ANPhA 2025

Recent Highlights from the STAR Experiment at RHIC

(nuclear structure across energy scales)

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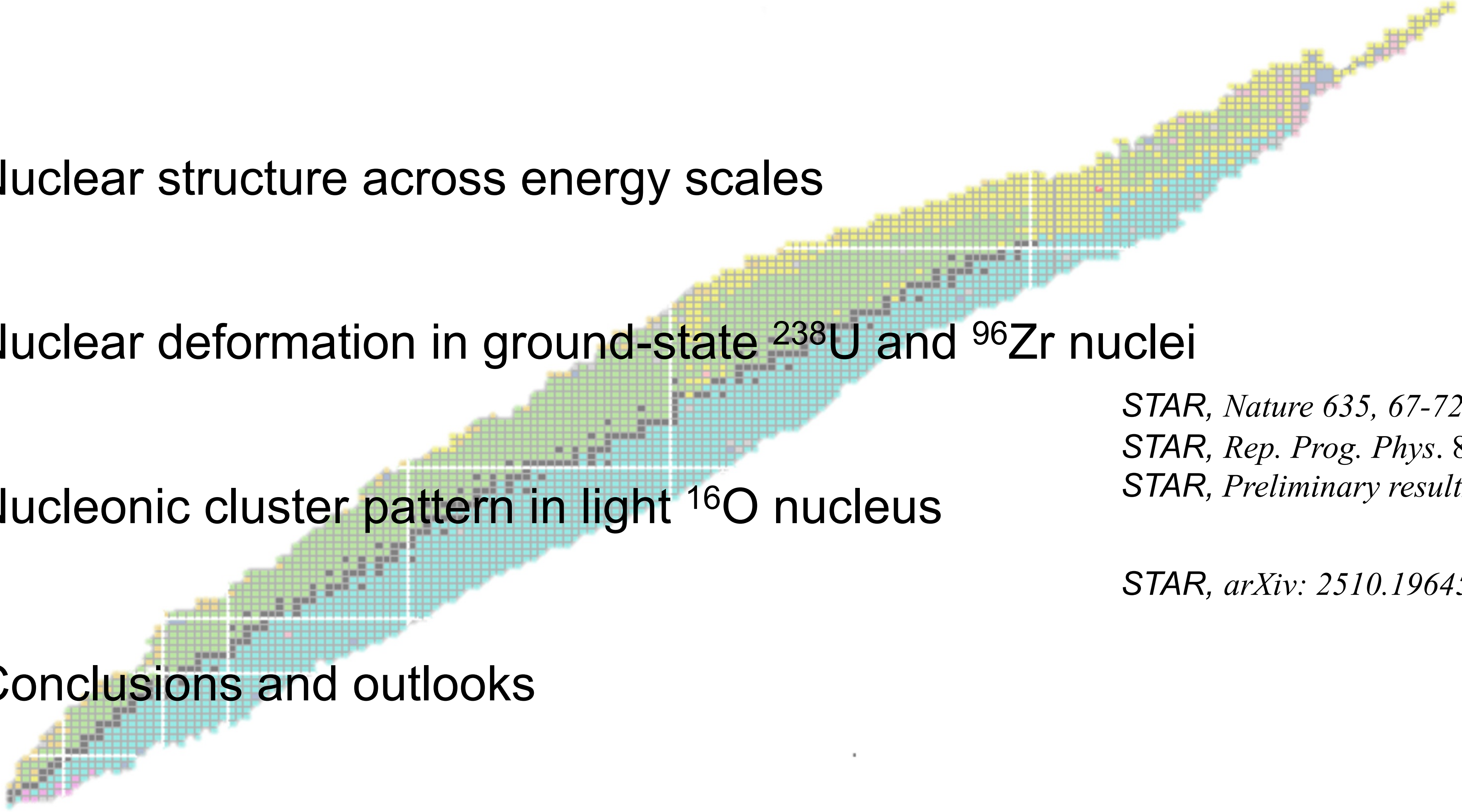
Fudan University

Nov 27-29, 2025, Institute of Physics, Academia Sinica

Outline



I. Nuclear structure across energy scales

II. Nuclear deformation in ground-state ^{238}U and ^{96}Zr nuclei

STAR, *Nature 635, 67-72 (2024)*
STAR, *Rep. Prog. Phys*. 88, 108601 (2025)
STAR, *Preliminary results*

III. Nucleonic cluster pattern in light ^{16}O nucleus

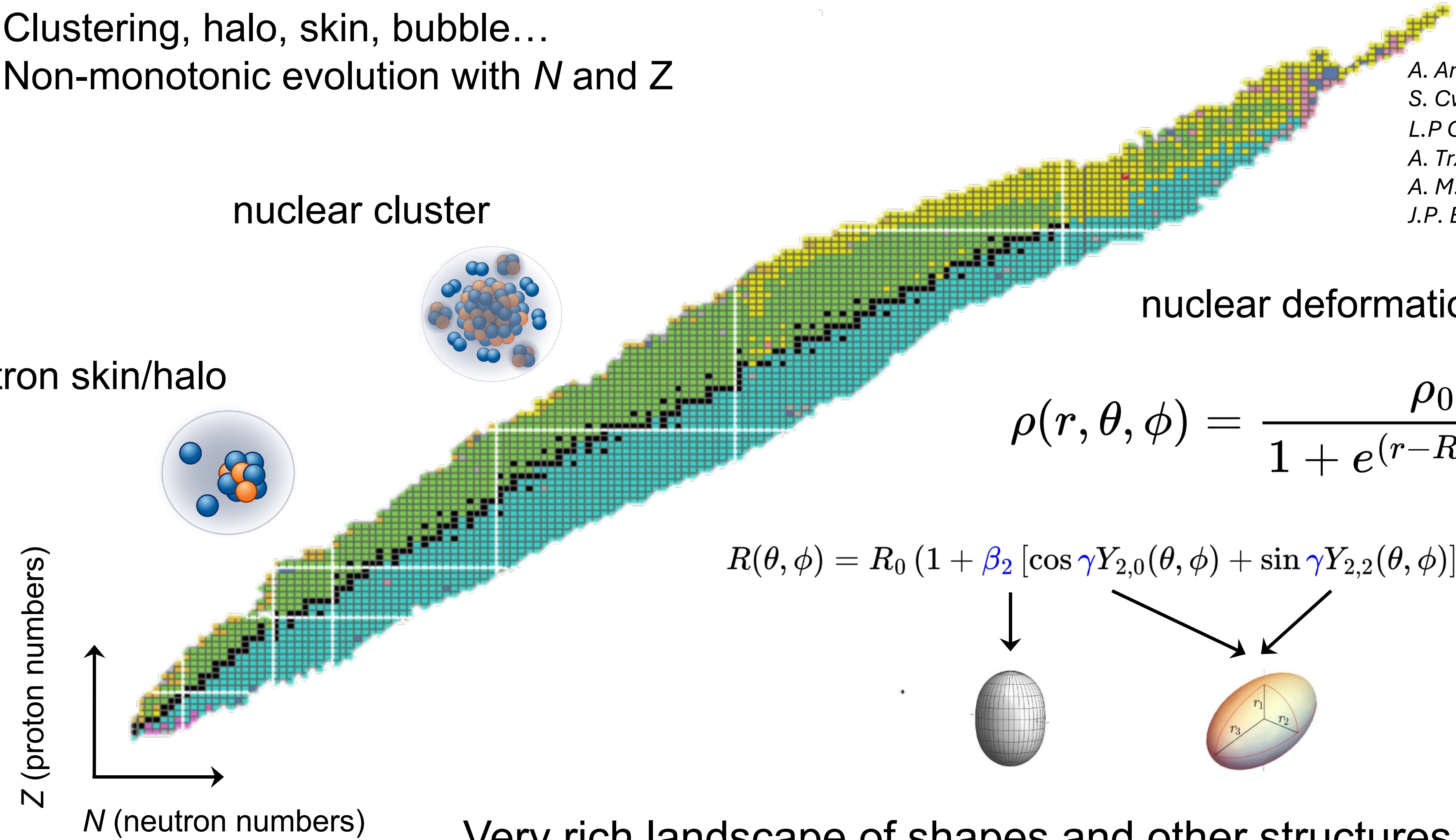
STAR, *arXiv: 2510.19645*

IV. Conclusions and outlooks

Shape of atomic nuclei

Emergent phenomena of the many-body quantum system, govern by short-range strong nuclear force

- Quadrupole/octupole/hexadecapole deformations
- Clustering, halo, skin, bubble…
- Non-monotonic evolution with *N* and *Z*



A. Andreyev et al., Nature 405, 430 (2000)
S. Cwiok et al., Nature 433, 705 (2005)
L.P Gaffney P. Butler et al., Nature 497, 199 (2013)
A. Trzcinska et al., PRL 87, 082501 (2001)
A. M. Centelles et al., PRL 102, 122502 (2009)
J.P. Ebran et al. Nature 487, 341 (2012)

nuclear deformation

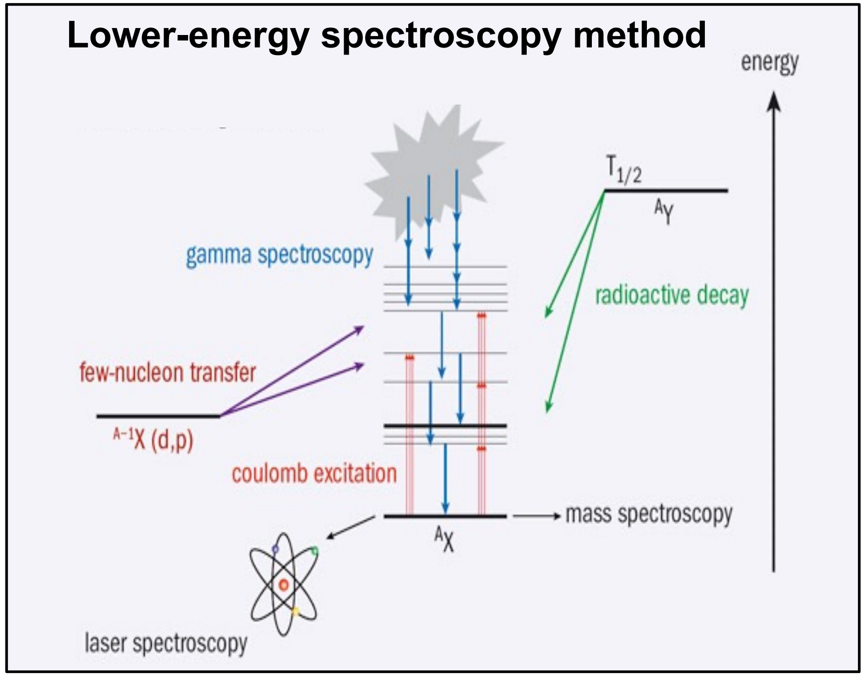
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

Very rich landscape of shapes and other structures

Y. Ye, X. Yang, H. Sakurai, B. Hu, Nature Review Physics, 7, 21-37 (2025); Y.-G. Ma, S. Zhang, Handbook of Nuclear Physics (2022)

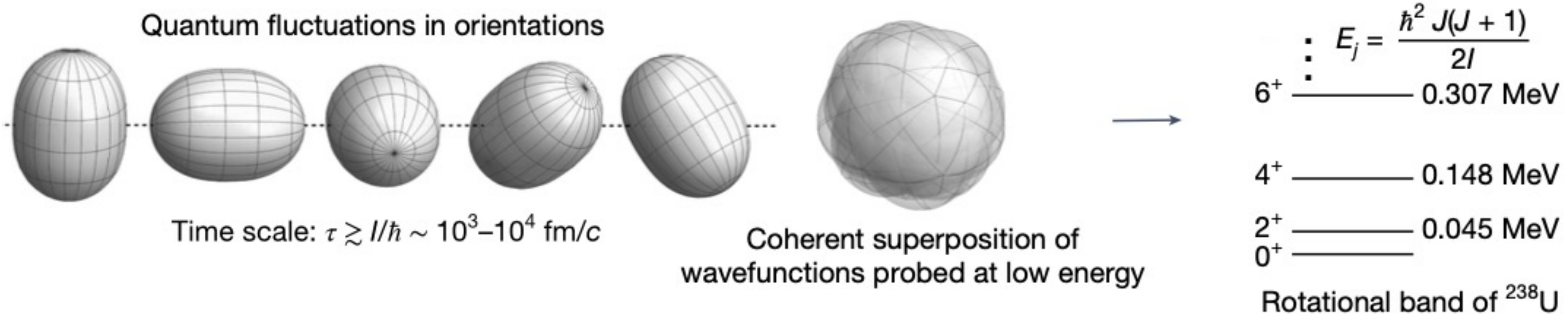
Nuclear shape at low energy: long exposure



Traditional imaging method taken before destruction

→ Low energy spectroscopic methods probe a superposition of these fluctuations.
→ Instantaneous shapes not directly seen, but inferred from model comparison.

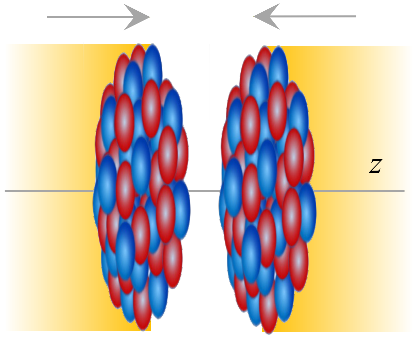
Each DOF has zero-point fluctuations within certain timescales.



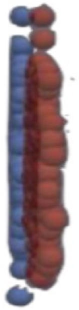
Imaging by smashing method

Take a snapshot | Evolution | Measurement

Nuclei collisions



$T_{\mu\nu}(\tau = 0)$

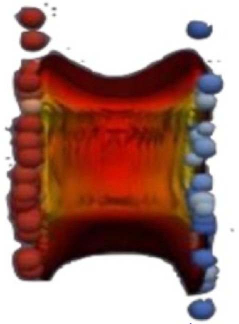


$\tau \sim 2R_0/\Gamma \sim 0.1\text{fm}/c$

exposure

$\partial_\mu T^{\mu\nu} = 0$, EOS, viscosity…

Pressure-driven expansion of Quark-gluon plasma (QGP)

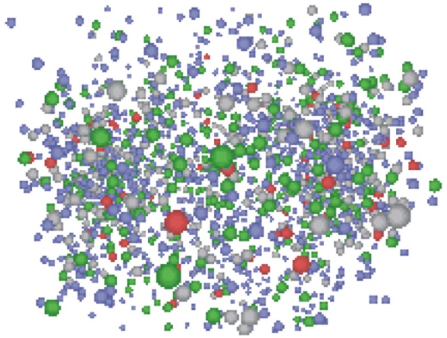


$\tau \sim 10\text{fm}/c$

expansion

free-streaming

$T_{\mu\nu}(\tau = \infty)$



$\tau \sim 10^{15}\text{fm}/c$

detection

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

- $\beta_2 \to$ quadrupole deformation
- $\beta_3 \to$ octupole deformation
- $\gamma \to$ triaxiality
- $a_0 \to$ surface diffuseness
- $R_0 \to$ nuclear size

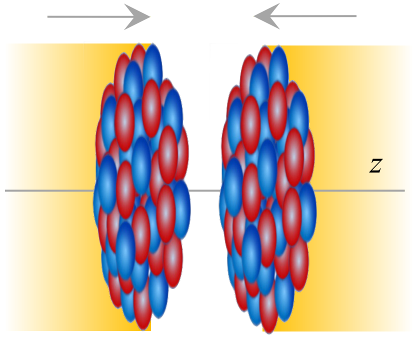
ab initio theory/shell model/DFT

J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024)*

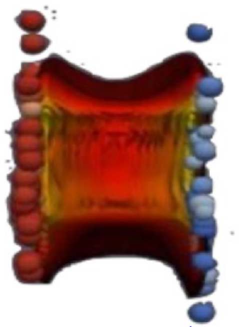
Imaging by smashing method

Take a snapshot — Evolution — Measurement

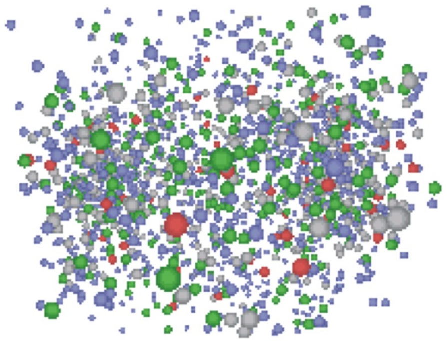
Nuclei collisions $T_{\mu\nu}(\tau=0)$ — $\partial_\mu T^{\mu\nu}=0$, EOS, viscosity… — $T_{\mu\nu}(\tau=\infty)$



