クォーク·グルーオンプラズマの物理とその周辺

Department of physics, Hiroshima University
International Institute for Sustainability with Knotted Chiral Meta Matter／SKCM^2.
Hiroshima University
Kobayashi Maskawa Institute, Nagoya University

Chiho NONAKA

Theoretical Particle and Hadron Physics Group

August 5, 2025@核融合研

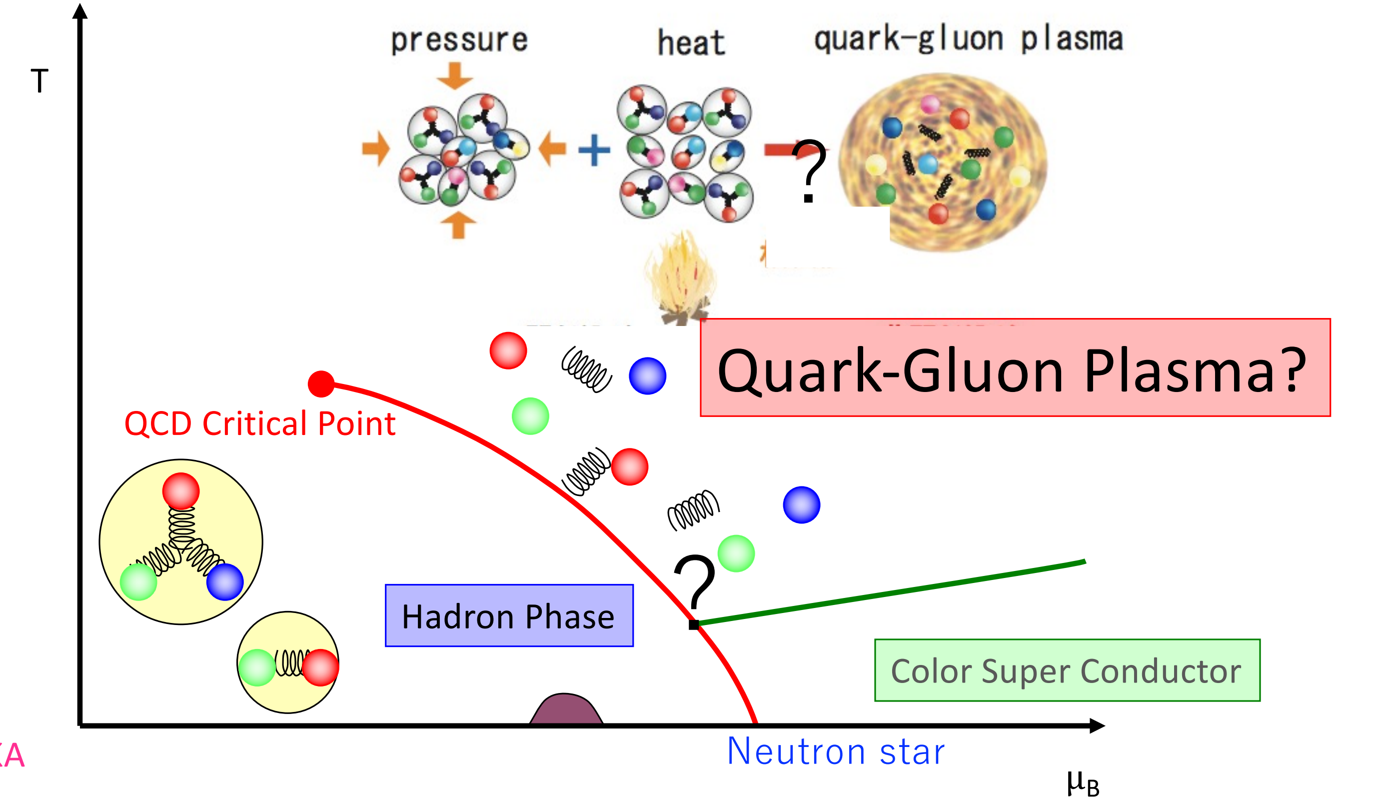
クォーク・グルーオン　プラズマの物理

- **世界規模の実験が稼働中：理論と実験の検証**
- **周辺物理との関連**
  - 理論的概念、ツール：共通点
  - 基礎理論
    - 相転移、相図
    - 平衡、非平衡物理
    - 熱力学量
  - ダイナミクスの記述
    - 相対論的流体模型
    - 分子動力学
    - Particle in Cell
  - データ解析、大規模計算
    - ベイジアン解析

クォークとグルーオンの多体系の物理

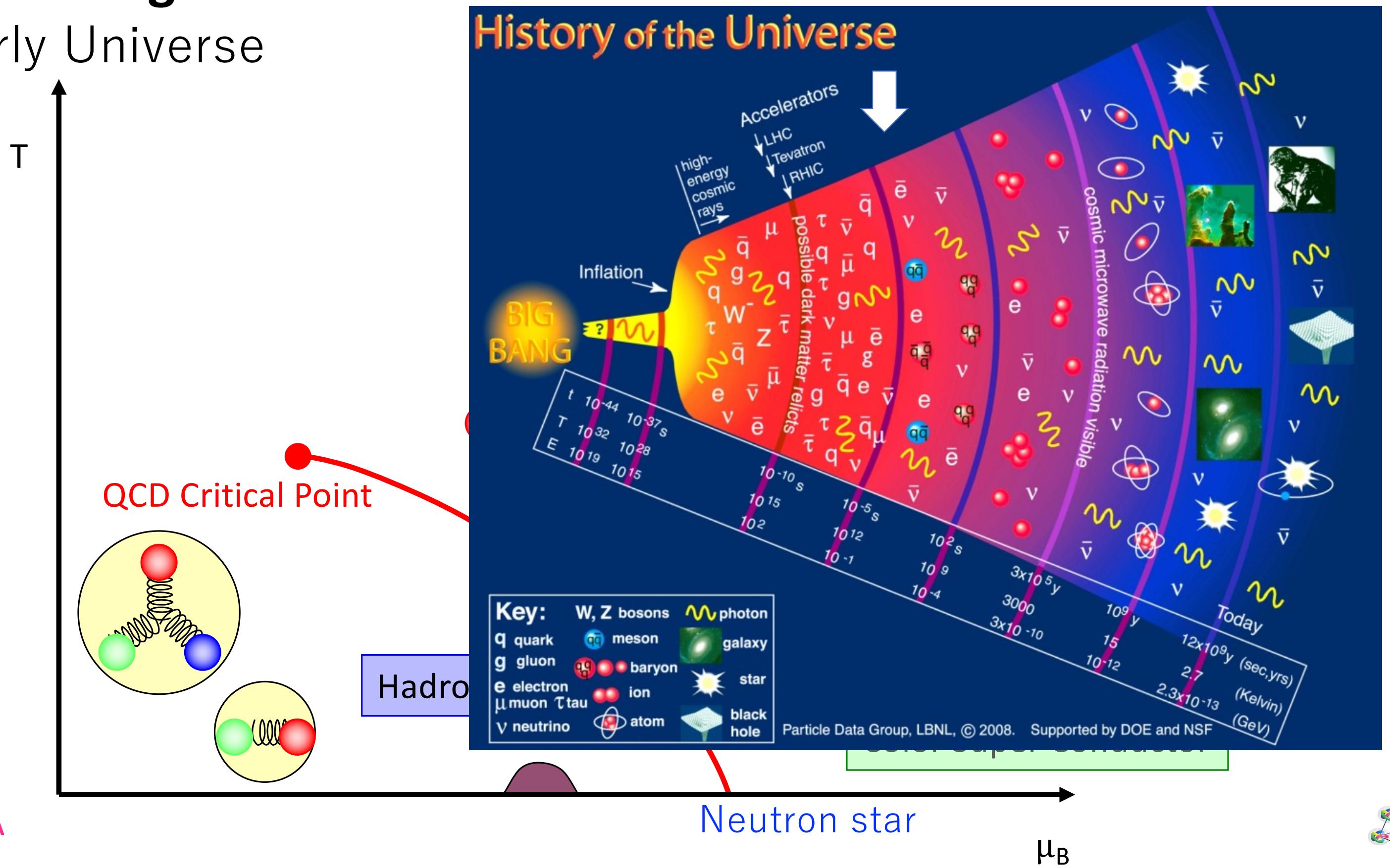
- **Quarks and gluons at extreme conditions**
  - High temperature and/or high density

Quark-Gluon Plasma



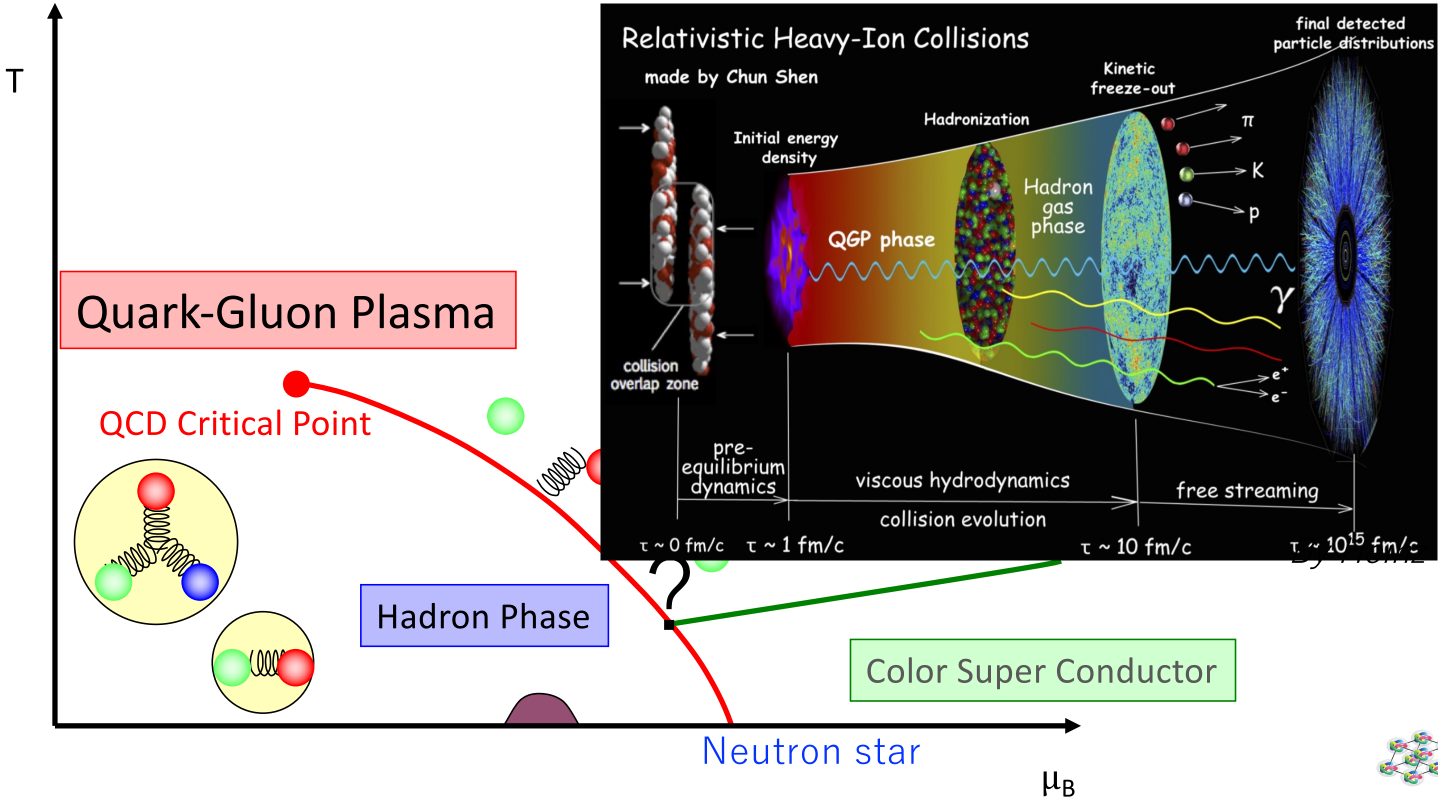
What is the QGP?

- **Quarks and gluons at extreme conditions**
  - Early Universe



What is the QGP?

- **Quarks and gluons at extreme conditions** Quark-Gluon Plasma
  - Relativistic Heavy Ion Collisions : Little Bang



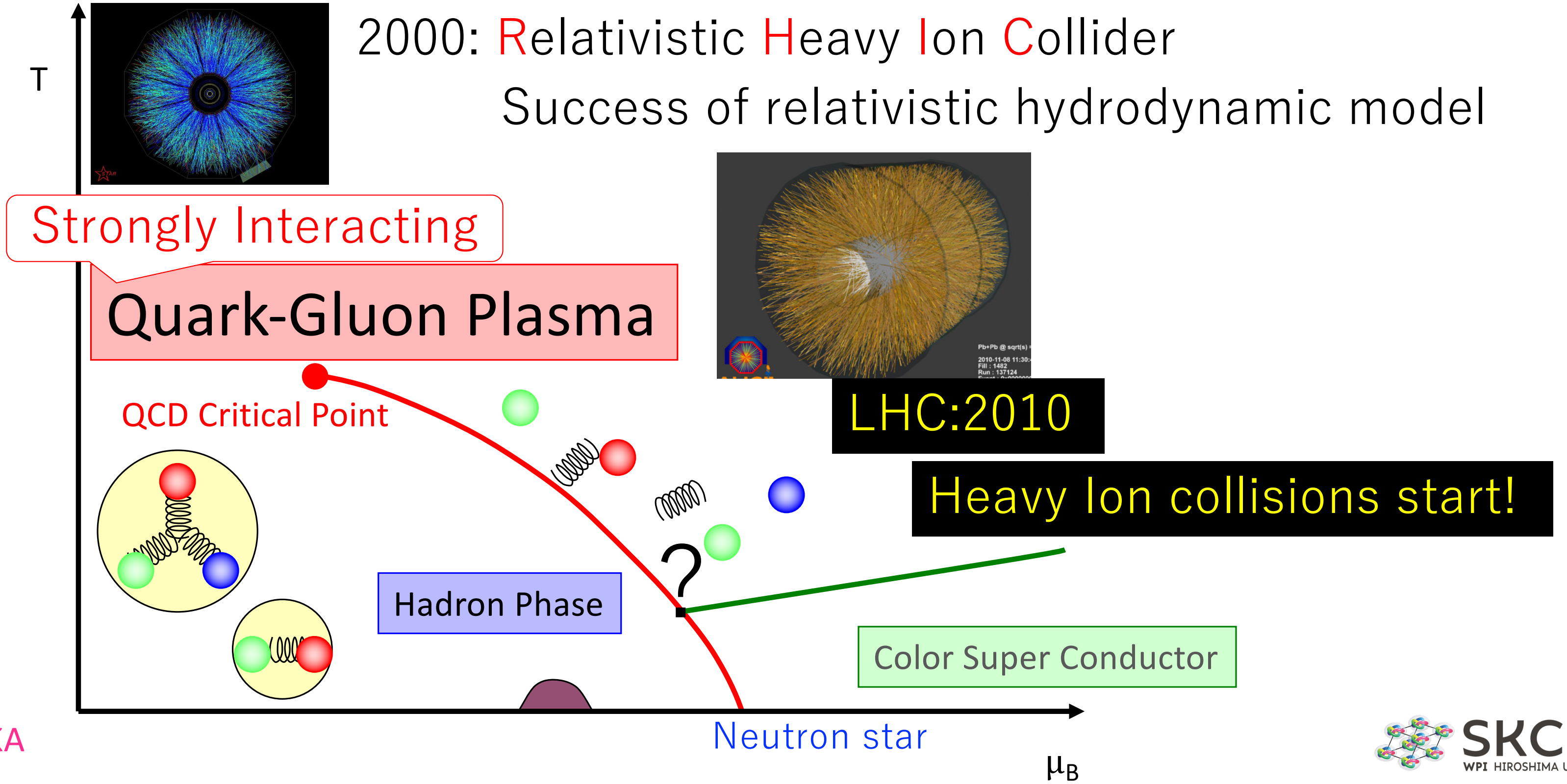
What is the sQGP?

