流体、バルク、フロー

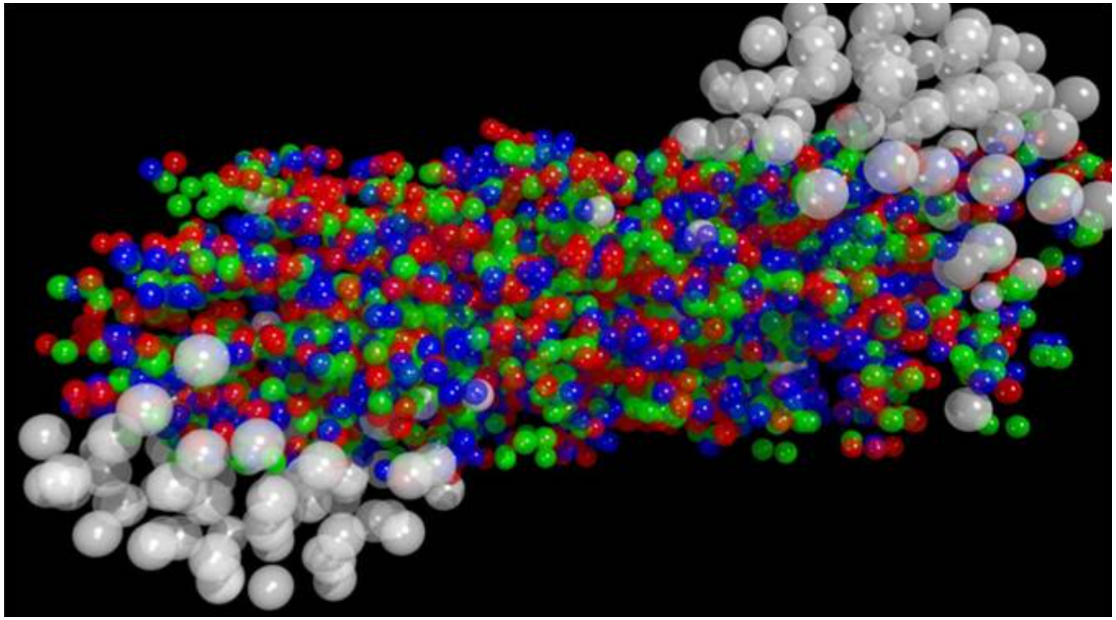
Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe
Department of Physics, Nagoya University
Duke University

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

Chiho NONAKA

April 8, 2017@Nagoya

QM2017@Chicago

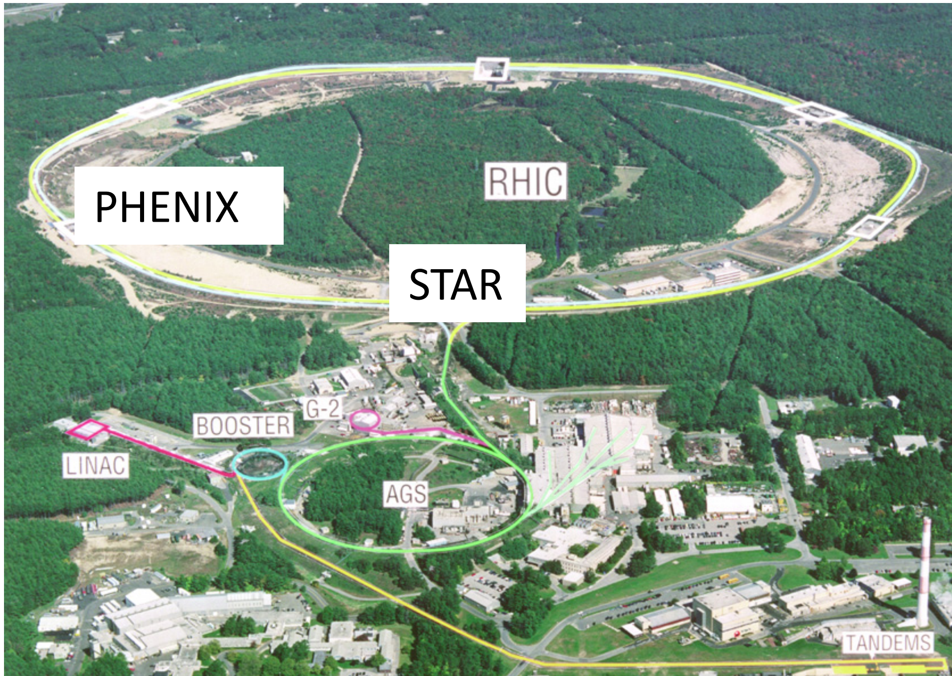


Quark Matter 2017

XXVI international conference on ultrarelativistic heavy-ion collisions

- From February 5 to February 11
- More than 700 participants!
- 37 plenary talks and 176 parallel talks + ~300 posters

Heavy Ion Collisions

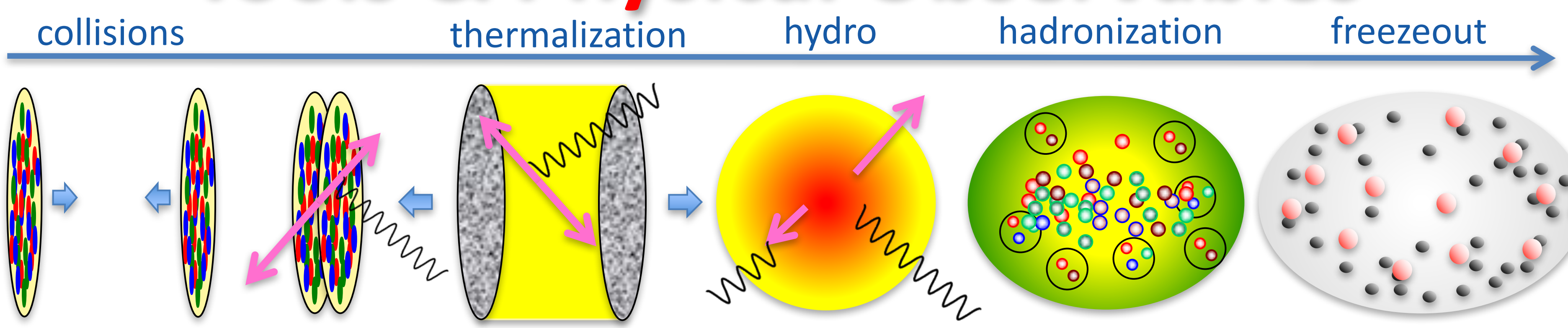


RHIC@BNL

Large Hadron Collider@CERN

C. NONAKA

Tools & Physical Observables



Tools

hydrodynamics

partons — event generator — hadrons

Color Glass Condensate

4 田屋：初期過程

recombination
fragmentation

3 本郷：カイラル磁気・渦効果、理論の発展

statistical model

Physical observables

6 山口 — photons/leptons

1 野中・2 中込 — bulk property

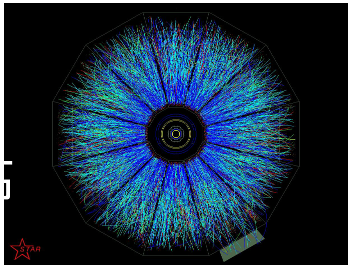
5 坂井 — Jets

7 渡辺 — heavy quarkonia

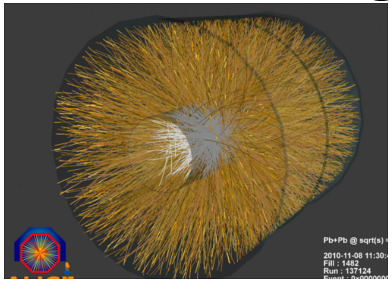
Heavy Ion Collisions@QM2017

Quark Matter 2017

STAR@RHIC



ALICE@LHC



Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

p+p,
d+Au,He+Au
U+U, Au+Au,
200

RHIC

Pb+Pb
2760

LHC

p+Pb
Pb+Pb
5020 GeV

$\sqrt{s_{NN}}$

Heavy Ion Collisions@QM2017

Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39 ?

p+p,
d+Au,He+Au ?
U+U, Au+Au,
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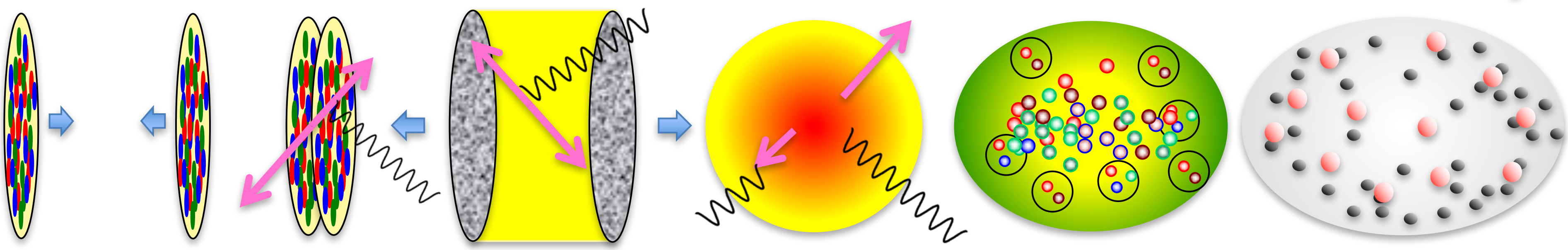
2760

p+p
p+Pb ?
Pb+Pb
5020 GeV

RHIC LHC $\sqrt{s_{NN}}$

流体模型

collisions thermalization hydro hadronization freezeout



Initial conditions	Hydrodynamics	Final state interactions
Fluctuations: Glauber, KLN, IP-Glasma…	QGP bulk property EoS: lattice QCD Shear and bulk viscosities	Cooper-frye+decay MC sampling Hadron based event generator

