HIC-HIP Post QM 研究会
2019/12/22 @ 名古屋大学

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

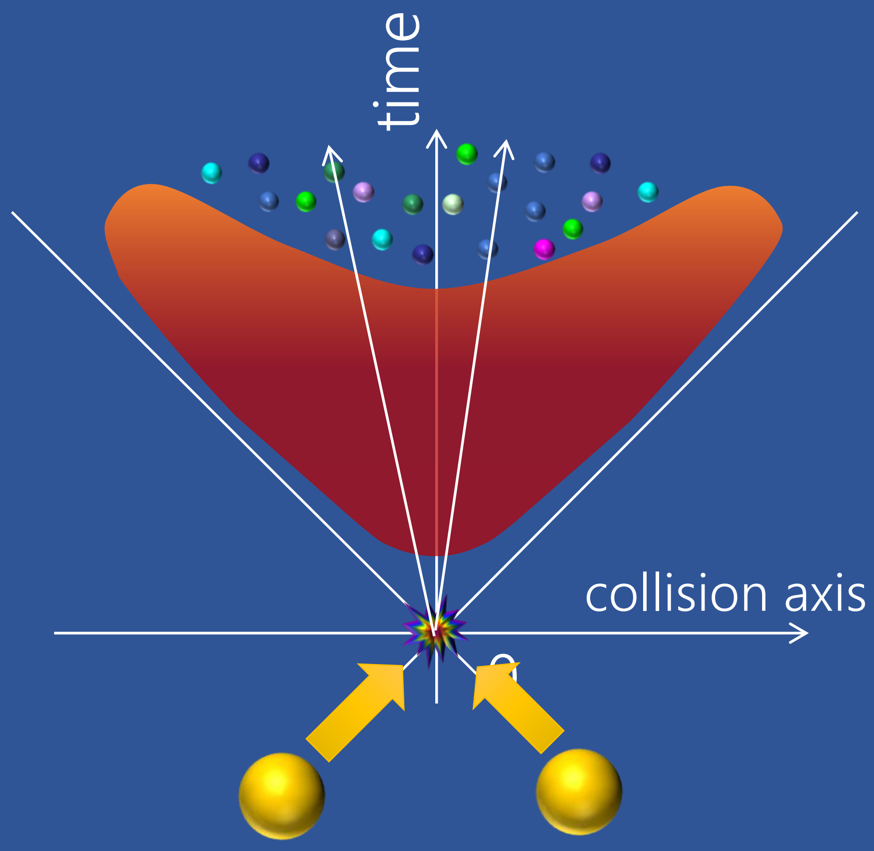
小さい衝突系

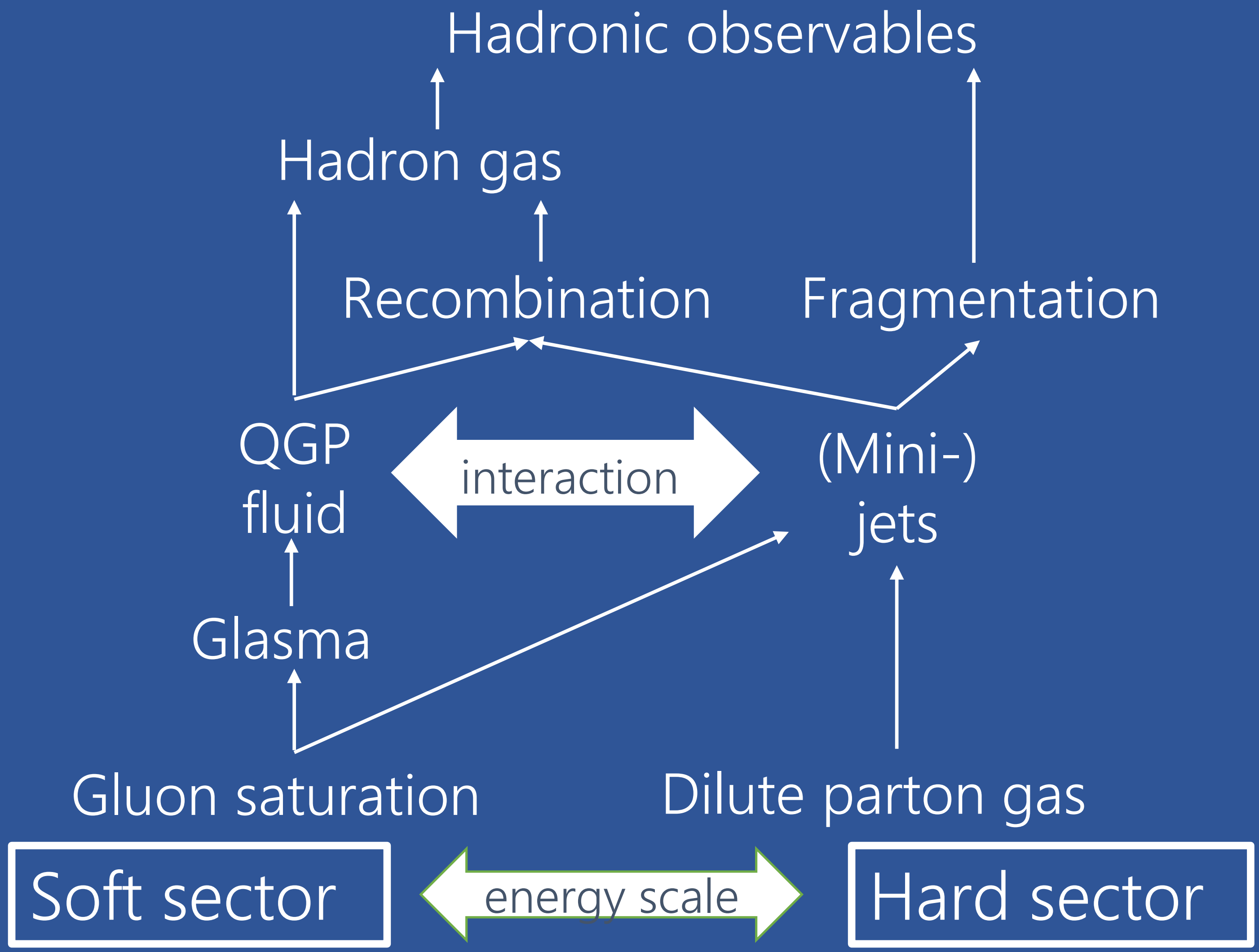
LHCやRHICにおける集団的振る舞いの発見
→ QGPはどれだけ小さくなれるか？

様々な衝突系

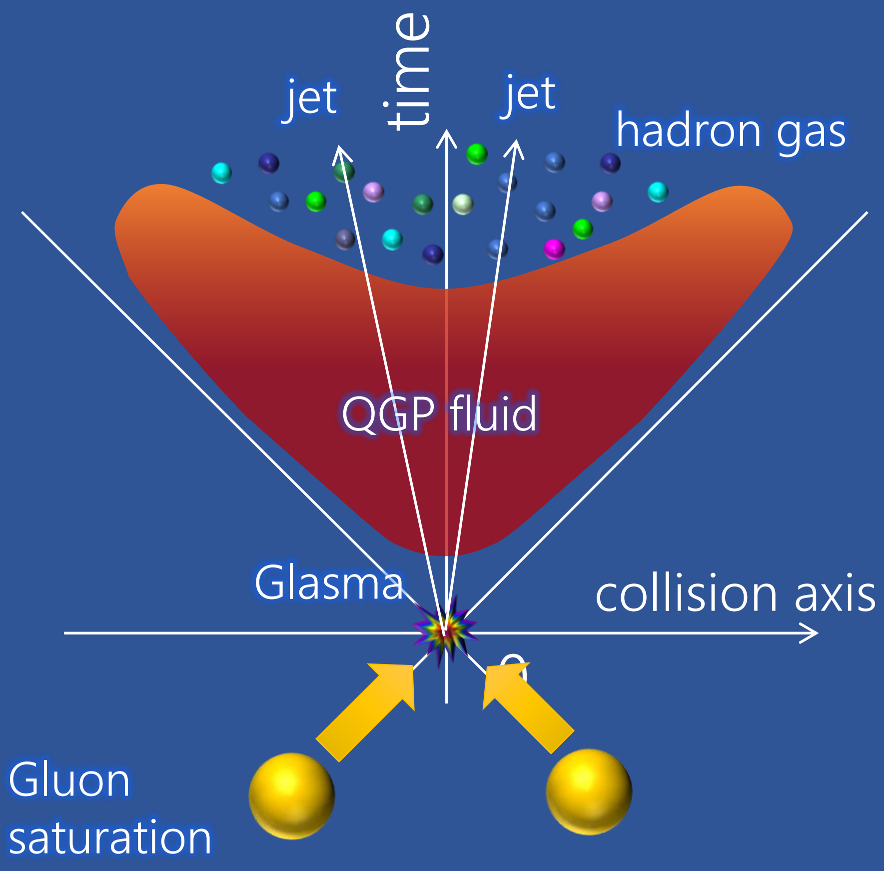
RHICビームエネルギースキャンプログラム(BES)
→ QGP生成のオンセット？
→ 超高密度物質の探究
（臨界点、相構造）

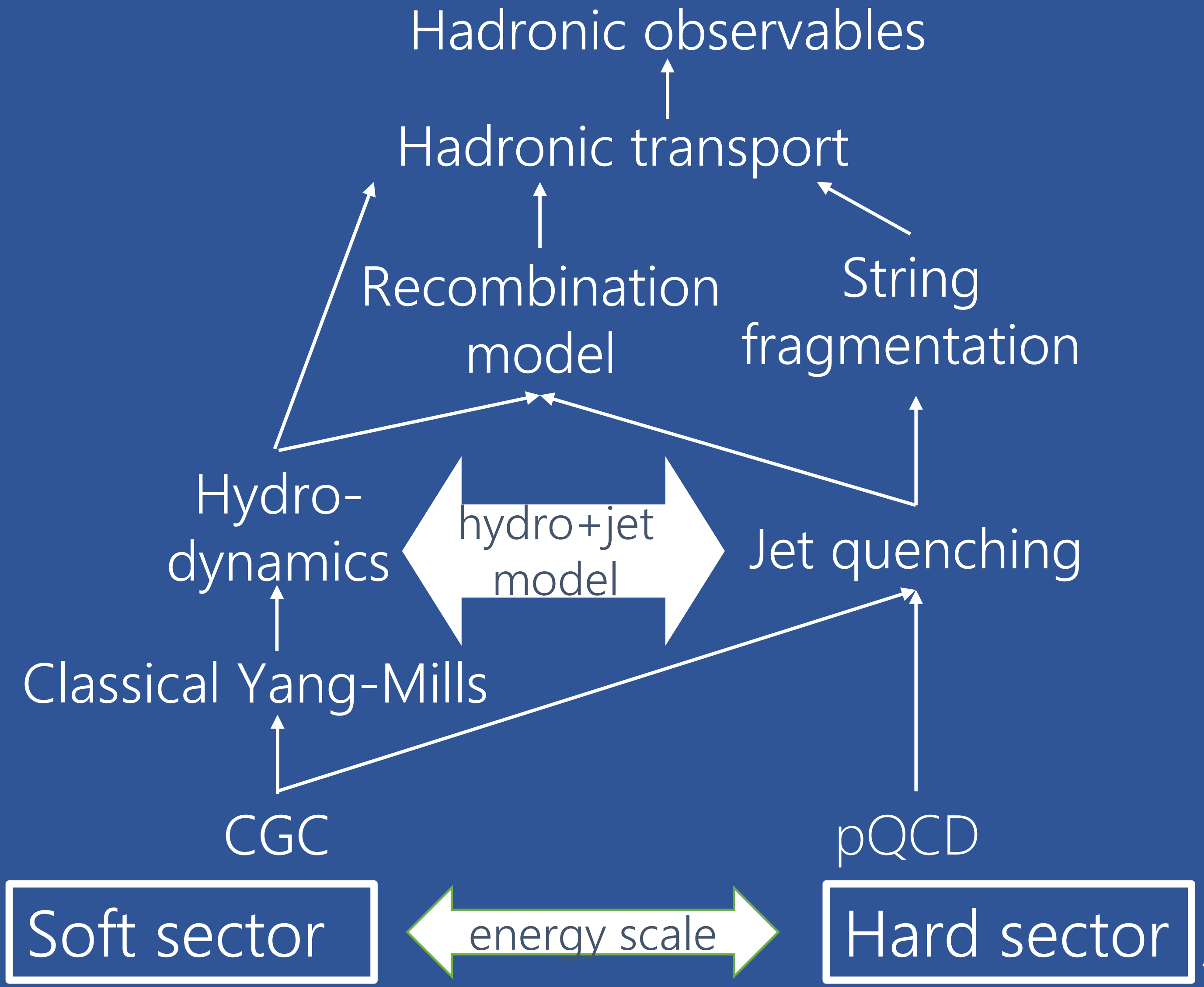
高エネルギー原子核衝突のダイナミクス



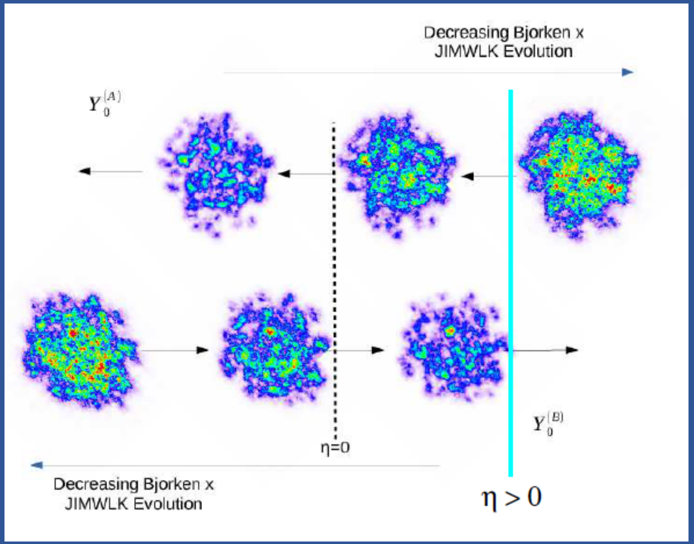


モデリングの一例


jet
time
jet
hadron gas
QGP fluid
Glasma
collision axis
Gluon
saturation


Hadronic observables
Hadronic transport
Recombination
model
String
fragmentation
Hydro-
dynamics
hydro+jet
model
Jet quenching
Classical Yang-Mills
CGC
pQCD
Soft sector
energy scale
Hard sector

