Longitudinal flow decorrelations with hydrodynamic fluctuations and nuclear deformation

Koichi Murase
YITP, Kyoto Universisty

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Fluctuations in heavy-ion collisions

- **Final observables**
  - flow coefficients v_n, etc.

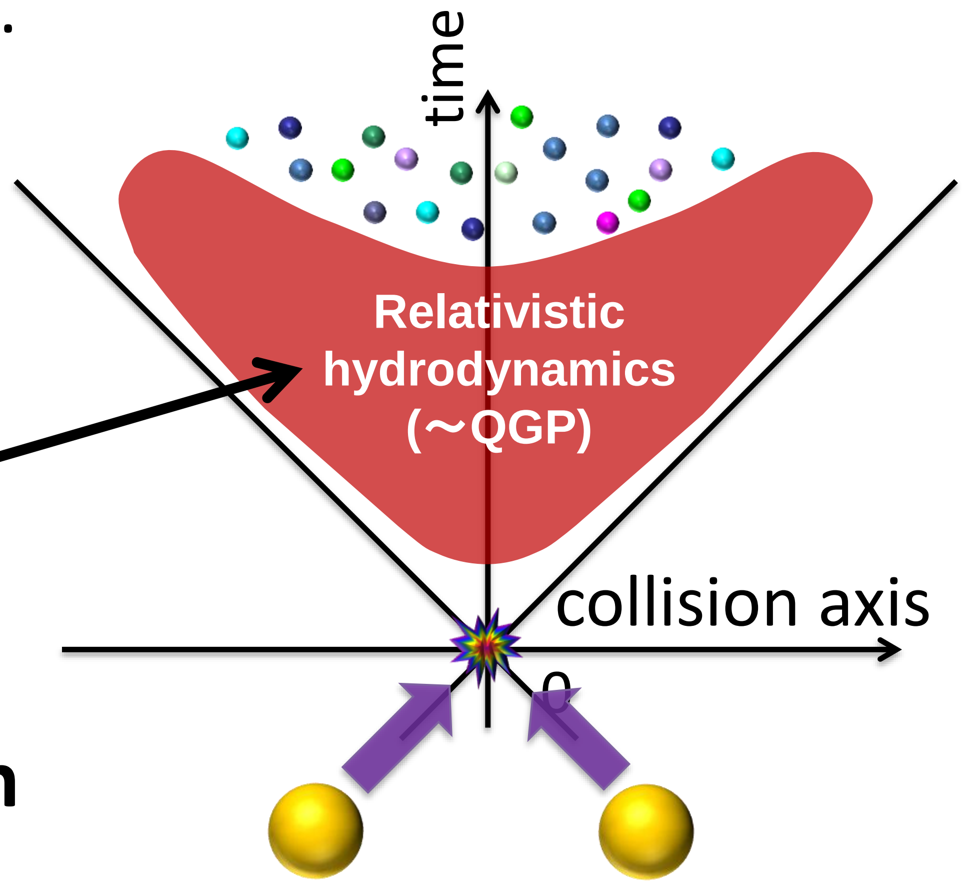
Matter response

EoS, η, ζ, τ_R, etc.

Additional fluctuations

+ hydro fluctuations

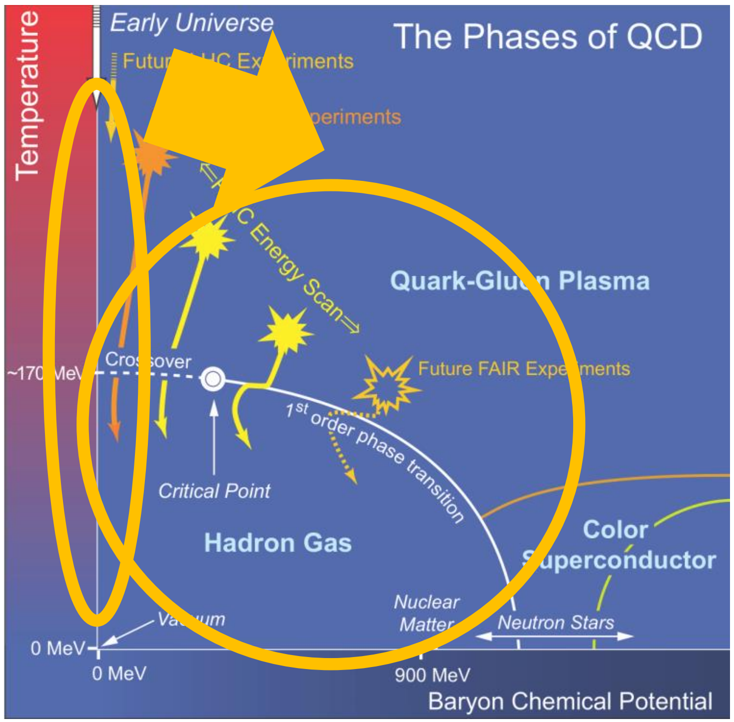
+ jets/mini-jets, etc



- **Initial state fluctuation**
  - nucleon distribution,
  - other fluctuations such as subnucleonic structure

QCD critical point search

Search of QCD critical point and 1st order phase transition



Schematic phase diagram of QCD
[taken from the 2007 NSAC Long Range Plan]

Dynamical models
for *high-energy* collisions
(Hydro + cascade + …)

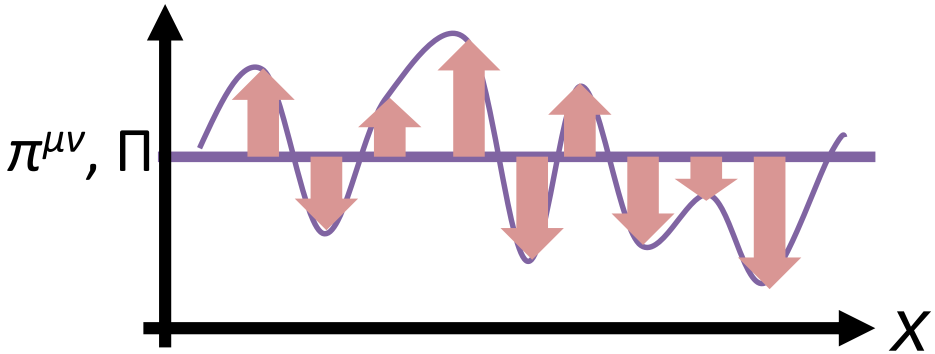
Needed extensions

- EoS modeling
- critical fluctuations
- dynamical initialization
- dynamical core-corona separation

Dynamical models
for *lower-energy* collisions?

