

ソフト、小さい系から

平野 哲文 (上智大学)



Disclaimer:

- 大きくバイアスのかかった選択
- 自分（のグループ）の研究に活かしたいネタ
- 選択されなかったトピック ≠ 重要でない

高エネルギー原子核衝突の潮流

発見ステージ ~2005

精密化, 新奇物理, ...

RHICにおけるQGP発見のステージ

エネルギーフロンティア

LHCの最高衝突エネルギーにおけるQGP物理

→ QGPの精密解析

小さい衝突系

LHCやRHICにおける集団的振る舞いの発見

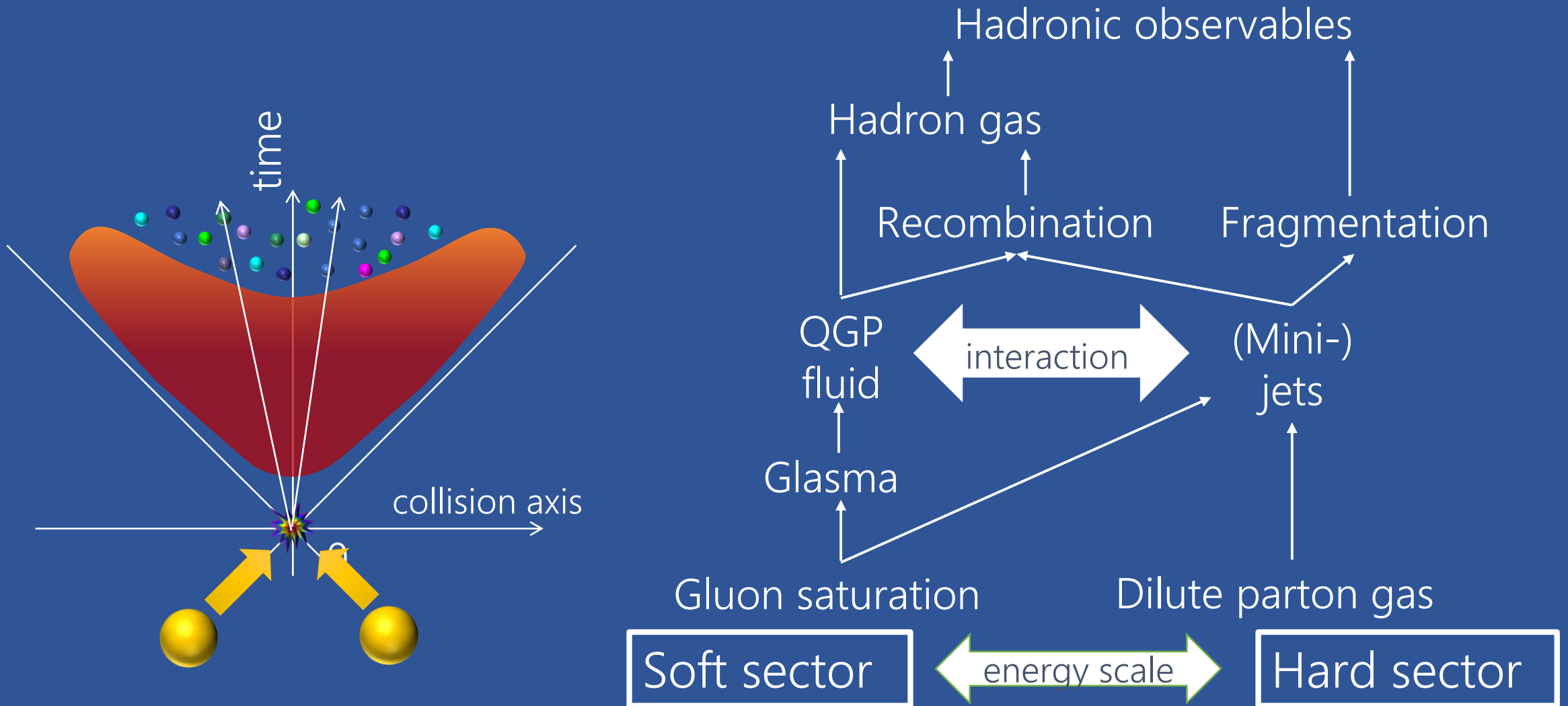
→ QGPはどれだけ小さくなれるか？

様々な衝突系

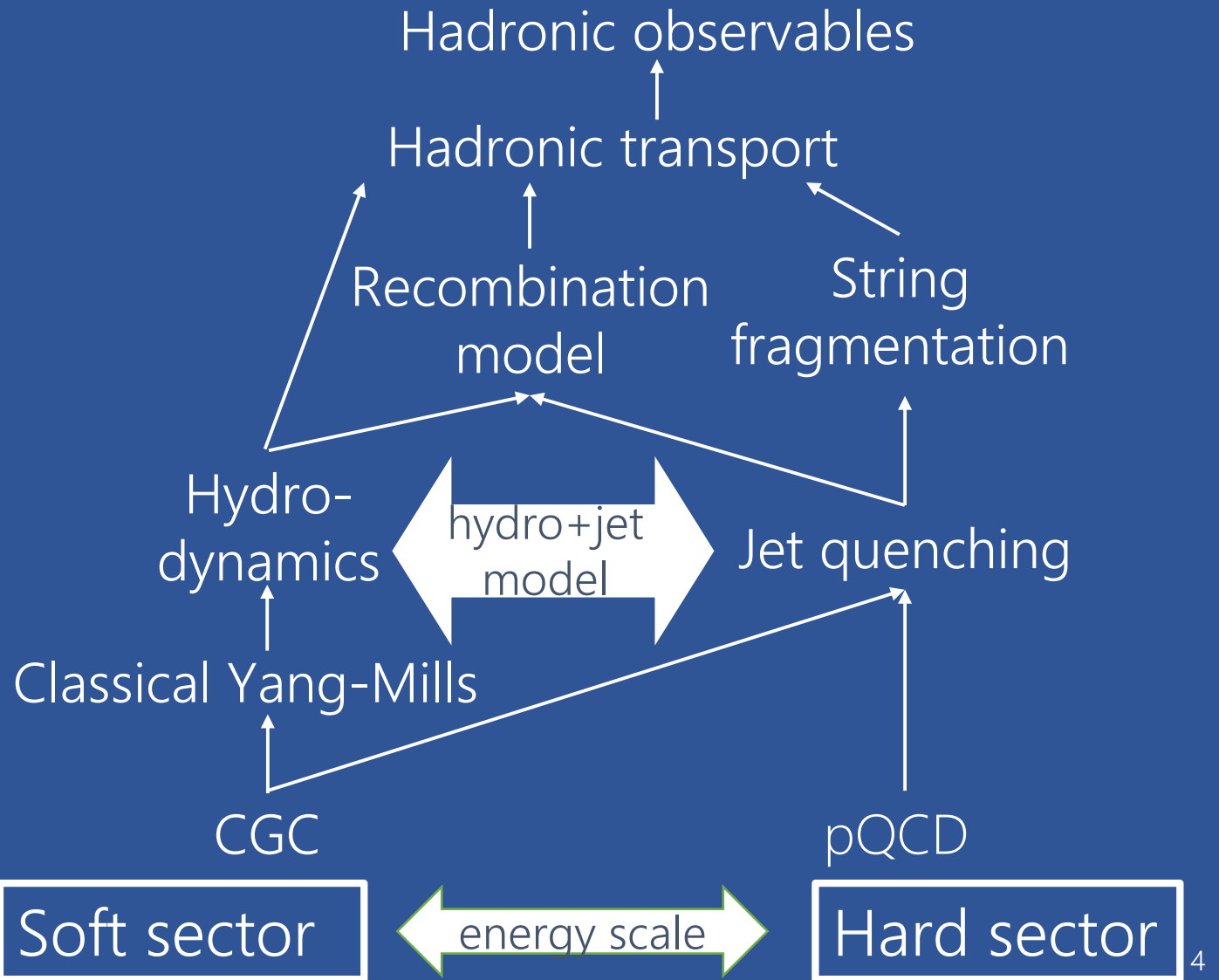
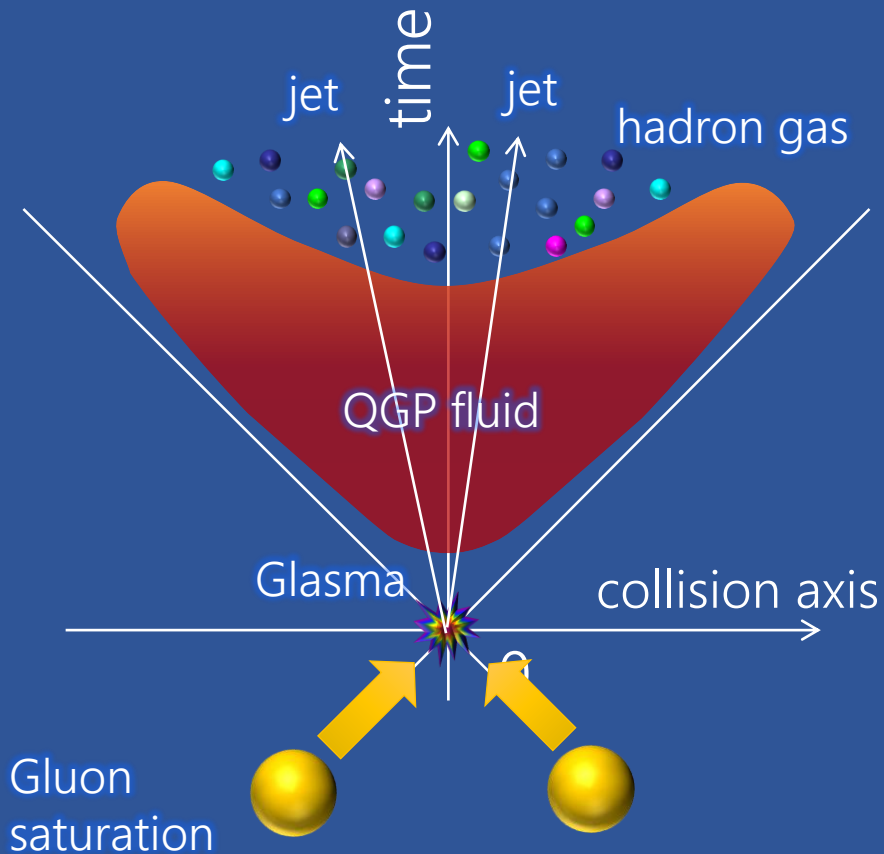
RHICビームエネルギースキャンプログラム(BES)

→ QGP生成のオンセット？
→ 超高密度物質の探究
(臨界点、相構造)

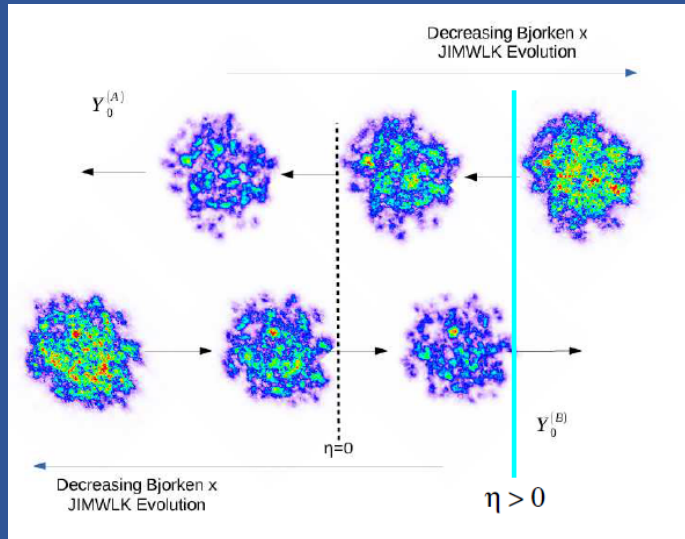
高エネルギー原子核衝突のダイナミクス



モデリングの一例

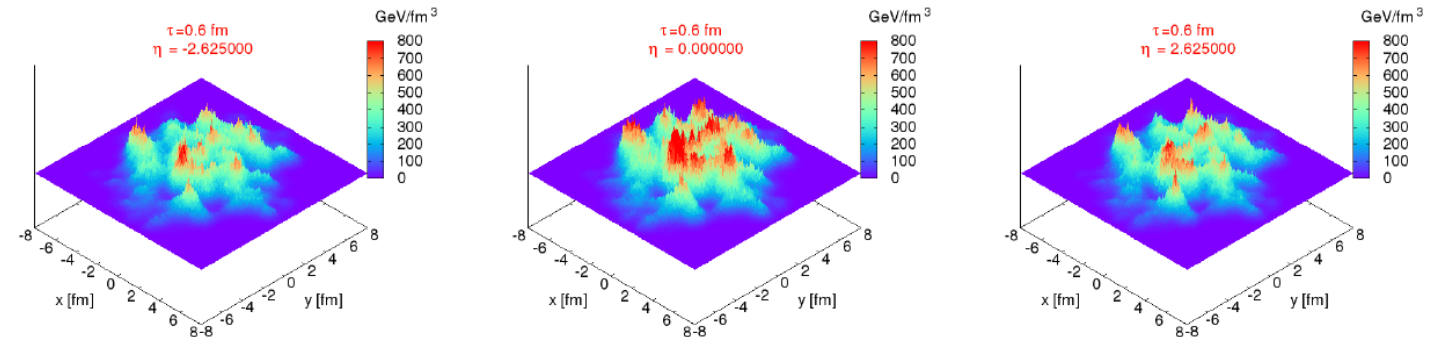


(Almost) full 3D Classical Yang-Mills



Energy density evolution

S.Jeon



- $\sqrt{s_{NN}} = 2.76 \text{ TeV}$
- This is within the “plateau”
- $\tau = 0.6 \text{ fm}$: Energy density reasonable for hydro
- Decorrelation visible

