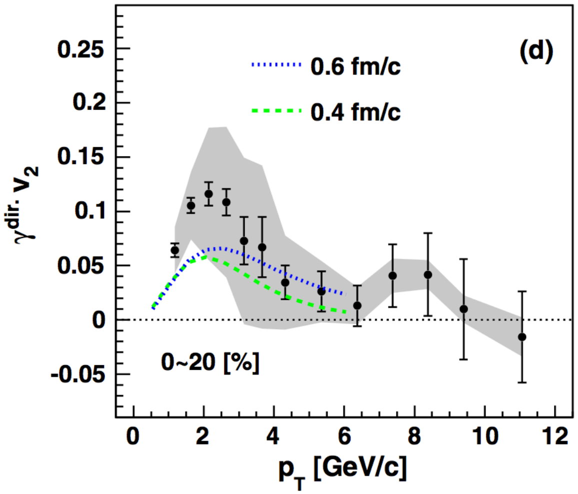


Introduction

■ Experimental results: photon anisotropy

- Direct photon v_2 is found to be large
  - Hydro models predicted much smaller v_2 (*earlier stages contribute*)
  - No definite answer so far; recognized as "photon v_2 puzzle"

PHENIX, PRL 109, 122302 (2012)



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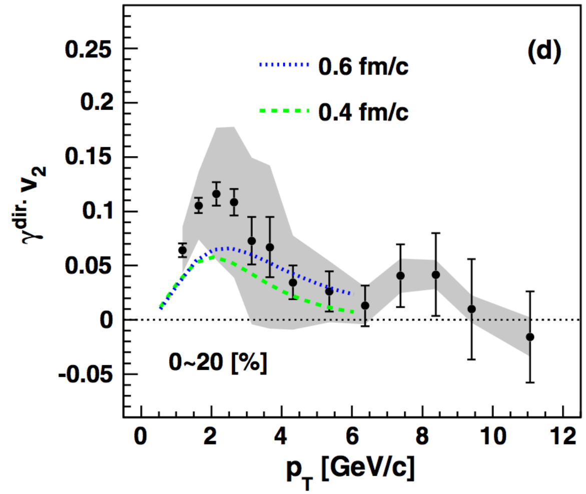

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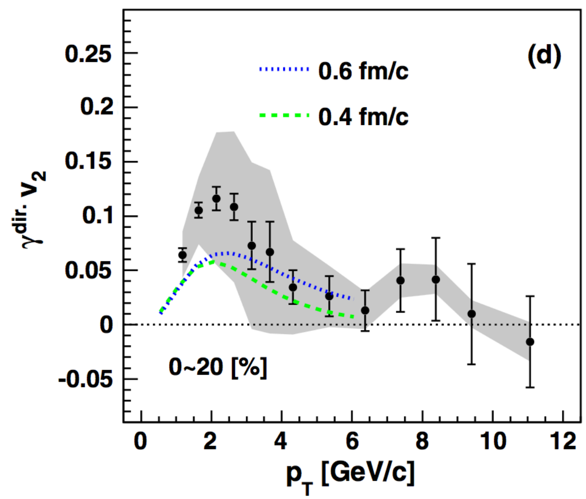
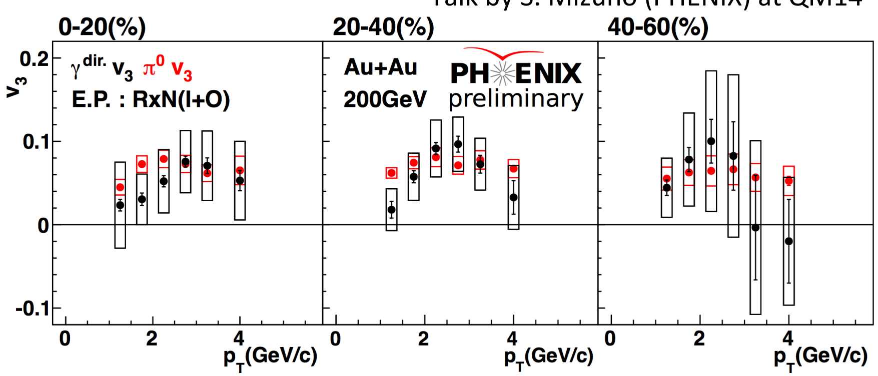


Direct photon v_3 is indicated to be large

Talk by S. Mizuno (PHENIX) at QM14

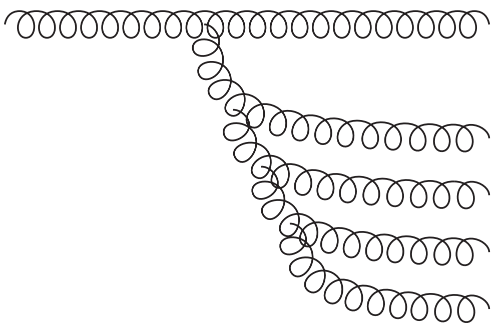


- Similar to hadron v_3
- The enhancement is at least partially due to the properties of bulk medium itself

Approach of this work

- Properties of bulk medium

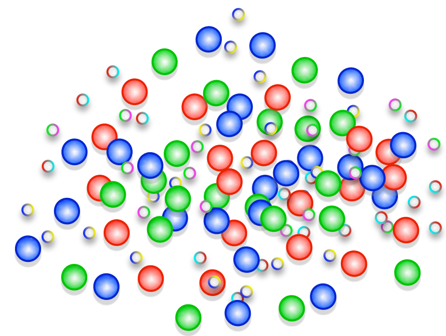
τ < 0 fm/c



- Color glass condensate: Colliding two nuclei are saturated gluons

"Little bang"

τ ~ 1-10 fm/c

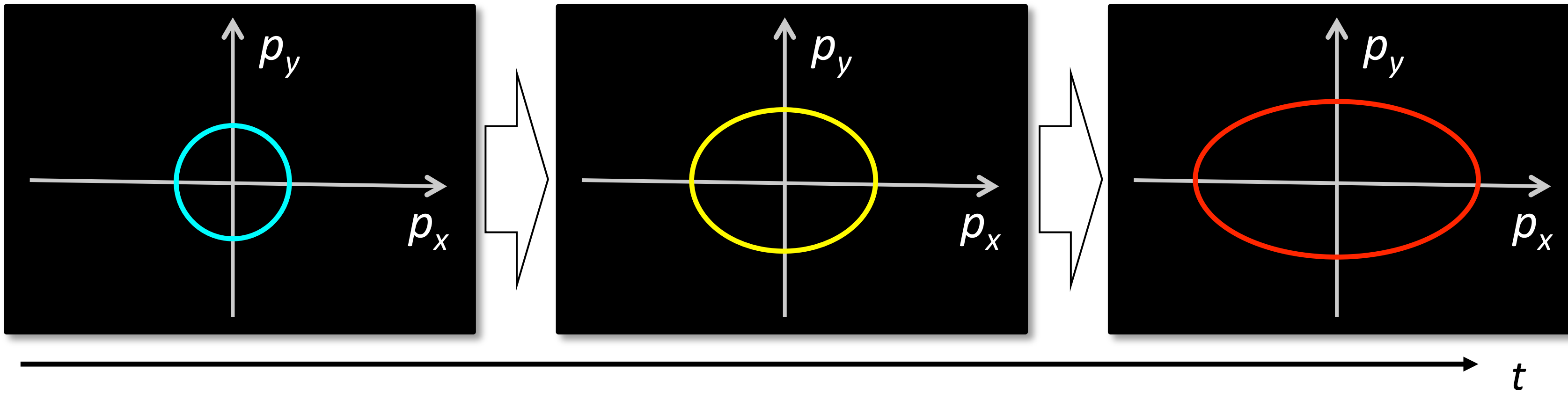


- QGP/hadronic fluid: A plasma of equilibrated quarks and gluons

⇨ Chemical equilibration does not necessarily coincide with thermalization (cf: AM and B. Müller, arXiv: 1403.7310)

Approach of this work

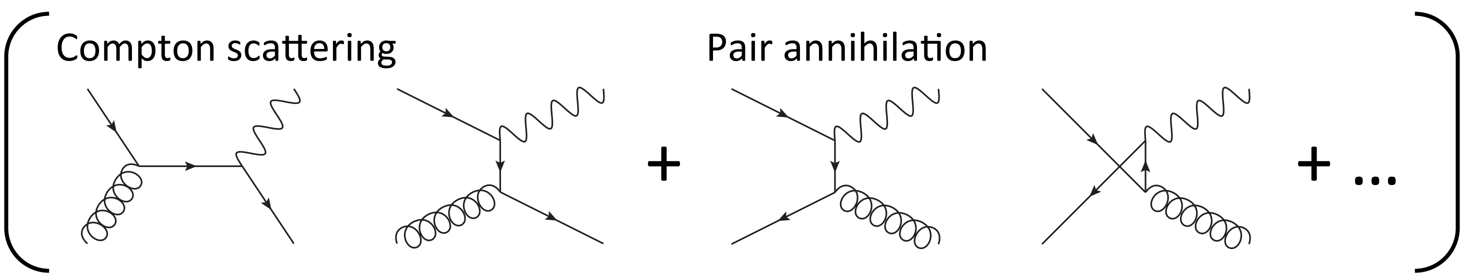
- Chemical non-equilibrium at the onset of QGP fluid



