Exploring the Nuclear Shape Phase Transition in Ultra-Relativistic Xe+Xe Collisions at the LHC

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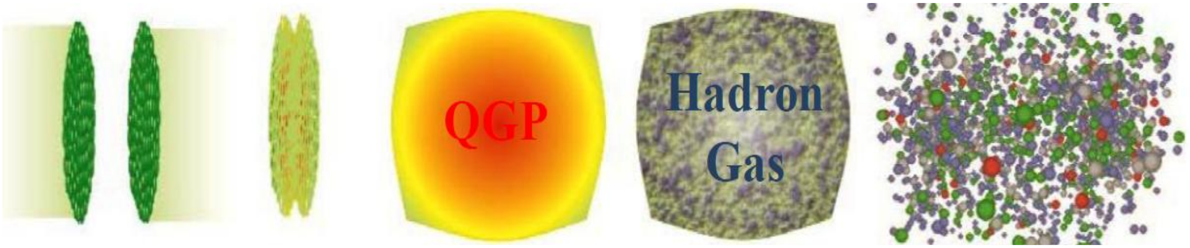
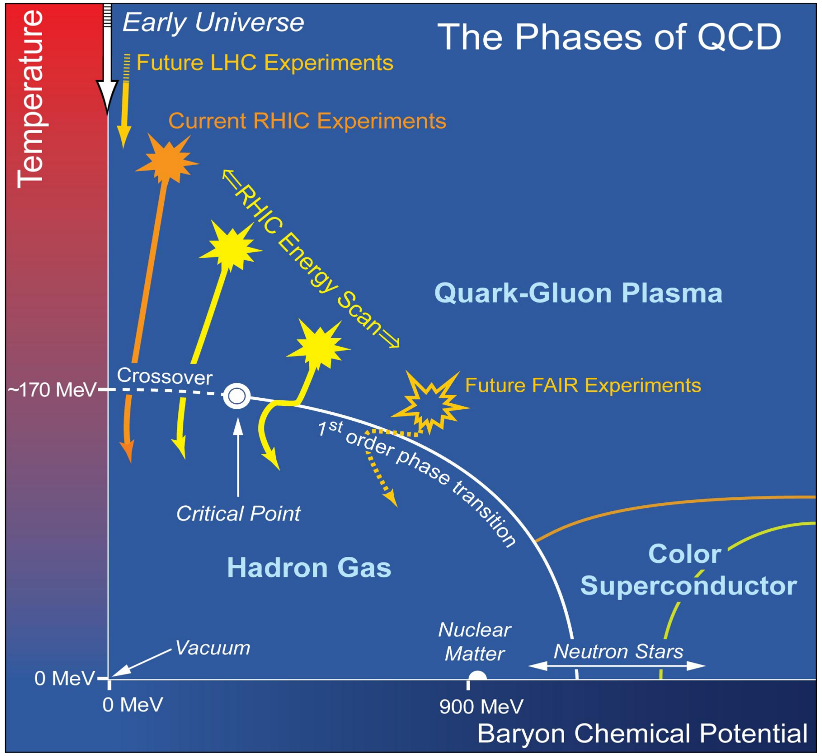
Relativistic Heavy-Ion Collisions





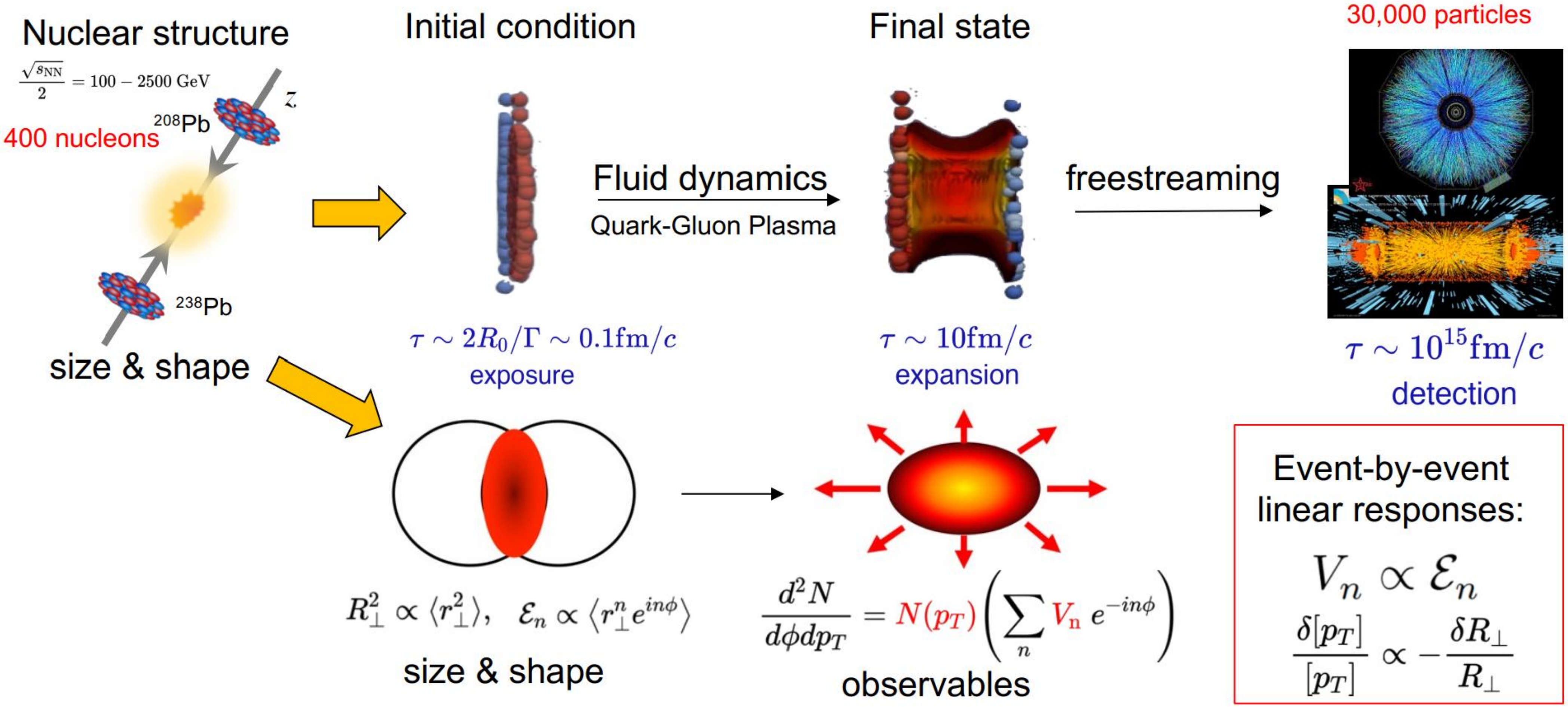
<u>Relativistic heavy ion collisions</u>