Pressure-driven expansion of Quark-gluon plasma (QGP)



free-streaming



$\tau \sim 2R_0/\Gamma \sim 0.1\mathrm{fm}/c$ exposure

$\tau \sim 10\mathrm{fm}/c$ expansion

$\tau \sim 10^{15}\mathrm{fm}/c$ detection

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

- $\beta_2 \rightarrow$ quadrupole deformation
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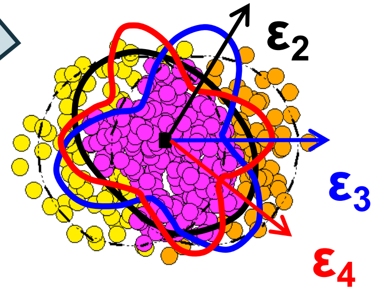


size & shape

J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024)*

$R_\perp^2 \propto \langle r_\perp^2 \rangle$ $\quad \mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

R_0 $\quad a_0$ $\quad \beta_n$

Observables $\frac{d^2N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$

Event-by-event linear responses:

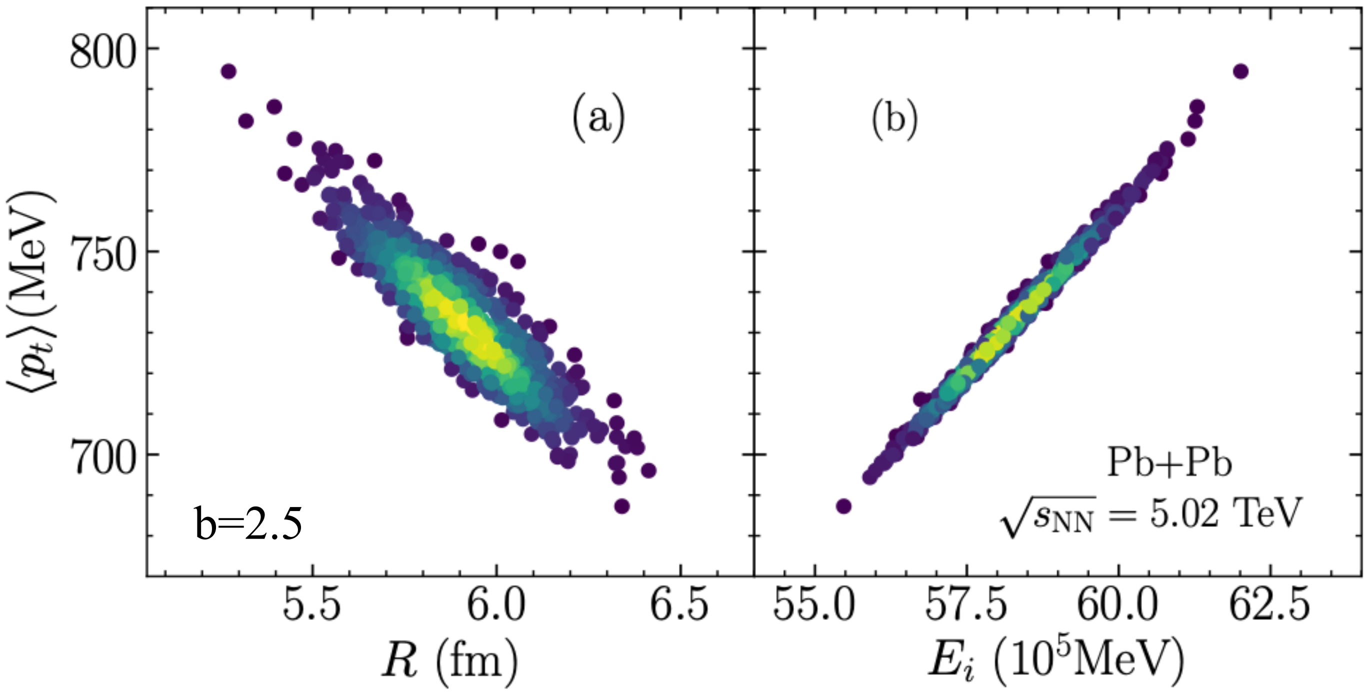
$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

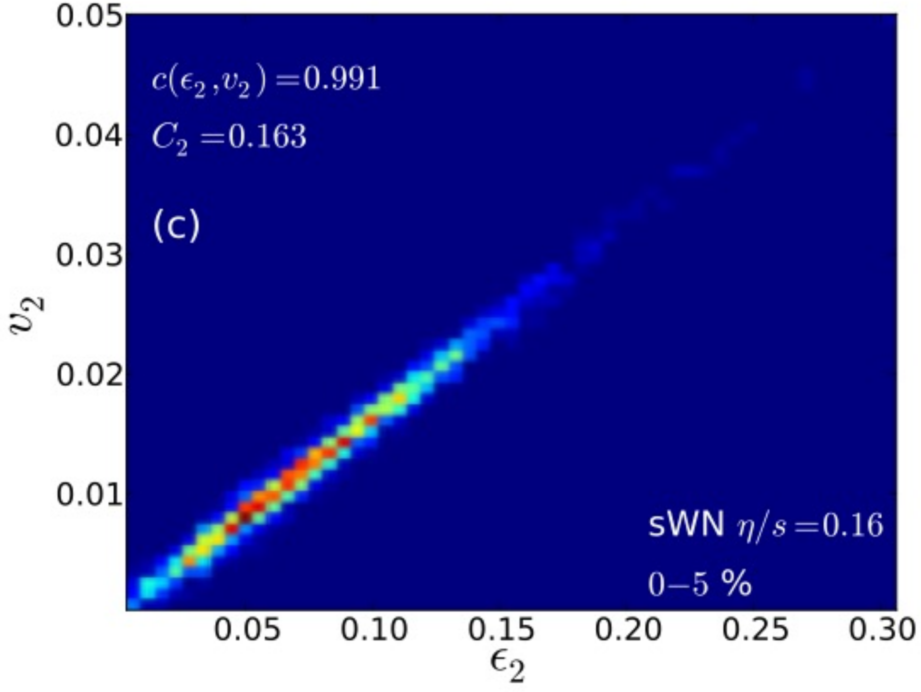
Linear response in ultra-central collisions

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

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



G. Giacalone, F. Gardim, J. Hostler, J. Ollitrault, et al, *PRC 103, 024909 (2021)*

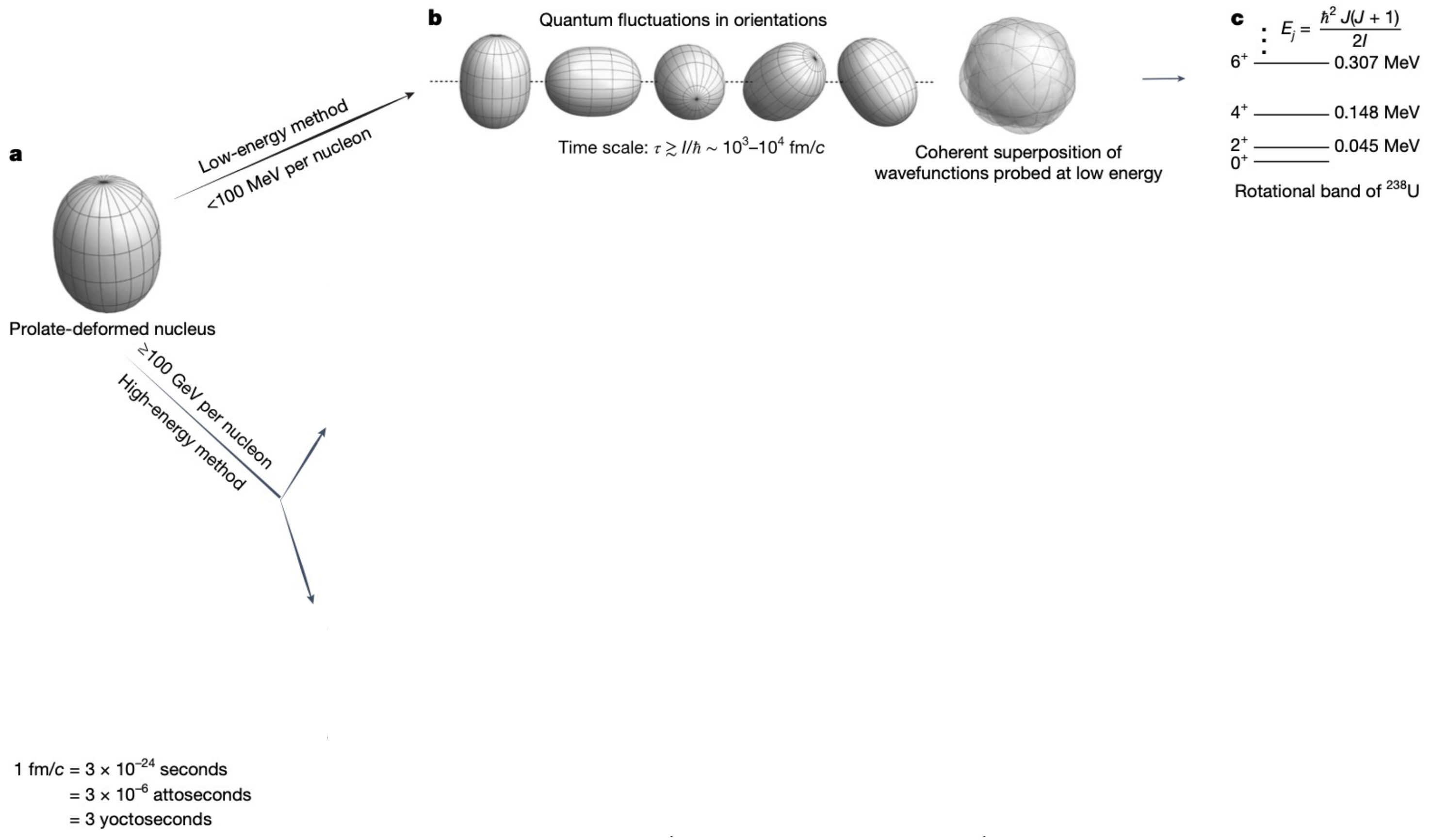


H. Niemi, G. Denicol, H. Holopainen, P. Huovinen, *PRC 87, 054901 (2013)*

Imaging nuclear shape in high-energy snapshot

- Nuclear shape in intrinsic (body-fixed) frame not directly visible in the lab frame

  --Mainly inferred from non-invasive spectroscopy methods.



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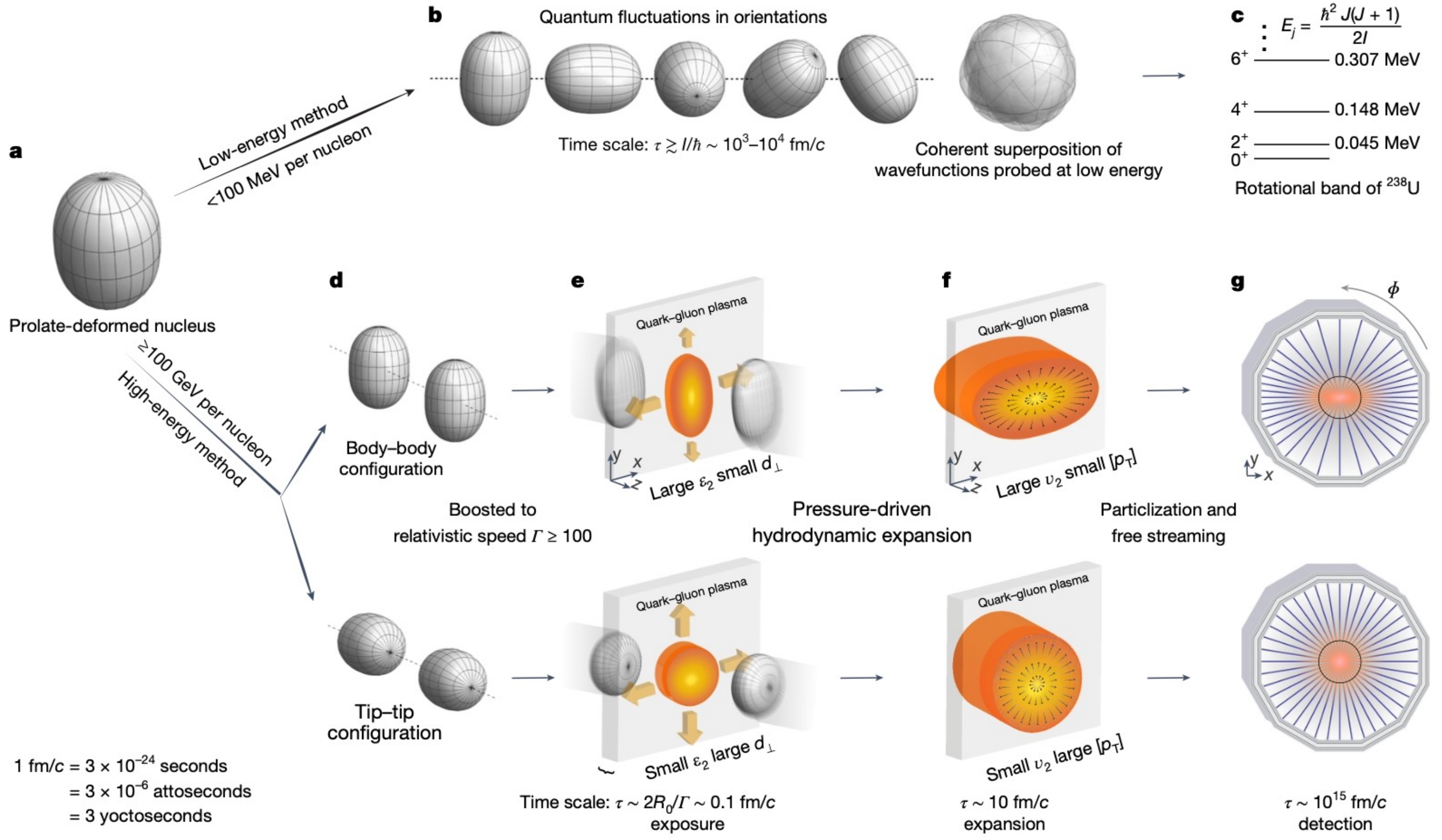


STAR, Nature 635, 67-72 (2024)

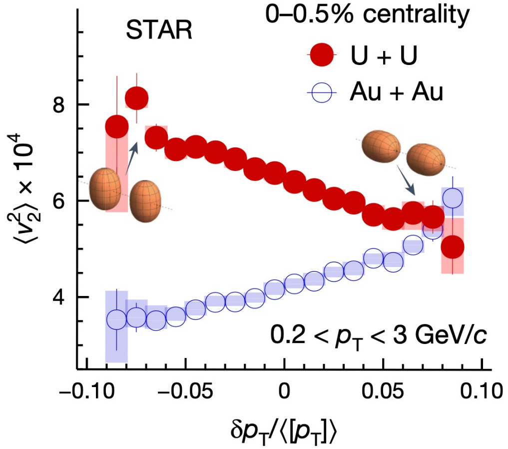
https://www.nature.com/articles/s41586-024-08097-2