- **Quarks and gluons at extreme conditions**
  - Relativistic Heavy Ion Collisions

Quark-Gluon Plasma

2000: Relativistic Heavy Ion Collider

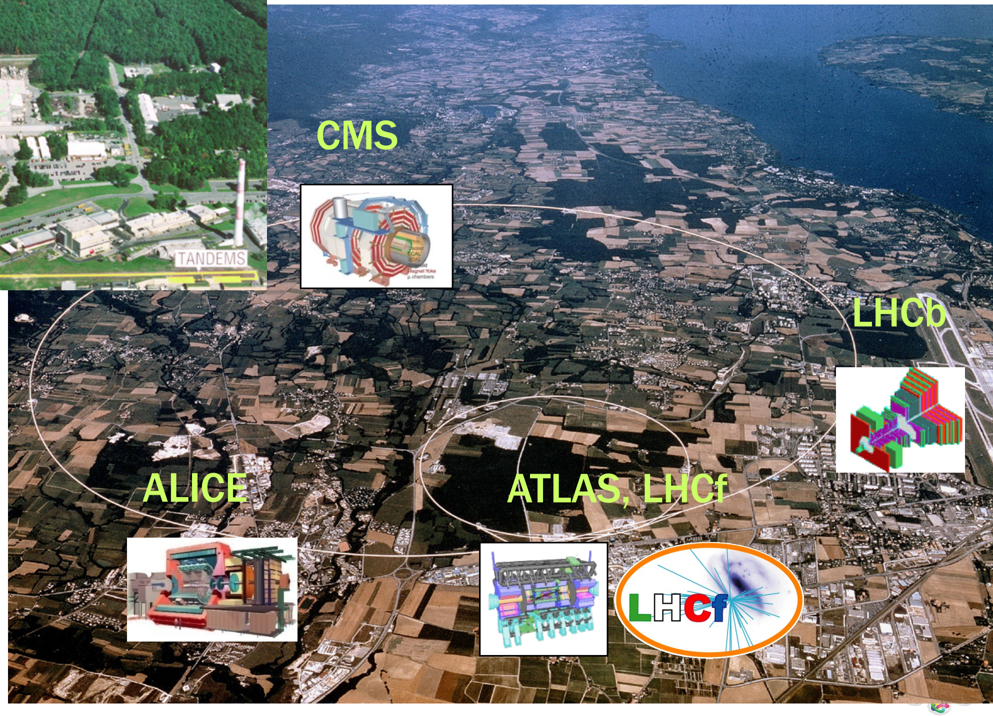
Success of relativistic hydrodynamic model



Heavy Ion Collisions

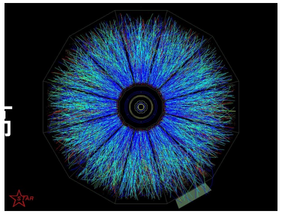
RHIC@BNL

Large Hadron Collider@CERN

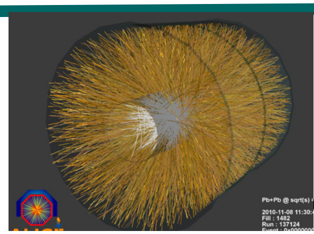


Heavy Ion Collisions

STAR@RHIC



ALICE@LHC



Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

p+p,
d+Au,He+Au
U+U, Au+Au,
200

RHIC

Pb+Pb
2760

p+Pb
Pb+Pb
5020

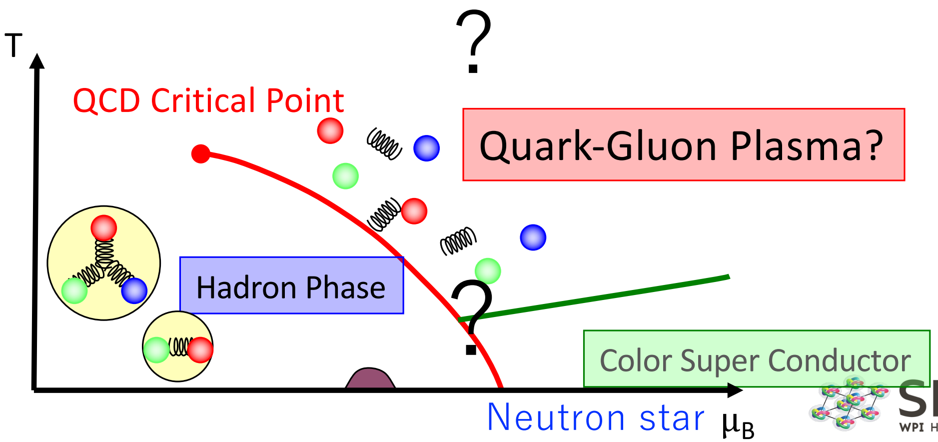
LHC

GeV

$\sqrt{s_{NN}}$

- 様々な衝突エネルギー
- 様々なものを衝突させている。

QCD 相図のどこに対応するのか？



C. NONAKA

SKCM²
WPI HIROSHIMA UNIVERSITY

統計模型

Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

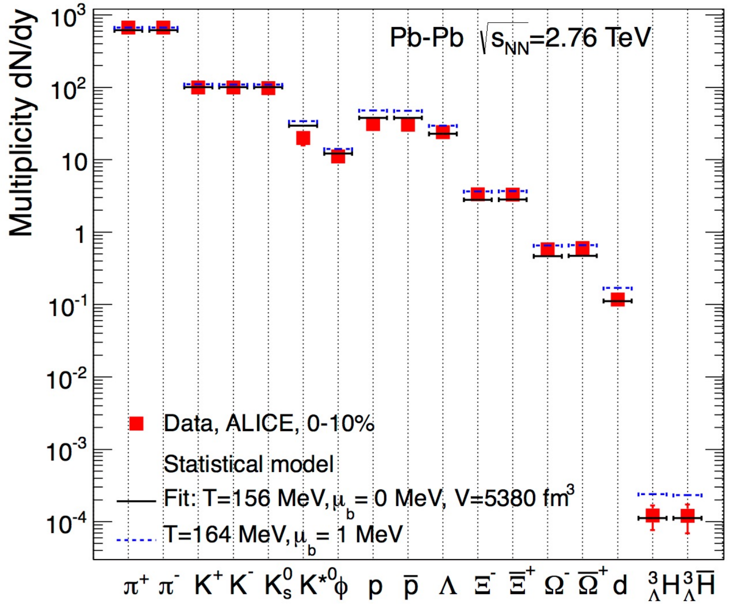
p+p,
d+Au,He+Au
U+U, Au+Au,
200

Pb+Pb
2760

p+p
p+Pb
Pb+Pb
5020

GeV

実験データ → QCD相図のどこを見ているのか？ $\sqrt{s_{NN}}$



Ex:Stachel et al, arXiv:1311.4662

$$n_i = N_i/V = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{-(\epsilon_i(p)-\mu)/T} \pm 1}$$

Pb+Pb 2760 GeV
-> ~ T=156 MeV,　μ=0

実験とQCD相図

Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

p+p,
d+Au,He+Au
U+U, Au+Au,
200

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p+p
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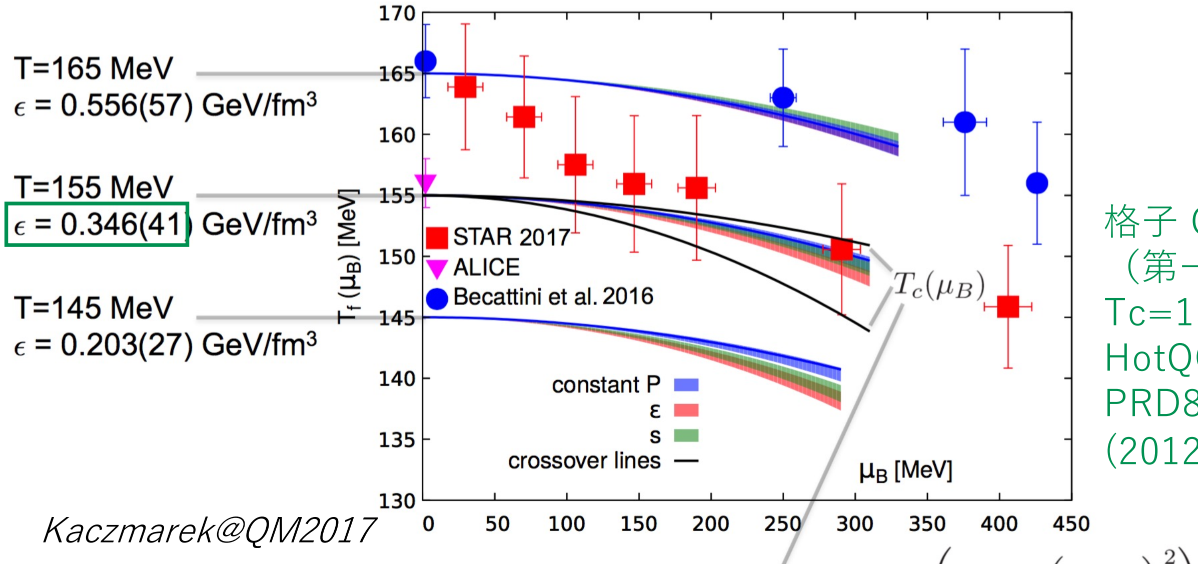
Pb+Pb
5020

GeV

$\sqrt{s_{NN}}$



Kaczmarek@QM2017

compare well with estimates of the crossover line: $T_c(\mu_B) = T_c(0)\left(1 - \kappa_2^c \left(\frac{\mu_B}{T_c(0)}\right)^2\right)$

格子 QCD
（第一原理計算）
Tc=154(9) MeV
HotQCD
PRD85,054503
(2012)

C. NONAKA

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実験とQCD相図

Au+Au(Beam Energy Scan)
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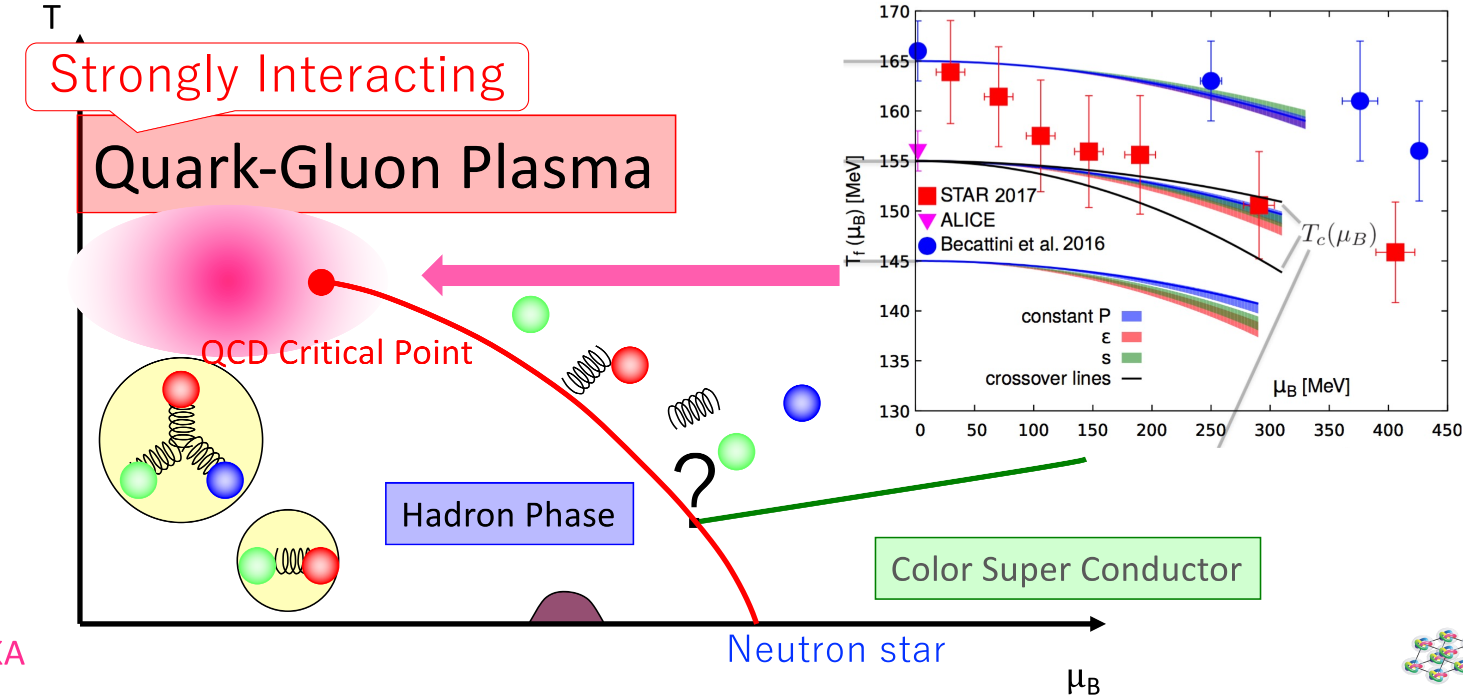
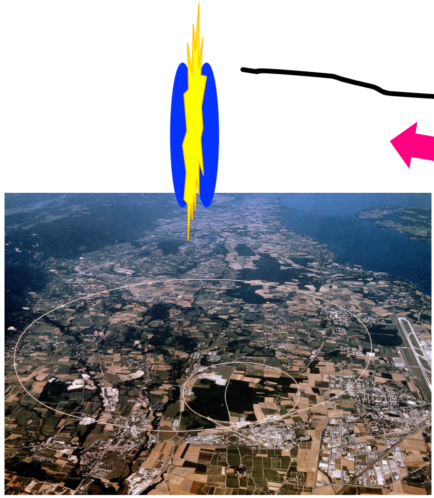
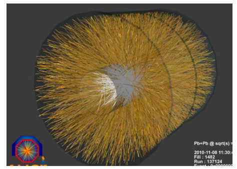
GeV $\sqrt{s_{NN}}$



QGP生成？

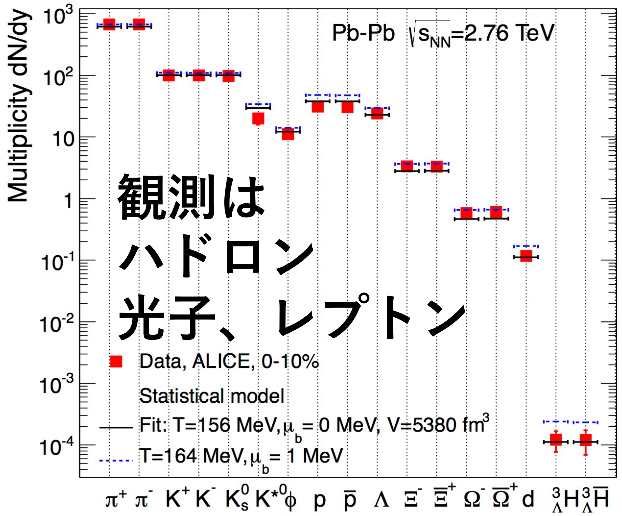


実験データ



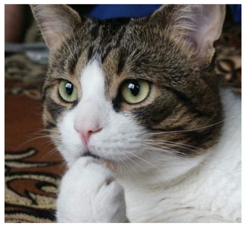
?

Theory, Model



QGP生成？

?

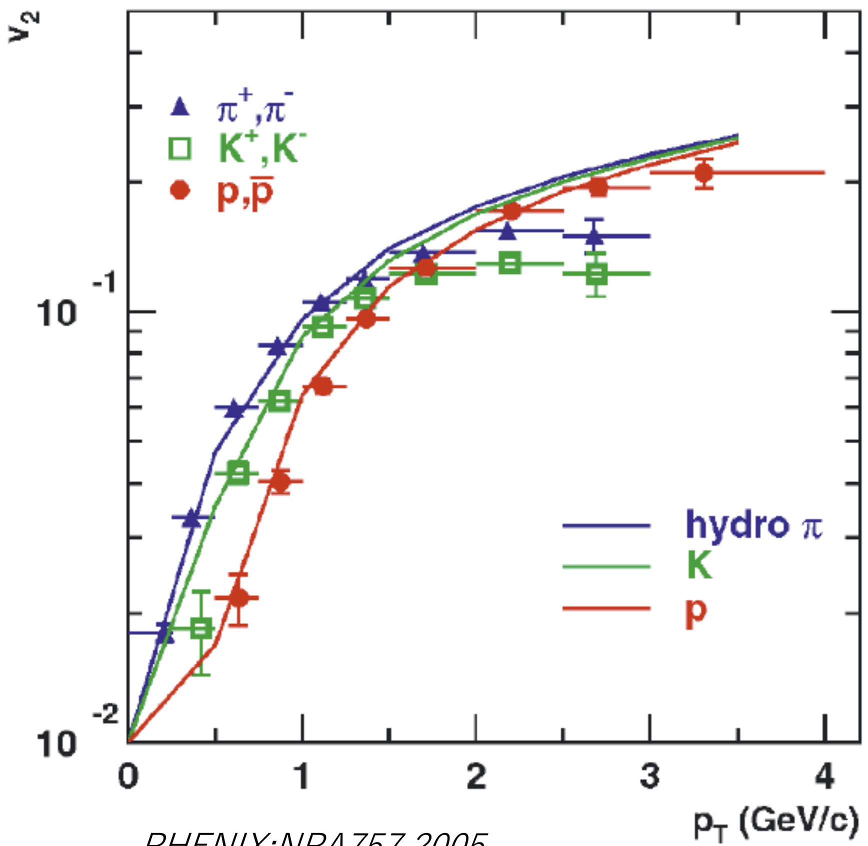


模型構築

- QGP生成のメカニズム
- 時間発展
- QGP, ハドロンの性質

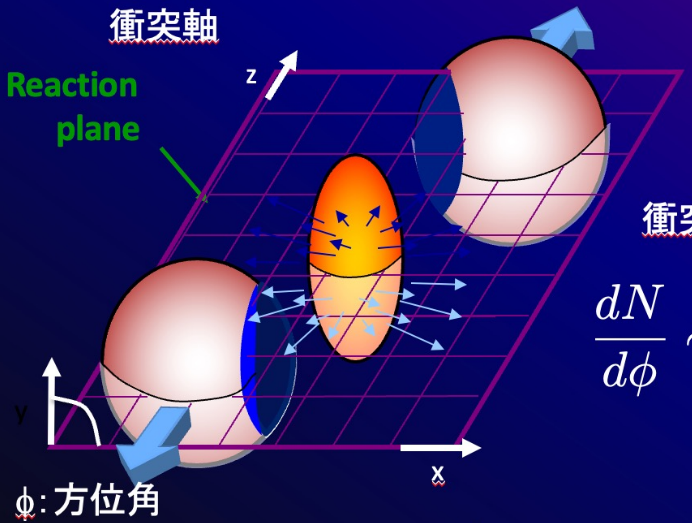
相対論的流体模型

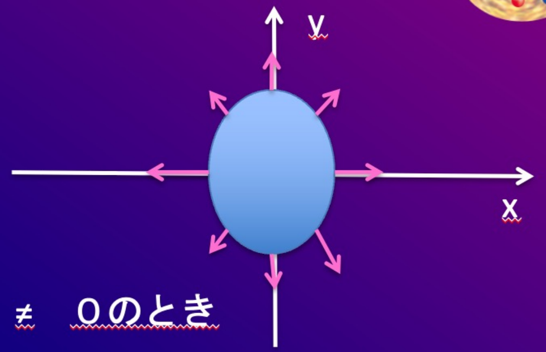
- 2001年RHIC稼働後標準的な模型に
  強い楕円フロー
- 衝突後の粒子多重発生
  流体描像で取り扱う
  Landau
  Bjorken



