Quark-Gluon Plasma: Recent Development of Phenomenological Models

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

Kobayashi Maskawa Institute, Nagoya University

Department of Physics, Nagoya University

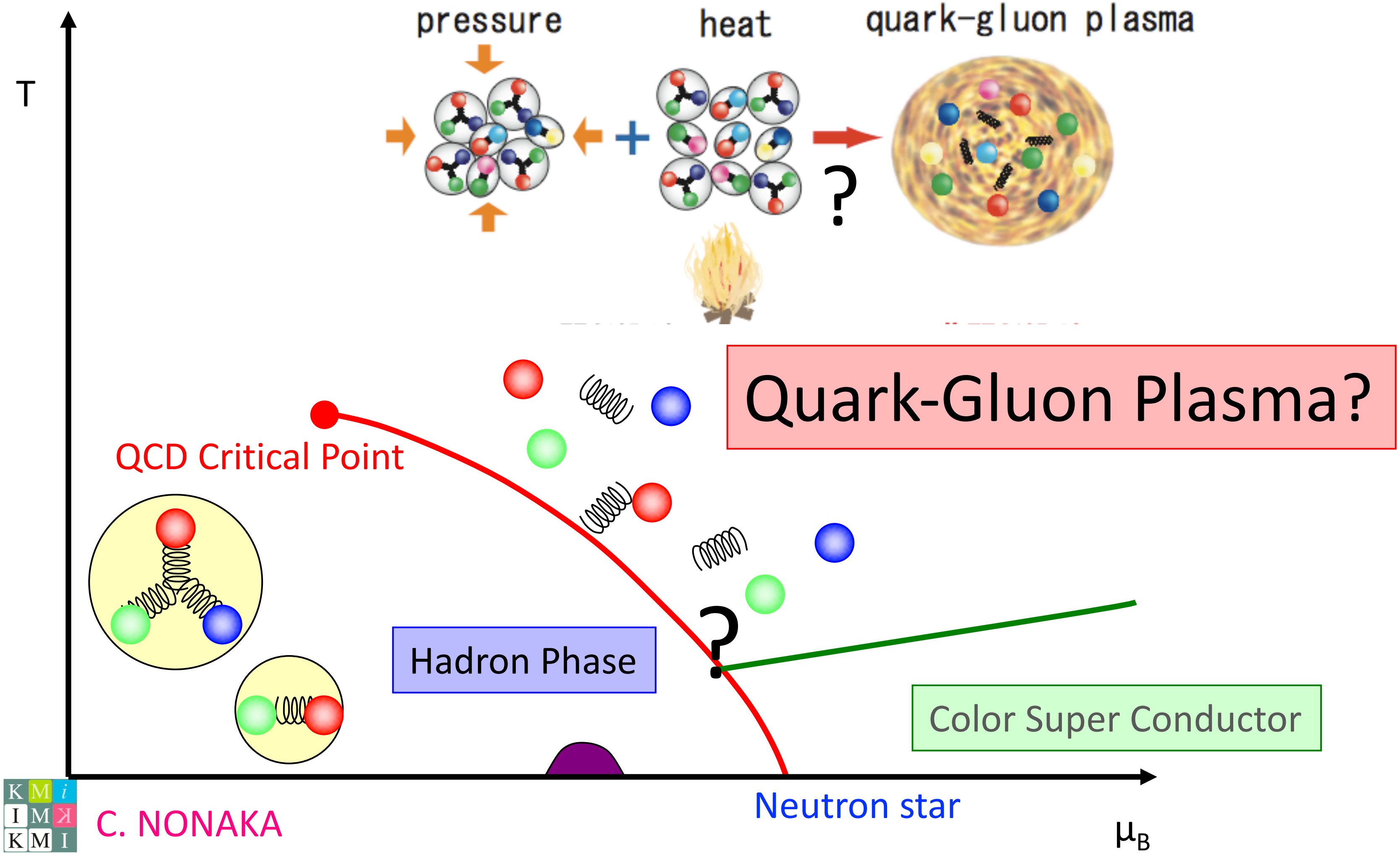
Chiho NONAKA

February 19, 2018@KMI2019

What is the QGP?

Quark-Gluon Plasma

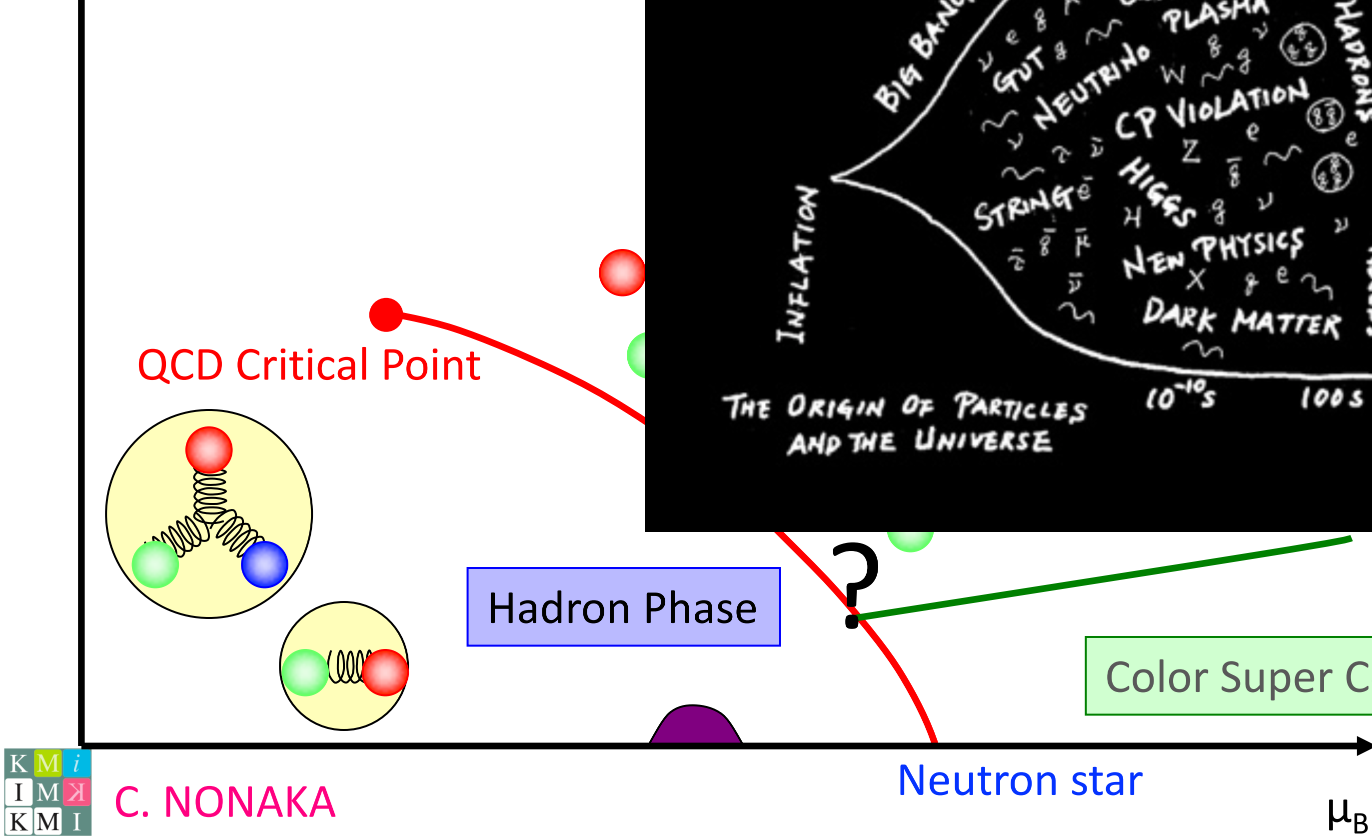
- Quarks and gluons at extreme conditions
  - High temperature and/or high density



What is the QGP?

Quark-Gluon Plasma

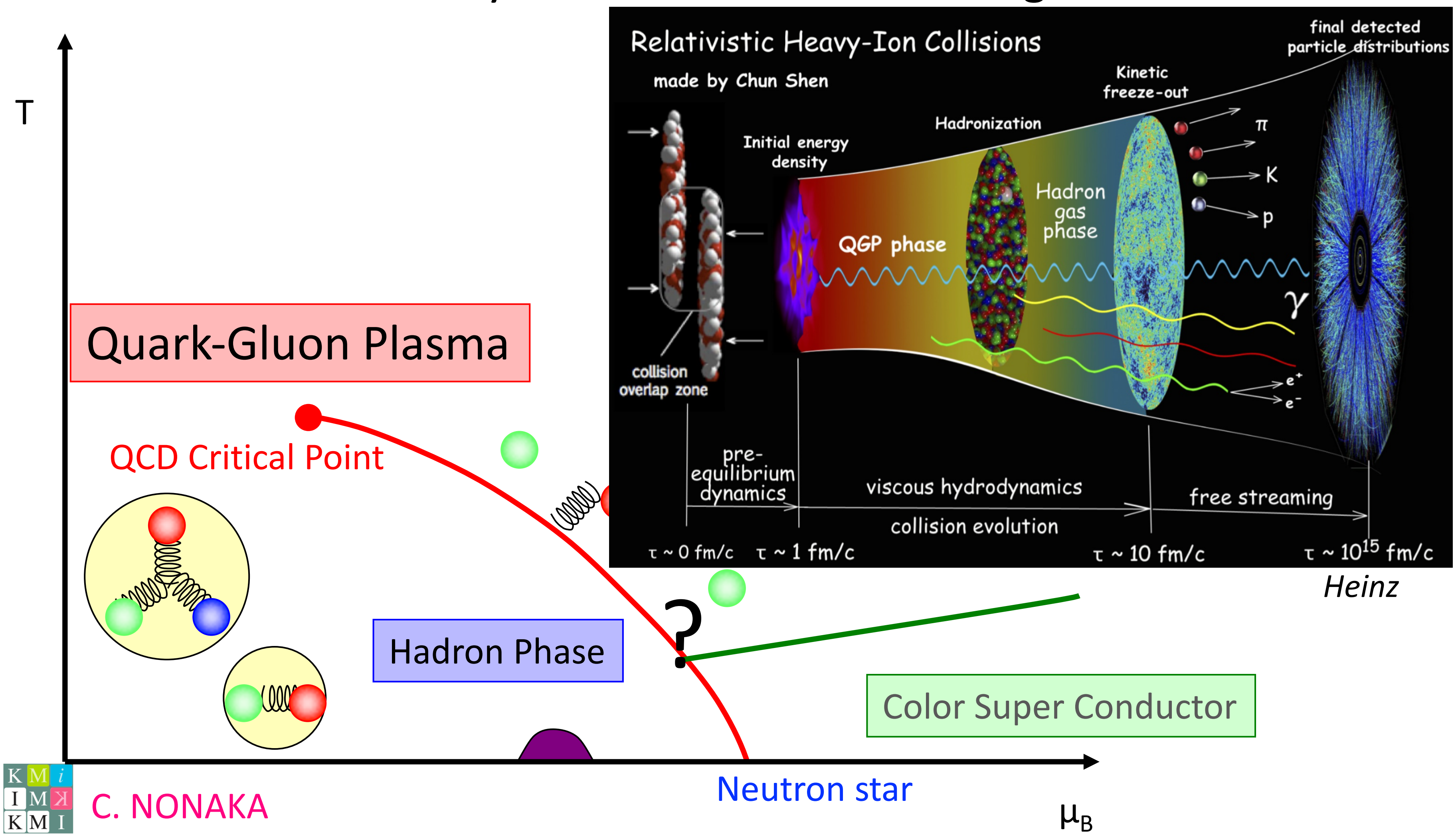
- Quarks and gluons at extreme conditions
  - Early Universe



What is the QGP?

Quark-Gluon Plasma

- Quarks and gluons at extreme conditions
  - Relativistic Heavy Ion Collisions : Little Bang



Heinz

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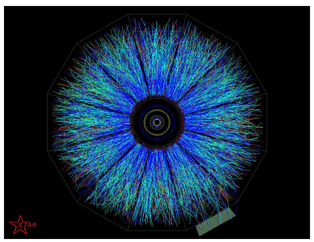
What is the sQGP?

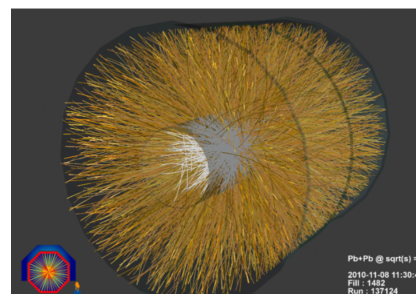
Quark-Gluon Plasma

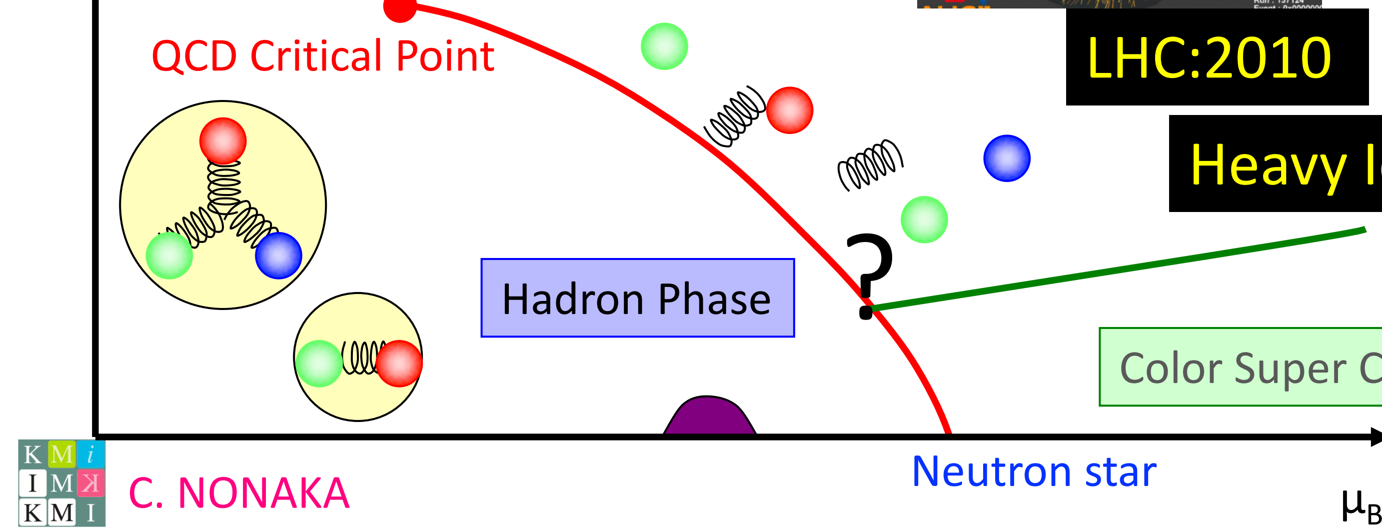
- Quarks and gluons at extreme conditions
  - Relativistic Heavy Ion Collisions

2000: Relativistic Heavy Ion Collider

Success of relativistic hydrodynamic model



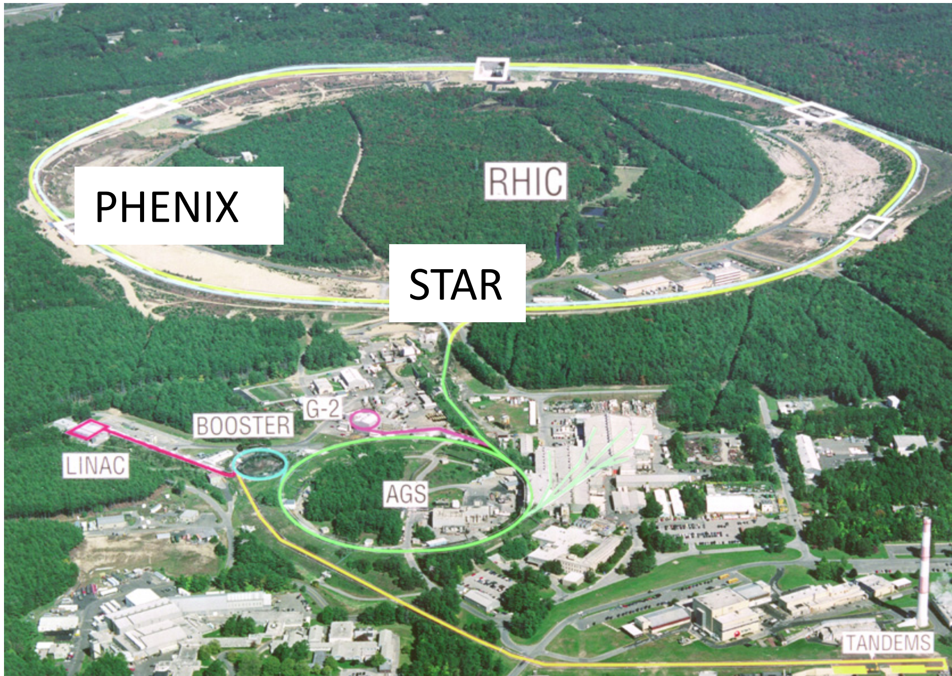




LHC:2010

Heavy Ion collisions start!

Heavy Ion Collisions



RHIC@BNL

Large Hadron Collider@CERN

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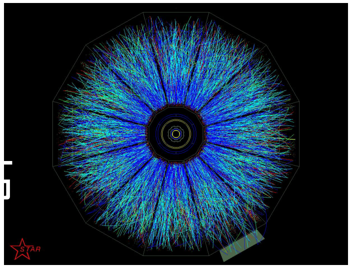
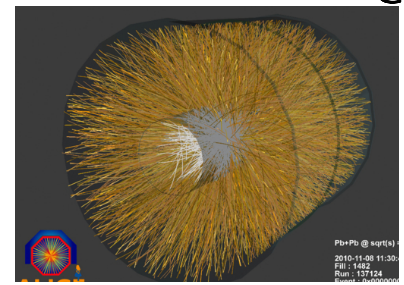
Heavy Ion Collisions

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

Pb+Pb
2760

p+Pb
Pb+Pb
5020 GeV

RHIC

LHC

$\sqrt{s_{NN}}$

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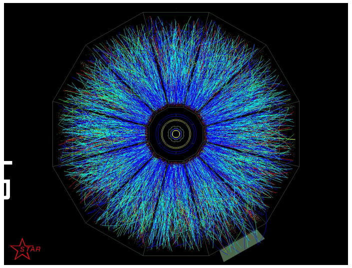
Heavy Ion Collisions

STAR@RHIC



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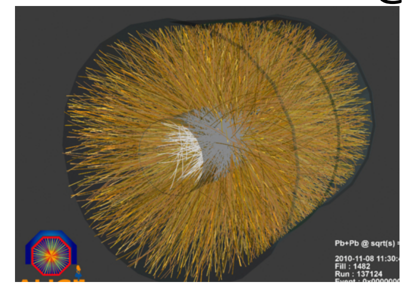

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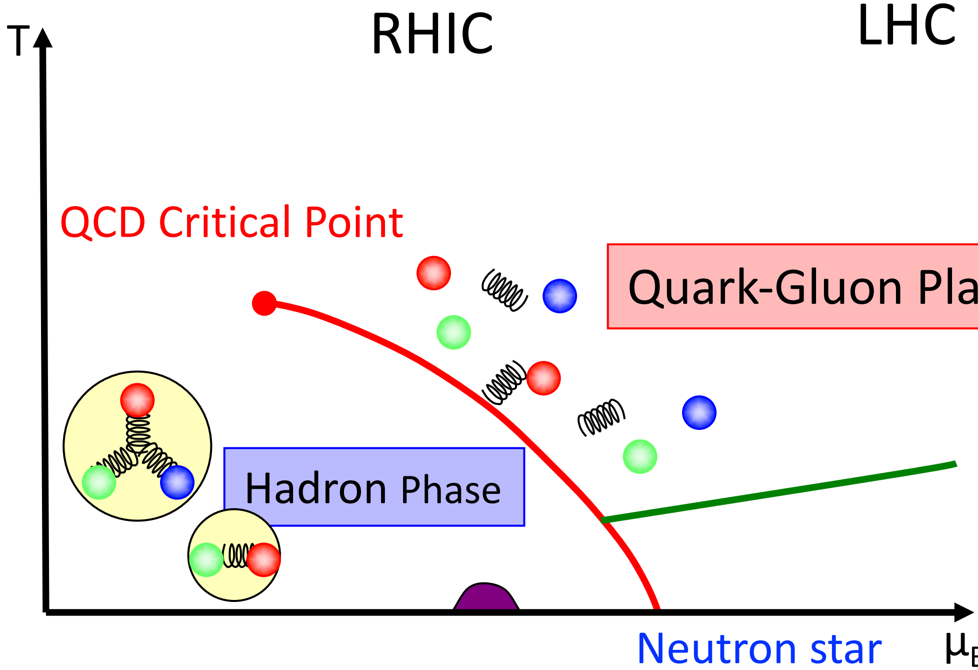

