International Workshop on Forward Physics
and Forward Calorimeter Upgrade in ALICE
CCS, Tsukuba Univ., March 7-9, 2019

Integrated dynamical approach from small to large colliding systems

Tetsufumi Hirano (Sophia Univ.)

References:

TH *et al.*, Prog. Part. Nucl. Phys. **70**, 108 (2013).
Y.Tachibana, TH, Phys. Rev. C**90**, 021902 (2014); C93, 054907 (2016).
K.Murase, Ph.D thesis, the Univ. of Tokyo (2015).
S.Takeuchi *et al.*, Phys. Rev. C**92**, 044907 (2015).
M.Okai *et al.*, Phys. Rev. C**95**, 054914 (2017).
Y.Kanakubo *et al.*, PTEP **2018**, 121D01 (2018).
A.Sakai *et al.*, (in preparation)

Outline

- Introduction
  - Importance of dynamical modeling in high-energy nuclear collisions
  - Standard picture and dynamical modeling
  - Current situations in our group
- Recent analyses
  - Integrated dynamical approach to soft physics in heavy-ion collisions
    - Fluctuating hydrodynamics
    - Rapidity decorrelation from hydrodynamic fluctuations
  - From large to small colliding systems
    - Dynamical initialization with core-corona picture
    - Enhancement of multi-strange hadrons in small colliding systems
- Summary and outlook

Introduction

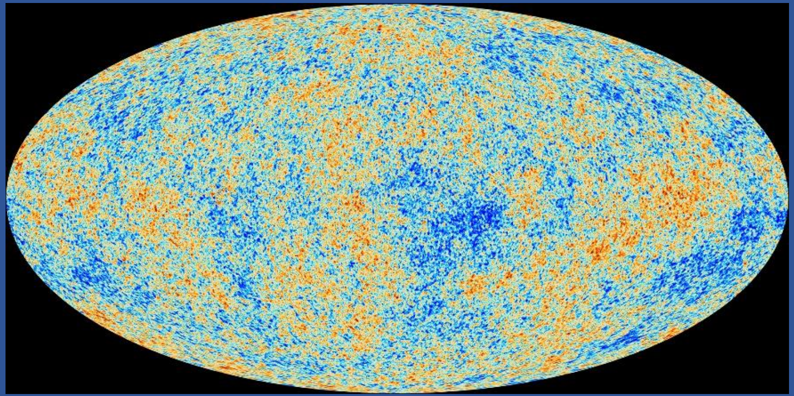
Towards understanding of

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

in high-energy nuclear collisions, "Standard Model" of dynamics is mandatory.

Analysis tool

Observational cosmology



Cosmic Microwave Background
Fluctuations of temperature （Planck）

CAMB, CMBFAST, CosmoMC,…

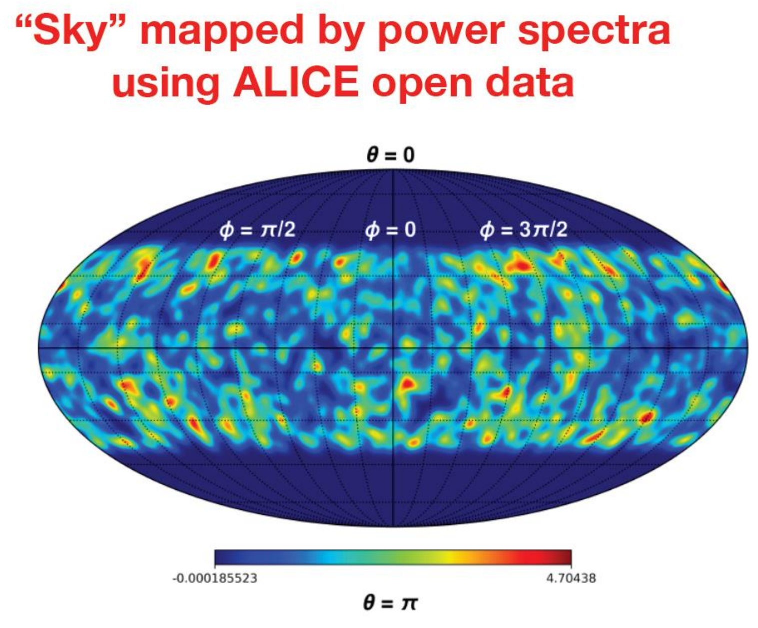
Cosmological parameters

- Energy budget
- Hubble constant (life time)
- Curvature (flatness)
- Information about inflation
- …

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

Analysis tool

Bottom-up approach in high-energy nuclear collisions



Y.Zhou, talk at QM2018

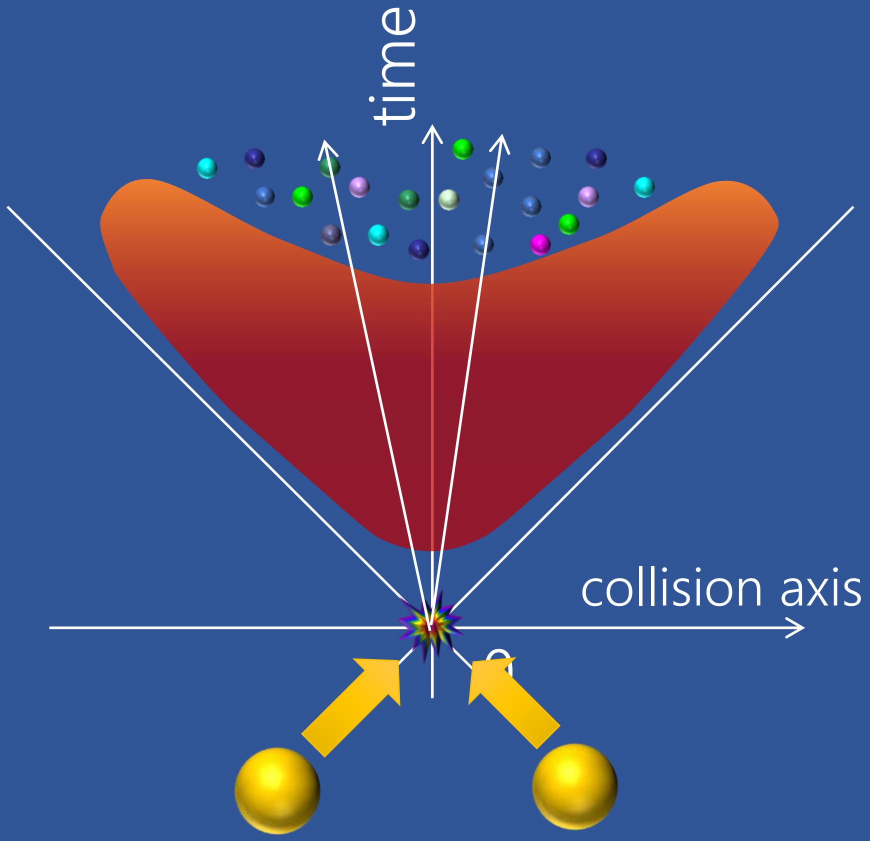
?

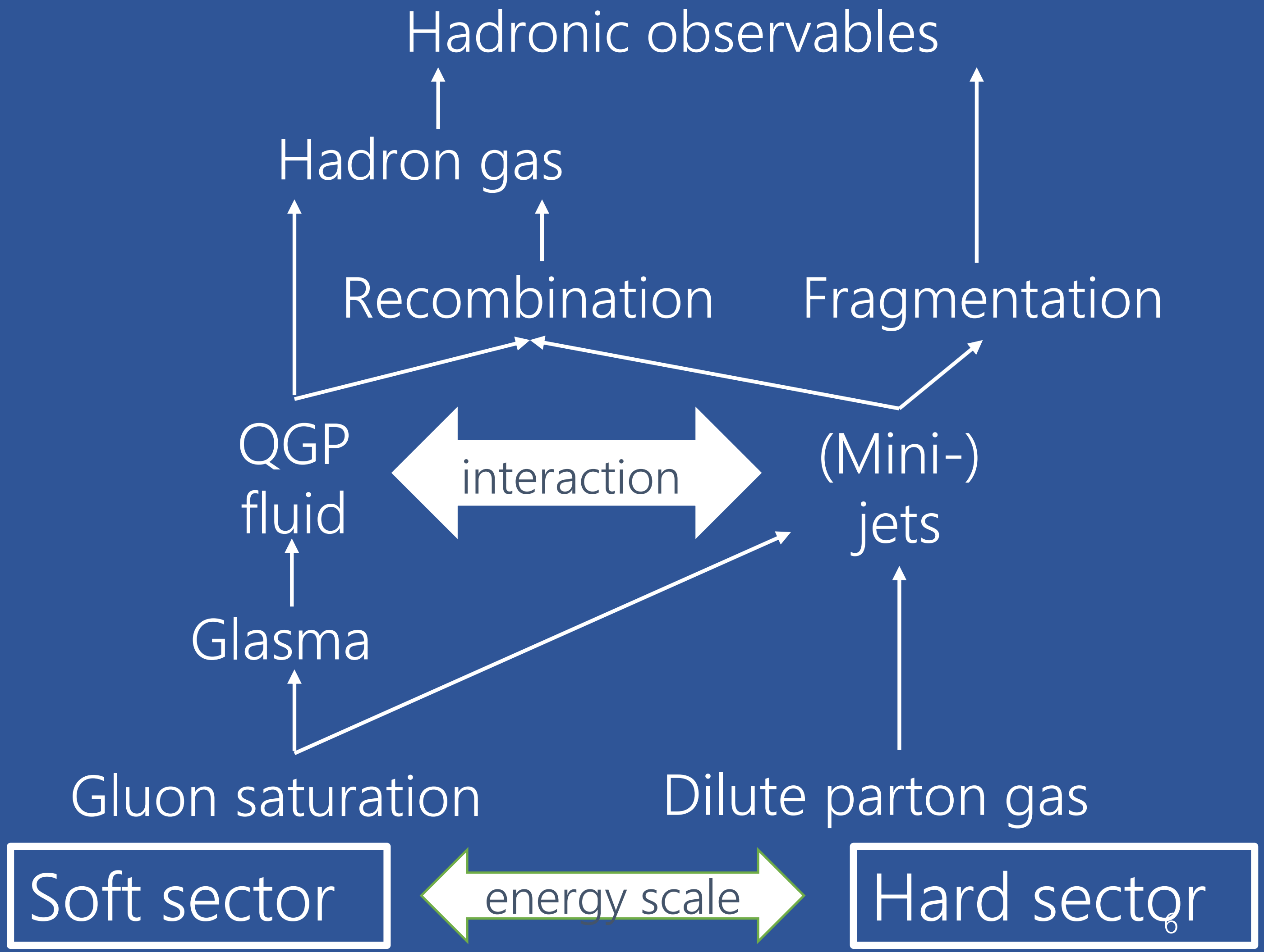
Physics properties of the QGP

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

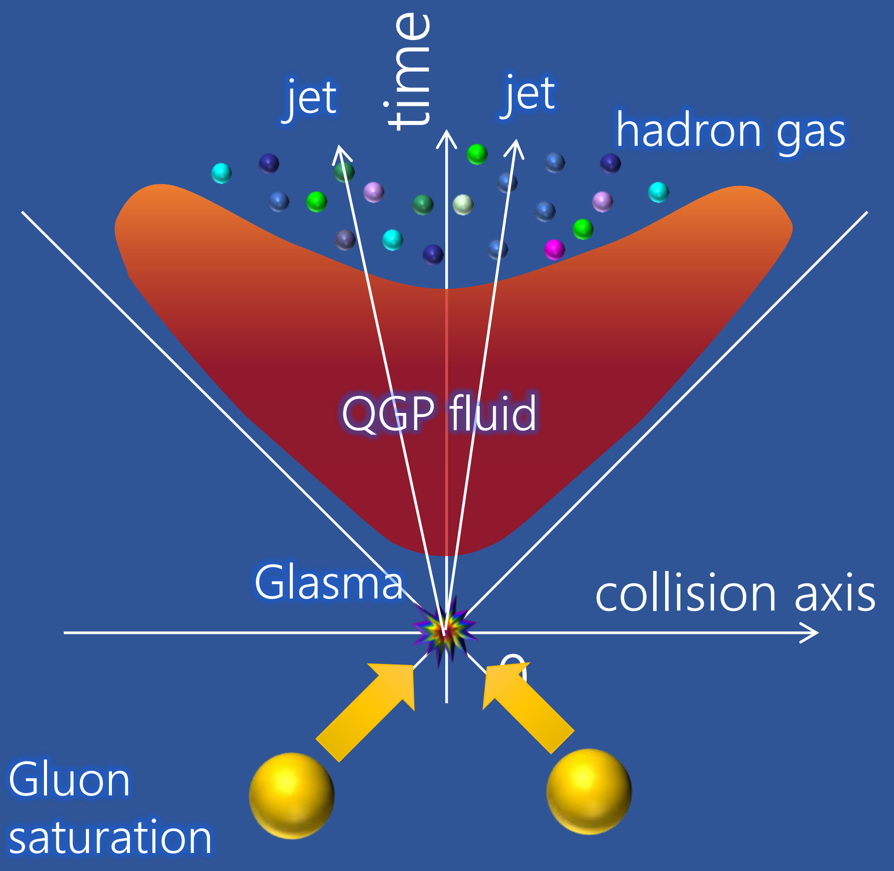
Need **Standard model/Analysis tool/Event generator** for high-energy nuclear collisions

