见微学术沙龙
USTC Jianwei Seminar

Imaging nuclear structure across energy scales: from heavy to light ions

Chunjian Zhang (Asst. Prof.)

Fudan University

December 26, 2025, University of Science and Technology of China

难忘岁月：博士研究生课程学习（2013.09至2014.07）

Outline

I. Nuclear structure across energy scales

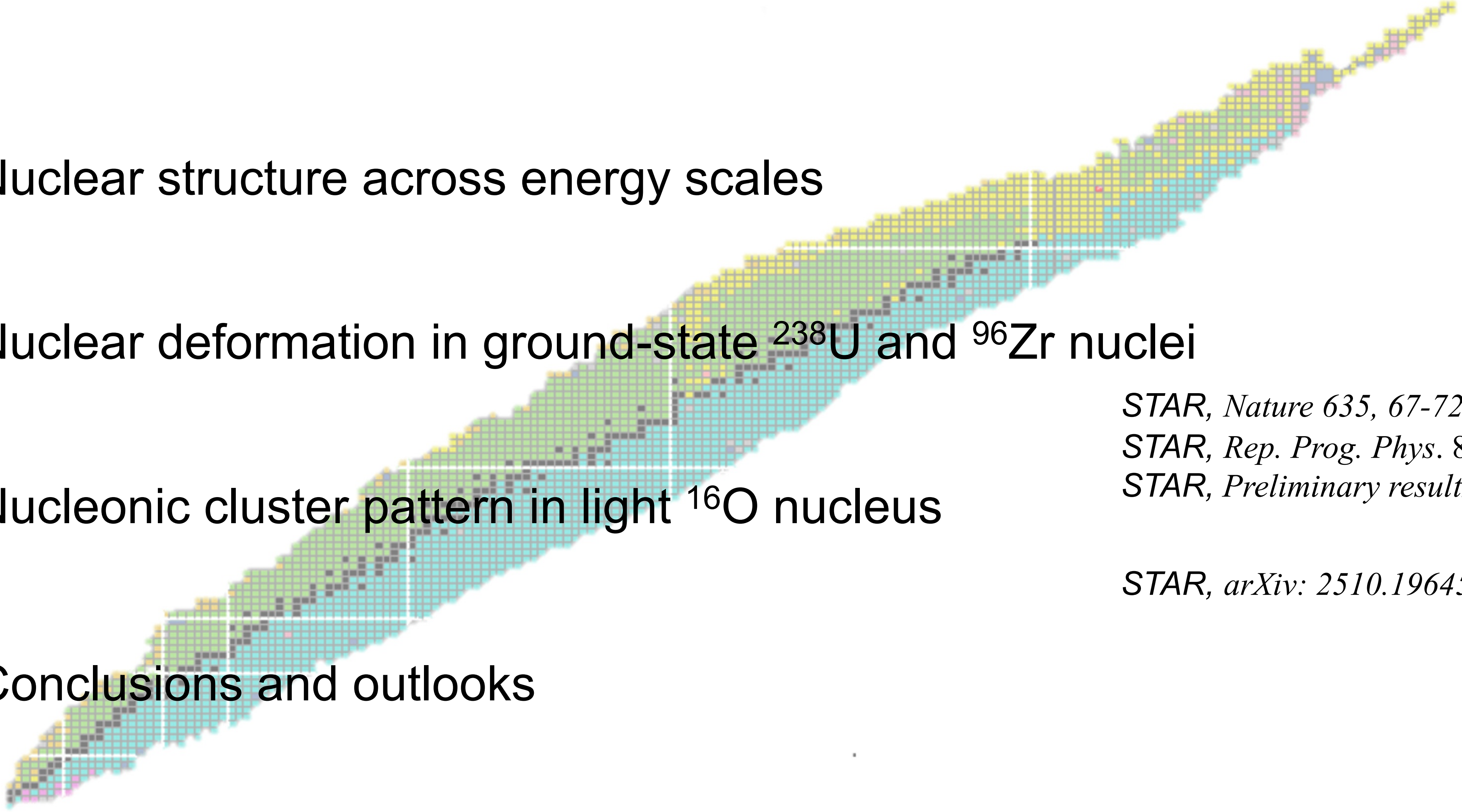
II. Nuclear deformation in ground-state ^{238}U and ^{96}Zr nuclei

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

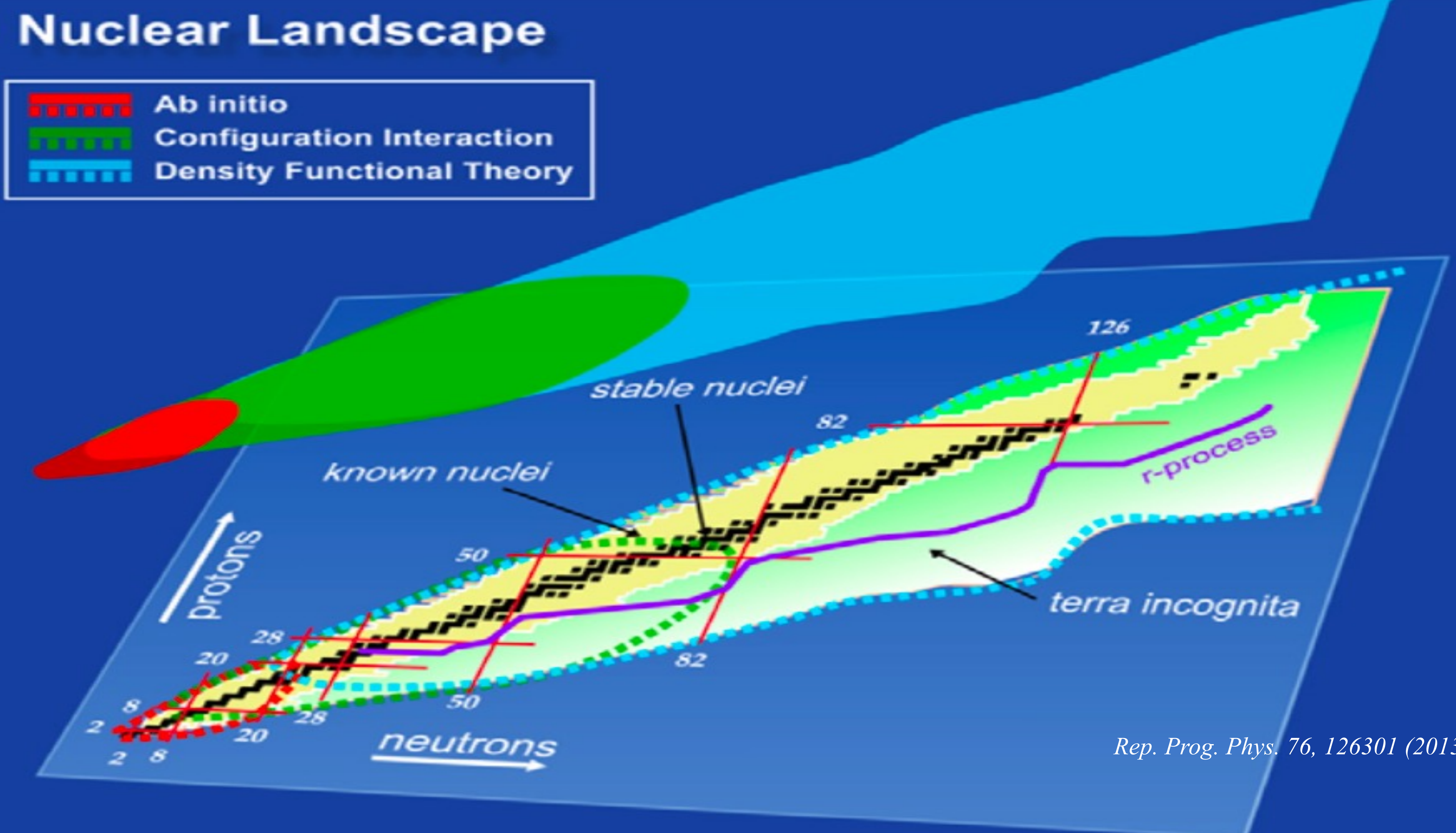
III. Nucleonic cluster pattern in light ^{16}O nucleus

STAR, *arXiv: 2510.19645*

IV. Conclusions and outlooks



Nuclear Landscape



Rep. Prog. Phys. 76, 126301 (2013)

Collective structure of atomic nuclei

- Emergent phenomena of the many-body quantum system
  - Non-monotonic evolution with N and Z
  - Quadrupole/octupole/hexadecapole deformations
  - Clustering, halo, skin, bubble…

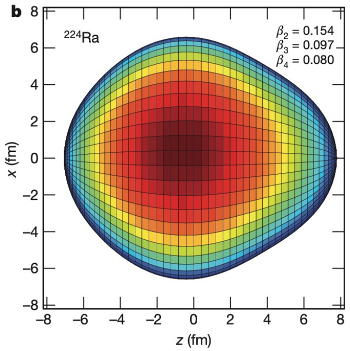
Y. Ye, X. Yang, H. Sakurai, B. Hu, *Nature Review Physics, 7, 21-37 (2025)*

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

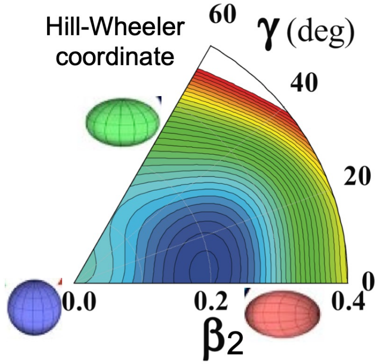
Quadrupole

S. Cwiok et al., *Nature 433, 705 (2005)*

Octupole



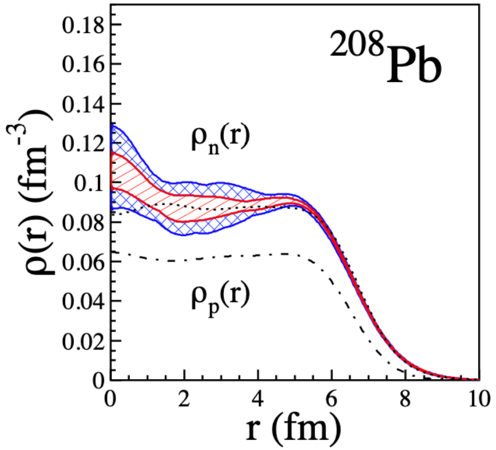
L.P Gaffney et al., *Nature 497, 199 (2013)*

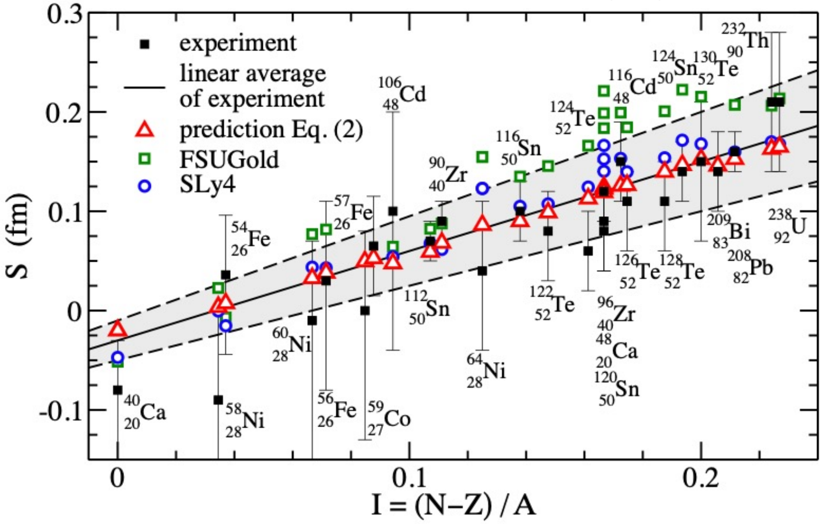


Triaxial spheroid

A. Andreyev et al., *Nature 405, 430 (2000)*

Neutron skin

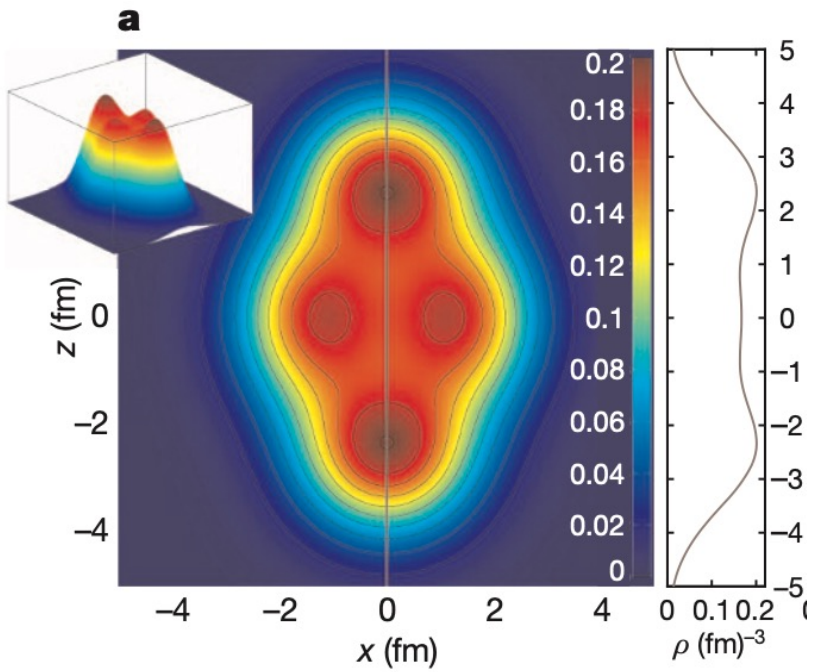




A. Trzcinska et al., *PRL 87, 082501 (2001)*

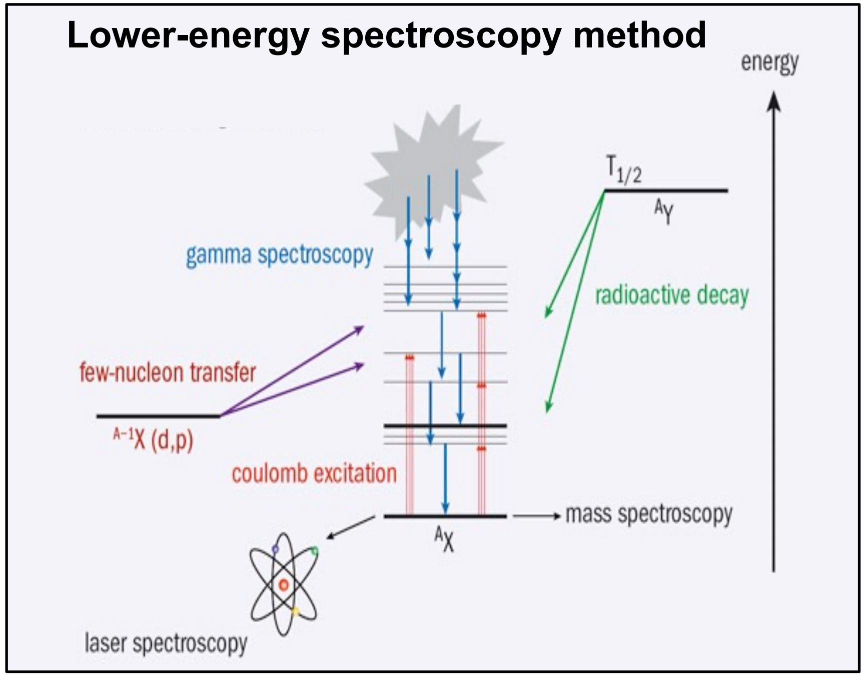
A. M. Centelles et al., *PRL 102, 122502 (2009)*

nucleonic clustering



J.P. Ebran et al., *Nature 487, 341 (2012)*

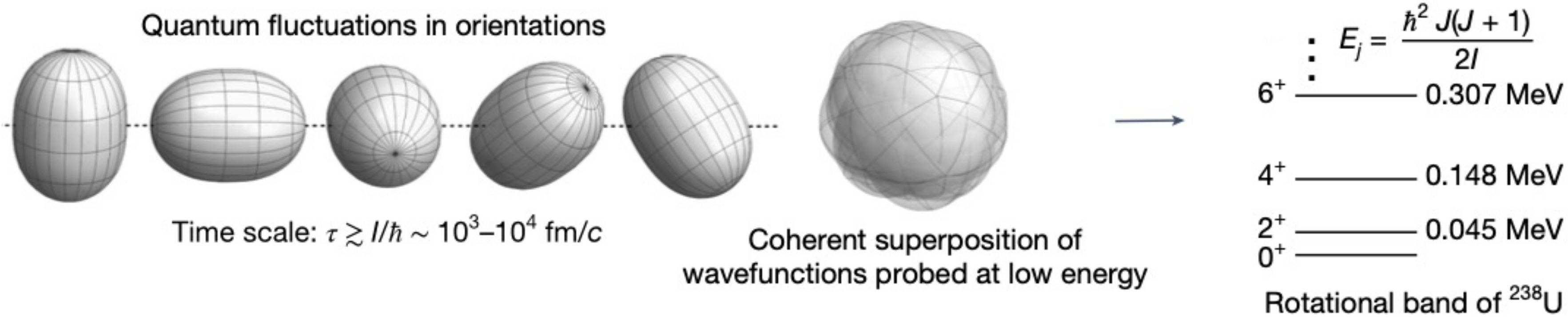
Nuclear shape at low energy: long exposure



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.



