Phenomenological Analyses in High-Energy Heavy Ion Collisions

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

Kobayashi Maskawa Institute
Department of Physics, Nagoya University

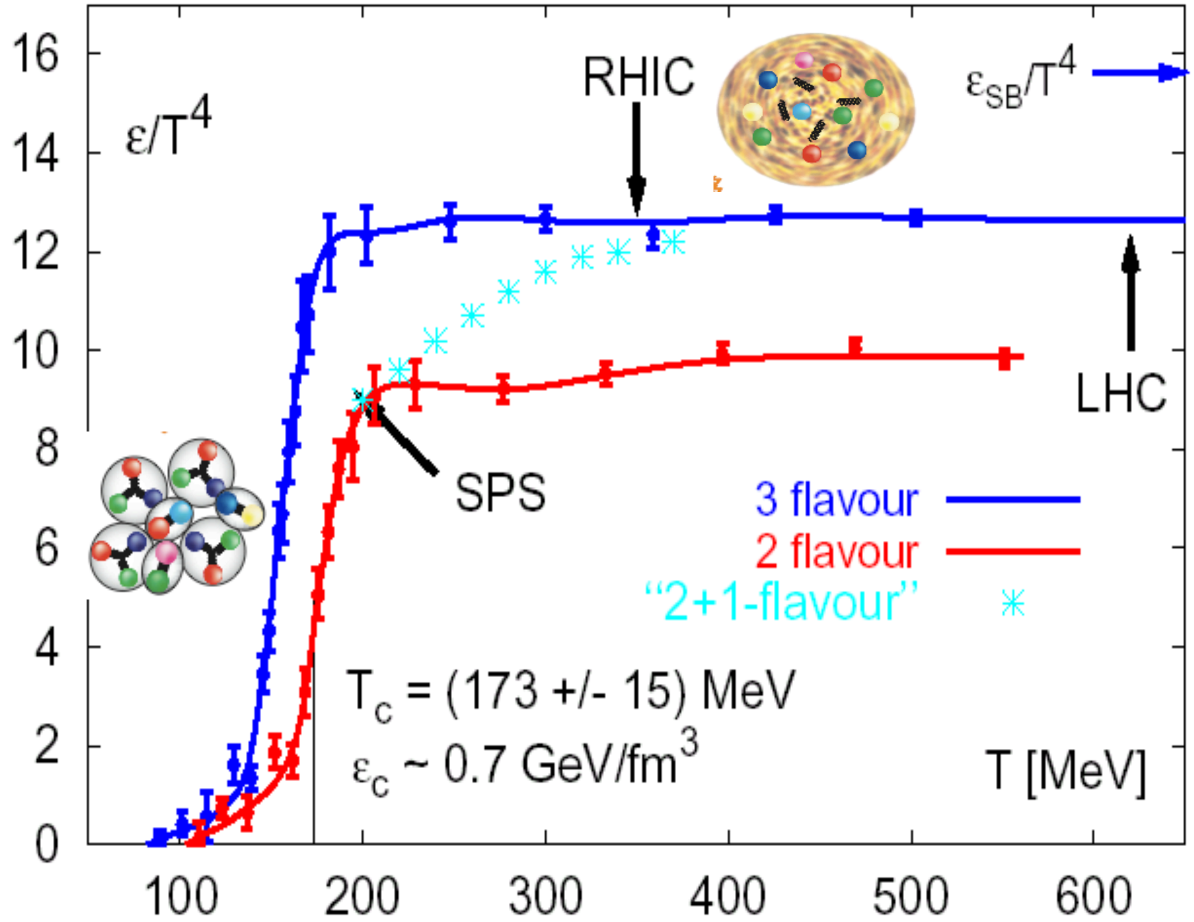
Chiho NONAKA

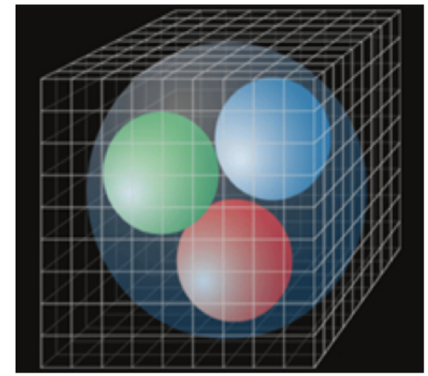
August 6, 2014@KMI Topics

Contents

- High-energy heavy ion collisions
  - QCD phase transition, Little Bang
  - Success of the QGP production:
    Experimental data and Phenomenological analyses
- Highlights of latest experimental data at RHIC and LHC
  - From Quark Matter 2014
- Relativistic Hydrodynamic Model
  - Description of dynamics of the high-energy heavy ion collisions
  - Importance of the numerical method:
    construction of the state-of-the-art algorithm
- Summary