Hydrodynamic fluctuations

Thermal fluctuations of fluid fields



spontaneous field fluctuations of fluid fields such as $\pi^{\mu\nu}$, Π, etc. at each t and each x

c.f. L. D. Landau and E. M. Lifshitz, Fluid Mechanics (1959)

Fluctuation-dissipation relation (FDR)

Magnitude of *fluctuations* $\delta\pi$, etc.
is determined by *dissipation* η, etc. (and temperature T)

$$\langle \delta\pi^{\mu\nu}(x)\delta\pi^{\alpha\beta}(x')\rangle = 4T\eta\Delta^{\mu\nu\alpha\beta}\delta^{(4)}(x-x')$$

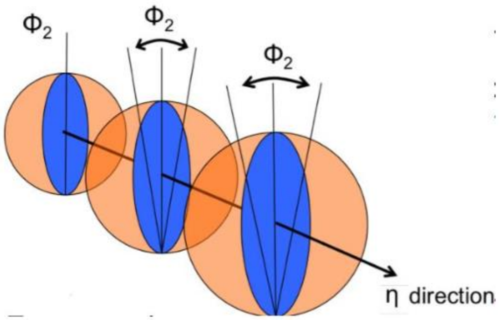
$\eta \neq 0$ ⇒ $\delta\pi \neq 0$

Longitudinal flow decorrelations

Flow correlation in longitudinal direction

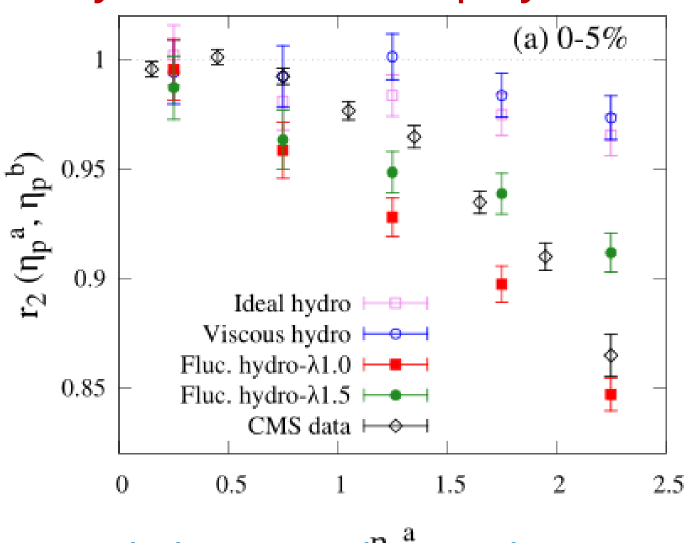
$$r_n(\eta_p^a, \eta_p^b) = \frac{V_{n\Delta}(-\eta_p^a, \eta_p^b)}{V_{n\Delta}(\eta_p^a, \eta_p^b)}$$

$$\sim \langle \cos n[\psi_n(-\eta) - \psi_n(\eta)] \rangle$$



Jia and Huo, PRC90 034905 (2014)