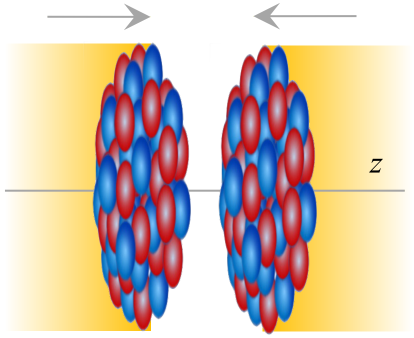
Imaging by smashing method

Take a snapshot

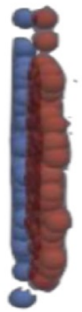
Evolution

Measurement

Nuclei collisions



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



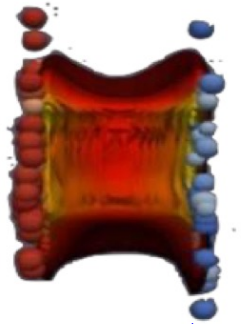
$\tau \sim 2R_0/\Gamma \sim 0.1\mathrm{fm}/c$

exposure

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

Pressure-driven expansion of

Quark-gluon plasma (QGP)

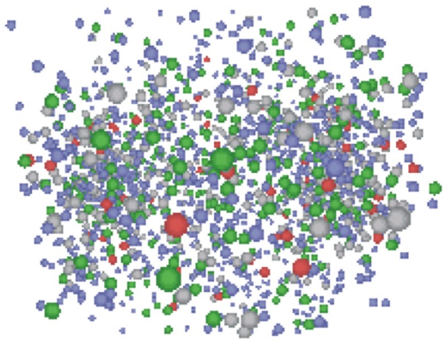


$\tau \sim 10\mathrm{fm}/c$

expansion

free-streaming

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



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

detection

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

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

ab initio theory/shell model/DFT

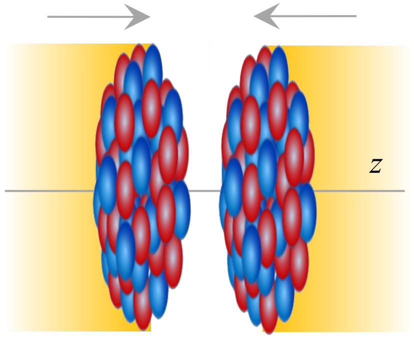
J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024)*

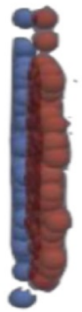
Imaging by smashing method

Take a snapshot

Nuclei collisions

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





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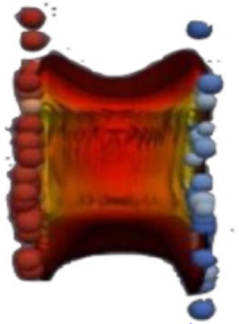

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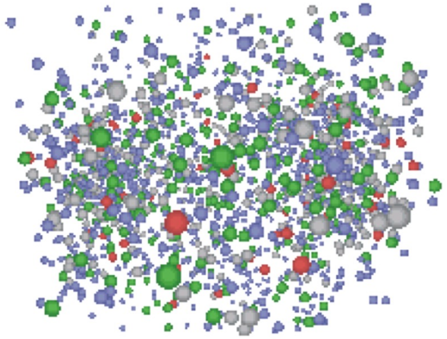

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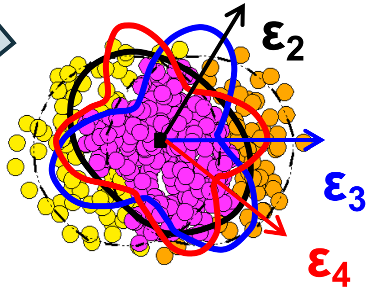


size & shape

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

Event-by-event linear responses:

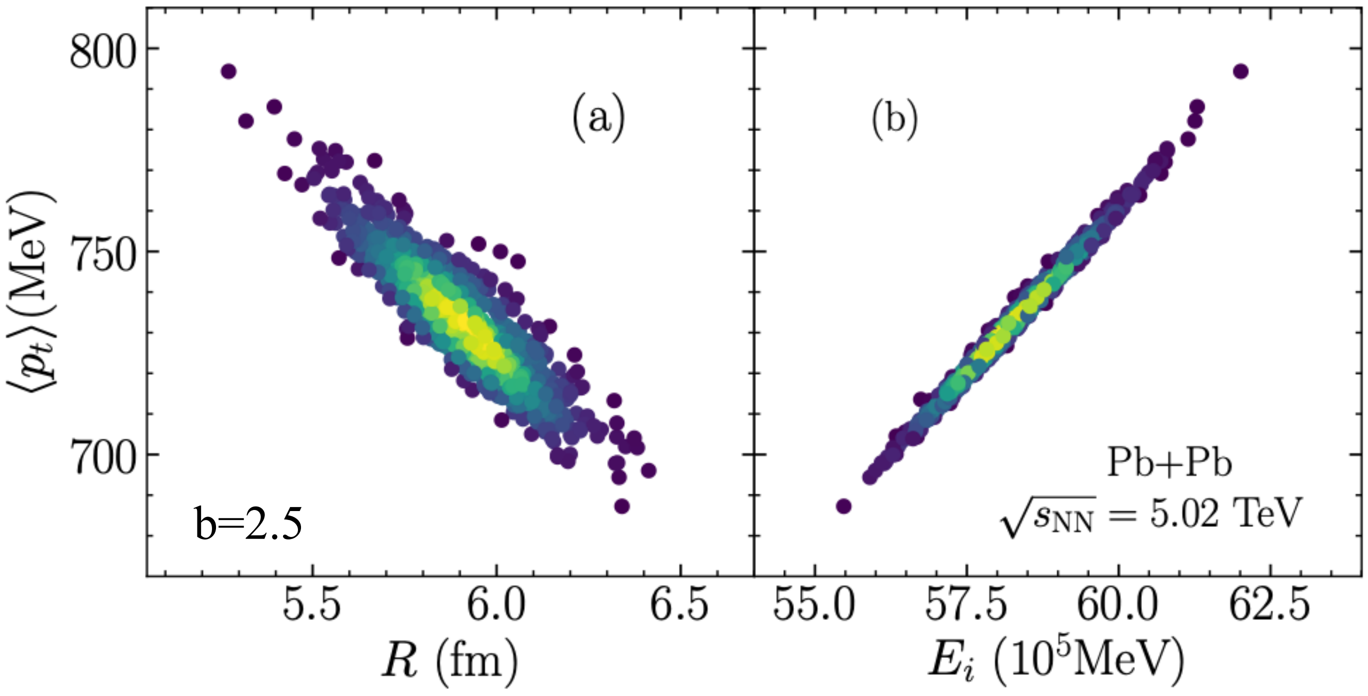
$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

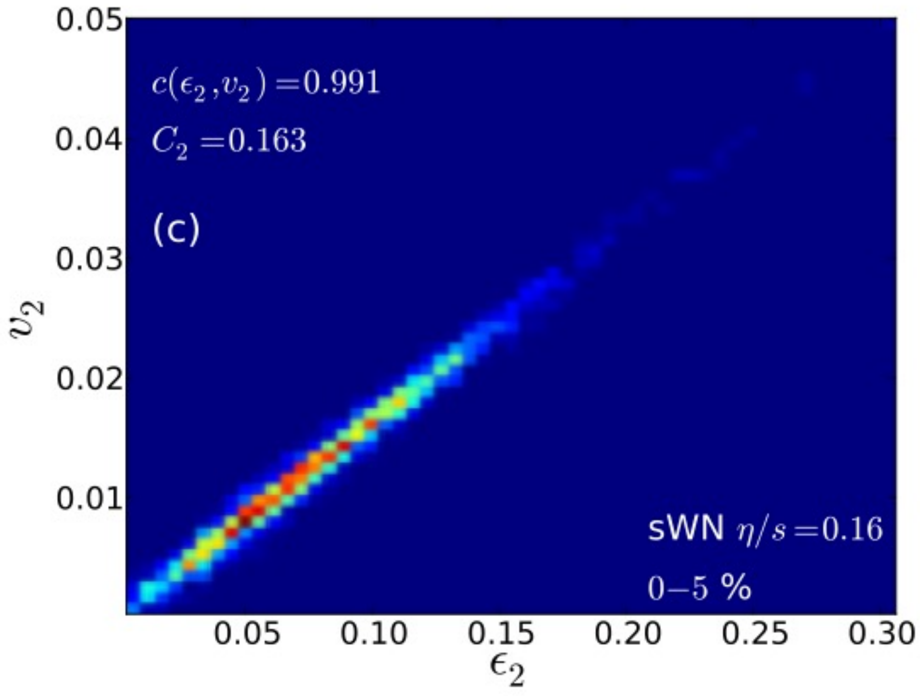
Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