QCD Phase Transition



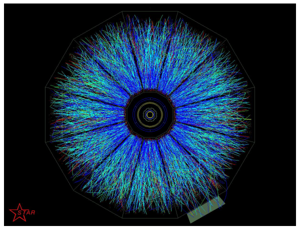


Lattice QCD

Karsch, Laermann, Peikert, PLB478(2000)447

Clear evidence of the QCD phase transition in changing the degree of freedom

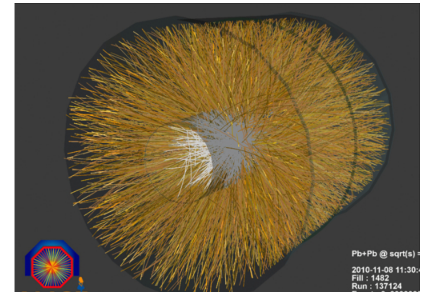
QCD Phase diagram & HIC



RHIC:2000

Strongly interacting QGP

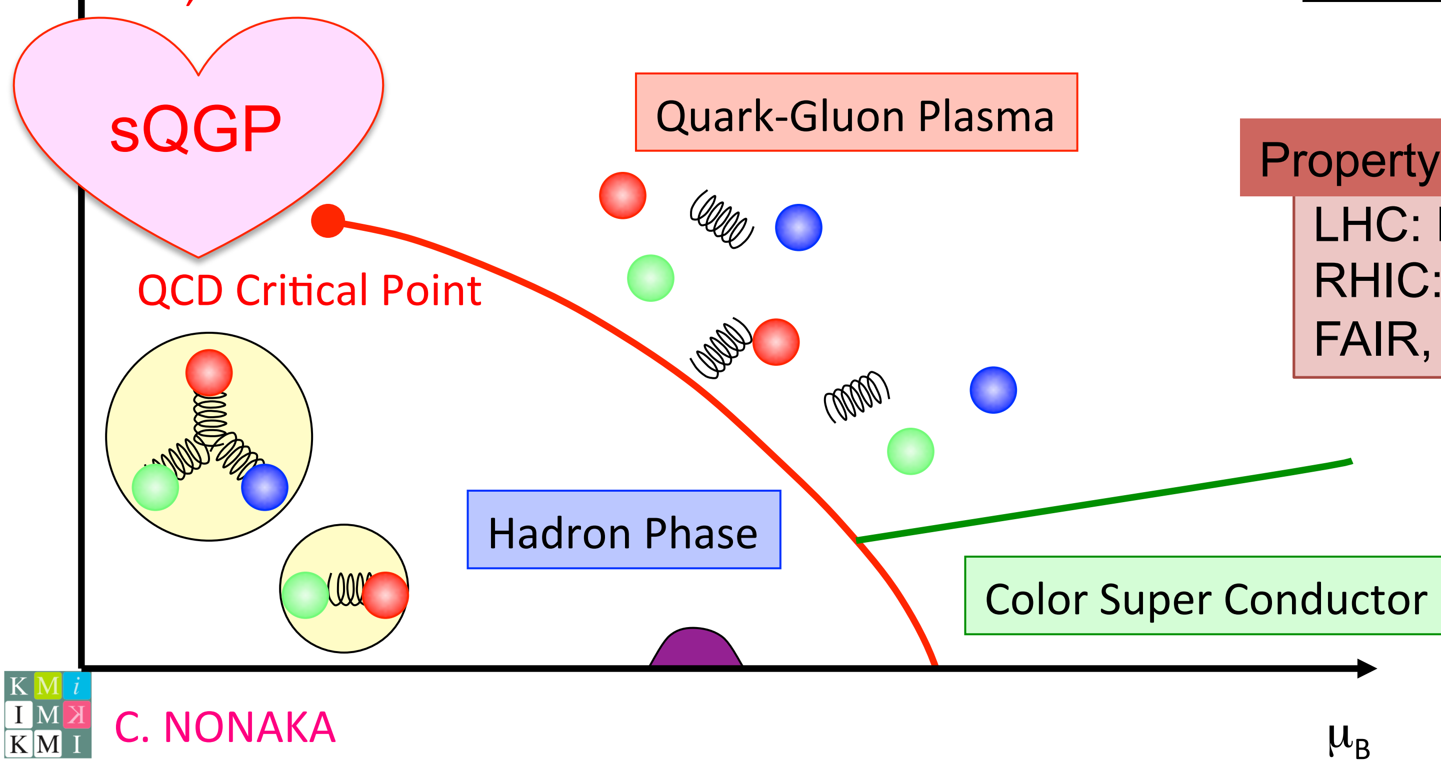
- Relativistic hydrodynamics
- Recombination model
- Jet quenching
- Color Glass Condensate



LHC:2010

Heavy Ion collisions start!

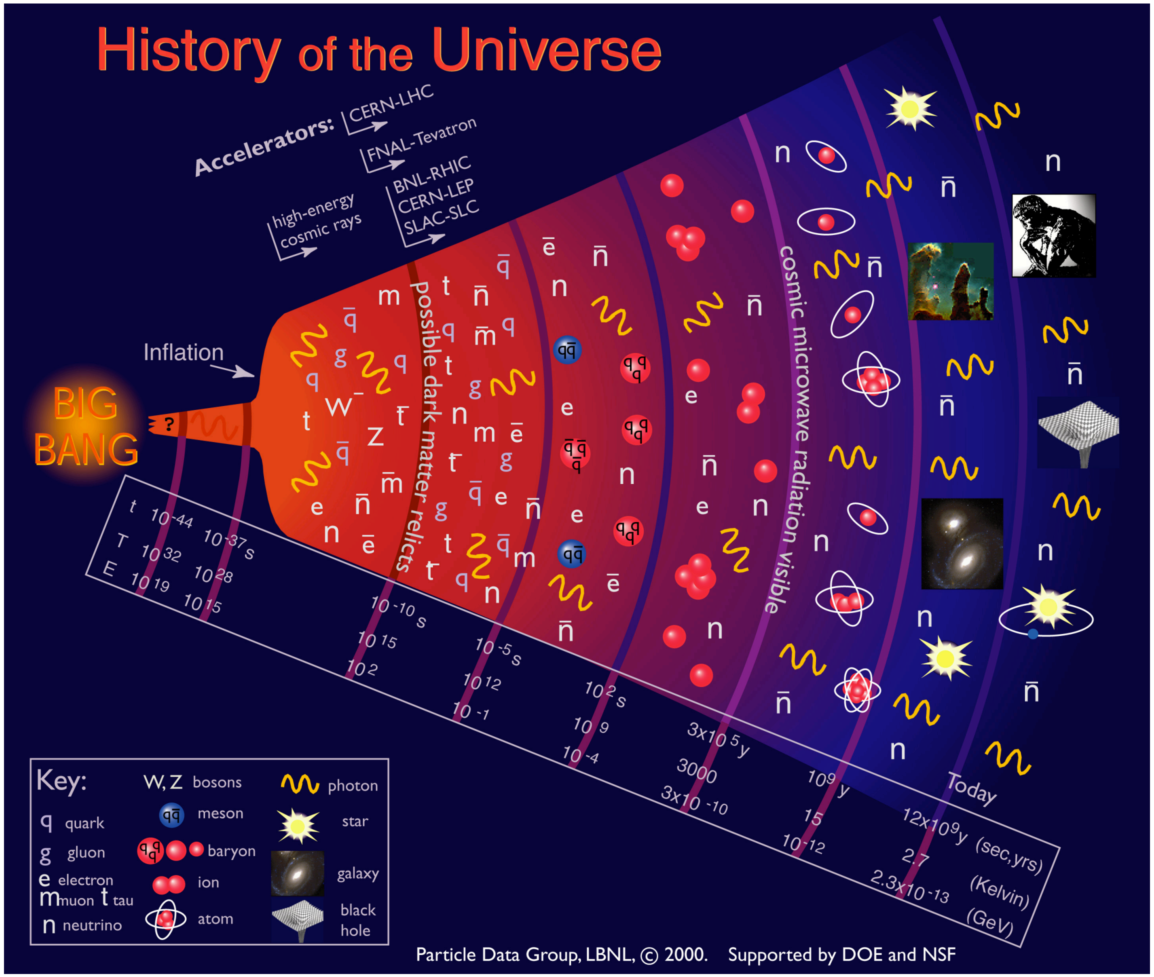
Heavy Ion Collisions : LHC,RHIC



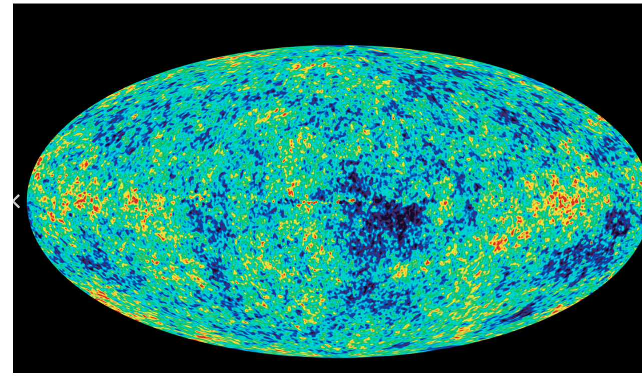
Property of QGP

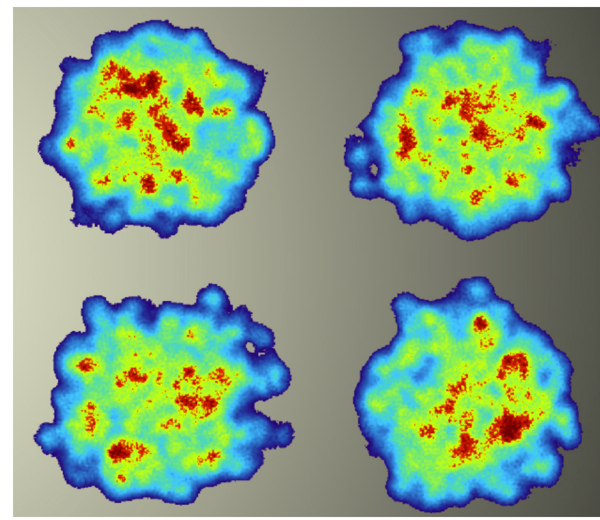
LHC: Energy frontier
RHIC: energy scan
FAIR, NICA : high density

