Red hydrodynamic model of quark matter in nuclear collisions

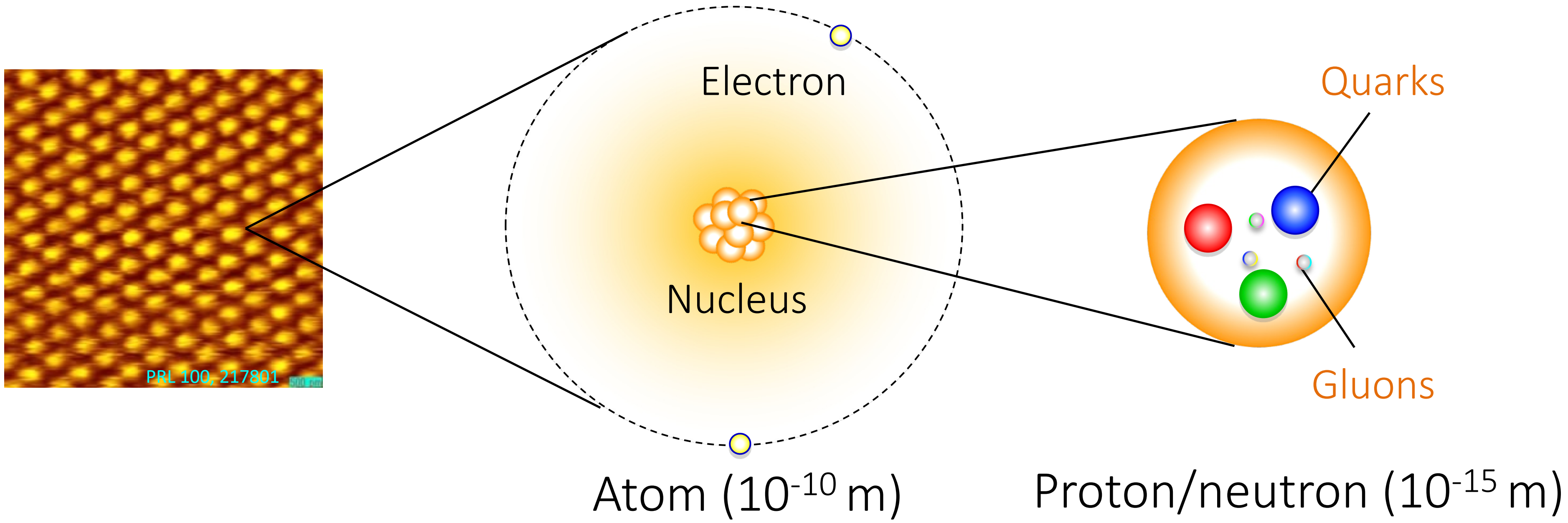
Akihiko Monnai (Osaka Institute of Technology)

AM, arXiv:2301.00588 [nucl-th]

Interdisciplinary Science Conference in Okinawa (ISCO 2023)
1st March 2023, OIST, Japan

Introduction

- The subatomic world



Matter is composed of elementary particles called quarks, bound by the strong force mediated by gluons

Introduction

■ Phases of matter

Ice (solid phase)

Water (liquid phase)

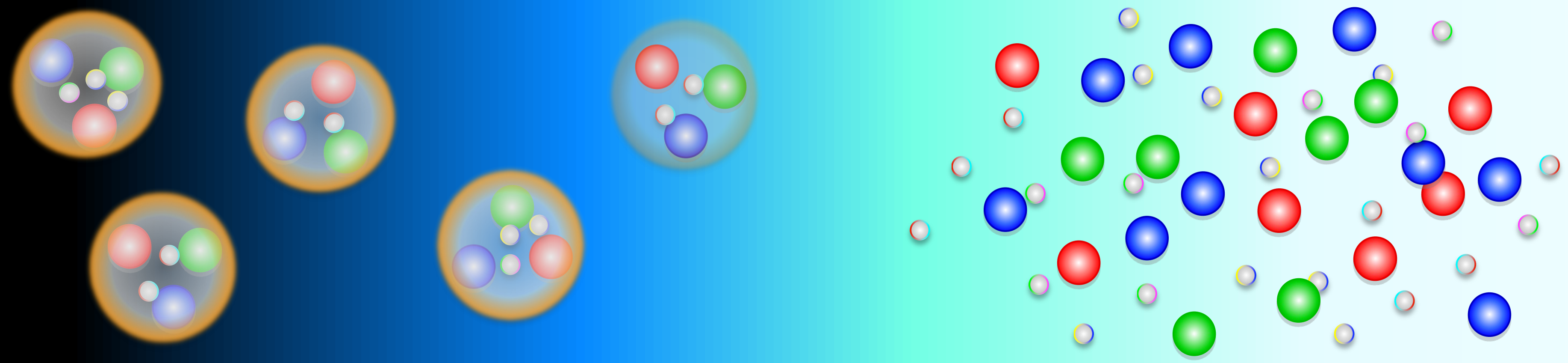
Vapor (gas phase)

Matter takes different states (phases) depending on temperature, pressure, etc.