hydro fluctuations play a role

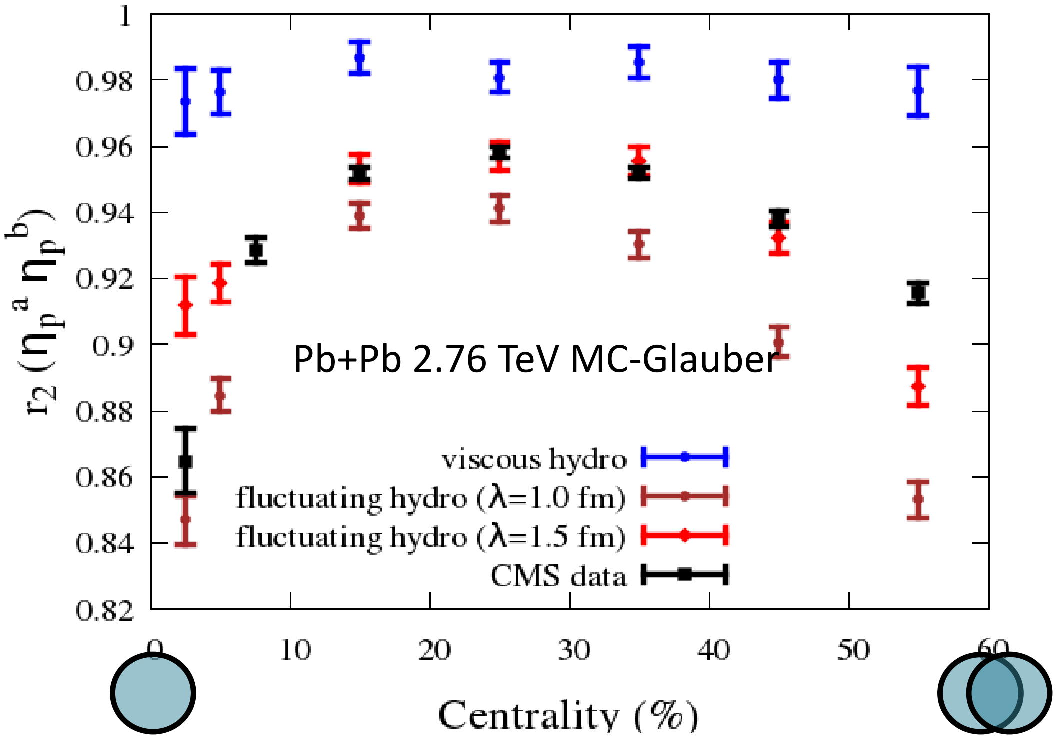


A Sakai, KM, T Hirano, Phys.Rev.C 102 (2020) 6, 064903

The effect of hydrodynamic fluctuations

Without initial longitudinal fluctuations

A Sakai, KM, T Hirano, Phys.Rev.C 102 (2020) 6, 064903



$$2.0 < \eta_p^a < 2.5,\ 3.0 < \eta_p^b < 4.0$$

Hydrodynamic fluctuations

↓

Longitudinal decorrelation

0-10%: cutoff λ = 1.0

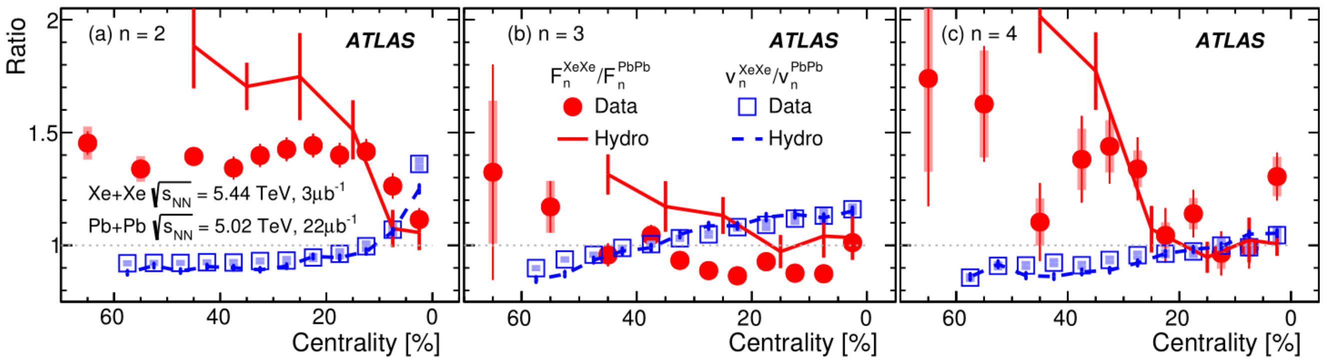
10-50%: cutoff λ = 1.5

Strong background flow → decorrelation weak

Central collisions weaker effects (hydro fluct ~ 1/VΔt)

Peripheral collisions stronger effects

Motivation: Xe-Xe collisions



ATLAS Collaboration, Georges Aad
Phys.Rev.Lett. 126 (2021) 12, 122301

Hydro (without fluctuations) fail

Always asked: Is there any clear ways to distinguish hydrodynamic fluctuations from other types of fluctuations?

→ Q: Is there any difference between the hydro fluctuations and initial fluctuations to the nuclear deformation?

Setup for the deformation

Woods-Saxon distribution deformed by spherical harmonics with coefficients β_2 & β_4

$$\rho = \frac{\rho_0}{1+\exp(\frac{r-R(\theta)}{a})}.$$

$$R(\theta) = R_0[1+\beta_2 Y_{20}(\theta)+\beta_4 Y_{40}(\theta)]$$

$$Y_{20} \propto 3\cos^2\theta - 1$$

R_0 = 5.42, a = 0.55, ρ_0 = 0.166

Deformed Xe

^{129}Xe

β_2 = 0.162,
β_4 = -0.003.

VS

Spherical Xe

^{129}Xe

β_2 = 0.0,
β_4 = 0.0.