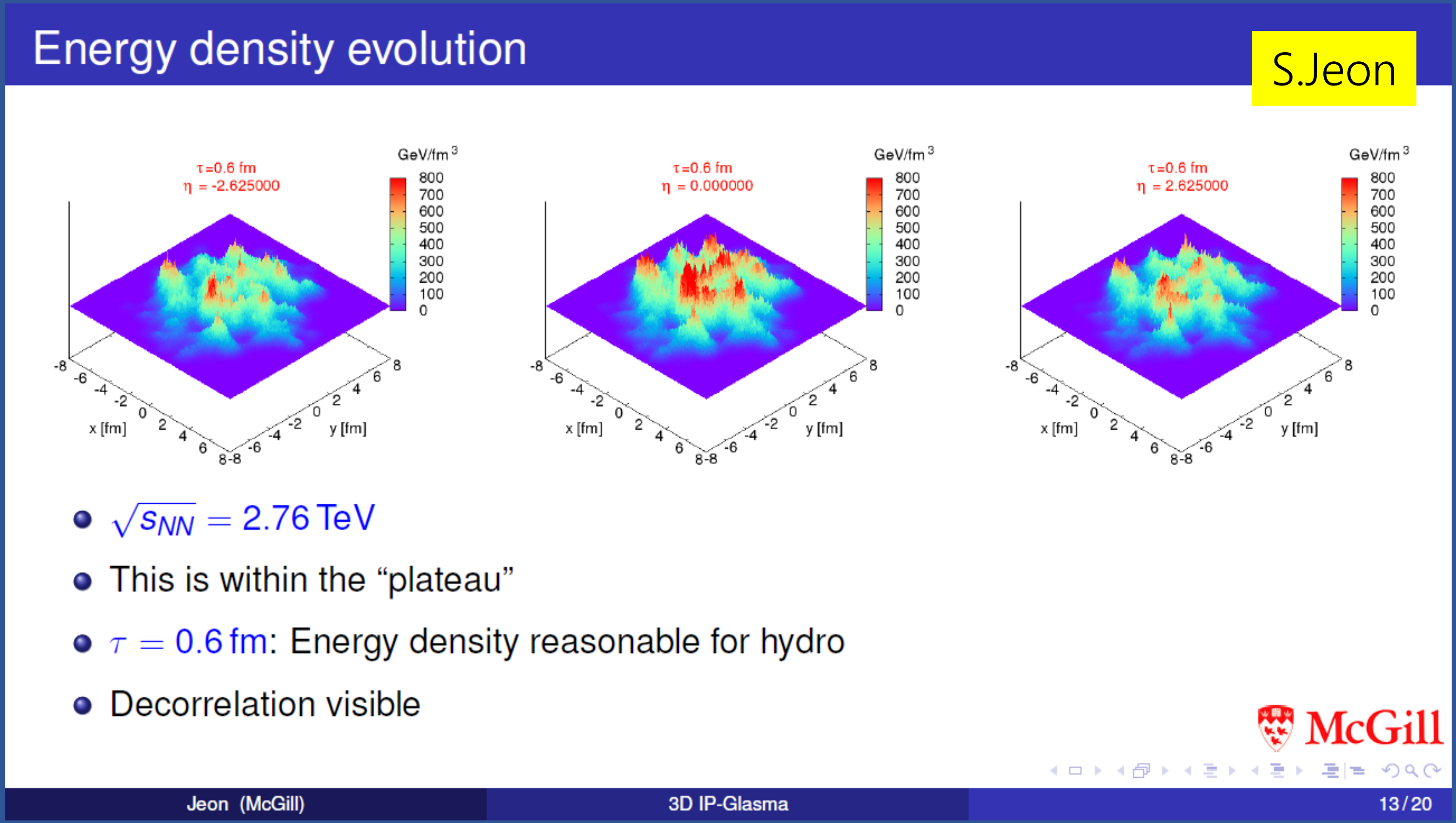
(Almost) full 3D Classical Yang-Mills



JIMWLKの初期条件

$y = \pm 4.25$

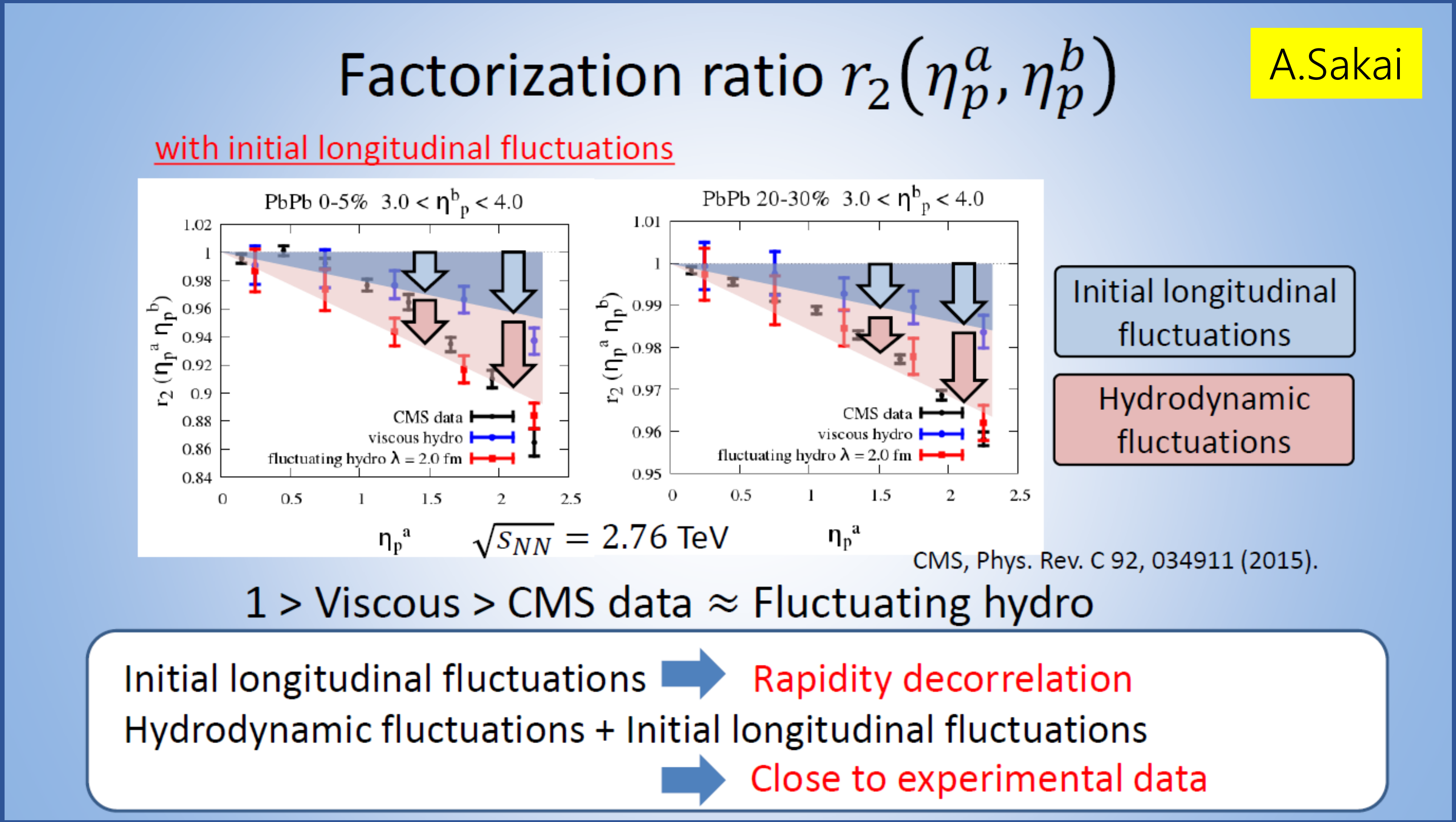
See also, B.Schenke and S.Schlichting
PRC94, 044907(2019)

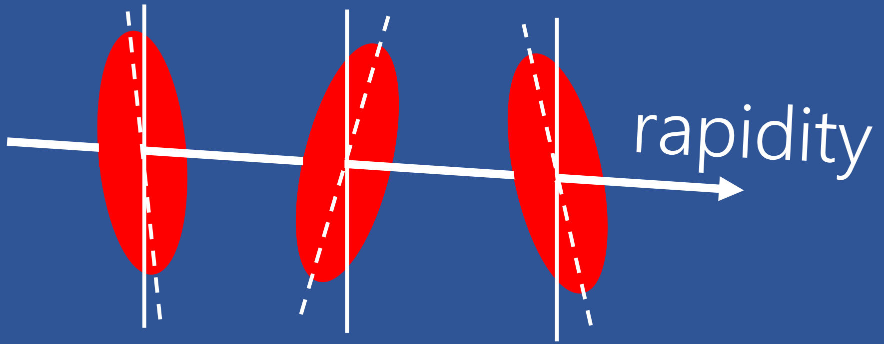


初めての3D IP-Glasma + MUSIC + UrQMD計算

→ 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





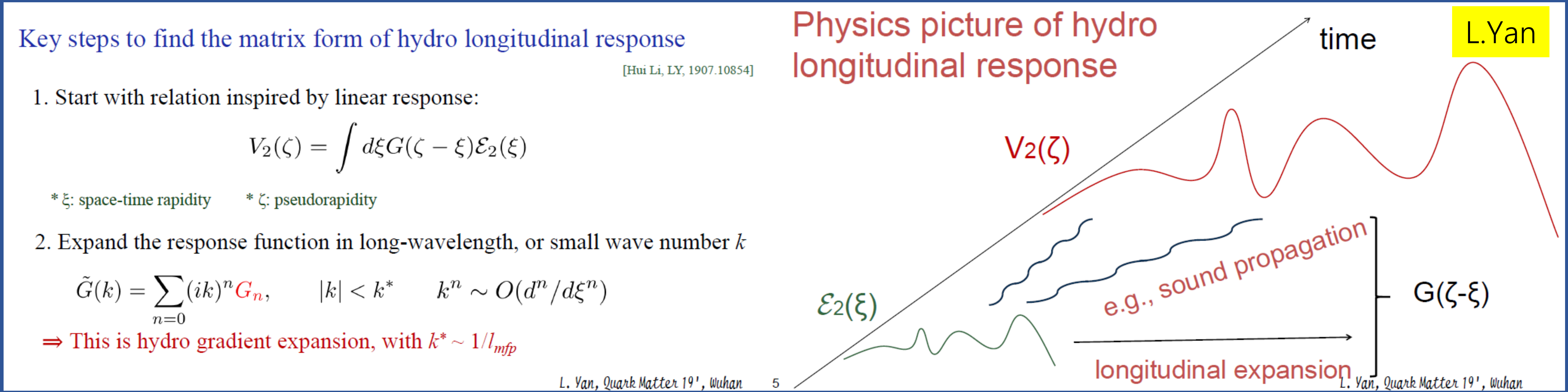
$-2.5 < \eta_p^a < -2.0$

$2.0 < \eta_p^a < 2.5$

$3.0 < \eta_p^b < 4.0$

- 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

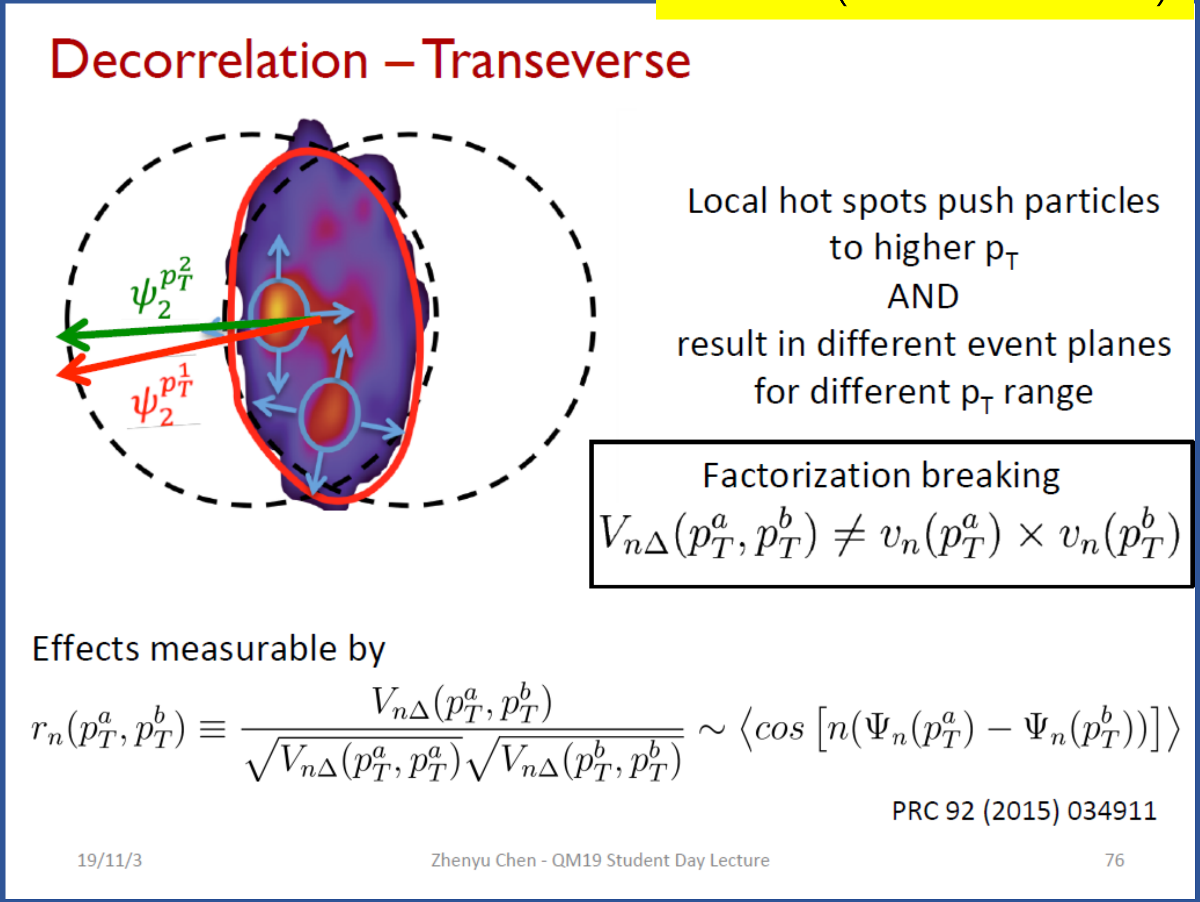
縦方向における初期形状と終期フローの関係



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)



主成分分析 (α=1が最大固有値)

