New Development of Hydrodynamics
and its Applications in Heavy-Ion Collisions
Fudan Univ., Oct.30-Nov.2, 2019

Fluctuations in hydrodynamic models

Tetsufumi Hirano (Sophia Univ.)

References:
TH *et al.*, Prog. Part. Nucl. Phys. **70**, 108 (2013).
K.Murase, Ph.D thesis, The University of Tokyo (2015).
M.Okai *et al.*, Phys. Rev. C**95**, 054914 (2017).
Y.Kanakubo *et al.*, PTEP **2018**, 121D01 (2018); arXiv:1910.10556.
A.Sakai *et al.*, in preparation.

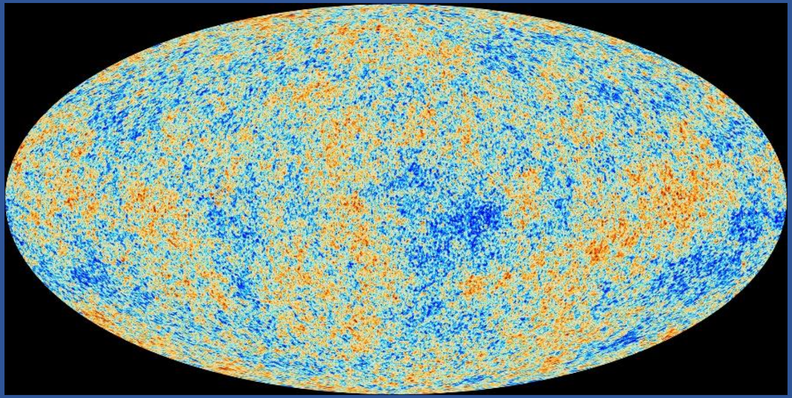
Quark Matter 2019@Wuhan
Oral presentation:
Y.Kanakubo, A.Sakai
Poster presentation:
Y.Gogun, K.Kuroki, R.Otsuka, Y.Yoshida

Outline

- Introduction
  - Importance of dynamical modeling in high-energy nuclear collisions
- Recent analyses
  - Integrated dynamical approach to soft physics in heavy-ion collisions
    - Fluctuating hydrodynamics
    - Factorization breaking in eta and in p_T from hydrodynamic fluctuations
    - Anisotropic flow from hydrodynamic fluctuations in ultra-central collisions
  - Towards unified description from small to large systems
    - Dynamical initialization with core-corona picture
    - Enhancement of multi-strange hadrons in small colliding systems
    - Dynamical initialization at RHIC-BES energies
    - Parametrized EoS with critical point and first order phase transition
- Summary and outlook

Introduction

Lessons from Observational Cosmology



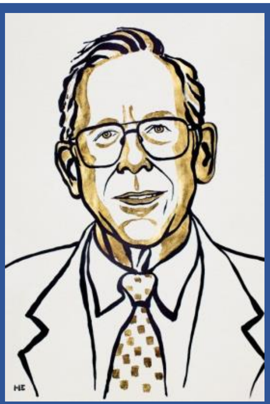
Cosmic Microwave Background
Fluctuations of temperature (Planck)

http://www.esa.int/spaceinimages/Images
/2013/04/Planck_CMB_black_background

Analysis tool

CAMB, CMBFAST,
CosmoMC,…

Cosmological parameters
- Energy budget
- Hubble constant (lifetime)
- Curvature (flatness)
- …

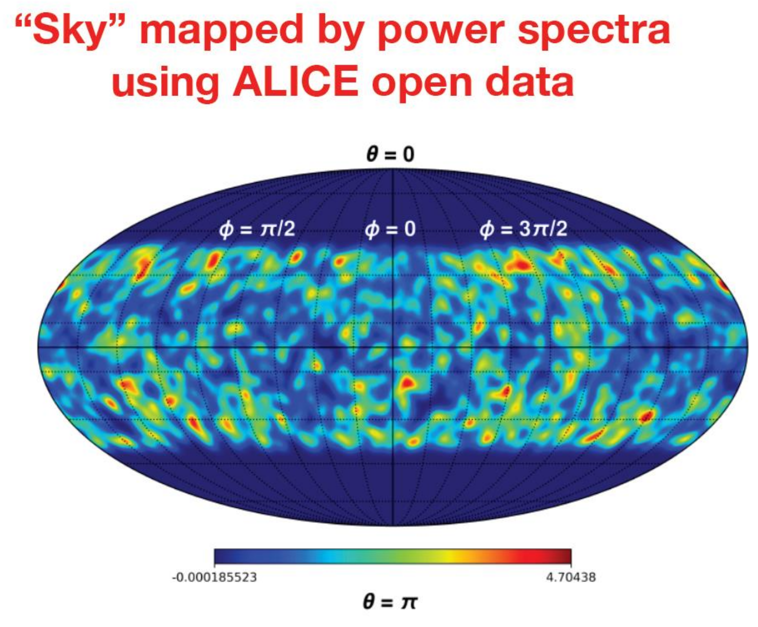


"Physical Cosmology"
James Peebles
The Novel prize in physics 2019

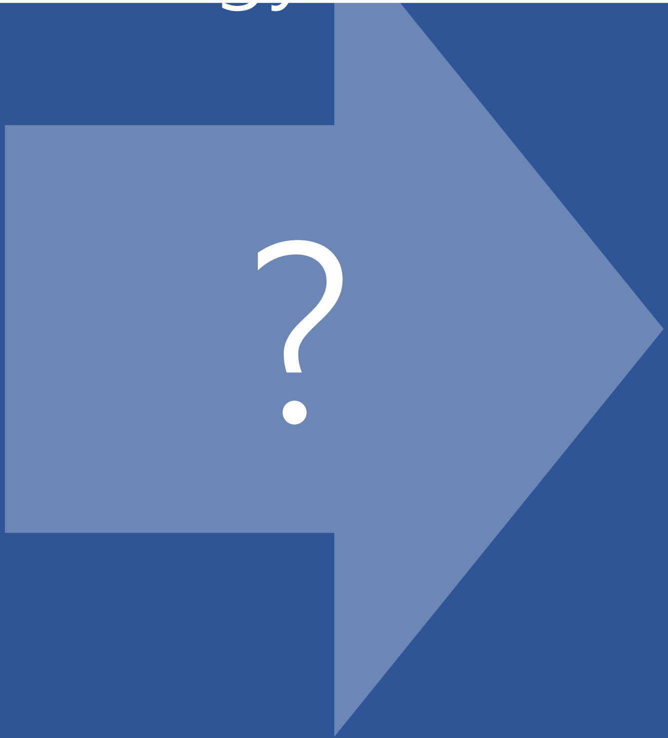
https://www.nobelprize.org/prizes/physics/2019/peebles/facts/

Analysis tool

Bottom-up approach in high-energy nuclear collisions


"Sky" mapped by power spectra using ALICE open data

Y.Zhou, talk at QM2018

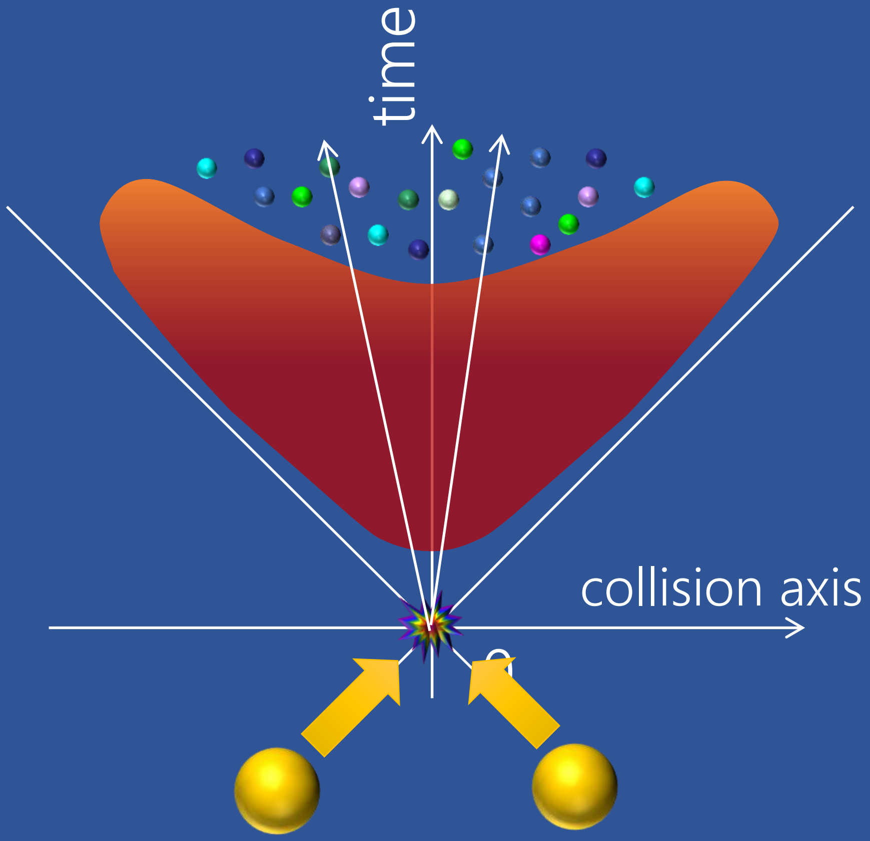


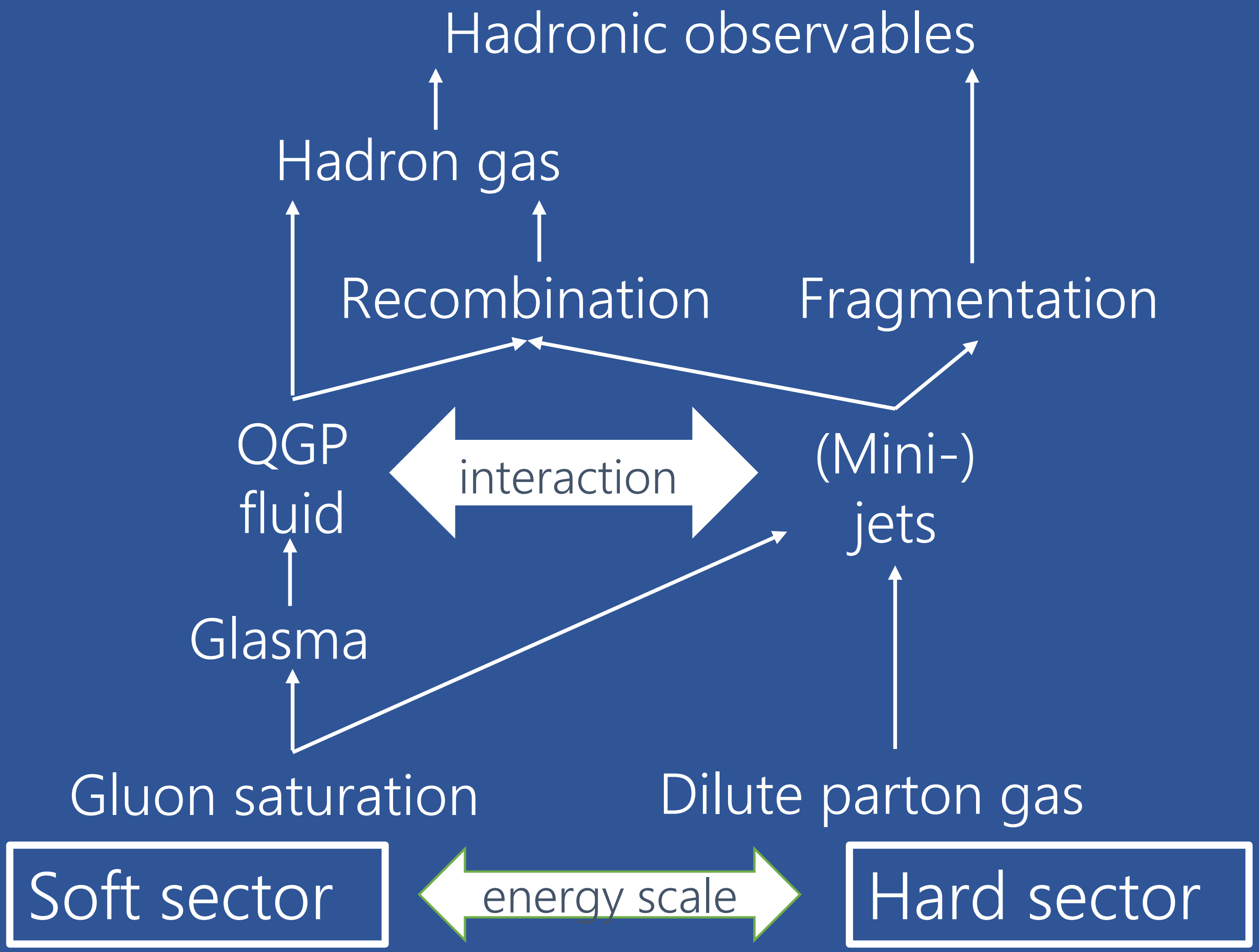
Physics properties of the QGP

- Equation of state
- Shear viscosity
- Bulk viscosity
- Stopping power
- …

Need Standard model/Analysis tool/Event generator for high-energy nuclear collisions