G. Giacalone, et al, Phys. Rev. C 97, 034904 (2018); P. Mller, et al, Atom. Data Nucl. Data Tabl. 109-110, 1 (2016).

Integrated dynamical model

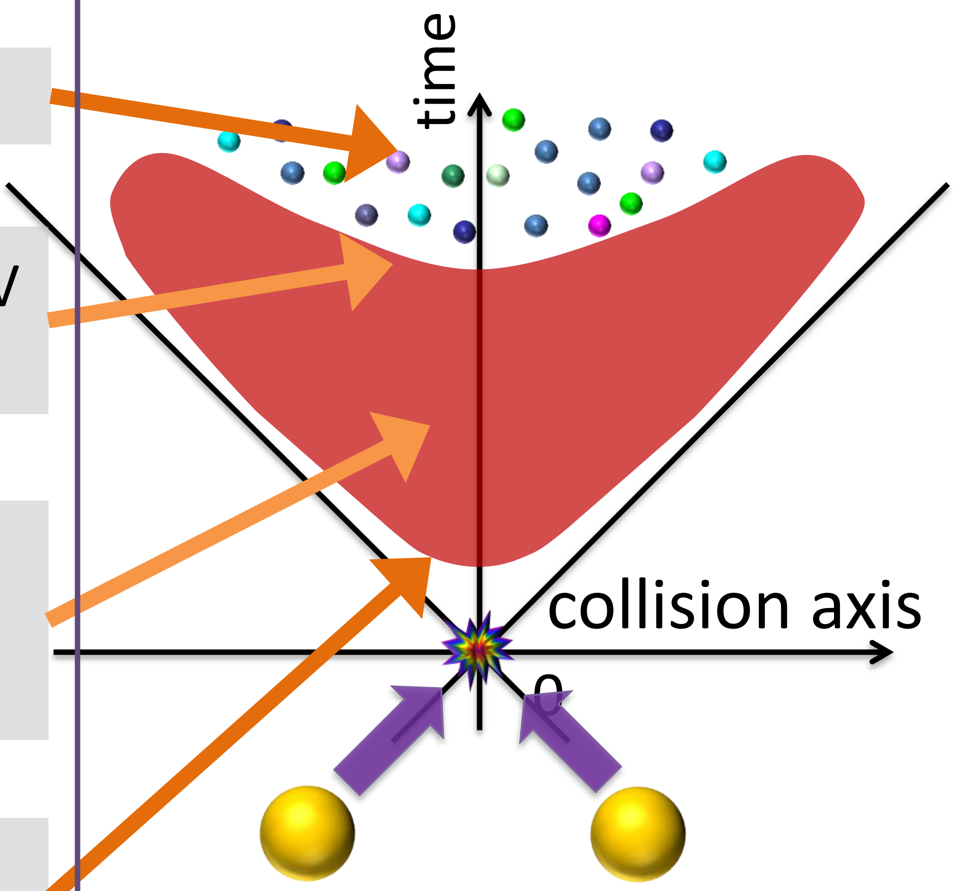
5. **Observables: v_n, r_n, etc.**

4. **JAM** (only decays at the moment)

3. **Particlization** at T_{sw} = 155 MeV
   Cooper-Frye formula: $f_0 + \delta f$

2. **(3+1)-dim. Relativistic Fluctuating Hydrodynamics**
   EoS: lattice QCD & HRG, $\eta/s = 1/4\pi$

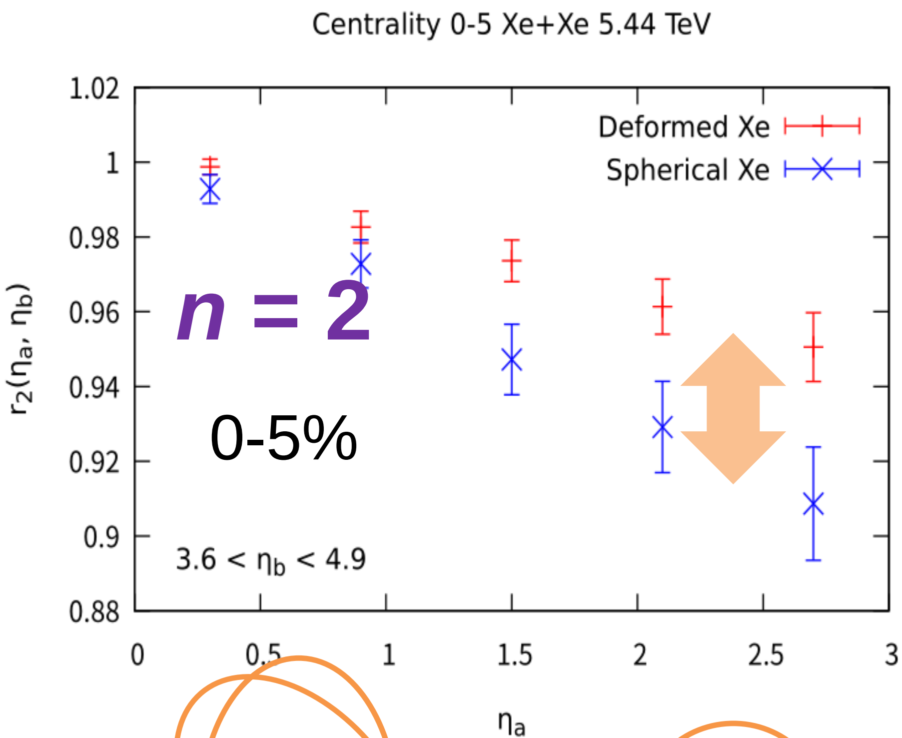
1. **Initial condition**
   MC-Glauber/modified BGK