C. NONAKA

Hydrodynamic Model@QM17

Speaker	IC	Hydro	Particlization	observables	system
Eskola	NLO pQCD + saturation	(2+1)-d,η	CF, decay, vis	v_n, correlation	Au+Au, Pb+Pb
Denicol	IP-Glasma	MUSIC,η,ζ	UrQMD	v_2,v_3	RHIC/LHC
Bernhard	TRENTO	(2+1)-d, η,ζ	UrQMD	Yield,$\langle P_T \rangle$,v_n	Pb+Pb
McDonald	IP-Glasma	MUSIC, η,ζ	UrQMD	Flow 全般	Pb+Pb
Gardim	NEXUS	SPHERIO	MC sampling	correlation	Au+Au
Luzum	NEXUS	SPHERIO	MC sampling	fluctuations	Au+Au
Sakai	MC-Glauber	Thermal fluc,η	JAM	factorization	Pb+Pb
Wang	AMPT	(3+1)-d, η	CF,decay	Λ, vorticity	Au+Au
Karpenko	UrQMD	(3+1)-d, η	UrQMD	Λ, vorticity	Au+Au(BES)
Auvinen	UrQMD	(3+1)-d, η	UrQMD	Yield, HBT,v_2	Au+Au(BES)
Shen	MC-Glauber+Lexus	MUSIC,η,κ	Hadron cascade	Yield	Au+Au(BES)
Moreland	TRENTO	(2+1)-d, η,ζ	UrQMD	Yield,v_n	P+Pb
Kawaguchi	MC-Glauber PYTHIA	(3+1)-d, η	JAM	Yield,v_n	P+Pb, p/d/He+Au

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Hydrodynamic Model@QM17

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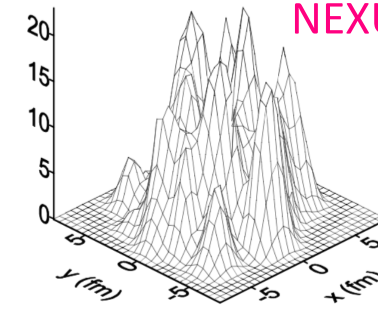
Auvinen	UrQMD
Bernhard	TRENTO
Moreland	TRENTO
Wang	AMPT

Fluctuating initial conditions

NEXUS



- Model
  - NLO pQCD + saturation
  - IP-Glasma: gluon, glasma
  - MC-Glauber: nucleon
  - TRENTO:Bayesian 解析に便利。IP-Glasma、KLN、Glauber風の初期条件。Normalization は決まらない。
  - MC-Glauber+PYTHIA for small systems

- Event generator
  - AMPT:HIJING(jet interaction)-ZPC(parton cascade)-ART(hadronic scattering)
  - NEXUS: Regge-Gribov theory
  - UrQMD : ハドロンベース - 低い衝突エネルギー

- New
  - MC-Glauber+Lexus for BES experiment
    低エネルギー衝突、流体は少しずつ作られる

TRENTO

TRENTo: parametric initial condition model

Ansatz: entropy density proportional to **generalized mean** of local nuclear density

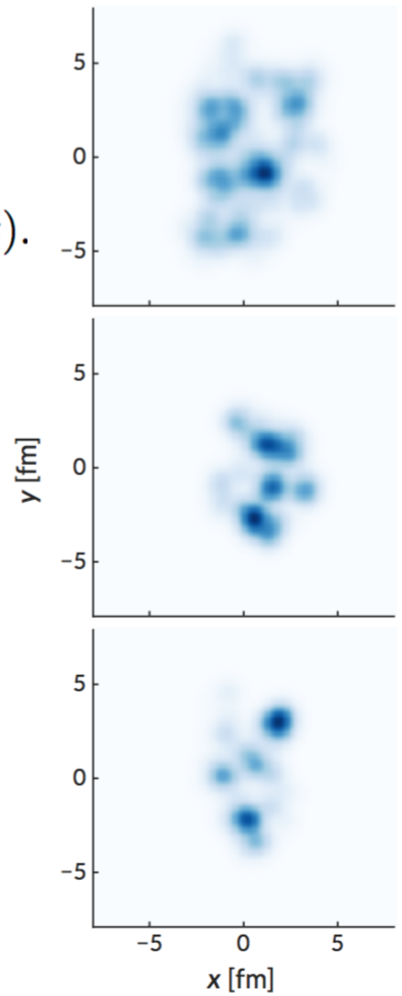
$$s \propto \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p} \quad T_{A,B}(x,y) = \int dz\, \rho_{A,B}^{\text{part}}(x,y,z).$$

$p \in (-\infty, \infty)$ = tunable parameter;
varying p mimics other models:

- $p = 1 \implies s \propto T_A + T_B$
  wounded nucleon model
- $p = 0 \implies s \propto \sqrt{T_A T_B}$
  similar to IP-Glasma, EKRT
- Previous work: $p = 0.0 \pm 0.2$

PRC 92 011901 [1412.4708]   PRC 94 024907 [1605.03954]

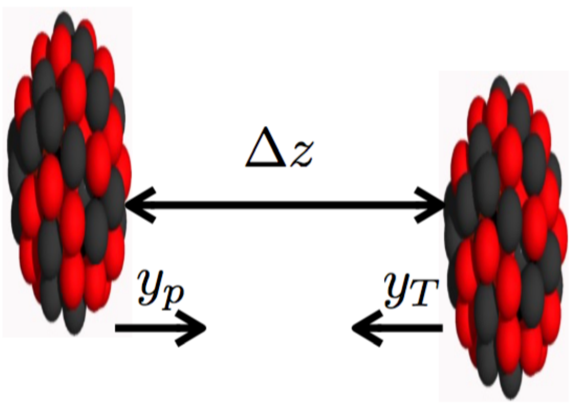
See talk by S. Moreland, Wed. 10:40

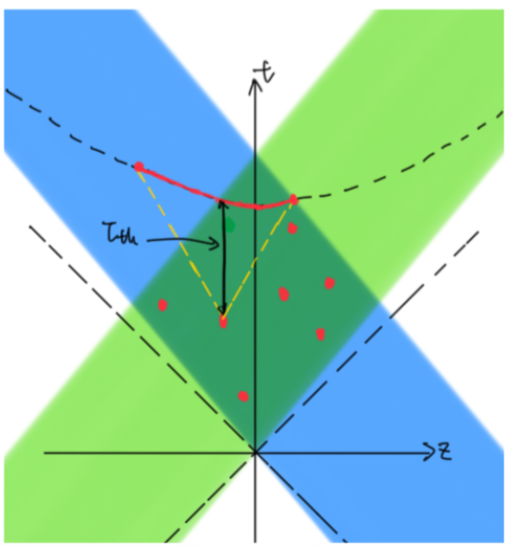


by Bernhard

MC-Glauber+Lexus

The 3D MCGlauber-LEXUS model





- Collision time and 3D spatial position are determined for every binary collision
- The rapidity loss is determined by the LEXUS model

$$P(y_p, y_T, y) = \lambda \frac{\cosh(y - y_T)}{\sinh(y_P - y_T)} + (1-\lambda)\delta(y - y_P)$$

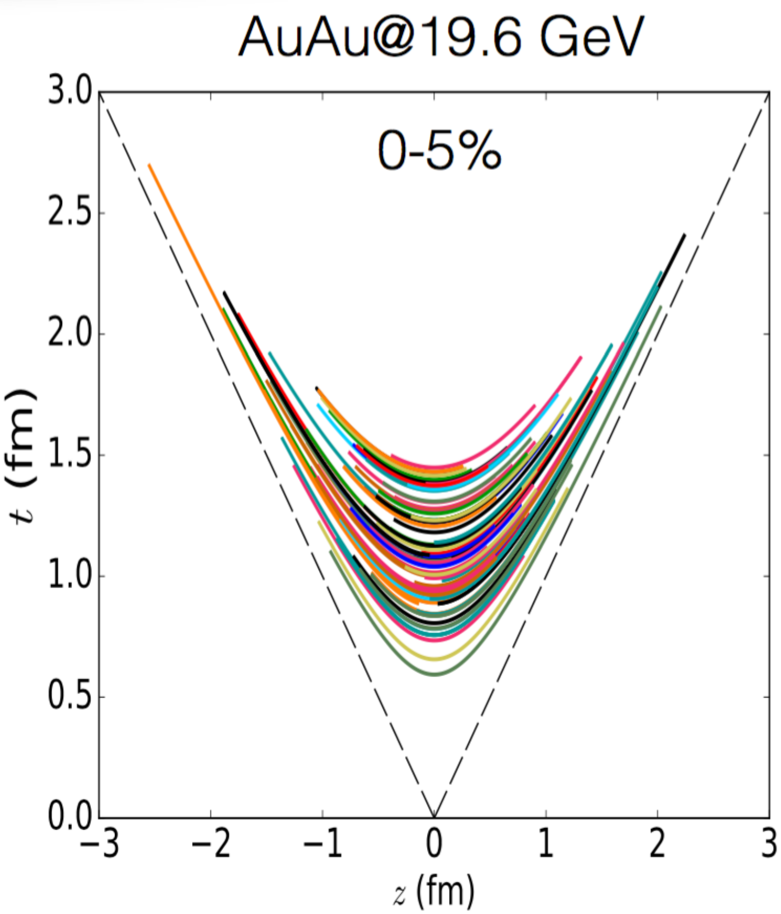
- QCD strings are free-streaming by $\tau_{\rm th} = 0.5 fm$ before thermalized to medium