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Statistical Model

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

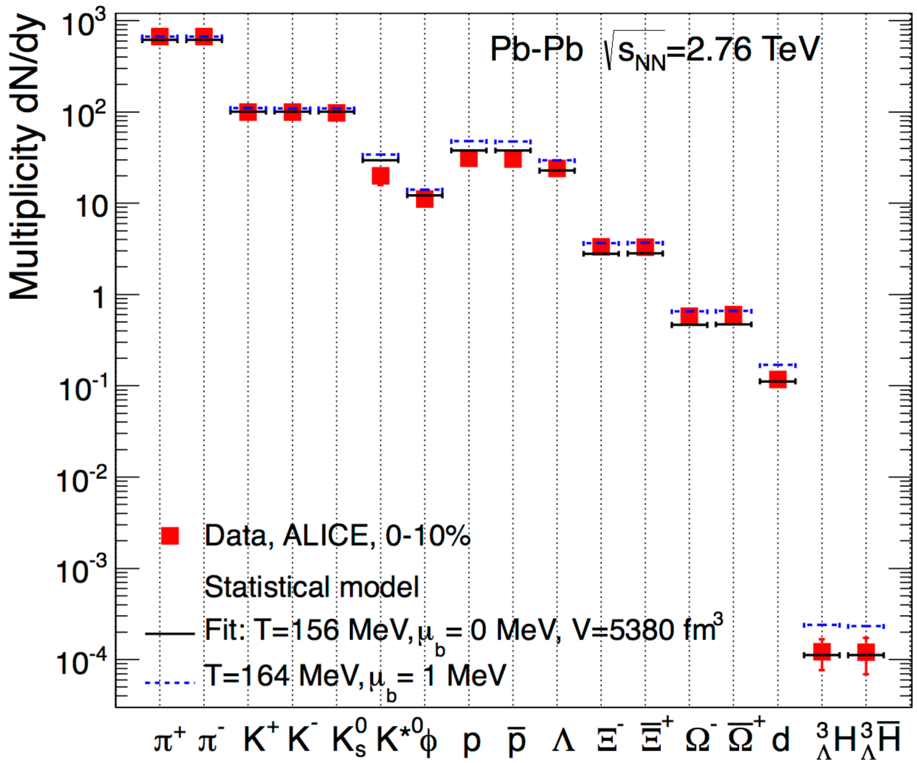
p+p, d+Au,He+Au U+U, Au+Au, 200

Pb+Pb 2760

p+p p+Pb Pb+Pb 5020

GeV

Experimental data → Location on the QCD Phase diagram



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

Pb+Pb 2760 GeV

-> ~ T=156 MeV, μ=0

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Ex:Stachel et al, arXiv:1311.4662

Heavy Ion Collisions and QCD phase diagram

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

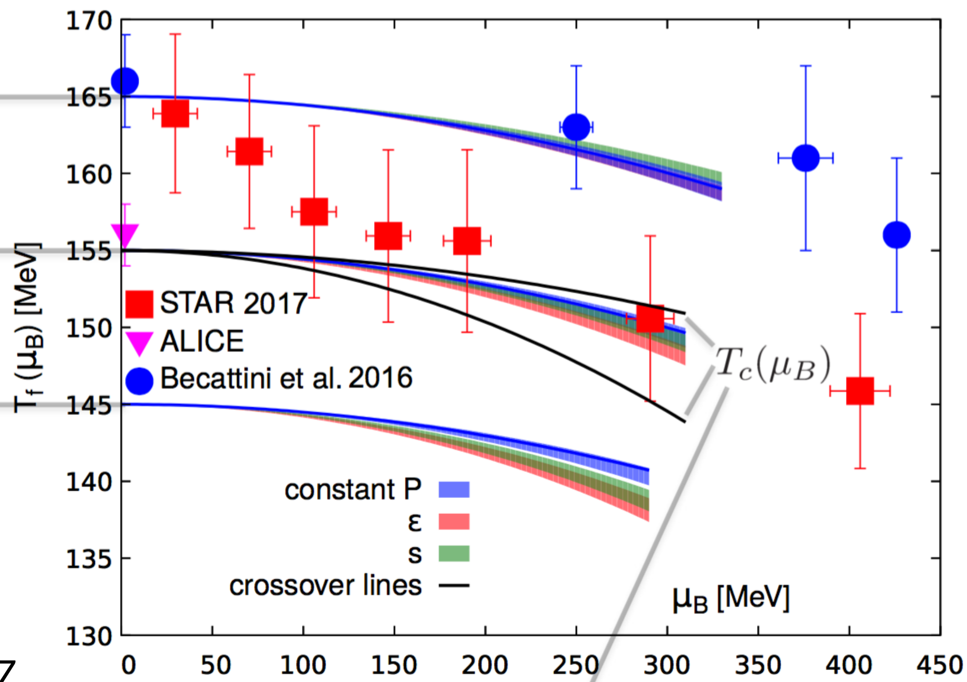
p+p
p+Pb
Pb+Pb
5020

GeV

T=165 MeV
ϵ = 0.556(57) GeV/fm^3

T=155 MeV
ϵ = 0.346(41) GeV/fm^3

T=145 MeV
ϵ = 0.203(27) GeV/fm^3



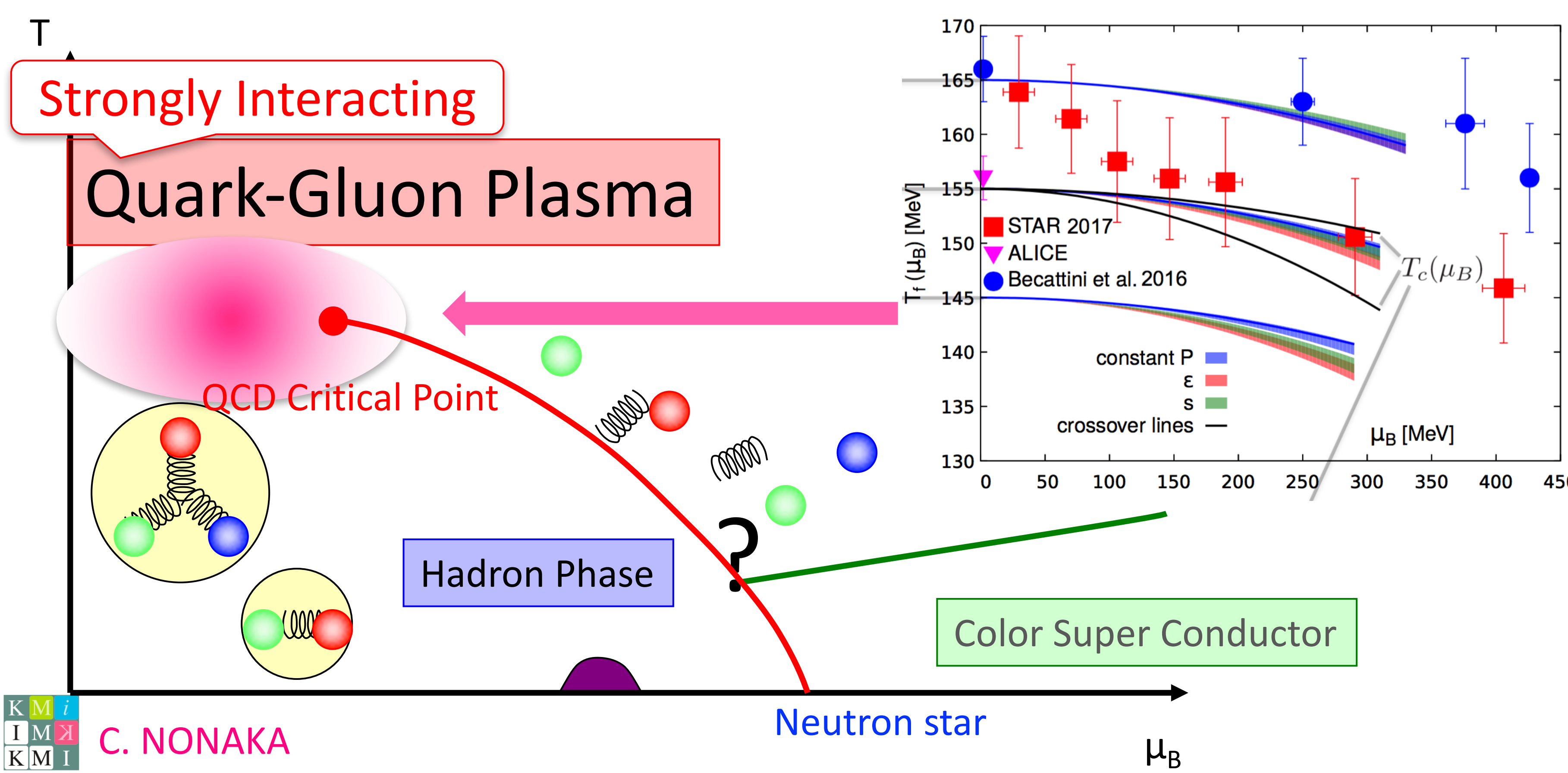
Lattice QCD
Tc=154(9) MeV
HotQCD
PRD85,054503
(2012)

Kaczmarek@QM2017

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

Heavy Ion Collisions and QCD phase diagram

Au+Au(Beam Energy Scan)	p+p, d+Au,He+Au U+U, Au+Au,	Pb+Pb	p+p p+Pb Pb+Pb	
7.7, 11.5, 19.8, 27, 39	200	2760	5020	GeV



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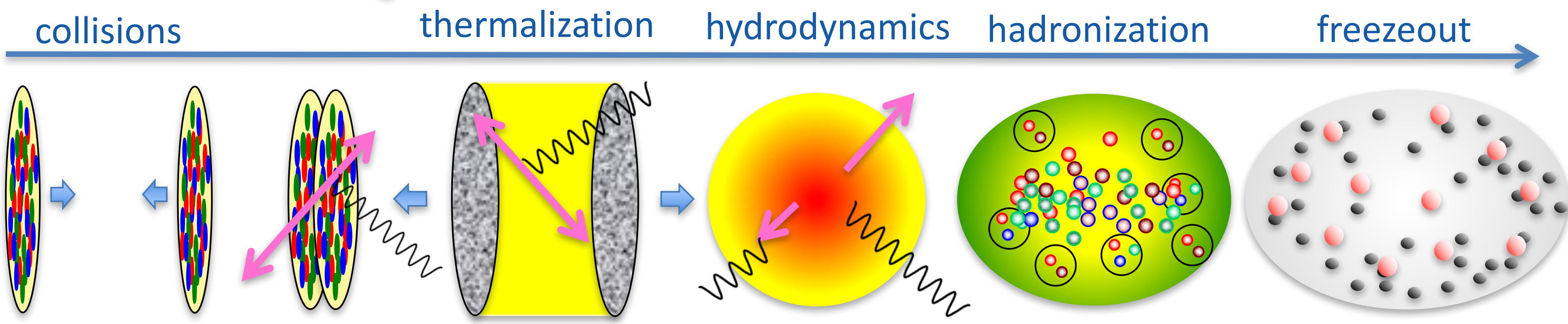
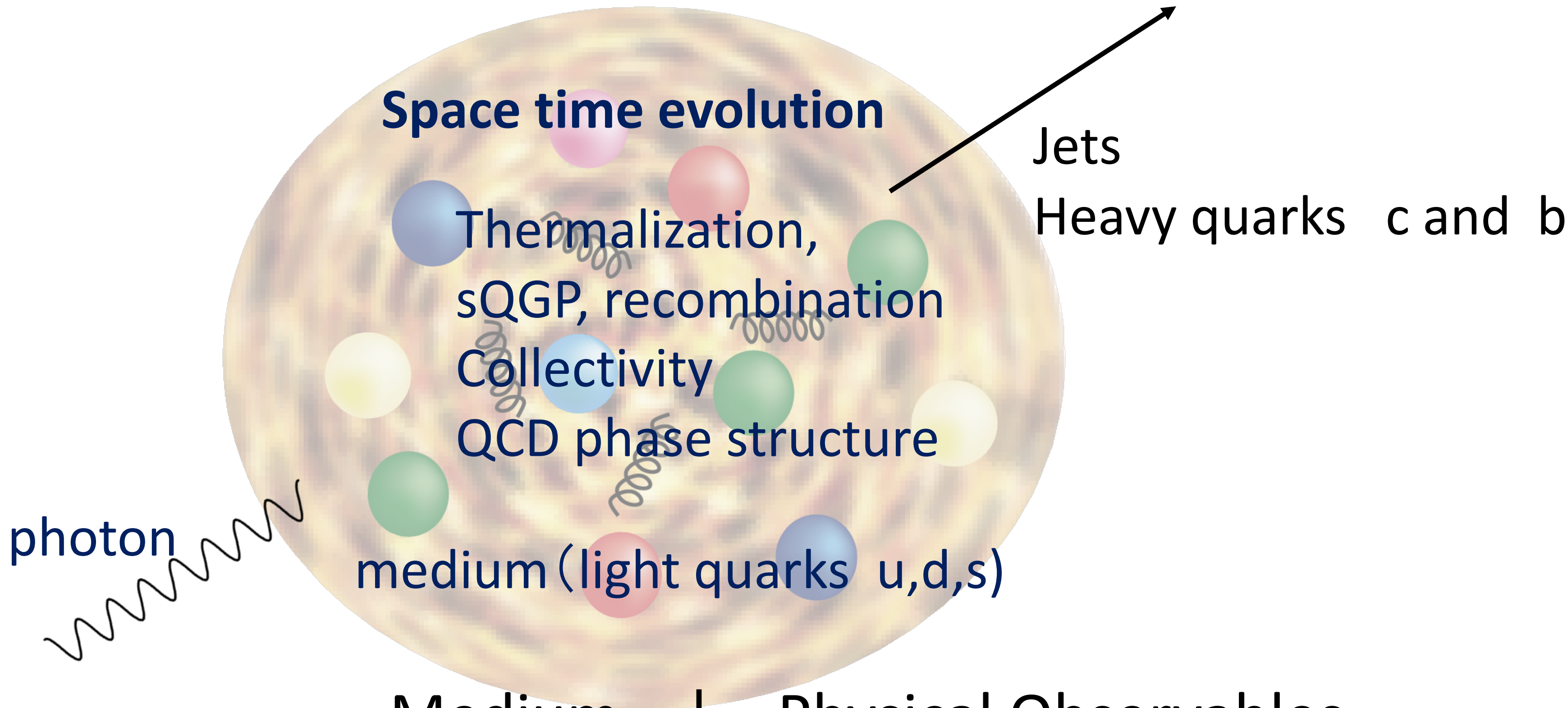
Space-Time Evolution





Medium ＋ Physical Observables

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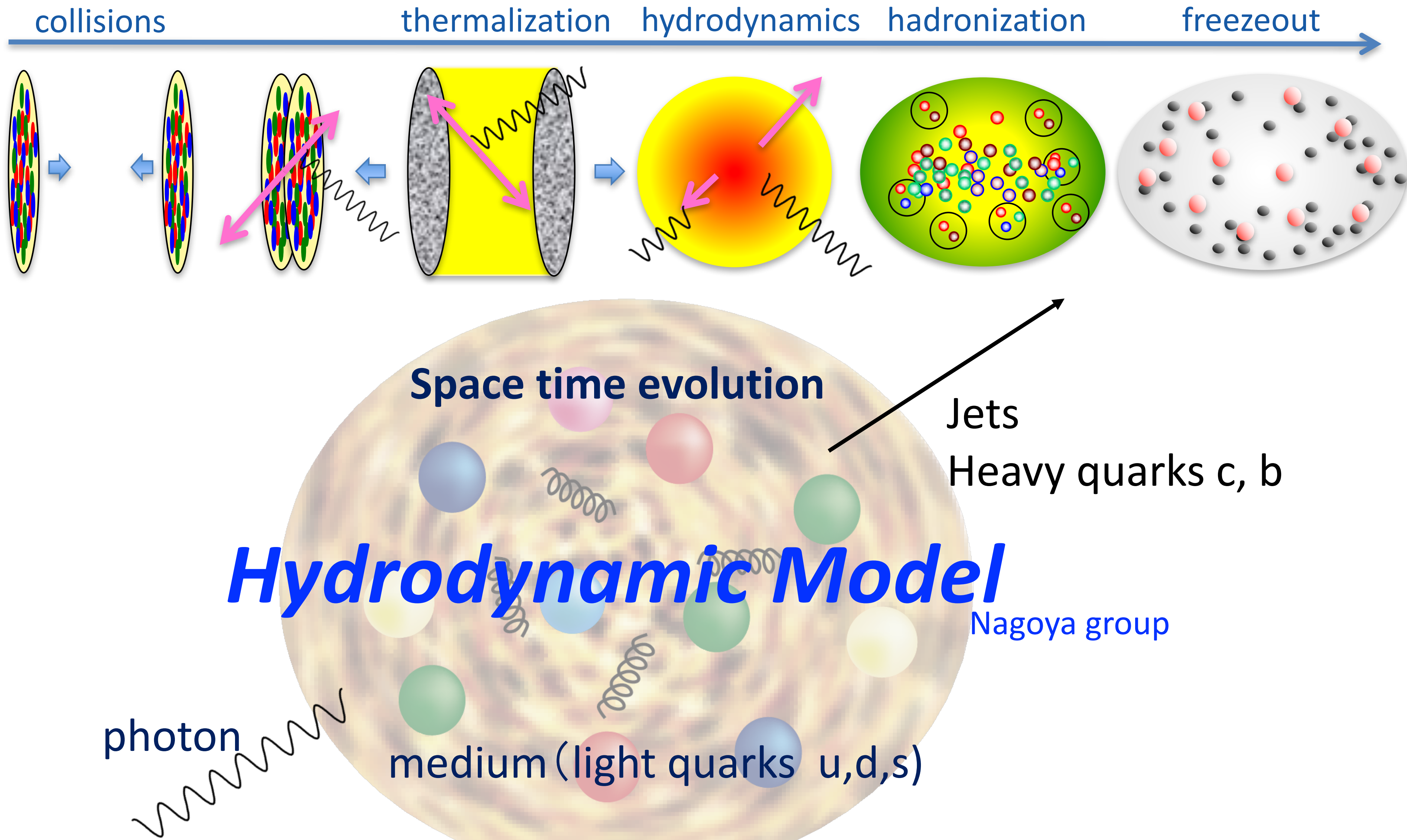
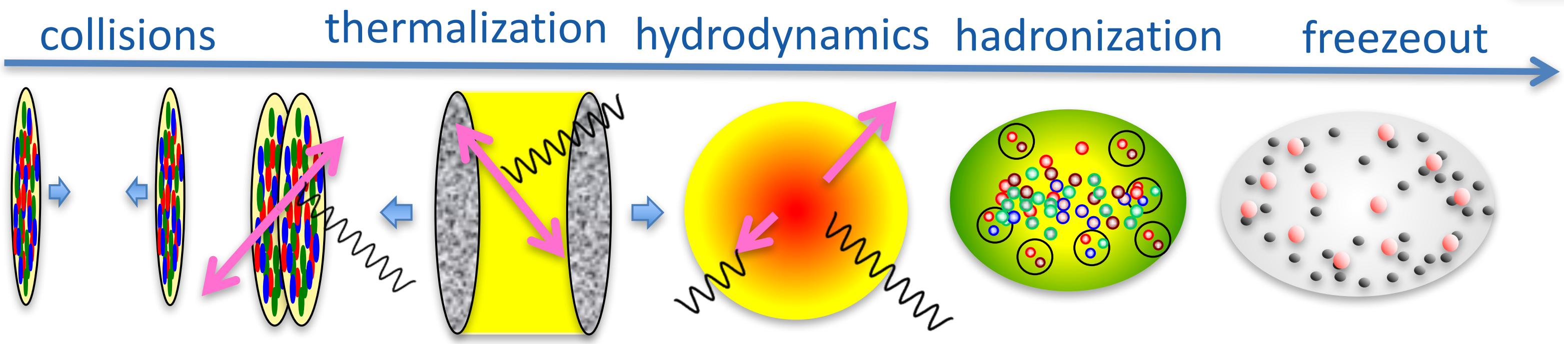
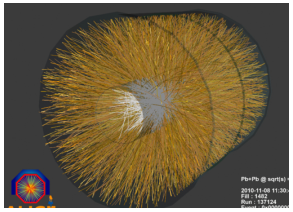
Space-Time Evolution