Heavy Ion Collisions



WMAP





Little Bang

C. NONAKA

Strongly Interacting QGP

- Relativistic Heavy Ion Collisions

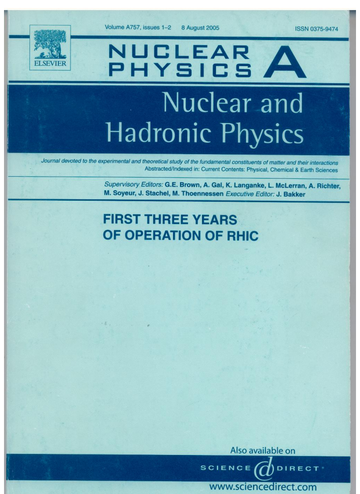
1970 1980 1990 2000 2010

AGS Si, 5
SPS S, 20 Pb, 17
Fixed target QGP production？

RHIC Au+Au, 200
Collider

LHC
Pb+Pb, 2700

- QGP production at RHIC (2005)



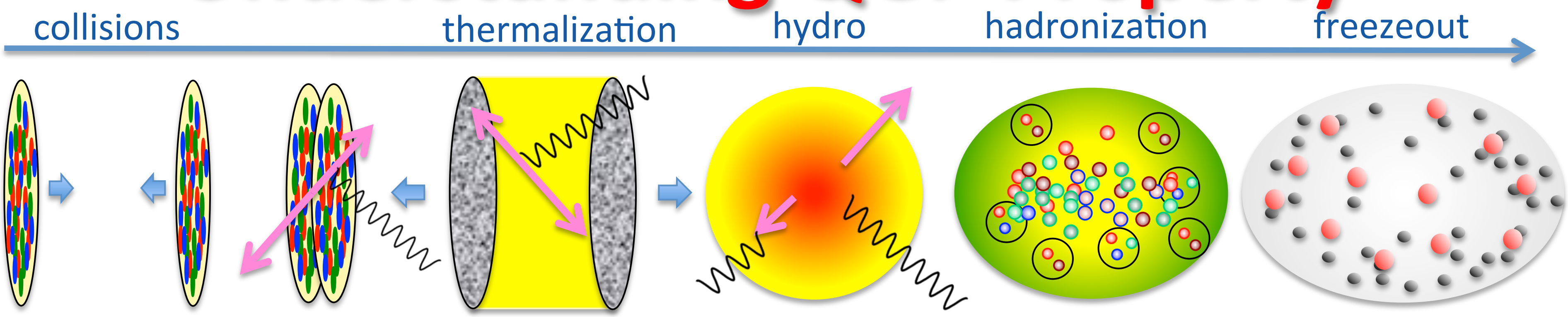
White papers : First three years of operation of RHIC
BRAHMS, PHOBOS, STAR, PHENIX

Phenomenological analyses and experiments

- Relativistic Hydrodynamic Models
- Recombination Models
- Jet Quenching
- Color Glass Condensate

→ **QGP properties**

Understanding QGP Property



Observables: QGP property ← a lot of experimental data at RHIC and LHC

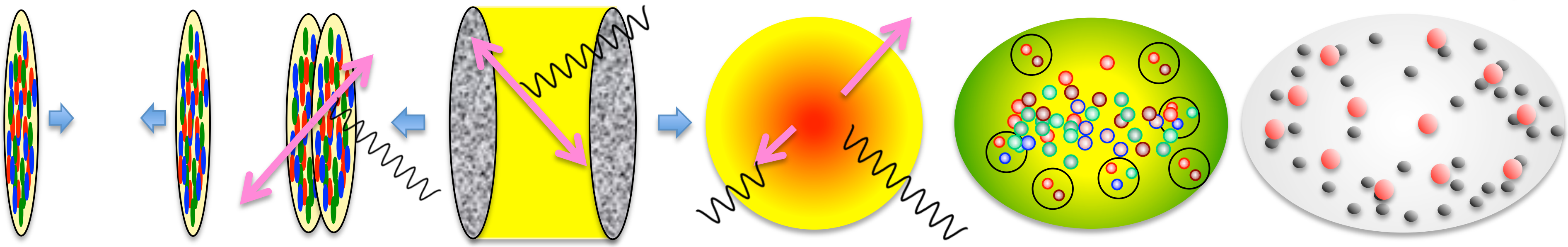
- photons/leptons
- bulk property
- Jets
- heavy quarkonia

Phenomenological models

- Hydrodynamics
- Partons — Event generators — Hadrons
- Color Glass Condensate
- Recombination
- Fragmentation
- Statistical Model

Phenomenology and Experiments

collisions thermalization hydro hadronization freezeout



Observables: QGP property ← a lot of experimental data at RHIC and LHC

photons/leptons

bulk property

Jets

heavy quarkonia

Hydrodynamic models: application to HIC, Landau 1953, Bjorken 1983

sQGP

Initial condition → **Hydrodynamics** → **Freezeout process**

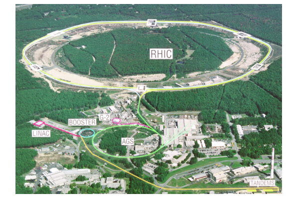
Input
?

Equation of State
lattice QCD
transport coefficients

Highlights of Recent Experiments

- Quark Matter 2014 (May 19-24, ~ 800 participants)
  - Experimental Group

    Relativistic Heavy Ion Collider@BNL (RHIC)

    - STAR, PHENIX

    Large Hadron Collider@CERN (LHC)

