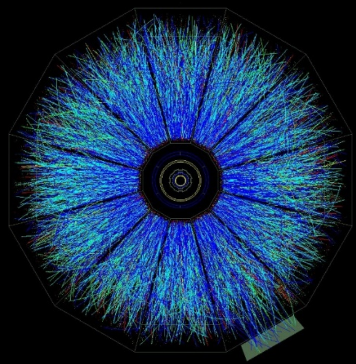
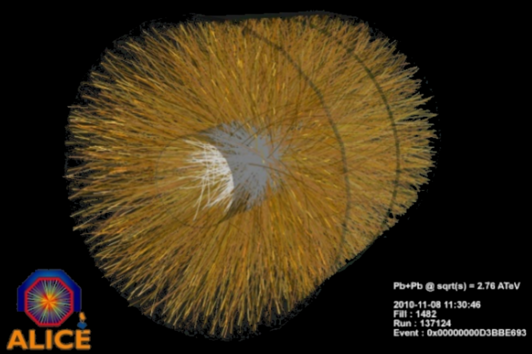


# Quark-Gluon Plasma in the Little Bang


Kobayashi-Maskawa Institute, Nagoya University
Department of Physics, Nagoya University

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

***Chiho NONAKA***

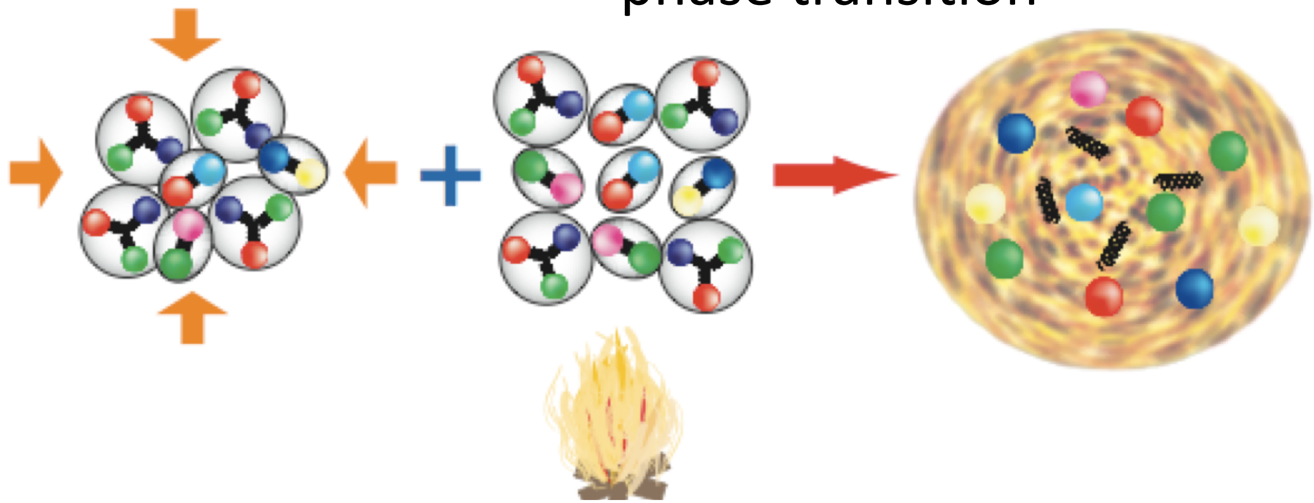




February 15, 2018@PACIFIC2018

# Quark Gluon Plasma

**hadrons** **QGP**

phase transition

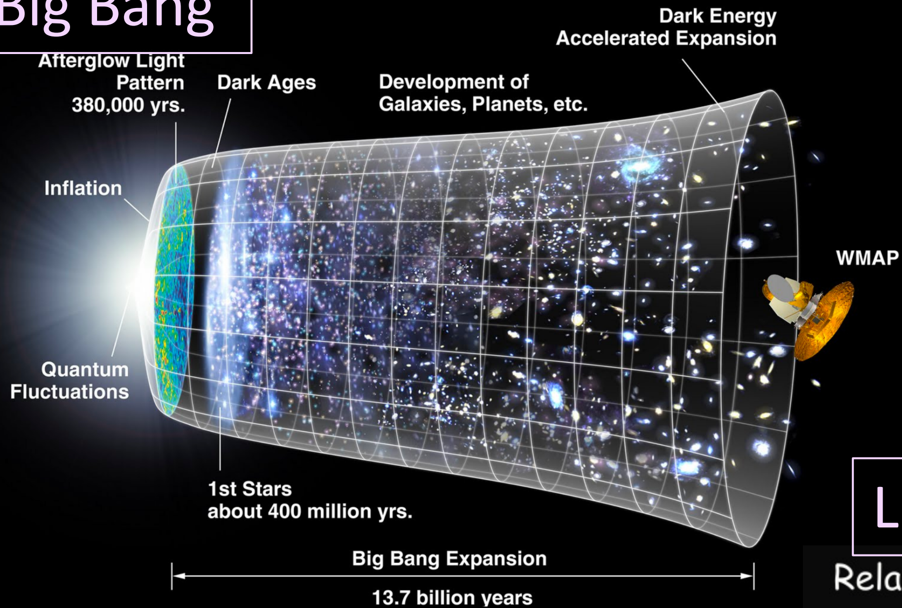


asymptotic freedom

**Early universe**
**High-energy heavy-ion collisions**

# Quark Gluon Plasma

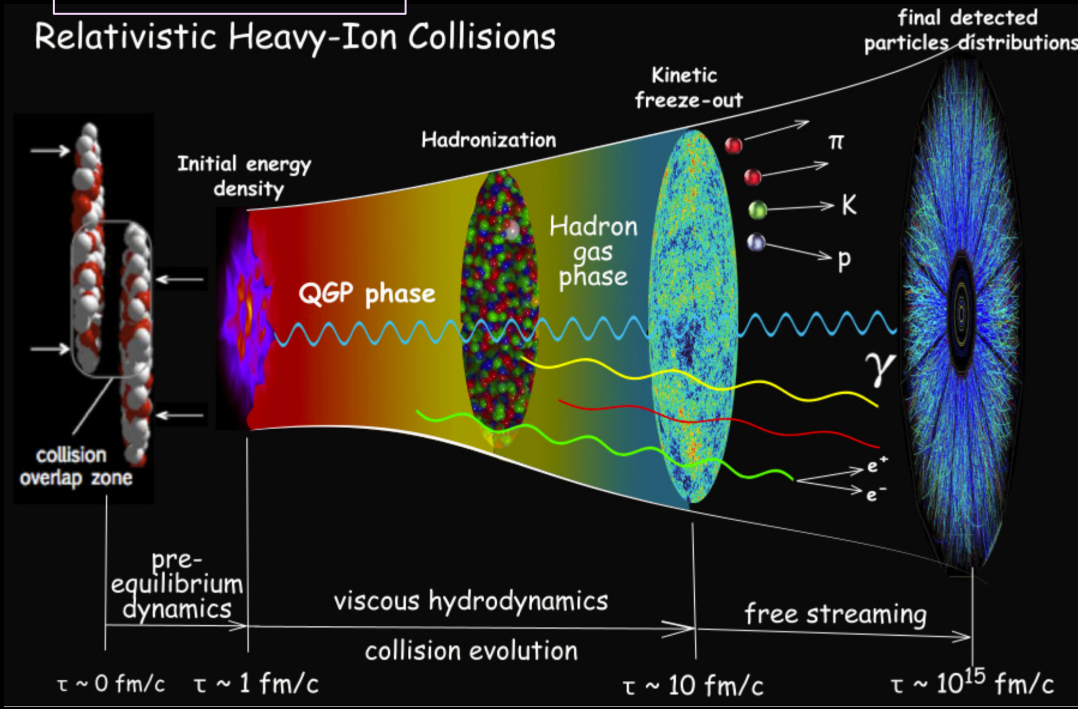
Big Bang




NASA

Little Bang

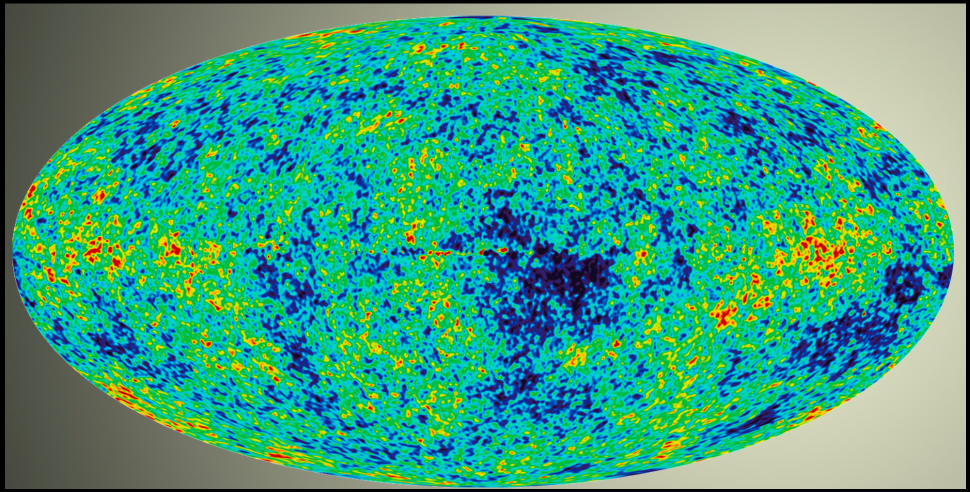
Sorensen, Shen



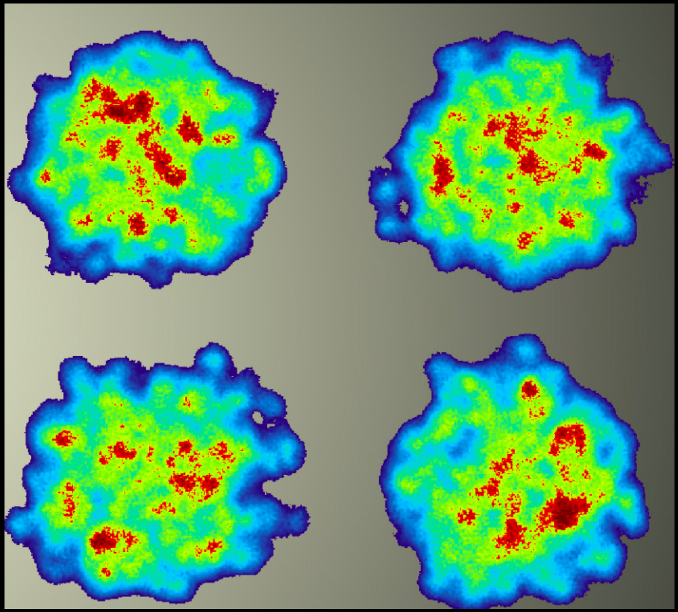

C. NONAKA

# Quark Gluon Plasma

Big Bang

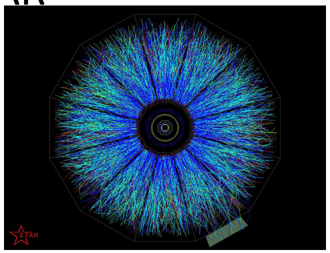


Little Bang



# Quark-Gluon Plasma

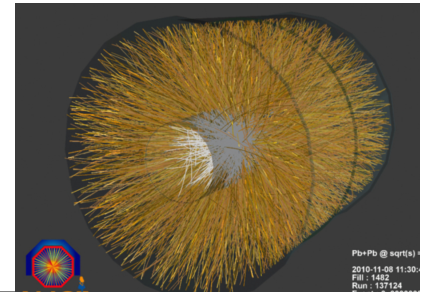
STAR



**RHIC:2000**

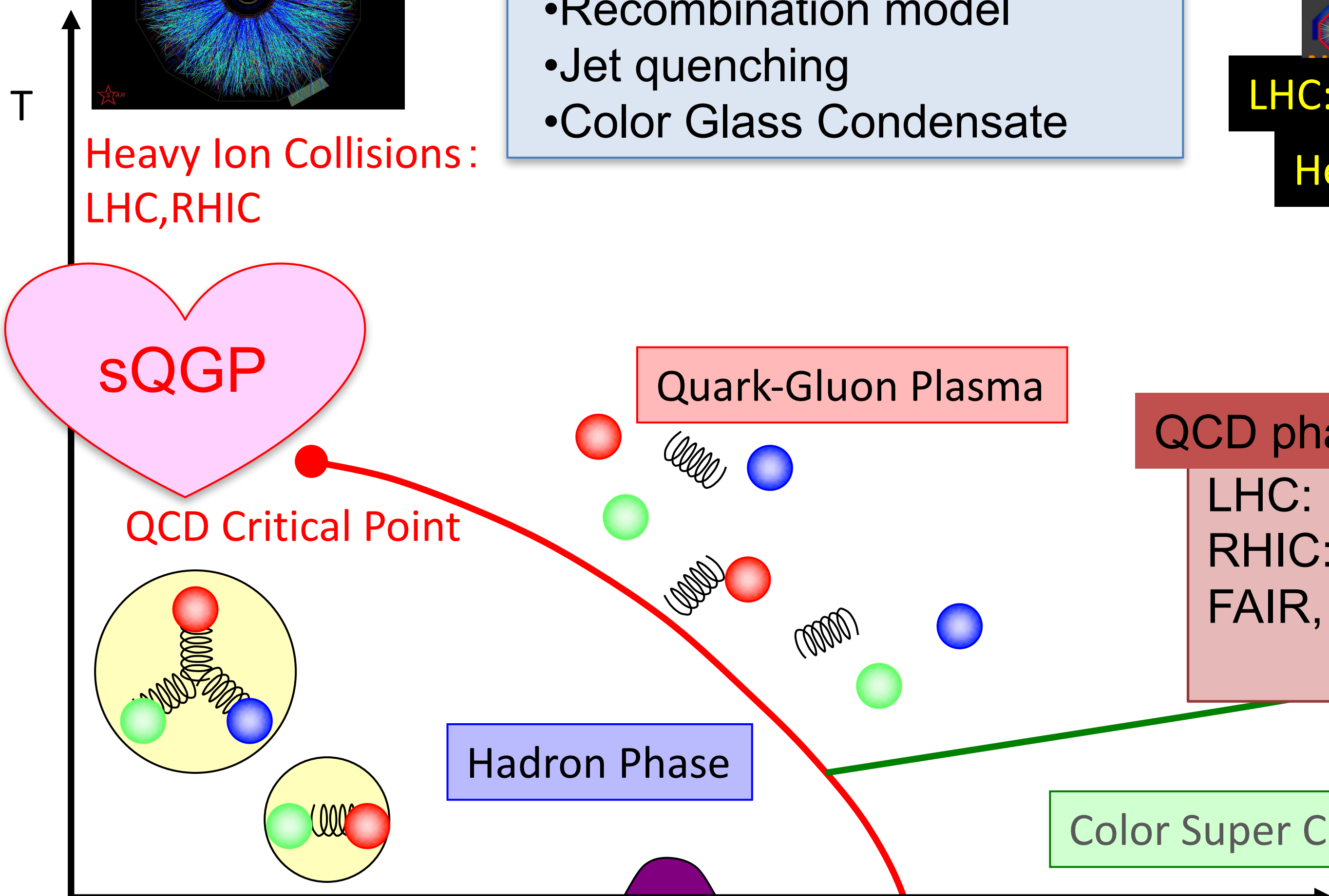
**Strongly interacting QGP**

- Relativistic hydrodynamics
- Recombination model