Body-body: large-eccentricity large-size

$v_2\nearrow$ $p_T\searrow$

Tip-tip : small-eccentricity small-size

$v_2\searrow$ $p_T\nearrow$



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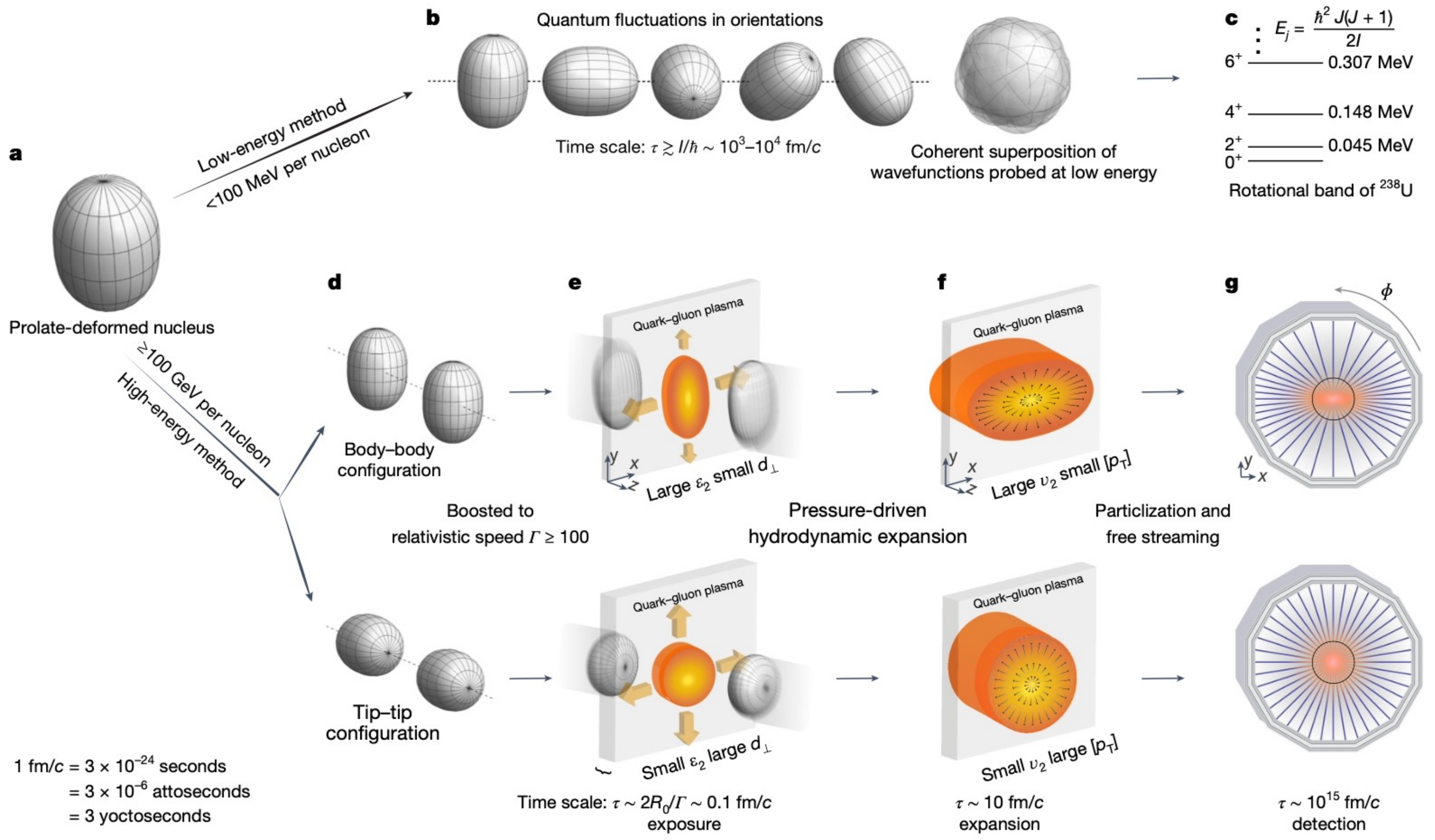


STAR, Nature 635, 67-72 (2024)
https://www.nature.com/articles/s41586-024-08097-2

across energy scales

Body-body: large-eccentricity large-size

$v_2\nearrow$ $p_T\searrow$

Tip-tip : small-eccentricity small-size

$v_2\searrow$ $p_T\nearrow$

$$\langle v_2^2\rangle = a_1 + b_1\beta_2^2,$$
$$\langle(\delta p_T)^2\rangle = a_2 + b_2\beta_2^2,$$
$$\langle v_2^2\delta p_T\rangle = a_3 - b_3\beta_2^3\cos(3\gamma).$$

G. Giacalone, J. Jia, C. Zhang, *PRL 127, 242301(2021)*

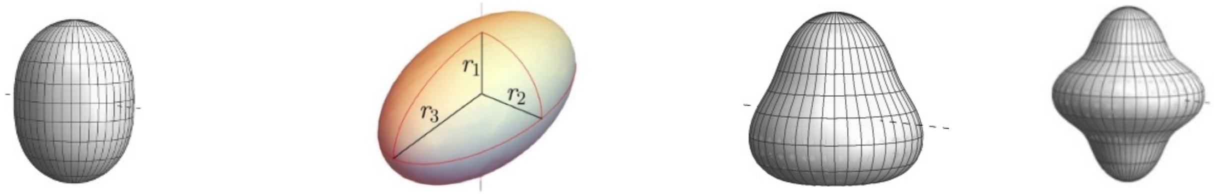
Shape-frozen like a snapshot during nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)

probe entire mass distribution in the intrinsic frame via multi-point correlations

II. Nuclear deformation in heavy ^{238}U and ^{96}Zr nucleus

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

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



W. Ryssens, G. Giacalone, B. Schenke, C. Shen, *PRL130, 212302(2023)*

DFT calculations predict a slightly small WS deformation $\beta_{2\mathrm{U}} \approx 0.28 \to \beta_{2\mathrm{U,WS}} \approx 0.25$

corresponding to a larger volume deformation in presence of $\boldsymbol{\beta}_{4\mathrm{U}}$~0.1 $\beta_{2,\mathrm{body}} = \frac{4\pi}{3R_0^2 A}\int d^3r\rho(\mathbf{r})r^2 Y_{20}$

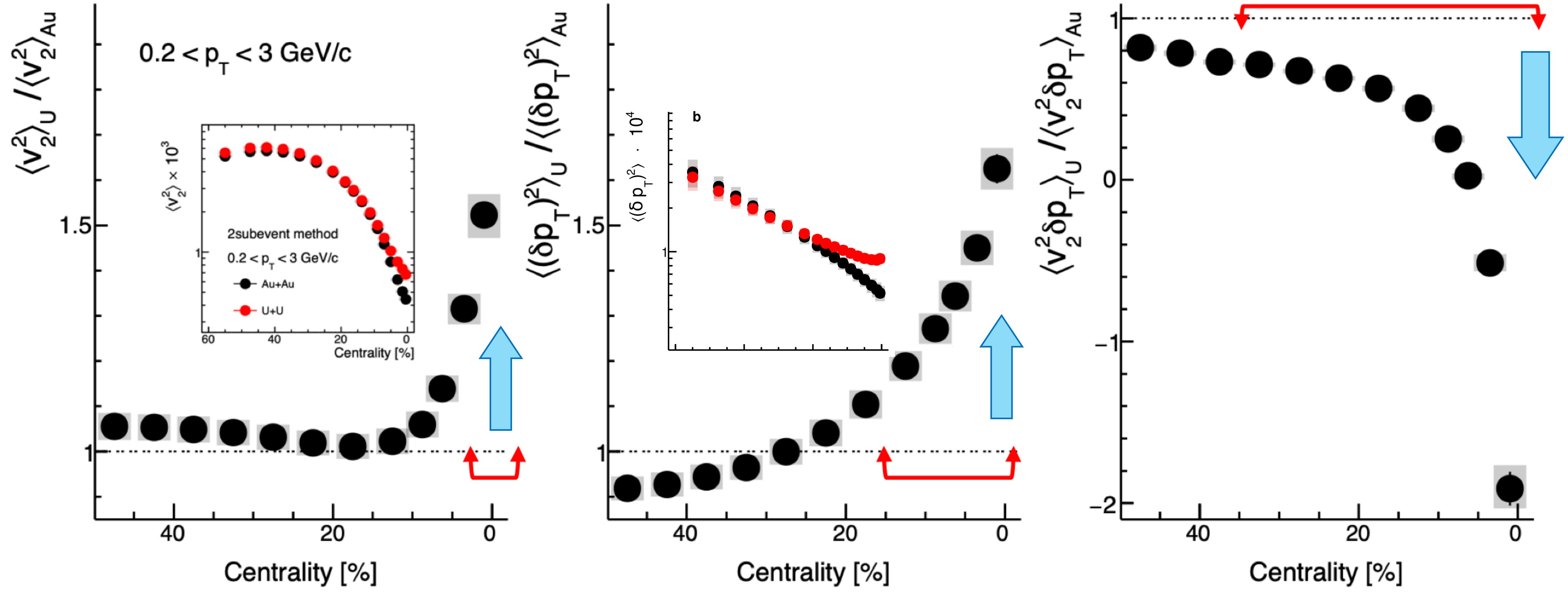
Low-energy estimate with rigid rotor assumption from B(E2) data $\beta_{2,\mathrm{LD}} = \frac{4\pi}{5R_0^2 Z}\sqrt{\frac{B(\mathrm{E2})}{e^2}}$

$\beta_{2\mathrm{U,LD}} = 0.287 \pm 0.007 \quad \gamma_{\mathrm{U,LD}} = 6^\circ - 8^\circ$

$\boldsymbol{\beta}_{3\mathrm{U}} \sim \boldsymbol{\beta}_{4\mathrm{U}} \sim 0.1$

B. Pritychenko et al., *J.ADT.107, 1(2016)*
C. Y. Wu et al., *PRC54, 2356(1996)*

Ratio of observables



$$R_{\langle v_2^2 \rangle} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$

$$R_{\langle (\delta p_{\mathrm{T}})^2 \rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$

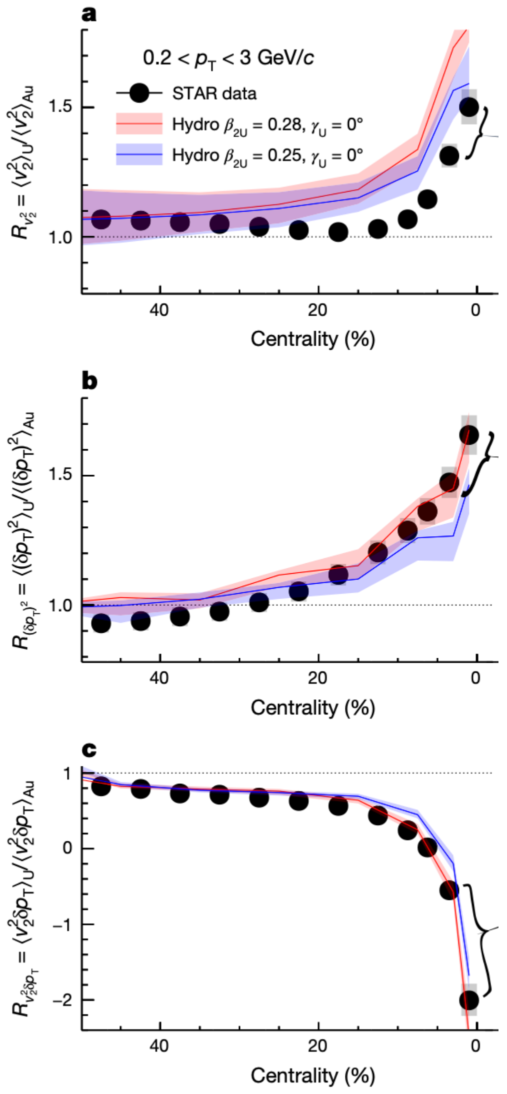
$$R_{\langle v_2^2 \delta p_{\mathrm{T}} \rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3 \cos(3\gamma)$$

- Elliptic flow and size fluctuation are enhanced by the nuclear deformation effect.

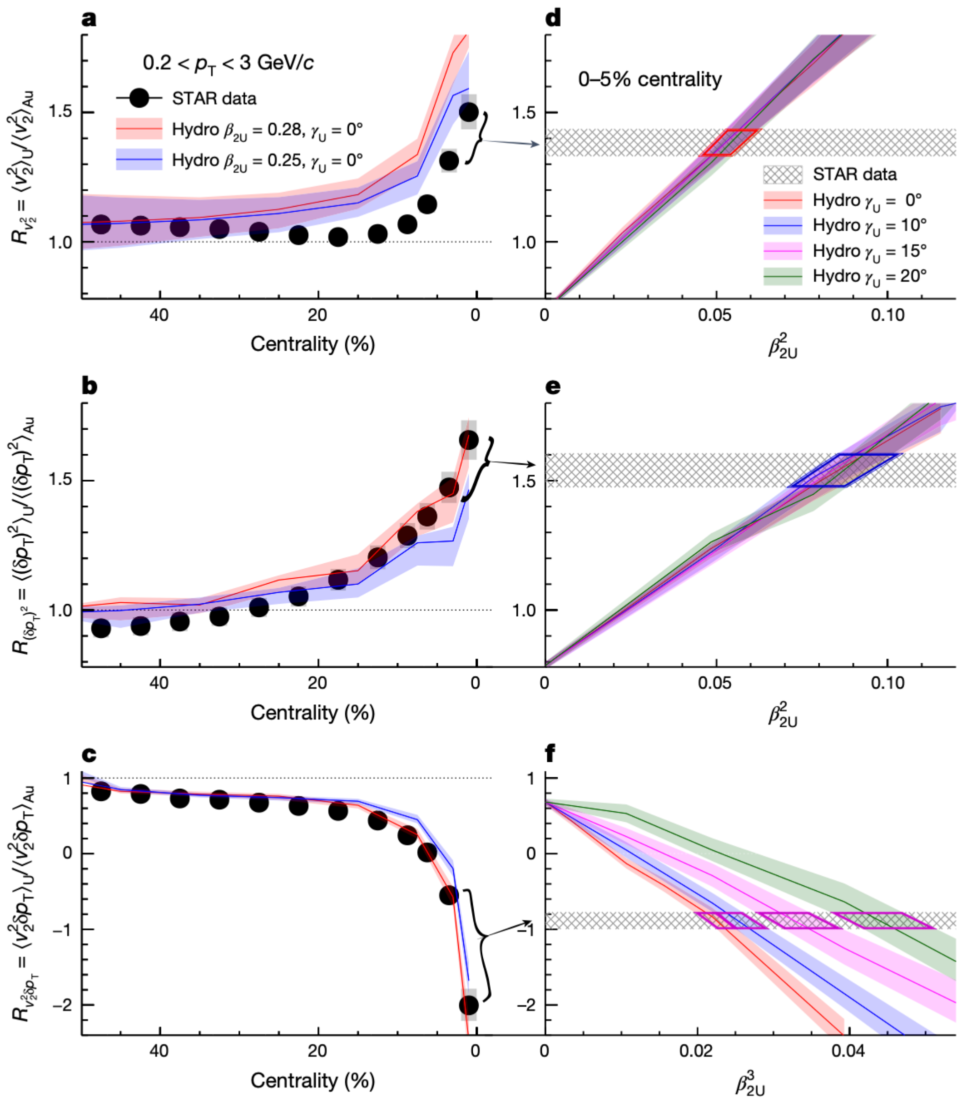
- Ratios cancel final state effects and isolate the effects of initial state/nuclear structures.