    - ALICE, CMS, ATLAS
  - Experimental data

    RHIC: Au+Au, d+Au $\sqrt{s} = 200\mathrm{GeV}$,

    Beam Energy Scan (BES) $\sqrt{s} = 7.7, 11.5, 14.5, 19.6, 27, 39\mathrm{GeV}$

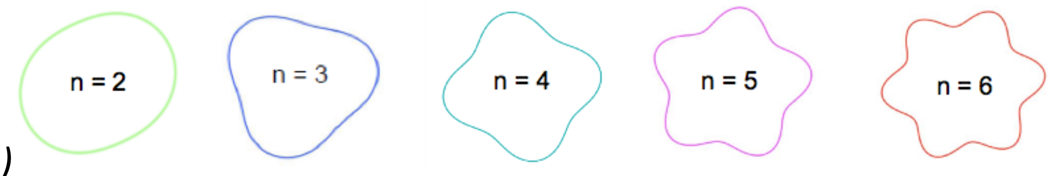
    U +U $\sqrt{s} = 193\mathrm{GeV}$

    LHC: p+p, Pb+Pb $\sqrt{s} = 2.76\mathrm{TeV}$,p+Pb $\sqrt{s} = 5.02\mathrm{TeV}$

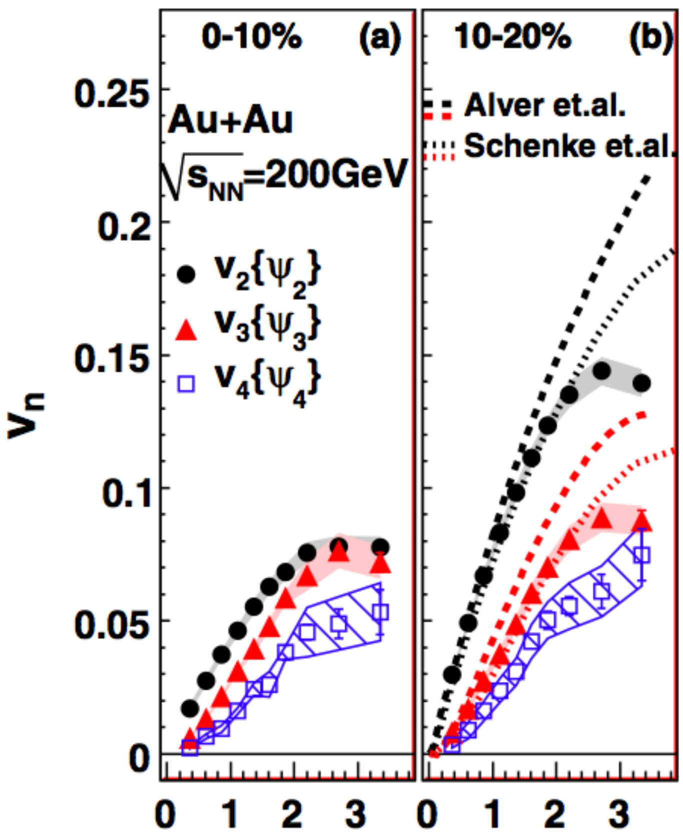
Higher Harmonics

$$\frac{dN}{dyd\phi} \propto 1+2v_1\cos(\phi-\Theta_1)+2v_2\cos 2(\phi-\Theta_2)+2v_3\cos 3(\phi-\Theta_3)+2v_4\cos 4(\phi-\Theta_4)+\cdots$$

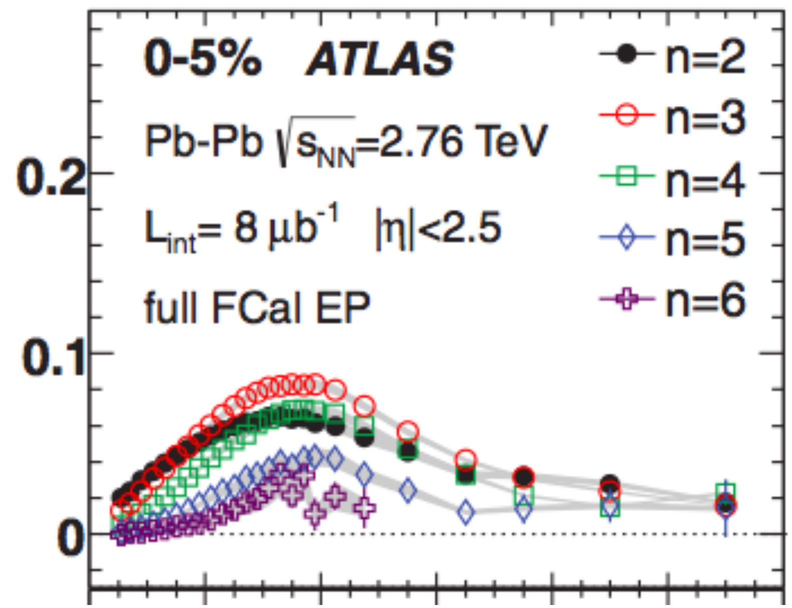
Origin: initial fluctuations



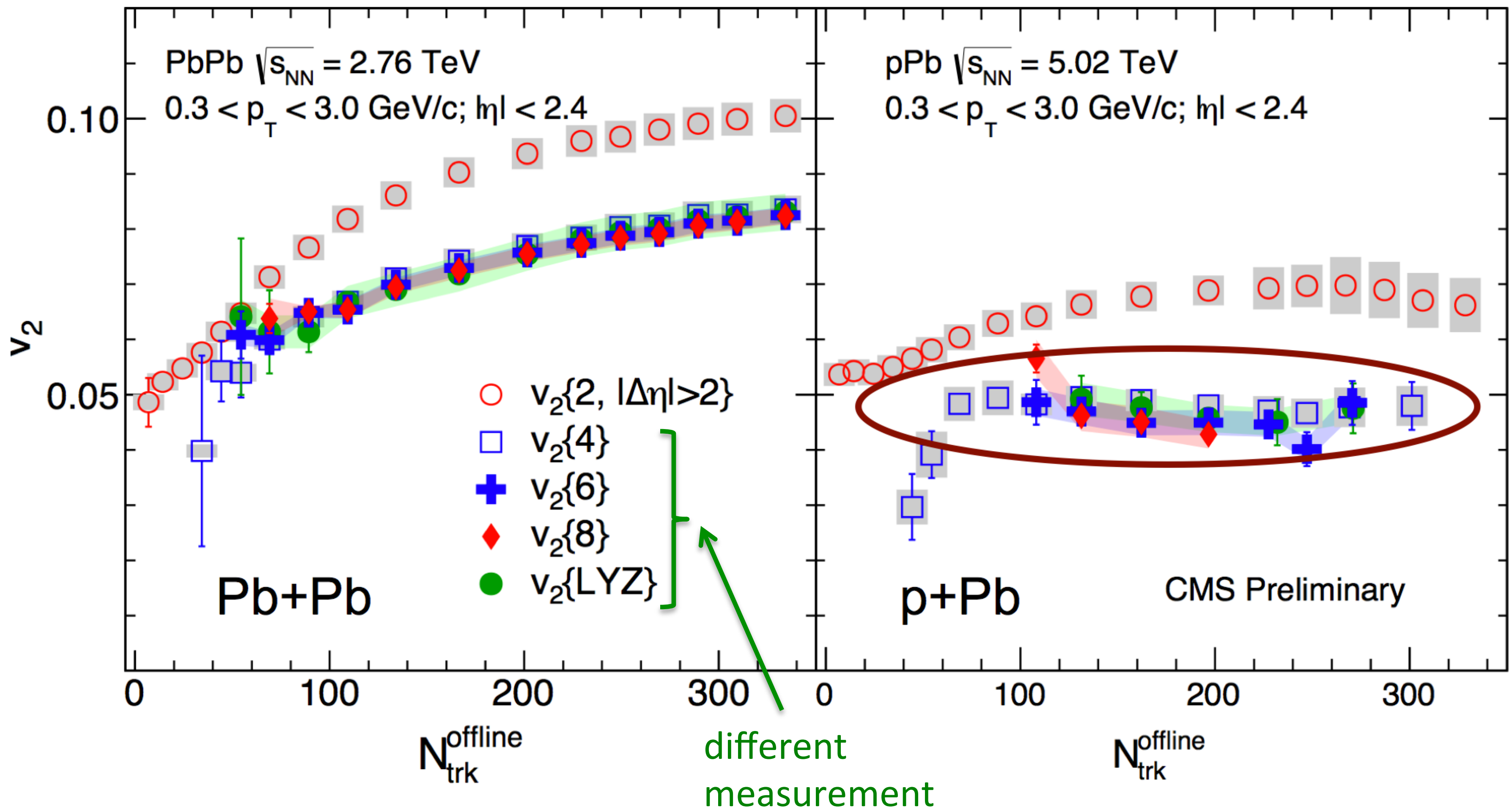
PHENIX@RHIC, PRL107,252301(2011)



ATLAS@LHC, PRC86,014907(2012)



Hydrodynamic Flow in p+Pb?



Finite elliptic flow in such small systems like pp, pPb: validity of hydrodynamic picture?