- Jet quenching
- Color Glass Condensate



LHC:2010

Heavy Ion collisions start!



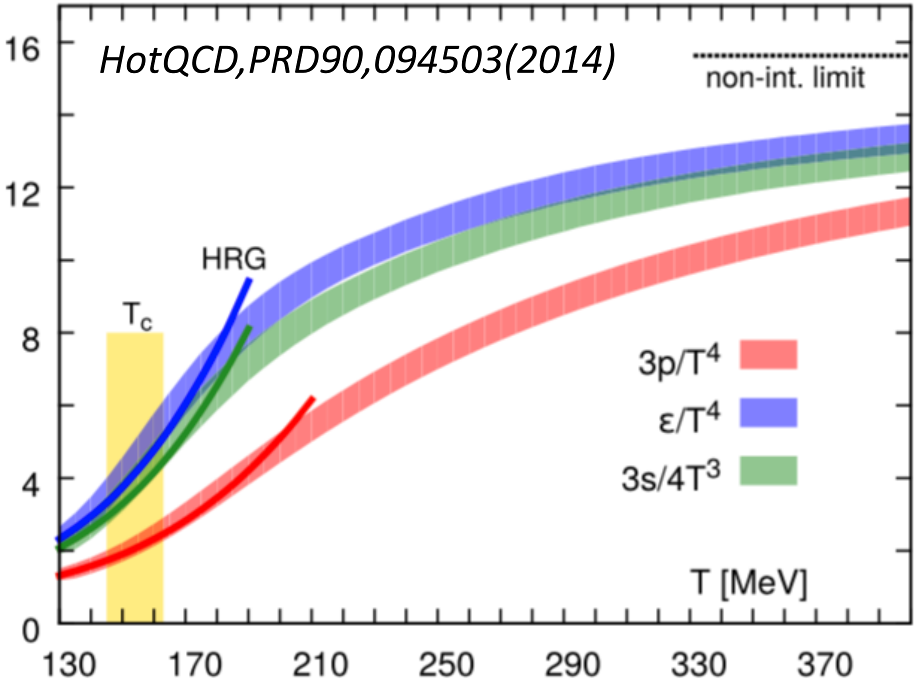

QCD phase diagram

LHC: Energy frontier
RHIC: Beam Energy Scan
FAIR, NICA, J-PARC
：high density

C. NONAKA

# Property of QGP

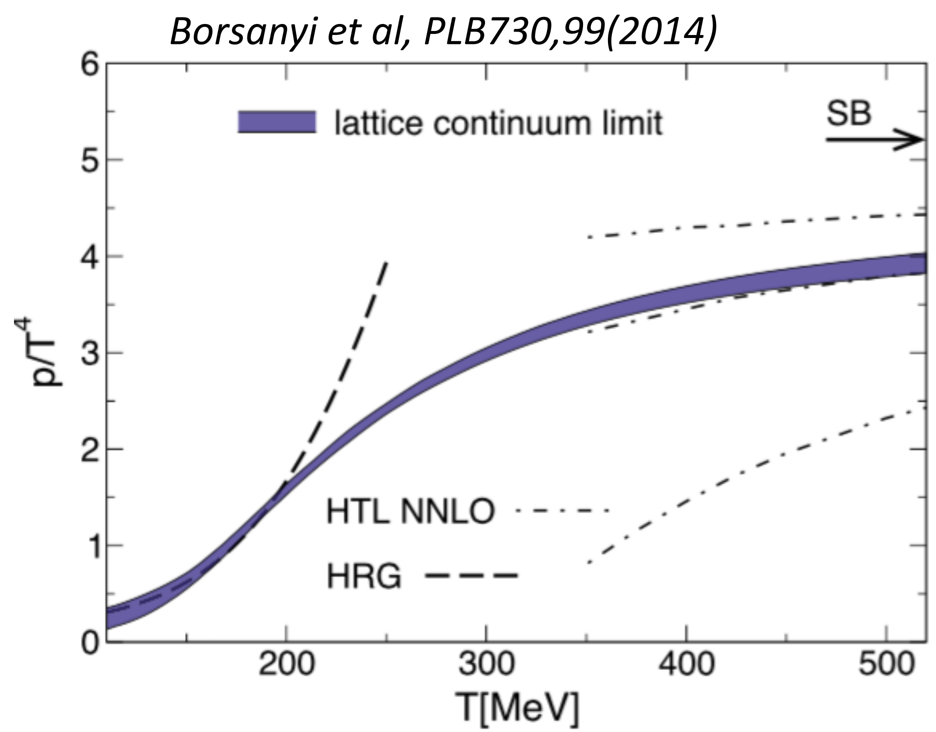
- Equation of State
  - Lattice QCD




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

Nt=6,8,10,12,Ns=4Nt → continuum limit

Parametrization of EoS




(2+1) flavor, Symanzik improved gauge and a stout- link improved staggered fermion action

Nt=6,8,10,12,16 → continuum limit

Parametrization of EoS

$T_c \sim 155$ MeV

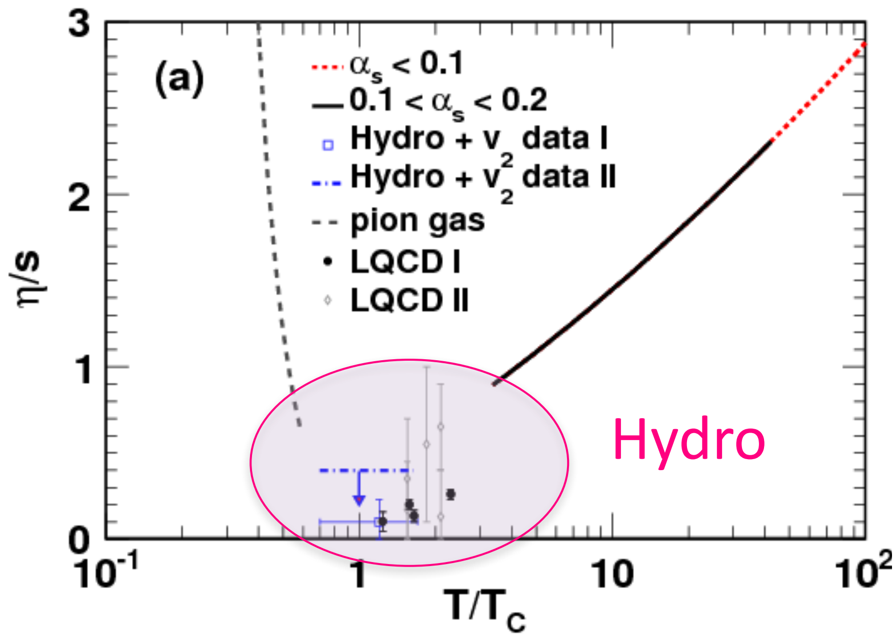
C. NONAKA

finite $\mu$: sign problem

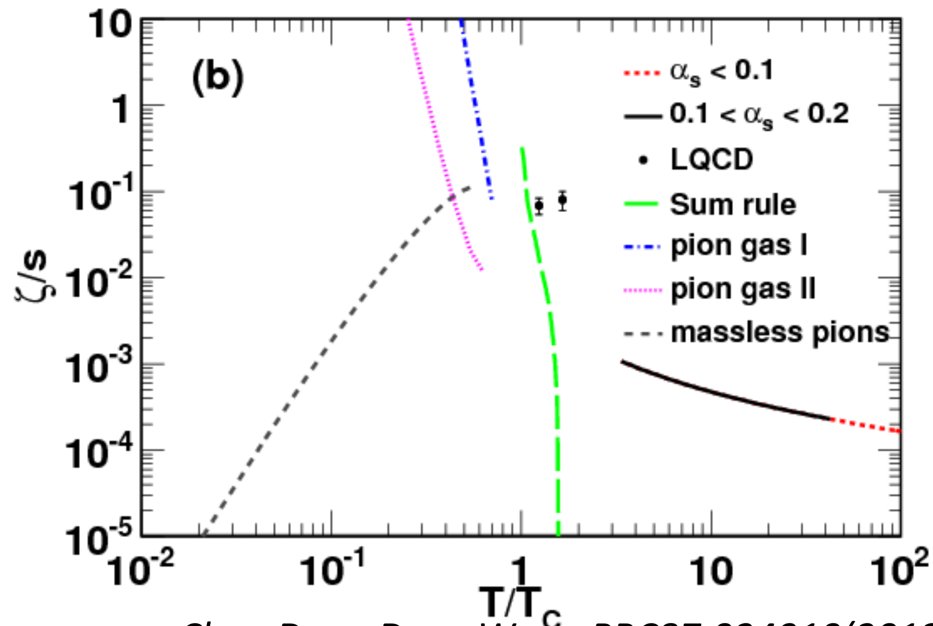
# Property of QGP

- Current Status for transport coefficients

shear viscosity




bulk viscosity




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

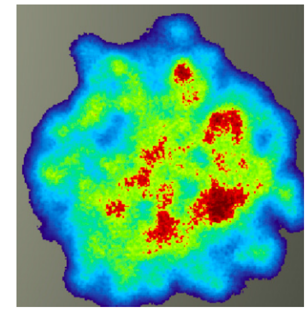
- Shear viscosity takes the minimum around $T_c$. Cf. $\eta/s=1/4\pi$ AdS/CFT
- Hydrodynamic model constant $\eta/s$