Medium ＋ Physical observables

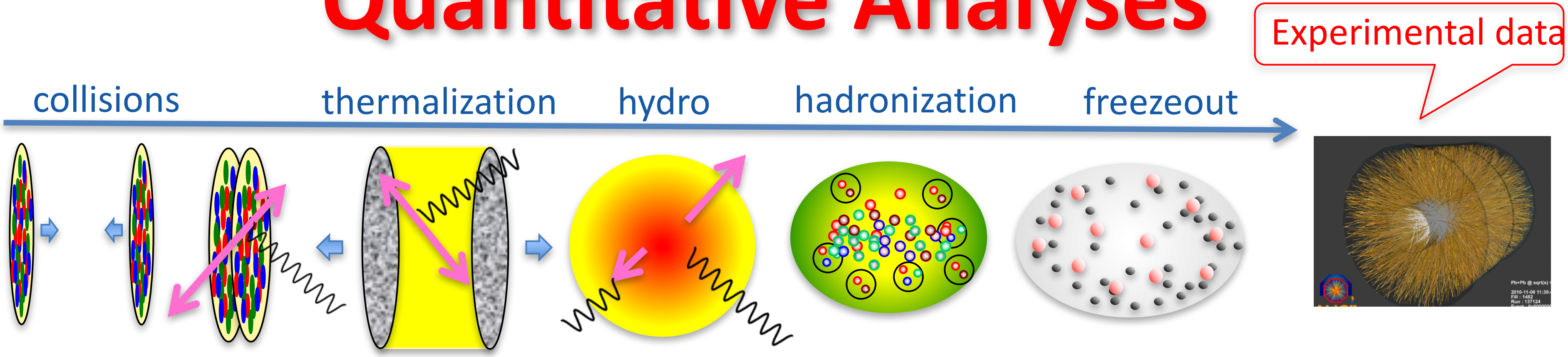
Quantitative Analyses





Hydrodynamics

Quantitative Analyses



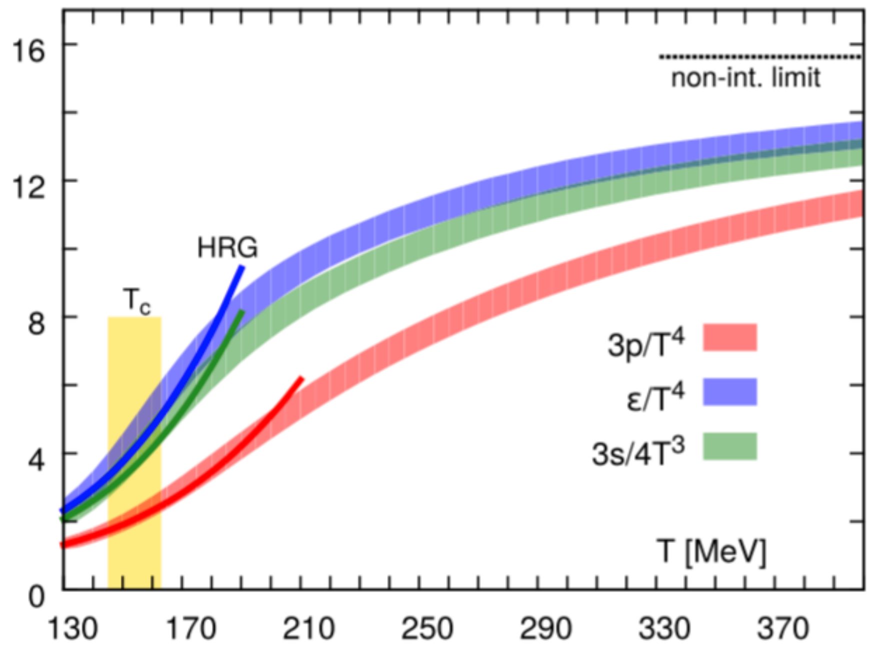
Hydrodynamics

QCD phase diagram
EoS: lattice QCD

Equation of State

- Equation of State
  - Lattice QCD

HotQCD,PRD90,094503(2014)

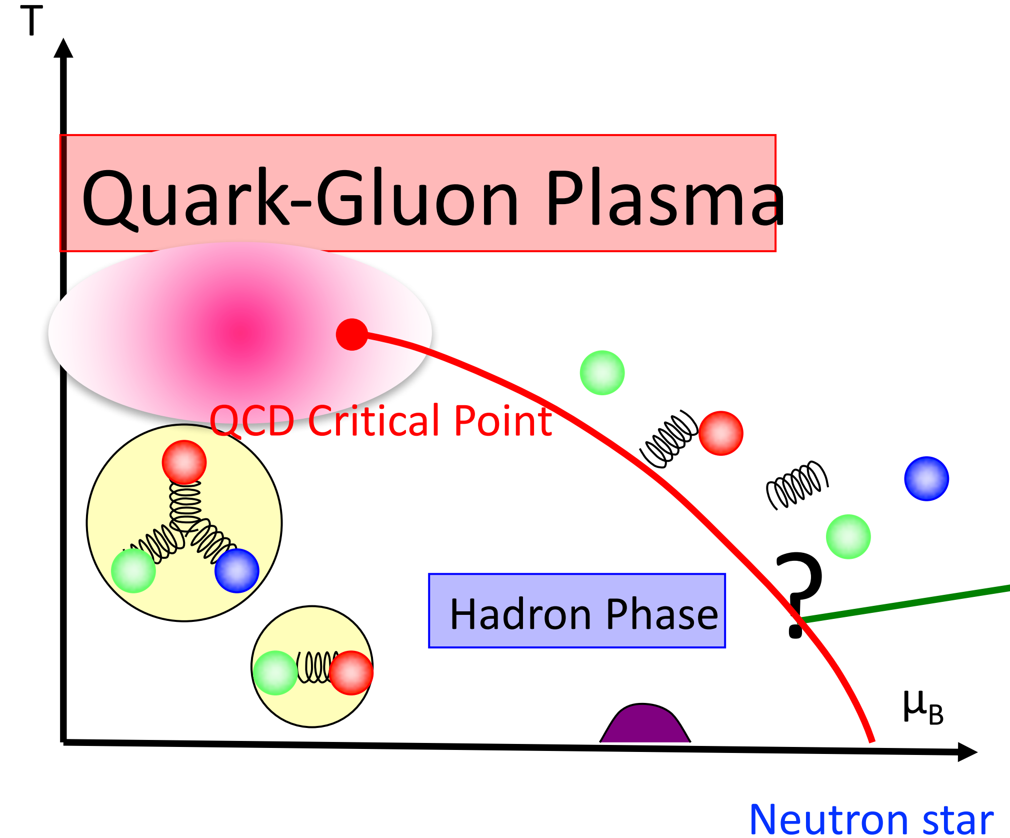


(2+1) flavor, Highly improved staggered quark action

Nt=6,8,10,12,Ns=4Nt → continuum limit

Parametrization of EoS

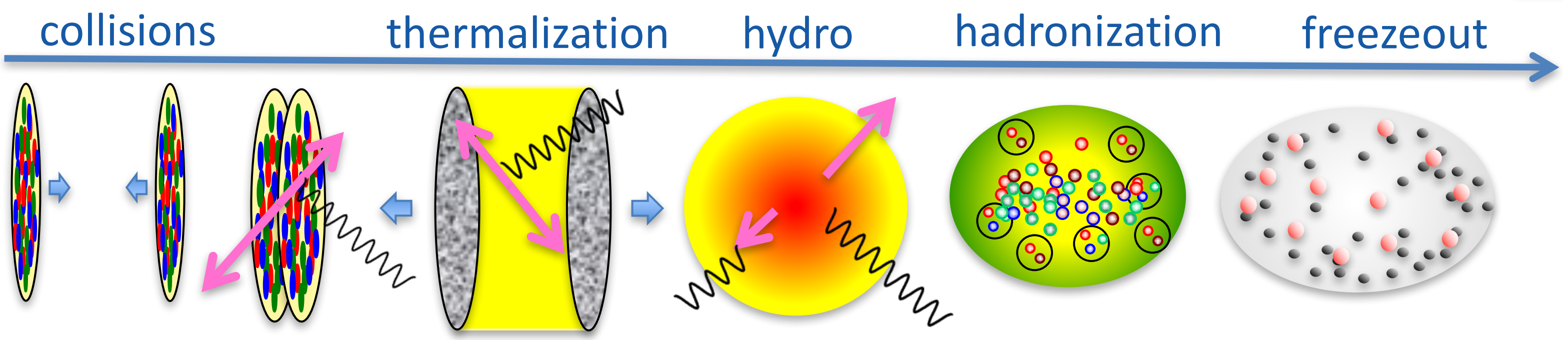
$T_c \sim 155$ MeV

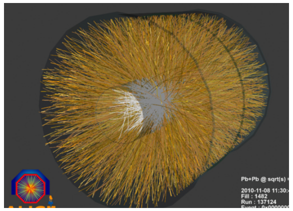


finite μ: sign problem

Quantitative Analyses

Experimental data





Hydrodynamics

QCD phase diagram

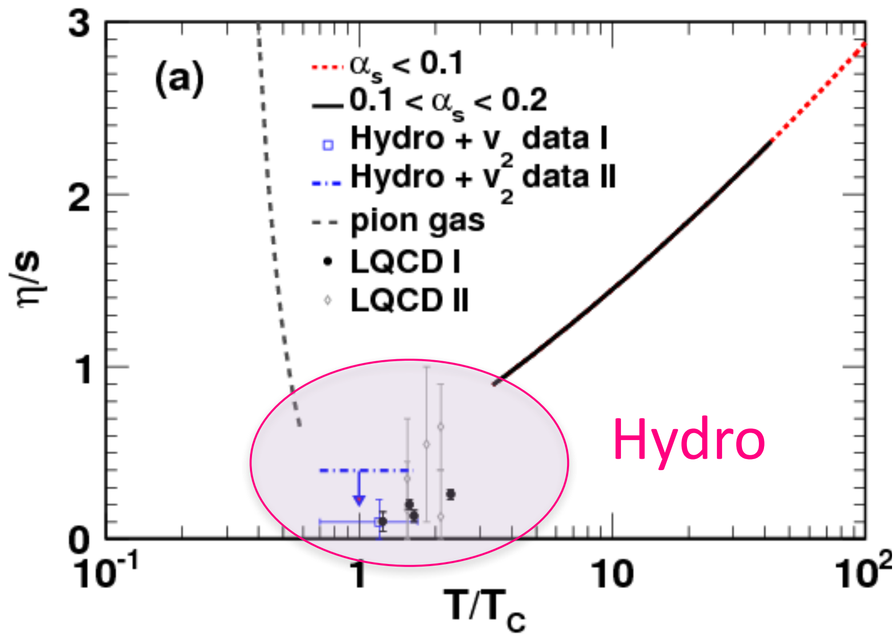
EoS: lattice QCD

Shear and bulk viscosities

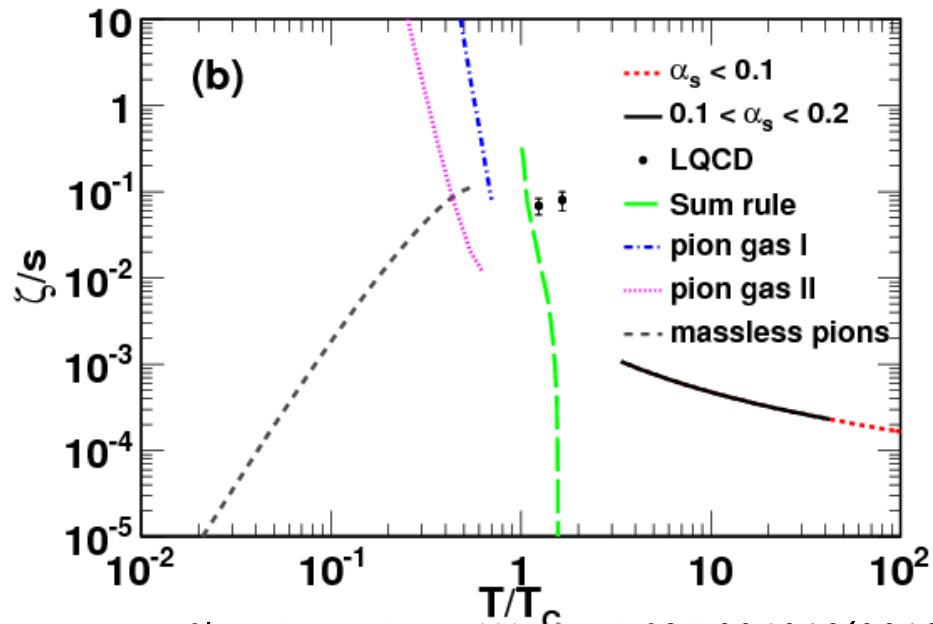
Property of QGP

- Current Status for transport coefficients

shear viscosity



bulk viscosity



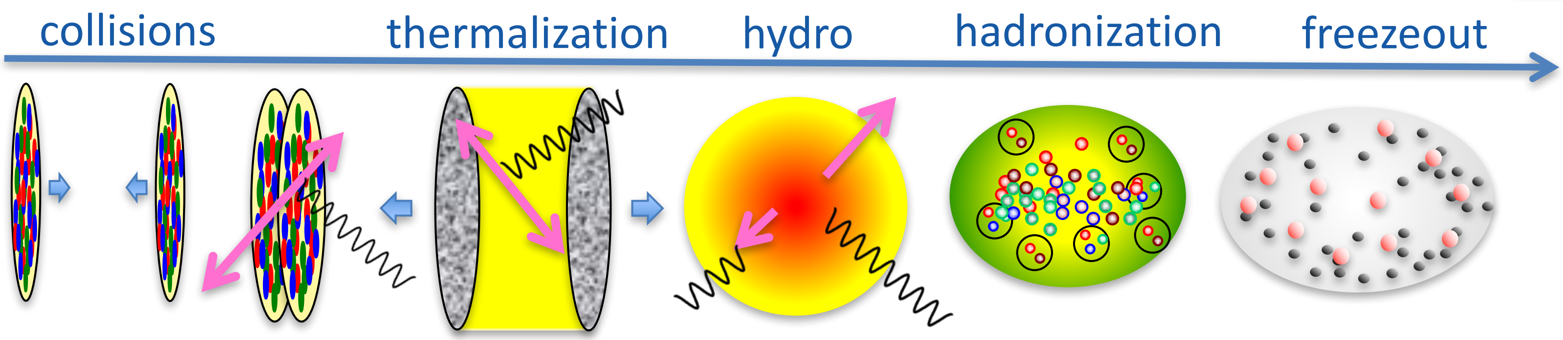
Chen,Deng,Dong,Wang,PRC87,024910(2013)

- 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

Detailed feature of shear and bulk viscosities

Quantitative Analyses



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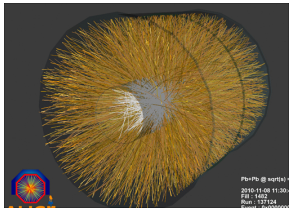

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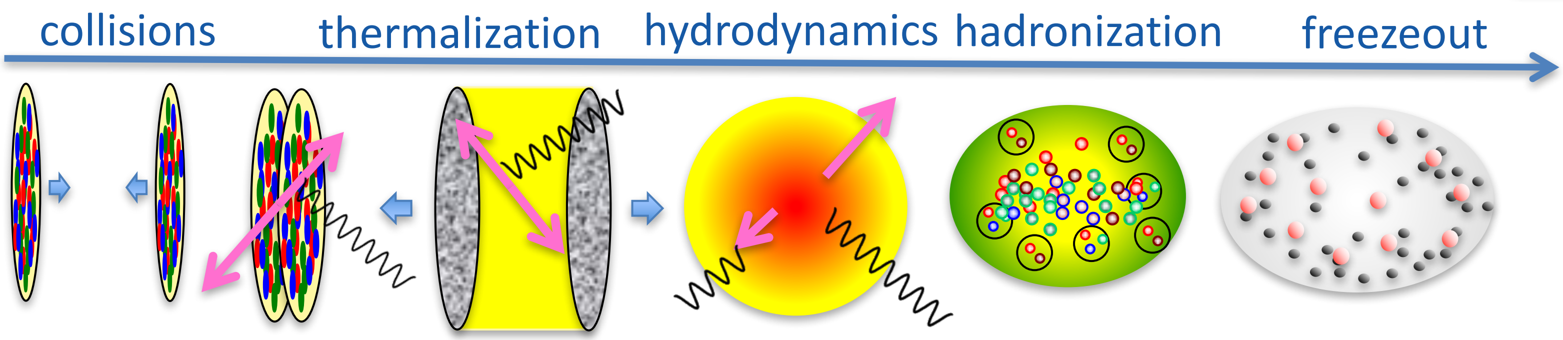
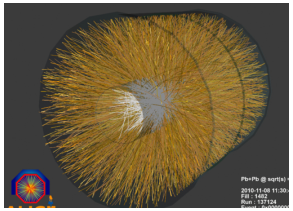
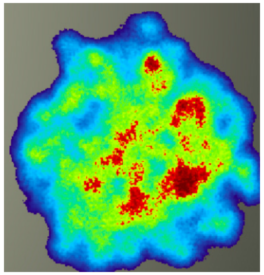




Initial conditions



Energy (entropy) density distributions

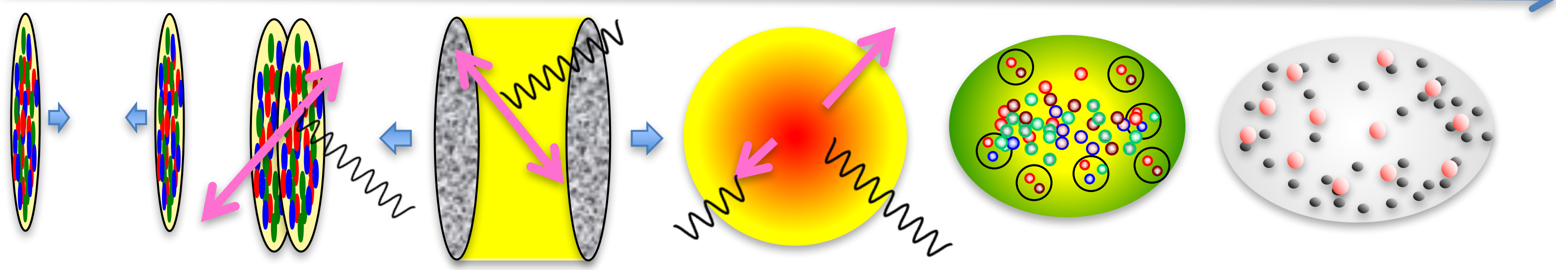
Hydrodynamics

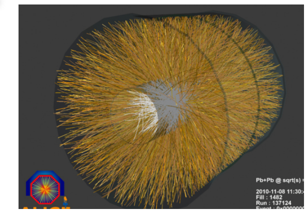
QCD phase diagram
EoS: lattice QCD
Shear and bulk viscosities

Quantitative Analyses

Experimental data

collisions thermalization hydro hadronization freezeout





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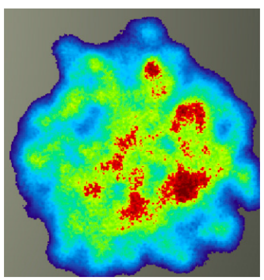


