

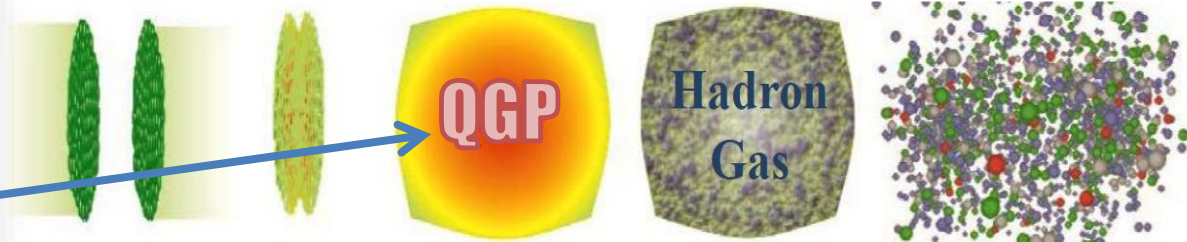
# Dynamical modeling of heavy ion collisions and probing the QGP initial conditions (Nuclear Structure)

Huichao Song  
Peking University

Intersection of nuclear structure and high-energy nuclear collisions 2026

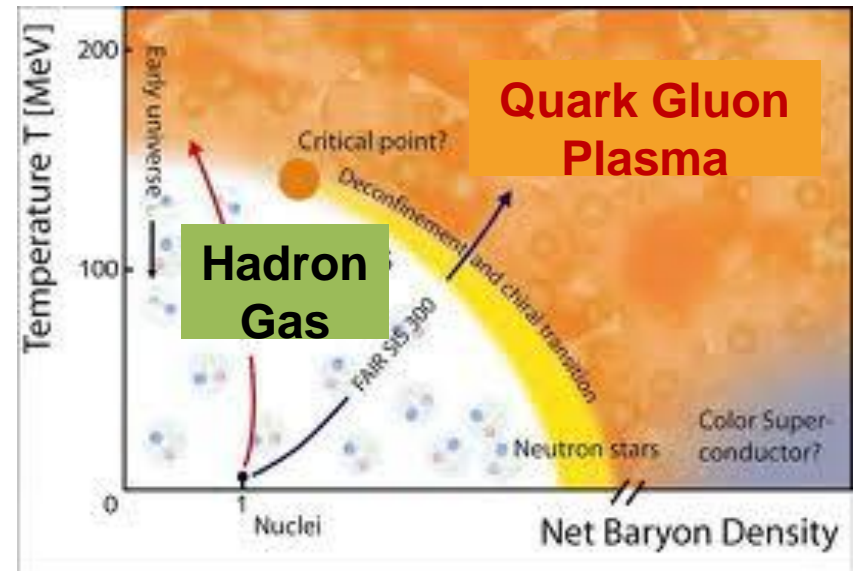
YITP April 13-24 2026

# Relativistic heavy ion physics

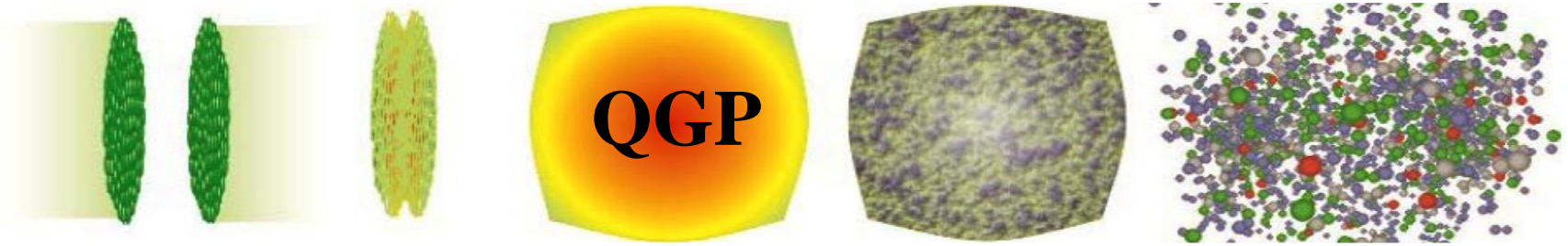


## Relativistic heavy ion collisions

- create and study QGP
- the QCD phase diagram
- the deconfinement & chiral phase transition
- the QCD vacuum



The QGP has been created in relativistic heavy ion collisions



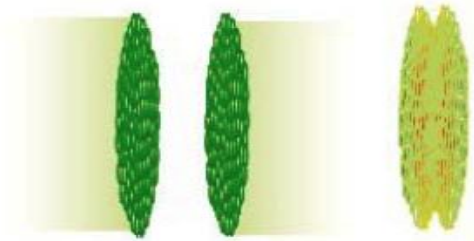
**Hottest Matter on Earth**



**Most Perfect Liquid**

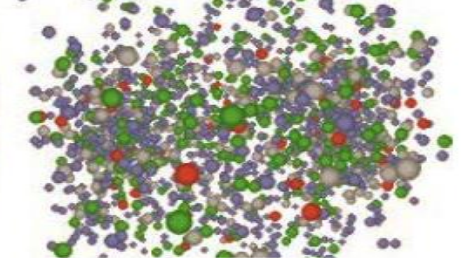
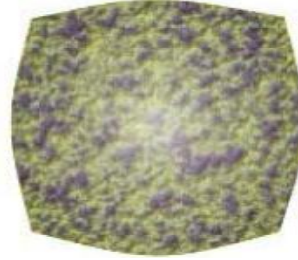


**Most Vortical Fluid**



Initial conditions:

Intersection study  
with nuclear structure



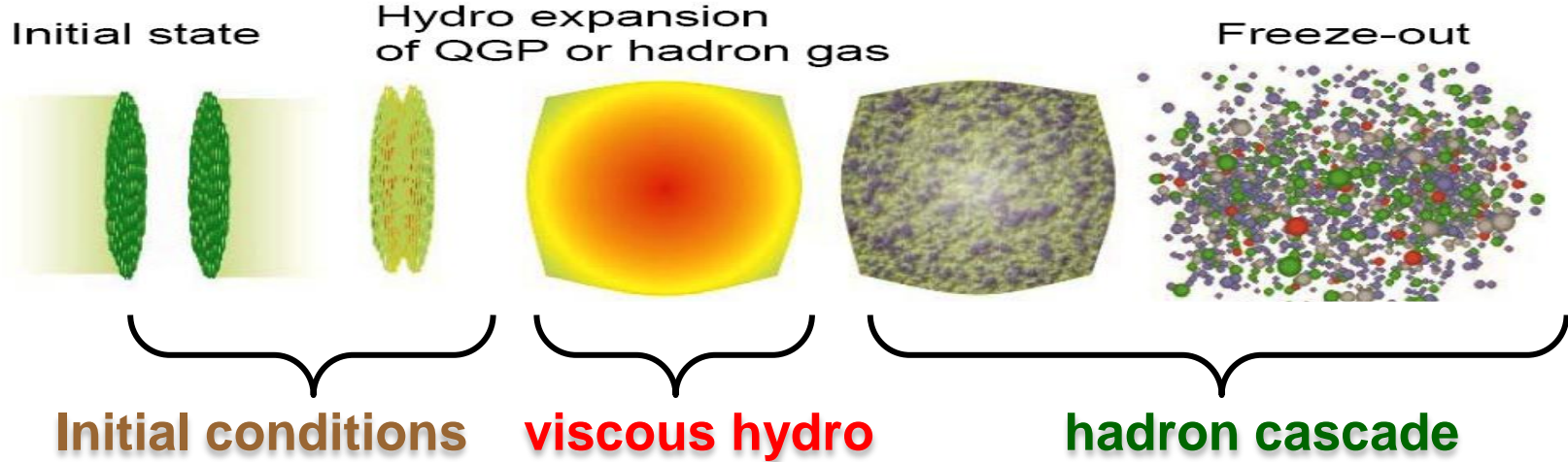
QGP+HRQ evolution:

main goal: QGP properties & QCD phase  
diagram

## Dynamical modeling for QGP evolution

- Traditional viscous hydro & its hybrid model
- Anisotropic viscous hydro for small & large systems

# Viscous hydro + hadron cascade hybrid approach



Conservation laws:

$$\partial_\mu T^{\mu\nu}(x) = 0, \quad \partial_\mu N_i^\mu(x) = 0,$$

2<sup>nd</sup> order I-S equ:

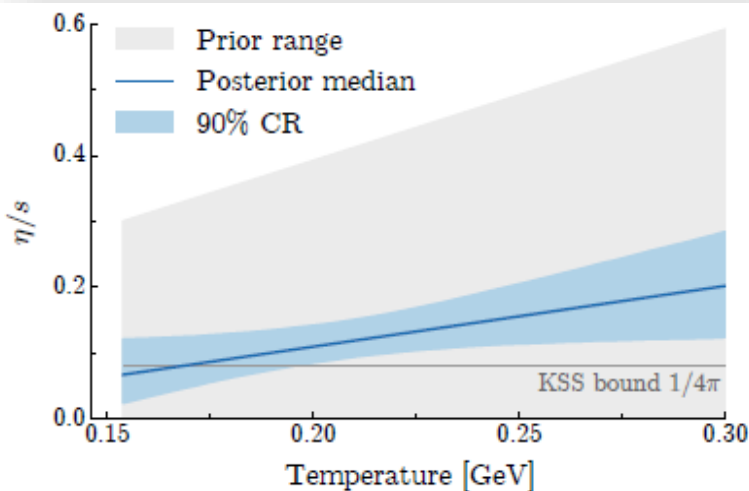
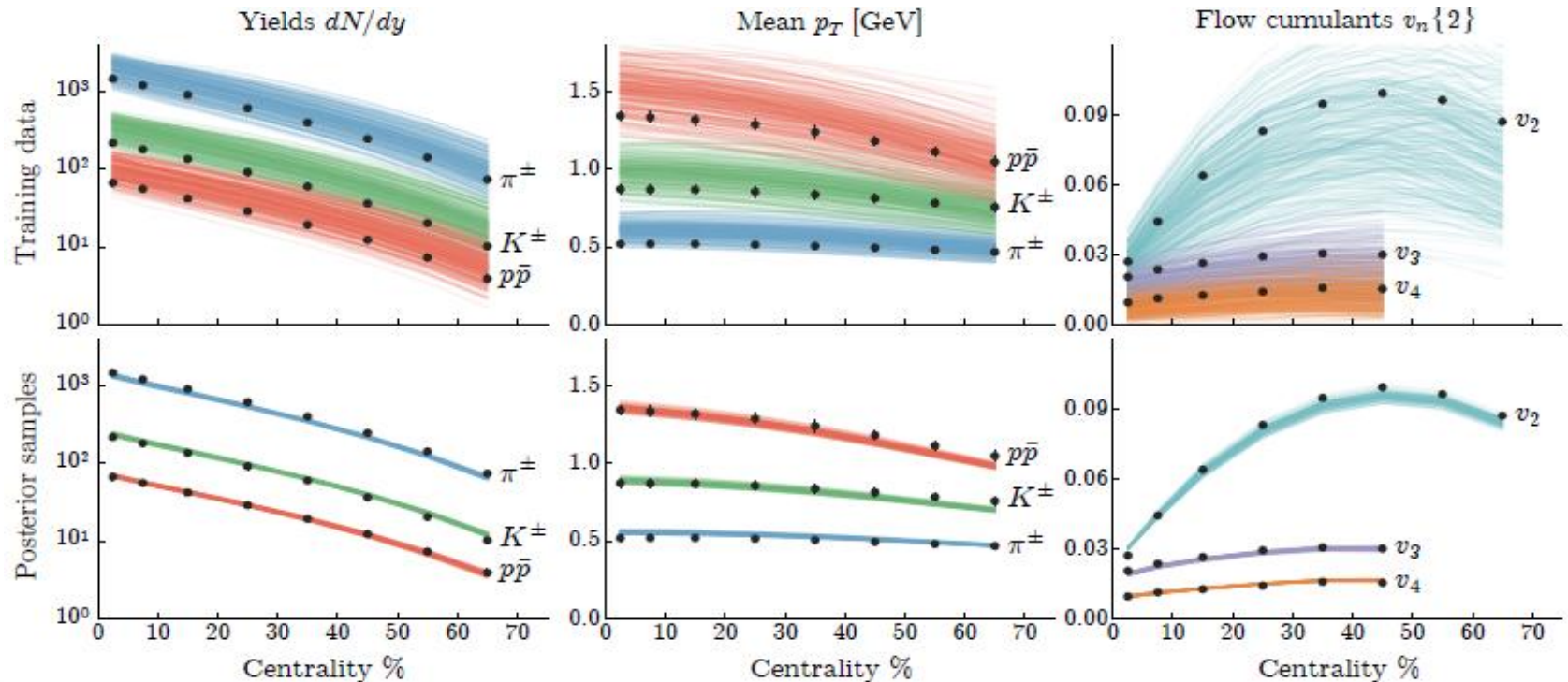
$$\dot{\Pi} = -\frac{1}{\tau_\Pi} \left[ \Pi + \zeta\theta - l_{\Pi q} \nabla_\mu q^\mu + \Pi \zeta T \partial_\mu \left( \frac{\tau_\Pi u^\mu}{2\zeta T} \right) \right],$$

$$\Delta_\nu^\mu \dot{q}^\nu = -\frac{1}{\tau_q} \left[ q_\mu + \lambda \frac{nT^2}{e+p} \nabla^\mu \frac{\nu}{T} + l_{q\pi} \nabla_\nu \pi^{\mu\nu} + l_{q\Pi} \nabla^\mu \Pi - \lambda T^2 q^\mu \partial_\mu \left( \frac{\tau_q u^\mu}{2\lambda T^2} \right) \right],$$

$$\Delta^{\mu\alpha} \Delta^{\nu\beta} \dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi} \left[ \pi^{\mu\nu} - 2\eta \nabla^{\langle\mu} u^{\nu\rangle} - l_{\pi q} \nabla^{\langle\mu} q^{\nu\rangle} + \pi_{\mu\nu} \eta T \partial_\alpha \left( \frac{\tau_\pi u^\alpha}{2\eta T} \right) \right],$$

Input: "EOS"  $\varepsilon = \varepsilon(p)$  initial and final conditions

# Hydo+Bayesian: extract the QGP viscosity

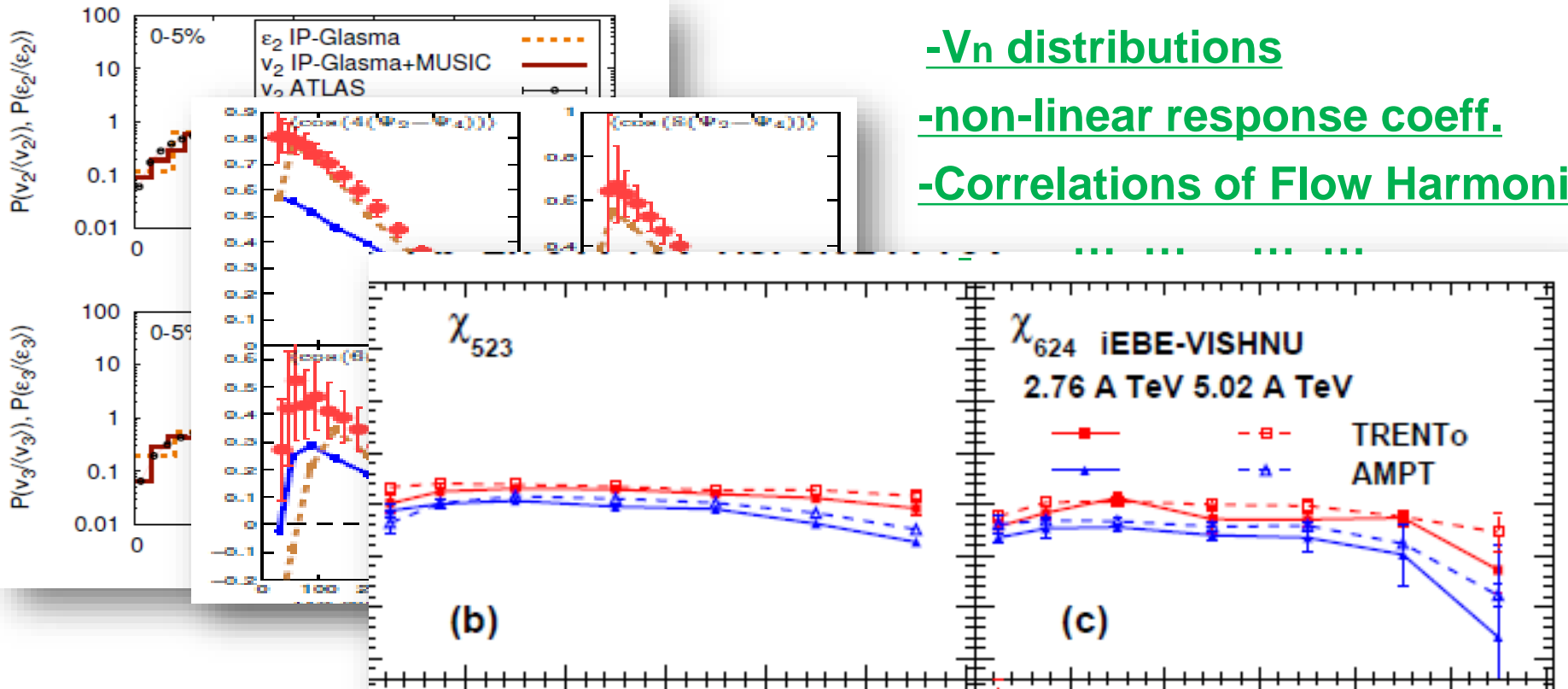


-An quantitative extraction of the QGP viscosity with **iEBE-VISHNU** (**Trento Initial conditions**) using **Bayesian analysis**

- $\eta/s(T)$  is very close to the KSS bound of  $1/4\pi$

J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015

# Powerful predictions from hydrodynamics



- $V_n$  distributions
- non-linear response coeff.
- Correlations of Flow Harmonics

-Hydrodynamics can quantitatively describe / predict various flow data  
 -perfect liquid for large systems

H. Xu, Z. Li and H. S\*, Phys. Rev. C93, no. 6, 064905 (2016); W. Zhao, H. Xu and H. S\*, Eur. Phys. J. C 77, no. 9, 645 (2017); X. Zhu, Y. Zhou, H. Xu and H. S\*, Phys. Rev. C95, no. 4, 044902 (2017); W. Zhao, L. Zhu, H. Zheng, C. M. Ko and H. S\*, Phys. Rev. C 98, no. 5, 054905 (2018); Li, Zhao, Zhou, H.S\*, in preparation (2020) ... ..

**-- How tiny the QGP droplet could be?**

# Small collisions systems at RHIC & LHC

## System size scan:

Pb+Pb Xe+Xe O+O p-Pb p-p collisions ...

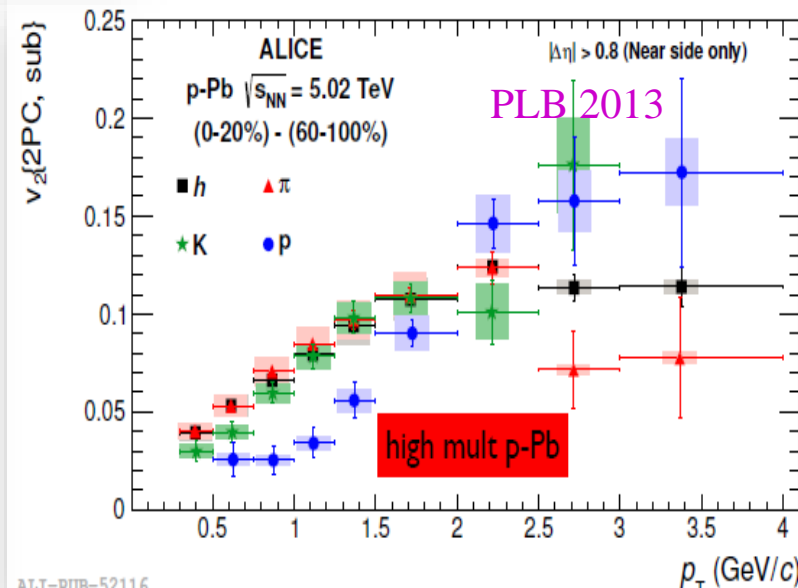
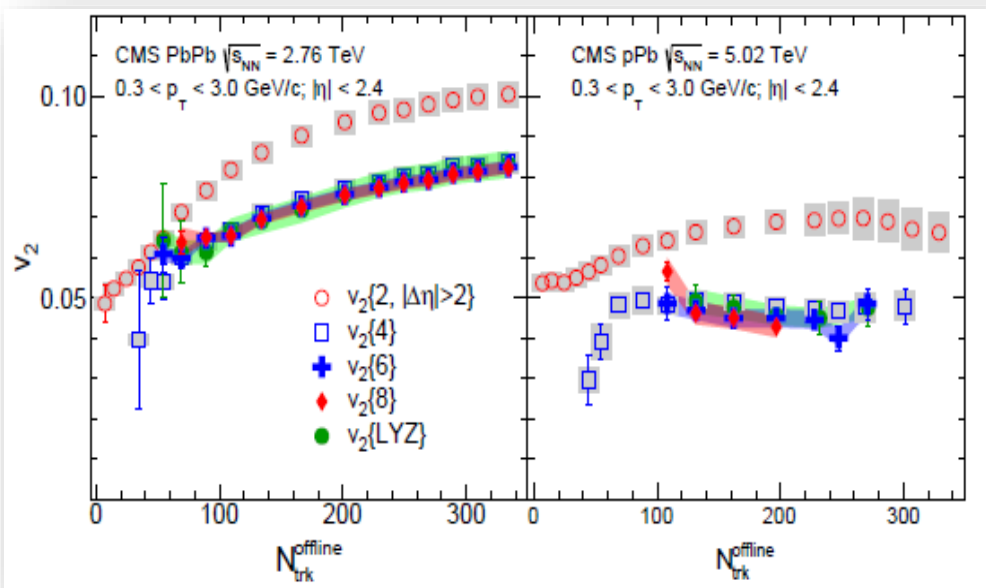
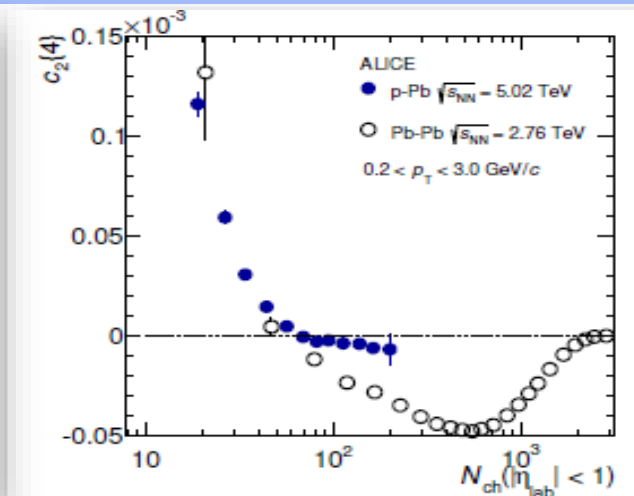
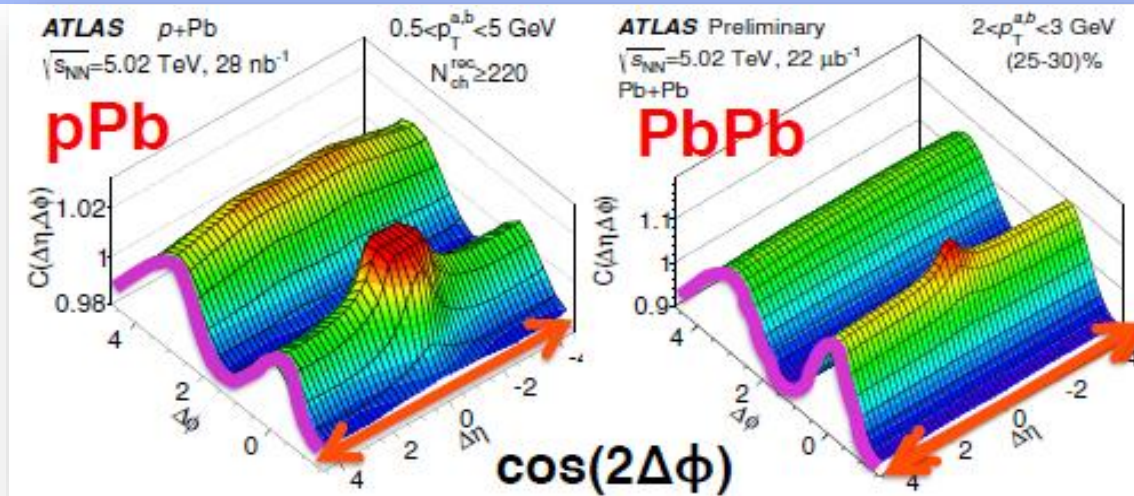
## Geometry scan:

p-Au d+Au He-Au collisions...