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

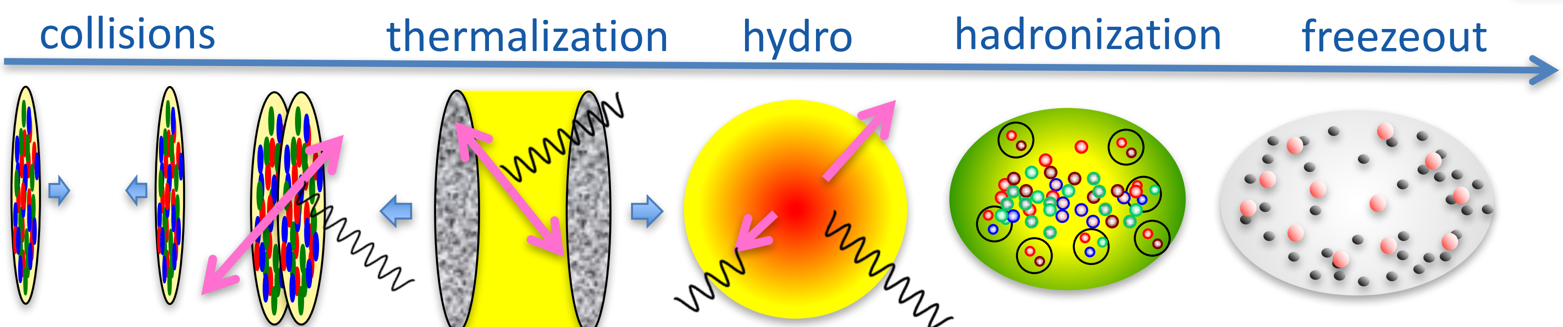
**Detailed feature of shear and bulk viscosities**

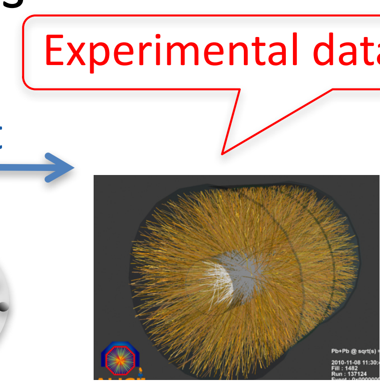
# Our Strategy

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



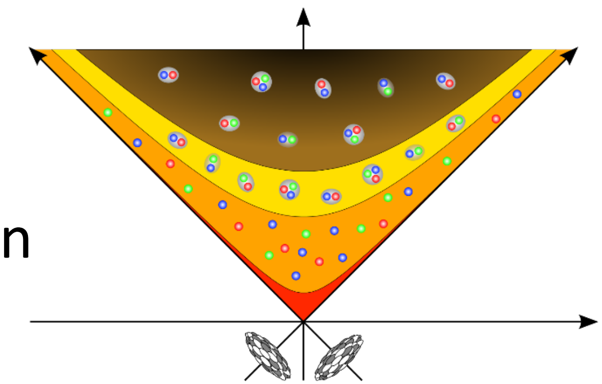
2. Application to phenomenological analyses of LHC data
   - Description of space-time expansion after collisions



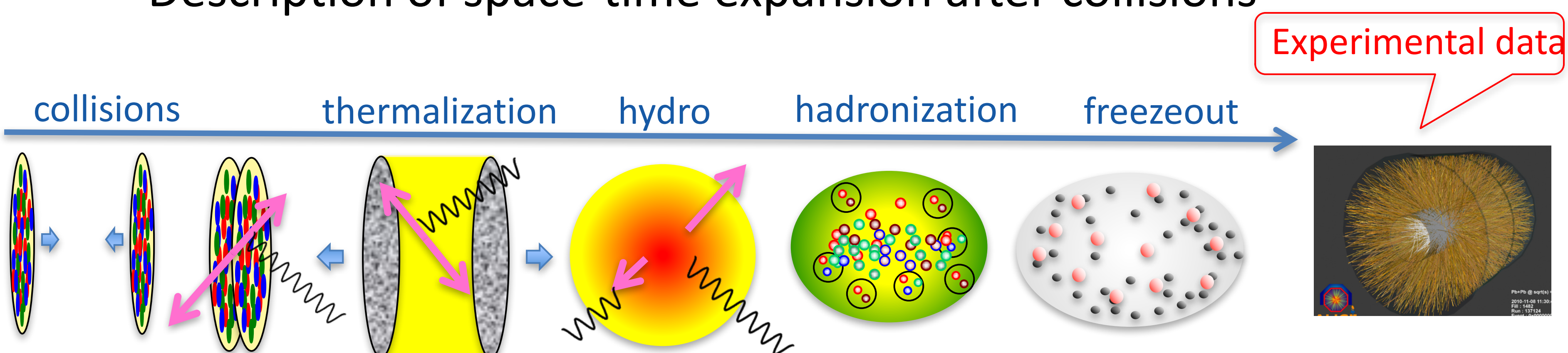



# Our Strategy

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

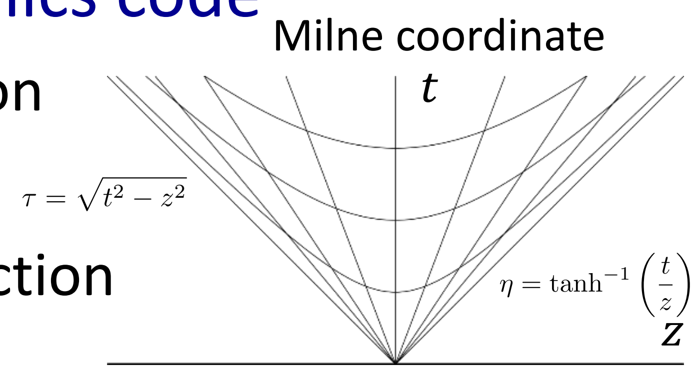


2. Application to phenomenological analyses of LHC data
   - Description of space-time expansion after collisions

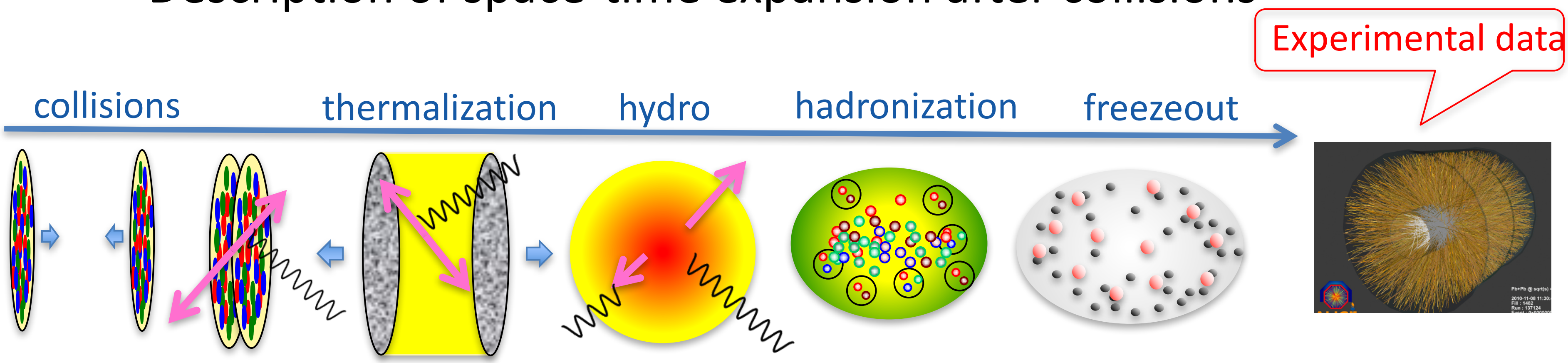


# Our Strategy

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



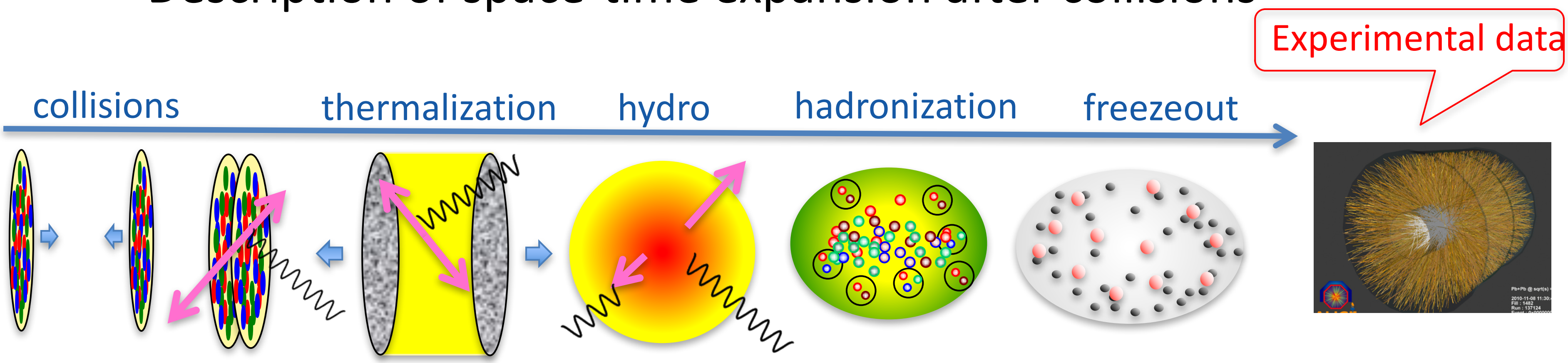

C. NONAKA

# Our Strategy

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

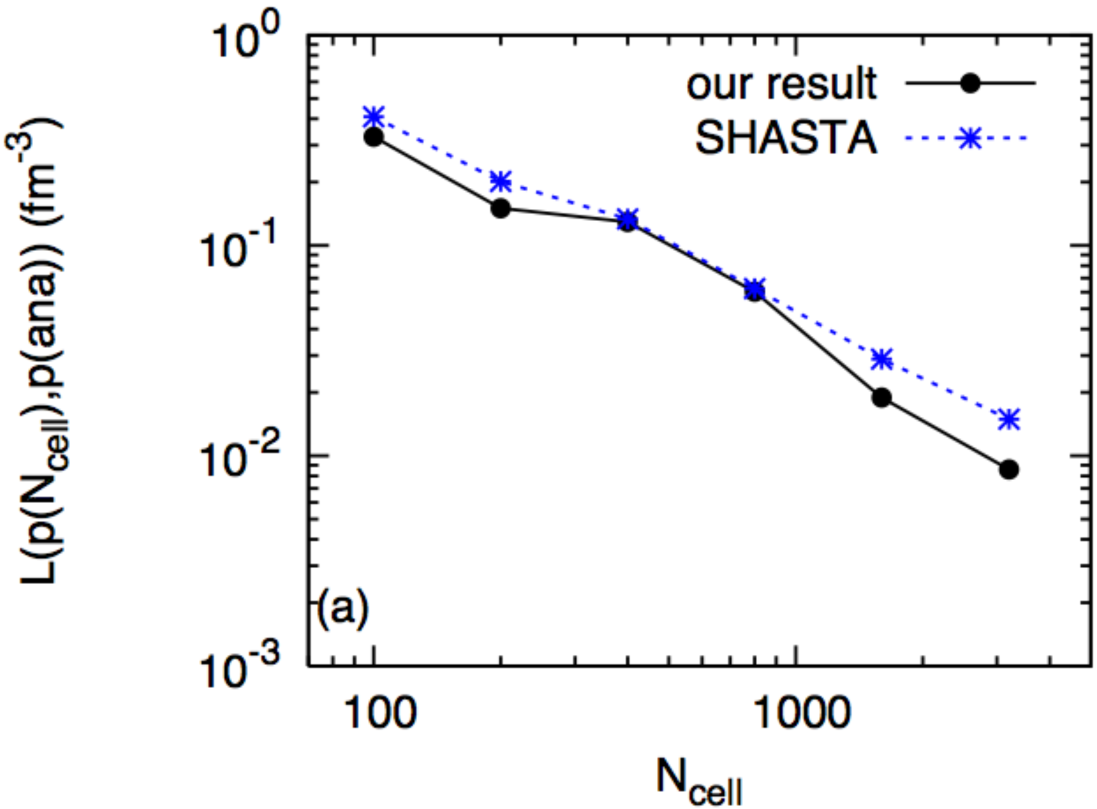
   Riemann solver in Milne coordinates

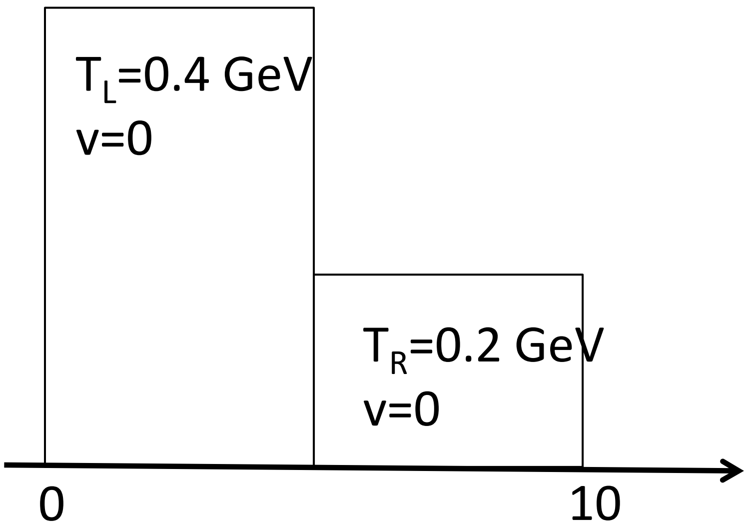
2. Application to phenomenological analyses of LHC data
   - Description of space-time expansion after collisions