PHENIX:NPA757,2005

粒子の集団運動:楕円フロー



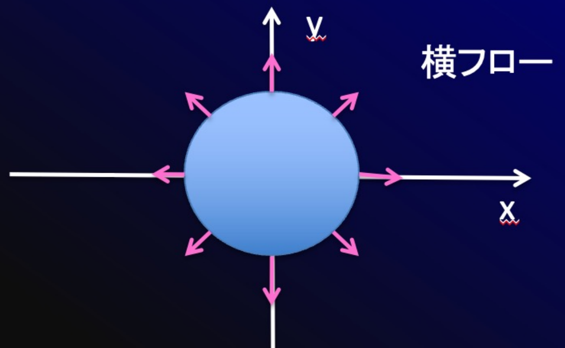


衝突係数 ≠ 0のとき

$$\frac{dN}{d\phi} \sim N_0(1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi)$$

直接　　楕円

横フロー



C.NONAKA

SKCM²
WPI HIROSHIMA UNIVERSITY

相対論的流体模型

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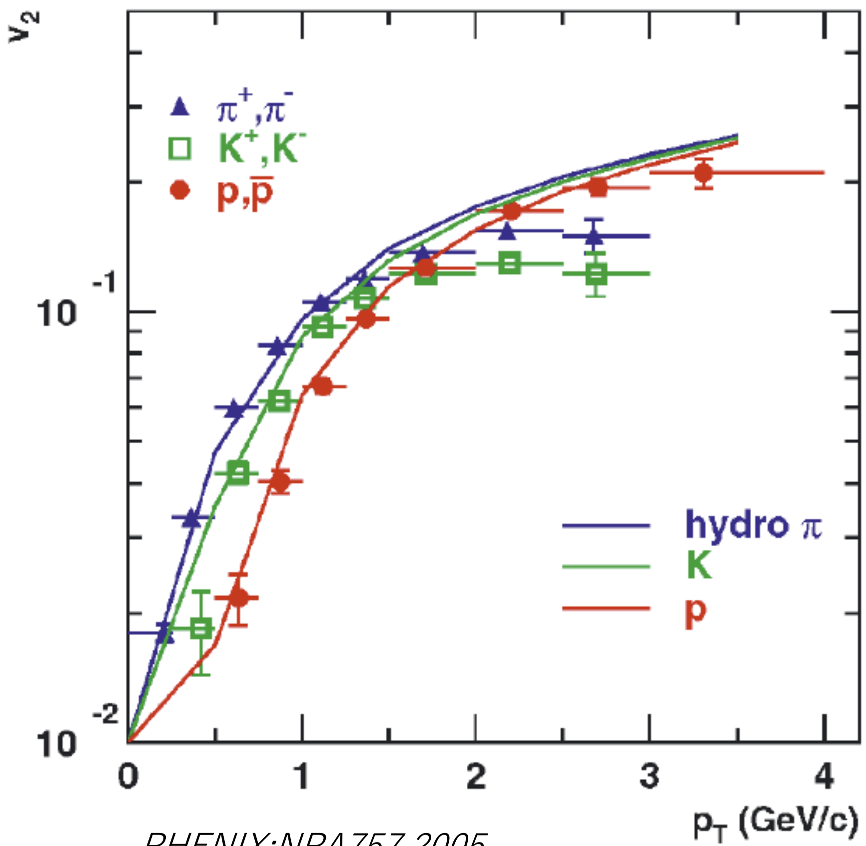
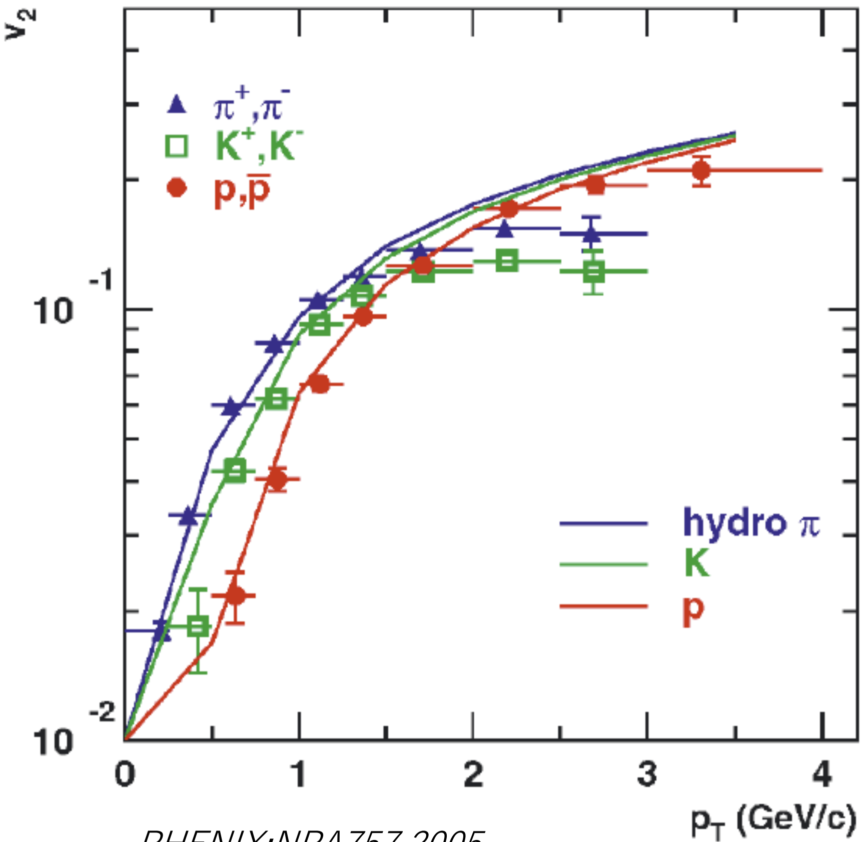


PHENIX:NPA757,2005

相対論的流体模型



PHENIX:NPA757,2005

特徴
•楕円フローの質量依存性
粒子の集団運動

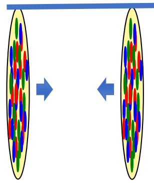
•衝突直後の熱平衡化
流体の初期時刻
$t_0 \sim 0.6$ fm

1 fm = 10^{-15} m

問題点も存在→現在はほとんど解決

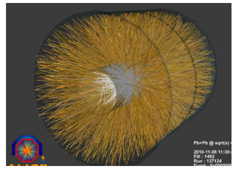
Hydrodynamic Model

collisions



QGP
Production
?

Experimental data



Hadrons
Leptons
Photons

Multiple particle production

➡ Hydrodynamic picture
Landau
Bjorken

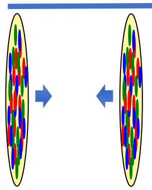
Success of hydrodynamic model at RHIC
Relativistic viscous hydrodynamic model
One of important phenomenological models

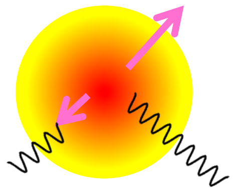
Equation of State

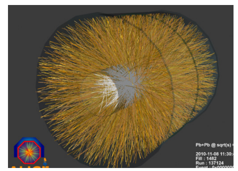
Experimental data

collisions

hydrodynamics







Hydrodynamics

QCD phase diagram

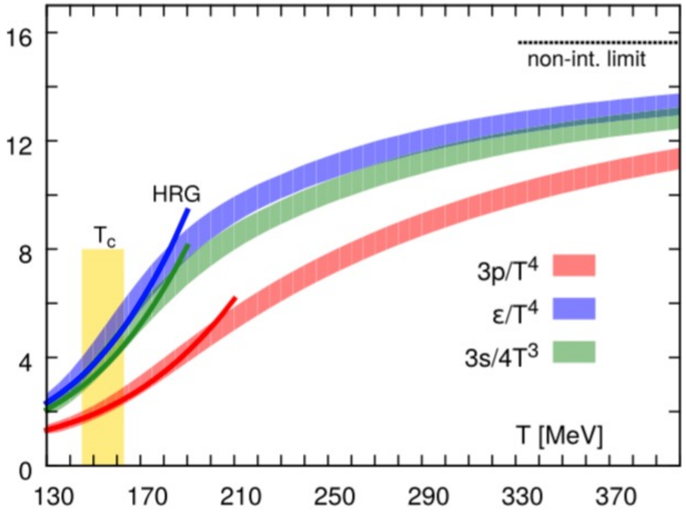
EoS: lattice QCD

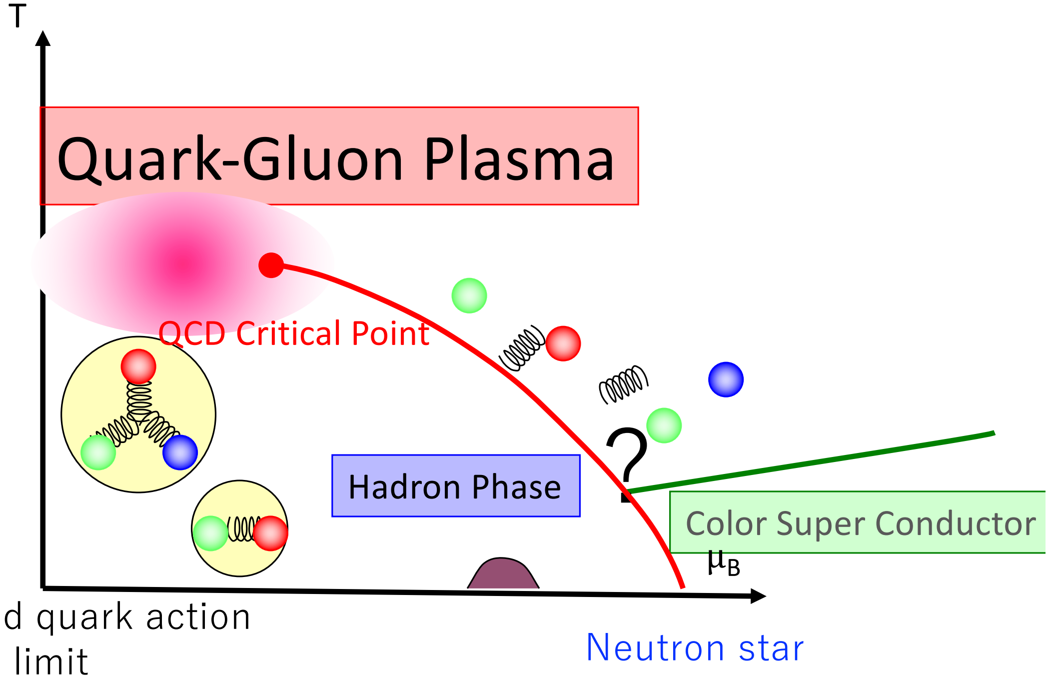
$$\partial_\mu T^{\mu\nu} = 0$$

Equation of State

- **Equation of State**
  - Lattice QCD

HotQCD,PRD90,094503(2014)



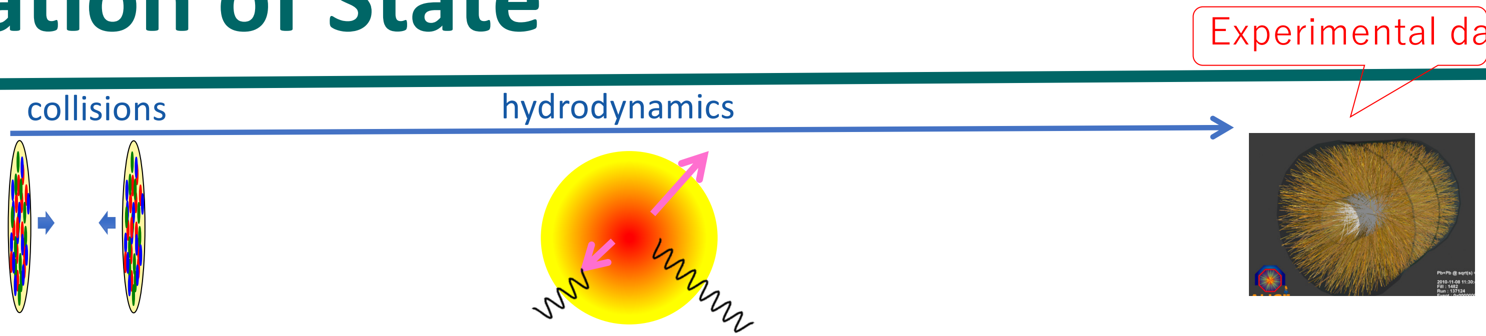


(2+1) flavor, Highly improved staggered quark action
Nt=6,8,10,12,Ns=4Nt → continuum limit
Parametrization of EoS

$T_c \sim 155$ MeV

finite μ: sign problem

Equation of State



Hydrodynamics

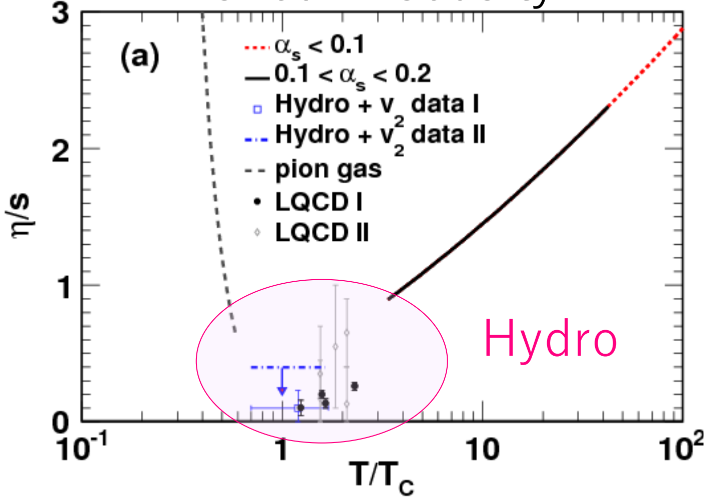
QCD phase diagram
EoS: lattice QCD
Shear and bulk viscosities

$$\partial_\mu T^{\mu\nu} = 0$$

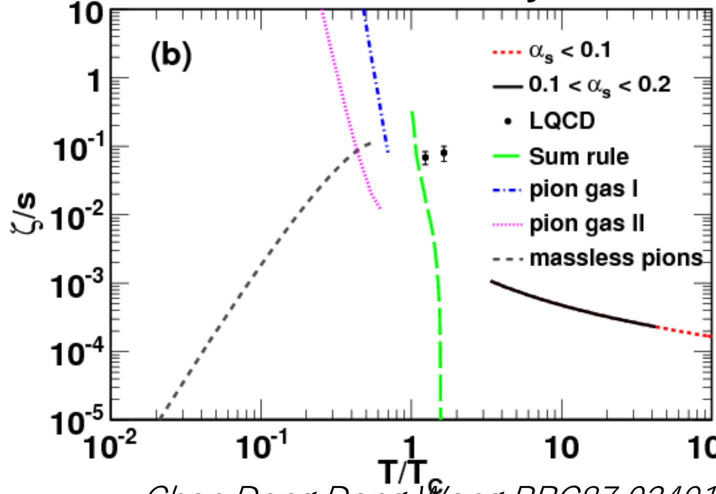
Property of QGP

- **Current Status for transport coefficients**

shear viscosity



bulk viscosity



Chen,Deng,Dong,Wang,PRC87,024910(2013)

- Shear viscosity takes the minimum around T_c. Cf. $\eta/s=1/4\pi$ AdS/CFT
- Hydrodynamic model constant η/s

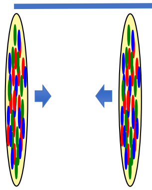
- Bulk viscosity Temperature dependence is unclear.
- Hydrodynamic model vanishing