Standard picture of dynamics





Hadronic observables

Hadron gas

Recombination

Fragmentation

QGP fluid

interaction

(Mini-) jets

Glasma

Gluon saturation

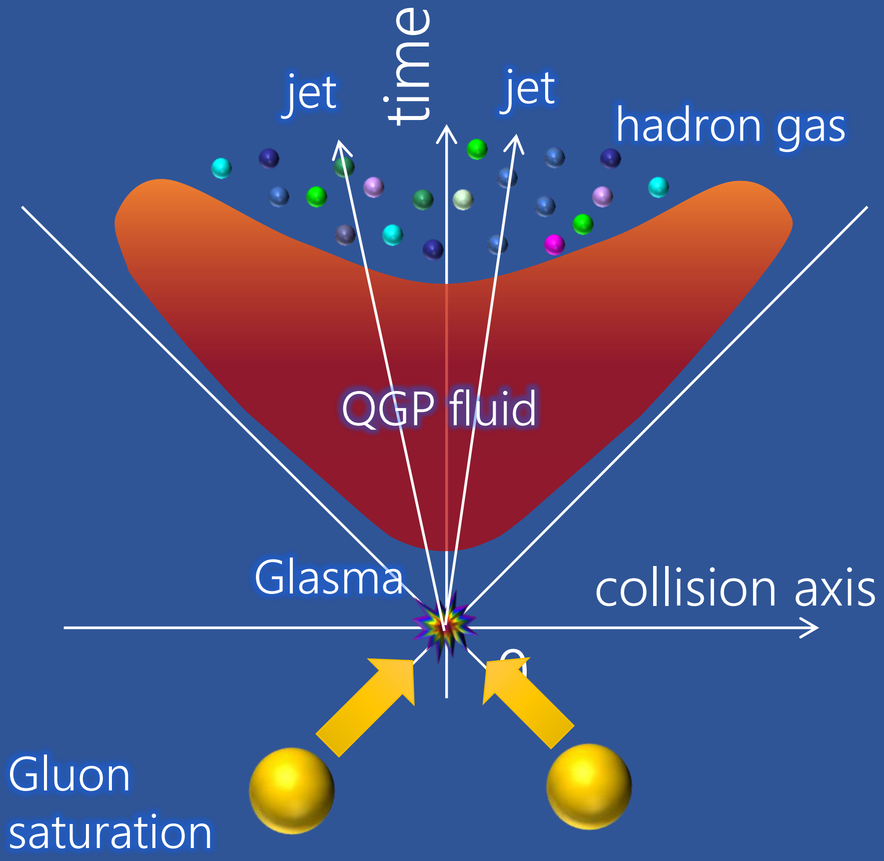
Dilute parton gas

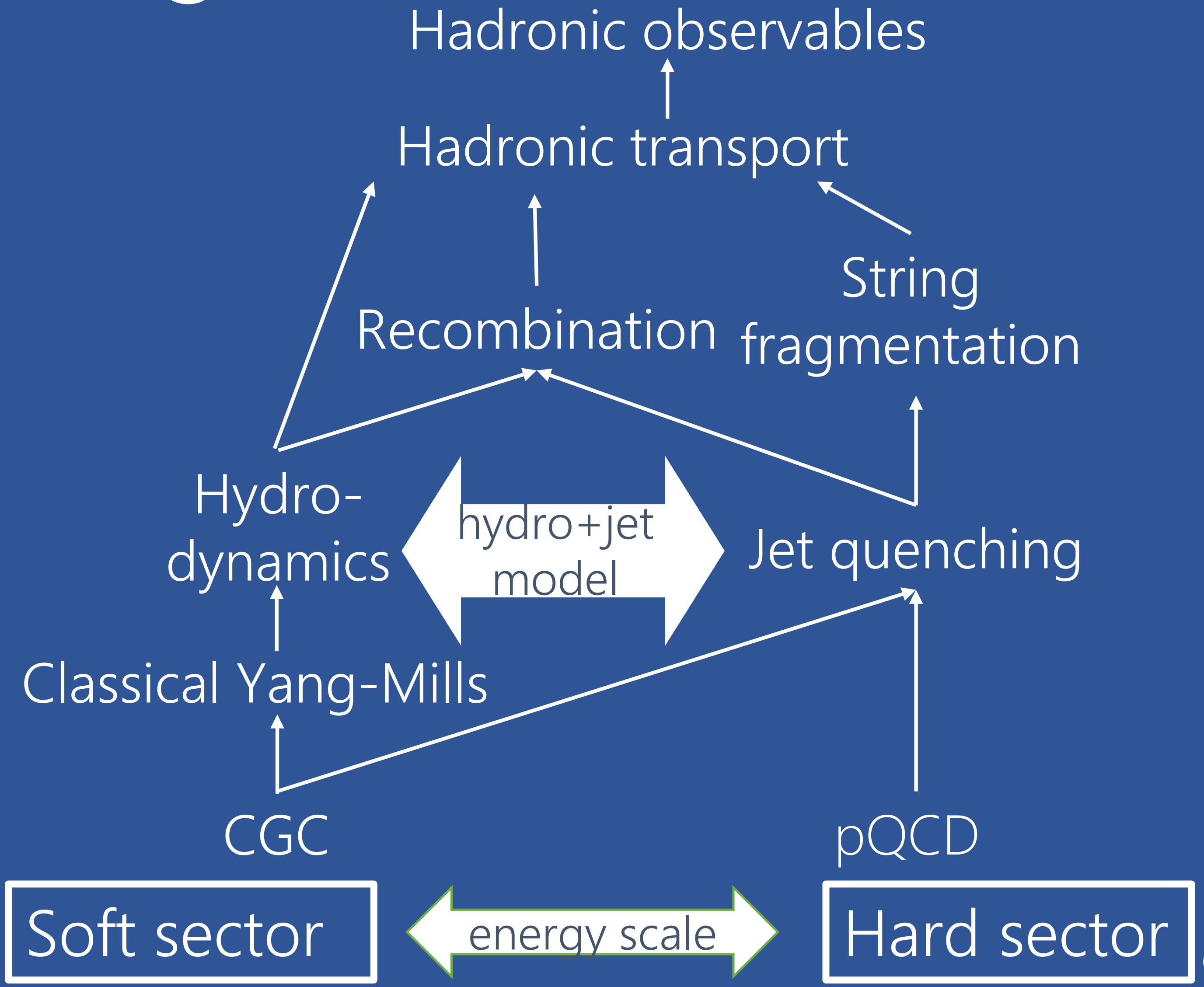
Soft sector

energy scale

Hard sector

Dynamical modeling in nuclear collisions





Hadronic observables

Hadronic transport

String fragmentation

Recombination

Hydro-dynamics

hydro+jet model

Jet quenching

Classical Yang-Mills

CGC

pQCD

Soft sector

energy scale

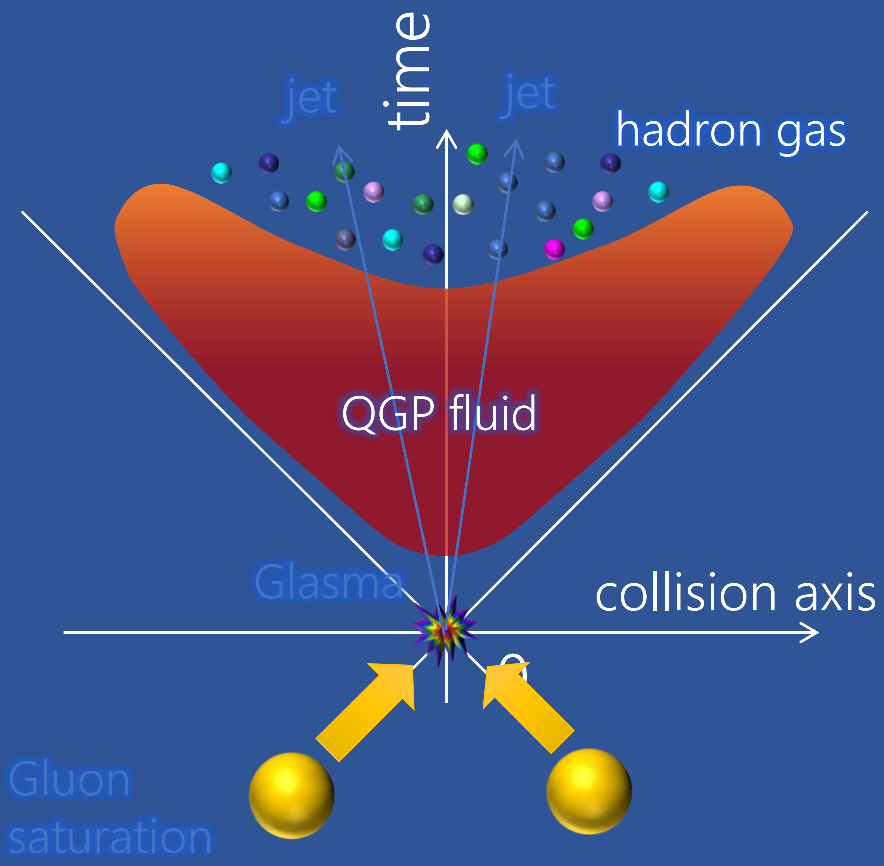
Hard sector

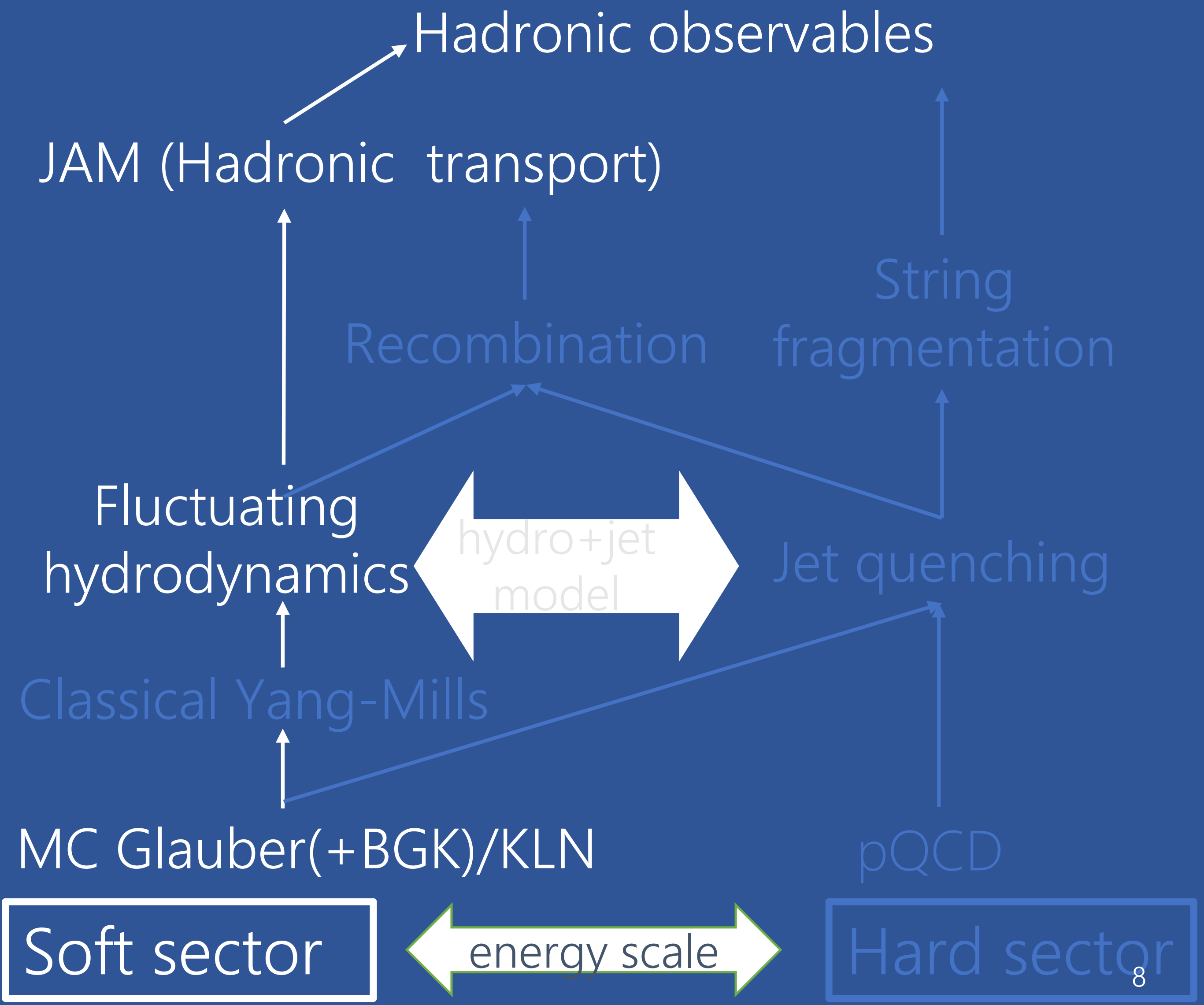
Recent analyses

Integrated dynamical approach to soft physics in heavy-ion collisions
Towards unified description from small to large systems

Fluctuating hydrodynamics: K.Murase, Ph.D thesis, The University of Tokyo(2015).
JAM: Y.Nara *et al.*, Phys. Rev. C**61,** 024901 (2000).