# Small Numerical Dissipation

- Numerical dissipation: deviation from analytical solution




For analysis of heavy ion collisions

$N_{cell}$=100: dx=0.1 fm

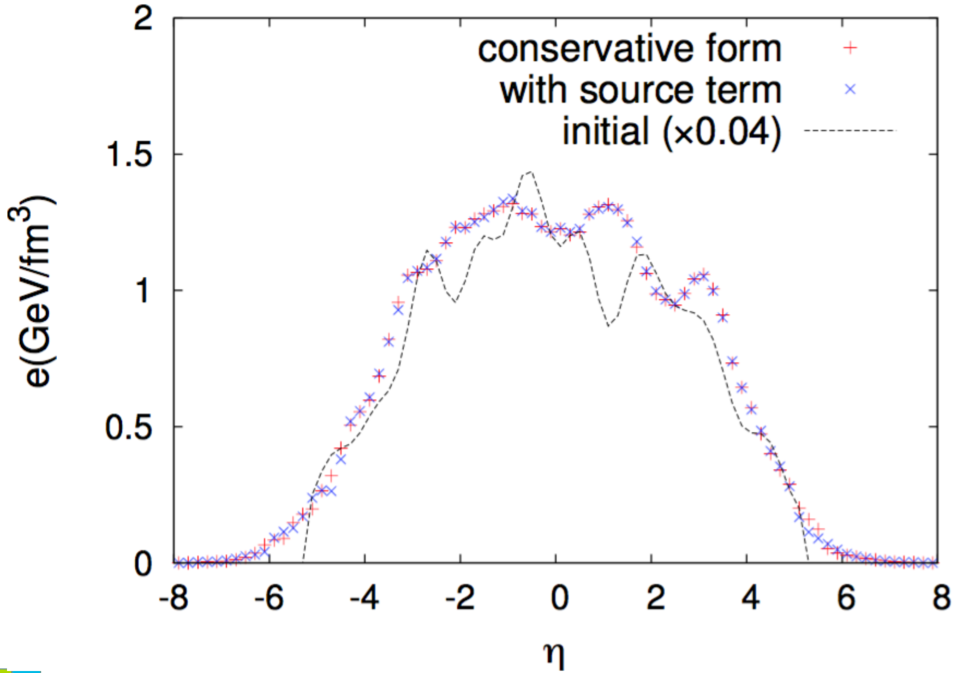
$$L(p(N_{\rm cell}), p({\rm anaytic})) = \sum_{i=1}^{N_{\rm cell}} |p(N_{\rm cell}) - p({\rm analytic})| \frac{\lambda}{N_{\rm cell}}$$

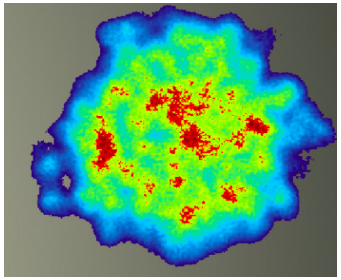
$\lambda$=10 fm

# 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

Sum of violation of conservation

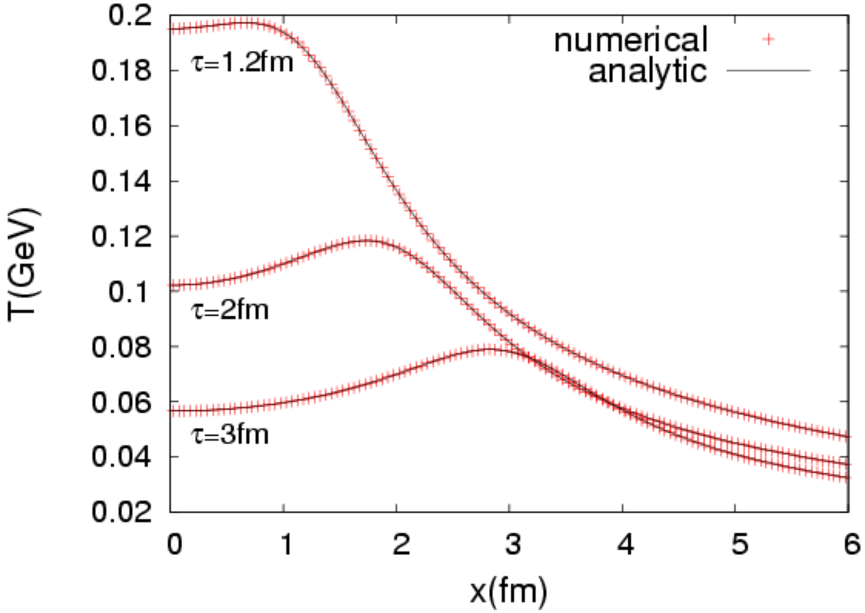
| | $\varepsilon_E$ | $\varepsilon_M$ |
|---|---|---|
| conservative | 1.38E-09 | 8.59E-09 |
| with souce | 1.27E-02 | 5.61E-02 |

# Gubser Flow with Finite $\eta/s$

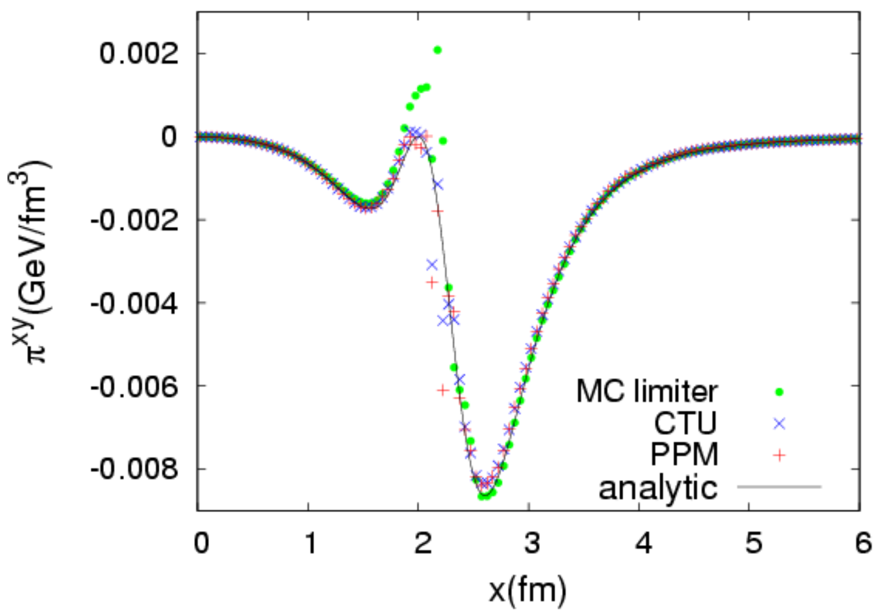
- Analytical solution $\tau = 3.0$ fm
  - Bjorken flow + transverse expansion

*Marrochio et al, PRC91,014903(2015)*

temperature




viscous stress tensor



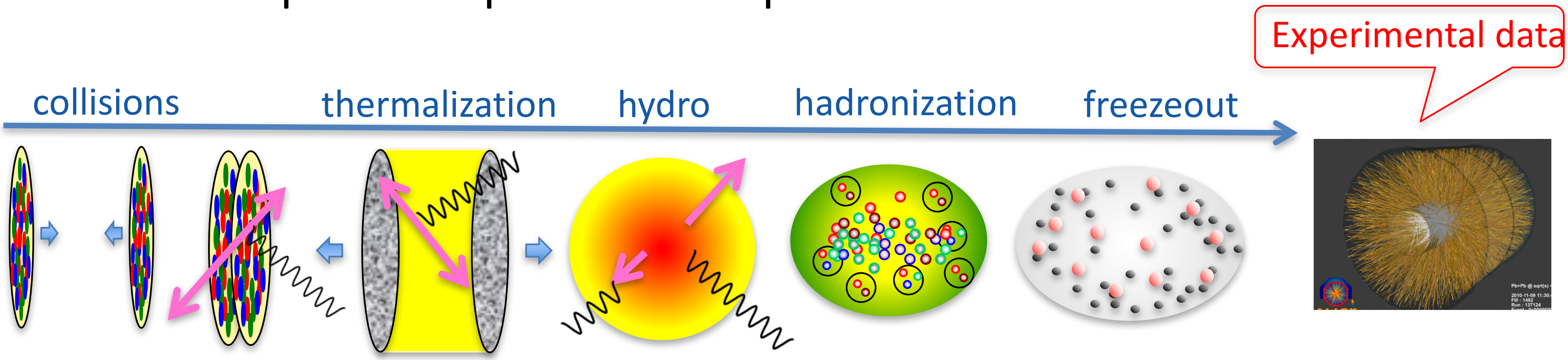

Our computed results show good agreement with analytical solution.

# Our Strategy

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

   Riemann solver in Milne coordinates

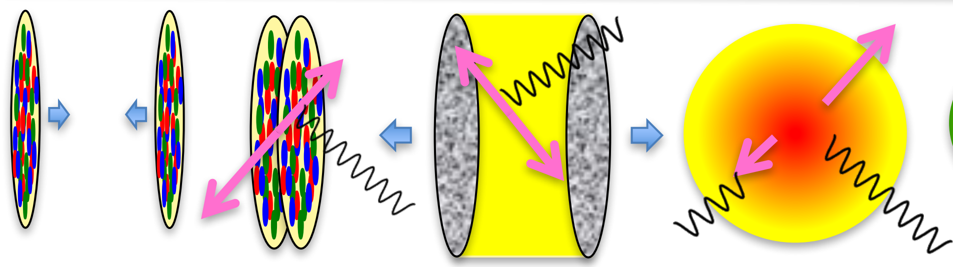
2. Application to phenomenological analyses of LHC data
   - Description of space-time expansion after collisions