Linear response in ultra-central collisions

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

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



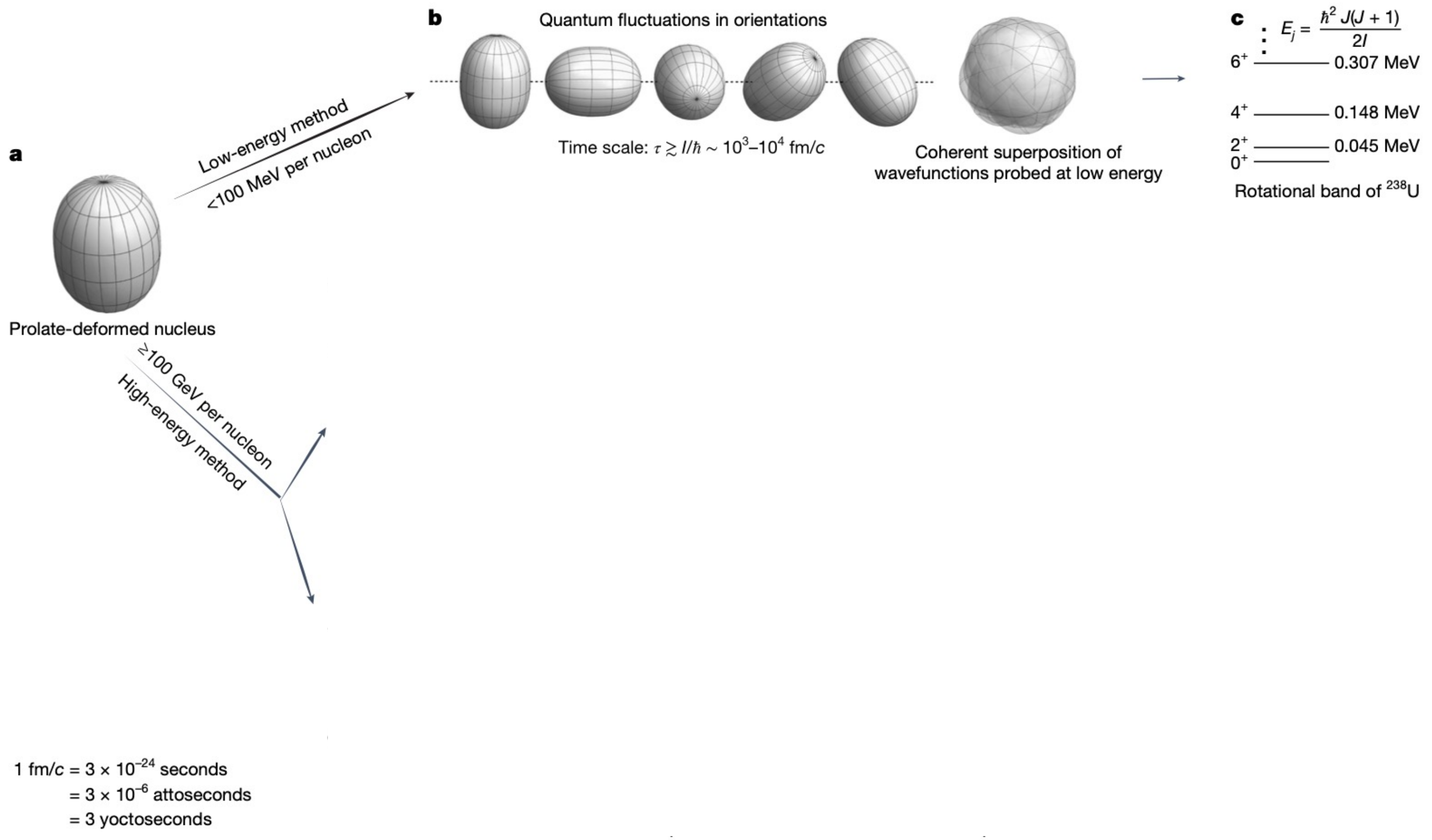


G. Giacalone, F. Gardim, J. Hostler, J. Ollitrault, et al, *PRC 103, 024909 (2021)*

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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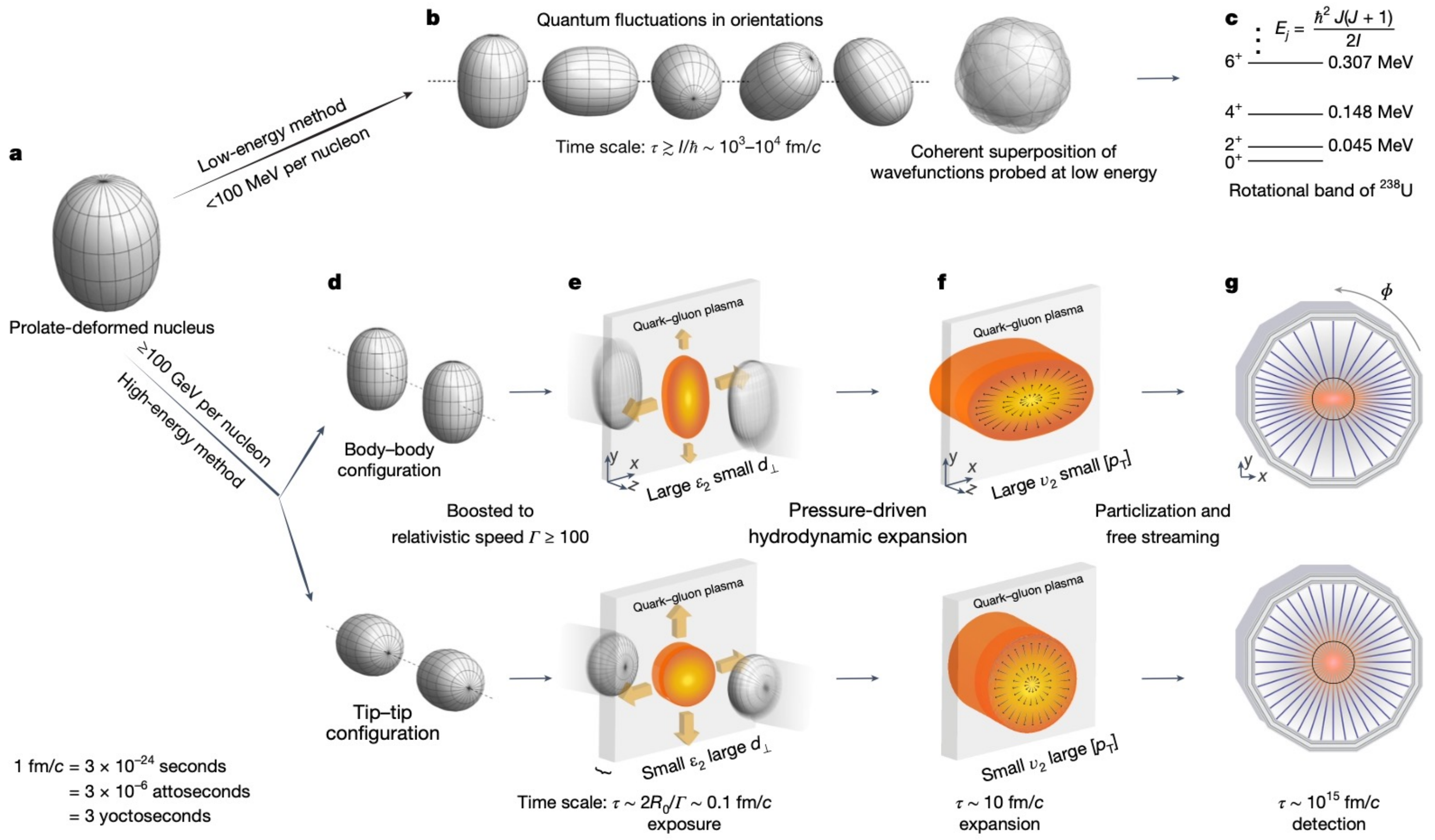


STAR, Nature 635, 67-72 (2024)

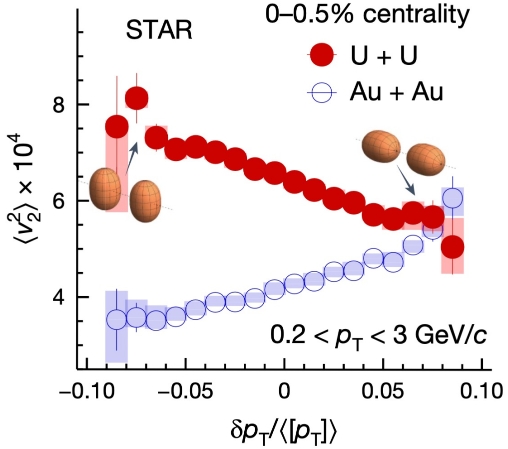
https://www.nature.com/articles/s41586-024-08097-2

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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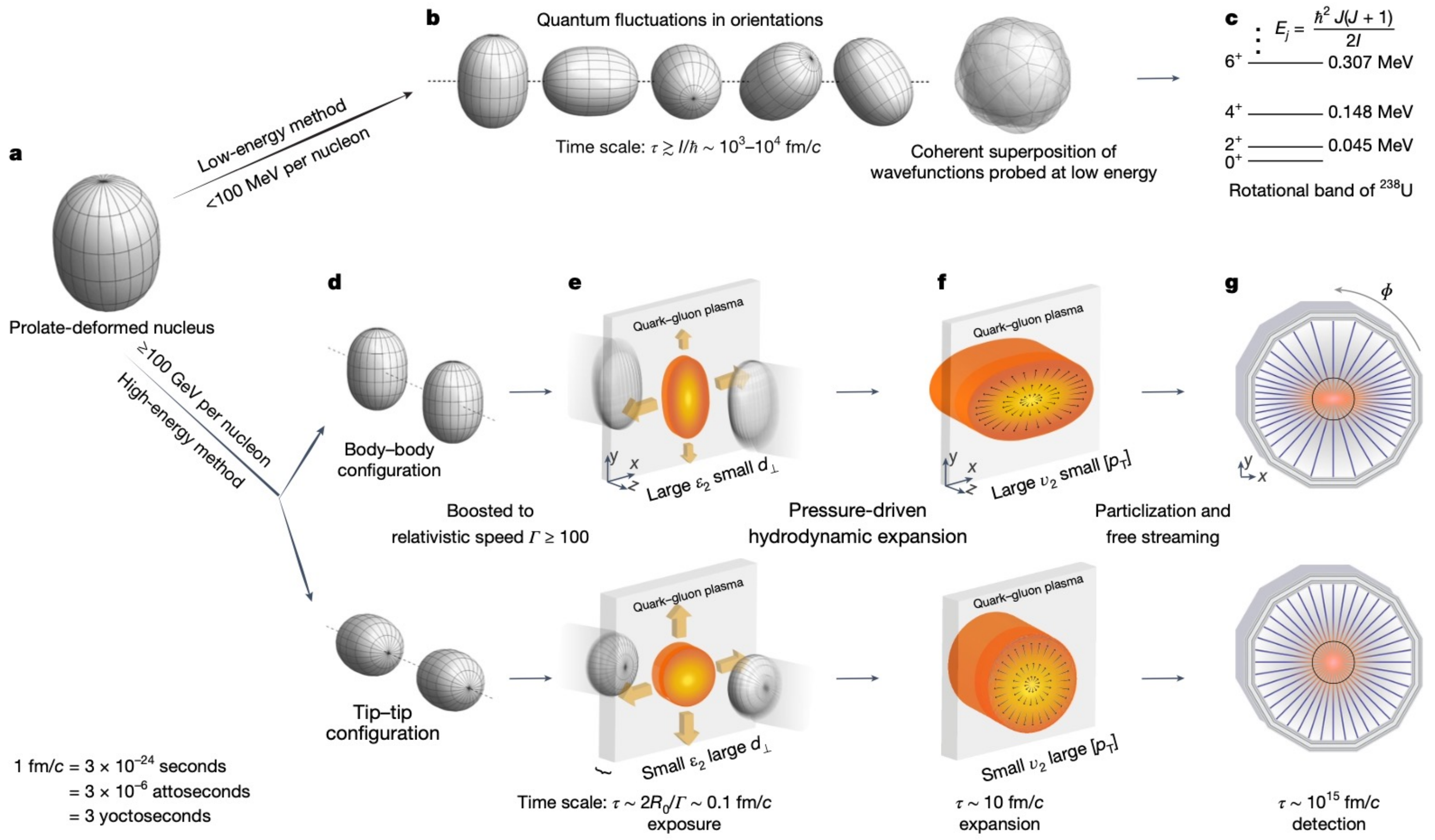


STAR, *Nature 635, 67-72 (2024)*
https://www.nature.com/articles/s41586-024-08097-2

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)*

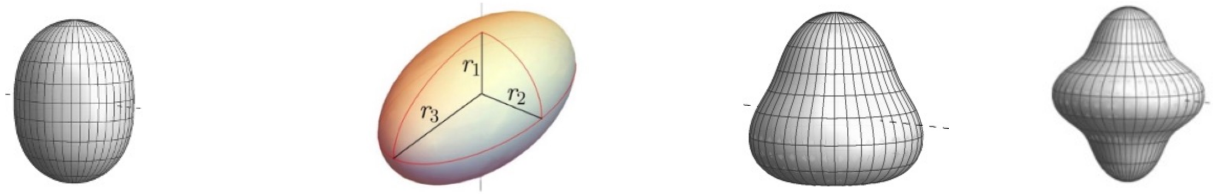
Shape-frozen like a snapshot during nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)

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 $\beta_{2U} \approx 0.28 \rightarrow \beta_{2U,WS} \approx 0.25$

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

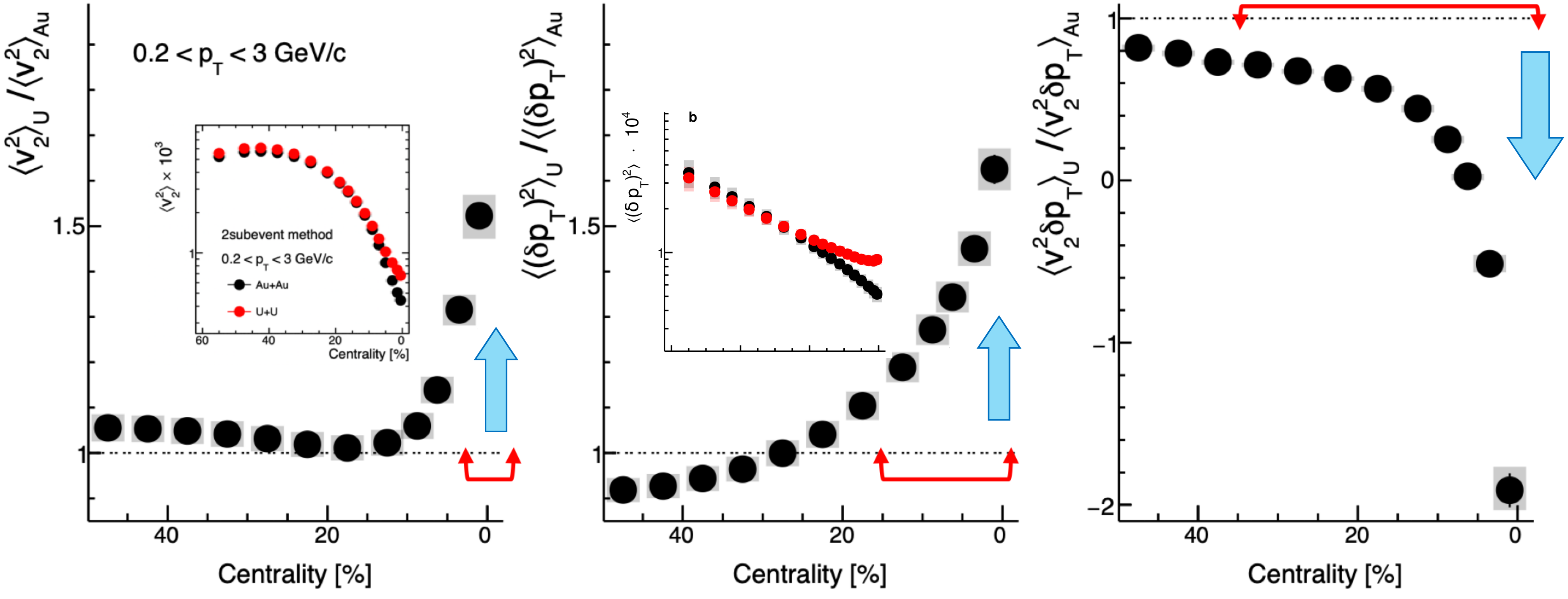
Low-energy estimate with rigid rotor assumption from B(E2) data $\beta_{2,\mathrm{LD}} = \frac{4\pi}{5R_0^2 Z}\sqrt{\frac{B(\mathrm{E2})}{e^2}}$

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

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

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

Ratio of observables



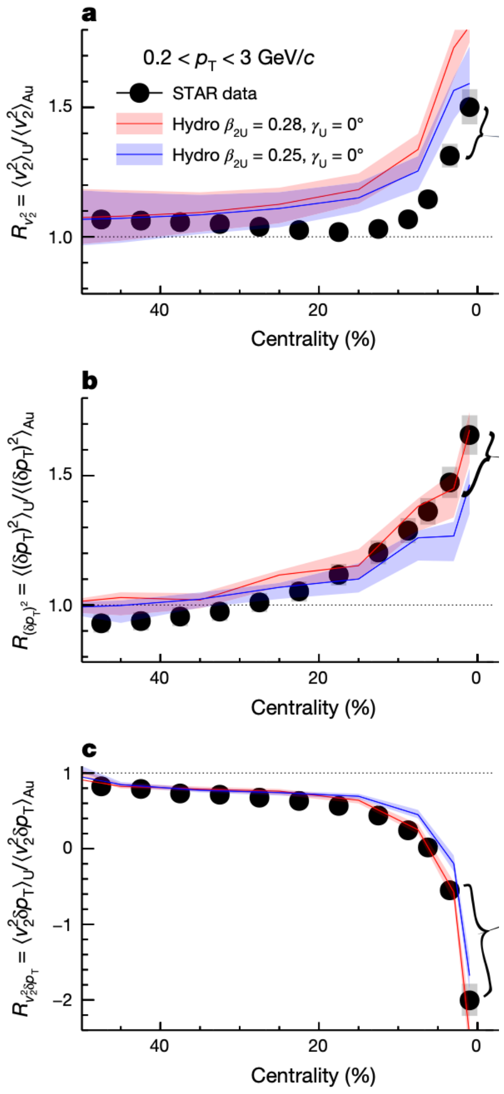
$$R_{\langle v_2^2\rangle} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$
$$R_{\langle(\delta p_T)^2\rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$
$$R_{\langle v_2^2 \delta p_T\rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3 \cos(3\gamma)$$

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

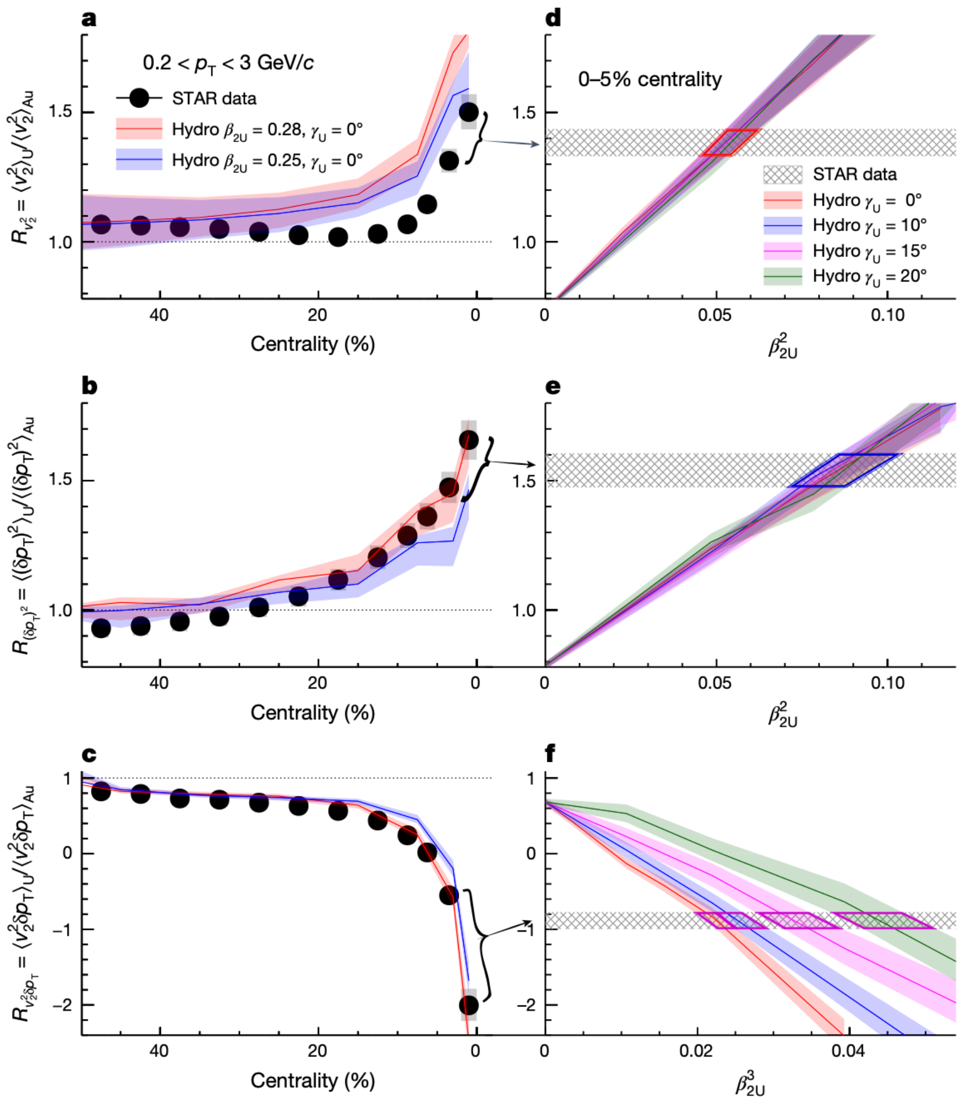
- Ratios cancel final state effects and isolate the effects of initial state/nuclear structures.