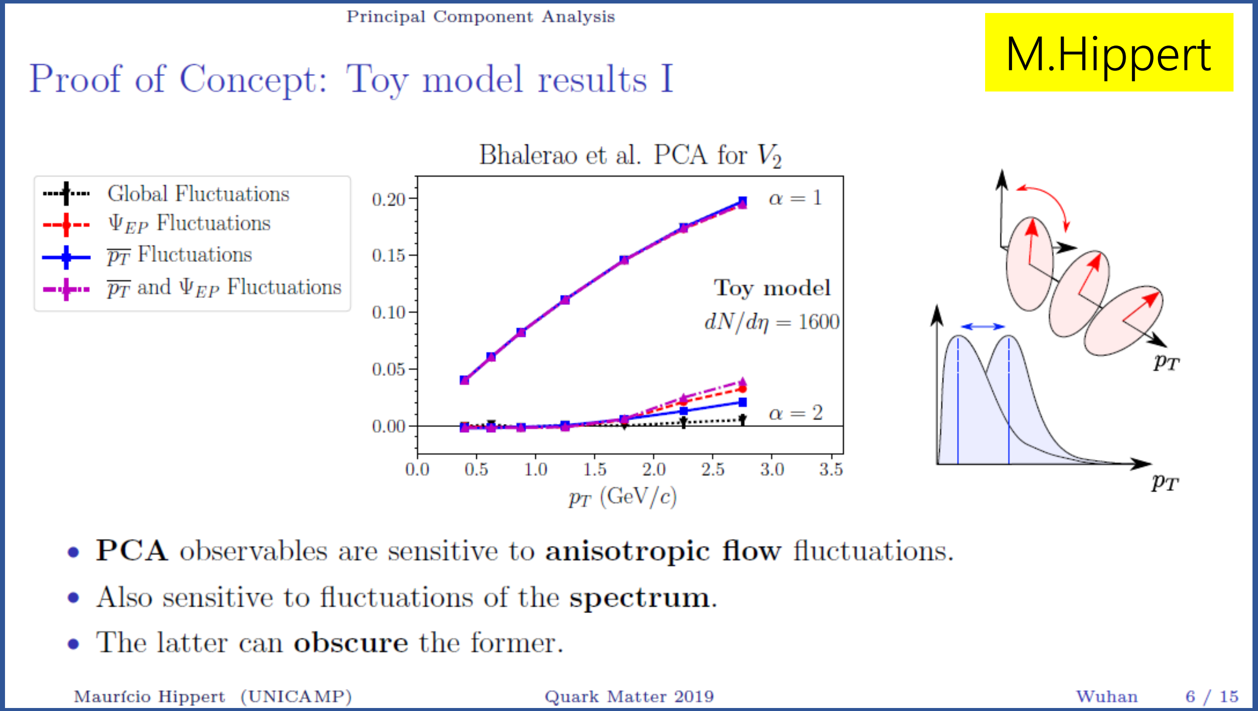
$$V_{n\Delta}(p_T^a, p_T^b) = \sum \lambda_\alpha \psi^{(\alpha)*}(p_T^a)\psi^{(\alpha)}(p_T^b)$$

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

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

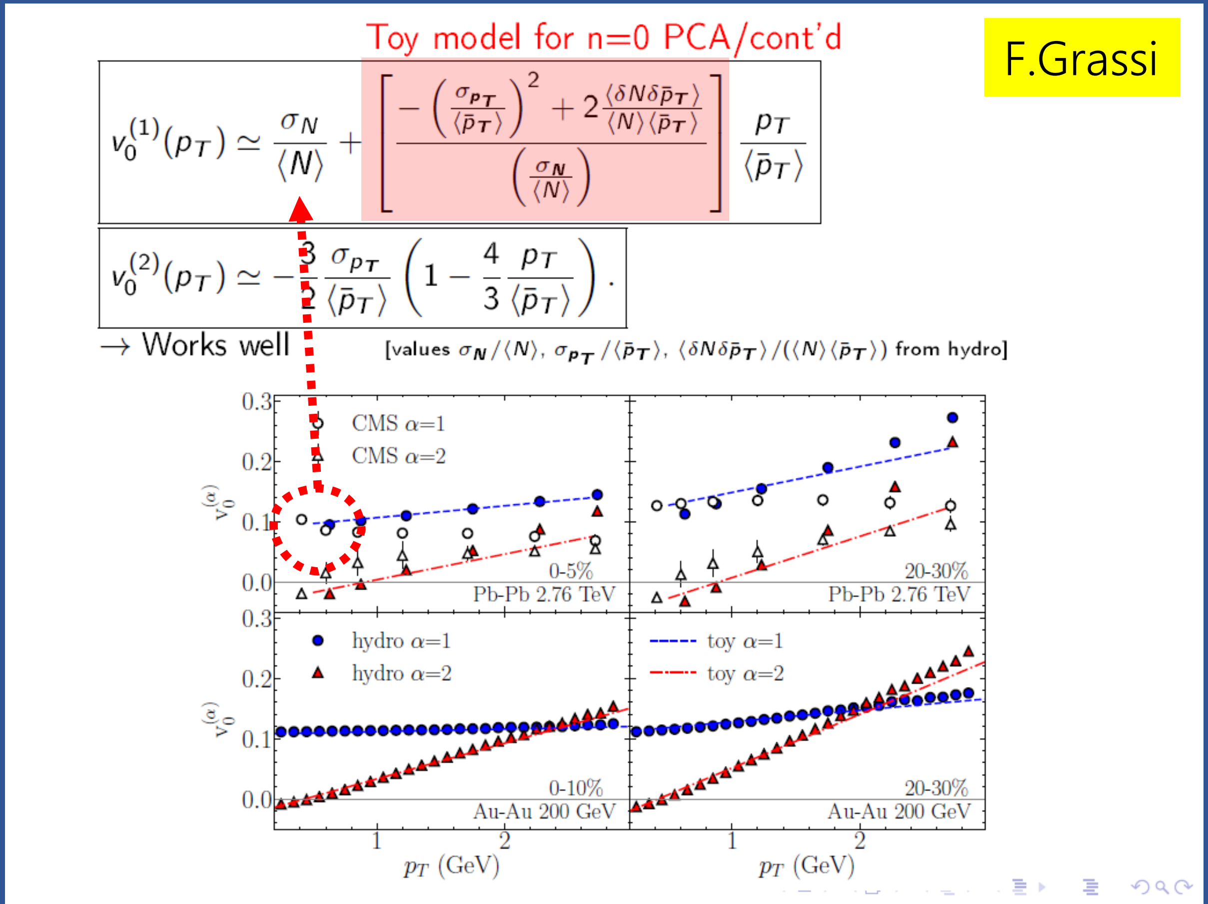
See also, R.S.Bhalerao *et al.*, PRL**114**,152301 (2015)

Proof of Concept



- 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



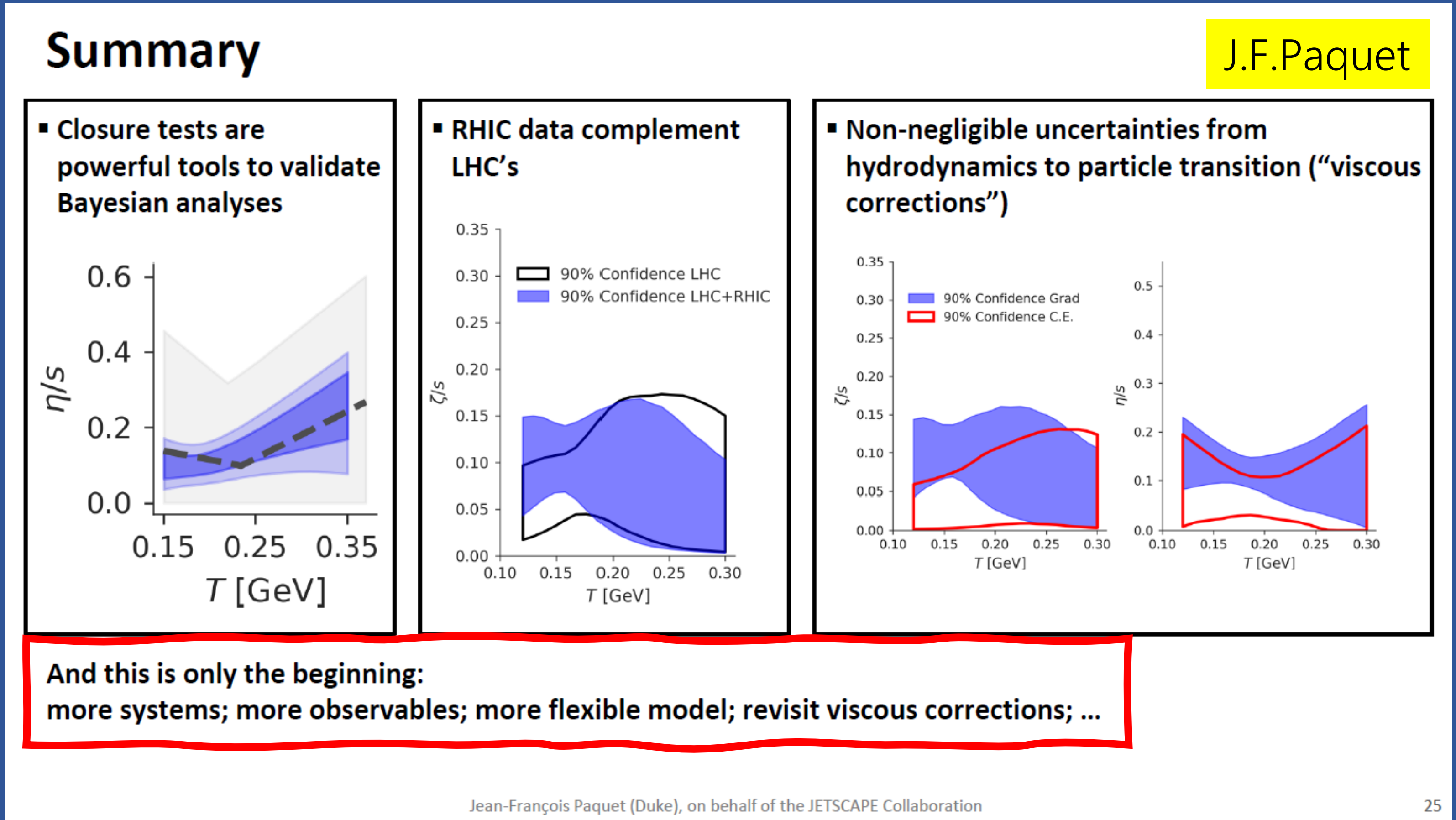
- n=2,3は流体と実験は合う
- n=0の主成分(α=1)が定性的に合わないことが知られている

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



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, $T_{\rm eff}$, and the effective volume, $V_{\rm eff}$, 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.

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

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

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

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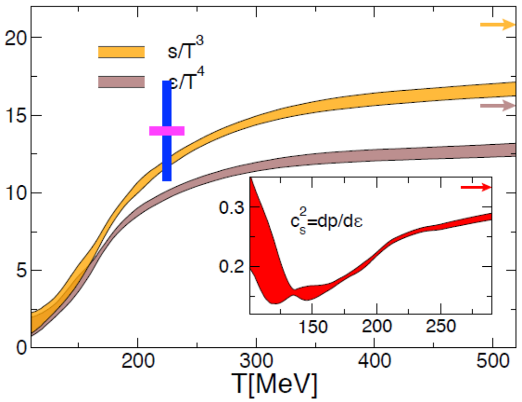
Comparison with lattice QCD



$T_{\rm eff}$=222 ± 9 MeV

$s(T_{\rm eff})/T_{\rm eff}^3$ = 14 ± 3.5

compatible with lattice.

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

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実験　　多重度

平均p_T

流体計算　　有効体積

→ 有効温度

エントロピー密度

*平均p_T=3.07$T_{\rm eff}$

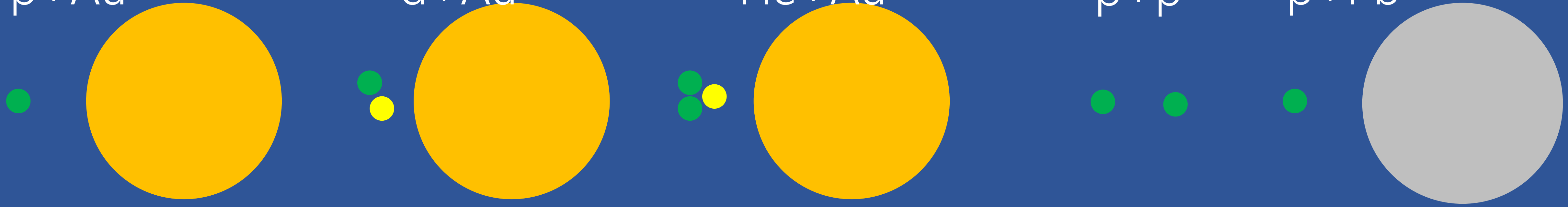
小さい系：To be QGP or not to be?

That is THE question!

RHIC

LHC

p+Au　d+Au　^{3}He+Au　p+p　p+Pb



2003~2010: 原子核効果の指標測定

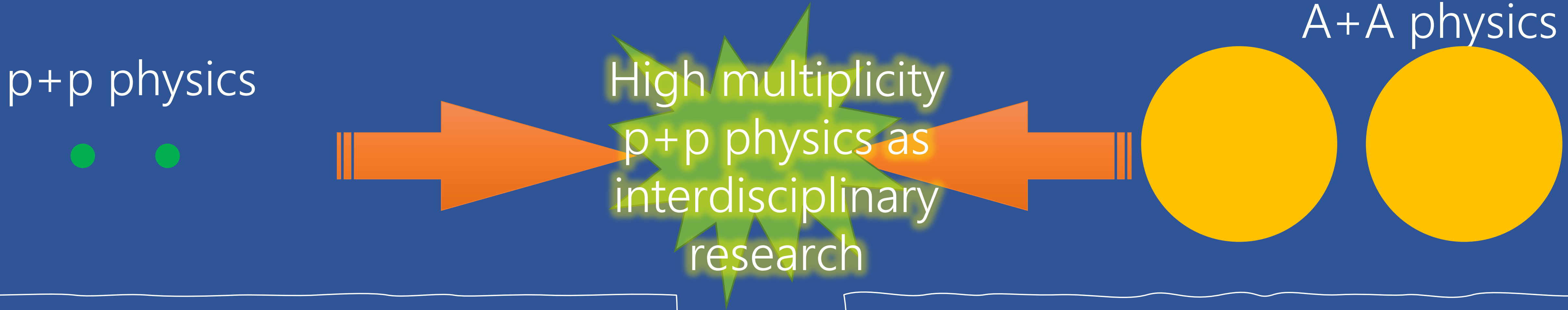
→ cold nuclear matter (CNM) 効果

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

See also, 平野哲文、原子核研究62, 41 (2018)

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



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.*, PLB**779**, 58 (2018)

Introducing GLEIPNIR (ᚷᛚᛖᛁᛈᚾᛁᚱ)

The string endpoints (quarks and glu… momentum, but the string itself cann…

transverse separation between flux tubes

The shoving gives a transverse push …

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

This push must be parallel to both string pieces.