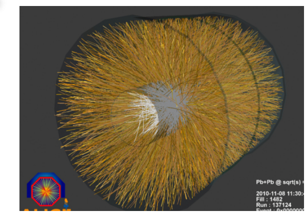


# Quantitative Analyses

Experimental data

collisions thermalization hydro hadronization freezeout





Initial conditions

Fluctuations:
Glauber, KLN,
IP-Glasma…

Hydrodynamics

QGP bulk property
EoS: lattice QCD
Shear and bulk
viscosities

Final state interactions

Hadron based event
generator

TRENTO

Phenomenological model
Parametrization

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

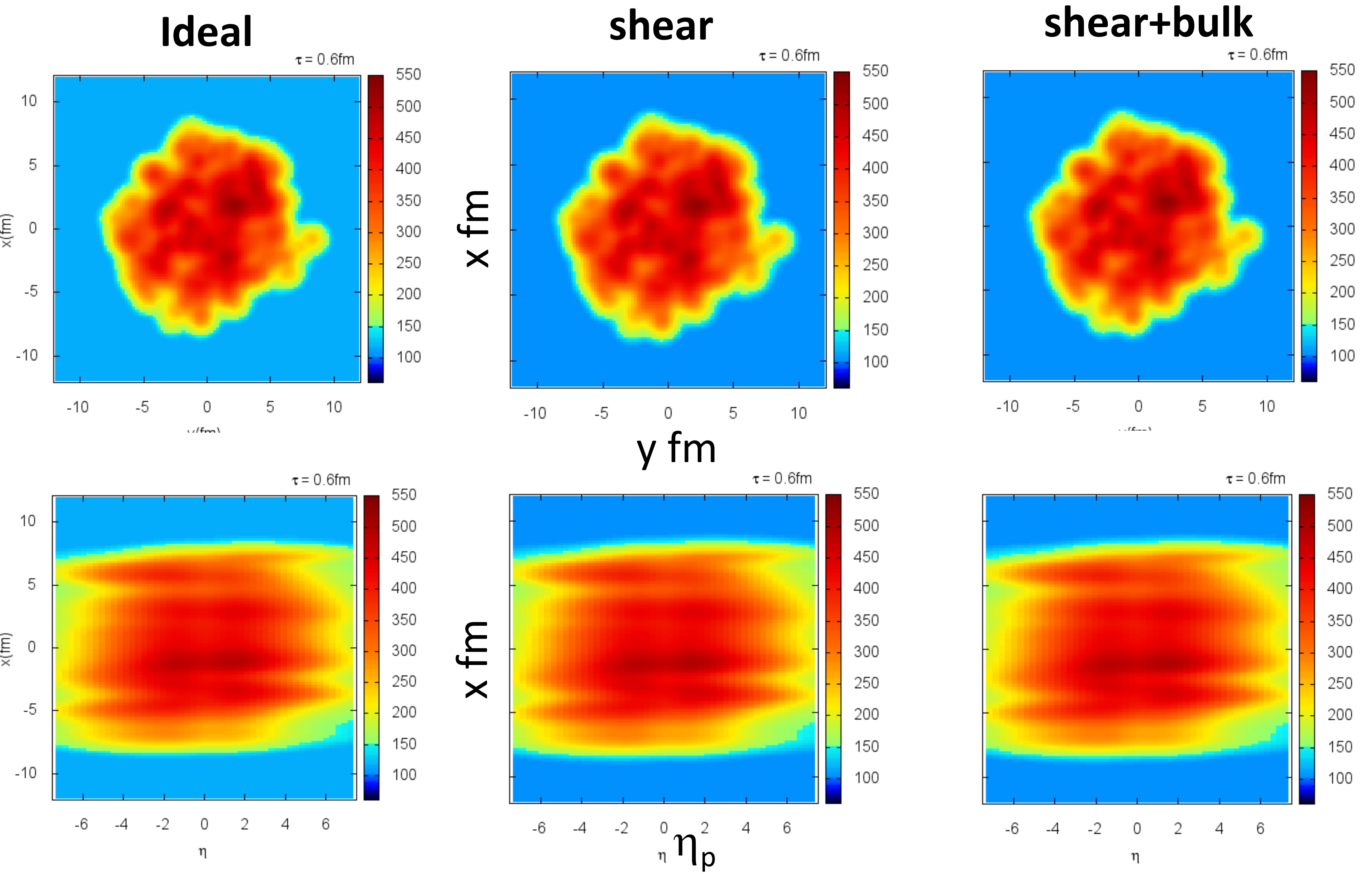
New
hydrodynamics
code

UrQMD

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

C. NONAKA

# Time Evolution of Temperature



# Shear and Bulk Viscosities

**shear viscosity**

$$\eta/s = 0.17$$

**shear + bulk viscosities**

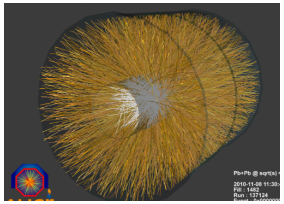
$$\eta/s = 0.17$$

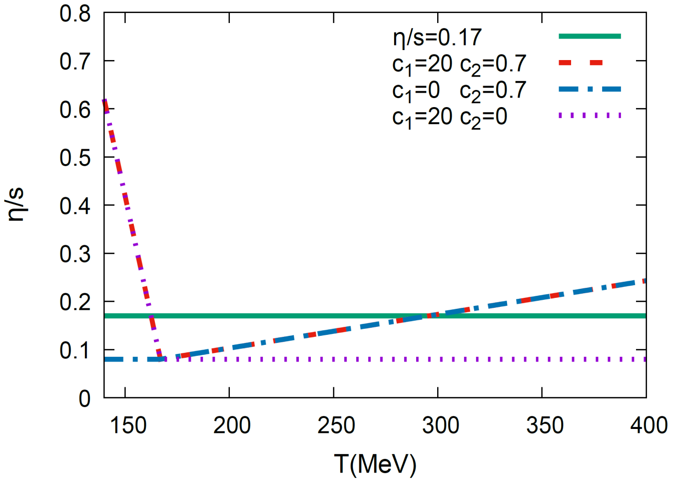
$$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2 \quad b = 40$$

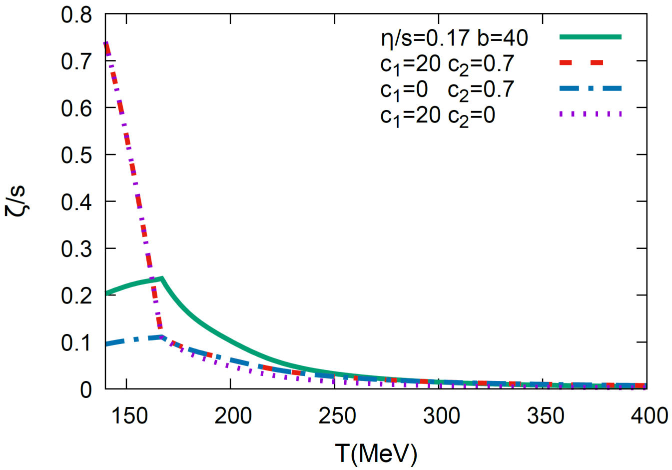
**temperature dependent shear + bulk viscosities**

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

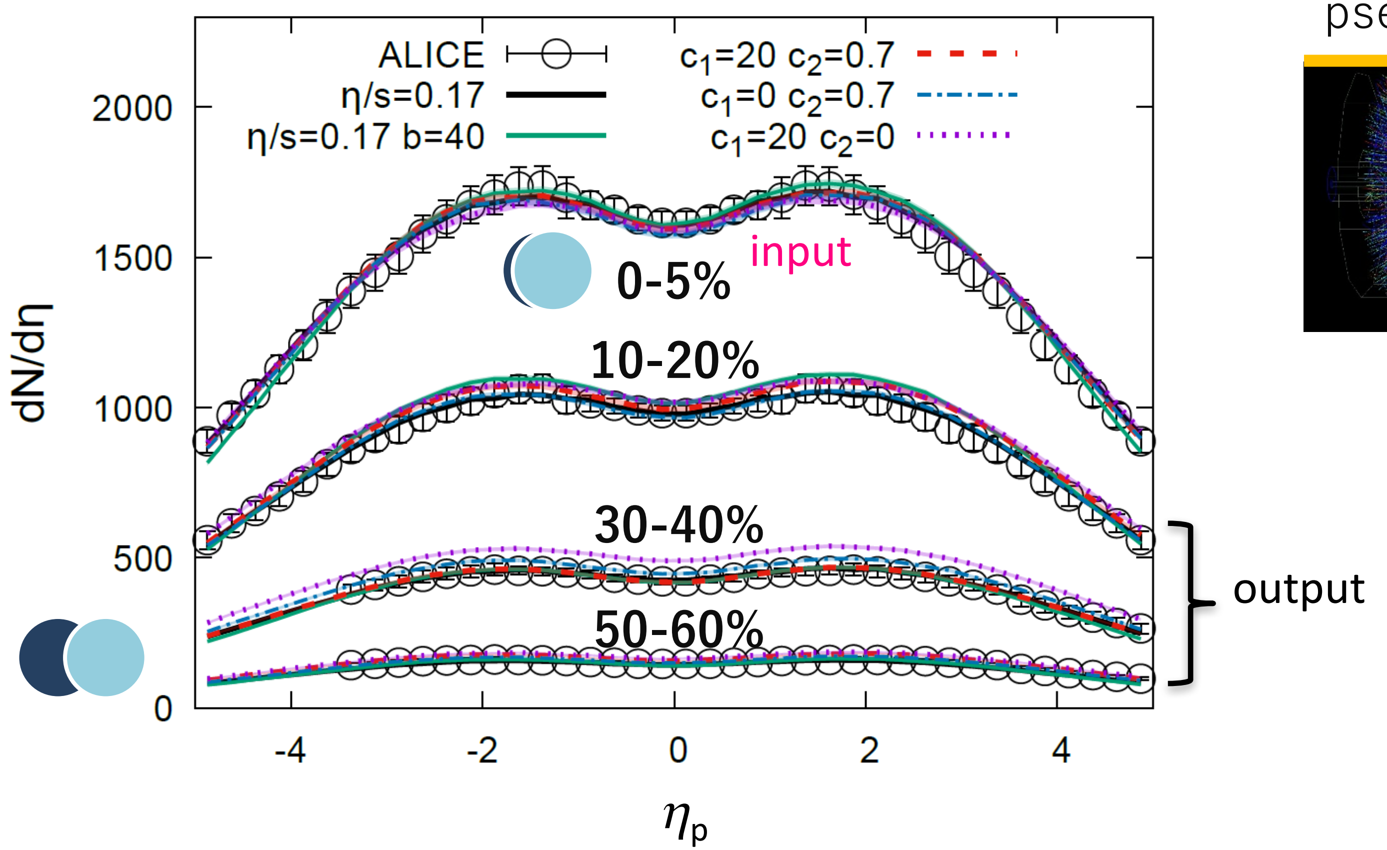
- ✓ Rapidity distributions
  central collision: parameter fixing
- ✓ $P_T$ distributions
- ✓ Mean $P_T$
- ✓ Collective flow $v_2$, $v_3$

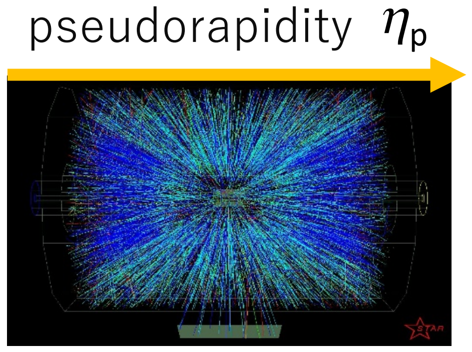




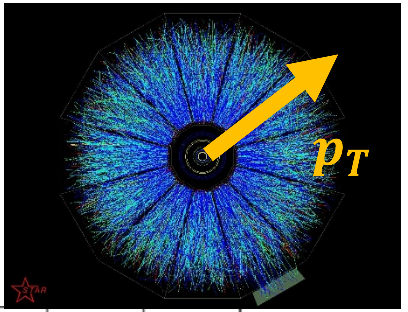
# Rapidity Distributions



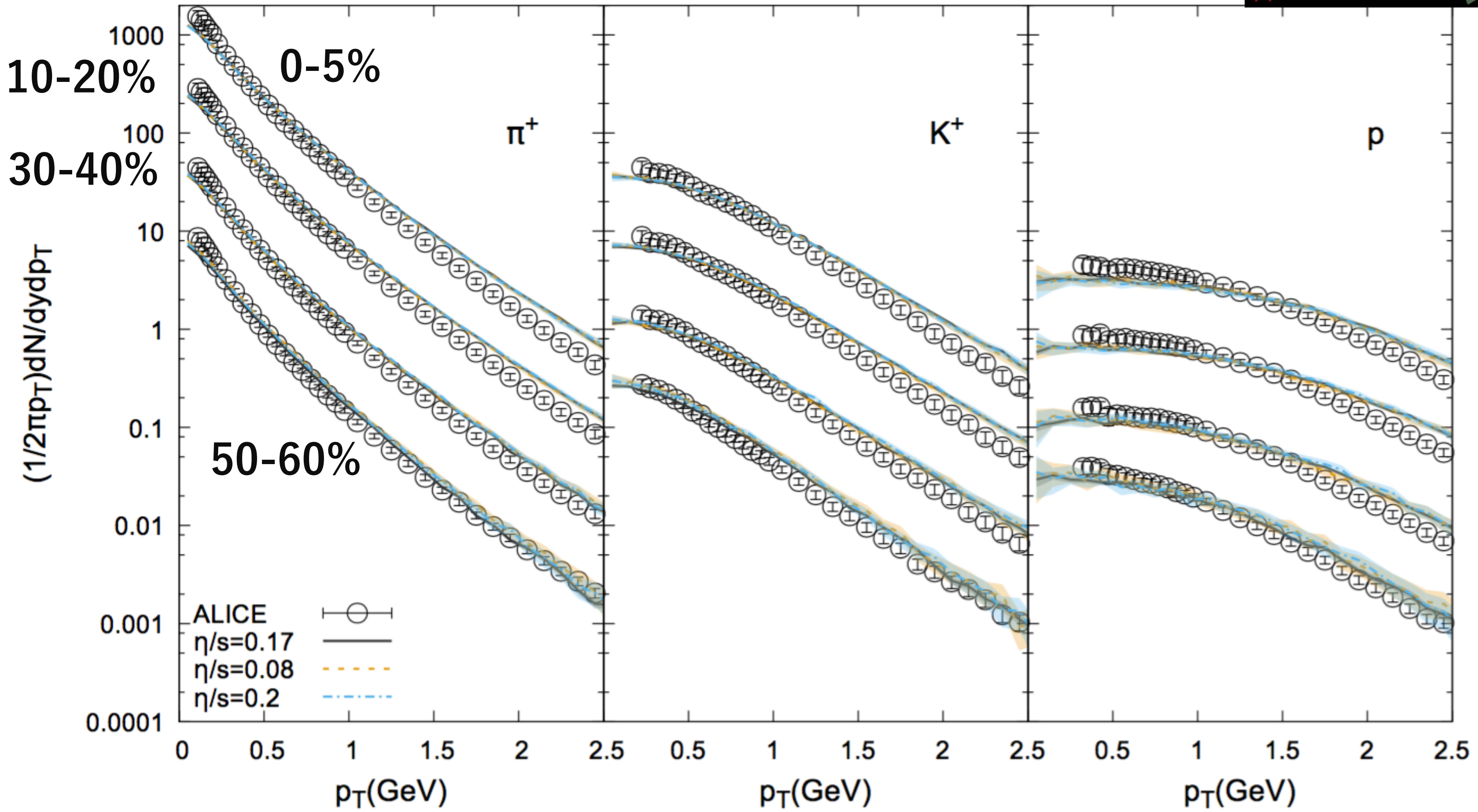




- Parameters in initial condition TRENTO are fixed from comparison with experimental data at 0-5 % centrality.