低エネルギー衝突での流体の取り扱い
流体：2つの原子核が通りに抜けた後？

by Shen

MC-Glauber+Lexus

The 3D MCGlauber-LEXUS model



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$$P(y_p, y_T, y) = \lambda \frac{\cosh(y - y_T)}{\sinh(y_P - y_T)} + (1-\lambda)\delta(y - y_P)$$

- QCD strings are free-streaming by $\tau_{\rm th} = 0.5 fm$ before thermalized to medium

by Shen

MC-Glauber+Lexus

Hydrodynamics with sources

Energy-momentum current and net baryon density are feed into hydrodynamic simulation as source terms

$$\partial_\mu T^{\mu\nu} = J^\nu_{\rm source}$$

$$\partial_\mu J^\mu = \rho_{\rm source}$$

流体がsource term を通じて徐々に作られる。

where

$$J^\nu_{\rm source} = \delta e u^\nu + (e+P)\delta u^\nu$$

$$\delta u^\nu = \frac{\Delta^\nu_\mu J^\mu_{\rm source}}{e+P}$$

heats up the system ($\delta e u^\nu$) accelerates the flow velocity ($(e+P)\delta u^\nu$)

$\rho_{\rm source}$ dopes baryon charges into the system

- Source terms are smeared with Gaussians in space and time

by Shen

Hydrodynamic Model@QM17

EoS from lattice QCD、viscous hydrodynamics

Speaker	Hydro	
Eskola	(2+1)-d,η	+ transient fluid-dynamics EoM $\pi^{\mu\nu}$, SHASTA
Denicol	MUSIC,h,z	+ transient fluid-dynamics EoM $\pi^{\mu\nu}$, KT scheme
McDonald	MUSIC, η,ζ	
Shen	MUSIC,η,κ	
Gardim	SPHERIO	Ideal, Smoothed particle hydrodynamics, 有限個の粒子によって表現
Luzum	SPHERIO	
Sakai	Thermal fluc,η	+ thermal fluctuations,
Kawaguchi	(3+1)-d, η	
Karpenko	(3+1)-d, η	*v*HLLE, EoS は密度も入っているはず。
Auvinen	(3+1)-d, η	
Bernhard	(2+1)-d, η,ζ	VISHNU(Ohio group), SHASTA
Moreland	(2+1)-d, η,ζ	
Wang	(3+1)-d, η	KT scheme

C. NONAKA

Hydrodynamic Fluctuations

Hydrodynamic fluctuations

Shear stress tensor

Fluctuating hydro

Viscous hydro

$$\pi^{\mu\nu}(x) = \langle 2\eta\partial^{\langle\mu}u^{\nu\rangle}\rangle + \delta\pi^{\mu\nu}(x)$$

η: shear viscosity

u^{μ}: four fluid velocity

Ensemble average

Fluctuations around mean value
→Hydrodynamic fluctuations

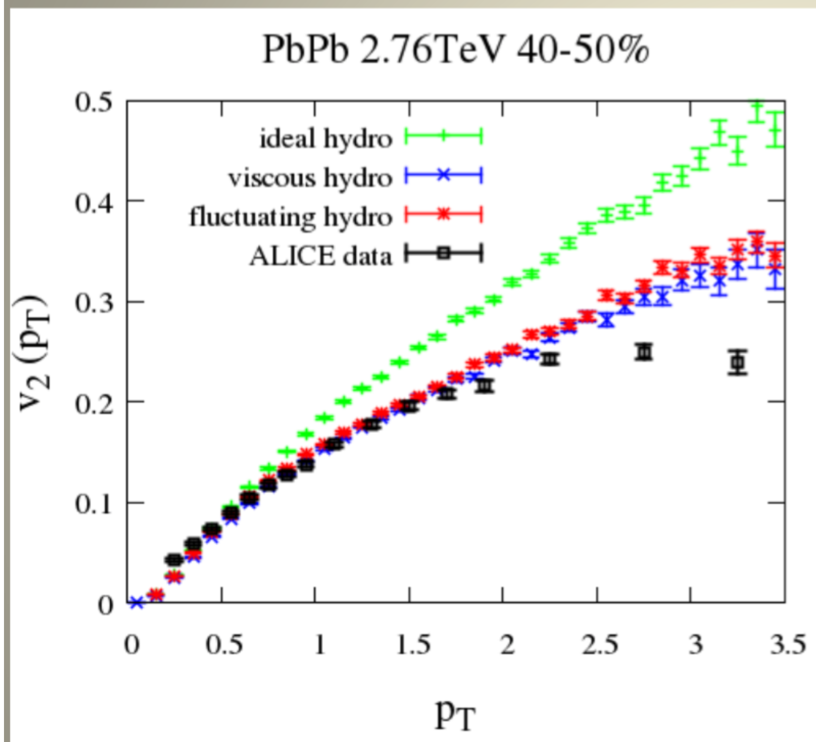
Note: Relaxation term needed in actual simulations

by Sakai

Hydrodynamic Fluctuations

Parameters in initial conditions <- Centrality dependence of multiplicity

p_T-differential v_2



ALICE Collaboration,
Phys. Rev. Lett. 116 (2016) 132302

Ideal hydro
→ Larger than ALICE data

Viscous & Fluctuating hydro ($\eta/s = 1/4\pi$)
→ Good agreement with ALICE data below p_T~1.5 GeV

by Sakai

流体ゆらぎを取り入れた現実的なモデルの発展

流体から粒子へ

Speaker	Particlization
Eskola	CF, decay, vis
Denicol	UrQMD
McDonald	UrQMD
Shen	Hadron cascade
Gardim	MC sampling
Luzum	MC sampling
Sakai	JAM
Kawaguchi	JAM
Karpenko	UrQMD
Auvinen	UrQMD
Bernhard	UrQMD
Moreland	UrQMD
Wang	CF, decay

- Cooper-Frye で粒子分布を計算
  - Freezeout hypersurface の書き出し
  - 共鳴粒子
  - 粘性効果

$$E\frac{d^3N}{dp^3} = \int_\sigma d\sigma_\mu p^\mu f(x,p)$$

$$f_i(x,p) = f_{0i}(x,p) + \delta f_i$$

$$f_{0i}(x,p) = \frac{g_i}{(2\pi)^3}\left[\exp\left(\frac{p_i^\mu u_\mu - \mu_i}{T}\right) \pm 1\right]^{-1}$$

- 崩壊
- MC sampling

Event generatorへ
- JAM
- UrQMD

Final state interactions

物理量

Speaker	observables	system
Eskola	v_n, correlation	Au+Au, Pb+Pb
Denicol	v_2,v_3	RHIC/LHC
McDonald	Flow 全般	Pb+Pb
Shen	Yield	Au+Au(BES)
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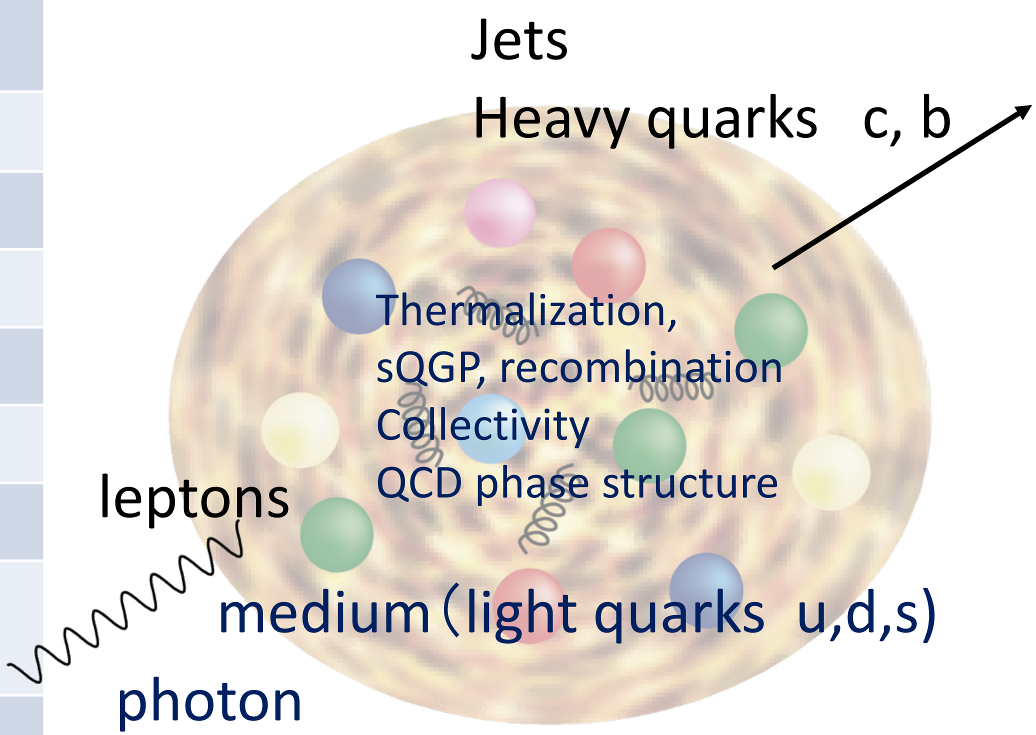

