跨能量尺度原子核结构实验研究新进展及展望

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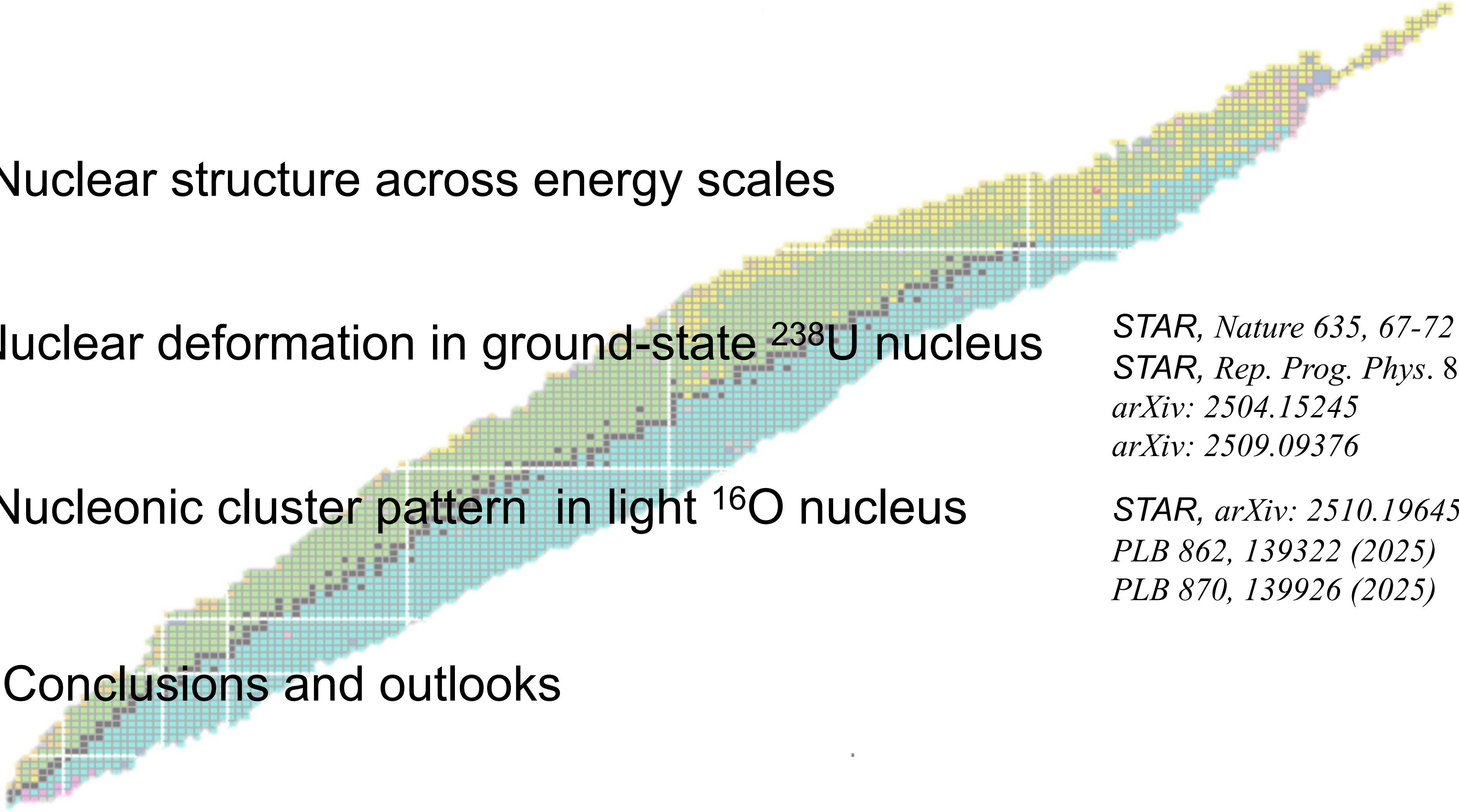
复旦大学

2025年11月24日，华南师范大学， 广州

Outline



I. Nuclear structure across energy scales

II. Nuclear deformation in ground-state ^{238}U nucleus

STAR, Nature 635, 67-72 (2024)
STAR, Rep. Prog. Phys. 88, 108601 (2025)
arXiv: 2504.15245
arXiv: 2509.09376

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

STAR, arXiv: 2510.19645
PLB 862, 139322 (2025)
PLB 870, 139926 (2025)

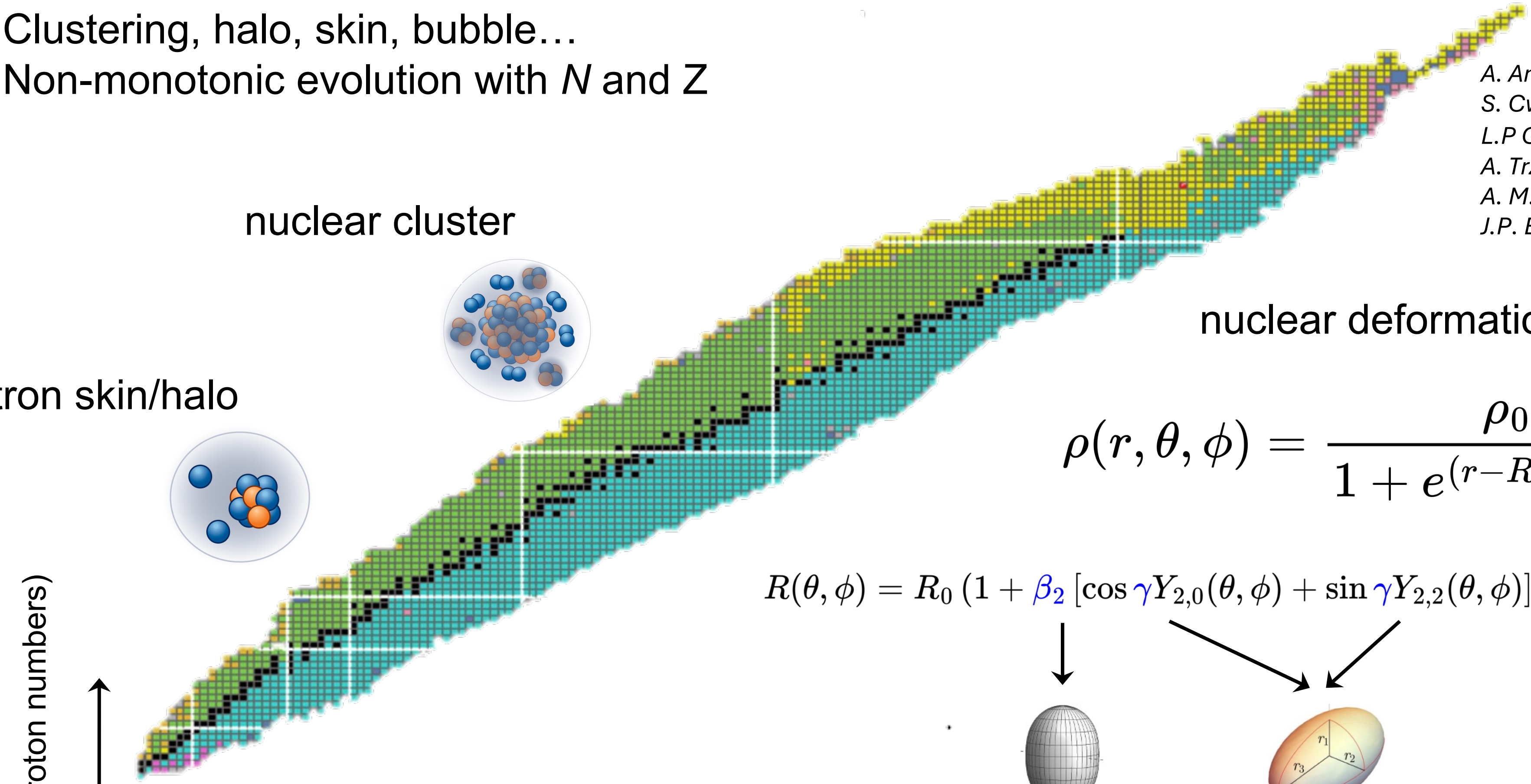
IV. Conclusions and outlooks

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

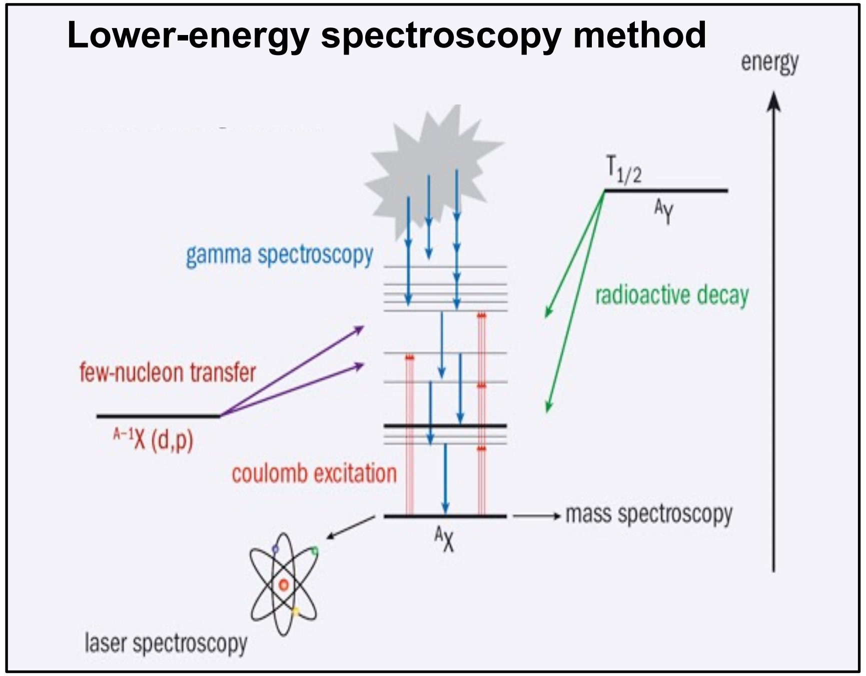
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

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

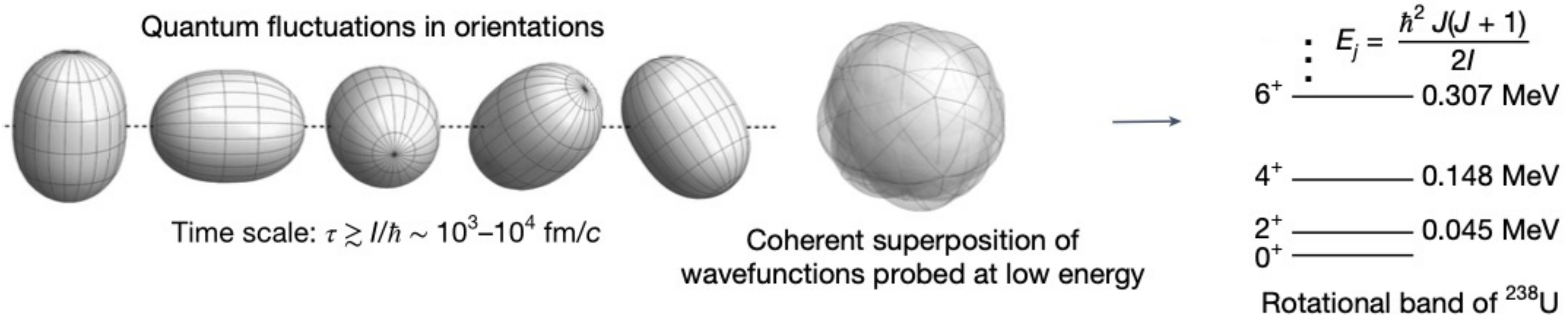


Traditional imaging method taken before destruction

→ 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.