Model Soft




Hadronic observables

JAM (Hadronic transport)

String fragmentation

Recombination

Fluctuating hydrodynamics

hydro+jet model

Jet quenching

Classical Yang-Mills

MC Glauber(+BGK)/KLN

pQCD

Soft sector

energy scale

Hard sector

Integrated dynamical approach to soft physics in heavy-ion collisions (model S)

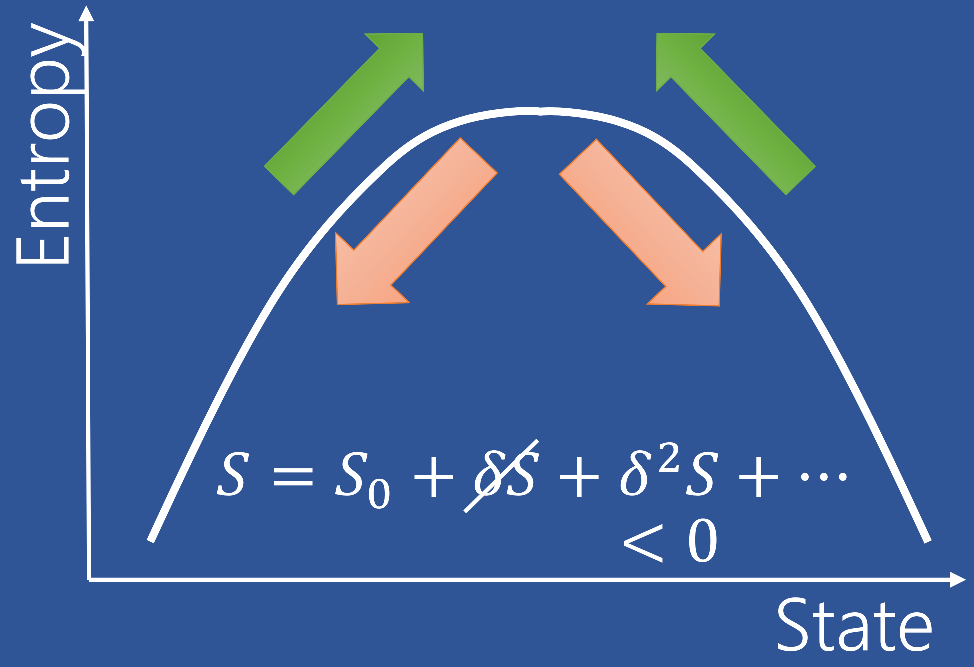
Main purpose:

- Description of low p_T hadrons from soup to nuts in large colliding systems towards understanding of bulk and transport properties of the QGP
- Investigation of effects of hydrodynamic fluctuations on observables

PeraltaRamos, Calzetta (2011), Kapusta, Muller, Stephanov (2011),
Moore, Kovtun, Romatschke (2011), Hirano, Murase (2013),
Young(2014), Akamatsu, Mazeliauskas, Teaney (2017)…

Hydrodynamic fluctuations

Fluctuation-Dissipation relations

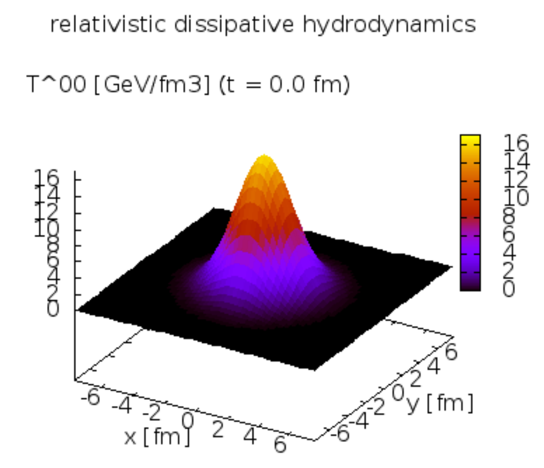


$$S = S_0 + \cancel{\delta S} + \underbrace{\delta^2 S}_{< 0} + \cdots$$

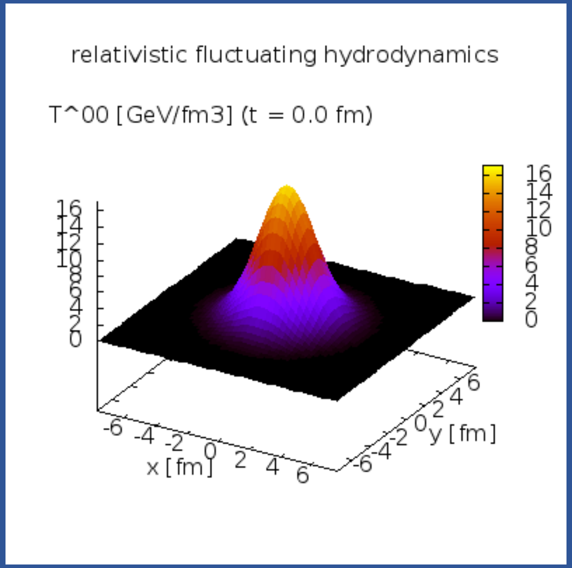
Fluctuations around maximum entropy state

QGP fluid simulation in a box

Courtesy of K.Murase



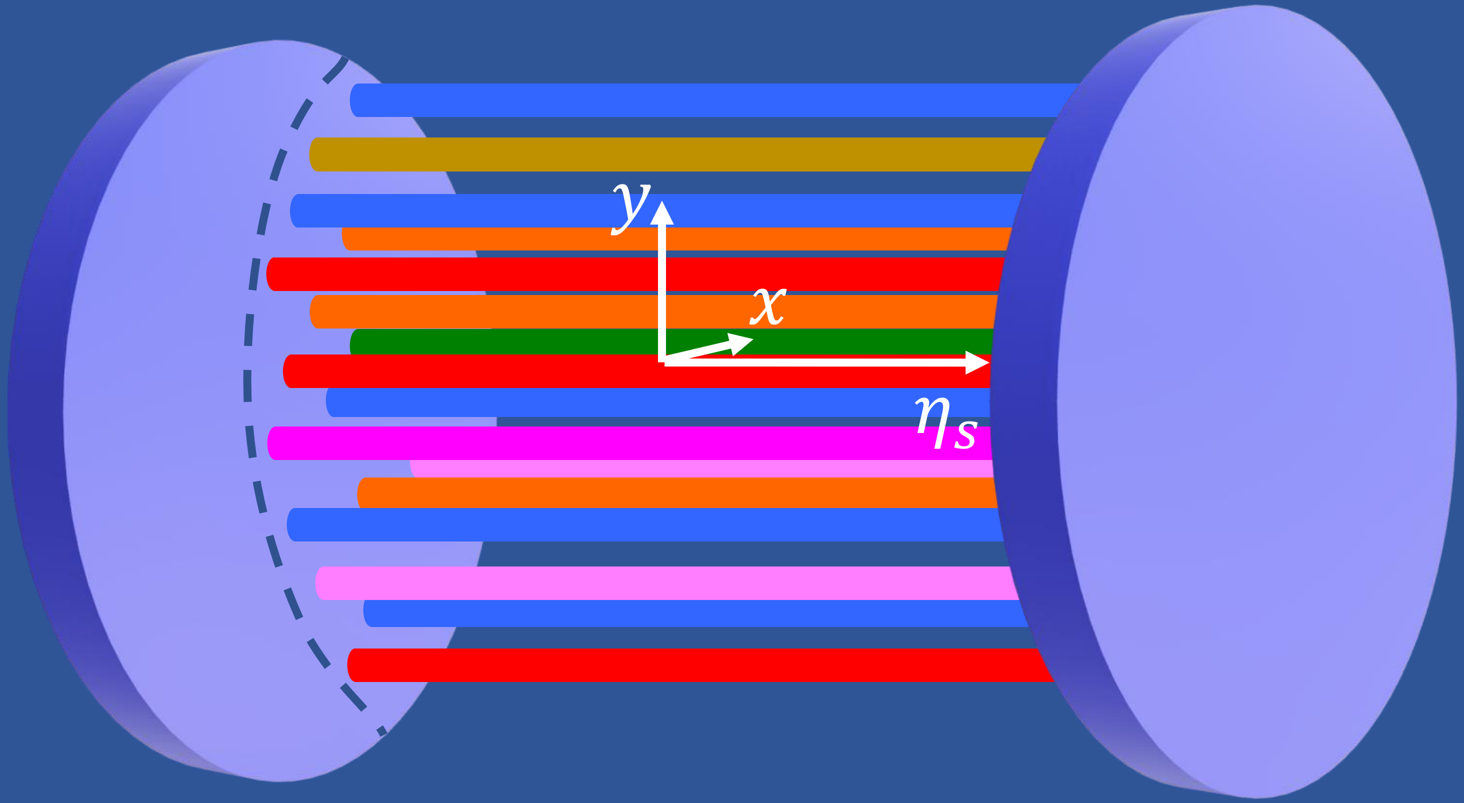
Dissipative hydro (2nd Generation)



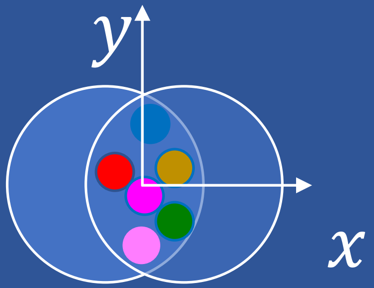
Fluctuating hydro (3rd Generation)

Dissipations ←→ Fluctuations

Correlations along collision axis



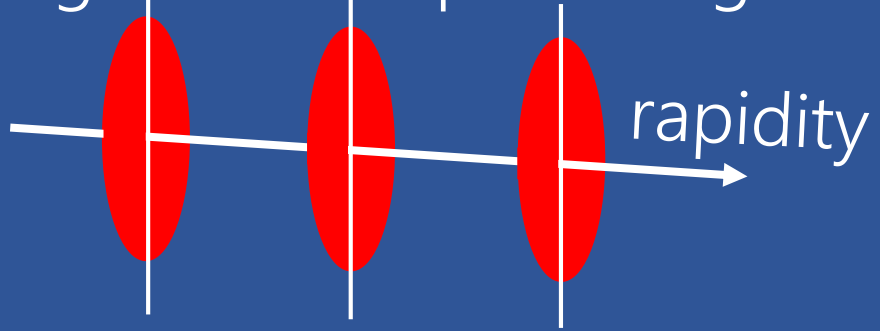
$\tau = 0^+$



Heavy ion collision as a chromoelectric capacitor
→ Approximately boost-invariant formation of color flux tubes
→ Correlation embedded in wide rapidity region

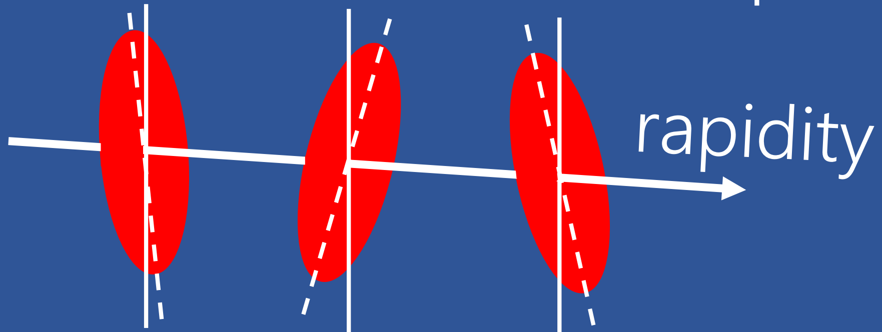
Event plane decorrelation from hydrodynamic fluctuations