流体モデルは様々な物理量と密接な関係がある。

物理量

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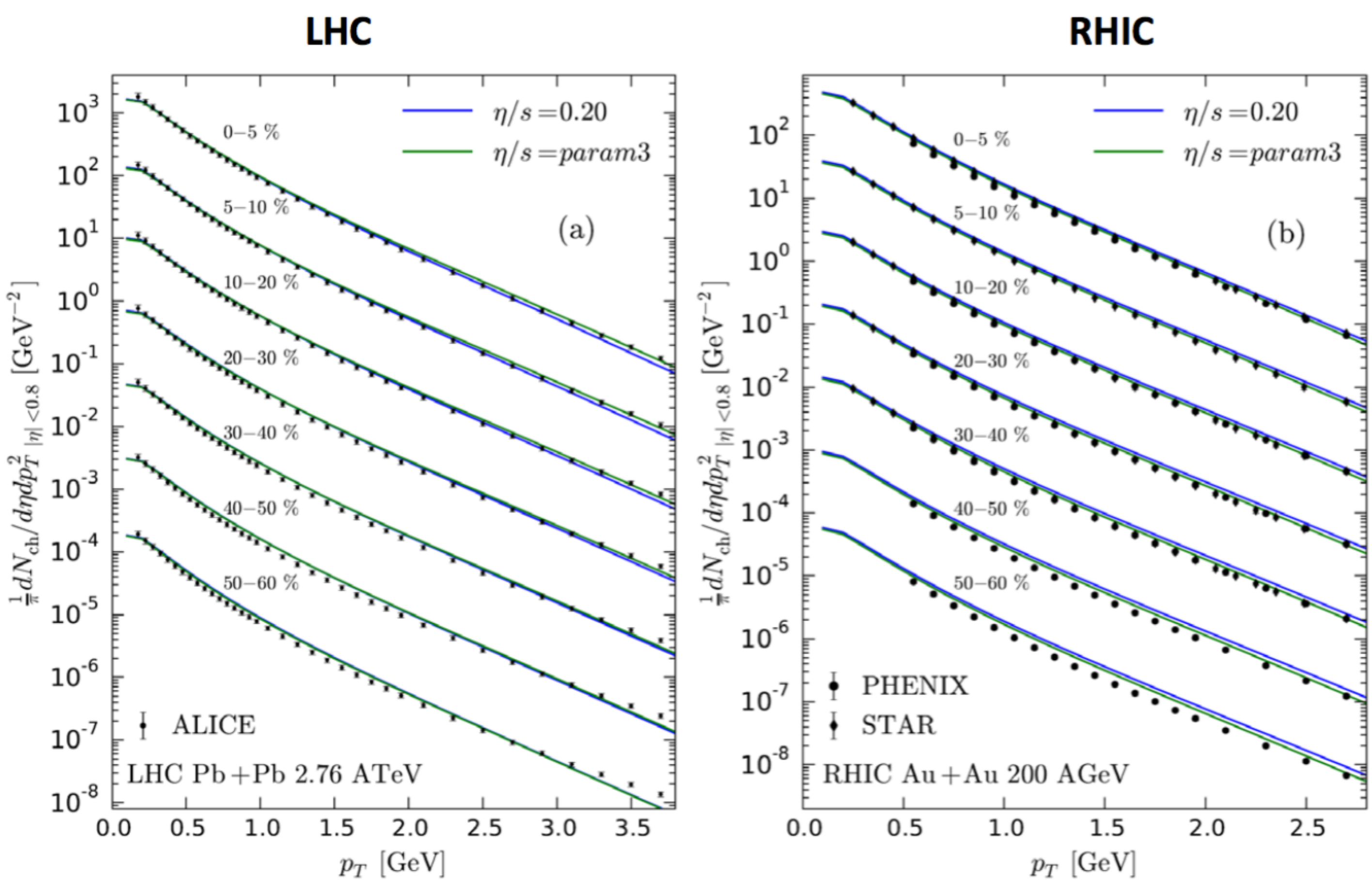
流体にとって基本的 （当たり前感）

- One-particle distributions
  π, K, p, strangeness particles…
  Flow, v_2, v_3

横運動量分布

[Niemi, KJE, Paatelainen, Phys.Rev. C93 (2016) 024907]

Centrality dependence of charged-hadron pT spectra ~OK



- (2+1)-d
- η/s の振る舞いはパラメトライズ:P_T 分布からではどれが良いのか決められない。

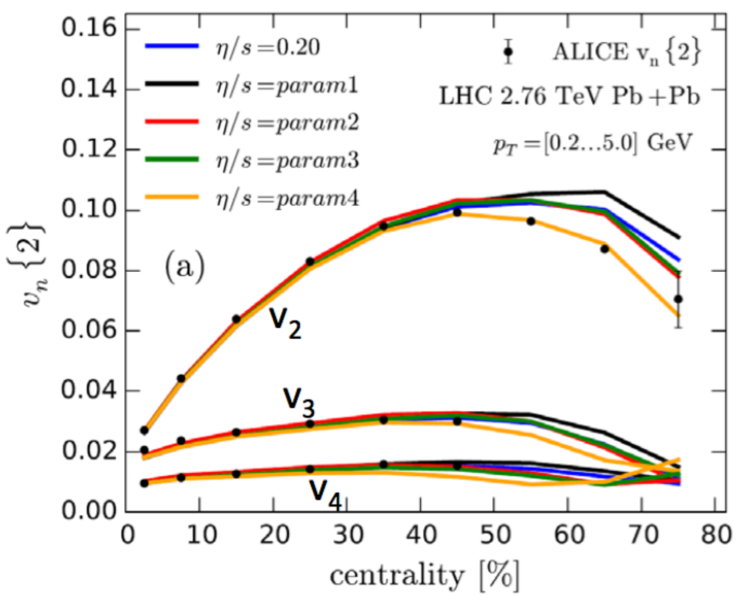
⇒ With T_{chem}= 175 MeV we get the low-pT part ~OK; essentially no constraints for η/s(T) from here, either

by Eskola

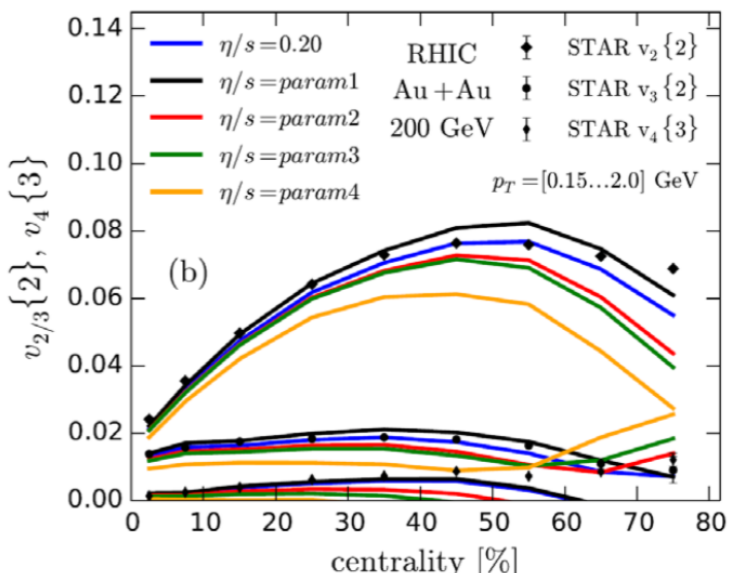
Flow からη/s の情報

Centrality dependence of 2,3-particle cumulant flow coefficients v_n

LHC



RHIC

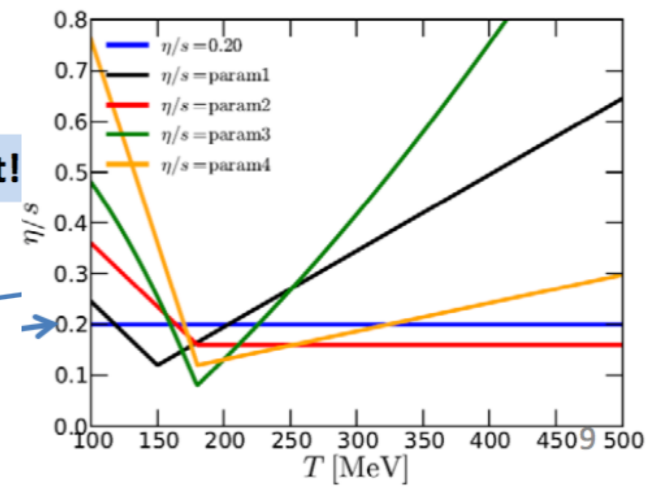


- LHCでは違いがなし。RHICでは違いが。
- Bayesian analysis

LHC v_ns well reproduced by **all** these η/s(T)