→ U deformation dominates the ultra-central collisions (UCC)

Constraining the ground-state ^{238}U: $\beta_{2,U}$ and γ_U



Constraining the ground-state ^{238}U: $\beta_{2,\mathrm{U}}$ and γ_{U}

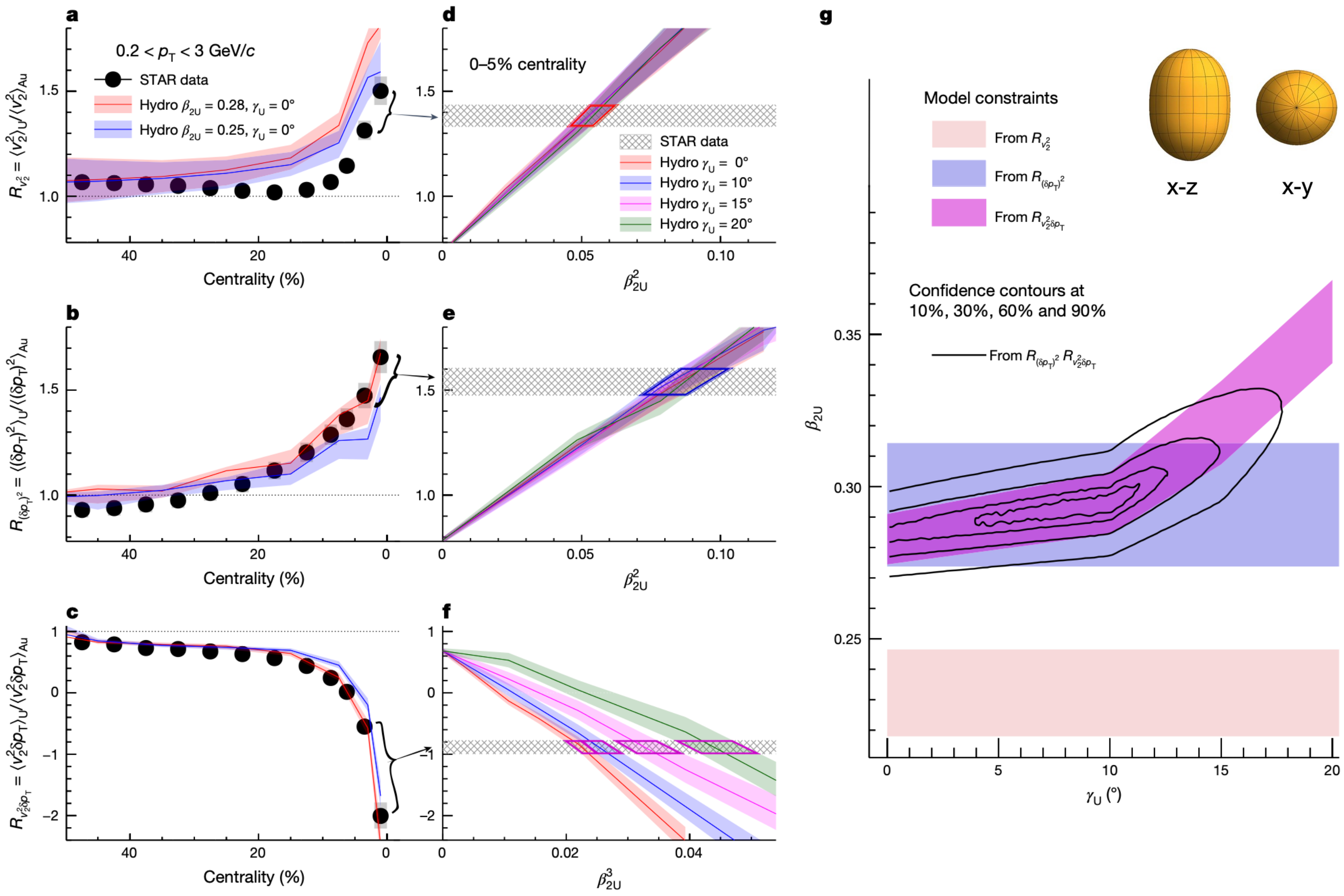


Sufficient precision is achieved from ratios in ultra-central collisions

Relation confirmed from hydro

$$R_{\langle v_2^2\rangle} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$
$$R_{\langle(\delta p_T)^2\rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$
$$R_{\langle v_2^2\delta p_T\rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3\cos(3\gamma)$$

Constraining the ground-state ^{238}U: $\beta_{2,\mathrm{U}}$ and γ_{U}



Sufficient precision is achieved from ratios in ultra-central collisions

Relation confirmed from hydro

$$R_{(v_2^2)} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$
$$R_{\langle(\delta p_\mathrm{T})^2\rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$
$$R_{\langle v_2^2 \delta p_\mathrm{T}\rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3\cos(3\gamma)$$

High-energy estimate (Ip-glasma+MUSIC and Trajectum)

$$\beta_{2\mathrm{U}} = 0.286 \pm 0.025$$
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

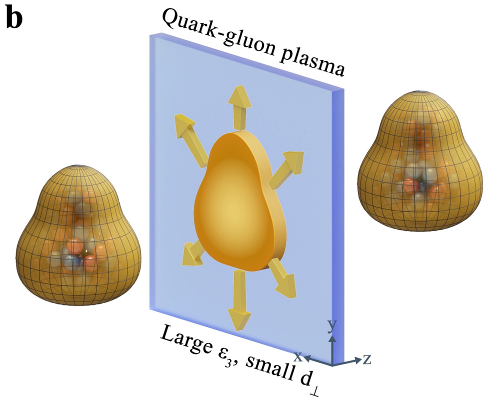
low-energy estimate:

$$\beta_{2\mathrm{U}} = 0.287 \pm 0.007$$
$$\gamma_U = 6^\circ - 8^\circ$$

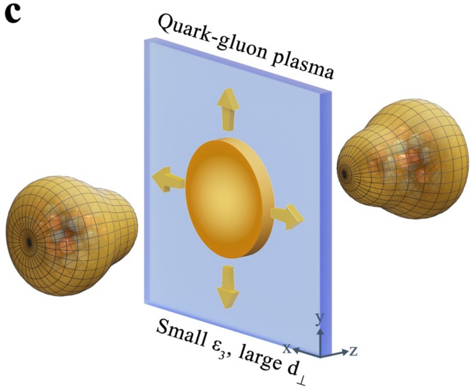
A large deformation with a slight deviation from axial symmetry in the nuclear ground-state

Evidence of octupole deformation $\beta_{3,\mathrm{U}}$

b



c



However, v_3 is fluctuation driven, expect in central

$$\langle v_3^2 \rangle \propto \langle \varepsilon_3^2 \rangle \sim 1/A$$

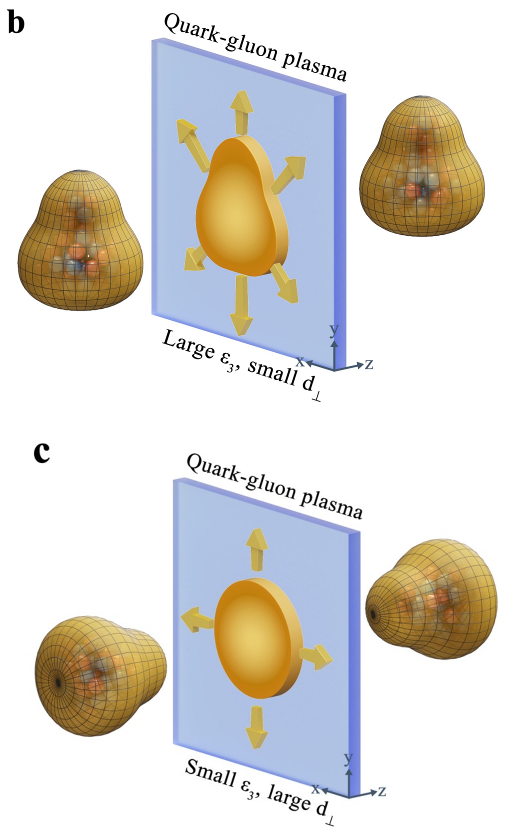
mass number

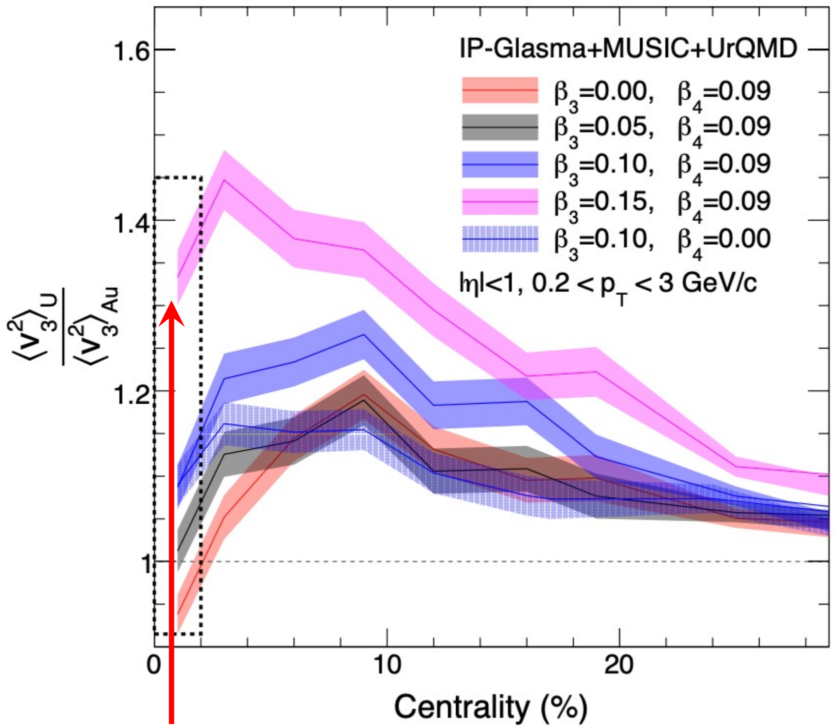
B. Alver and G. Roland, *PRC 81, 054905 (2010)*

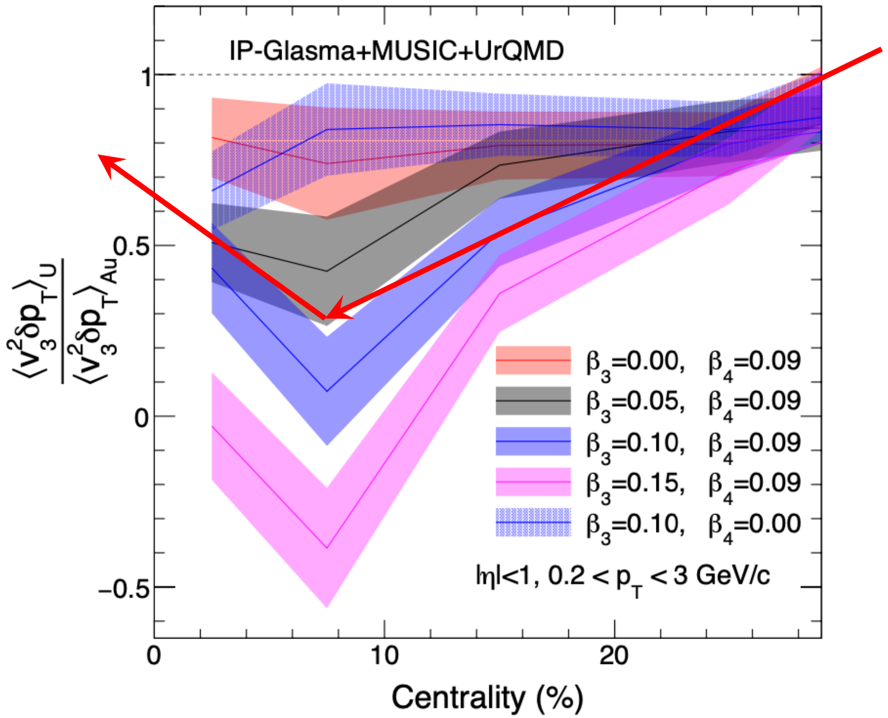
Evidence of octupole deformation $\beta_{3,\mathrm{U}}$

IP-Glasma+MUSIC calculations

C. Zhang, J. Jia, J. Chen, C. Shen, L. Liu, 2504.15245







$$R_{v_3^2} = \frac{\langle v_3^2\rangle_{\mathrm{U+U}}}{\langle v_3^2\rangle_{\mathrm{Au+Au}}} \approx \frac{a_{3\mathrm{U}}}{a_{3\mathrm{Au}}} + \frac{b_{3,3}}{a_{3\mathrm{Au}}}\beta_3^2 + \frac{b_{3,4}}{a_{3\mathrm{Au}}}\beta_4^2,$$

$$R_{v_3^2\delta p_T} = \frac{\langle v_3^2\delta p_{\mathrm{T}}\rangle_{\mathrm{U+U}}}{\langle v_3^2\delta p_{\mathrm{T}}\rangle_{\mathrm{Au+Au}}} \approx a - b\beta_2\beta_3^2.$$

However, v_3 is fluctuation driven, expect in central

$$\langle v_3^2\rangle \propto \langle \varepsilon_3^2\rangle \sim 1/A$$

mass number

$\langle v_3^2\rangle$ follows a linear increase with β_3^2,

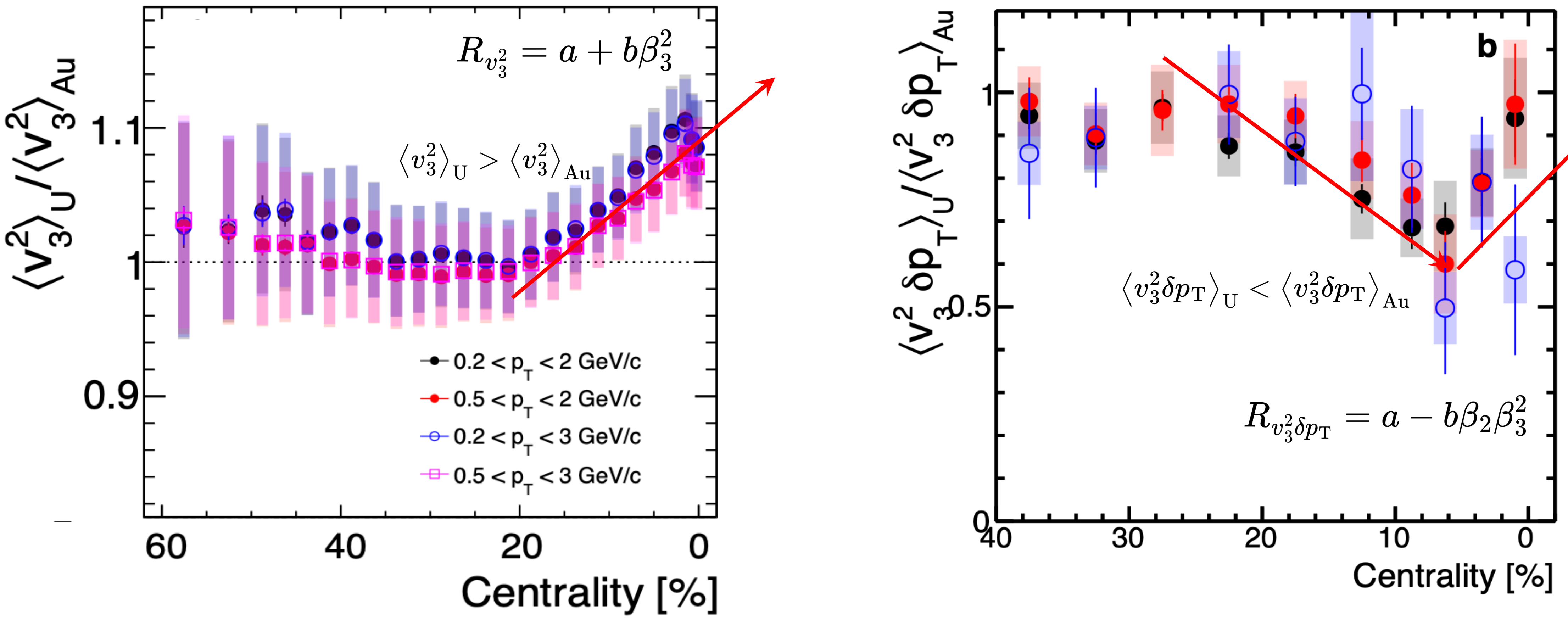
Characteristic anticorrelation in $\langle v_3^2 \delta p_{\mathrm{T}}\rangle$ shows a pronounced β_3-dependent suppression.