# $\eta/s$ dependence



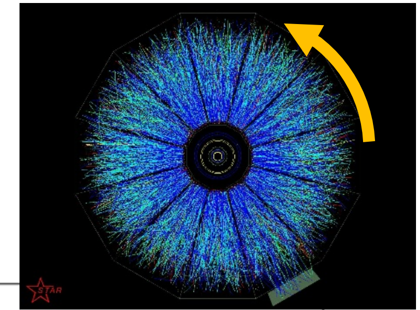

- $p_T$ spectra



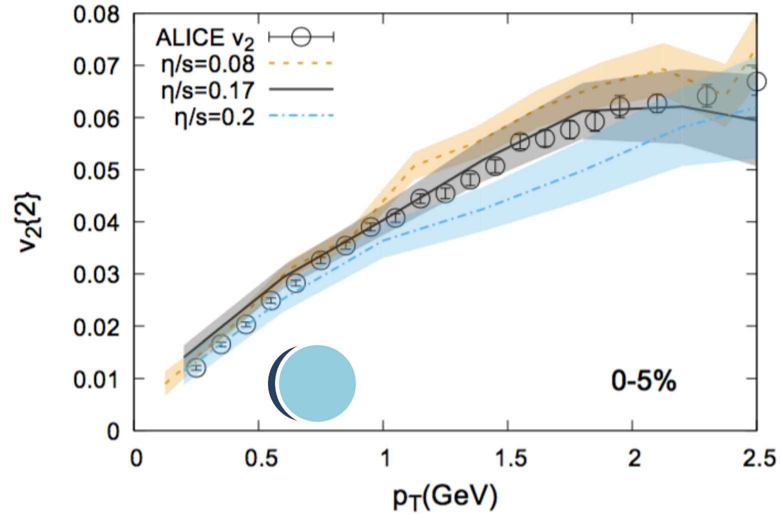

C. NONAKA

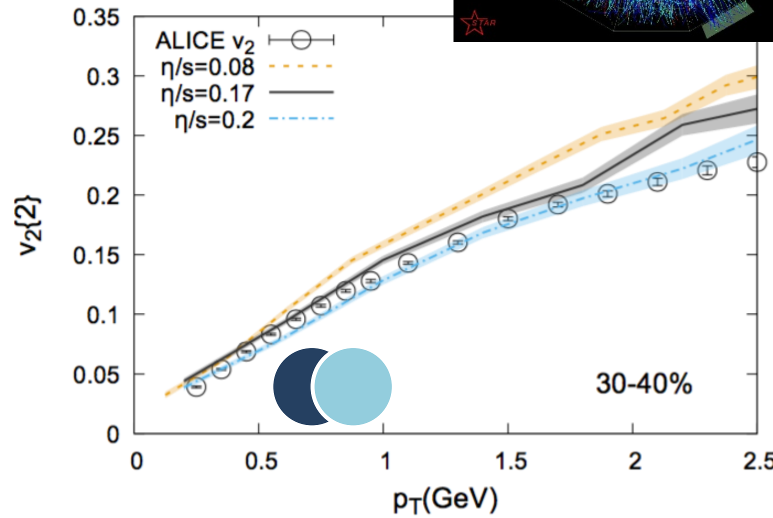
$P_T$ spectra do not depend on η/s.

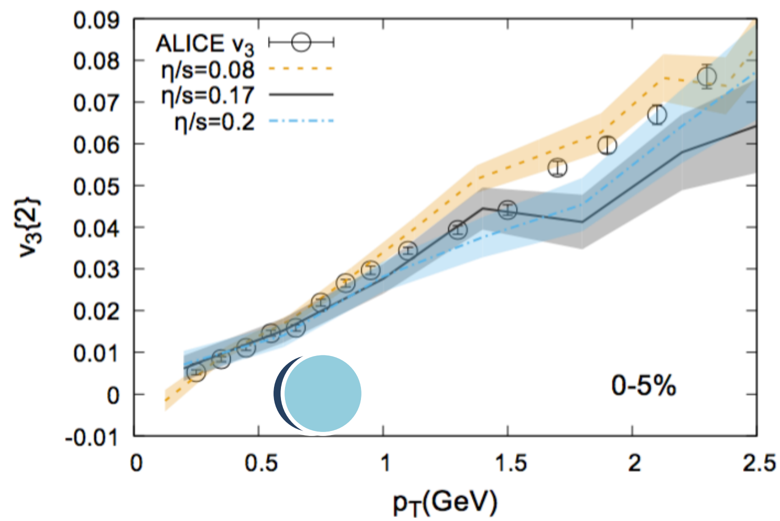
# $\eta/s$ dependence

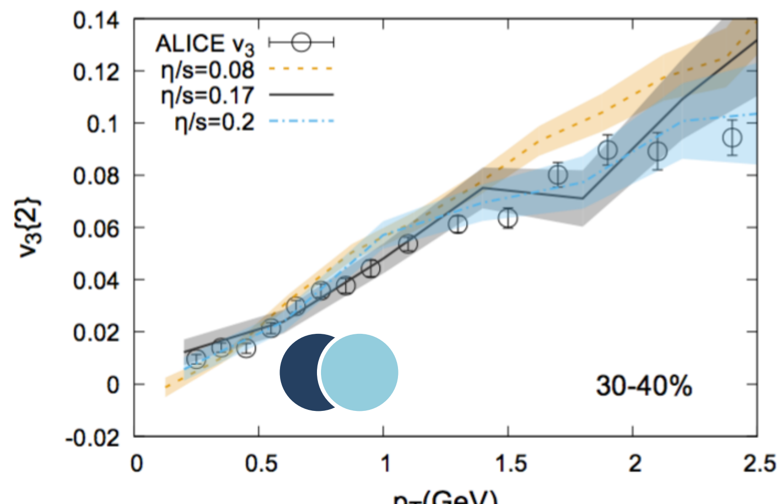


- Collective Flows



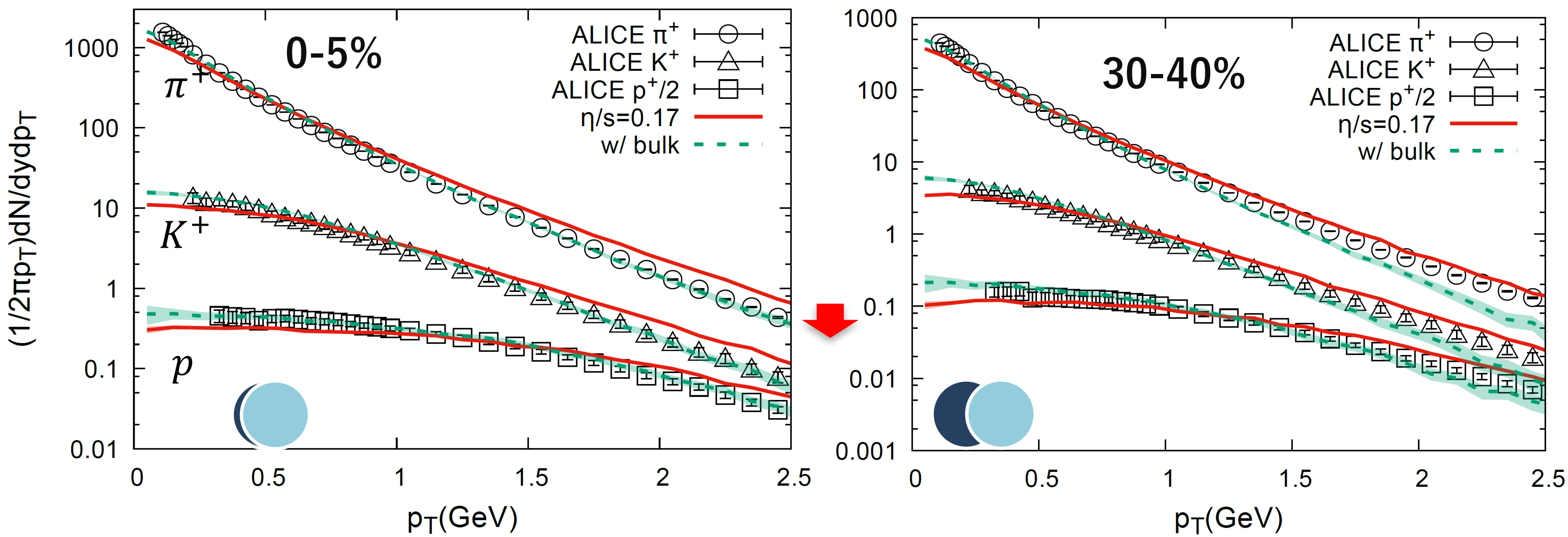




$v_2$ and $v_3$ are smaller at larger $\eta/s$. → $\eta/s=0.17$

C. NONAKA

# Effect of Bulk Viscosity

- Shear + Bulk viscosities



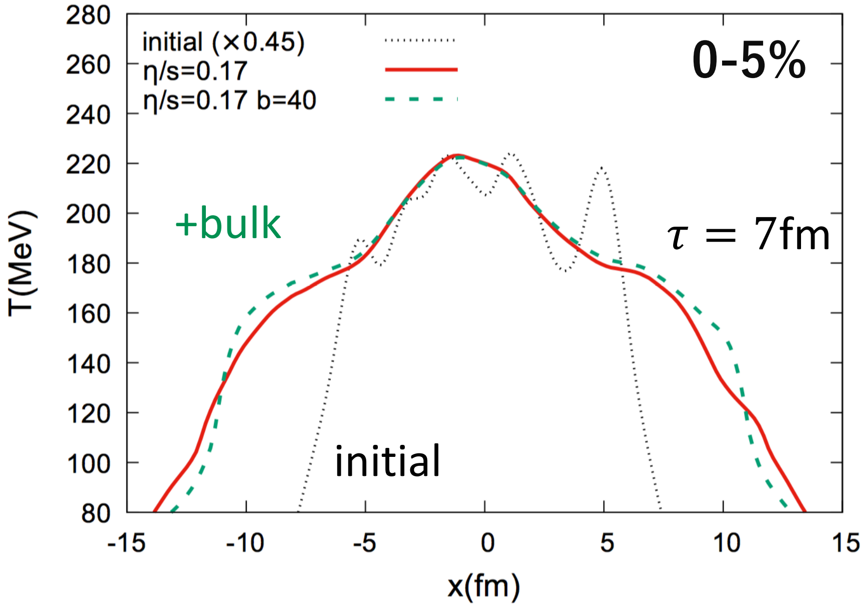

Bulk viscosity reduces the transverse expansion.