W. Ke, *2509.09549*

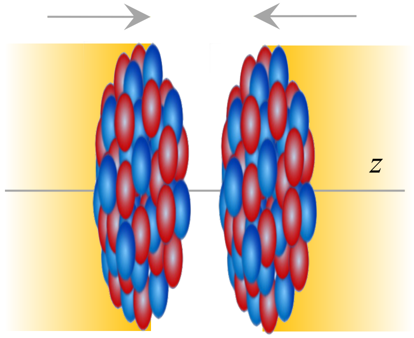
Imaging by smashing method

Take a snapshot

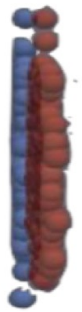
Evolution

Measurement

Nuclei collisions



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



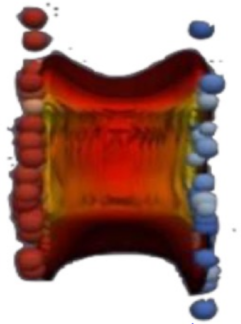
$\tau \sim 2R_0/\Gamma \sim 0.1\mathrm{fm}/c$

exposure

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

Pressure-driven expansion of

Quark-gluon plasma (QGP)

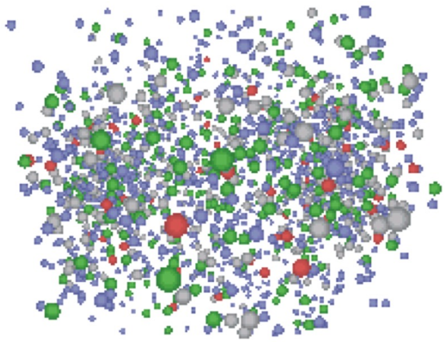


$\tau \sim 10\mathrm{fm}/c$

expansion

free-streaming

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



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

detection

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

$\beta_2 \longrightarrow$ quadrupole deformation

$\beta_3 \longrightarrow$ octupole deformation

$\gamma \longrightarrow$ triaxiality

$a_0 \longrightarrow$ surface diffuseness

$R_0 \longrightarrow$ nuclear size

ab initio theory/shell model/DFT

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

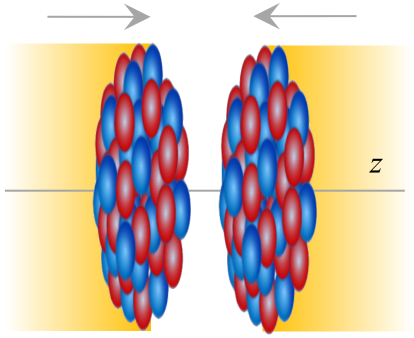
Imaging by smashing method

Take a snapshot

Evolution

Measurement

Nuclei collisions



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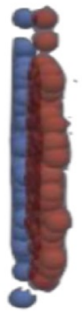

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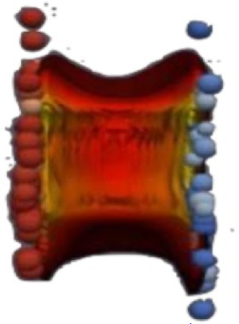
$\partial_\mu T^{\mu\nu}=0$, EOS, viscosity…

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



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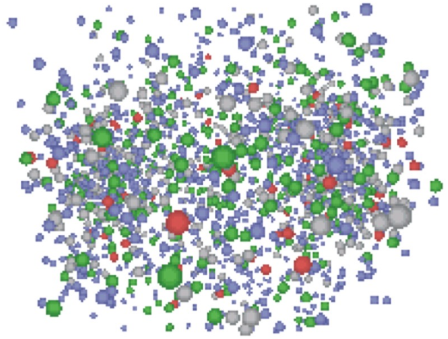

$\tau \sim 10^{15}\mathrm{fm}/c$
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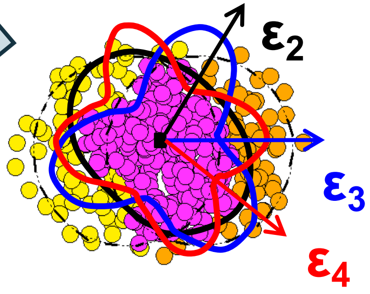


size & shape

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 $\quad$ β_n

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

Event-by-event linear responses:

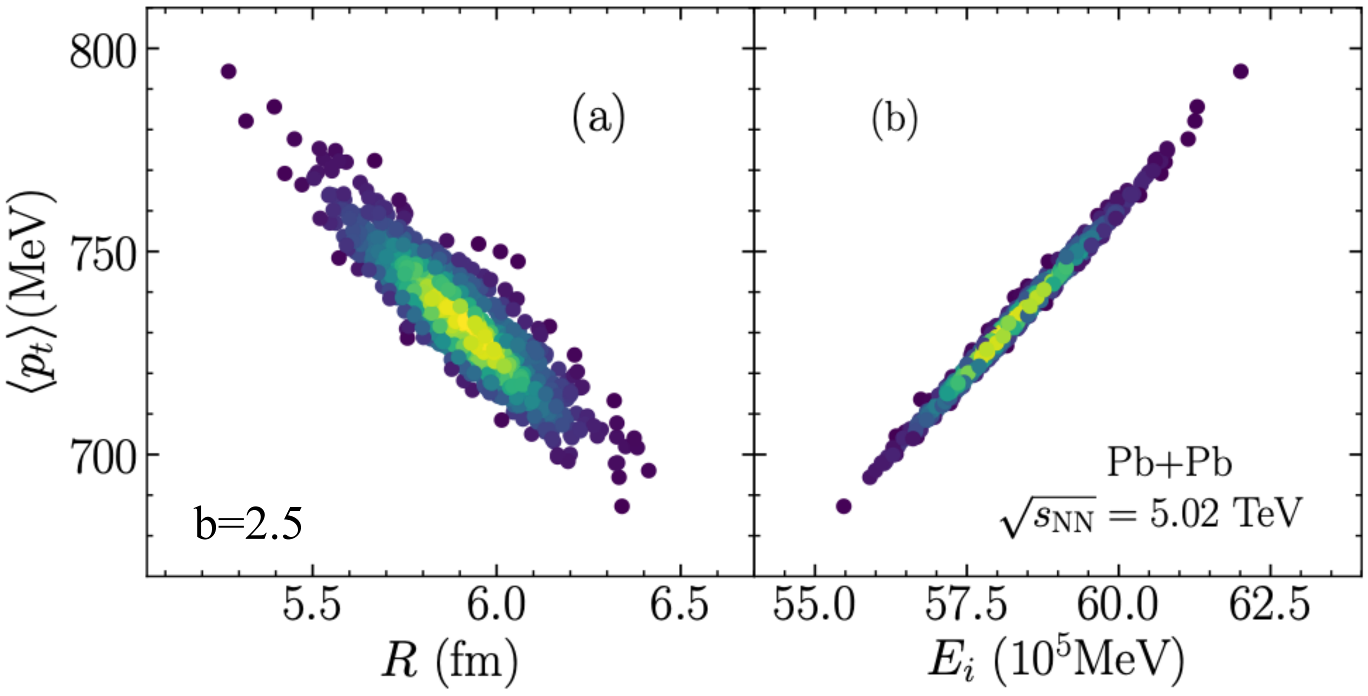
$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

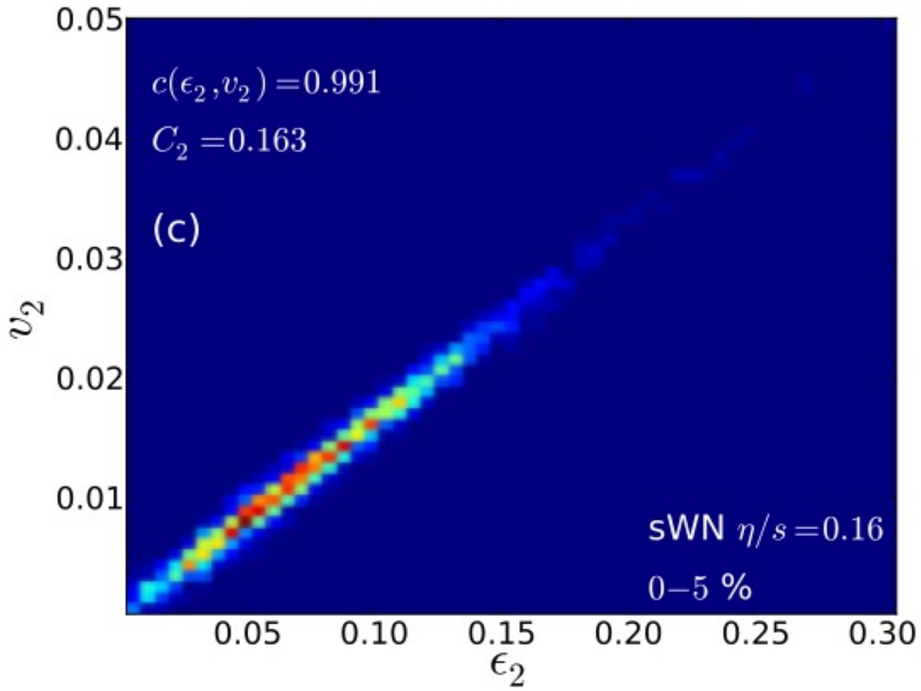
Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