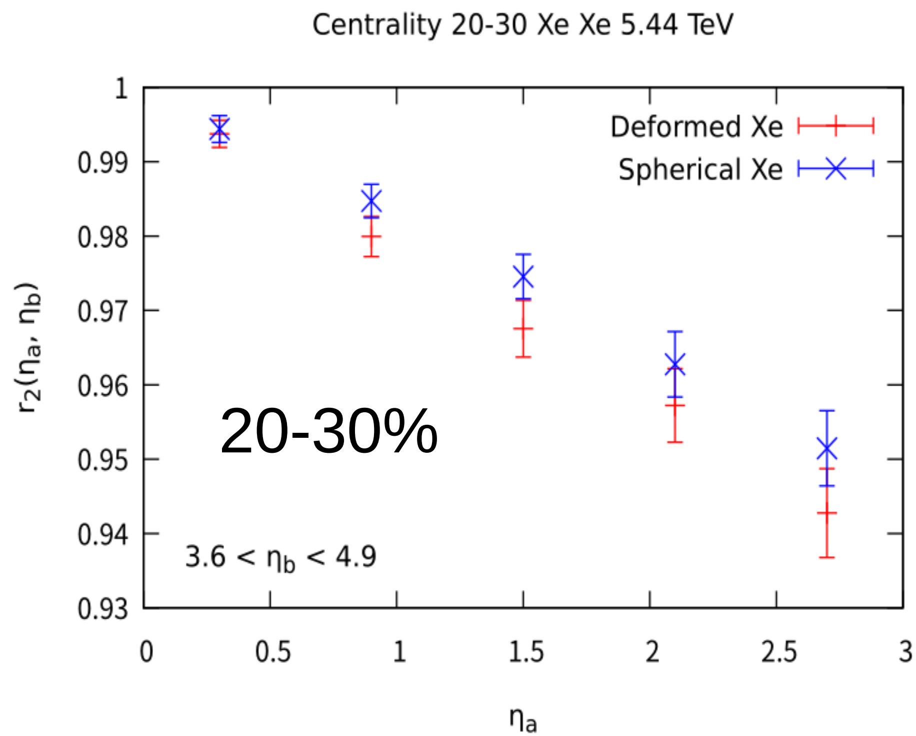


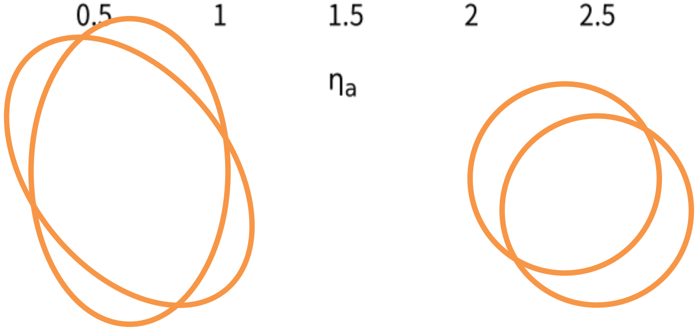
T. Hirano, P. Huovinen, KM, Y. Nara, Prog. Part. Nucl. Phys. 70 (2013) 108;
KM, T. Hirano, Nucl. Phys. A956 (2016) 276

Longitudinal flow decorrelation (n=2)

purely caused by hydrodynamic fluctuations (cutoff λ = 2.0 fm)





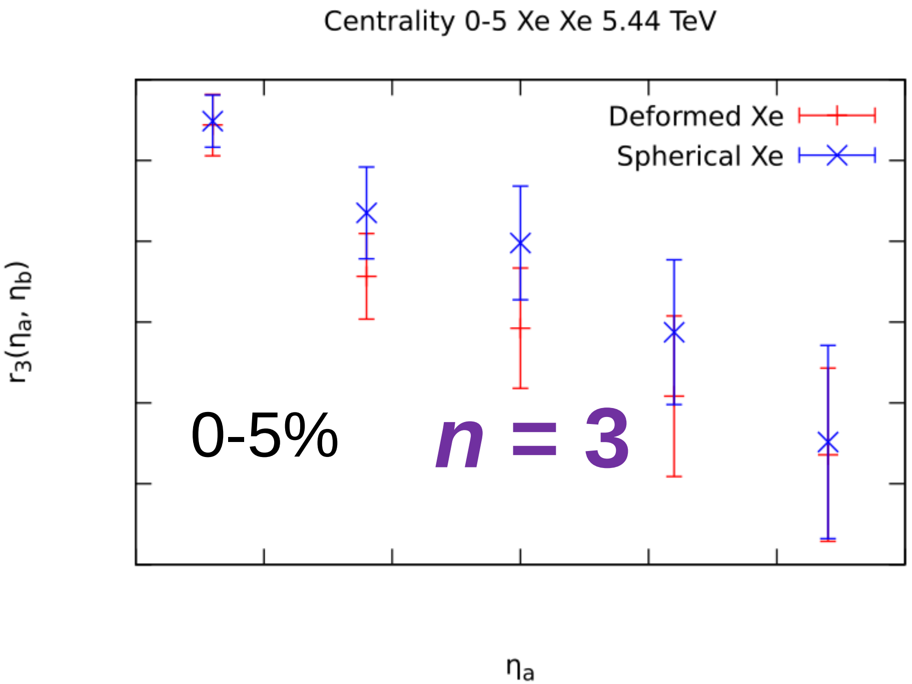


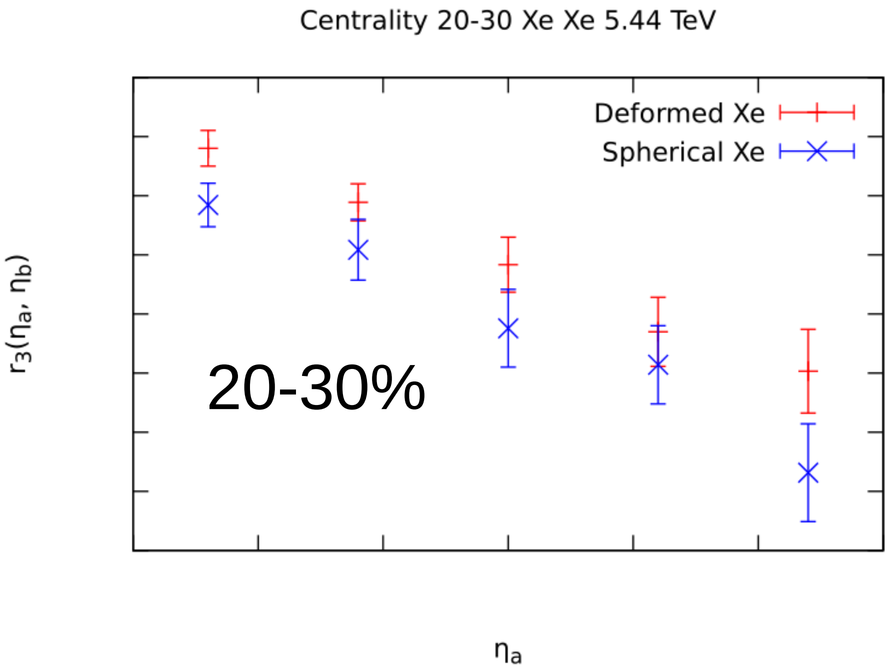
No clear difference

Effect of deformation

Longitudinal flow decorrelation (n=3)

purely caused by hydrodynamic fluctuations (cutoff λ = 2.0 fm)