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

QGP is initially "dim" since photons are emitted from quarks;
photon v_2 can be enhanced by larger contribution of later t

Compton scattering　　Pair annihilation



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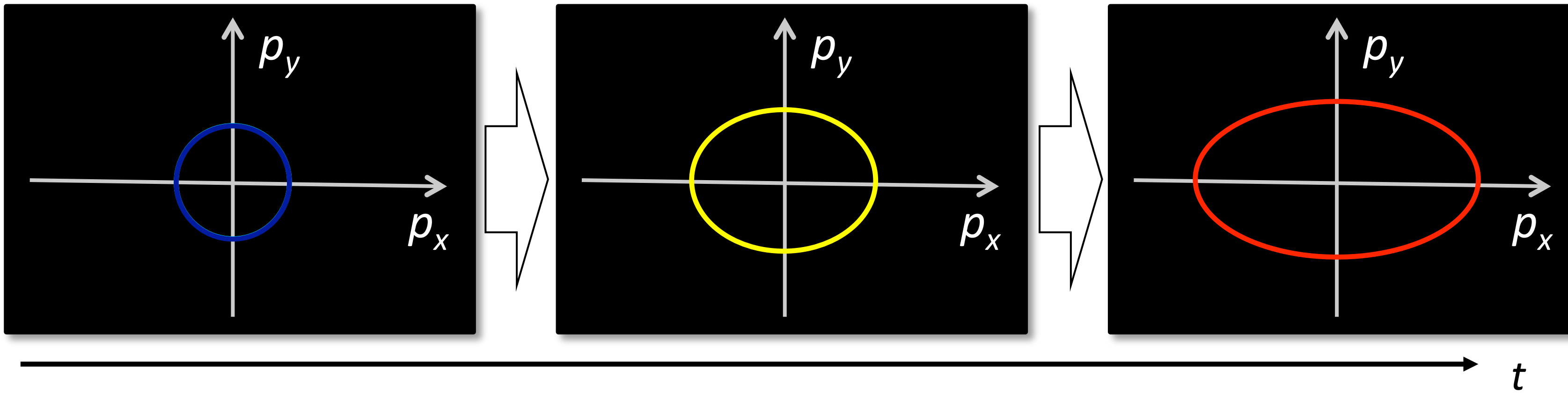

quark-GLUON plasma | quark-gluon plasma | Quark-gluon plasma

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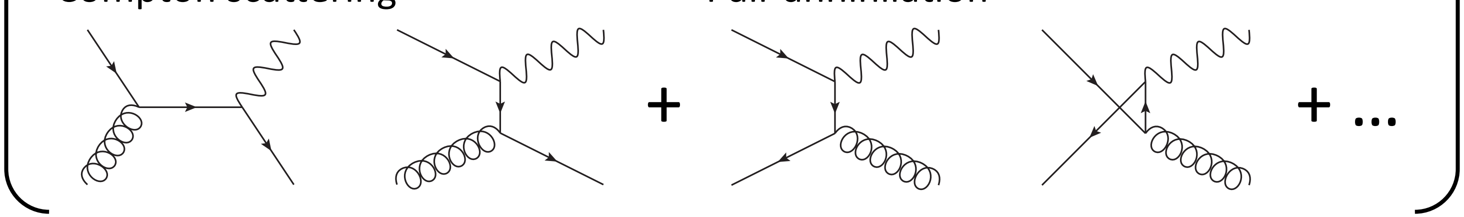

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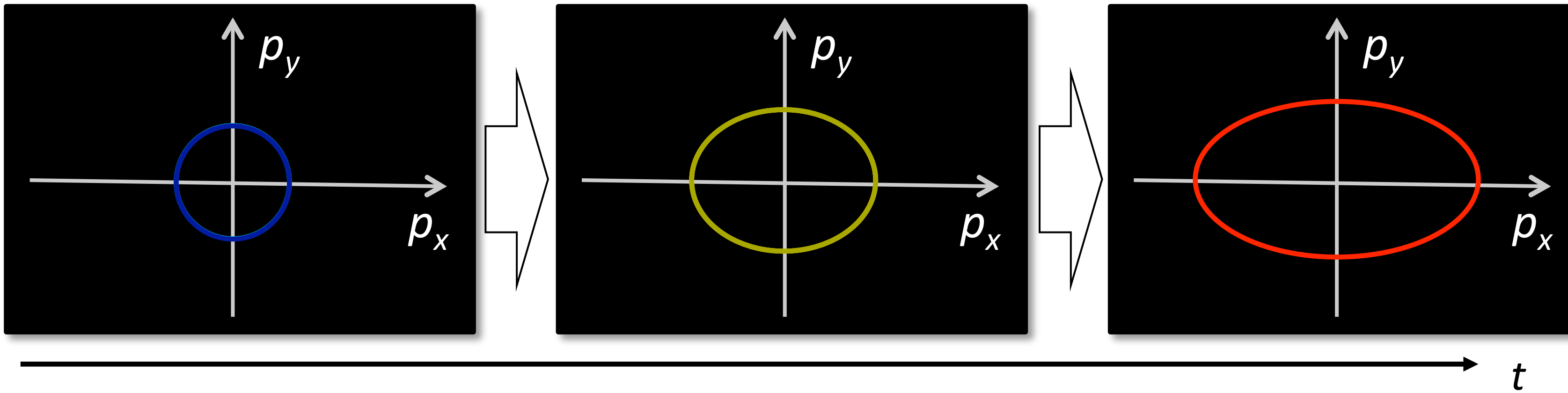

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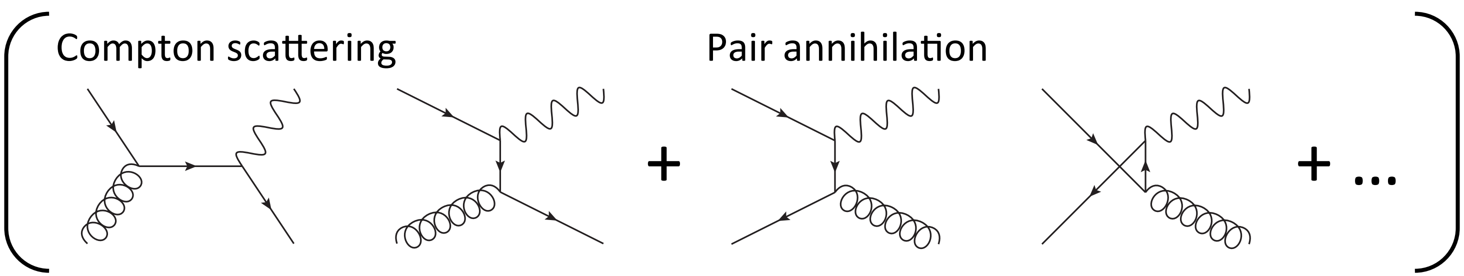


The model

- (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

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

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

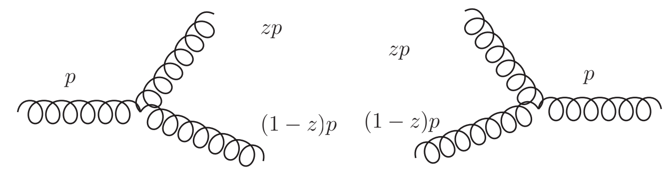
r_a, r_b, r_c : reaction rates

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

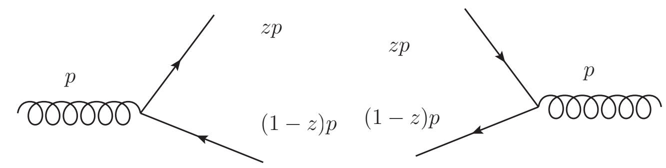
⇨ Late quark chemical equilibration implies $r_b < r_a, r_c$

Chemical equilibration times: $\tau_i \sim 1/r_i$

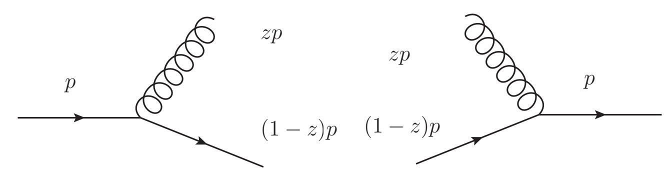
(a) gluon splitting



(b) quark pair production



(c) gluon emission from a quark



Input for numerical analyses

- Hydrodynamic parameters (Initial conditions + fluid properties)

  - Gluon energy distribution: Kolb et al., PRC 62, 054909 (2000) for RHIC 200 GeV Au-Au
  - 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