→ 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

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

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

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

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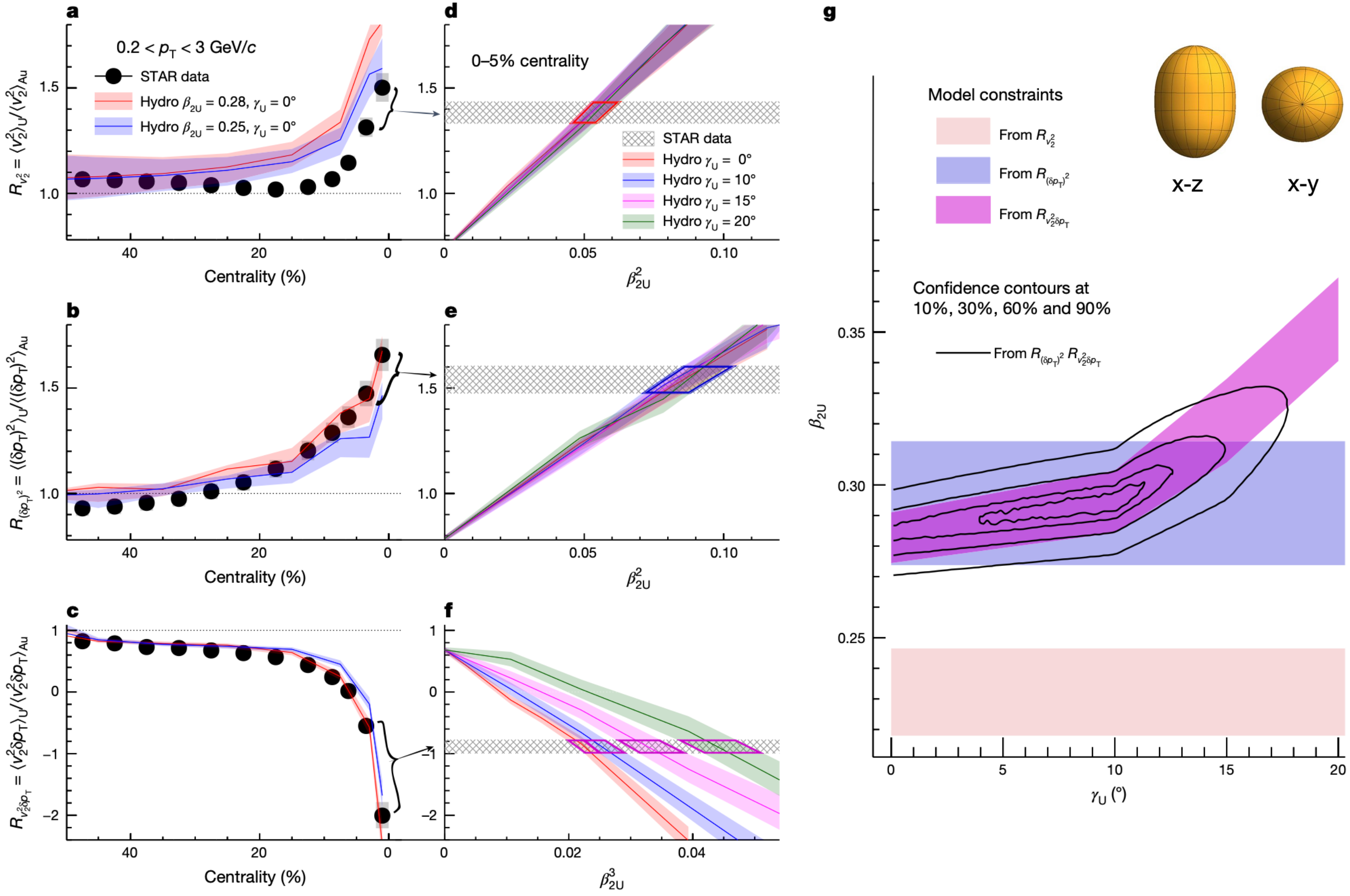

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$$R_{\langle v_2^2\delta p_T\rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3\cos(3\gamma)$$

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

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

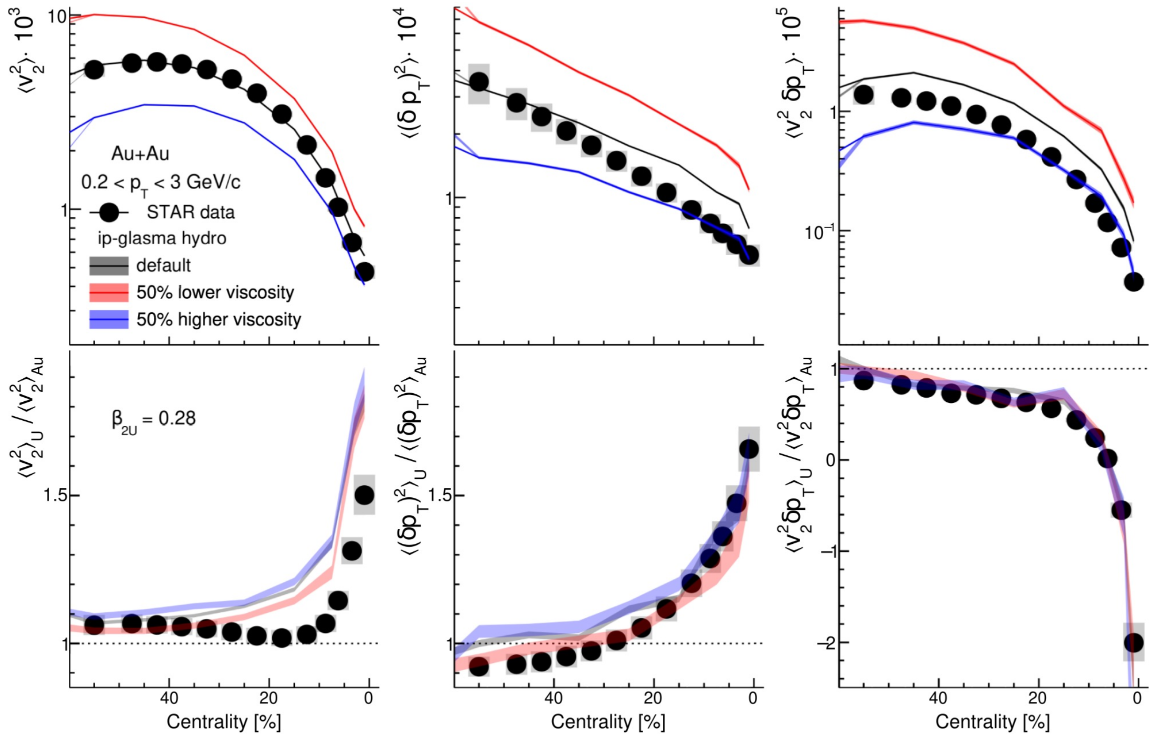
low-energy estimate:

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

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

Viscosity, nuclear parameters, and model variations

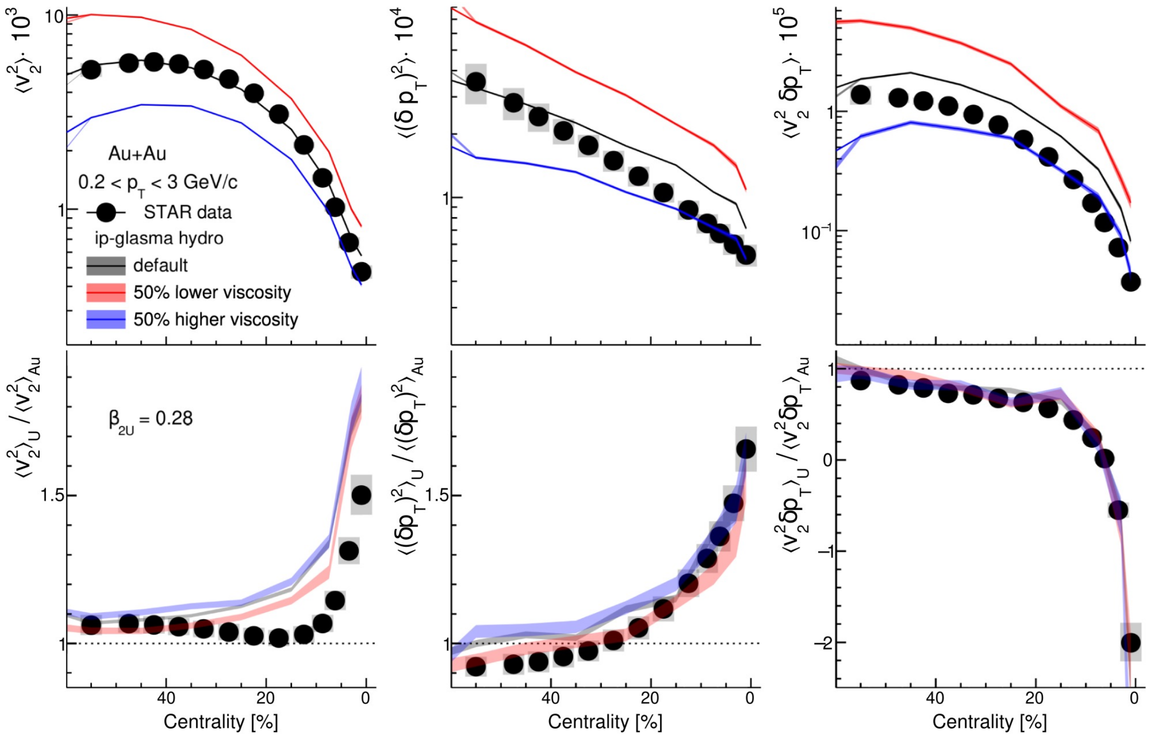
1) Taking the ratios cancels the viscosity effects.

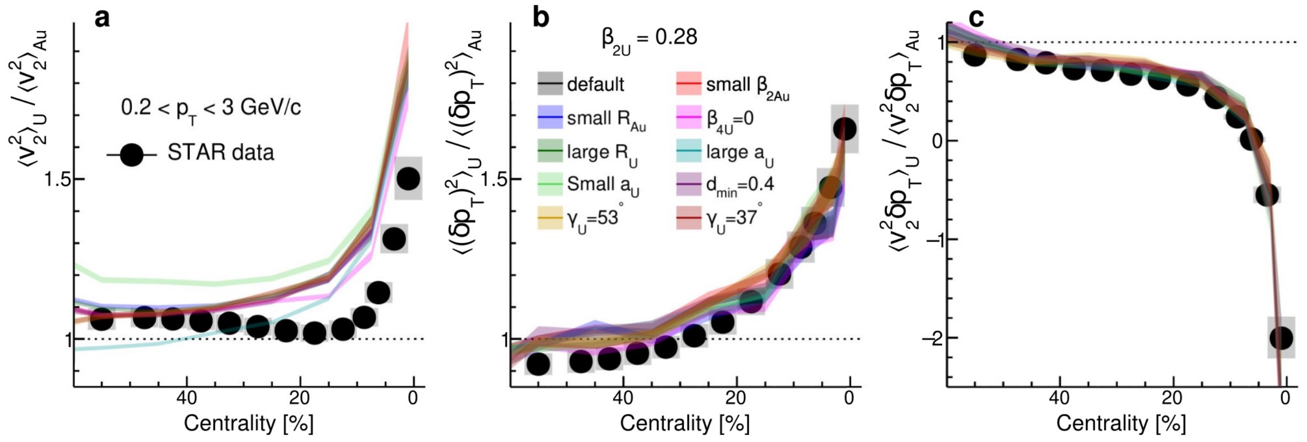


Viscosity, nuclear parameters, and model variations

2) Effect from nuclear parameters are small, included as model systematics.

1) Taking the ratios cancels the viscosity effects.





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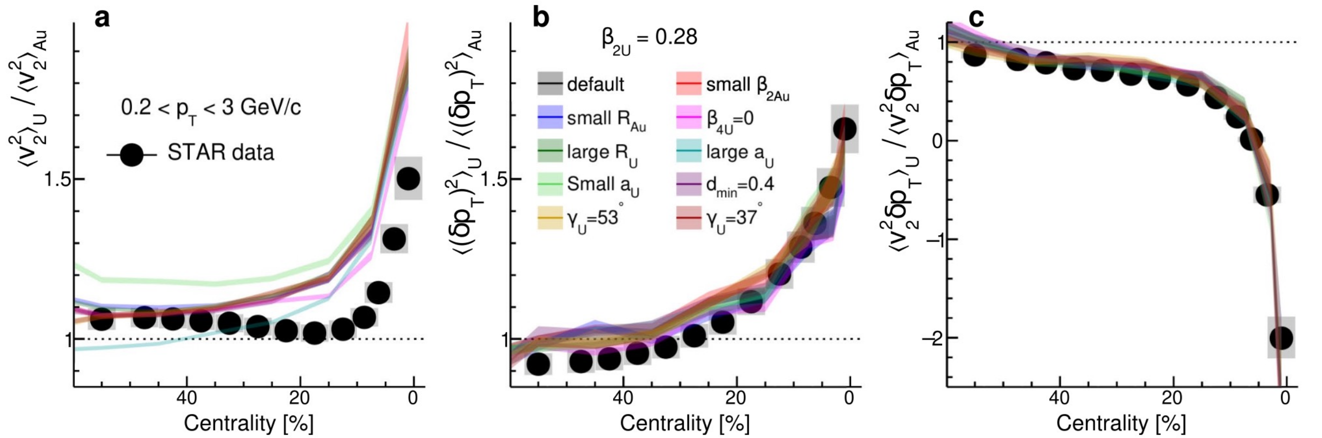