## Other collision systems:

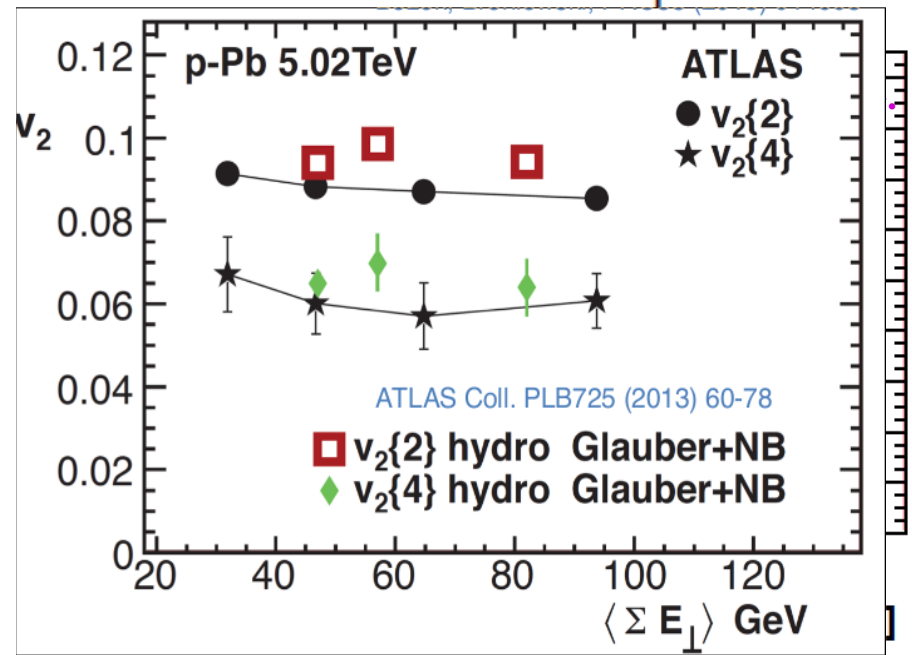
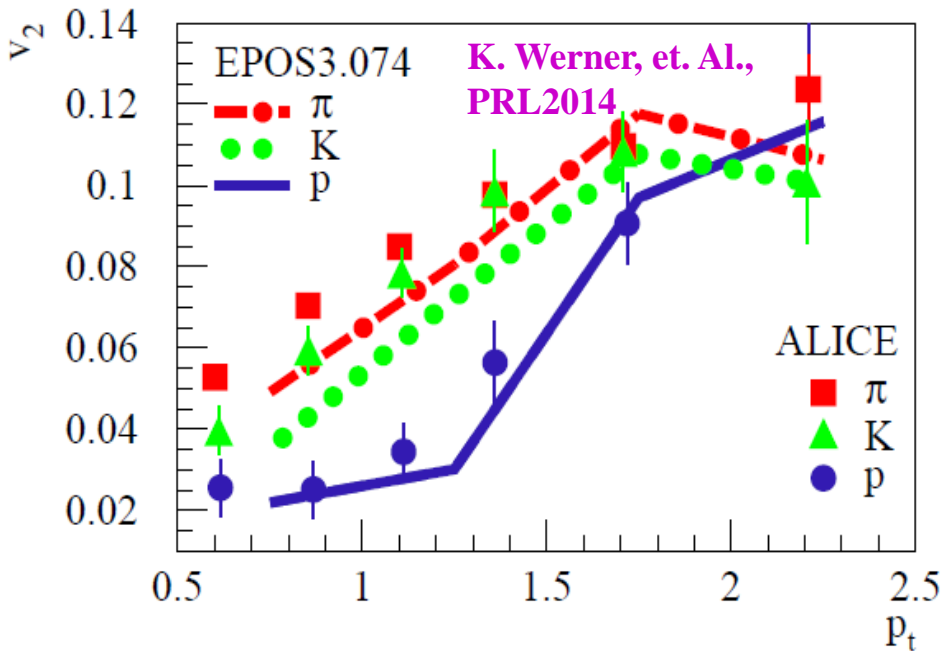
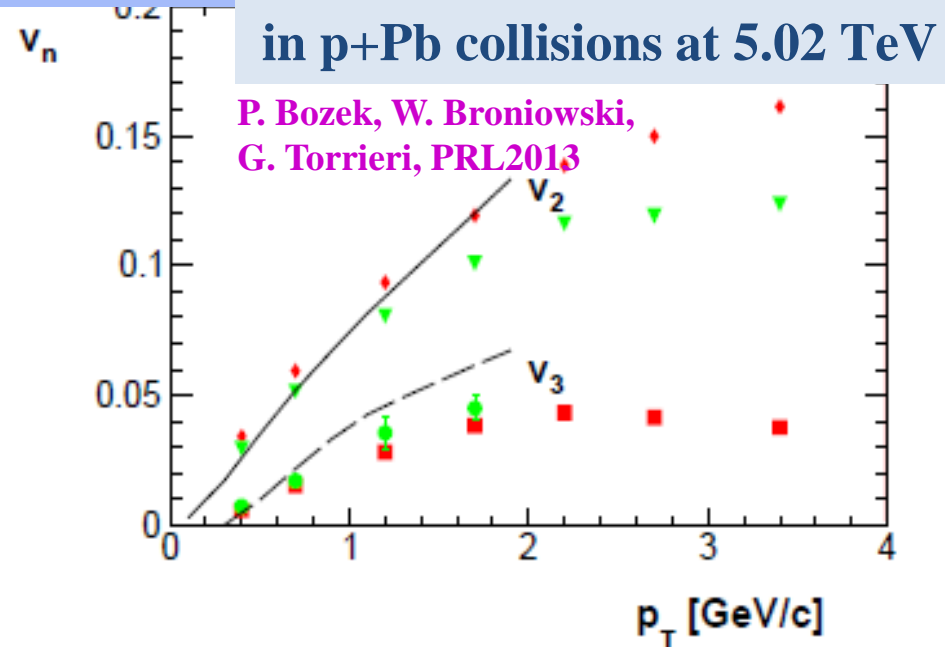
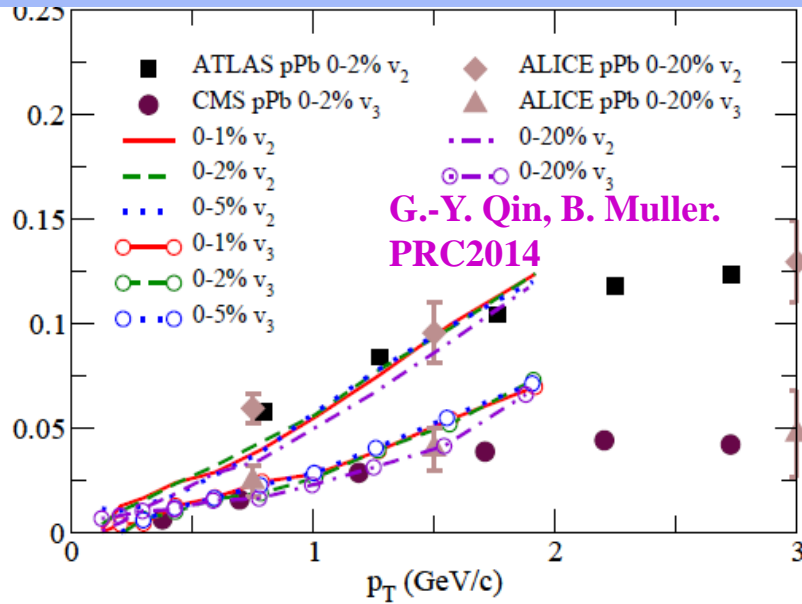
OBSERVABLES	A–A	p–A (high mult.)	pp (high mult.)	pp (low mult.)	UPC	ep	e <sup>+</sup> e <sup>-</sup> (high mult.)	e <sup>+</sup> e <sup>-</sup>
Near-side ridge yield	✓ [1,2]	✓ [30,32,33]	✓ [30,31]	✓ [34]	—	✗ [74,75]	✓ [77]	✗ [76]
Anisotropic flow	✓ [3,4]	✓ [36,37,38,39]	✓ [35,37]	✓ [30]	✓ [72,73]	✗ [74,75]	✓ [77]	—
Multiparticle cumulants	✓ [5]	✓ [40-45]	✓ [40,41,45]	—	—	—	—	—
Mass ordering	✓ [6]	✓ [47-49]	✓ [46,48]	—	—	—	—	—

# Correlations & Flow in small systems

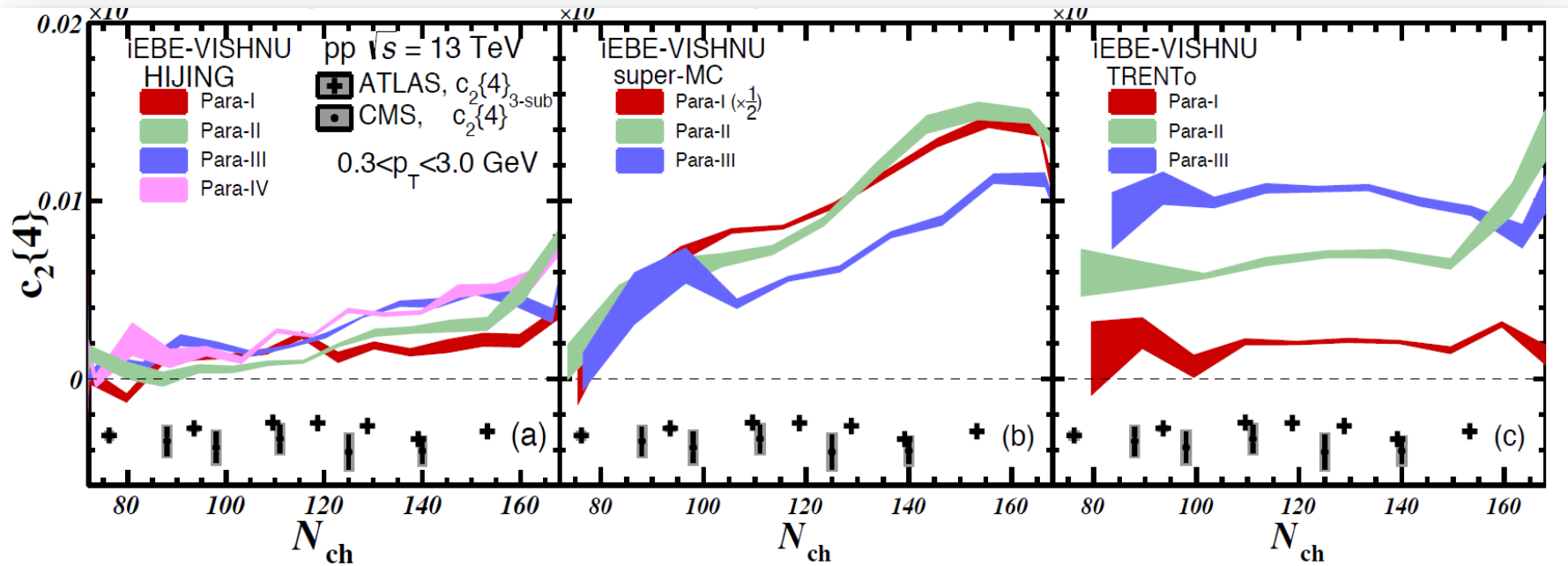


-Many flow-like signals have been observed in high multiplicity p-Pb collisions

# Traditional Hydro calculations for small systems

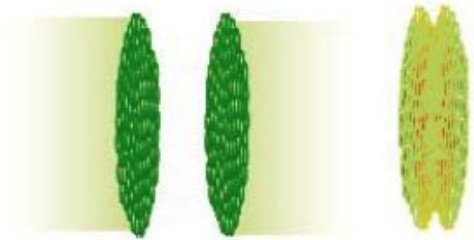


# Traditional hydro: $C_2\{4\}$ puzzle in p-p collisions



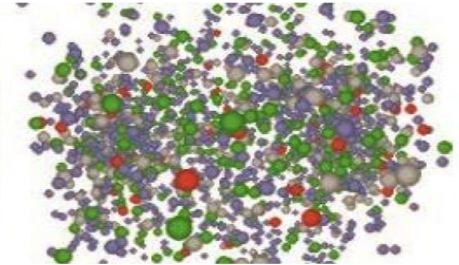
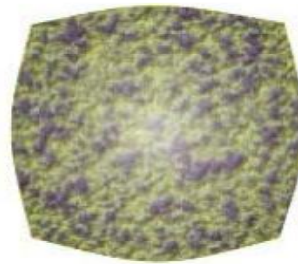
Traditional hydro fails to reproduce the negative  $C_2\{4\}$  with different initial conditions

W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B 780, 495 (2018);



Initial conditions:

Intersection study  
with nuclear structure



QGP+HRQ evolution:

main goal: QGP properties & QCD phase  
diagram

## Dynamical modeling for QGP evolution

- Traditional viscous hydro & its hybrid model
- Anisotropic viscous hydro for small & large systems

# Small systems: from traditional to anisotropic hydro

traditional hydro:

$$T^{\mu\nu} = \mathcal{E} u^\mu u^\nu - (\mathcal{P}_{\text{eq}} + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}.$$

$$f = f_{\text{eq}} + \delta f \quad \delta f = \frac{p^\mu p^\nu \pi_{\mu\nu}}{2T^2(\mathcal{E} + \mathcal{P}_{\text{eq}})} \quad |\delta f| \ll f_{\text{eq}}.$$

Validity of traditional hydro

Knudsen number:  $K_n = \tau_\pi \theta = 5 \frac{\eta \theta}{sT},$

Anisotropic hydro

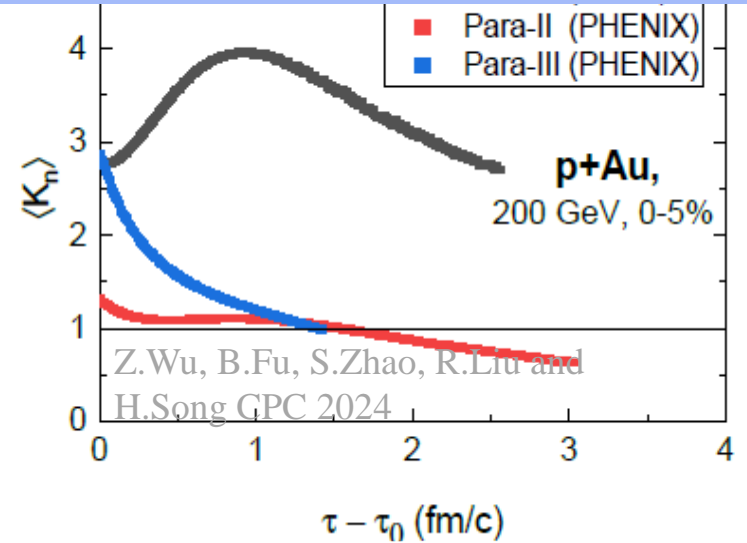
$$\Delta^{\mu\nu} = \Xi^{\mu\nu} - z^\mu z^\nu, \quad \Xi^{\mu\nu} \equiv g^{\mu\nu} - u^\mu u^\nu + z^\mu z^\nu$$

$$\Rightarrow T^{\mu\nu} = \mathcal{E} u^\mu u^\nu + \mathcal{P}_L z^\mu z^\nu - \mathcal{P}_\perp \Xi^{\mu\nu} + 2W_{\perp z}^{(\mu} z^{\nu)} + \pi_{\perp}^{\mu\nu}.$$

$$\left. \begin{array}{l} \pi^{\mu\nu} \\ \mathcal{P}_{\text{eq}} + \Pi \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \mathcal{P}_L = z_\mu z_\nu T^{\mu\nu}, \\ \mathcal{P}_\perp = -\frac{1}{2} \Xi_{\mu\nu} T^{\mu\nu}, \\ W_{\perp z}^\mu = -\Xi_\alpha^\mu T^{\alpha\nu} z_\nu, \\ \pi_{\perp}^{\mu\nu} = \Xi_{\alpha\beta}^{\mu\nu} T^{\alpha\beta}, \end{array} \right.$$

M. McNelis, D. Bazow,  
and U. Heinz, Com.  
Phys. Comm 267,  
108077 (2021)

S. Zhao, Y. Peng, U. Heinz,  
H. Song 2509.03841



$$f(x, p) = f_a(x, p) + \delta \tilde{f}(x, p) \quad f_a(x, p) = f_{\text{eq}}(\sqrt{\Omega_{\mu\nu}(x) p^\mu p^\nu} / \Lambda(x))$$

# Viscous Anisotropic hydro (VAH)

$$\partial_\mu T^{\mu\nu} = 0.$$

$$f_a(x, p) = f_{\text{eq}} \left( \frac{\sqrt{\Omega_{\mu\nu} p^\mu p^\nu}}{\Lambda(x)} \right),$$

$$T^{\mu\nu} = \mathcal{E} u^\mu u^\nu + \mathcal{P}_L z^\mu z^\nu - \mathcal{P}_\perp \Xi^{\mu\nu} + 2 W_{\perp z}^{(\mu} z^{\nu)} + \pi_\perp^{\mu\nu}.$$

$$\Omega_{\mu\nu} p^\mu p^\nu = m^2 + \frac{p_{\perp, \text{LRF}}^2}{\alpha_\perp^2} + \frac{p_{z, \text{LRF}}^2}{\alpha_L^2},$$

$$\begin{aligned} \dot{\mathcal{P}}_L^{(k)} = & -\frac{\bar{\mathcal{P}}^{(k)} - \mathcal{P}_{\text{eq}}^{(k)}}{\tau_\Pi} - \frac{\mathcal{P}_L^{(k)} - \mathcal{P}_\perp^{(k)}}{3\tau_\pi/2} + \bar{\zeta}_z^{L(k)} z_\mu D_z u^\mu + \bar{\zeta}_\perp^{L(k)} \theta_\perp - 2W_{\perp z}^\mu \dot{z}_\mu + \bar{\lambda}_{Wu}^{L(k)} W_{\perp z}^\mu D_z u_\mu \\ & + \bar{\lambda}_{W\perp}^{L(k)} W_{\perp z}^\mu z_\nu \nabla_{\perp\mu} u^\nu - \bar{\lambda}_\pi^{L(k)} \pi_\perp^{\mu\nu} \sigma_{\perp, \mu\nu}, \end{aligned}$$

$$\begin{aligned} \dot{\mathcal{P}}_\perp^{(k)} = & -\frac{\bar{\mathcal{P}}^{(k)} - \mathcal{P}_{\text{eq}}^{(k)}}{\tau_\Pi} + \frac{\mathcal{P}_L^{(k)} - \mathcal{P}_\perp^{(k)}}{3\tau_\pi} + \bar{\zeta}_z^\perp(k) z_\mu D_z u^\mu + \bar{\zeta}_\perp^\perp(k) \theta_\perp + W_{\perp z}^\mu \dot{z}_\mu + \bar{\lambda}_{Wu}^\perp(k) W_{\perp z}^\mu D_z u_\mu \\ & - \bar{\lambda}_{W\perp}^\perp(k) W_{\perp z}^\mu z_\nu \nabla_{\perp\mu} u^\nu + \bar{\lambda}_\pi^\perp(k) \pi_\perp^{\mu\nu} \sigma_{\perp, \mu\nu}, \end{aligned}$$