B. Alver and G. Roland, PRC 81, 054905 (2010)

Evidence of octupole deformation $\beta_{3,U}$

New

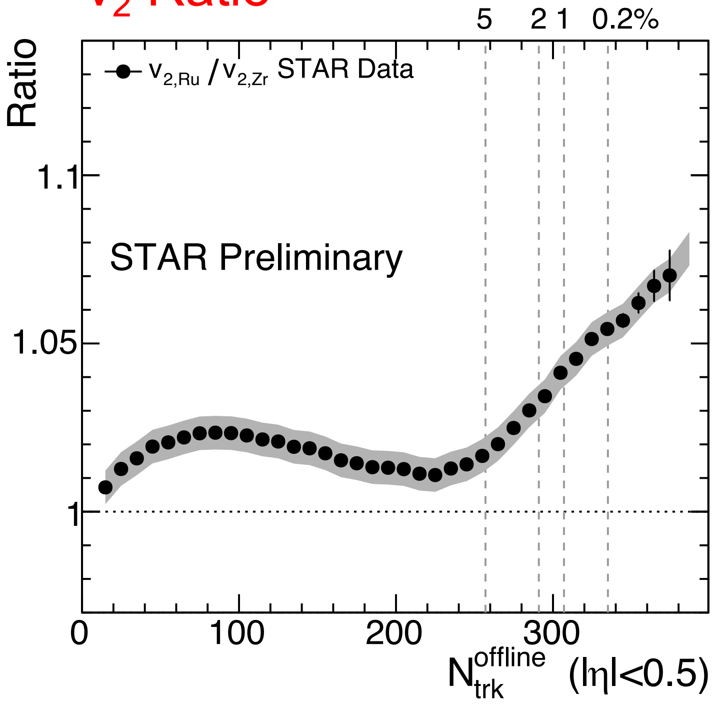
STAR, *Rep. Prog. Phys.* **88,** 108601 (2025)



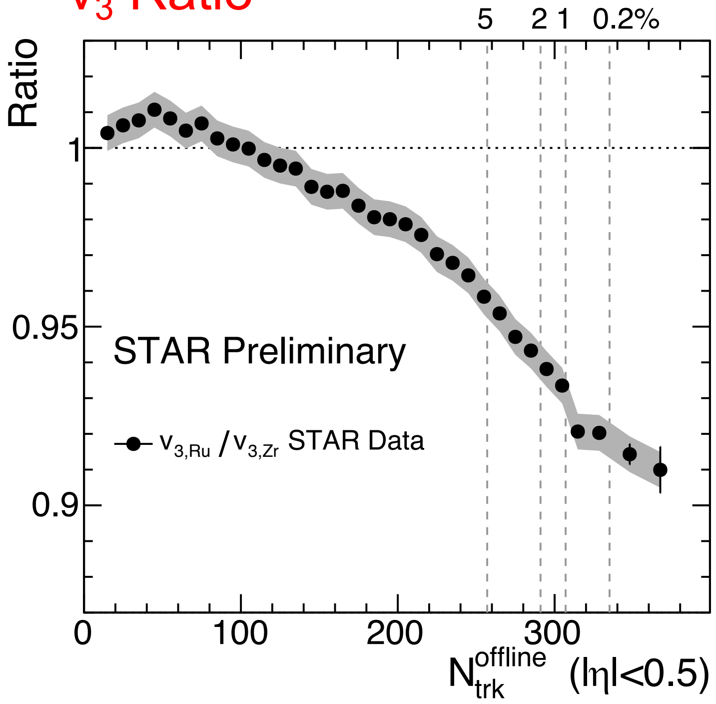
- No apparent p_T dependence
- Order of v_3 and v_3-p_T reversed by considering non-zero $\beta_{3,U}$, $\beta_{4,U}$.
- An evidence and modest $\beta_{3,U} \sim 0.08$-0.10 are confirmed and $\beta_{3U} \sim \beta_{4U}$

Nuclear structure via collectivity v_n ratio

v_2 Ratio



v_3 Ratio



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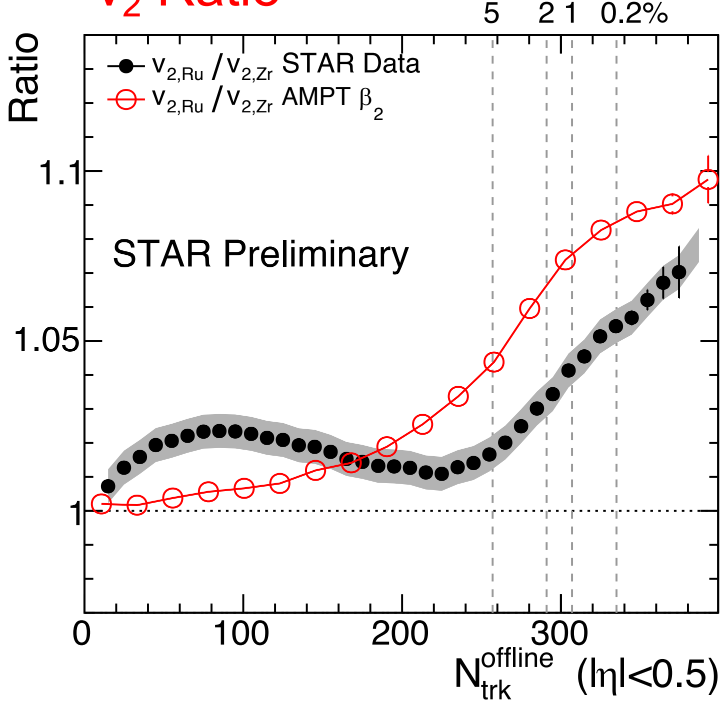
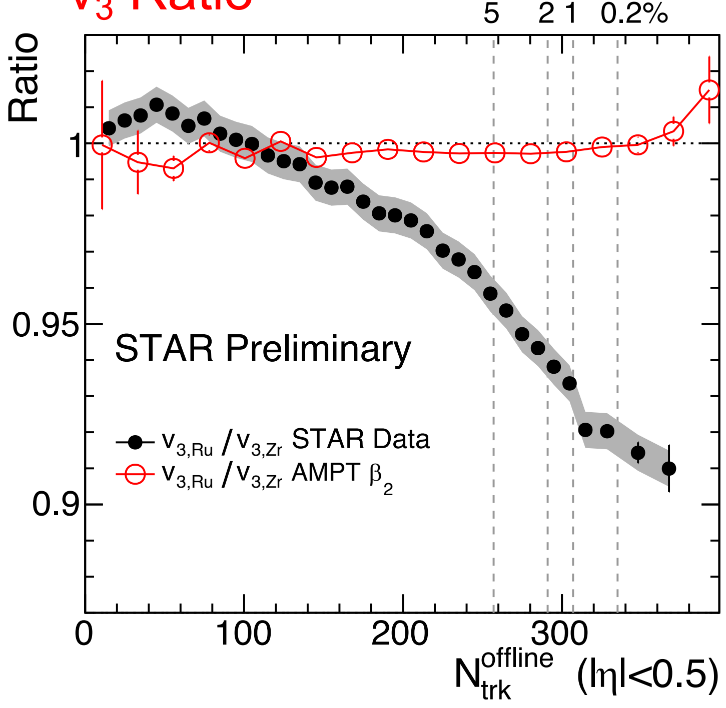
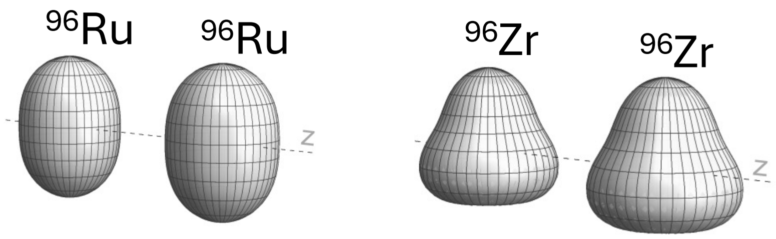


v_3 Ratio



$\beta_{2,Ru}$ ~ 0.16 increase v_2, no influence on v_3 ratio



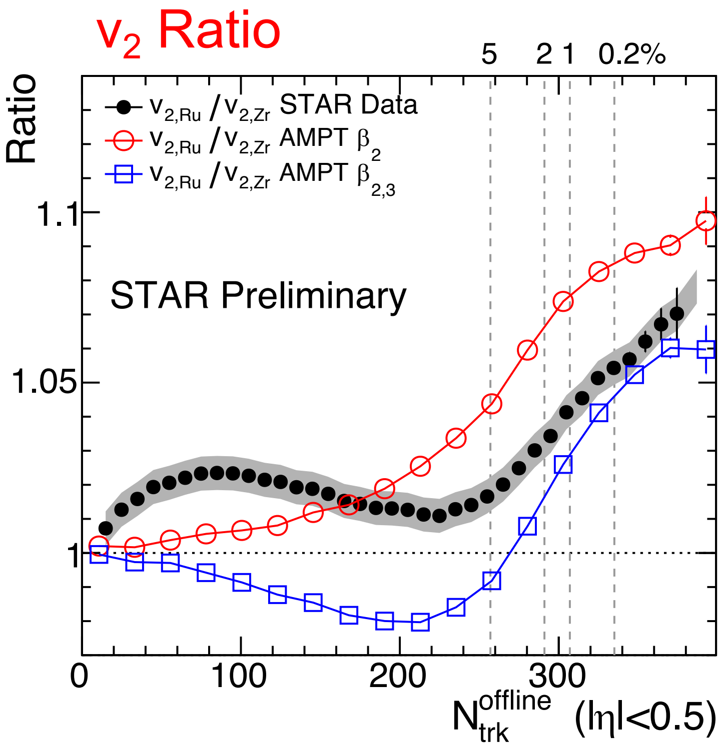
$$\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$$

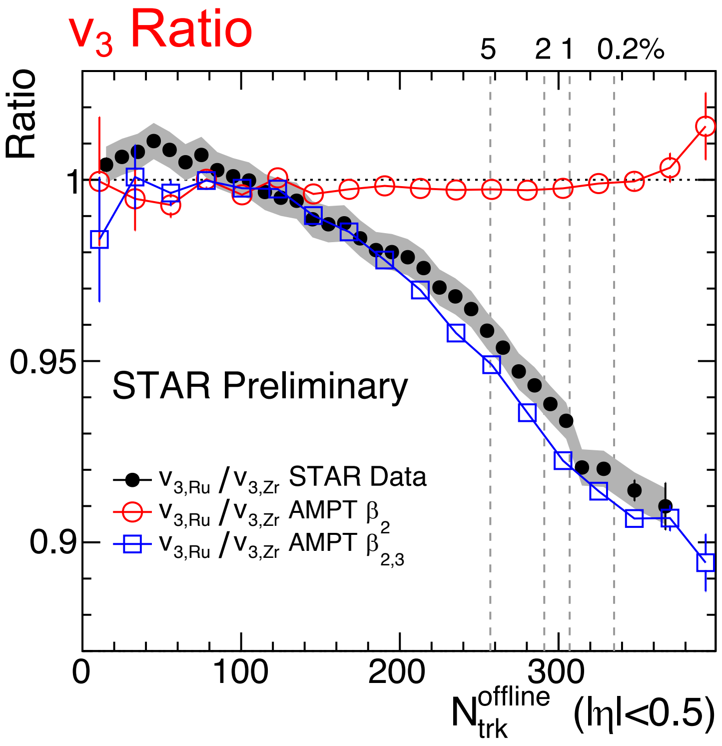
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, C. Zhang, PRC 107, L012901 (2023)

Nuclear structure via collectivity v_n ratio

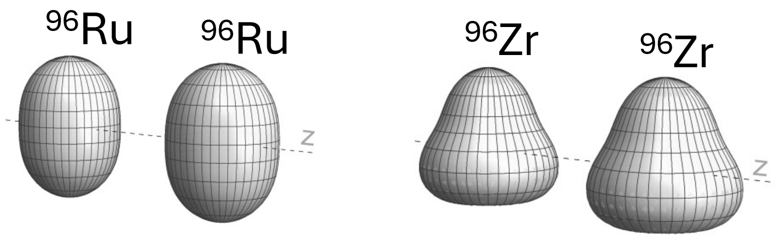




$\beta_{2,Ru} \sim 0.16$ increase v_2, no influence on v_3 ratio

$\beta_{3,Zr} \sim 0.2$ decrease v_2 in mid-central, decrease v_3 ratio

- Direct observation of octupole deformation in ^{96}Zr nucleus



$\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$

$\beta_{3,\mathrm{Zr}} = 0.20 \pm 0.02$

difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

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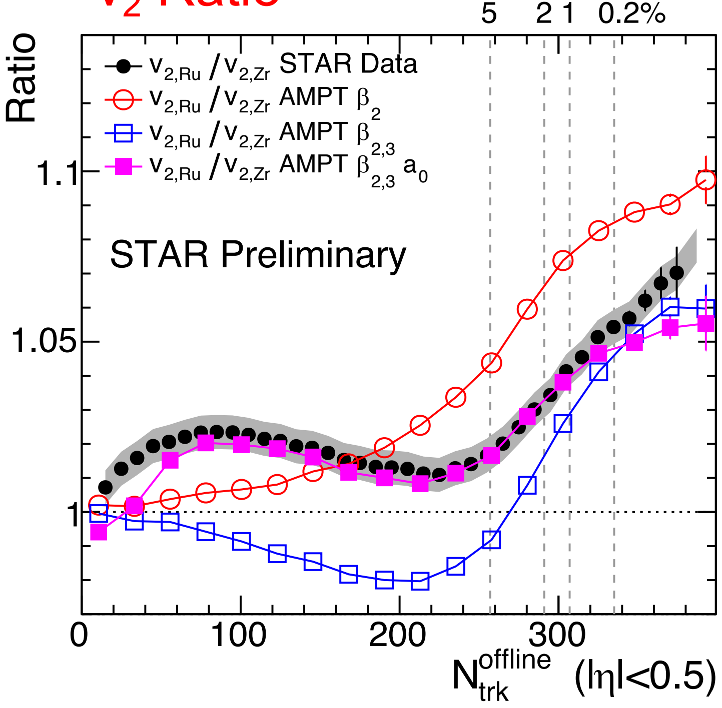
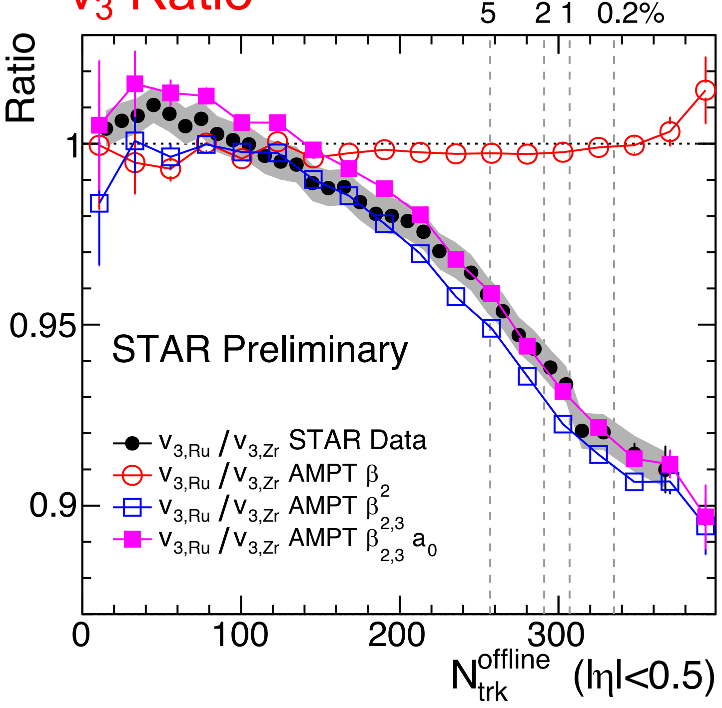
Nuclear structure via collectivity v_n ratio

v_2 Ratio



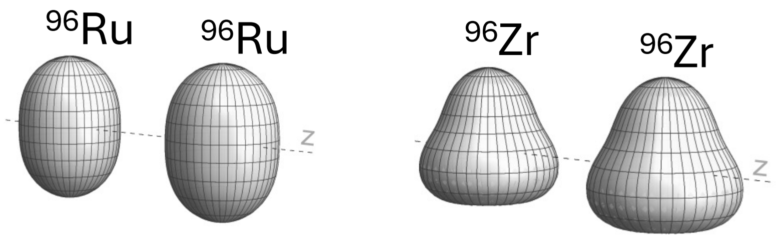
v_3 Ratio



$\beta_{2,Ru} \sim 0.16$ increase v_2, no influence on v_3 ratio

$\beta_{3,Zr} \sim 0.2$ decrease v_2 in mid-central, decrease v_3 ratio

$\Delta a_0 = -0.06$ fm increase v_2 mid-central, small impact on v_3



- Direct observation of octupole deformation in ^{96}Zr nucleus
- Imply the neutron skin difference between ^{96}Ru and ^{96}Zr

$\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$ $\beta_{3,\mathrm{Zr}} = 0.20 \pm 0.02$