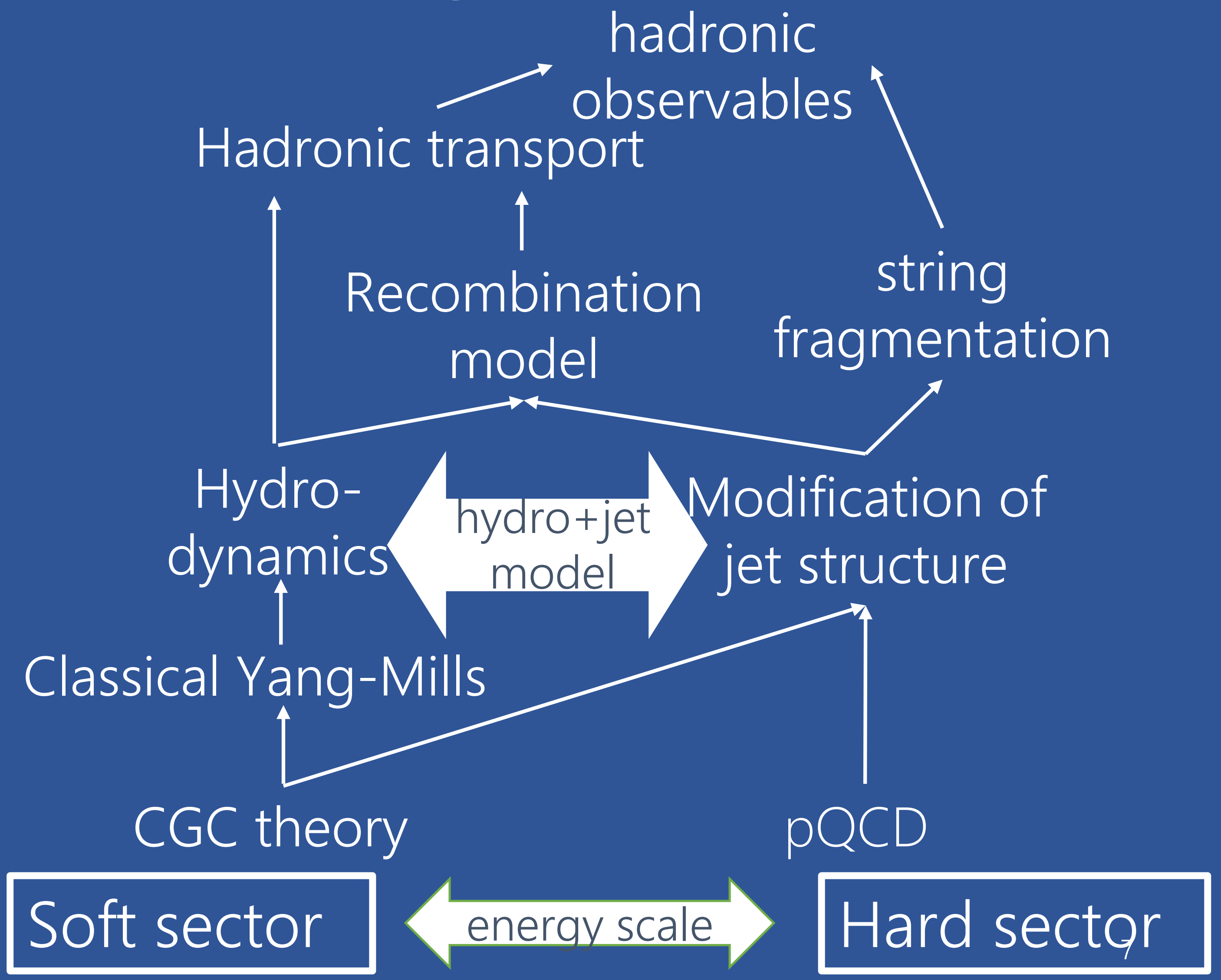
Standard picture of dynamics





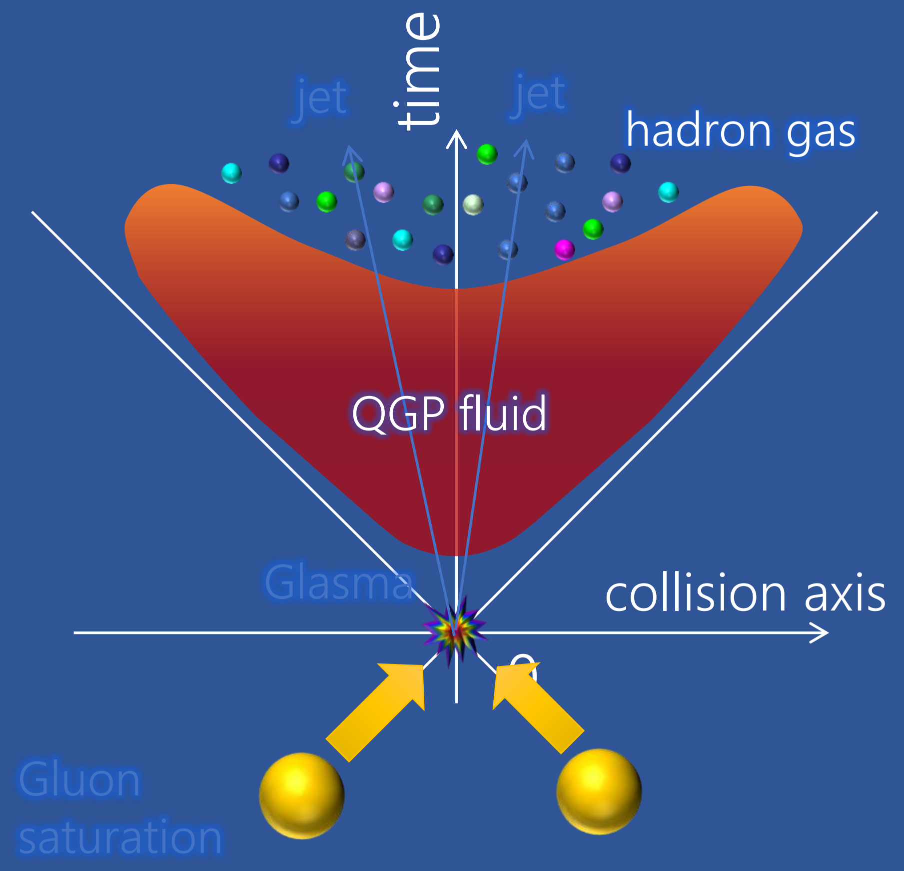
(Ideal?) Dynamical modeling

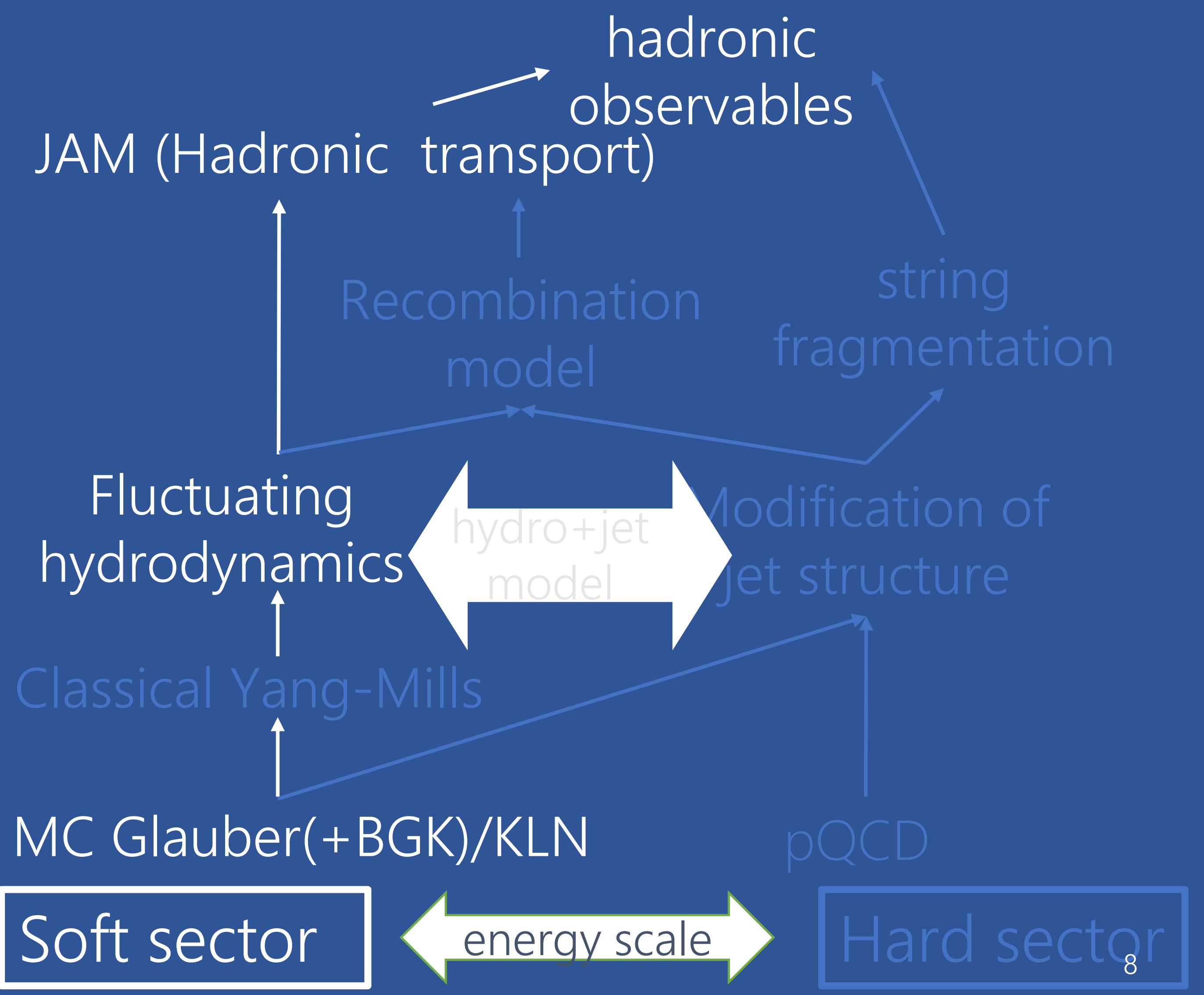




TH *et al.* (2013); K. Murase (2015); S.Takeuchi *et al.* (2015); A.Sakai *et al.*(2019).