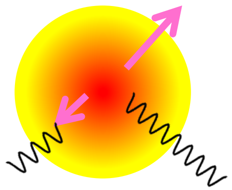
パラメータを仮定＋ベイジアン解析

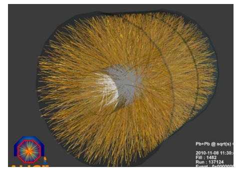
Equation of State

Experimental data

collisions　　　hydrodynamics





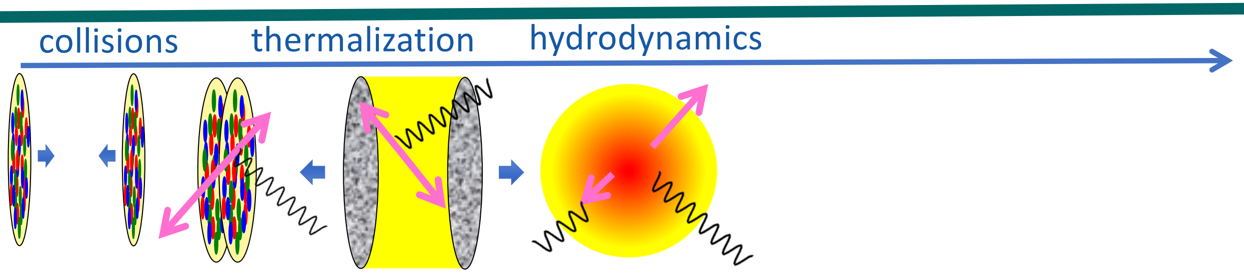


Hydrodynamics

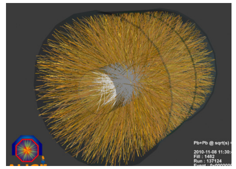
QCD phase diagram
EoS: lattice QCD
Shear and bulk viscosities

$$\partial_\mu T^{\mu\nu} = 0$$

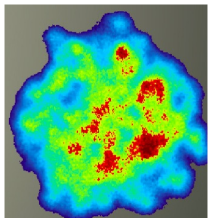
Initial Condition



Experimental data



Initial conditions



Energy (entropy)
density distributions

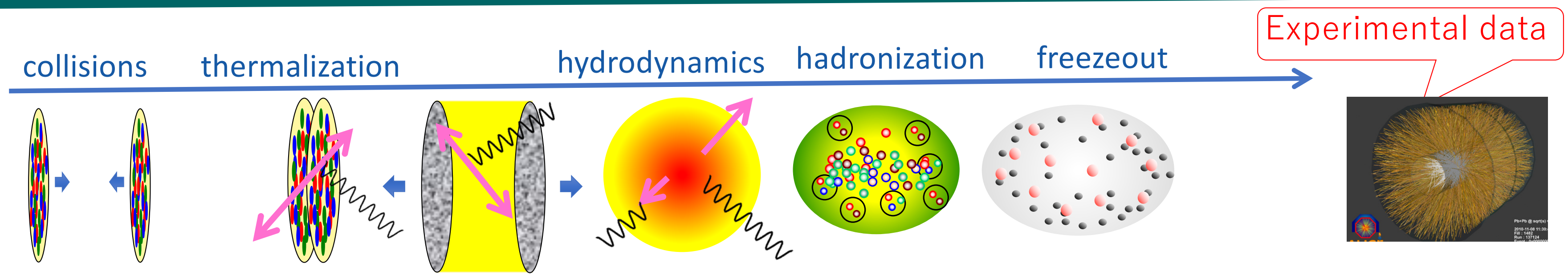
最も難しい問題の一つ

Hydrodynamics

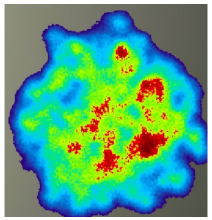
QCD phase diagram
EoS: lattice QCD
Shear and bulk viscosities

$$\partial_\mu T^{\mu\nu} = 0$$

From Fluid to Particle



Initial conditions



Energy (entropy) density distributions

Hydrodynamics

QCD phase diagram
EoS: lattice QCD
Shear and bulk viscosities

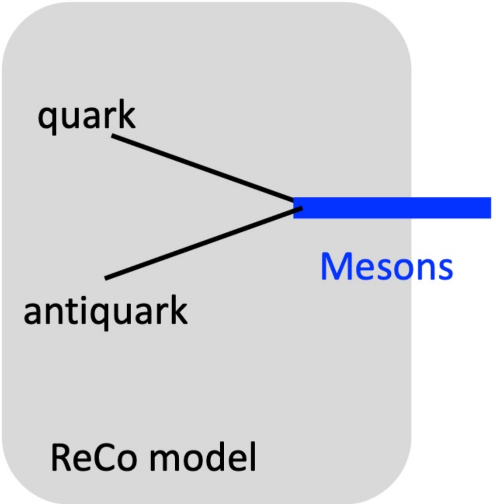
Hadronization

Recombination Model

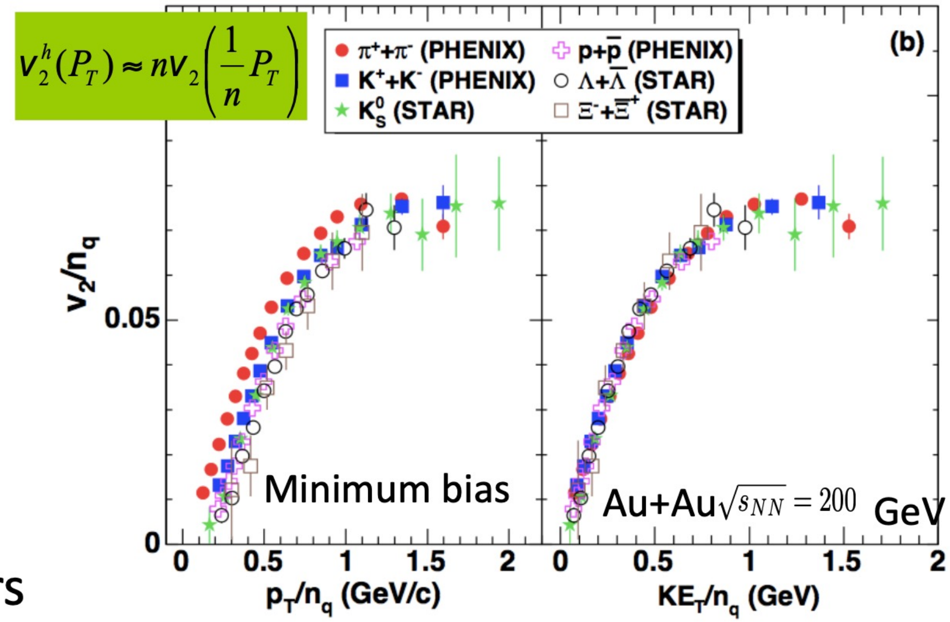
Recombination Model

Fries, Mueller, CN and Bass, PRC68(2003)

- One of successful models



Ex: Quark number scaring



PHENIX,nucl-ex:0608033

- Baryon/Meson ratios
- Nuclear modification factors
- Quark number scaling in elliptic flow

Radiative Recombination in QGP

Fujii, Itakura, CN, NPA 967 (2017)

One of Photon Production Processes

Fujii, Itakura, Miyachi, CN,
Phys.Rev.C 106 (2022) 3, 034906

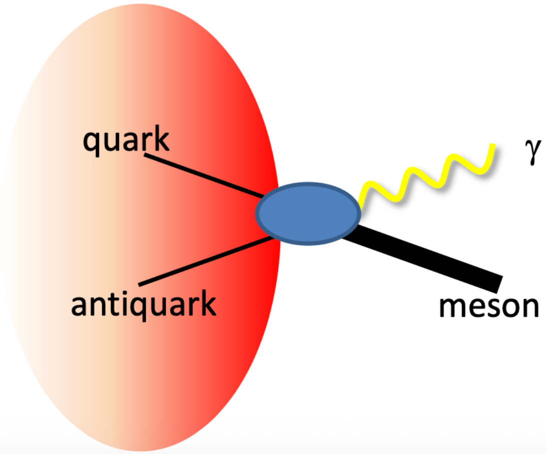
- Photon emission at hadronization process
  – Photon's flow is as strong as hadrons' flow.
- A photon is produced from pairing of quarks
  – Radiative recombination brings enhancement of photon yield.

Radiative Recombination in QGP

- Non perturbative process
- No inverse process in HIC
- Non equilibrium process

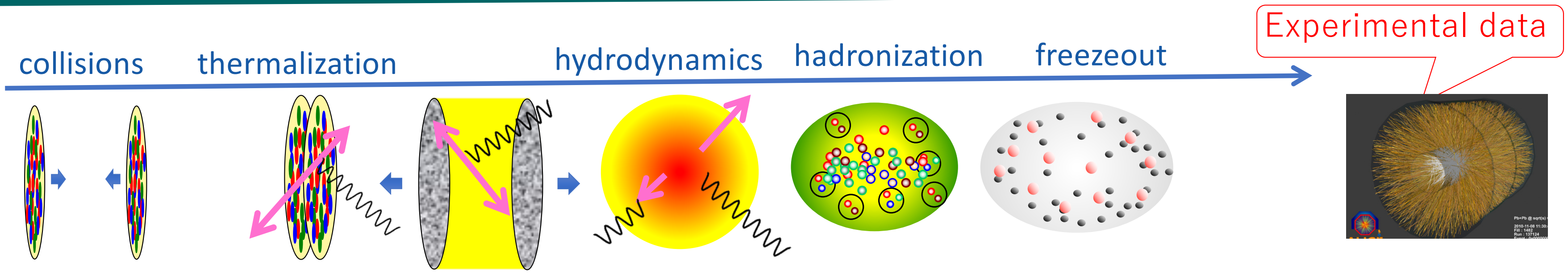
⇨ Construction of dynamical model

Recombination Model

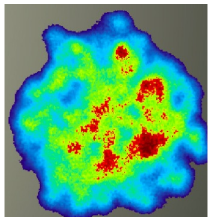


スクリーンショット

From Fluid to Particle



Initial conditions



Energy (entropy) density distributions

Hydrodynamics

QCD phase diagram

EoS: lattice QCD

Shear and bulk viscosities

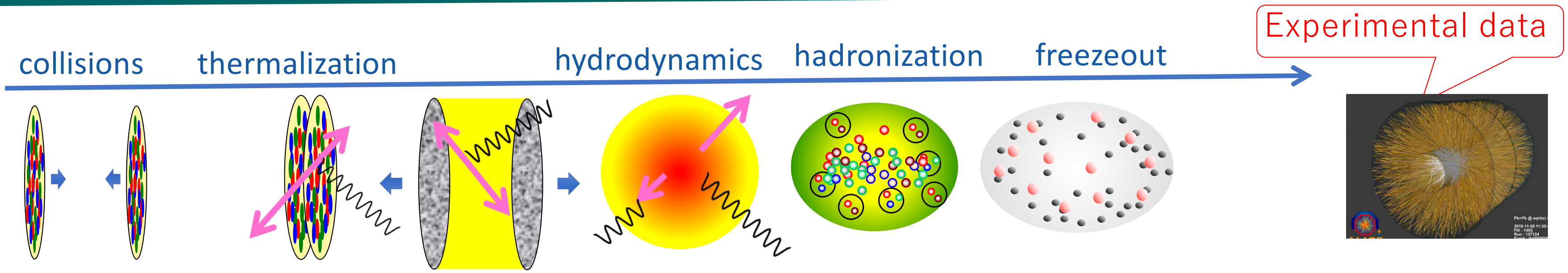
Final state interactions

Hadron based event generator

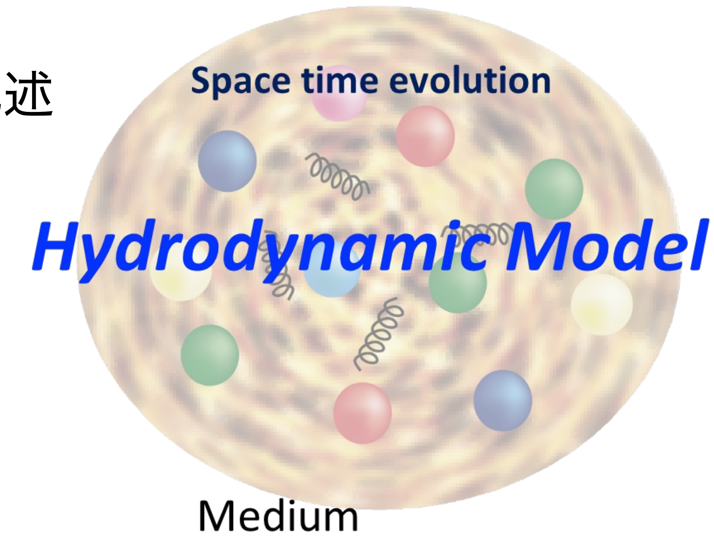
Hadronization

Recombination Model

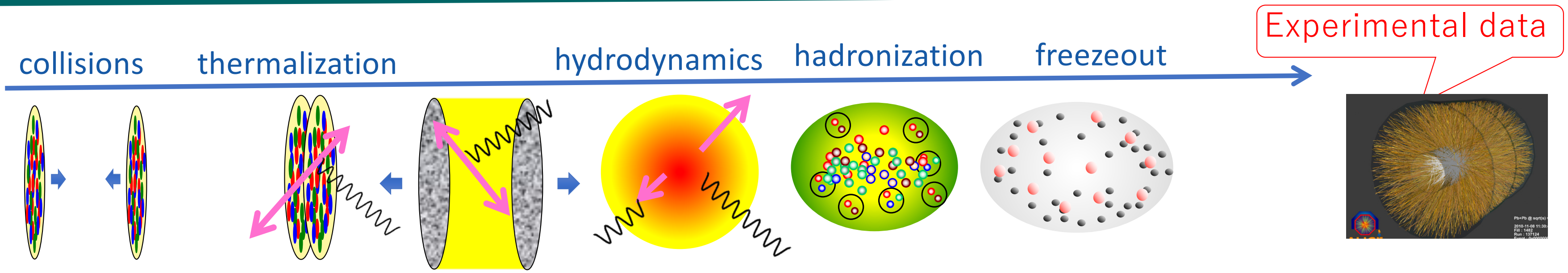
QGP物理の理解

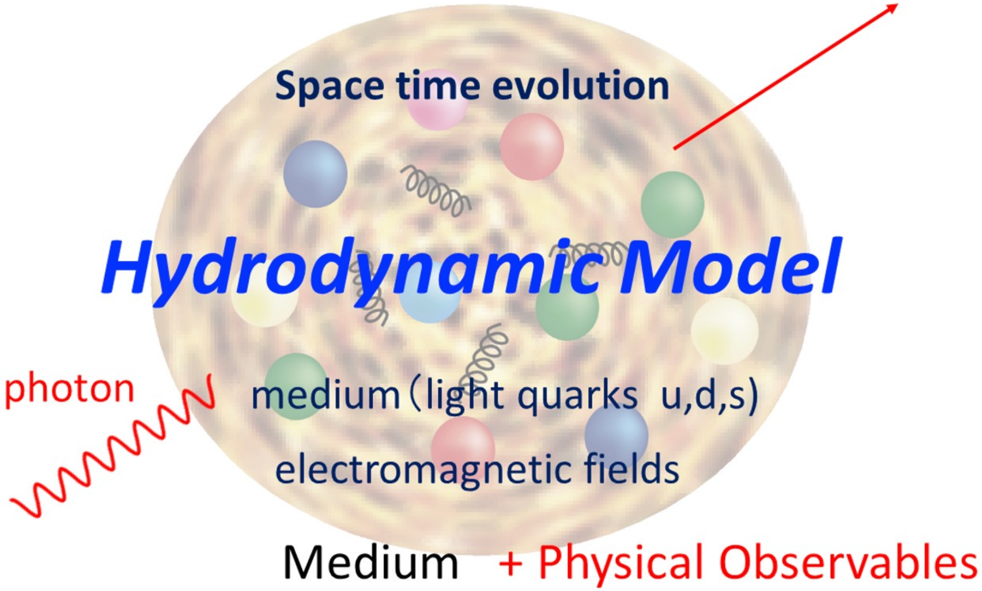


ダイナミクスの記述

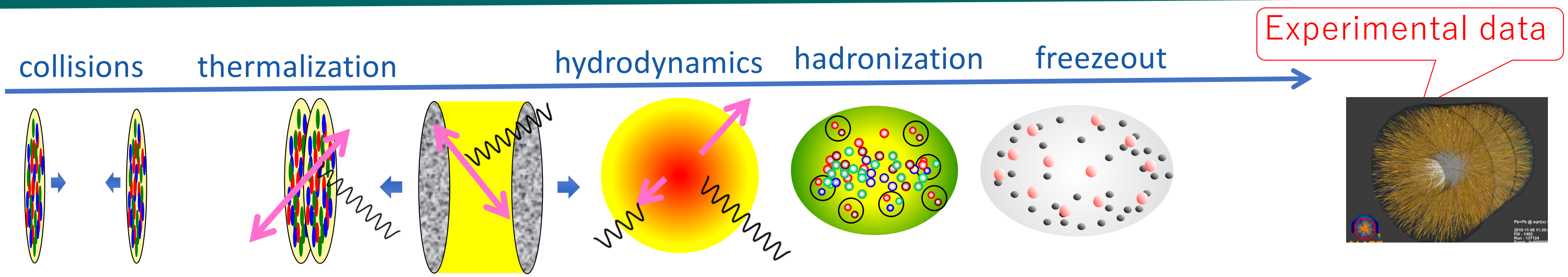


QGP物理の理解

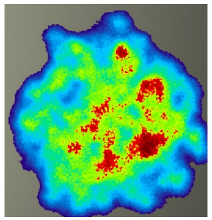

collisions
thermalization
hydrodynamics
hadronization
freezeout
Experimental data


Space time evolution
Hydrodynamic Model
photon
medium（light quarks u,d,s)
electromagnetic fields
Medium + Physical Observables

From Fluid to Particle



Initial conditions



Energy (entropy) density distributions

TRENTO

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Shear and bulk viscosities

New hydrodynamics code

$$\partial_\mu T^{\mu\nu} = 0$$

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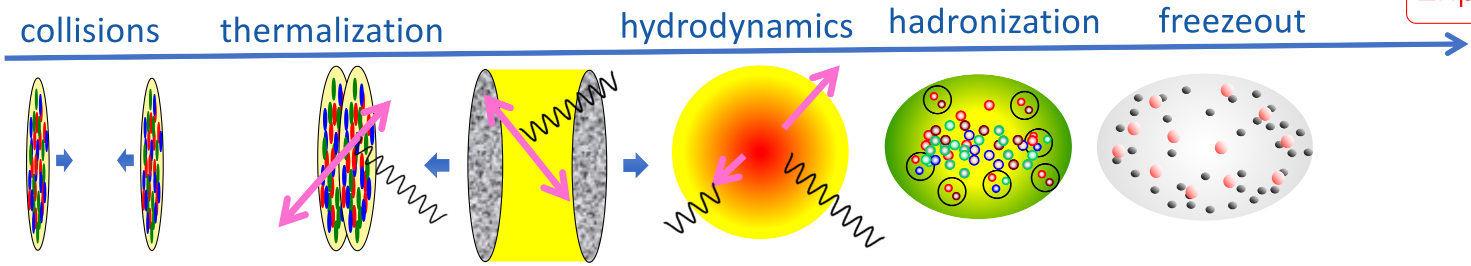
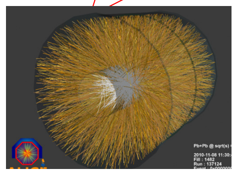
Cooper-Frye Formula

Akamatsu et al, JCP256,34(2014)
Okamoto, Akamatsu, Nonaka, EPJC76,579(2016)
Okamoto and Nonaka, EPJC77,383(2017)