A change from one phase to another is called phase transition

Introduction

- Phase transition of quarks

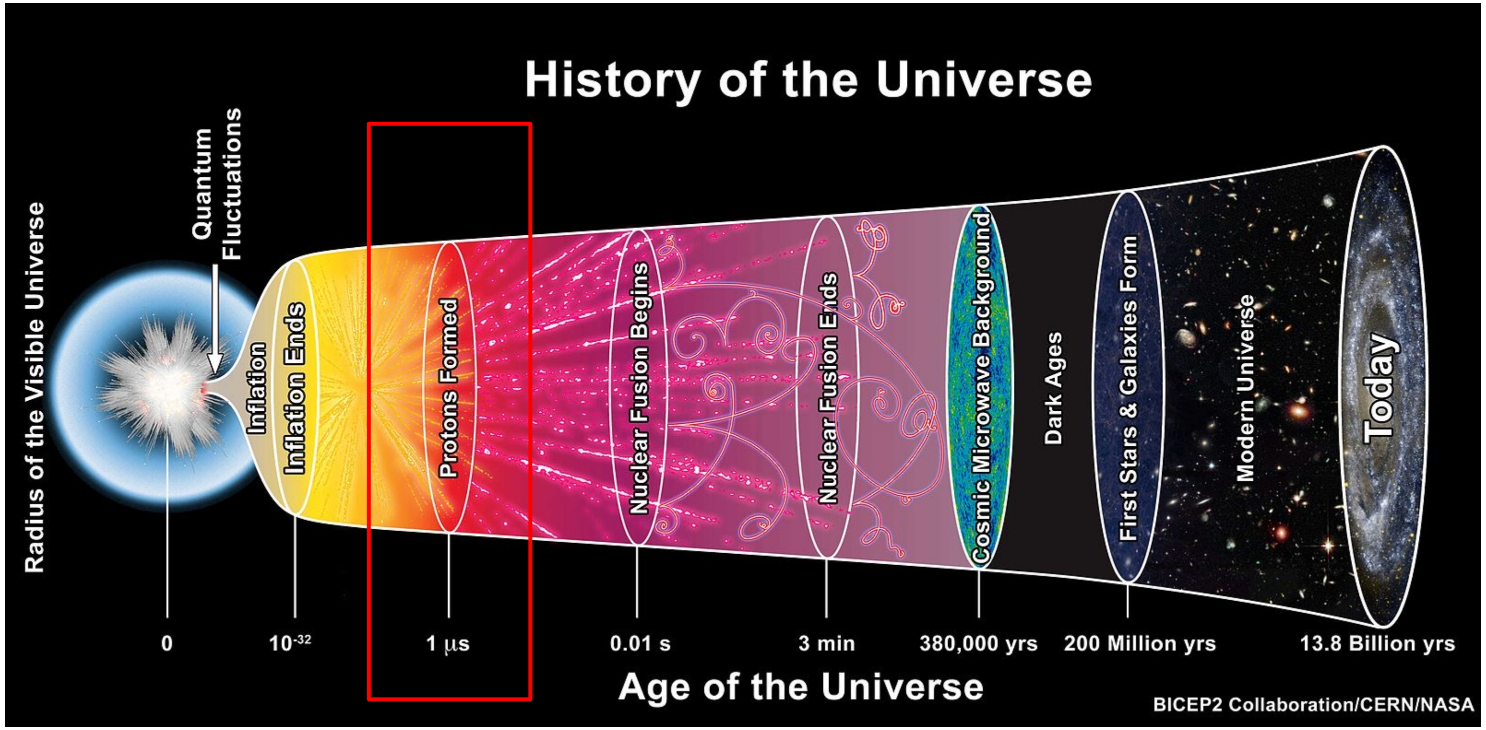


Protons and neutrons "melt" into quark-gluon plasma (QGP) above around 2 trillion degrees Kelvin

Introduction

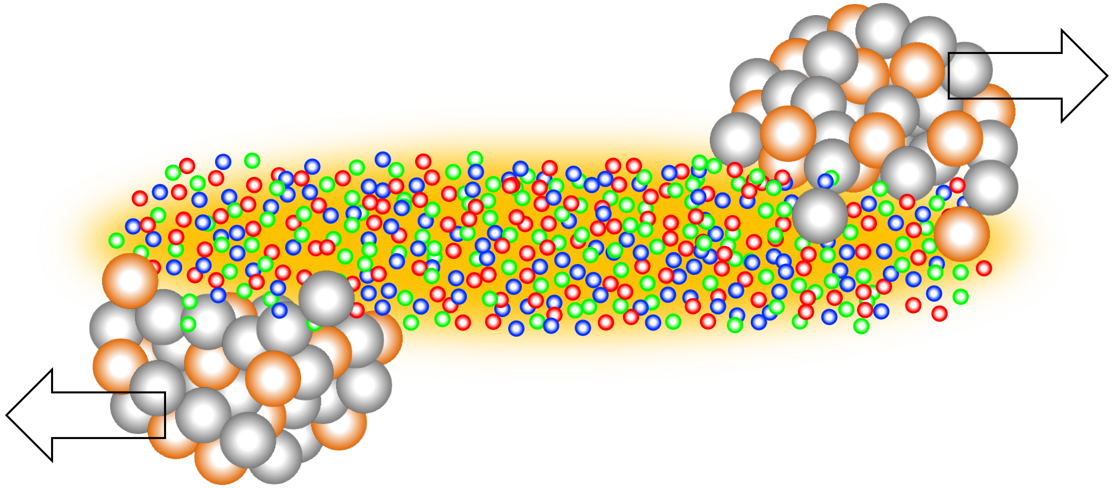
- Where is the quark-gluon plasma?

  The QGP had filled the Universe around 10^{-5} seconds after the Big Bang



Introduction

- How to make the quark-gluon plasma on earth



Smash two big nuclei (such as gold or lead) almost at the speed of light

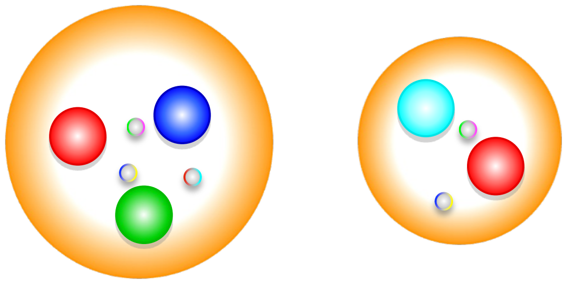
BNL Relativistic Heavy Ion Collider (2000-)
CERN Large Hadron Collider (2010-)

Introduction

■ What can be observed in experiments?

- Hadrons

  Quarks are frozen back into "quark ice" called hadrons (include protons and neutrons)