⇒ **Simultaneous LHC & RHIC analysis very important!**

⇒ **Constraints for eta/s(T):**
Small η/s(T) in the HRG seems favored



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Wang	Λ, vorticity	Au+Au

流体にとって基本的　（当たり前感）

- One-particle distributions
  π, K, p, strangeness particles…
- Flow, v_2, v_3

実験を説明するのは少し困難かも？

- Correlations, HBT
- fluctuations

中込さん

Λ, vorticity

- 良い流体アルゴリズムの必要あり
- 衝撃波、小さな人工粘性

Cf. ジェットエネルギー損失

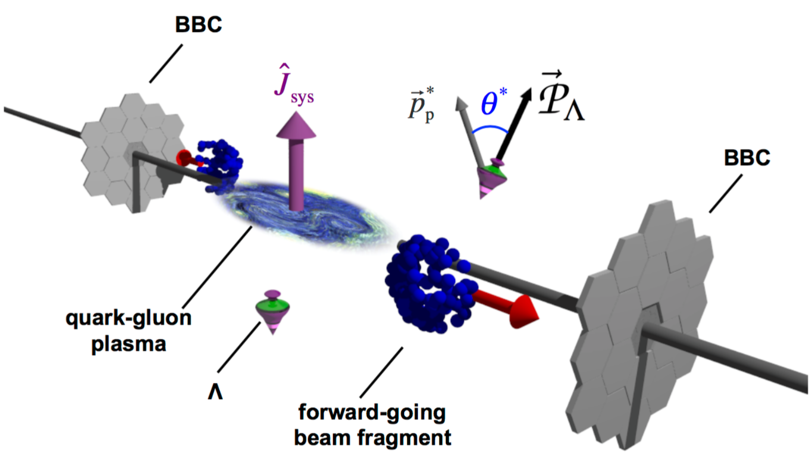
by Tachibana

Global Lambda Polarization

STAR, arXiv:1701.06657

Vortical structure of the QGP fluid

⇔ Internal quantum structure of particle

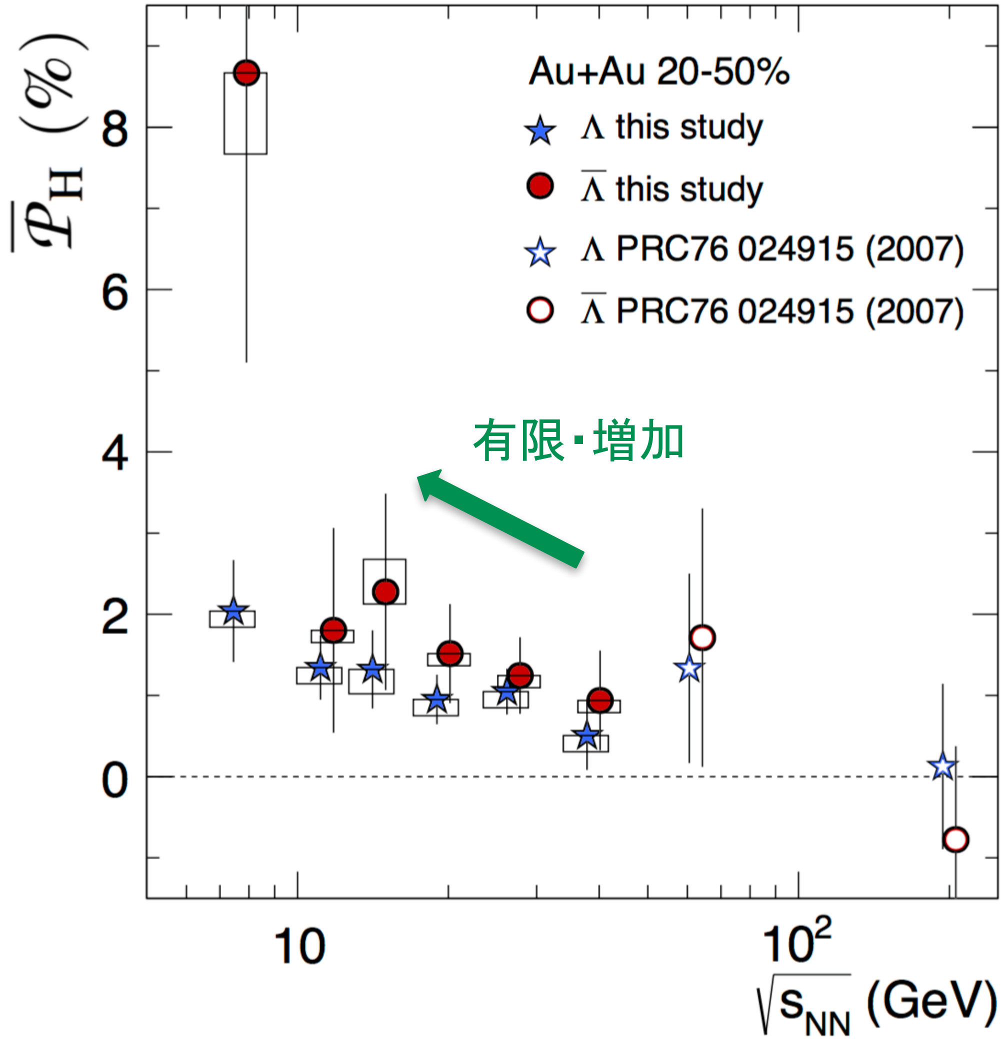


$\Lambda \to p + \pi^-$

$\vec{\mathcal{P}}_\Lambda$ は運動量に依存しない
平均を取るとJ_{sys}と平行

$$\overline{\mathcal{P}}_H \equiv \langle \vec{\mathcal{P}}_H \cdot \hat{J}_{sys} \rangle = \frac{8}{\pi \alpha_H} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{sys}}\right)\right\rangle}{R_{EP}^{(1)}}$$

“Golobal polarization”



Vorticity Structure in QGP

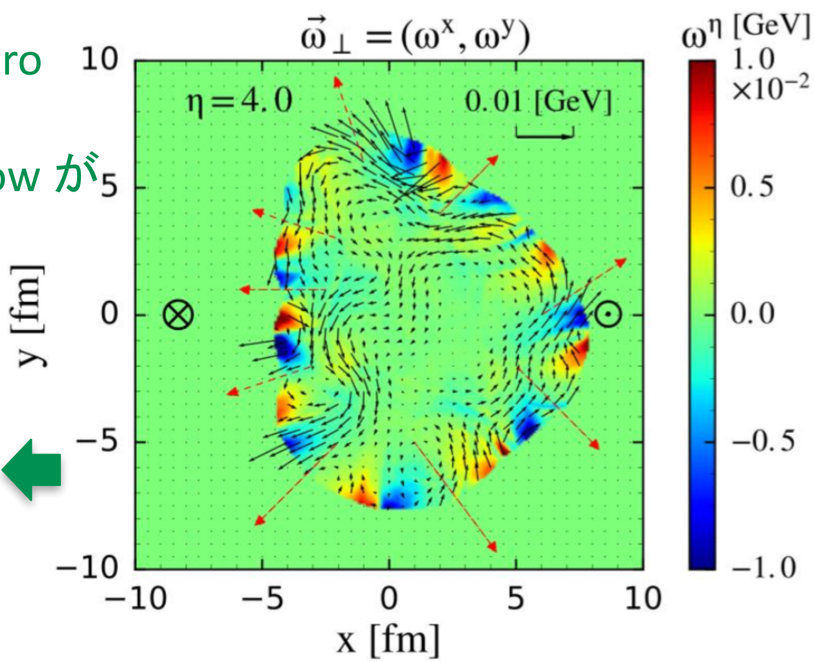
AMPT-HIJING
+3D viscous hydro
Au+Au 20-30%
初期のShear flow が
Vorticity を形成

Polarization of hypersurface

↓

Λ Polarization

Complex local vorticity structure

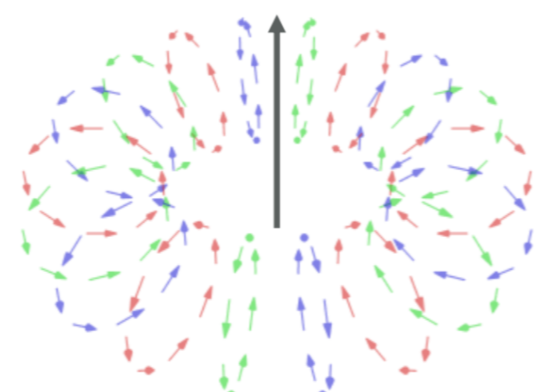


L.G.Pang, H.Petersen, Q.Wang & XNW
PRL 117, 192301 (2016)

- Vortex pair in 2D
- Vortex ring in 3D = Toroidal (smoke ring) vortical fluid

- Vortex ring appears in the longitudinal direction
- Ridge-like vortex pairs in the transverse plane.