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

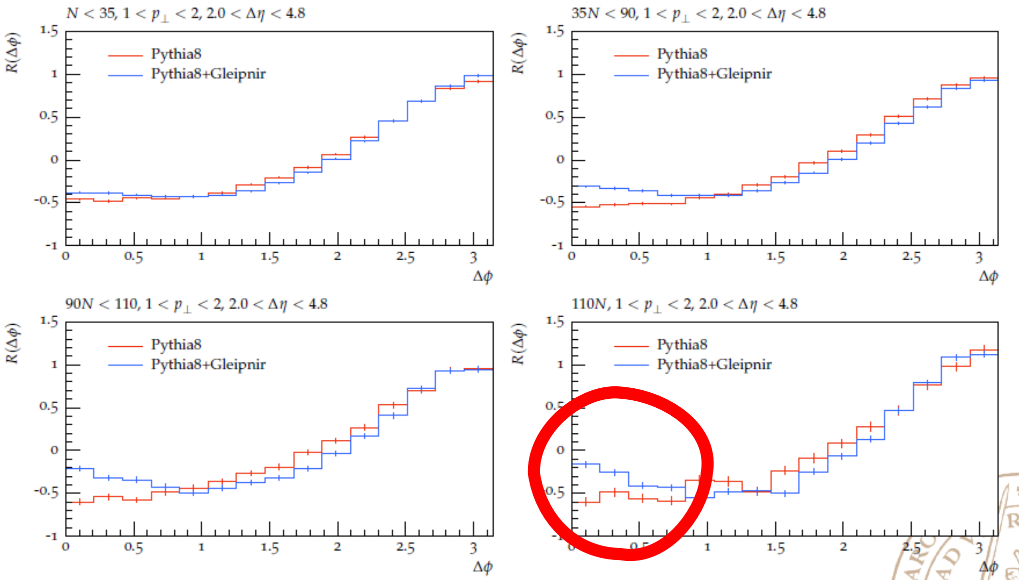
But there is always a frame where they lie in parallell planes at any given time.

[work in progress]

Angantyr
Gleipnir

L.Lönnblad

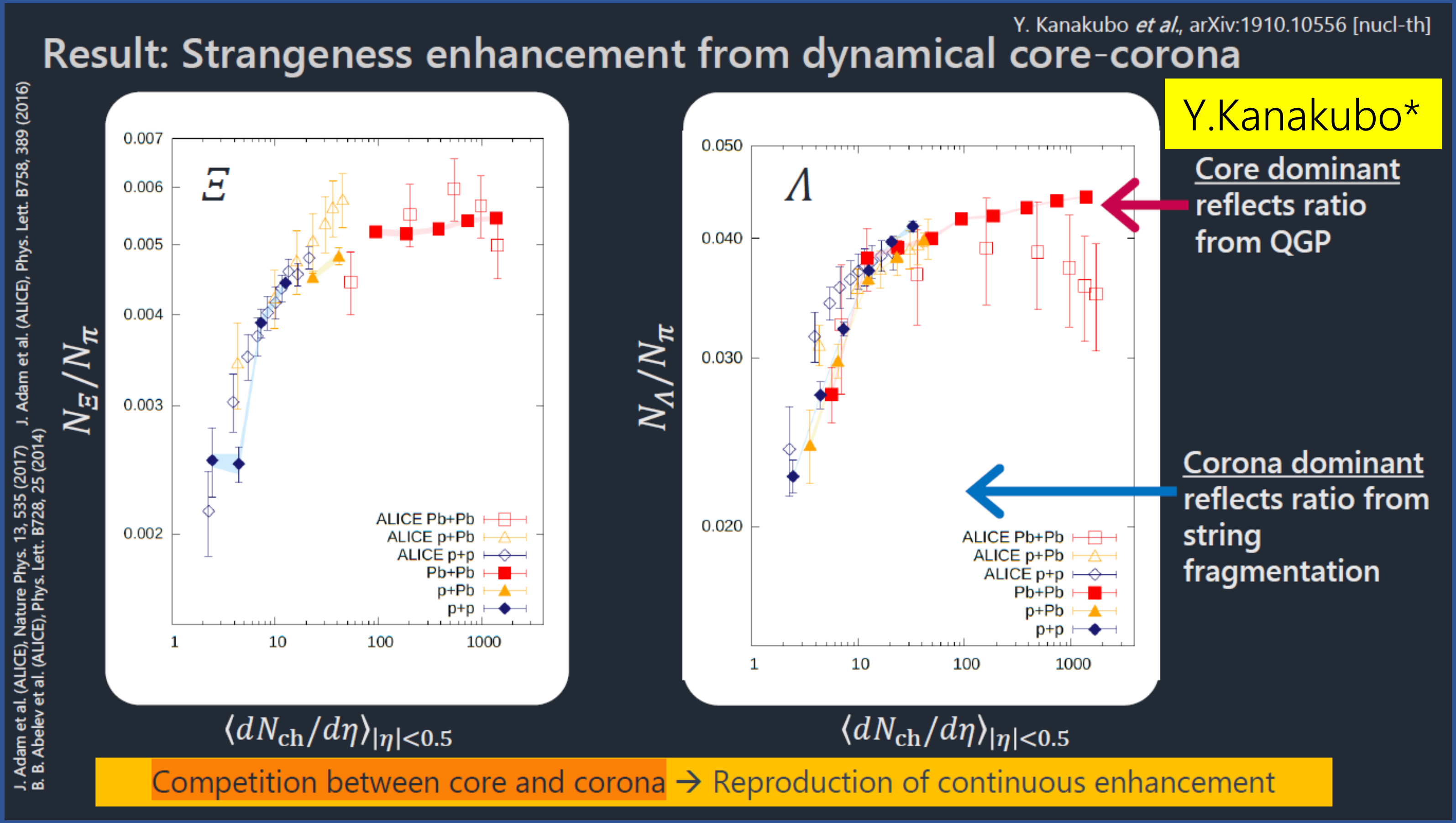
We have a ridge!



[arXiv:1009.4122]

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

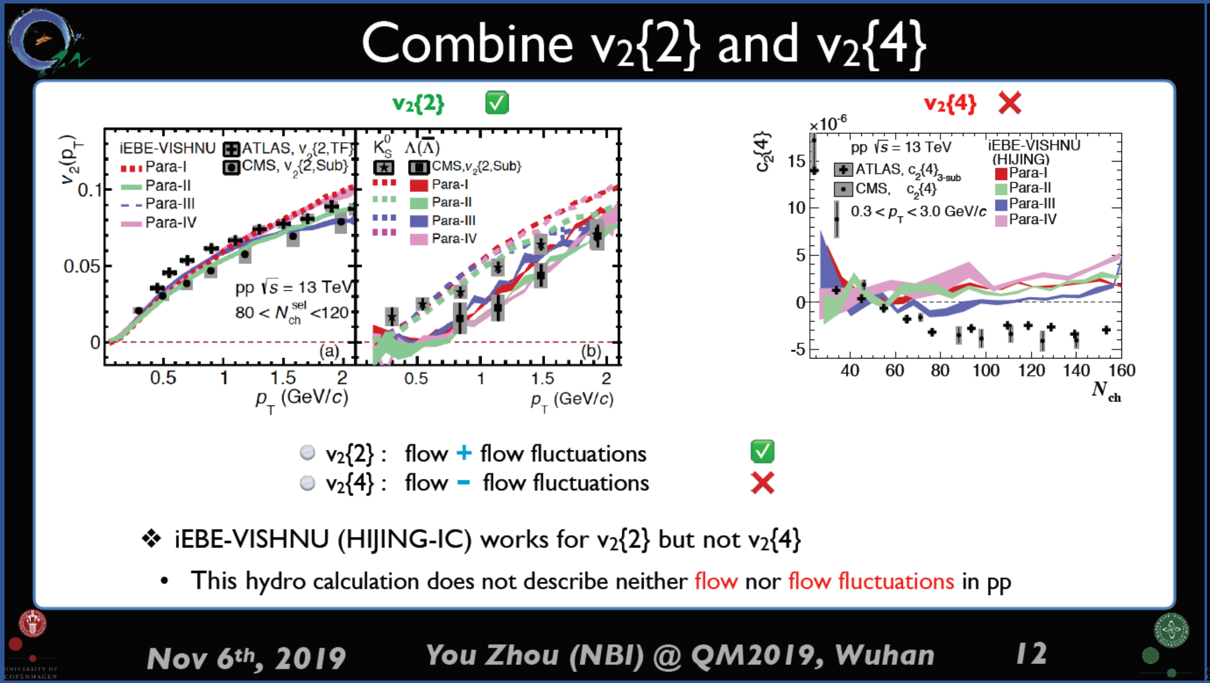
From AA to pp within hydro

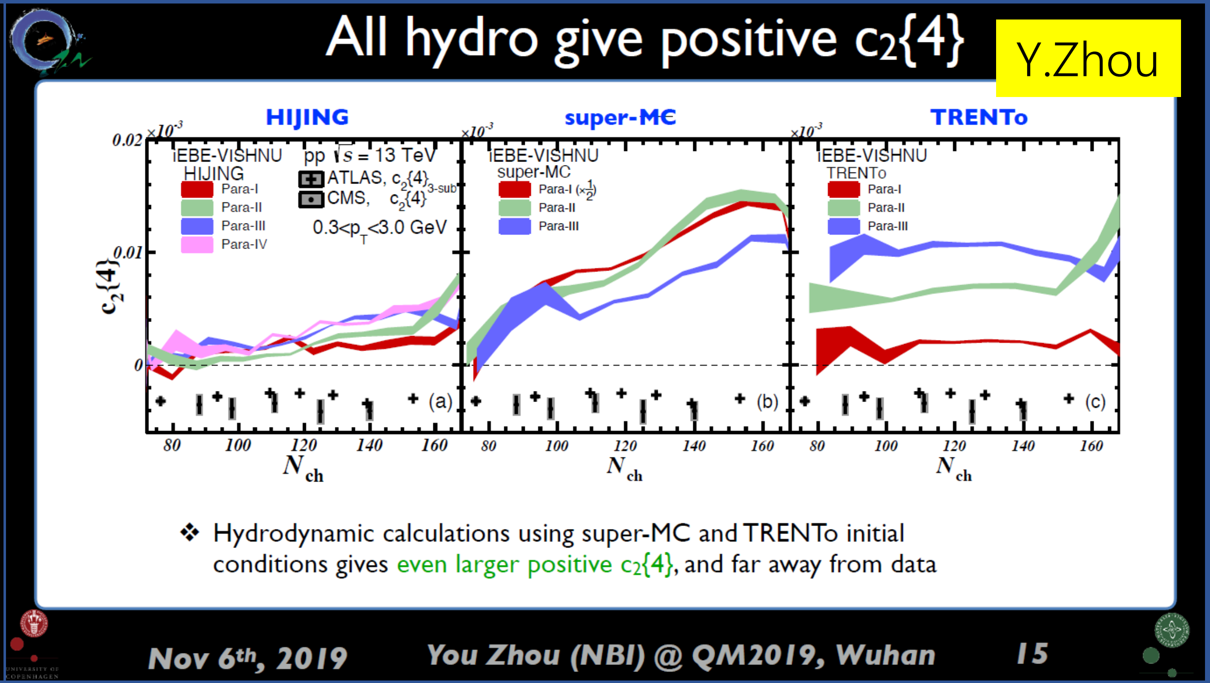


- 大きい系から小さい系から統一的に
- 動的コアーコロナ初期化
- PYTHIA初期設定に対するアフターバーナー
- AAからの拡張
- ジェットも見据えた大描像

*Nuclear Physics A Elsevier Young Scientist Award

"One fluid may not rule them all"





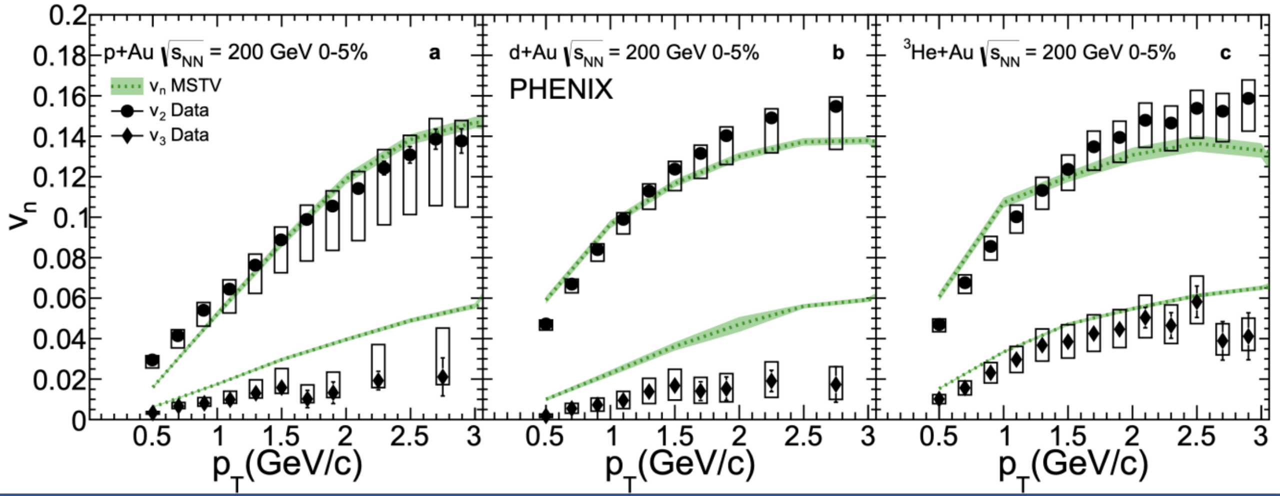
$$v_2\{4\}^4 = 2\langle v_n^2\rangle - \langle v_n^4\rangle = -c_2\{4\}$$

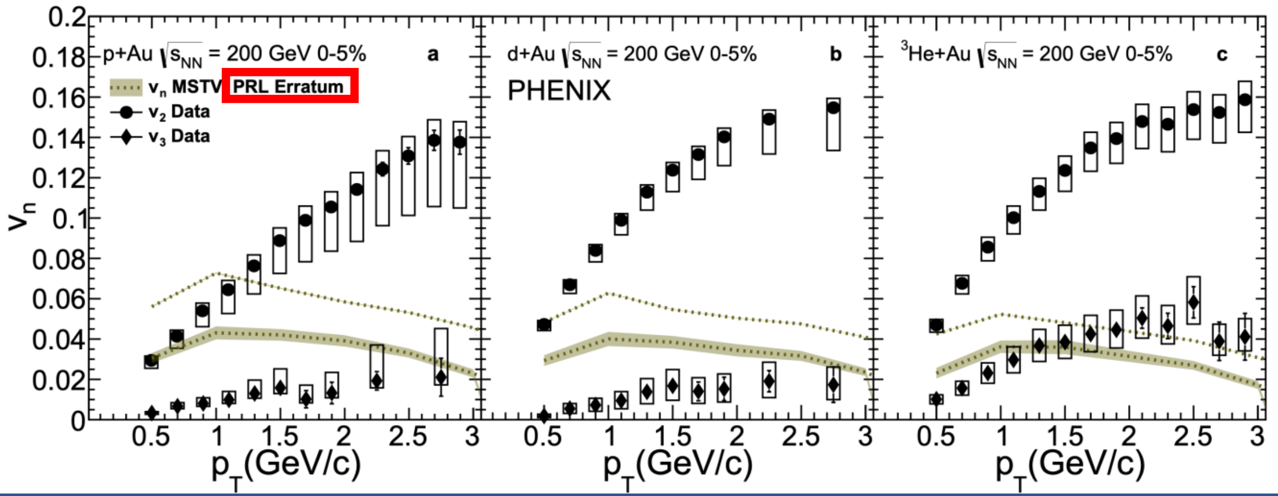
$$\langle v_n^2\rangle = \langle v_n\rangle^2 + \sigma_{v_n}^2$$