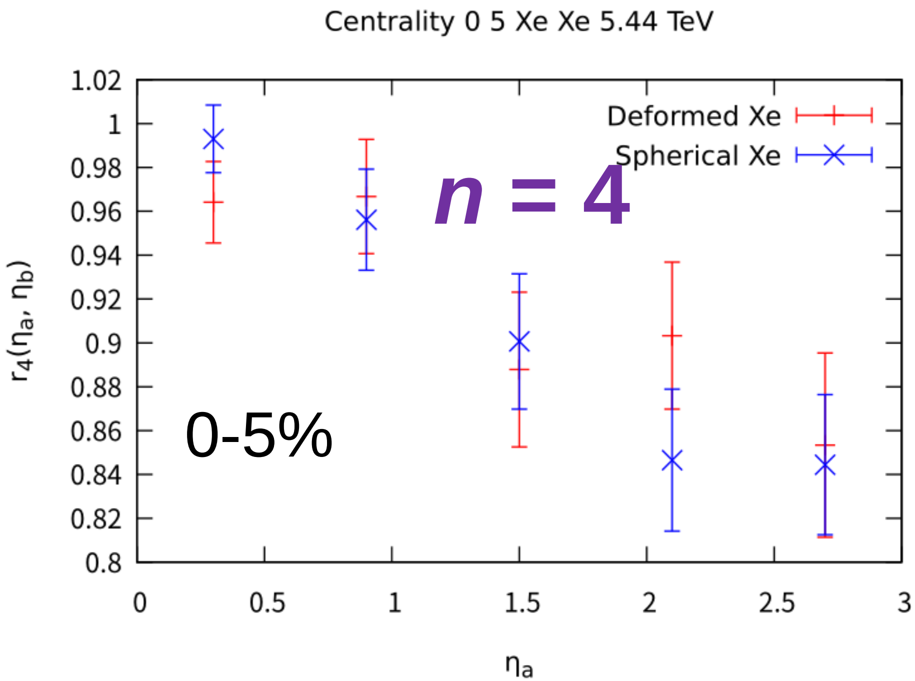


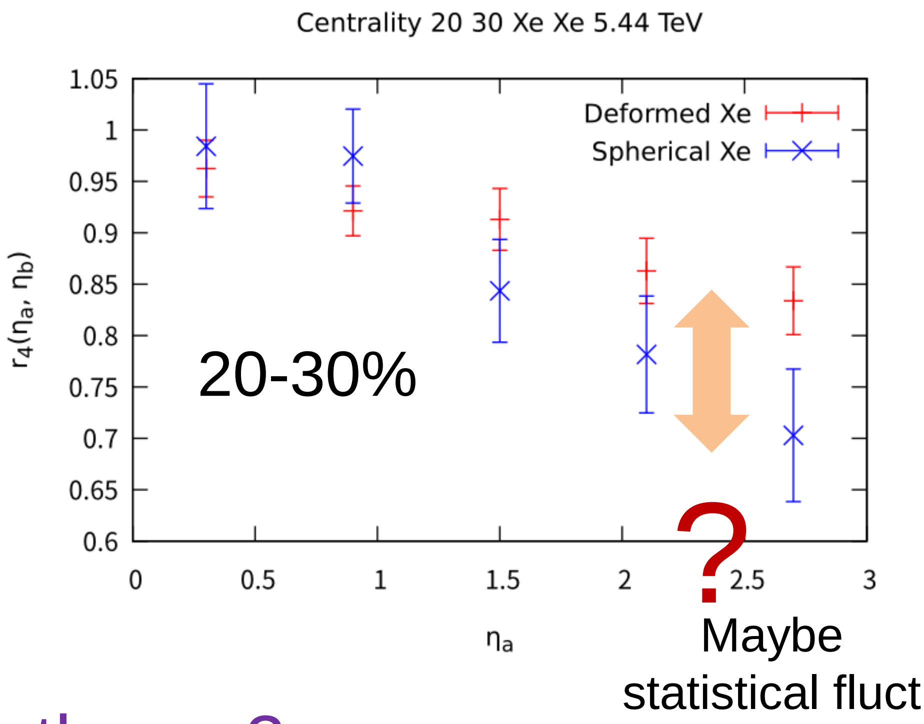


No clear tendencies as the *n*=2 case
at the central collisions

Longitudinal flow decorrelation (n=4)

purely caused by hydrodynamic fluctuations (cutoff λ = 2.0 fm)