Linear response in ultra-central collisions

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

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



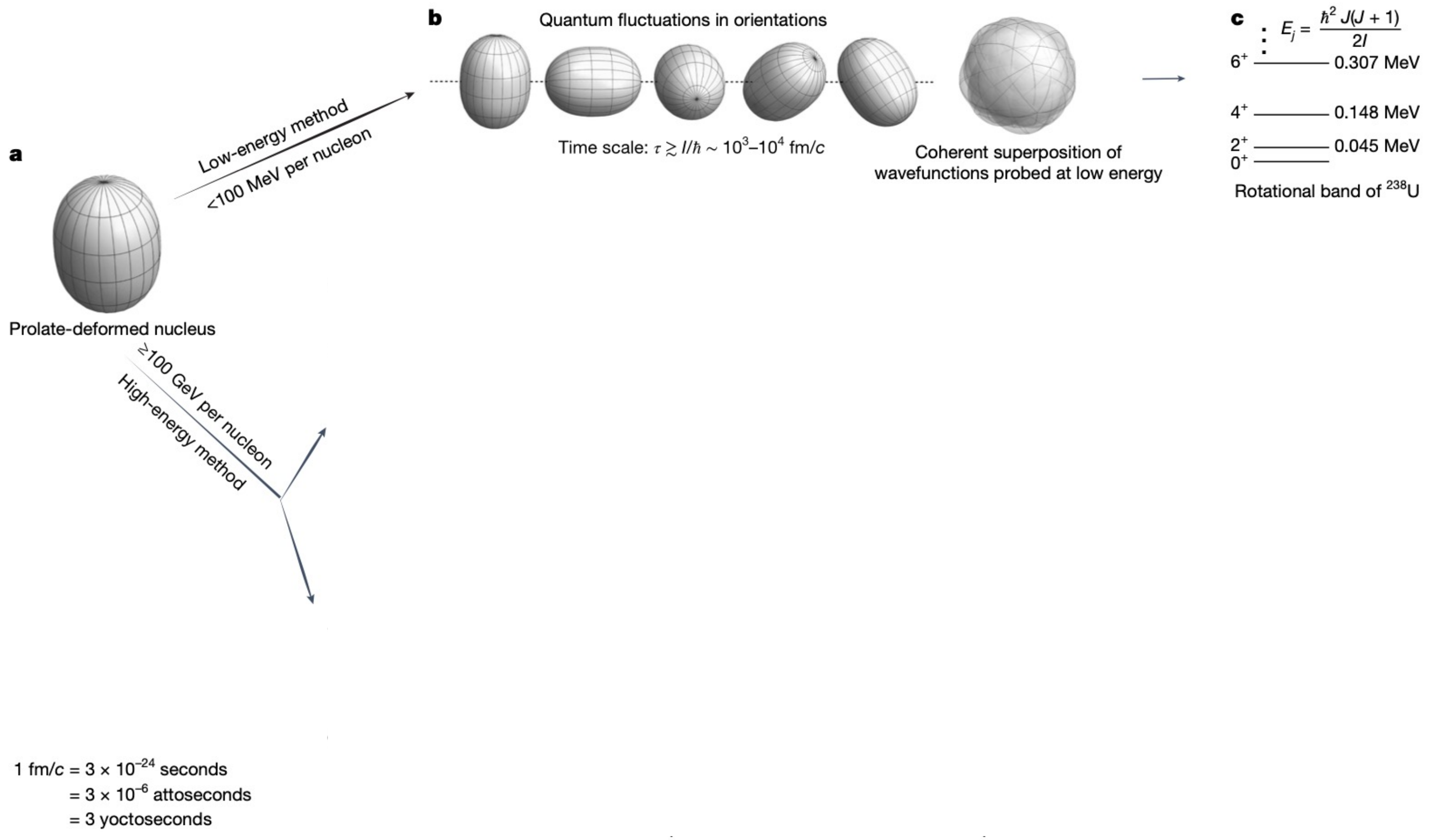


G. Giacalone, F. Gardim, J. Hostler, J. Ollitrault, et al, PRC 103, 024909 (2021)

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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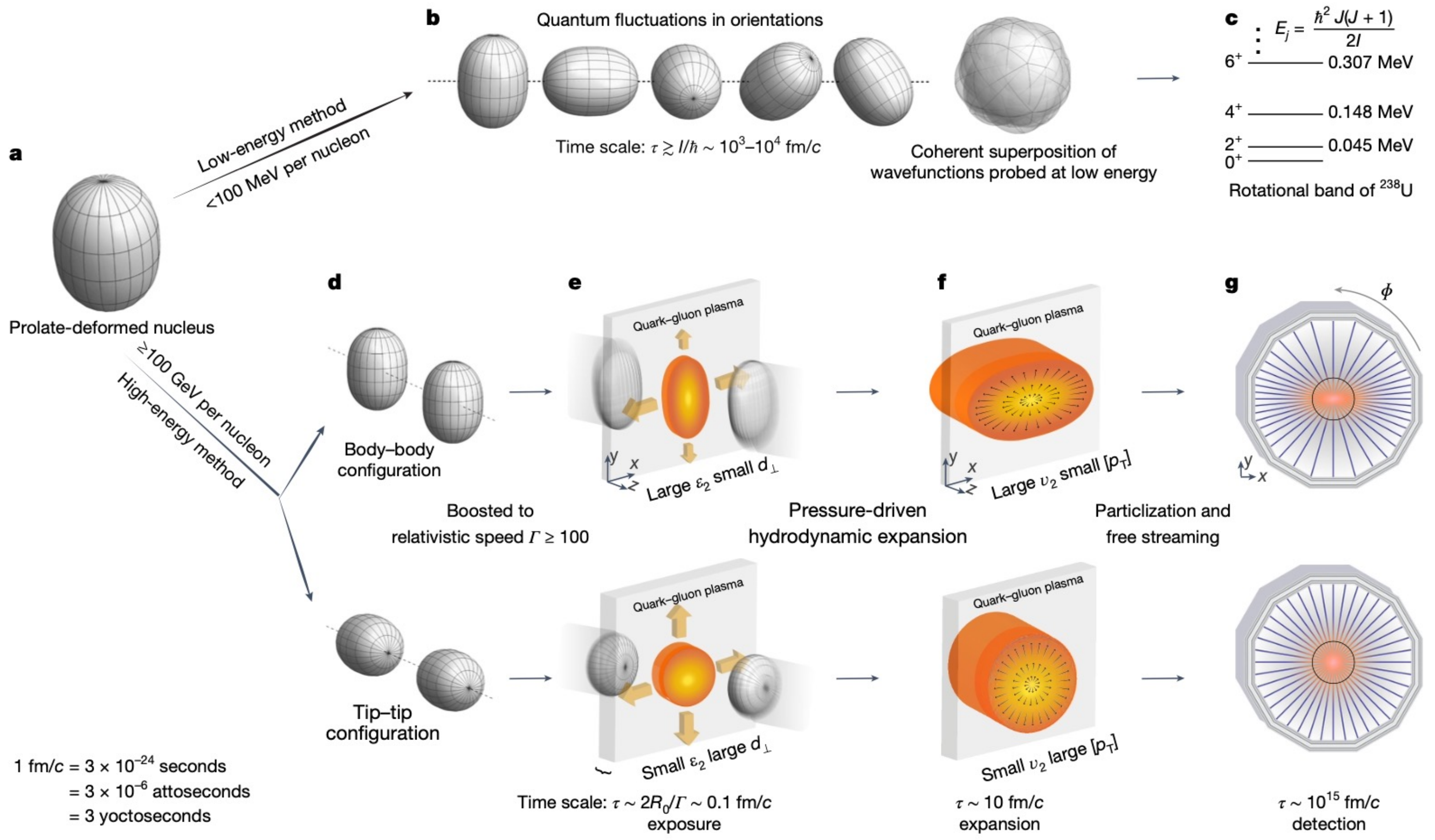


STAR, *Nature 635, 67-72 (2024)*

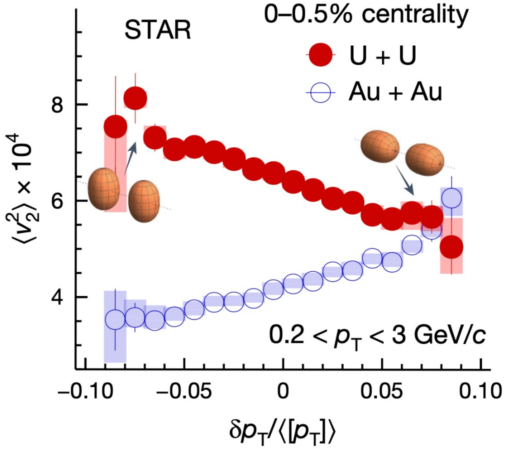
https://www.nature.com/articles/s41586-024-08097-2

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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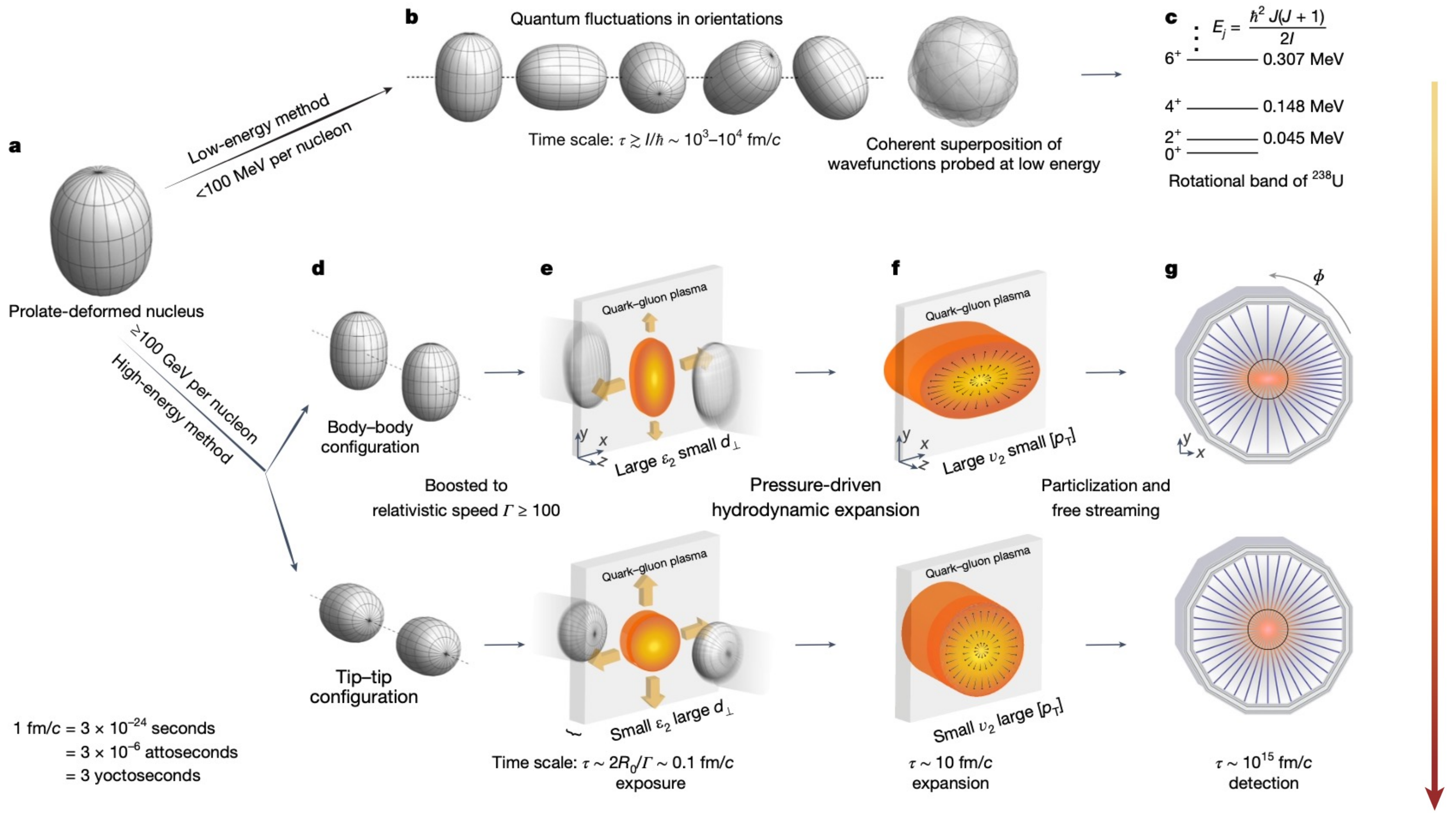


STAR, Nature 635, 67-72 (2024)
https://www.nature.com/articles/s41586-024-08097-2

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)*

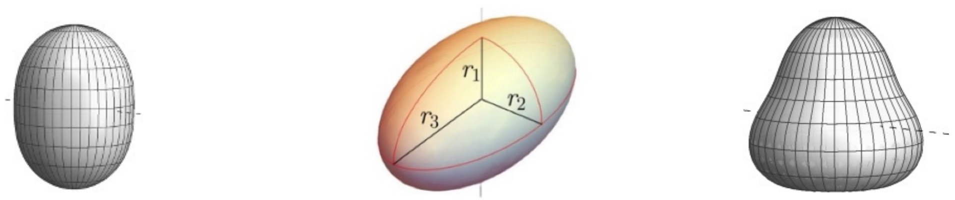
Shape-frozen like a snapshot during nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)

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

II. Nuclear deformation in heavy ^{238}U 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 $\beta_{2U} \approx 0.28 \rightarrow \beta_{2U,WS} \approx 0.25$