- create and study QGP

- the QCD phase diagram

- the QCD vacuum

Relativistic Heavy-Ion Collisions



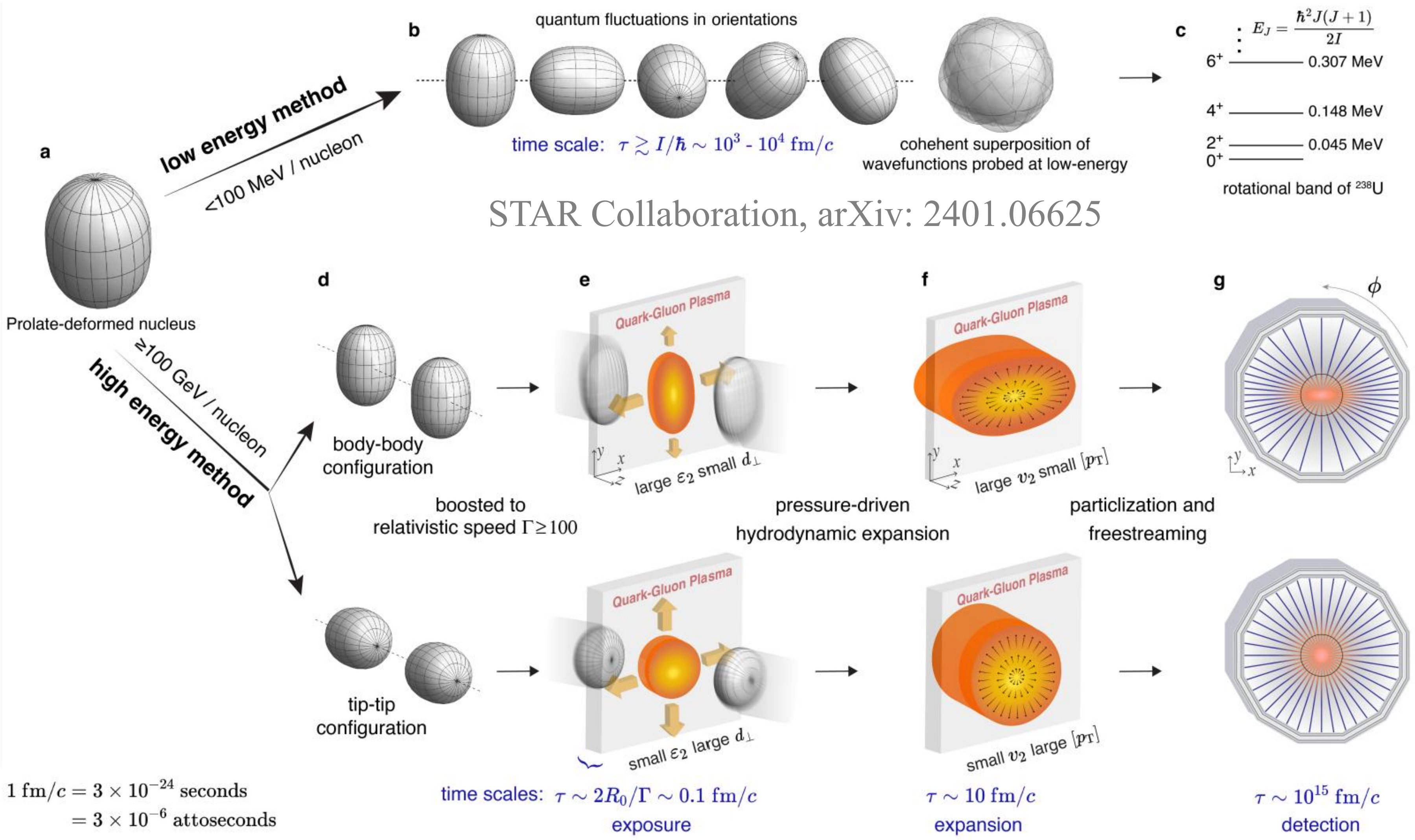
Probing Nuclear Shape in Heavy-Ion Collisions

Relativistic heavy-ion collisions providing a novel way for detecting the intrinsic shape of nuclei.

Event-by-event linear responses:

$$V_n \propto \mathcal{E}_n$$

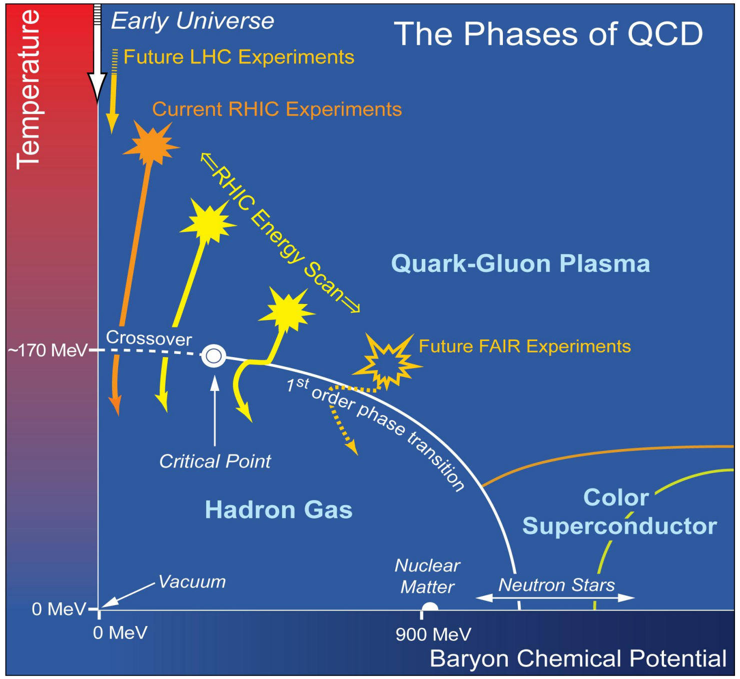
$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$$



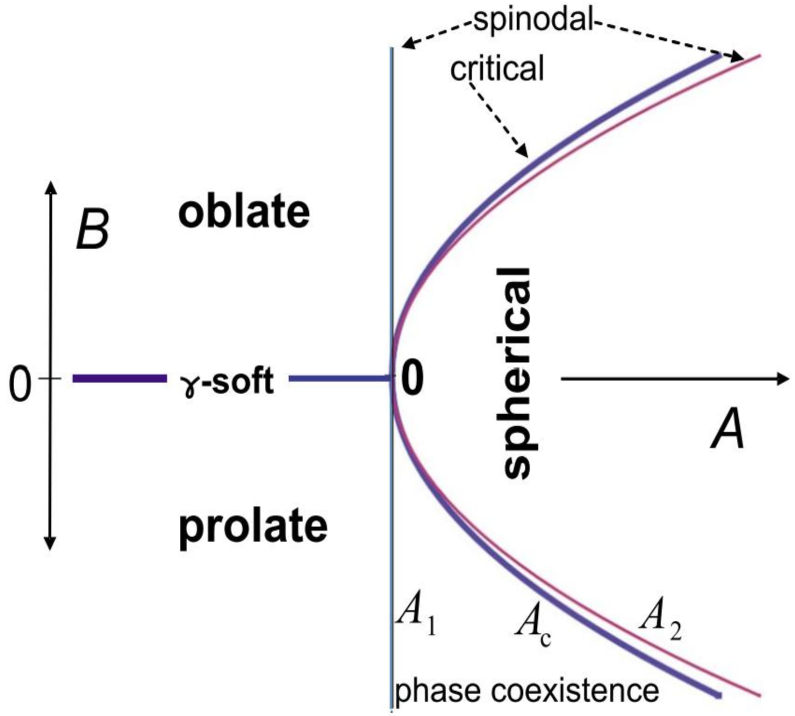
STAR Collaboration, arXiv: 2401.06625

Shape Phase Transition in Nuclear Theory

The phase transition has been studied extensively in various research areas of physics.