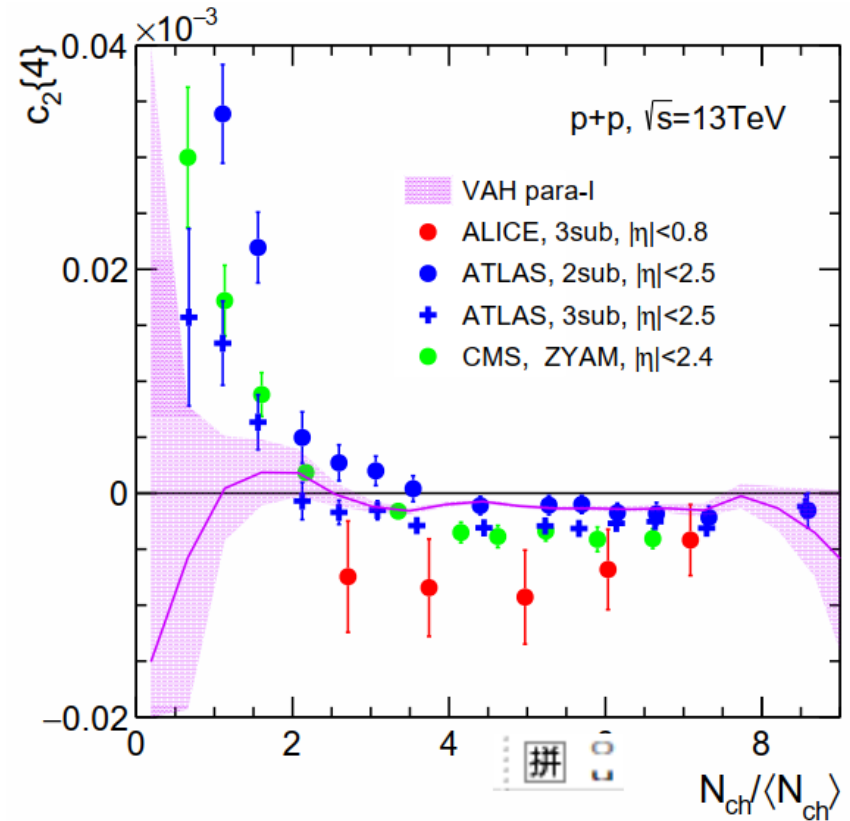
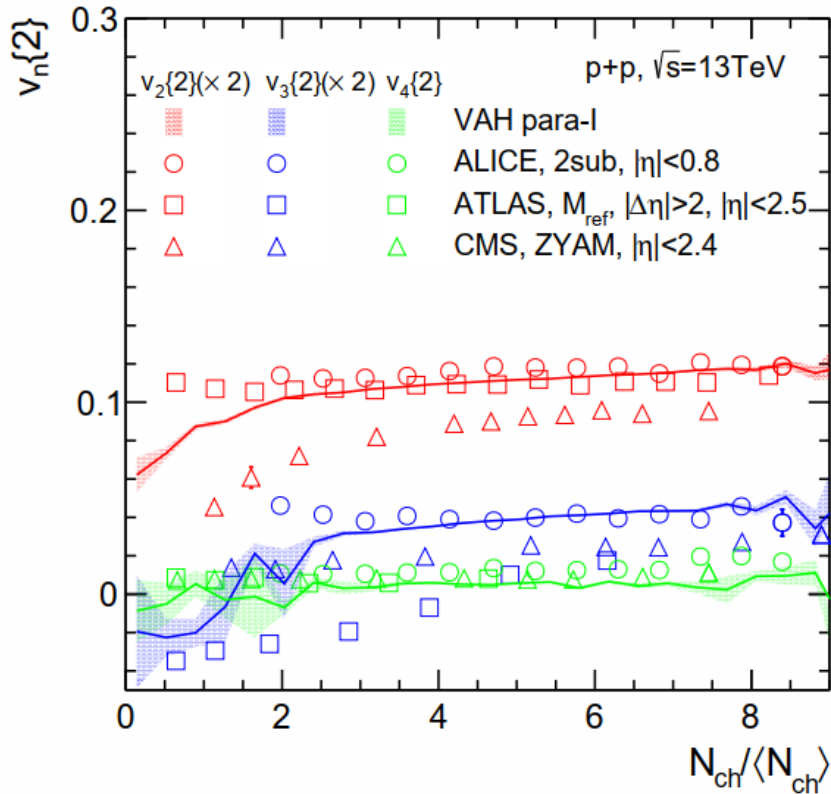
$$\begin{aligned} \dot{W}_{\perp z}^{\{\mu\}} = & -\frac{W_{\perp z}^\mu}{\tau_\pi} + 2\bar{\eta}_u^W \Xi^{\mu\nu} D_z u_\nu - 2\bar{\eta}_\perp^W z_\nu \nabla_\perp^\mu u^\nu - (\bar{\tau}_z^W \Xi^{\mu\nu} + \pi_\perp^{\mu\nu}) \dot{z}_\nu + \bar{\delta}_W^W W_{\perp z}^\mu \theta_\perp \\ & - \bar{\lambda}_{Wu}^W W_{\perp z}^\mu z_\nu D_z u^\nu + \bar{\lambda}_{W\perp}^W \sigma_\perp^{\mu\nu} W_{\perp z, \nu} + \omega_\perp^{\mu\nu} W_{\perp z, \nu} + \bar{\lambda}_{\pi u}^W \pi_\perp^{\mu\nu} D_z u_\nu - \bar{\lambda}_{\pi\perp}^W \pi_\perp^{\mu\nu} z_\alpha \nabla_{\perp\nu} u^\alpha, \end{aligned}$$

$$\begin{aligned} \dot{\pi}_\perp^{\{\mu\nu\}} = & -\frac{\pi_\perp^{\mu\nu}}{\tau_\pi} + 2\bar{\eta}_\perp \sigma_\perp^{\mu\nu} - 2W_{\perp z}^{\{\mu} \dot{z}^{\nu\}} - \bar{\delta}_\pi^\pi \pi_\perp^{\mu\nu} \theta_\perp - \bar{\tau}_\pi^\pi \pi_\perp^{\alpha\{\mu} \sigma_{\perp, \alpha}^{\nu\}} + 2\pi_\perp^{\alpha\{\mu} \omega_{\perp, \alpha}^{\nu\}} + \bar{\lambda}_\pi^\pi \pi_\perp^{\mu\nu} z_\alpha D_z u^\alpha \\ & - \bar{\lambda}_{Wu}^\pi W_{\perp z}^{\{\mu} D_z u^{\nu\}} + \bar{\lambda}_{W\perp}^\pi W_{\perp z}^{\{\mu} z_\alpha \nabla_\perp^{\nu\}} u^\alpha. \end{aligned}$$

M. McNelis, D. Bazow, and U. Heinz, Com. Phys. Comm 267, 108077 (2021)

S. Zhao, Y. Peng, U. Heinz, H. Song 2509.03841

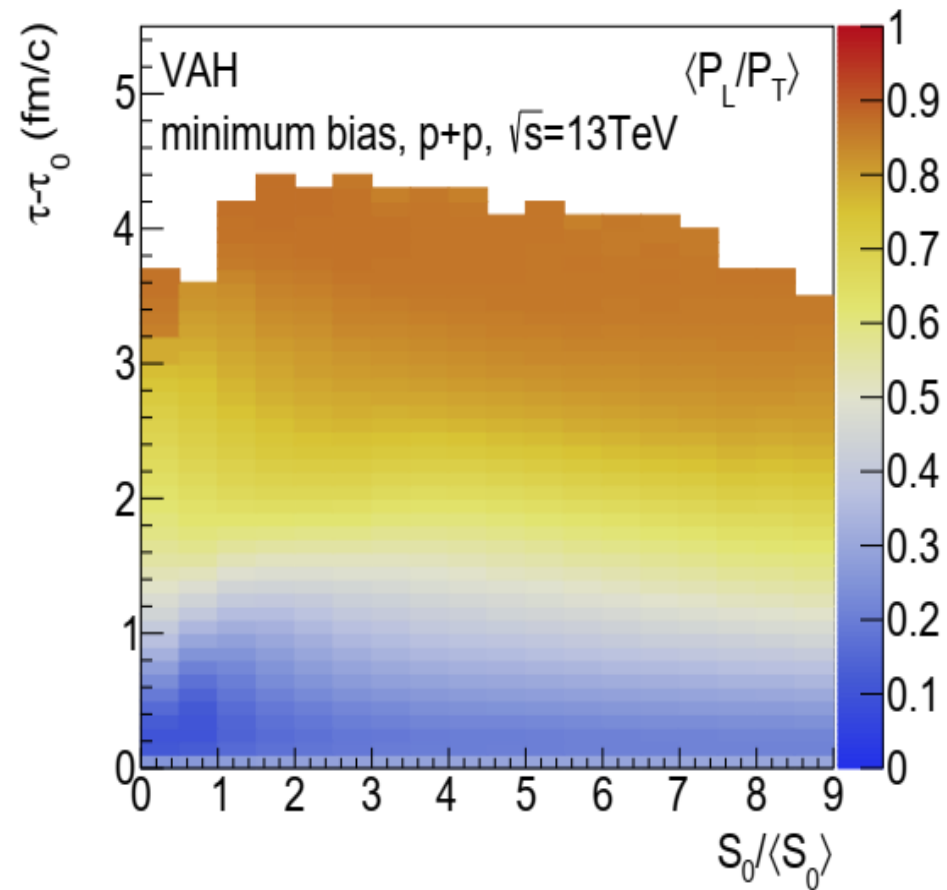
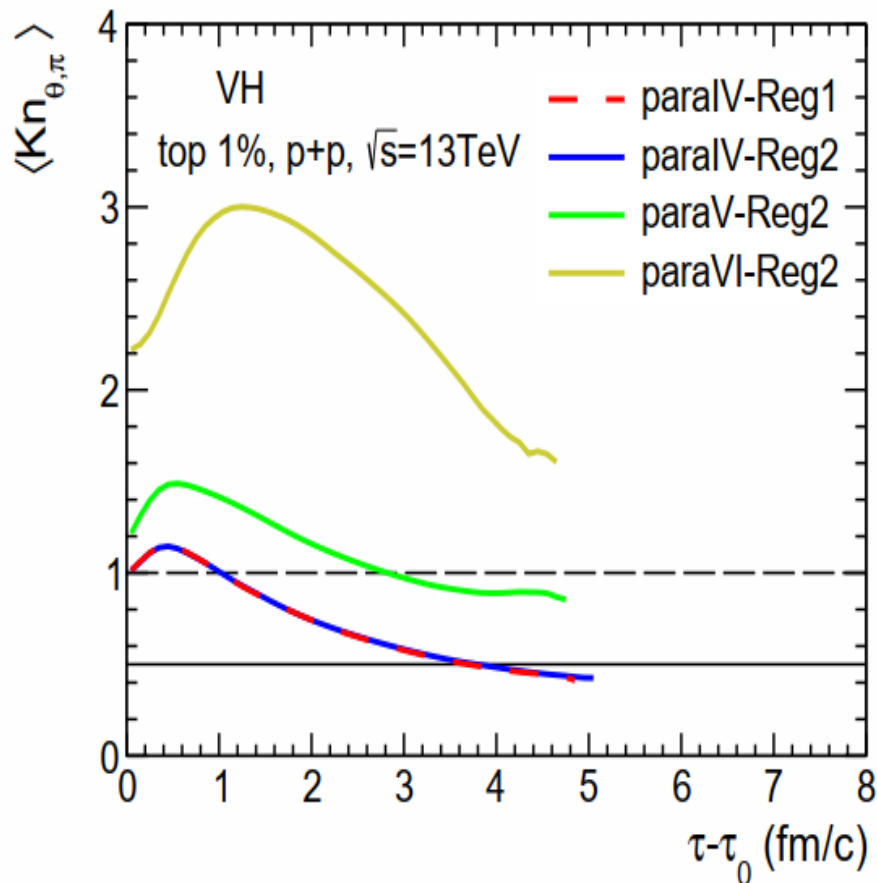
# $V_n\{2\}$ and $C_2\{4\}$ in p-p collisions (from VAH)



Viscous anisotropic hydro (VAH) roughly fits  $v_2\{2\}$ ,  $v_3\{2\}$  and  $v_4\{2\}$

VAH reproduced a negative  $C_2\{4\}$ , the  $C_2\{4\}$  puzzle is naturally solved

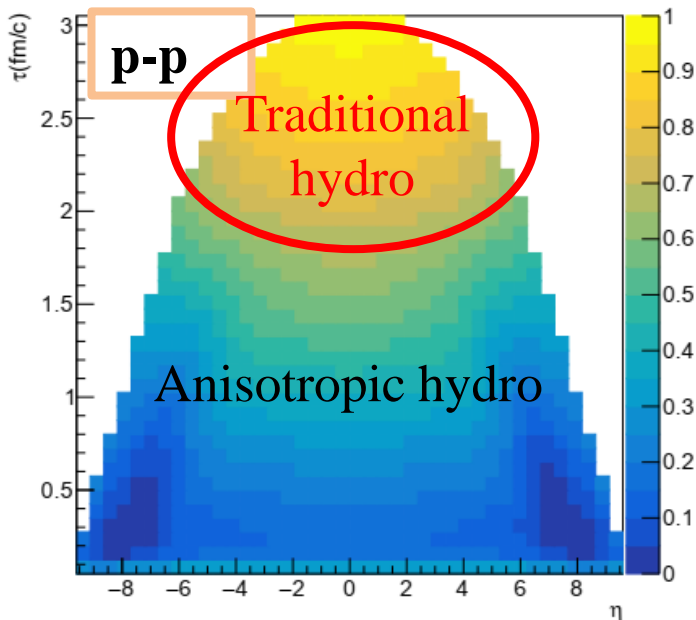
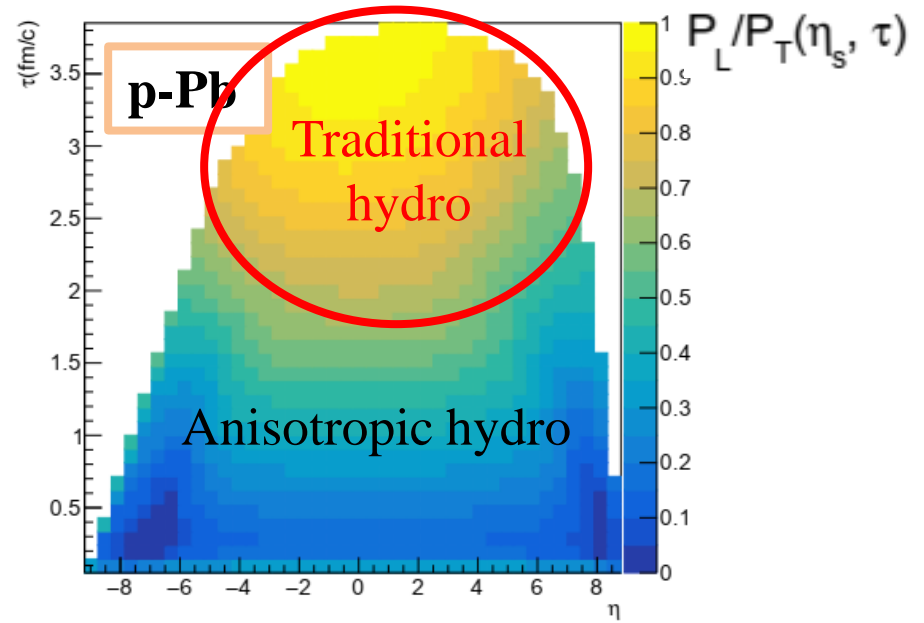
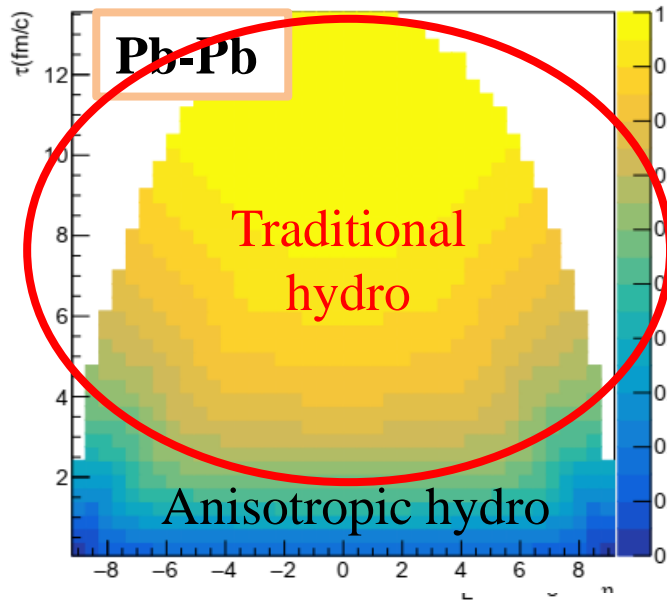
# Limitation of traditional hydro



Small systems: Traditional hydro fails

traditional hydro --- > anisotropic hydro

# Evaluating isotropization from VAH

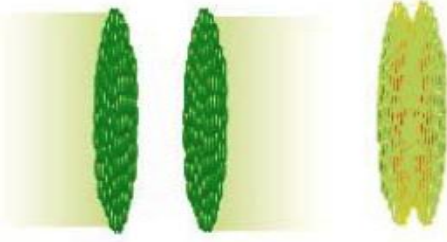


Evolution of  $P_L/P_T(\eta_s, \tau)$

Smaller systems are harder to reach isotropization.

Traditional hydro works well for large systems (Pb+Pb)

S. Zhao, U.Heinz, H.Song paper in preparation.

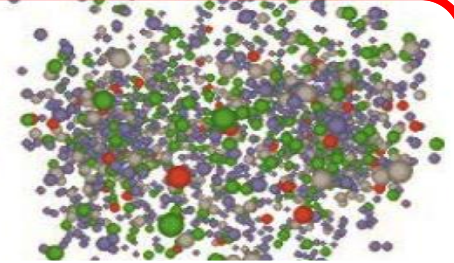
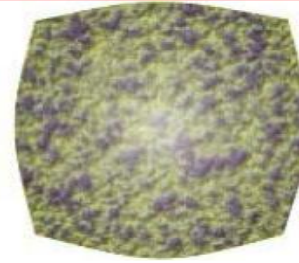


Initial conditions:

Intersection study  
with nuclear structure



**QGP**



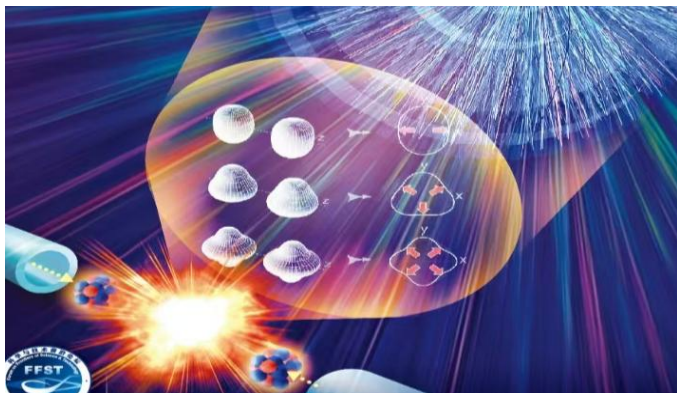
QGP+HRQ evolution:

main goal: QGP properties & QCD phase  
diagram

Large system (Au+Au Pb+Pb U+U Xe+Xe Ru+Ru Zr+Zr):

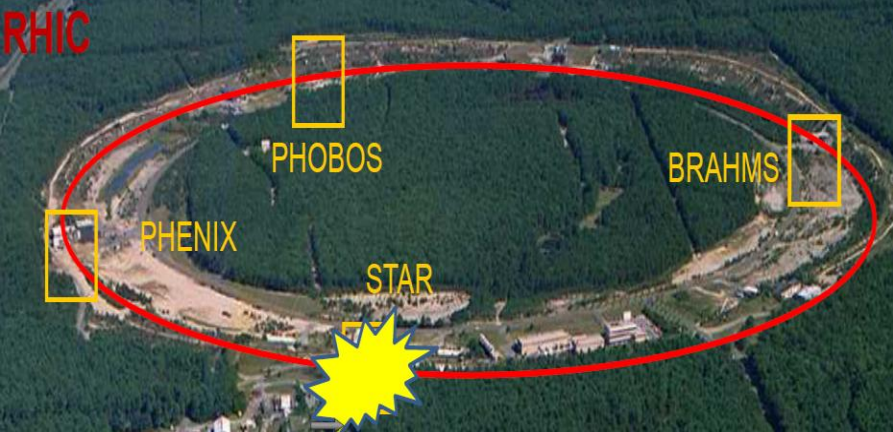
**Theory:** Traditional **Hydro** are **powerful tool**