- Photons

  "Particles of light" are also produced

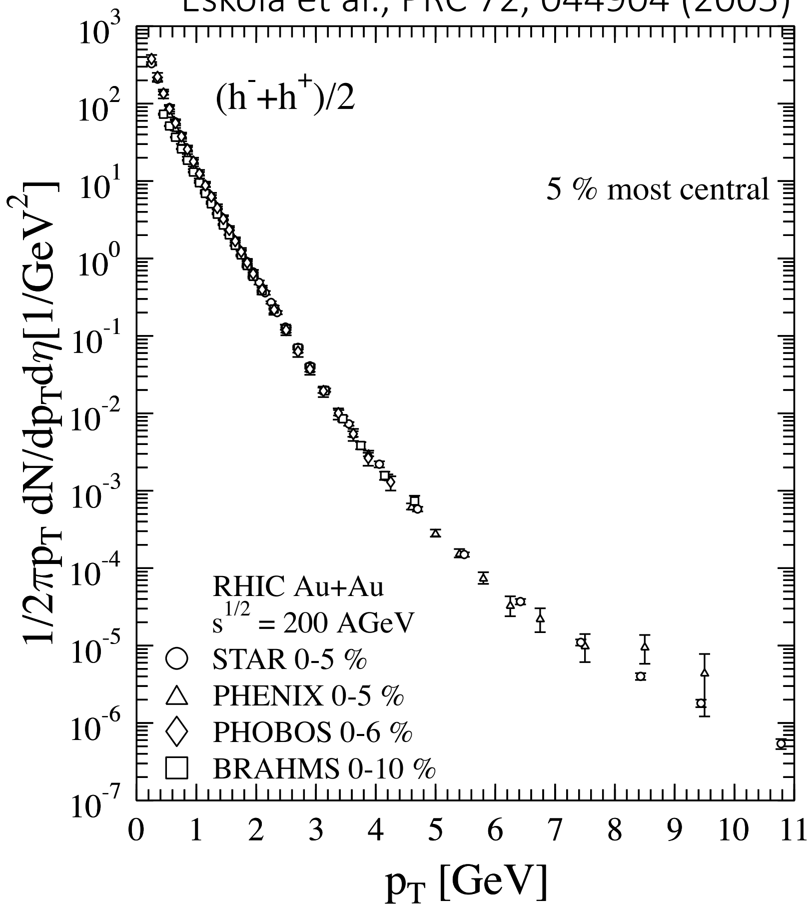
- Charged leptons, weak bosons, etc.

Introduction

$1\ \text{GeV} \simeq 1.6\times10^{-10}\text{J}$
$1\ \text{GeV}/c \simeq 5.3\times10^{-19}\text{kg}\cdot\text{m/s}$

- Interpretation of the momentum distribution

Eskola et al., PRC 72, 044904 (2005)



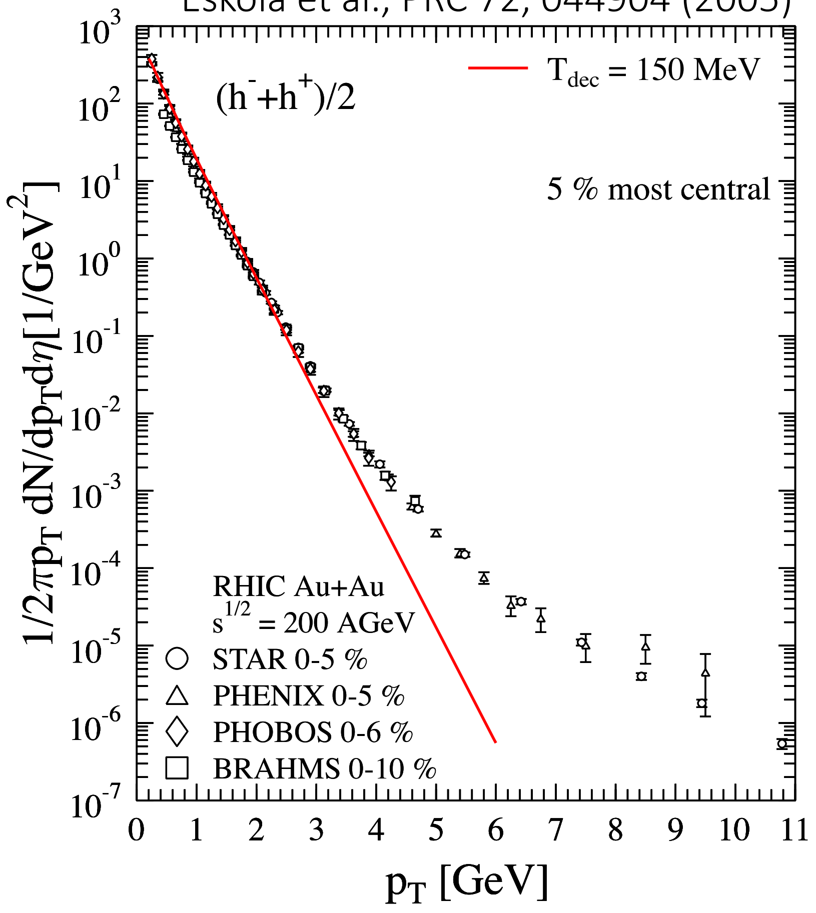
Introduction

$1\ \mathrm{GeV} \simeq 1.6\times10^{-10}\mathrm{J}$

$1\ \mathrm{GeV}/c \simeq 5.3\times10^{-19}\mathrm{kg}\cdot\mathrm{m/s}$

■ Interpretation of the momentum distribution

Eskola et al., PRC 72, 044904 (2005)



Low momentum region (< 2-4 GeV)

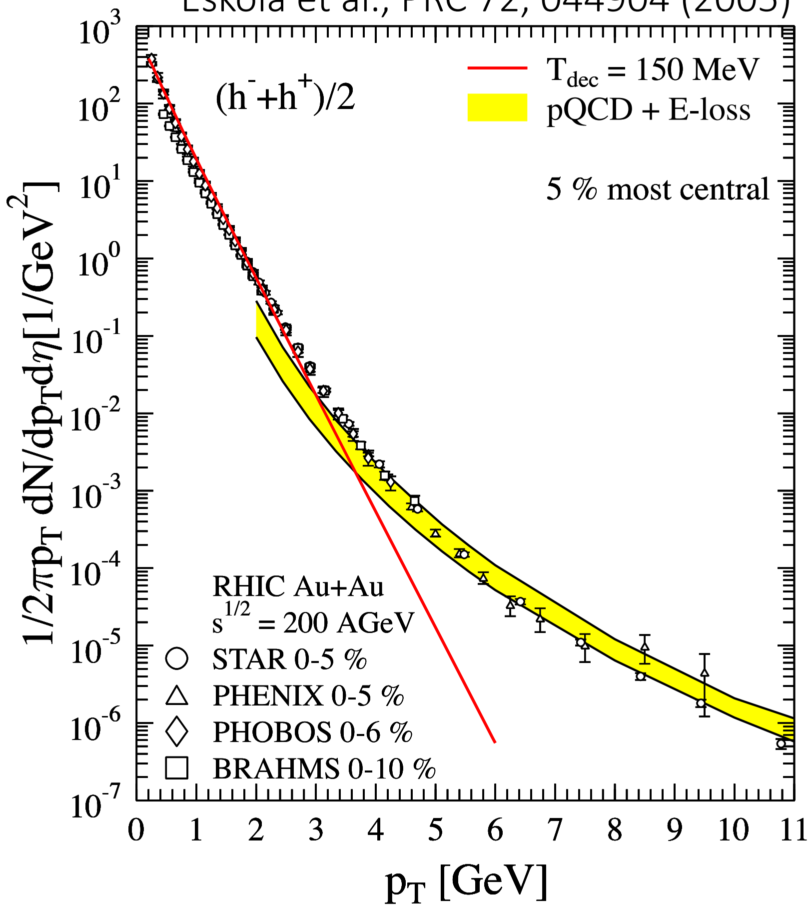
Hydrodynamic model (strongly-coupled)