From Fluid to Particle

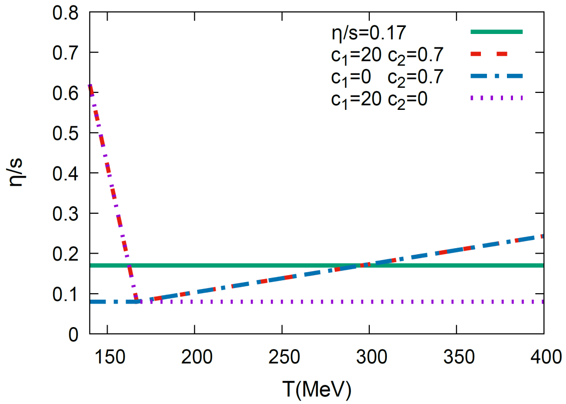


Experimental data



Our Model ⟷ ***Experimental data***

Shear viscosity



Bulk viscosity

$$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2 \quad b = 40$$

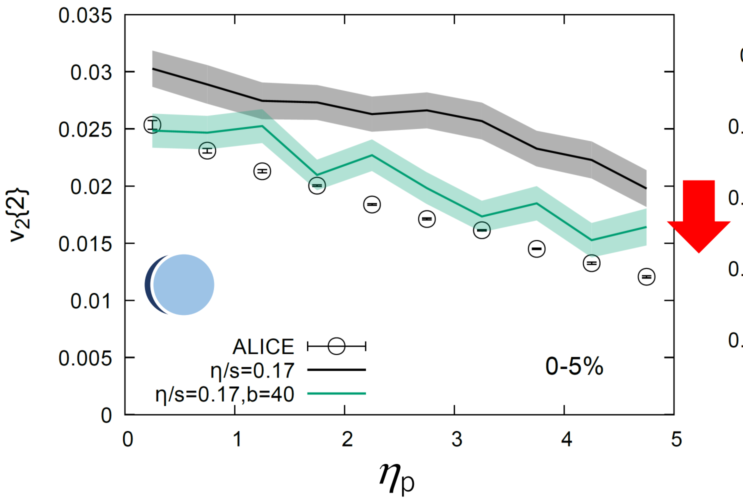
ALICE Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV, LHC

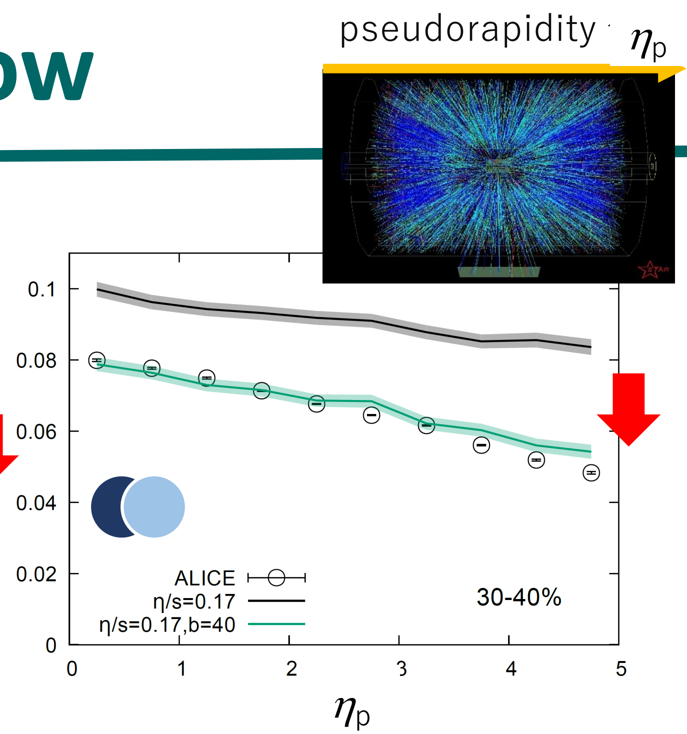
- ✓ Rapidity distributions
- ✓ P_T distributions
- ✓ Mean P_T
- ✓ Collective flows v_2 and v_3

What physical observable is interesting?

Effect on Collective Flow

- Collecti

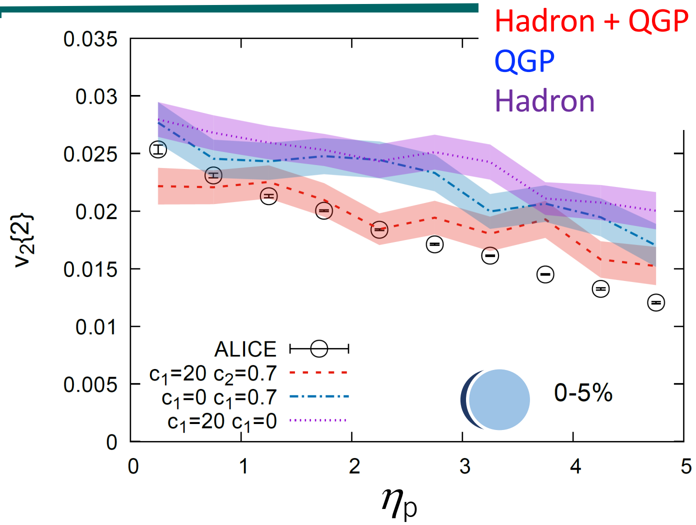


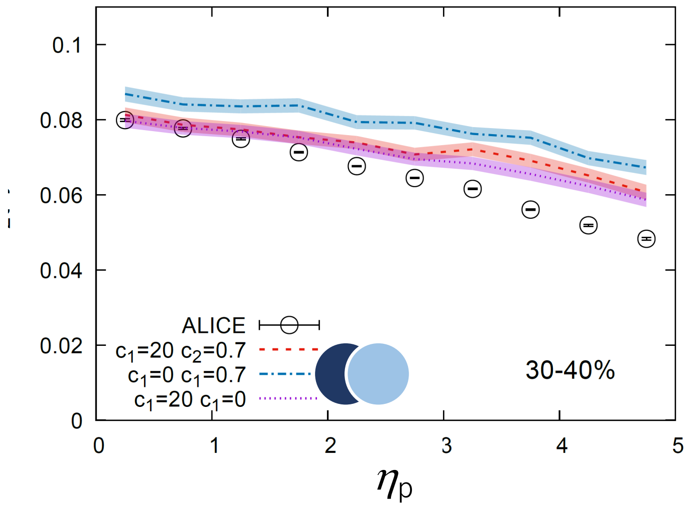


- (3+1)-d calculation
- v_n with bulk viscosity is much closer to the ALICE data: amplitude and slope
- Effect of bulk viscosity at forward rapidity is large.

Finite bulk viscosity

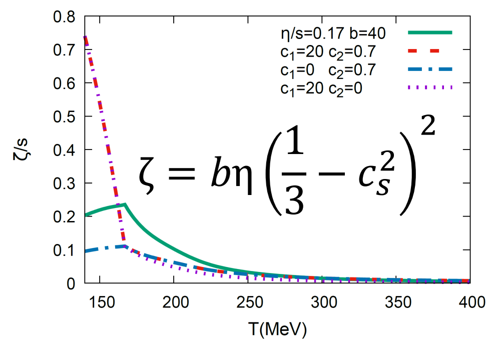
Temperature Dependent η/s

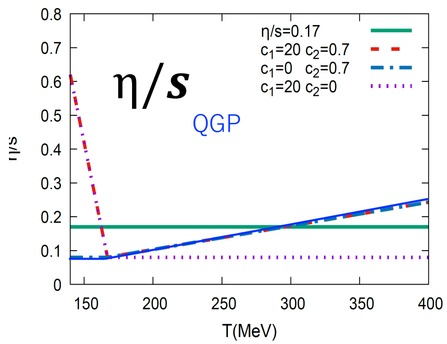




QGP phase: $\eta/s(T)$
Hadron phase: $\eta/s=0.08$

In both centrality classes
$v_2(\eta_p)$ is larger.

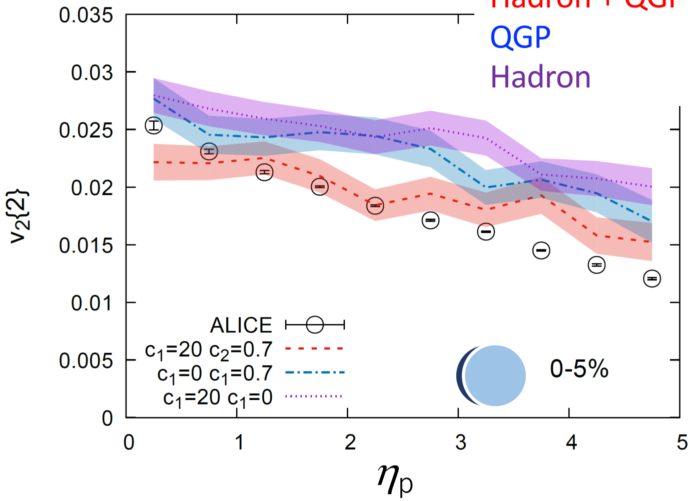


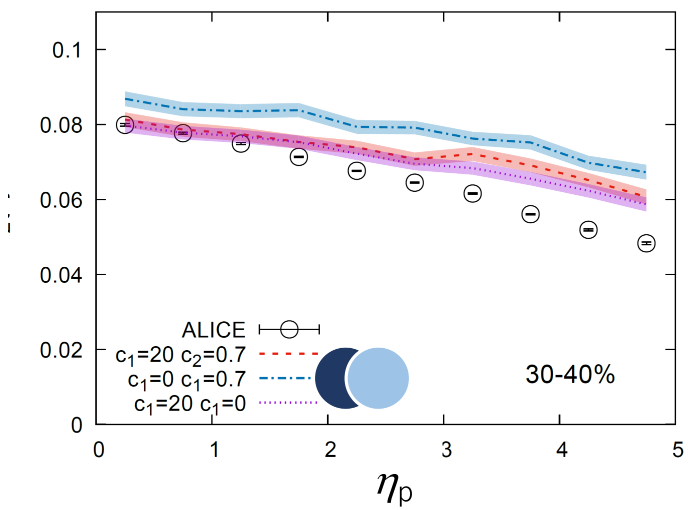


$T_{\rm SW} = 150$ MeV

Temperature Dependent η/s

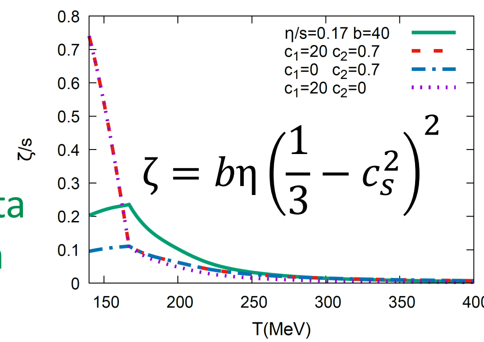
Hadron + QGP
QGP
Hadron

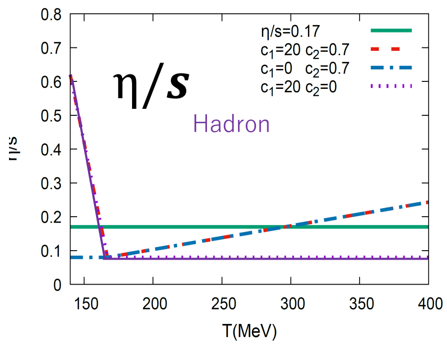




QGP phase: η/s=0.08
Hadron phase: η/s(T)

0-5%: larger than ALICE data
30-40%: close to ALICE data

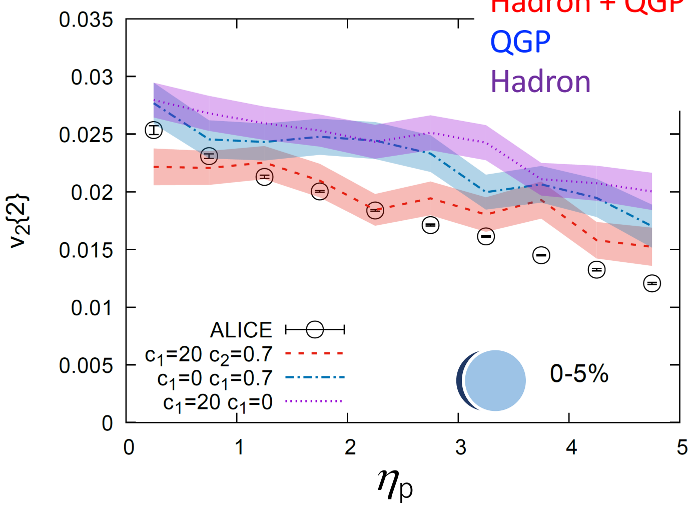


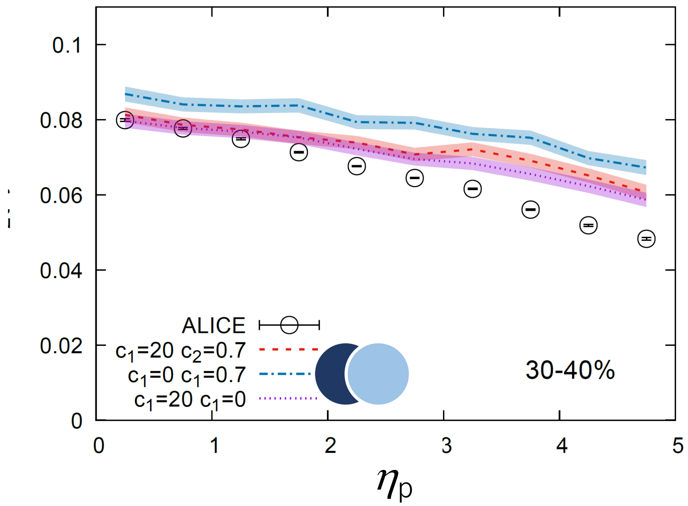


$T_{\mathrm{SW}} = 150$ MeV

Temperature Dependent η/s

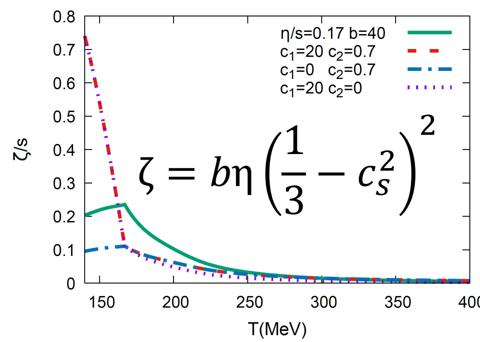
Hadron + QGP
QGP
Hadron



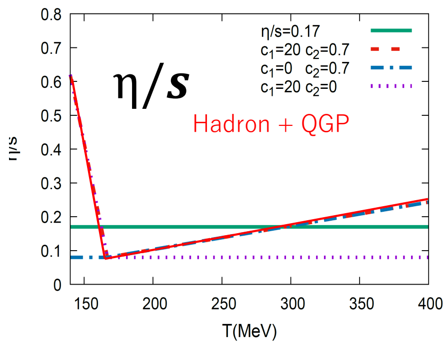


QGP phase: $\eta/s(T)$
Hadron phase: $\eta/s(T)$

In both central classes,
close to ALICE data

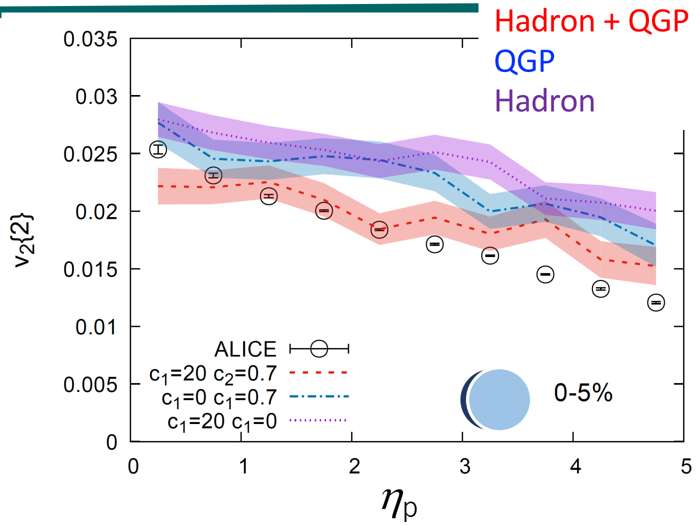


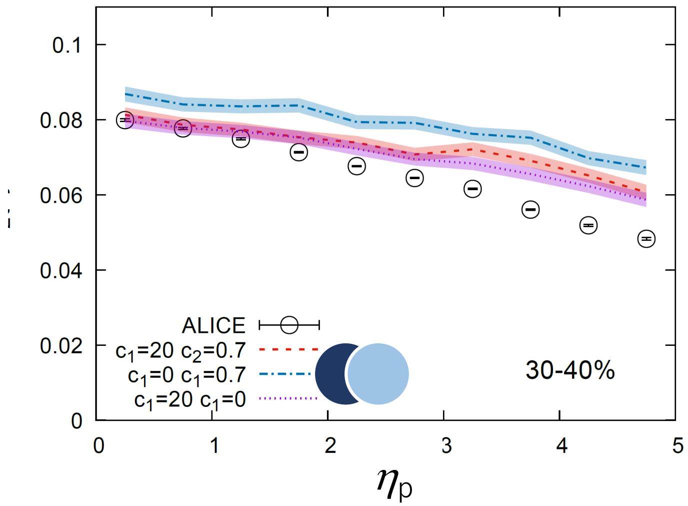
$$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2$$



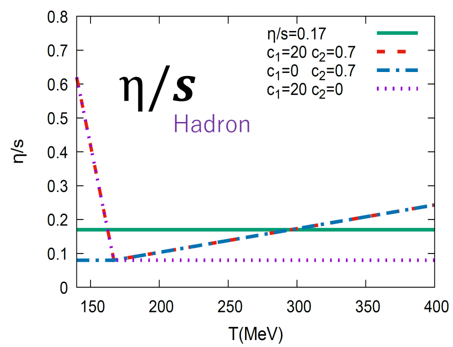
$T_{SW} = 150$ MeV

Temperature Dependent η/s





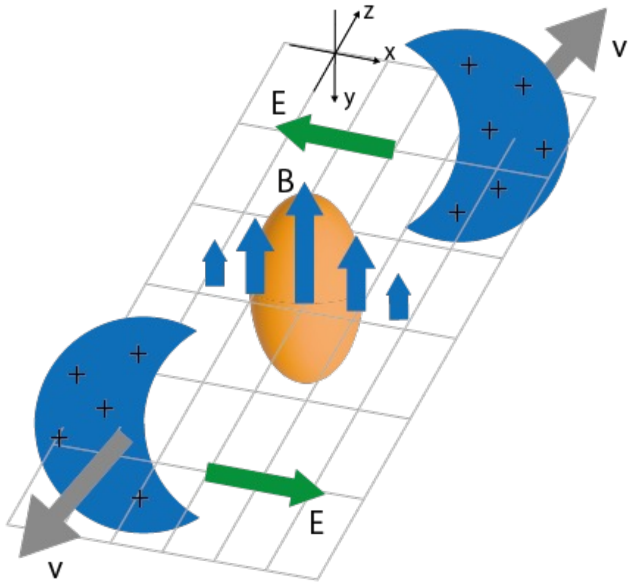
- 0-5 % centrality
  η/s of QGP and hadron phases is important.
- 30-40 % centrality
  η/s of hadron phase is important.