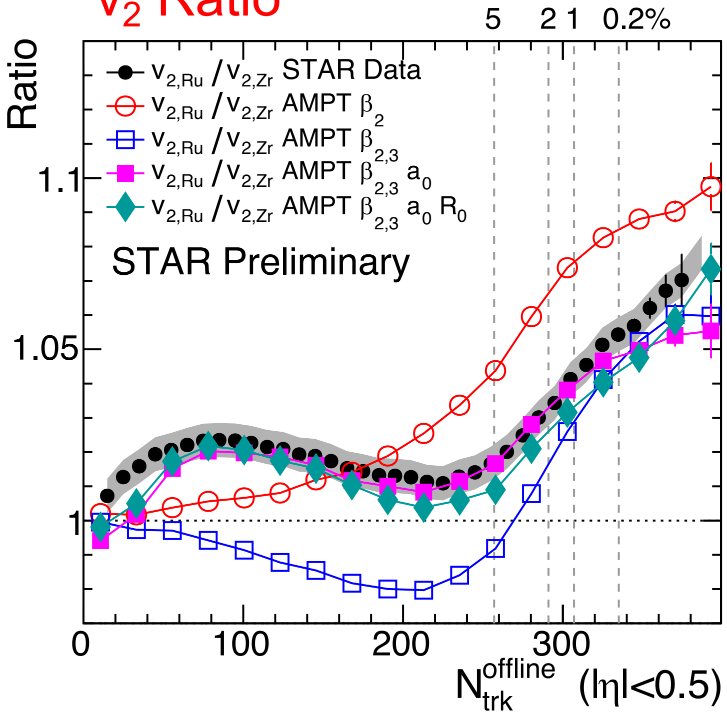
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

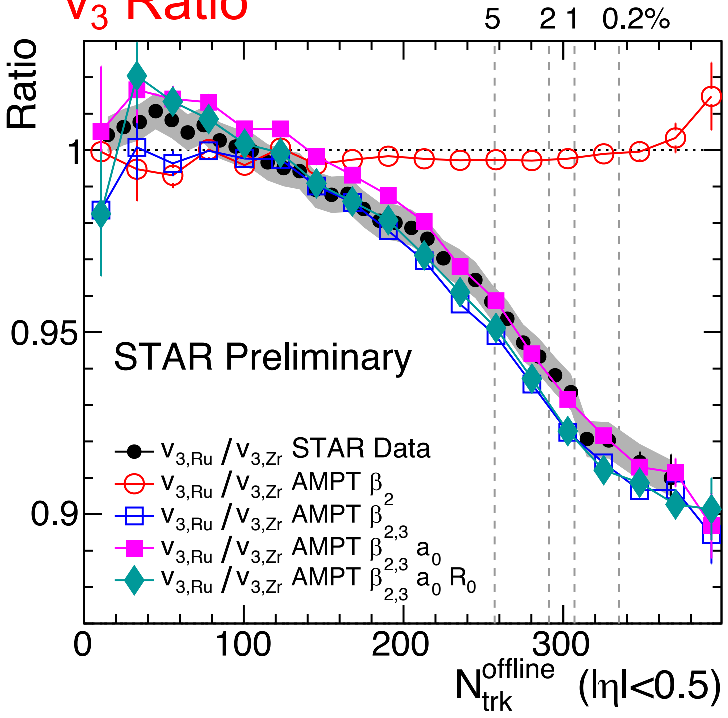
C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, C. Zhang, PRC 107, L012901 (2023)

Nuclear structure via collectivity v_n ratio

v_2 Ratio



v_3 Ratio

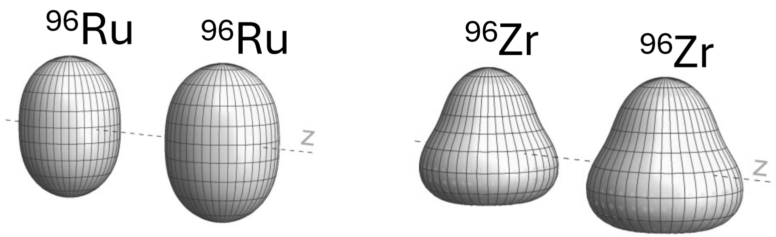


$\beta_{2,Ru} \sim 0.16$ increase v_2, no influence on v_3 ratio

$\beta_{3,Zr} \sim 0.2$ decrease v_2 in mid-central, decrease v_3 ratio

$\Delta a_0 = -0.06$ fm increase v_2 mid-central, small impact on v_3

Radius $\Delta R_0 = 0.07$ fm only slightly affects v_2 and v_3 ratio.



- Direct observation of octupole deformation in ^{96}Zr nucleus
- Imply the neutron skin difference between ^{96}Ru and ^{96}Zr
- Simultaneously constrain parameters using Bayesian analysis

$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\text{Ru}}}{\mathcal{O}_{\text{Zr}}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$$

$\beta_{2,\text{Ru}} = 0.16 \pm 0.02$ $\quad$ $\beta_{3,\text{Zr}} = 0.20 \pm 0.02$

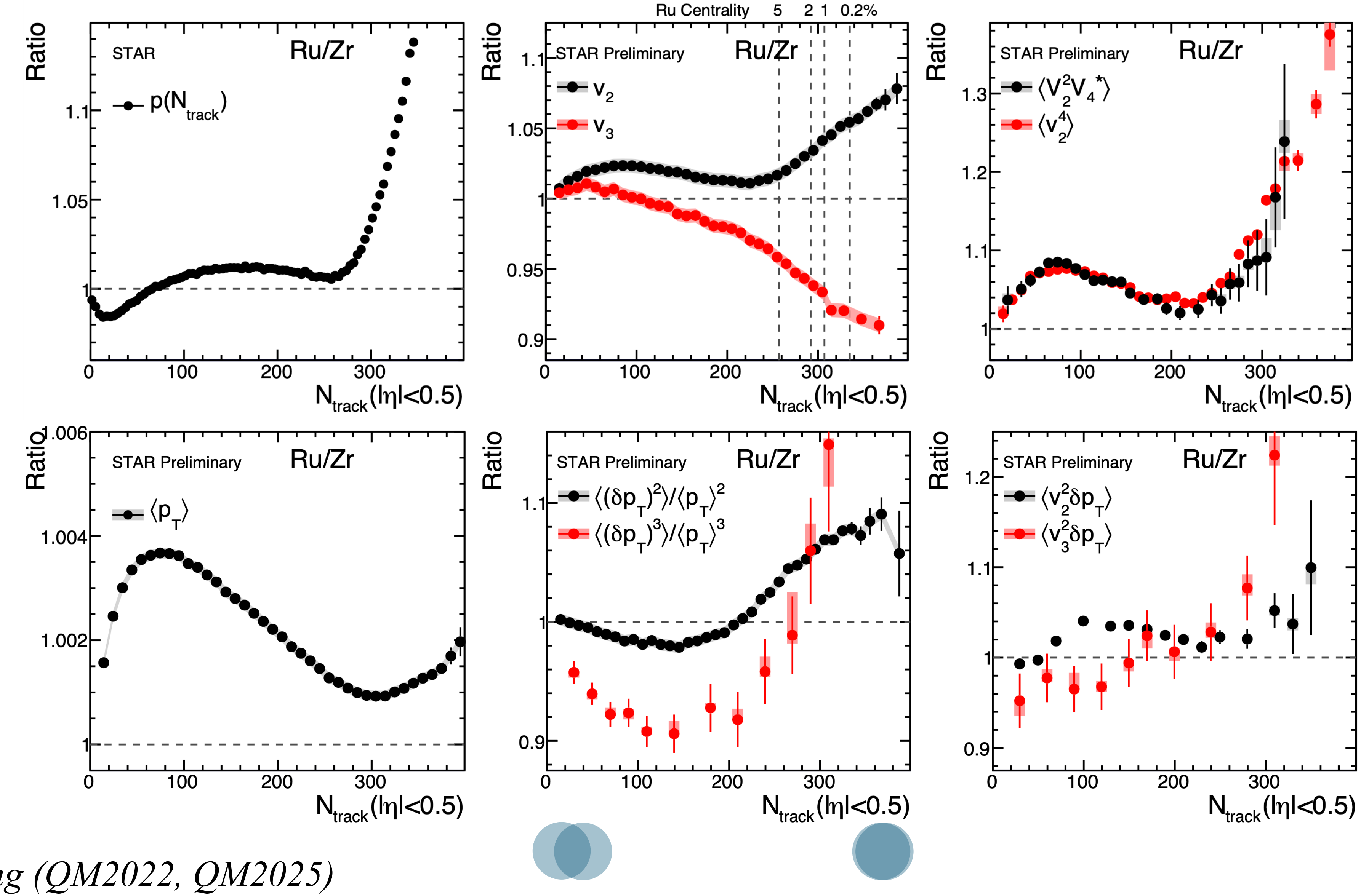
	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
difference	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

C. Zhang and J. Jia, *PRL128, 022301(2022)*; J. Jia, C. Zhang, *PRC 107, L012901 (2023)*

Nuclear structure is inherent of heavy-ion probes

One-body distribution *Two-body correlations* *Three-body correlations*



Chunjian Zhang (QM2022, QM2025)

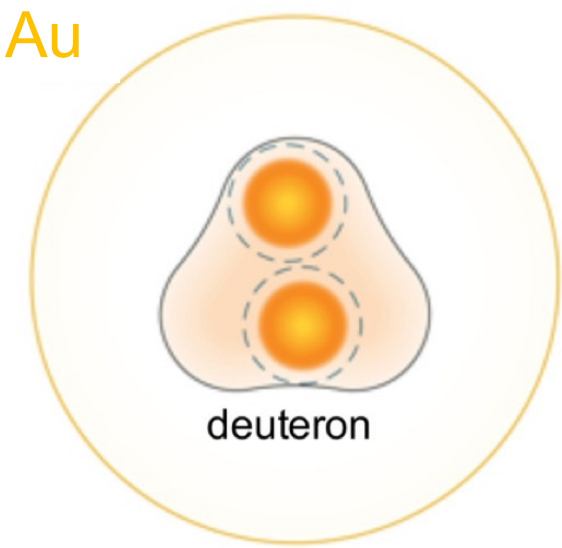
III. Nucleonic cluster pattern in light ^{16}O nucleus

--- from one-body distribution to many-body nucleon correlations

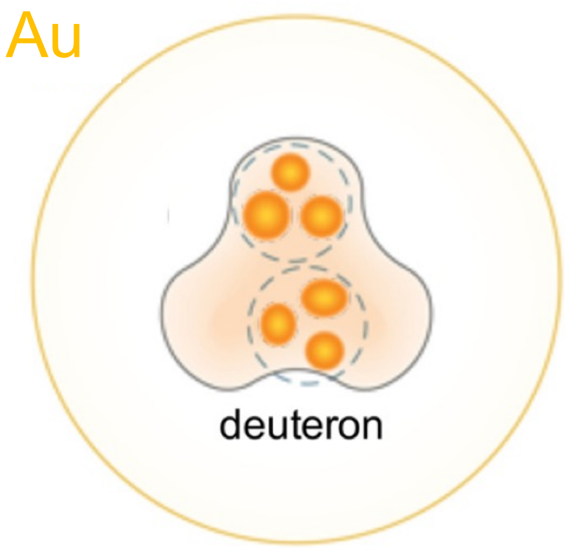
$$\rho(r) \propto \frac{1 + w\left(r^2/R^2\right)}{1 + e^{(r-R)/a_0}}$$ → Modern *ab* initio first-principle calculations

Light nuclear geometry and nucleon-nucleon correlations

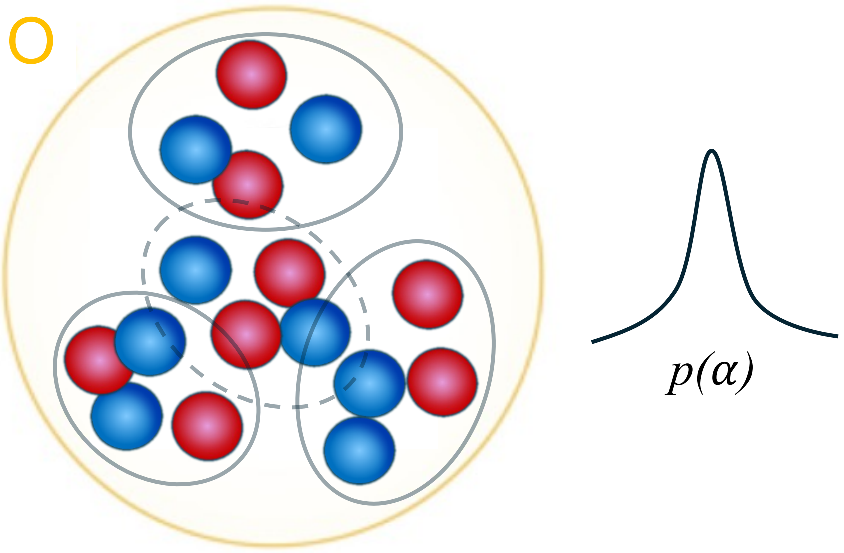
Nucleon fluctuation



subnucleon fluctuation



NN correlation (cluster pattern)



ab initio calculations

STAR, PRL 130, 242301 (2023)

STAR, PRC 110, 064902 (2024)

W. He, Y.-G. Ma et al., PRL 113, 032506 (2014)

Y.-G. Ma, S. Zhang, Handbook of Nuclear Physics (2022)

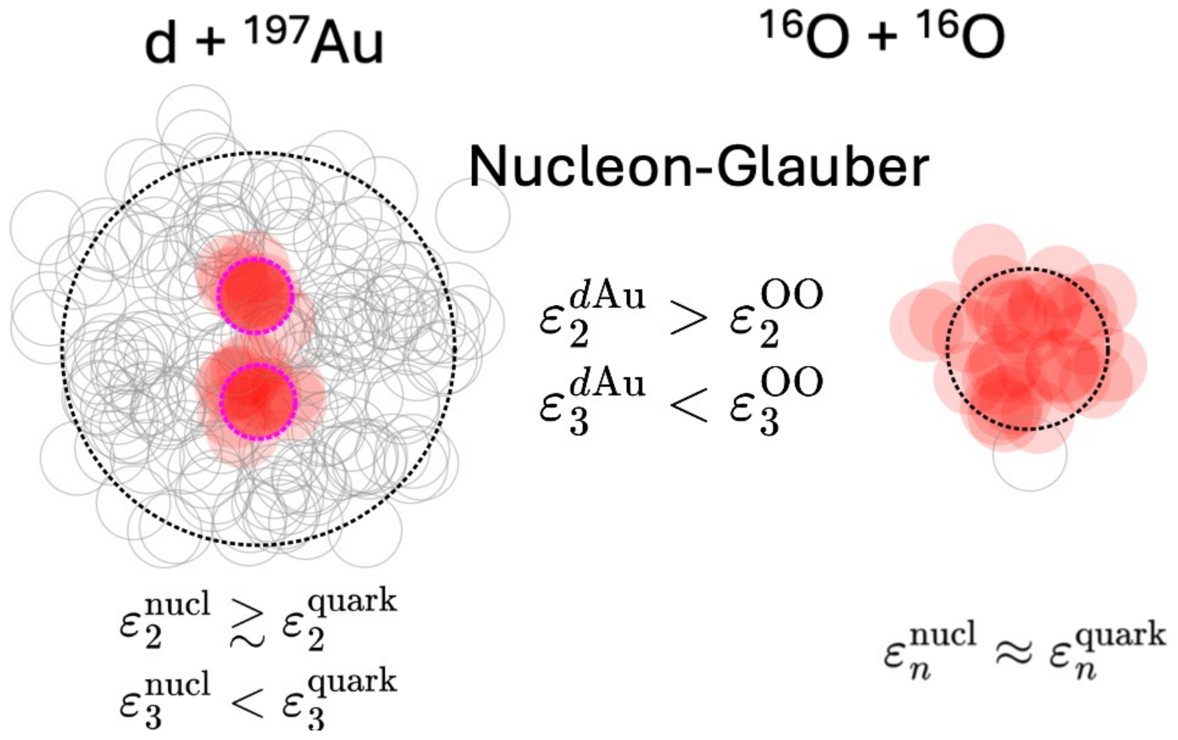
C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, PLB 862, 139322 (2025)