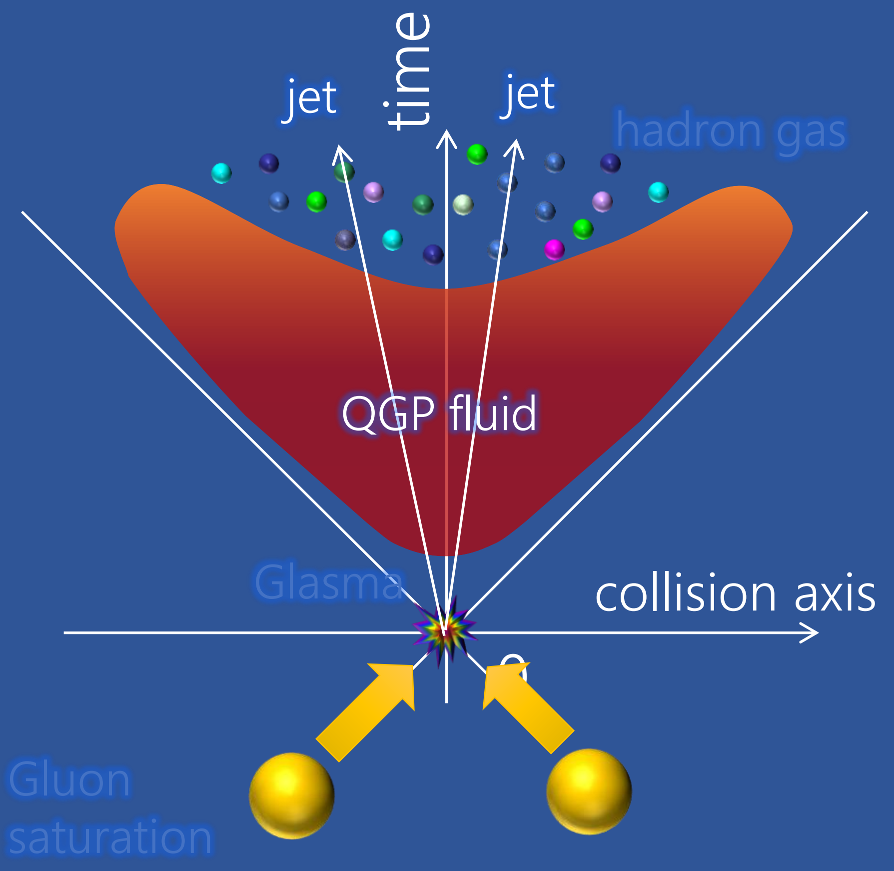
Our current situation (model S_{OFT})

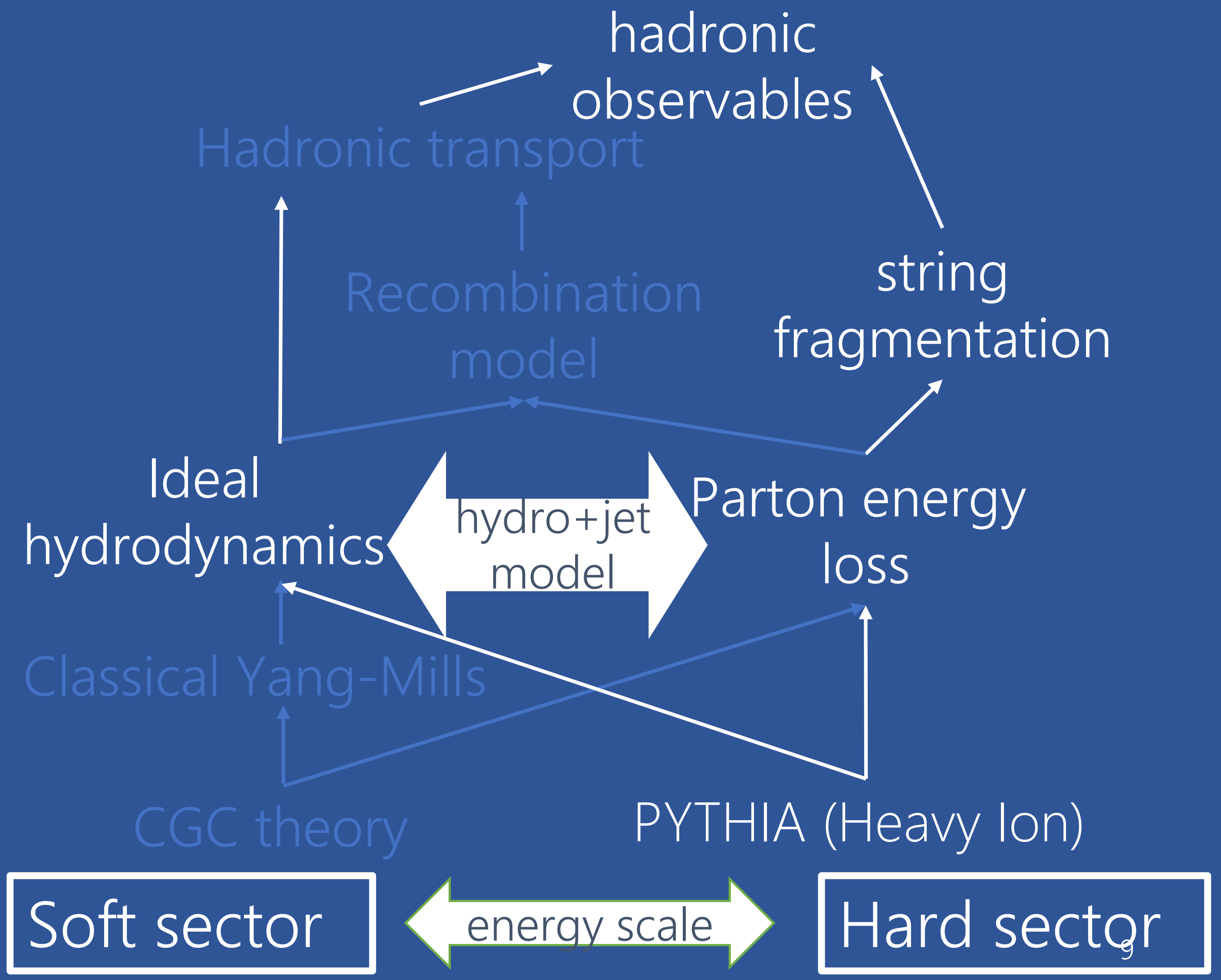




Y.Tachibana, TH, (2014, 2016); M.Okai *et al.*, (2017); Y.Kanakubo *et al.*, (2018).

Our current situation (model SOFT-HARD)

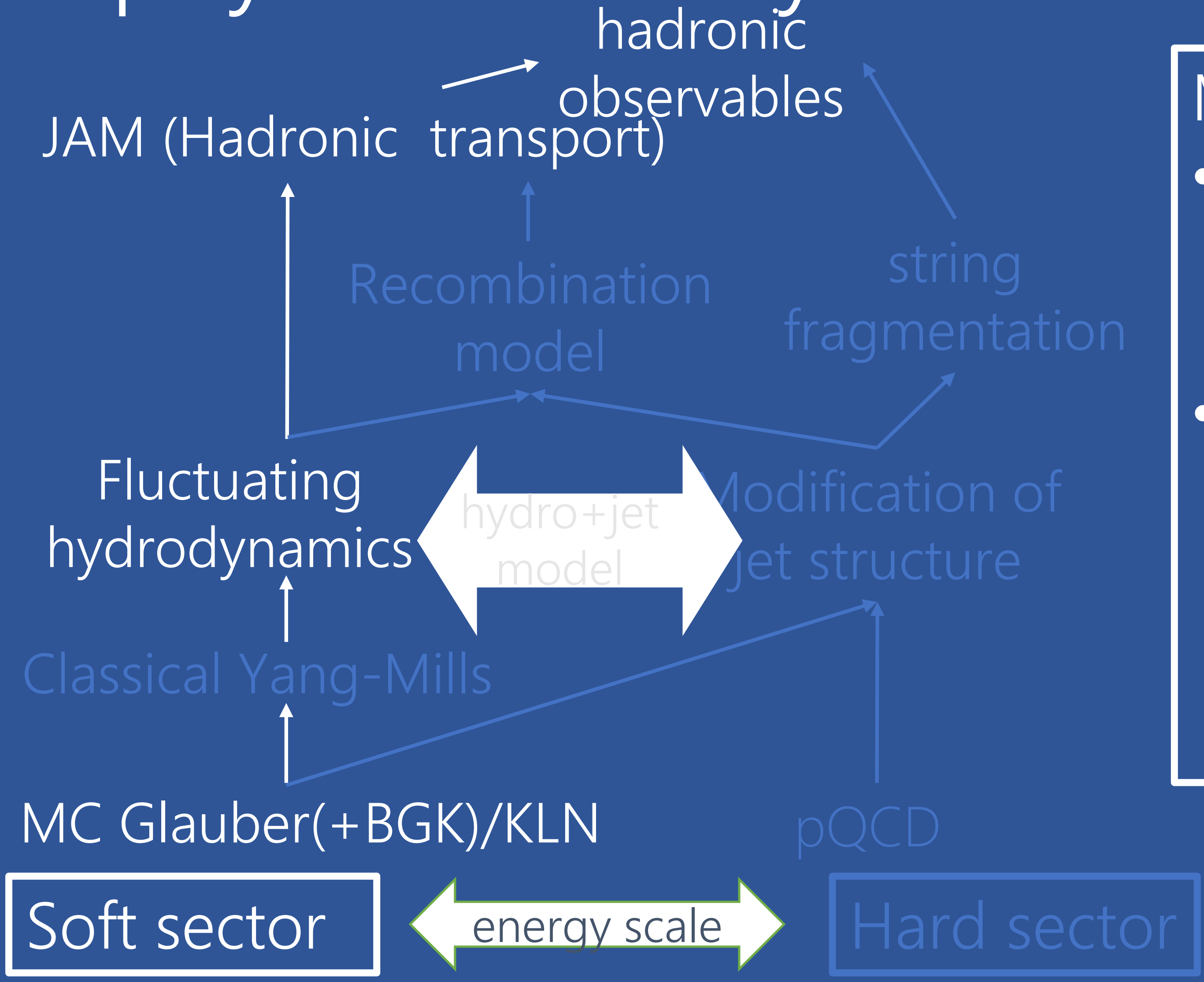




Recent analyses

Integrated dynamical approach to soft physics in heavy-ion collisions
From large to small colliding systems

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



Main purpose:

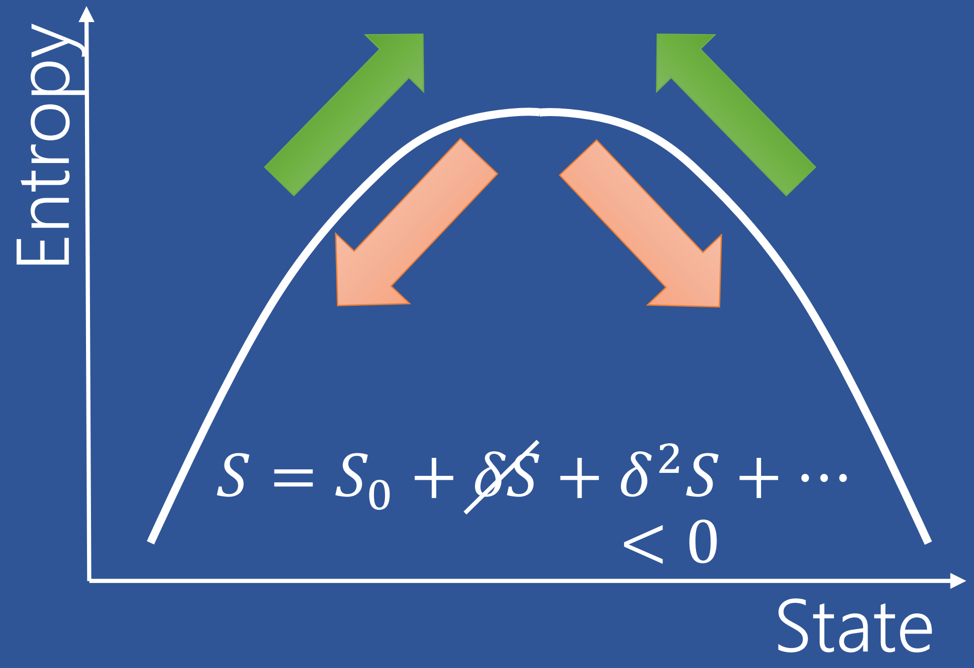
- Description of low p_T hadrons from soup to nuts in large colliding systems
- Investigation of hydrodynamic fluctuations on observable toward understanding of **initial conditions along rapidity** and transport properties

JAM: Y.Nara *et al.*, Phys. Rev. C**61** 024901 (2000)