Aligned event plane angle



$r_2 = 1$

“Random walk” of event plane angle



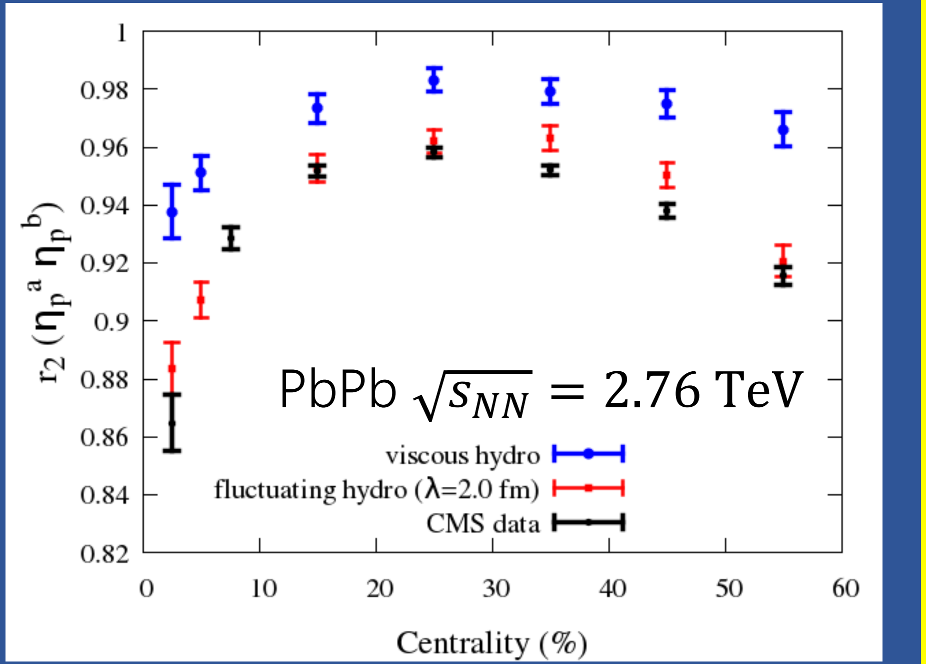
$-2.5 < \eta_p^a < -2.0$

$2.0 < \eta_p^a < 2.5$

$3.0 < \eta_p^b < 4.0$

$r_2 < 1$

Factorization ratio

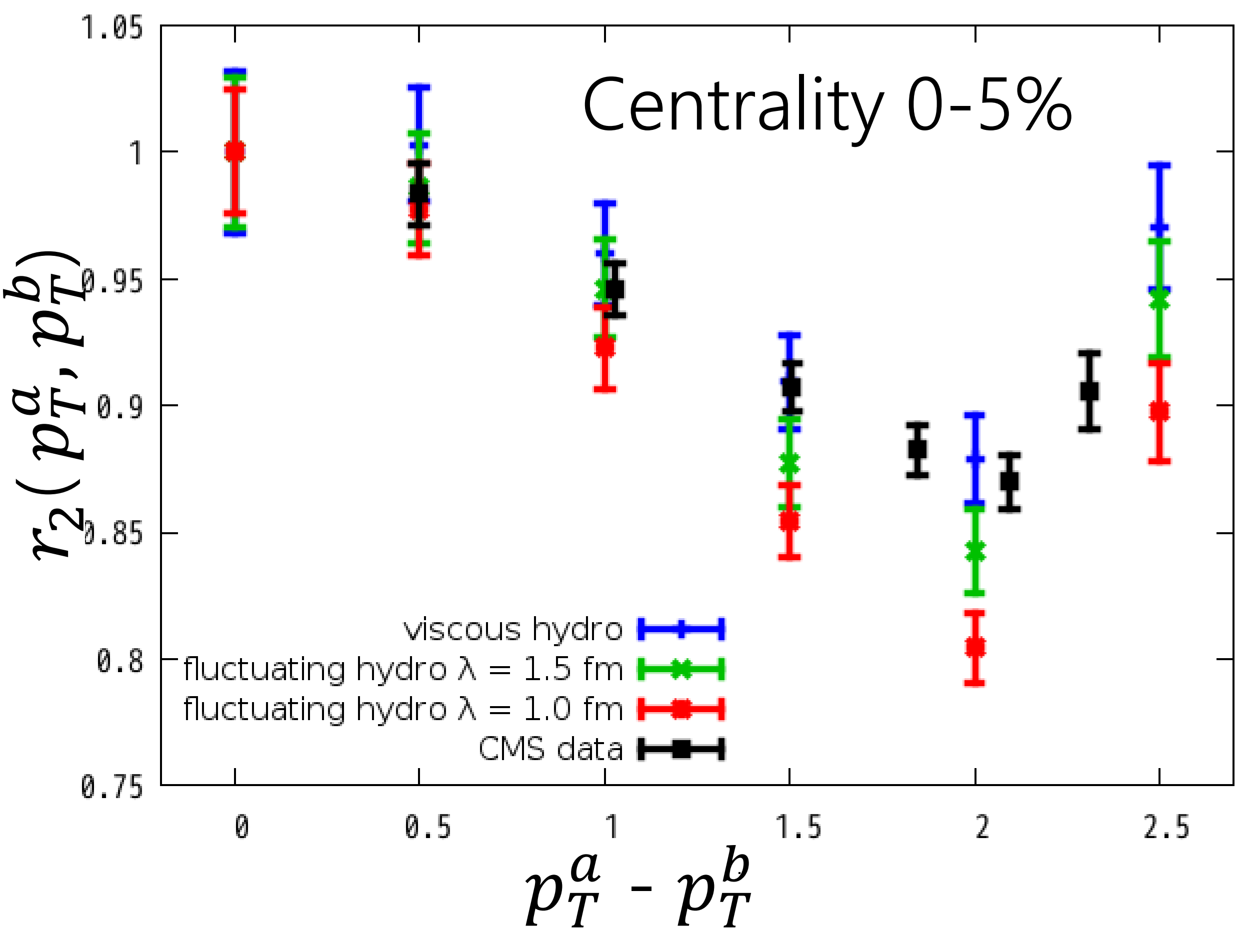


A. Sakai, talk on Nov. 1; talk at QM2019

New opportunity to constrain transport coefficients and initial conditions in rapidity space

Event plane decorrelation in transverse momentum

Y.Gogun, poster at QM2019

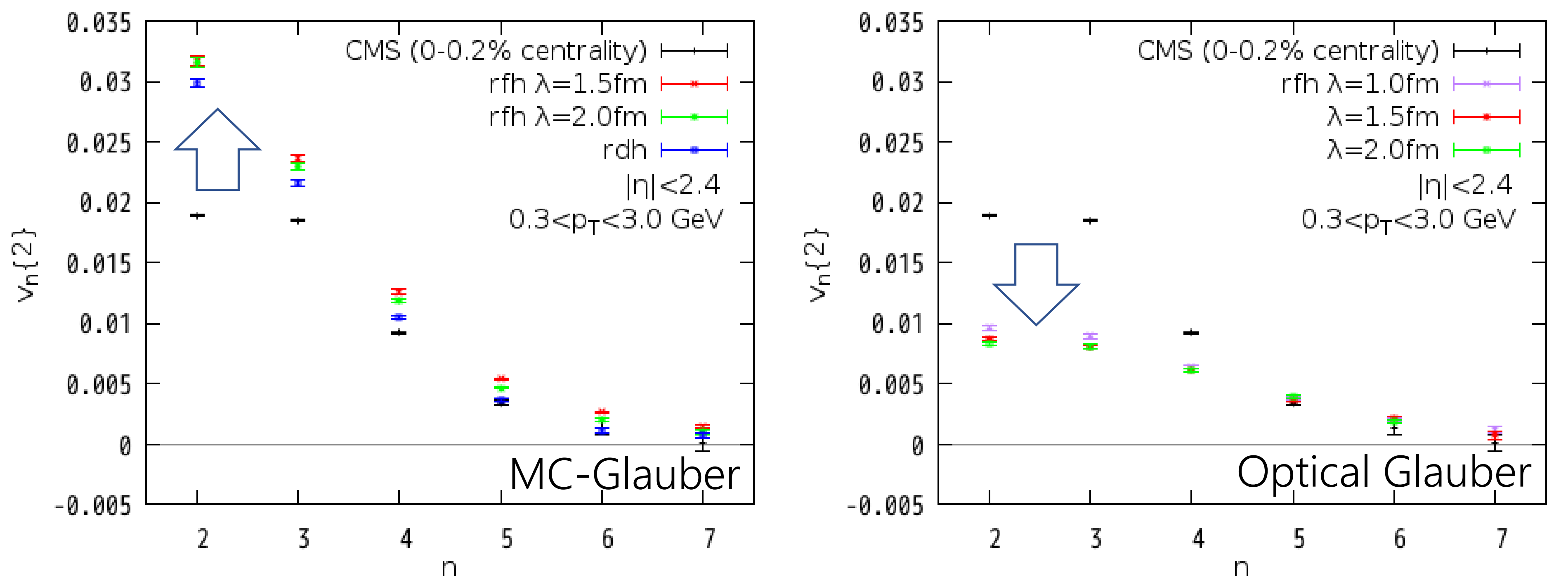


Initial state fluctuations + hydrodynamic fluctuations

- Effects of hydrodynamic fluctuations
  → Not so significant in transverse momentum
- Need detailed analysis of bumpiness in transverse profile

Anisotropic flow “puzzle” in ultra-central collisions

K.Kuroki, poster at QM2019



Initial + hydrodynamic fluctuations → $v_2 > v_3$

Only hydrodynamic fluctuations → $v_2 \approx v_3$

Importance of interplay between initial and hydrodynamic fluctuations?

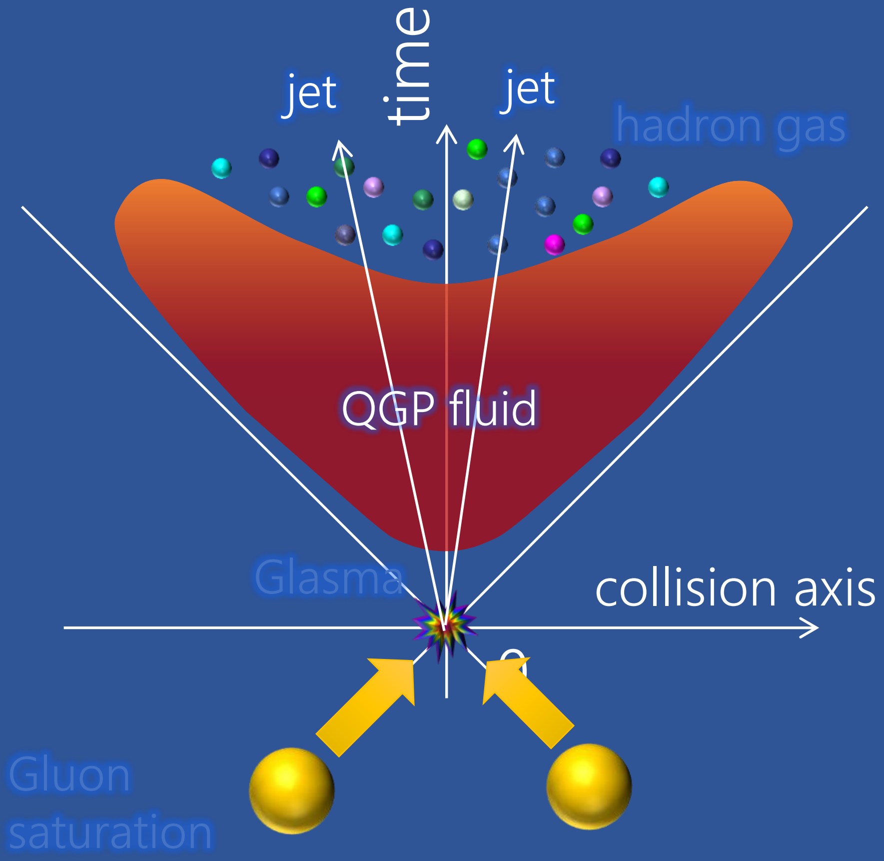
Recent analyses

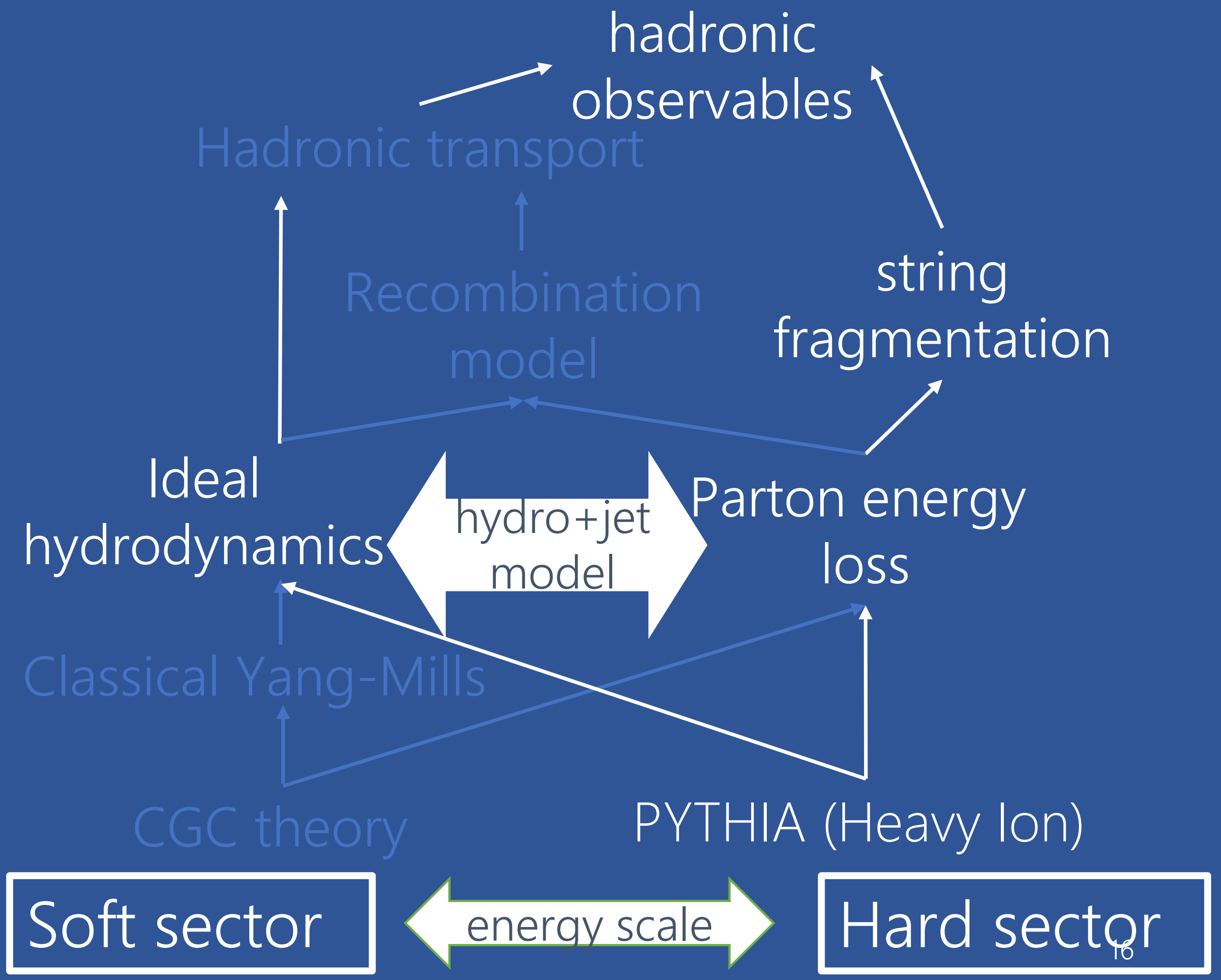
Integrated dynamical approach to soft physics in heavy-ion collisions