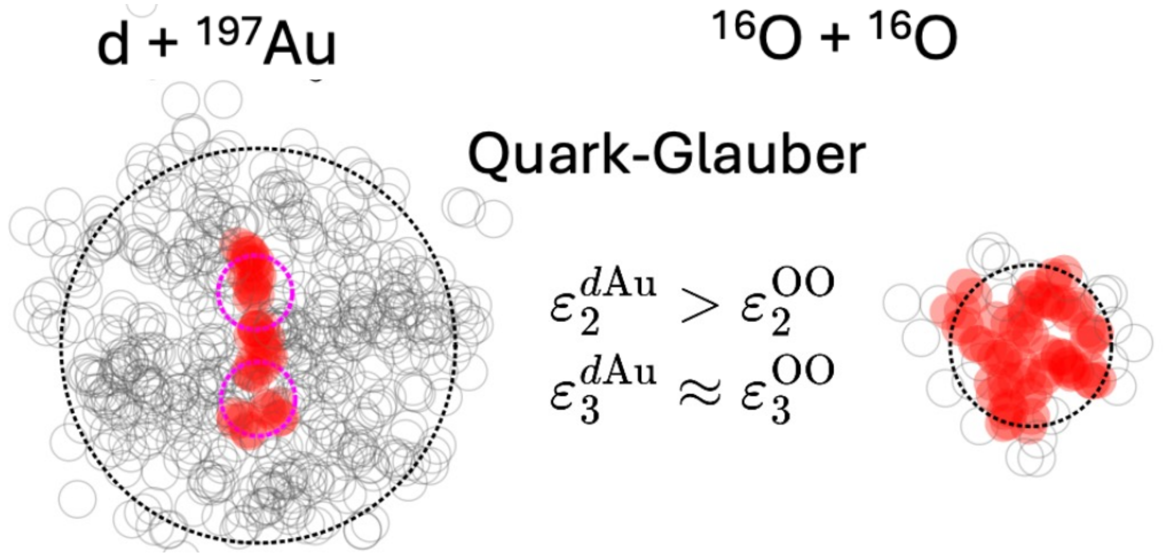
S. Huang, J. Jia, C. Zhang, PLB 870, 139926 (2025)

d+Au collision, 200 GeV ⟷ Nearly same N_{ch} ⟷ O+O collision, 200 GeV

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645*



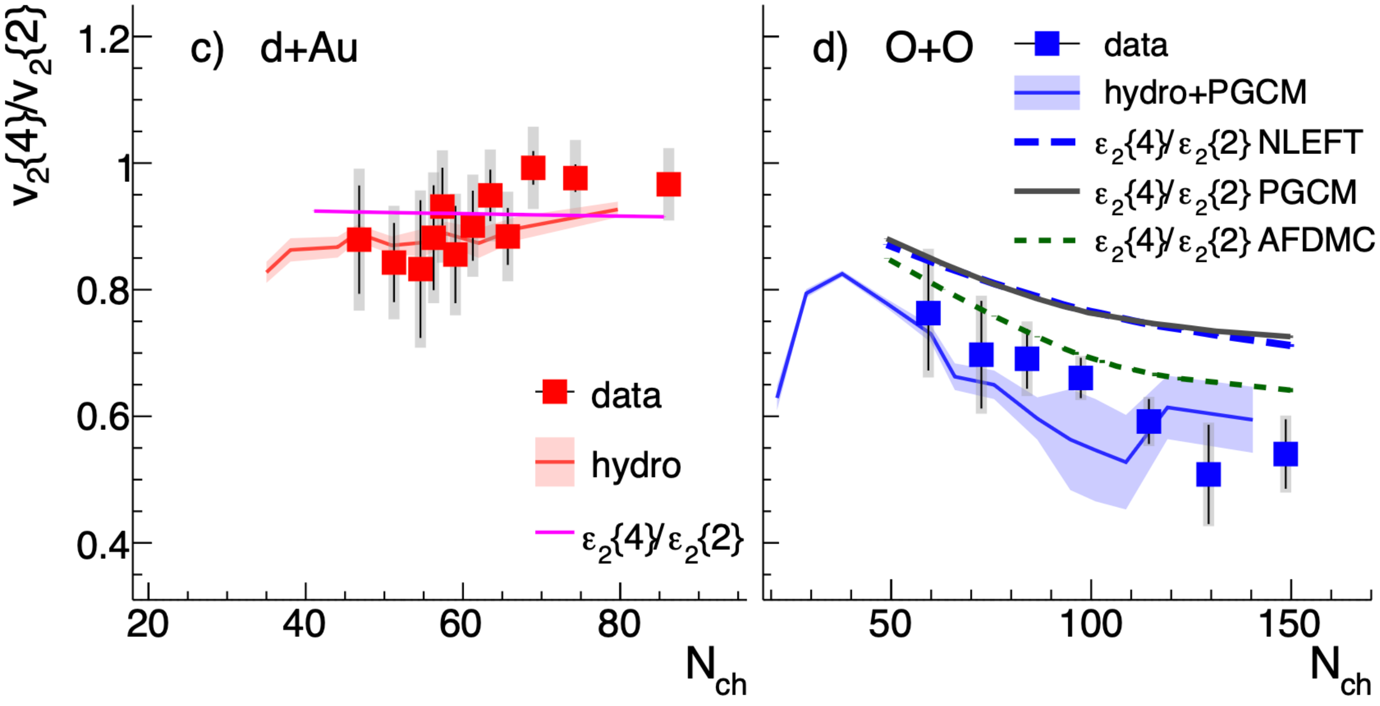


Nucleon-Glauber and quark-Glauber yield different triangular v_3

Benchmarking geometric tomography of ^{16}O nucleus

New

STAR, *2510.19645*



$\varepsilon_2\{4\}\,/\varepsilon_2\{2\}$ from three models:
AFDMC vs. EFT/PGCM have a visible difference.

Can many-nucleon correlations significantly impact the eccentricity fluctuations? YES!

C. Zhang et al., *PLB 862, 139322 (2025)*

The interplay between sub-nucleon fluctuation and many-nucleon correlation.

STAR, *PRL 130, 242301 (2023)*

S. Huang, J. Jia, C. Zhang, *PLB 870, 139926 (2025)*

$$(v_n\{2\})^2 = c_n\{2\} = \langle v_n^2 \rangle \qquad \varepsilon_2\{2\}^2 = \langle \varepsilon_2^2 \rangle$$

$$(v_n\{4\})^4 = -c_n\{4\} = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle \qquad \varepsilon_2\{4\}^4 = 2\langle \varepsilon_2^2 \rangle^2 - \langle \varepsilon_2^4 \rangle$$

Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022);* W. He, Y.-G. Ma et al, *PRL 113, 032506 (2014)*
G. Giacalone, G. Nijs et al., PRL135, 012302 (2025), G. Giacalone, W. Zhao et al., *PRL134, 082301 (2025);* P. Li, B. Zhou, G.-L. Ma, *2504.04688*
Y. Wang, S. Zhao, B. Cao, H. Xu, H. Song, *PRC 109, L051904 (2024);* X. Zhao, G.-L. Ma. Y. Zhou, Z. Lin, C. Zhang, *2404.09780*; S. Jahan, Roch, C. Shen, *2507. 11394*

Benchmarking geometric tomography of ^{16}O nucleus

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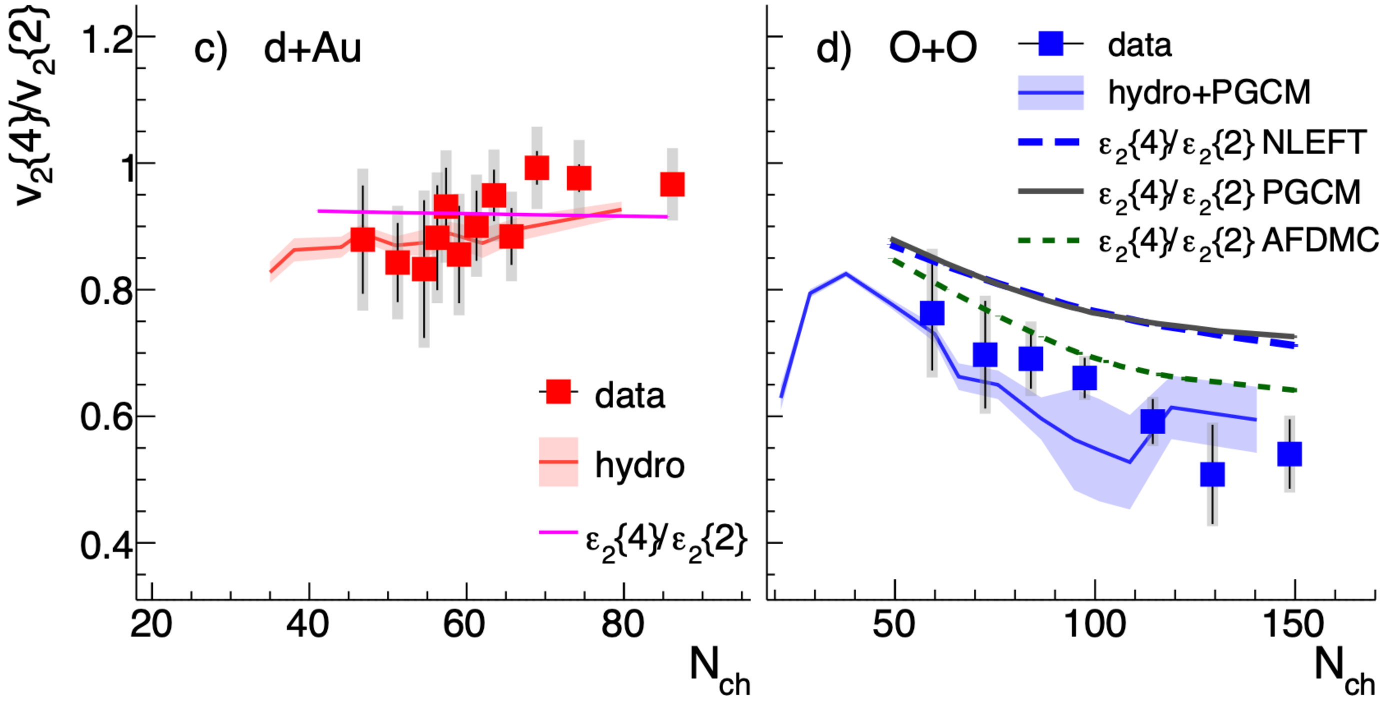
STAR, *2510.19645*



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STAR, *PRL 130, 242301 (2023)*

S. Huang, J. Jia, C. Zhang, *PLB 870, 139926 (2025)*

Geometric scan elucidates nuclear tomography and strong nuclear force?

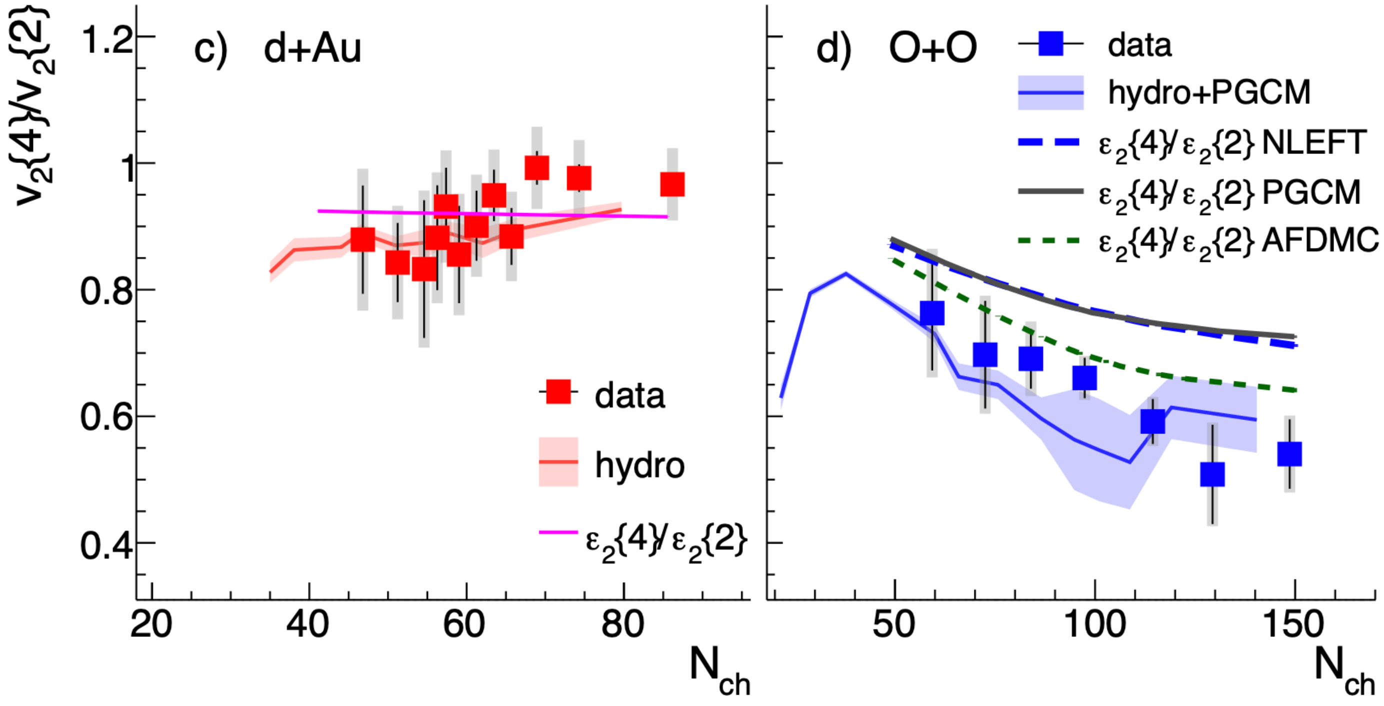
more low-energy model inputs & revisit

Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022);* W. He, Y.-G. Ma et al, *PRL 113, 032506 (2014)*
G. Giacalone, G. Nijs et al., PRL135, 012302 (2025), G. Giacalone, W. Zhao et al., *PRL134, 082301 (2025);* P. Li, B. Zhou, G.-L. Ma, *2504.04688*
Y. Wang, S. Zhao, B. Cao, H. Xu, H. Song, *PRC 109, L051904 (2024);* X. Zhao, G.-L. Ma. Y. Zhou, Z. Lin, C. Zhang, *2404.09780*; S. Jahan, Roch, C. Shen, *2507. 11394*

Benchmarking geometric tomography of ^{16}O nucleus

New

STAR, *2510.19645*



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$$(v_n\{4\})^4 = -c_n\{4\} = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle \qquad \varepsilon_2\{4\}^4 = 2\langle \varepsilon_2^2 \rangle^2 - \langle \varepsilon_2^4 \rangle$$

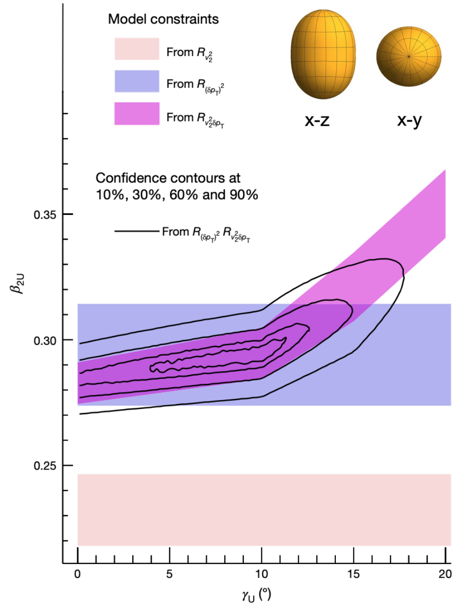
LHC (ALICE, ATLAS, CMS, LHCb) also released the O+O/Ne+Ne.
Shape imaging method for light ions (New avenue)

Y.-G. Ma, S. Zhang, Handbook of Nuclear Physics (2022); W. He, Y.-G. Ma et al, PRL 113, 032506 (2014)
G. Giacalone, G. Nijs et al., PRL135, 012302 (2025), G. Giacalone, W. Zhao et al., *PRL134, 082301 (2025);* P. Li, B. Zhou, G.-L. Ma, *2504.04688*
Y. Wang, S. Zhao, B. Cao, H. Xu, H. Song, *PRC 109, L051904 (2024);* X. Zhao, G.-L. Ma. Y. Zhou, Z. Lin, C. Zhang, *2404.09780*; S. Jahan, Roch, C. Shen, *2507. 11394*