- ***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



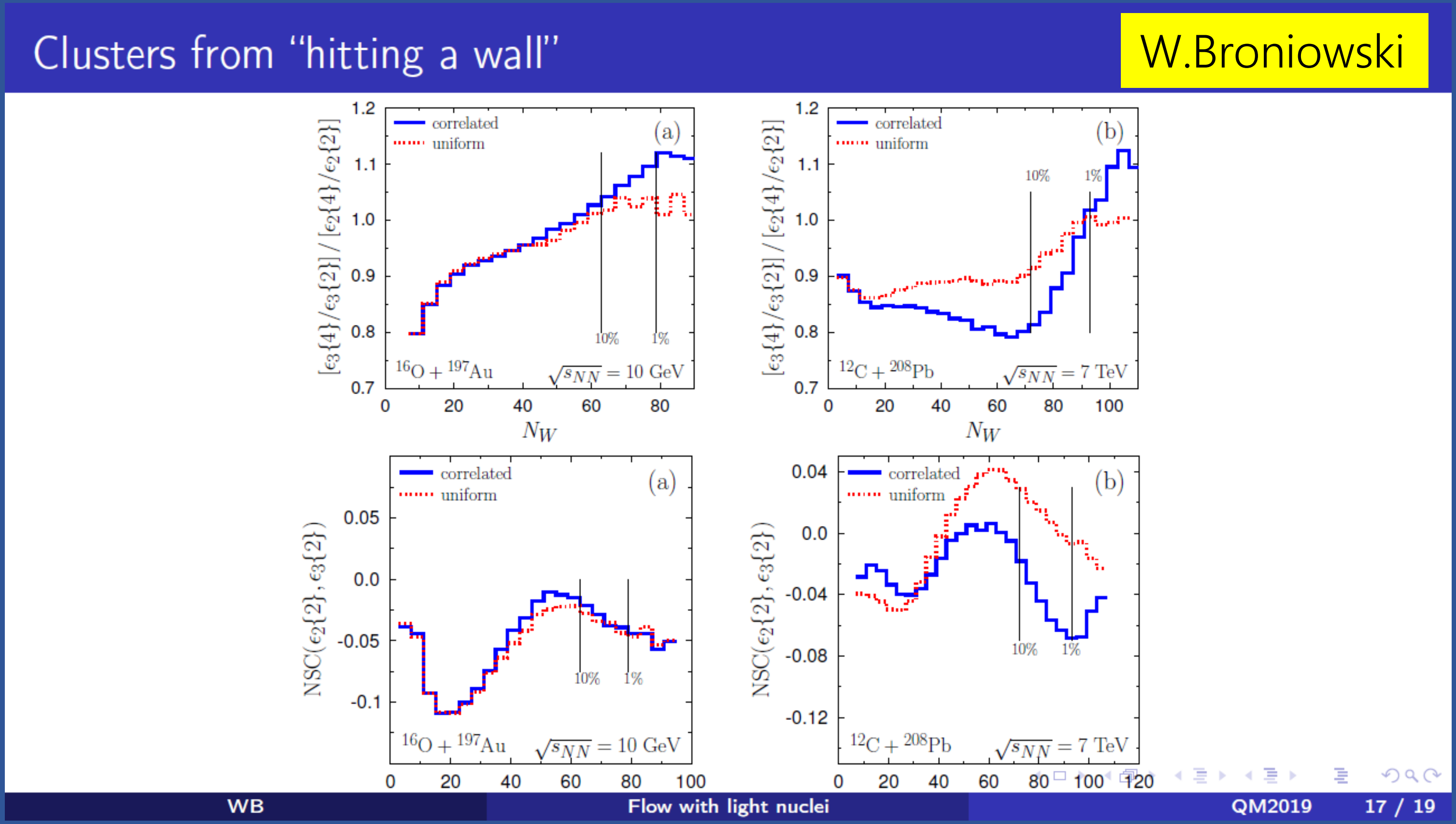


- $v_2(p) > v_2(d) > v_2(^3He)$
- $v_2(p) > v_2(d) > v_2(^3He)$

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, PRL**123**,039901(E) (2019)