The QCD Phase Transition
in high energy nuclear physics



The Shape Phase Transition along certain isotope/isotone chain in nuclear structure side

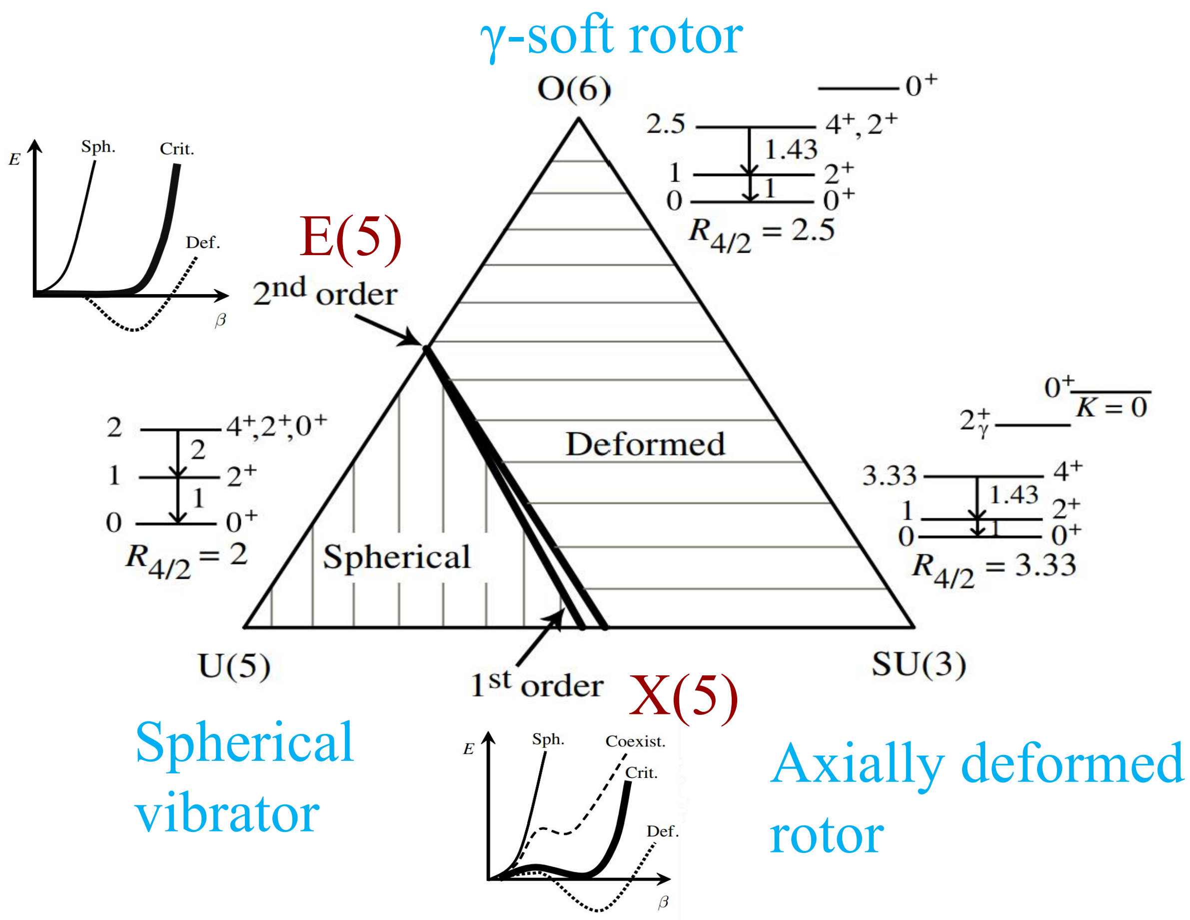
Critical Point Symmetry (CPS)

Critical Point Symmetry capture different times of SPT.

IBM framework: the Xe isotopes undergo a shape phase transition from a γ-soft rotor to a spherical vibrator

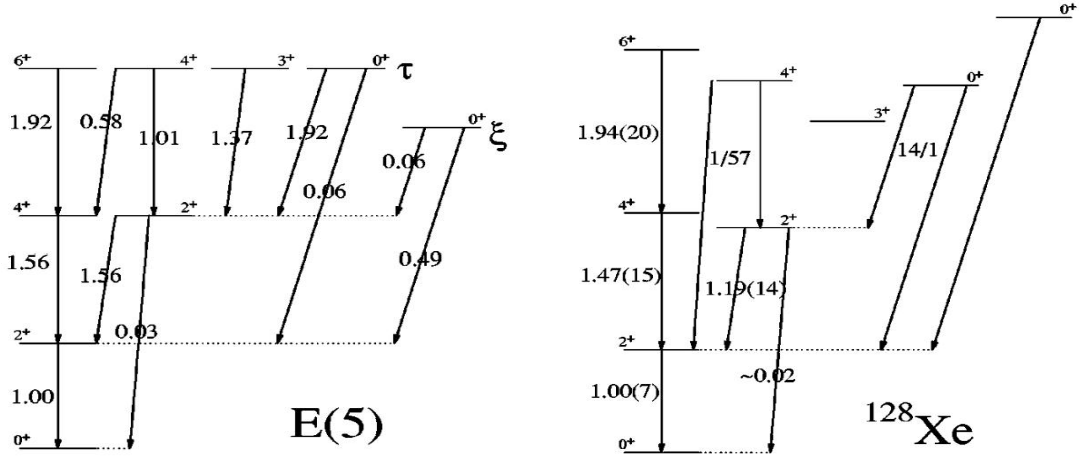
R. F. Casten, Nucl. Phys. A 439, 289 (1985). G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. A 348, 109 (1980). R. F. Casten and P. Von Brentano, Phys. Lett. B 152, 22 (1985).

The critical point is described by the $E(5)$ symmetry, associated with a 2nd order phase transition



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

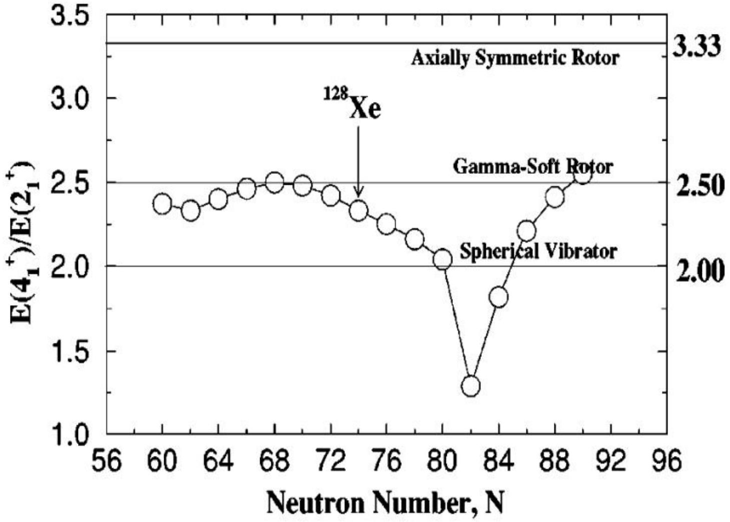
Exp evidence of E(5) symmetry for ^{128}Xe



Nucleus	$E(4_1^+)/E(2_1^+)$	$E(0_2^+)/E(2_1^+)$	$E(0_3^+)/E(2_1^+)$
^{128}Xe	2.33	3.57	4.24
^{130}Xe	2.25	(3.35)	(3.76)
^{132}Xe	2.16		
^{134}Xe	2.04		

Energy spectroscopy: good agreement with E(5) prediction

^{128}Xe lies in between γ-soft rotor and spherical vibrator.