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

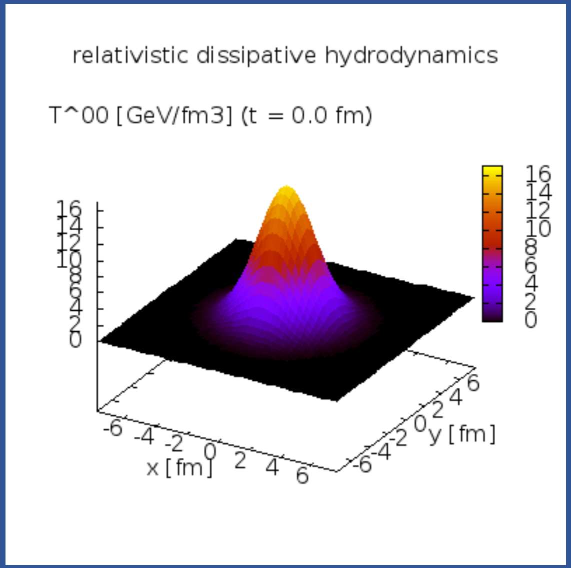


$$S = S_0 + \cancel{\delta S} + \delta^2 S + \cdots$$
$$< 0$$

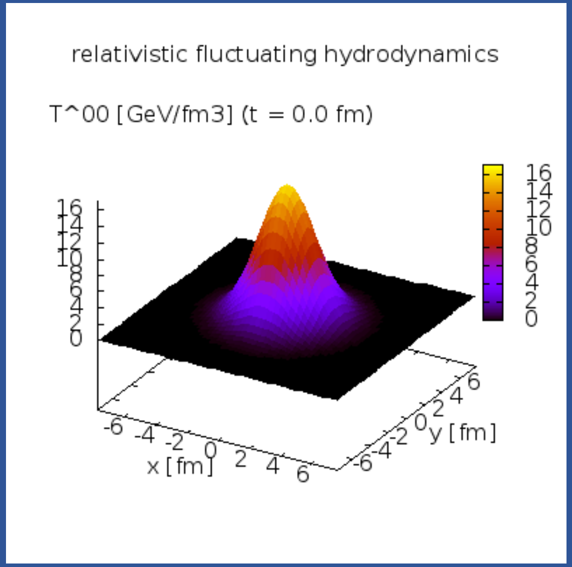
Fluctuations around maximum entropy state

QGP fluid simulation in a box

Courtesy of K.Murase



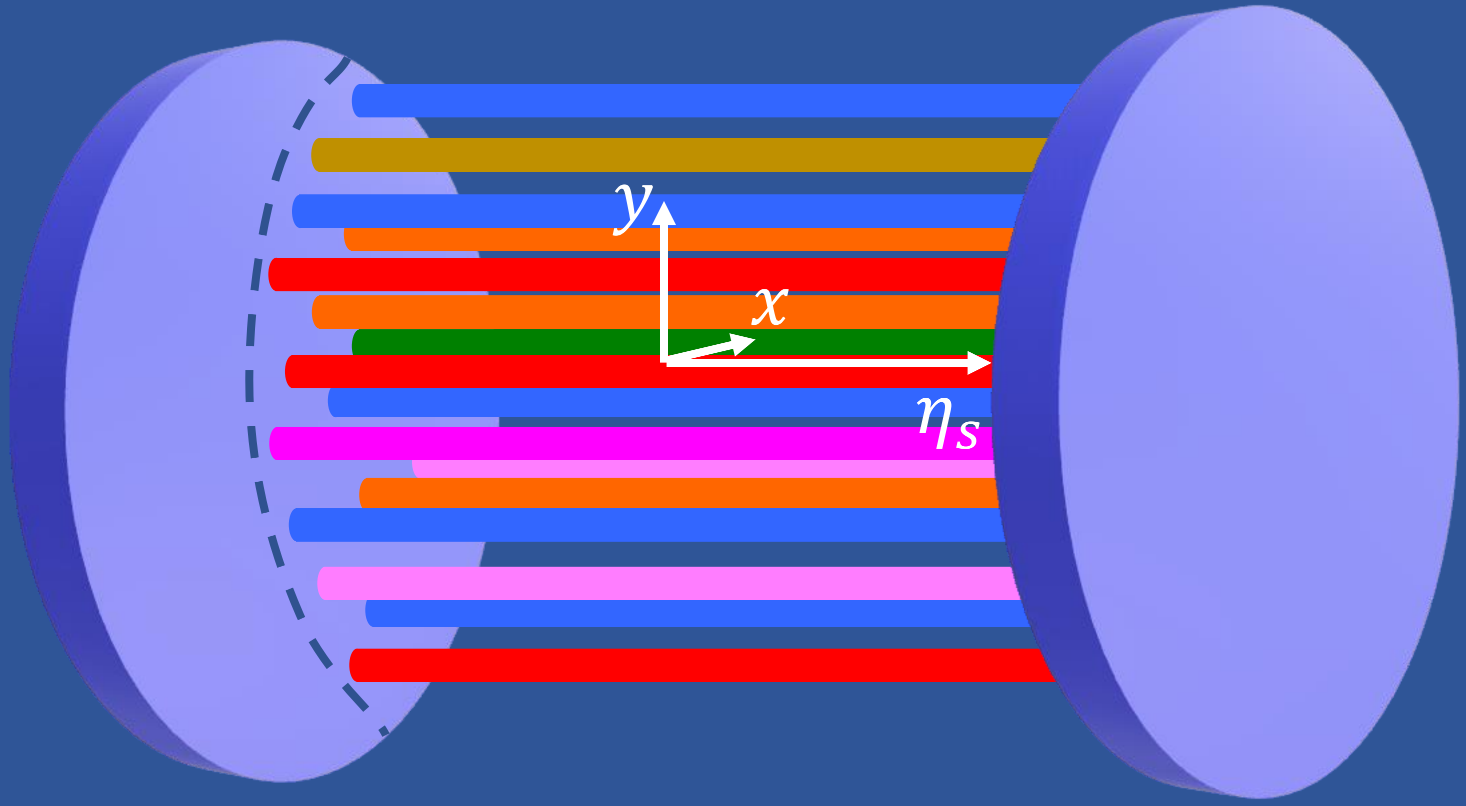
Dissipative hydro (2nd Generation)



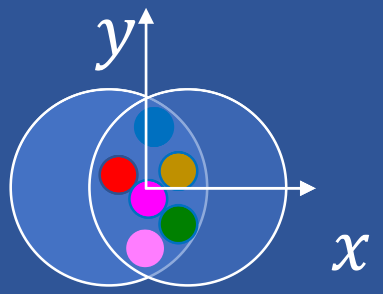
Fluctuating hydro (3rd Generation)

Dissipations ←→ Fluctuations

Correlations along collision axis



$\tau = 0^+$



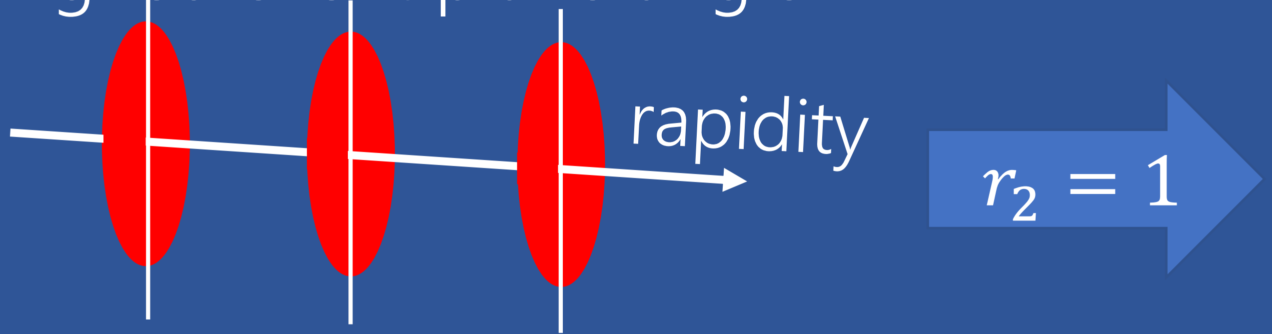
Heavy ion collision as a chromoelectric capacitor

→ Approximately boost-invariant formation of color flux tubes

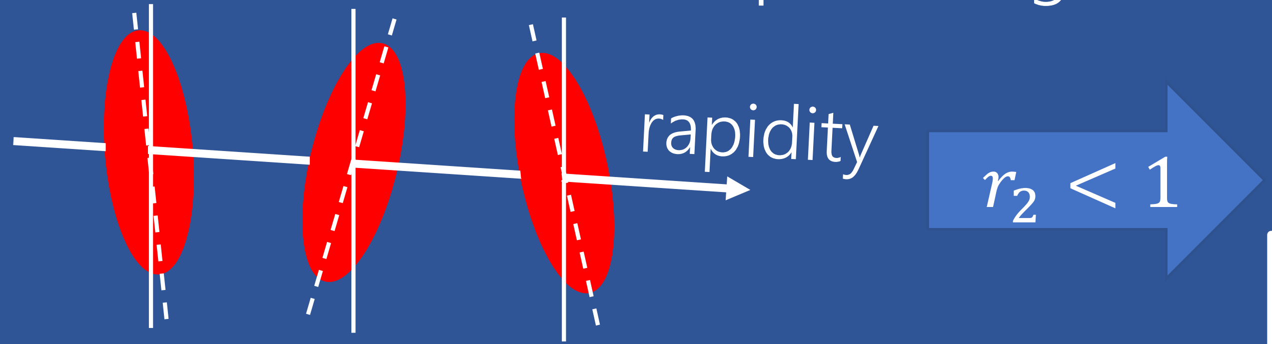
→ Correlation embedded in wide rapidity region