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

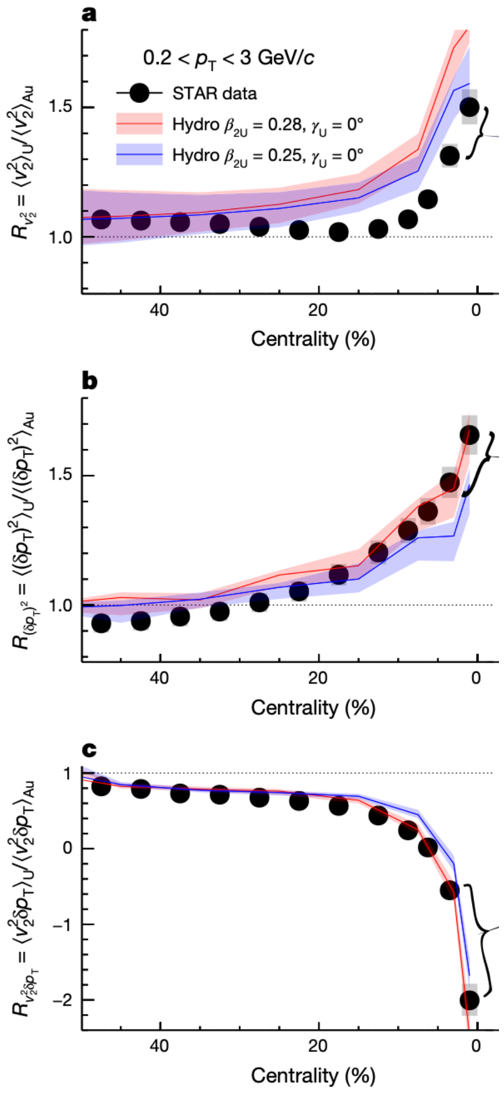
Low-energy estimate with rigid rotor assumption from B(E2) data $\beta_{2,\mathrm{LD}} = \frac{4\pi}{5R_0^2 Z}\sqrt{\frac{B(\mathrm{E2})}{e^2}}$

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

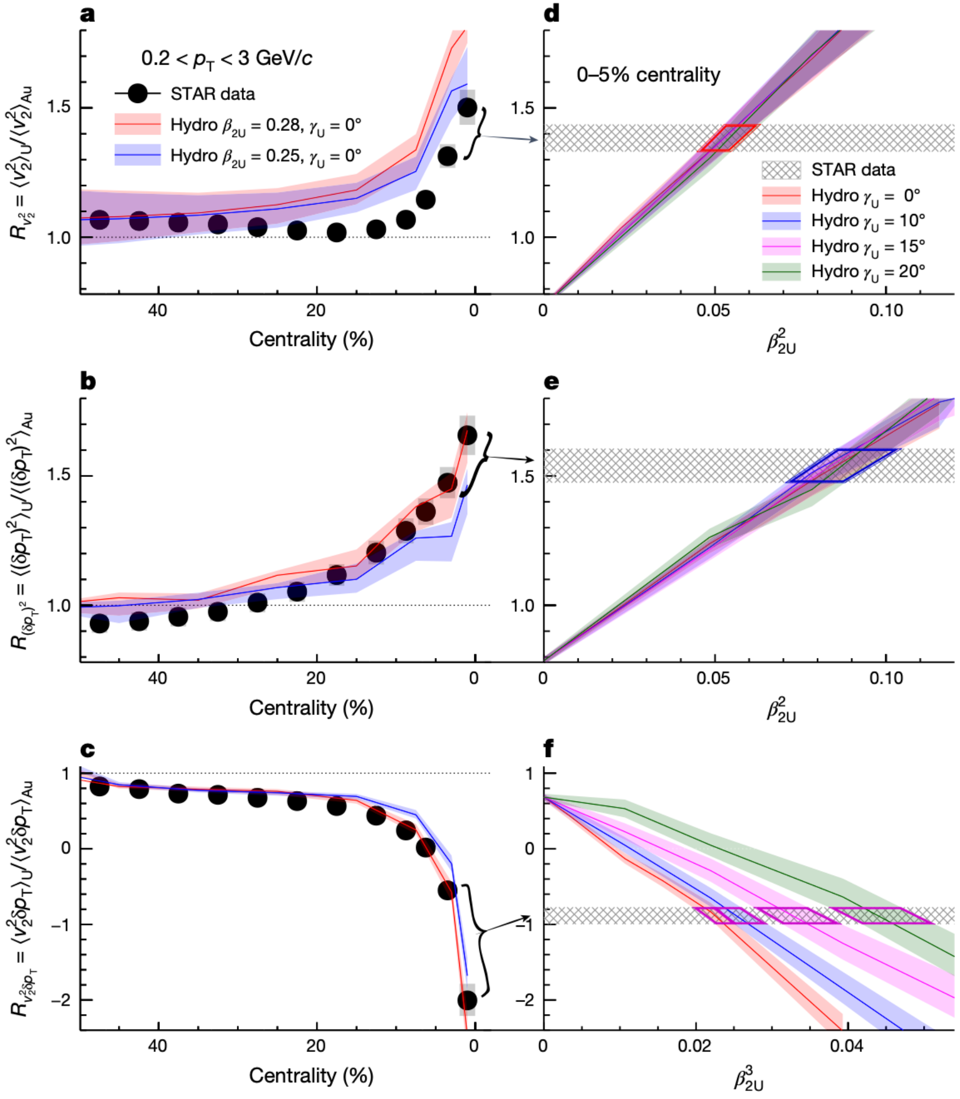
$\boldsymbol{\beta}_{3U} \sim \boldsymbol{\beta}_{4U} \sim 0.1$

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

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



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

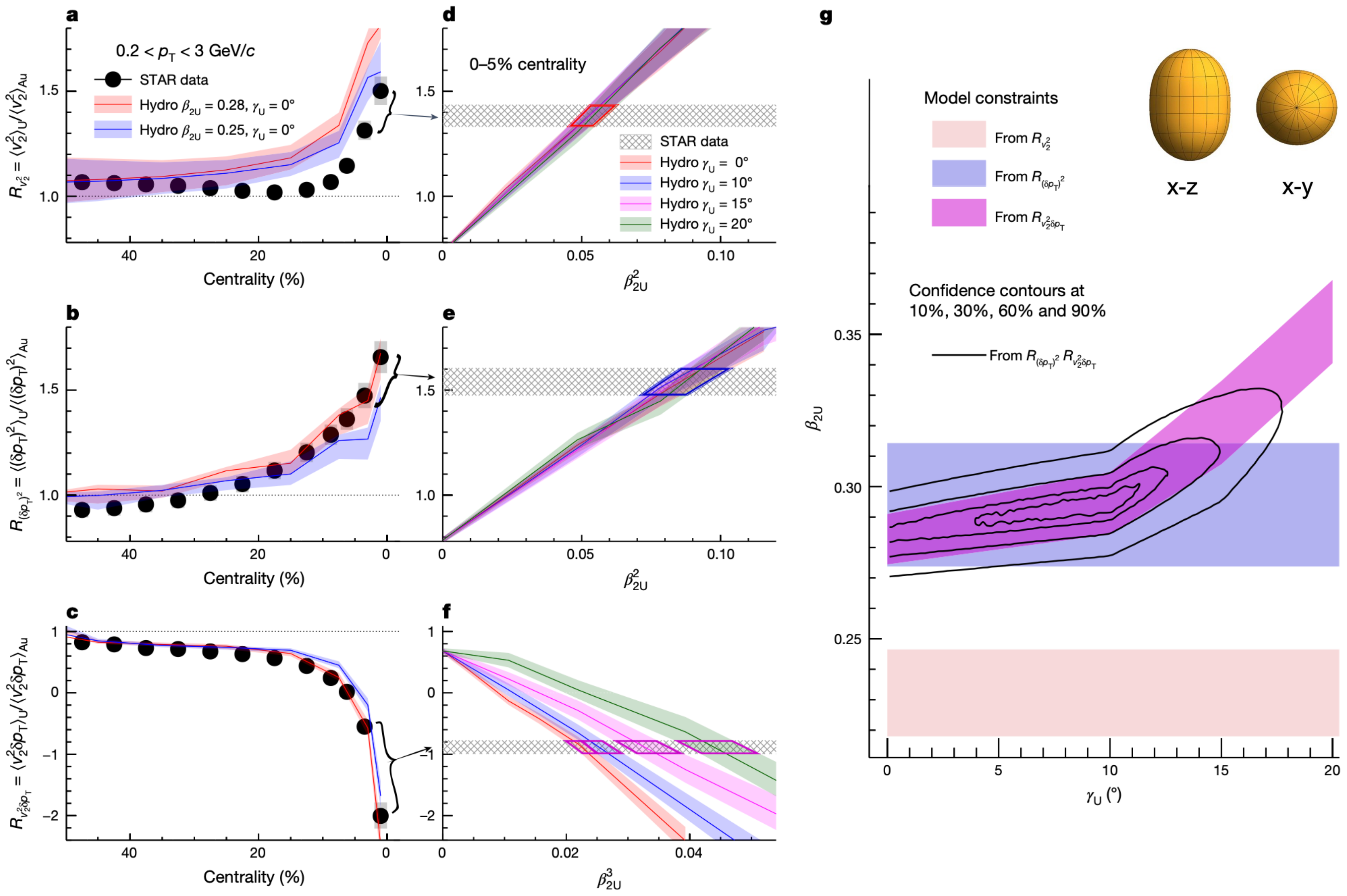


Sufficient precision is achieved from ratios in ultra-central collisions

Relation confirmed from hydro

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

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



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

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

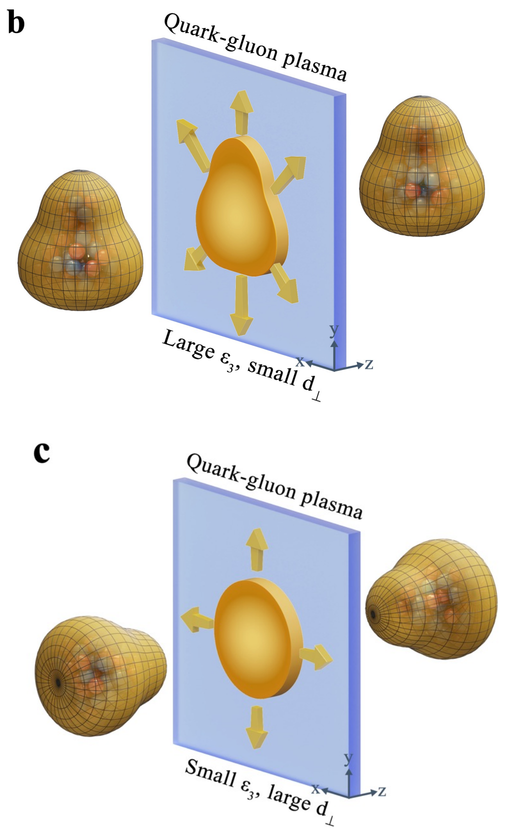
$$\beta_{2U} = 0.286 \pm 0.025$$
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

low-energy estimate:

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

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

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



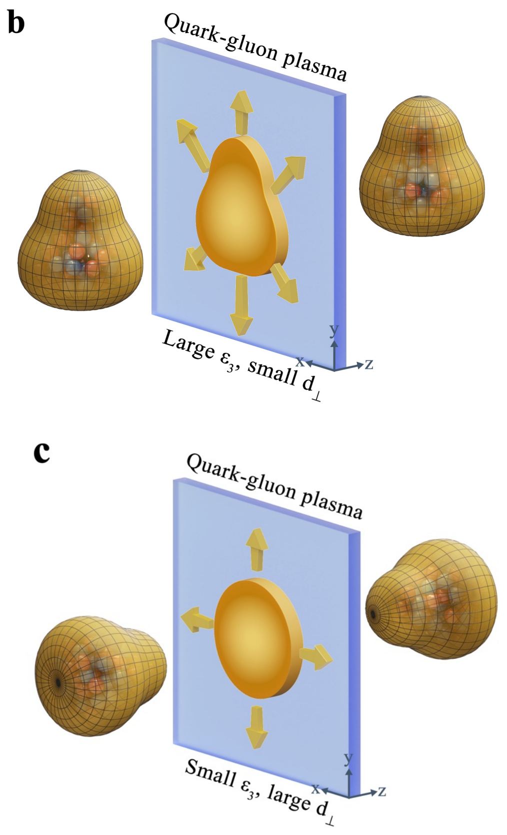
However, v_3 is fluctuation driven, expect in central