Towards unified description from small to large systems

Y.Tachibana, TH, (2014, 2016); M.Okai *et al.*, (2017); Y.Kanakubo *et al.*, (2018).
PYTHIA: T. Sjöstrand *et al.*, Comput. Phys. Commun. **191**, 159 (2015).
*Heavy ion mode available from ver.8.230

Model Soft-Hard





hadronic observables

Hadronic transport

Recombination model

string fragmentation

Ideal hydrodynamics

hydro+jet model

Parton energy loss

Classical Yang-Mills

CGC theory

PYTHIA (Heavy Ion)

Soft sector

energy scale

Hard sector

From large to small colliding systems (model S-H)

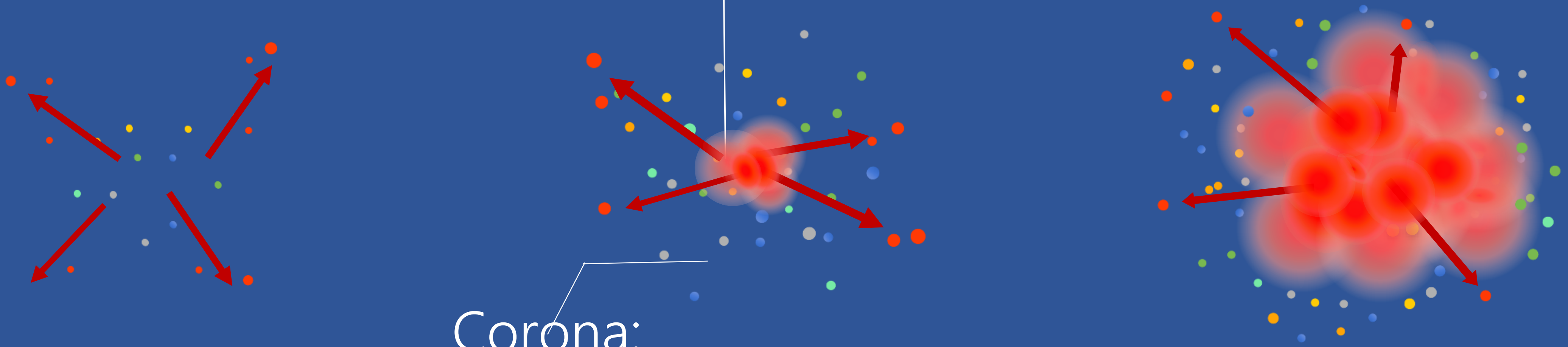
Main purpose:

- Universal description of high-energy nuclear collisions from small to large colliding systems, from low to high collision enegies, and from low to high p_T
- Investigation of core-corona picture on bulk and flow observables

Bozek (2005,2009), Aichelin, Werner (2009), Becattini, Manninen (2009),
Pierog *et al.* (2015), Akamatsu *et al.* (2018), Kanakubo *et al.* (2018)

Core-corona picture

Figures: Courtesy of Y.Kanakubo



Core: Chemically equilibrated matter →QGP fluids

Corona: Unscathed partons

Low ⟵ Multiplicity ⟶ High

Key to describe dynamics

from small (low) to large (high) systems (multiplicity)

Dynamical core-corona initialization

$$\partial_\mu T_{\mathrm{f}}^{\mu\nu} = J^{\nu}_{\mathrm{p}\to\mathrm{f}}$$

Phenomenological parametrization for source term

M.Okai *et al.* (2017), Y.Kanakubo *et al.*(2018)&(2019).

$$J^{\mu}_{\mathrm{p}\to\mathrm{f}} = -\sum_i \frac{d{p_i}^{\mu}}{dt} G(\boldsymbol{x} - \boldsymbol{x}_i(t))$$

G : Gaussian smearing

p_i : Parton four momentum

$\boldsymbol{x}_i$: Parton position

Fluidization rate per particle

Y.Kanakubo *et al.* (2018)&(2019).

$$\frac{d{p_i}^{\mu}(t)}{dt} = -a_0 \frac{\rho_i\left(x_i(t)\right)}{{p_{\mathrm{T},i}}^2} {p_i}^{\mu}(t) \approx -\frac{{p_i}^{\mu}(t)}{\lambda_i}$$

ρ_i : Parton density

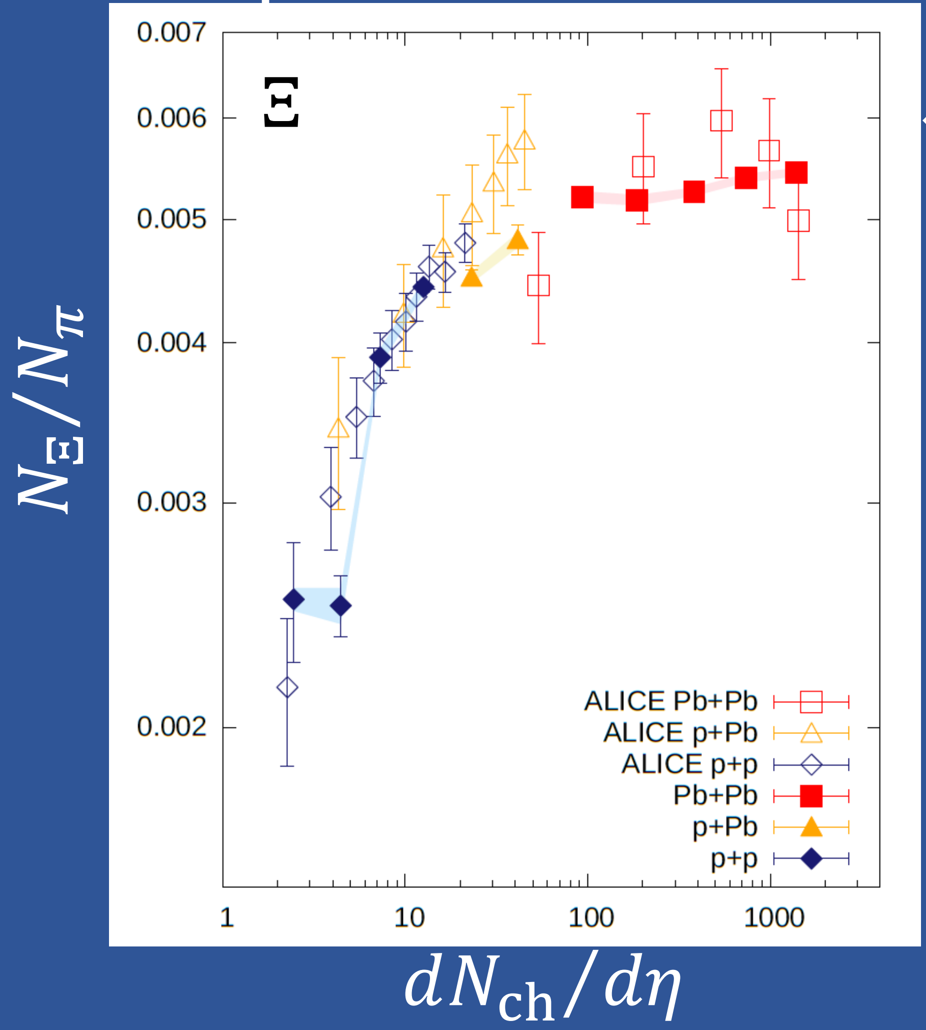
a_0 : Control parameter

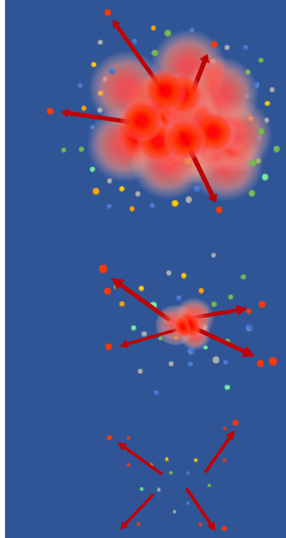
λ_i : Mean free path

$$\text{Automatic separation between} \left\{ \begin{array}{l} \text{core and corona} \\ \text{soft and hard} \end{array} \right.$$

Core-corona effects on ratio of cascades to pions

Y.Kanakubo, talk on Nov.2; talk at QM2019





QGP limit:
hadron production only from fluids
(Chemically equilibrated matter)

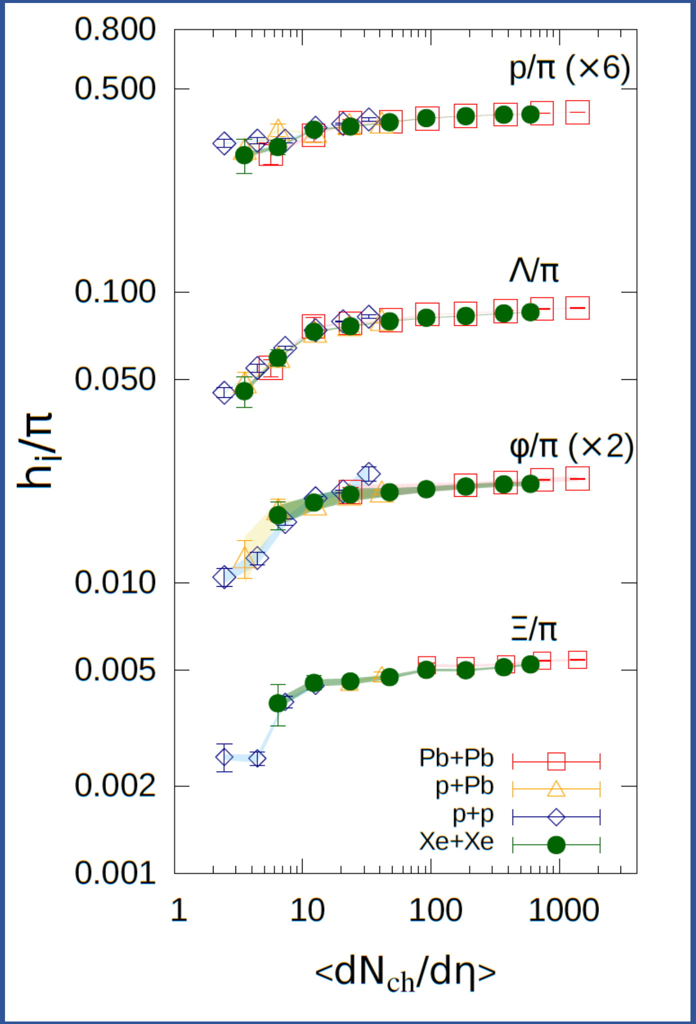
$\frac{dN_{\text{ch}}}{d\eta} \gtrsim 100$ ⇨ QGP formation dominance