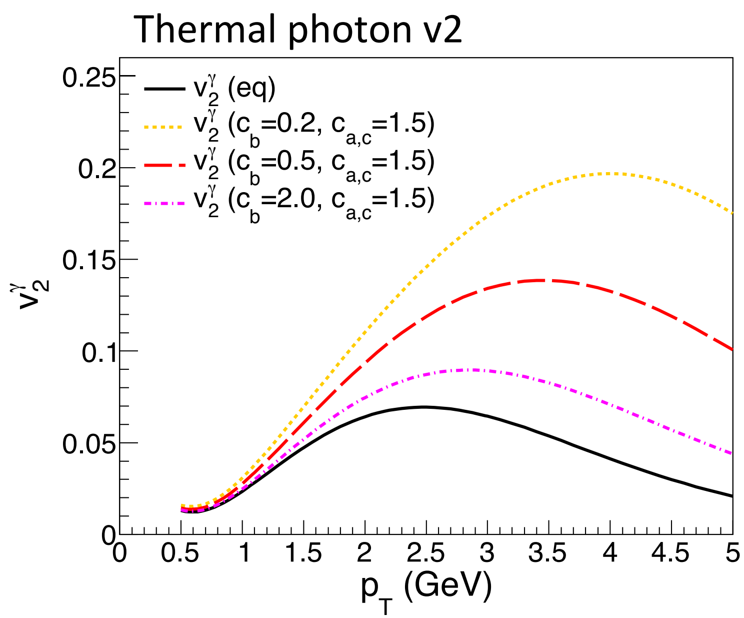
  - $$E\frac{dR^\gamma}{d^3p} = \frac{1}{2}\left(1 - \tanh\frac{T - T_c}{\Delta T}\right)E\frac{dR^\gamma_{\text{hadron}}}{d^3p} + \frac{1}{2}\left(1 + \tanh\frac{T - T_c}{\Delta T}\right)E\frac{dR^\gamma_{\text{QGP}}}{d^3p}$$

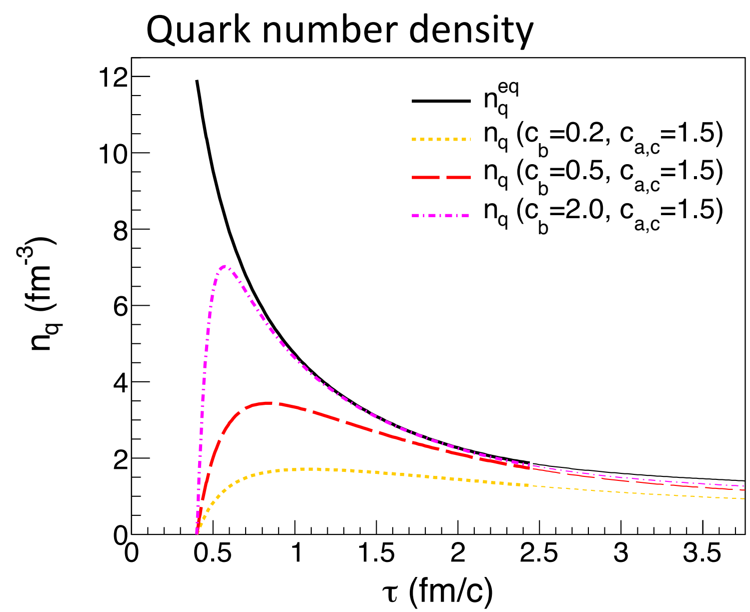
    Turbide, Rapp and Gale, PRC 69, 014903 — Traxler and Thoma, PRC 53, 1348

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

Results

- Elliptic flow of thermal photons – c_b dependence





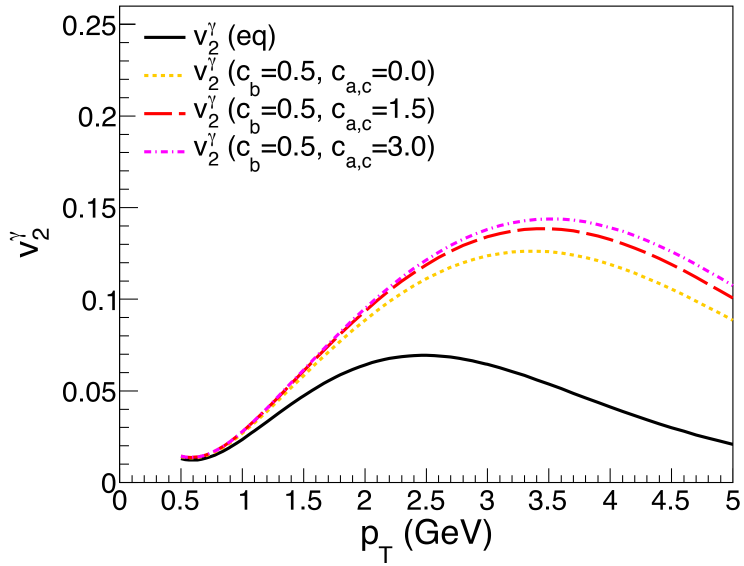
Late quark chemical equilibration ($\tau_{\rm chem} \sim 1/c_b T$) leads to enhancement of thermal photon v_2

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

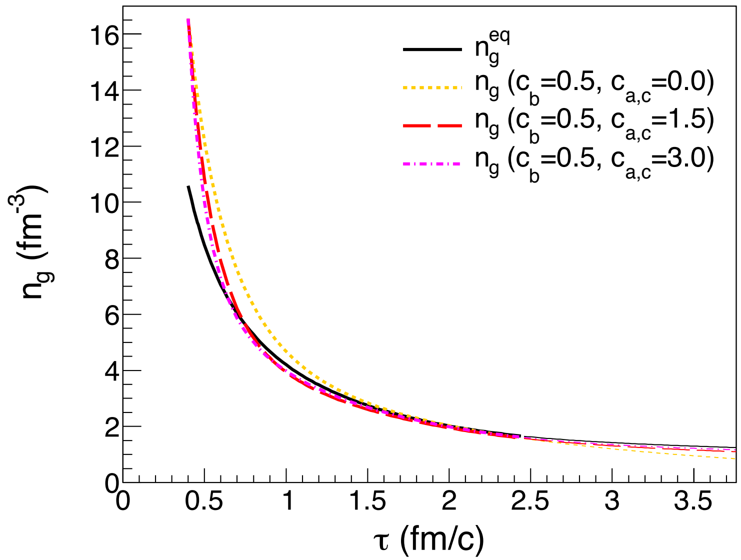
Results

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

Thermal photon v2



Gluon number density

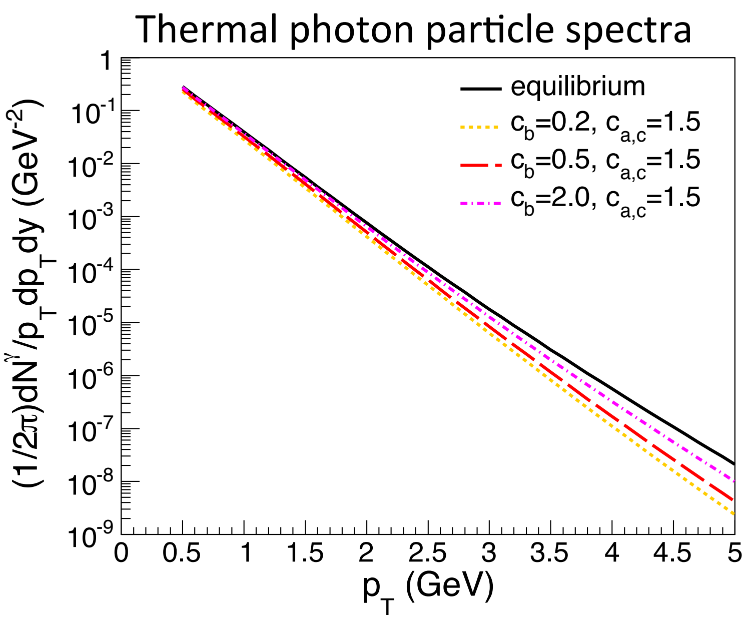


Thermal photon v_2 is slightly enhanced for faster gluon-involved equilibration processes

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

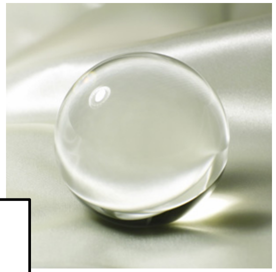
- Thermal photon v_2 from chemically non-equilibrated QGP is investigated
  - Late quark production leads to visible enhancement of v_2, contributing positively to resolution of "photon v_2 puzzle"
    - ⇨ Evolution of bulk medium from CGC to QGP is a key
  - Late gluon equilibration slightly reduces 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 chemical non-equilibrium effects, e.g., on heavy quarks

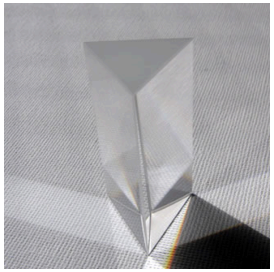
Prompt photon v_n

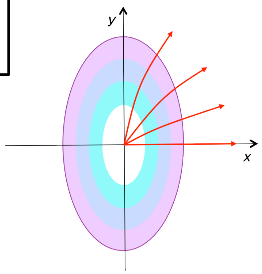
■ QGP optics: medium refraction

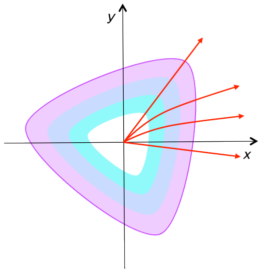
AM, arXiv:1408.1410 [nucl-th]

- A transparent QCD medium can work as a 4-dimensional lens



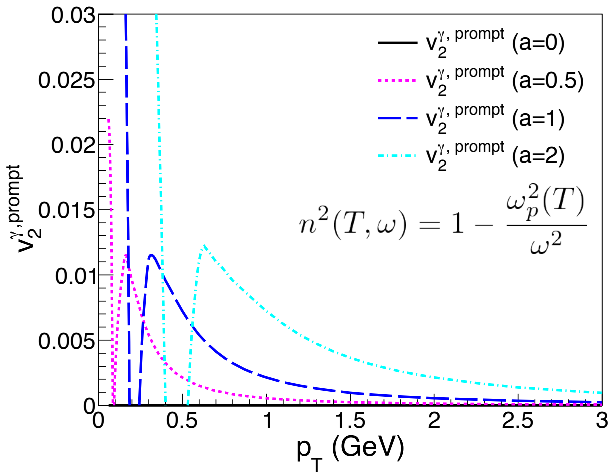






⇨ Geometrical anisotropy (ε_2, ε_3, …) is directly mapped onto photon flow harmonics (v_2, v_3, …)

- Prompt photon v_2 (= 0 if no refraction)



Positive prompt photon v_2 above QGP plasma frequency ω_p

⇨ Refractive index is based on HTL results; correction around T_c for more v_2?