Energy (entropy) density distributions

Hydrodynamics

QCD phase diagram
EoS: lattice QCD
Shear and bulk viscosities

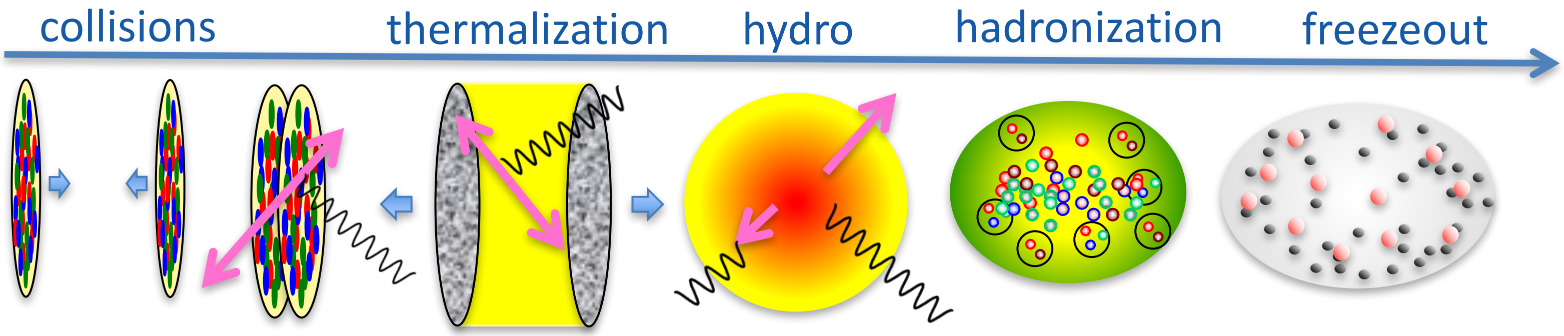
Final state interactions

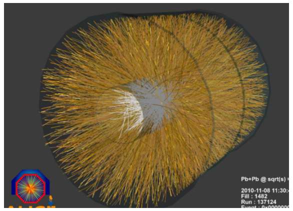
Hadron based event generator

Hydrodynamics ⟶ particle

Quantitative Analyses

Experimental data





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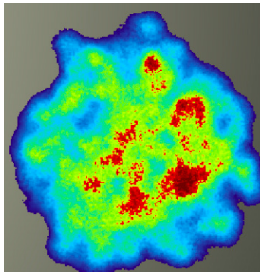

Energy (entropy) density distributions

Hydrodynamics

QCD phase diagram
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Shear and bulk viscosities

New hydrodynamics code

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

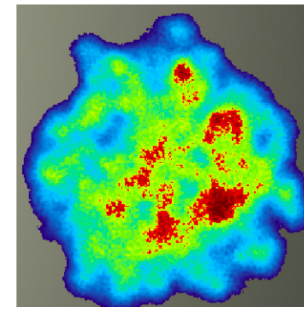
Final state interactions

Hadron based event generator

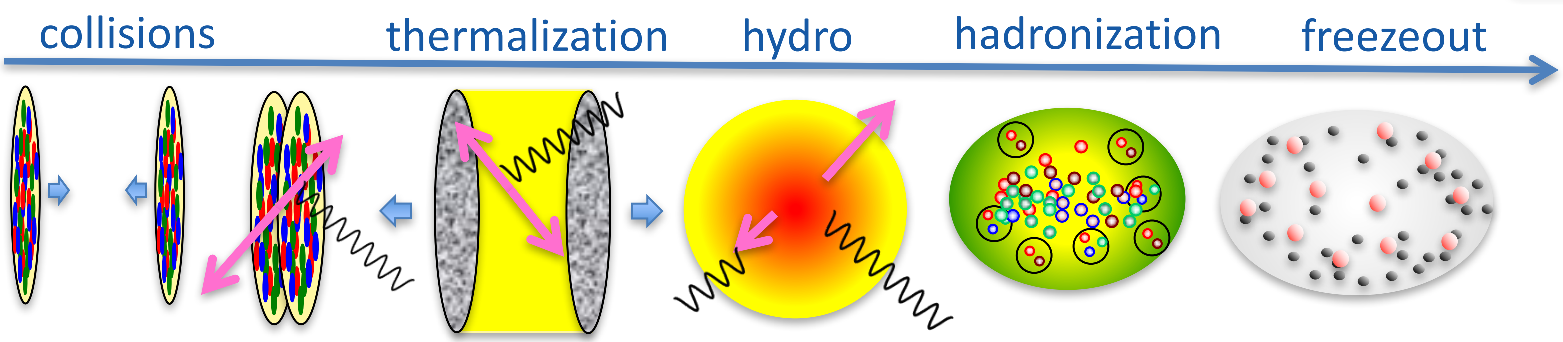
Akamatsu et al, JCP256,34(2014)
Okamoto, Akamatsu, Nonaka, EPJC76,579(2016)
Okamoto and Nonaka, EPJC77,383(2017)

New Hydrodynamics Code

1. Development of new hydrodynamics code
   - Stable with small numerical dissipation
   - Shock wave
   - Strong expansion in longitudinal direction
   - Conservation property



2. Application to phenomenological analyses of LHC data
   - Description of space-time expansion after collisions



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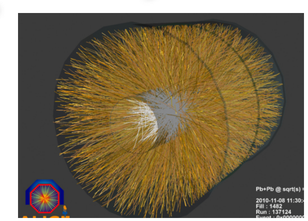

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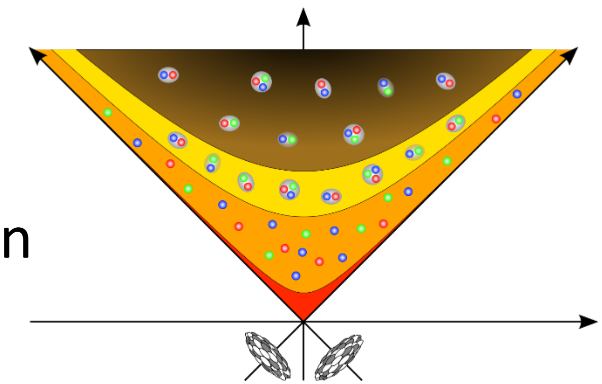

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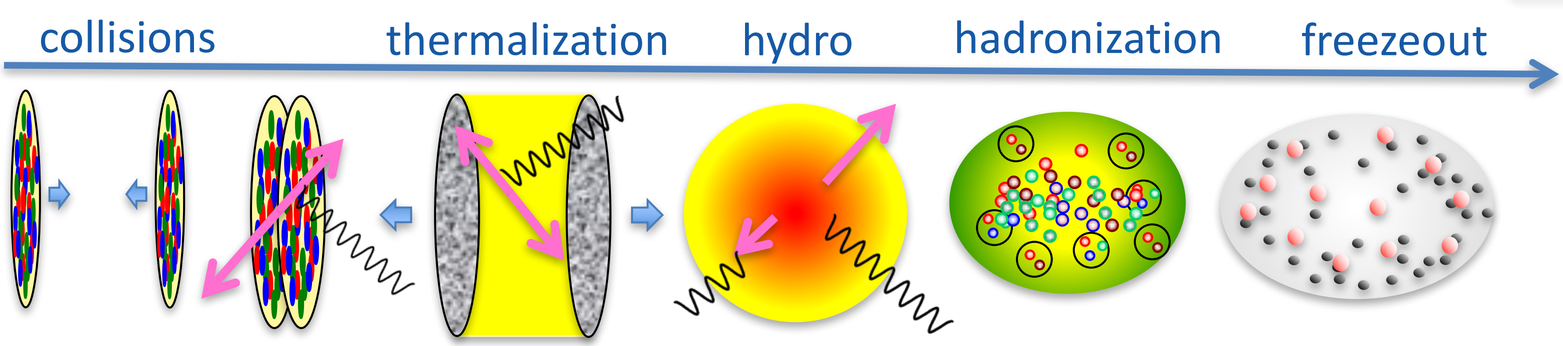
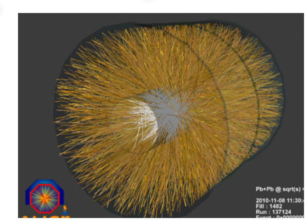


Experimental data



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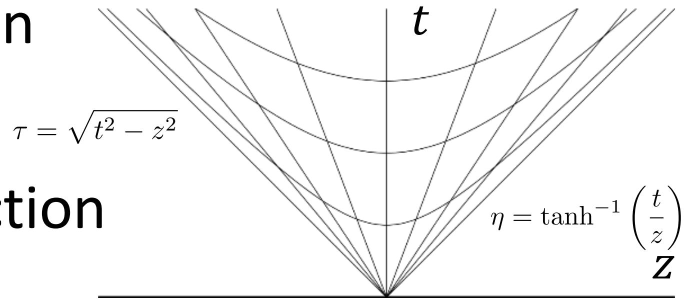
Milne coordinate



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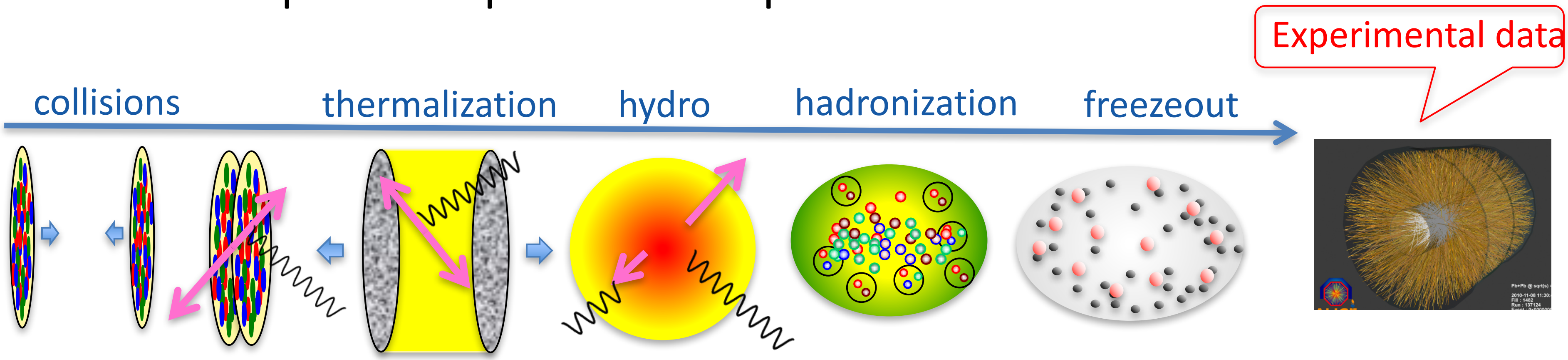

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   } Riemann solver in Milne coordinates

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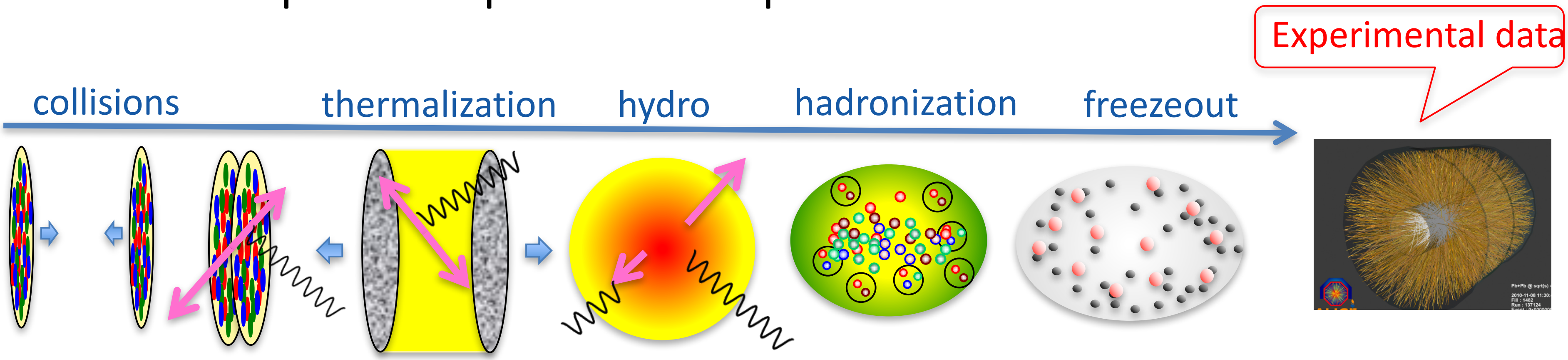
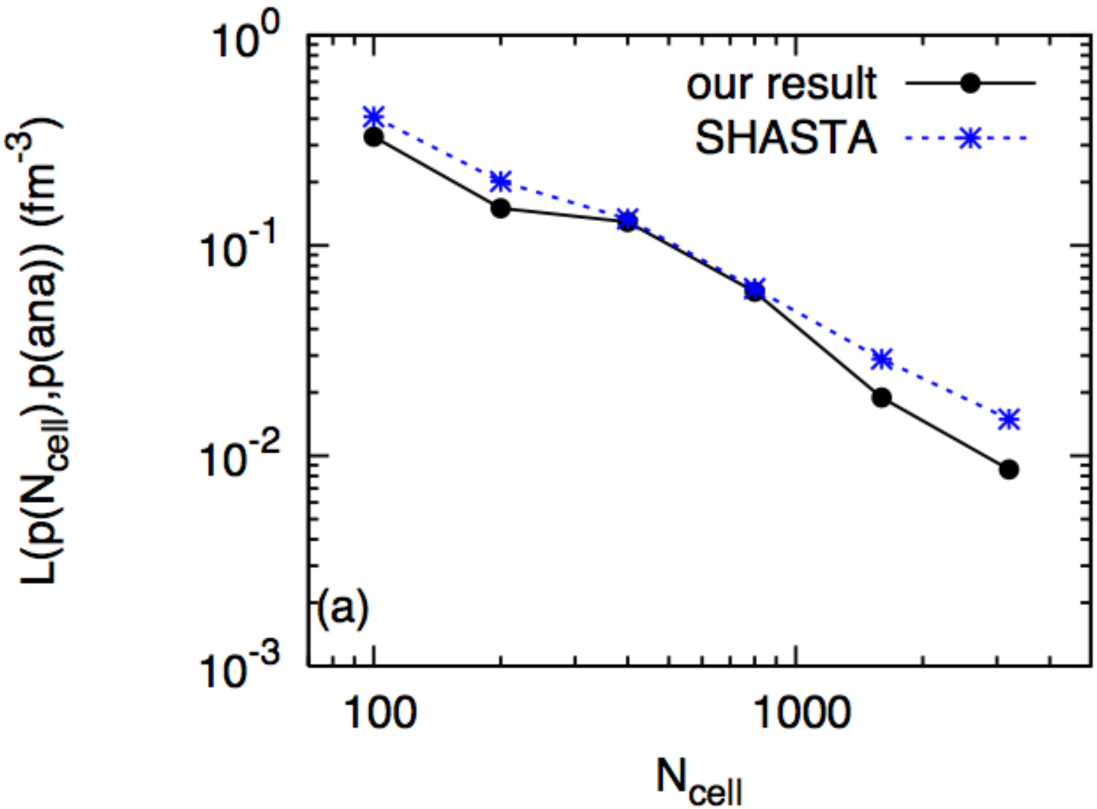
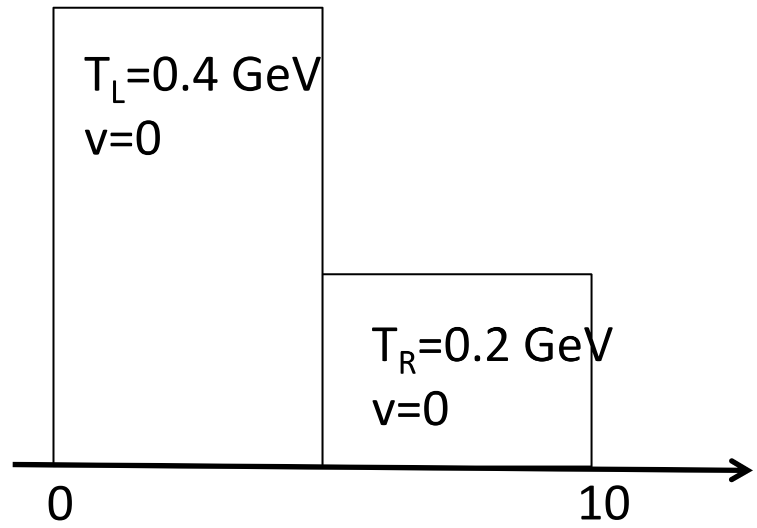


Small Numerical Dissipation

Akamatsu et al, JCP256,34(2014)

- Numerical dissipation: deviation from analytical solution





For analysis of heavy ion collisions

N_{cell}=100: dx=0.1 fm

$$L(p(N_{\rm cell}), p({\rm anaytic})) = \sum_{i=1}^{N_{\rm cell}} |p(N_{\rm cell}) - p({\rm analytic})| \frac{\lambda}{N_{\rm cell}}$$

λ=10 fm

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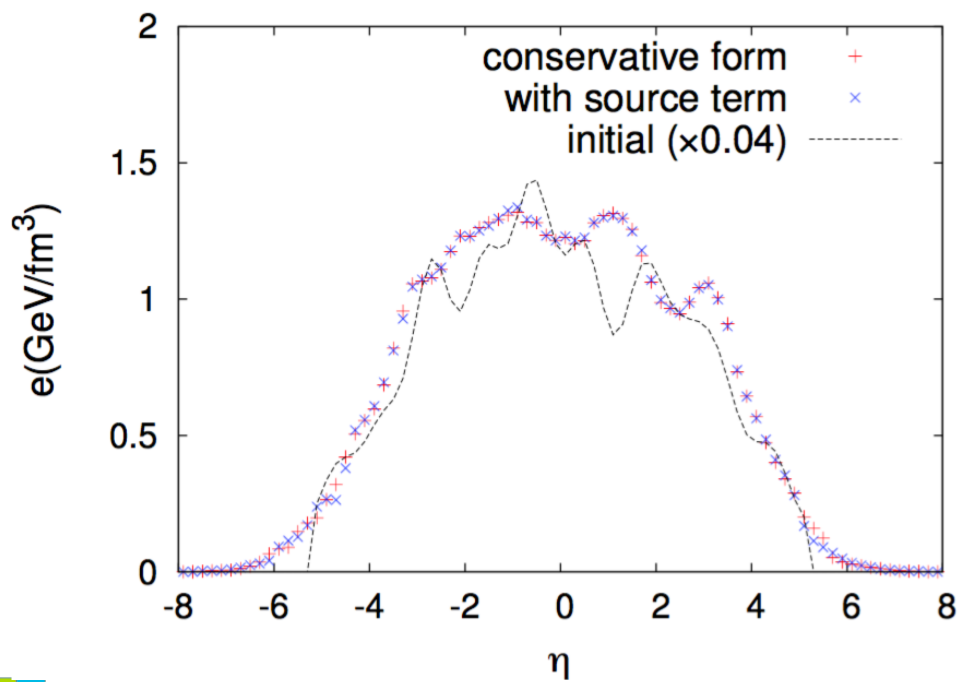
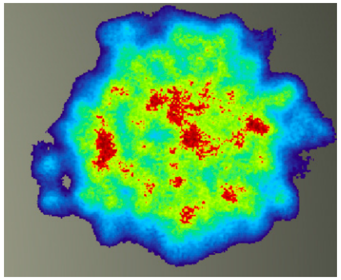
Numerical Tests in 1D

- ✓ Bjorken's scaling solutions
- ✓ Landau-Khalatnikov Solution (1D)
- ✓ Longitudinal fluctuations
- ✓ Conservation property

K. Okamoto, Y. Akamatsu and CN, Eur. Phys. J. C76 (2016)579





fluctuations
In initial conditions

Sum of violation of conservation

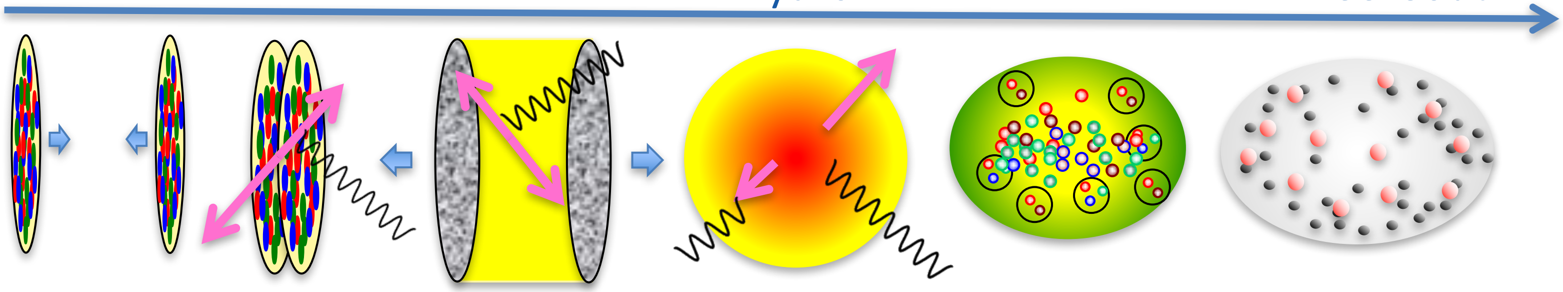
	ε_E	ε_M
conservative	1.38E-09	8.59E-09
with souce	1.27E-02	5.61E-02