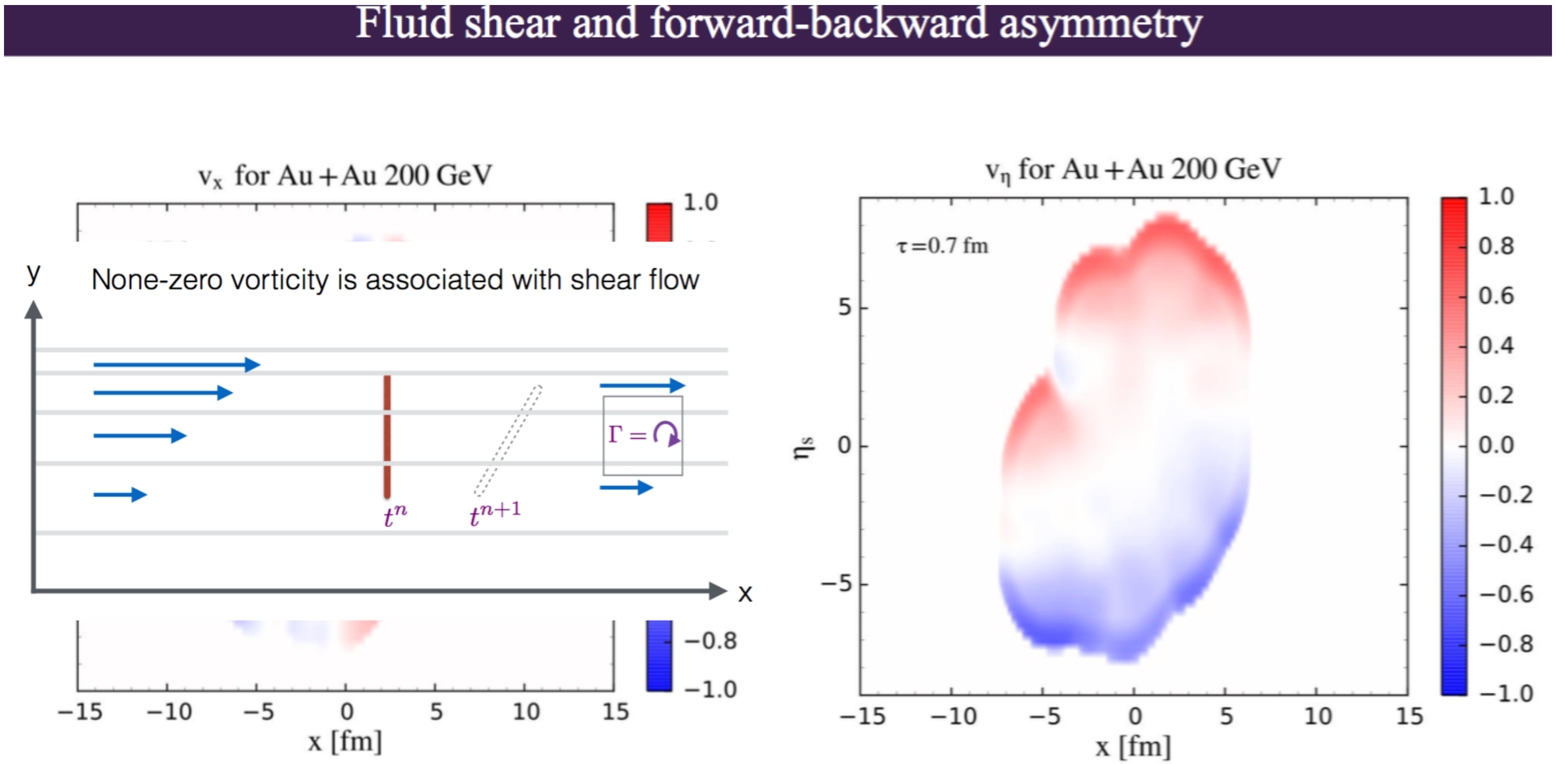
beam direction



by Lucas V. Barbosa
from WiKi Pedia

by Wang

Shear Flow to Vorticity



- AMPT initial condition + hydrodynamics
- Start with: $v_x = v_y = v_\eta = 0$ at $\tau = 0.4$fm

by Wang

Vorticity Structure in QGP

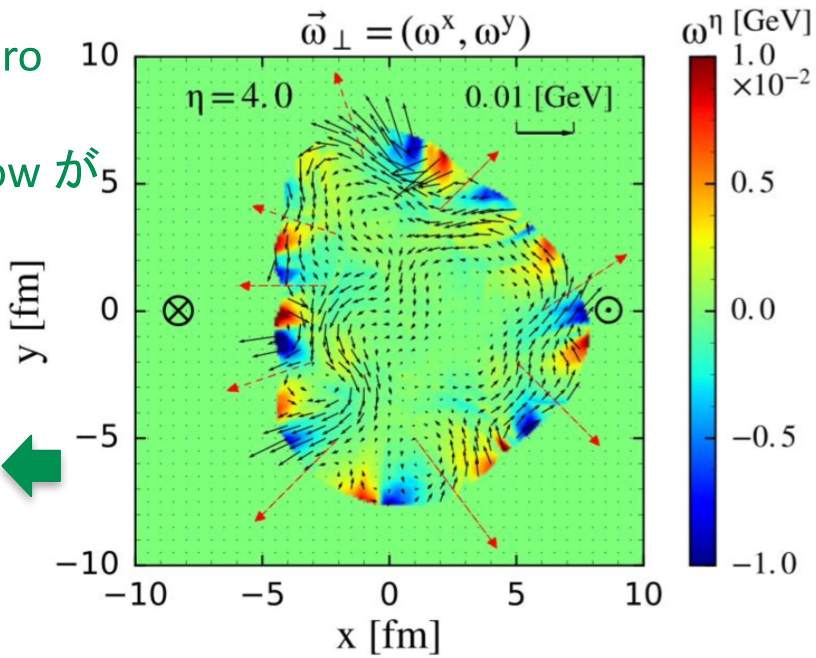
AMPT-HIJING
+3D viscous hydro
Au+Au 20-30%
初期のShear flow が
Vorticity を形成

Polarization of hypersurface

⬇

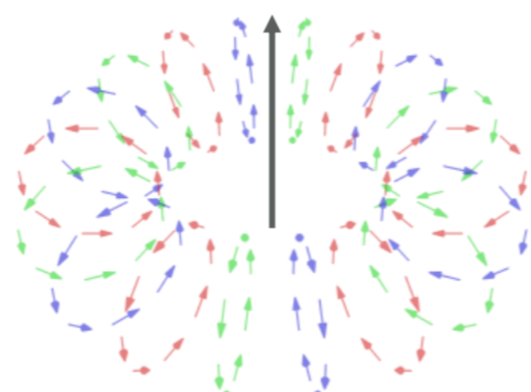
Λ Polarization

Complex local vorticity structure



L.G.Pang, H.Petersen, Q.Wang & XNW
PRL 117, 192301 (2016)

- Vortex pair in 2D
- Vortex ring in 3D = Toroidal (smoke ring) vortical fluid



by Lucas V. Barbosa
from WiKi Pedia

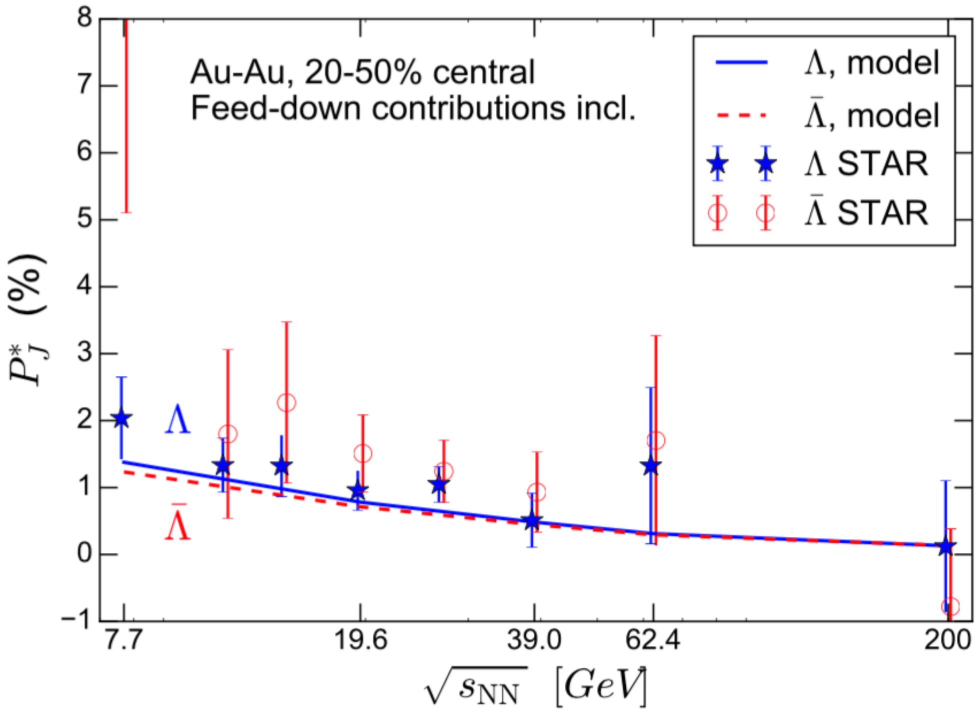
- Vortex ring appears in the longitudinal direction
- Ridge-like vortex pairs in the transverse plane.

by Wang

実験との比較

Λ and $\bar{\Lambda}$: UrQMD+vHLLE vs experiment

NEW



実験結果をおおよそ再現

- Λ within experimentan error bars.
- Much smaller and opposite sign $\bar{\Lambda}$-Λ splitting. Only μ_B effect in the model, and it is small.
- MHD interpretation: vorticity creates the average $\Lambda+\bar{\Lambda}$, magnetic field makes the splitting.
- Magnetic field at particlization?

by Karpenko

Hydrodynamic Model@QM17

Speaker	IC	Hydro	Particlization	observables	system
Eskola	NLO pQCD + saturation	(2+1)-d,η	CF, decay, vis	v_n, correlation	Au+Au, Pb+Pb
Denicol	IP-Glasma	MUSIC,η,ζ	UrQMD	v_2,v_3	RHIC/LHC
Bernhard	TRENTO	(2+1)-d, η,ζ	UrQMD	Yield,$\langle P_T \rangle$,v_n	Pb+Pb
McDonald	IP-Glasma	MUSIC, η,ζ	UrQMD	Flow 全般	Pb+Pb
Gardim	NEXUS	SPHERIO	MC sampling	correlation	Au+Au
Luzum	NEXUS	SPHERIO	MC sampling	fluctuations	Au+Au
Sakai	MC-Glauber	Thermal fluc,η	JAM	factorization	Pb+Pb
Wang	AMPT	(3+1)-d, η	CF,decay	Λ, vorticity	Au+Au
Karpenko	UrQMD	(3+1)-d, η	UrQMD	Λ, vorticity	Au+Au(BES)
Auvinen	UrQMD	(3+1)-d, η	UrQMD	Yield, HBT,v_2	Au+Au(BES)
Shen	MC-Glauber+Lexus	MUSIC,η,κ	Hadron cascade	Yield	Au+Au(BES)
Moreland	TRENTO	(2+1)-d, η,ζ	UrQMD	Yield,v_n	P+Pb
Kawaguchi	MC-Glauber PYTHIA	(3+1)-d, η	JAM	Yield,v_n	P+Pb, p/d/He+Au