**Experiment:** various flow observable

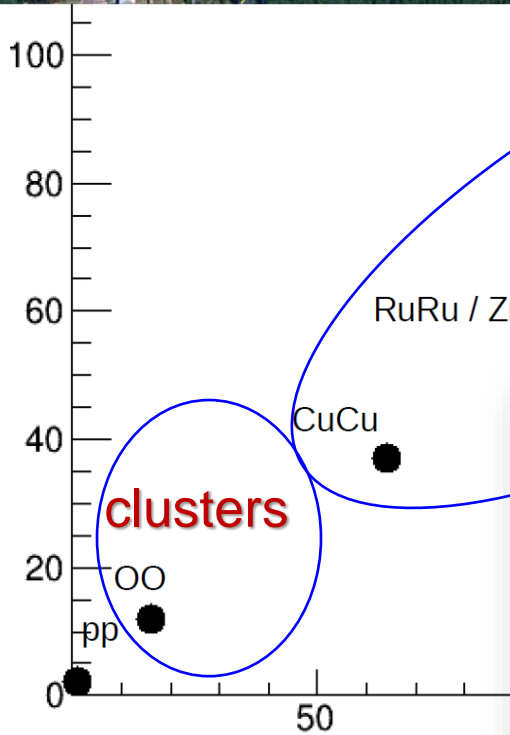


-We are ready to focus on the  
initial state of the QGP

nuclear structure of colliding  
nuclei



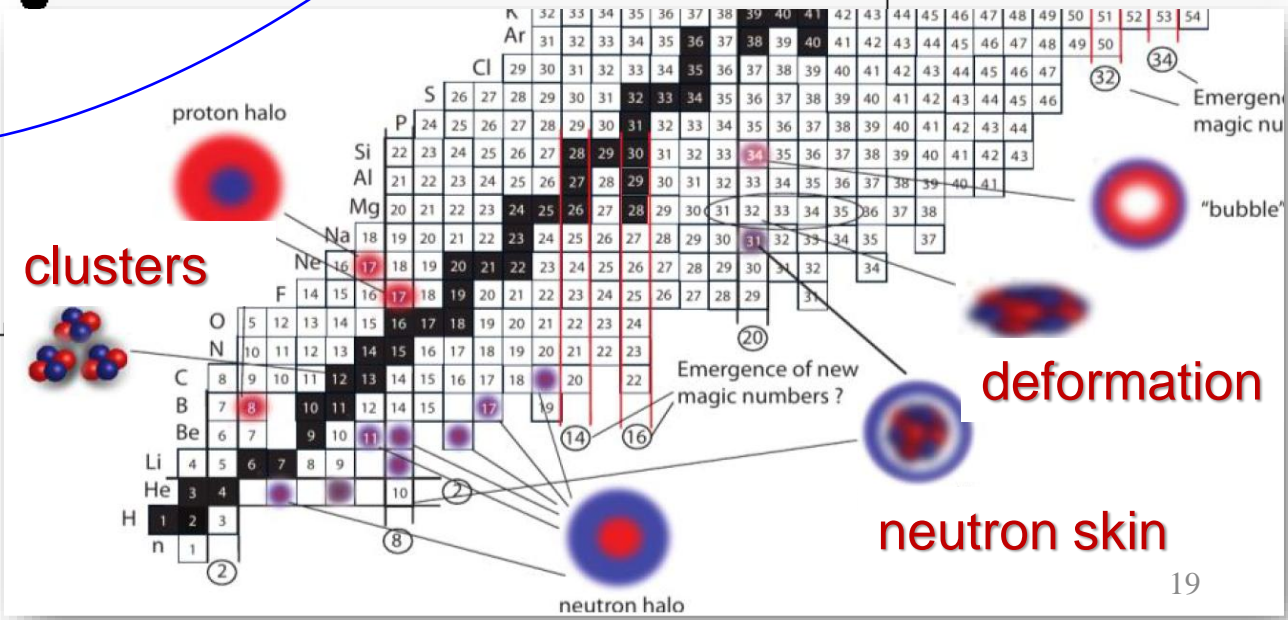
# Rich collision systems at RHIC & the LHC



clusters

deformation

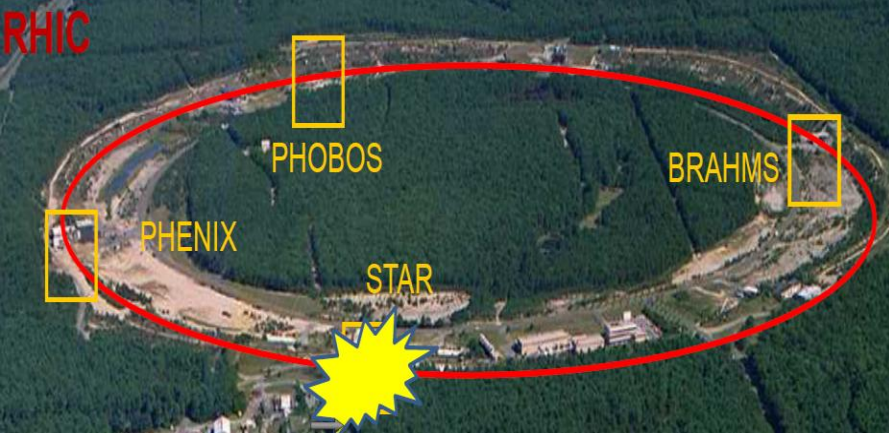
neutron skin



clusters

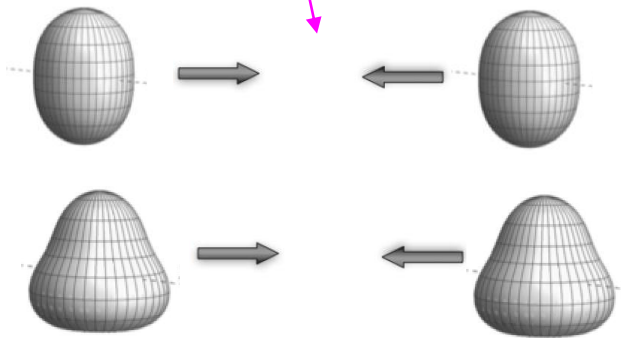
deformation

neutron skin



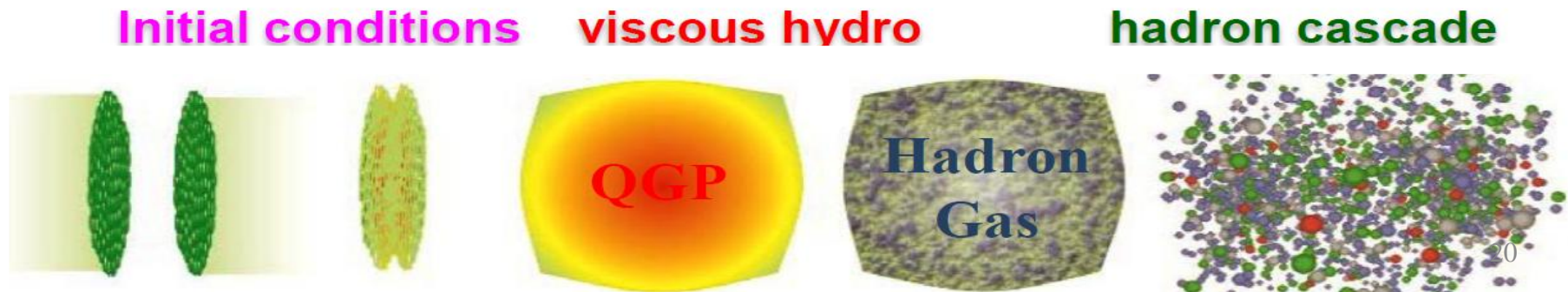
# Probe nuclear structure with relativistic heavy ion collisions

- Relativistic heavy collisions **start from nuclei, rich collision systems**
- Collision time  $< 10^{-24}$  s  
directly **probe the ground state of nuclei**
- **Well calibrated calculations for QGP evolution;** to focus on the initial state

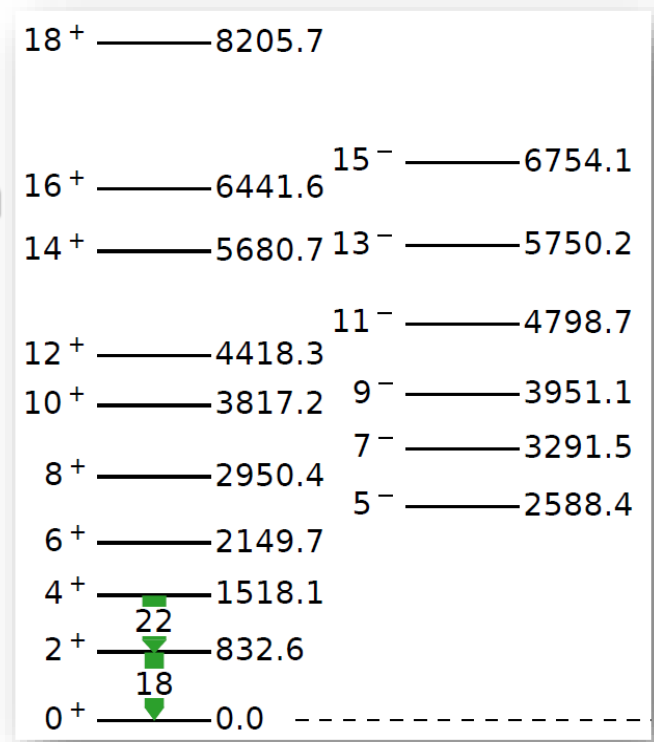
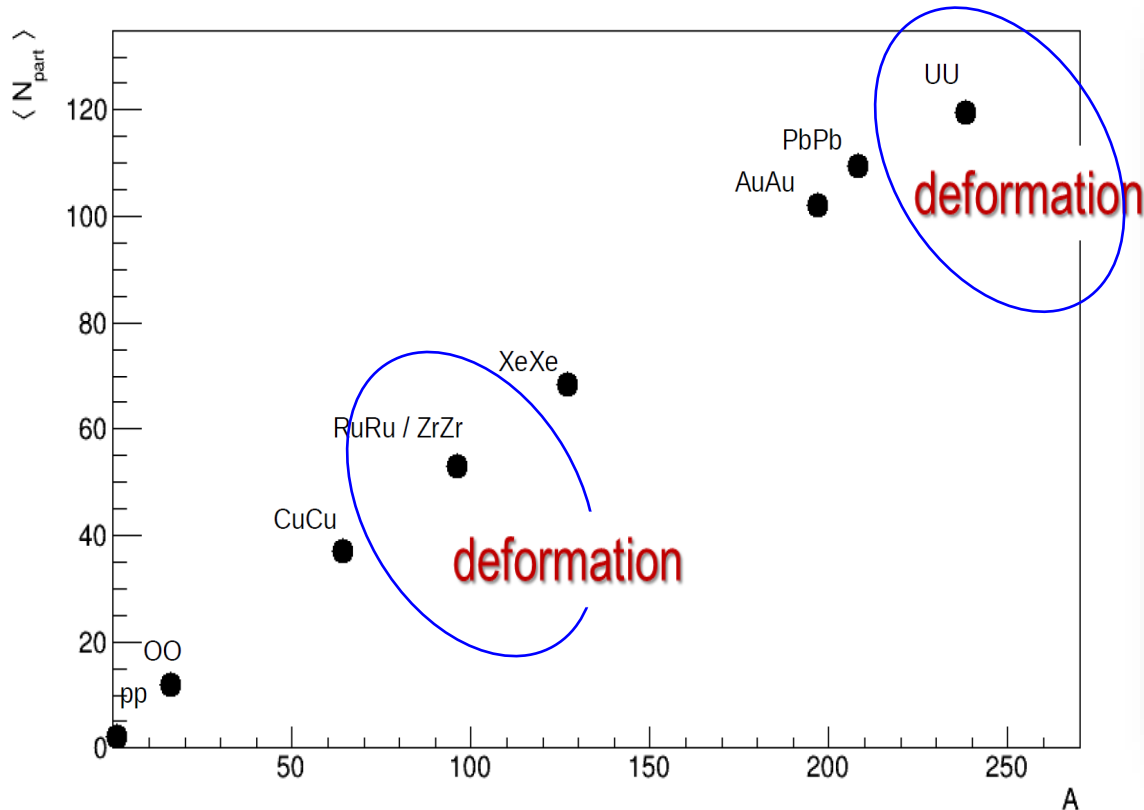


initial state with deformation

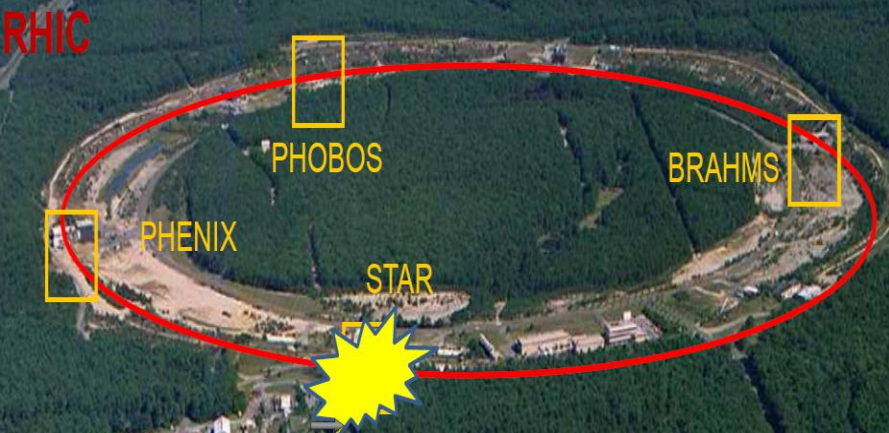
## Well calibrated calculations



# Study nuclear deformation with heavy ion collisions

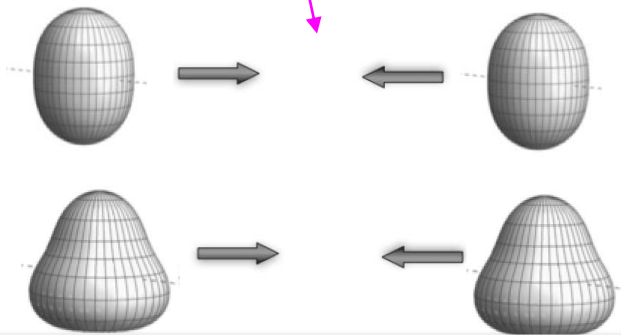


Nuclear structure physics obtain the deformation information from the spectrum with certain model calculations  
 (not directly image the deformation in position space)



# Probe nuclear structure with relativistic heavy ion collisions

- Relativistic heavy collisions **start from nuclei**
- Collision time  $< 10^{-24}$  s **directly probe the ground state of nuclei**
- **Well calibrated calculations for QGP evolution**; to focus on the initial state



## Initial conditions (TRENTO, etc )

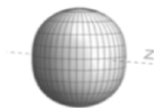
- Sample nucleon position in deformed nuclei with Woods-Saxon :

$$\rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{(r-R(\theta, \phi))/a_0}}$$

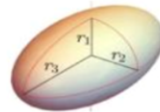
$$R(\theta, \phi) = R_0 \left( 1 + \beta_2 [\cos \gamma Y_{2,0} + \sin \gamma Y_{2,2}] + \beta_3 \sum_{m=-3}^3 \alpha_{3,m} Y_{3,m} + \beta_4 \sum_{m=-4}^4 \alpha_{4,m} Y_{4,m} \right)$$

Nuclear surface deformation

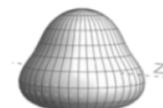
Quadrupole:



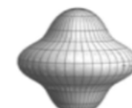
Triaxle:



Octupole:



Hexadecapole:



# Imaging the deformation $^{238}\text{U}$ at RHIC

nature

Explore content ▾ About the journal ▾ Publish with us ▾

nature > articles > article

Article | [Open access](#) | Published: 06 November 2024

## Imaging shapes of atomic nuclei in high-energy nuclear collisions

[STAR Collaboration](#)

*Nature* 635, 67–72 (2024) | [Cite this article](#)

51k Accesses | 177 Altmetric | [Metrics](#)

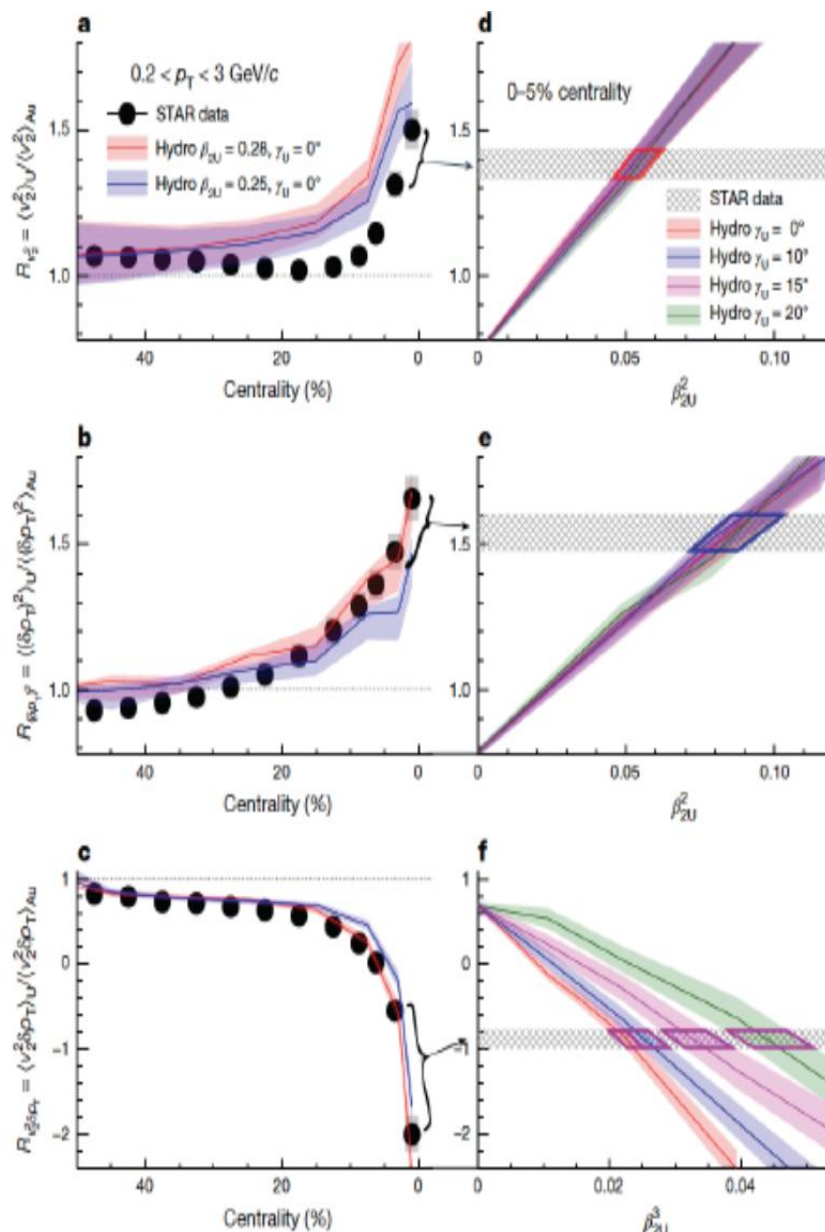
$$\langle v_2^2 \rangle = a_1 + b_1 \beta_2^2$$

$$\langle (\delta p_T)^2 \rangle = a_2 + b_2 \beta_2^2$$

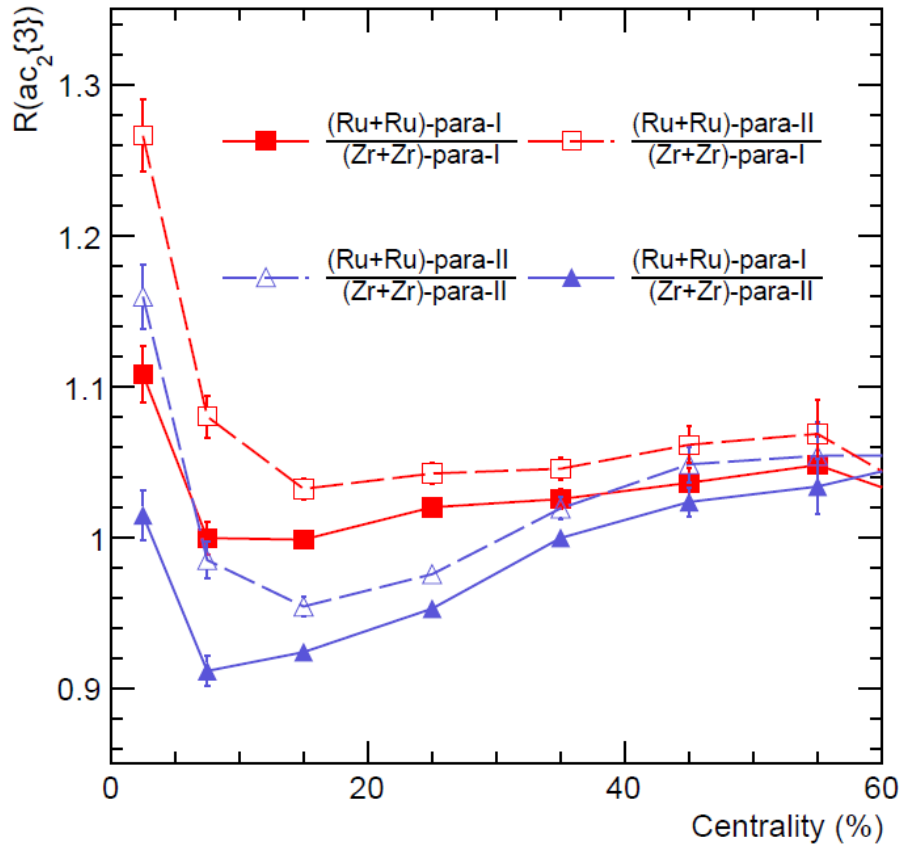
$$\langle v_2^2 \delta p_T \rangle = a_3 - b_3 \beta_2^3 \cos(3\gamma)$$