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

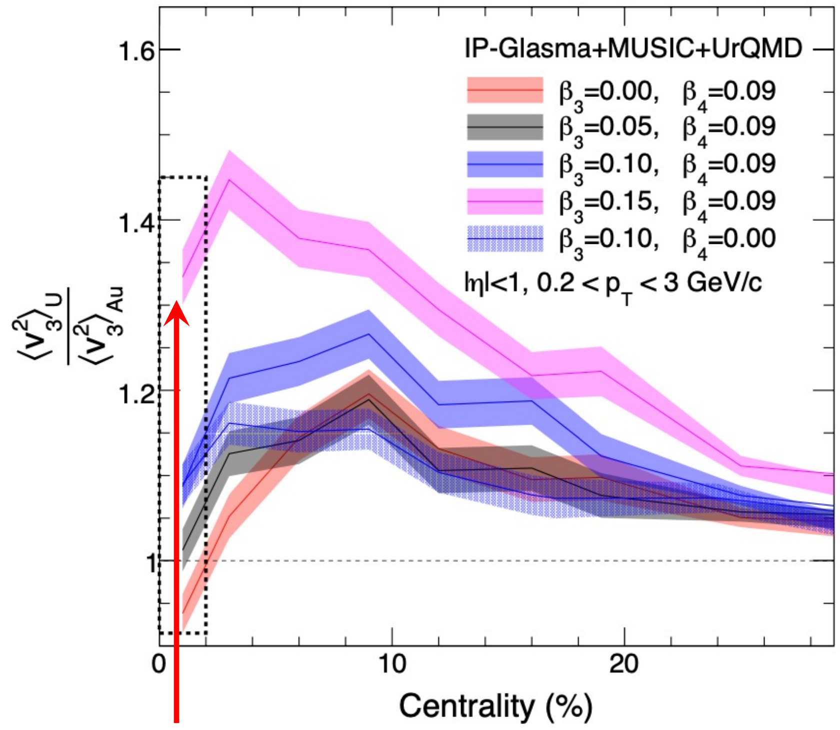
mass number

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

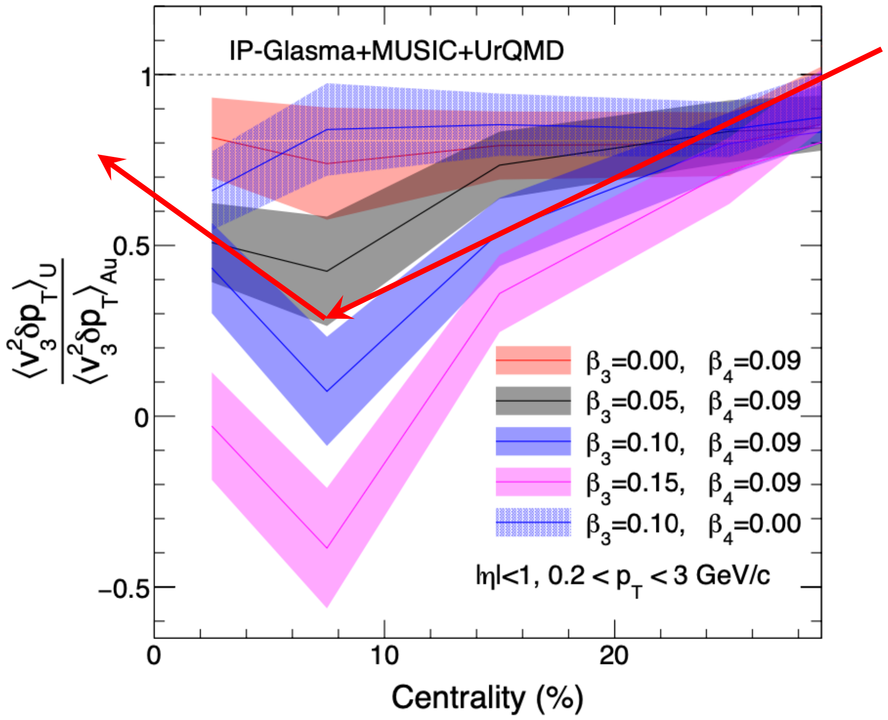
Evidence of octupole deformation $\beta_{3,\mathrm{U}}$



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,

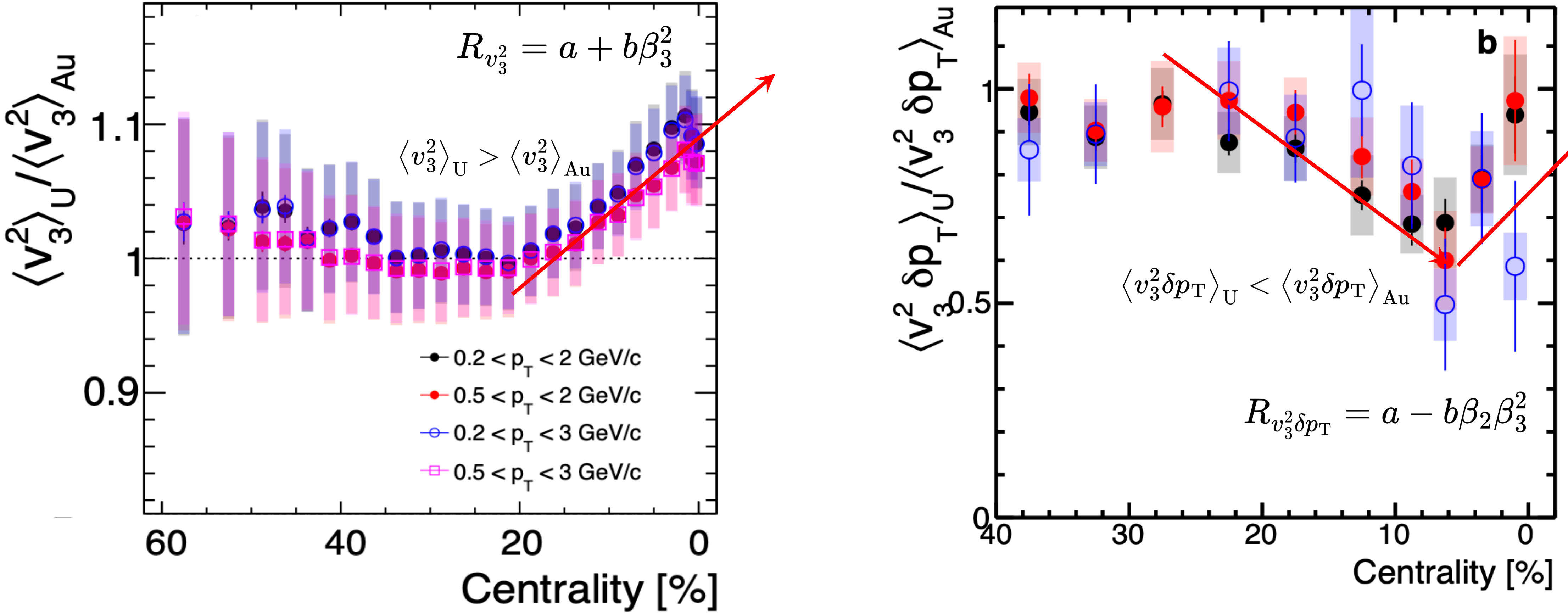
Characteristic anticorrelation in $\langle v_3^2\delta p_{\mathrm{T}}\rangle$ shows a pronounced β_3-dependent suppression.

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

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

New

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

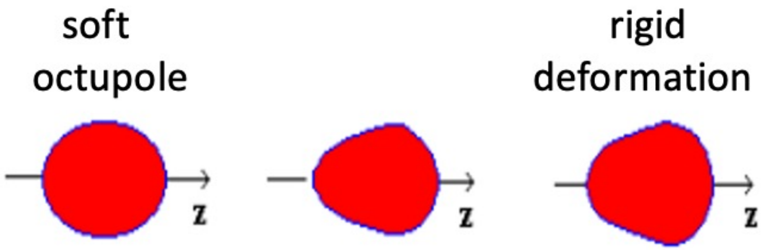


- No apparent p_T dependence
- Order of v_3 and v_3-p_T reversed by considering non-zero $\beta_{3,\mathrm{U}}$, $\beta_{4,\mathrm{U}}$.
- An evidence and modest $\beta_{3,\mathrm{U}} \sim 0.08$-$0.10$ are confirmed and $\beta_{3\mathrm{U}} \sim \beta_{4\mathrm{U}}$

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

Octupole collectivity

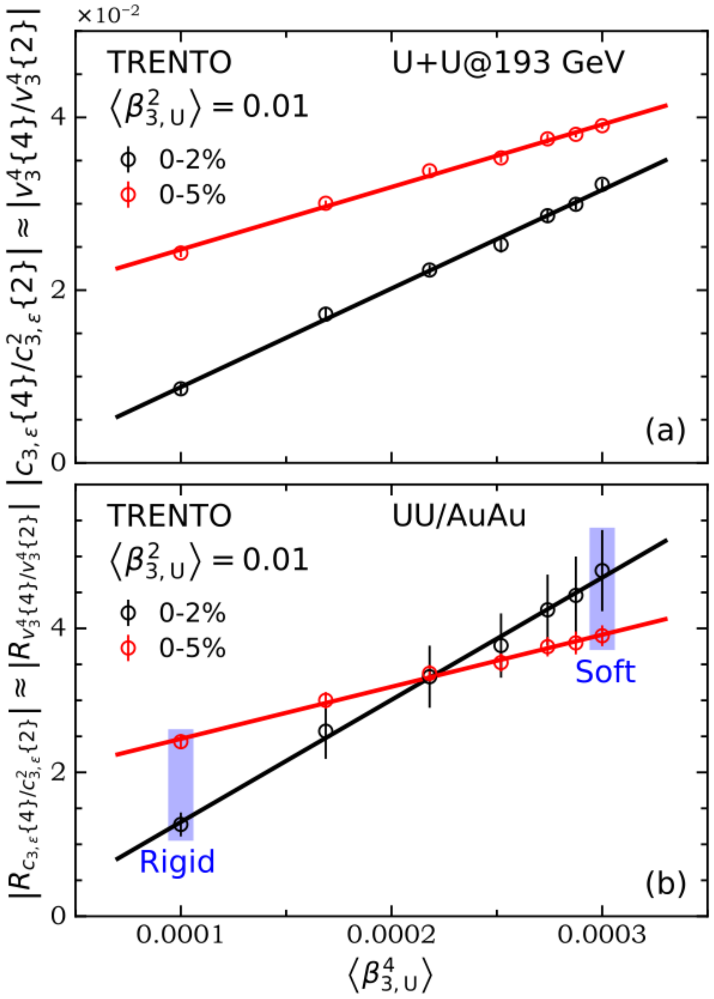
L. Liu, C. Zhang, J. Chen, J. Jia, X. Huang, Y.-G. Ma, 2509.09376