Bayesian Analysis

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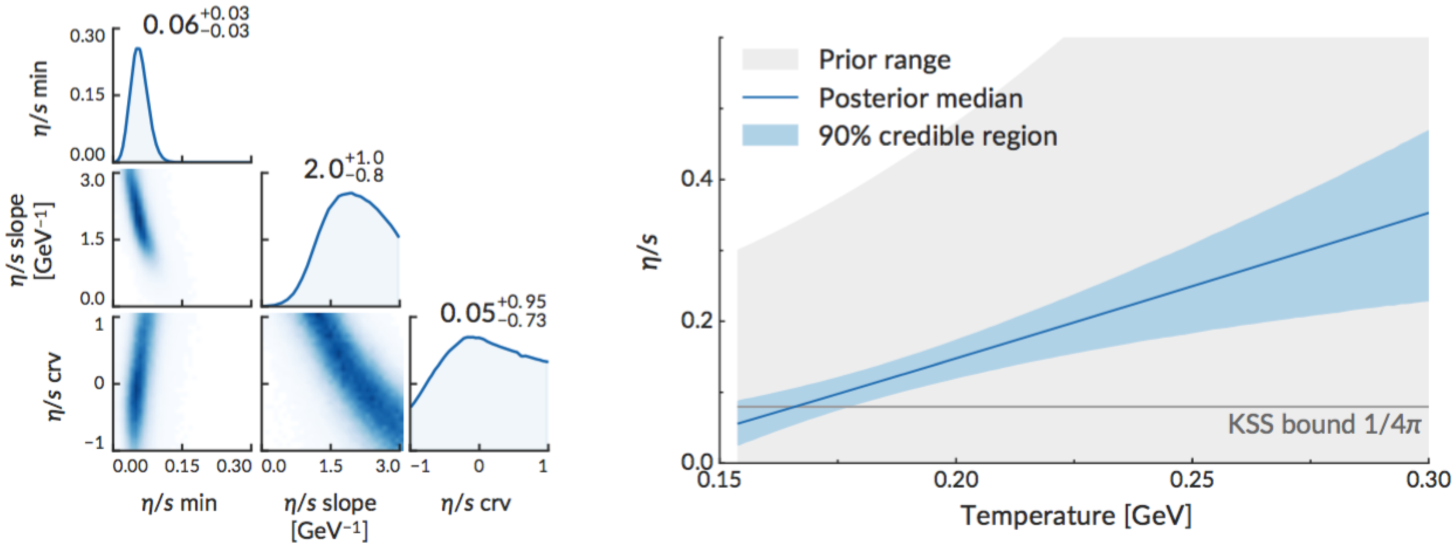
Shear Viscosity

Shear viscosity

LHC Pb+Pb 2.76 and 5.02 GeV

$$(\eta/s)(T) = (\eta/s)_{\min} + (\eta/s)_{\text{slope}}(T - T_c) \times \left(\frac{T}{T_c}\right)^{(\eta/s)_{\text{crv}}}$$



- Zero η/s excluded; min consistent with AdS/CFT
- Constant η/s excluded
- Best constrained $T \lesssim 0.23$ GeV
- RHIC data could disambiguate slope and curvature

by Bernhard

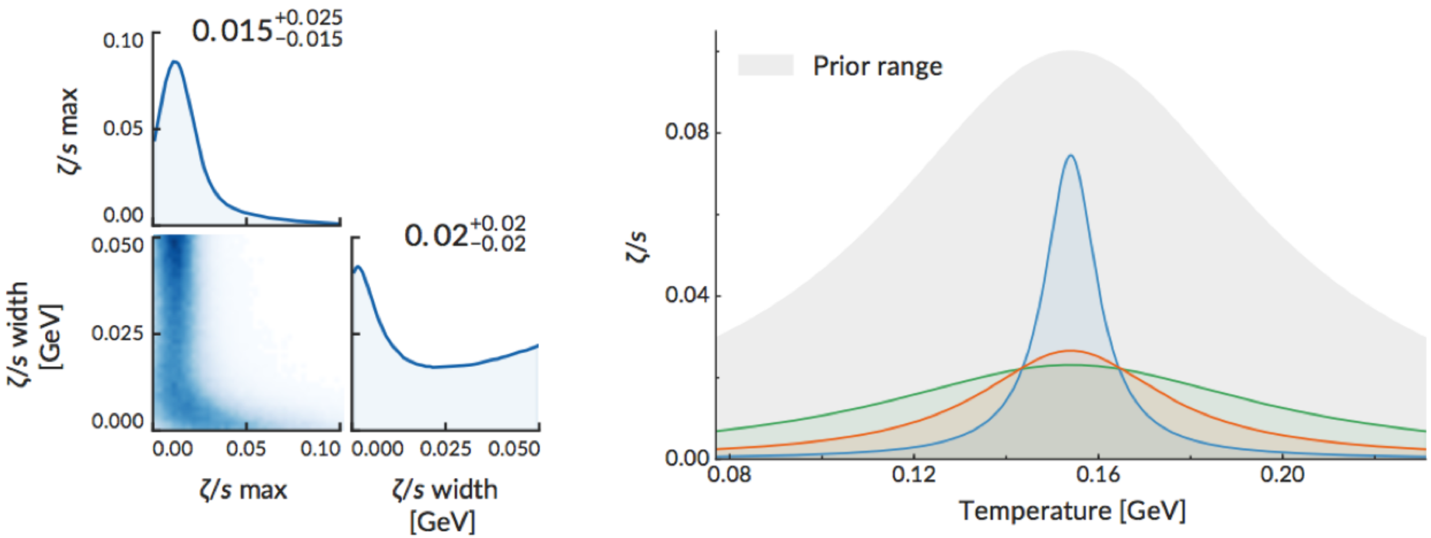
Bulk Viscosity

LHC Pb+Pb 2.76 and 5.02 GeV

Bulk viscosity

$$(\zeta/s)(T) = \frac{(\zeta/s)_{\max}}{1 + \left(\frac{T - T_c}{(\zeta/s)_{\mathrm{width}}}\right)^2}$$

ピークの位置は固定



- Can be “tall” or “wide”, but not both
- Short and wide (green) slightly favored

See also talk by G. Denicol, Wed. 17:30

by Bernhard

Bayesian Analysis

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  η/s, ζ/s の温度依存性

Bulk Viscosity

Model

Ryu *et al*, PRL 115, no. 13, 132301 (2015)

IP-Glasma + MUSIC + Cooper-Frye

$\tau_0 = 0.4$ fm T_{fo}=145 MeV

← 固定

Emulator from MADAI See S. Pratt lecture, S. Bass plenary talk
Novak et al, PRC89, 034917 (2014), 1303.5769.

500 random parameter samples (100 events per parameter sample)

Observables considered (20-30%) ← 1つのcentrality

RHIC

Observable	N^{π^+}	$\langle p_T^{\pi^+} \rangle$	$v_2\{2\}$	$v_3\{2\}$
p_T cut (GeV)	$p_T > 0$	$p_T > 0$	$p_T > 0.15$	$p_T > 0.15$
Value	135	0.411 GeV	0.0642	0.0183
Uncertainty	10	0.021 GeV	0.000075	0.0001

LHC

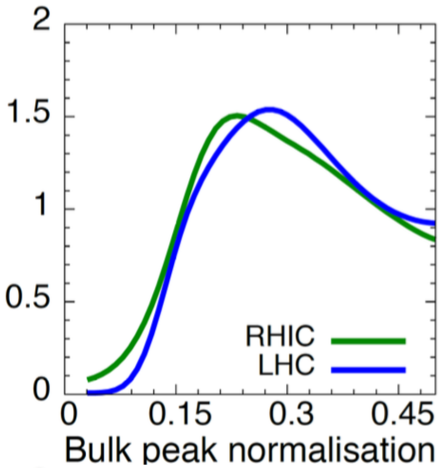
N^{π^+}	$\langle p_T^{\pi^+} \rangle$	$v_2\{2\}$	$v_3\{2\}$
$p_T > 0$	$p_T > 0$	$p_T > 0.2$	$p_T > 0.2$
307	0.512 GeV	0.0831	0.0293
20	0.017 GeV	0.0034	0.0015