$$\beta_{2U} = 0.297 \pm 0.015$$

$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

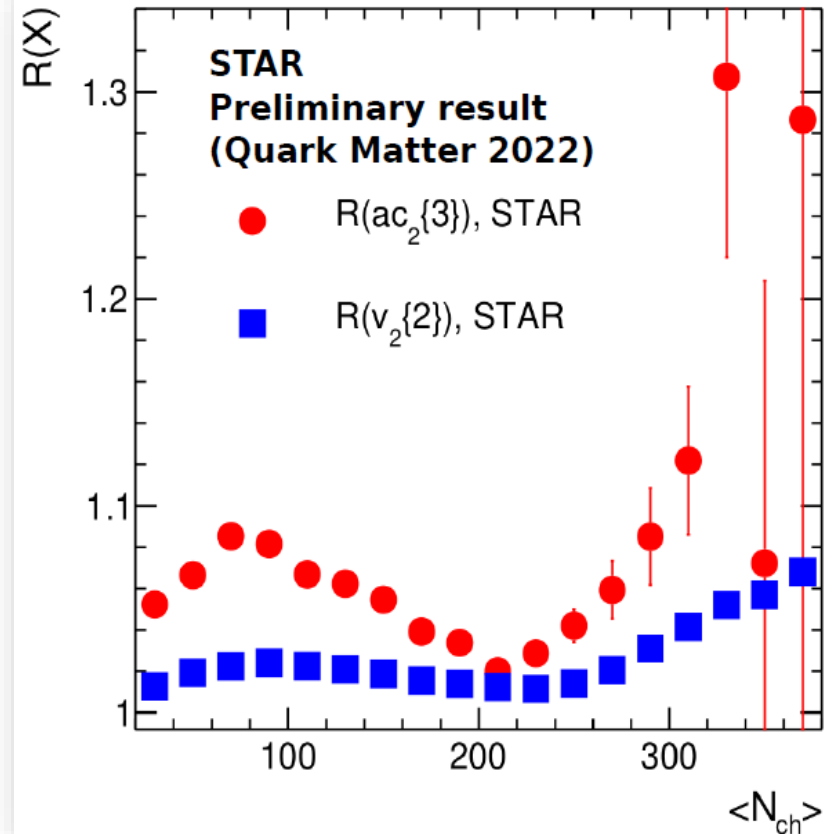


# $ac_2\{3\}$ for Ru+Ru and Zr+Zr collisions

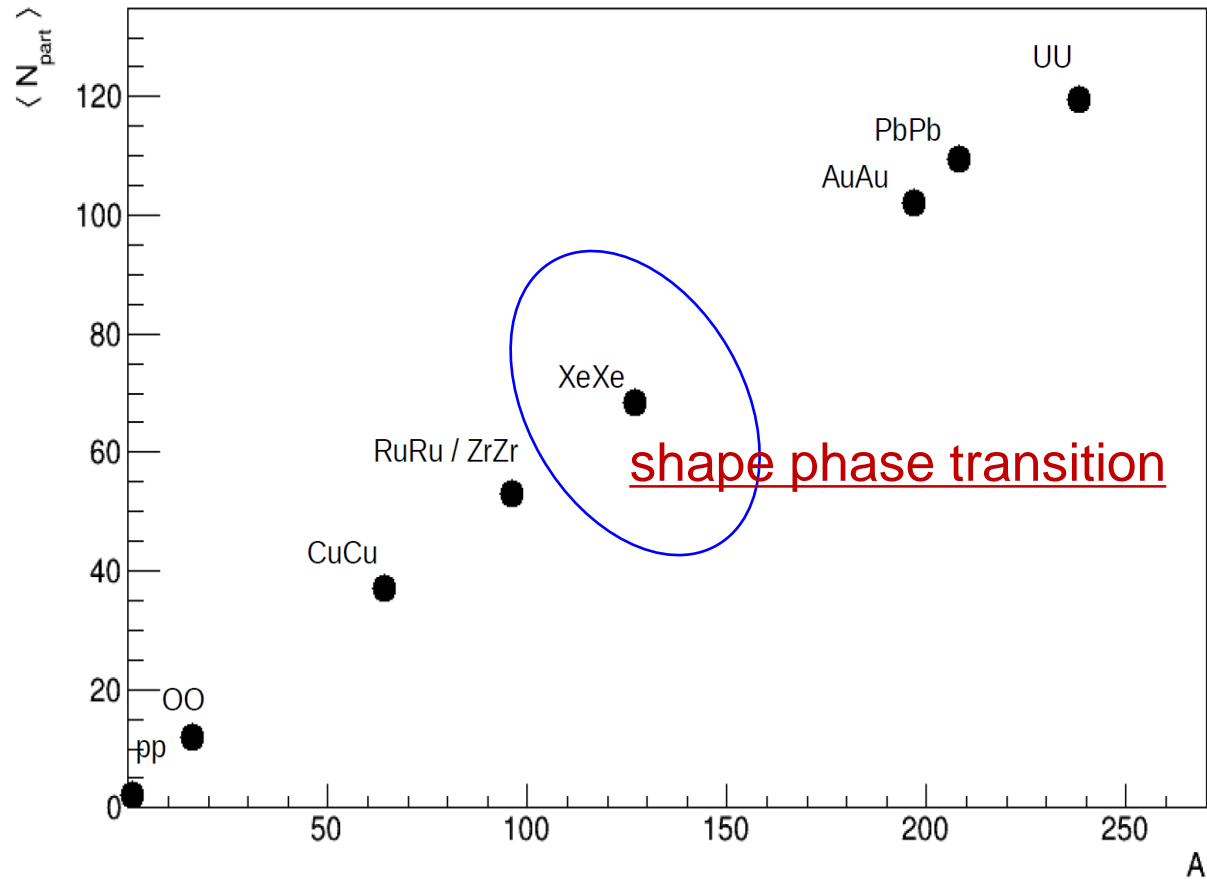


$ac_2\{3\}$  is sensitive to quadrupole and octupole deformations

$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle,$$



# Probe the shape phase transition with Xe +Xe collisions



# Shape phase transition for Xe isotopes

## The shape phase transition:

- rapid structural change along certain isotope or isotone chains
- the dynamic interplay between the spherical-driving pairing interaction and the deformation-driving proton-neutron interaction

## The shape phase transition for the Xe isotopes:

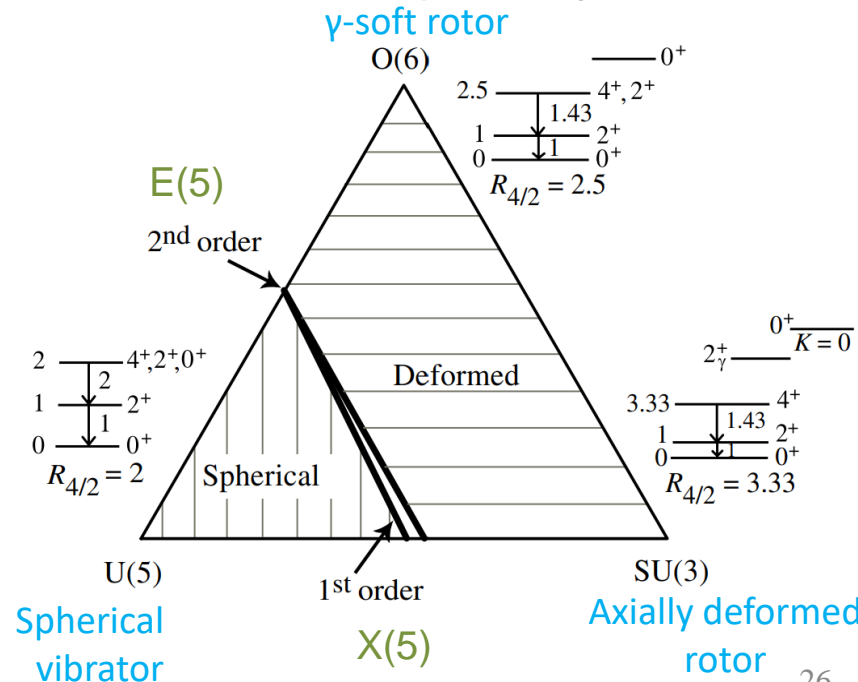
-Within the the framework of the interacting boson model (IBM), the Xe isotopes undergo a shape phase transition from a  $\gamma$ -soft rotor to a spherical vibrator

R. F. Casten, Nucl. Phys. A 439, 289 (1985). G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. A 348, 109 (1980). R. F. Casten and P. Von Brentano, Phys. Lett. B 152, 22 (1985).

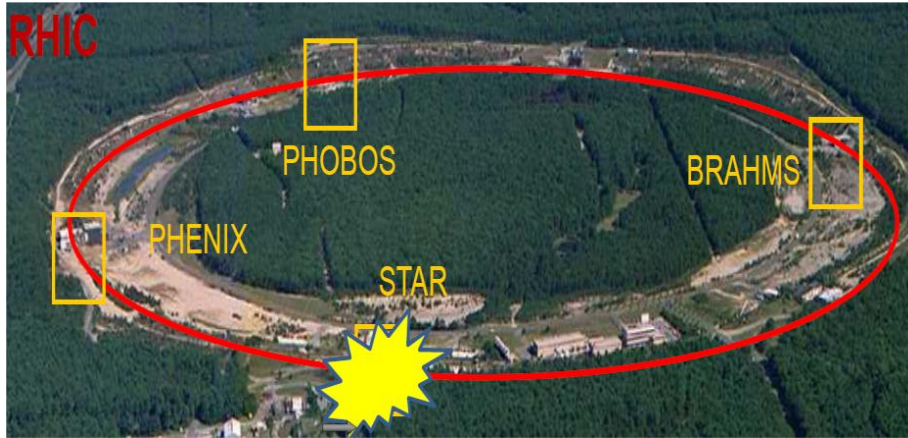
-the critical point is described by the  $E(5)$  symmetry, associated with a 2<sup>nd</sup> order phase transition

F. Iachello, Phys. Rev. Lett. 87, 052502 (2001).  
F. Iachello, Phys. Rev. Lett. 85, 3580 (2000).

## The critical point symmetries



# The Phase Transition



## $^{129}\text{Xe} + ^{129}\text{Xe}$ collision

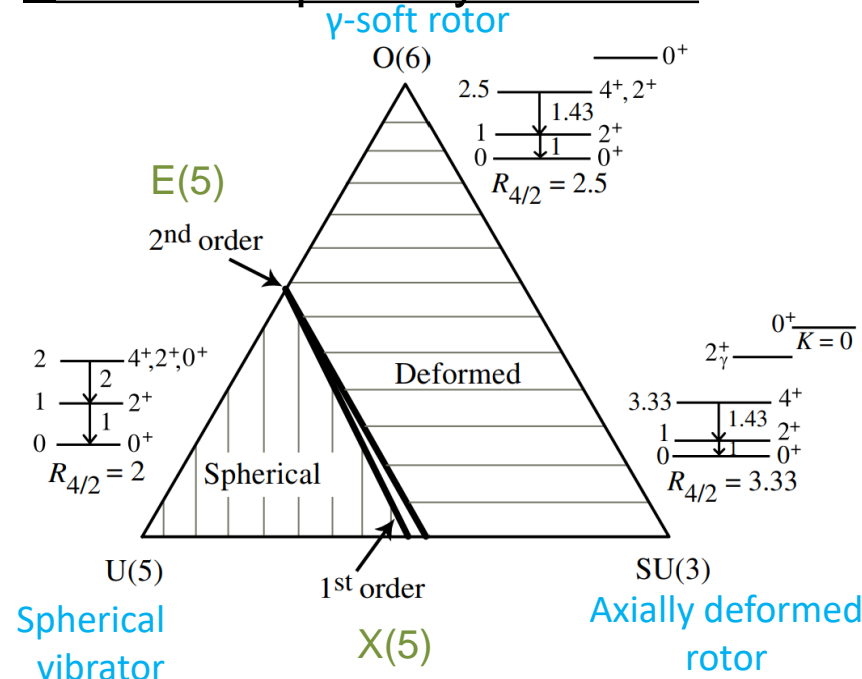
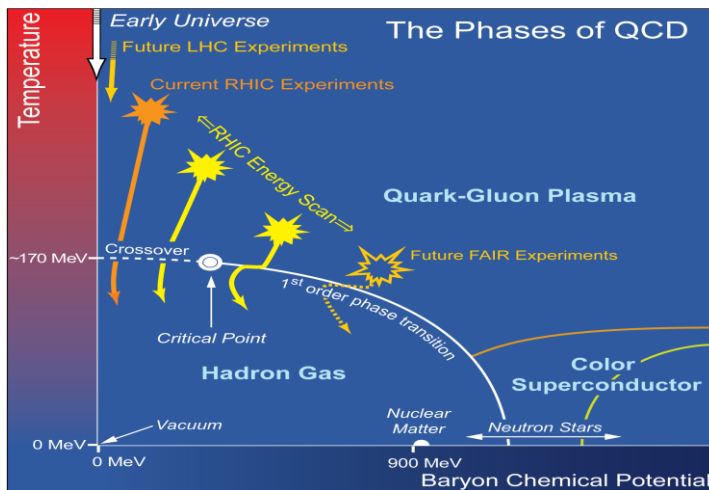
-explore the second-order shape phase transition occurring in the vicinity of  $^{128-130}\text{Xe}$

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th]

## Relativistic heavy ion collisions

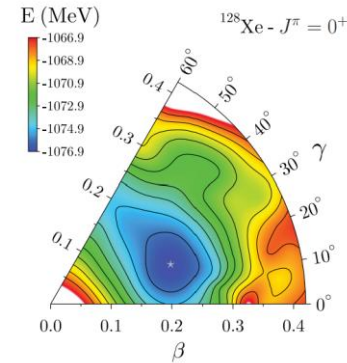
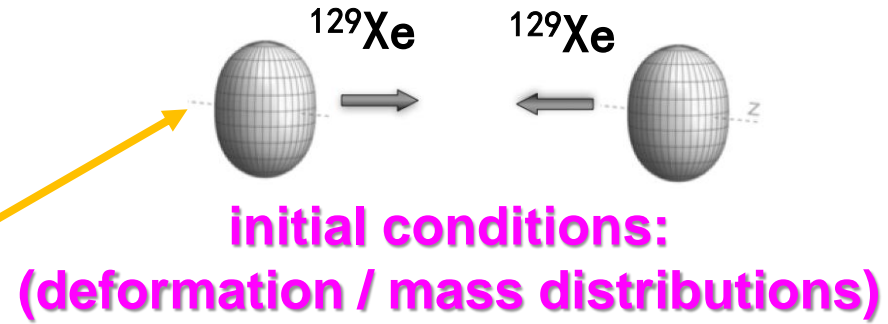
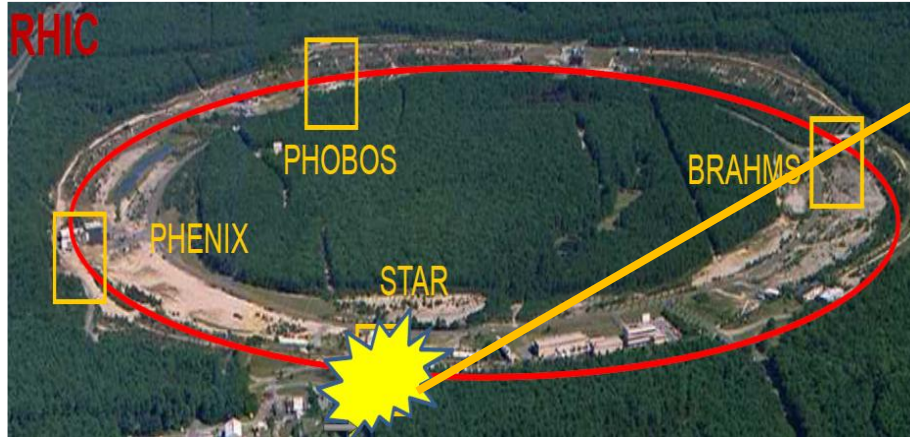
-mainly aim to explore QCD Phase Transition

## The critical point symmetries



# Probe the $\gamma$ -soft deformation of $^{129}\text{Xe}$

## Relativistic heavy ion collisions



Rigid triaxial deformation ( $\gamma=30^\circ$ )

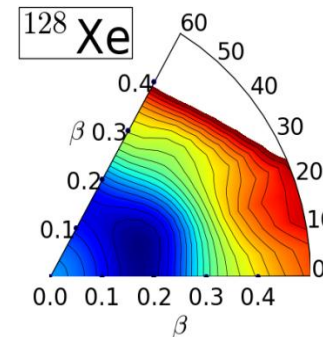
Bally et. al. Eur.Phys.J. A 58 (2022) 9, 187,

## Initial conditions (TRENTO)

- Sample nucleon position in deformed nuclei with:

$$\rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{(r-R(\theta, \phi))/a_0}}$$

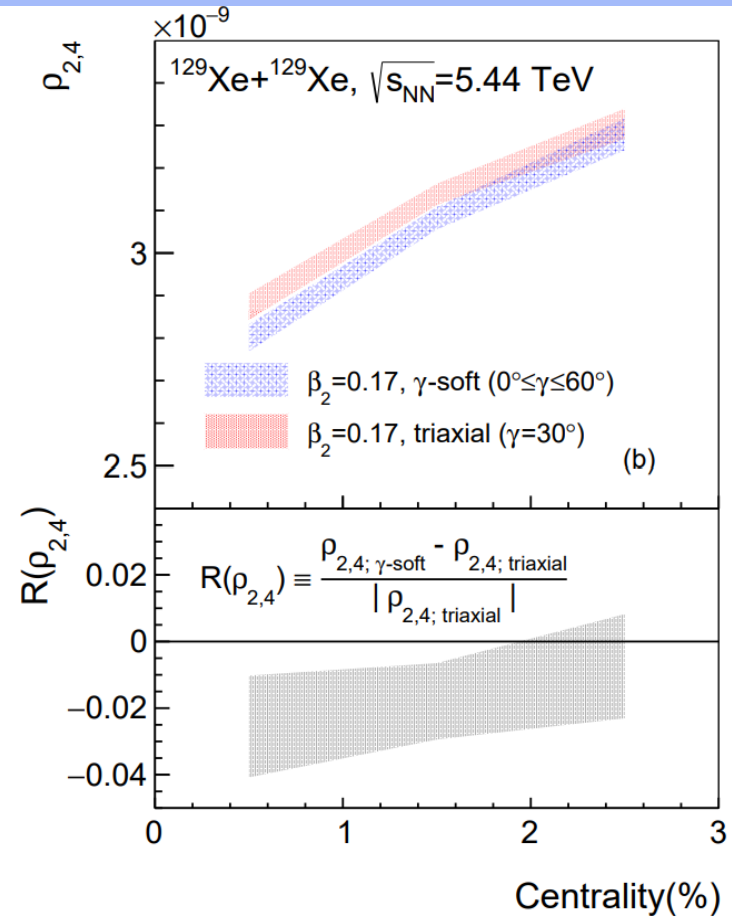
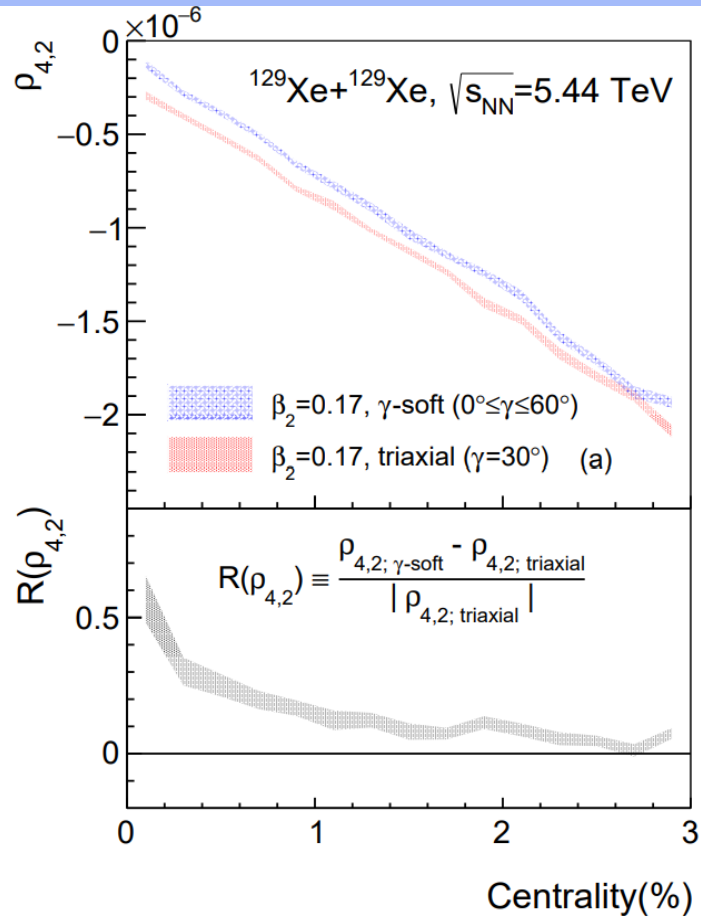
$$R(\theta, \phi) = R_0(1 + \beta_2[\cos \gamma Y_{2,0}(\theta, \phi) + \sin \gamma Y_{2,2}(\theta, \phi)]).$$



$\gamma$ -soft (flat distribution in  $0 \leq \gamma \leq 60^\circ$ )

Z. P. Li, et. al. Phys. Rev. C 81, 034316 (2010),

# 6-particle correlations-Theoretical Predictions



$$\rho_{4,2} \equiv \left( \frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \right)_c$$

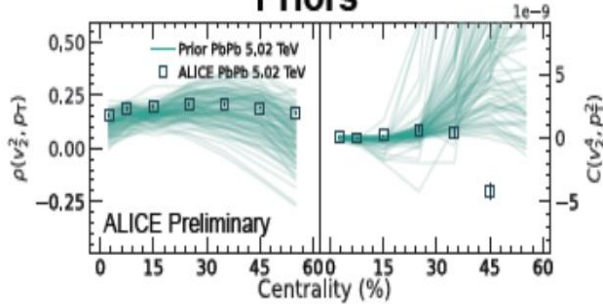
$$\rho_{2,4} \equiv \left( \frac{\langle \varepsilon_2^2 \delta d_\perp^4 \rangle}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \right)_c$$

The  $\gamma$ -soft deformation of  $^{129}\text{Xe}$  lead to a clear enhancement of 6-particle correlations  $\rho_{4,2}$  in ultra-central Xe+Xe collisions, can be used to probe the 2<sup>nd</sup> order shape phase Transition.