Introduction

$1\ \mathrm{GeV} \simeq 1.6\times10^{-10}\mathrm{J}$
$1\ \mathrm{GeV}/c \simeq 5.3\times10^{-19}\mathrm{kg}\cdot\mathrm{m/s}$

- Interpretation of the momentum distribution

Eskola et al., PRC 72, 044904 (2005)



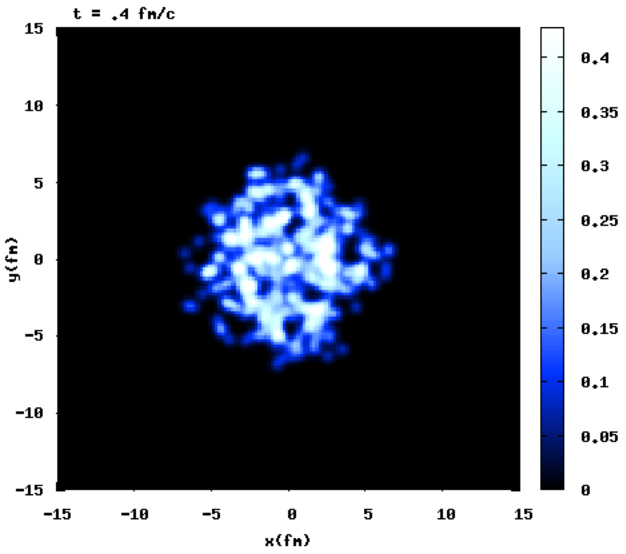
Low momentum region (< 2-4 GeV)
Hydrodynamic model (strongly-coupled)

+

Mid-high momentum region (> 4-5 GeV)
perturbative QCD (weakly-coupled)

Motivation

- Relativistic hydrodynamic model



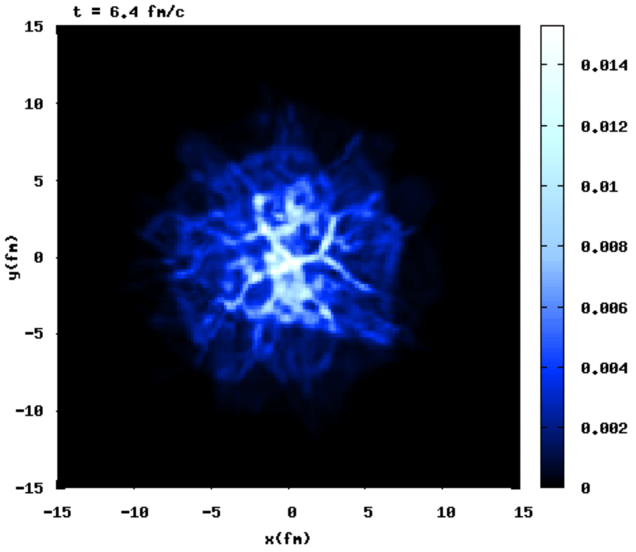
Equation of state

*A relation among state variables such as pressure, temperature, etc.

Initial condition → Hydro evolution → Hadronic decay → Observa-bles

Motivation

- Relativistic hydrodynamic model



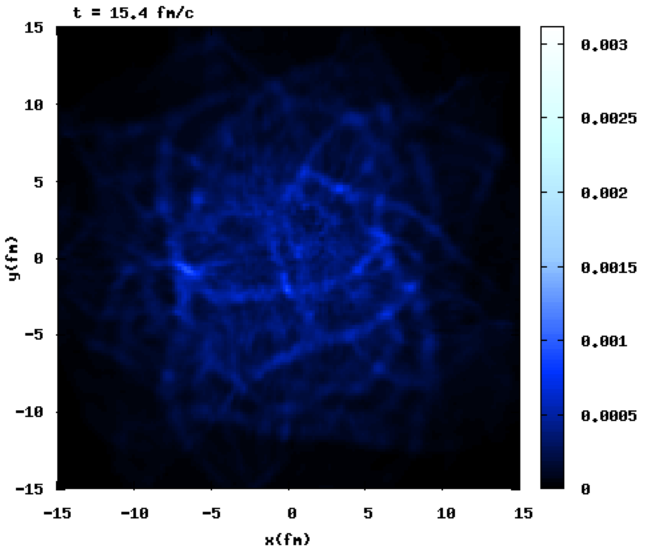
Equation of state

*A relation among state variables such as pressure, temperature, etc.

Initial condition → Hydro evolution → Hadronic decay → Observa-bles

Motivation

- Relativistic hydrodynamic model



Equation of state

*A relation among state variables such as pressure, temperature, etc.