Central dependence of $v_2(\eta_p)$ reveals temperature dependence of viscosities.

Electromagnetic Fields in Heavy Ion Collisions ?

- **Strong Electromagnetic field ?**
  - Au + Au ($\sqrt{s_{NN}} = 200$ GeV) : 10^{14} T ~10 m_π^2
  - Pb + Pb ($\sqrt{s_{NN}} = 2.76$ TeV) : 10^{15} T



Electromagnetic Fields and Property of QGP

- **Electric Conductivity**

  - **Dissipation of electric field**

    $\vec{B}$: magnetic field
    $\vec{E}$: electric field

    - Ampere's law： $\partial_t \vec{E} - \nabla\times\vec{B} = -\vec{j}$

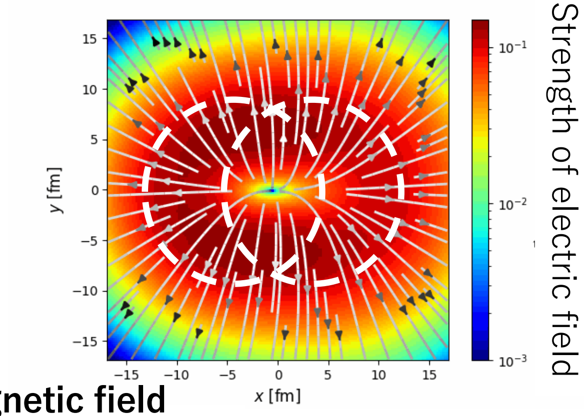
    Ohm's law makes electric field dissipate

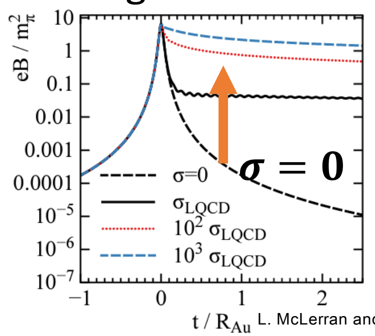
    ➡ **Dissipated energy to fluid (medium)**

  - **Charge is induced by electric field**
    - Induced charge depends on charge conductivity

  - **Dissipation of magnetic field**

    Charge conductivity of QGP





$\sigma \neq 0$

Suppresses of dissipation

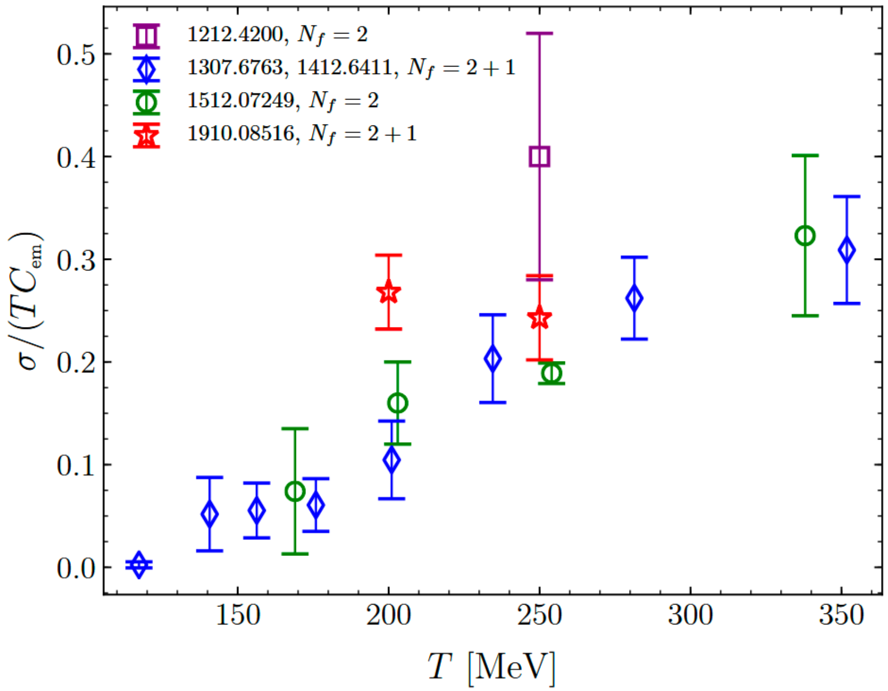
Electric field is dissipated.

L. McLerran and V. Skokov, Nucl. Phys. A 929 (2014), 184-190

⬅ **dissipation of electromagnetic fields and charge distribution QGP**

Electric Conductivity of QCD Matter

- **Lattice QCD**



Aarts, Nikolaev, EPJ.A 57, 118 (2021); 2008.12326 [hep-lat]

Electric Conductivity on the Lattice

$$\sigma = \frac{1}{6}\frac{\partial}{\omega}\left(\int d^4x e^{i\omega t}\langle[j_\mu^{\rm em}(t,x), j_\mu^{\rm em}(0,0)]\rangle\right)|_{\omega=0}$$

Uses linear-response theory (Kubo formula)
Low energy limit of the electromagnetic spectral function

- Does not include external magnetic field effects
- Uses approximately realistic pion mass
- General agreement among results using a variety of methods and parameters

Relativistic resistive magnetohydrodynamics

Understanding of QGP Property

Charge conductivity of QGP from analysis of high-energy heavy-ion collisions

Physical property	Observables	Quantitative analysis
Charge conductivity	Charge dependent flow, EM probes..	Just started
Shear viscosity	Azumithal anisotoropy v_n	○
Bulk viscosity	P_T distributions	○
Diffusion coefficient	Jet energy loss	○

Charge dependent directed flow

Asymmetic collisions → i.e., Hirono, Hongo, and Hirano, PRC 90, 021903 (2014).

Symmetric collisions

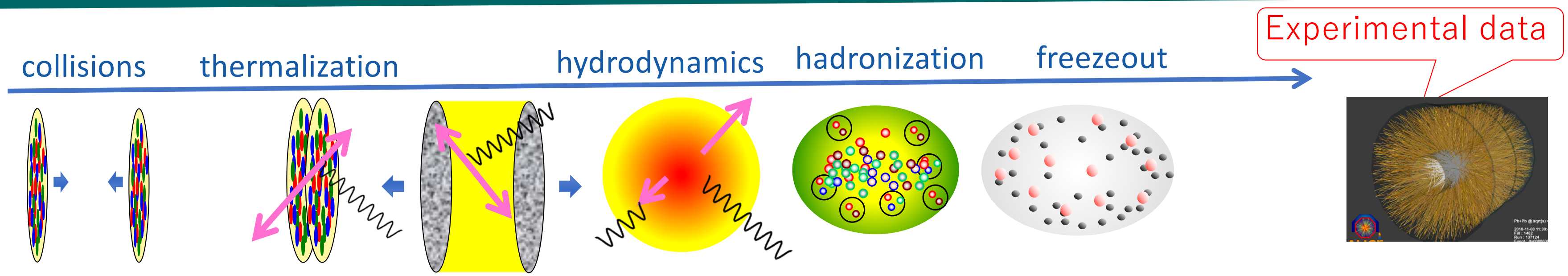
Proposed EM observables

Dileptons → i.e., Akamatsu, Hamagaki, Hatsuda, and Hirano, PRC 85, 054903 (2012).

Photons → i.e., Sun and Yan, PRC 109, 034917 (2024).

Construction of relativistic resistive magnetohydrodynamics

Space-Time Evolution of HIC



Initial condition Hydrodynamics Final state interactions

+ EM fields

Initial condition Magnetohydrodynamics Final state interactions

Smoothed Initial Condition

Tuchin, Phys.Rev.C88,024911(2013)

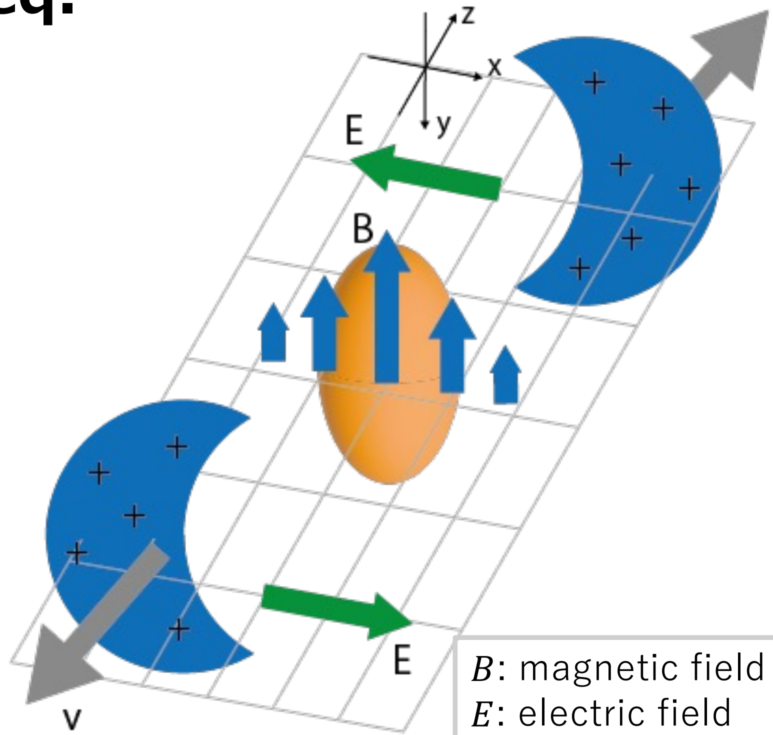
■Asymptotic solution of Maxwell eq.

➢Electromagnetic field made by point charge moving in the longitudinal axis

- Proton distribution in nucleus : uniform sphere
- Constant charge conductivity (σ =0.023 fm^{-1})

$$\nabla \cdot \boldsymbol{B} = 0\,, \quad \nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}\,,$$
$$\nabla \cdot \boldsymbol{D} = e\delta(z - vt)\delta(\boldsymbol{b})\,,$$
$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \sigma \boldsymbol{E} + ev\hat{z}\delta(z - vt)\delta(\boldsymbol{b})$$

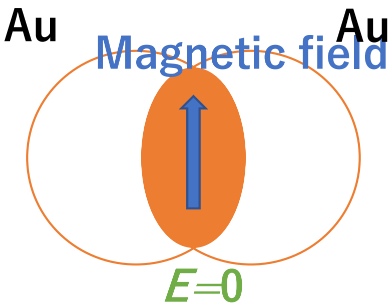
Integration of the asymptotic solutions over the charge distribution inside of nucleus



B: magnetic field
E: electric field
v: velocity of heavy ion

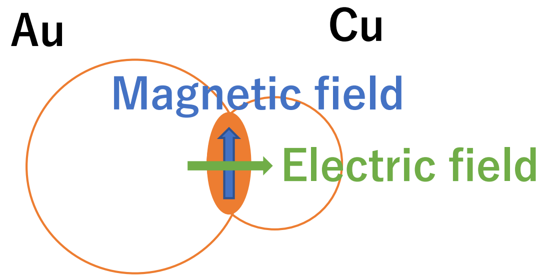
Electromagnetic Field in Symmetric and Asymmetric Systems

■**Au-Au collisions**



- Magnetic field
  - Strong magnetic field
- Electric field
  - No electric field

■**Cu-Au collisions**



- Magnetic field
  - Strong magnetic field
- Electric field
  - $E \neq 0$ **due to the asymmetry of the charge distribution**

Hirono, Hongo, Hirano

Initial Condition：QGP Medium

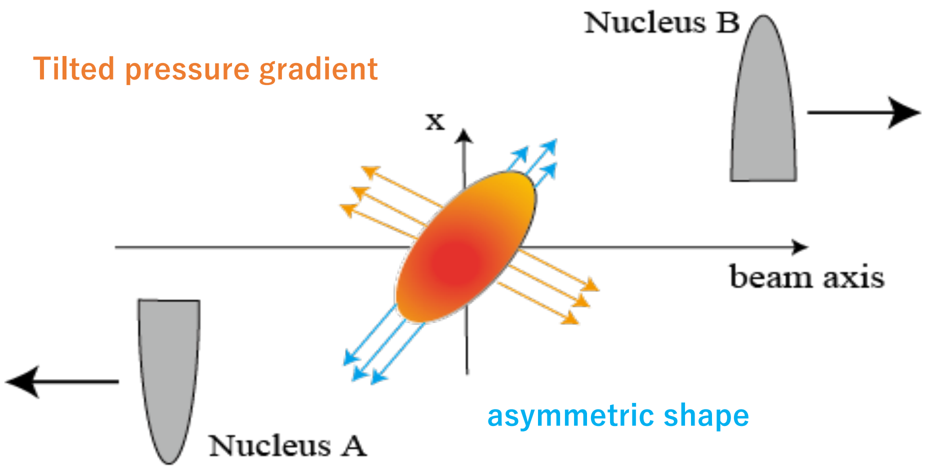
■ Tilted Glauber model

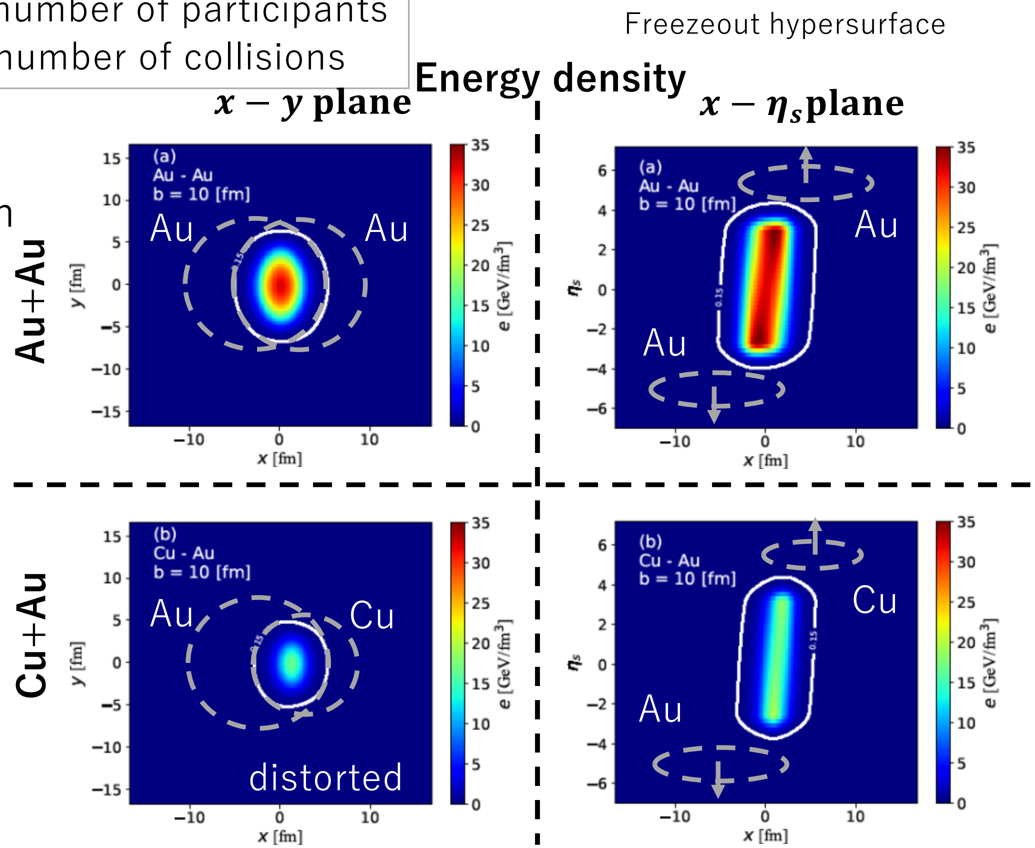
n_p : number of participants
n_c : number of collisions

Bozek, et al, Phys. Rev. C 81, 054902(2010)

- Energy density is scaled by n_p and n_c
- Tilted distribution in the longitudinal direction

For directed flow v_1





Initial Condition：Electromagnetic Fields ($\eta_s = 0$)

Tuchin, Phys.Rev.C88,024911(2013)