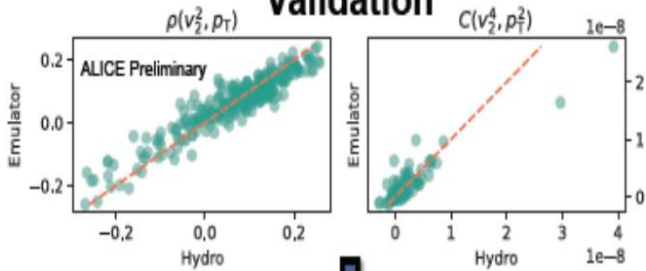
# ALICE Measurements & Bayesian Analysis

Posterior distributions and parameter correlations from Bayesian framework

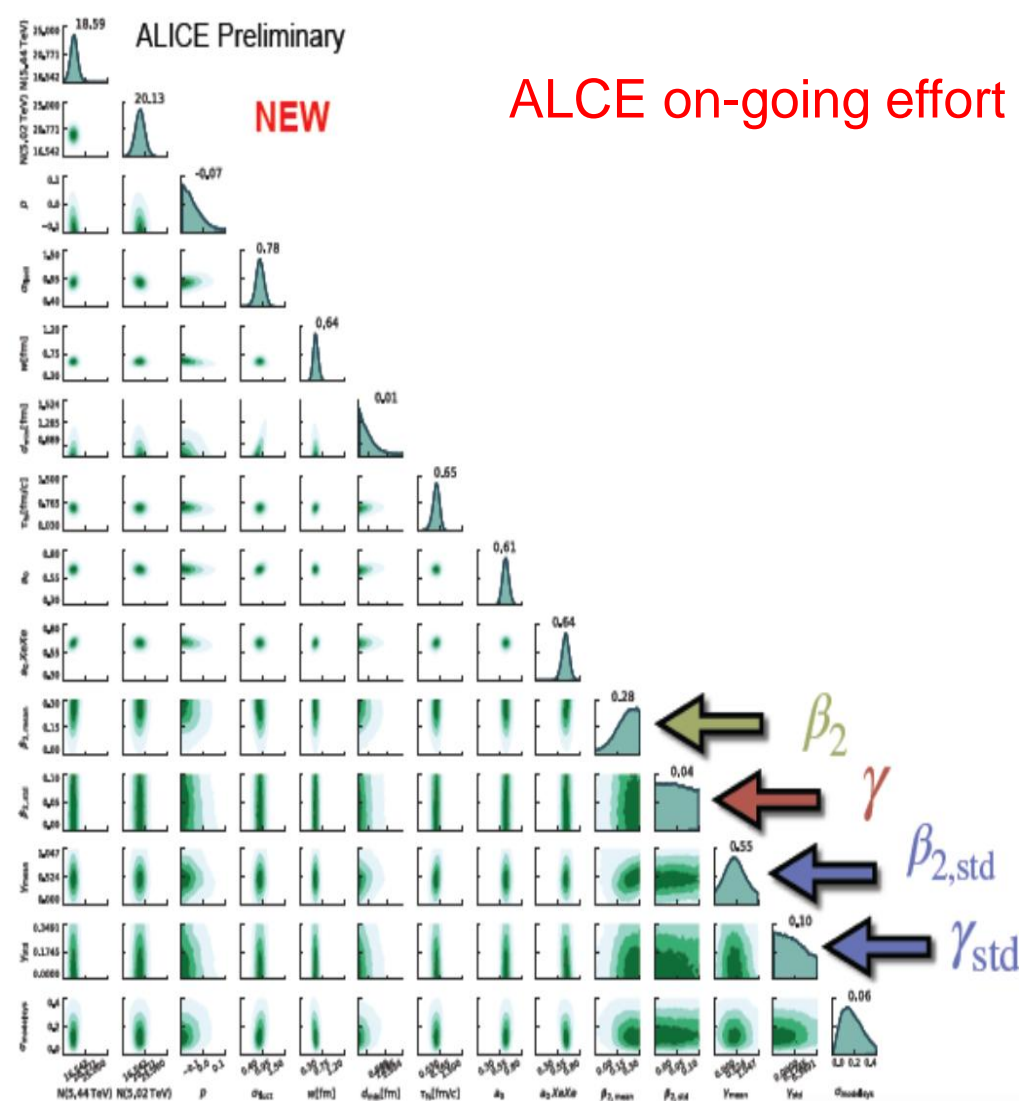
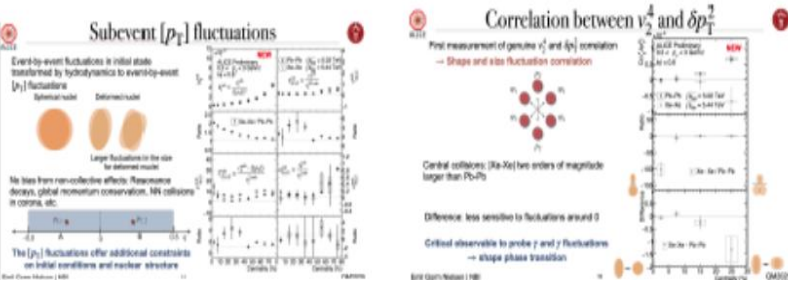
Priors



Validation

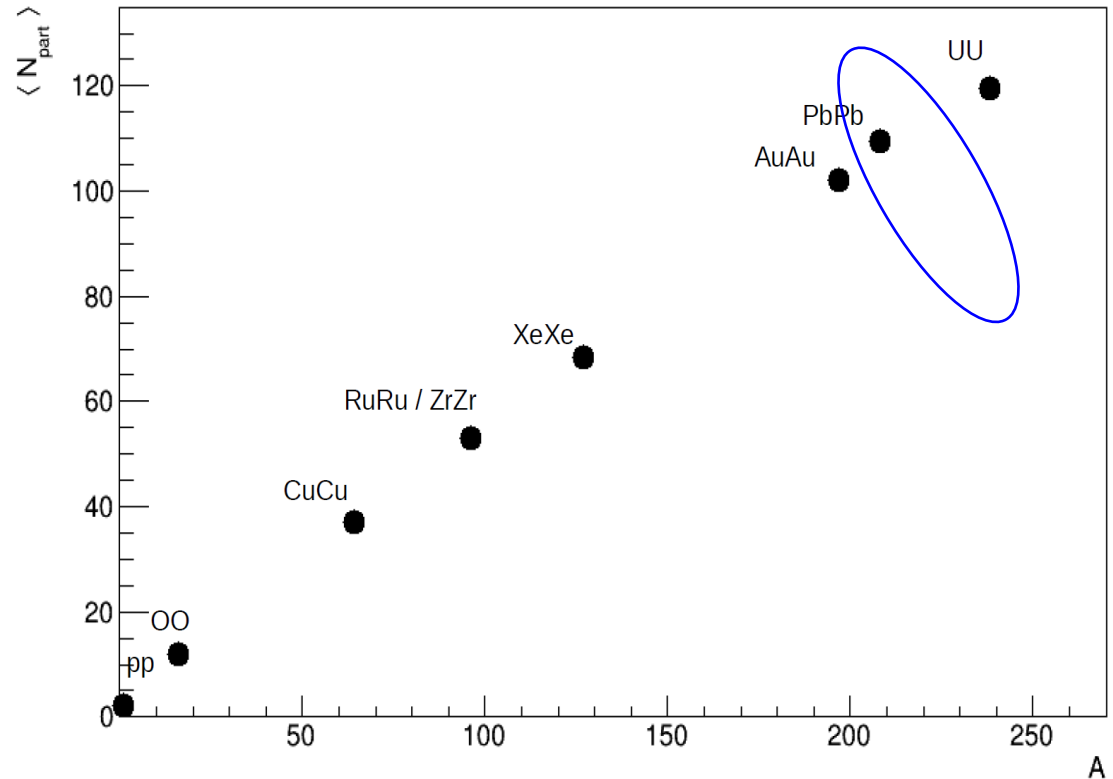
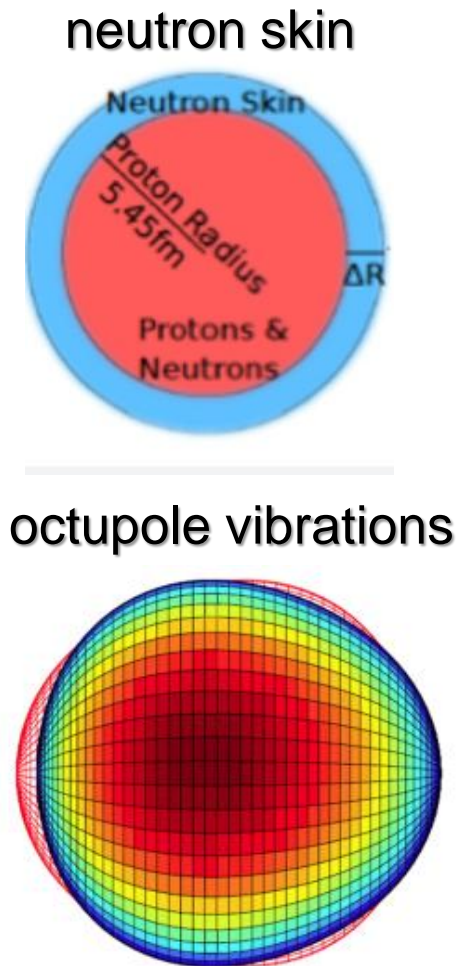


Exp. data



ALICE on-going effort

# Probe the structure of $^{208}\text{Pb}$ at Pb+Pb collisions



Q.Liu, S.Zhao, H.j.Xu and **H.Song**, Phys.Rev.C 109 3, 034912 (2024).

H.j.Xu, D.Xu, S.Zhao, W.Zhao, **H.Song** and F.Wang, Phys. Rev. C 112, no.5, L051901 (2025).

# Probing the neutron skin at Pb+Pb collisions

## Flow & soft physics

- $dN/dy$  mean  $P_T$   $v_2\{2\}$   $v_2\{4\}$   $v_3\{2\}$  in Pb+Pb collision  $<5\%$  effects to neutron skin  
- $v_2\{2\}/v_3\{2\}$ ,  $v_2\{4\}/v_3\{2\}$ ,  $v_2\{4\}/v_2\{2\}$ , : more sensitive to neutron skins of Pb,

Q. Liu, H. Xu and H. Song. Phys.Rev.C 109 (2024) 3, 034912;

G.Giacalone Phys. Rev. Lett 131, 202302 (2023) ... ..

- $\rho_{422}$   $\rho_{523}$  :  $\rho_2(v_2^2, [p_T])$   $\sigma_{p_T}/\langle p_T \rangle$  somewhat sensitive to neutron skin

H.Mantysaari, B.Schenke, C.Shen and W.Zhao Phys. Rev. C110, 5, 054913 (2024)

- $asc_{224}$  SC(2,3) SC(2,4) NSC(2,3) NSC(2,4) sensitive to neutron skin?

Z.Wang, J.Chen, J.Jia, Y.G.Ma and C.Zhang, arXiv:2409.15040.

**Neutron skin definition:** woods-saxon (halo, skin full) DFT

Xu, et.al., Phys. Lett B819, 136453 (2021).

## Other observables

Net-charge multiplicities in ultra-peripheral collisions of isobar runs

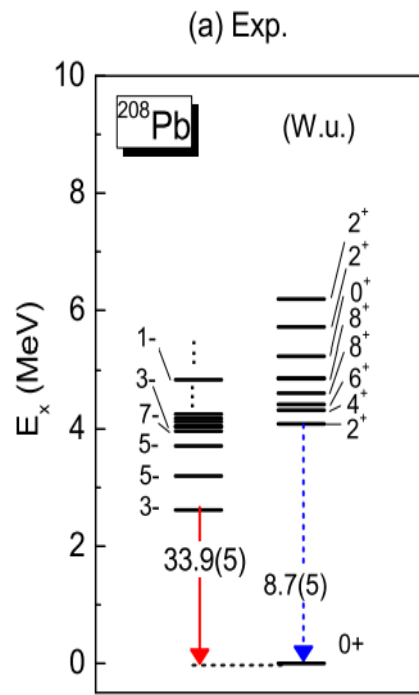
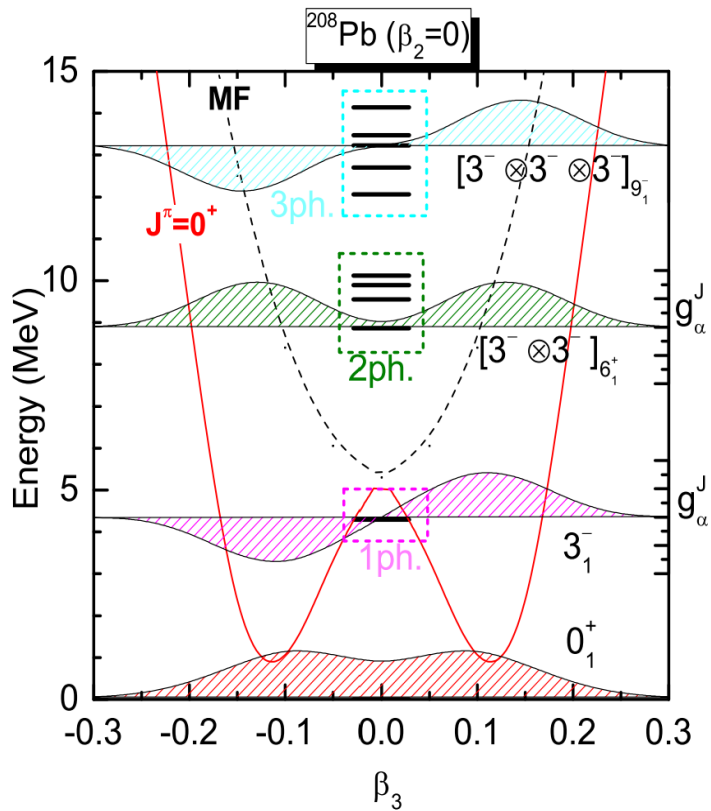
Xu, Li, Zhou, Wang, Zhao, Chen, Wang, Phys. Rev.C105, L014901 (2022).

Hard probes in isobar collisions as a probe of the neutron skin

W.van der Schee, Y.J.Lee, G.Nijs and Y.Chen, Phys. Lett. B856, 138953 (2024)

... ..

# Octupole vibration of doubly magic $^{208}\text{Pb}$ (Nuclear Structure)



$^{208}_{82}\text{Pb}_{126}$ : a double magic nucleus

→ spherical

$$\langle \beta_3 \rangle = 0$$

but, the shape can fluctuate

→ octupole vibration

$$\langle (\beta_3)^2 \rangle \neq 0$$

from the measured  $B(E3)$

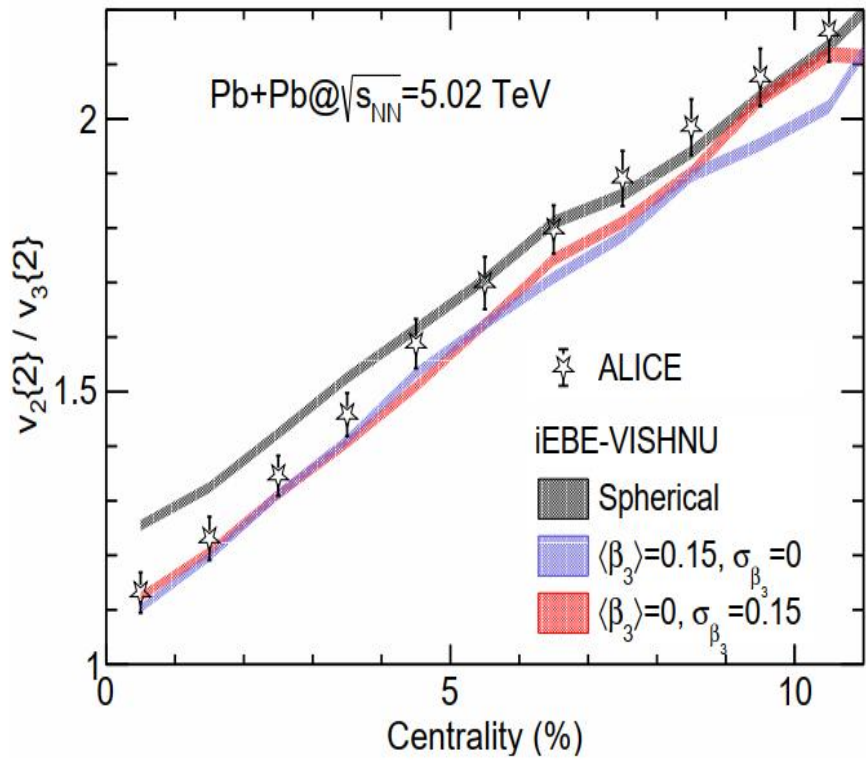
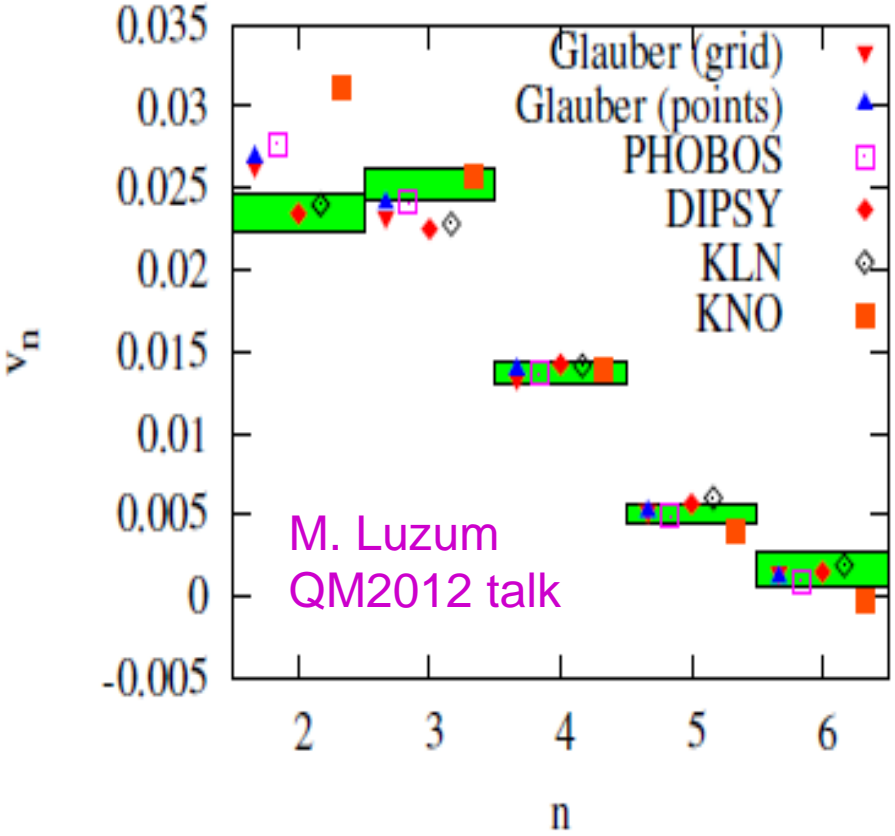
$$\sqrt{\langle \beta_3^2 \rangle} = \frac{4\pi}{3ZR^3} \sqrt{\frac{B(E3 : 0^+ \rightarrow 3^-)}{e^2}} \sim$$

-The framework of generator coordinate method (GCM) predict a dynamical octupole vibration for the ground state  $^{208}\text{Pb}$

-the measured strong transition strength,  $B(E3)$ , of  $^{208}\text{Pb}$  suggests a soft potential energy surface allowing the octupole vibration around the spherical shape

# Probe octupole vibration of $^{208}\text{Pb}$ (heavy ion collisions)

-toward solving the  $v_2$ - $v_3$  puzzle in ultra-central collisions

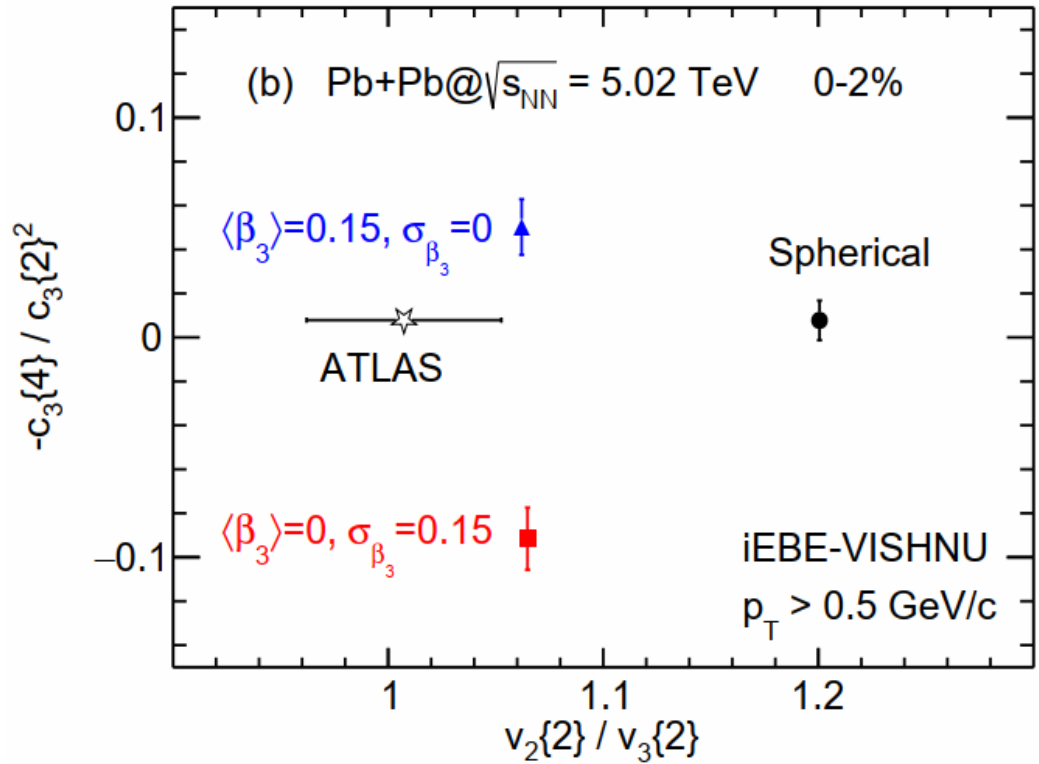
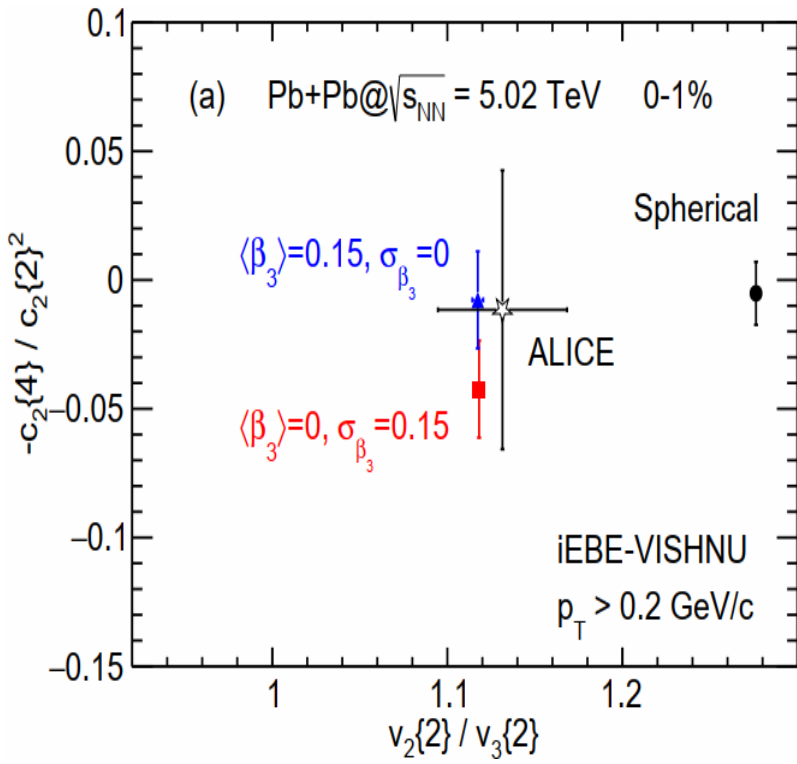