JIMWLKの初期条件
 $y = \pm 4.25$

See also, B.Schenke and S.Schlichting
PRC94, 044907(2019)



Jeon (McGill)

3D IP-Glasma

13/20

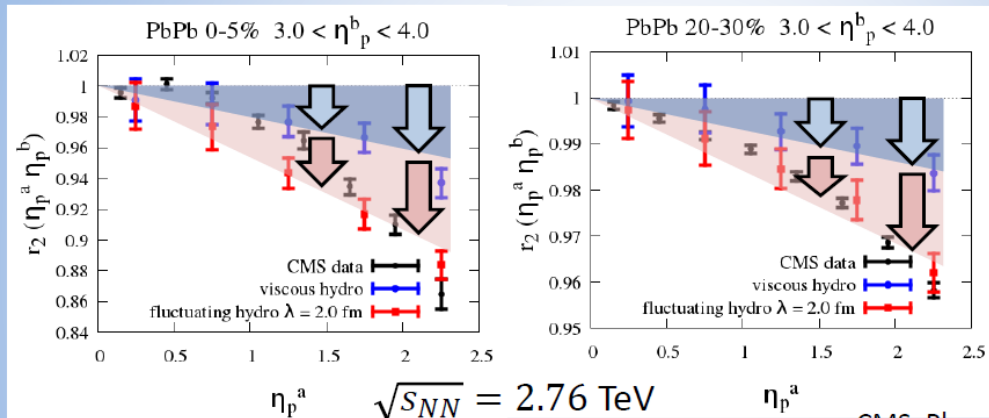
初めての3D IP-Glasma + MUSIC + UrQMD計算
→ ソフトでは現状の最高到達点か？

縦ダイナミクスにおける流体揺らぎの影響

Factorization ratio $r_2(\eta_p^a, \eta_p^b)$

A.Sakai

with initial longitudinal fluctuations

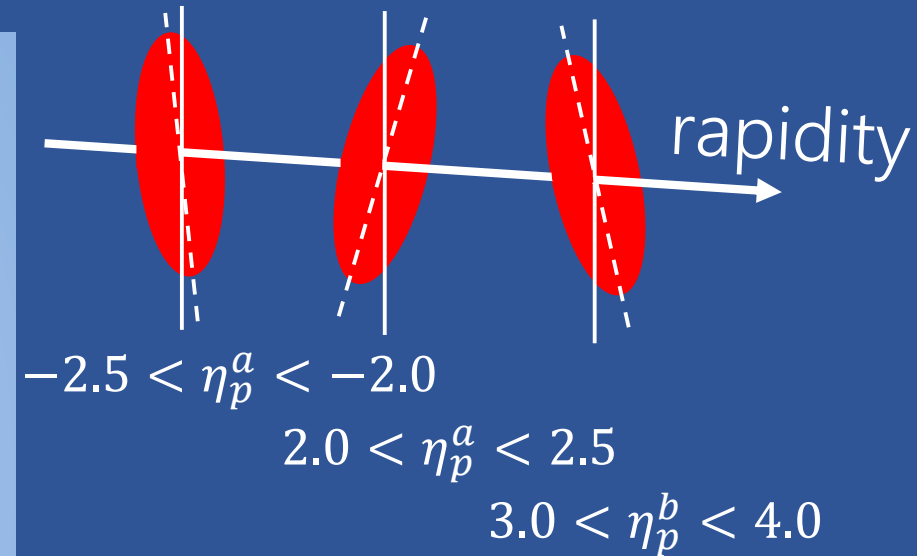


Initial longitudinal fluctuations
Hydrodynamic fluctuations

CMS, Phys. Rev. C 92, 034911 (2015).

$1 > \text{Viscous} > \text{CMS data} \approx \text{Fluctuating hydro}$

Initial longitudinal fluctuations → Rapidity decorrelation
Hydrodynamic fluctuations + Initial longitudinal fluctuations → Close to experimental data



- 衝突反応を3次元的に精査
- 流体揺らぎの重要性を観測量を通して初めて定量的に示唆

縦方向における初期形状と終期フローの関係

Key steps to find the matrix form of hydro longitudinal response

[Hui Li, LY, 1907.10854]

1. Start with relation inspired by linear response:

$$V_2(\zeta) = \int d\xi G(\zeta - \xi) \mathcal{E}_2(\xi)$$

* ξ : space-time rapidity * ζ : pseudorapidity

2. Expand the response function in long-wavelength, or small wave number k

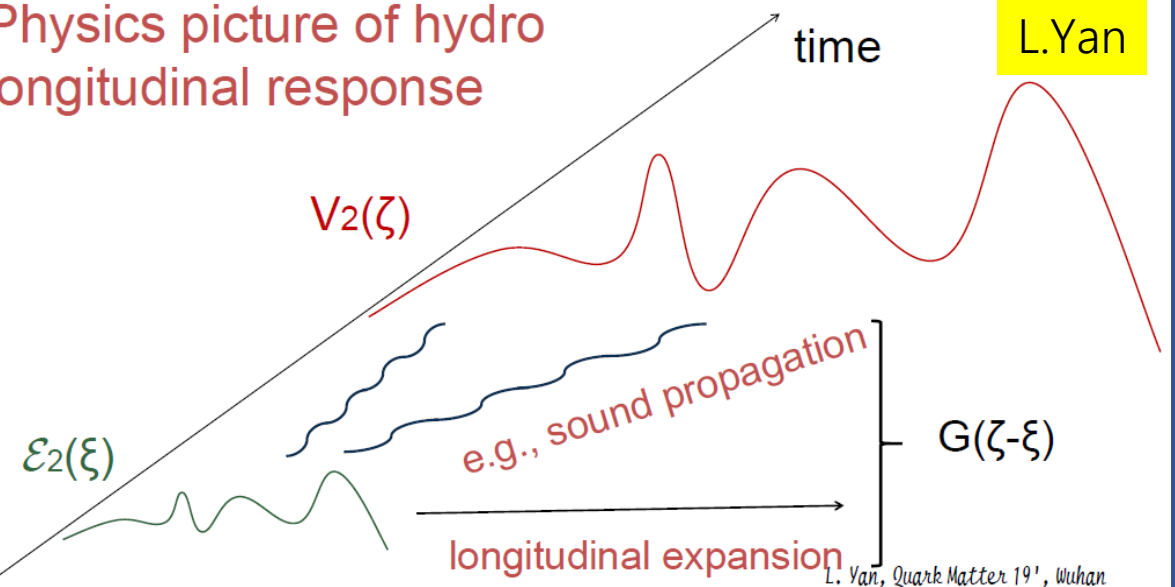
$$\tilde{G}(k) = \sum_{n=0} (ik)^n G_n, \quad |k| < k^* \quad k^n \sim O(d^n / d\xi^n)$$

⇒ This is hydro gradient expansion, with $k^* \sim 1/l_{mfp}$

L. Van, Quark Matter 19', Wuhan

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Physics picture of hydro longitudinal response



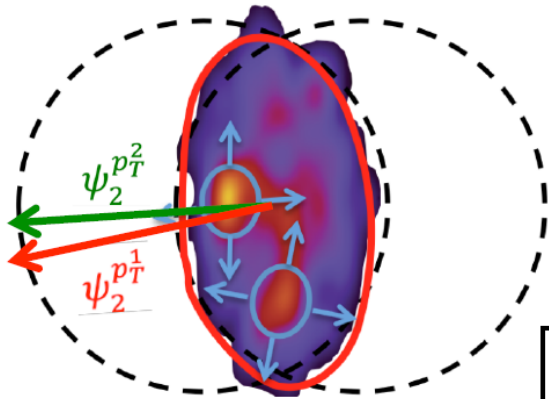
L. Van, Quark Matter 19', Wuhan

座標のラピディティ ξ における形状の応答として擬ラピディティ ζ でのフロー
 ← 流体の解から応答関数を導出
 ※無次元 k の収束半径が平均自由行程で決定？

事象平面角の揺らぎと主成分分析

Z.Chen (student lecture)

Decorrelation – Transverse



Local hot spots push particles to higher p_T
AND
result in different event planes for different p_T range

Factorization breaking
 $V_{n\Delta}(p_T^a, p_T^b) \neq v_n(p_T^a) \times v_n(p_T^b)$

Effects measurable by

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}} \sim \langle \cos [n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \rangle$$

PRC 92 (2015) 034911

19/11/3

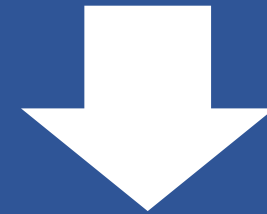
Zhenyu Chen - QM19 Student Day Lecture

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主成分分析 ($\alpha=1$ が最大固有値)

$$V_{n\Delta}(p_T^a, p_T^b) = \sum \lambda_\alpha \psi^{(\alpha)*}(p_T^a) \psi^{(\alpha)}(p_T^b)$$

$$= \sum V_n^{(\alpha)*}(p_T^a) V_n^{(\alpha)}(p_T^b)$$



$$r_n \approx 1 - \frac{1}{2} \left| \frac{V_n^{(2)}(p_T^a)}{V_n^{(1)}(p_T^a)} - \frac{V_n^{(2)}(p_T^b)}{V_n^{(1)}(p_T^b)} \right|^2$$

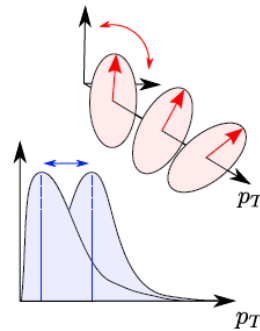
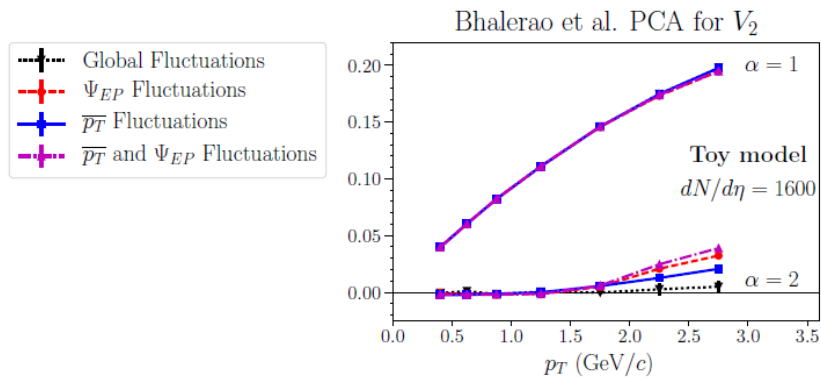
See also, R.S.Bhalerao *et al.*, PRL114,152301 (2015)

Proof of Concept

Principal Component Analysis

Proof of Concept: Toy model results I

M.Hippert



- PCA observables are sensitive to **anisotropic flow** fluctuations.
- Also sensitive to fluctuations of the **spectrum**.
- The latter can **obscure** the former.