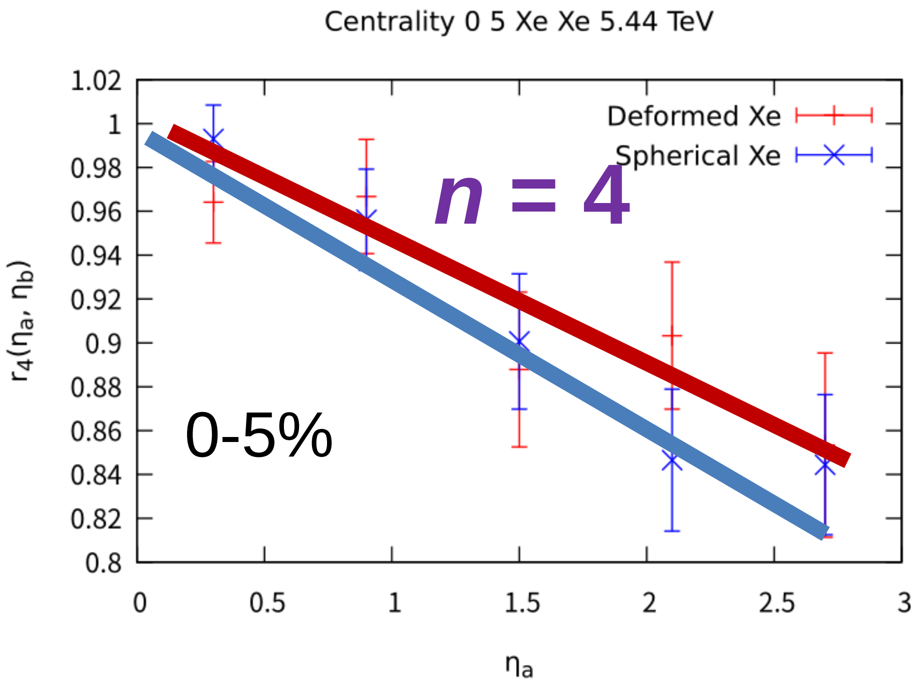


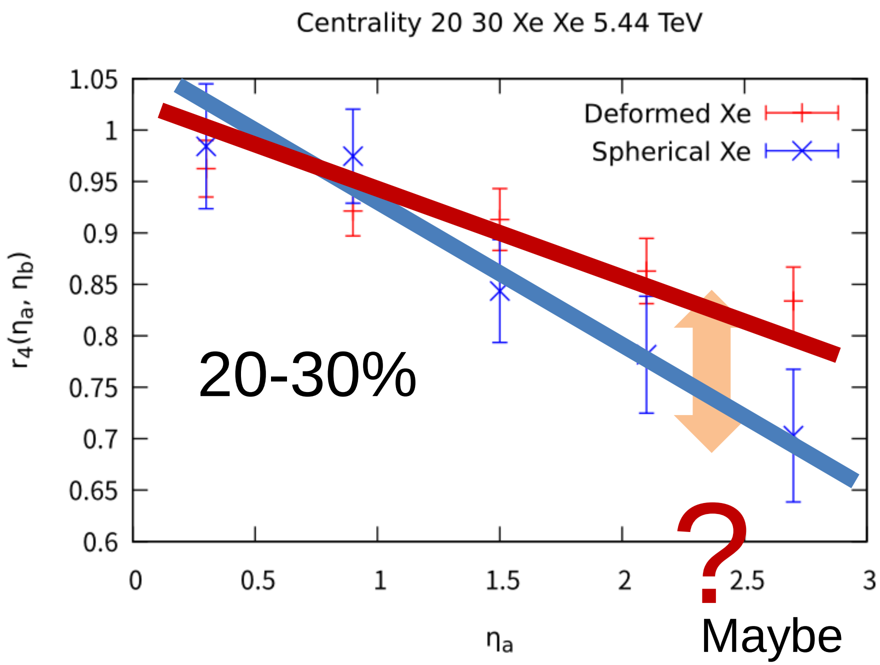
No clear tendencies as the *n*=2 case
at the central collisions

Some structures? needs statistics

Longitudinal flow decorrelation (n=4)

purely caused by hydrodynamic fluctuations (cutoff λ = 2.0 fm)





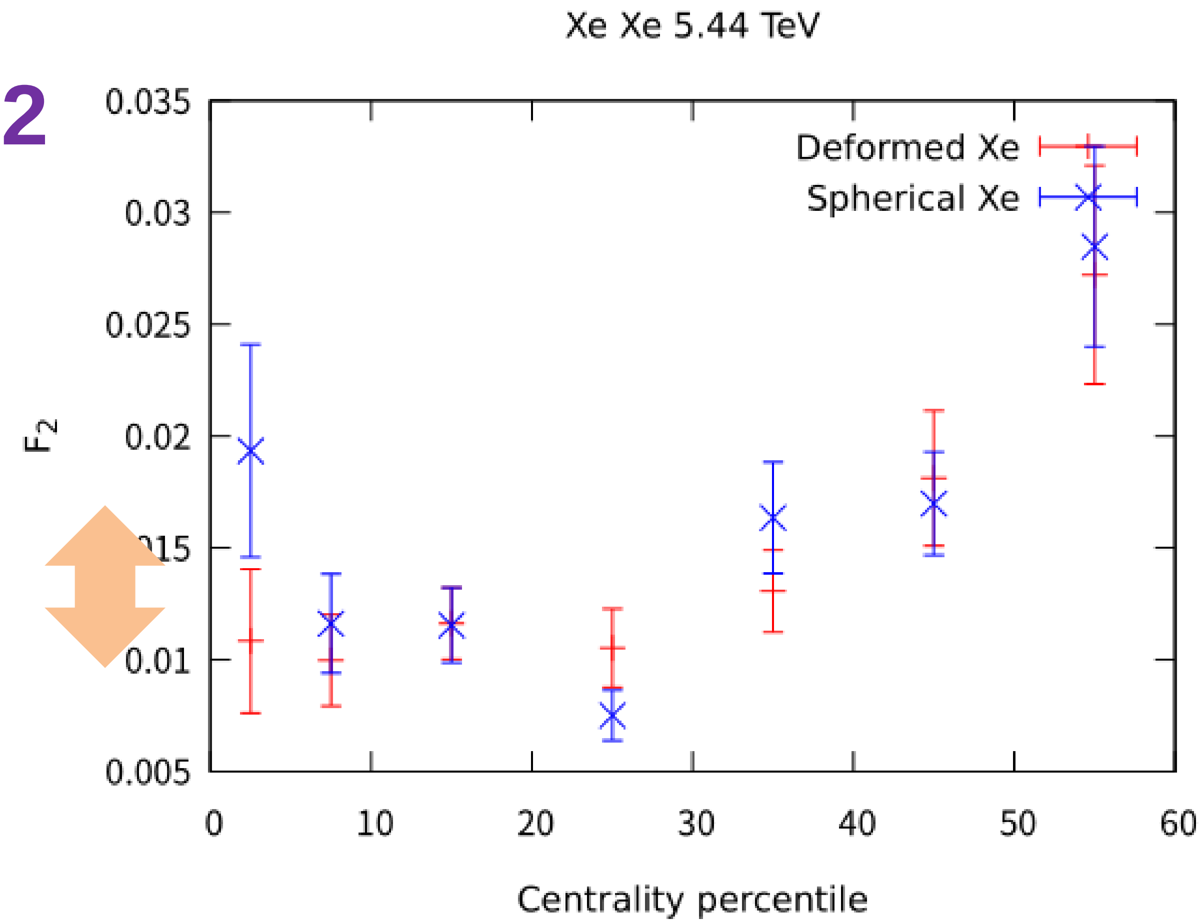
No clear tendencies as the *n*=2 case
at the central collisions