Hydrodynamic Model

$$\partial_\mu T^{\mu\nu} = 0 \quad T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu} + \Delta T^{\mu\nu}$$

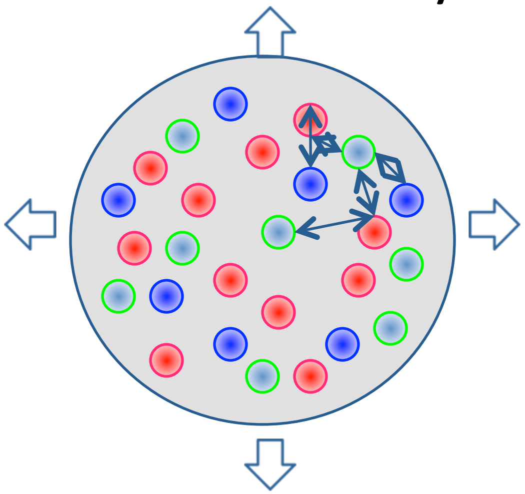
ideal

viscous

Landau 1943, Bjorken 1983

- Assumption
  - Local thermodynamical equilibrium

Thermalization ??



Microscopic reaction rate: Γ

~cross section (σ) · local particle density (n)

$\gg$

Macroscopic expansion rate: θ

$$\sigma >> \theta / n$$

Strong elliptic flow

Hydrodynamic Model

$$\partial_\mu T^{\mu\nu} = 0 \quad T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu} + \Delta T^{\mu\nu}$$

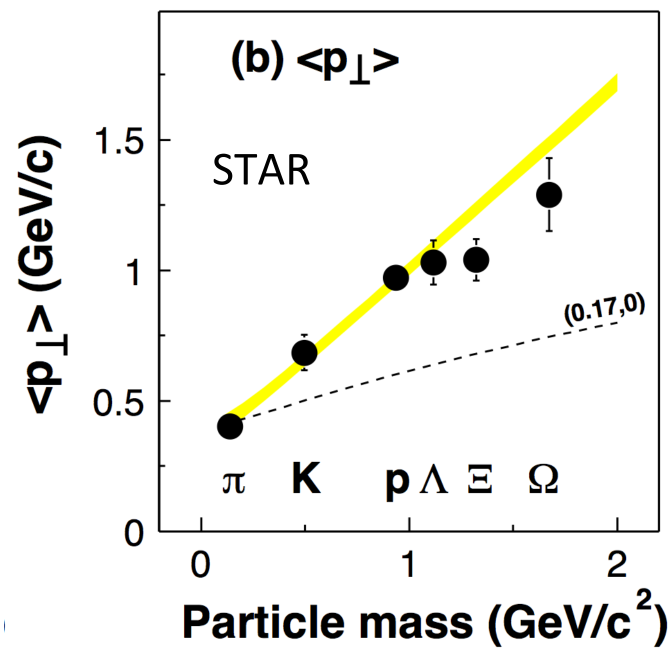
ideal

viscous

Landau 1943, Bjorken 1983

- Assumption
  - Local thermodynamical equilibrium
  - Collectivity

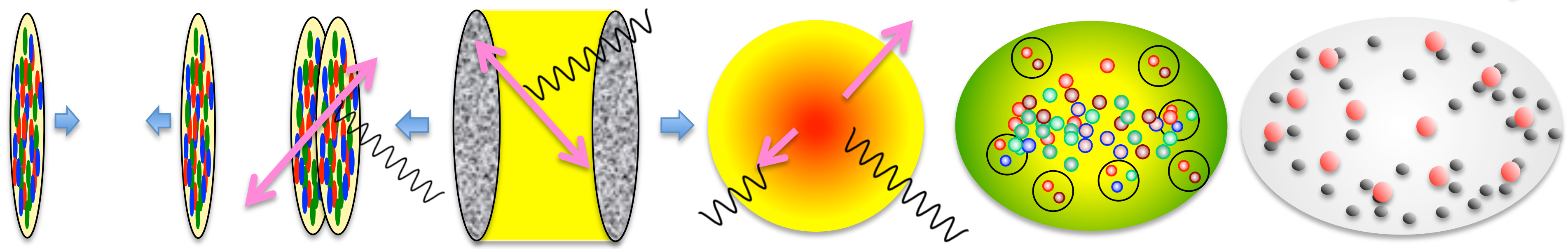
Thermalization ??



$$\langle P_T \rangle \sim m v_T$$

Hydrodynamic Model

collisions thermalization hydro hadronization freezeout

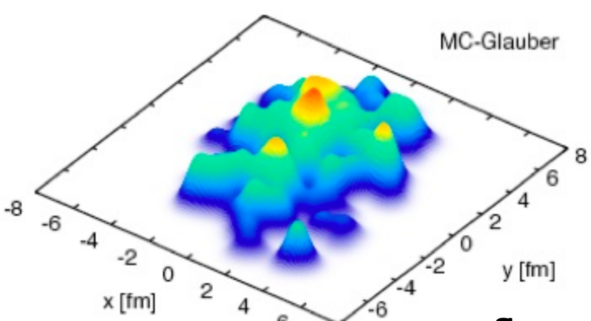


Hydrodynamic models: application to HIC, Landau 1953, Bjorken 1986

sQGP

Initial condition → **Hydrodynamics** → **Freezeout process**

Input
?



fluctuations

Equation of State
lattice QCD
transport coefficients

Relativistic viscous hydrodynamic
Shock wave

Viscous Hydrodynamic Model

- Relativistic viscous hydrodynamic equation

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu} + \Delta T^{\mu\nu}$$

  - First order in gradient: acausality
  - Second order in gradient: which one is suitable for HIC?
    - Israel-Stewart
    - Ottinger and Grmela
    - AdS/CFT
    - Grad's 14-momentum expansion
    - Renormalization group

Numerical scheme

- Shock-wave capturing schemes

Numerical Scheme

- Lessons from wave equation
  - First order accuracy: large dissipation
  - Second order accuracy : numerical oscillation

    -> artificial viscosity, flux limiter
- Hydrodynamic equation
  - Shock-wave capturing schemes: Riemann problem
    - Godunov scheme: analytical solution of Riemann problem, Our scheme
    - SHASTA: the first version of Flux Corrected Transport algorithm, Song, Heinz, Chaudhuri
    - Kurganov-Tadmor (KT) scheme, McGill

Numerical Scheme

- Israel-Stewart Theory

Akamatsu, Inutsuka, CN, Takamoto, arXiv:1302.1665、J. Comp. Phys. (2014)34

1. Dissipative fluid equation

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

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - pg^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu + \tau^{\mu\nu}$$

$$= T_{\rm ideal} + T_{\rm dissip}$$

Ideal part:

Riemann solver for QGP: Godunov method

Two shock approximation *Mignone, Plewa and Bodo, Astrophys. J. S160, 199 (2005)*

2. Relaxation equation

$$\hat{D}\Pi = \frac{1}{\tau_\Pi}(\Pi_{NS} - \Pi) - I_\Pi,$$

$$\hat{D}\pi^{\mu\nu} = \frac{1}{\tau_\pi}(\pi^{\mu\nu}_{NS} - \pi^{\mu\nu}) - I^{\mu\nu}_\pi,$$

$$\hat{D}q^\mu = \frac{1}{\tau_q}(q^\mu_{NS} - q^\mu) - I^\mu_q,$$

$$\hat{D} = u^\mu \partial_u$$

I: second order terms

$$\left(\frac{\partial}{\partial t} + v^j \frac{\partial}{\partial x^j}\right)\Pi = -\frac{I_\Pi}{\gamma}, \quad + \quad \frac{\partial}{\partial t}\Pi = \frac{1}{\gamma\tau_\Pi}(\Pi_{NS} - \Pi),$$