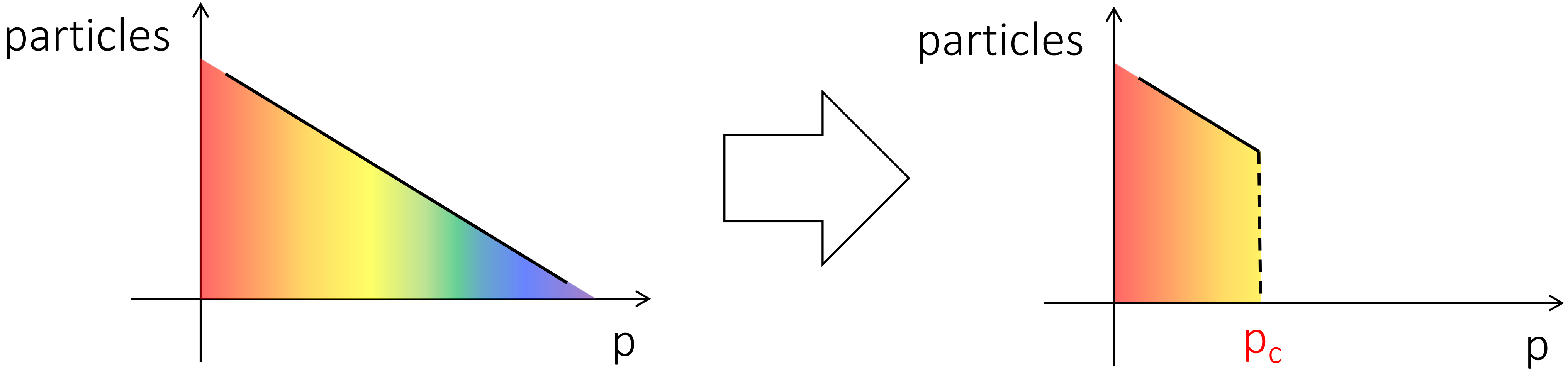
Initial condition → Hydro evolution → Hadronic decay → Observa-bles

A caveat of the conventional model:
Equation of state & particle production include the contribution of high-momentum particles

This work

- “Red” hydrodynamic model

*low momentum = long wavelength = “red”

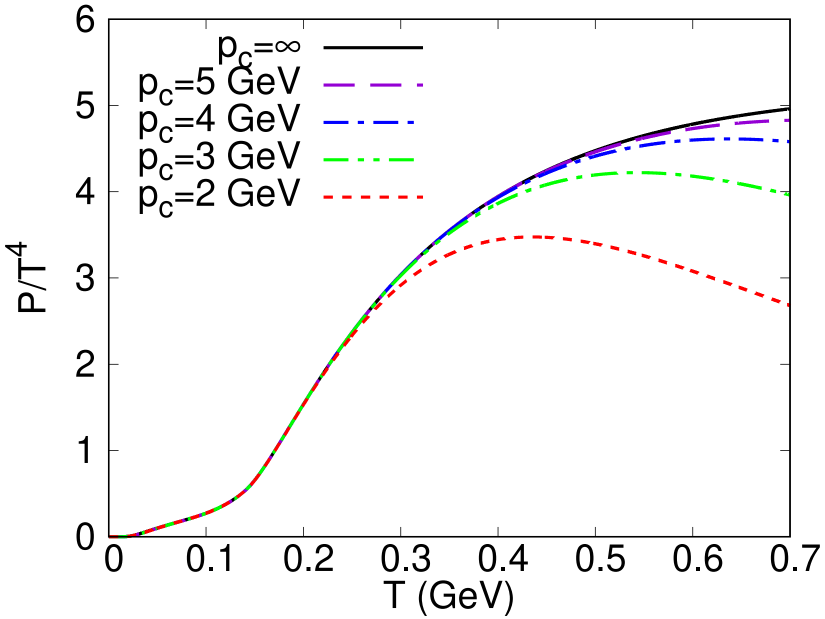


We introduce an upper limit (p_c) for the momenta of strongly-coupled components

Equation of state

$0.1\ \mathrm{GeV} \simeq 1.16\times10^{12}\mathrm{K}$

- Results



Pressure: $P = \pm T \sum_i \int_0^{p_c} \frac{g_i d^3p}{(2\pi)^3} \ln\left[1 \pm \exp\left(-\frac{E_i}{T}\right)\right]$

i: index for particle species

Hadronic phase …

QGP phase …

Smoothly connect the pressures of the 2 phases

Effects of momentum cutoff is larger at higher temperatures; mostly negligible in the hadronic phase

Hydrodynamic evolution

- (2+1)-dimensional inviscid model

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

Initial condition: Monte-Carlo Glauber model (event-averaged)
2.76 TeV Pb+Pb collisions at b = 4.6 fm (~ 0-20%)

Initial time: τ_{ini} = 0.4 fm/c

Freezeout temperature: T_f = 140 MeV

Thermal photon estimated down to: T_{ph} = 110 MeV

Hadronic decay: Sollfrank, Koch, and Heinz, Phys. Lett. B 252, 256 (1990)

Hydrodynamic evolution

- (2+1)-dimensional inviscid model

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

Initial condition: Monte-Carlo Glauber model (event-averaged)
2.76 TeV Pb+Pb collisions at b = 4.6 fm (~ 0-20%)

Initial time: τ_{ini} = 0.4 fm/c

Freezeout temperature: T_f = 140 MeV

Thermal photon estimated down to: T_{ph} = 110 MeV

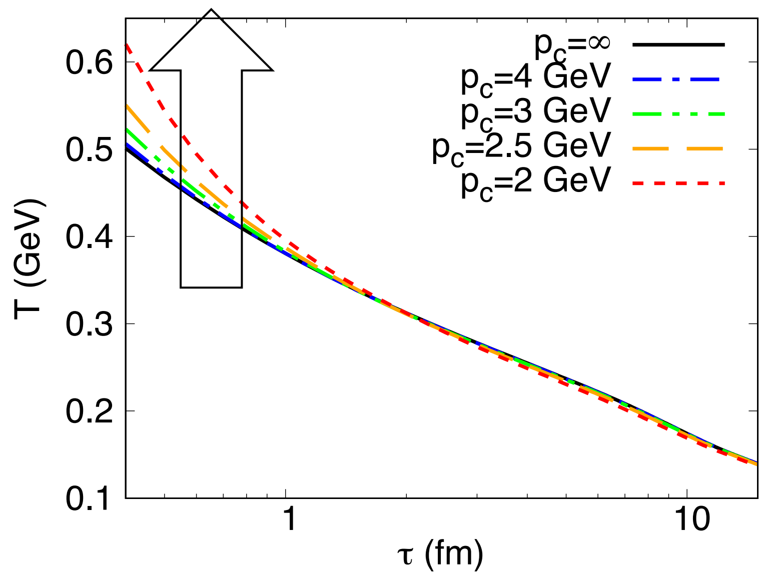
Hadronic decay: Sollfrank, Koch, and Heinz, Phys. Lett. B 252, 256 (1990)