■**Au+Au**

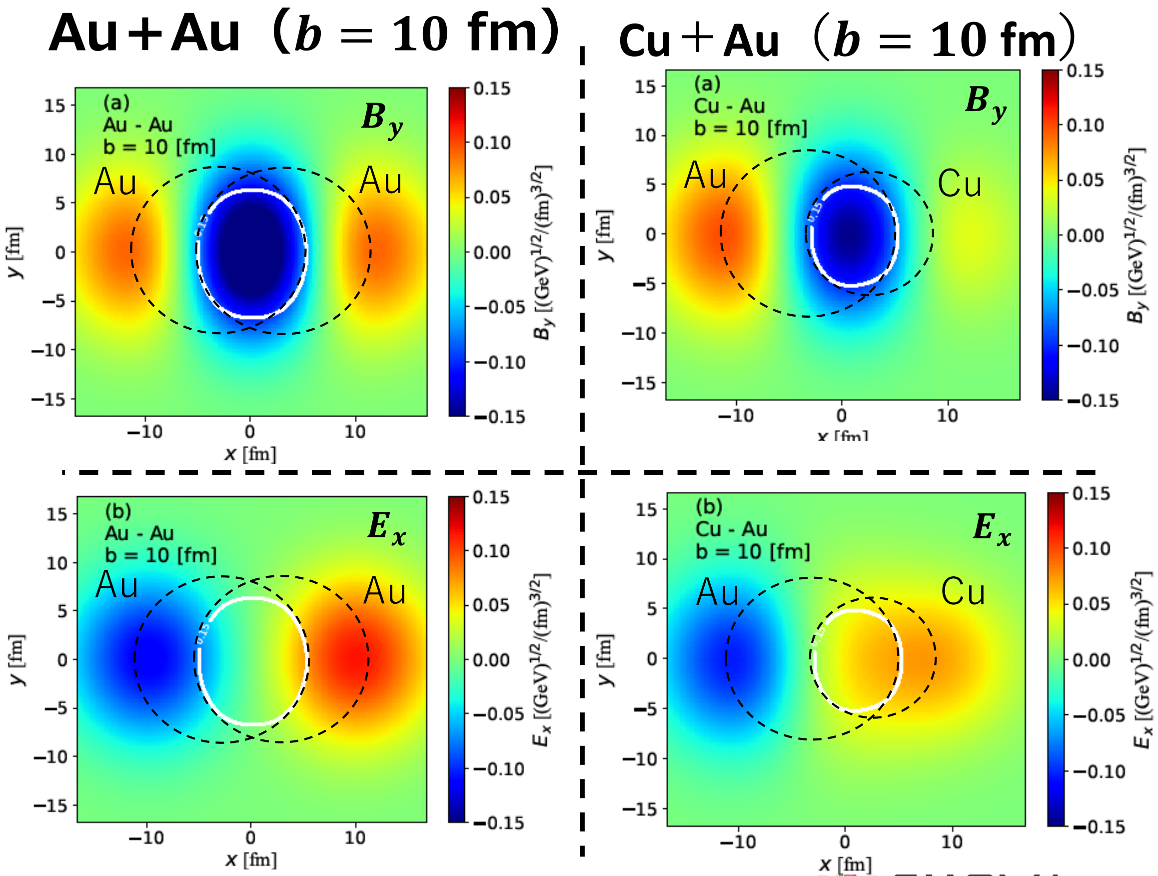
➢Strong magnetic fields in QGP

➢Electric field ～0 in QGP

■**Cu+Au**

➢Strong magnetic field in QGP

➢Finite electric field in QGP



Freezeout hypersurface

Magnetohydrodynamics

- **Magnetohydrodynamics**
  - Conservation law

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\Downarrow$$

$$\nabla_\mu T^{\mu\nu}_m = -J_\mu F^{\mu\nu}$$

Energy momentum tensor

$$T^{\mu\nu} = T^{\mu\nu}_m + T^{\mu\nu}_f$$

matter

$$T^{\mu\nu}_m = (e+p)u^\mu u^\nu + p g^{\mu\nu}$$

Maxwell eq.

$$\nabla_\mu F^{\mu\nu} = -J^\nu$$

EM field

$$T^{\mu\nu}_f = F^{\mu\lambda}F^\nu_\lambda - \frac{1}{4}g^{\mu\nu}F^{\lambda\kappa}F_{\lambda\kappa};$$

$$\nabla_\mu T^{\mu\nu}_f = J_\mu F^{\mu\nu}$$

- Ohm's law *Blackman and Field, PRL71,3481(1993)*

$$J^\mu = \sigma F^{\mu\nu}u^\nu + q u^\mu$$

Electrical conductivity

$$q = -J^\mu u_\mu$$

Magnetohydrodynamics

- **Magnetohydrodynamics**
  - Conservation law

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\nabla_\mu T^{\mu\nu}_m = -J_\mu F^{\mu\nu}$$

Energy momentum tensor

$$T^{\mu\nu} = T^{\mu\nu}_m + T^{\mu\nu}_f$$

matter

$$T^{\mu\nu}_m = (e+p)u^\mu u^\nu + p g^{\mu\nu}$$

+viscosity, *Hattori..*

Maxwell eq.

$$\nabla_\mu F^{\mu\nu} = -J^\nu$$

EM field

$$T^{\mu\nu}_f = F^{\mu\lambda}F^\nu_\lambda - \frac{1}{4}g^{\mu\nu}F^{\lambda\kappa}F_{\lambda\kappa};$$

$$\nabla_\mu T^{\mu\nu}_f = J_\mu F^{\mu\nu}$$

- Ohm's law *Blackman and Field, PRL71,3481(1993)*

$$J^\mu = \sigma F^{\mu\nu}u^\nu + q u^\mu$$

Electrical conductivity

$$q = -J^\mu u_\mu$$

Charge diffusion, *Dash et al., PRD107,056003(2023)*

Magnetohydrodynamics

- **RRMHD equation**
  - Conservation law + Maxwell eq. + Ohm's law

$$\partial_\mu T^{\mu\nu} = F^{\nu\lambda} J_\lambda$$

$$J^\mu = J_c^\mu + q u^\mu$$

e: energy density
p: pressure
$p_{em} = (E^2 + B^2)/2$

$$\varepsilon = (e+p)\gamma^2 - p + p_{em}$$
$$m^i = (e+p)\gamma^2 v^i + \epsilon^{ijk} B_j E_k$$
$$\Pi^{ij} = (e+p)\gamma^2 v^i v^j + (p + p_{em}) g^{ij} - E^i E^j - B^i B^j$$

Energy Conservation

$$\partial_t \varepsilon + \nabla \cdot m = 0$$

Momentum conservation

$$\partial_t m^i + \nabla \cdot \Pi^i = 0$$

Faraday's law

$$\partial_t \vec{B} + \nabla \times \vec{E} = 0$$

Ohm's law

$$\vec{J} = q\vec{v} + \underbrace{\sigma\gamma[\vec{E} + \vec{v}\times\vec{B} - (\vec{v}\cdot\vec{E})\vec{v}]}_{=:\vec{J}_c}$$

Ampere's law

$$\partial_t \vec{E} - \nabla\times\vec{B} = -\vec{J}$$

$$\partial_t \vec{E} - \nabla\times\vec{B} = q\vec{v}$$

$$\partial_t \vec{E} = \vec{J}_c$$

operator splitting

- Integration with quasi-analytic solutions

$$\vec{E}_\perp = -\vec{v}\times\vec{B} + (E_\perp^0 + \vec{v}\times\vec{B}) \exp(-\sigma\gamma t)$$
$$\vec{E}_\parallel = E_\parallel^0 \exp(-\sigma t/\gamma)$$

Benoit, Miyoshi, C. N., and Takahashi, ArXiv: 2502.04611
Nakamura, Miyoshi, C. N. and Takahashi, Phys. Rev. C 107, (2023) 014901
Nakamura, Miyoshi, C. N. and Takahashi, Eur.Phys.J.C 83 (2023) 3, 229.
Nakamura, Miyoshi, C. N. and Takahashi, Phys. Rev. C 107 (2023) 3, 034912

RRMHD Equation in Milne Coordinates

New

- **Milne coordinates**
  - **Expanding systems in the longitudinal direction (τ, x, y, η_s)**
    - Strong expansion in the longitudinal direction is effectively included.
    - Number of grid of fluid is saved.

$$\tau = \sqrt{t^2 - z^2}$$
$$\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$$

RRMHD Equation

$$\partial_\tau(\tau U) + \partial_i(\tau F^i) = \tau S$$

$$U = \begin{pmatrix} D \\ m_j \\ \varepsilon \\ B^j \\ E^j \\ q \end{pmatrix}, \mathrm{F^i} = \begin{pmatrix} Dv^i \\ \Pi^{ji} \\ m^i \\ \varepsilon^{jik} E_k \\ \varepsilon^{jik} B_k \\ J^i \end{pmatrix}, S = \begin{pmatrix} 0 \\ \frac{1}{2} T^{ik} \partial_j g_{ik} \\ -\frac{1}{2} T^{ik} \partial_0 g_{ik} \\ 0 \\ J_c^i \\ 0 \end{pmatrix}$$

The first RRMHD code in Milne coordinates

Validation of the Code

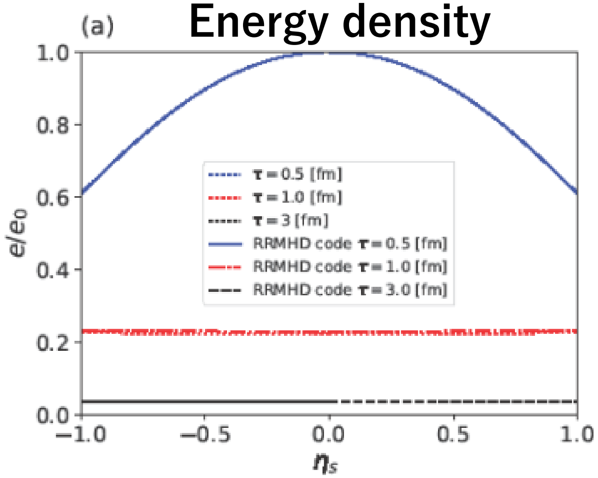
- **RRMHD in the Milne coordinates**

Nakamura, Miyoshi, CN and Takahashi, Eur.Phys.J.C 83 (2023) 3, 229.

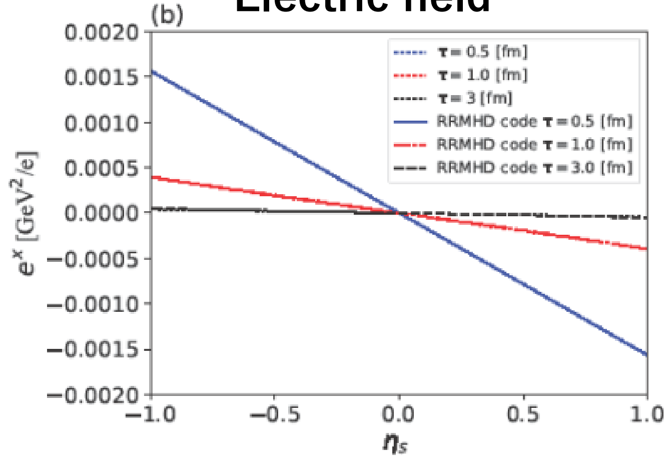
New Test Problem

- **(1+1) dimensional expansion system** $u^\mu = (\cosh Y, 0, 0, \sinh Y)$
  - Comparison between quasi-analytical solution and RRMHD simulation

Energy density



Electric field



Solid line : RRMHD code
Dashed line: quasi-analytical solution

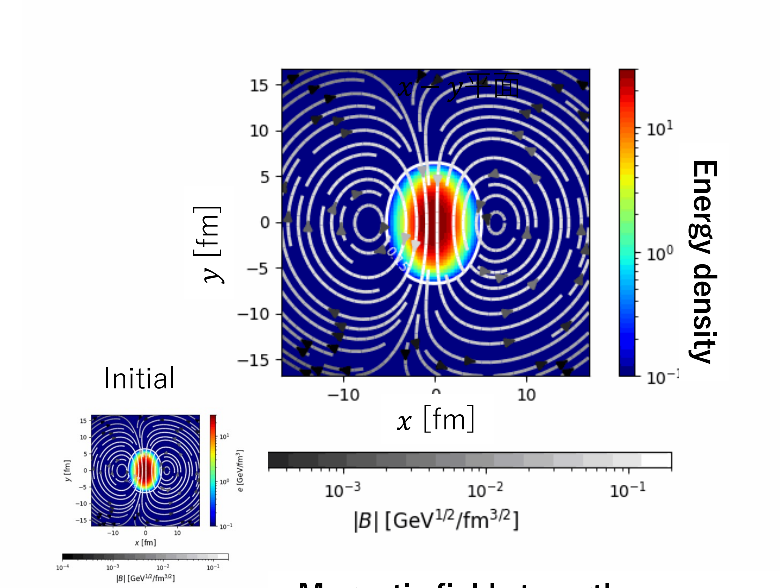
➡ **Application to Heavy Ion Collisions**

Space-time Evolution

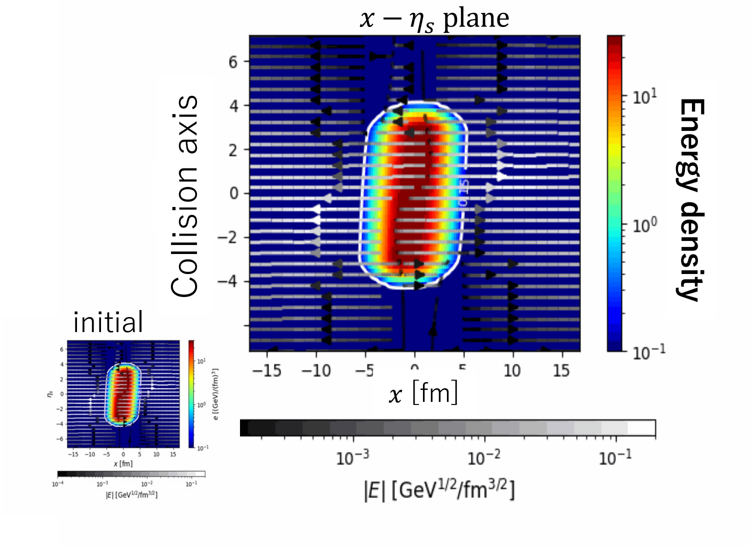
Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