$\frac{dN_{\text{ch}}}{d\eta} \lesssim 100$ ⇨ Partial creation of QGP

String fragmentation limit:
hadron production only from string fragmentation

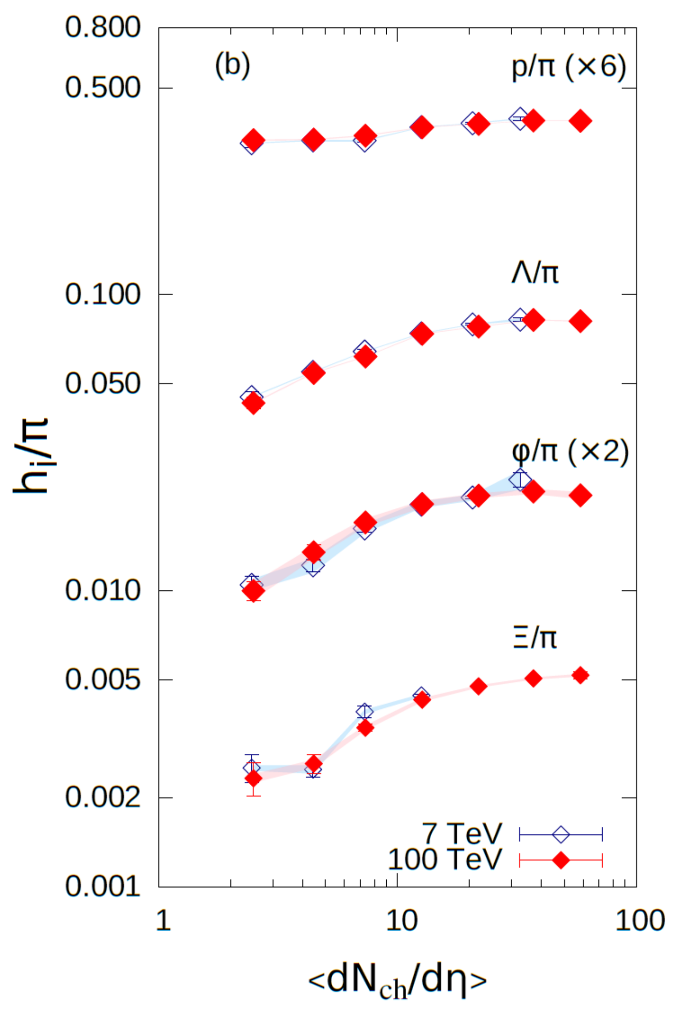
Size and collision energy dependence

Y.Kanakubo, talk on Nov.2; talk at QM2019

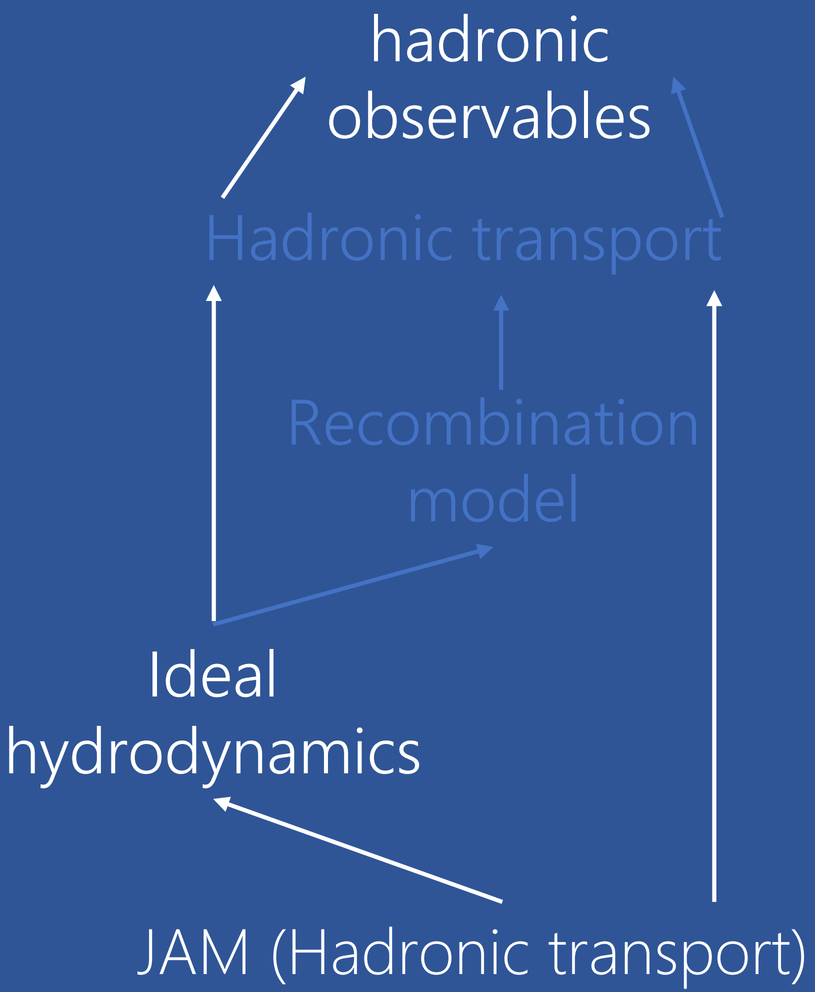


Almost no size or collision energy dependence

in dynamical core-corona model



Model Low


hadronic observables

Hadronic transport

Recombination model

Ideal hydrodynamics

JAM (Hadronic transport)

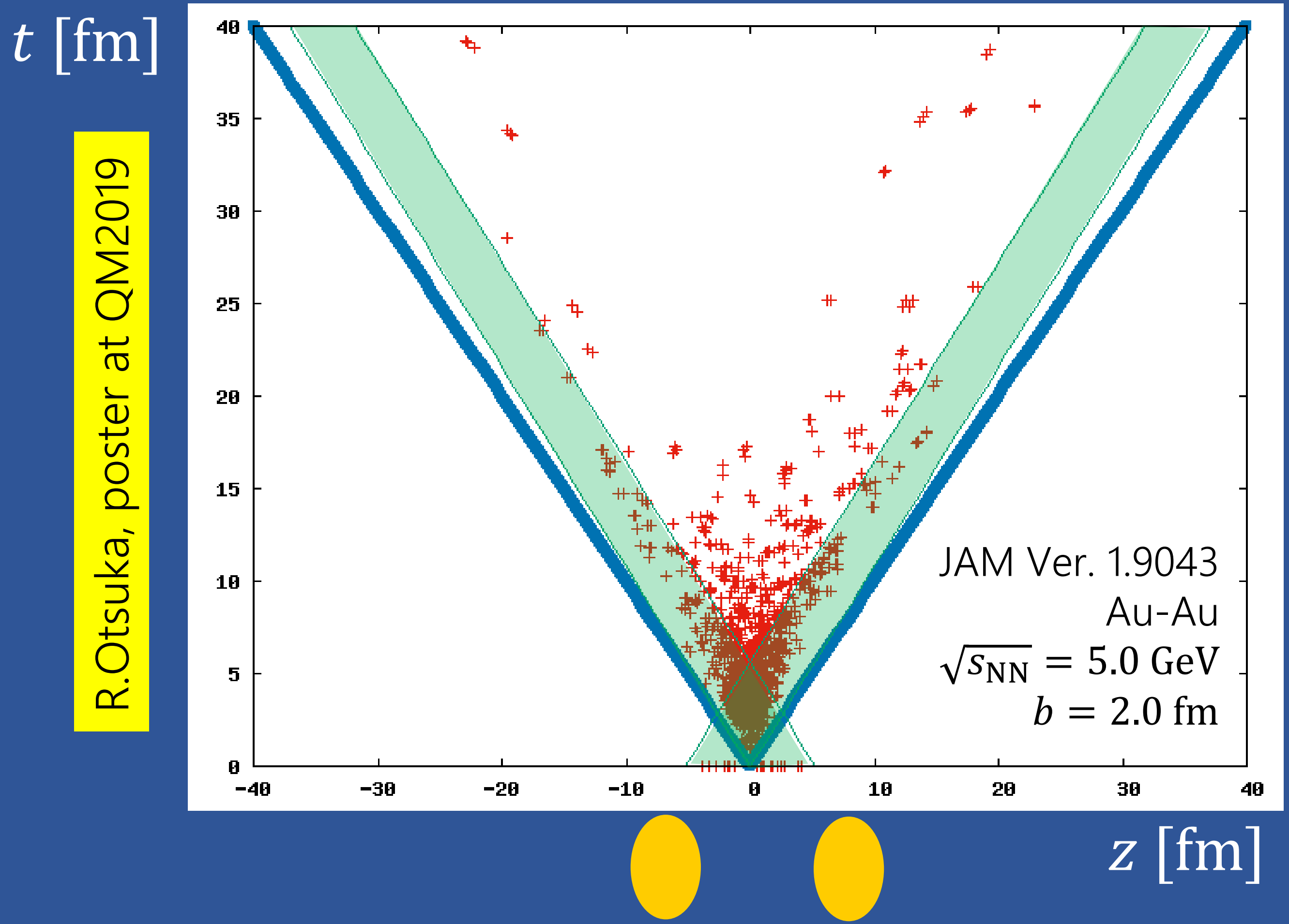
Soft sector

Low energy mode in dynamical initialization
→ Aim at RHIC-BES, FAIR, NICA and J-PARC-HI

Main purpose:

- **Dynamical initialization** in lower collision energies
- Investigation of phase diagram at finite baryon density

Dynamical initialization at RHIC-BES energies



R.Otsuka, poster at QM2019

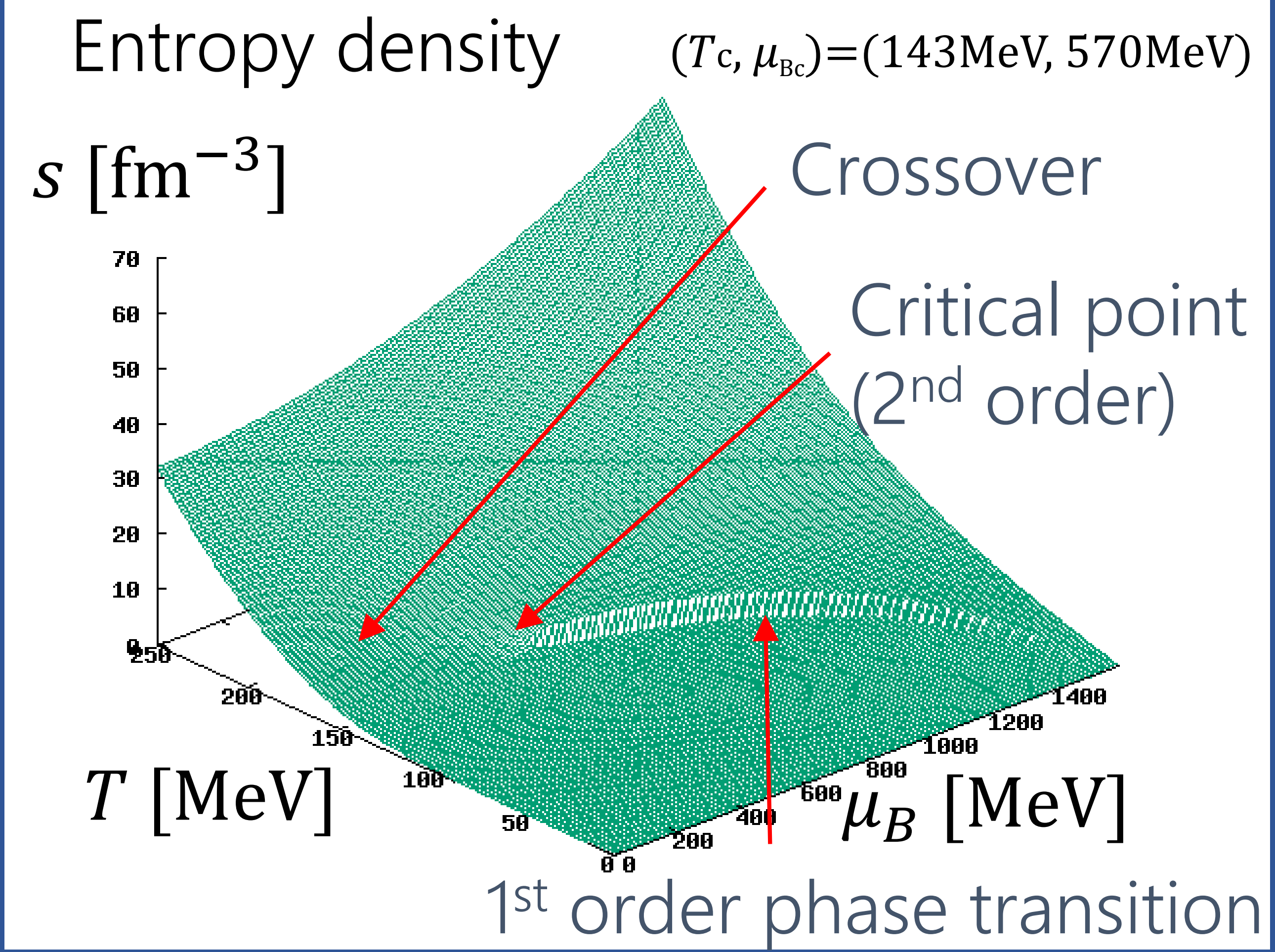
Initialization of fluids at constant time
→ How to initialize fluids during overlapping?
→ Scattered production points in the overlapping region

Neither $\tau = {\rm const.}$ or $t = {\rm const.}$
→ Need dynamical initialization
(Work in progress)

(See also, Y.Akamatsu *et al.* Phys.Rev.**98**, 024909 (2018).)

Parametrized equation of state with critical point and first order phase transition

Y.Yoshida, poster at QM2019



Entropy density

(Tc, μ_{Bc})=(143MeV, 570MeV)

Crossover

Critical point (2nd order)

1st order phase transition

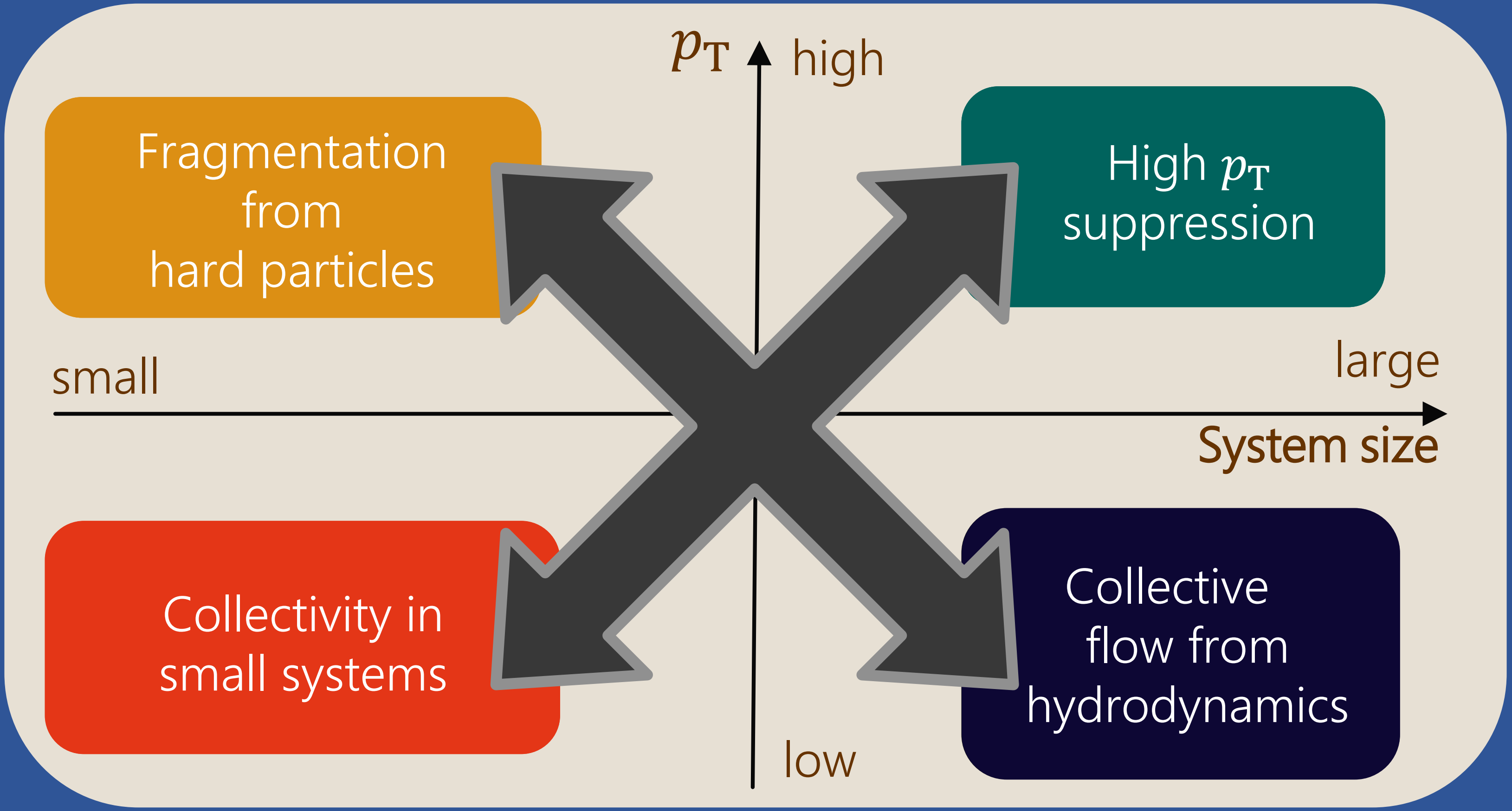
3D Ising model
+ Lattice QCD results
+ Hadron resonance gas
w. repulsive mean field
+ Bag model