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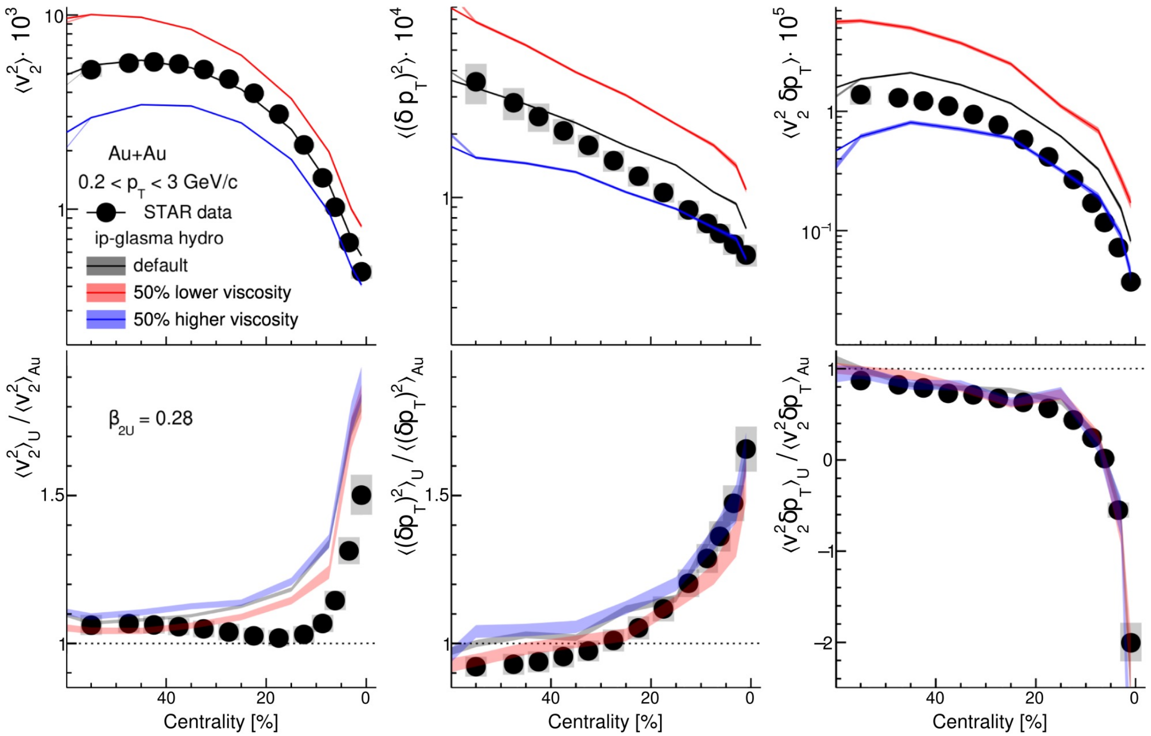
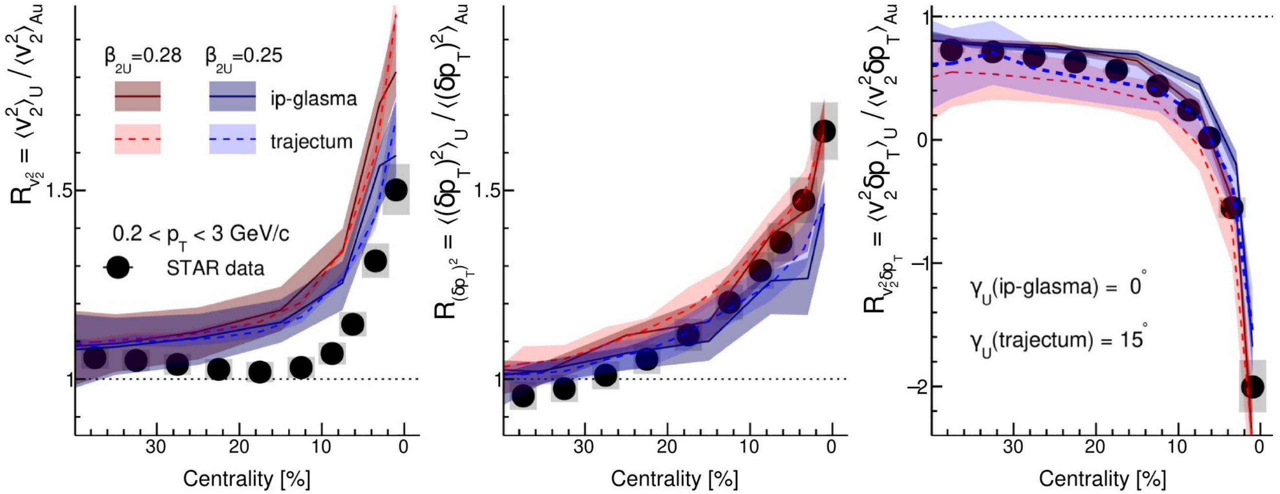
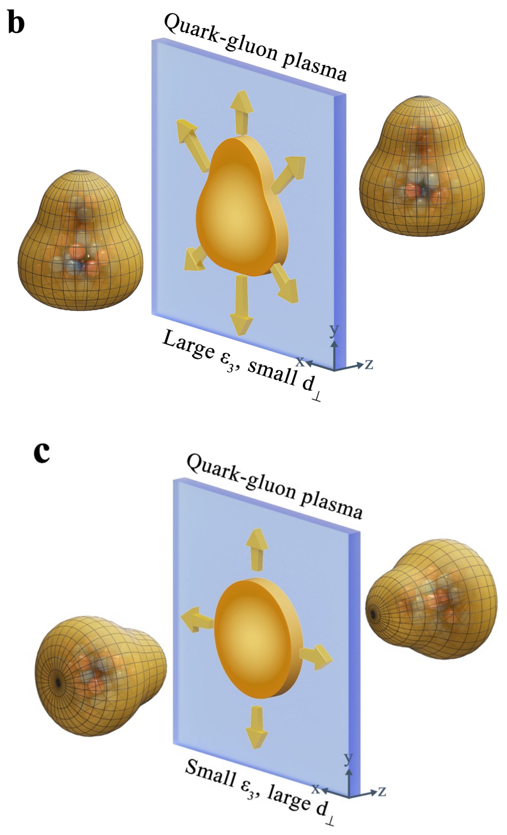


3) Another hydrodynamics model, Trajectum, shows rather consistent extractions even if it was not tuned to RHIC data.



Extracted $\beta_{2,\mathrm{U}}$ and γ_{U} values are robust.

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



However, v_3 is fluctuation driven, expect in central

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

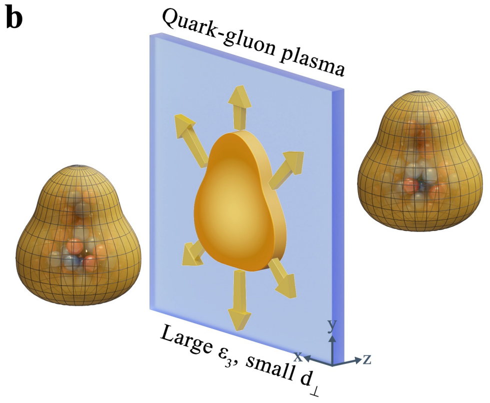
mass number

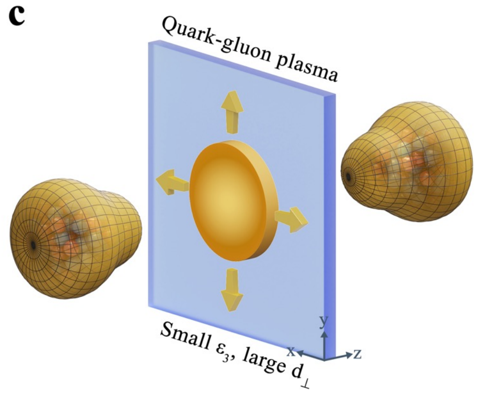
B. Alver and G. Roland, PRC 81, 054905 (2010)

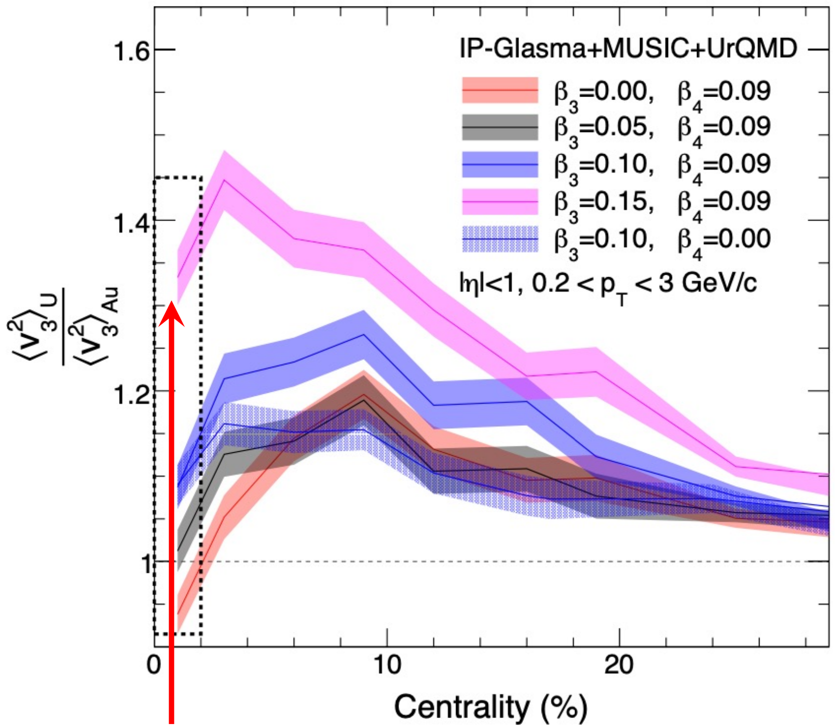
Evidence of octupole deformation $\beta_{3,\mathrm{U}}$

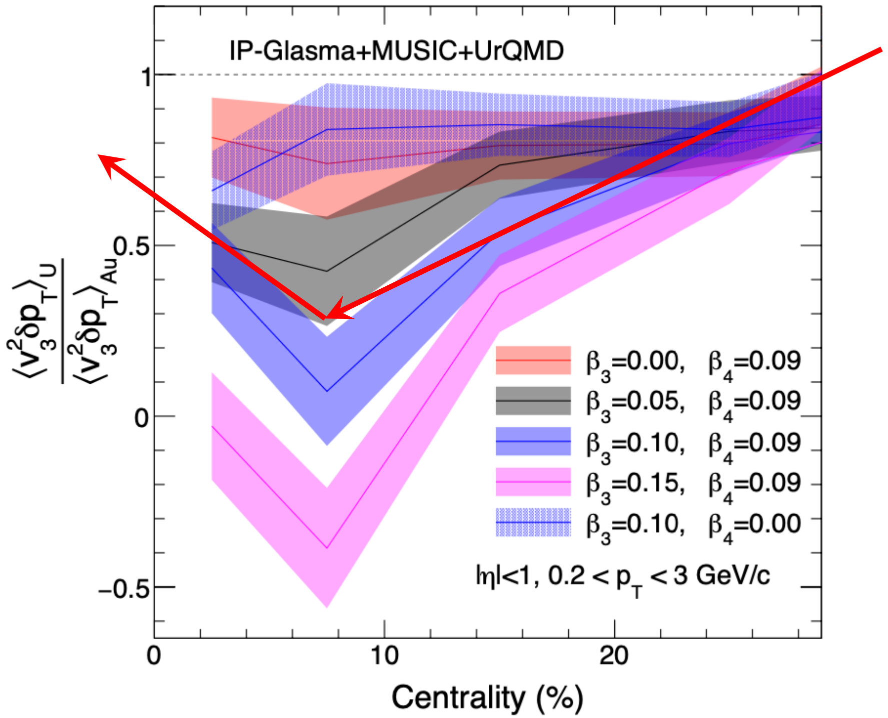
IP-Glasma+MUSIC calculations

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

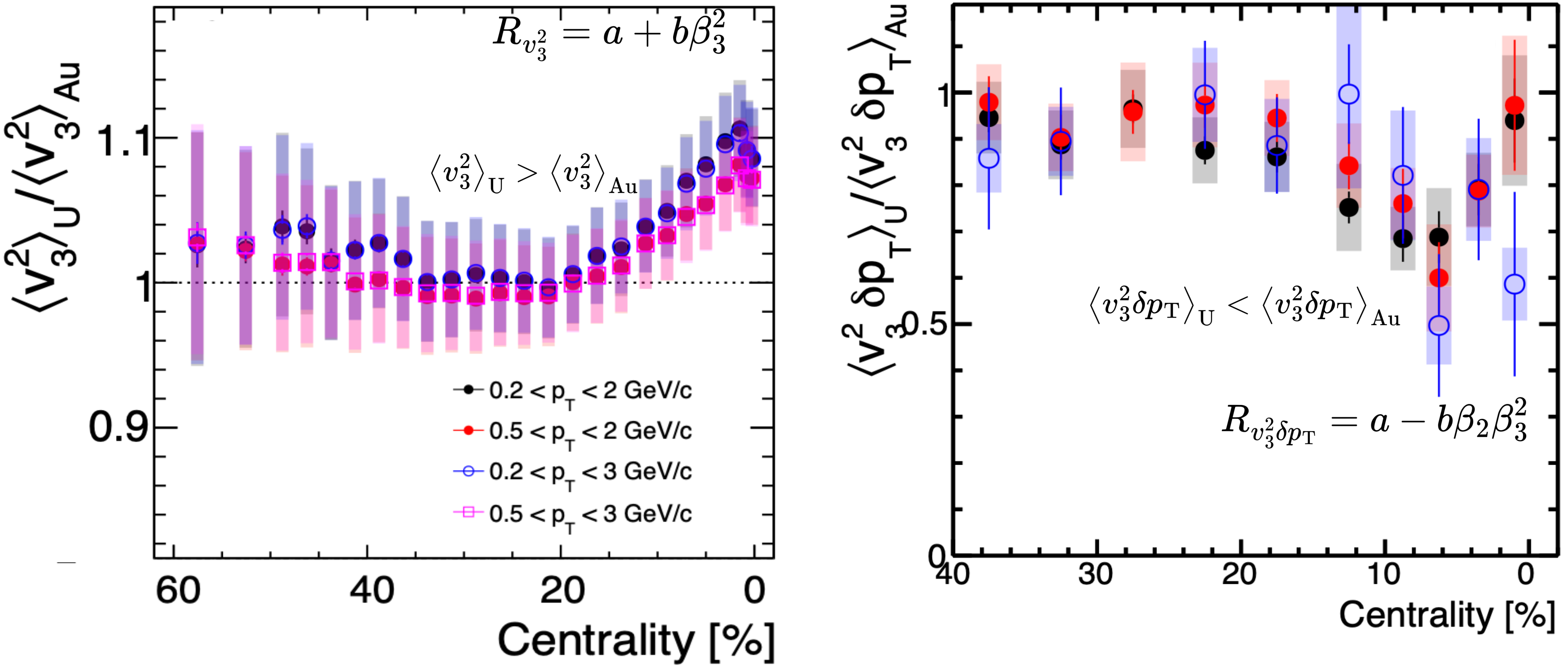
$\langle v_3^2\rangle$ follows a linear increase with β_3^2,

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 $\beta_{3,\mathrm{U}}$

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

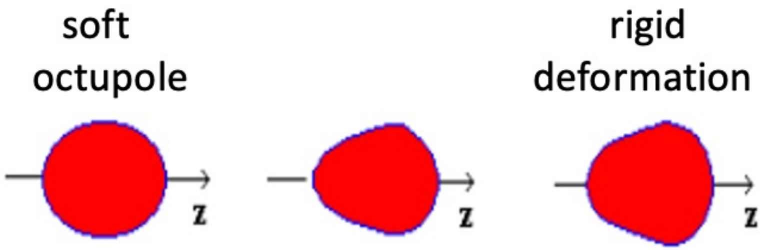


- No apparent p_T dependence
- Order of v_3 and v_3-p_T reversed by considering non-zero $\beta_{3,U}$, $\beta_{4,U}$.
- An evidence and modest $\beta_{3,U}$ ~ 0.08-0.10 are confirmed and $\beta_{3U} \sim \beta_{4U}$