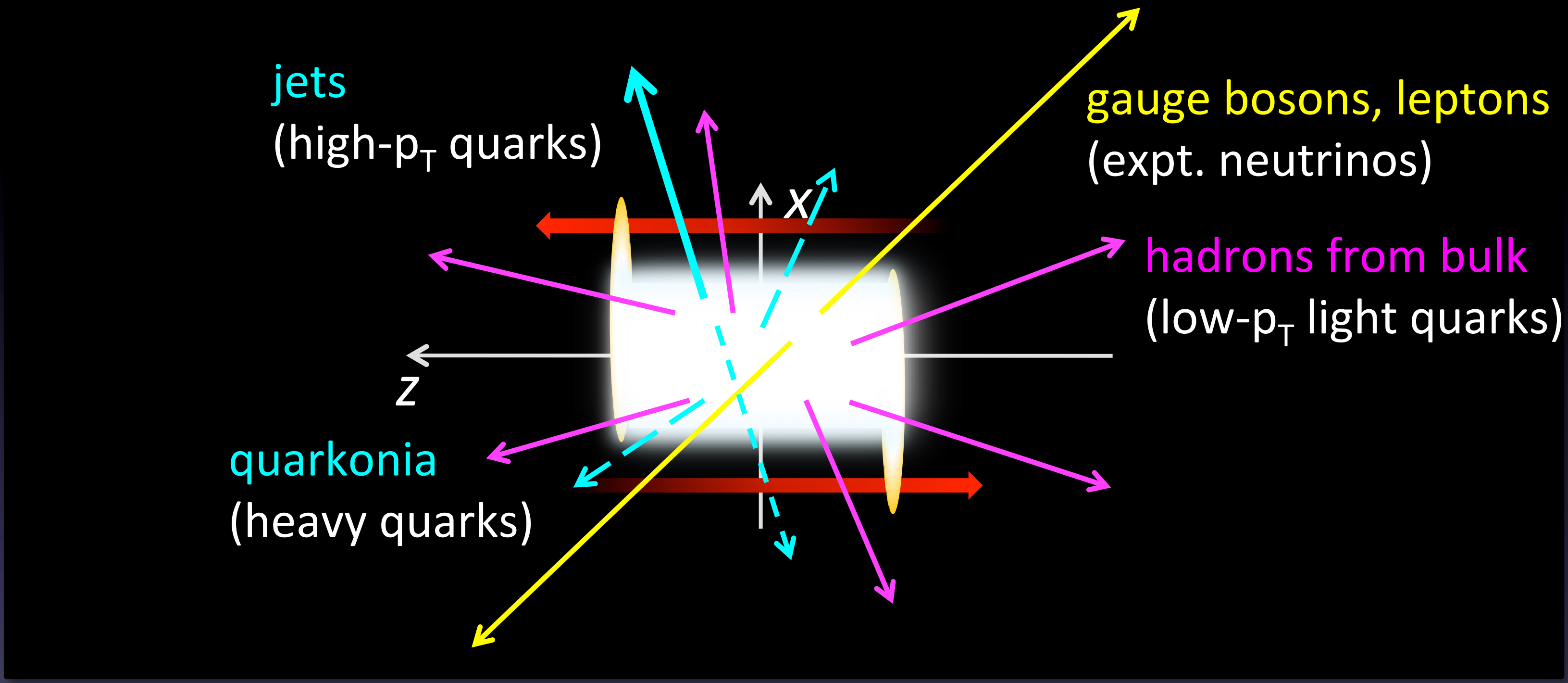
Ultra-low v_2 provides constraints on ω_p

The end

- Gracias por su atención!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/

Introduction

- What do heavy-ion observables tell us about QGP?



Electroweak probes: ⇨ EW transparency
Jet quenching, heavy quarks: ⇨ color opaqueness
Hydrodynamic medium: ⇨ strong coupling

Introduction

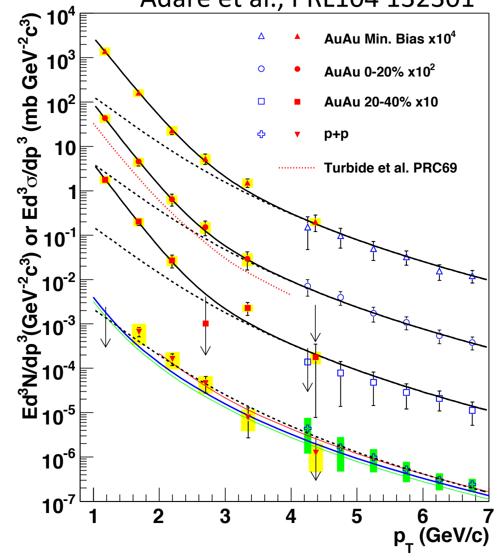
- Direct photons are informative

- Transverse momentum spectra

Thermal photon slope T = 221 ± 38 MeV

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

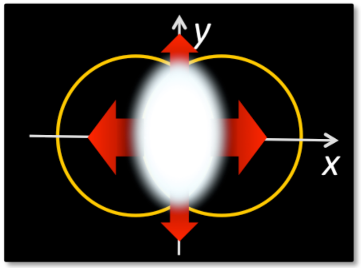
Adare et al., PRL104 132301



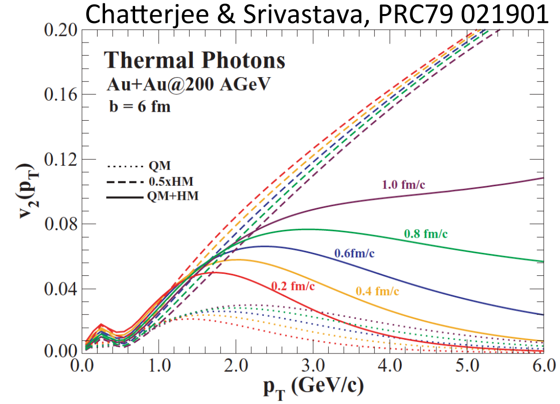
- Elliptic flow v_2 – azimuthal momentum anisotropy