→ Hydrodynamic analysis at RHIC-BES energies

Summary and outlook

- Development of standard model for high-energy nuclear collisions from small to large colliding systems, from low to high collision energies, and from low to high p_T
- Current status
  - Event plane decorrelation as a tool to investigate effects of hydrodynamic fluctuations
  - Universal description of chemistry brought by dynamical core-corona initialization

Toward "Standard Model" in high-energy nuclear collisions



Fragmentation from hard particles

High p_T suppression

Collectivity in small systems

Collective flow from hydrodynamics

Backups

Introduction

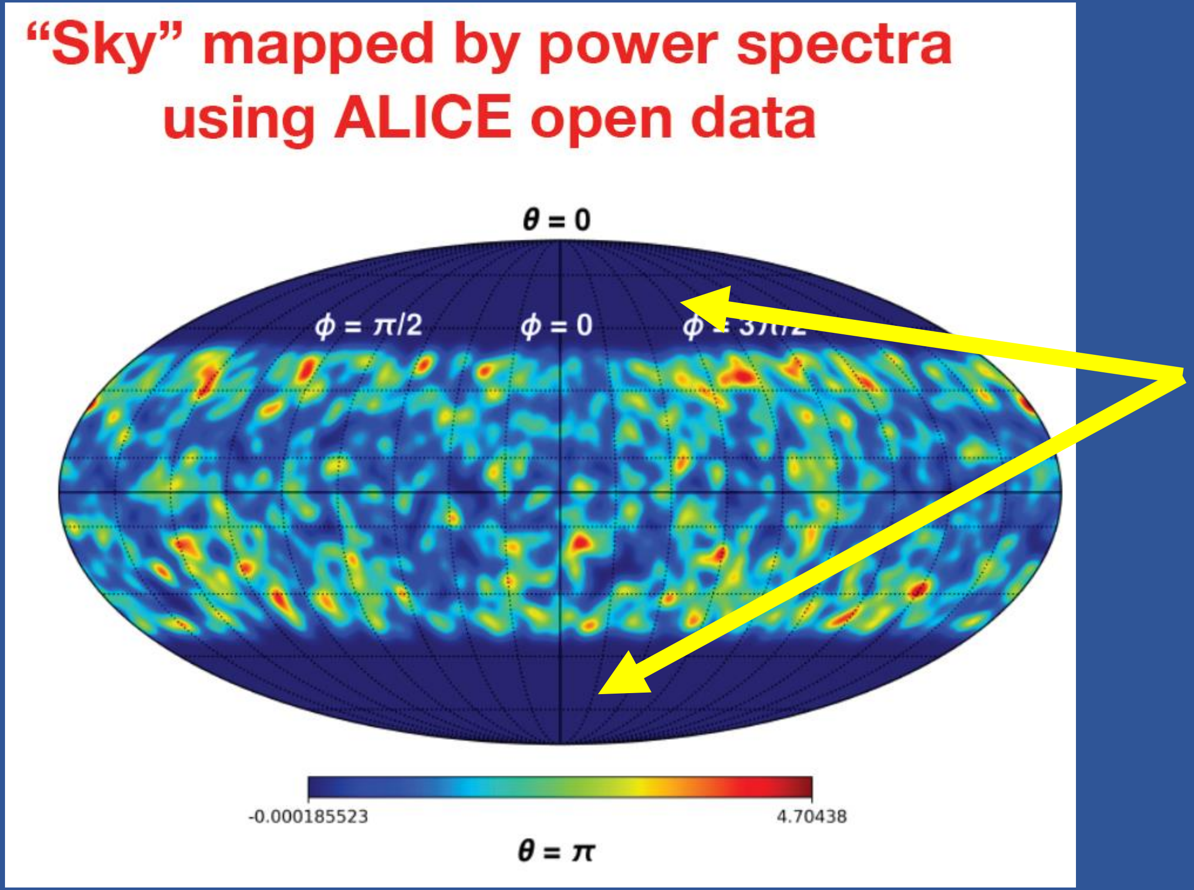
We have been developing

"Standard Model"

of dynamics in high-energy nuclear collisions towards understanding of

- Bulk and transport properties
- Structure of vacuum (chiral symmetry restoration)
- Electromagnetic radiation
- Stopping power
- Thermalization/Fluidization mechanism
- New physics
- …

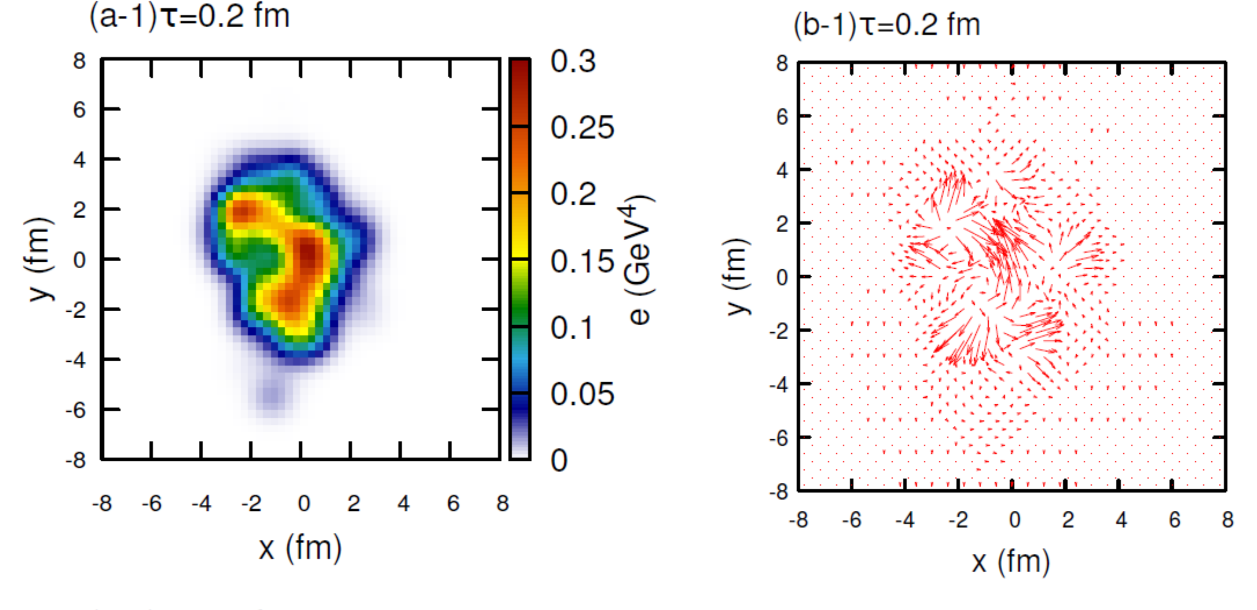
Expectation to LHC-ALICE experiment



Fill the blank (forward/backword) region?!

Energy density and transverse flow fluctuations without core-corona picture

Pb+Pb $\sqrt{s_{NN}} = 2.76\ \mathrm{TeV},\ b = 10.08\ \mathrm{fm}$



energy density distribution

transverse flow velocity distribution

Initial parton phase space distribution from event to event

↓

Dynamical initialization obeying momentum conservation

↓

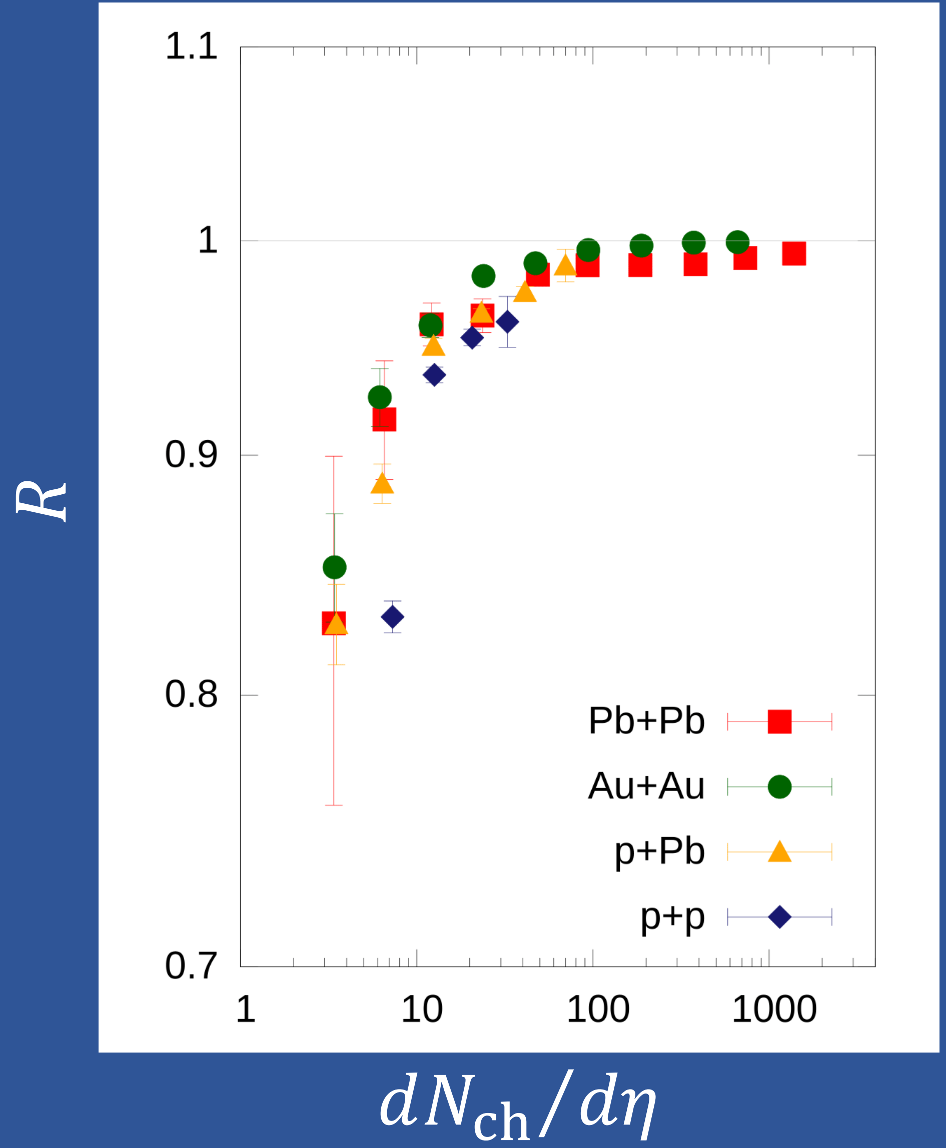
Initial random transverse flow velocity

↓

Anisotropy interpreted from initial random (geometry+flow)

M.Okai (2018)