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

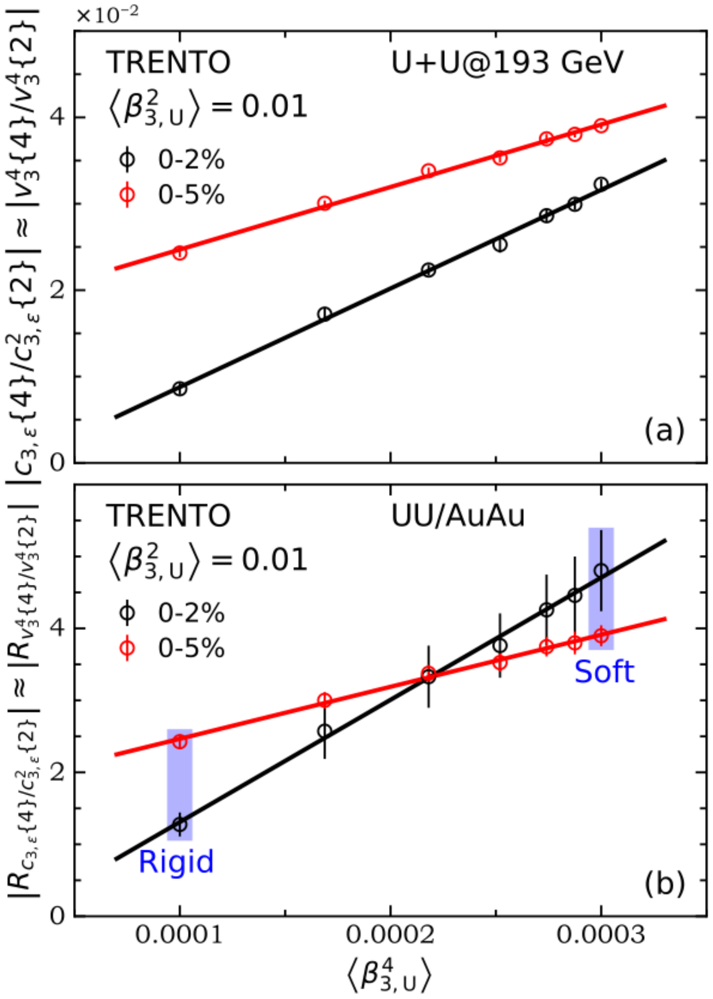


$$\langle \beta_3^2 \rangle = \bar{\beta}_3^2 + \sigma_{\beta_3}^2$$

Case	$\bar{\beta}_3$	σ_{β_3}	$\langle\beta_3^2\rangle$	$\langle\beta_3^4\rangle$
$\mathrm{U_{case0}}$	0.00	0.100	0.01	0.000300
$\mathrm{U_{case1}}$	0.05	0.087	0.01	0.000288
$\mathrm{U_{case2}}$	0.06	0.080	0.01	0.000274
$\mathrm{U_{case3}}$	0.07	0.071	0.01	0.000252
$\mathrm{U_{case4}}$	0.08	0.060	0.01	0.000218
$\mathrm{U_{case5}}$	0.09	0.044	0.01	0.000169
$\mathrm{U_{case6}}$	0.10	0.000	0.01	0.000100

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

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



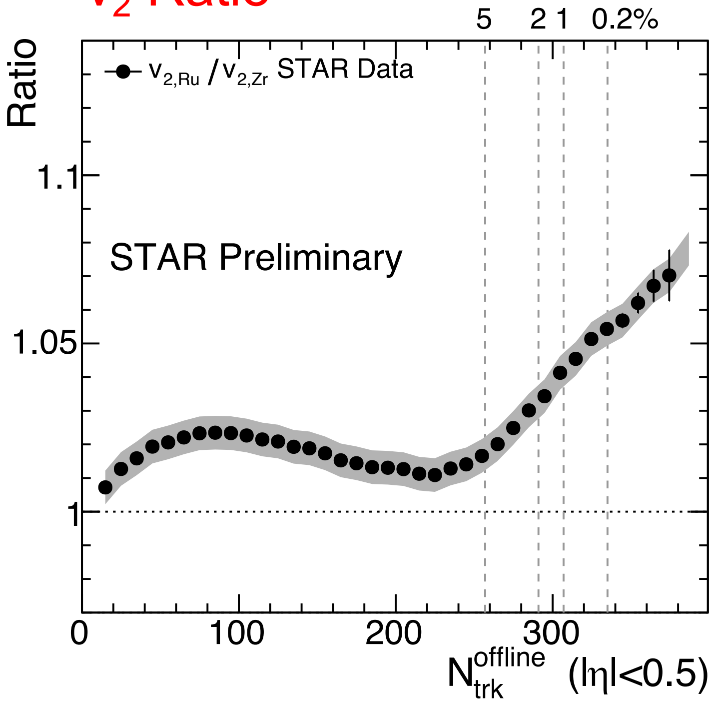
Four-particle correlation is linearly scaled to $\langle \beta_{3,\mathrm{U}}^4 \rangle$.

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

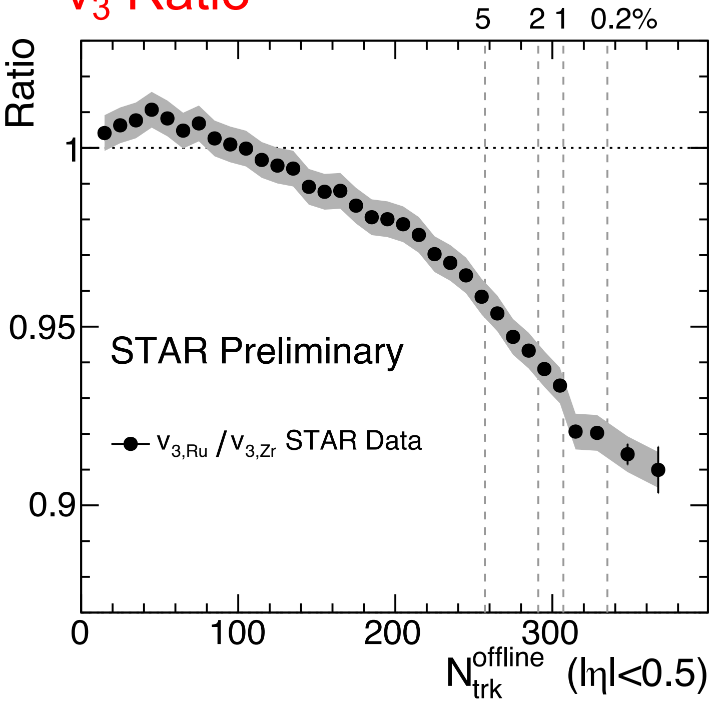
B. G. Zakharov, *JETP Lett. 112, 393 (2020);* P. Carzon et al., *PRC 102, 054905 (2020);* H. Xu *et al., PRC112, L051901 (2025);* K. Hagino and M. Kitazawa, 2508.05125

Nuclear structure via collectivity v_n ratio

v_2 Ratio

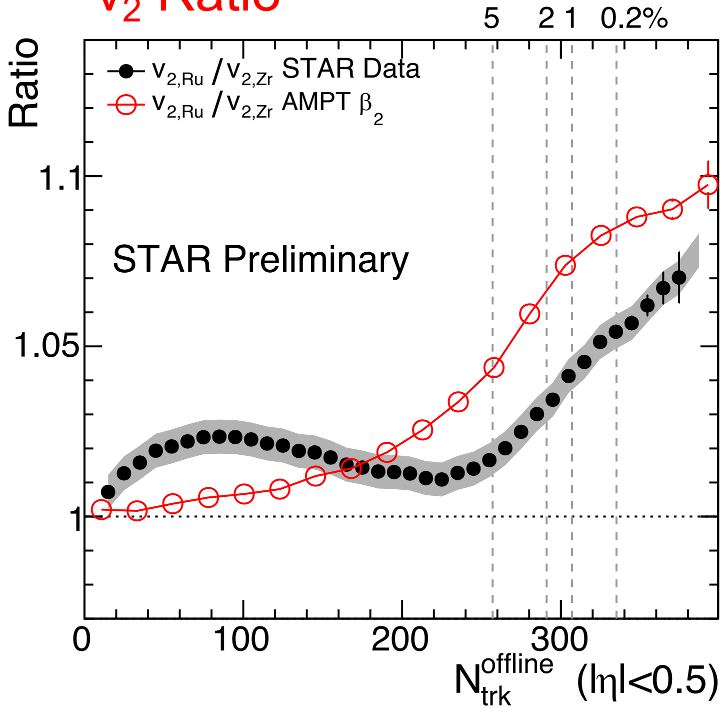


v_3 Ratio

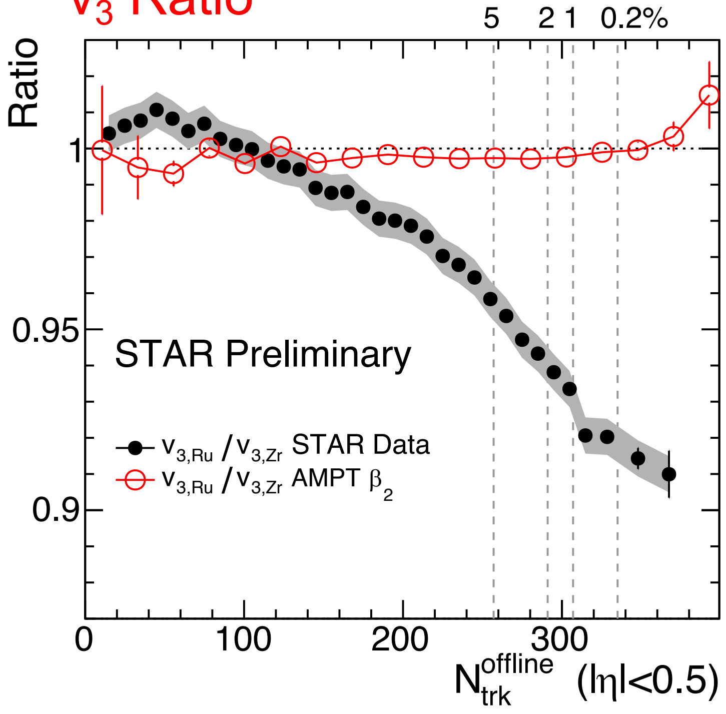


Nuclear structure via collectivity v_n ratio

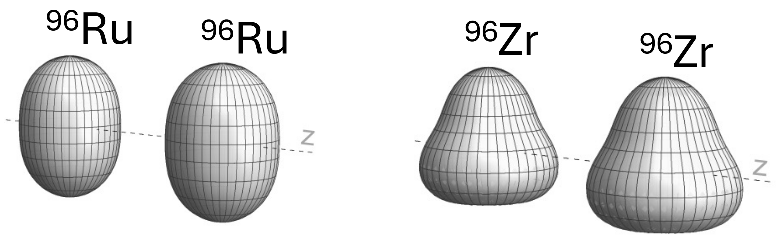
v_2 Ratio



v_3 Ratio



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



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

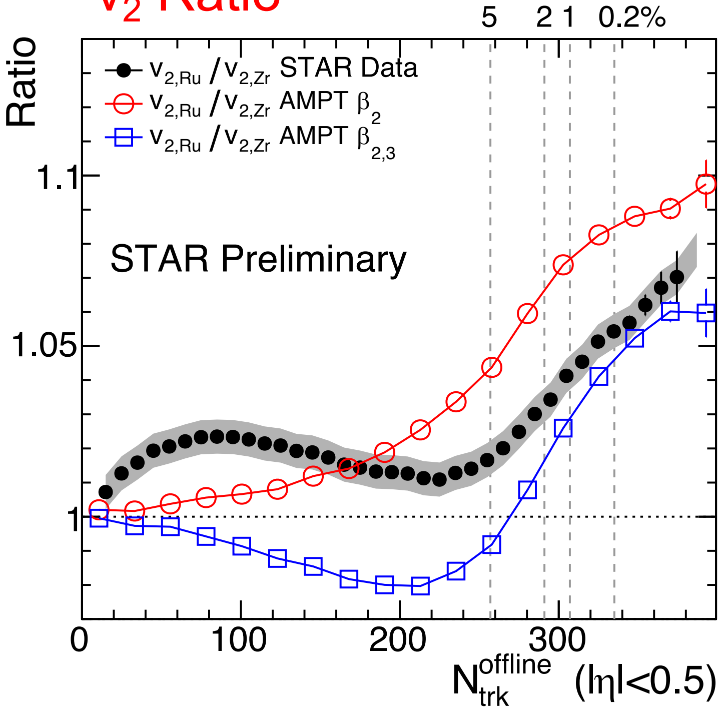
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

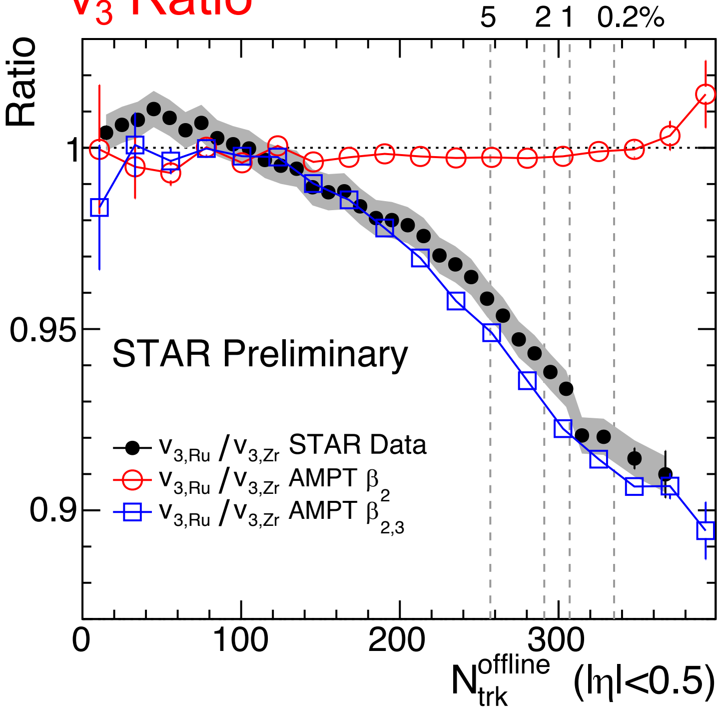
C. Zhang and J. Jia, *PRL128, 022301(2022)*; J. Jia, C. Zhang, *PRC 107, L012901 (2023)*

Nuclear structure via collectivity v_n ratio

v_2 Ratio



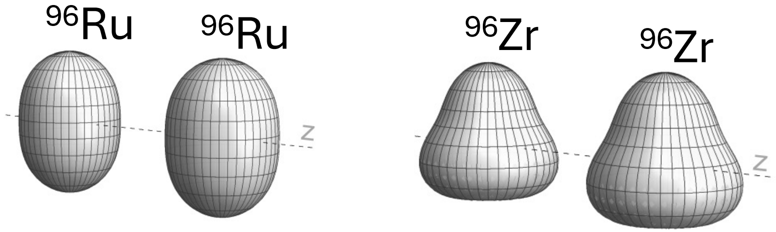
v_3 Ratio



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

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

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



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

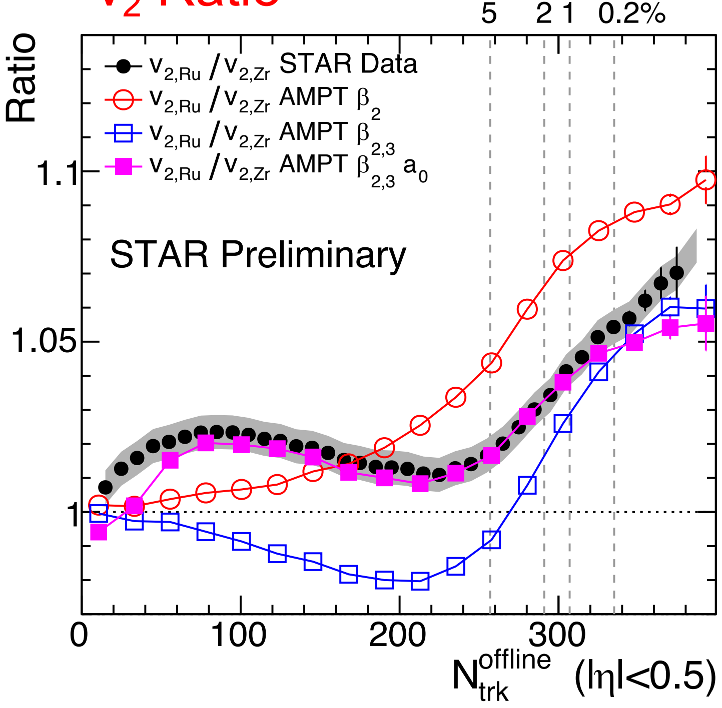
	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
difference	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