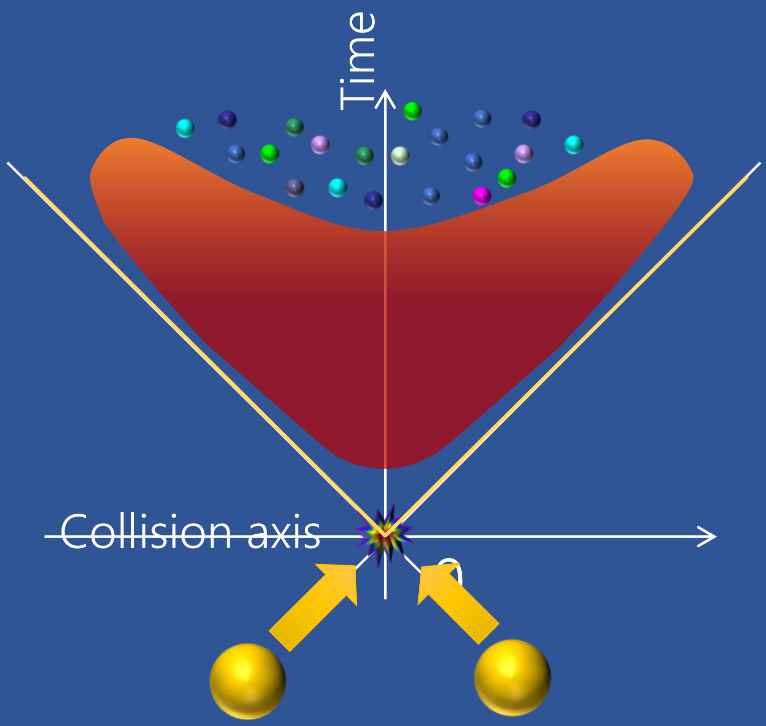
^{12}Cのαクラスター状態？

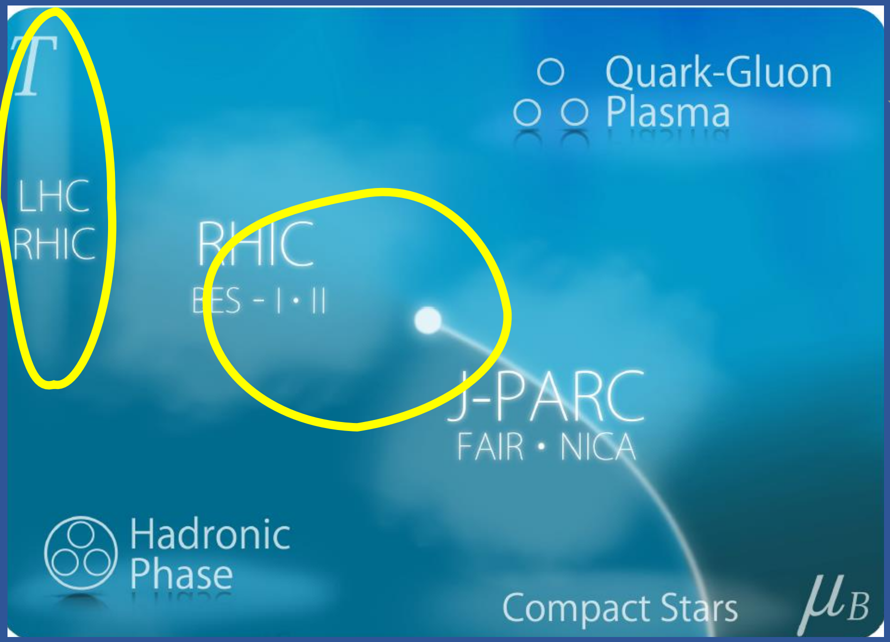


- 重イオン衝突反応で^{12}Cのクラスター状態を探れるか？
- 形起源のtriangular flowで見えるか？
- そもそも励起状態ではないのか？

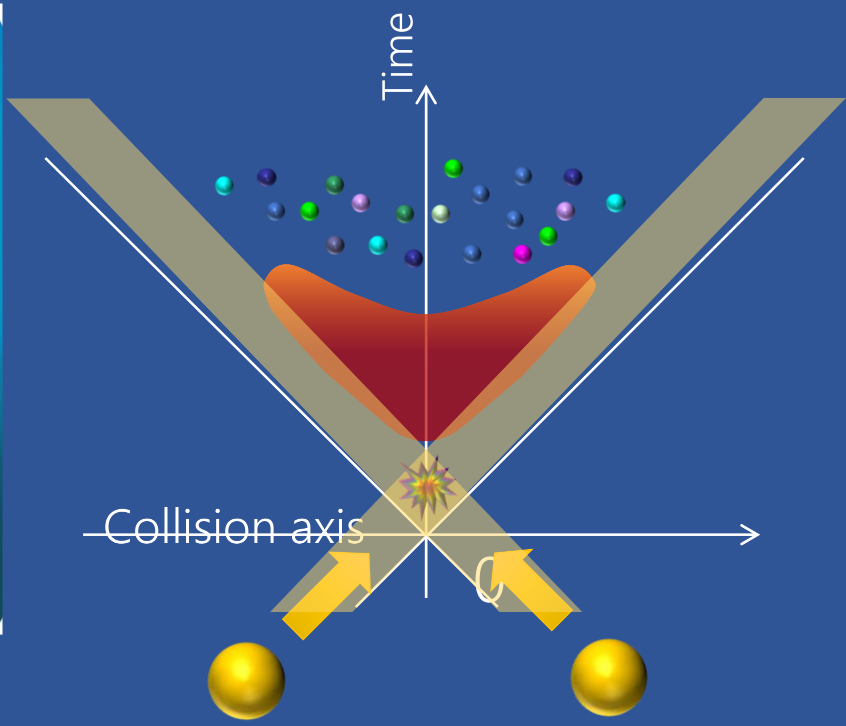
「科研費：クラスター階層」の方々？

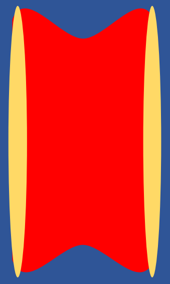
衝突エネルギーの違い



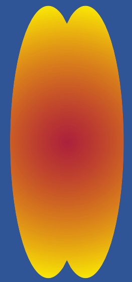


J-PARC-HI white paper

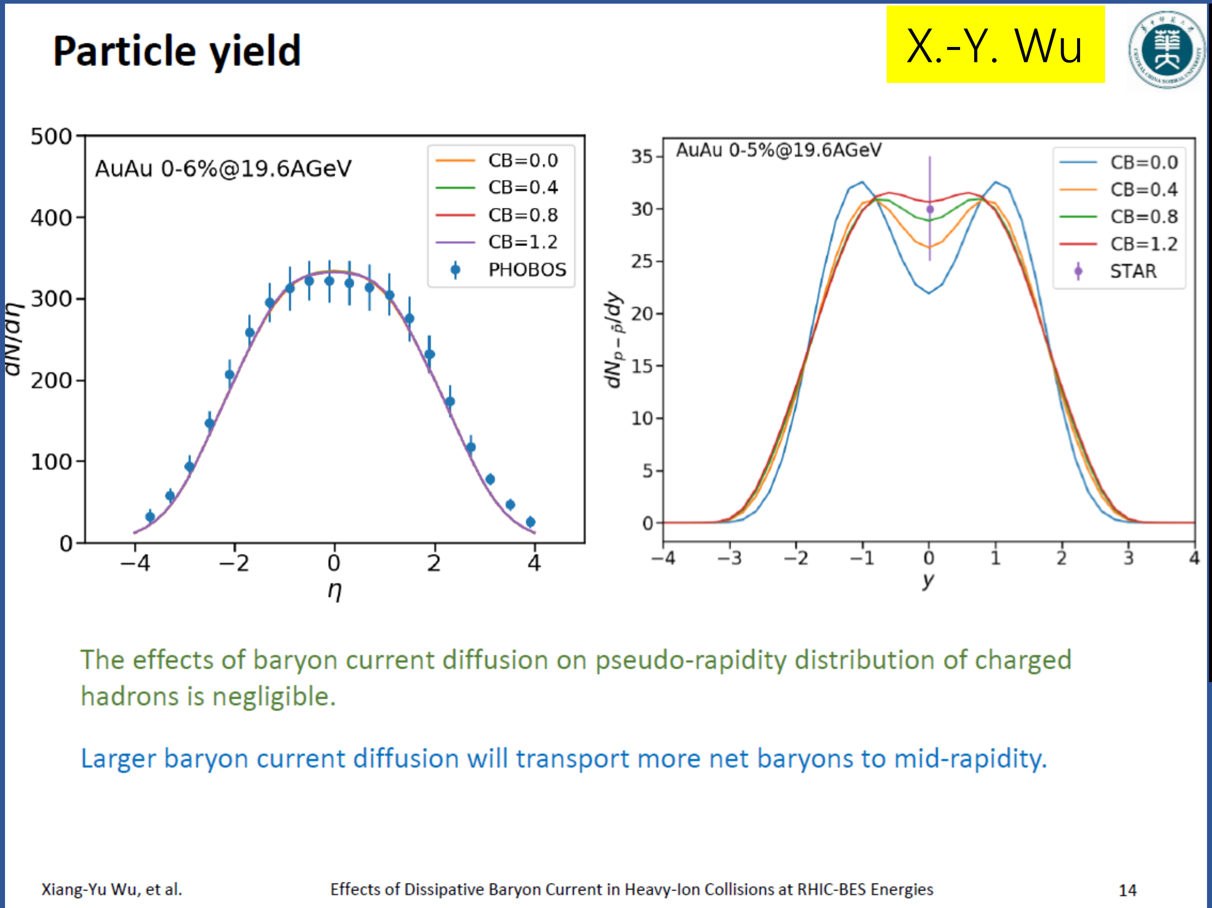


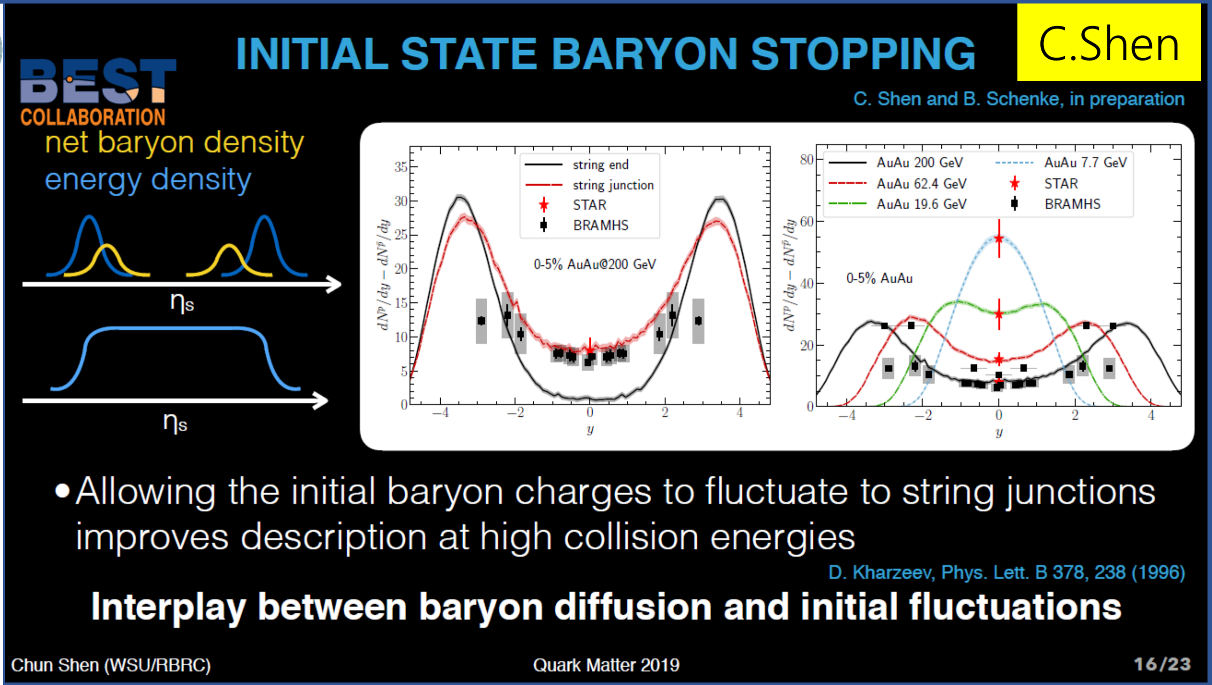


- 保存量の拡散
- 状態方程式の構築
- 臨界現象の探索



保存量の拡散 1

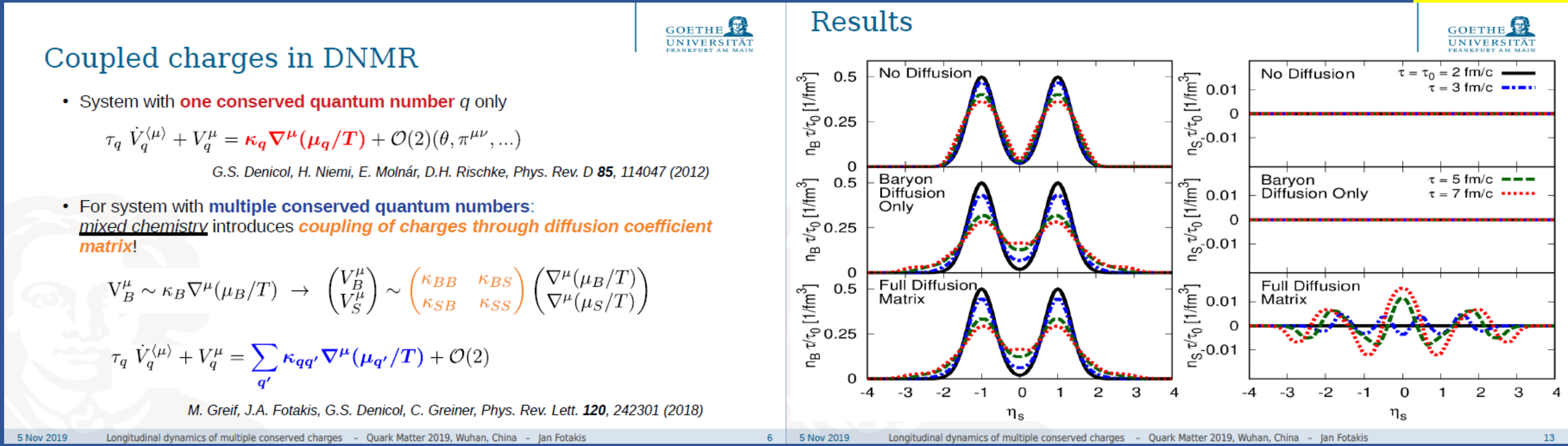




- ストリングジャンクションとバリオン数拡散の拮抗
- 正味陽子数分布の重要性大
- CP探索にも重要？

保存量の拡散２

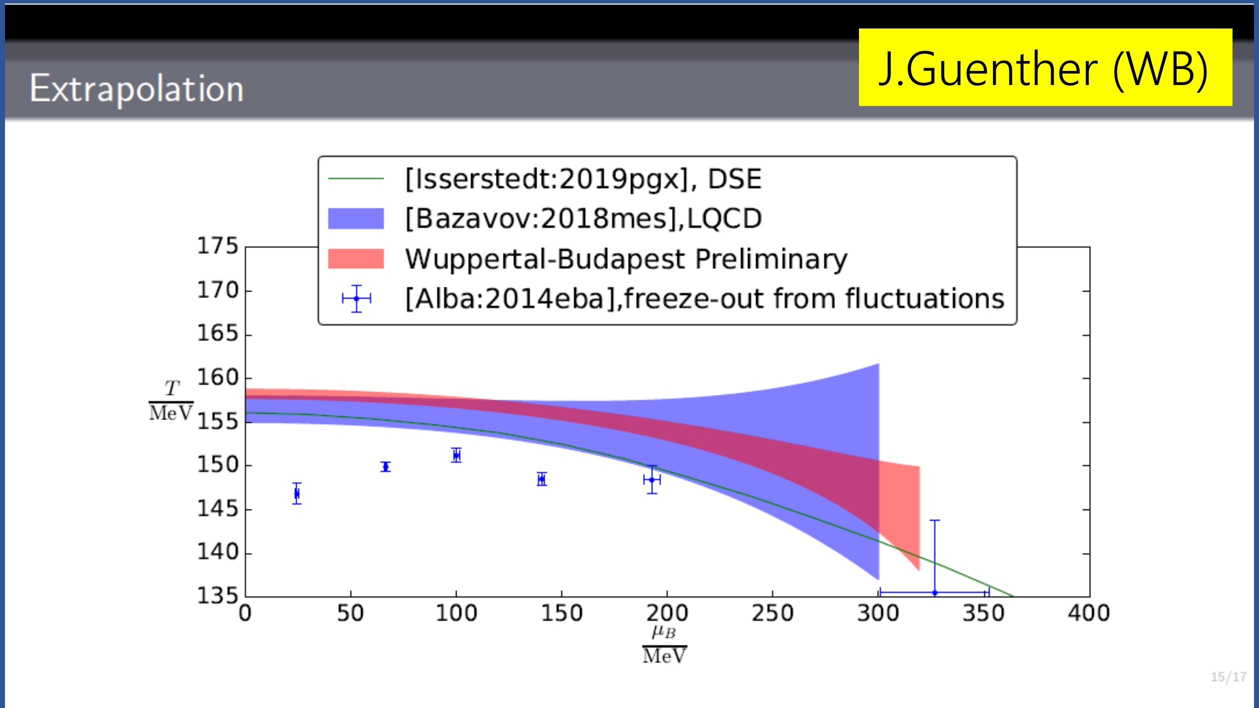
J.Fotakis



- 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 muからの解析接続
- カイラル感受率のピーク位置

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

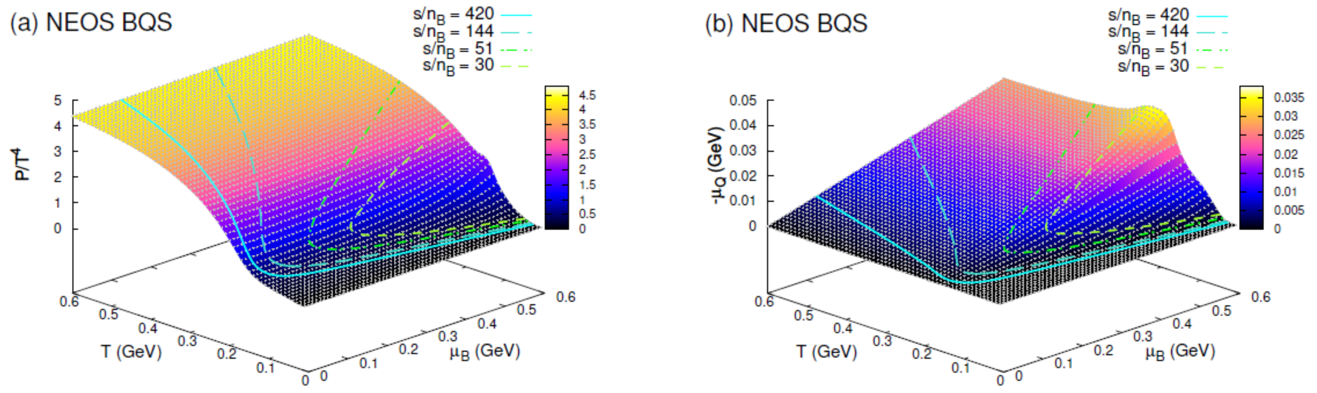
$$T_c(0) \sim 158\ \mathrm{MeV}, \kappa_2 \sim 0.015, \kappa_4 \sim 0$$

重イオン衝突反応(流体計算)用状態方程式

Equation of state

A.Monnai

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



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

Akihiko Monnai (KEK), Quark Matter 2019, 6th November 2019

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- 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？

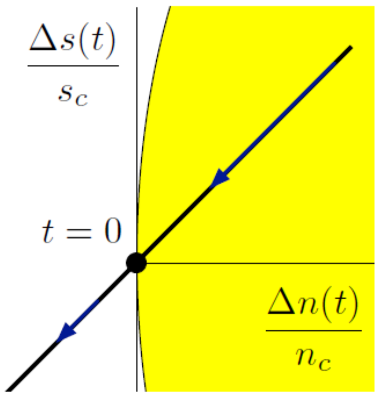
⇩

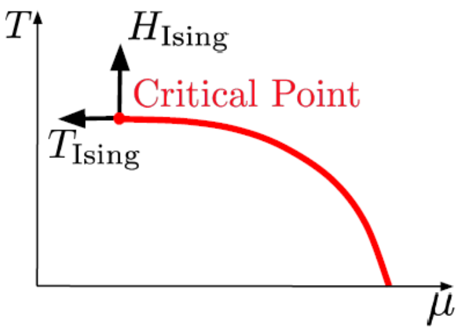
有限密度計算のスタンダードに

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:

$$\Delta s \longleftrightarrow \Delta M_{\rm Ising} \qquad \Delta T_{\rm QCD} \longleftrightarrow \Delta H_{\rm Ising}$$

$$\Delta n \longleftrightarrow \Delta e_{\rm Ising} \qquad -\Delta \mu_{\rm QCD} \longleftrightarrow \Delta T_{\rm Ising}$$

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

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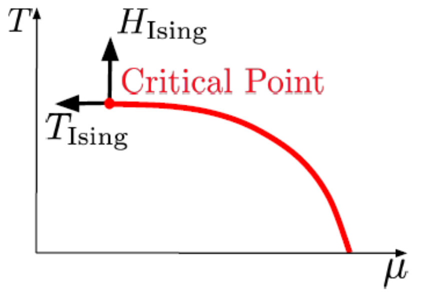
Rethinking the QCD to Ising Map

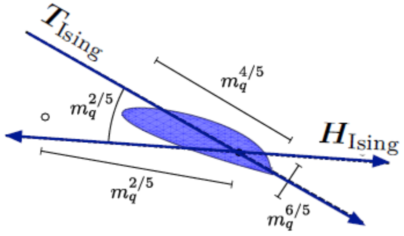
M. Pradeep, Stephanov 1905.13247

- 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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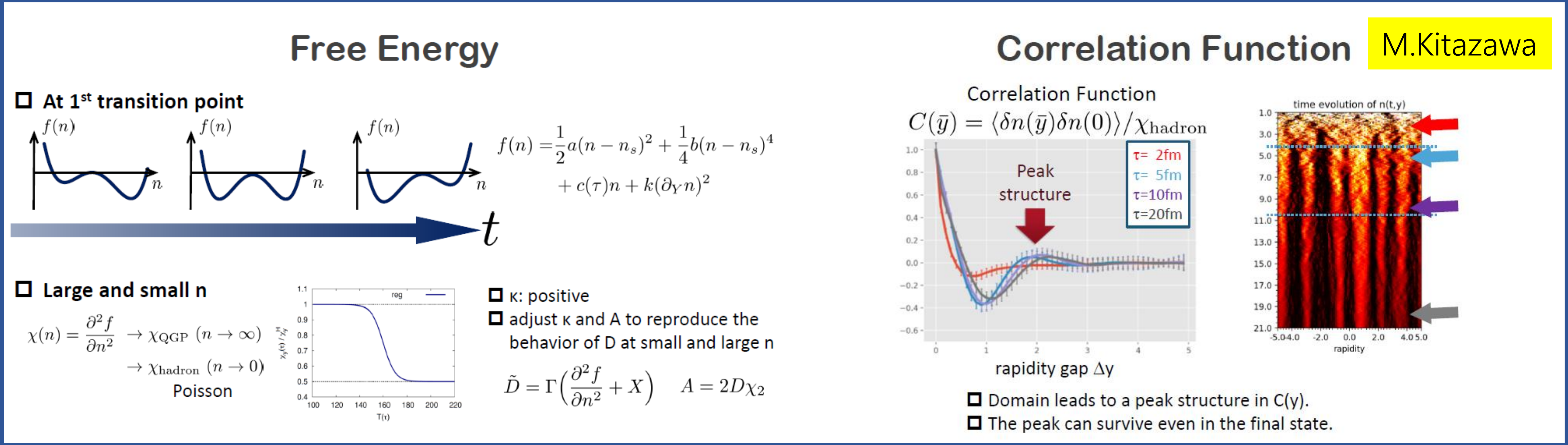
See also, Y.Akamatsu *et al.*, PRC**100**, 044901 (2019)

See also, M.S.Pradeep and M.Stephanov, PRD**100**, 056003 (2019)