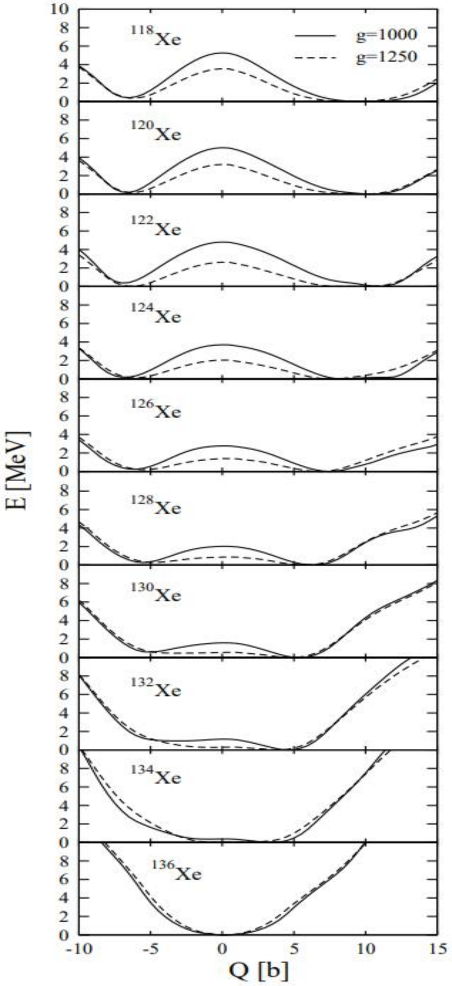


Evolution of $E(4_1^+)/E(2_1^+)$ ratio close to 2.2

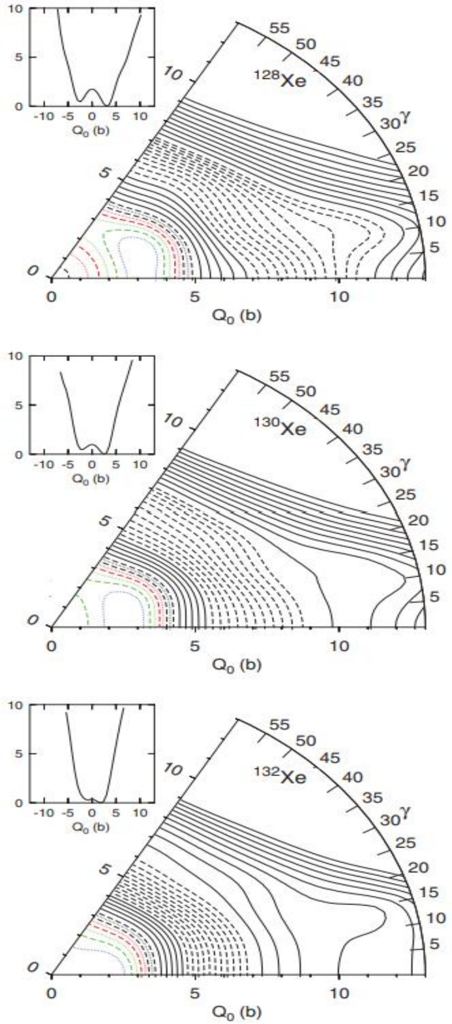
Existence of two 0^+ states with $3<E(0_n^+)/E(2_1^+)<4$

R. M. Clark, et. al. Phys. Rev. C 69, 064322 (2004)

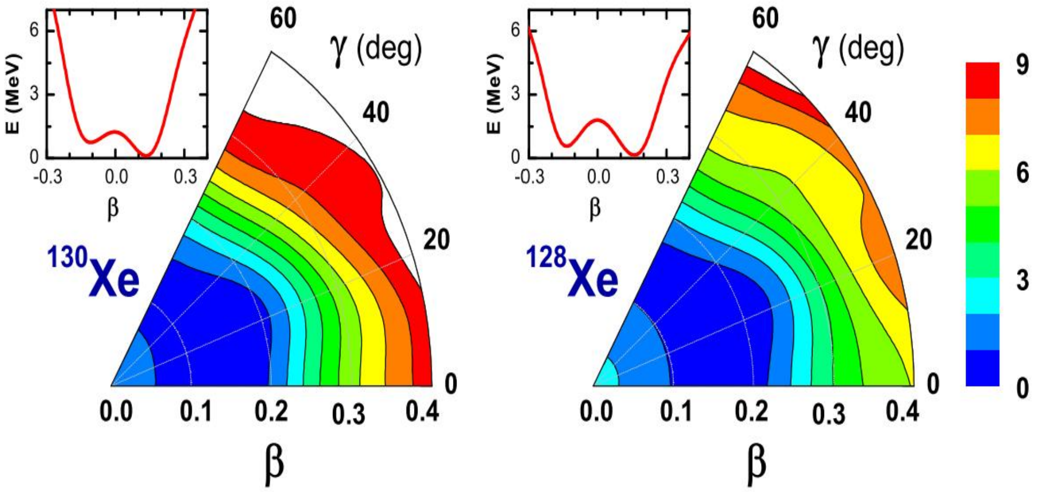
Th. predictions on E(5) symmetry near $^{128\text{-}130}$Xe