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

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

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



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*

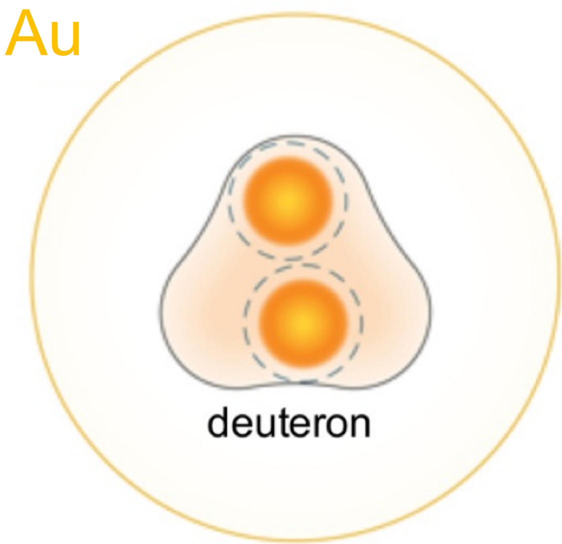
III. Nucleonic cluster pattern in light ^{16}O nucleus

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

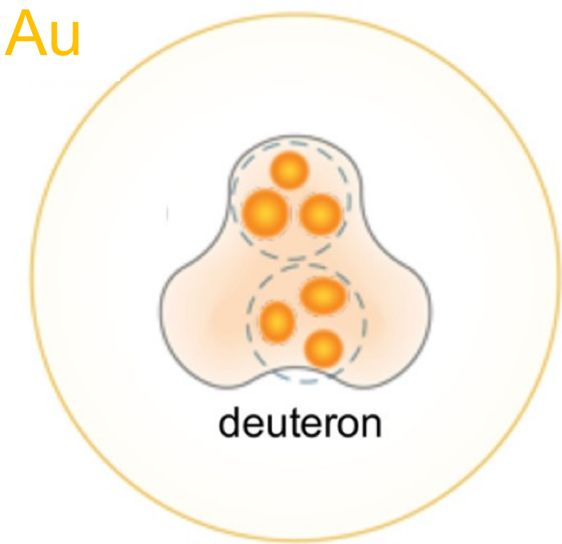
$$\rho(r) \propto \frac{1 + w\left(r^2/R^2\right)}{1 + e^{(r-R)/a_0}} \longrightarrow \text{Modern } ab \text{ initio first-principle calculations}$$

Light nuclear geometry and nucleon-nucleon correlations

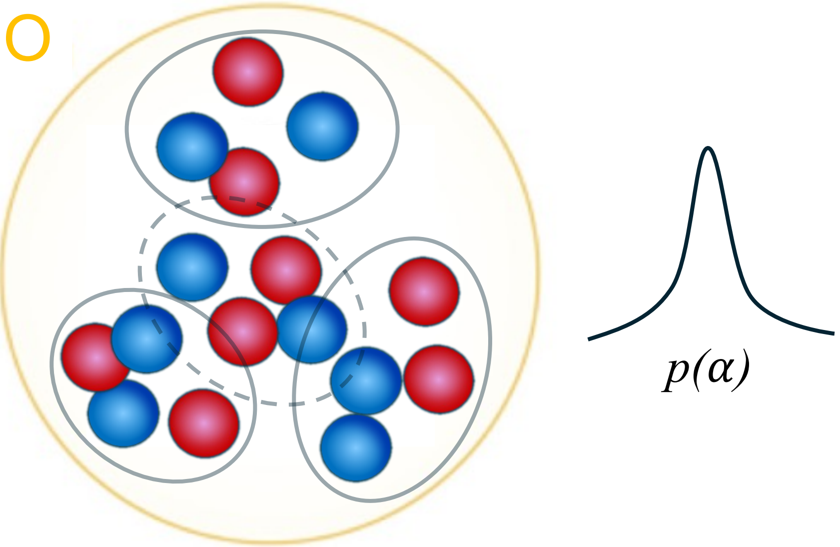
Nucleon fluctuation



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)

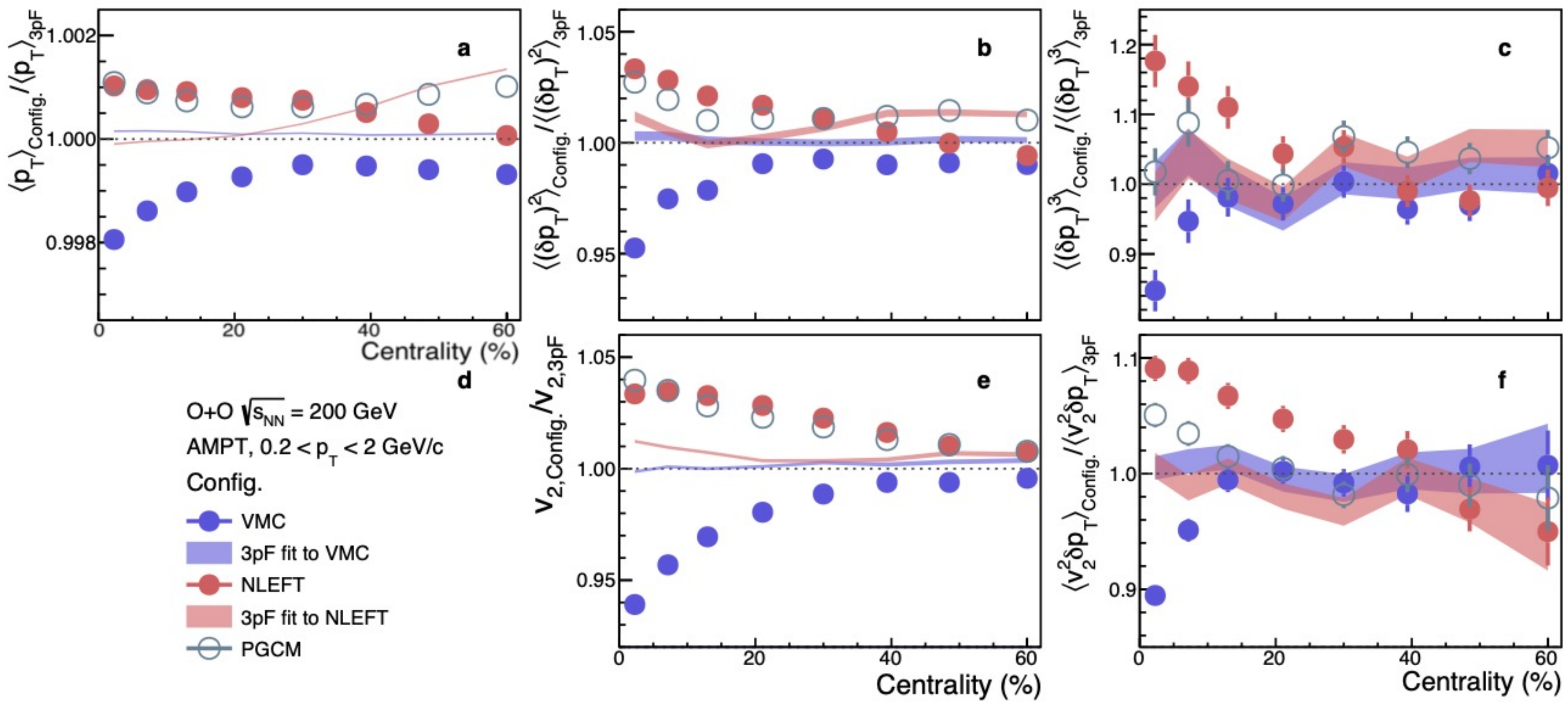
…

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

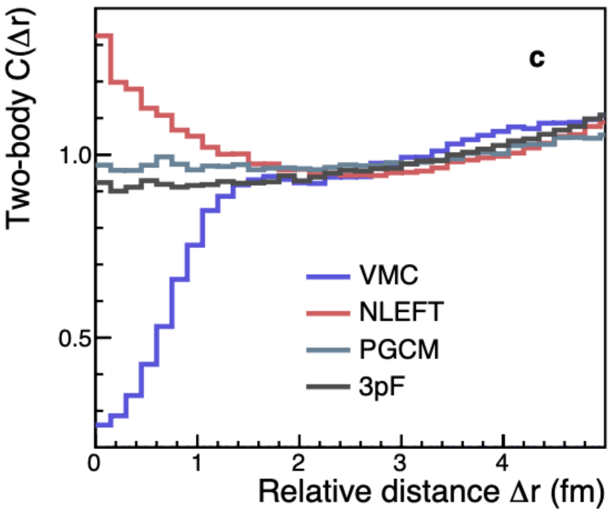
Ab-initio nucleon-nucleon correlations and their impact on high-energy

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



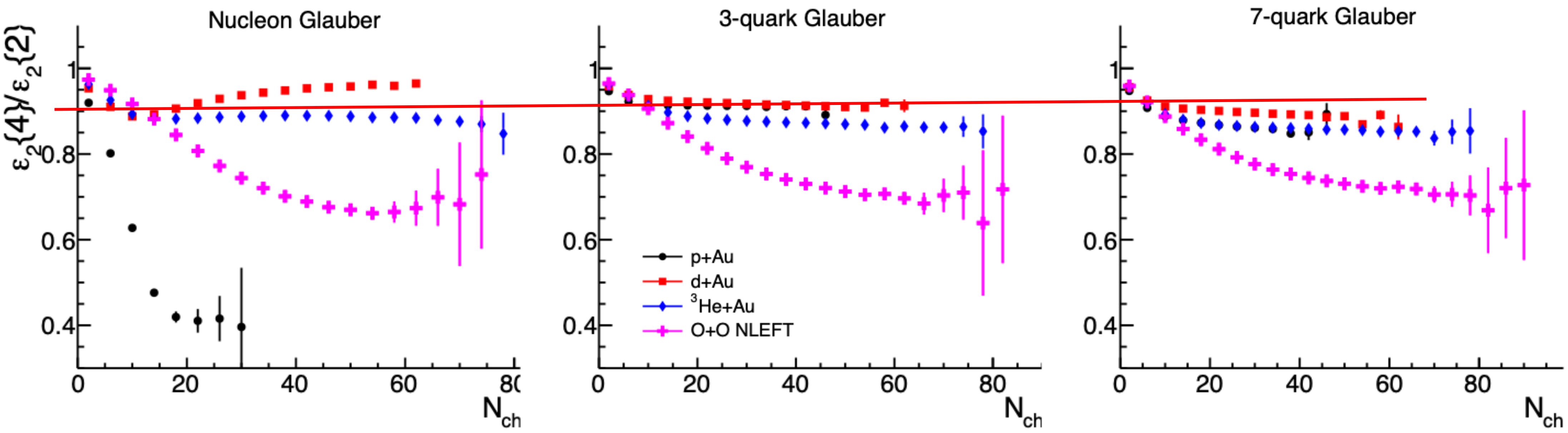
$$C(\Delta r) = \frac{\int d^3\mathbf{s} f(\mathbf{s}+\frac{\mathbf{r}}{2}, \mathbf{s}-\frac{\mathbf{r}}{2})}{\int d^3\mathbf{s} f(\mathbf{s}+\frac{\mathbf{r}}{2}) f(\mathbf{s}-\frac{\mathbf{r}}{2})}$$

- 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.