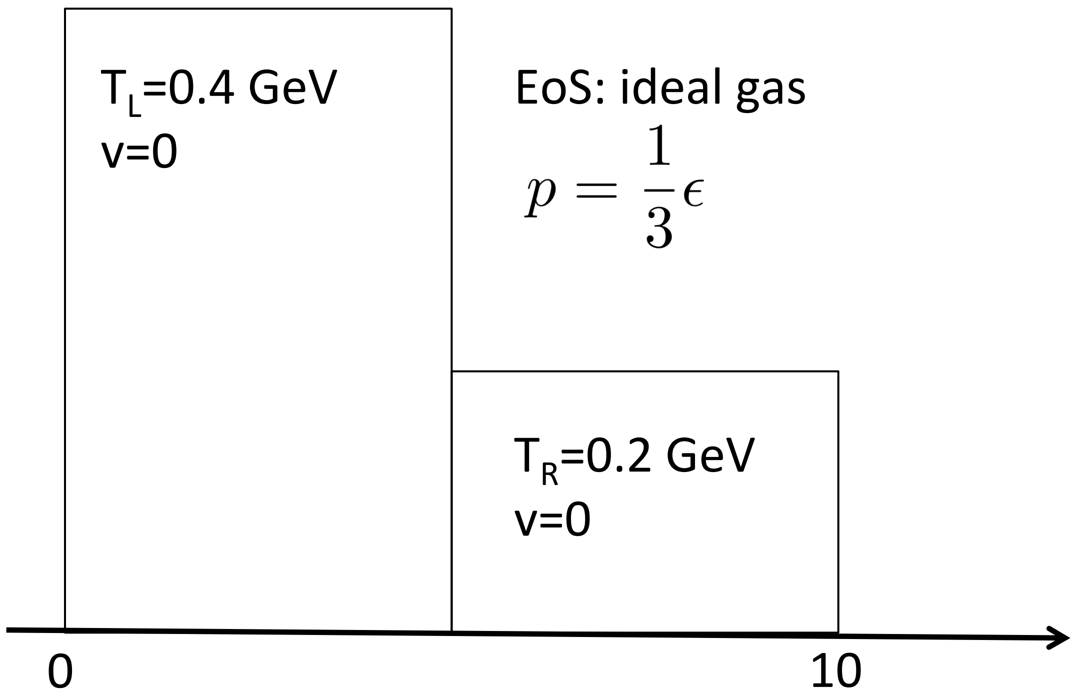
advection stiff equation

$$\Delta t < \tau_{\rm relax} << \tau_{\rm fluid}$$

$$\tau^{\mu\nu} = \Pi\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Comparison

- Shock Tube Test : *Molnar, Niemi, Rischke*, Eur.Phys.J.C65,615(2010)