R. Rodriguez-Guzman, et. al. Phys. Rev. C 76, 064303 (2007)



L.M.Robledo, et. al. Phys. Rev.C 78 (2008) 034314

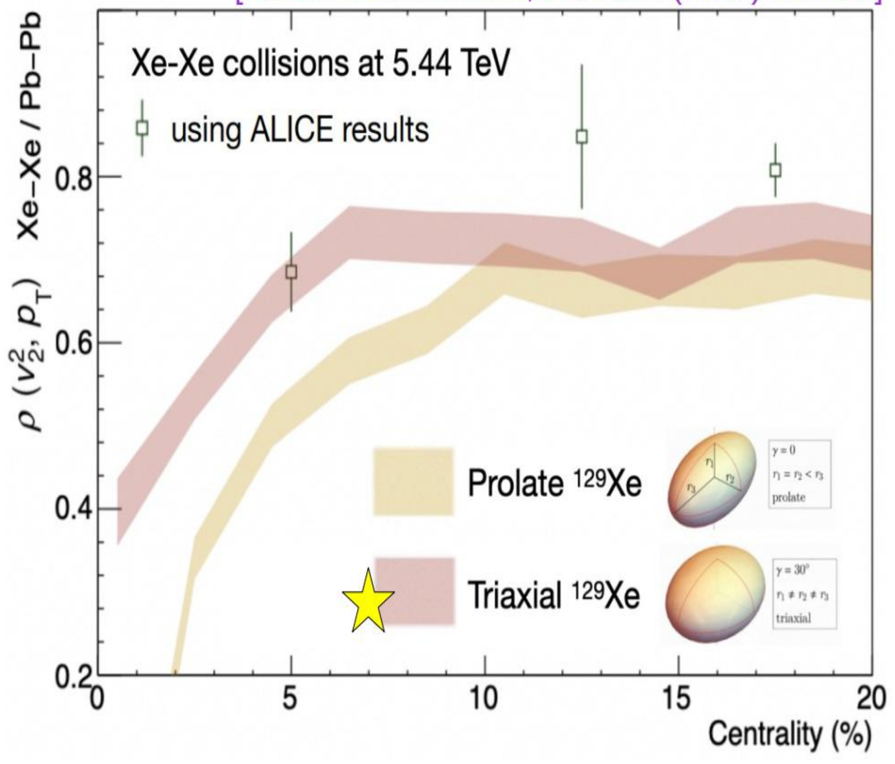


Z. P. Li, T. Niksic, D. Vretenar, and J. Meng (2010)

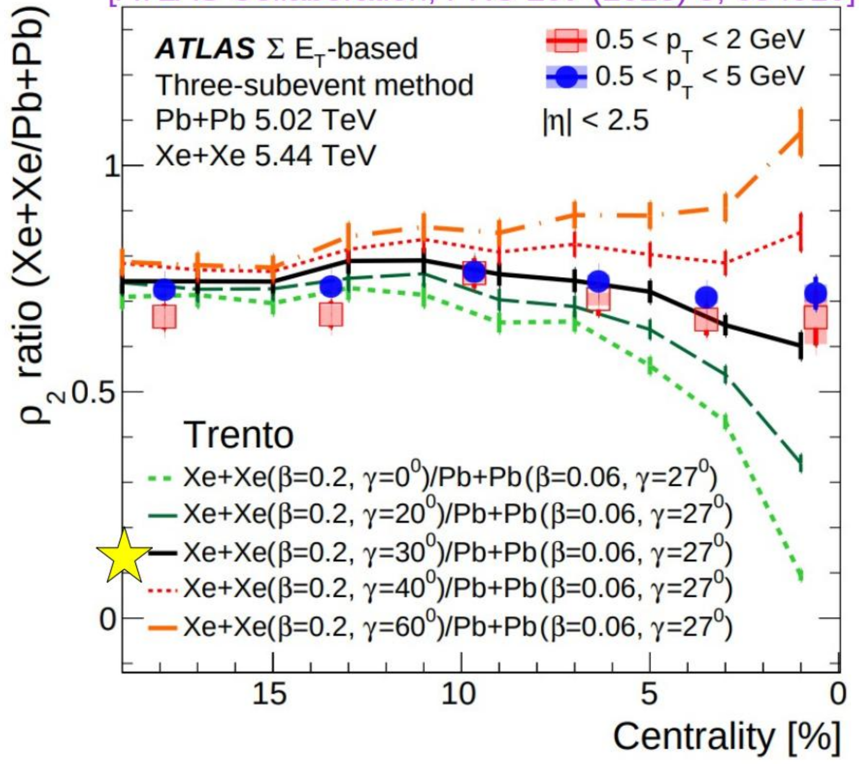
Various theoretical calculations indicate a critical point of the second-order shape phase transition (E(5) symmetry) lies in the vicinity of $^{128-130}$Xe, associated with a γ-soft deformation

Probing triaxial deformation in Xe+Xe collisions

[ALICE Collaboration, PLB **834** (2022) 137393]



[ATLAS Collaboration, PRC **107** (2023) 5, 054910]



Distinguish rigid triaxial and γ-soft configuration in heavy-ion collisions.
Explore the possible 2nd order shape phase transition of Xe isotopes.

B. Bally, M. Bender, G. Giacalone, V. Somà, Phys. Rev. Lett. 128 (8) (2022) 082301

Involving γ fluctuation at initial stage

Initial Conditions (TRENTO)

Nucleons are sampled from Woods-Saxon distribution:

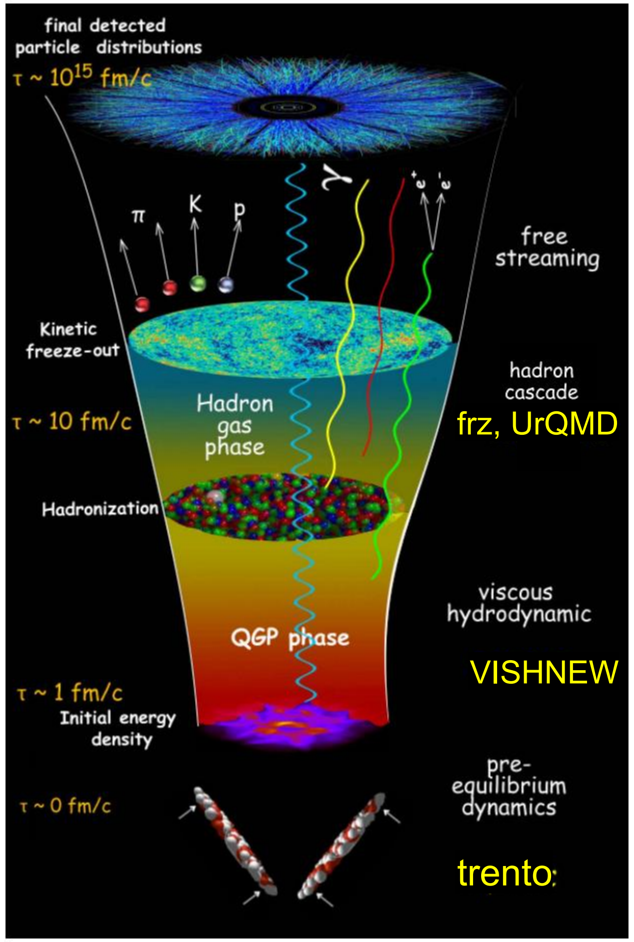
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

$0 \le \gamma \le \pi/3$

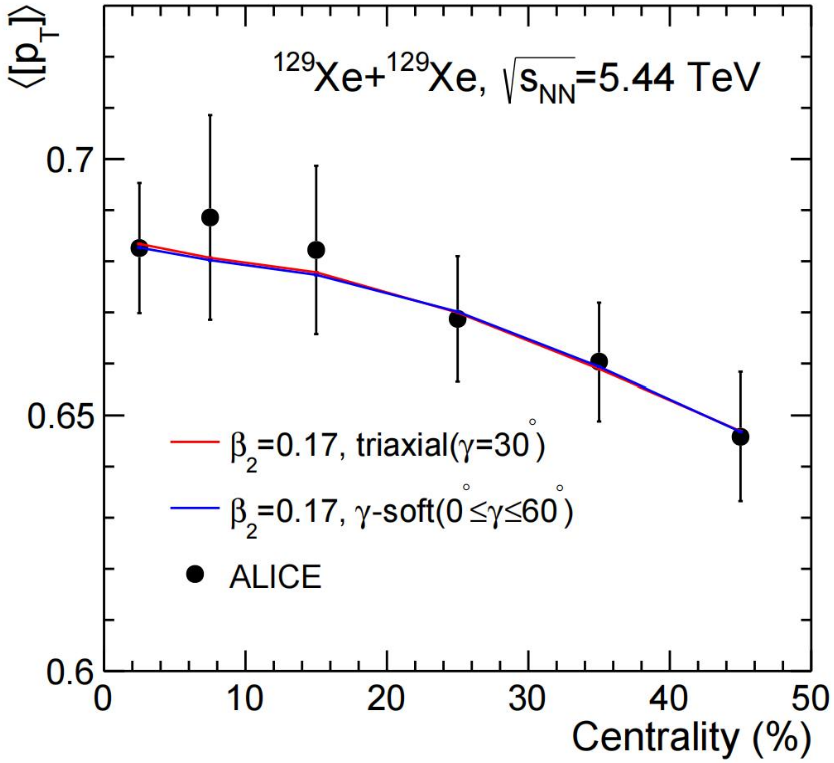
Sample the triaxial parameter gamm with different distribution:

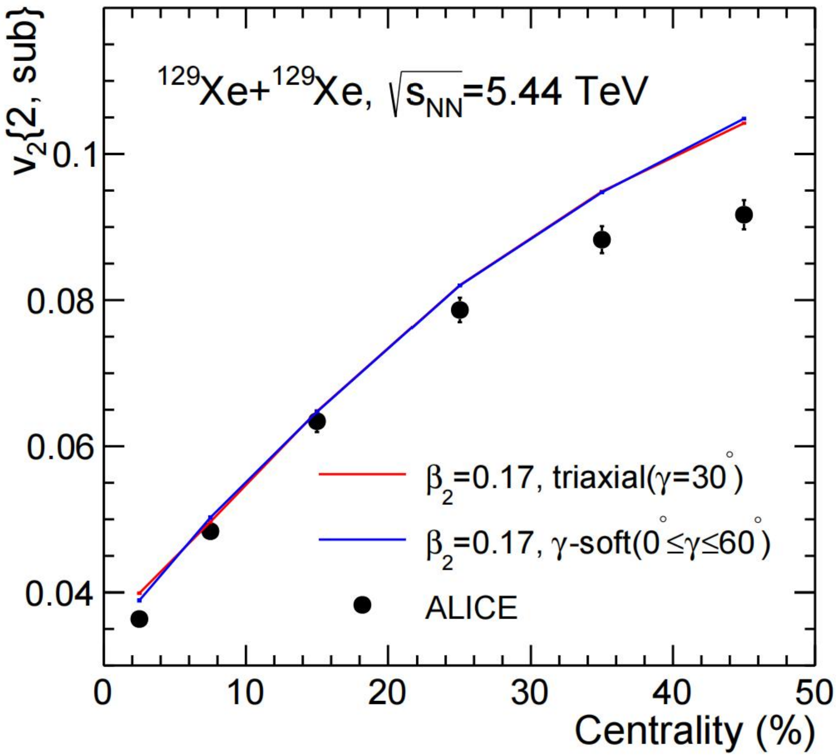
- Rigid triaxial deformation (γ=30º)
- γ-soft (flat distribution in 0≤γ≤60º)



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

Parameter Validation





With the parameters obtained from previous Bayesian analysis (Pb+Pb coll), our iEBE-VISHNU, with rigid triaxial or γ-soft deformation of ^{129}Xe, can describe most of the bulk observables in Xe+Xe collisions

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

Results: 3-particle correlations

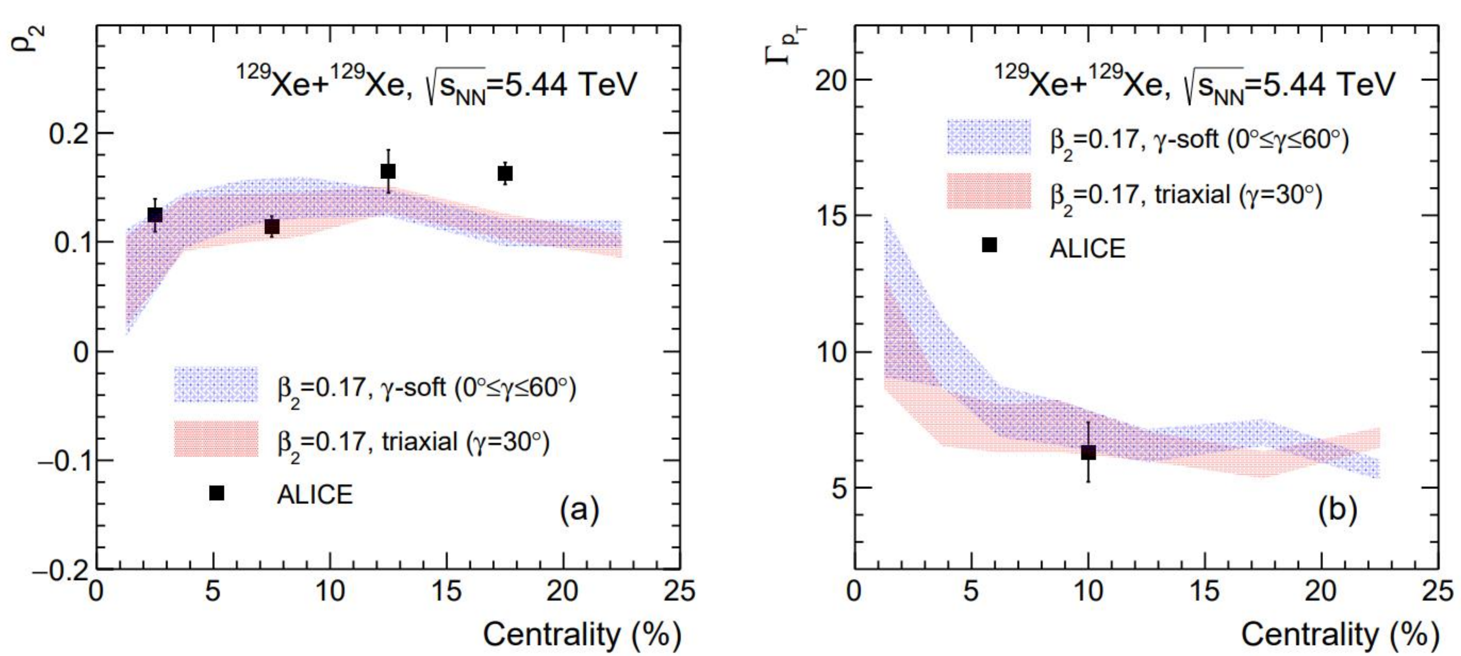
Liquid-drop model prediction:

$$\rho_2, \Gamma_{p_T} \propto \beta_2^3 \cos(3\gamma)$$

3-particle correlation can also be explained by the γ-soft ^{129}Xe.

higher order correlations between v_2 and $[p_T]$ is crucial for distinguish the two different γ configuration.

$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}. \qquad \Gamma_{p_T} = \frac{\langle \delta p_{T,i}\delta p_{T,j}\delta p_{T,k}\rangle\langle[p_T]\rangle}{\langle \delta p_{T,i}\delta p_{T,j}\rangle^2},$$



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

Results: 6-particle correlations

Here we propose the following two 6-particle correlations at the initial stage:

$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \right)_c \equiv \frac{1}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \left[\langle \varepsilon_2^4 \delta d_\perp^2 \rangle + 4 \langle \varepsilon_2^2 \rangle^2 \langle \delta d_\perp^2 \rangle - \langle \varepsilon_2^4 \rangle \langle \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \rangle \langle \varepsilon_2^2 \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \delta d_\perp \rangle^2 \right]$$

$$\rho_{2,4} \equiv \left(\frac{\langle \varepsilon_2^2 \delta d_\perp^4 \rangle}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \right)_c \equiv \frac{1}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \left[\langle \varepsilon_2^2 \delta d_\perp^4 \rangle - 6 \langle \varepsilon_2^2 \delta d_\perp^2 \rangle \langle \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \delta d_\perp \rangle \langle \delta d_\perp^3 \rangle - \langle \varepsilon_2^2 \rangle \langle \delta d_\perp^4 \rangle + 6 \langle \varepsilon_2^2 \rangle \left(\langle \delta d_\perp^2 \rangle \right) \right].$$

The calculations based on the liquid-drop model suggest that

$$\langle \varepsilon_2^4 \rangle \rho_{4,2} = A \beta_2^6 (53 + 16 \langle \cos(6\gamma) \rangle) + f_{4,2}(\beta_2^6, \langle \cos(3\gamma) \rangle),$$

$$\langle \varepsilon_2^2 \rangle \rho_{2,4} = \frac{A}{16} \beta_2^6 (43 - 14 \langle \cos(6\gamma) \rangle) + f_{2,4}(\beta_2^6, \langle \cos(3\gamma) \rangle),$$

Thus it would be possible for distinguish the two cases (traixial shape with γ=30^o and γ-soft in 0≤γ≤60^o) using the two 6-particle correlations.