- 主成分は他の揺らぎに対してロバスト
- 事象平面、平均 p_T の揺らぎの影響

主成分分析による実験と流体の比較

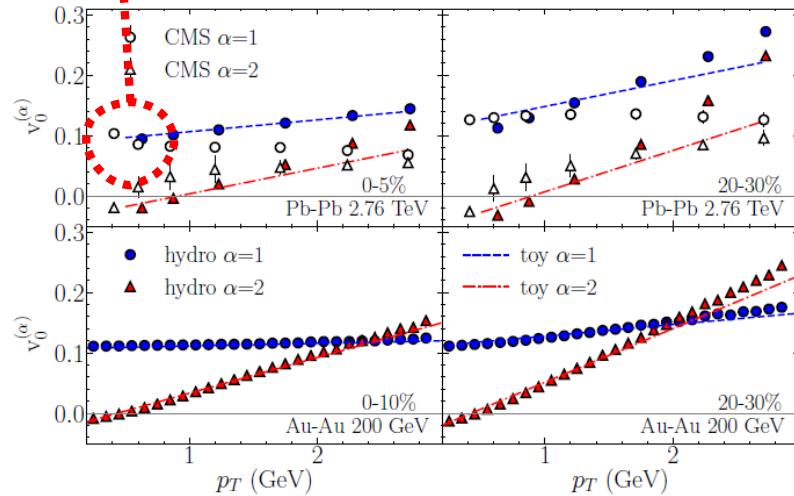
Toy model for n=0 PCA/cont'd

F.Grassi

$$v_0^{(1)}(p_T) \simeq \frac{\sigma_N}{\langle N \rangle} + \left[\frac{-\left(\frac{\sigma_{p_T}}{\langle \bar{p}_T \rangle}\right)^2 + 2\frac{\langle \delta N \delta \bar{p}_T \rangle}{\langle N \rangle \langle \bar{p}_T \rangle}}{\left(\frac{\sigma_N}{\langle N \rangle}\right)} \right] \frac{p_T}{\langle \bar{p}_T \rangle}$$

$$v_0^{(2)}(p_T) \simeq -\frac{3}{2} \frac{\sigma_{p_T}}{\langle \bar{p}_T \rangle} \left(1 - \frac{4}{3} \frac{p_T}{\langle \bar{p}_T \rangle}\right).$$

→ Works well [values $\sigma_N/\langle N \rangle$, $\sigma_{p_T}/\langle \bar{p}_T \rangle$, $\langle \delta N \delta \bar{p}_T \rangle/(\langle N \rangle \langle \bar{p}_T \rangle)$ from hydro]



- n=2,3は流体と実験は合う
- n=0の主成分($\alpha=1$)が定性的に合わないことが知られている

energy	centrality		$\frac{\sigma_N}{\langle N \rangle}$	$\frac{\sigma_{p_T}}{\langle \bar{p}_T \rangle}$	$\sqrt{\frac{\langle \delta N \delta \bar{p}_T \rangle}{\langle N \rangle \langle \bar{p}_T \rangle}}$
2.76 TeV	0-5 %	hydro	0.12	0.026	0.041
		CMS	0.09	0.010	0.
	20-30 %	hydro	0.16	0.041	0.070
		CMS	0.13	0.019	0.020
200 GeV	0-10 %	hydro	0.11	0.017	0.017
	20-30%	hydro	0.12	0.025	0.031

多重度揺らぎOK

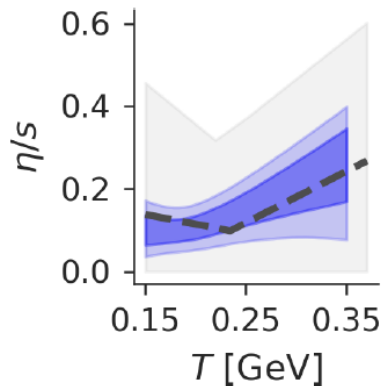
p_T の揺らぎ? 多重度と p_T の共分散?

ベイズ推定法の最新結果

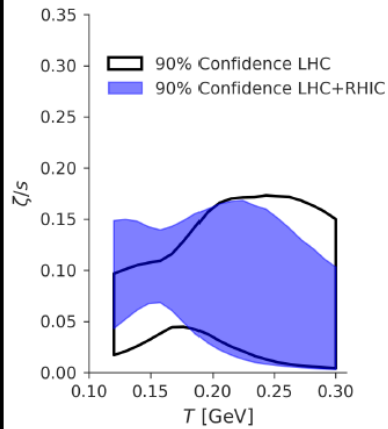
Summary

J.F.Paquet

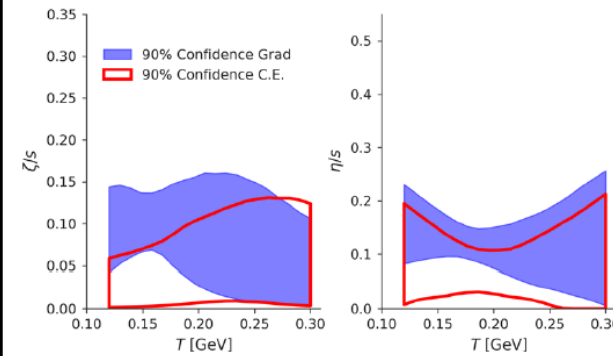
- Closure tests are powerful tools to validate Bayesian analyses



- RHIC data complement LHC's



- Non-negligible uncertainties from hydrodynamics to particle transition ("viscous corrections")



And this is only the beginning:
more systems; more observables; more flexible model; revisit viscous corrections; ...

Jean-François Paquet (Duke), on behalf of the JETSCAPE Collaboration

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PID粒子数、平均 p_T , $v_{\{2,3,4\}}$



パラメータ(90% confidence)

モデル依存性に注意が必要

- 初期フリーストリーミング
- 流体は2D
- 粒子化のモデル

実験結果から“有効”熱力学量の導出？

J.-Y. Ollitrault

Effective temperature, effective volume

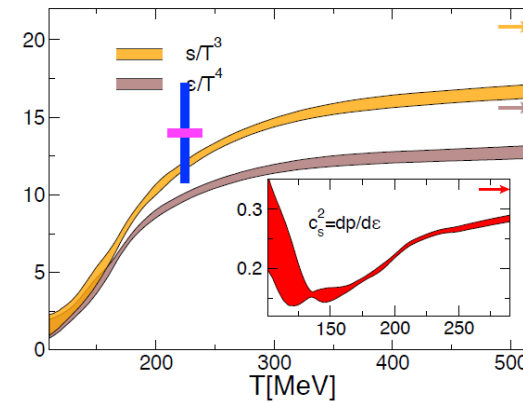
We define the effective temperature, T_{eff} , and the effective volume, V_{eff} , of the quark-gluon plasma, as those of a **uniform fluid at rest** which would have the same energy E and entropy S as the fluid at freeze-out.

$$E = \int_{\text{f.o.}} T^{0\mu} d\sigma_{\mu} = \epsilon(T_{\text{eff}}) V_{\text{eff}},$$

$$S = \int_{\text{f.o.}} s u^{\mu} d\sigma_{\mu} = s(T_{\text{eff}}) V_{\text{eff}},$$

I will show that T_{eff} and $s(T_{\text{eff}})$ can be obtained from experiment.

Comparison with lattice QCD



$T_{\text{eff}} = 222 \pm 9 \text{ MeV}$
 $s(T_{\text{eff}})/T_{\text{eff}}^3 = 14 \pm 3.5$

compatible with lattice.

Confirms large number of degrees of freedom, implying that color is liberated: deconfinement observed!

実験

多重度

平均 p_T



有効温度

エントロピー密度

流体計算

有効体積

*平均 $p_T = 3.07 T_{\text{eff}}$

小さい系：To be QGP or not to be?

That is THE question!

RHIC

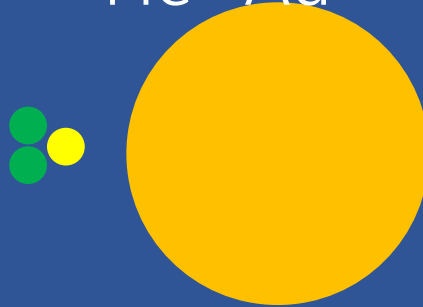
p+Au



d+Au



$^3\text{He}+\text{Au}$



LHC

p+p



p+Pb



2003~2010: 原子核効果の指標測定

→ cold nuclear matter (CNM) 効果

2010: CMSによる陽子+陽子衝突におけるリッジの発見

2010~today: QGP生成可否を含む新奇物理描像の構築

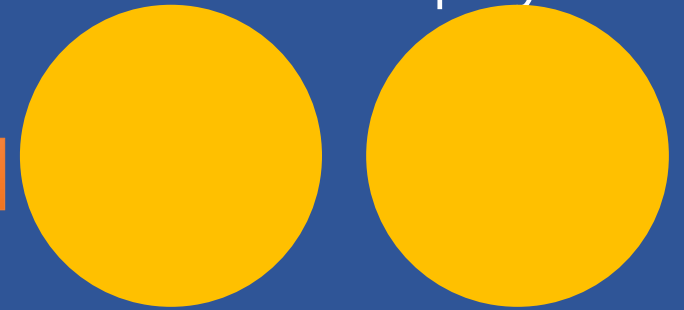
高エネルギー物理屋の見方 vs 重イオン衝突物理屋の見方

p+p physics



High multiplicity
p+p physics as
interdisciplinary
research

A+A physics



HEP (Generic purpose MC)

- ジェットの普遍性
 - $e^+ + e^-$ 衝突における破砕関数
→ p+p衝突への適用
 - 粒子比の多重度非依存性
- 実験結果解釈における非摂動論的な現象論、模型の必要性

HIC (Dynamical modeling)

- A+A衝突における動的模型の成功
→ QGP流体パラダイム
- A+A衝突の理解のp+p衝突におけるテスト
- QGPは小さい衝突系で作られたか？
- QGP流体はどれだけ小さくなれるか？

“Do we really need a QGP ?”

See also, C.Bierlich *et al.*, PLB779, 58 (2018)

Angantyr
Gleipnir

Introducing GLEIPNIR (XFMIC+IR)

The string endpoints (quarks and gluons) carry transverse momentum, but the string itself cannot. The shoving gives a transverse push

transverse separation between flux tubes

$$\frac{dp_{\perp}}{dt dz} = \frac{g\kappa\delta_{\perp}(t)}{R^2} \exp\left(-\frac{\delta_{\perp}^2(t)}{4R^2}\right).$$

This push must be parallel to both string pieces.

There is no frame where two random string pieces are parallel.

But there is always a frame where they lie in parallel planes at any given time.

[work in progress]



Angantyr

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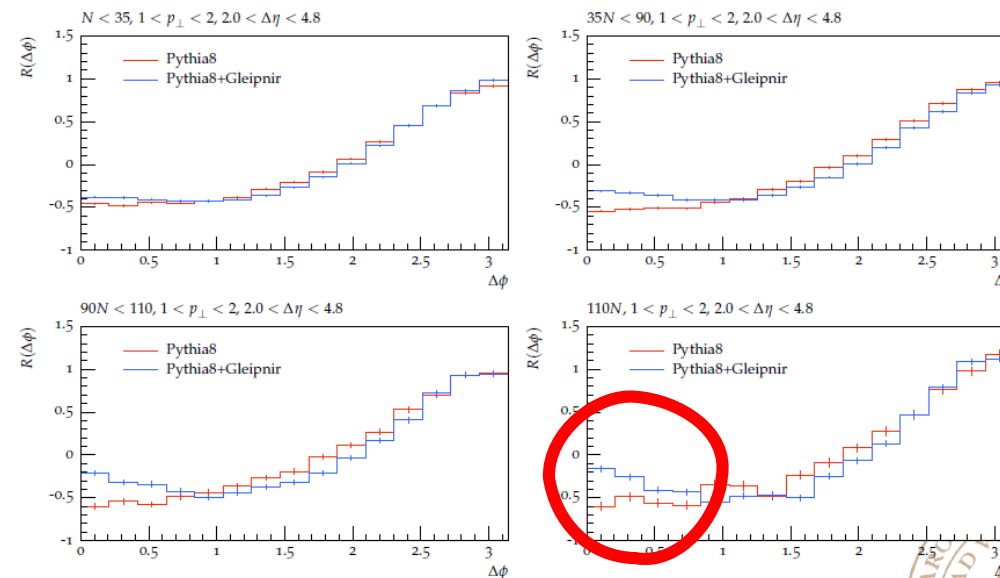
Leif Lönnblad

Lund University

Angantyr
Gleipnir

L.Lönnblad

We have a ridge!

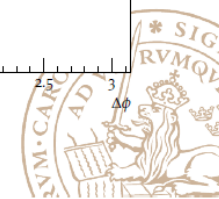


[arXiv:1009.4122]

Angantyr

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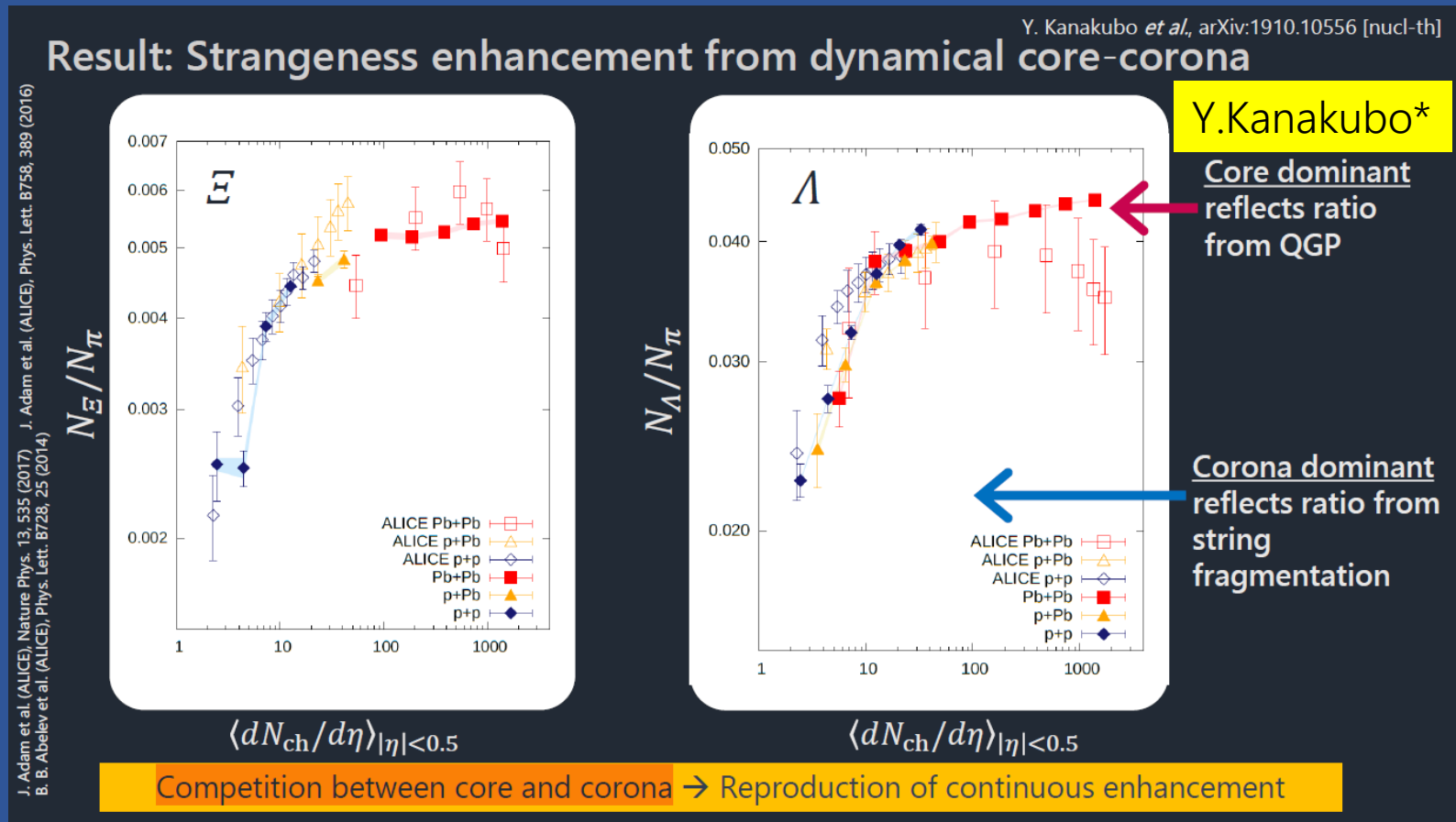
Leif Lönnblad