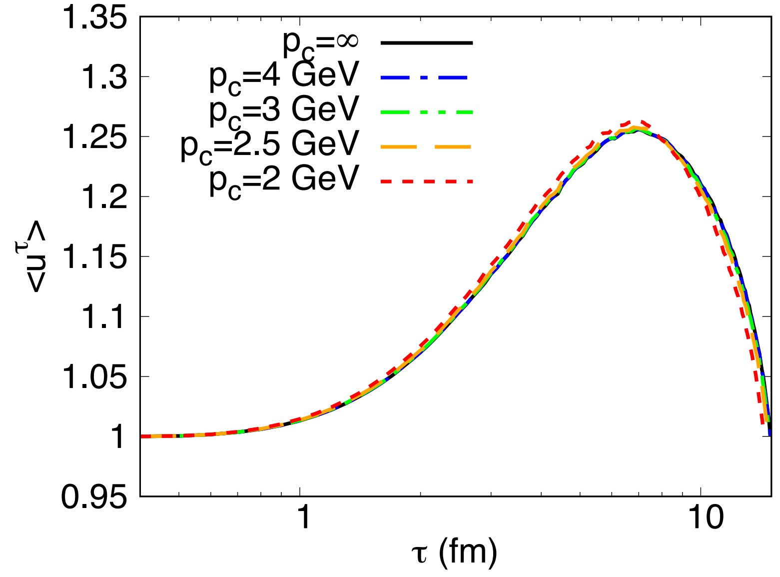
⇨ Simulations of nuclear collisions at the Large Hadron Collider

Hydrodynamic evolution

$1\ \mathrm{fm}/c \simeq 3.3\times10^{-24}\mathrm{s}$

- Numerical results



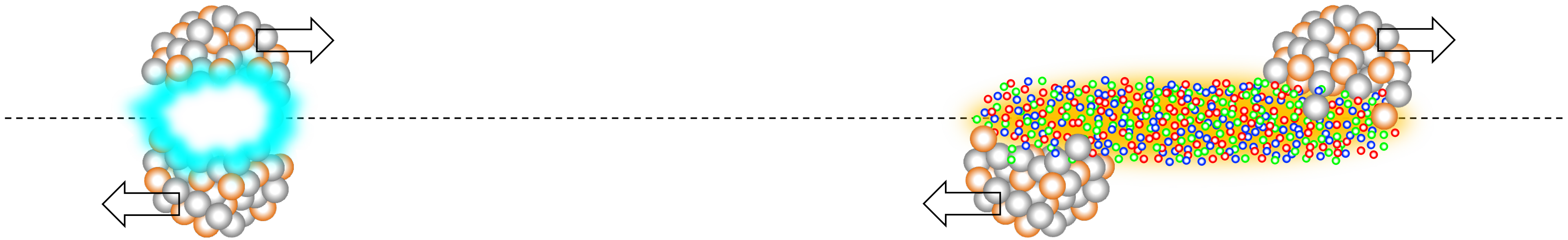


Initial temperature is higher with lower cutoff momentum; the flow development is mostly unaffected

Photons

Review: AM, Int. J. Mod. Phys. A 37(11n12), 2230006 (2022)

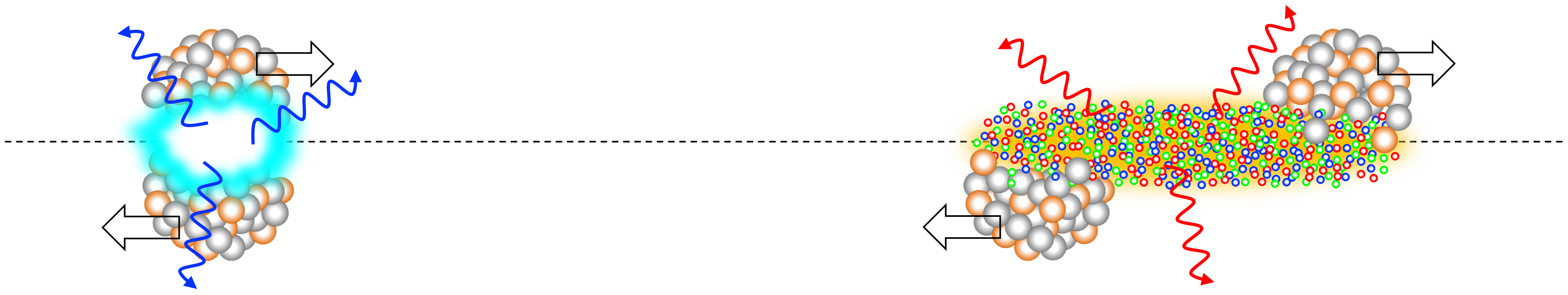
- Sources of direct photons (conventional)



Photons

Review: AM, Int. J. Mod. Phys. A 37(11n12), 2230006 (2022)

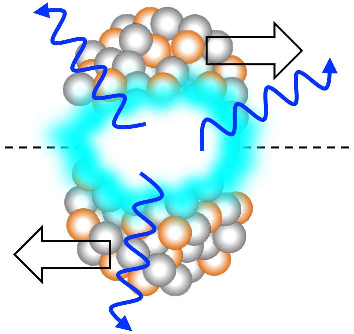
- Sources of direct photons (conventional)

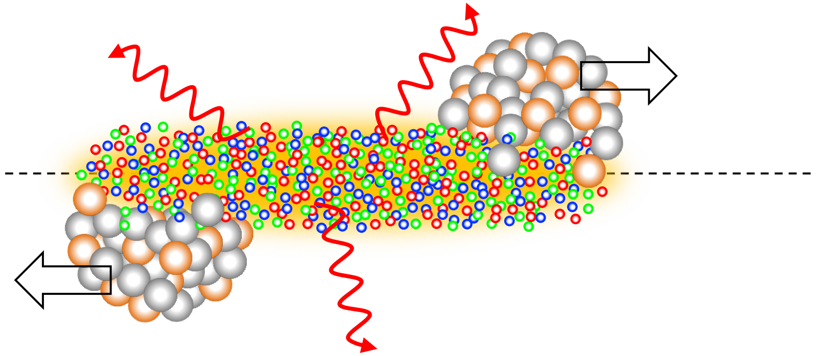


Photons

Review: AM, Int. J. Mod. Phys. A 37(11n12), 2230006 (2022)

- Sources of direct photons (conventional)