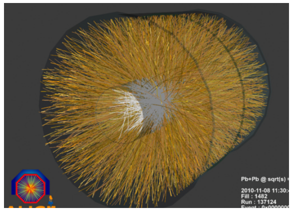
Quantitative Analyses

Okamoto and Nonaka, Phys.Rev. C98 (2018) 054906

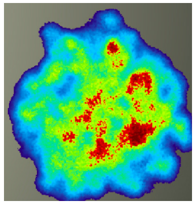
Experimental data

collisions thermalization hydro hadronization freezeout





Initial conditions



Hydrodynamics

QGP bulk property

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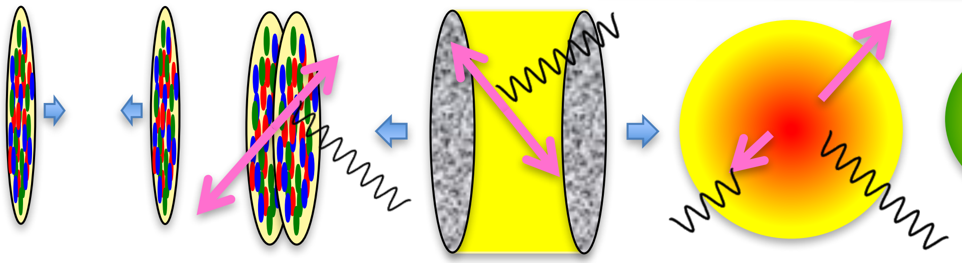
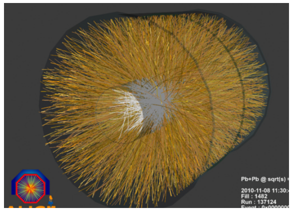
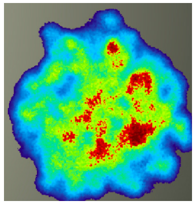
Experimental data





Initial conditions



TRENTO

Phenomenological model
Parametrization

Moreland et al.,PRC92,011901(2015)
Ke et al.,PRC96,044192(2017)

Hydrodynamics

QGP bulk property
EoS: lattice QCD
Shear and bulk viscosities

New hydrodynamics code

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

Final state interactions

Hadron based event generator

UrQMD

Bass et al., Prog.Part.Nucl.Phys.(1998)
Bleicher et al., J.Phys.G25,1859(1999)

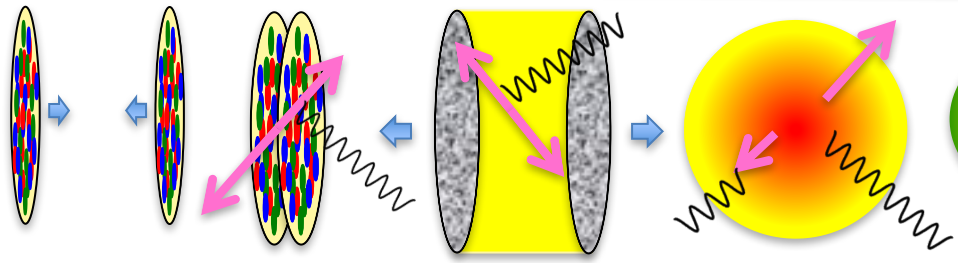
Application to analyses of RHIC and LHC data

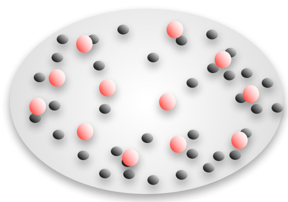
Bulk Property of QGP

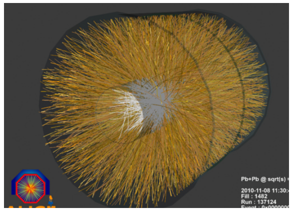
Okamoto and Nonaka, Phys.Rev. C98 (2018) 054906

Experimental data

collisions thermalization hydro hadronization freezeout



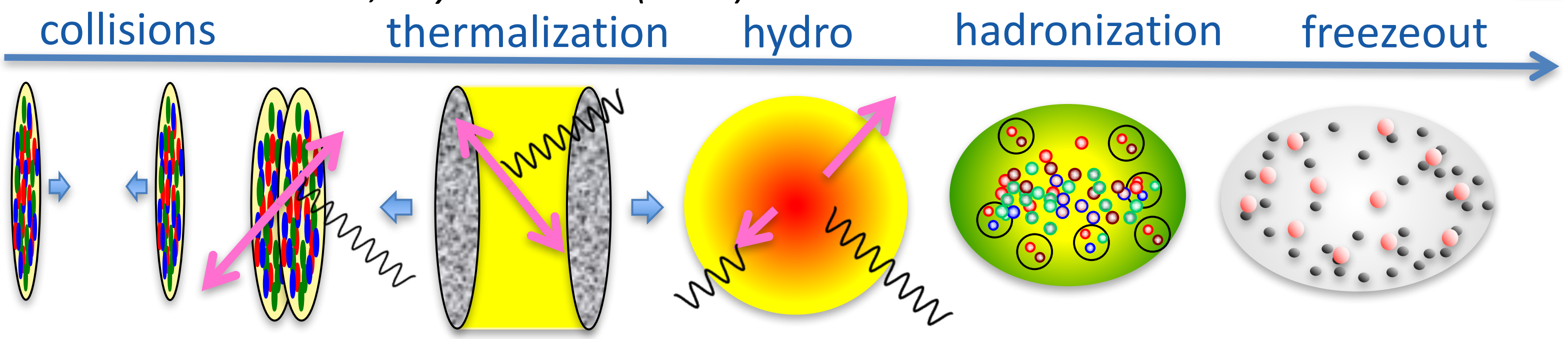


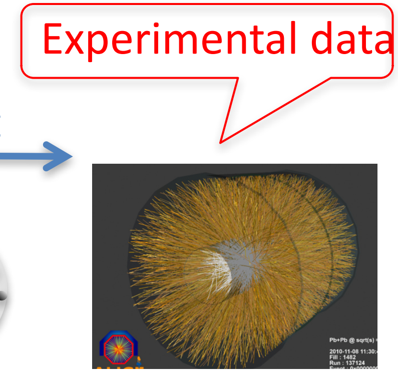


Our Model ⟷ ***Experimental data***

Bulk Property of QGP

Okamoto and Nonaka, Phys.Rev. C98 (2018) 054906





Our Model ⟷ ***Experimental data***

temperature dependence of transport coefficients

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

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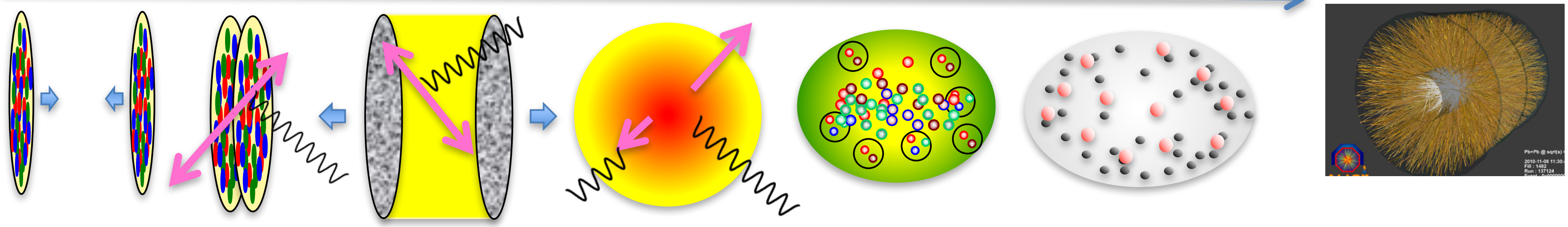
What physical observable is interesting?

Bulk Property of QGP

Okamoto and Nonaka, Phys.Rev. C98 (2018) 054906

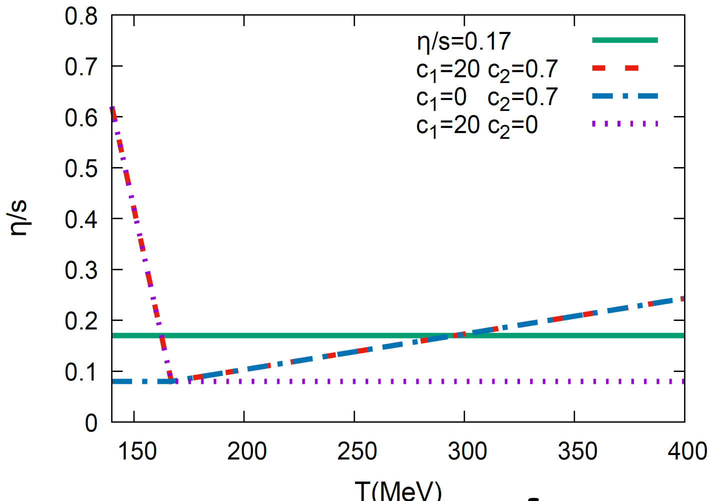
collisions thermalization hydro hadronization freezeout

Experimental data



Our Model ⟷ *Experimental data*

Shear viscosity



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

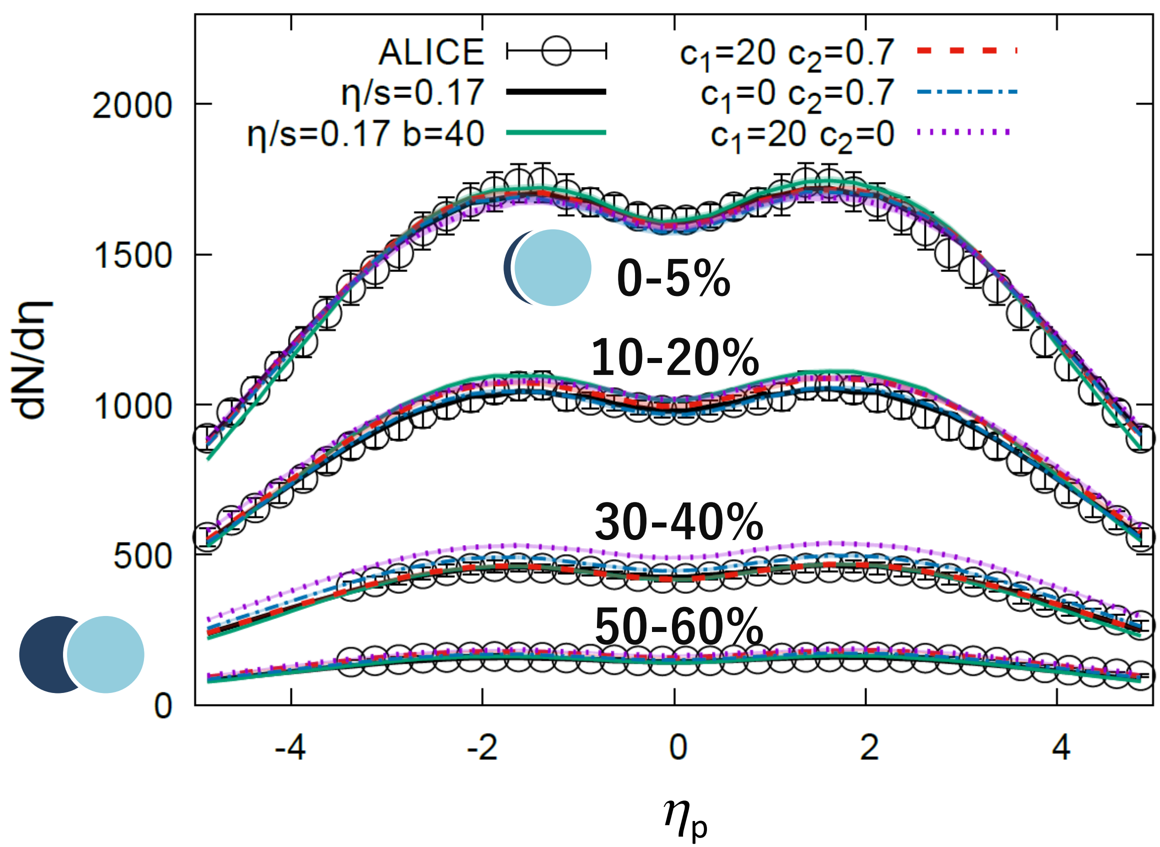
- ✓ Rapidity distributions
- ✓ P_T distributions
- ✓ Mean P_T
- ✓ Collective flows v_2 and v_3

Bulk viscosity

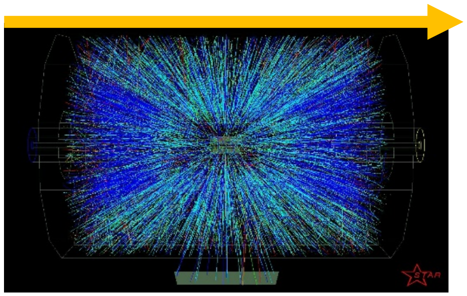
$$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2 \quad b = 40$$

What physical observable is interesting?

Rapidity Distributions



pseudorapidity η_p



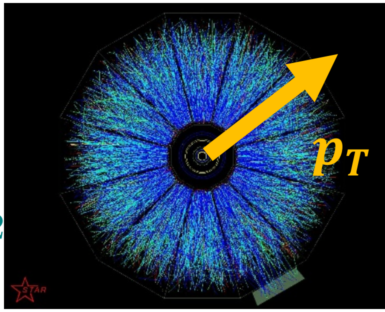
colission axis

Parameters fixed in initial conditions

output

- Parameters in initial condition TRENTO are fixed from comparison with experimental data at 0-5 % centrality.

Effect of Bulk Viscosity

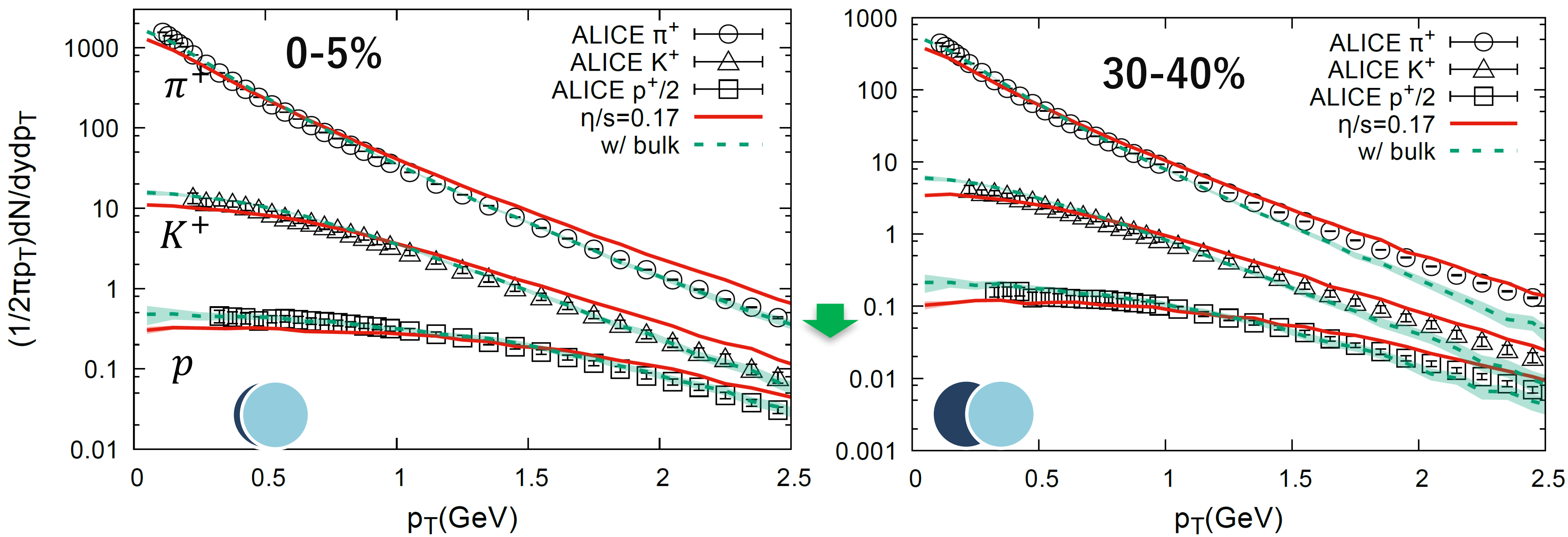


- Shear + Bulk viscosities

$$\eta/s = 0.17$$

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

Transverse momentum spectra



Bulk viscosity reduces the transverse expansion.

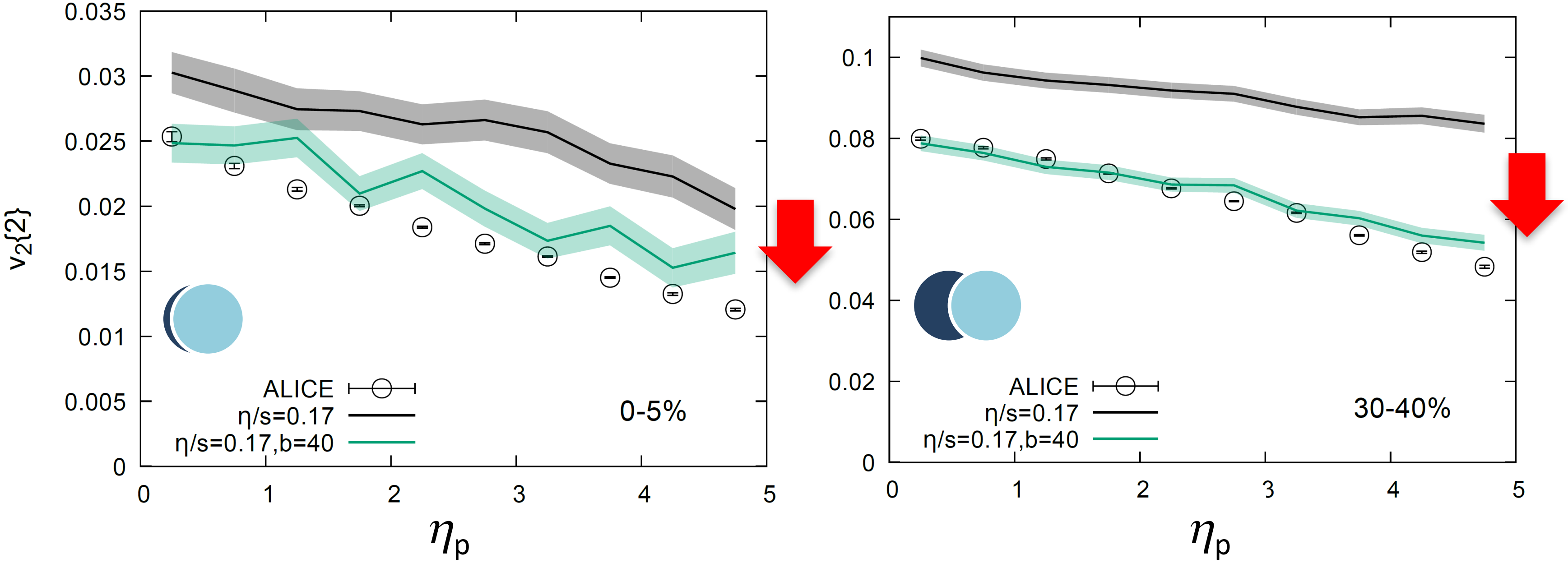
-> Slope of P_T spectra becomes steep.

-> Close to ALICE data.