Lund University

PYTHIA + String Shoving = Ridge and flow ← ppからの拡張

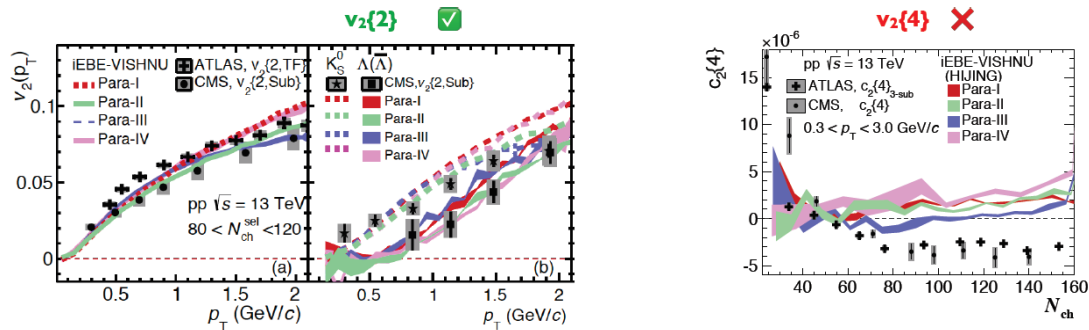
From AA to pp within hydro



- 大きい系から小さい系から統一的に
- 動的コア-コロナ初期化
- PYTHIA初期設定に対するアフターバーナー
- AAからの拡張
- ジェットも見据えた大描像

"One fluid may not rule them all"

Combine $v_2\{2\}$ and $v_2\{4\}$



- $v_2\{2\}$: flow + flow fluctuations
- $v_2\{4\}$: flow - flow fluctuations

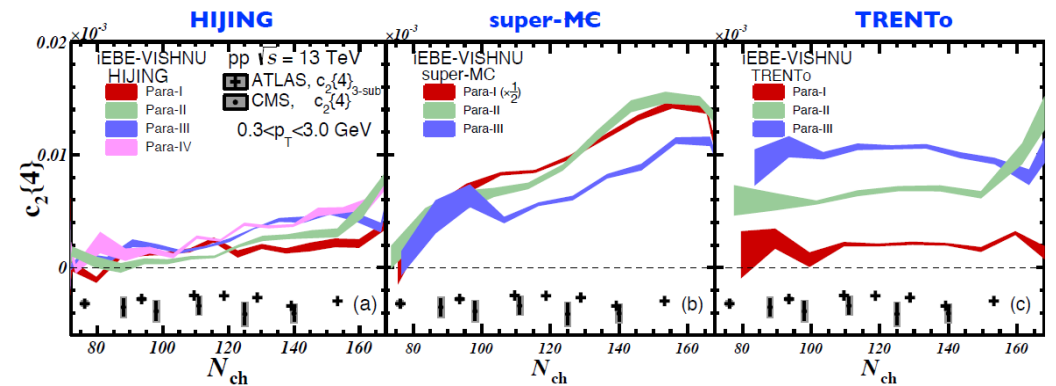


❖ iEBE-VISHNU (HIJING-IC) works for $v_2\{2\}$ but not $v_2\{4\}$

- This hydro calculation does not describe neither flow nor flow fluctuations in pp

All hydro give positive $c_2\{4\}$

Y.Zhou



❖ Hydrodynamic calculations using super-MC and TRENTo initial conditions gives even larger positive $c_2\{4\}$, and far away from data

Nov 6th, 2019

You Zhou (NBI) @ QM2019, Wuhan

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Nov 6th, 2019

You Zhou (NBI) @ QM2019, Wuhan

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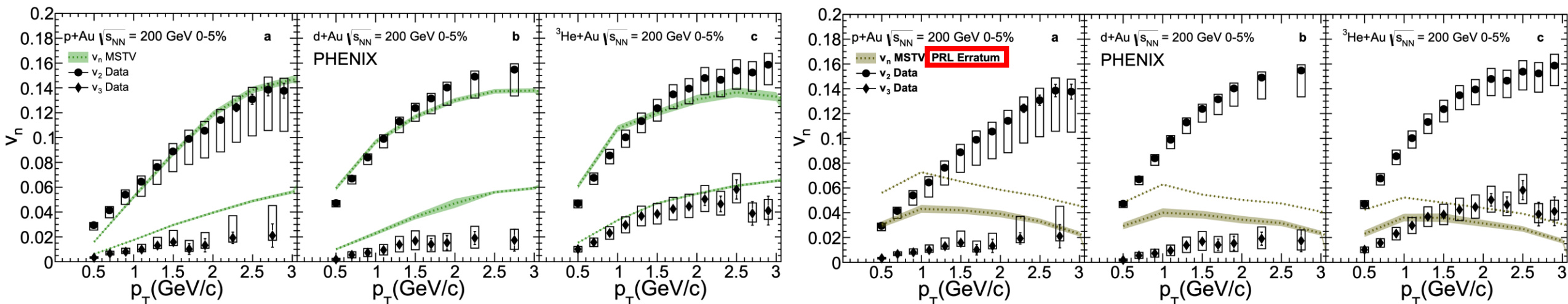
$$v_2\{4\}^2 = 2\langle v_n^2 \rangle - \langle v_n^4 \rangle = -c_2\{4\}$$

$$\langle v_n^2 \rangle = \langle v_n \rangle^2 + \sigma_{v_n}^2$$

- Positive $c_2\{4\}$ does not necessarily suggest non-flow**
- Negative $c_2\{4\}$ does not necessarily imply hydrodynamic flow**

"Corrected" CGC results

J.Nagle



- $v_2(p) > v_2(d) > v_2(^3\text{He})$

- $v_2(p) > v_2(d) > v_2(^3\text{He})$

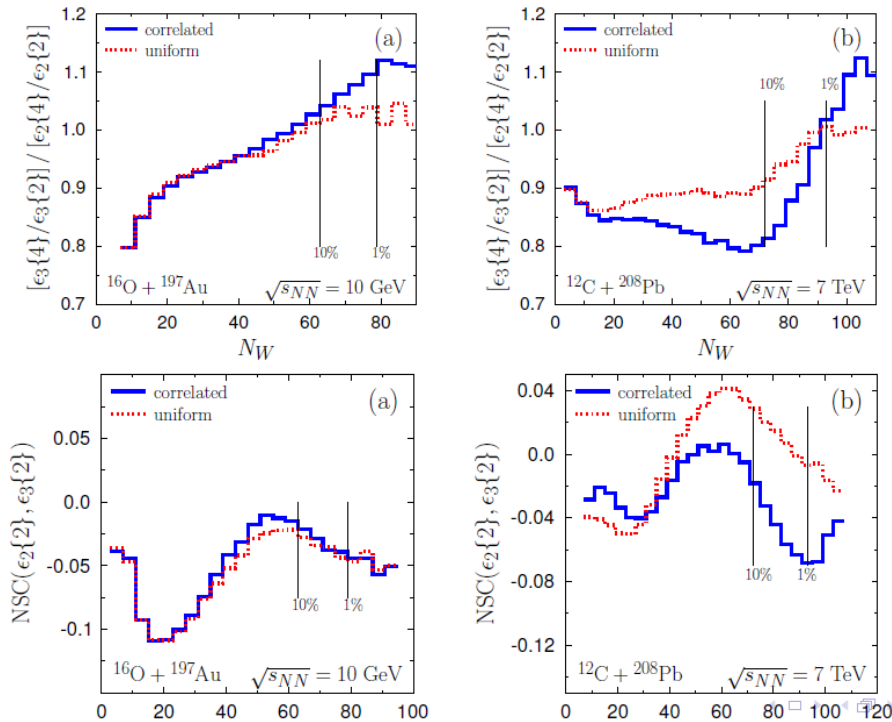
現状ではCGCのみで v_2, v_3 を定性的にも定量的にも説明不可

*See also, MSTV, PRL123,039901(E) (2019)

^{12}C の α クラスター状態？

Clusters from "hitting a wall"

W.Broniowski



WB

Flow with light nuclei

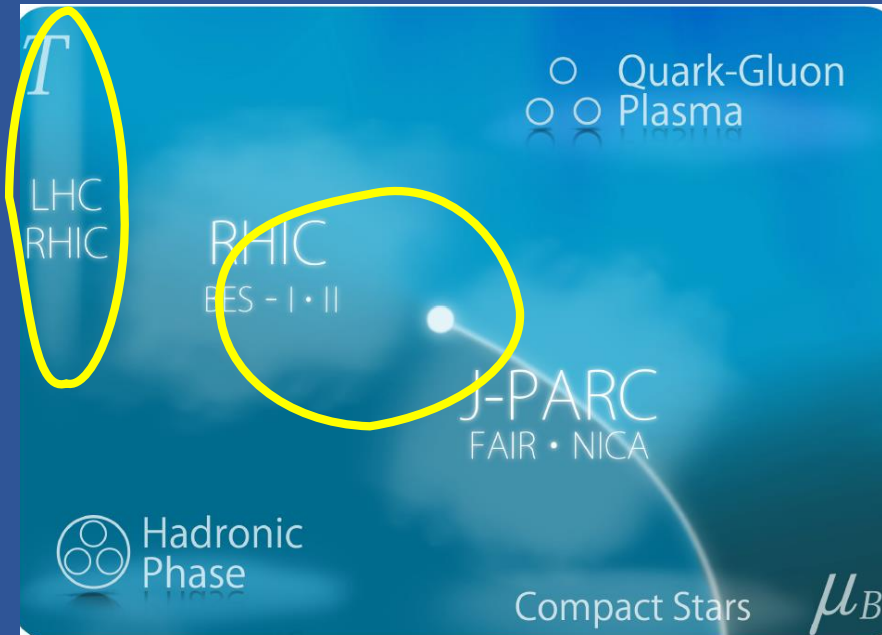
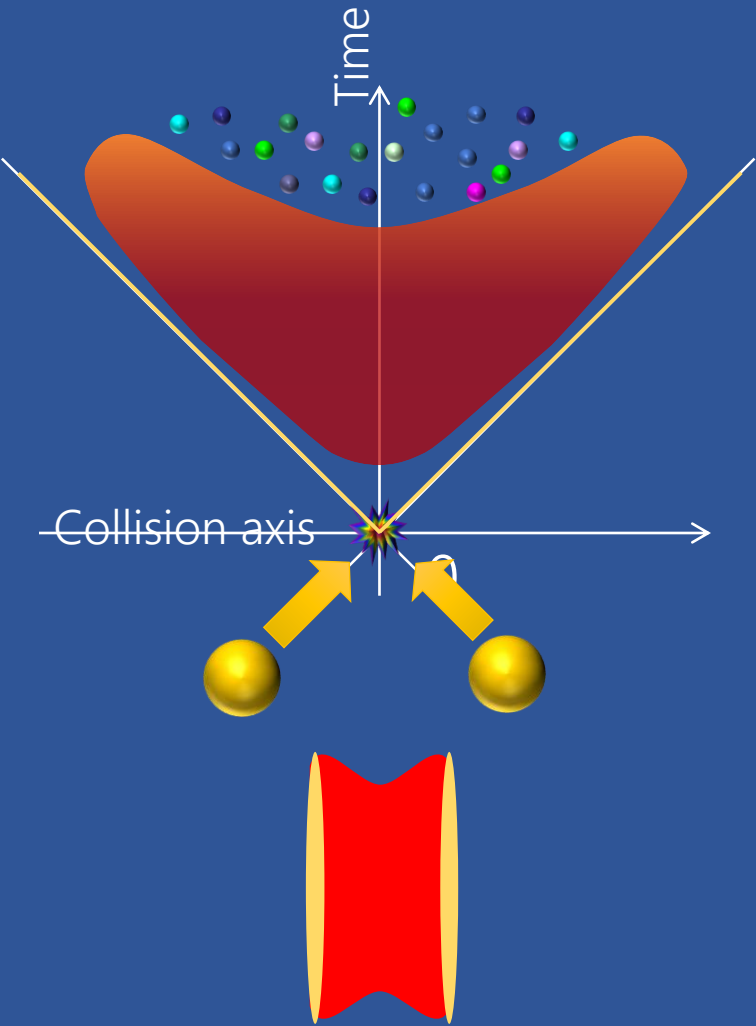
QM2019