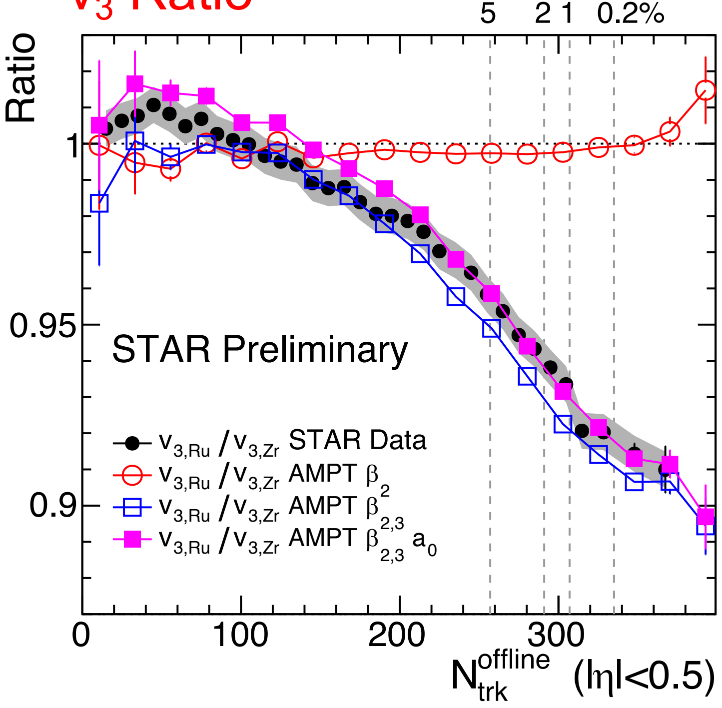
C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, C. Zhang, PRC 107, L012901 (2023)

Nuclear structure via collectivity v_n ratio

v_2 Ratio



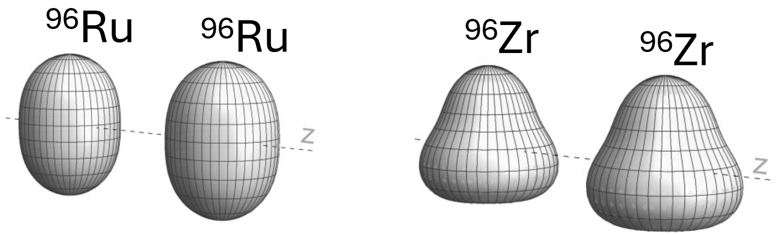
v_3 Ratio



$\beta_{2,Ru} \sim 0.16$ 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

Δa_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

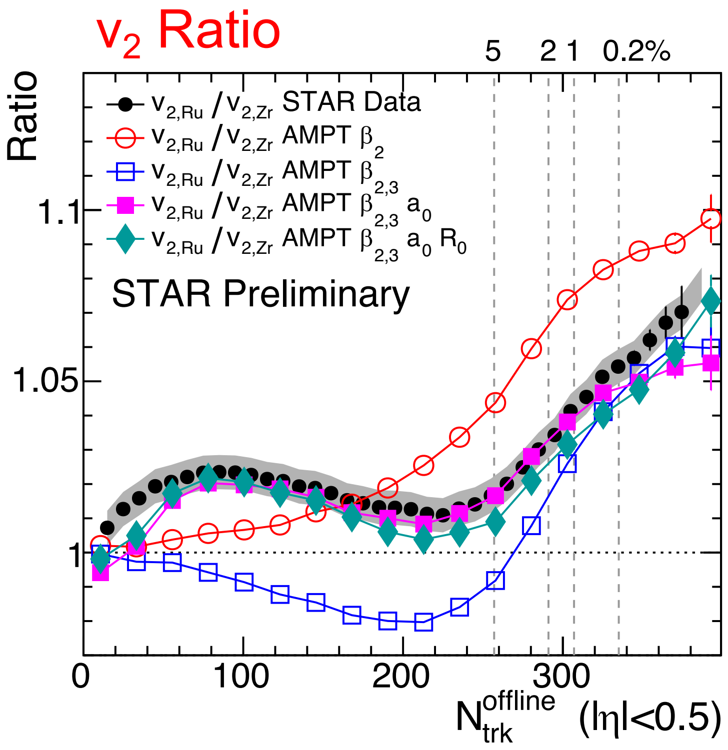
$\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$ $\beta_{3,\mathrm{Zr}} = 0.20 \pm 0.02$

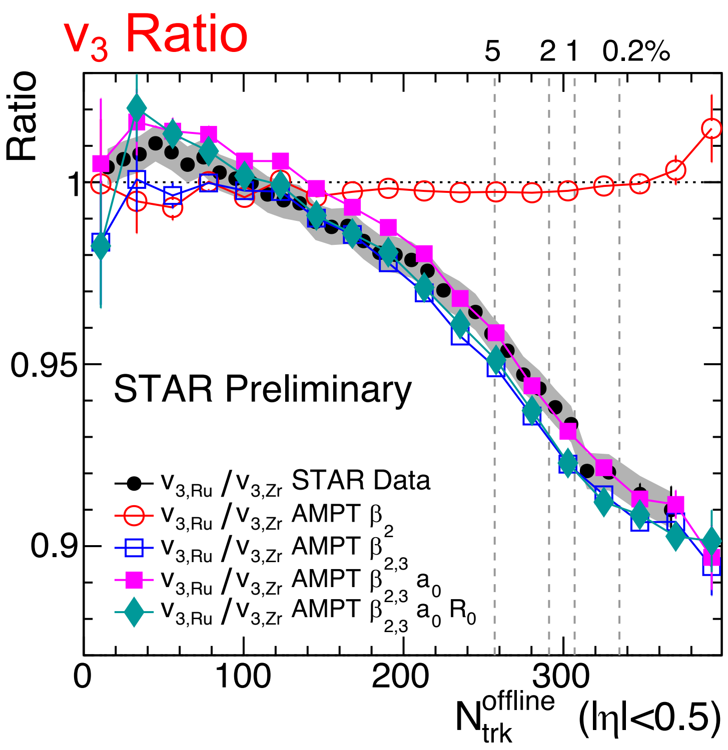
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

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



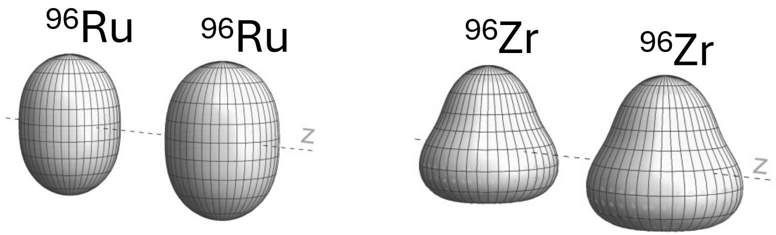


$\beta_{2,Ru} \sim 0.16$ increase v_2, no influence on v_3 ratio

$\beta_{3,Zr} \sim 0.2$ 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

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

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

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

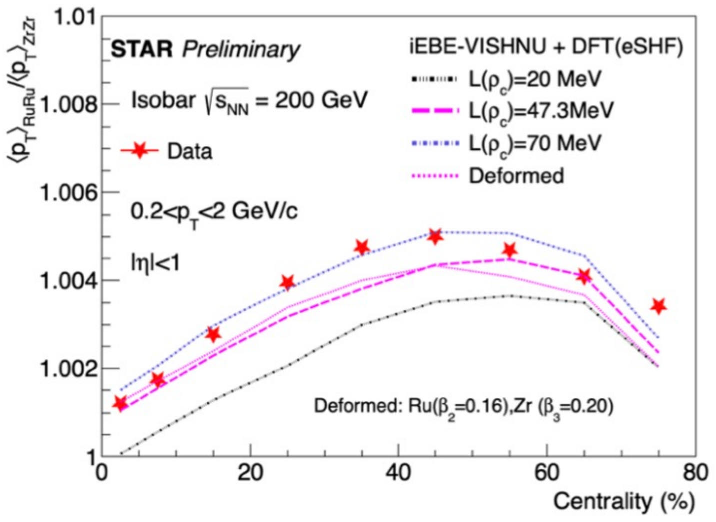
Current estimation is from transport model

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

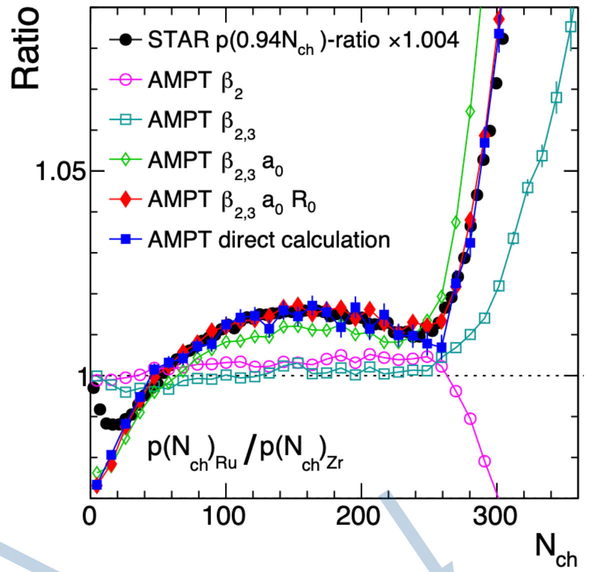
Imaging the radial structures (neutron skin)

Radial parameters R_0, a_0 are properties of one-body distribution → $\langle p_T \rangle$, $\langle N_{ch} \rangle$, $v_2^{RP} \sim v_2\{4\}$, σ_{tot},

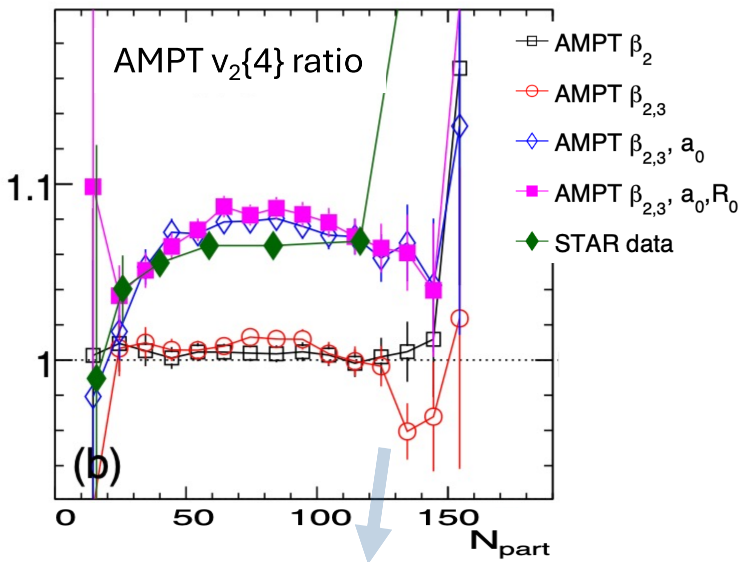
H. Xu, QM2023



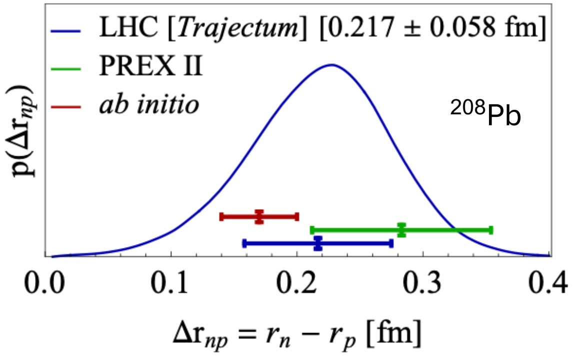
J. Jia, C. Zhang, PRC 107, L02901 (2023)