Finite bulk viscosity

Effect on Collective Flow

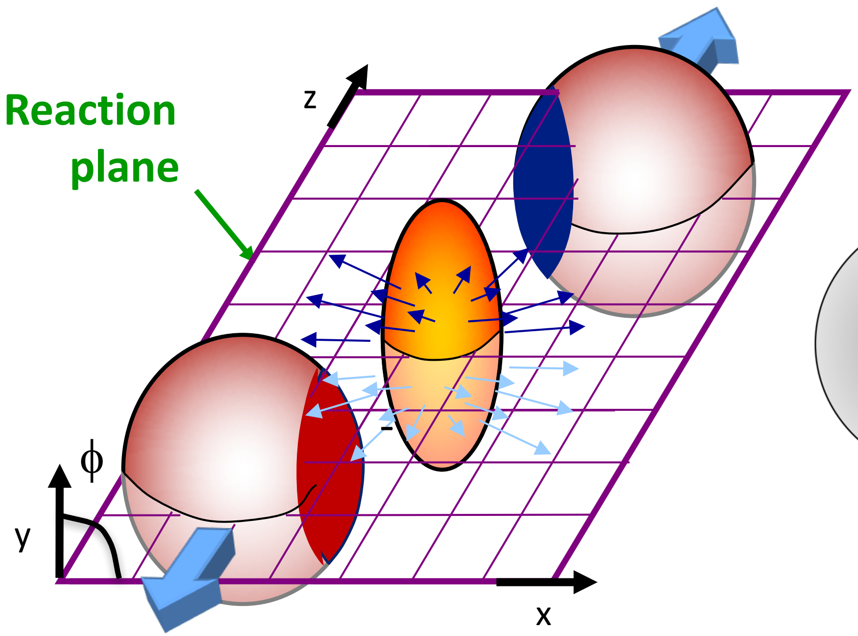
- Collective flow as a function of η_p

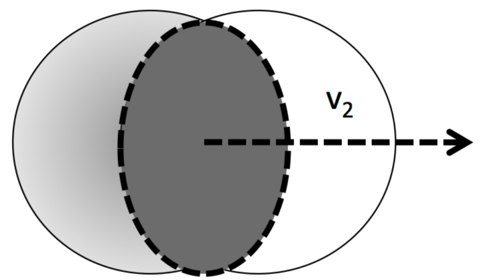


- (3+1)-d calculation
- v_n with bulk viscosity is much closer to the ALICE data: amplitude and slope
- Effect of bulk viscosity at forward rapidity is large.

Finite bulk viscosity

Collective Flow

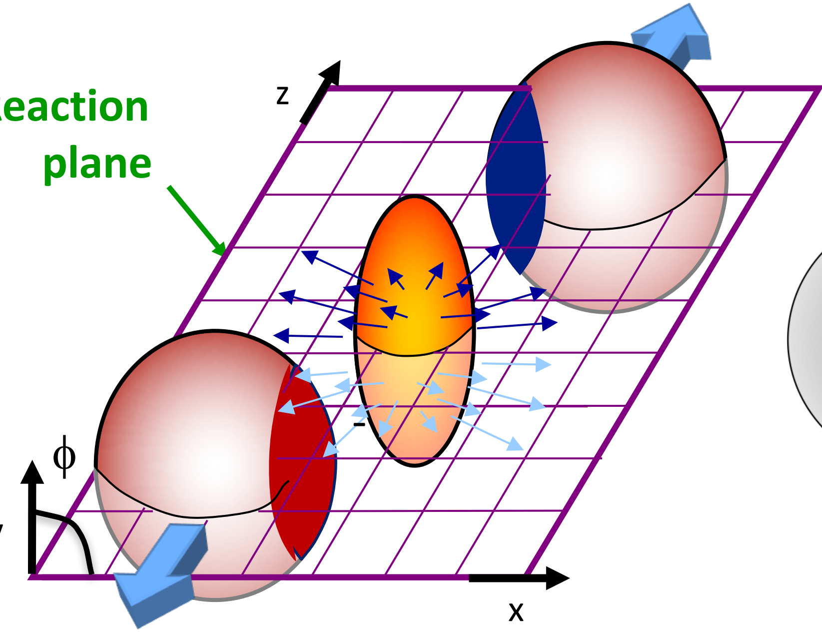


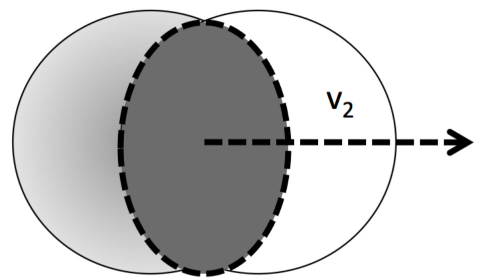


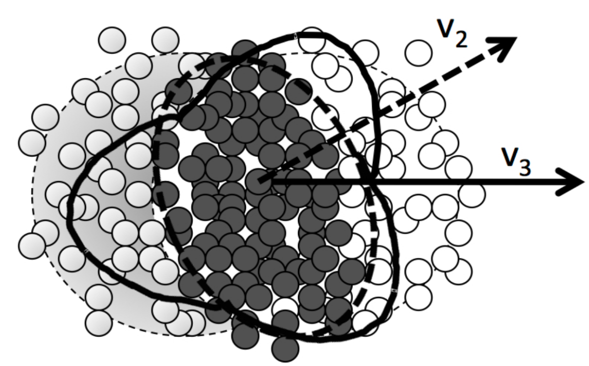
$$\frac{dN}{d\phi} \sim N_0(1 + 2v_1 \cos\phi + \underline{2v_2} \cos 2\phi)$$

Elliptic flow

Collective Flow



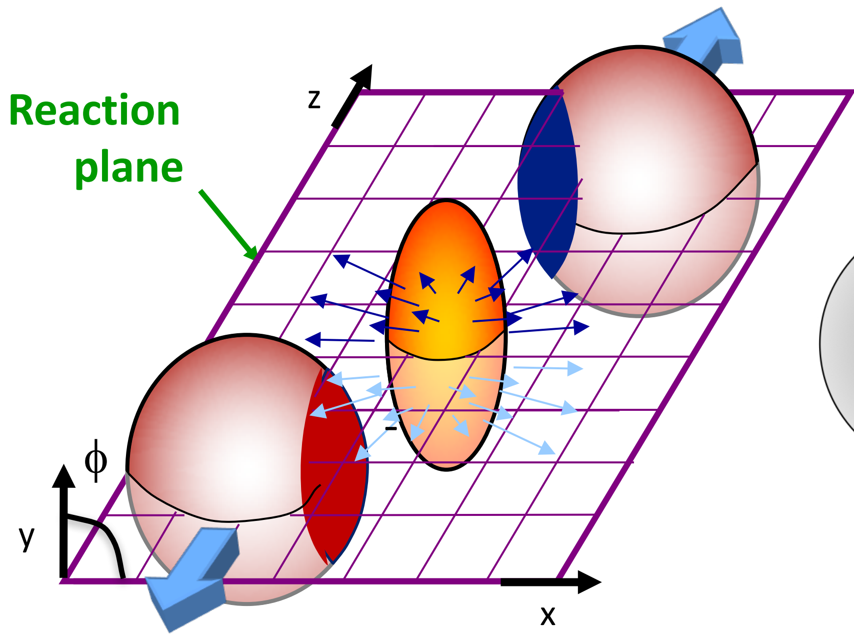




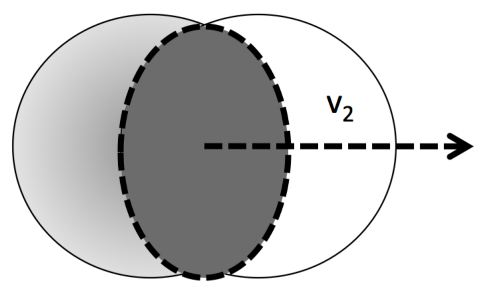
$$\frac{dN}{d\phi} \sim N_0(1 + 2v_1 \cos\phi + \underline{2v_2} \cos 2\phi)$$

Elliptic flow

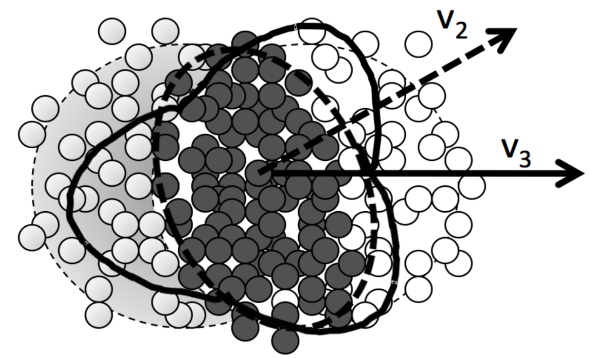
Collective Flow



almond shape



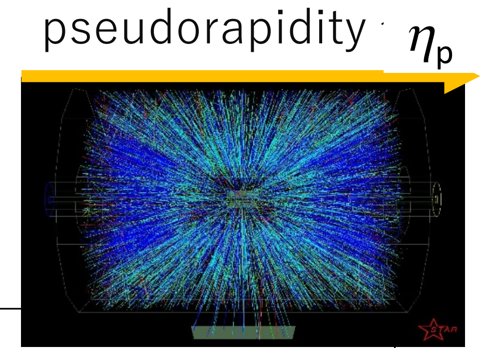
more realistic....



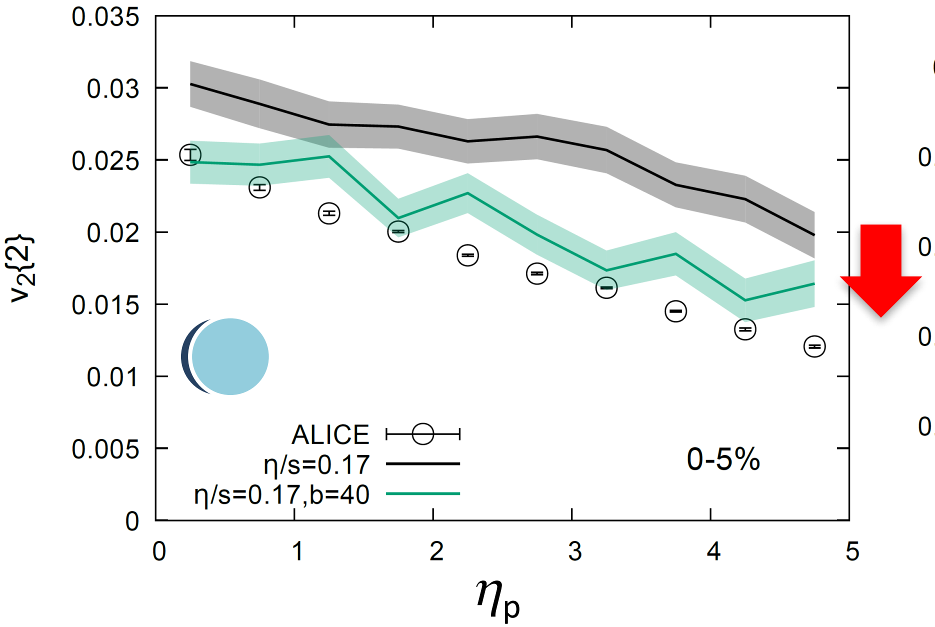
$$\frac{dN}{d\phi} \sim N_0(1 + 2v_1\cos\phi + \underline{2v_2}\cos 2\phi + 2v_3\cos 3\phi + 2v_4\cos 4\phi + \cdots)$$

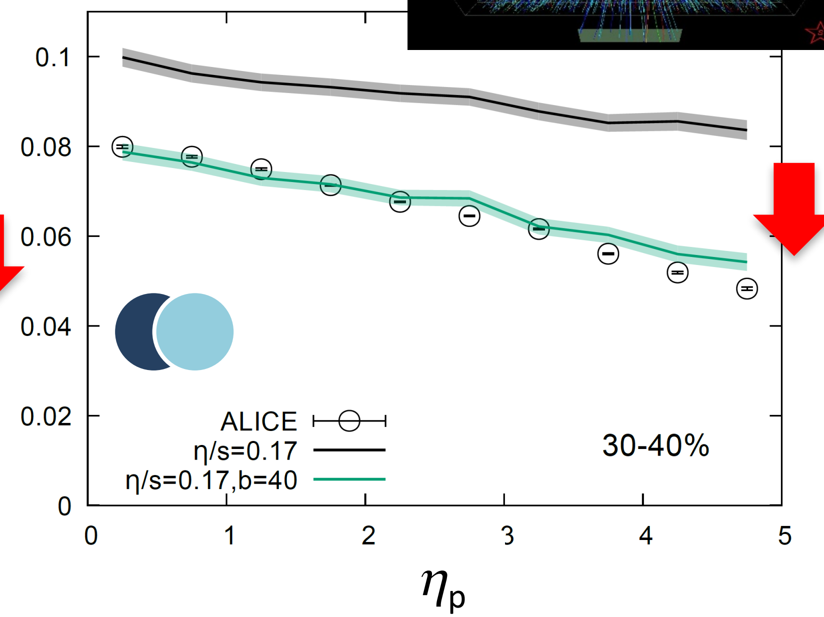
Elliptic flow

Effect on Collective Flow



- Collective flow as a function of η_p

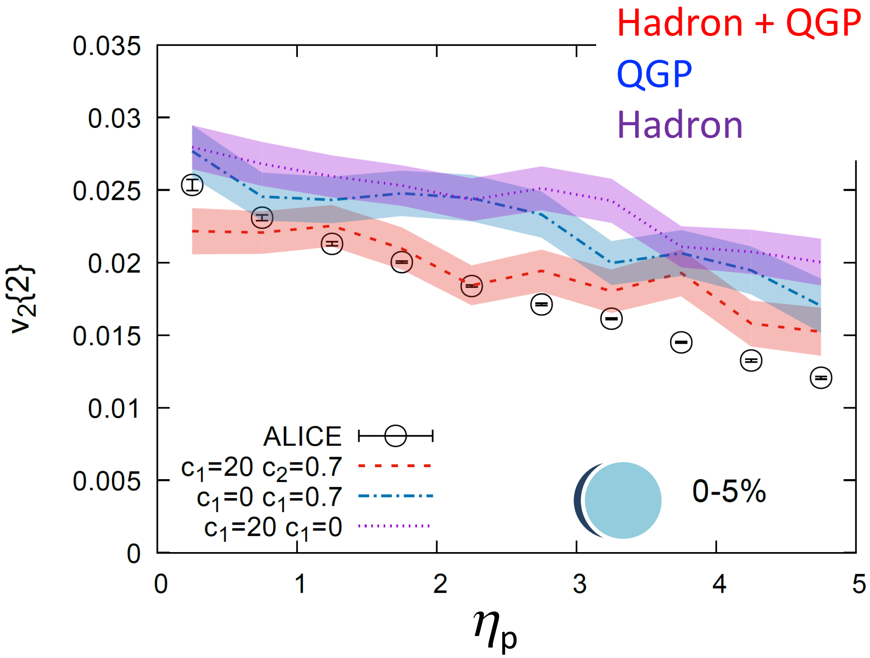


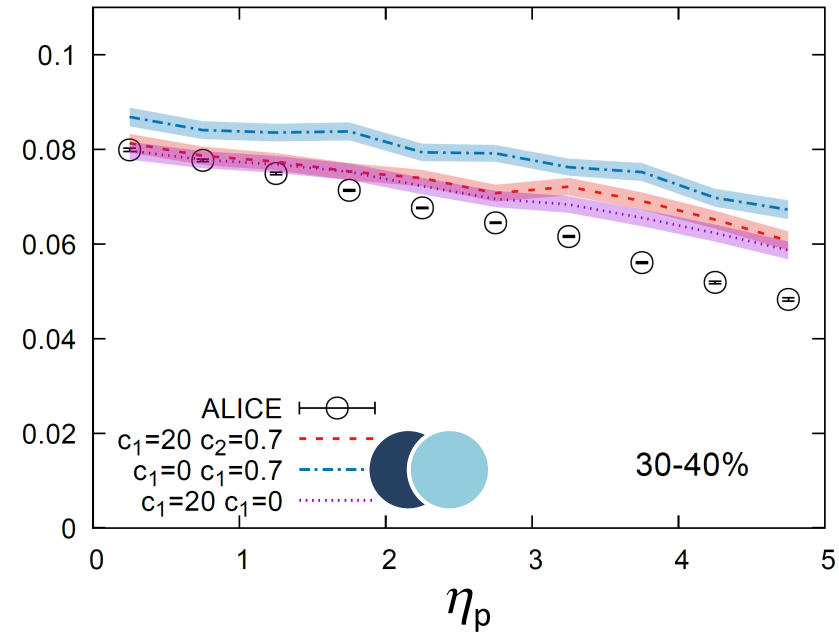


- (3+1)-d calculation
- v_n with bulk viscosity is much closer to the ALICE data: amplitude and slope
- Effect of bulk viscosity at forward rapidity is large.

Finite bulk viscosity

Temperature Dependent η/s



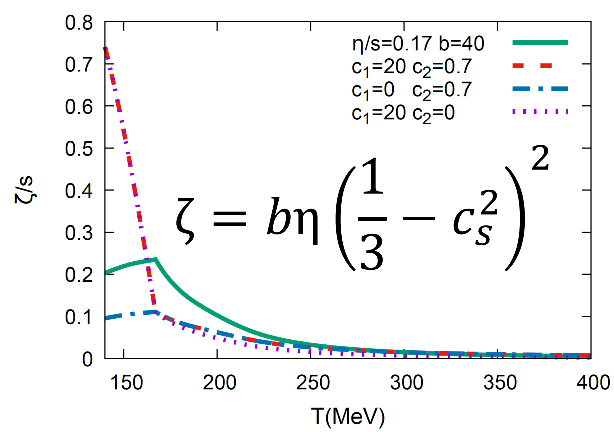


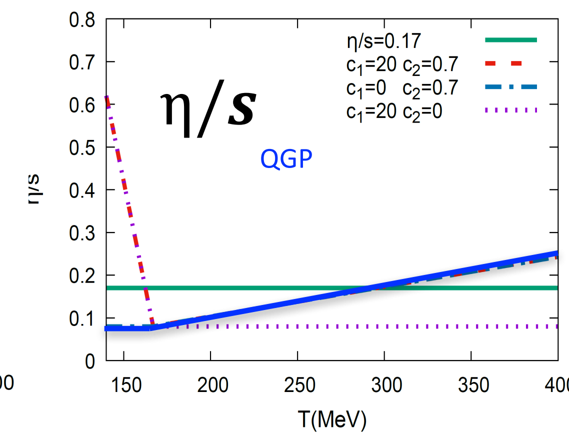
QGP phase: $\eta/s(T)$

Hadron phase: $\eta/s=0.08$

In both centrality classes

$v_2(\eta_p)$ is larger.