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

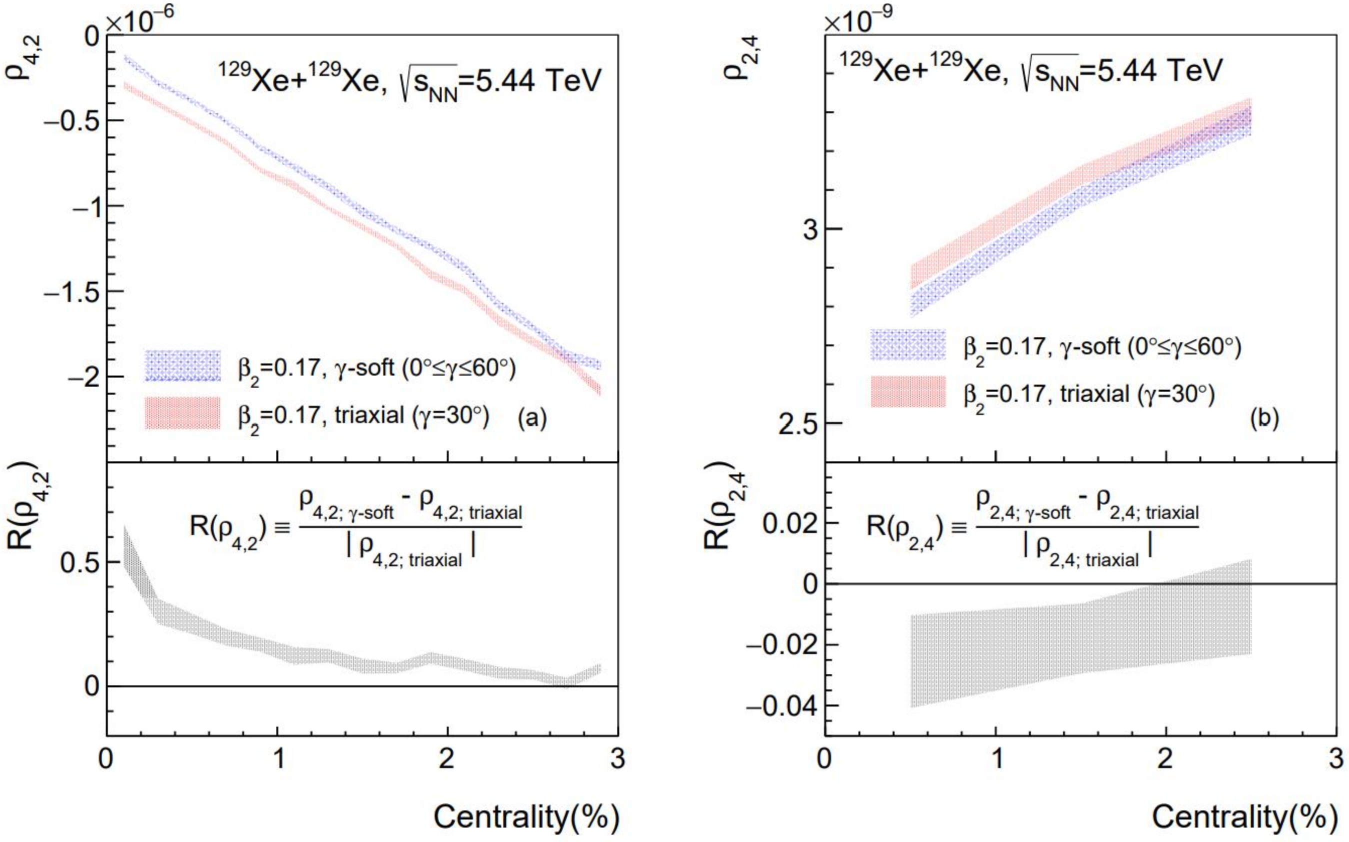
Results: 6-particle correlations

Clear enhencement (suppression) for the γ-soft (regid triaxial) shape, consistent with liquid drop calculations.

Effects on $\rho_{4,2}$ are one magnitude larger than $\rho_{2,4}$.

By constraining 3- and 6-particle correlations simultaneously, it would be possible to determine the details of traxial shape of ^{129}Xe.

$$R(\rho_{m,n}) = \frac{\rho_{m,n;\ \gamma\text{-soft}} - \rho_{m,n;\ \text{triaxial}}}{|\rho_{m,n;\ \text{triaxial}}|}.$$



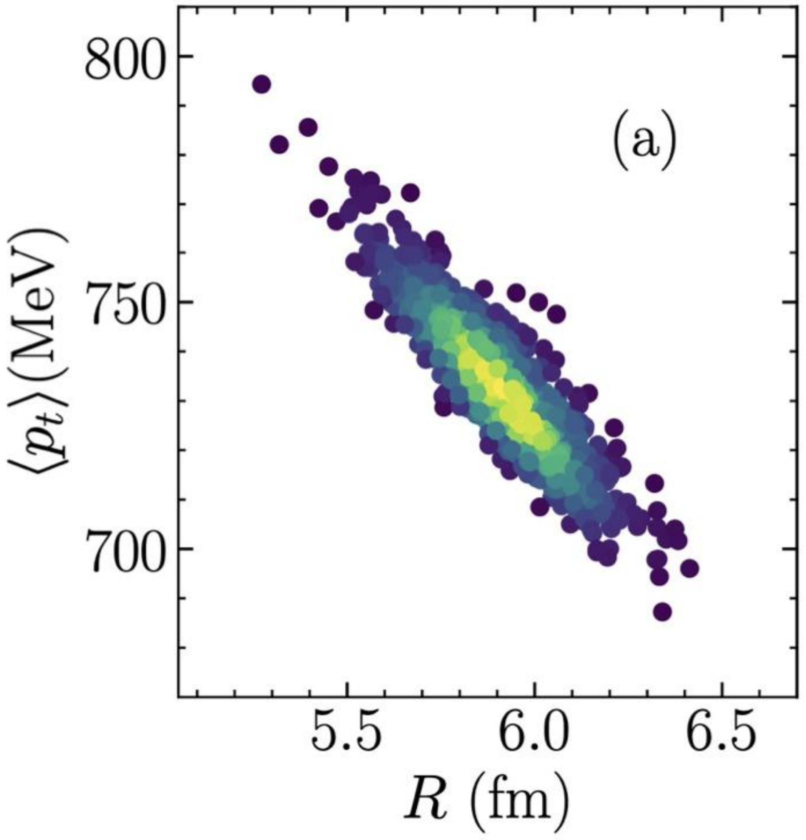
S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th]