9

by Denicol

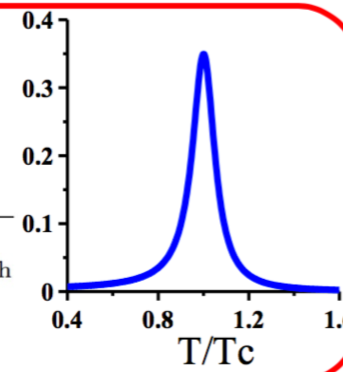
Bulk Viscosity

Results – probability distributions

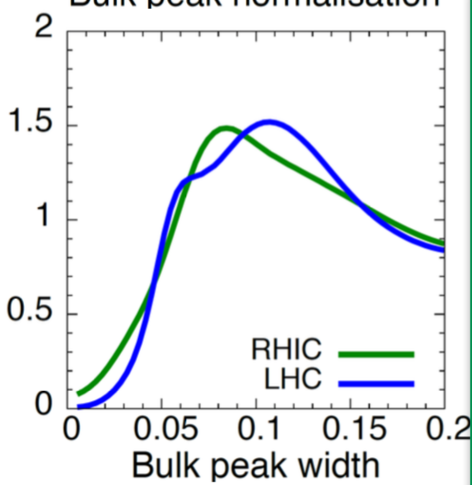


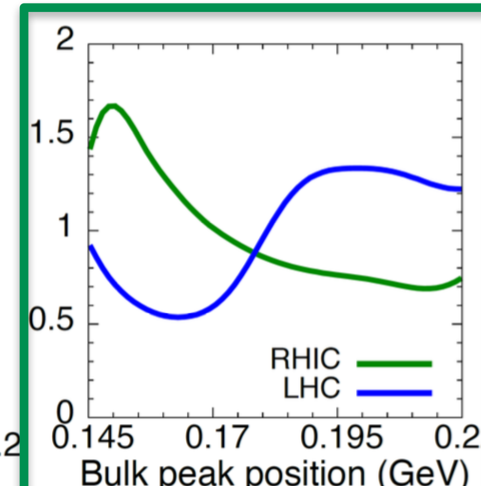
ζ/s(T) parametrized as

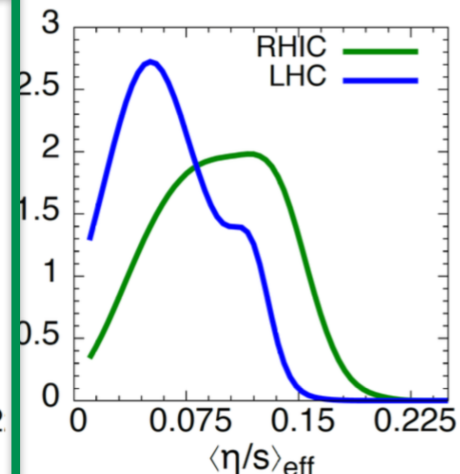
$$\frac{\zeta}{s}(T) = B_{\rm norm}\frac{B_{\rm width}^2}{\left(\frac{T^2}{T_{\rm peak}^2}-1\right)^2 + B_{\rm width}^2}$$



ピークの位置もパラメータ







RHICとLHCでζ/s のピークの位置が異なる？！

by Denicol

C. NONAKA

Bayesian Analysis

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- Bernhard:もっとも綺麗な結果を得るのに成功している。
  η/s, ζ/s の温度依存性
- Denicol: ζ/sの振る舞いがRHICとLHCで異なる？ Bayesian analyses の正しい評価？
  Bernhard との違い：Initial condition を固定している。
  一つのcentralityのみ
  おそらくは（３＋１）次元の流体計算が重いためでは？

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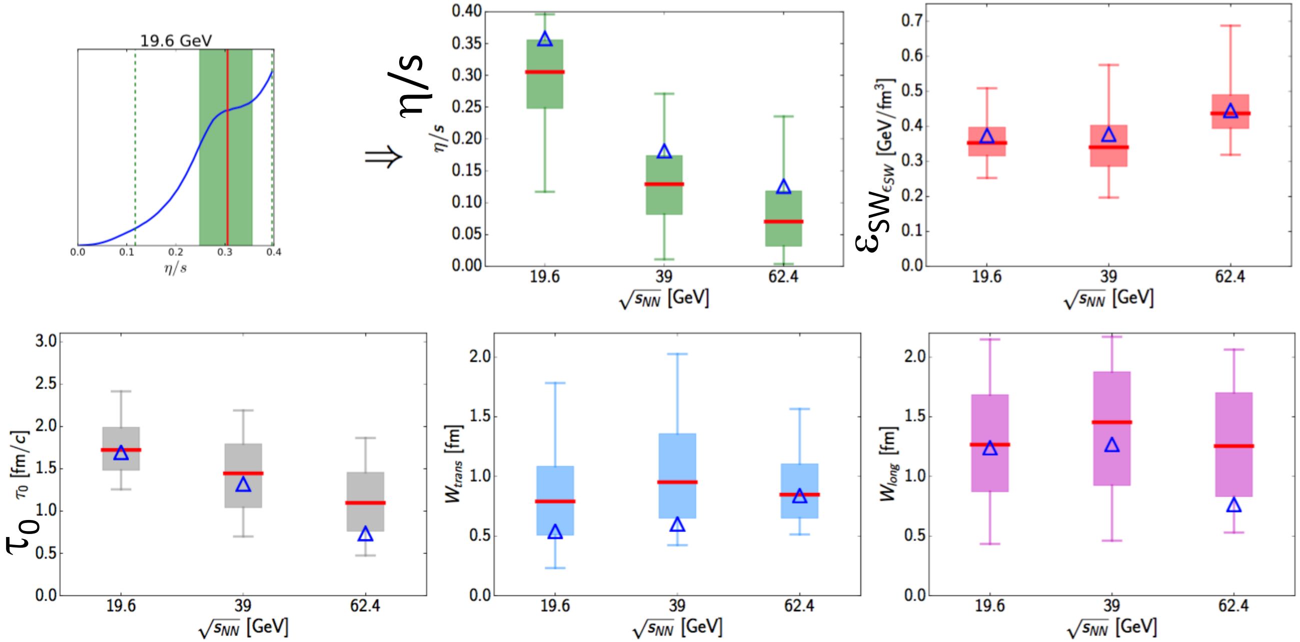
BES

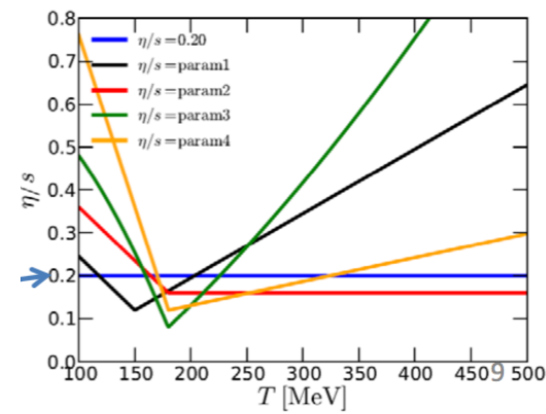
Parameter dependence on collision energy

η/s and τ_0 show clear increasing trend towards lower energies (however, minimum of τ_0 increases by construction)



Boxes: 50% confidence range

Whiskers: 95% confidence range



by Eskola

η/s :低衝突エネルギーほど増加

by Auvinen

Bayesian Analysis

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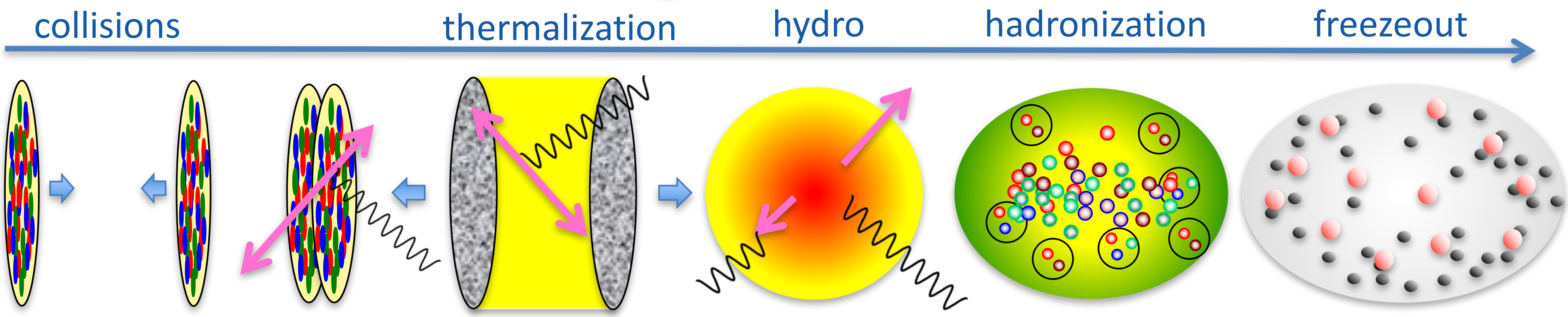
  一つのcentralityのみ
  おそらくは（３＋１）次元の流体計算が重いためでは？
- Auvinen：BES 実験に適用。
  η/s~0 <- Bernhard とη/s の振る舞いが inconsistent
- Moreland: small system に適用。挑戦的な計算。まだ途中か

強力な解析手法だが、モデル、input が大事。信頼の置ける結果を得るには多くの実験結果、膨大な計算量が必要。

C. NONAKA

まとめ



Initial conditions	Hydrodynamics	Final state interactions
Fluctuations: Glauber, KLN, IP-Glasma...	QGP bulk property EoS: lattice QCD Shear and bulk viscosities	Cooper-frye+decay MC sampling Hadron based event generator

- 流体模型の発展は著しい
- 現実的な実験解析が可能に
  - Bayesian 解析：実験結果からモデルのパラメータ、QGPの物性を探る。
- 流体模型の枠組みの発展
  - 流体ゆらぎ
  - Anisotropic hydrodynamics