Some structures? needs statistics

Slope parameter F_n

$$r_n = 1 - 2\, F_n\, \eta_a$$

***n* = 2**

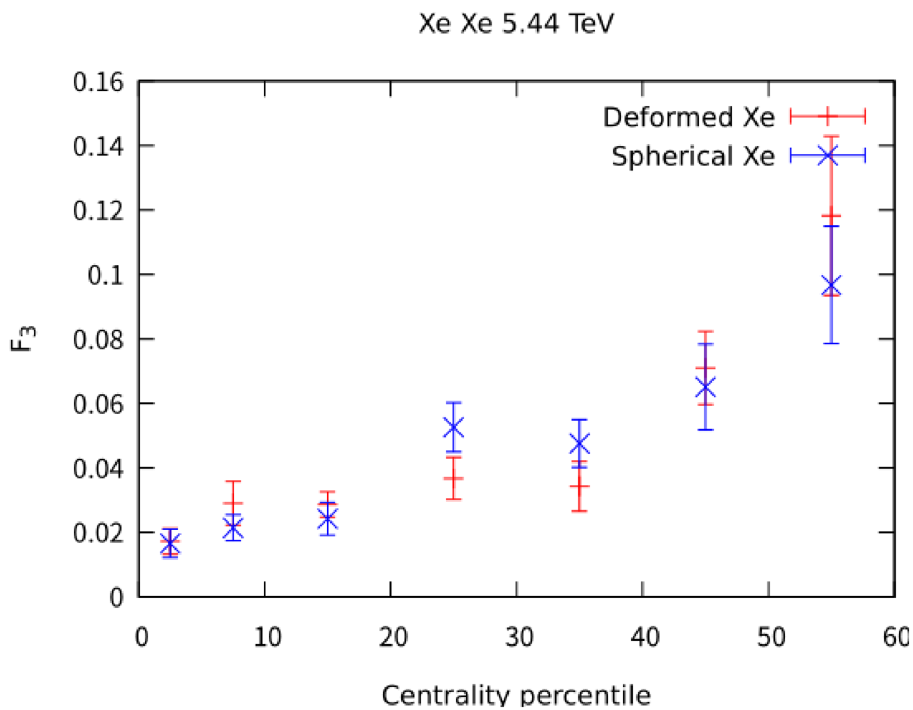


The effect of hydrodynamic fluctuations has differences by the deformation in central collisions

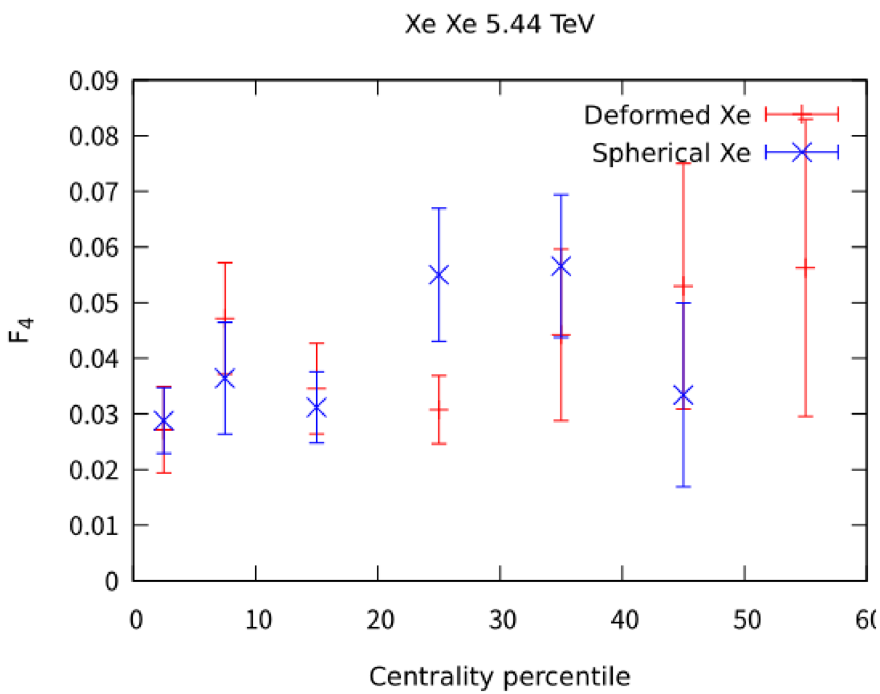
Slope parameter F_n

$$r_n = 1 - 2\,F_n\,\eta_a$$

***n* = 3**



***n* = 4**



No strong tendencies for n=3,4

Summary

✓ Hydrodynamic fluctuations are thermal fluctuations of fluid dynamics

✓ They affect the dynamics through the noise term in hydro eqs.

The effect of the hydrodynamic fluctuations to the longitudinal decorrelation actually depends on the initial geometry.

- Larger initial anisotropy stabilizes the event plane so that the decorrelations by *hydrodynamic fluctuations* are suppressed just the same as that by *initial fluctuations*.
- First attempt of calculating Xe-Xe 5.44 TeV collisions with *hydrodynamic fluctuations* in a dynamical model.
  Compared the deformed Xe and spherical Xe results.
  → The decorrelation is weaker with deformed Xe
  in central collisions with larger v_2
- Qualitatively similar with other longitudinal fluctuations:
  Needs more statistics/analysis for quantitative discussion