Decorrelation from initial conditions and hydrodynamic fluctuations

Aligned event plane angle



“Random walk” of event plane angle

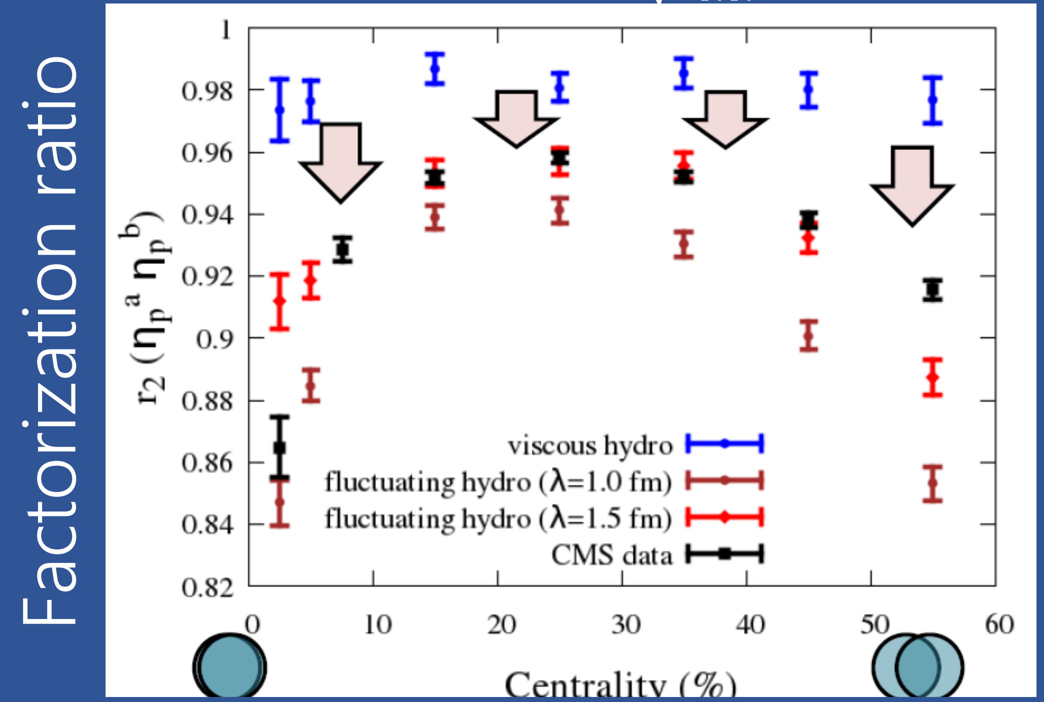


$-2.5 < \eta_p^a < -2.0$

$2.0 < \eta_p^a < 2.5$

$3.0 < \eta_p^b < 4.0$

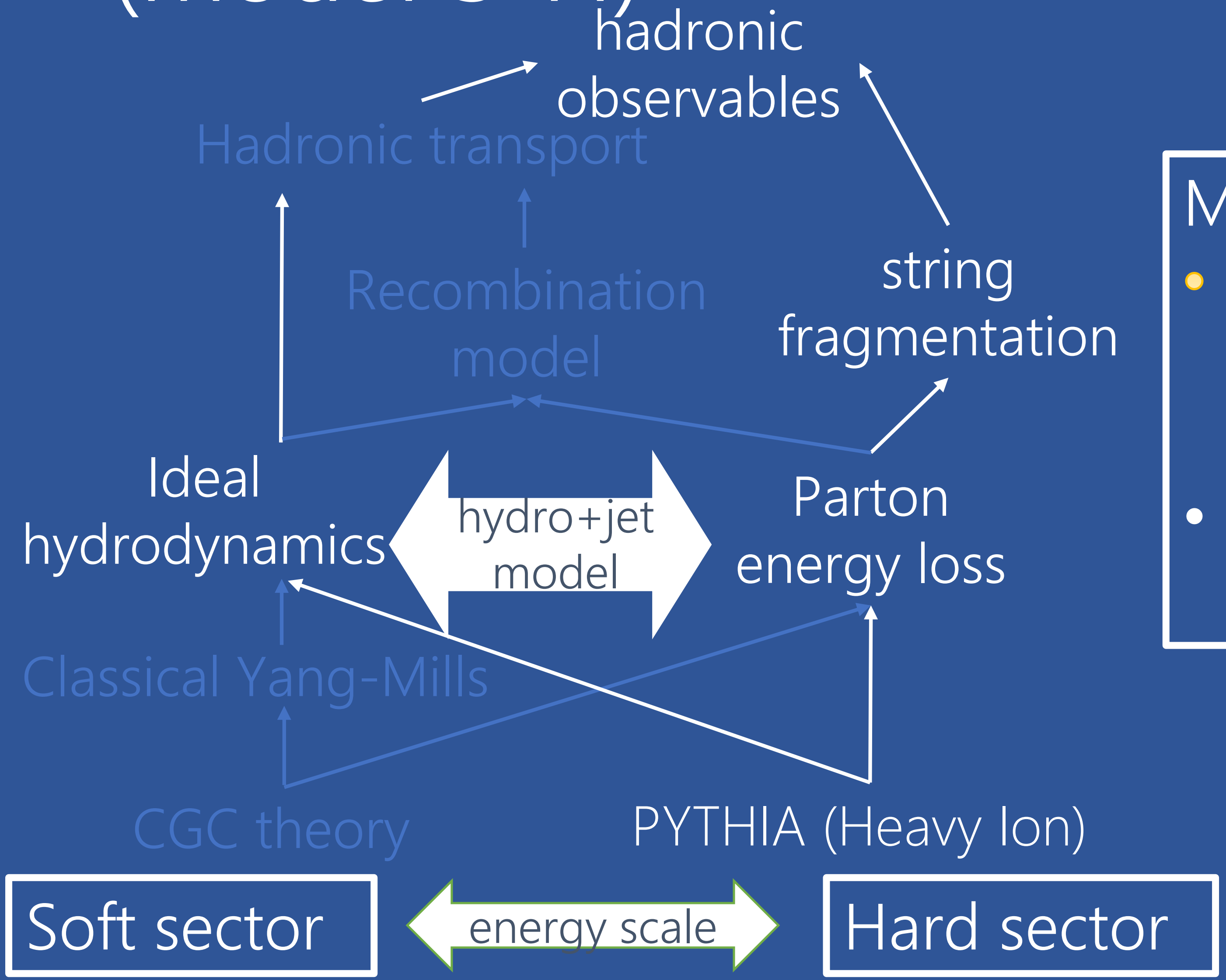
PbPb $\sqrt{s_{NN}} = 2.76$ TeV



A. Sakai, talk at QM2018

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

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



Main purpose:
- Universal initialization from small to large colliding systems
- Investigation of core-corona picture on bulk observables

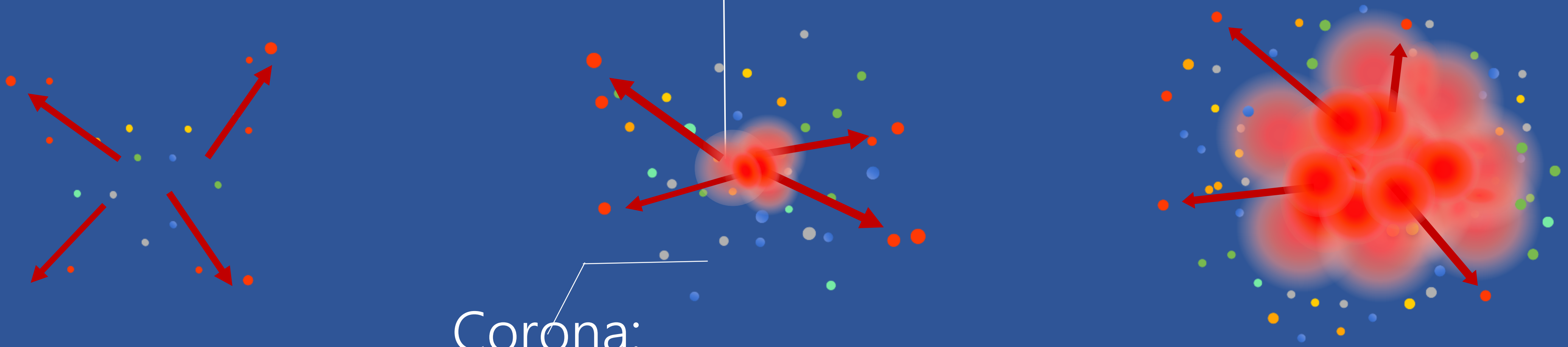
PYTHIA: T. Sjöstrand *et al.*,
Comput. Phys. Commun. **191**, 159 (2015).
*Heavy ion mode available from ver.8.230

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)

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

G : Gaussian smearing

p_i : Parton four momentum

$\boldsymbol{x}_i$: Parton position

Fluidization rate per particle Y.Kanakubo *et al.* (2018)

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

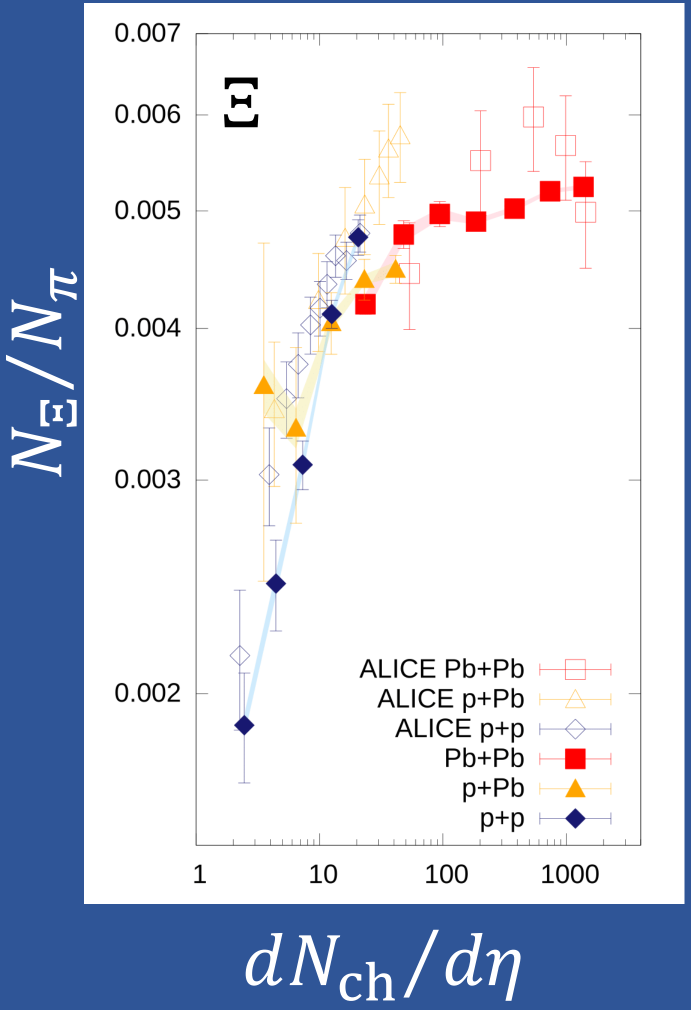
ρ_i : Parton density

a_0 : Control parameter

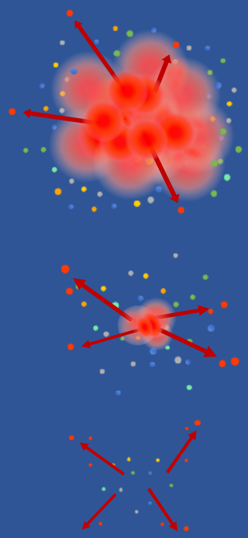
λ_i : Mean free path

Automatic separation between { core and corona / soft and hard }

Core-corona effects on ratio of cascades to pions



Y.Kanakubo *et al.*(2018)



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

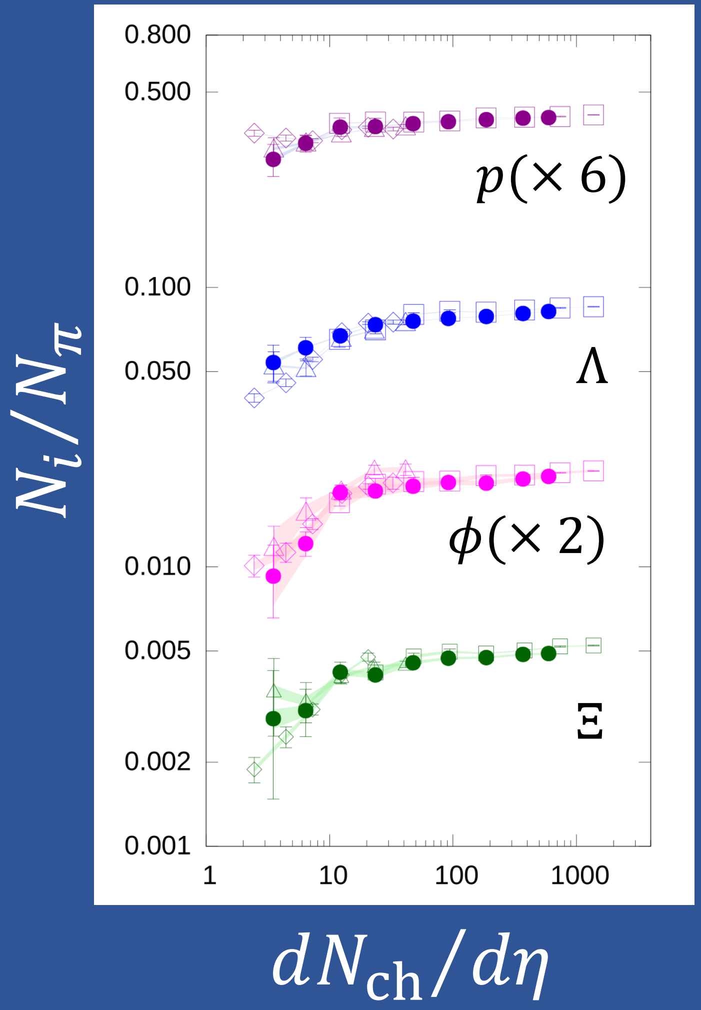
$\frac{dN_{\mathrm{ch}}}{d\eta} \gtrsim 100$ ⇒ QGP formation dominance