$T_{SW} = 150$ MeV

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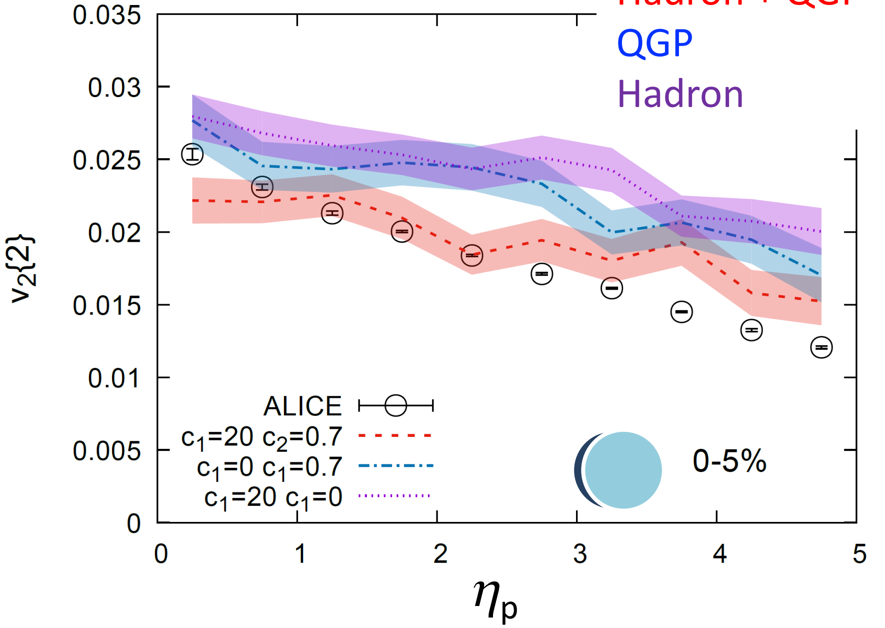
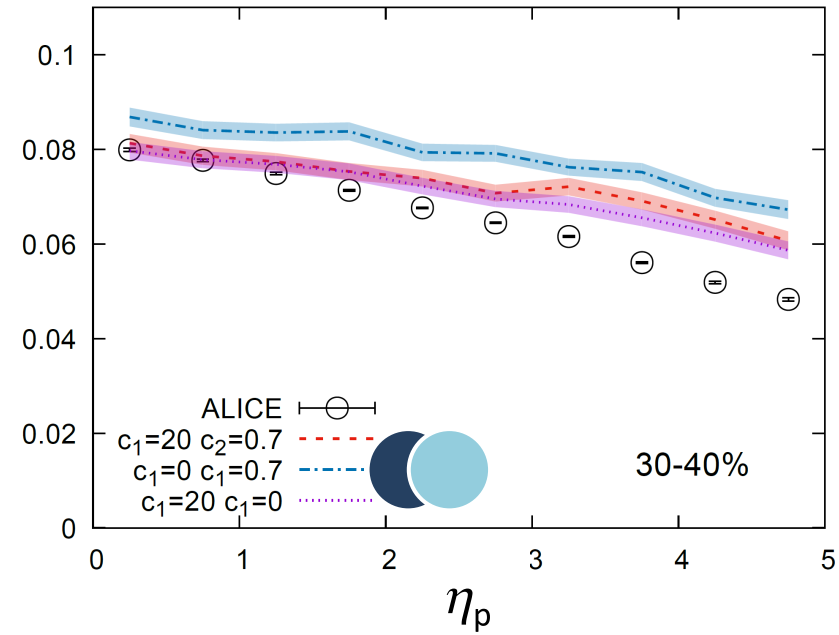
Temperature Dependent η/s



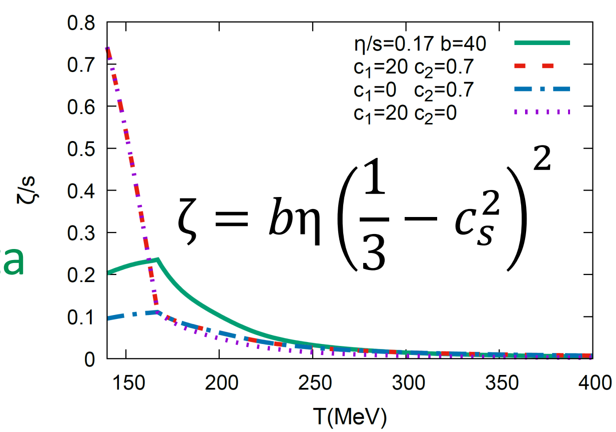


QGP phase: η/s=0.08

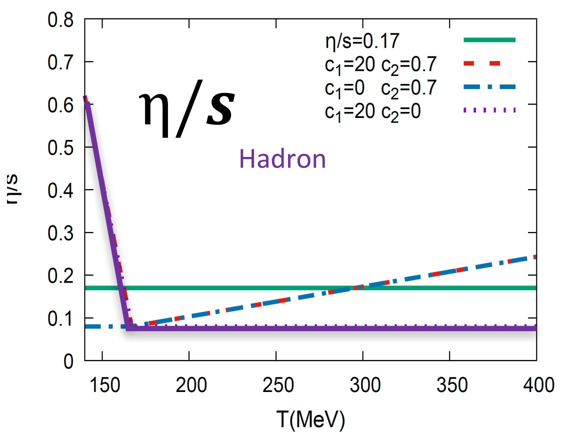
Hadron phase: $\eta/s(T)$

0-5%: larger than ALICE data

30-40%: close to ALICE data



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



$T_{\rm SW} = 150$ MeV

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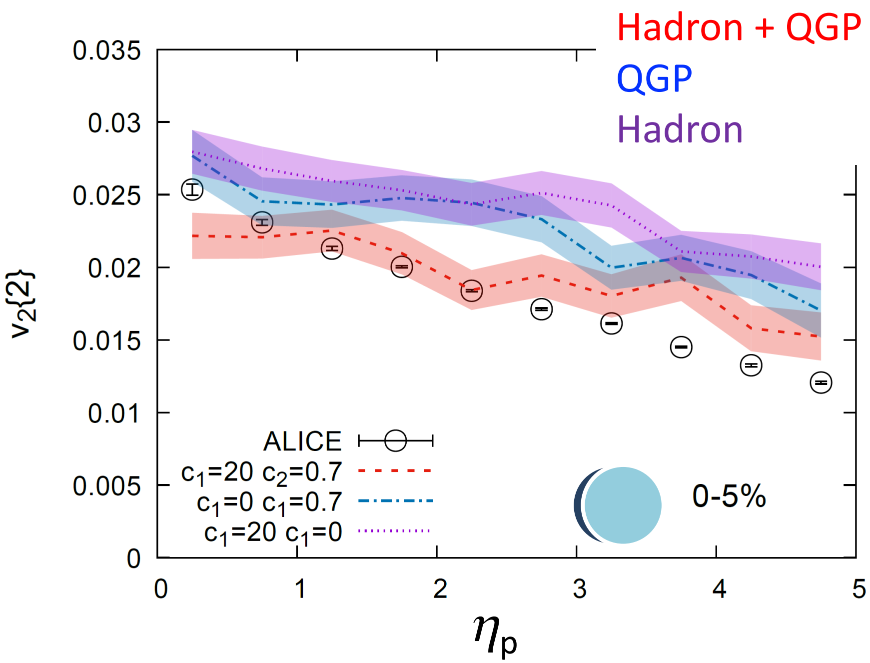
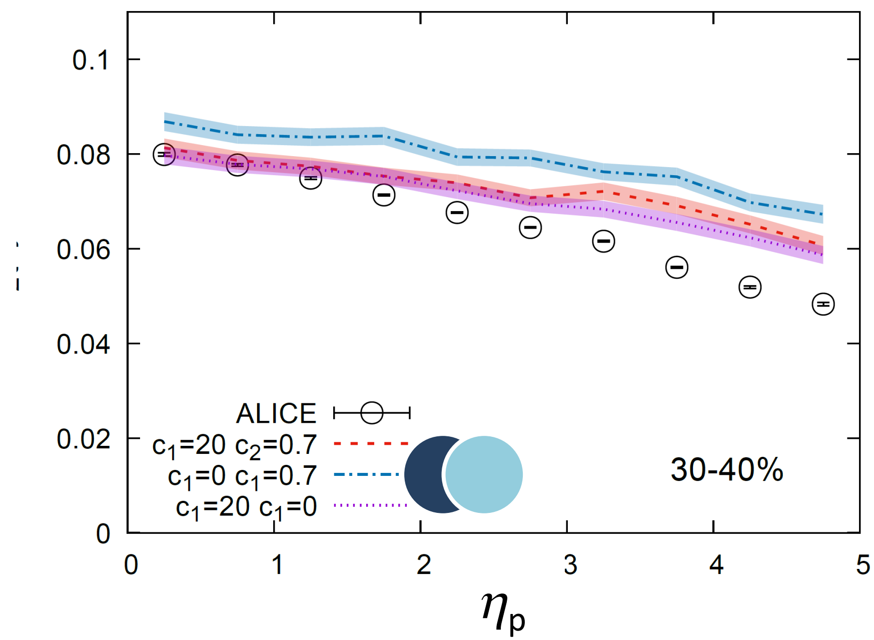
Temperature Dependent η/s

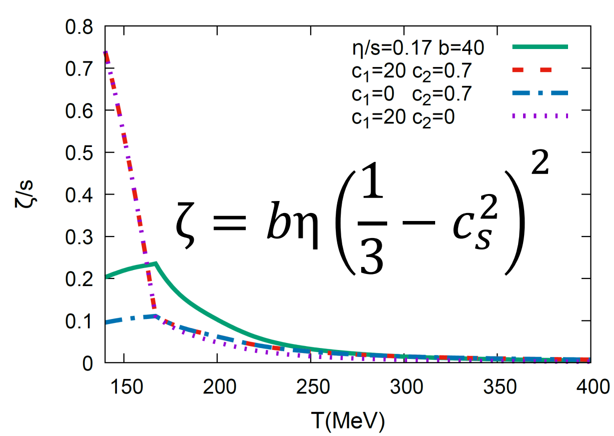


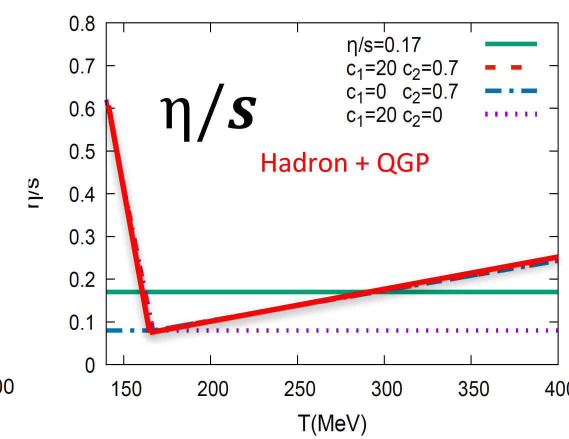


QGP phase: $\eta/s(T)$

Hadron phase: η/s(T)

In both central classes, close to ALICE data





$T_{\rm SW} = 150$ MeV

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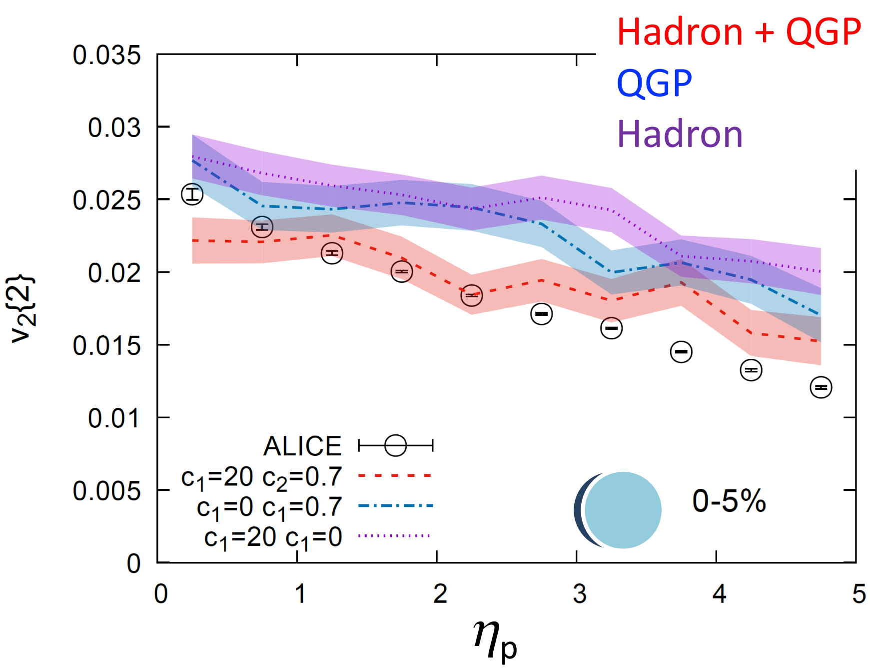
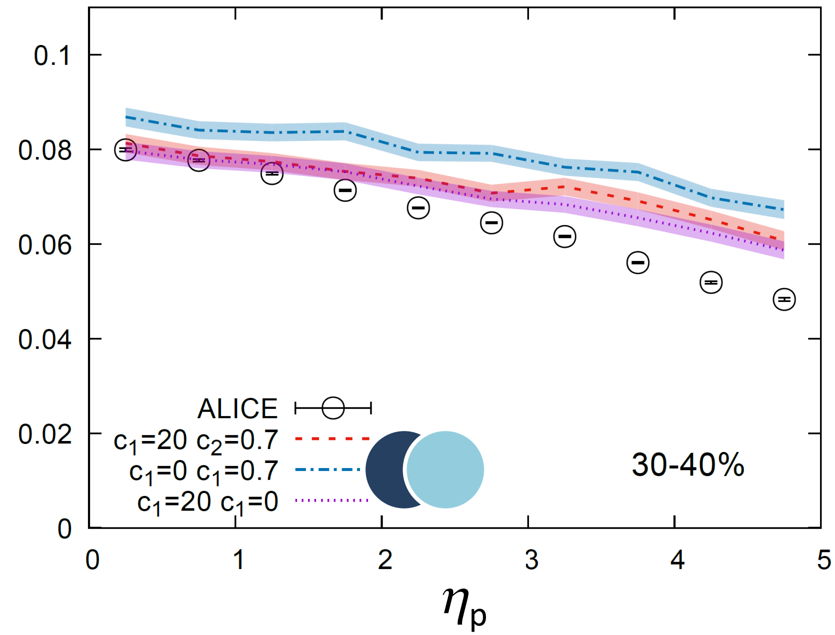
Temperature Dependent η/s



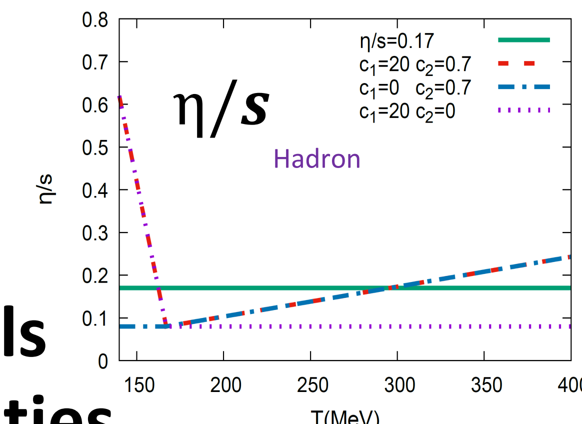


- 0-5 % centrality

  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.

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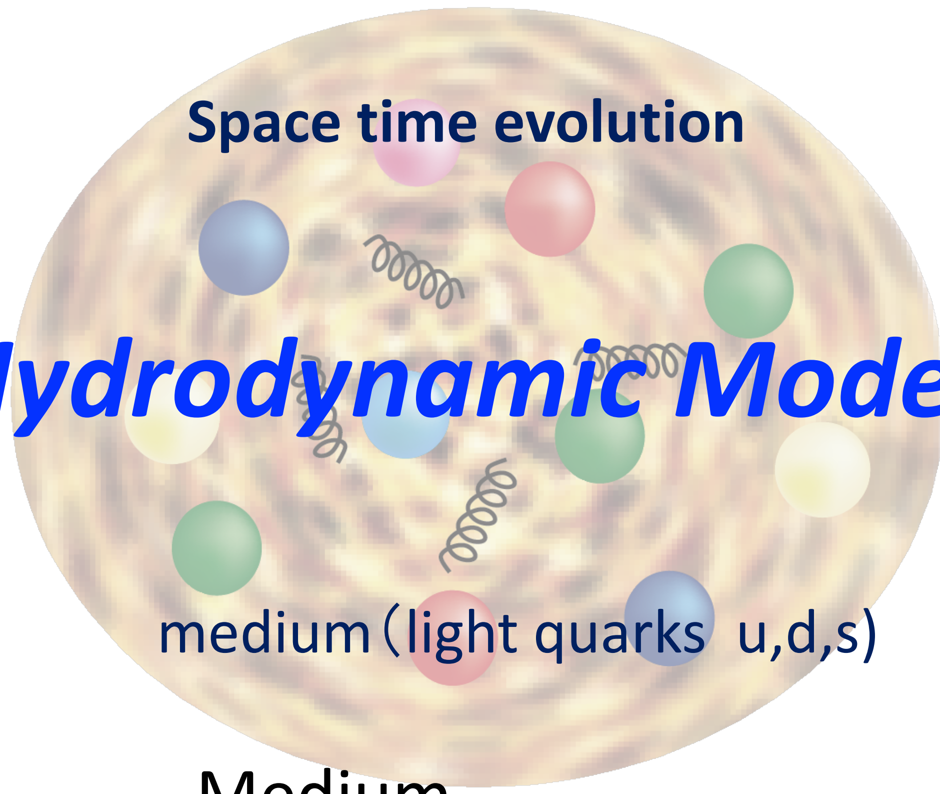
Summary

- **Tools for analyses of relativistic heavy ion collisions**
  - New relativistic viscous hydrodynamics code
    - Quantitative analyses of QGP bulk property
    - More detailed structure of QGP fluid   ex. vorticity



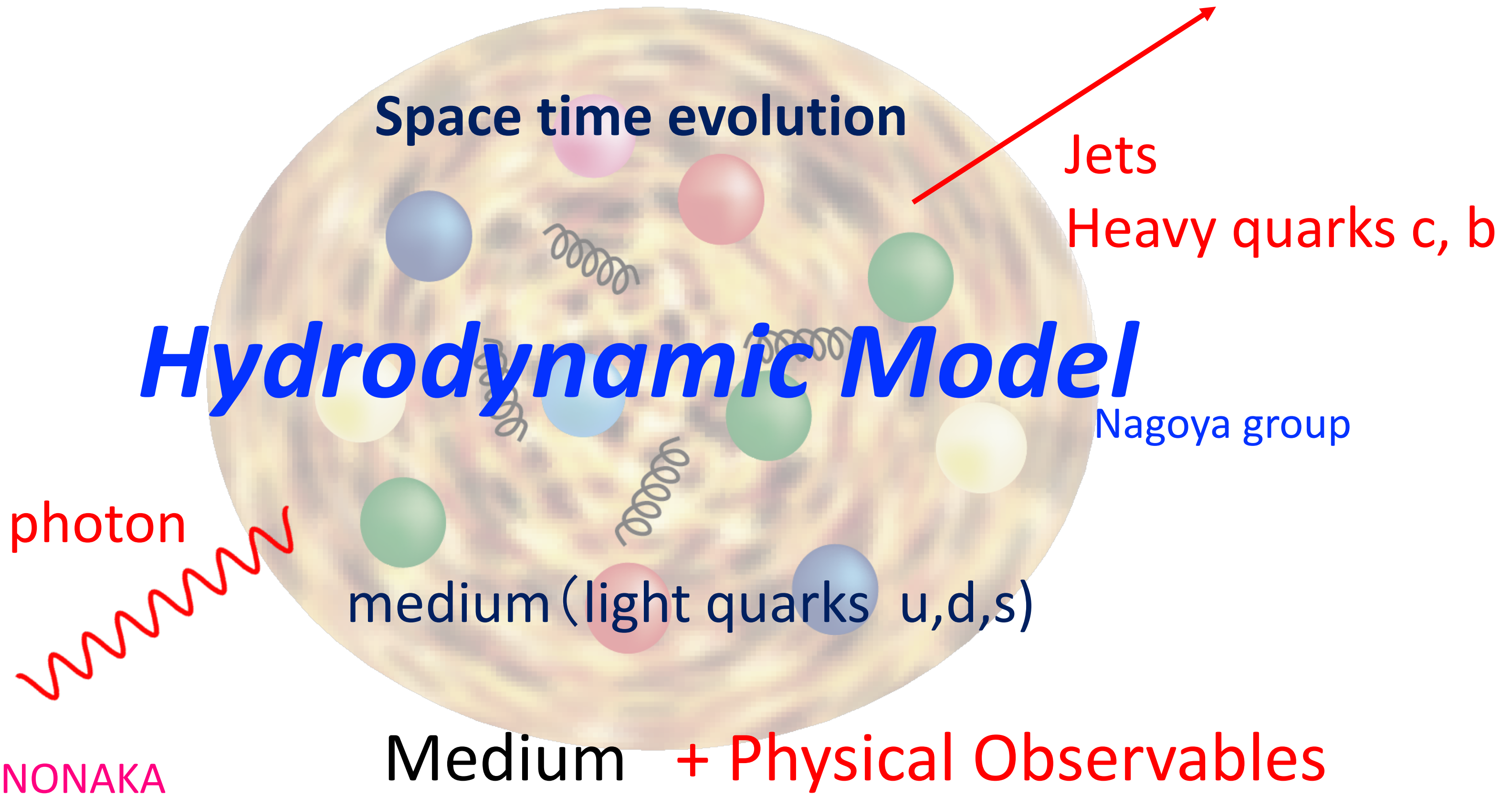
temperature dependence of viscosities

Nagoya group

Summary

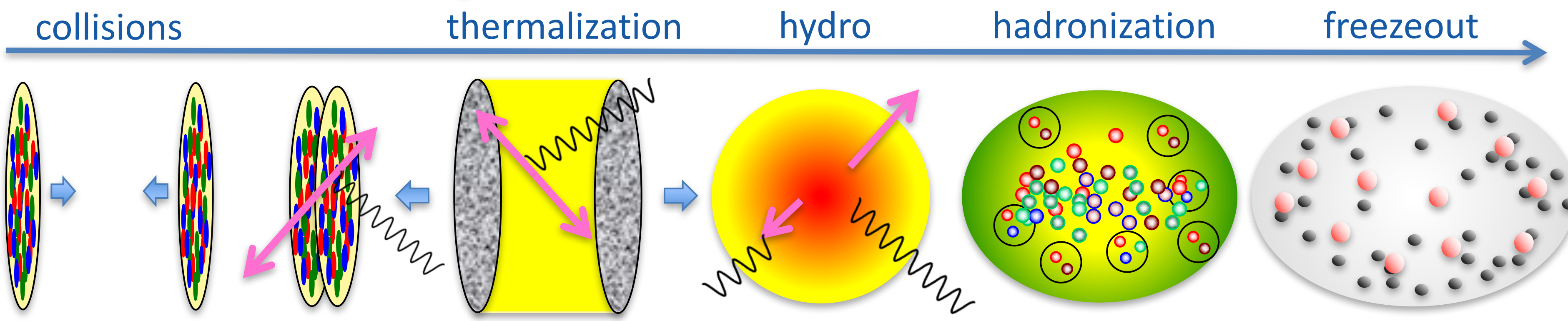
- **Tools for analyses of relativistic heavy ion collisions**
  - Application to other physical observables