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

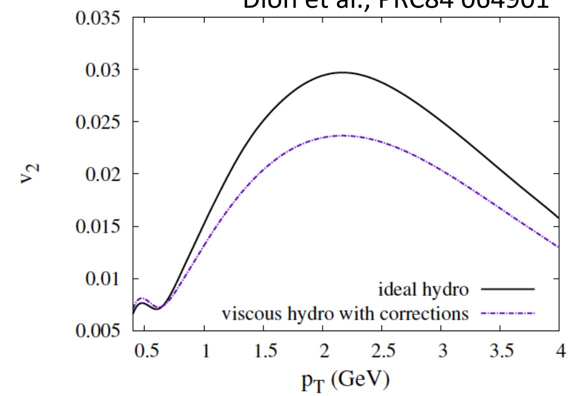
⇨ Initial time, viscosity, etc …



Chatterjee & Srivastava, PRC79 021901

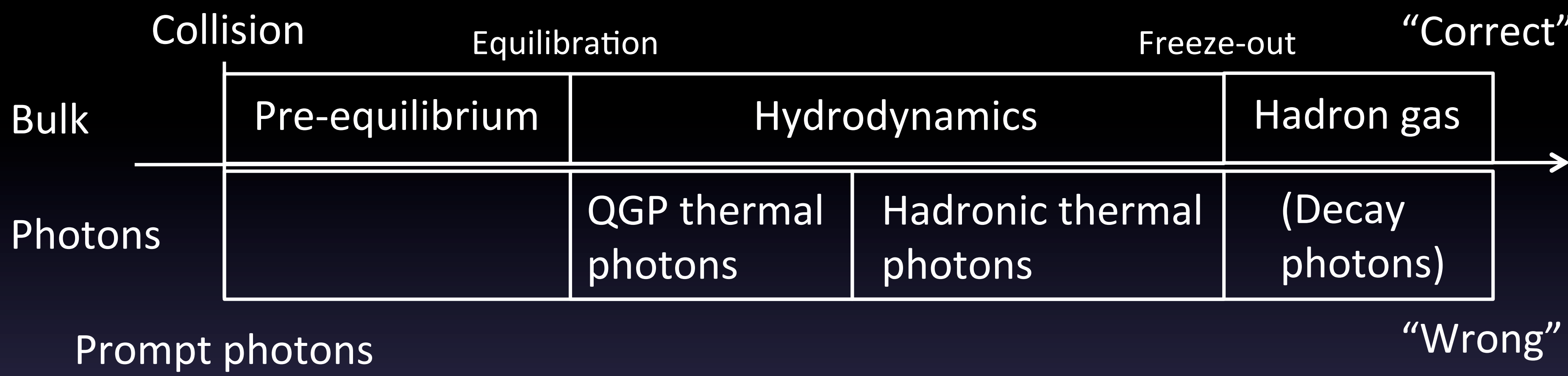


Dion et al., PRC84 064901



Photon v_n puzzle

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



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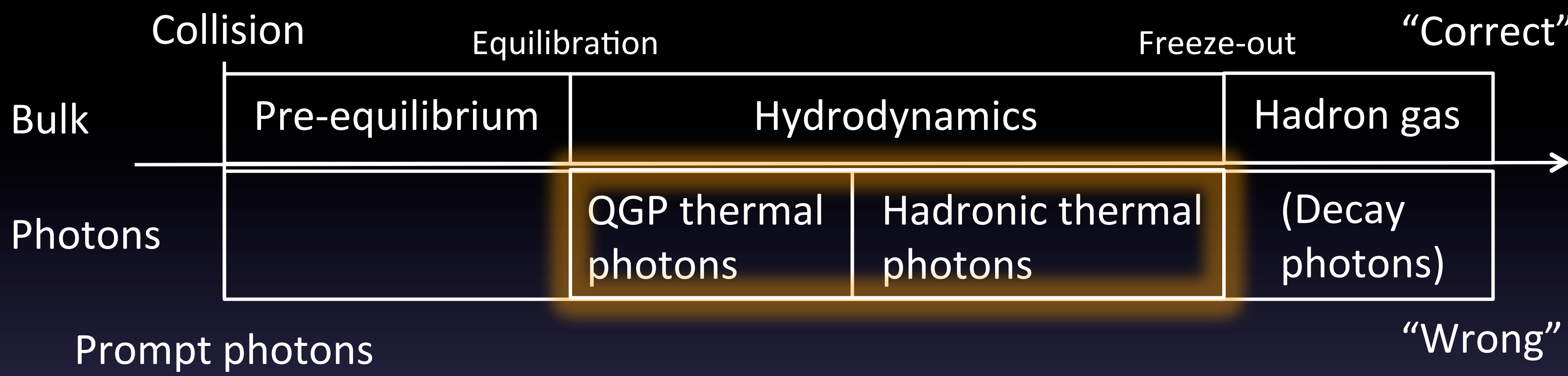

- Thermal photon emission/v_n estimate needs modification

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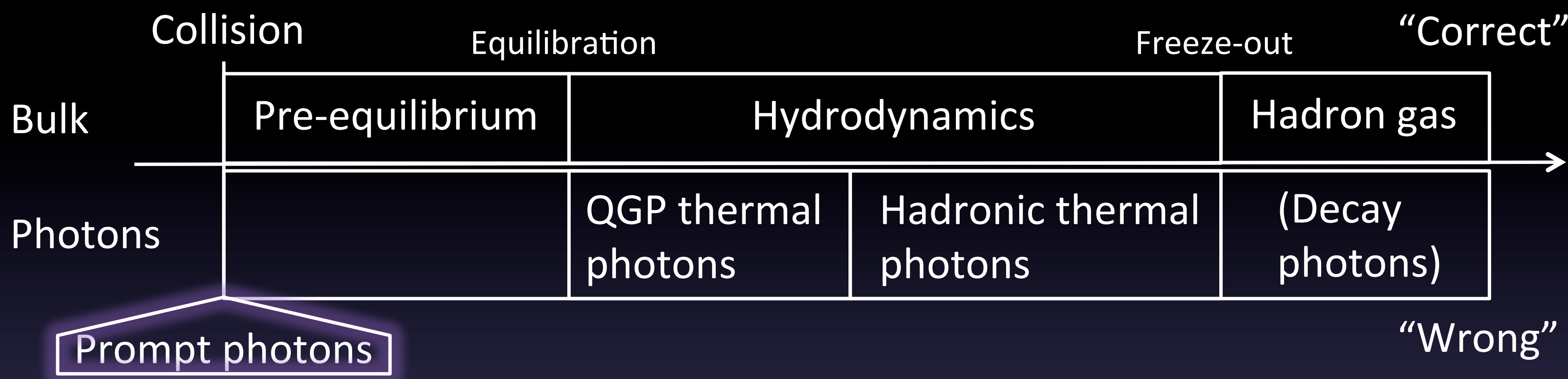

- Thermal photon emission/v_n estimate needs modification
- Prompt photon emission/v_n estimate needs modification

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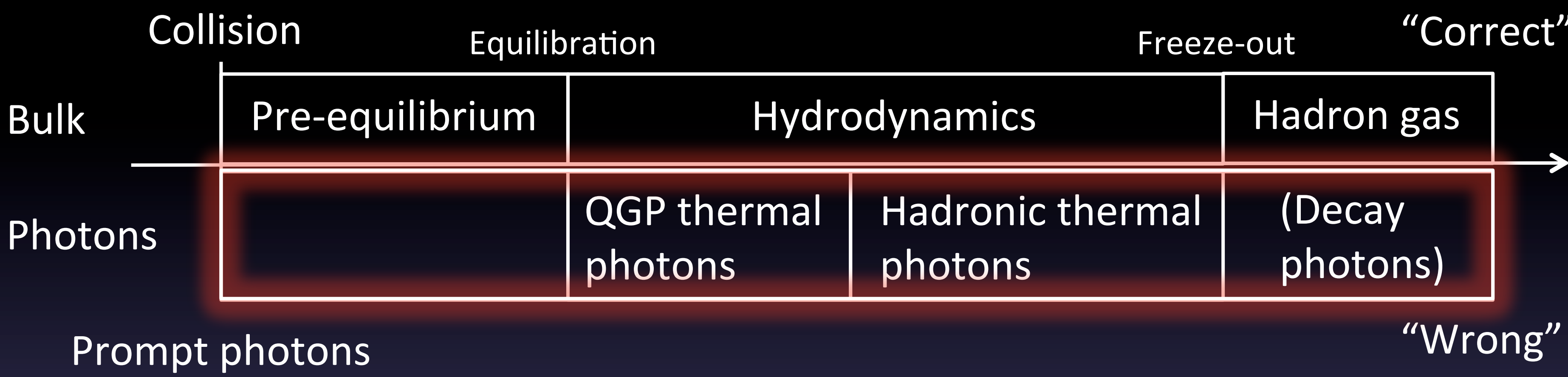

- Thermal photon emission/v_n estimate needs modification
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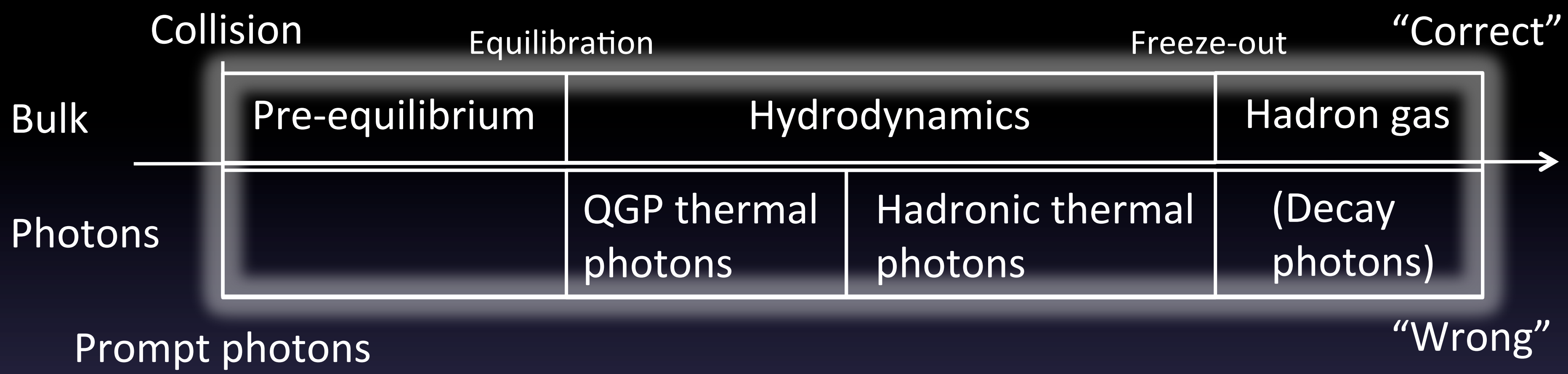
- Other sources of photons are not considered