IV. Conclusions and Outlooks

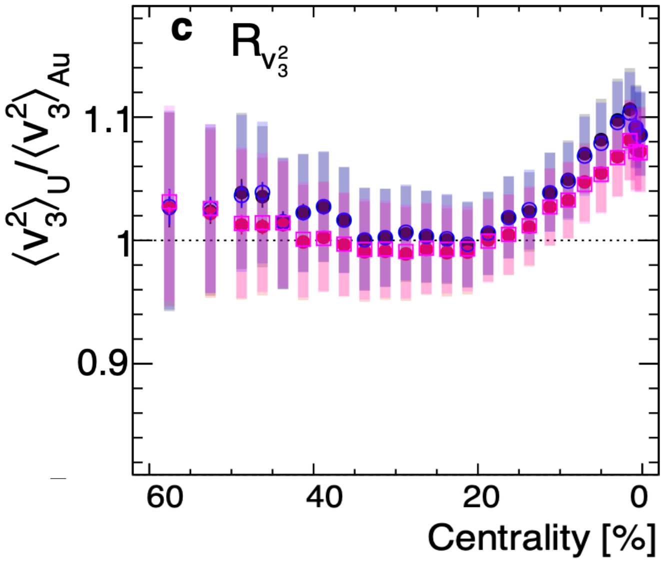
1. The signatures of nuclear structure in nuclear collisions are ubiquitous:

STAR, Nature 635, 67-72 (2024)



$\beta_{2U} = 0.286 \pm 0.025$; $\gamma_U = 8.5^\circ \pm 4.8^\circ$

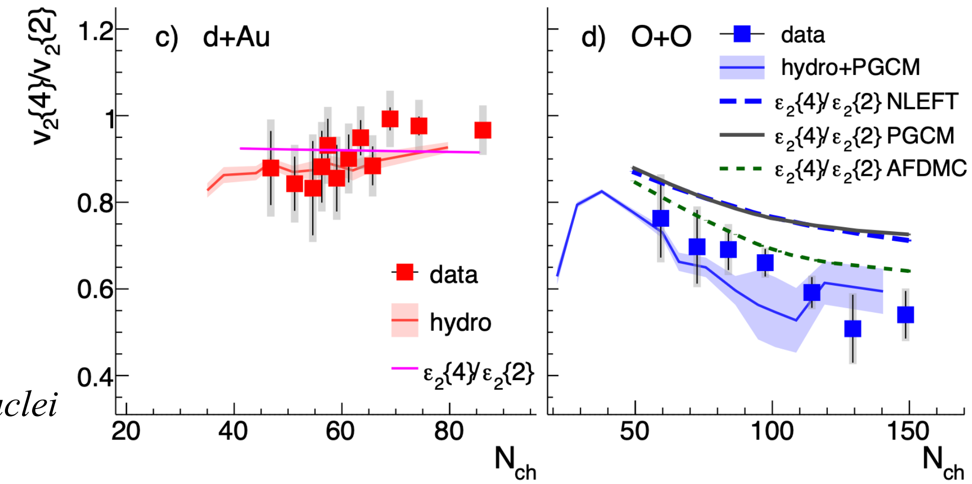
STAR, Rep. Prog. Phys. **88,** 108601 (2025)



$\beta_{3U} = 0.08 - 0.1$; $\beta_{3U} \sim \beta_{4U}$

from ***large*** *to* ***small*** *nuclei*

STAR, *2510.19645*

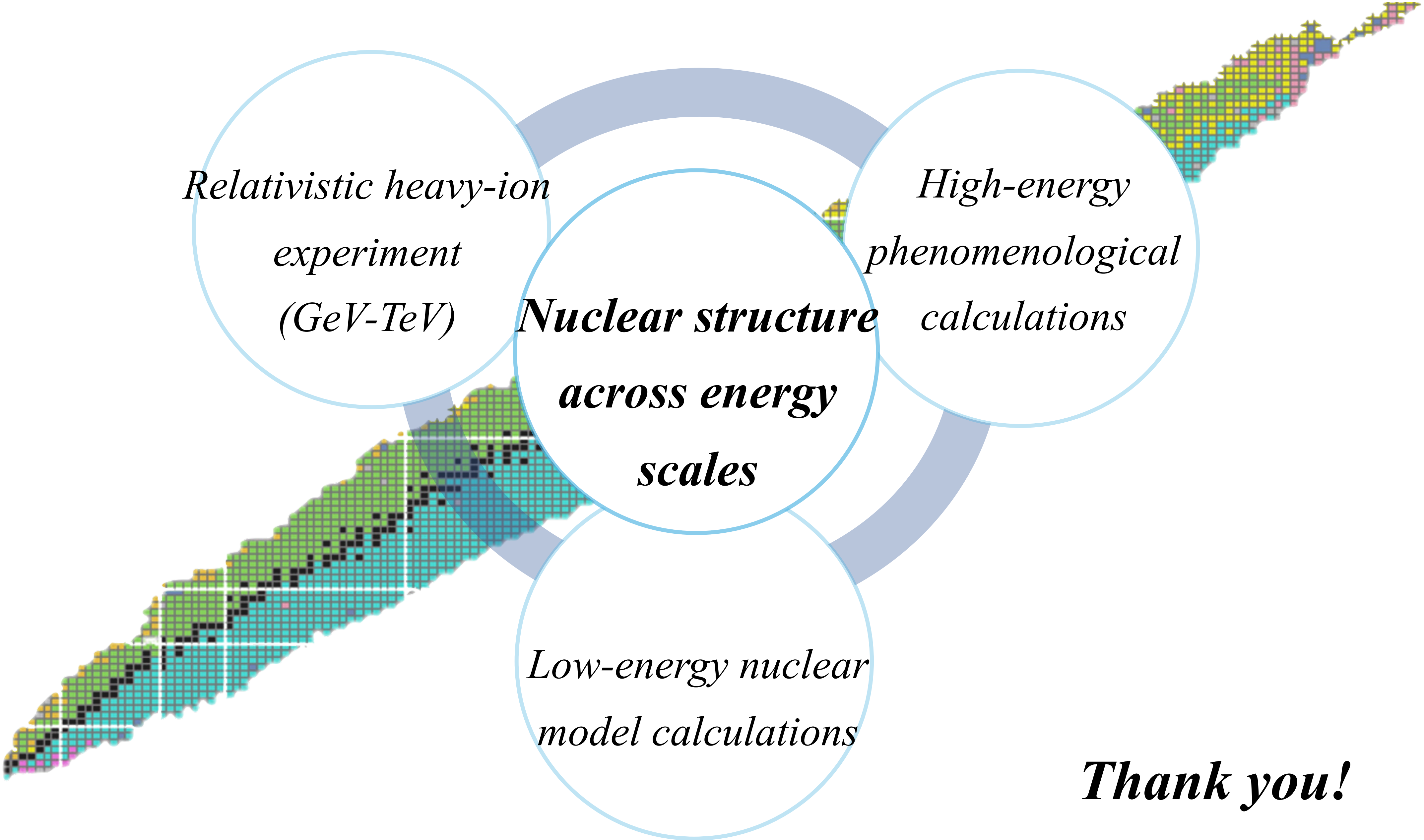


NN correlations is remarkable

2. Many potential applications from large to small collision systems :

- → Rigid and soft β_n and γ (shape fluctuations/coexistence)
- → Neutron skin & symmetry energy constraints
- → Energy evolution between GeV/TeV and MeV in even-and odd-A nuclei
- → Confronted with ab initio calculations and more light-ion studies
- → Intersection with other research: Nucleosynthesis, nuclear fission, $0\nu\beta\beta$

IV. Conclusions and Outlooks



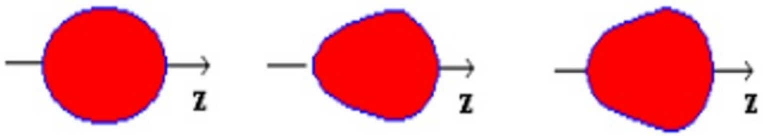
Thank you!

Probe $\beta_{3,\mathrm{U}}$ and its fluctuation

Octupole collectivity

L. Liu, C. Zhang, J. Chen, J. Jia, X. Huang, Y.-G. Ma, 2509.09376

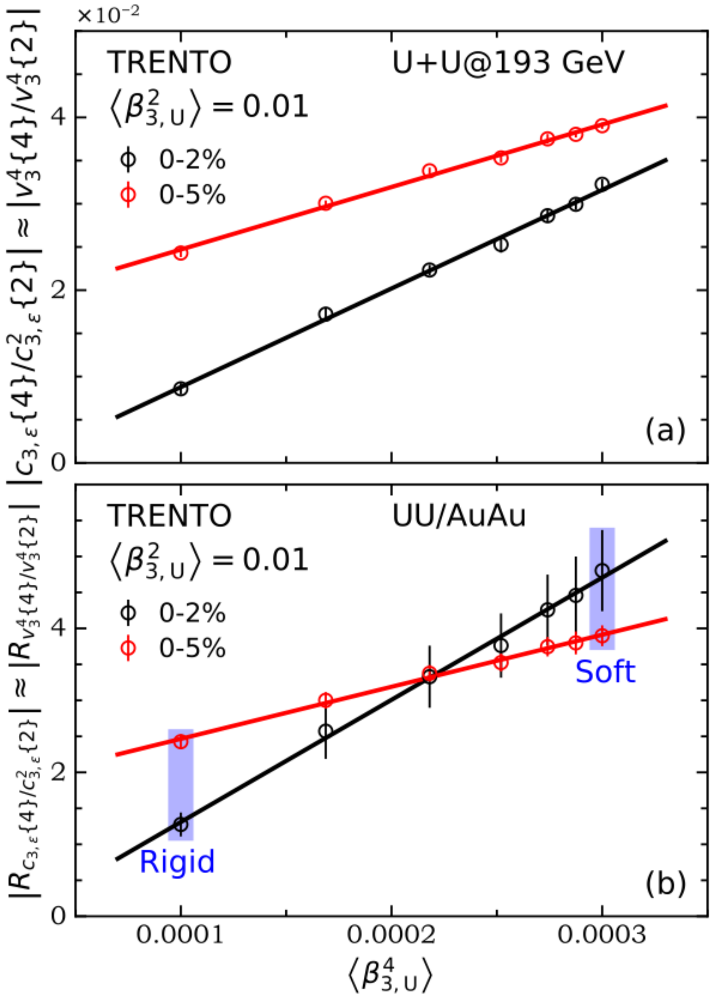
soft octupole | rigid deformation



$$\langle\beta_3^2\rangle = \bar{\beta}_3^2 + \sigma_{\beta_3}^2$$

$$c_{n,\varepsilon}\{2\} = \langle\varepsilon_n^2\rangle \approx \langle\varepsilon_{n,0}^2\rangle + \langle p_n p_n^*\rangle \langle\beta_n^2\rangle$$

$$c_{n,\varepsilon}\{4\} = \langle\varepsilon_n^4\rangle - 2\langle\varepsilon_n^2\rangle^2$$
$$\approx \langle\varepsilon_{n,0}^4\rangle - 2\langle\varepsilon_{n,0}^2\rangle^2 + \langle p_n^2 p_n^{2*}\rangle \langle\beta_n^4\rangle - 2\langle p_n p_n^*\rangle^2 \langle\beta_n^2\rangle^2$$



Four-particle correlation is linearly scaled to $\langle\beta_{3,\mathrm{U}}^4\rangle$.

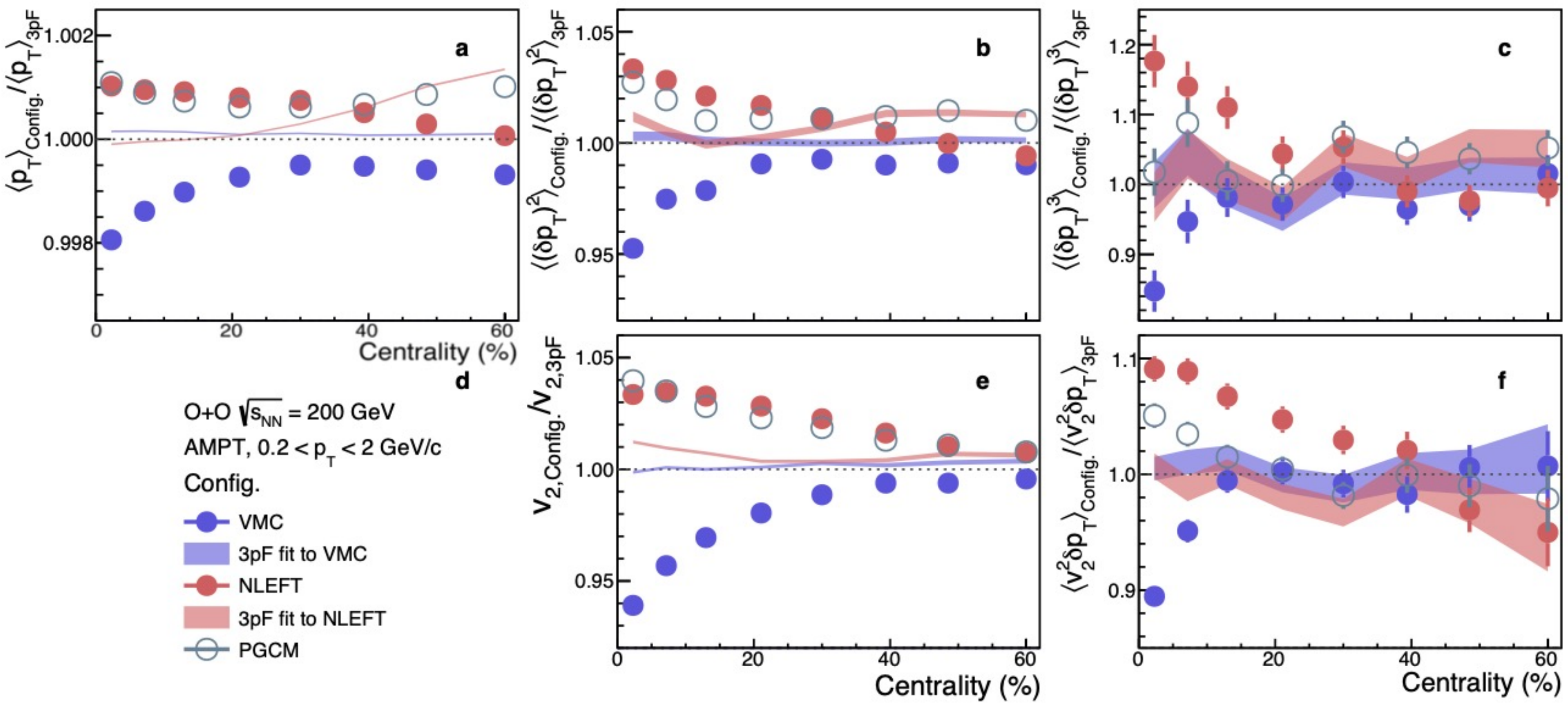
A way to discriminate between static and dynamic collective modes in high-energy nuclear collisions

B. G. Zakharov, *JETP Lett. 112, 393 (2020);* P. Carzon et al., *PRC 102, 054905 (2020);* H. Xu *et al.*, *PRC112, L051901 (2025);* K. Hagino and M. Kitazawa, *2508.05125*

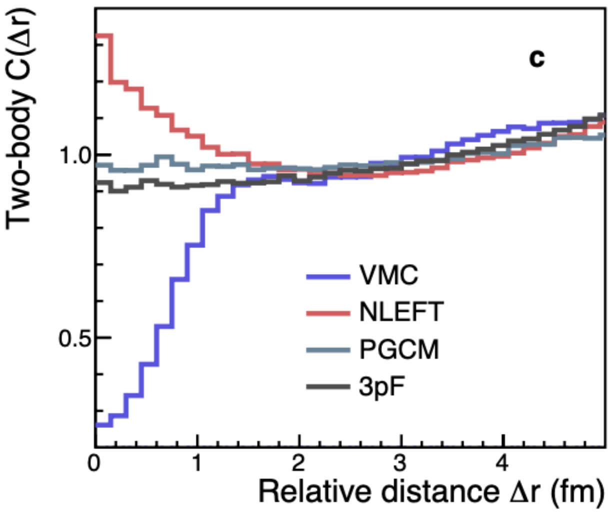
Ab-initio nucleon-nucleon correlations and their impact on high-energy

C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*

Multiple final-state observables



Two-body correlations in coordinate space



$$C(\Delta r) = \frac{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}, \mathbf{s}-\frac{\mathbf{r}}{2}\right)}{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}\right) f\left(\mathbf{s}-\frac{\mathbf{r}}{2}\right)}$$

- 3pF as the baseline can NOT capture the NN correlations.
- Distinct differences are observed between VMC and NLEFT/PGCM.
- Central collision is prominent.

Data analysis is ongoing and will be presented in sQM.