$\frac{dN_{\mathrm{ch}}}{d\eta} \lesssim 100$ ⇒ Partial creation of QGP

String fragmentation limit:
hadron production only from string fragmentation

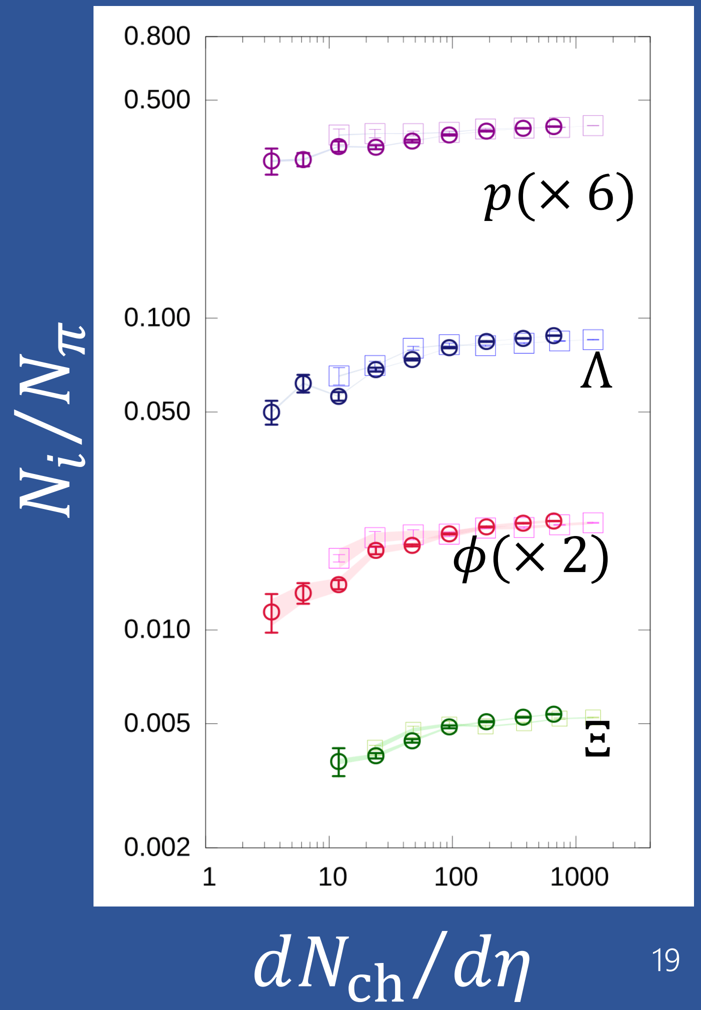
Size and collision energy dependence

XeXe (closed) vs.
pp, pPb and PbPb (open)



Almost no size or collision energy dependence
in dynamical core-corona model

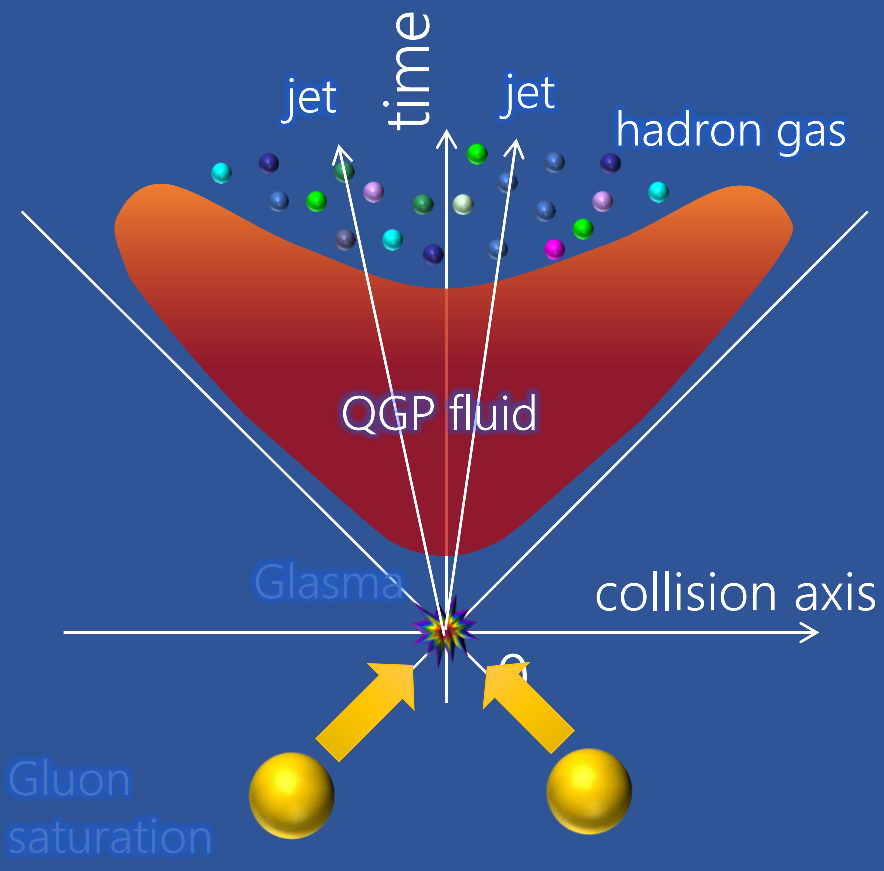
PbPb@2.76TeV (thin)
vs. AuAu@0.2TeV (thick)

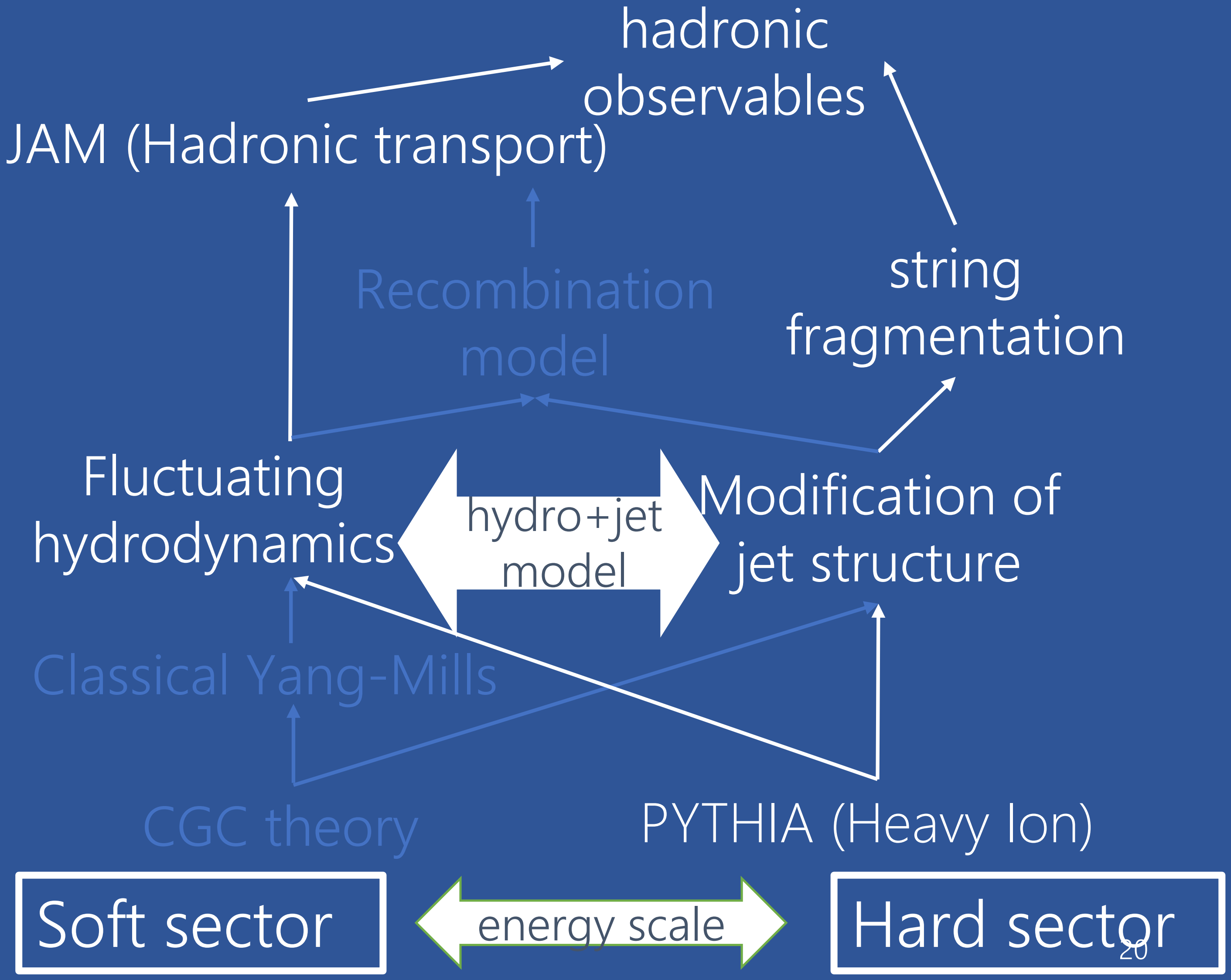


Y.Kanakubo *et al.* (in preparation)

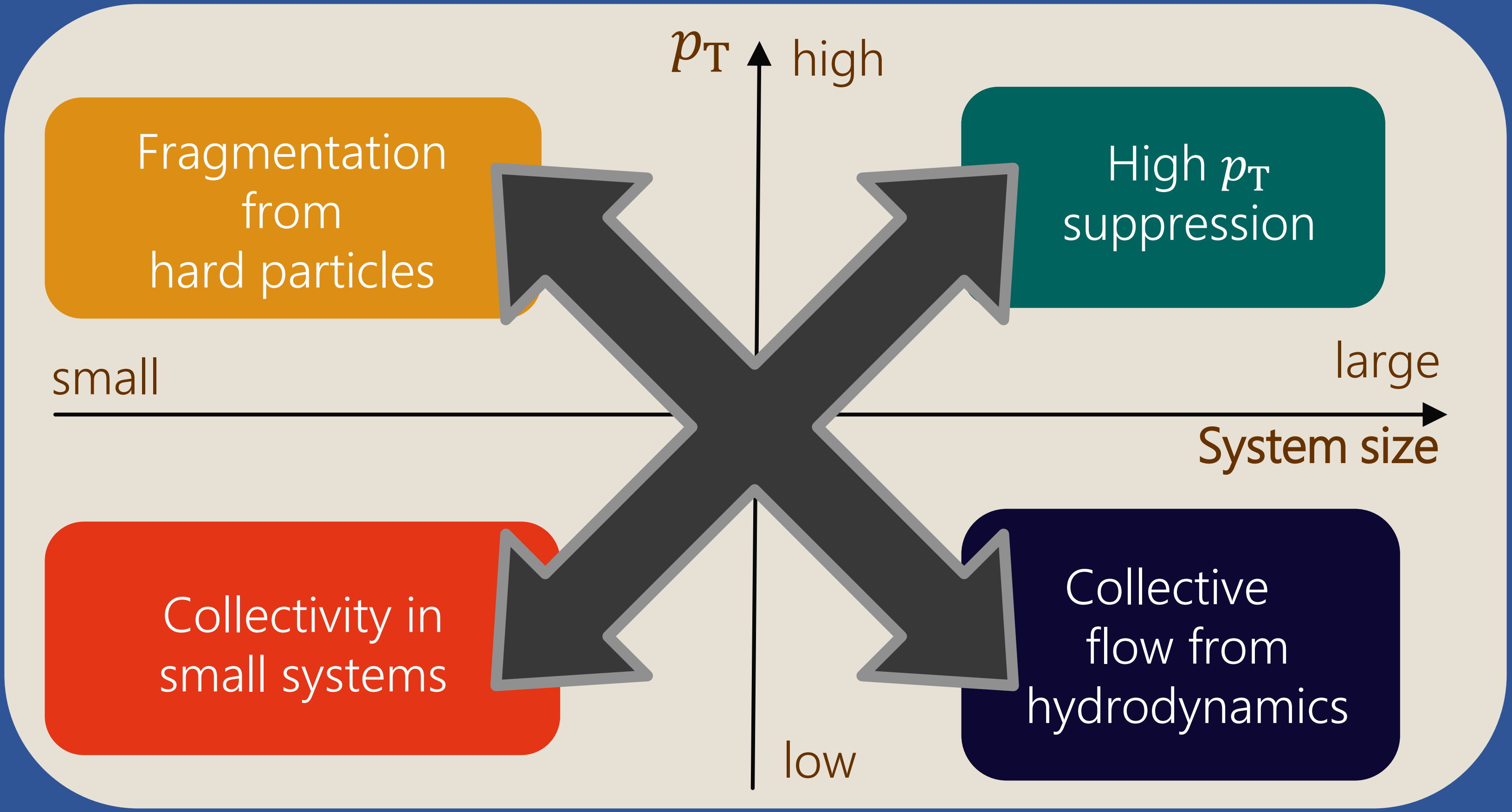
Y.Kanakubo, K. Murase, Y. Tachibana, TH (work in progress)