Summary

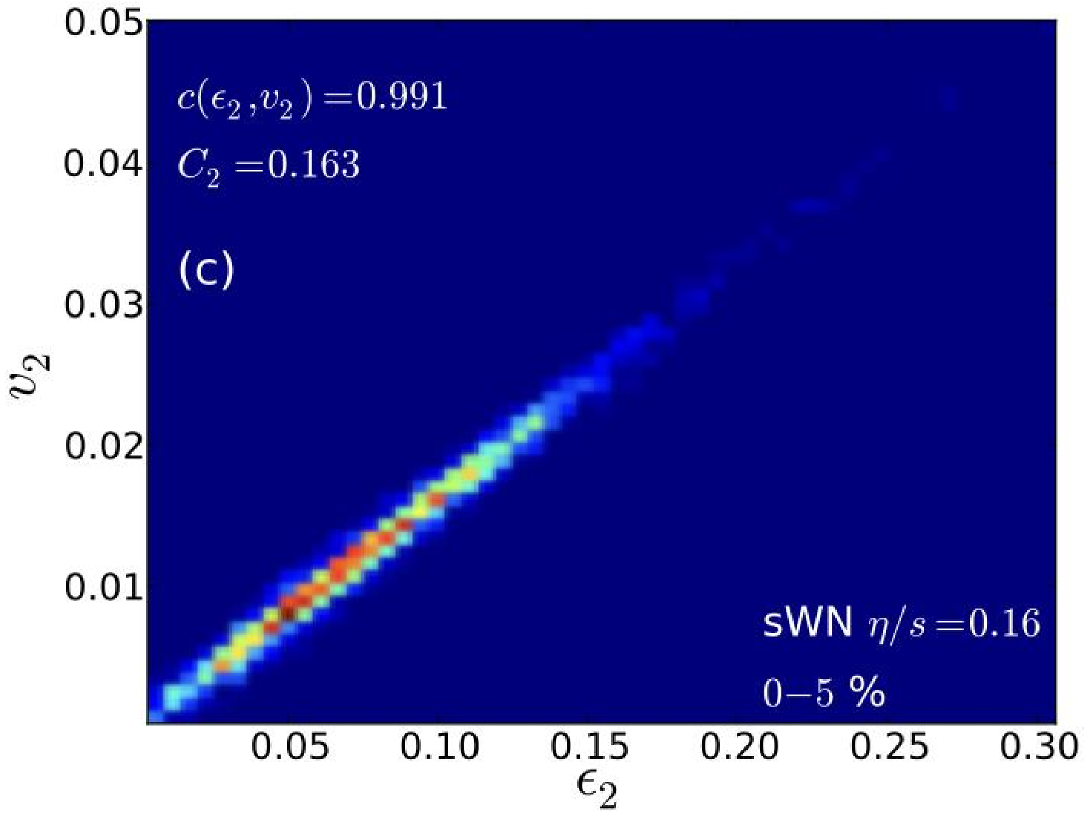
- ^{129}Xe may lay in the critical region of the second order shape phase transition along the Xe isotropes. Studing the traxial structure in ^{129}Xe may help for a better understanding the shape phase transition.
- 3-particle correlations cannot distinguish the traxial and γ-soft configurations of ^{129}Xe.
- By measuring the 3- and 6-particle correlations simultaneously, it would be possible to impose a constraint on the γ configuration of ^{129}Xe.
- This work suggest the possibility for studing the nuclear shape phase transition using relativistic heavy-ion collisions.

Backup

Linear response between ini. & fin. stage

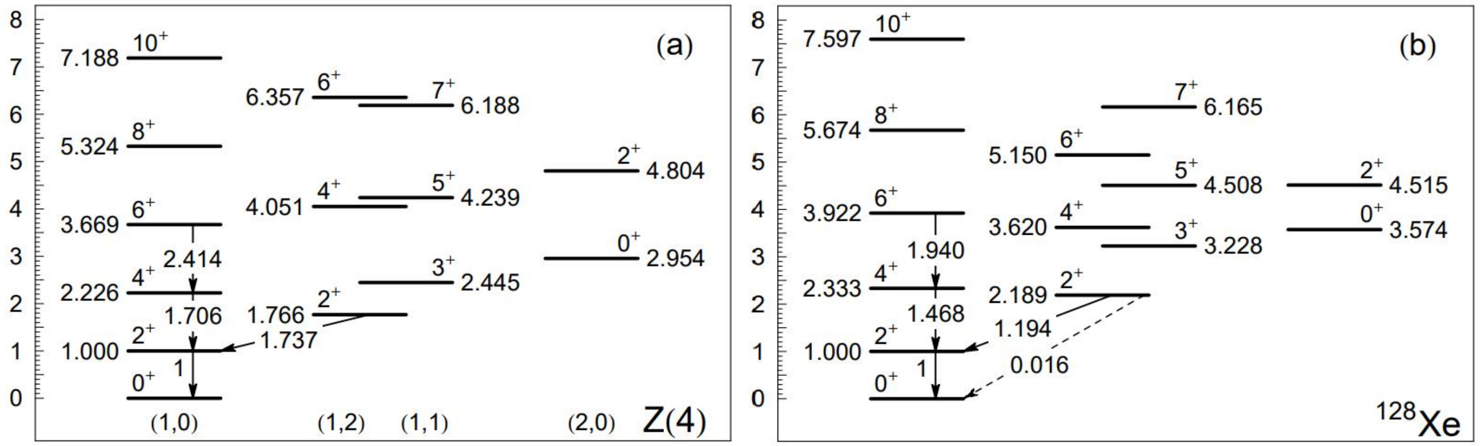


$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$$



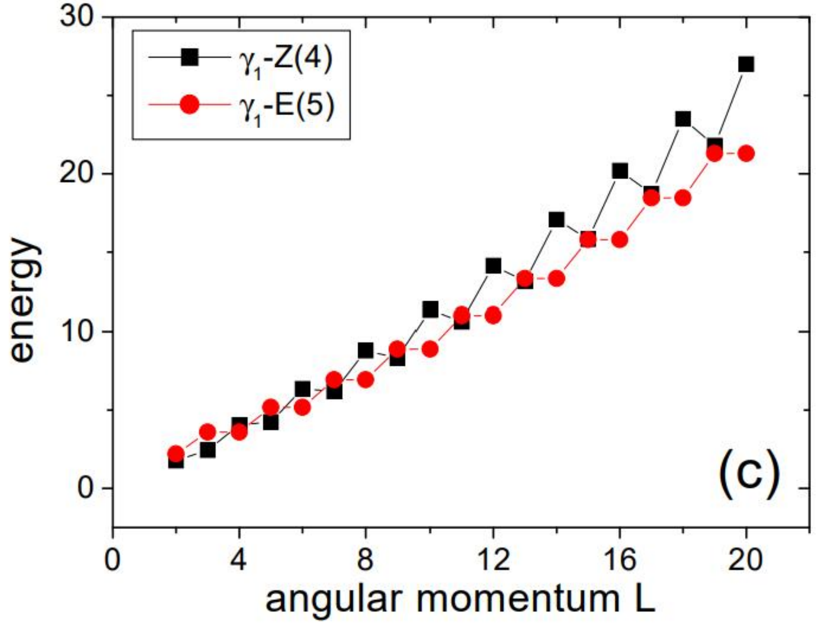
$$V_n \propto \mathcal{E}_n$$

E(5) v.s. Z(4) ?



Z(4) symmetry with a frozen γ at 30º can also describe the spectra and $B(E2)$ rates for ^{128,130,132}Xe

D. Bonatsos, D. Lenis, D. Petrellis, P. A. Terziev, and I. Yigitoglu, Phys. Lett. B 621, 102 (2005),



The mean difference between E(5) and Z(4) is the pair order of energy levels in the γ band.

However, It’s hard to dintinguish the E(5) and Z(4) nuclei in low energy nuclear physics.