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- 重イオン衝突反応で ^{12}C のクラスター状態を探れるか？
- 形起源のtriangular flowで見えるか？
- そもそも励起状態ではないのか？

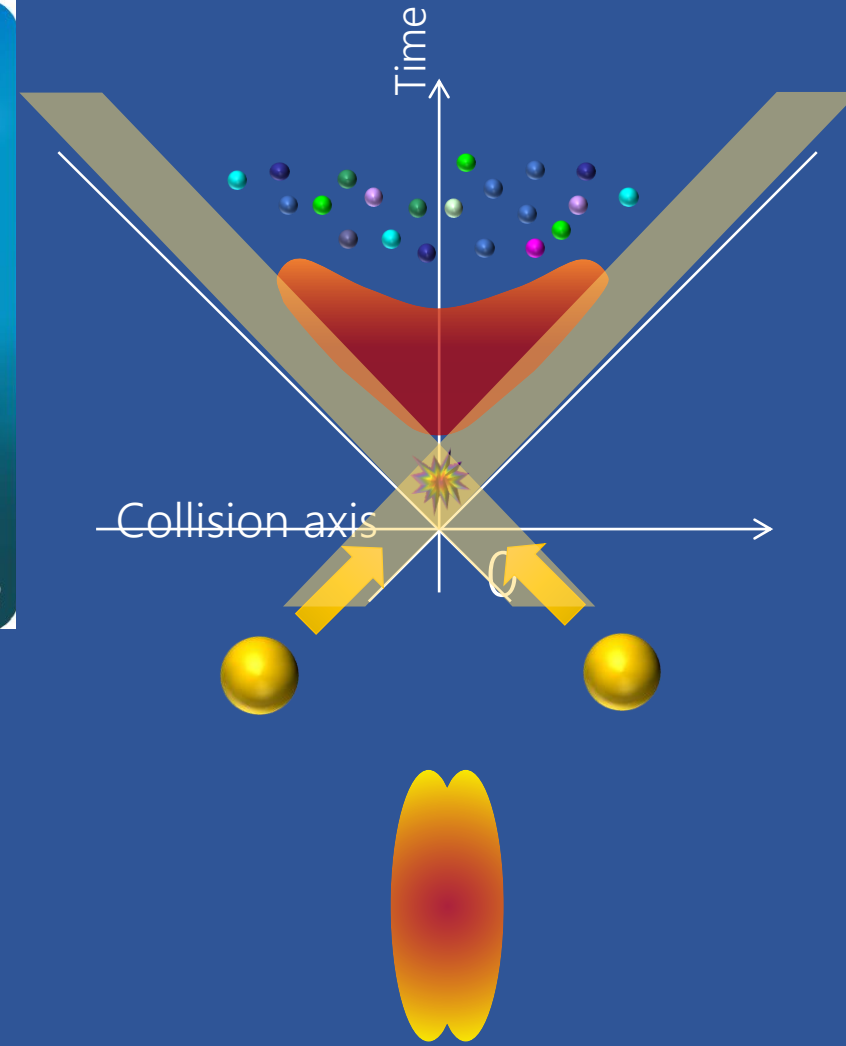
「科研費：クラスター階層」の方々？

衝突エネルギーの違い



J-PARC-HI white paper

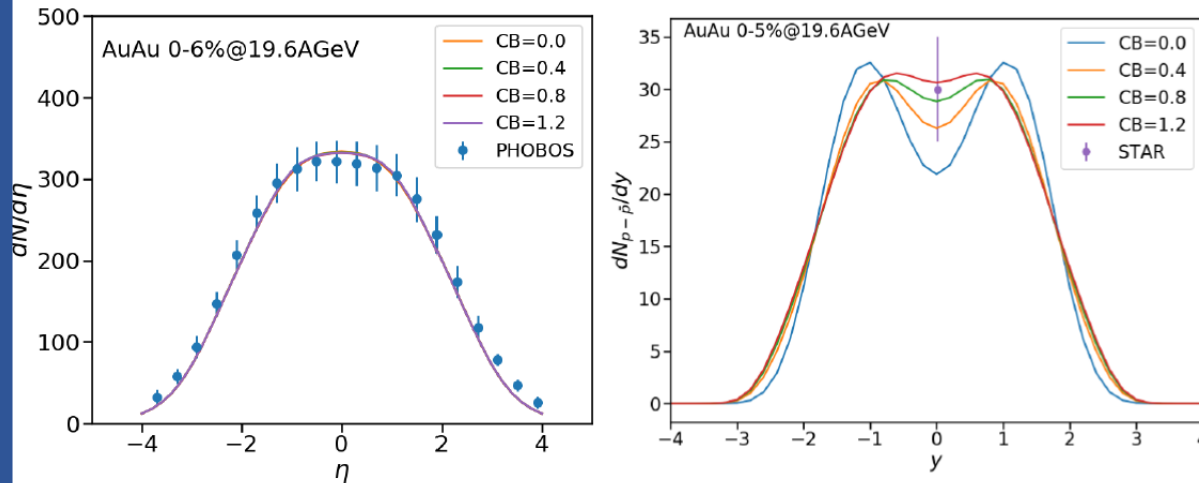
- 保存量の拡散
- 状態方程式の構築
- 臨界現象の探索



保存量の拡散 1

Particle yield

X.-Y. Wu

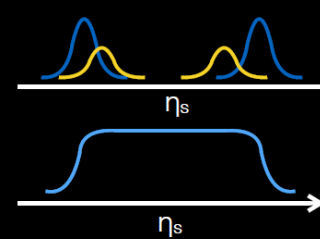


The effects of baryon current diffusion on pseudo-rapidity distribution of charged hadrons is negligible.

Larger baryon current diffusion will transport more net baryons to mid-rapidity.

BEST
COLLABORATION

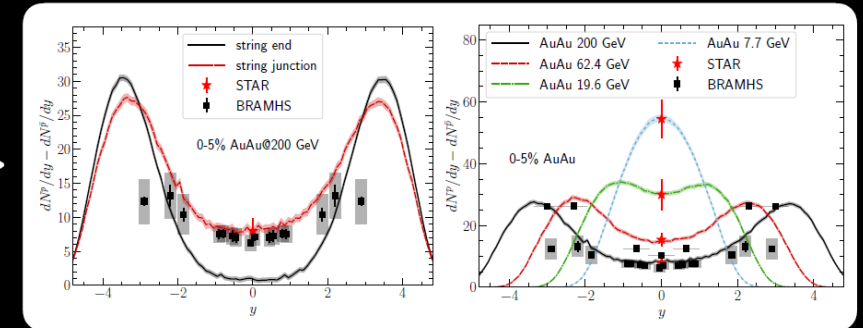
net baryon density
energy density



INITIAL STATE BARYON STOPPING

C. Shen

C. Shen and B. Schenke, in preparation



- Allowing the initial baryon charges to fluctuate to string junctions improves description at high collision energies

D. Kharzeev, Phys. Lett. B 378, 238 (1996)

Interplay between baryon diffusion and initial fluctuations

- スtringジャンクションとバリオン数拡散の拮抗
- 正味陽子数分布の重要性大
- CP探索にも重要？

保存量の拡散 2

J.Fotakis

Coupled charges in DNMR

- System with **one conserved quantum number** q only

$$\tau_q \dot{V}_q^{(\mu)} + V_q^\mu = \kappa_q \nabla^\mu (\mu_q/T) + \mathcal{O}(2)(\theta, \pi^{\mu\nu}, \dots)$$

G.S. Denicol, H. Niemi, E. Molnár, D.H. Rischke, *Phys. Rev. D* **85**, 114047 (2012)

- For system with **multiple conserved quantum numbers**: mixed chemistry introduces **coupling of charges through diffusion coefficient matrix!**

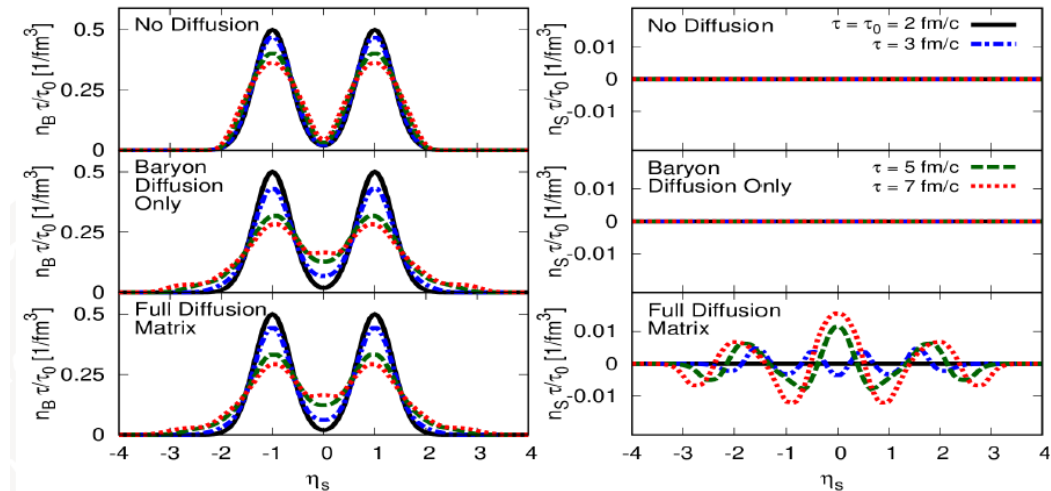
$$V_B^\mu \sim \kappa_B \nabla^\mu (\mu_B/T) \rightarrow \begin{pmatrix} V_B^\mu \\ V_S^\mu \end{pmatrix} \sim \begin{pmatrix} \kappa_{BB} & \kappa_{BS} \\ \kappa_{SB} & \kappa_{SS} \end{pmatrix} \begin{pmatrix} \nabla^\mu (\mu_B/T) \\ \nabla^\mu (\mu_S/T) \end{pmatrix}$$

$$\tau_q \dot{V}_q^{(\mu)} + V_q^\mu = \sum_{q'} \kappa_{qq'} \nabla^\mu (\mu_{q'}/T) + \mathcal{O}(2)$$

M. Greif, J.A. Fotakis, G.S. Denicol, C. Greiner, *Phys. Rev. Lett.* **120**, 242301 (2018)



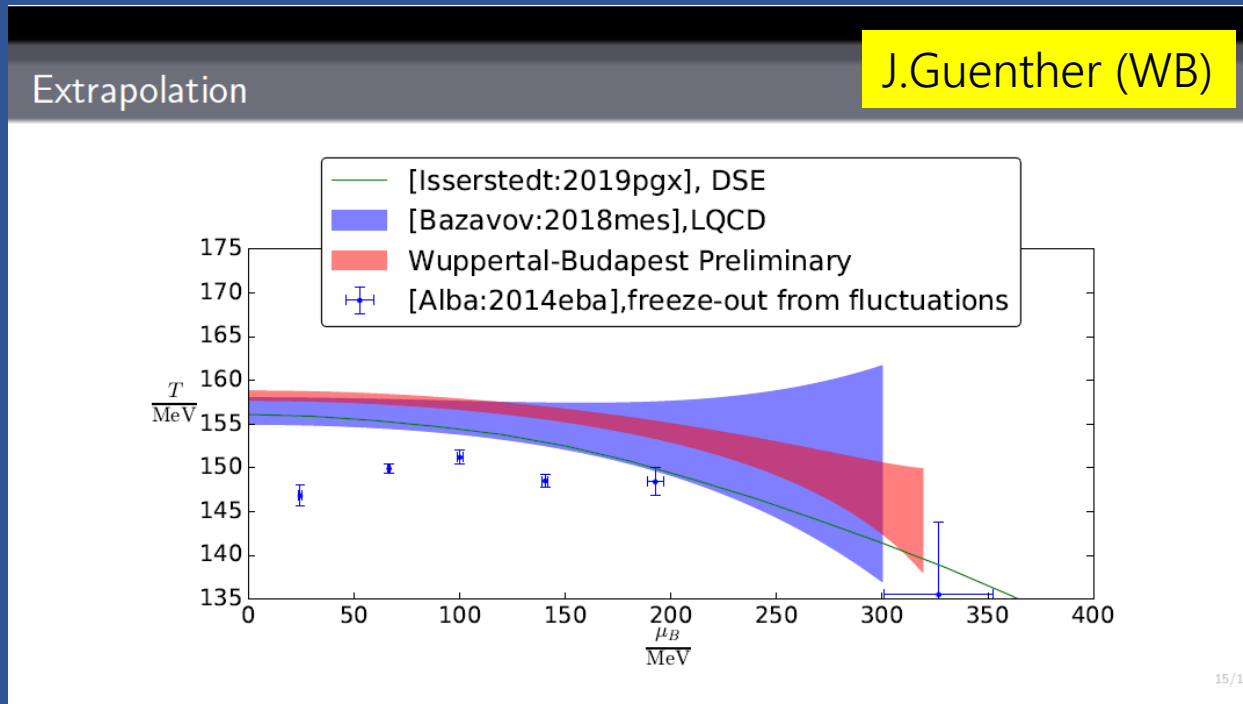
Results



- オンサーガー相反定理
- 重イオン衝突でSoret効果（温度勾配による拡散）やDufour効果（化学ポテンシャル勾配による熱伝導）が見えるか？

See also, A.Monnai and TH, *NPA*847, 283 (2010);
M.Greif *et al.*, *PRL*120, 242301 (2018)