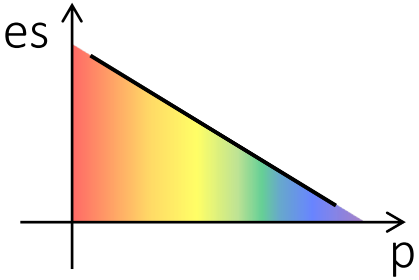




Prompt photons
produced at the collision

Turbide, Rapp and Gale, PRC 69, 014903
Heffernan, Hohler, and Rapp, PRC 91, 027902
Holt, Hohler, and Rapp, NPA 945, 1
Berges et. al., PRC 95, 054904 (2017)
Tanji and Venugopalan PRD 95, 094009 (2017)

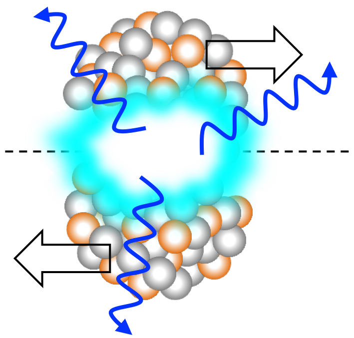
Thermal photons
produced from the medium

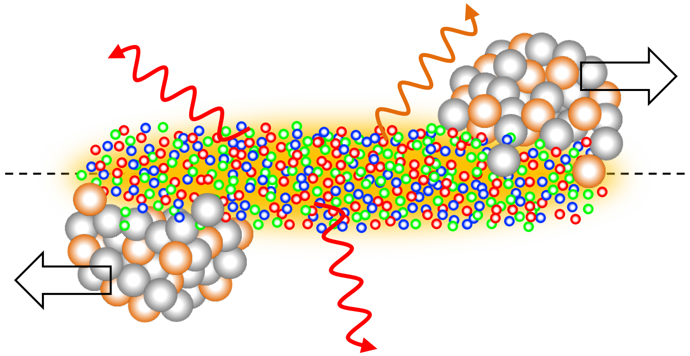


Photons

Review: AM, Int. J. Mod. Phys. A 37(11n12), 2230006 (2022)

- Sources of direct photons (this work)





Prompt photons

produced at the collision

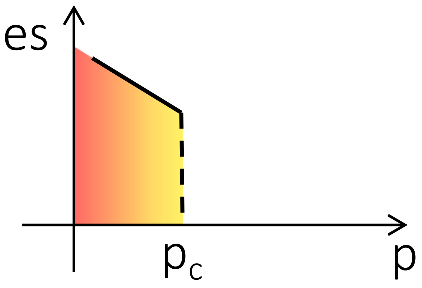
Thermal photons

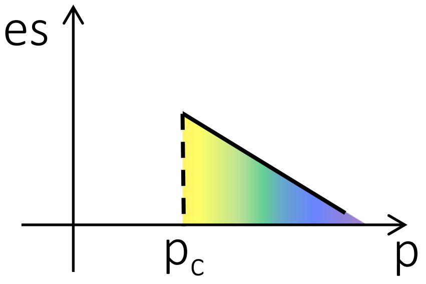
produced from the medium (low momentum only)

High p_T photons

produced from the non-thermal components

Turbide, Rapp and Gale, PRC 69, 014903
Heffernan, Hohler, and Rapp, PRC 91, 027902
Holt, Hohler, and Rapp, NPA 945, 1
Berges et. al., PRC 95, 054904 (2017)
Tanji and Venugopalan PRD 95, 094009 (2017)

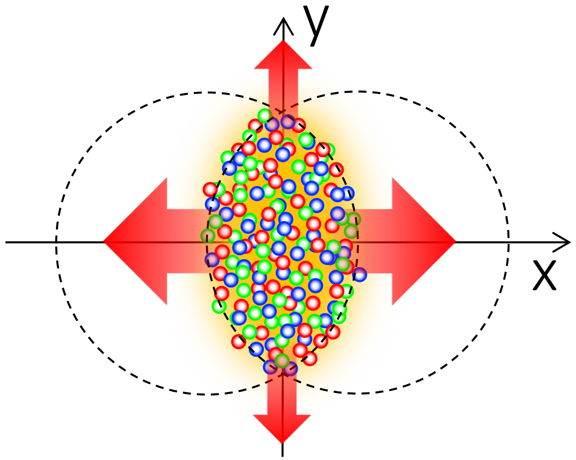




Elliptic flow

Ollitrault, PRD 46, 229 (1992)
Poskanzer and Voloshin, PRC 58, 1671 (1998)

- From spatial anisotropy to momentum anisotropy



Pressure gradients drive particles faster in the direction of the minor axis

⇒ The momentum distribution of hadrons has anisotropy (elliptic flow v_2)

Direct photons are also anisotropic

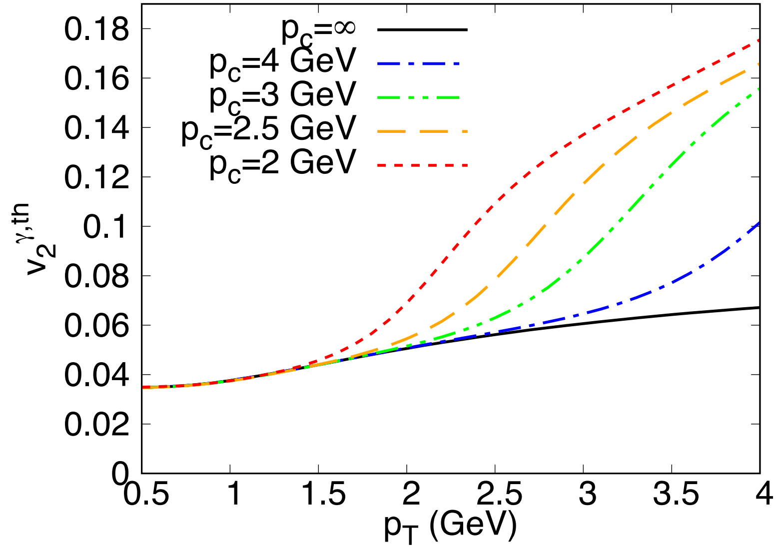
- Prompt photons: isotropic
- Thermal photons: anisotropic
- High p_T photons: isotropic