Fluidization rate



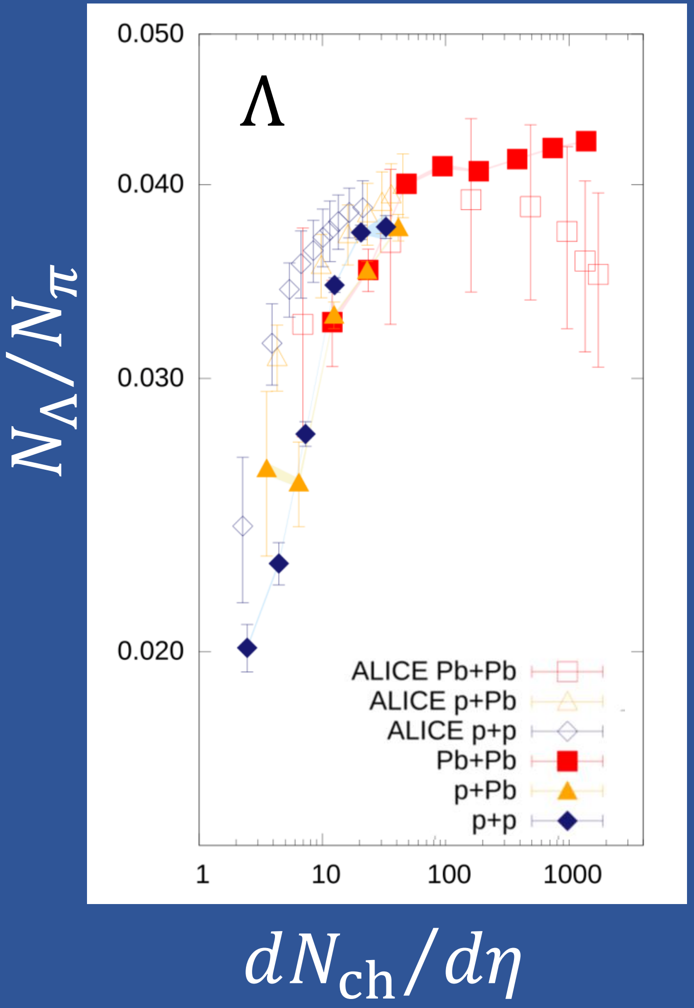
Core energy at midrapidity

$$R = \frac{dE_{\mathrm{core}}/d\eta_s}{dE_{\mathrm{tot}}/d\eta_s}$$

Total energy at midrapidity
← Partons forced to be fluidized at the first time step

Monotonic increase + saturation
→ Core part dominance in high multiplicity events

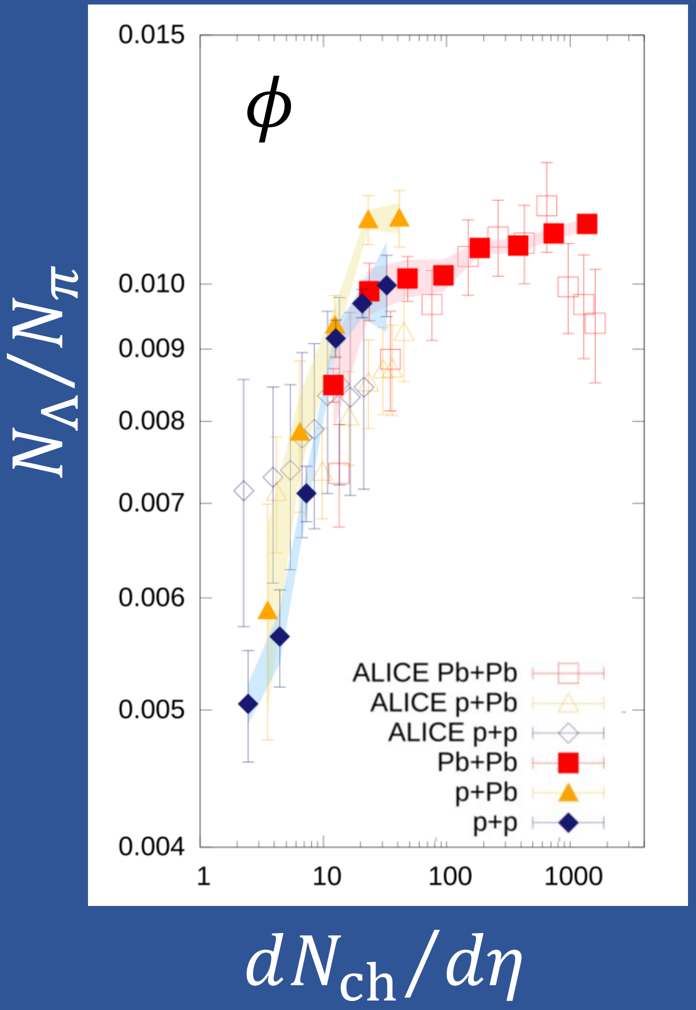
Lambdas ($|S| = 1$)



Similar trends to Cascade ($|S| = 2$)

- Rapid increase with multiplicity
- Saturation above $dN_{\text{ch}}/d\eta \sim 100$
- Scale solely with multiplicity regardless of system size

Phi mesons ($|S| = 0$)



Similar trends to Lambda and Cascade
→ Enhancement of ratio with multiplicity even for $|S| = 0$

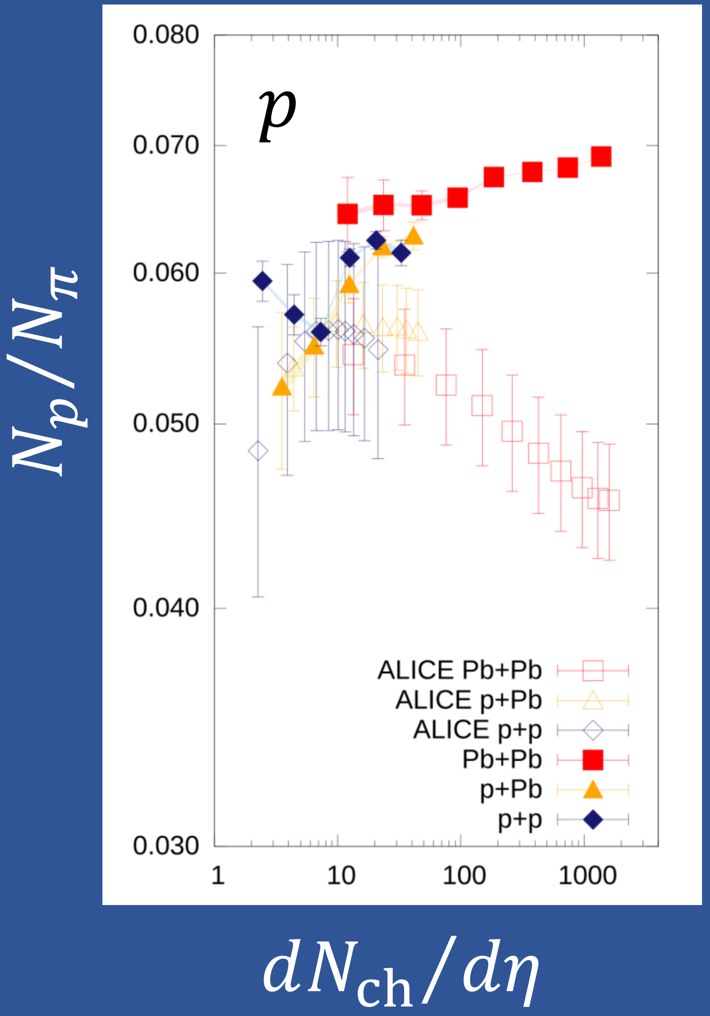
(*Same conclusion as in, e.g., Becattini and Manninen (2009))

⇕

Canonical suppression scenario
← Suppression of strange hadron yields due to absence of bath of strangeness in small systems
← Phi mesons are NOT suppressed

See, e.g., Vislavicius and Kalweit, arXiv:1610.03001

Protons

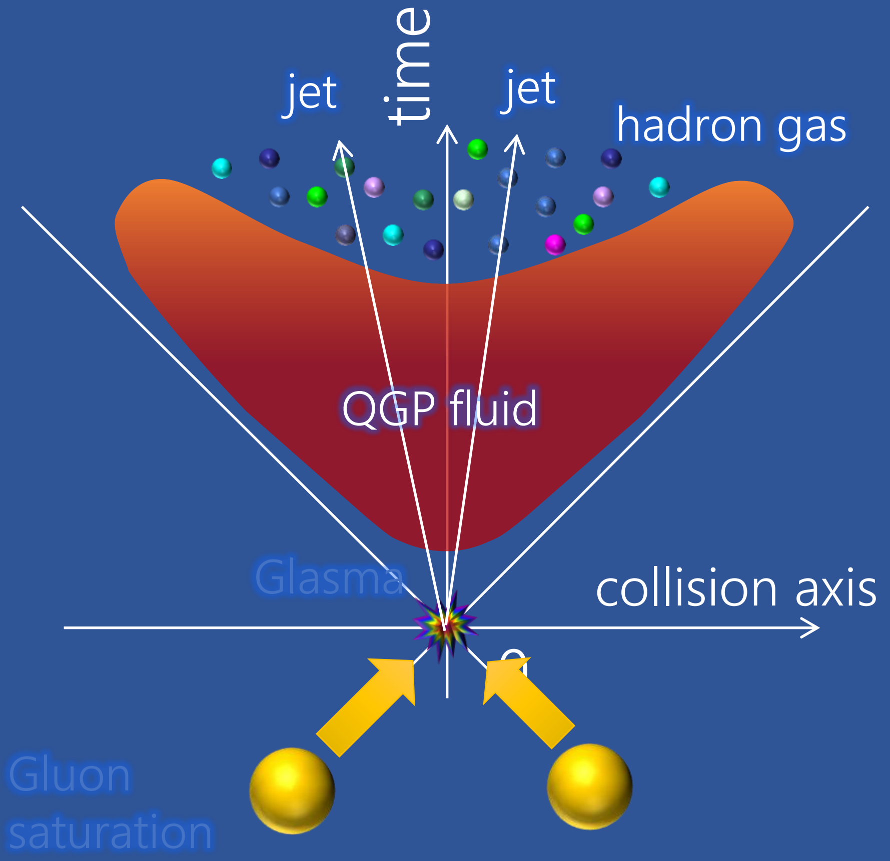


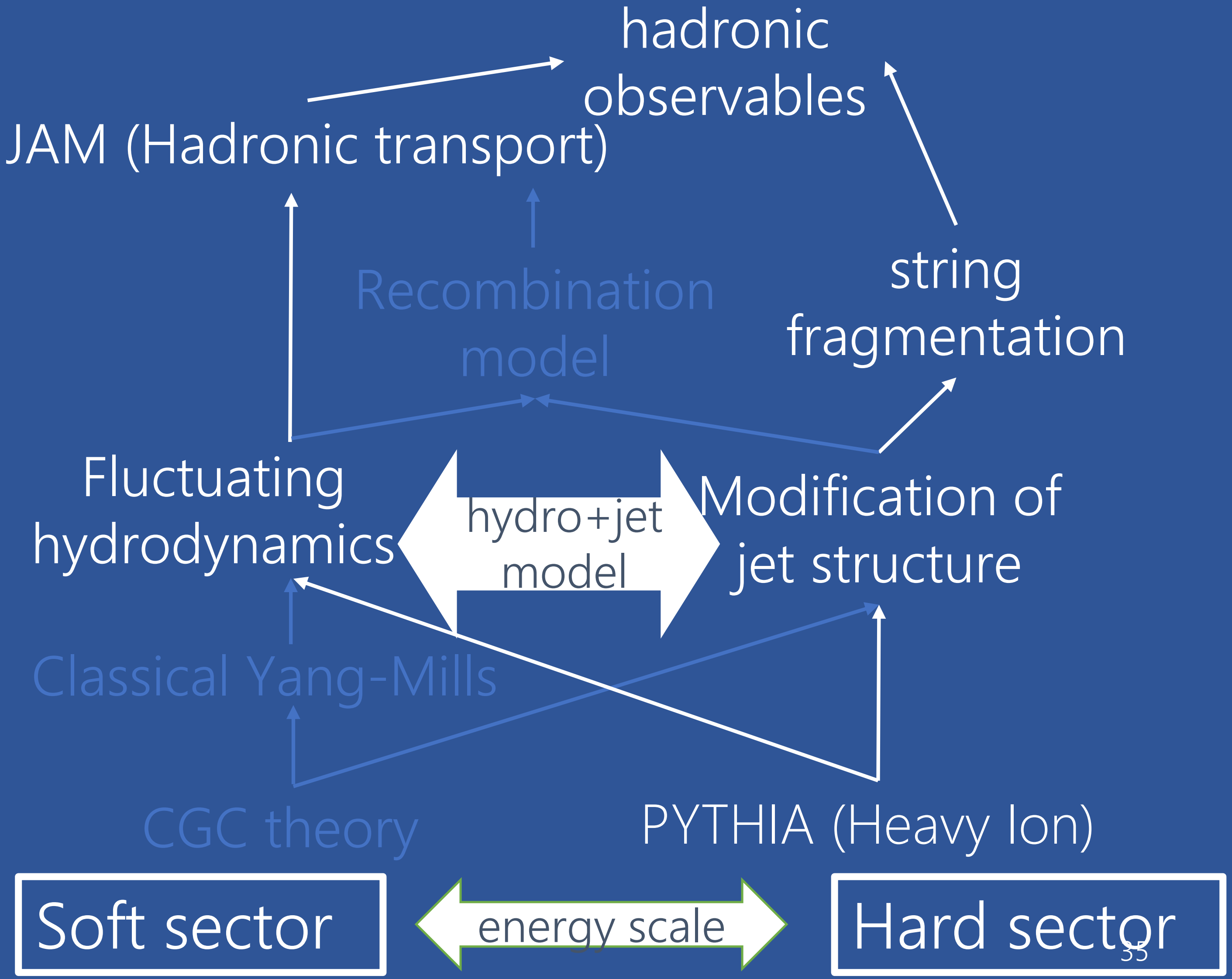
Opposite trends to exp. data

- Moderate enhancement in dynamical core-corona model
  ← similar ratios both in hydro and string fragmentation
- p-pbar annihilation at high multiplicity could resolve the discrepancy
  ← Need hadronic afterburner

Y.Kanakubo, K. Murase, Y. Tachibana, TH (work in progress)

Combination of model S and S-H





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