クロスオーバー線



- Imaginary μ からの解析接続
- カイラル感受率のピーク位置

$$\frac{T_c(\mu_B)}{T_c(0)} \approx 1 - \kappa_2 \left(\frac{\mu_B}{T_c(0)} \right)^2 - \kappa_4 \left(\frac{\mu_B}{T_c(0)} \right)^4$$

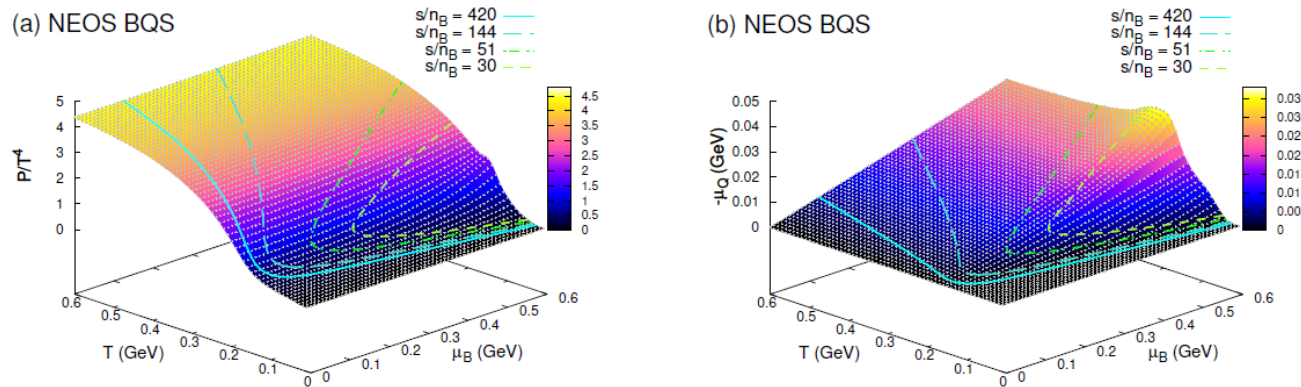
$$T_c(0) \sim 158 \text{ MeV}, \kappa_2 \sim 0.015, \kappa_4 \sim 0$$

重イオン衝突反応(流体計算)用状態方程式

Equation of state

A.Monnai

- $n_S = 0, n_Q = 0.4n_B$ (realistic in HIC; denoted as NEOS BQS)



- ▶ Finite negative μ_Q owing to the condition $n_Q = 0.4n_B$
- ▶ Pressure similar in NEOS BS and BQS because $\mu_Q = 0$ implies $n_Q \sim 0.5n_B$

- 格子+レゾナンスガス
 - ストレンジネス中性
 - アイソスピン
 - 公開中
- ※ $\mu_B = 0$ での
Huovinen & Petreczky
との違いは？

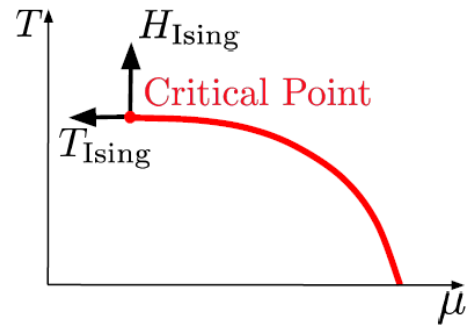
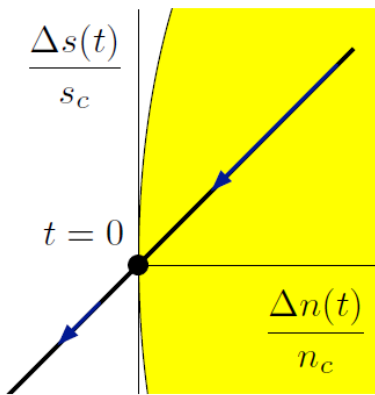


有限密度計算の
スタンダードに

QCDと3D Isingのマッピング

Trajectories in n, s plane and mapping QCD to the Ising model

D. Teaney



- The EOS and correlation length $\xi(t)$ vs. time are known, after specifying the QCD to Ising map:

$$\Delta s \longleftrightarrow \Delta M_{\text{Ising}}$$

$$\Delta T_{\text{QCD}} \longleftrightarrow \Delta H_{\text{Ising}}$$

$$\Delta n \longleftrightarrow \Delta e_{\text{Ising}}$$

$$-\Delta \mu_{\text{QCD}} \longleftrightarrow \Delta T_{\text{Ising}}$$

Most modeling has used this simple map, and not a linear combination

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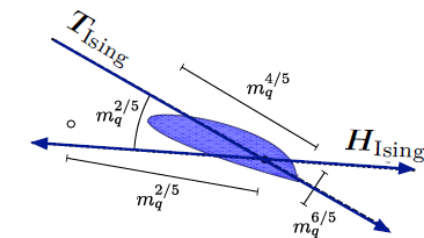
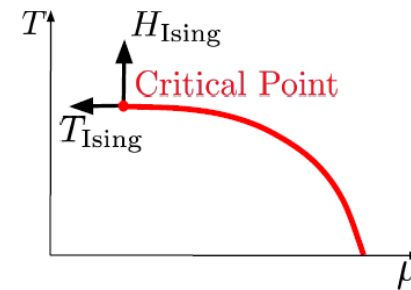
Rethinking the QCD to Ising Map

M. Pradeep, Stephanov 1905.13247

- Close to the chiral limit $m_q = 0$, the CP is close to a tri-critical point.
- This leads to the following expectations:

Usual Modeling

New theoretical expectation



- Changes (non-universal) estimates of bulk viscosity near CP:
Martinez, Schäfer, Skokov 1906.11306

$$\frac{\zeta}{s} \simeq \underbrace{(0.00042 \leftrightarrow 0.8)}_{\text{usual} \leftrightarrow \text{new}} \left(4\pi \frac{\eta_0}{s}\right) \left(\frac{\xi}{\xi_0}\right)^{2.8}$$

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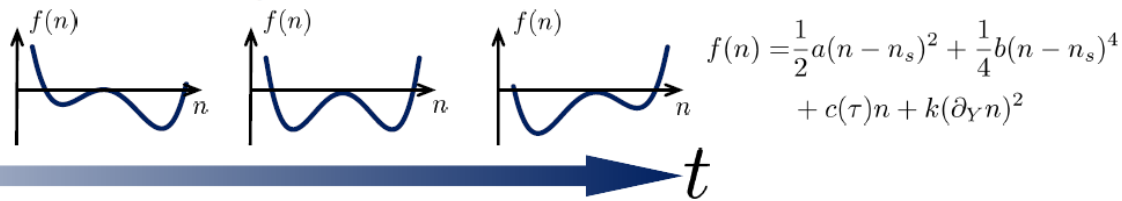
See also, Y.Akamatsu *et al.*, PRC100, 044901 (2019)

See also, M.S.Pradeep and M.Stephanov, PRD100, 056003 (2019)

1次相転移によるドメイン形成

Free Energy

□ At 1st transition point

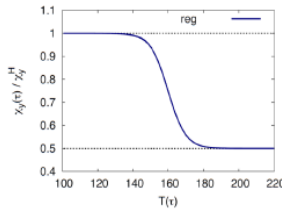


□ Large and small n

$$\chi(n) = \frac{\partial^2 f}{\partial n^2} \rightarrow \chi_{\text{QGP}} (n \rightarrow \infty)$$

$$\rightarrow \chi_{\text{hadron}} (n \rightarrow 0)$$

Poisson



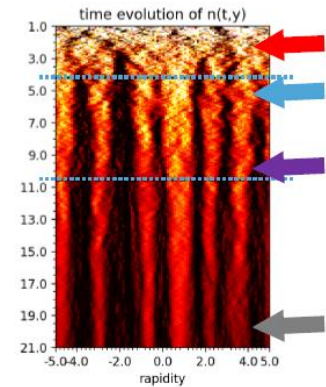
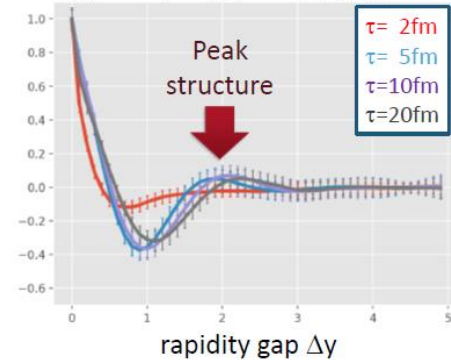
- κ : positive
- adjust κ and A to reproduce the behavior of D at small and large n

$$\tilde{D} = \Gamma\left(\frac{\partial^2 f}{\partial n^2} + X\right) \quad A = 2D\chi_2$$

Correlation Function

M.Kitazawa

Correlation Function
 $C(\bar{y}) = \langle \delta n(\bar{y}) \delta n(0) \rangle / \chi_{\text{hadron}}$



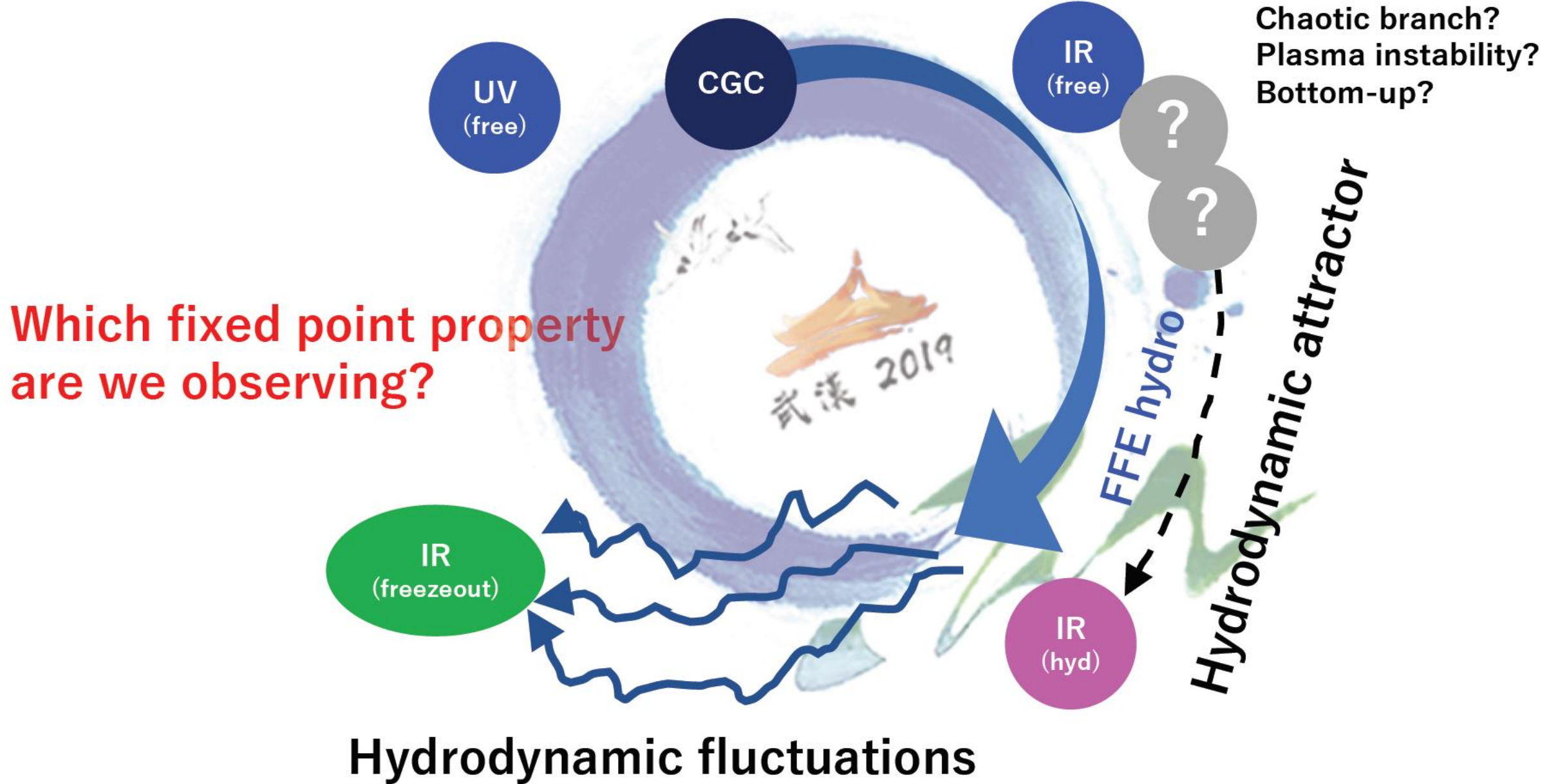
- Domain leads to a peak structure in $C(y)$.
- The peak can survive even in the final state.