1次相転移によるドメイン形成

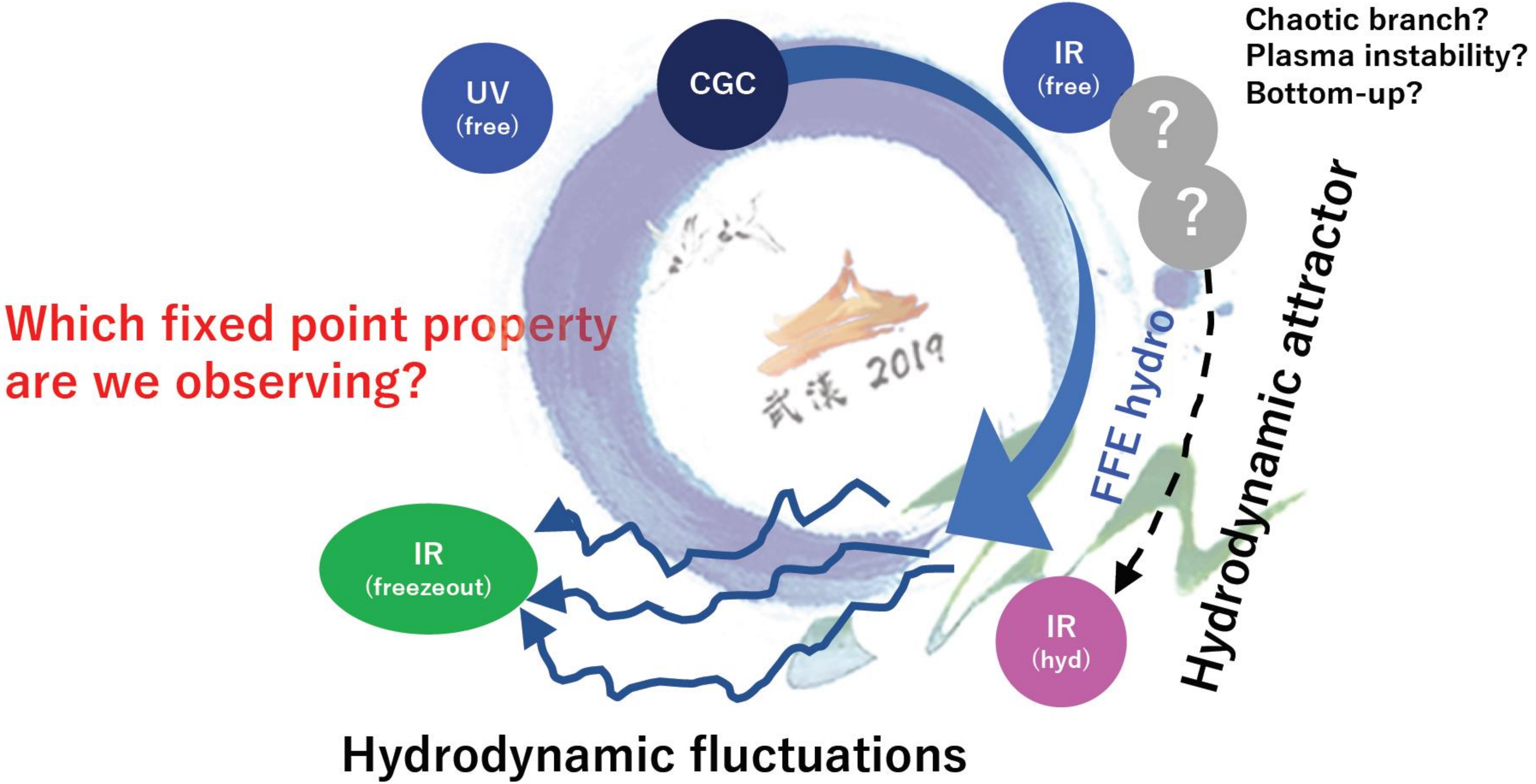


臨界点ピンポイントではなく、
その先の1次相転移線を通った場合

- 相関関数にピークΔy~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

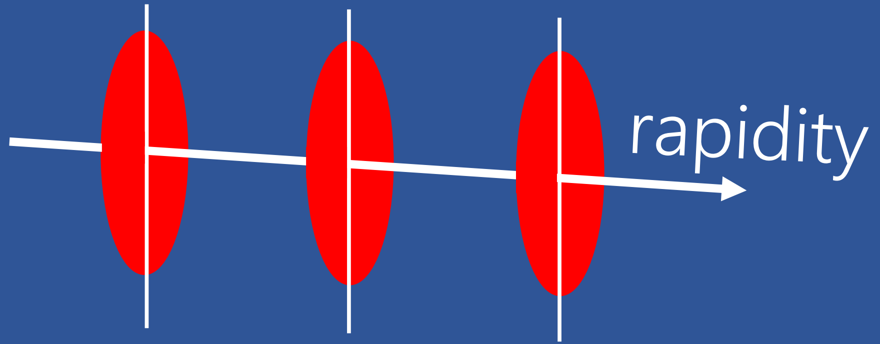
Factorization ratio and event plane decorrelation

<u>Factorization ratio</u>

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

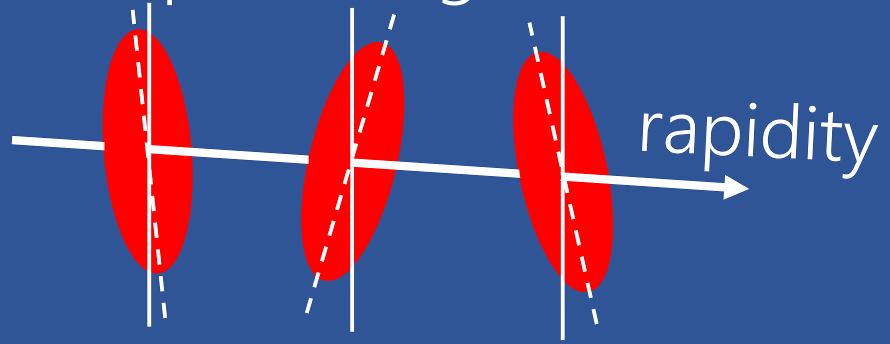
$$V_{n\Delta} = \langle \cos(n\Delta\phi) \rangle$$

Aligned event plane angle



$r_2 = 1$

Event plane angle decorrelation



$r_2 < 1$

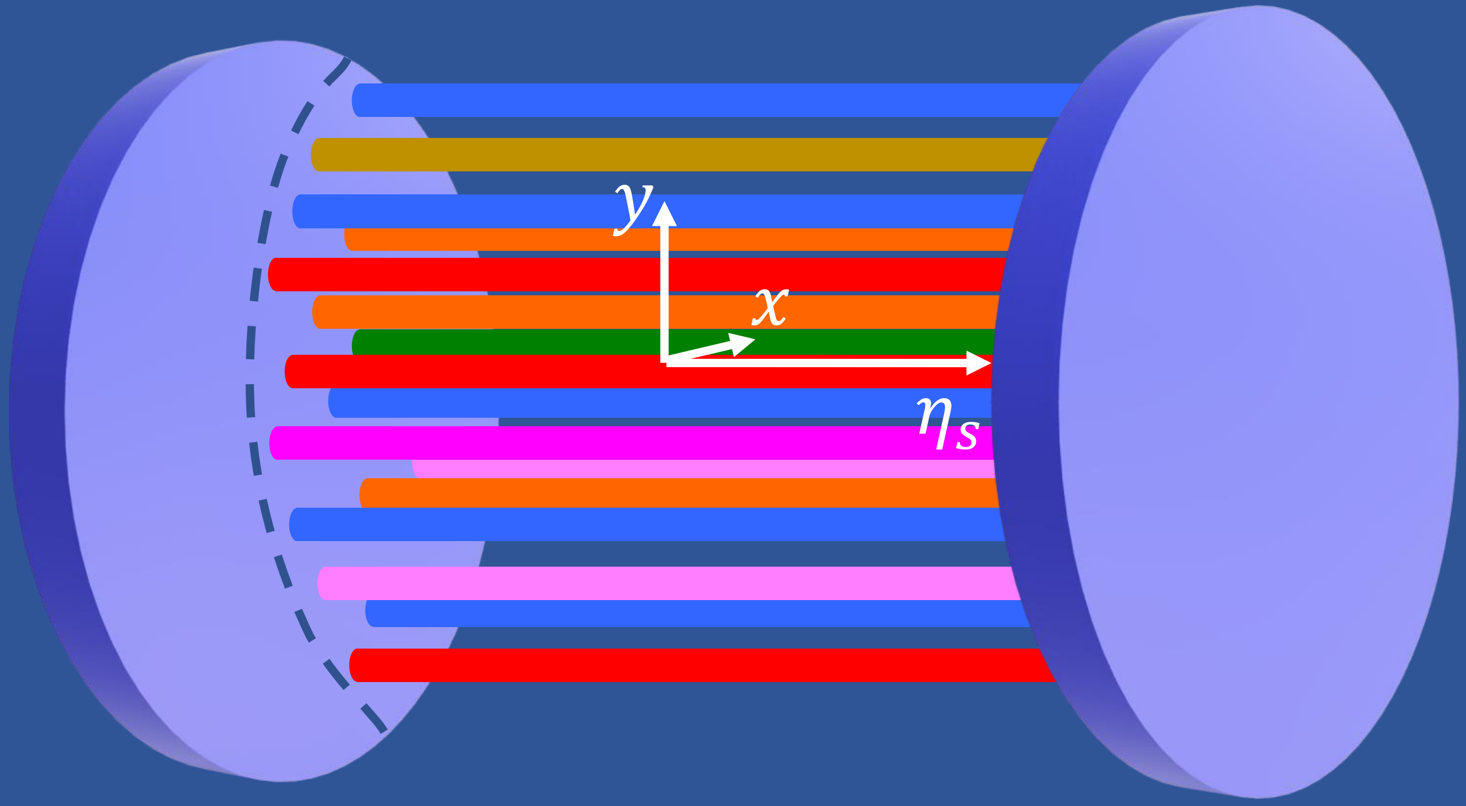
$-2.5 < \eta_p^a < -2.0$

$2.0 < \eta_p^a < 2.5$

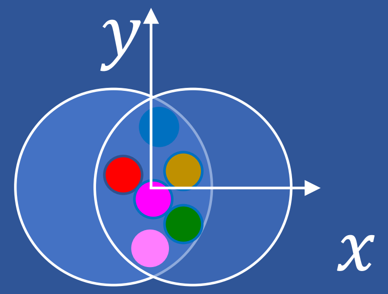
$3.0 < \eta_p^b < 4.0$

F. G. Gardim, F. Grassi, M. Luzum, and J.-Y. Ollitrault, Phys. Rev. **C87**, 031901 (2013),

Correlations along collision axis



$\tau = 0^+$



Heavy ion collision as a chromoelectric capacitor

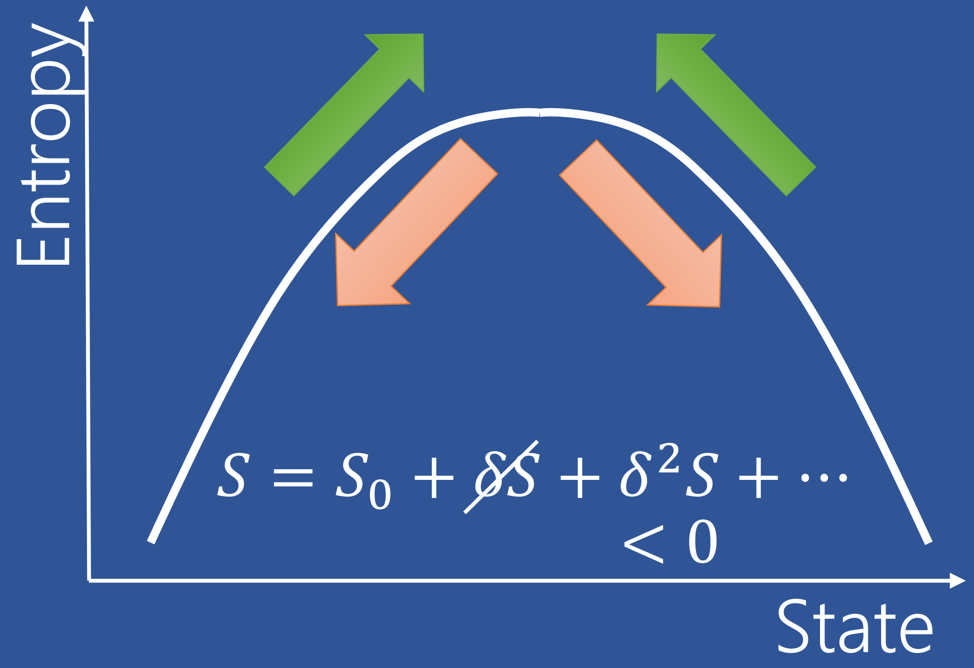
→ Approximately boost-invariant formation of color flux tubes

→ Correlation embedded in wide rapidity region

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

Hydrodynamic fluctuations

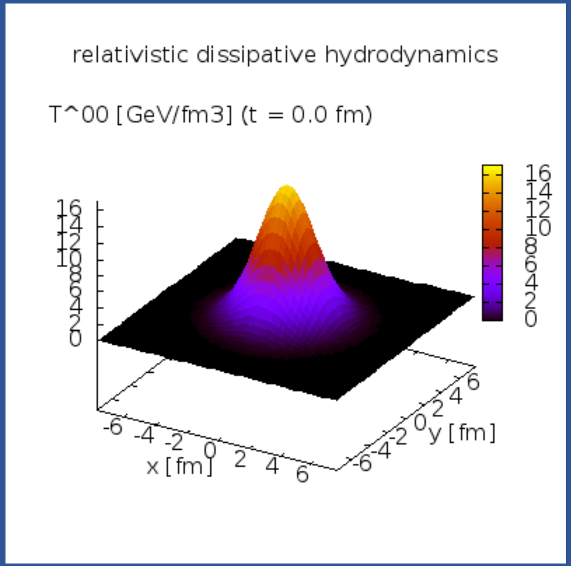
Fluctuation-Dissipation relations



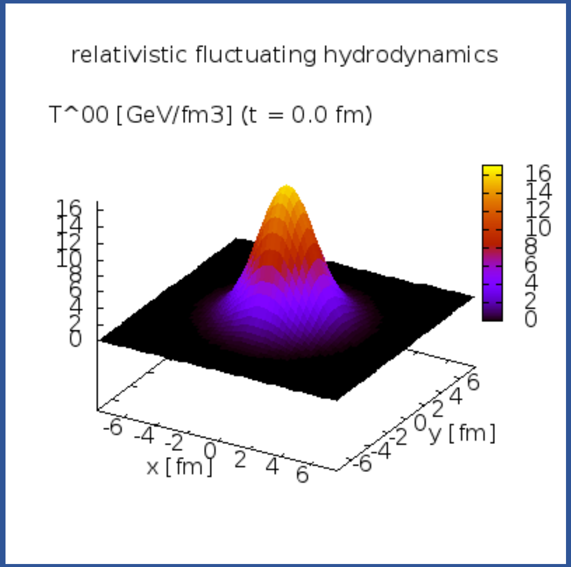
Fluctuations around maximum entropy state

QGP fluid simulation in a box

Courtesy of K.Murase



Dissipative hydro (2nd Generation)

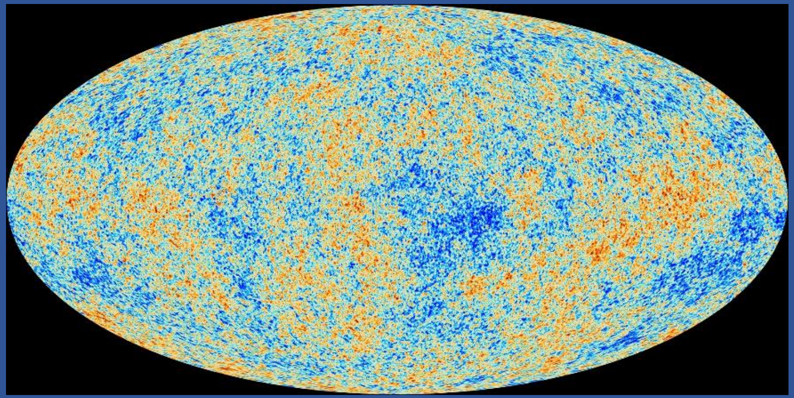


Fluctuating hydro (3rd Generation)