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

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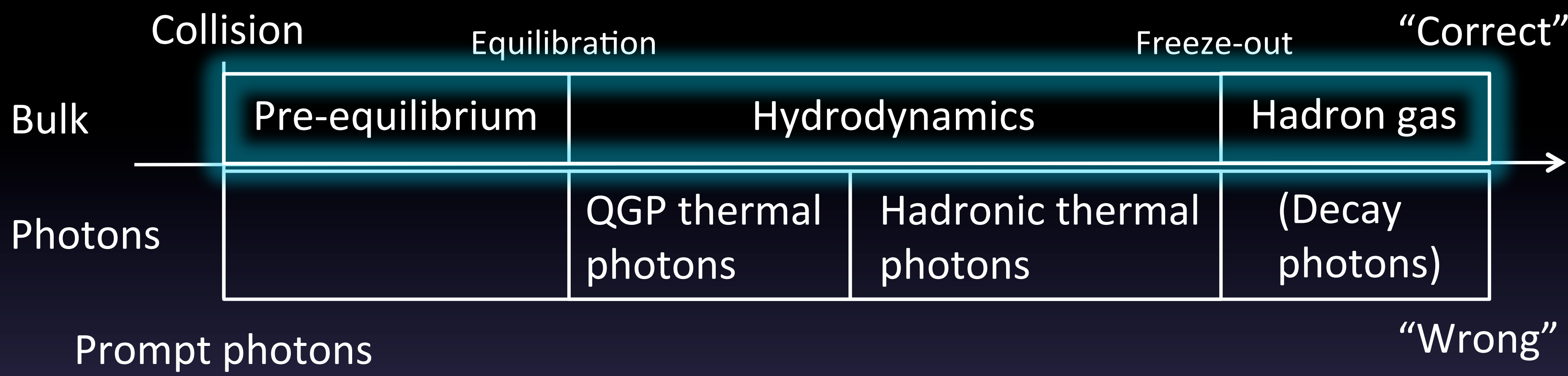

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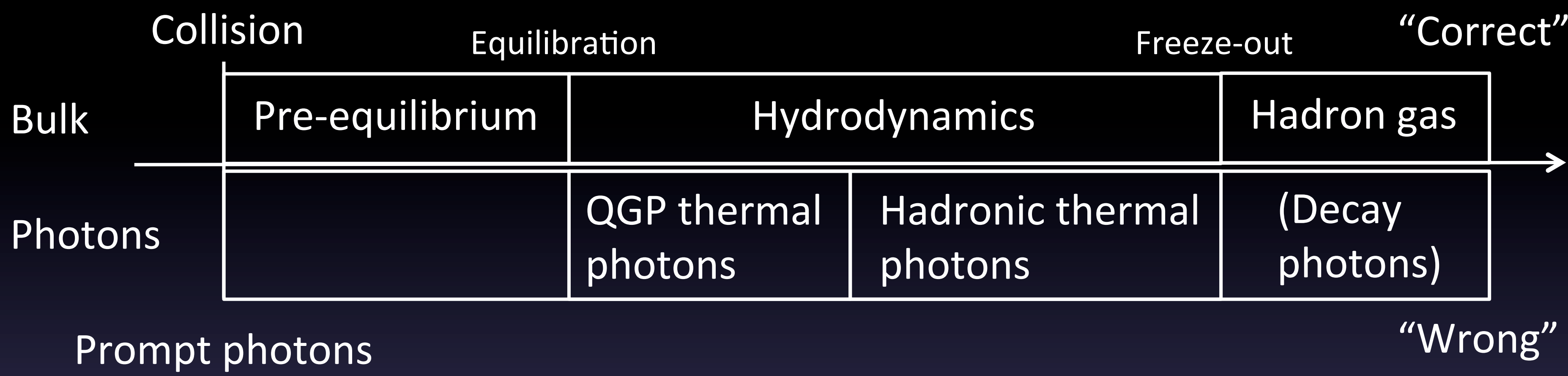

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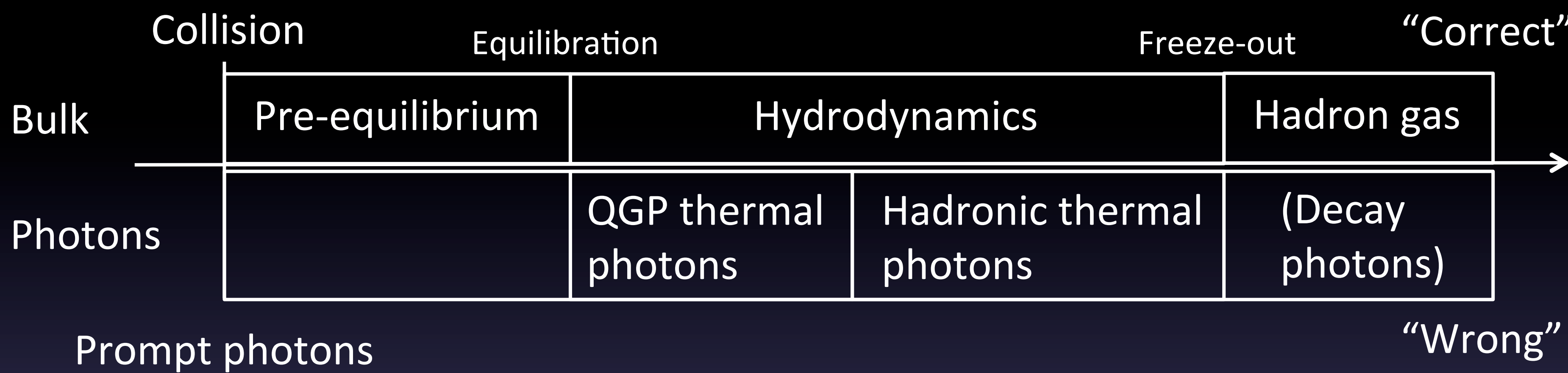

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This talk

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

Properties of bulk medium

- The system transits from CGC to QGP

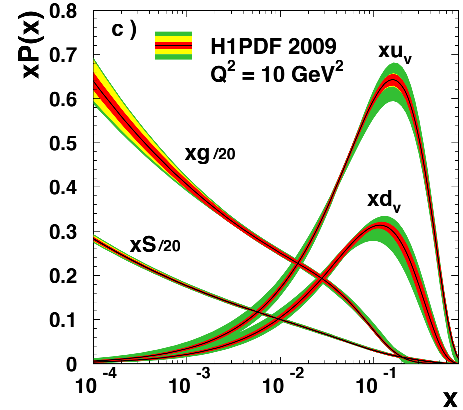
Color glass condensate (CGC) (τ < 0 fm/c)

- 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

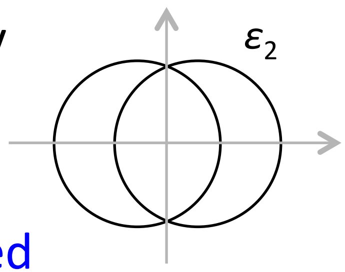
gluon gluon

H1 Collaboration (2009)

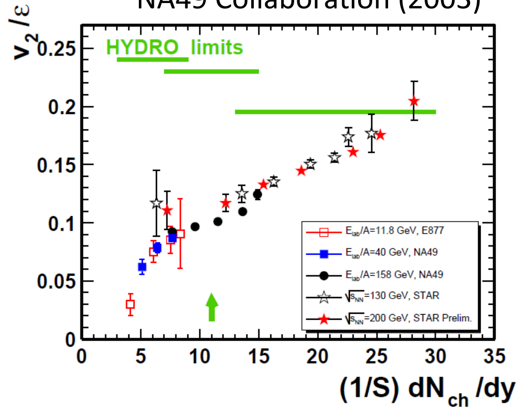


QGP/hadornic fluid (τ ~ 1-10 fm/c)

- 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



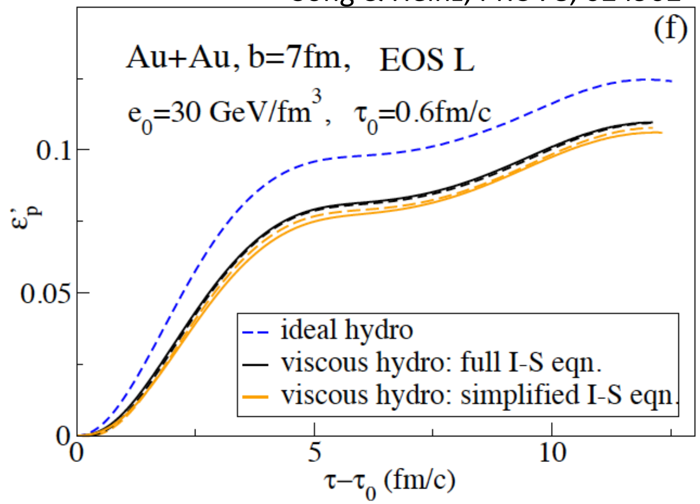
NA49 Collaboration (2003)



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 $N_f = 0$).