臨界点ピンポイントではなく、
その先の1次相転移線を通った場合

- 相関関数にピーク $\Delta y \sim 2$
- ピークの位置は何で決まる？

Overall picture I have as of 19/11/7

Y.Akamatsu



Backup

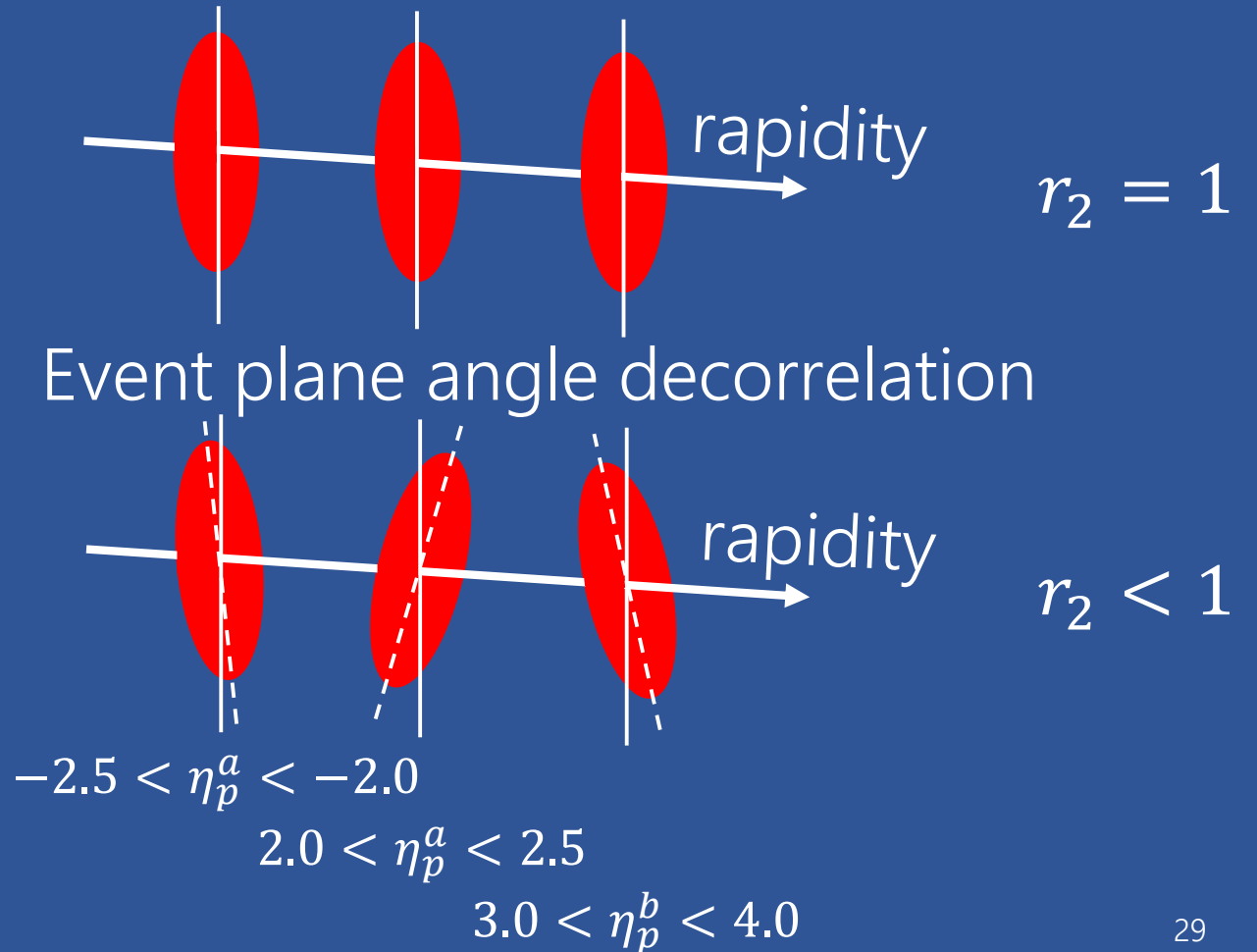
Factorization ratio and event plane decorrelation

Factorization ratio

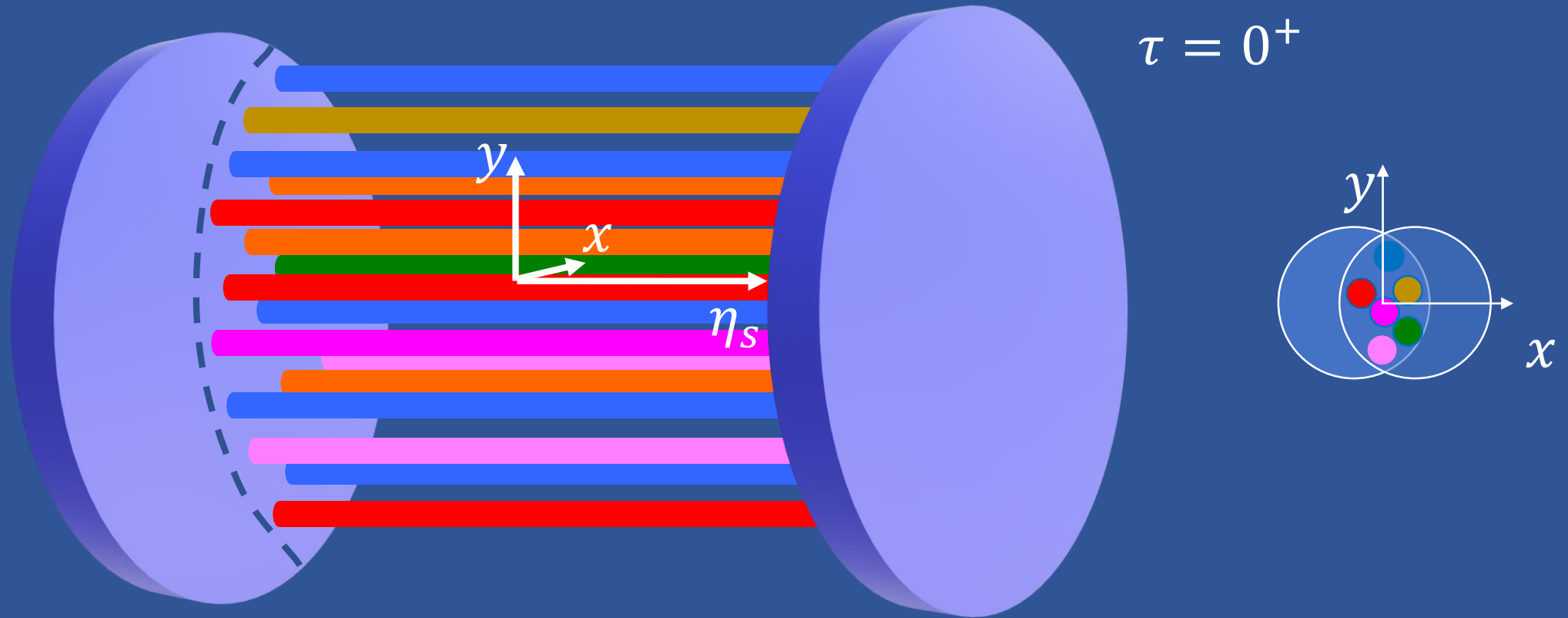
$$r_n(\eta_p^a, \eta_p^b) = \frac{V_{n\Delta}(-\eta_p^a, \eta_p^b)}{V_{n\Delta}(\eta_p^a, \eta_p^b)}$$

$$V_{n\Delta} = \langle \cos(n\Delta\phi) \rangle$$

Aligned event plane angle



Correlations along collision axis

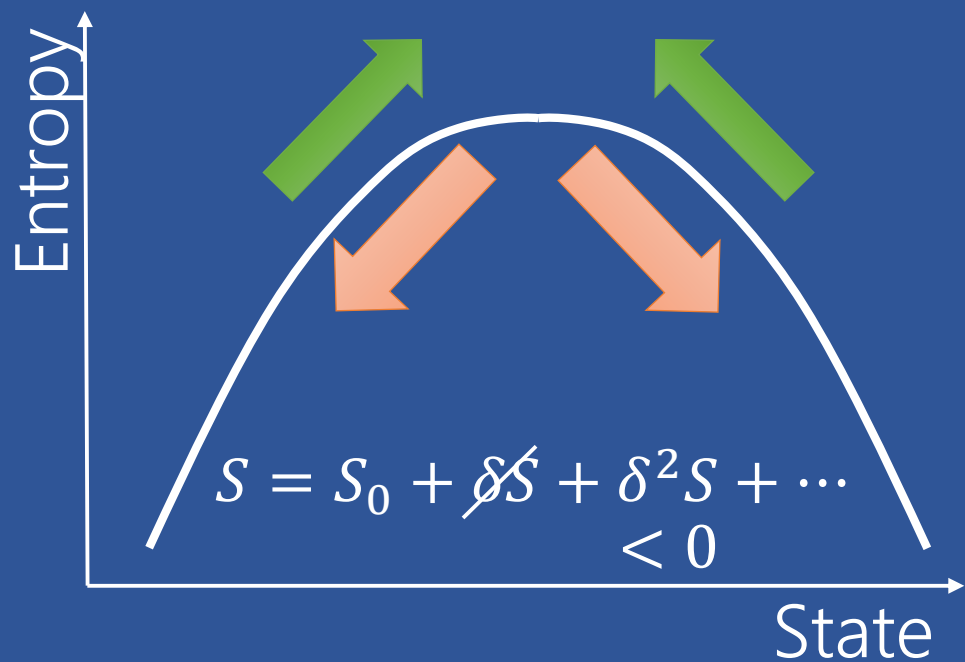


Heavy ion collision as a chromoelectric capacitor

- Approximately boost-invariant formation of color flux tubes
- Correlation embedded in wide rapidity region

Hydrodynamic fluctuations

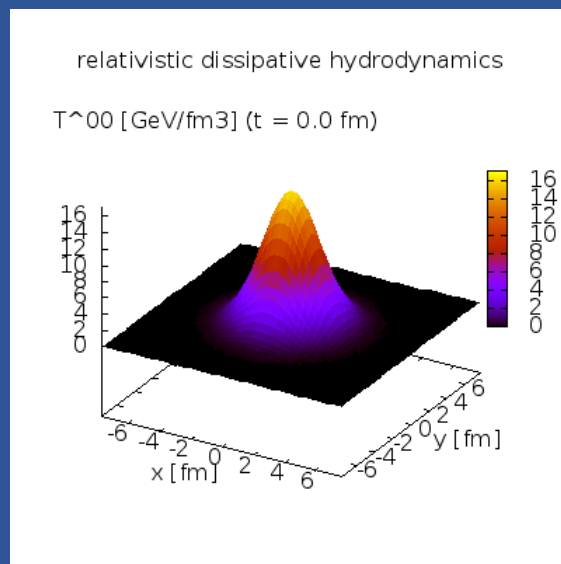
Fluctuation-Dissipation relations



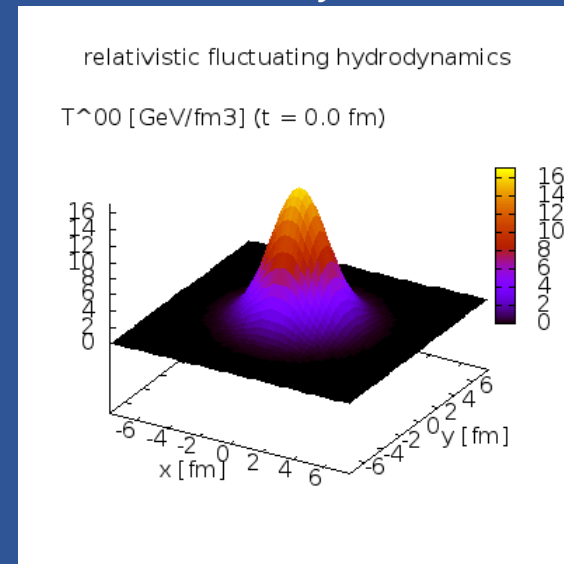
Fluctuations around maximum entropy state

QGP fluid simulation in a box

Courtesy of K.Murase



Dissipative hydro (2nd Generation)

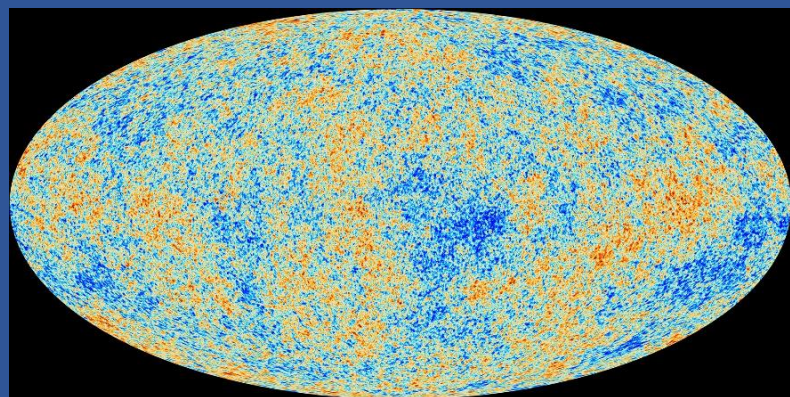


Fluctuating hydro (3rd Generation)

Dissipations \leftrightarrow Fluctuations

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,...