Disentangling nuclear structure and subnucleonic structure effects

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

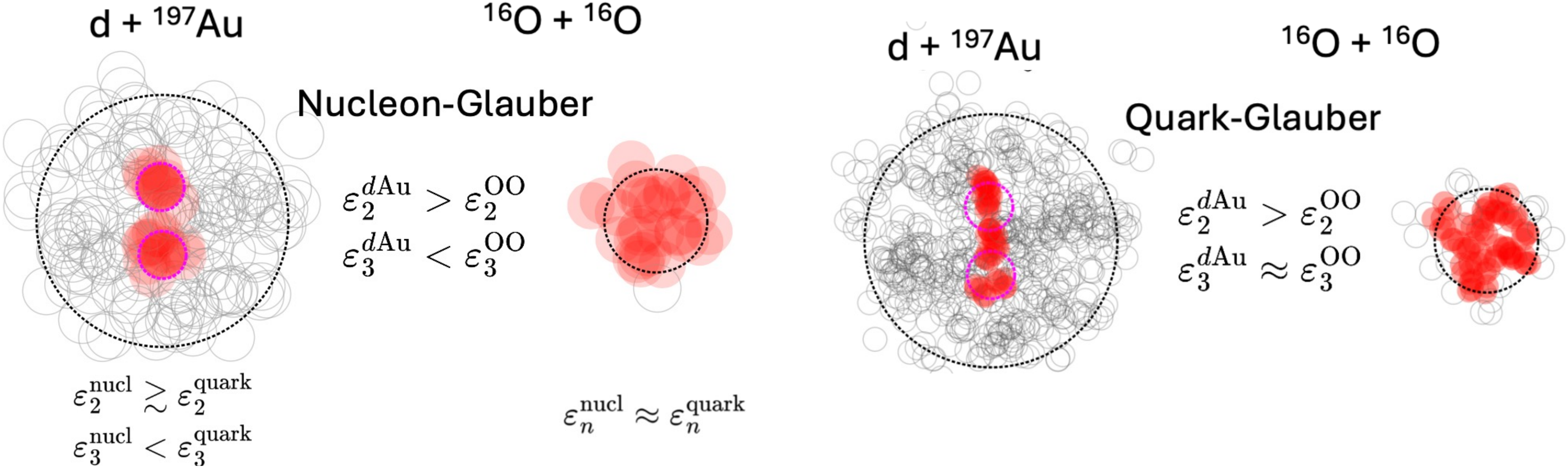


- Quark Glauber is more flattened in d+Au, indicating subnucleon hints
- No clear difference beyond 3 quarks inside of proton.
- Similar behavior in p_T fluctuations.

Benchmarking geometric tomography of ^{16}O nucleus

New

STAR, *2510.19645*



Nucleon-Glauber and quark-Glauber yield different triangular v_3

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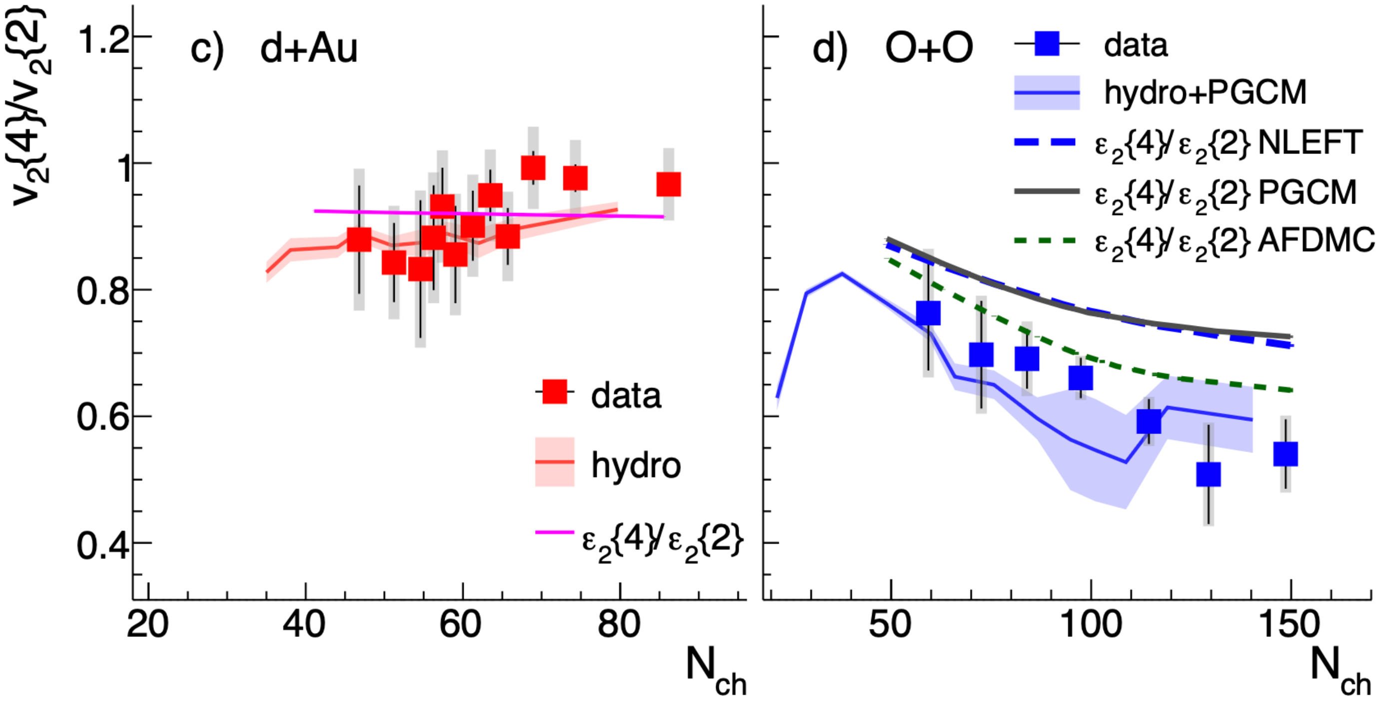

$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from three models:
AFDMC vs. EFT/PGCM have a visible difference.

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)*

$$(v_n\{2\})^2 = c_n\{2\} = \langle v_n^2 \rangle \qquad \varepsilon_2\{2\}^2 = \langle \varepsilon_2^2 \rangle$$
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Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022);* W. He, Y.-G. Ma et al, *PRL 113, 032506 (2014)*
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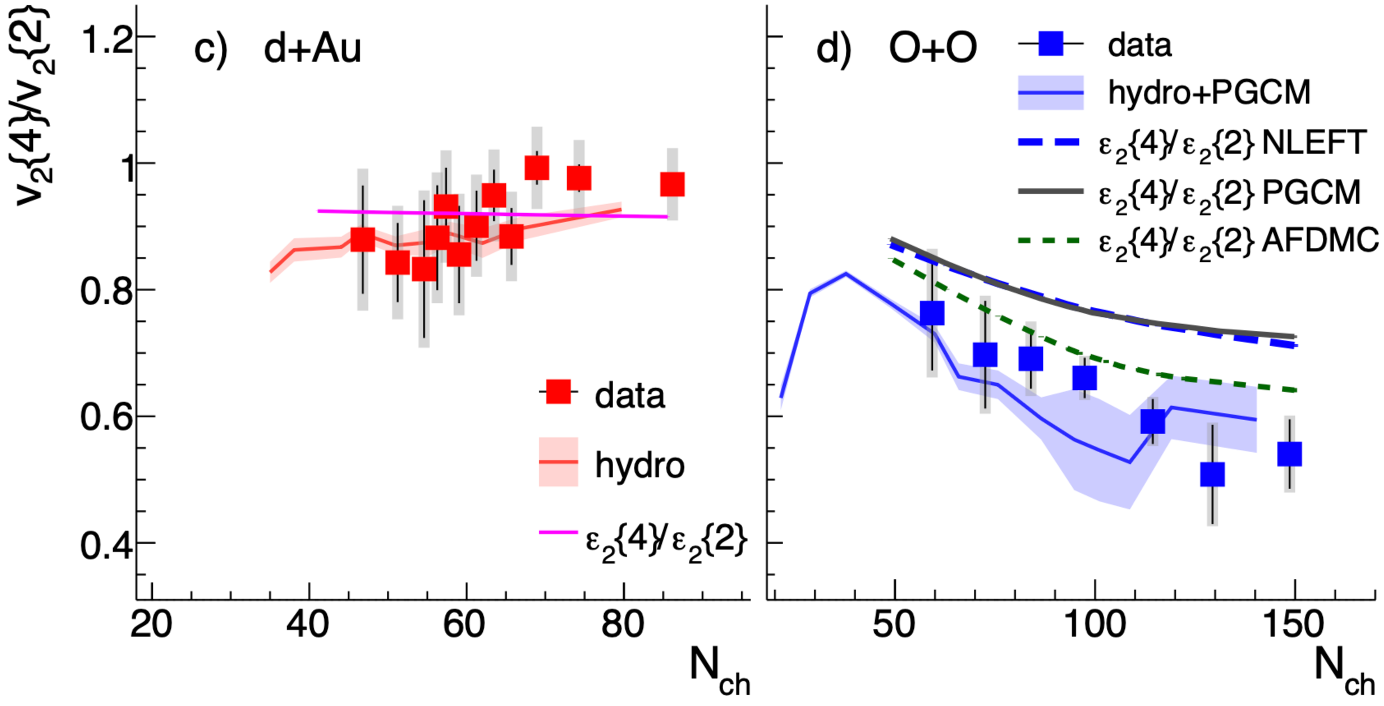

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Geometric scan elucidates nuclear tomography and strong nuclear force?

more low-energy model inputs & revisit

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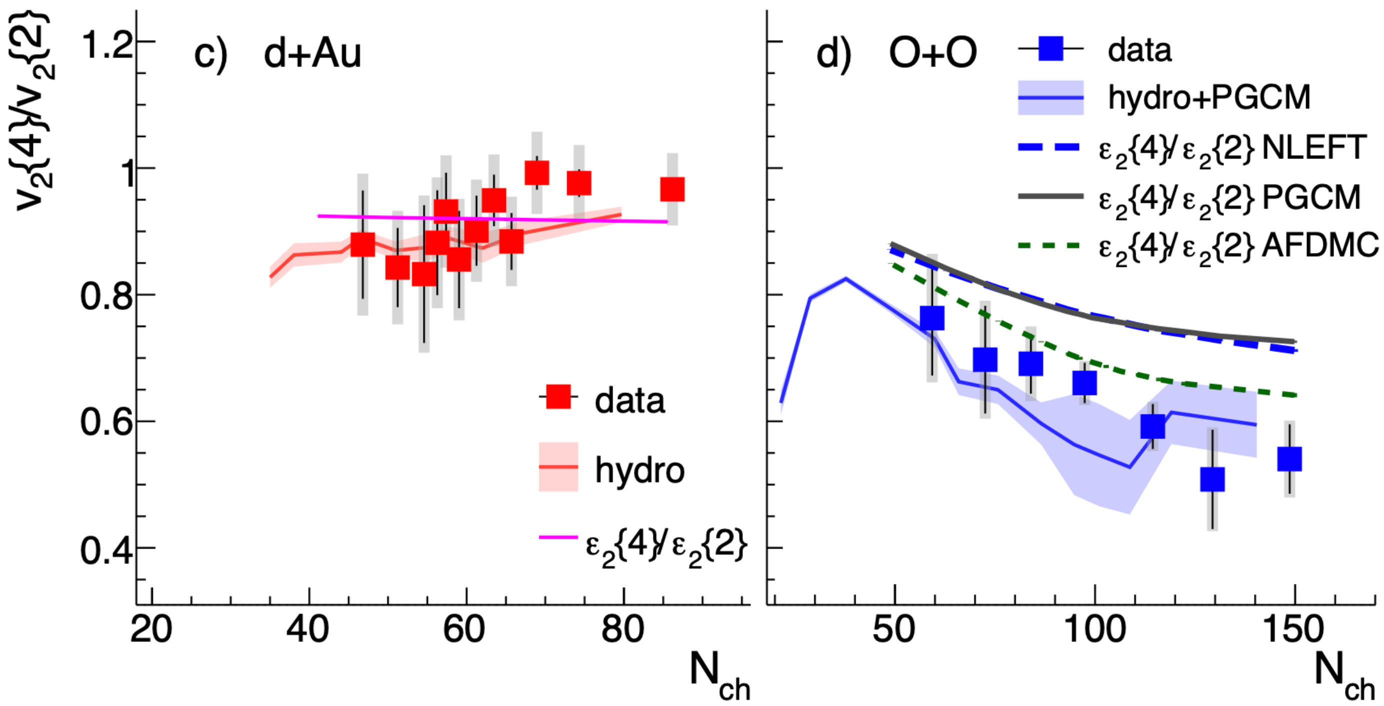