-hydro/various initial conditions models (spherical  $^{208}\text{Pb}$ ) fails to describe  $v_2$ - $v_3$  in ultra-central Pb+Pb collisions ----  $v_2$ - $v_3$  puzzle for more than 10 years

-With the octupole shape fluctuation of  $^{208}\text{Pb}$   $v_2$ - $v_3$  in ultra-central collisions can be described by hydro simulations

# Probe octupole vibration of $^{208}\text{Pb}$ (heavy ion collisions)

-toward solving the  $v_2$ - $v_3$  puzzle in ultra-central collisions



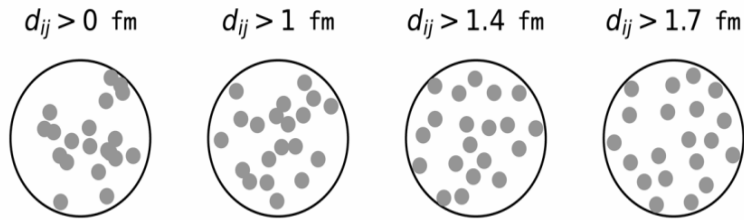
-solving the  $v_2$ - $v_3$  puzzle in ultra-central collisions requires simultaneously fit other flow data

$-C_3\{4\}$  is more sensitive to the octupole shape fluctuation of  $^{208}\text{Pb}$

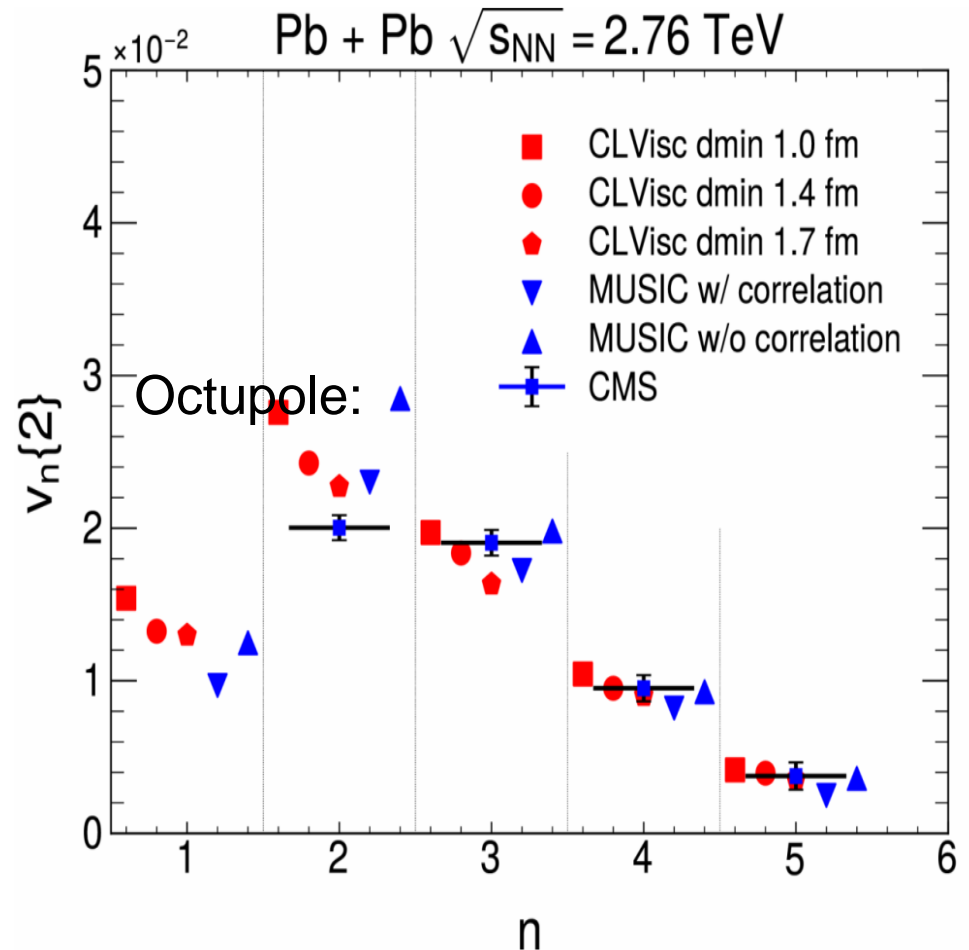
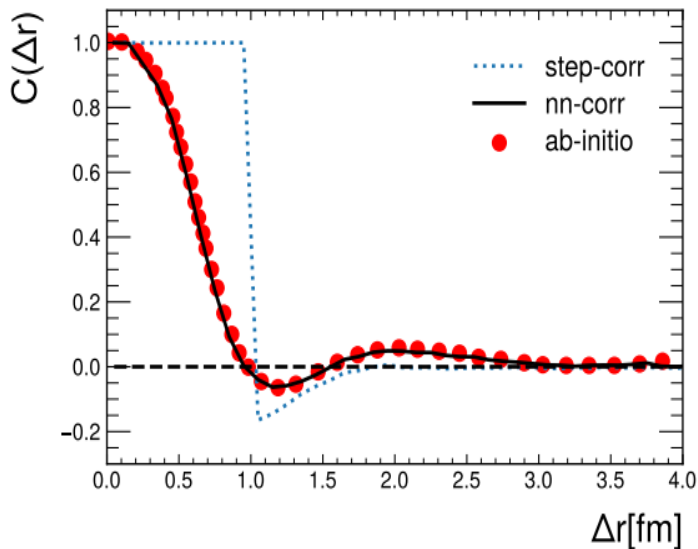
# Pb+Pb collisions with NN correlations

-toward solving the  $v_2$ - $v_3$  puzzle in ultra-central collisions

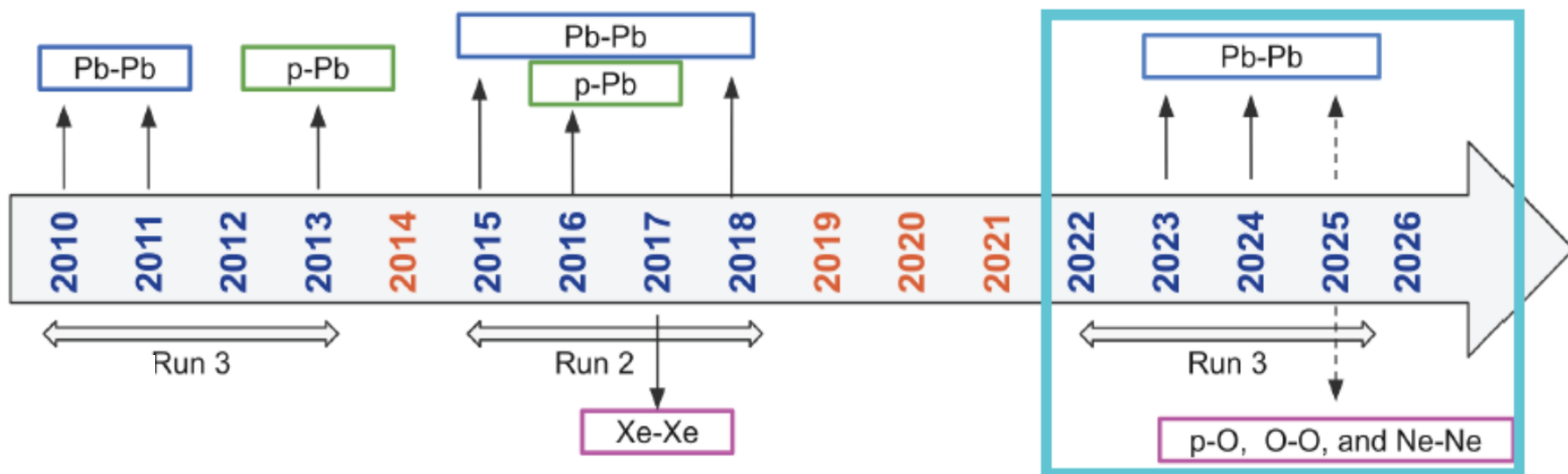
## TRENTo with min d between nucleons (repulsive NN correlations)



## IP-Glasma with NN correlations



# Physics opportunities from light ion collisions at the LHC (Theory)



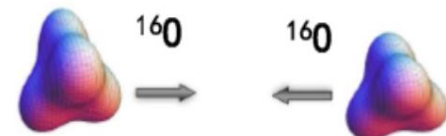
# Probe cluster structure with light ion collisions

## Probe the structure of $^{16}\text{O}$ with O+O collisions

Li, Zhang & Ma, Phys. Rev. C **102**,054907 (2020)

Wang, Zhao, Cao, Xu and Song. *Phys.Rev.C* 109 5, L051904 (2024)

.....

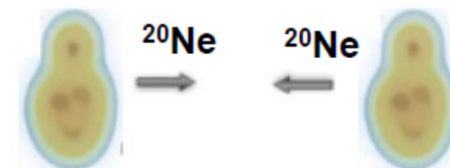


## Probe the Bowling pin structure of $^{20}\text{Ne}$ with Ne+Ne collisions

Giaccaone, Bally, Nijs, Shen, et al, arXiv: 2402.05995

Li, Zhou and Ma, arXiv:2504.04688 [nucl-th].

.....

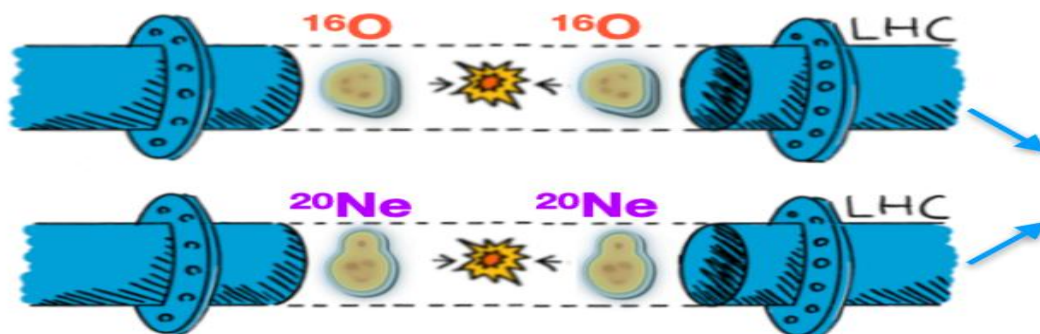
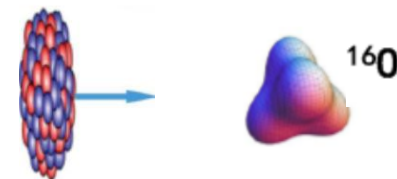


## Probe the cluster structure Pb+Ne/Pb+O run at LHCb (SMOG)

Giaccaone, Zhao, et al, Phys. Rev. Lett.134 082301 (2025)

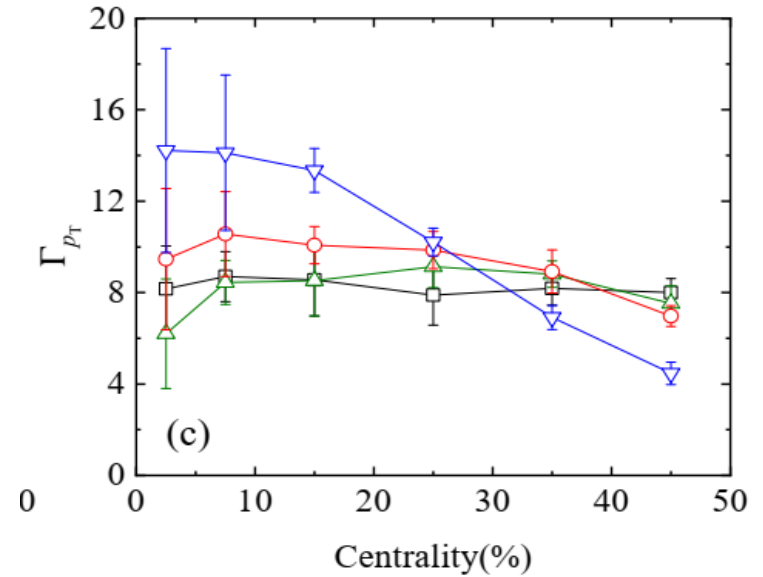
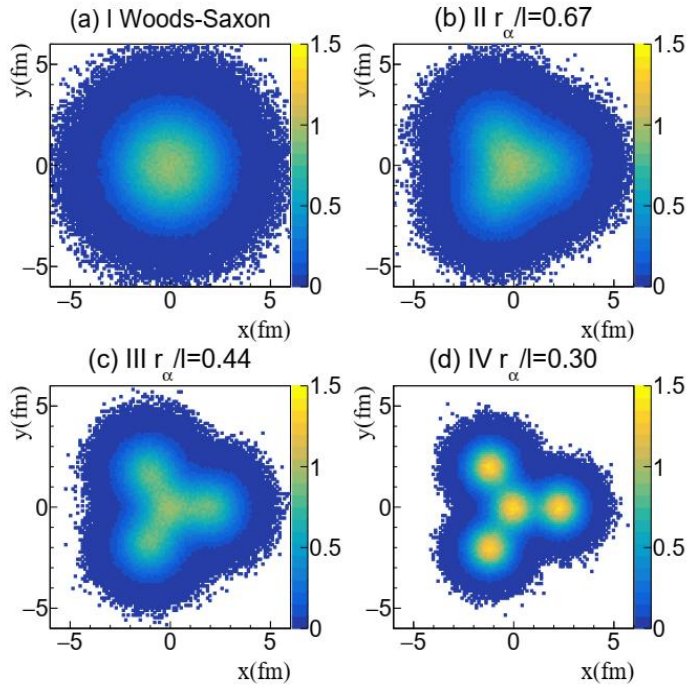
Lu, Zhao, Nielsen, Li and Zhou, arXiv:2501.14852 [nucl-th]

.....



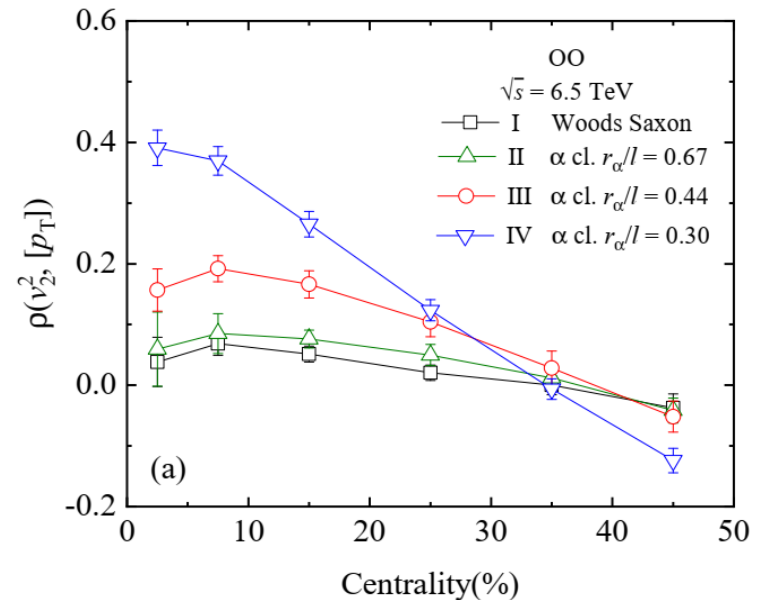
**July, 2025!**

# Traditional Hydro: sensitive observables for $\alpha$ -clustering



$\Gamma$  and  $v_n - p_T$  correlations in  $^{16}\text{O}+^{16}\text{O}$  collisions are sensitive to the compactness of the  $\alpha$  cluster in  $^{16}\text{O}$

Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song.  
*Phys.Rev.C* 109 5, L051904 (2024)



**Traditional hydrodynamics**

# Small systems: from traditional to anisotropic hydro

traditional hydro:

$$T^{\mu\nu} = \mathcal{E} u^\mu u^\nu - (\mathcal{P}_{\text{eq}} + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}.$$

$$f = f_{\text{eq}} + \delta f \quad \delta f = \frac{p^\mu p^\nu \pi_{\mu\nu}}{2T^2(\mathcal{E} + \mathcal{P}_{\text{eq}})} \quad |\delta f| \ll f_{\text{eq}}.$$

Validity of traditional hydro

Knudsen number:  $K_n = \tau_\pi \theta = 5 \frac{\eta\theta}{sT},$

Anisotropic hydro

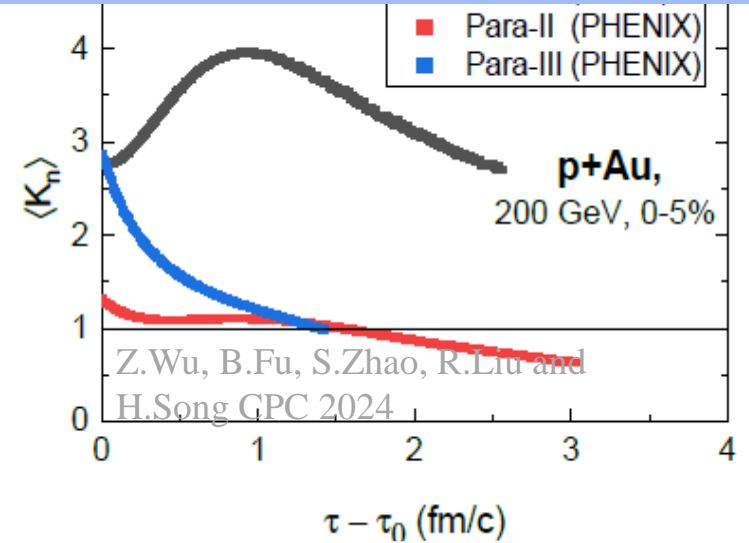
$$\Delta^{\mu\nu} = \Xi^{\mu\nu} - z^\mu z^\nu, \quad \Xi^{\mu\nu} \equiv g^{\mu\nu} - u^\mu u^\nu + z^\mu z^\nu$$

$$\Rightarrow T^{\mu\nu} = \mathcal{E} u^\mu u^\nu + \mathcal{P}_L z^\mu z^\nu - \mathcal{P}_\perp \Xi^{\mu\nu} + 2W_{\perp z}^{(\mu} z^{\nu)} + \pi_{\perp}^{\mu\nu}.$$

$$\left. \begin{array}{l} \pi^{\mu\nu} \\ \mathcal{P}_{\text{eq}} + \Pi \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \mathcal{P}_L = z_\mu z_\nu T^{\mu\nu}, \\ \mathcal{P}_\perp = -\frac{1}{2} \Xi_{\mu\nu} T^{\mu\nu}, \\ W_{\perp z}^\mu = -\Xi_\alpha^\mu T^{\alpha\nu} z_\nu, \\ \pi_{\perp}^{\mu\nu} = \Xi_{\alpha\beta}^{\mu\nu} T^{\alpha\beta}, \end{array} \right.$$

M. McNelis, D. Bazow,  
and U. Heinz, Com.  
Phys. Comm 267,  
108077 (2021)

S. Zhao, Y. Peng, U. Heinz,  
H. Song 2509.03841

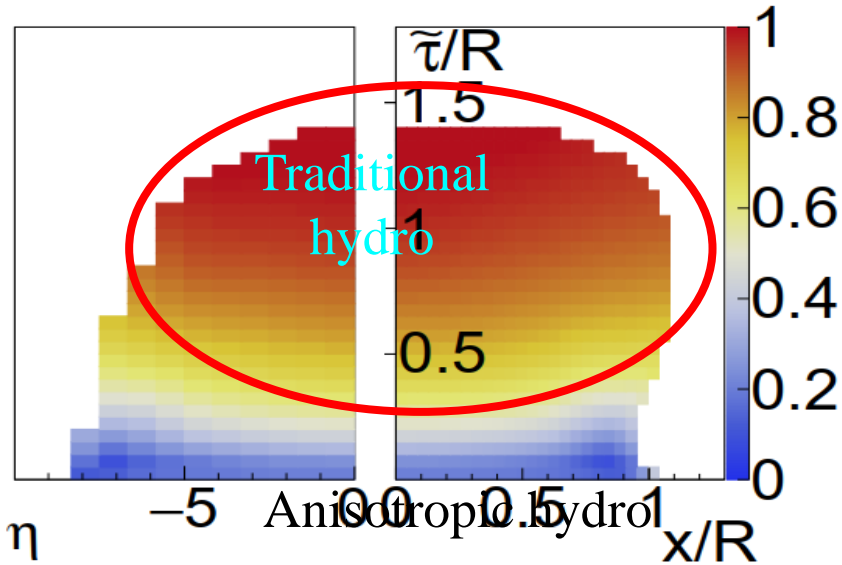


Z. Wu, B. Fu, S. Zhao, R. Liu and  
H. Song GPC 2024

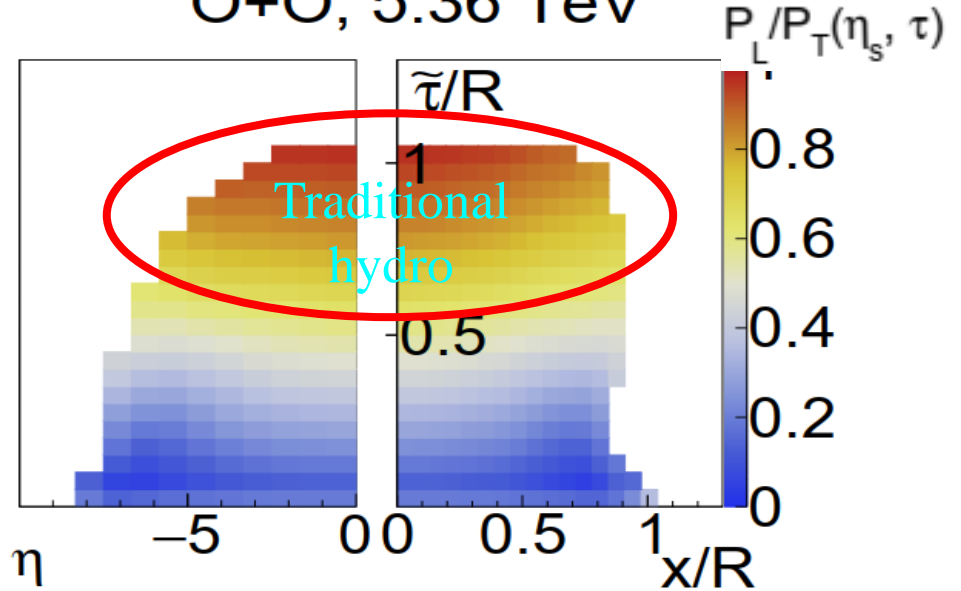
$$f(x, p) = f_a(x, p) + \delta \tilde{f}(x, p) \quad f_a(x, p) = f_{\text{eq}}(\sqrt{\Omega_{\mu\nu}(x) p^\mu p^\nu} / \Lambda(x))$$