Au+Au collision system

First calculation in HIC with RRMHD code



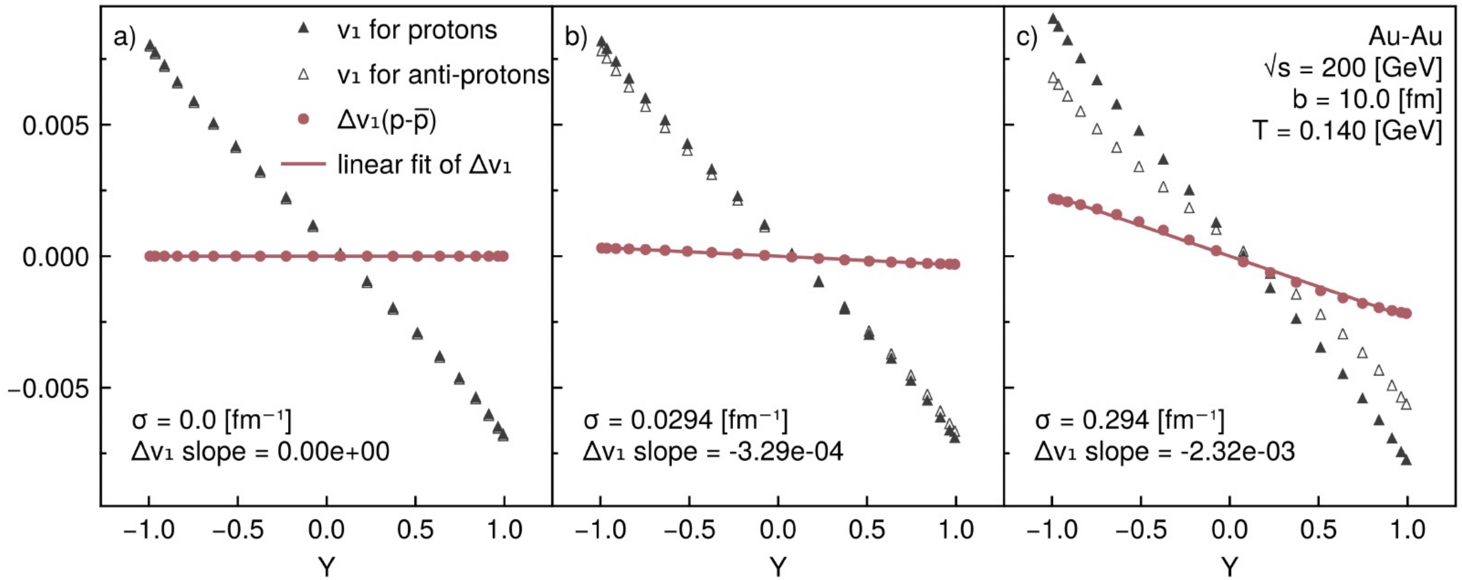
Magnetic field strength



Electric field strength

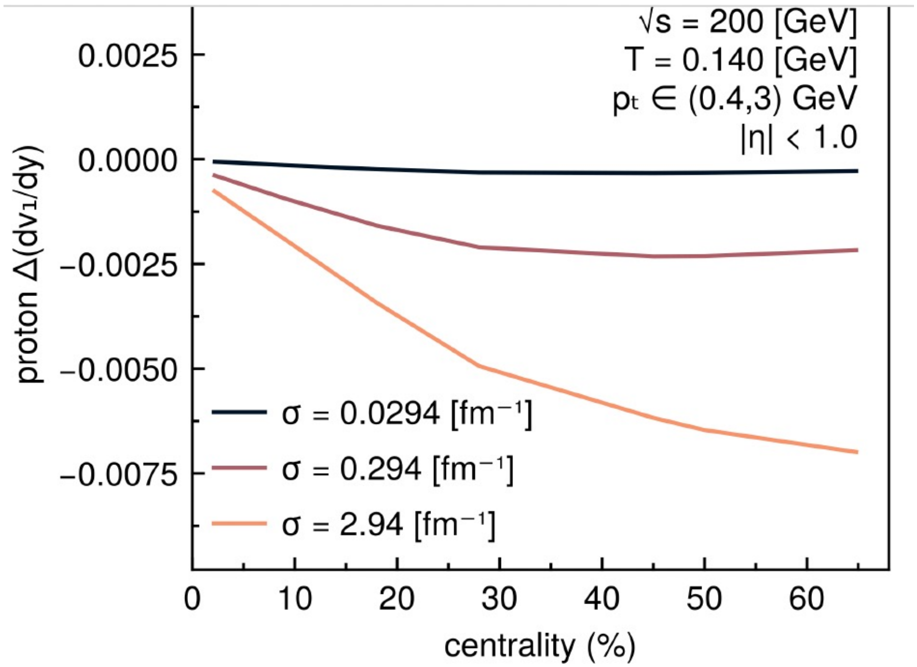
Analysis of Heavy Ion Collisions

Charge Dependent Directed Flow

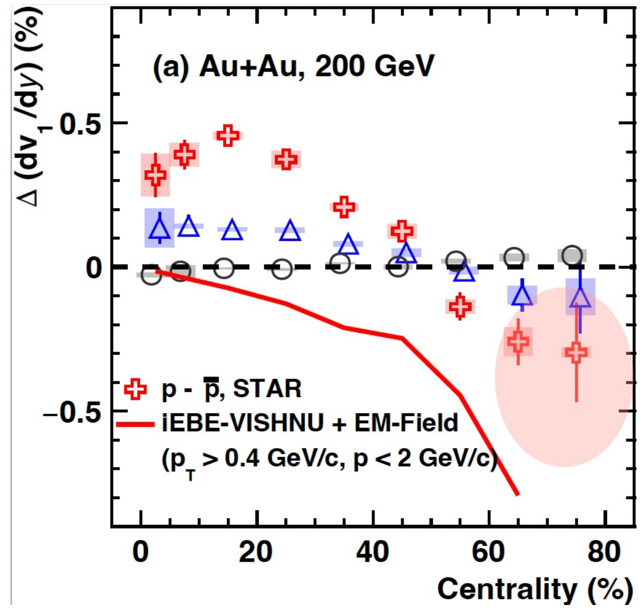


Benoit, Miyoshi, C. N., and Takahashi, ArXiv: 2502.04611

Charge Dependent Flow



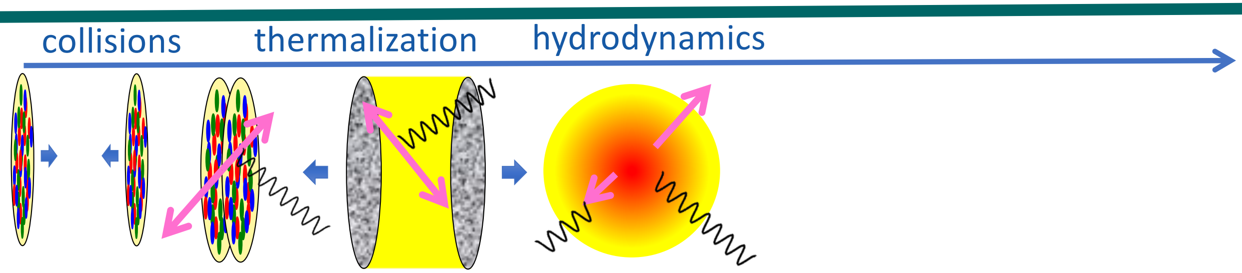
Benoit, Miyoshi, C. N., and Takahashi, ArXiv: 2502.04611



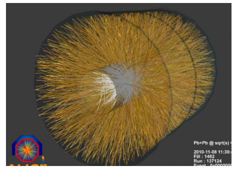
Caveat:

- No baryon current
- Initial condition
- EoS
- Final state interactions

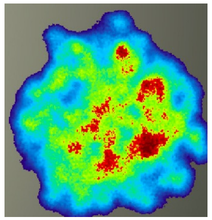
Initial Condition



Experimental data



Initial conditions



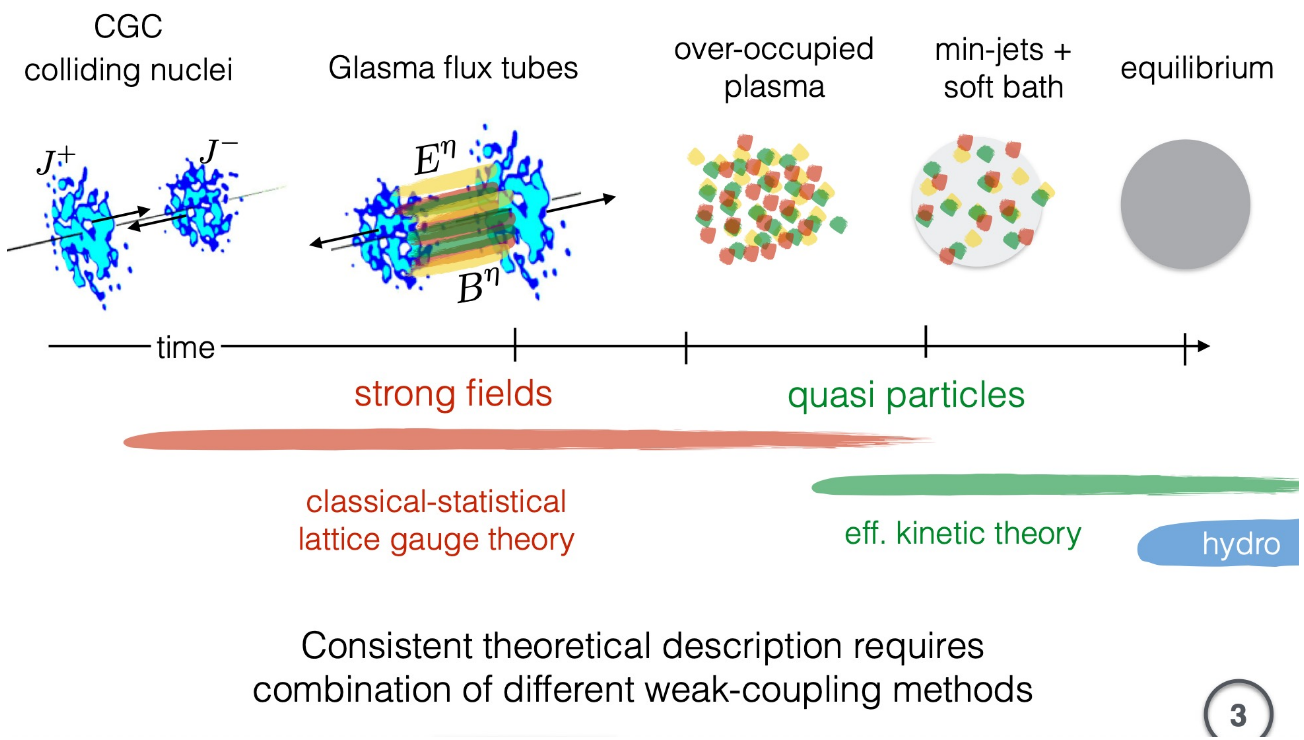
Energy (entropy) density distributions

最も難しい問題の一つ

Hydrodynamics

QCD phase diagram
EoS: lattice QCD
Shear and bulk viscosities

General picture at weak-coupling



Schlichting [Initial Stages 2016]

Initial Condition (Thermalization)

Abdi

- Transport model : approximation solution to Boltzmann Transport Equation.

$$\frac{\partial}{\partial t} f(t,\vec{r},\vec{p}) + \frac{\vec{p}}{m}\nabla_{\vec{r}} f(t,\vec{r},\vec{p}) - \nabla_{\vec{r}} U(\vec{r}) \nabla_{\vec{p}} f(t,\vec{r},\vec{p}) = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

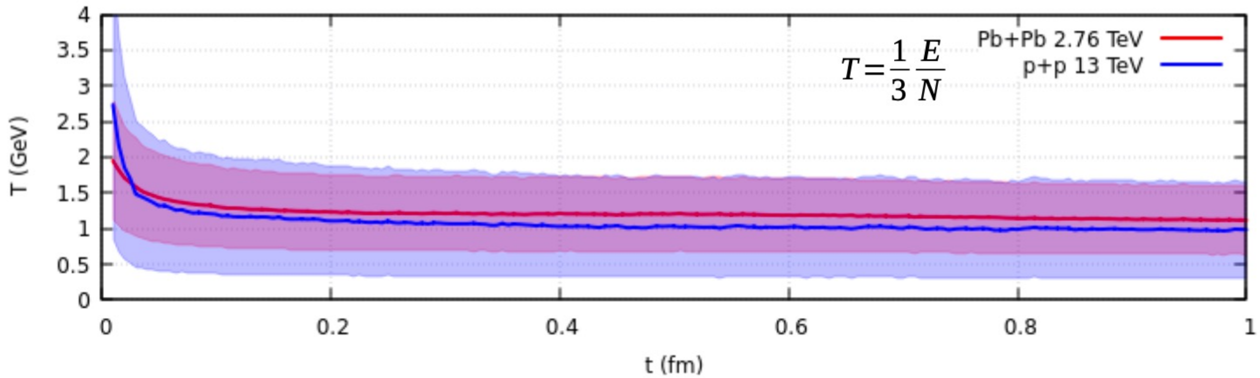
Time evolution　Diffusion　External field　Interparticle collision

- Applicable to far-from-equilibrium quark-gluon plasma.
- Bottom up approach to quark-gluon plasma thermal and chemical equilibration.
- Based on Hadronic transport model SMASH[1] reconfigured for quark-gluon plasma case.

Goal : Create a realistic initial condition generator model for hydrodynamic simulation with the minimum number of free parameters.

Parton Cascade Model

[1] J. Weil, V. Steinberg, J. Staudenmaier, L. G. Pang, D. Oliinyche Goldschmidt, B. Bäuchle, J. Auvinen, M. Attems, and H. Petersen



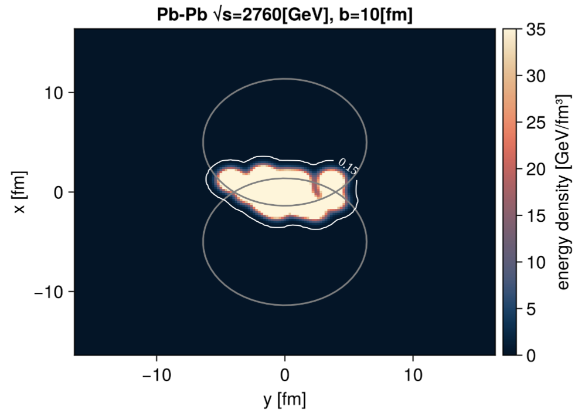
- Temperature is constantly decreasing due to the expanding medium
- Saturation behaviour can be seen well before 0.2 fm for both collision systems

C. NONAKA

Initial Conditions : Quark Production

Benoit, Taya

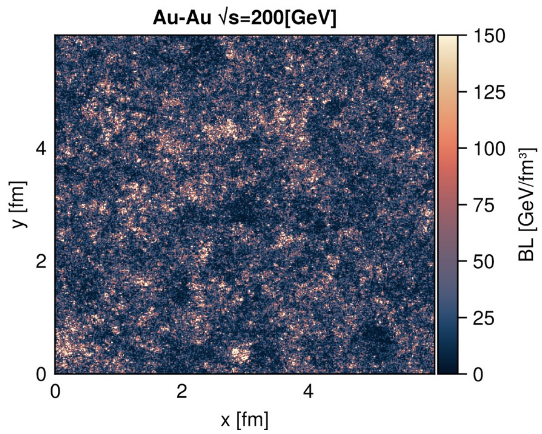
- **Smoothed initial conditions**
- **Fluctuating initial conditions**
  - Smaller B field, Larger E field
- **Glasma initial condition**

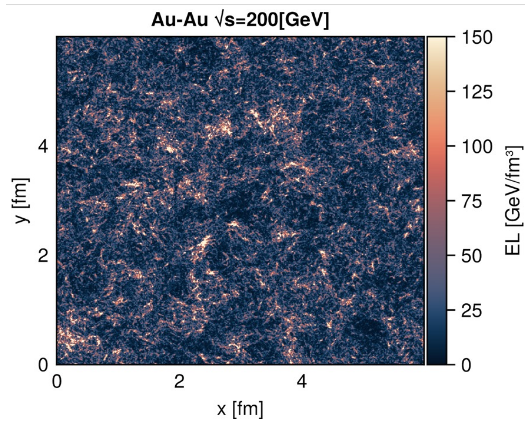


Benoit

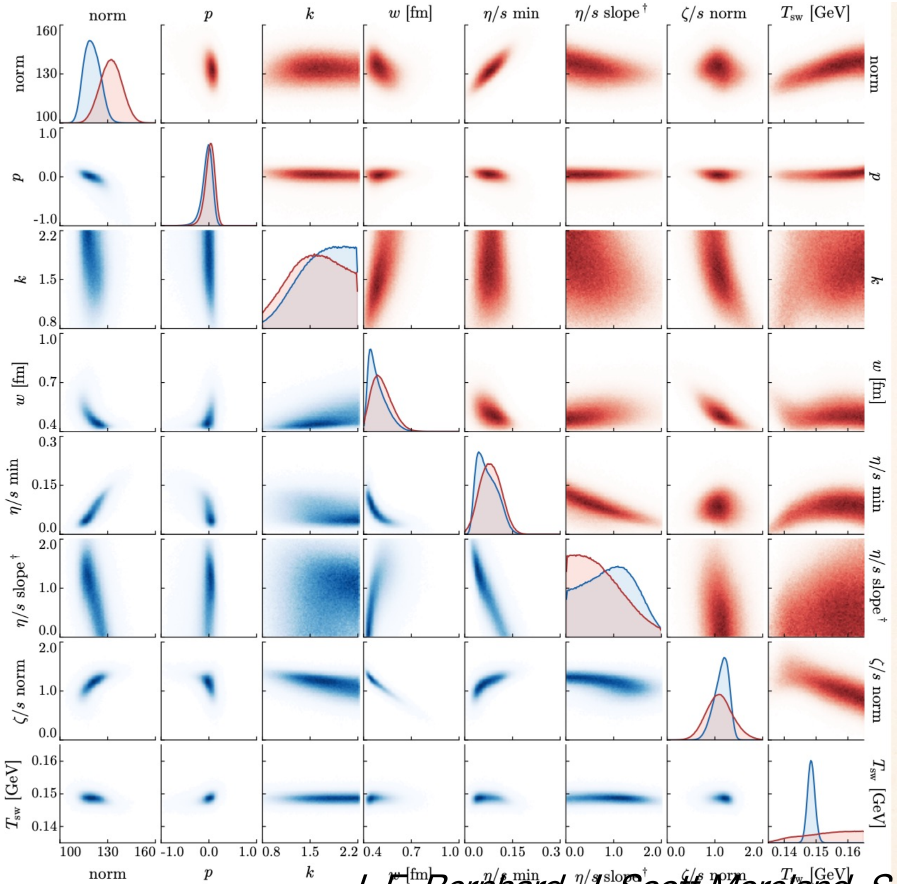
Gluon場中の粒子

Particle in Cell





ベイジアン解析



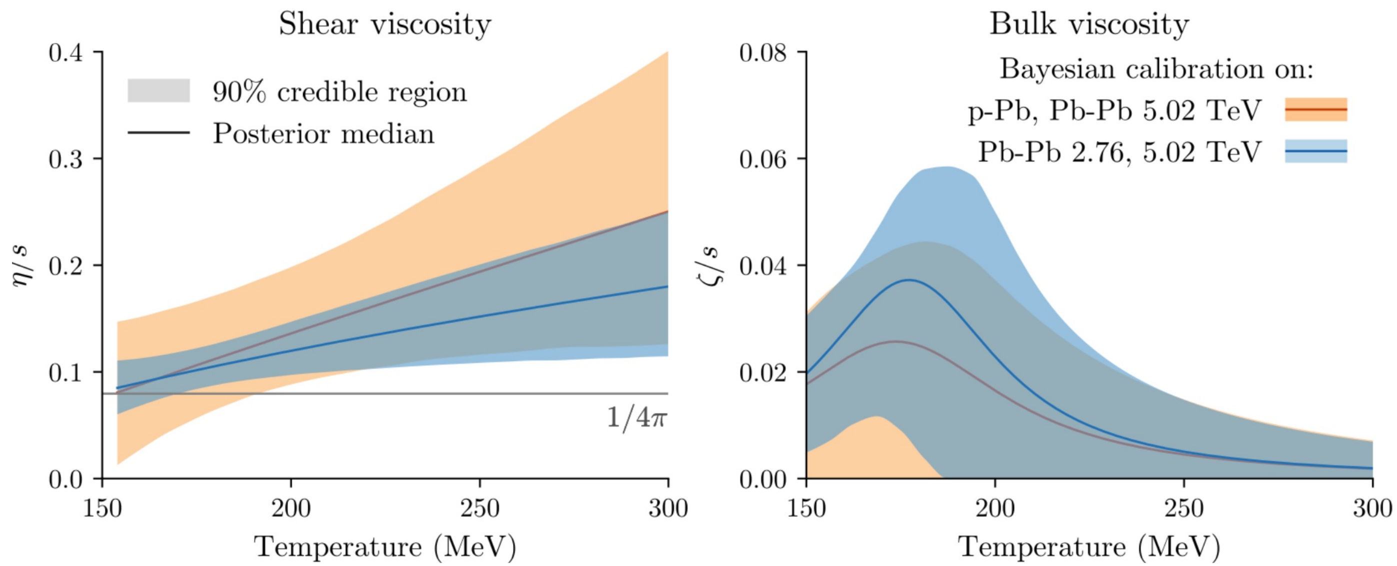
流体模型中の
パラメータ

↕

複数の実験結果

J. E. Bernhard, J. Scott Moreland, S. A. Bass, J. Liu, U. Heinz, PRC 94.024907(2016)

粘性の温度依存性



あくまでも模型内での結果

クォーク・グルーオン　プラズマの物理

- **世界規模の実験が稼働中：理論と実験の検証**
- **周辺物理との関連**
  - 理論的概念、ツール：共通点
  - 基礎理論
    - 相転移、相図
    - 平衡、非平衡物理
    - 熱力学量
  - ダイナミクスの記述
    - 相対論的流体模型
    - 分子動力学
    - Particle in Cell
  - データ解析、大規模計算
    - ベイジアン解析