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LHC (ALICE, ATLAS, CMS, LHCb) also released the O+O/Ne+Ne.
Shape imaging method for light ions (New avenue)

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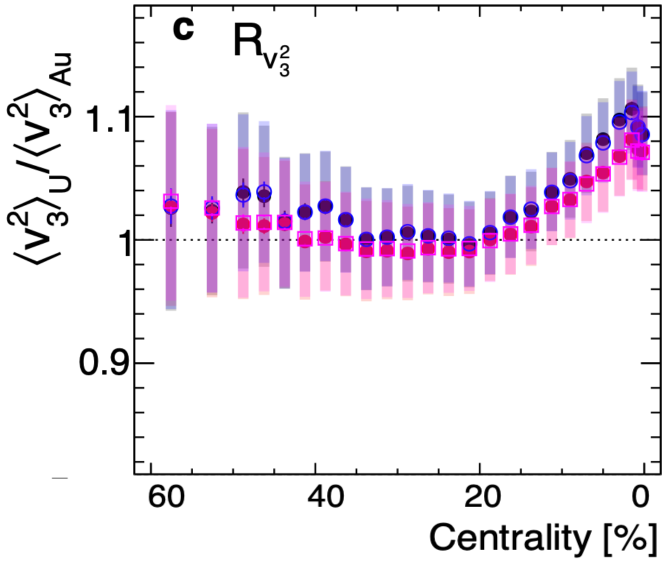
IV. Conclusions and Outlooks

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

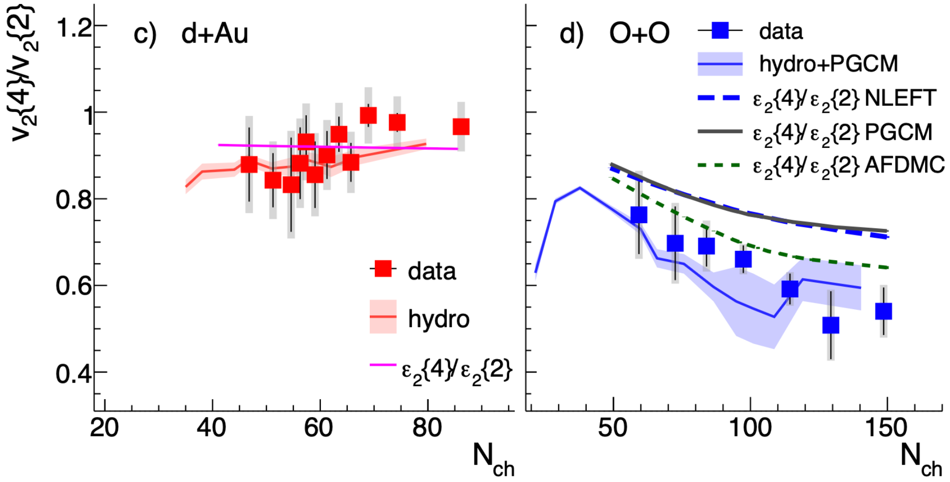
STAR, *Rep. Prog. Phys.* **88,** 108601 (2025)



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

*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)

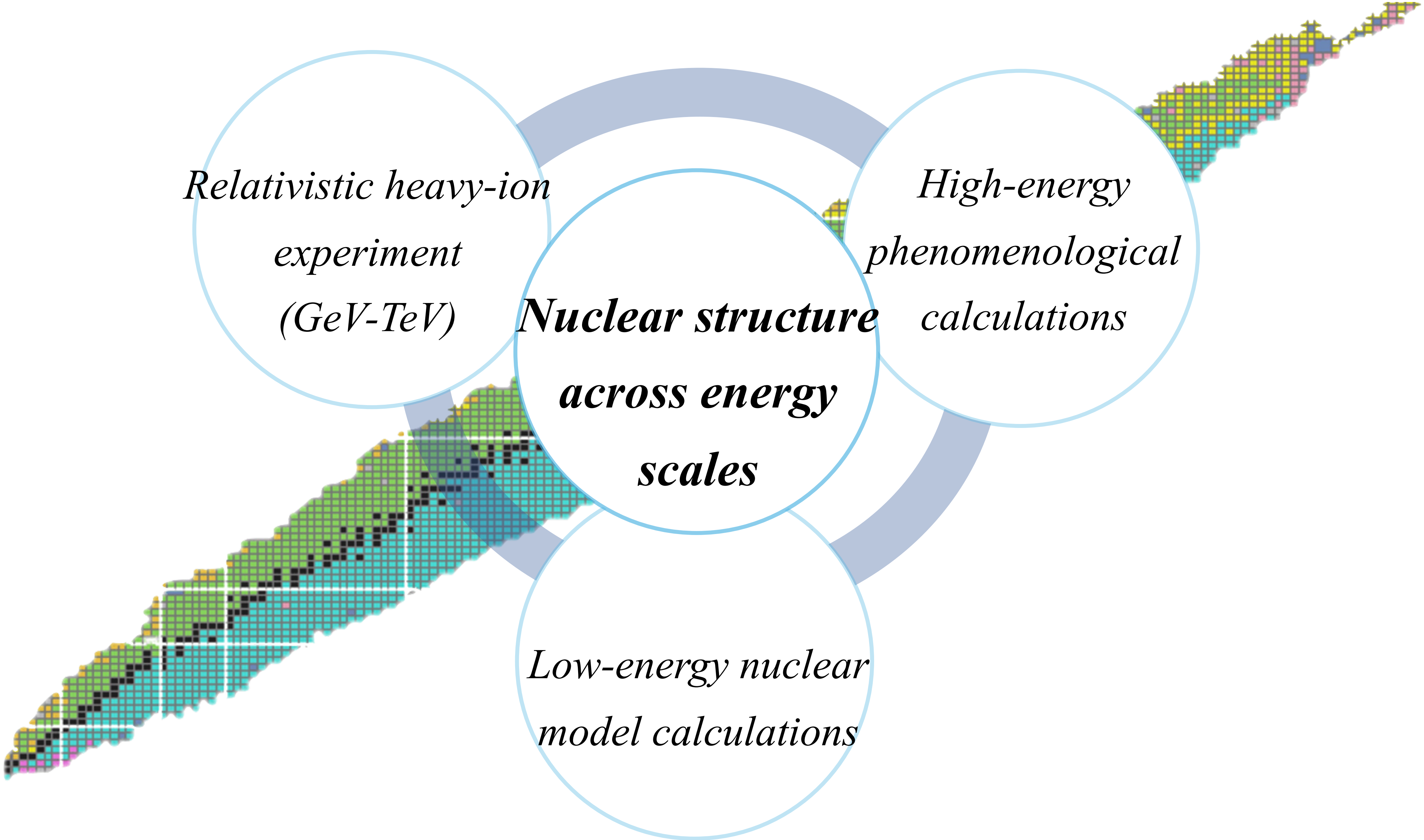
→ Neutron skin & symmetry energy constraints

→ Energy evolution between GeV/TeV and MeV in even-and odd-A nuclei

→ Confronted with ab initio calculations and more light-ion studies

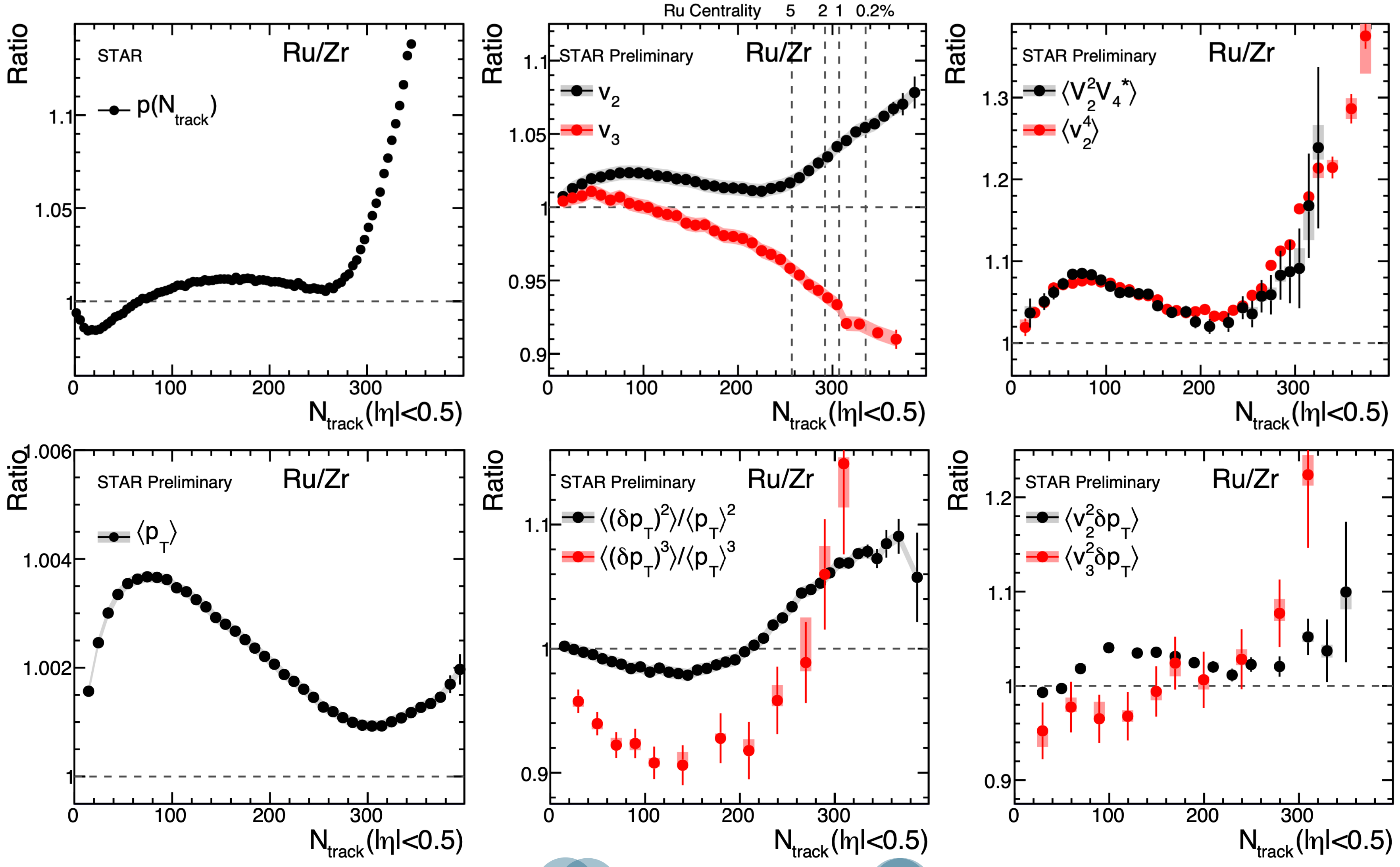
→ Intersection with other research: Nucleosynthesis, nuclear fission, $0\nu\beta\beta$

IV. Conclusions and Outlooks



Nuclear structure is inherent of heavy-ion probes

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



Chunjian Zhang (QM2022, QM2025)