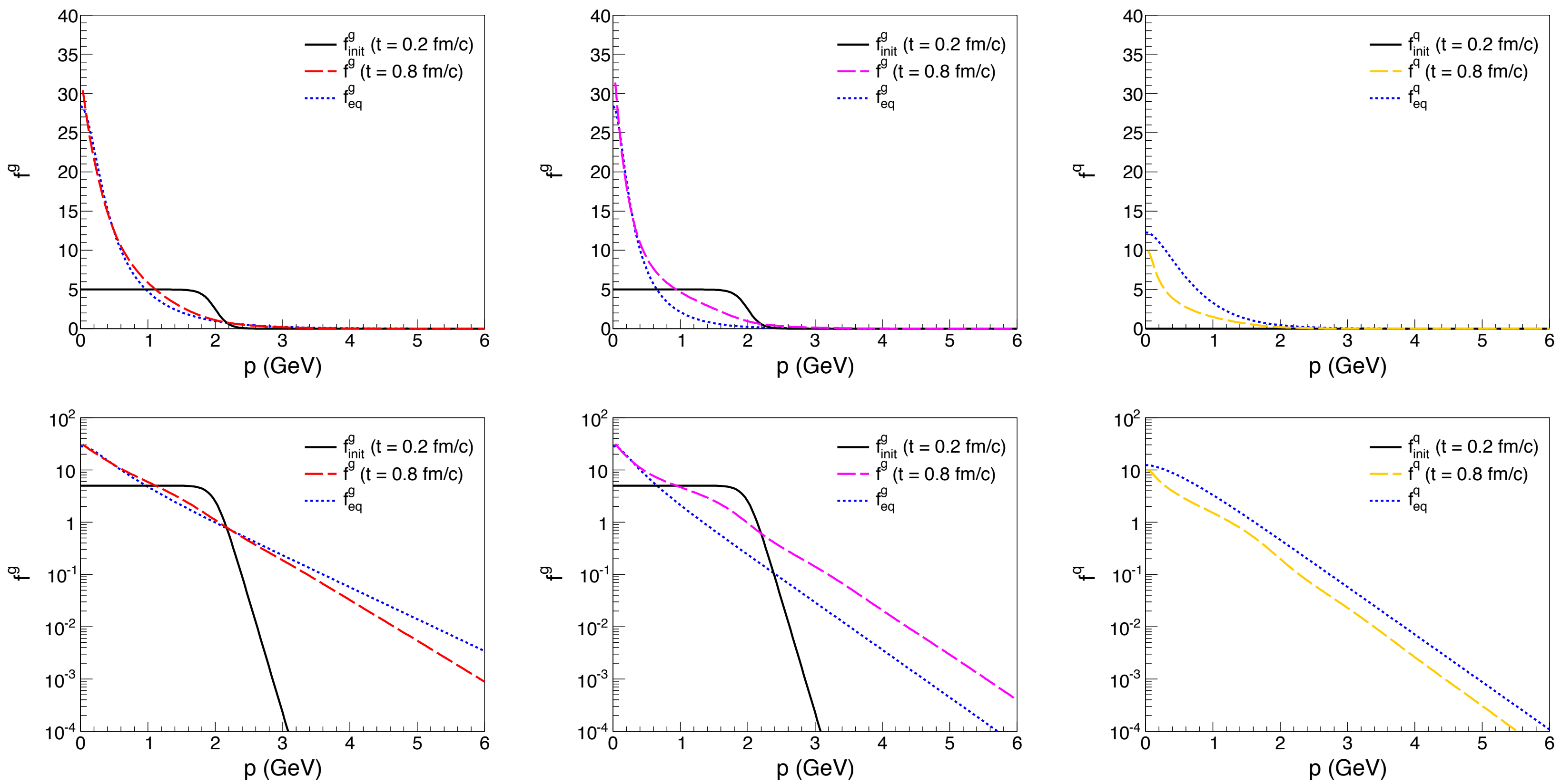
Also gluon overpopulation may increase the effective DoF.

	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]

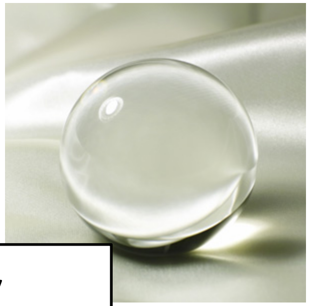
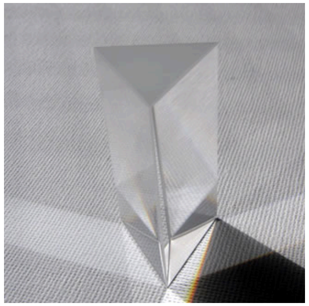


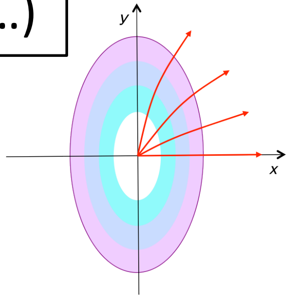
- Comparison of f_g (pure gauge), f_g (N_f = 3) and f_q (N_f = 3)

Optical aspects of QGP

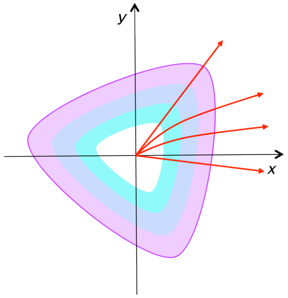
A lens and prism

- A transparent medium can be refractive
  - ⇨ A transparent QCD medium can work as a 4-dimensional lens
  - ⇨ Geometrical anisotropy (ε_2, ε_3, …) is directly mapped onto photon flow harmonics (v_2, v_3, …)
  - ⇨ I investigate the effects of medium refraction



Elliptic flow



Triangular flow

- Fermat's principle

$$\frac{d^2x}{d\tau} = \frac{1}{2}\frac{dn^2}{dx}, \quad \frac{d^2y}{d\tau} = \frac{1}{2}\frac{dn^2}{dy}$$

  - ⇨ The path of a ray is determined by the gradient in refractive index *n*

Optical aspects of QGP

A model for the refractive index

- Hard thermal loop estimations imply

$$n^2(T,\omega) = 1 - \frac{\omega_p^2(T)}{\omega^2}$$

Parameterized as
$$\omega_p^2(T) = a^2 T^2$$

Doppler effects (due to flow)
$$\omega = \frac{\omega_0}{\gamma(1+\beta\cos\Delta\phi)}$$

This is a model – one may find, e.g., a pseudo critical behavior

- Speed of light in the plasma

Phase velocity: $v_{\mathrm{ph}} = \frac{1}{n} > 1$

Refraction in the medium

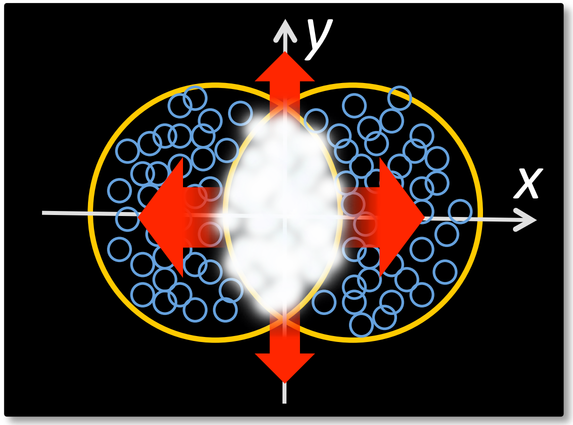
Group velocity: $v_{\mathrm{g}} = \frac{\partial \omega}{\partial k} = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} < 1$

Causality is not violated

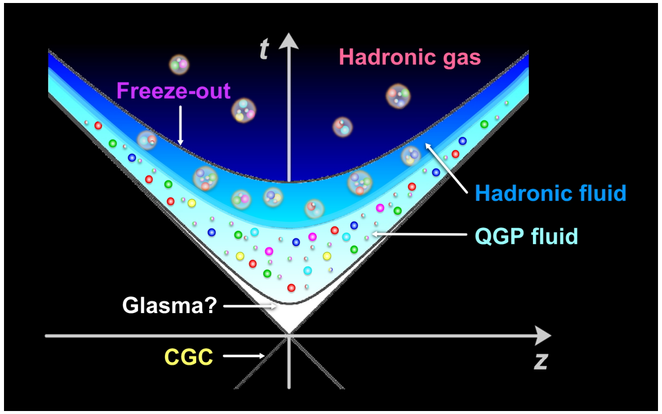
QGP medium

- Scales of relevance

Size of the medium ~ 10 fm   Lifetime of the medium ~ 10 fm/c



Comparable



Dynamical evolution should be taken into account in addition to inhomogeneous geometry

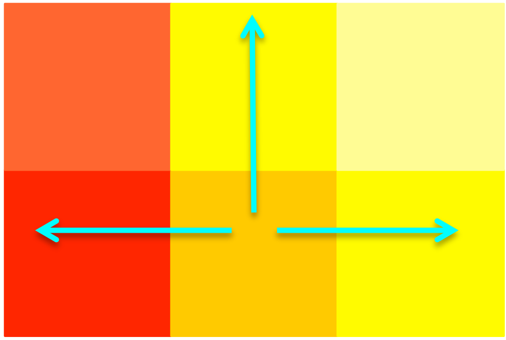
⇨ (2+1)-dimensional hydrodynamic model is used

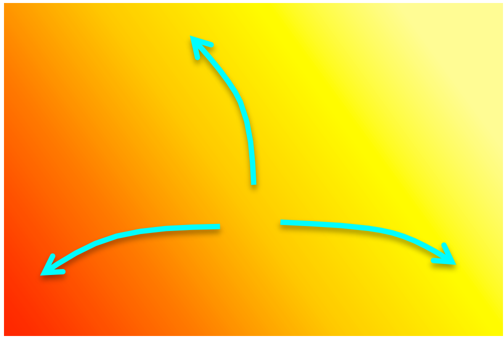
+ Monte-Carlo Glauber initial conditions
+ Lattice QCD equation of state