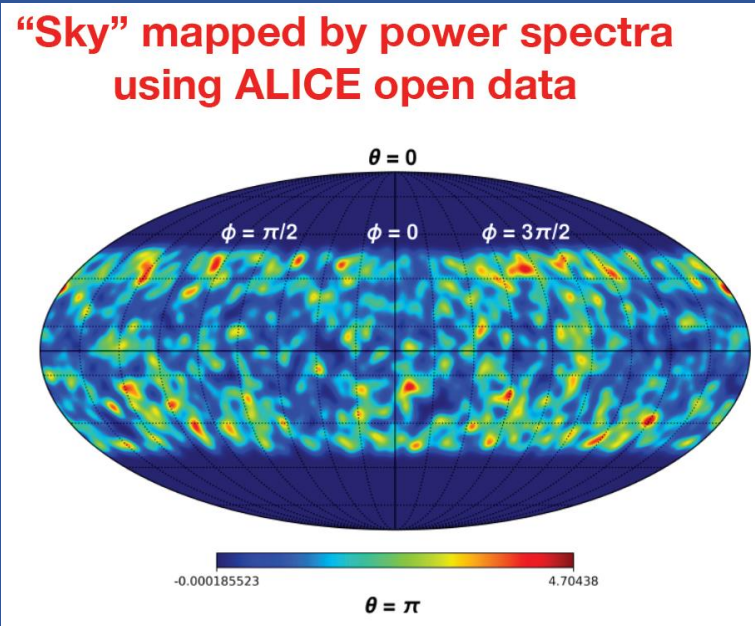
- Cosmological parameters
- Energy budget
 - Hubble constant (lifetime)
 - Curvature (flatness)
 - ...

“Physical Cosmology”
James Peebles
The Nobel prize in physics 2019

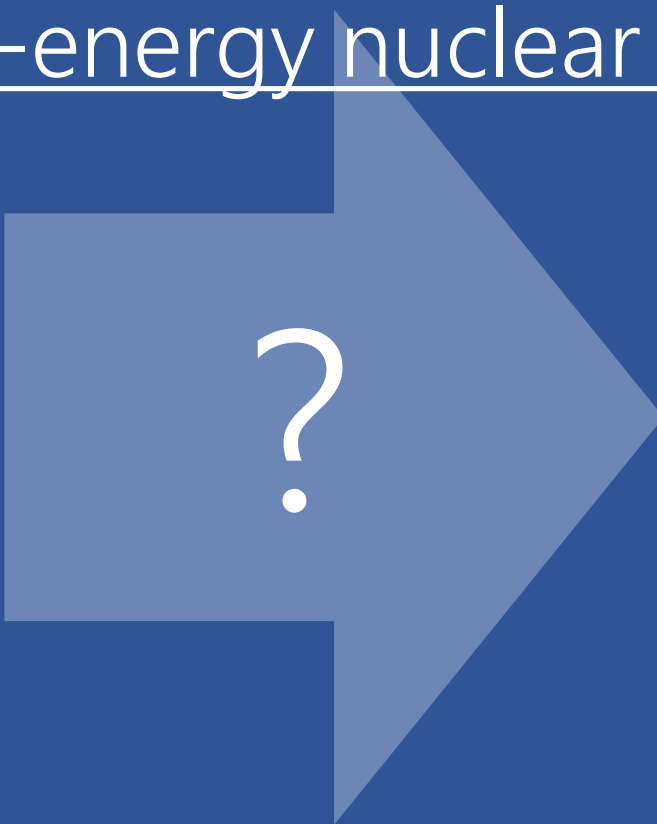


Analysis tool

Bottom-up approach in high-energy nuclear collisions



Y.Zhou, talk at QM2018



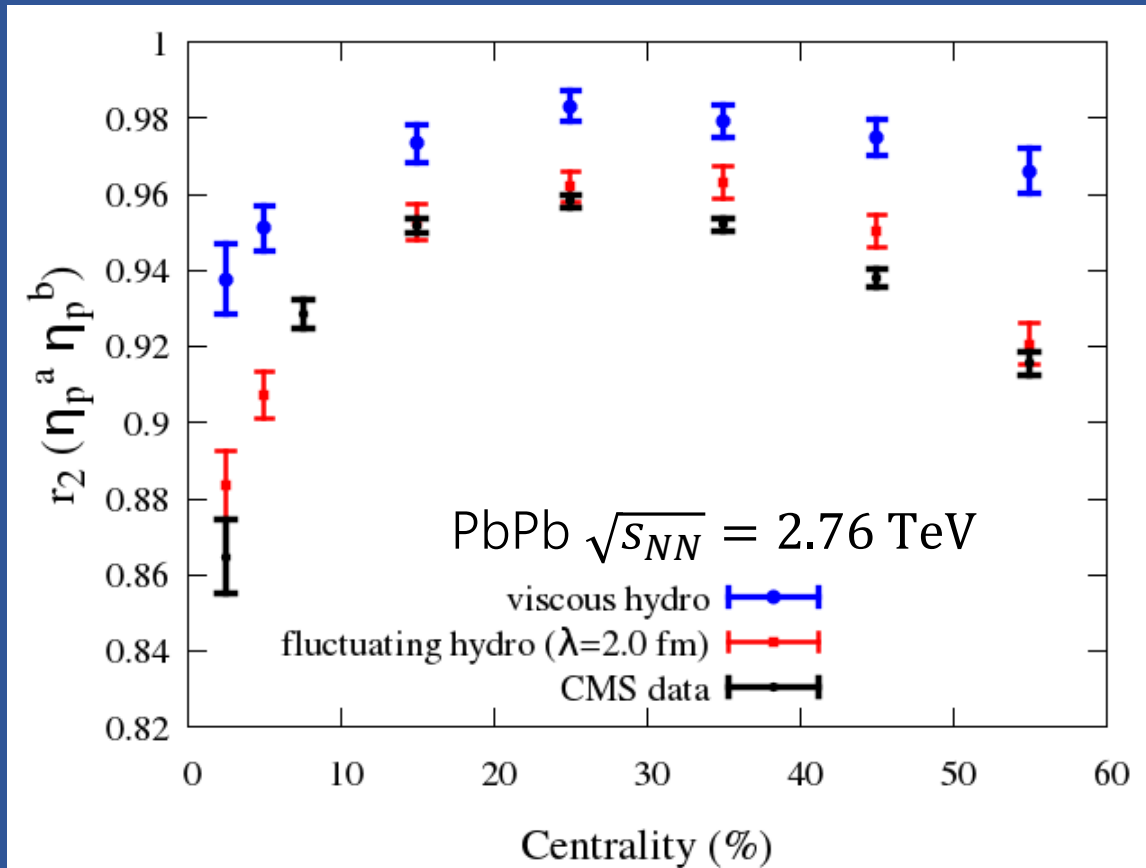
Physics properties of the QGP

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

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

Centrality dependence of event plane decorrelation

A.Sakai



Initial longitudinal fluctuations
→ Insufficient to reduce r_2
Both initial and hydrodynamic
fluctuations needed

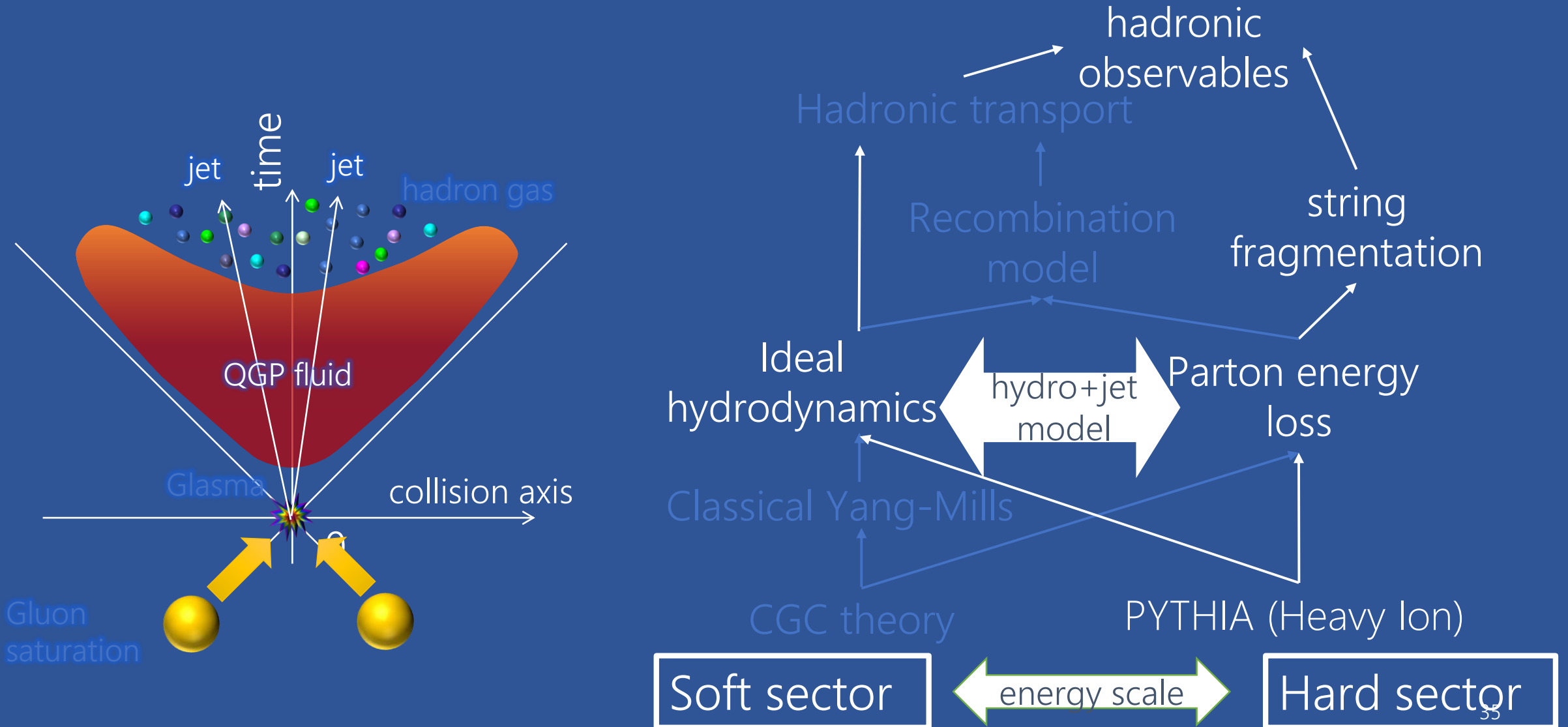
New opportunity to constrain
transport coefficients and initial
conditions in rapidity space

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

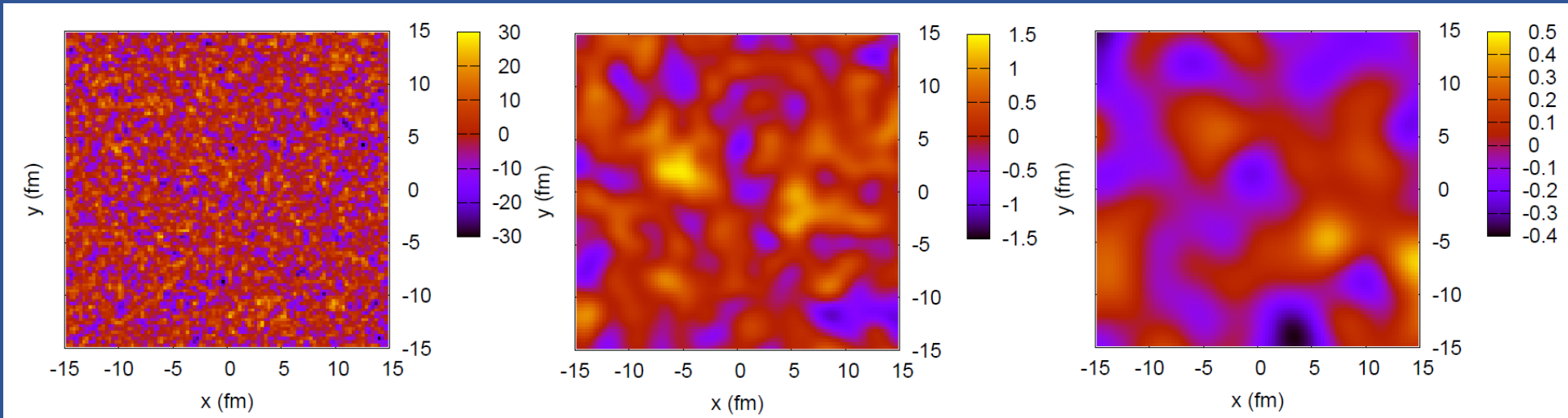
PYTHIA: T. Sjöstrand *et al.*, Comput. Phys. Commun. **191**, 159 (2015).

*Heavy ion mode available from ver.8.230

Model $S_{\text{OFT}}-H_{\text{ARD}}$



Cutoff parameter dependence



λ

0 fm
(Mesh size)

1.0 fm

2.0 fm