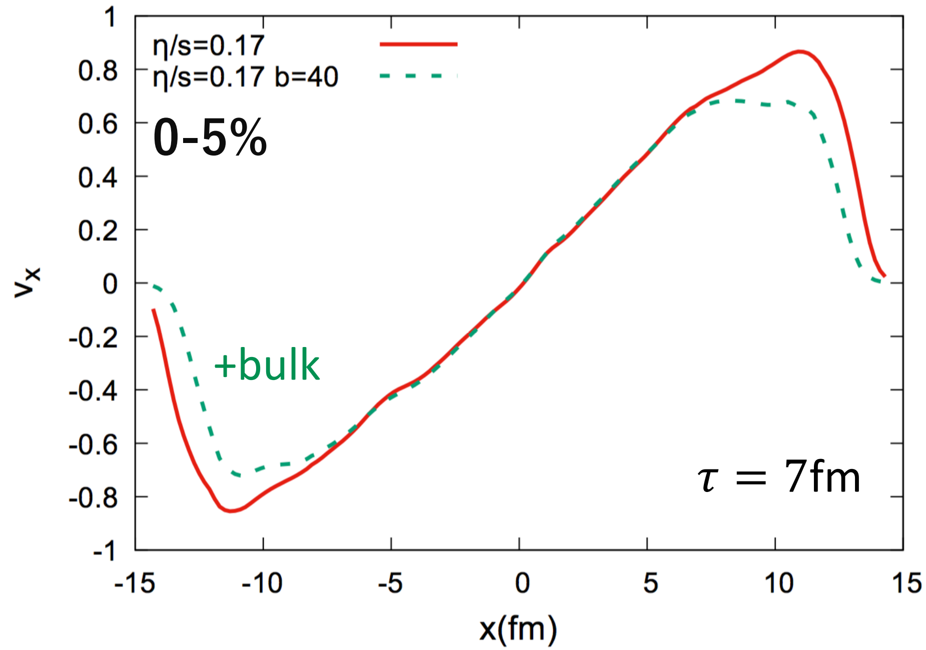
-> Slope of $P_T$ spectra becomes steep.

-> Close to ALICE data.

**Finite bulk viscosity**

# Effect on Expansion



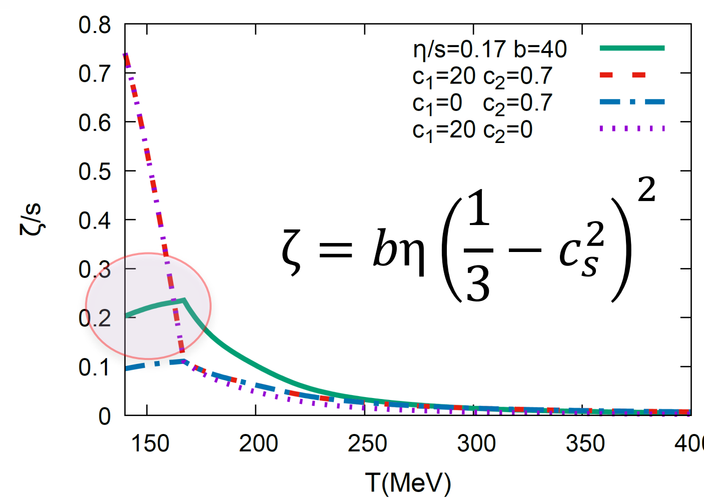




Bulk viscosity is large below 200 MeV.

-> Its effect appears around $T_c$ ~160 MeV.

-> Expansion rate decreases in lower temperature region.

-> Volume elements of fluid keep around $T_c$ temperature longer.

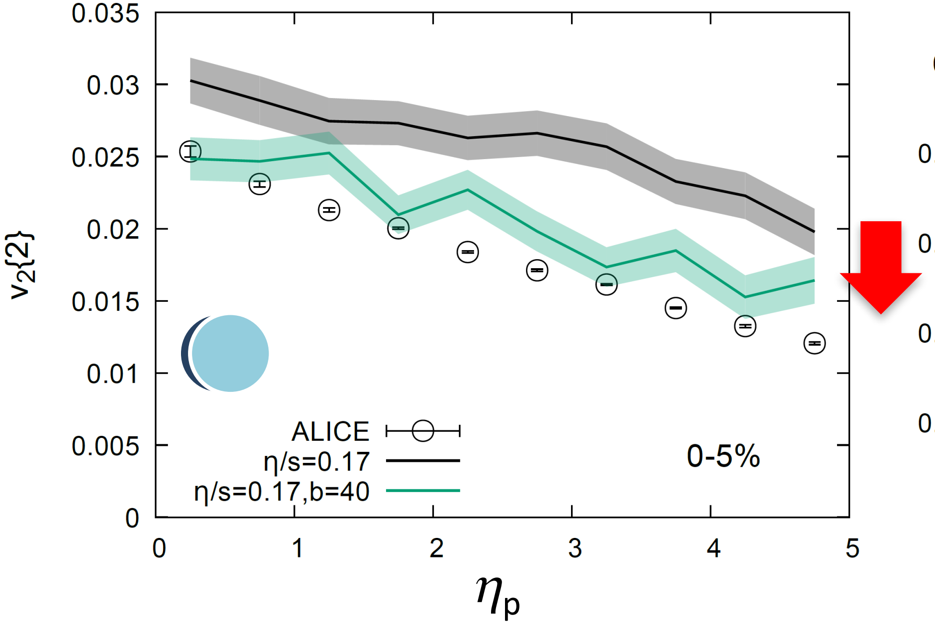


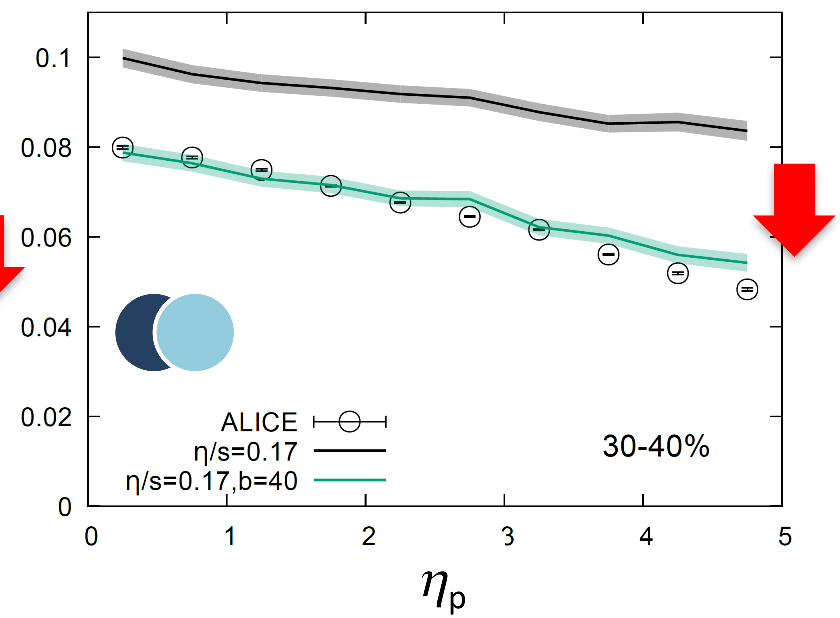

$$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2$$

C. NONAKA

# Effect on Collective Flow

- Collective flow as a function of $\eta_p$

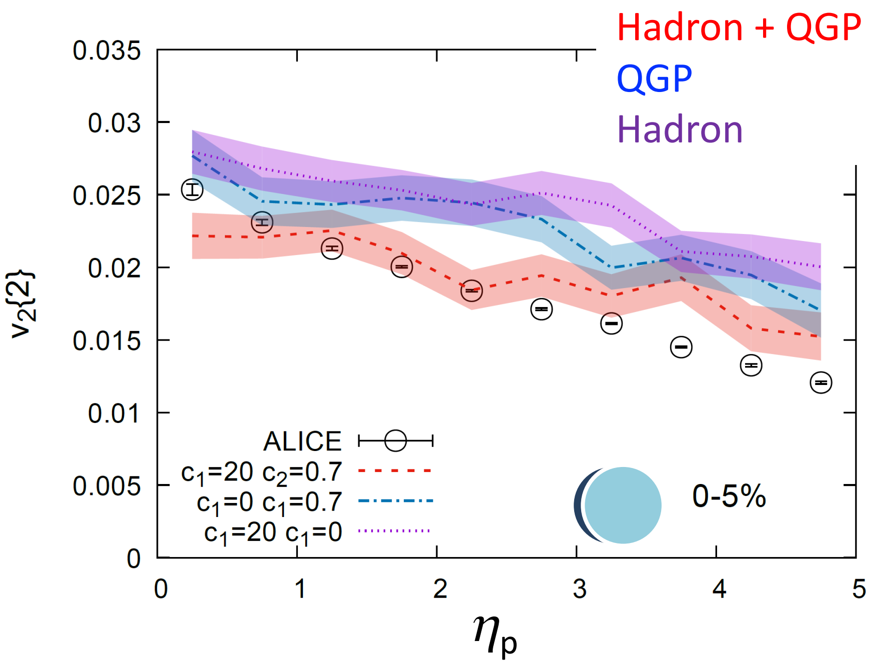


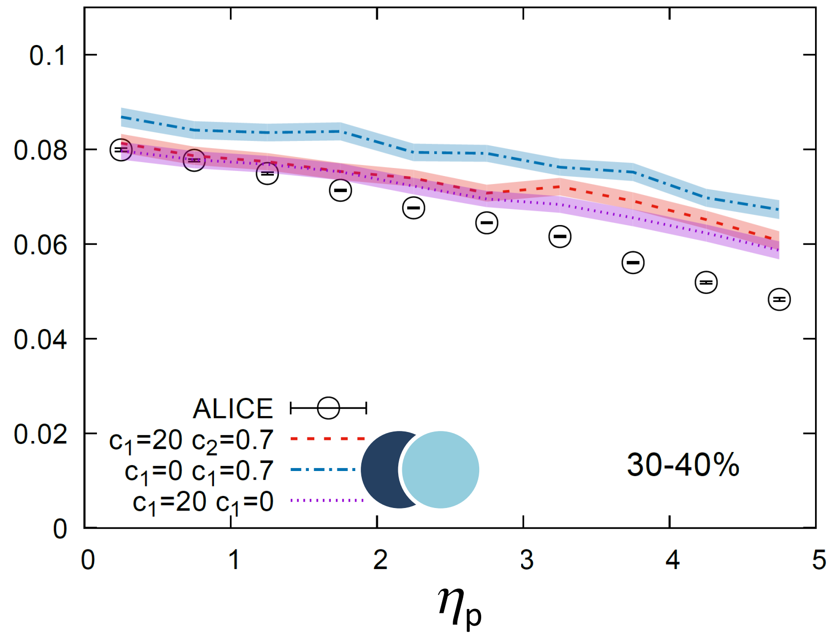



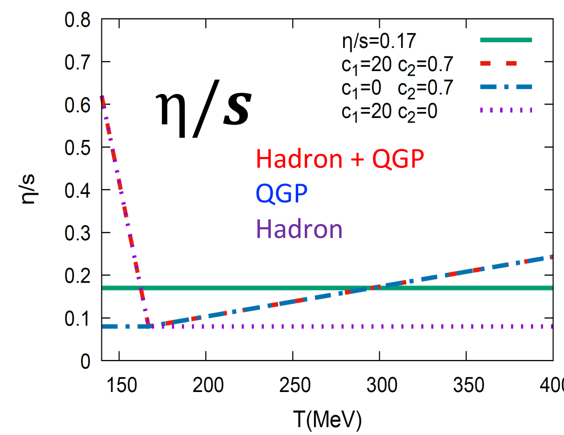

- (3+1)-d calculation
- $v_n$ with bulk viscosity is much closer to the ALICE data. amplitude and slope
- Effect of bulk viscosity at forward rapidity is large.