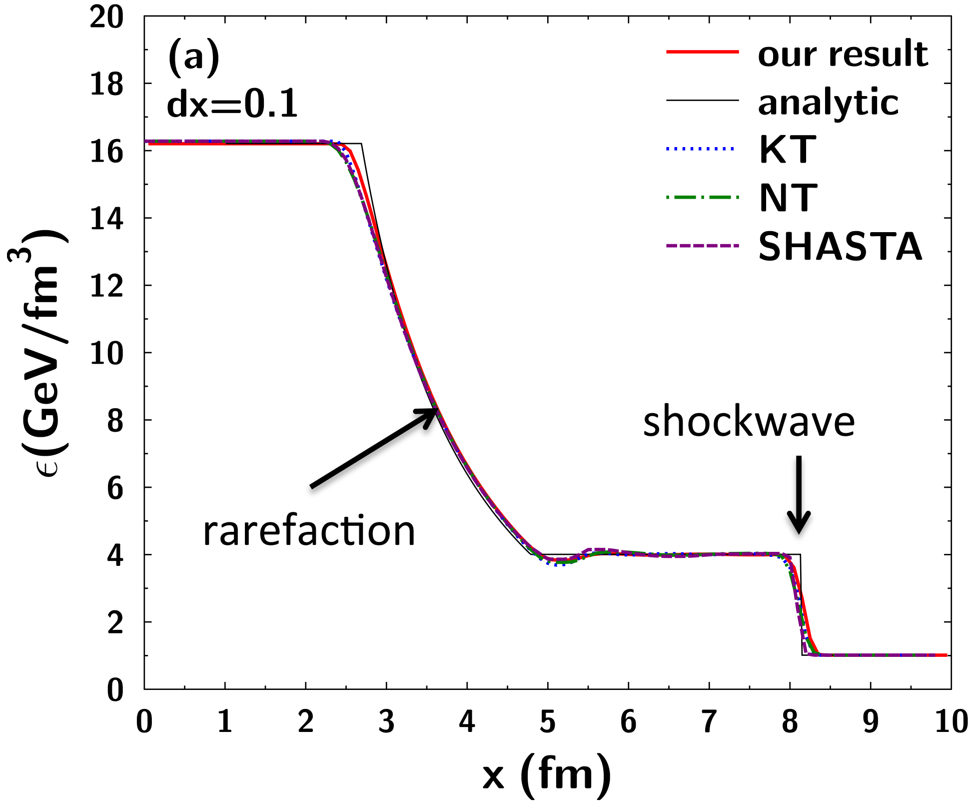


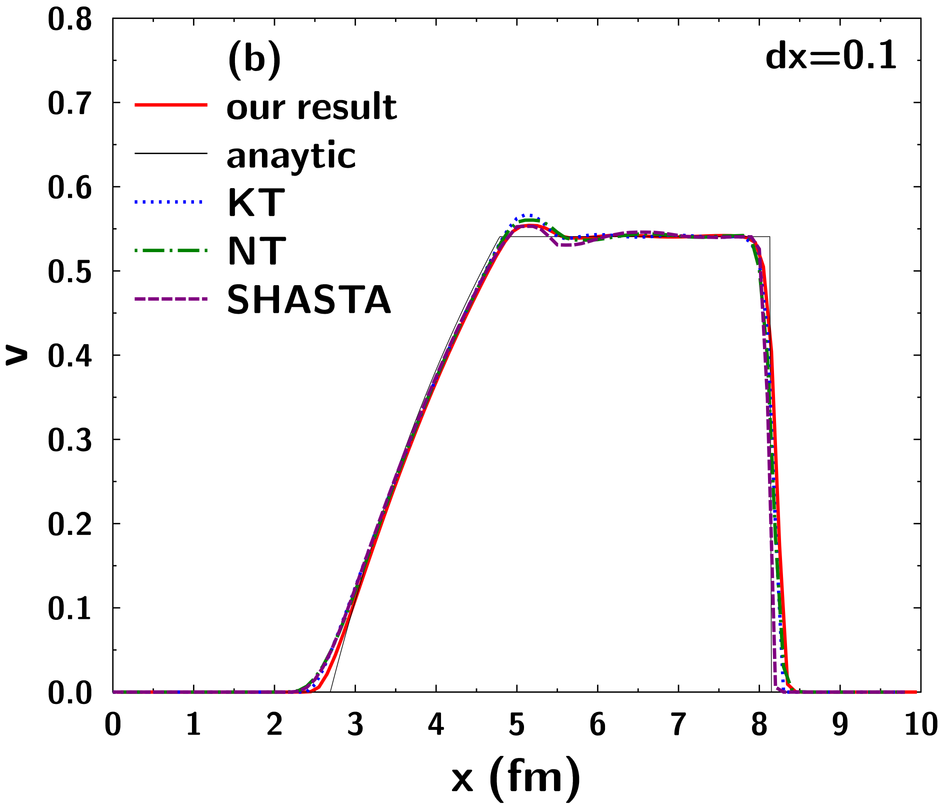
Nx=100, dx=0.1, dt=0.04

- Analytical solution
- Numerical schemes
  SHASTA, KT, NT
  Our scheme

Shock tube problem

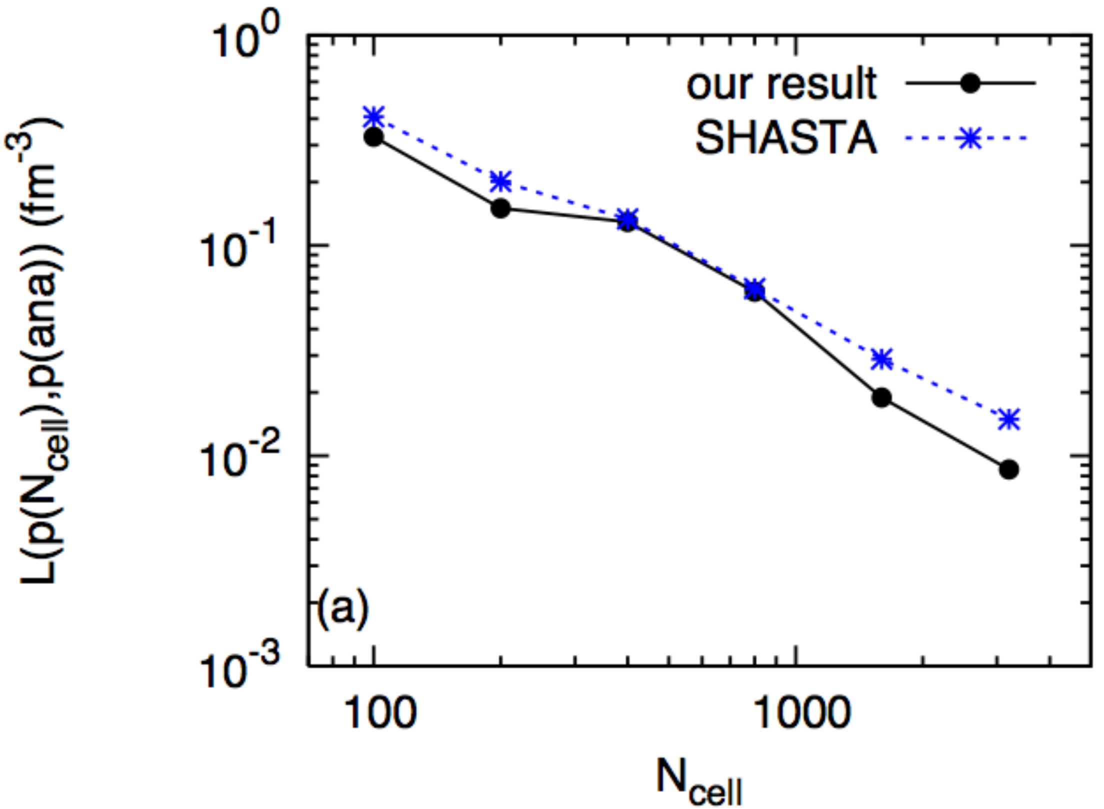
- Ideal case

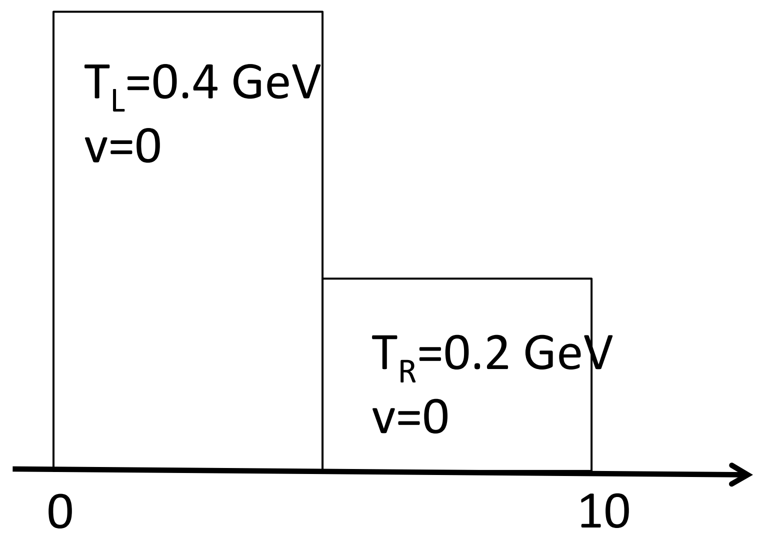




L1 Norm

- Numerical dissipation: deviation from analytical solution





For analysis of heavy ion collisions

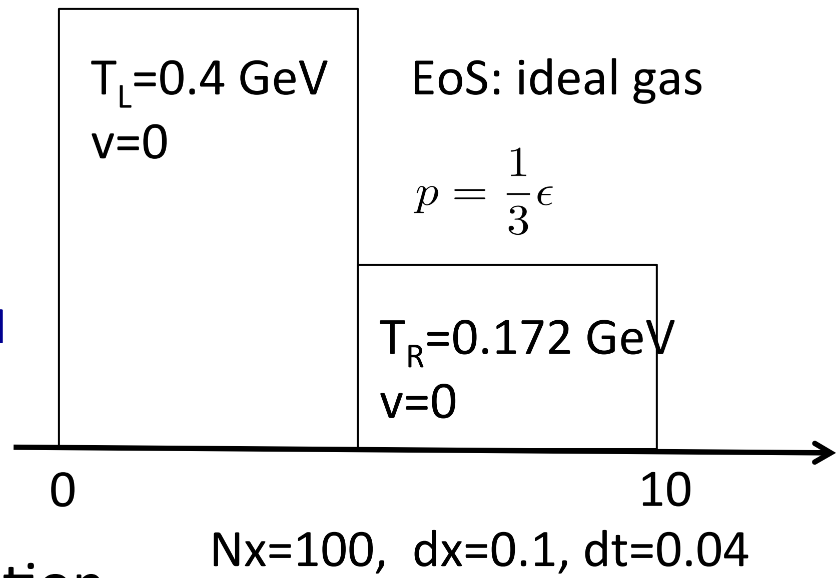
N_{cell}=100: dx=0.1 fm

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

λ=10 fm

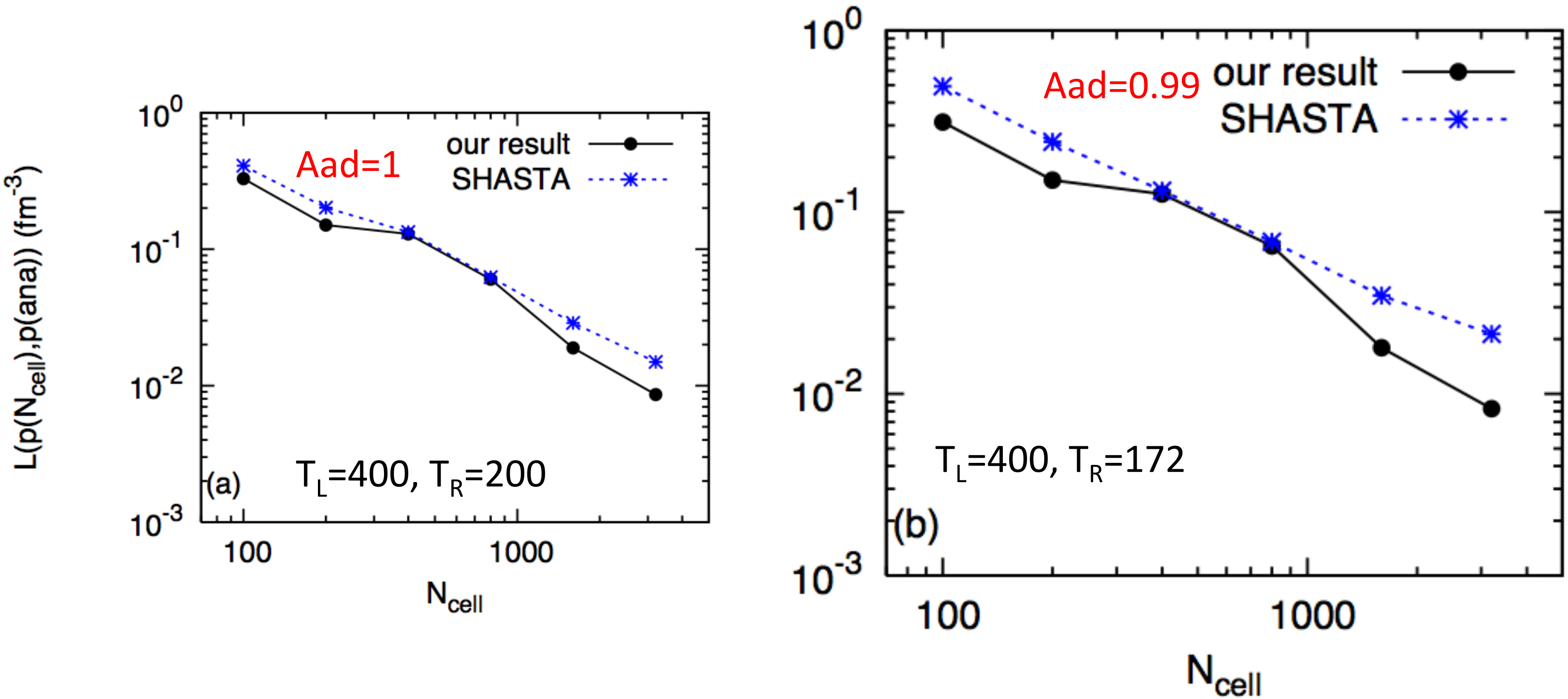
Large ΔT difference

- T_L=0.4 GeV, T_R=0.172 GeV
  - SHASTA becomes unstable.
  - Our algorithm is stable.
- SHASTA: anti diffusion term, A_{ad}
  - A_{ad} = 1 : default value, unstable
  - A_{ad} =0.99: stable,
    more numerical dissipation



L1 norm

- SHASTA with small A_{ad} has large numerical dissipation

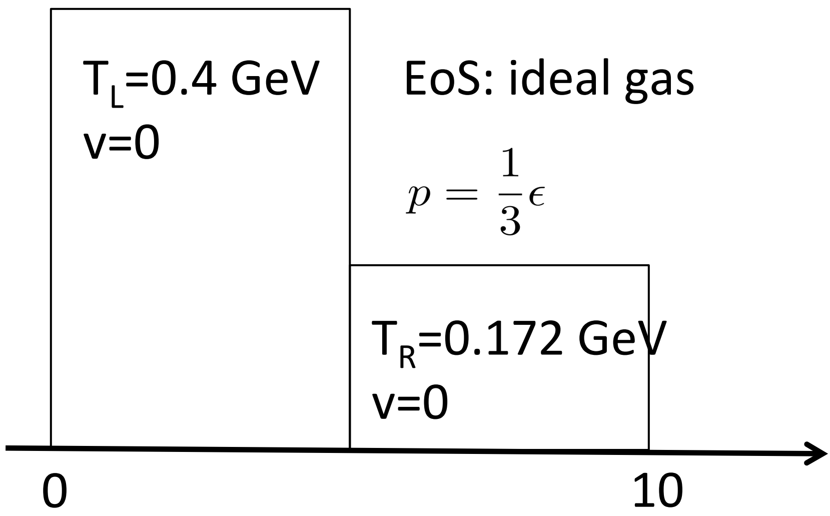


$$L(p(N_{\rm cell}), p(\text{anaytic})) = \sum_{i=1}^{N_{\rm cell}} |p(N_{\rm cell}) - p(\text{analytic})| \frac{\lambda}{N_{\rm cell}}$$

λ=10 fm

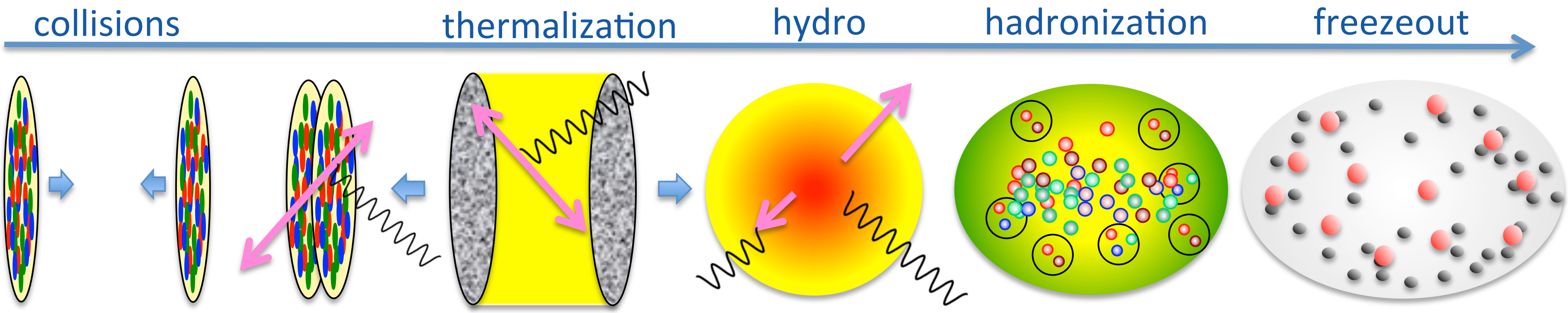
Large ΔT difference

- T_L=0.4 GeV, T_R=0.172 GeV
  - SHASTA becomes unstable.