Combination of model S and S-H





Toward "Standard Model" from small to large colliding systems

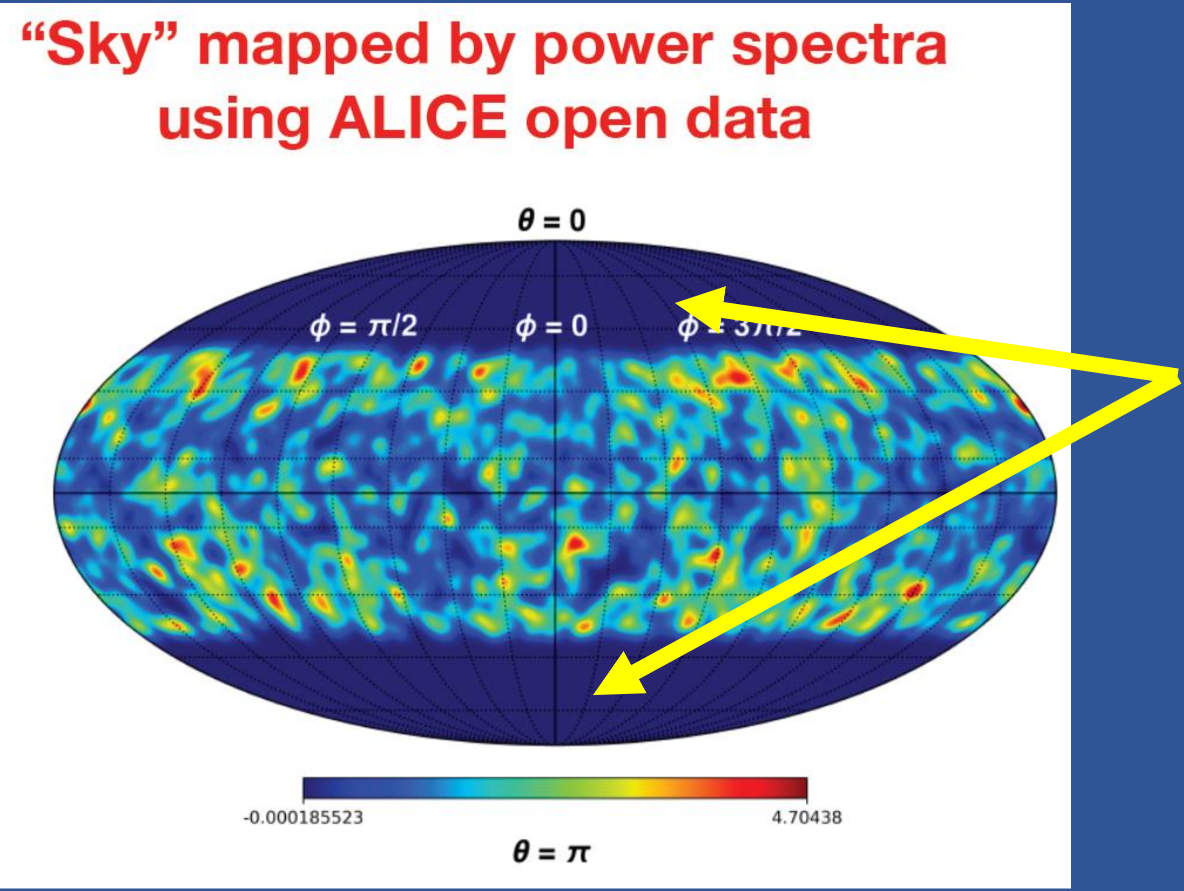


Summary and outlook

- Development of standard model for high-energy nuclear collisions from small to large colliding systems
- Current status
  - Rapidity decorrelation as a tool to investigate initial conditions in rapidity direction
  - Universal description of dynamics brought by dynamical core-corona initialization
- Check list for future dynamical model in backups

Backups

Expectation to LHC-ALICE experiment



Fill the blank
(forward/backword)
region?!

Check lists towards future dynamical model

- Initial conditions
- Hydrodynamics
- Hadronization and hadronic transport

Caveat:
All topics are IMHO.
Some topics include long-standing problem(s)

Initial conditions

- ✓ Event-by-event basis
- ✓ Full 3D (No boost invariance)
- ✓ Colliding energetic hadron/nuclei as "unified" parton distribution
  - Color glass condensate (small x)
  - Collinear PDF ($Q^2 \gg Q_s^2(x)$)
- ✓ Non-equilibrium evolution to hydrodynamic regime
- ✓ Definition of hydrodynamization rate?
- ✓ Energy-momentum conservation as a whole
- ✓ Separation between soft and hard

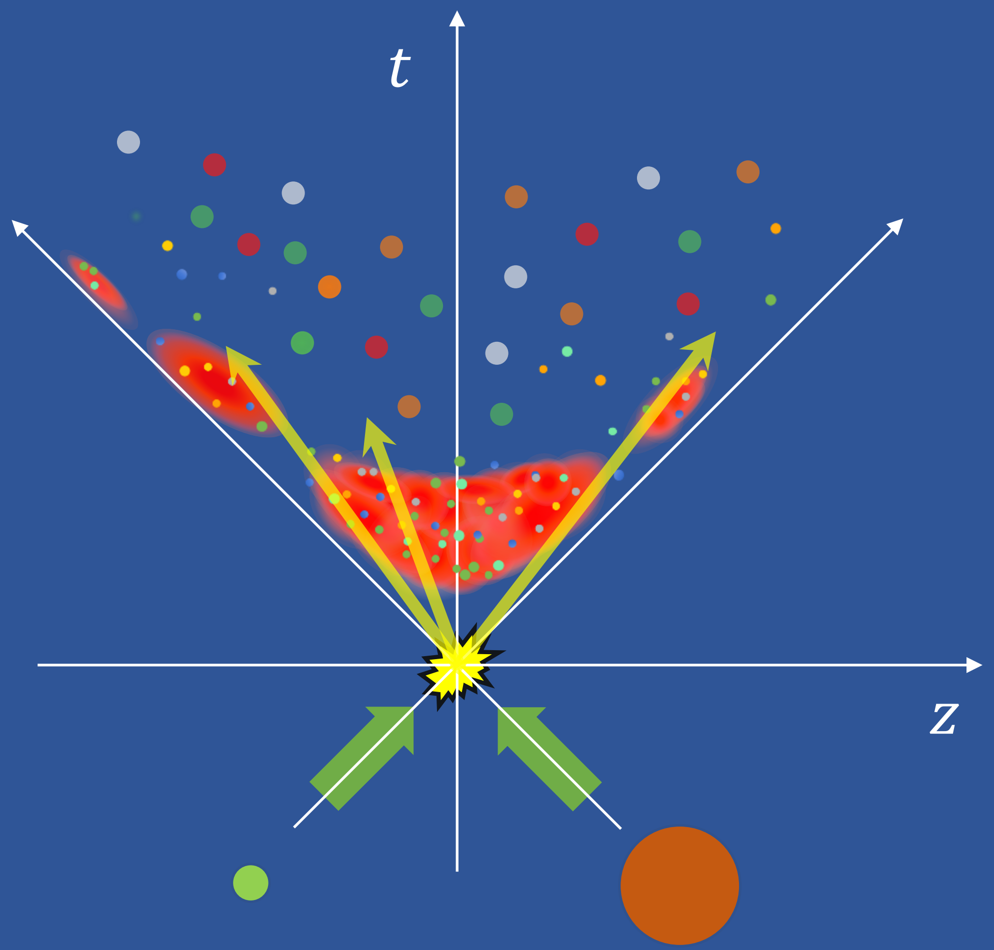
Hydrodynamics

- ✓ Full 3D (no boost invariance)
- ✓ Event-by-event basis
- ✓ (Hydrodynamic) Fluctuations and dissipations
- ✓ Dynamical initialization with core-corona separation
- ✓ Interface with jet physics
- ✓ Critical dynamics (n_B, σ)
- ✓ Equation of state
  - $N_f = 2 + 1$ or $2 + 1 + 1$ from lattice QCD
  - Finite μ_i $(i = B, S, I_3)$ (Caveat: Sign problem)
  - Critical point and first order phase transition (optional)

Hadronization and hadronic transport

- ✓ Development of a transport theory/model between hydrodynamics and Boltzmann eq.
- ✓ Interface with hydrodynamics
  ← Beyond Cooper-Frye prescription
  - Negative contribution
  ← Simultaneous simulation with hydro
- ✓ Energy-momentum conservation on event-by-event basis
- ✓ Hadronization between soft and hard

Model S-H



3. Hadronization

Core: Particlization through Cooper-Frye formula ($T_{\mathrm{sw}} = 170\ \mathrm{MeV}$) + correction factors for resonance decays

Corona: Lund string fragmentation (PYTHIA)

2. Dynamical initialization + fluid evolution

Y. Tachibana, TH, Phys. Rev. C **90**, no. 2, 021902 (2014).

M.Okai et al., Phys. Rev. C **95**, 054914 (2017).

+Core-corona picture

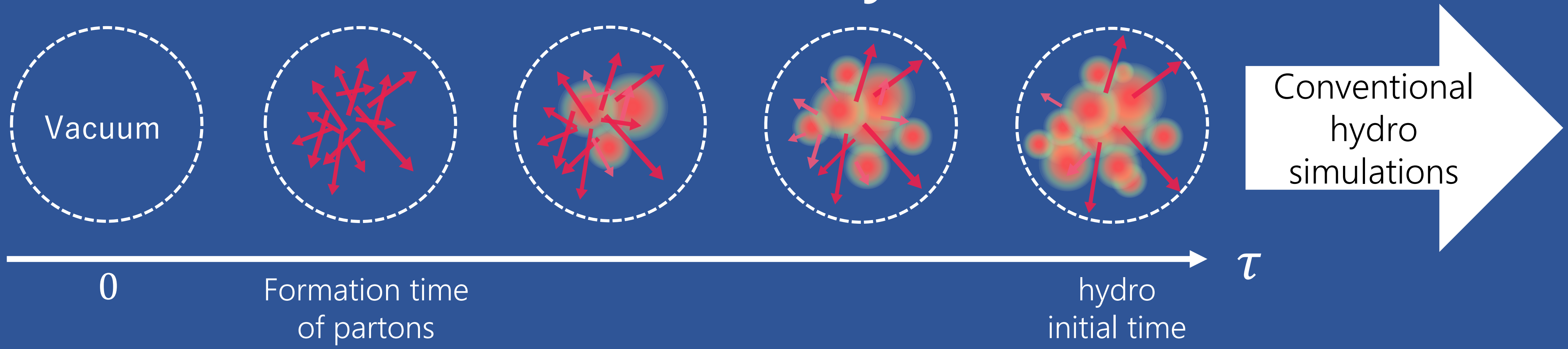
Y. Kanakubo et al., PTEP **2018**, 121D01

1. Initial parton generation → PYTHIA ver. 8.230

T. Sjöstrand et al., Comput. Phys. Commun. **191**, 159 (2015).

M.Okai, K.Kawaguchi, Y.Tachibana, TH (2017)