Dissipations ←→ Fluctuations

Introduction

Lessons from Observational Cosmology



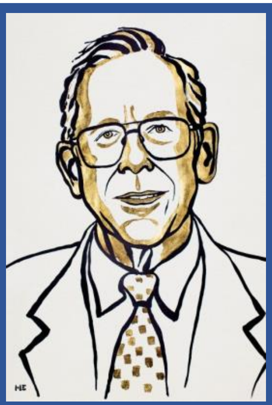
Cosmic Microwave Background
Fluctuations of temperature (Planck)
http://www.esa.int/spaceinimages/Images/2013/04/Planck_CMB_black_background

Analysis tool

CAMB, CMBFAST, CosmoMC,…

Cosmological parameters

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

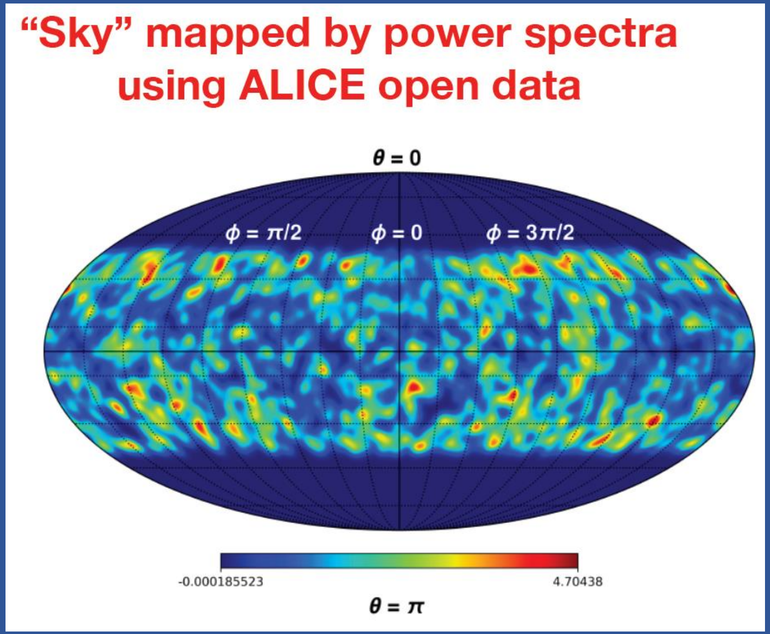


"Physical Cosmology"
James Peebles
The Novel prize in physics 2019

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

Analysis tool

Bottom-up approach in high-energy nuclear collisions



Y.Zhou, talk at QM2018

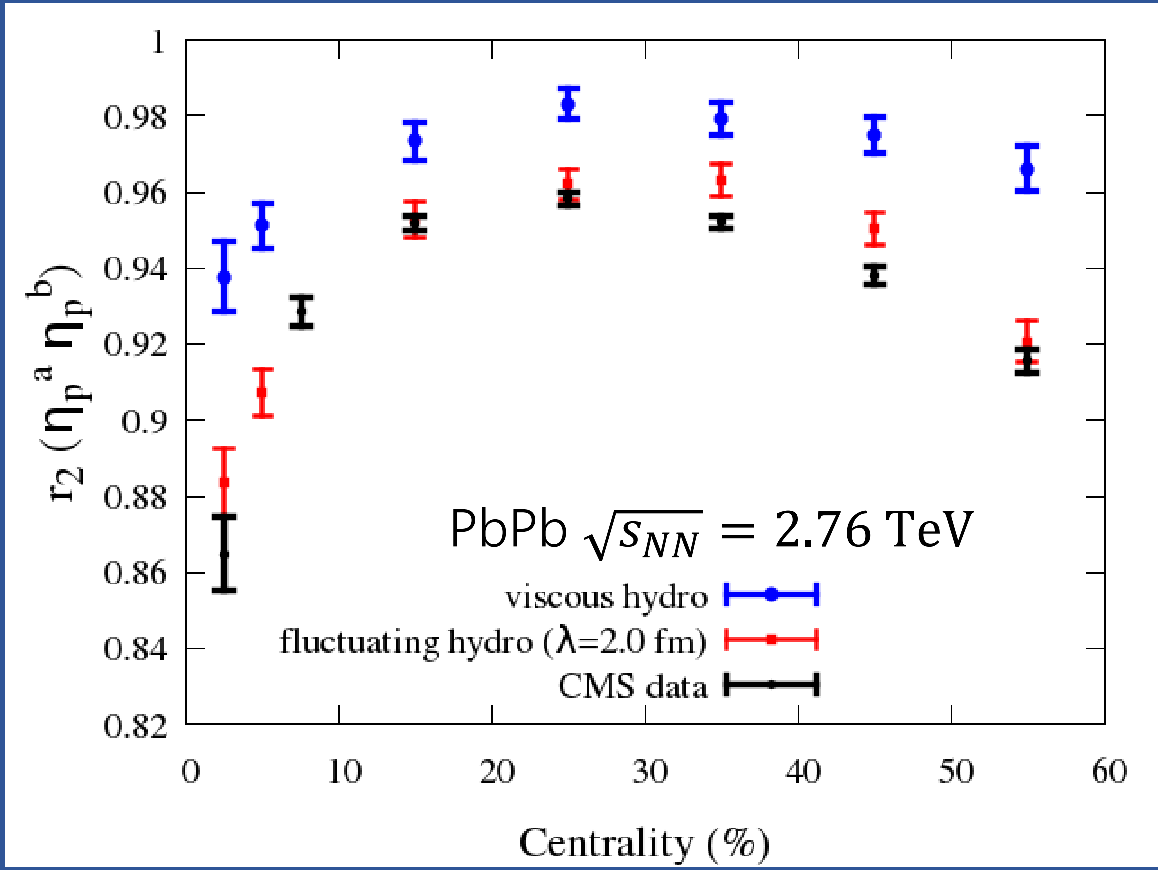
?

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

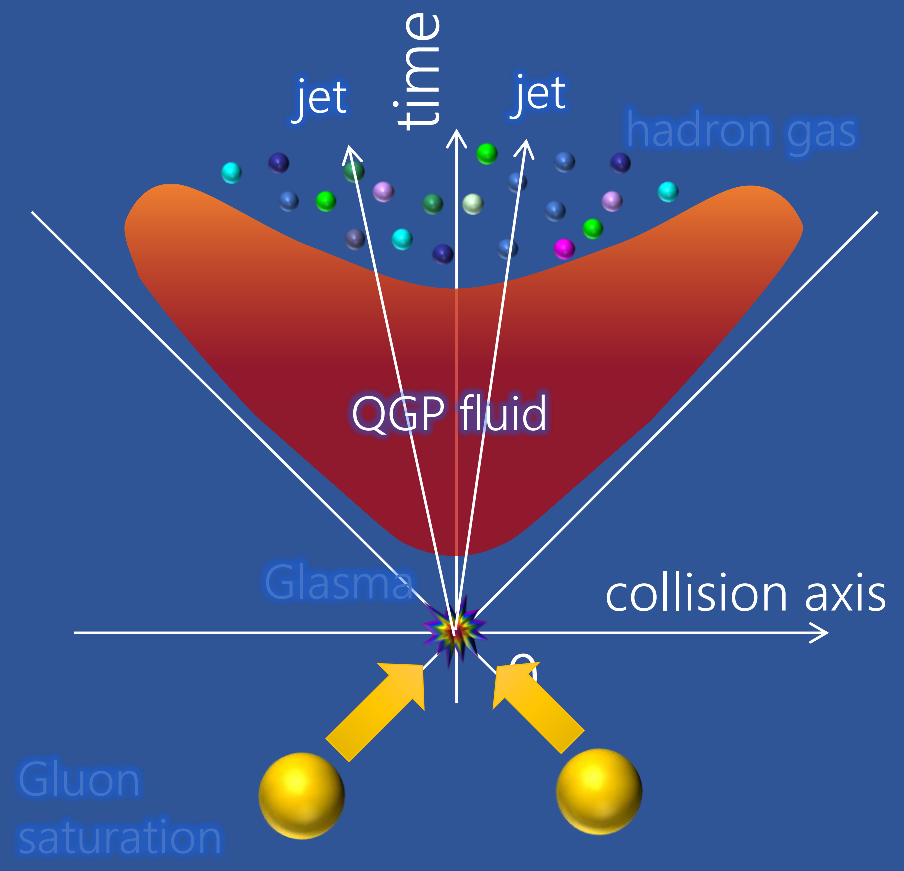


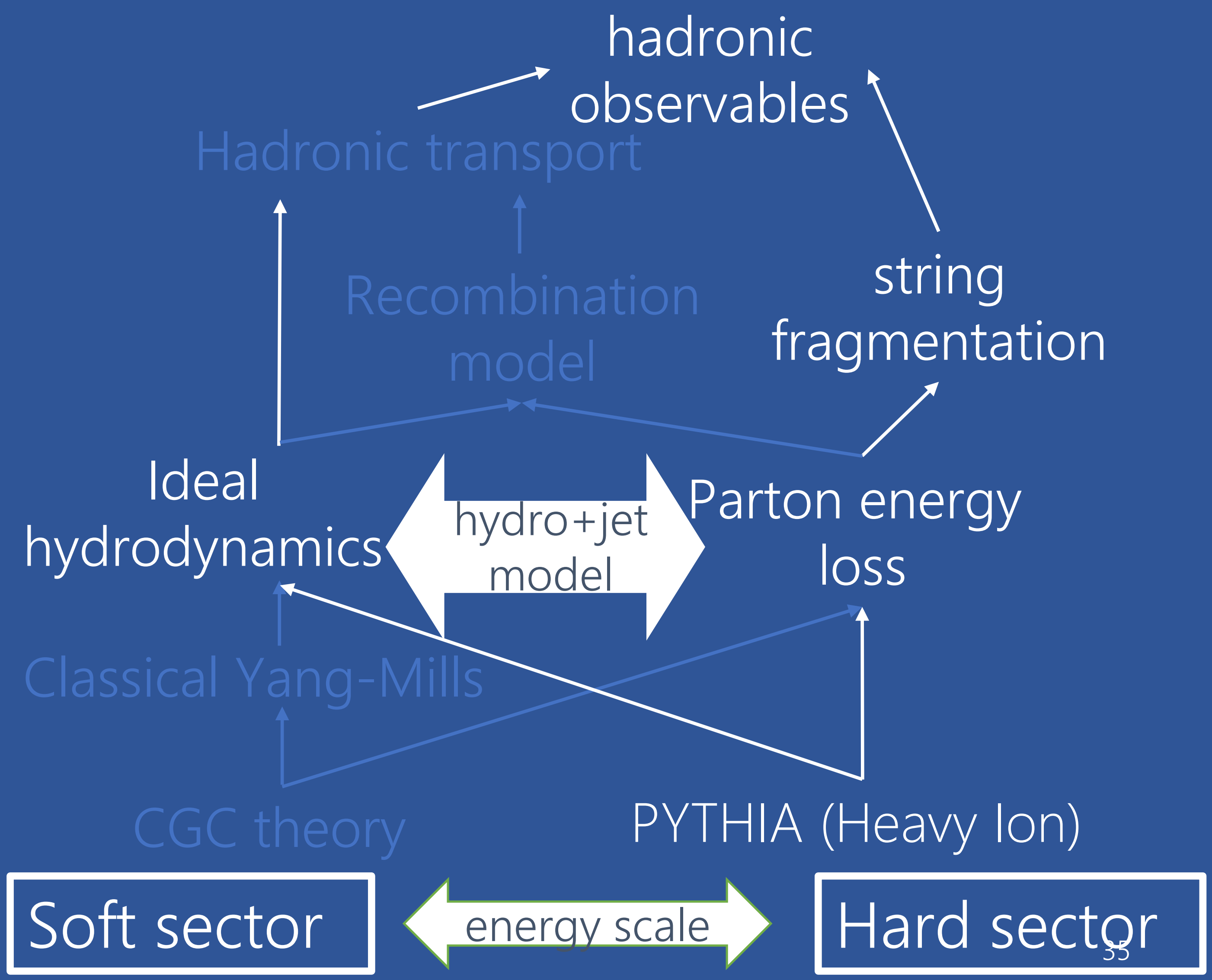
Initial longitudinal fluctuations
→ Insufficient to reduce r_2
Both initial and hydrodynamic fluctuations needed

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

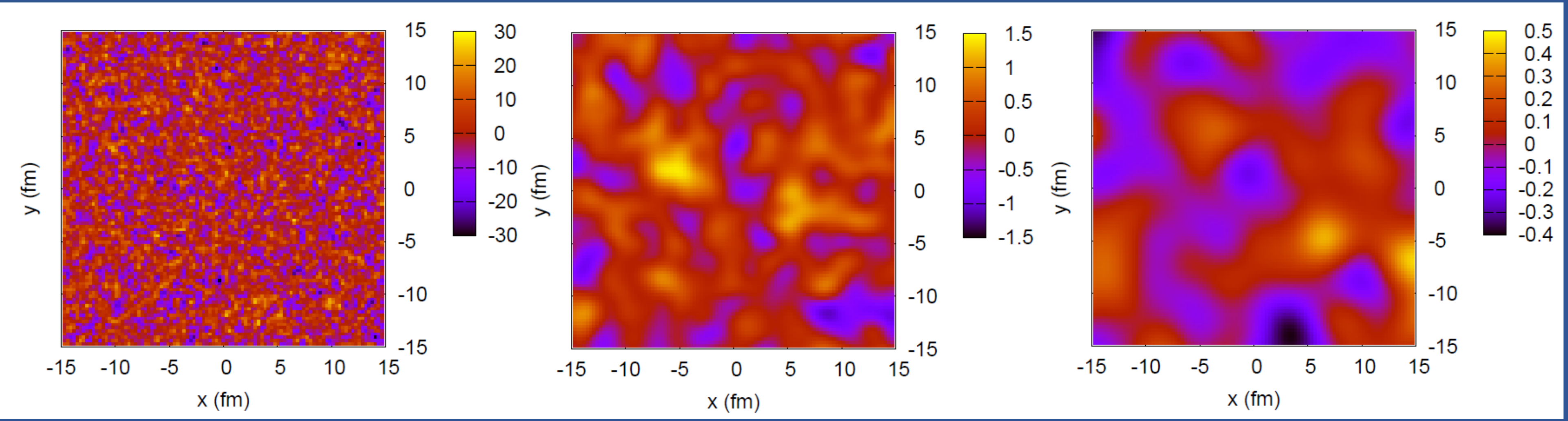
Y.Tachibana, TH, (2014, 2016); M.Okai *et al.*, (2017); Y.Kanakubo *et al.*, (2018).
PYTHIA: T. Sjöstrand *et al.*, Comput. Phys. Commun. **191**, 159 (2015).
*Heavy ion mode available from ver.8.230

Model Soft-Hard





Cutoff parameter dependence



λ	0 fm (Mesh size)	1.0 fm	2.0 fm

K. Murase, Ph. D thesis, The Univ. of Tokyo (2015)