Numerical estimation

- Hydrodynamic lattice effects

▸ Coarse grid distribution vs. smoothed distribution





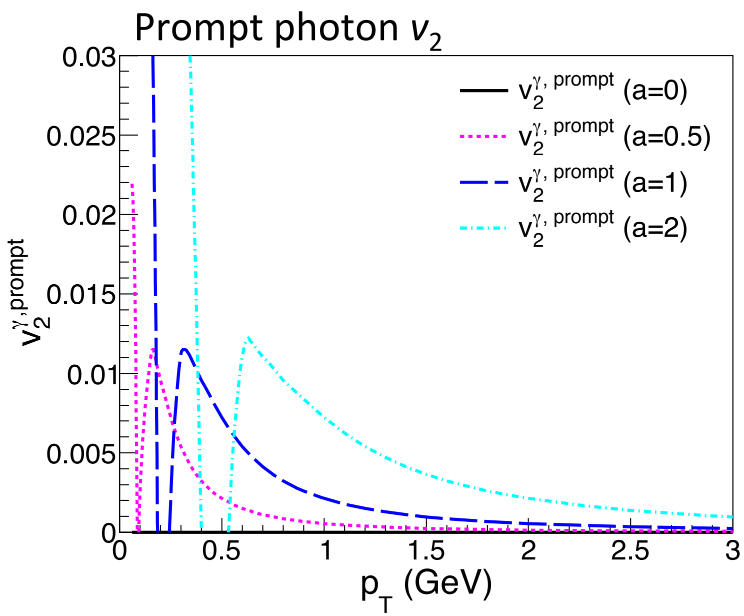
⇨ The coarse grid creates artificial "free paths" for the ray traveling perpendicular to the boundary

⇨ v_n with the same symmetry as the lattice can be unphysically enhanced, regardless of the size of the lattice

⇨ I smooth the gradient field of the refractive index with bilinear interpolation method

Results

- Prompt photon flow harmonics (= 0 if no refraction)



(I) Positive prompt photon v_2 is generated for non-absorptive region

Not large enough to explain the large direct photon v_2

- Thermal photons are necessary
- Pseudo-critical behavior of refractive index?

(II) Negative prompt photon v_2 in ultra-low momentum region

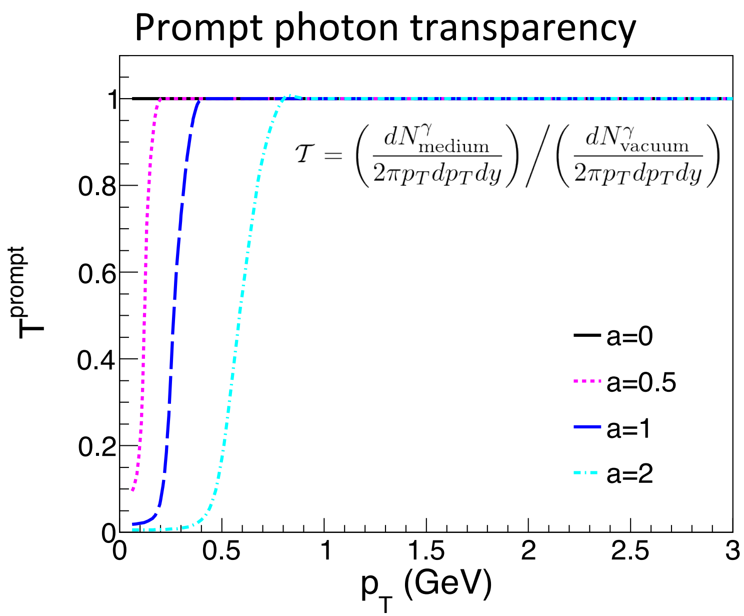
Absorptive region with $n^2 < 0$ forms a "dark core"

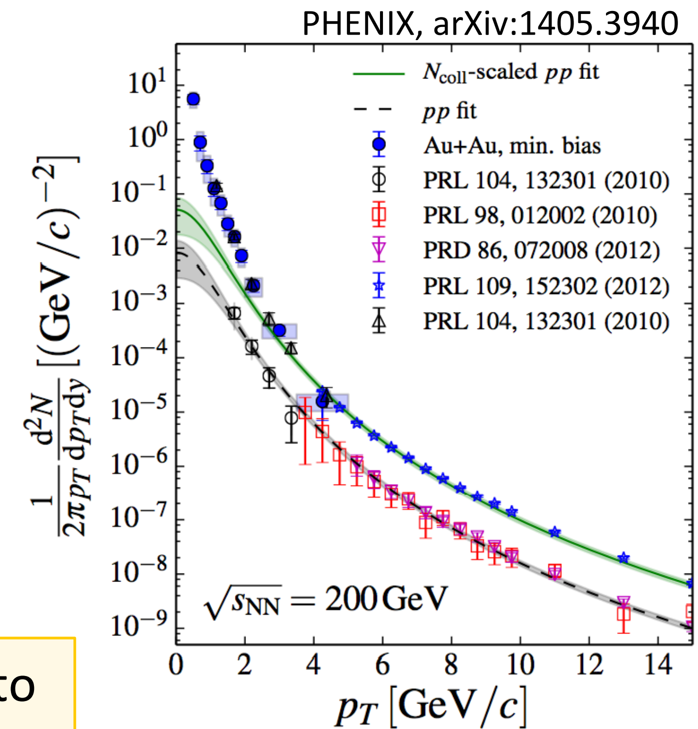
(III) Positive prompt photon v_2 near p_T = 0

Semi-opaque medium: easier to come out of minor axis

Results

- Prompt photon transparency





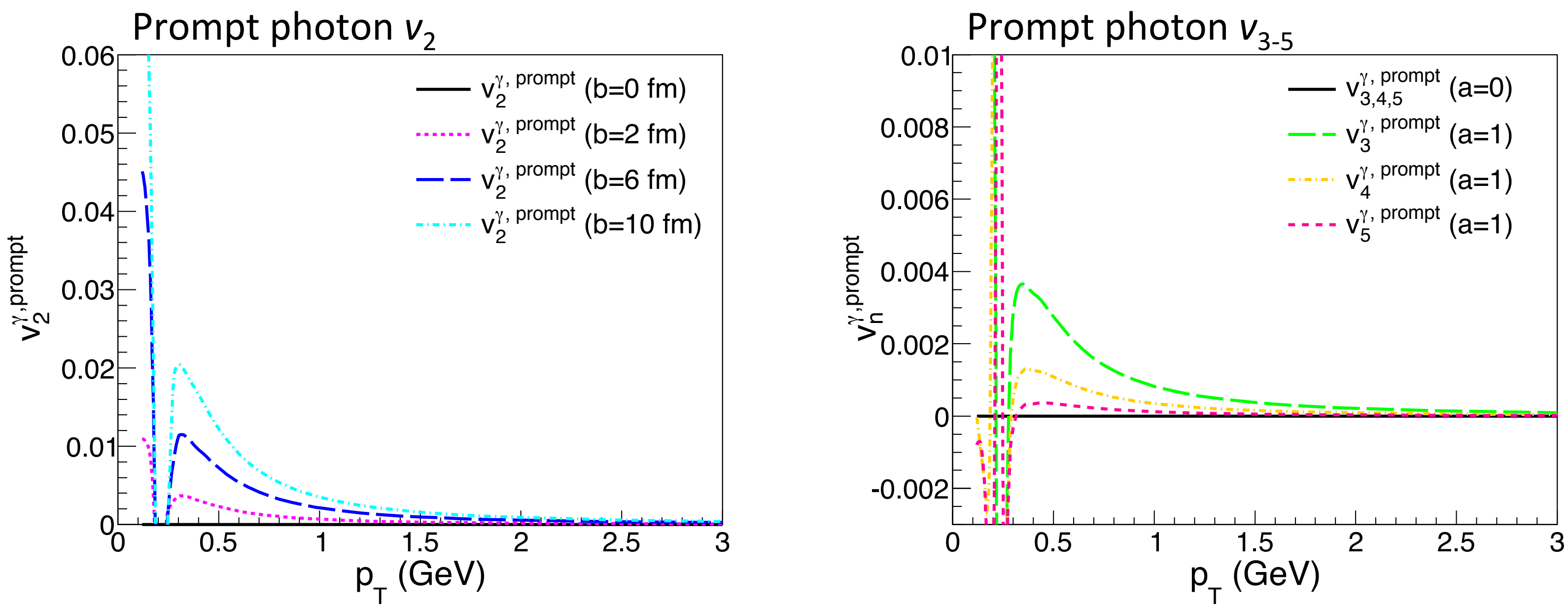
The transparency decreases below ω_p due to imaginary refractive index

Experimental data seem to show no sudden reduction above 0.5 GeV

⇨ a < 1-2 is preferred; constraint on QGP plasma frequency?

Results

- Prompt photon flow harmonics (II)



Prompt photon v_2 is larger for peripheral collisions

Prompt photon $v_{3\text{-}5}$ is positive; smaller for higher-order harmonics

ε_2 = 0, 0.074, 0.202 and 0.395 for b = 0, 2, 6 and 10 fm

Caution: smoothed initial conditions