  - Our algorithm is stable.
- SHASTA: anti diffusion term, A_{ad}
  - A_{ad} = 1 : default value
  - A_{ad} =0.99: stable, more numerical dissipation
- Large fluctuation (ex initial conditions)
  - Our algorithm is stable even with small numerical dissipation.



Nx=100, dx=0.1, dt=0.04

Our Hybrid Model



Fluctuating Initial conditions

Hydrodynamic expansion

Freezeout process
- From Hydro to particle
- Final state interactions

Akamatsu, Inutsuka, CN, Takamoto,
arXiv:1302.1665、J. Comp. Phys. (2014)34

MC-Glauber
MC-KLN → hydrodynamic model → Cornelius → Oscar sampler → UrQMD

http://www.aiu.ac.jp/~ynara/mckln/
Nara

Cornelius: Freezeout hypersurface finder
Huovinen, Petersen

Oscar sampler: *Ohio group*

Simulation setups:
- Free gluon EoS
- Hydro in 2D boost invariant simulation

Summary

- High-energy heavy ion collisions
  - QCD phase transition, success of the QGP production
  - QGP properties : comprehensive analyses of observables
- Highlights of latest experimental data at RHIC and LHC
  - Flow in A+A, p+A
- Relativistic Hydrodynamic Model
  - Description of dynamics of the high-energy heavy ion collisions
  - Importance of the numerical method:
    construction of the state-of-the-art algorithm