***High p_T photons are conjectured as thermal photons with no anisotropy in this study**

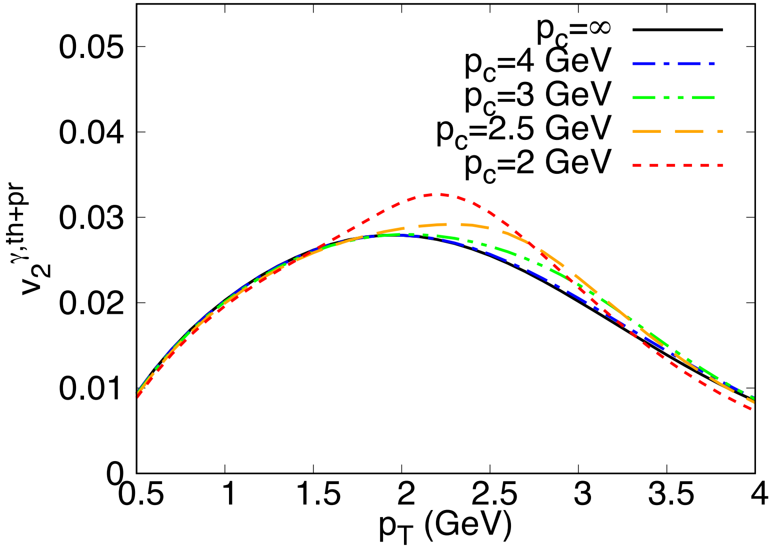
Elliptic flow

- Numerical results

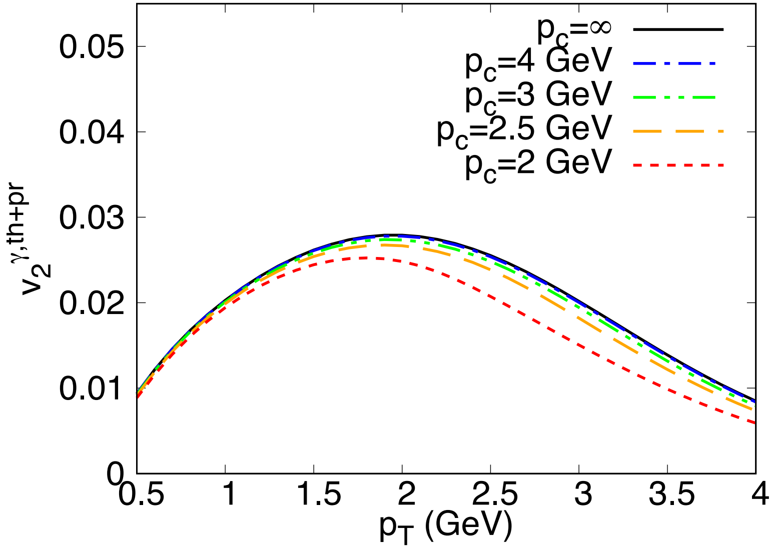
thermal



thermal + prompt



thermal + prompt + *high p_T

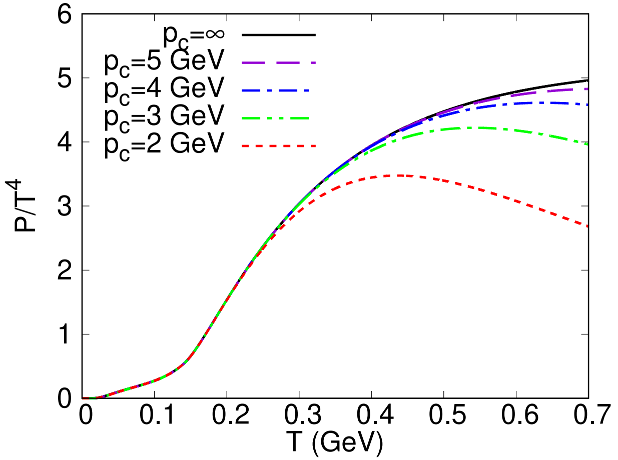


Photon v_2 is sensitive to the choice of p_c; whether it is enhanced or not depends on the high p_T contributions

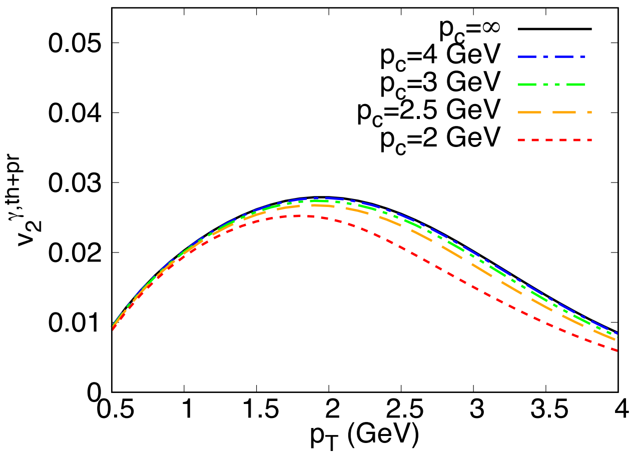
Summary

- We developed a "red" hydrodynamic model of the QGP

  - Equation of state is constructed only with low momentum components
  - High p_T photon emission is assumed to be non-thermal



  - Initial temperature can be higher
  - Direct photon elliptic flow can be sensitive to the cutoff momentum p_c



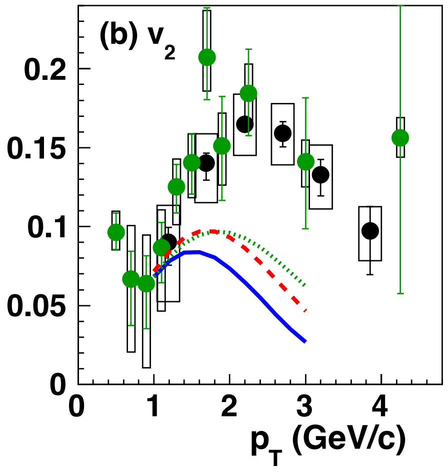
Outlook

- Future directions

  - Introduction of viscous corrections (including estimation of transport coefficients)
  - Event-by-event estimation for quantitative analyses of elliptic flow
  - Comparison with the experimental data for understanding the *photon puzzle**

  *The discrepancy between the theoretical estimations and experimental data of direct photon v_2

PHENIX, Phys. Rev. C 94, 064901 (2016)



The end

Thank you for listening!