    Jets, heavy quarks, photons, electromagnetic probes…



BackUp

Physical Observables



Pre-Equilibrium & Initial State

Strongly coupled QGP, Thermalization, Quark recombination
Collectivity in small systems, Correlations & Fluctuations

QCD at Finite Temperature and Density

QCD phase structure

Hadron Thermodynamics and Chemistry

Electromagnetic probes, Jet quenching
High temperature matter, Search for Chiral symmetry restoration

Algorithm

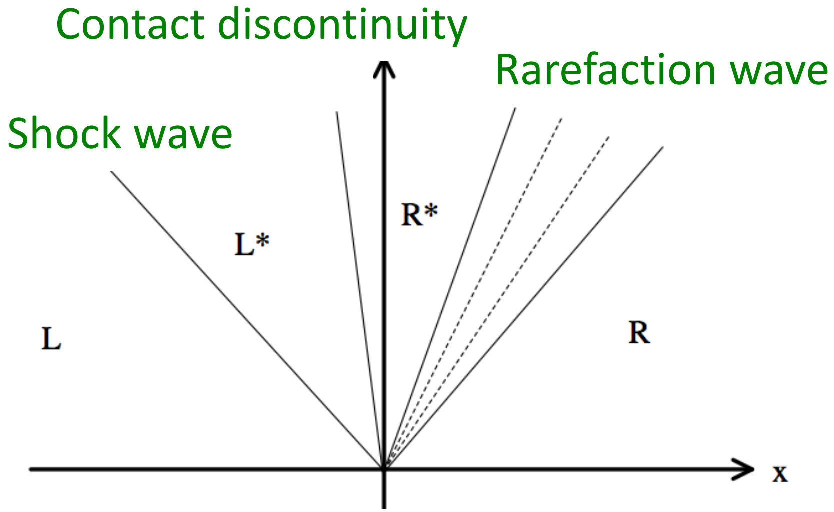
Takamoto and Inutsuka, arXiv:1106.1732
Akamatsu et al, JCP256,34(2014)
Okamoto, Akamatsu, Nonaka, EPJC76,579(2016)
Okamoto and Nonaka, EPJC77,383(2017)

- Relativistic viscous hydrodynamics: $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + \Delta T^{\mu\nu}$$

1. dissipative fluid dynamics = advection + dissipation

exact solution



Riemann solver: Godunov method

Two shock approximation

Mignone, Plewa and Bodo, Astrophys. J. S160, 199 (2005)

Rarefaction wave ⟶ shock wave

Stable with small numerical viscosity

2. relaxation equation = advection + stiff equation

Shear and Bulk Viscosities

shear viscosity

$$\eta/s = 0.17$$

shear + bulk viscosities

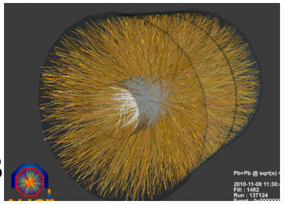
$$\eta/s = 0.17$$

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

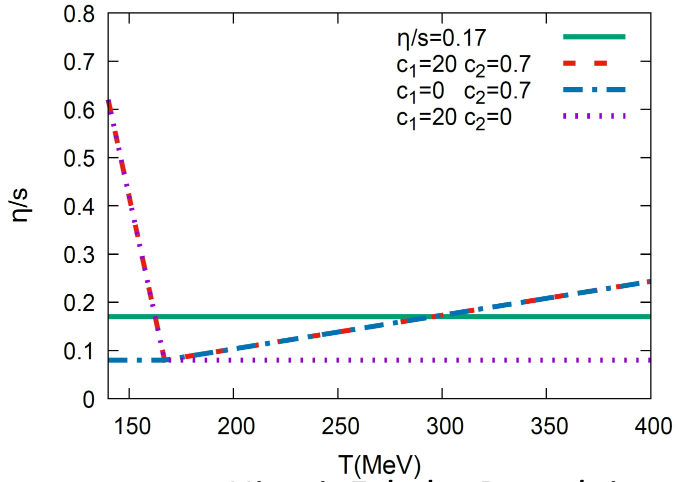
Molnar et al., PRC89,074010(2014)

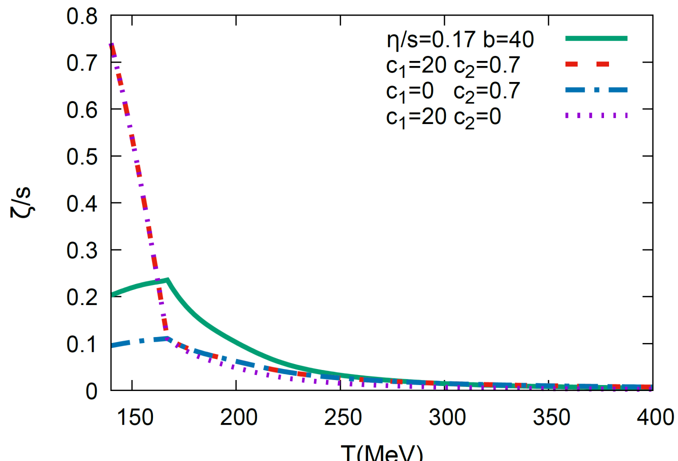
ALICE Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV, LHC

- √ Rapidity distributions
  central collision: parameter fixing
- √ P_T distributions
- √ Mean P_T
- √ Collective flows v_2 and v_3



temperature dependent shear + bulk viscosities

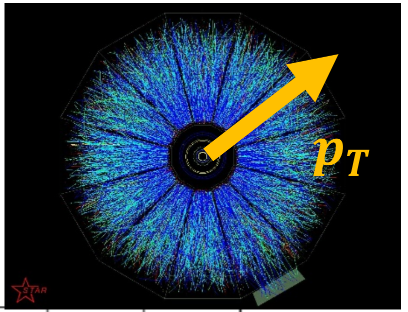




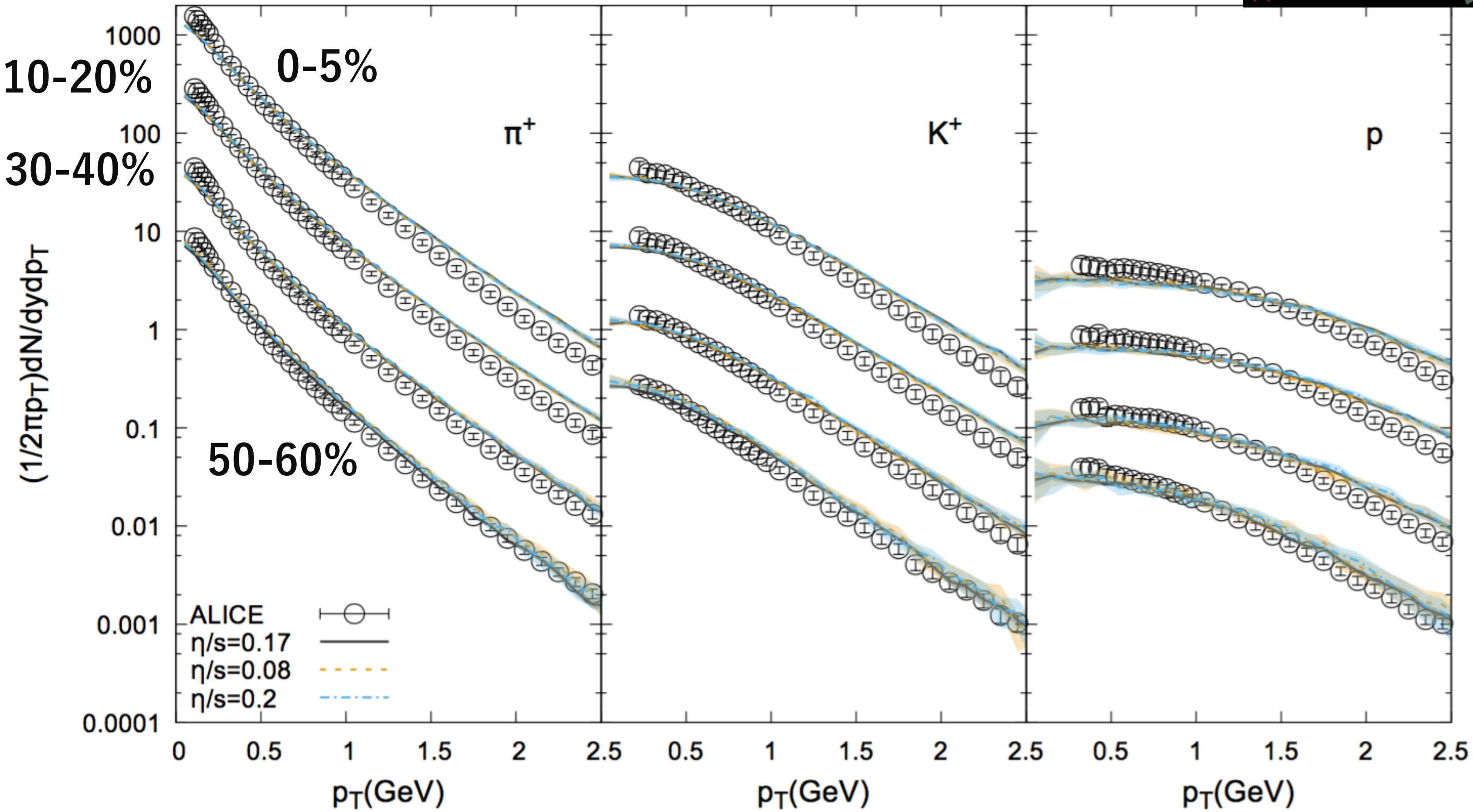
Niemi, Eskola, Paatelainen, PRC93, 024907(2016)

Denicol, Monnai, Schenke, PRL 116, 212301 (2016)

η/s dependence



- p_T spectra



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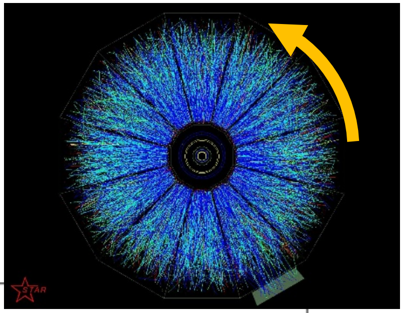
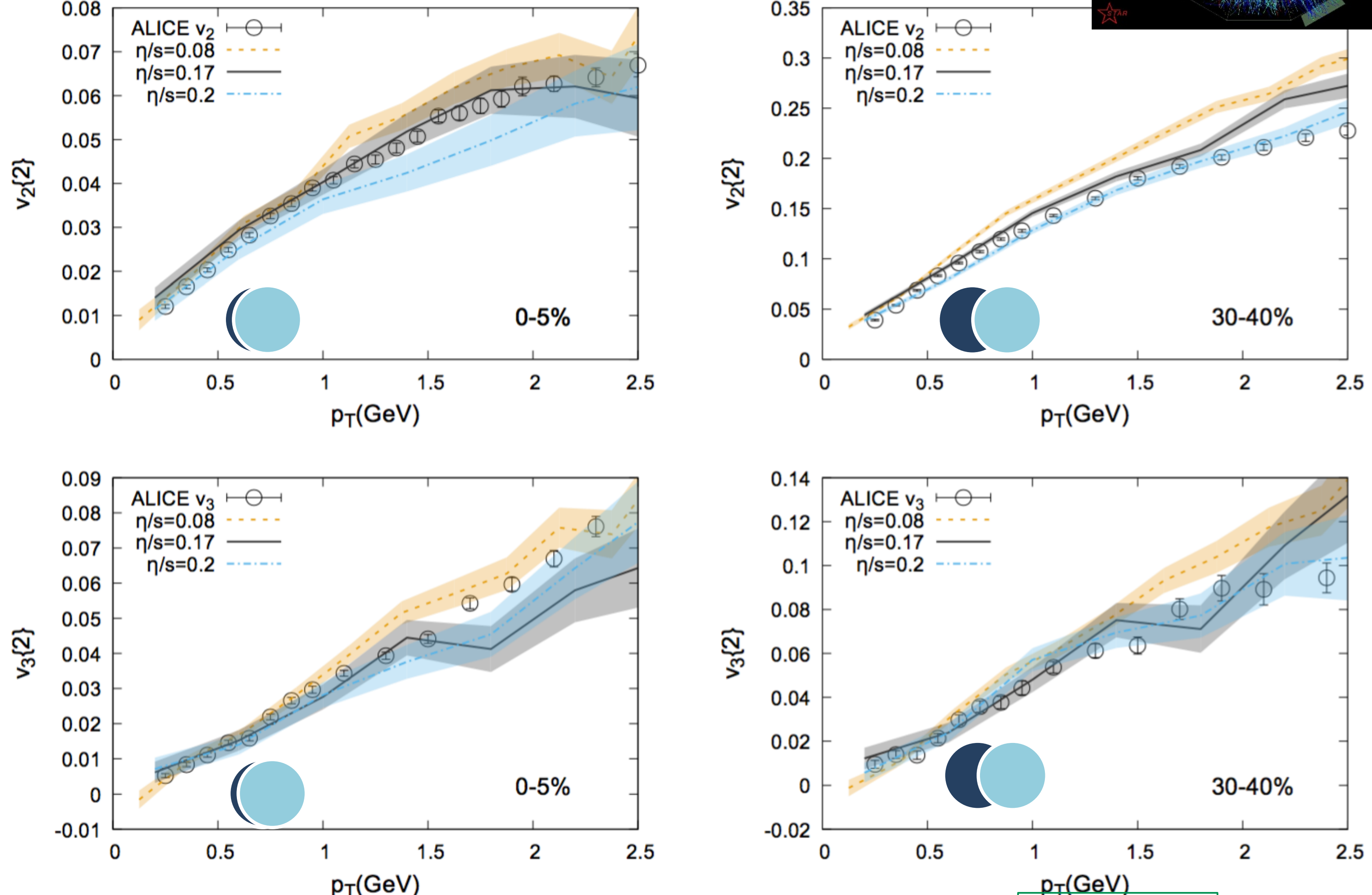
P_T spectra do not depend on η/s.

η/s dependence



- Collective Flows



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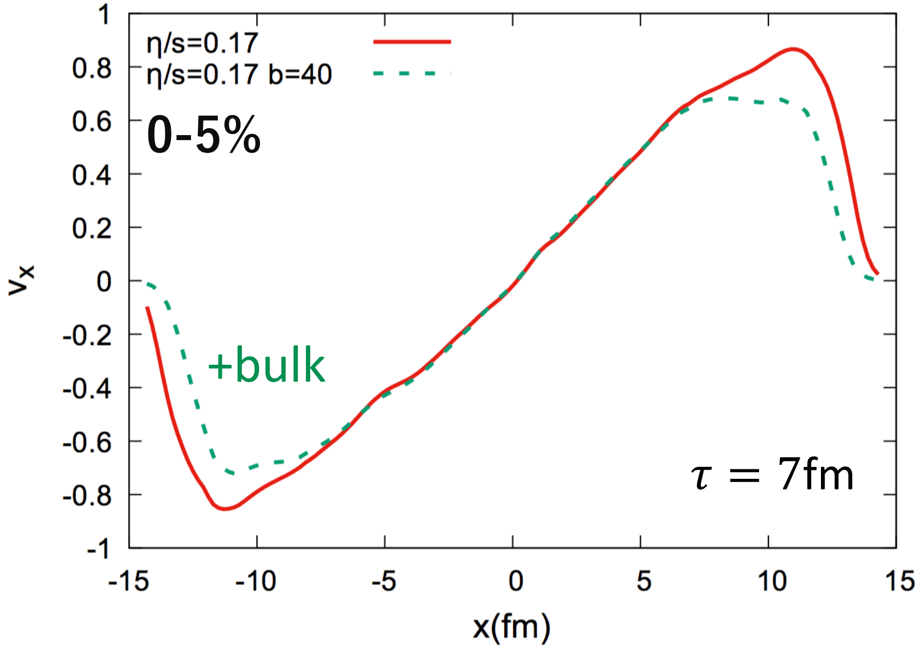
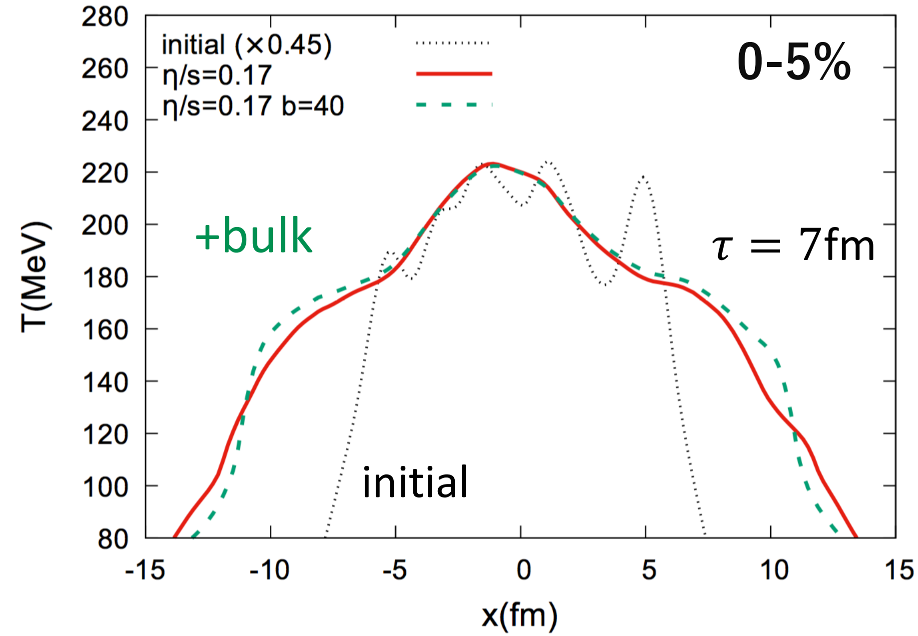
v_2 and v_3 are smaller at larger η/s. → $\eta/s=0.17$

Effect on Expansion



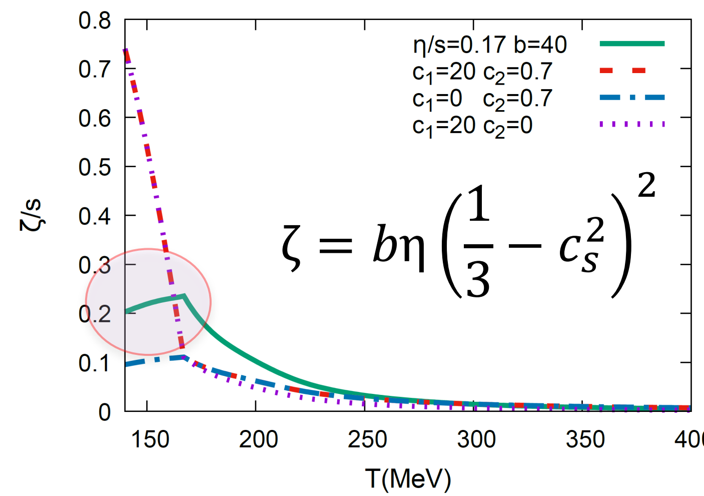


Bulk viscosity is large below 200 MeV.

-> Its effect appears around T_c ~160 MeV.

-> Expansion rate decreases in lower temperature region.

-> Volume elements of fluid remain around T_c temperature longer.



C. NONAKA