# Evaluating isotropization from VAH

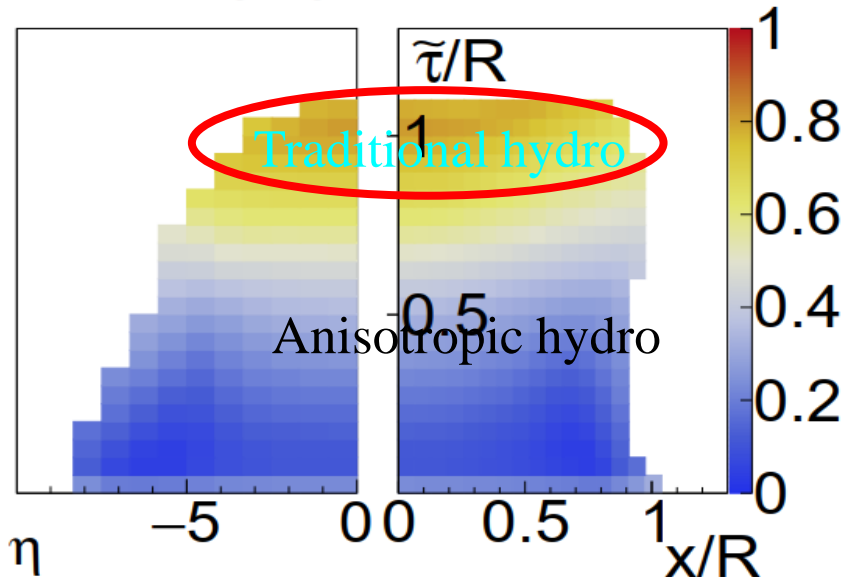
Pb+Pb, 5.02 TeV



O+O, 5.36 TeV



p+p, 13 TeV



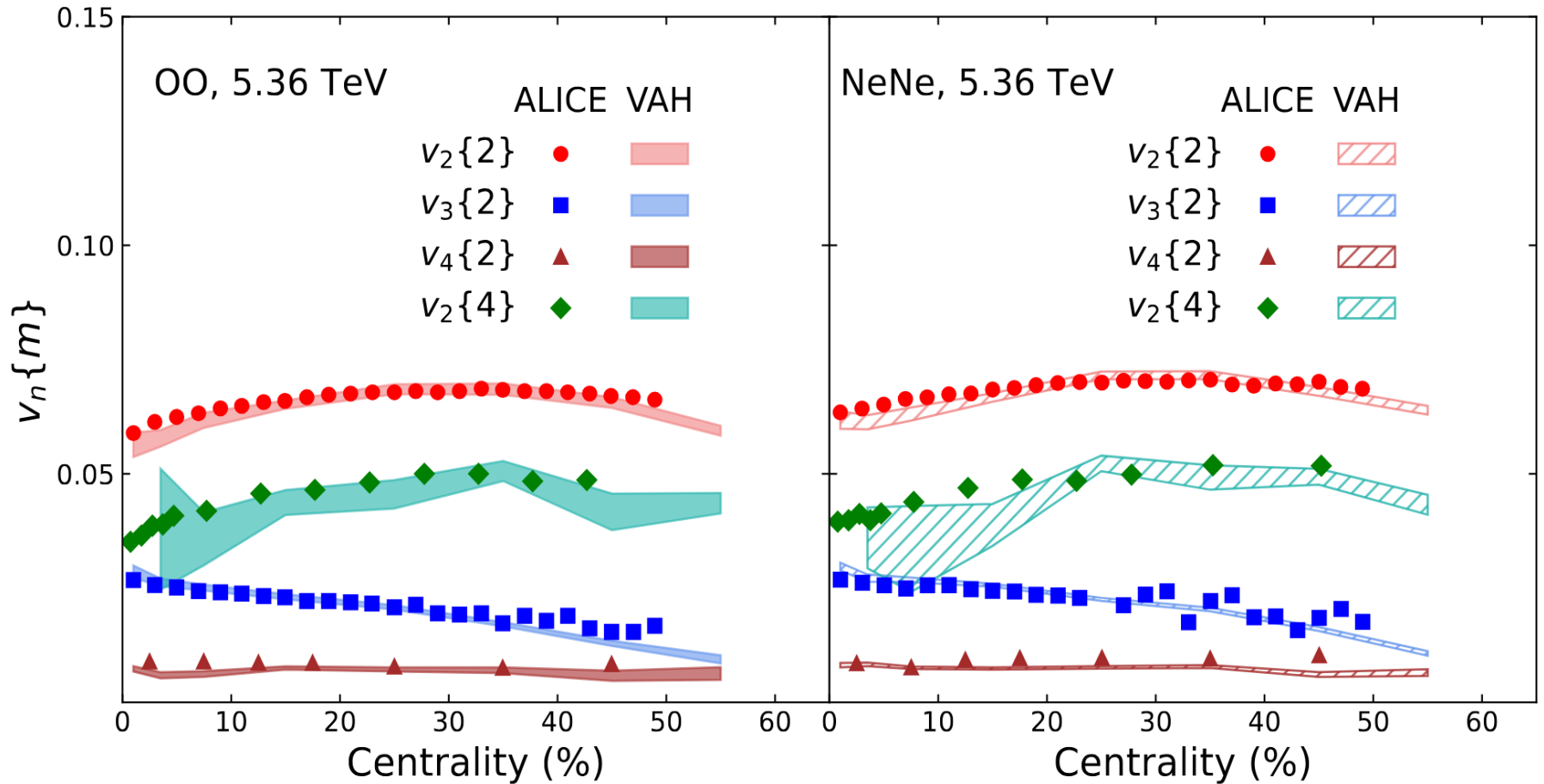
Evolution of  $P_L/P_T(\eta_s, \tau)$

Smaller systems are harder to reach isotropization.

Traditional hydro works well for large systems (Pb+Pb)

S. Zhao, U.Heinz, H.Song paper in preparation.

# VAH: flow for O+O & Ne+Ne collisions

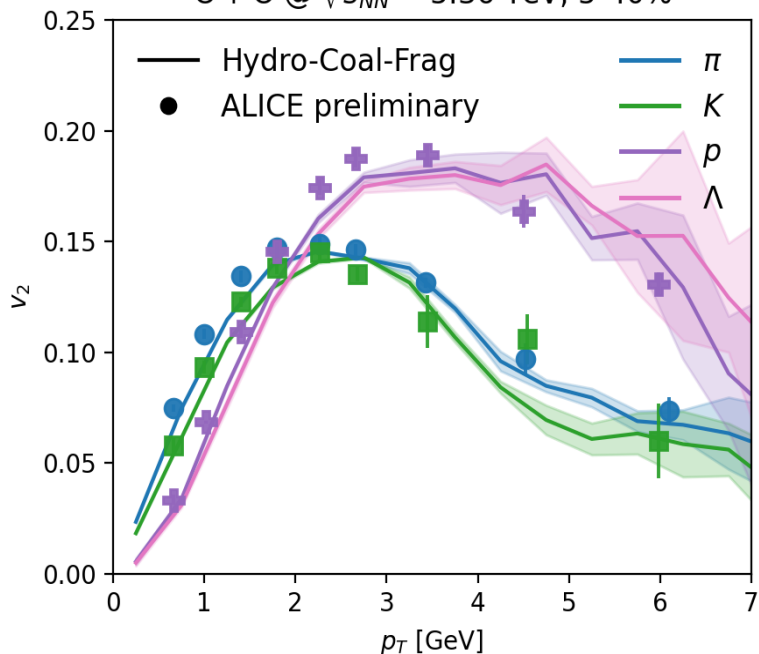


-Initial condition: Tranto3D + PGCM.

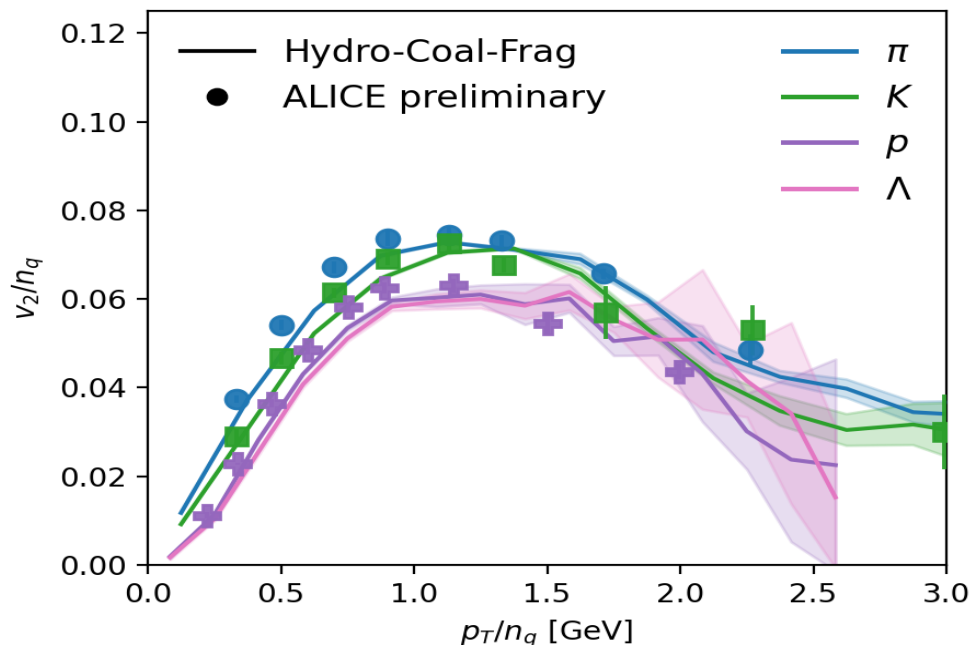
-VAH describes the flow data well for O+O and Ne+Ne collisions.

# VAH+Coal+Frag: partonic flow for O+O Collisions

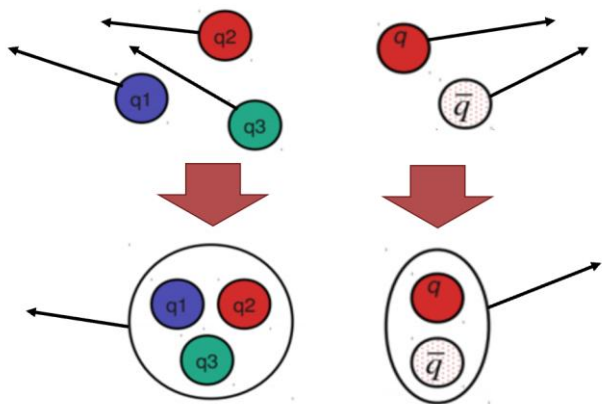
O + O @  $\sqrt{s_{NN}} = 5.36$  TeV, 5-40%



O + O @  $\sqrt{s_{NN}} = 5.36$  TeV, 5-40%

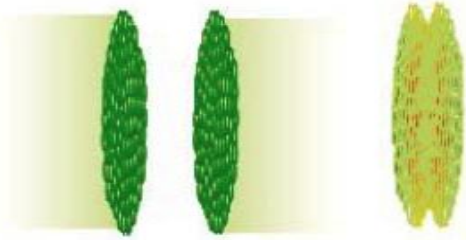


Intermediate  $P_T$



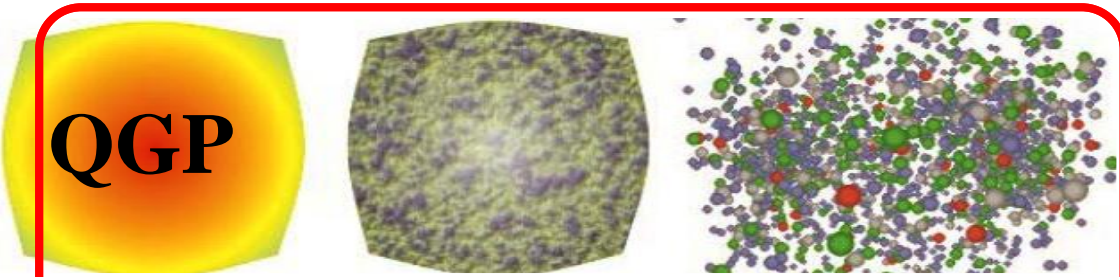
**VAH+Coal+Frag:**

- nice description of  $v_2(P_T)$  for 0-6GeV
- NCQ scaling behavior at intermediate  $p_T$
- O+O collisions produce small fluid systems. **but with anisotropic fluid behavior**
- future study of the cluster structure need aHydro



### Initial conditions:

Intersection study with nuclear structure



**QGP**

### QGP+HRQ evolution:

main goal: QGP properties & QCD phase diagram

### Nuclear deformation:

U+U Ru+Ru/Zr+Zr Pb+Pb

### Shape phase transition:

Xe+Xe

### Neutron Skin/ octupole var.:

Pb+Pb ...

### Cluster of light nuclei:

O+O Ne+Ne Pb+O Pb+Ne

### Traditional Viscous Hydro & hybrid model:

Pb+Pb Au+Au p-Pb p+p ...

### Anisotropic Viscous Hydro & hybrid model:

p+p p+Pb O+O .... Pb+Pb

To extract QGP & nuclear structure info needs **Bayesian Analysis**

# Bayesian Analysis- QGP viscosity

**JETSCAPE**

## Multi-system Bayesian constraints on the transport coefficients of QCD matter

2021

D. Everett,<sup>1</sup> W. Ke,<sup>2,3</sup> J.-F. Paquet,<sup>4</sup> G. Vujanovic,<sup>5</sup> S. A. Bass,<sup>4</sup> L. Du,<sup>1</sup> C. Gale,<sup>6</sup> M. Heffernan,<sup>6</sup> U. Heinz,<sup>1</sup> D. Liyanage,<sup>1</sup> M. Luzum,<sup>7</sup> A. Majumder,<sup>5</sup> M. McNelis,<sup>1</sup> C. Shen,<sup>5,8</sup> Y. Xu,<sup>4</sup> A. Angerami,<sup>9</sup> S. Cao,<sup>5</sup> Y. Chen,<sup>10,11</sup> J. Coleman,<sup>12</sup> L. Cunqueiro,<sup>13,14</sup> T. Dai,<sup>4</sup> R. Ehlers,<sup>13,14</sup> H. Elfner,<sup>15,16,17</sup> W. Fan,<sup>4</sup> R. J. Fries,<sup>18,19</sup> F. Garza,<sup>18,19</sup> Y. He,<sup>20</sup> B. V. Jacak,<sup>2,3</sup> P. M. Jacobs,<sup>2,3</sup> S. Jeon,<sup>6</sup> B. Kim,<sup>18,19</sup> M. Kordell II,<sup>18,19</sup> A. Kumar,<sup>5</sup> S. Mak,<sup>12</sup> J. Mulligan,<sup>2,3</sup> C. Nattrass,<sup>13</sup> D. Oliinychenko,<sup>3</sup> C. Park,<sup>6</sup> J. H. Putschke,<sup>5</sup> G. Roland,<sup>10,11</sup> B. Schenke,<sup>21</sup> L. Schwiebert,<sup>22</sup> A. Silva,<sup>13</sup> C. Sirimanna,<sup>5</sup> R. A. Soltz,<sup>5,9</sup> Y. Tachibana,<sup>5</sup> X.-N. Wang,<sup>20,2,3</sup> and R. L. Wolpert<sup>12</sup>

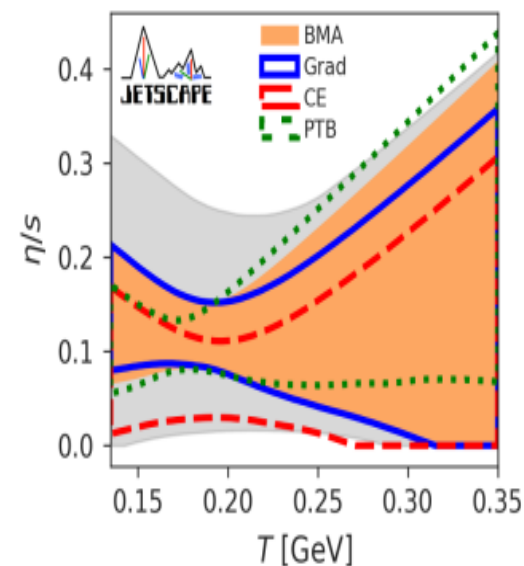
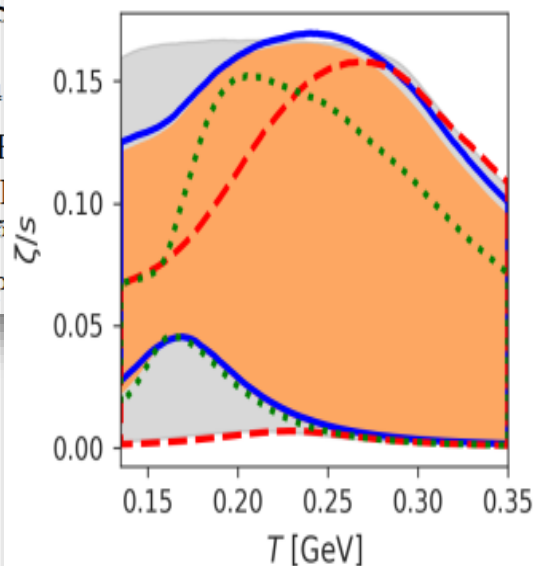
(The JETSCAPE Collaboration)

## Phenomenological constraints on the transport properties of QCD matter with data-driven model averaging

2021

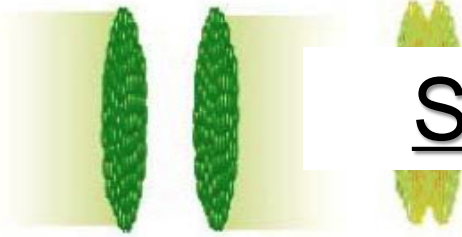
D. Everett,<sup>1</sup> W. Ke,<sup>2,3</sup> J.-F. Paquet,<sup>4</sup> G. Vujanovic,<sup>5</sup> S. A. Bass,<sup>4</sup> L. Du,<sup>1</sup> C. Gale,<sup>6</sup> M. Heffernan,<sup>6</sup> U. Heinz,<sup>1</sup> D. Liyanage,<sup>1</sup> M. Luzum,<sup>7</sup> A. Majumder,<sup>5</sup> M. McNelis,<sup>1</sup> C. Shen,<sup>5,8</sup> Y. Xu,<sup>4</sup> A. Angerami,<sup>9</sup> S. Cao,<sup>5</sup> Y. Chen,<sup>10,11</sup> J. Coleman,<sup>12</sup> L. Cunqueiro,<sup>13,14</sup> T. Dai,<sup>4</sup> R. Ehlers,<sup>13,14</sup> H. Elfner,<sup>15,16,17</sup> W. Fan,<sup>4</sup> R. J. Fries,<sup>18,19</sup> F. Garza,<sup>18,19</sup> Y. He,<sup>20</sup> B. V. Jacak,<sup>2,3</sup> P. M. Jacobs,<sup>2,3</sup> S. Jeon,<sup>6</sup> B. Kim,<sup>18,19</sup> M. Kordell II,<sup>18,19</sup> A. Kumar,<sup>5</sup> S. Mak,<sup>12</sup> J. Mulligan,<sup>2,3</sup> C. Nattrass,<sup>13</sup> D. Oliinychenko,<sup>3</sup> C. Park,<sup>6</sup> J. H. Putschke,<sup>5</sup> G. Roland,<sup>10,11</sup> B. Schenke,<sup>21</sup> L. Schwiebert,<sup>22</sup> A. Silva,<sup>13</sup> C. Sirimanna,<sup>5</sup> R. A. Soltz,<sup>5,9</sup> Y. Tachibana,<sup>5</sup> X.-N. Wang,<sup>20,2,3</sup> and R. L. Wolpert<sup>12</sup>

(The JETSCAPE Collaboration)



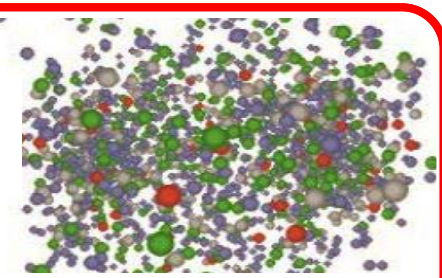
Including different viscous correction  $\delta f$  in hadronization

# Summary & outlook



## Initial conditions:

Intersection study with nuclear structure



## QGP+HRQ evolution:

main goal: QGP properties & QCD phase diagram

## Nuclear deformation:

U+U Ru+Ru/Zr+Zr Pb+Pb

## Shape phase transition:

Xe+Xe

## Neutron Skin/ octupole var.:

Pb+Pb ...

## Cluster of light nuclei:

O+O Ne+Ne Pb+O Pb+Ne

## Traditional Viscous Hydro & hybrid model:

Pb+Pb Au+Au p-Pb p+p ...

## Anisotropic Viscous Hydro & hybrid model:

p+p p+Pb O+O .... Pb+Pb

More expected  
for the future!

To extract QGP & nuclear structure info needs **Bayesian Analysis**

**Many Thanks**