**Finite bulk viscosity**

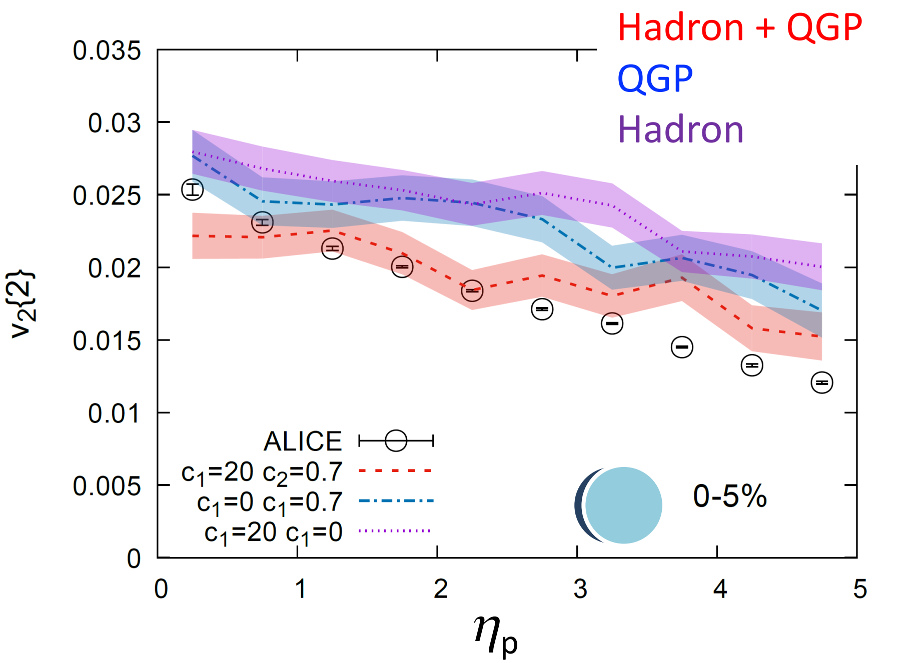
# Temperature Dependent $\eta/s$

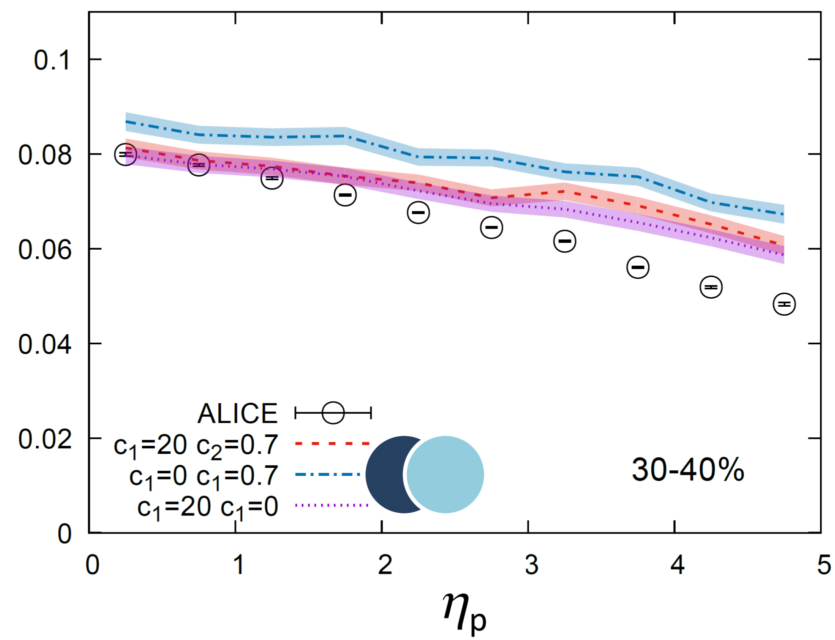


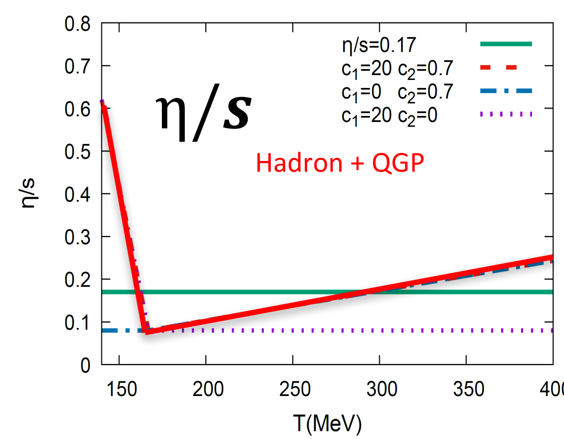



# Temperature Dependent $\eta/s$

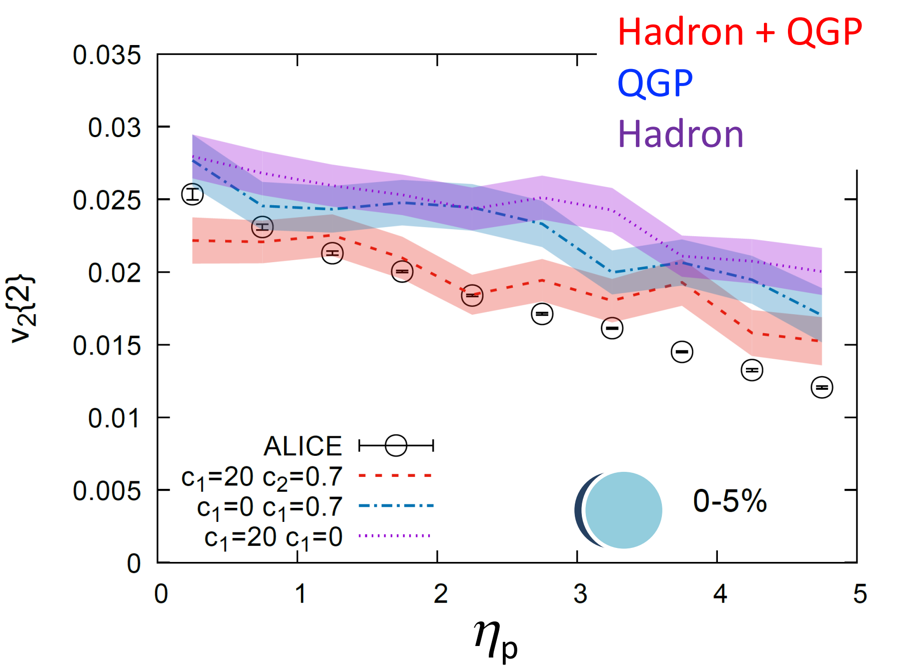


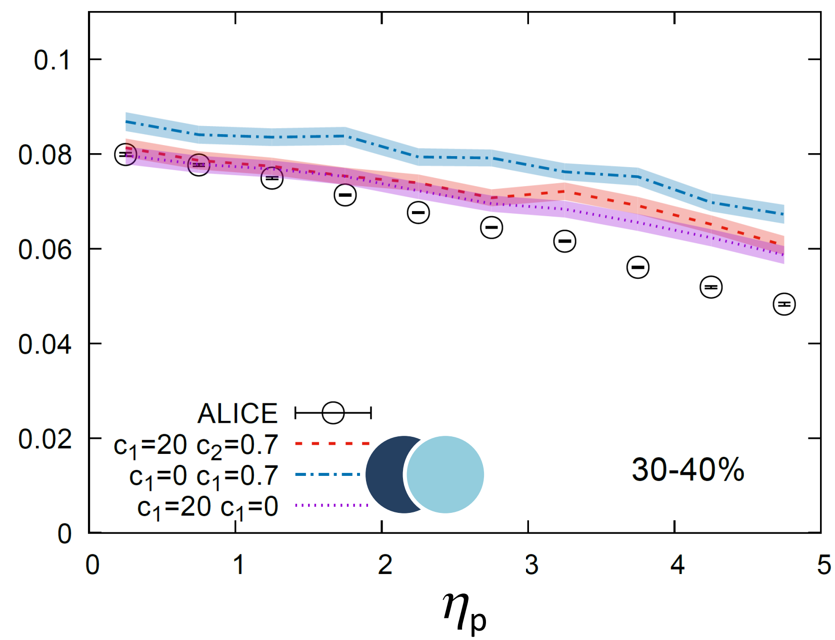



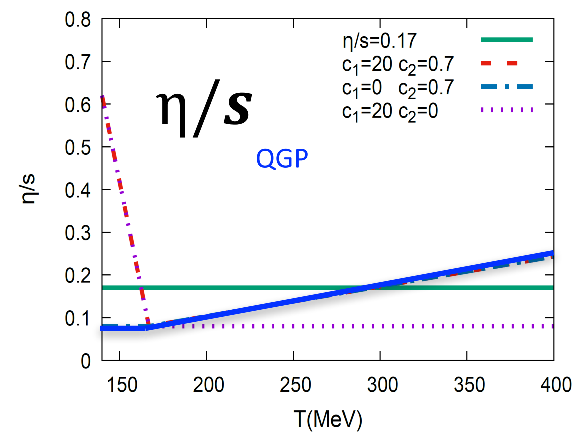




C. NONAKA

# Temperature Dependent $\eta/s$

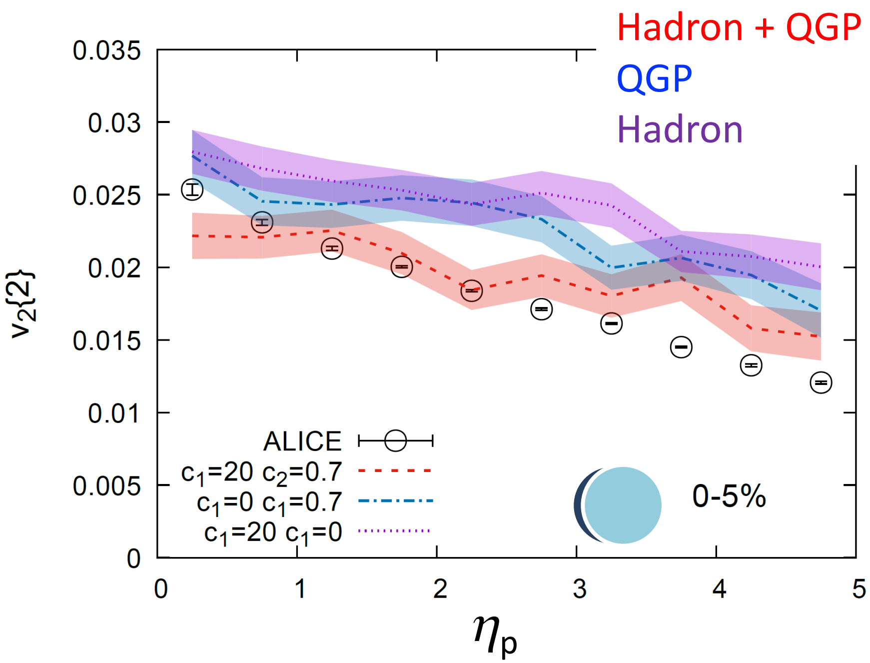


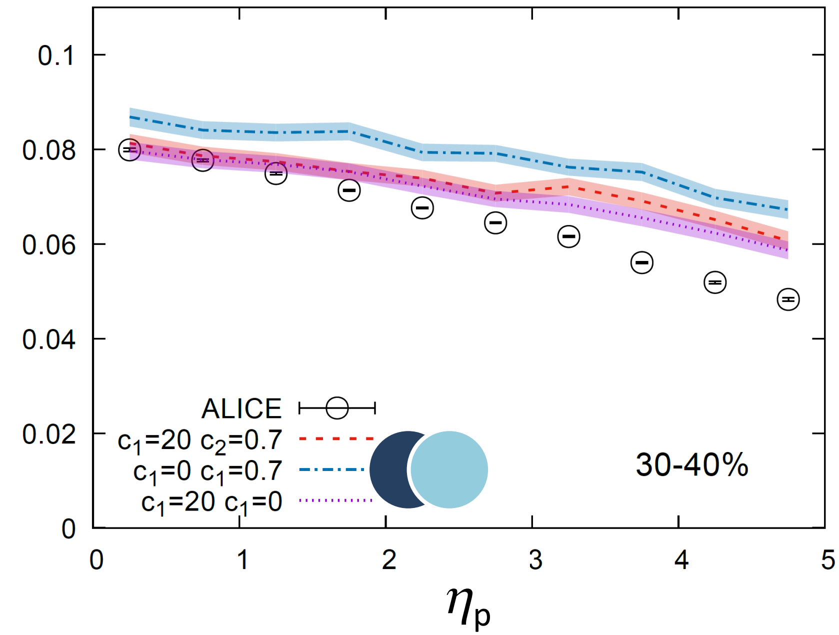




KMI
C. NONAKA

# Temperature Dependent $\eta/s$

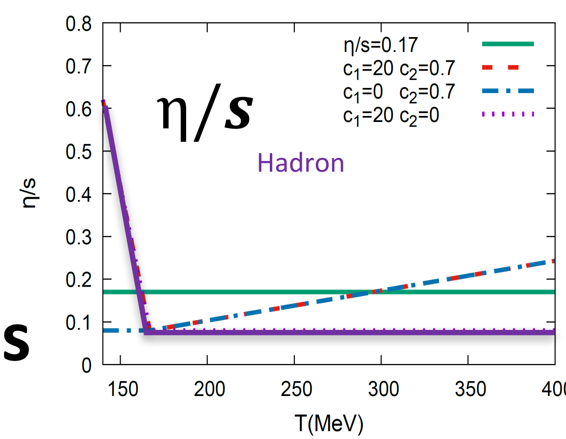



- 0-5 % centrality

  $\eta/s$ of QGP and hadron phases is important.
- 30-40 % centrality

  $\eta/s$ of hadron phase is dominant.




**Central dependence of $v_2(\eta_p)$ reveals temperature dependence of $\eta/s$.**

C. NONAKA

# Summary

## Understanding QGP bulk property

- New relativistic viscous hydrodynamics code
  - Stable with small numerical dissipation
  - Phenomenological model : TRENTO — Hydro — UrQMD
  - Quantitative analyses

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

- QGP bulk property
  - Shear and bulk viscosity
  - Finite bulk viscosity, central dependence of $v_2(\eta_p)$

*Okamoto and Nonaka, arXiv:1712.00923*

- Future works
  - Two particle correlations（HBT）
  - Electromagnetic probes