Dynamical initialization in hydro models



Fluids

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

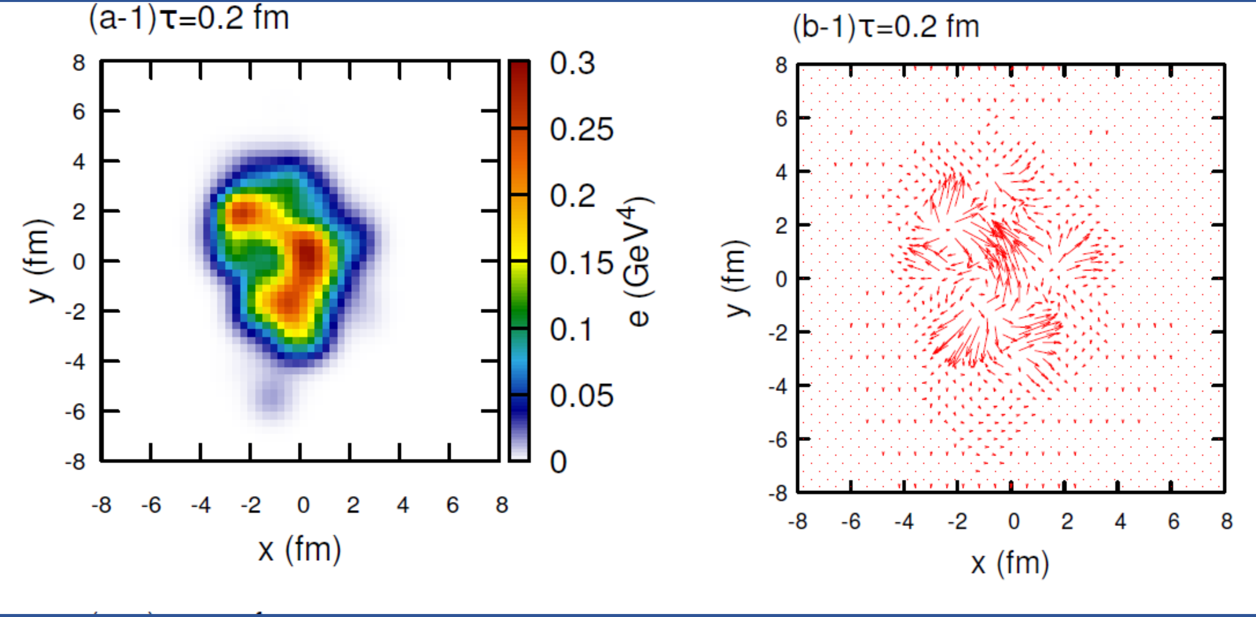
Partons

"Fluidization" through source terms

→ Energy-momentum conservation as a whole

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

⇩

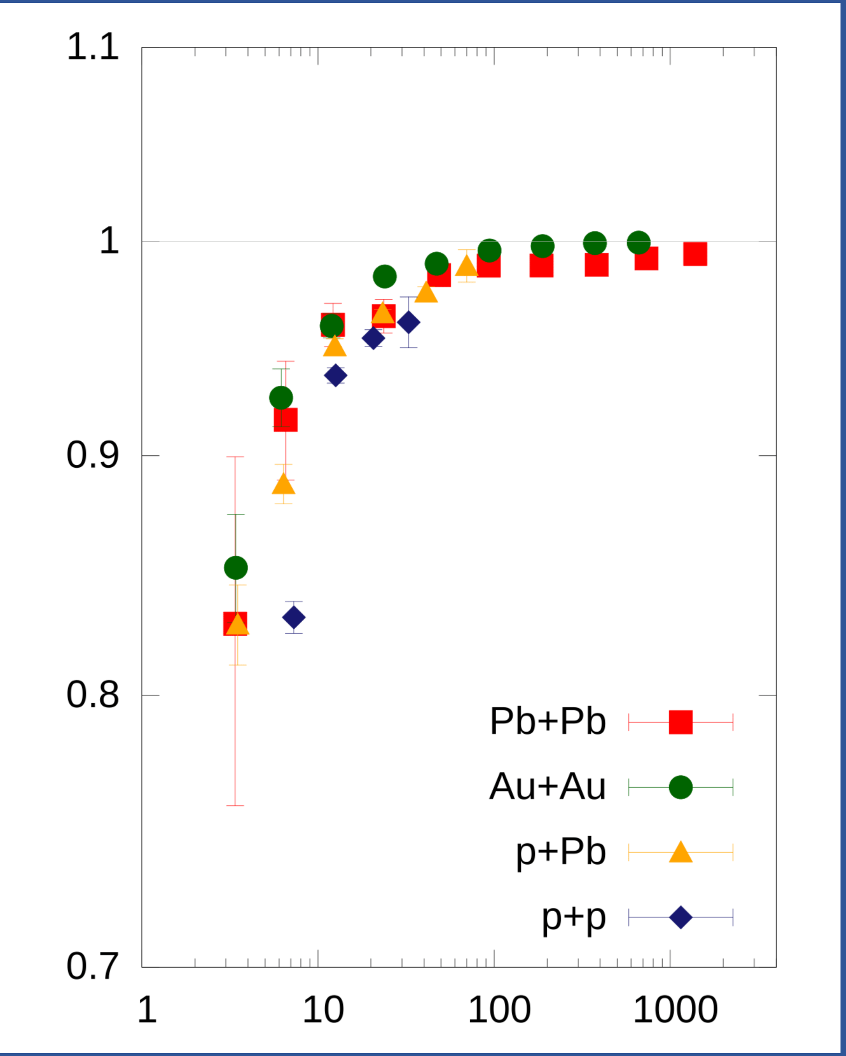
Initial random transverse flow velocity

⇩

Anisotropy interpreted from initial random (geometry+flow)

M.Okai (2018)

Fluidization rate



R

$dN_{\mathrm{ch}}/d\eta$

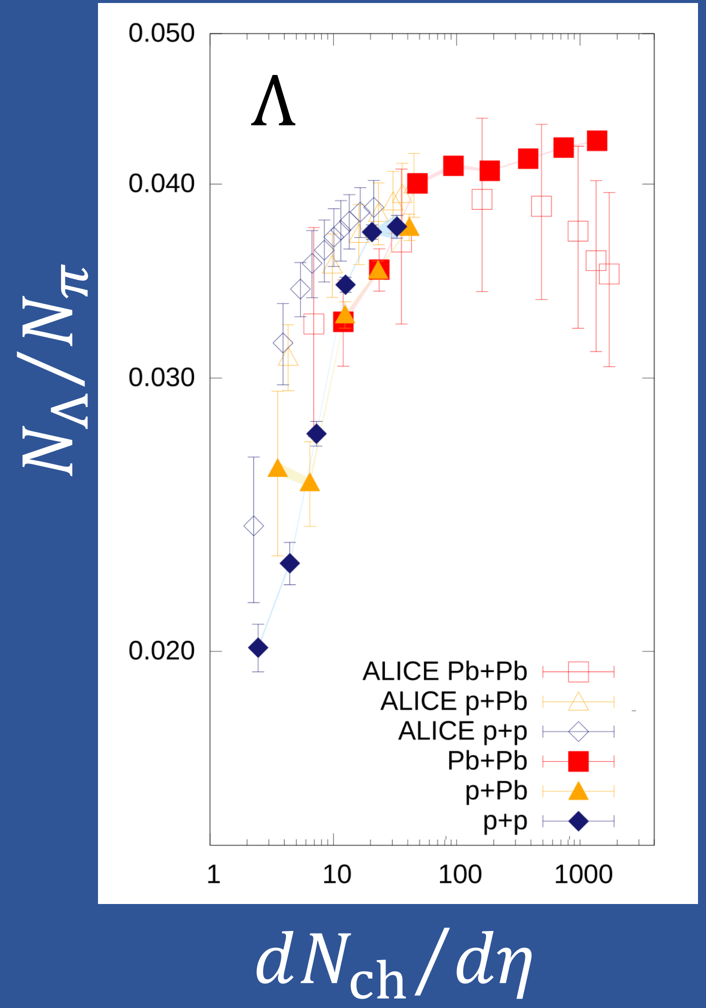
Core energy at midrapidity

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

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

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

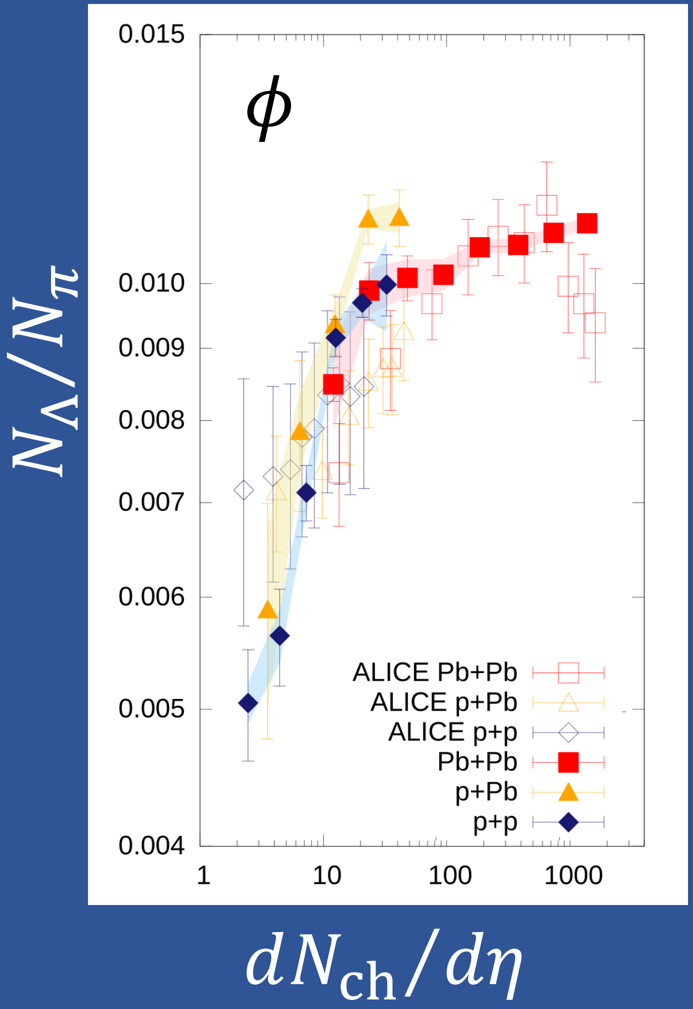
Lambdas ($|S| = 1$)



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

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

Phi mesons ($|S| = 0$)



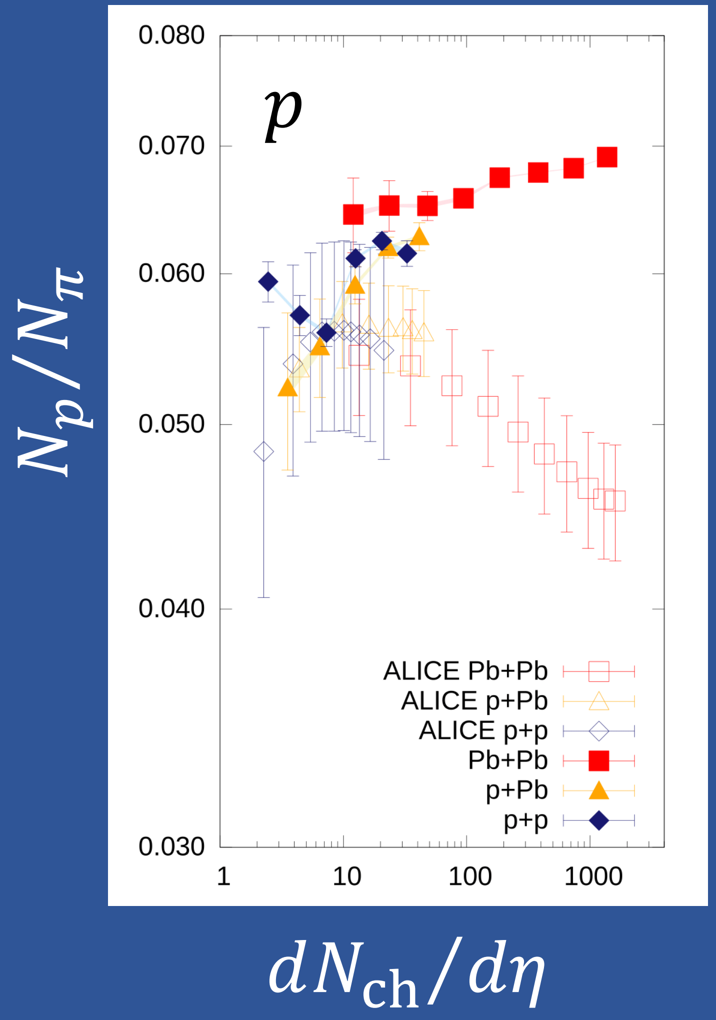
Similar trends to Lambda and Cascade
→ Enhancement of ratio with multiplicity even for $|S| = 0$

(*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