J. Jia, G. Giacalone, C. Zhang, PRL 131, 022301(2023)

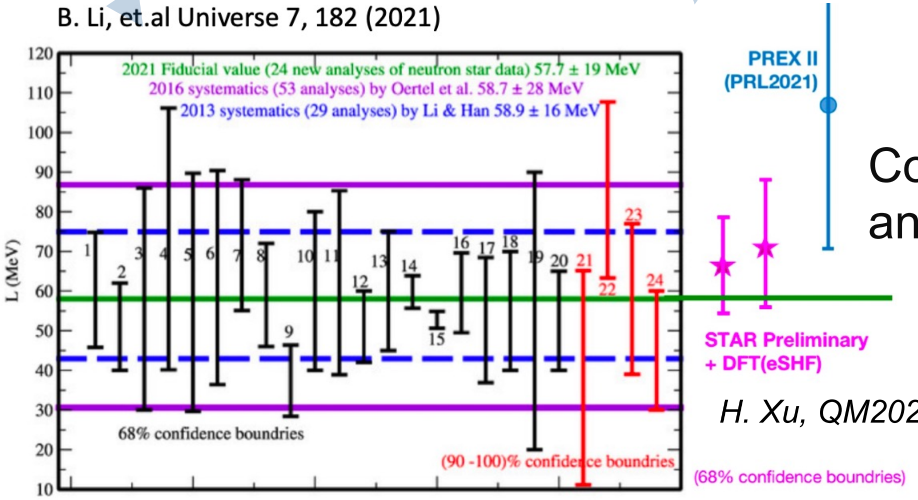


Current puzzle in low-energy nuclear physics



G. Giacalone, G. Nijs, W. Schee, PRL 131, 202302 (2023)

B. Li, et.al Universe 7, 182 (2021)

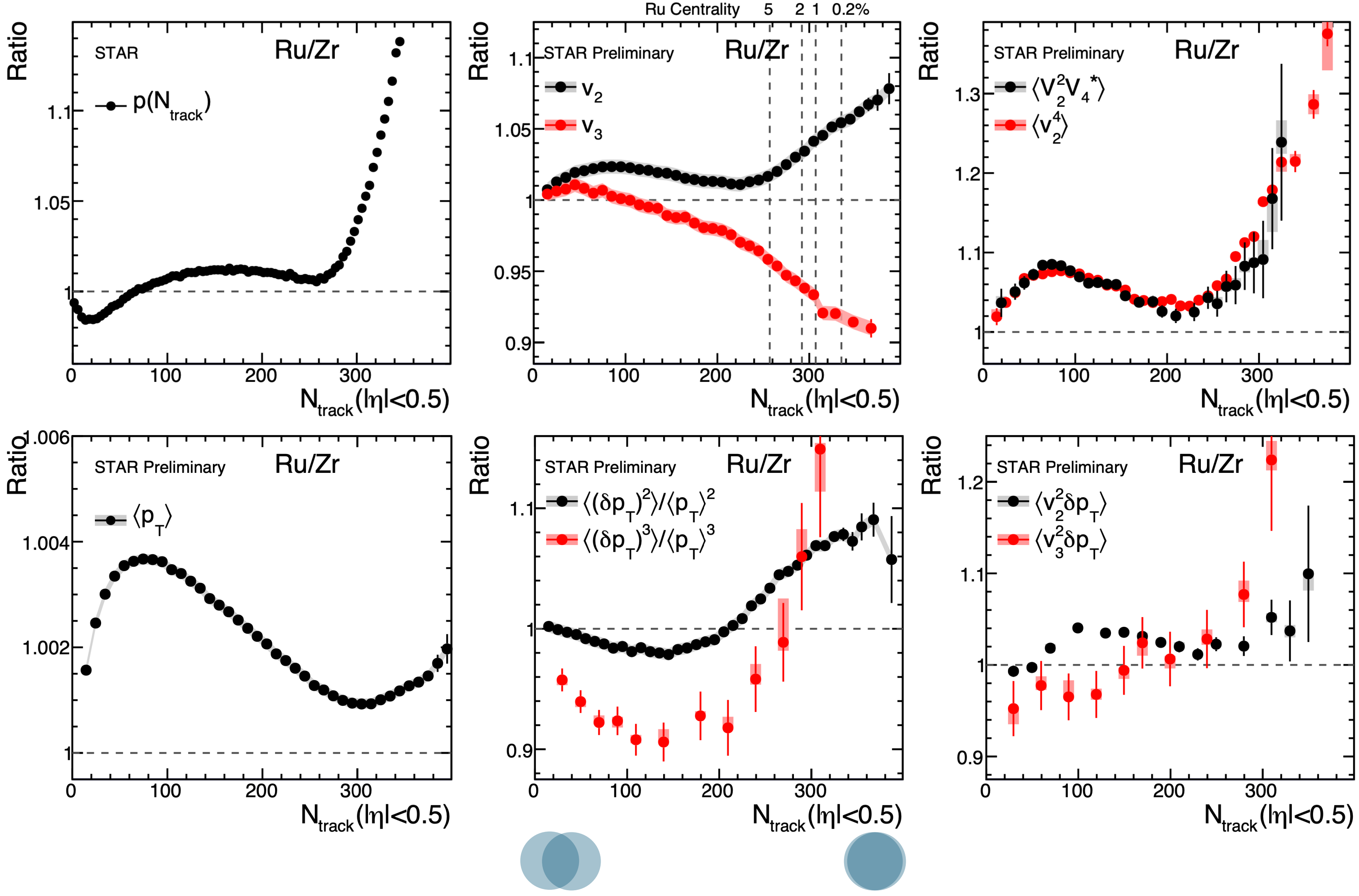


Constrain neutron skin and symmetry energy

H. Xu, QM2023

Nuclear structure is inherent of heavy-ion probes

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



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

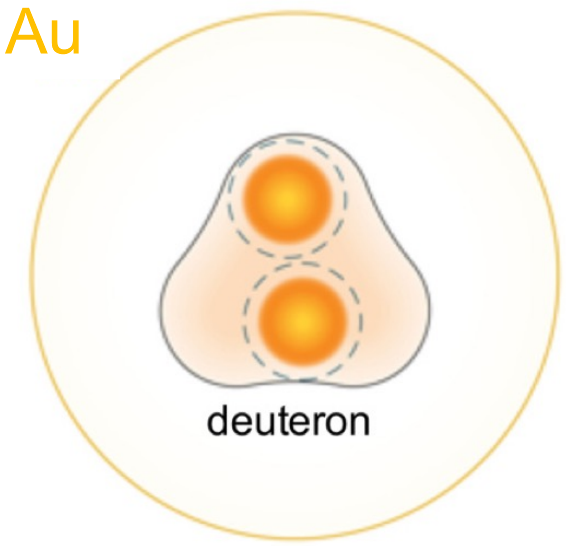
--- from one-body distribution to many-body nucleon correlations

$$\rho(r) \propto \frac{1 + w\left(r^2/R^2\right)}{1 + e^{(r-R)/a_0}}$$

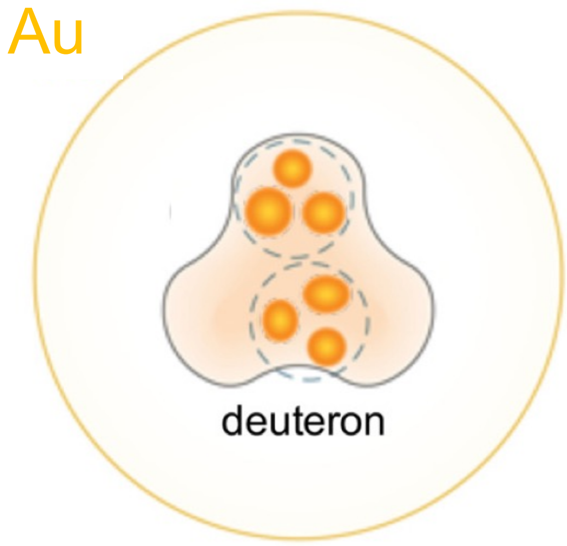
→ Modern *ab* initio first-principle calculations

Engineering QGP shape and nucleon-nucleon correlations

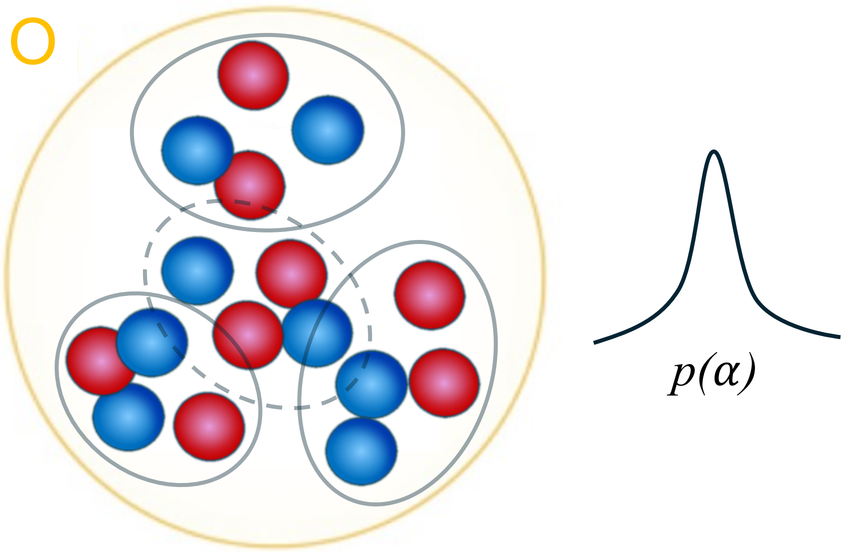
Nucleon fluctuation



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)

W. Broniowshi, E.R. Arriola, PRL 112, 112501 (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)

G. Giacalone et al., *PRL135, 012302 (2025), PRL134, 082301 (2025)*

S. Jahan, Roch, C. Shen, *2507. 11394; …*

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

Nucleon-nucleon correlations in finite quantum many-body systems

Possible cluster in ground-state $^{16}_{8}O$ nuclei based on low energy, but NO clear experimental evidence.

***Woods-Saxon:** without many-body nuclear correlation*

***Nuclear Lattice Effective Field theory (NLEFT):** model with many-nucleon **correlation** including α clusters*

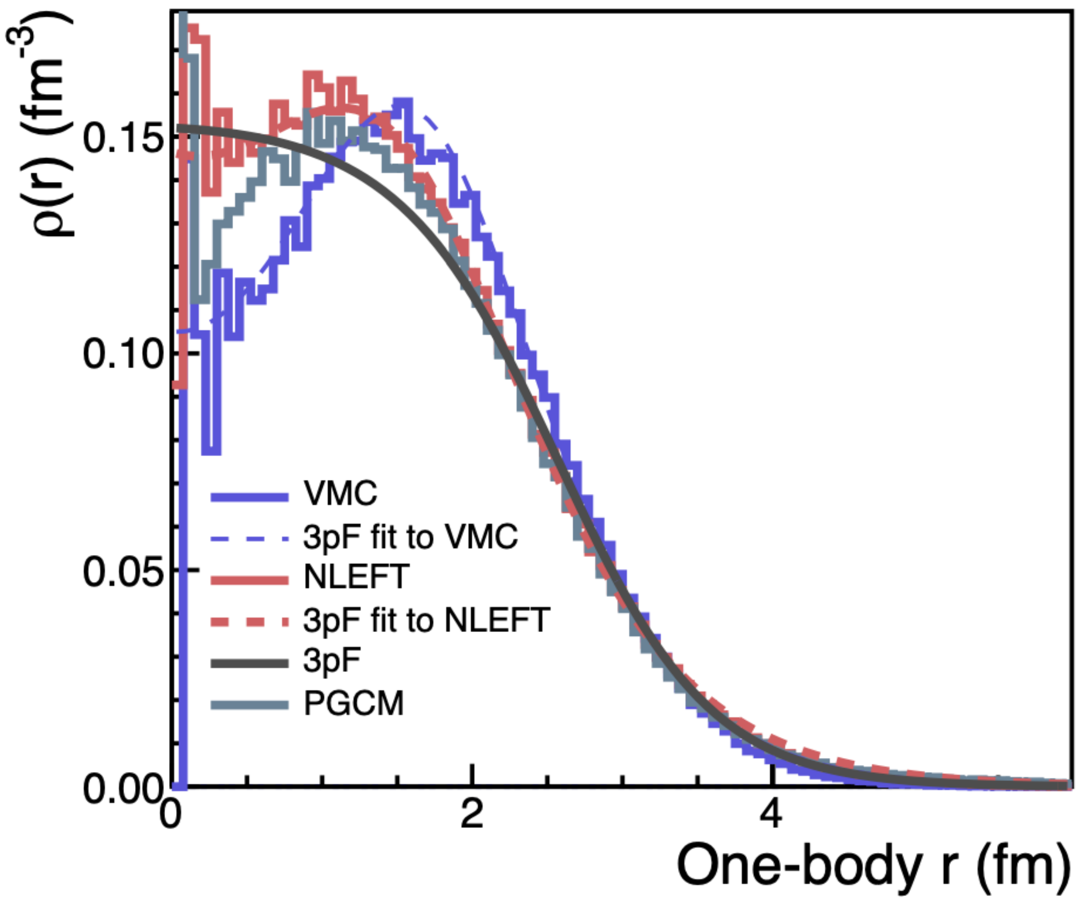
Lu et al., *PLB 797, 134863 (2019)*
M. Freer et al., *Rev. Mod. Phys. 90, 035004 (2018)*
S. Elhatisari et al. *Nature 630, 59 (2024)*

***Variational auxiliary field diffusion Monte Carlo (VMC):** MC solution of Schrödinger eq. from the time evolution of trial wave function.*

A. Lonardoni et al., *PRC97, 044318 (2018)*
J. Carlson and R. Schiavilla, *Rev. Mod. Phys. 70, 743 (1998)*

***ab-initio Projected Generator Coordinate Method (PGCM):** Wave function from variational calculation (as in density functional theory*)

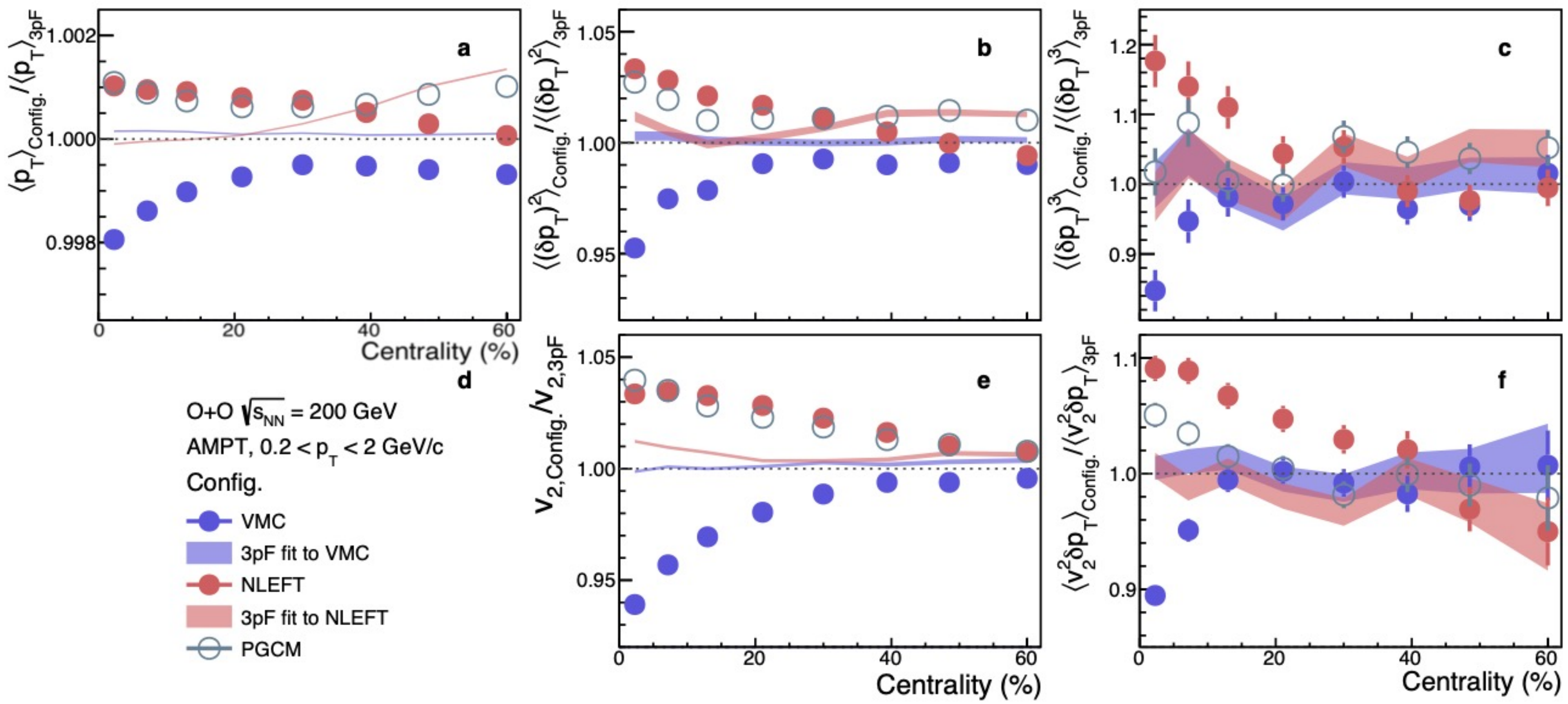
Frosini et al., *EPJA 58, 62 (2022); EPJA 58, 63 (2022); EPJA 58, 64 (2022)*



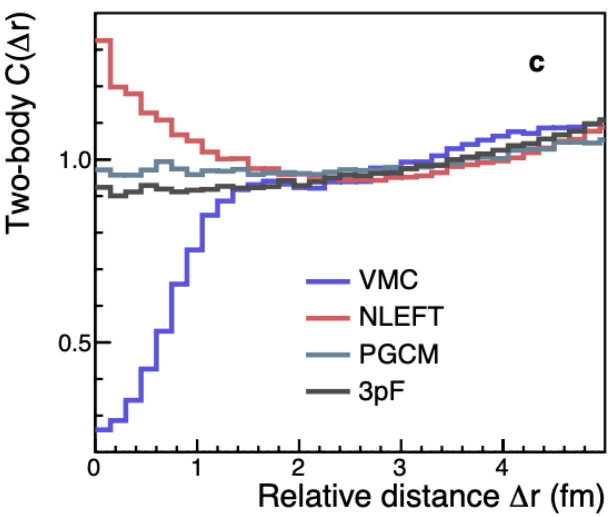
Ab-initio nucleon-nucleon correlations and their impact on high-energy

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



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

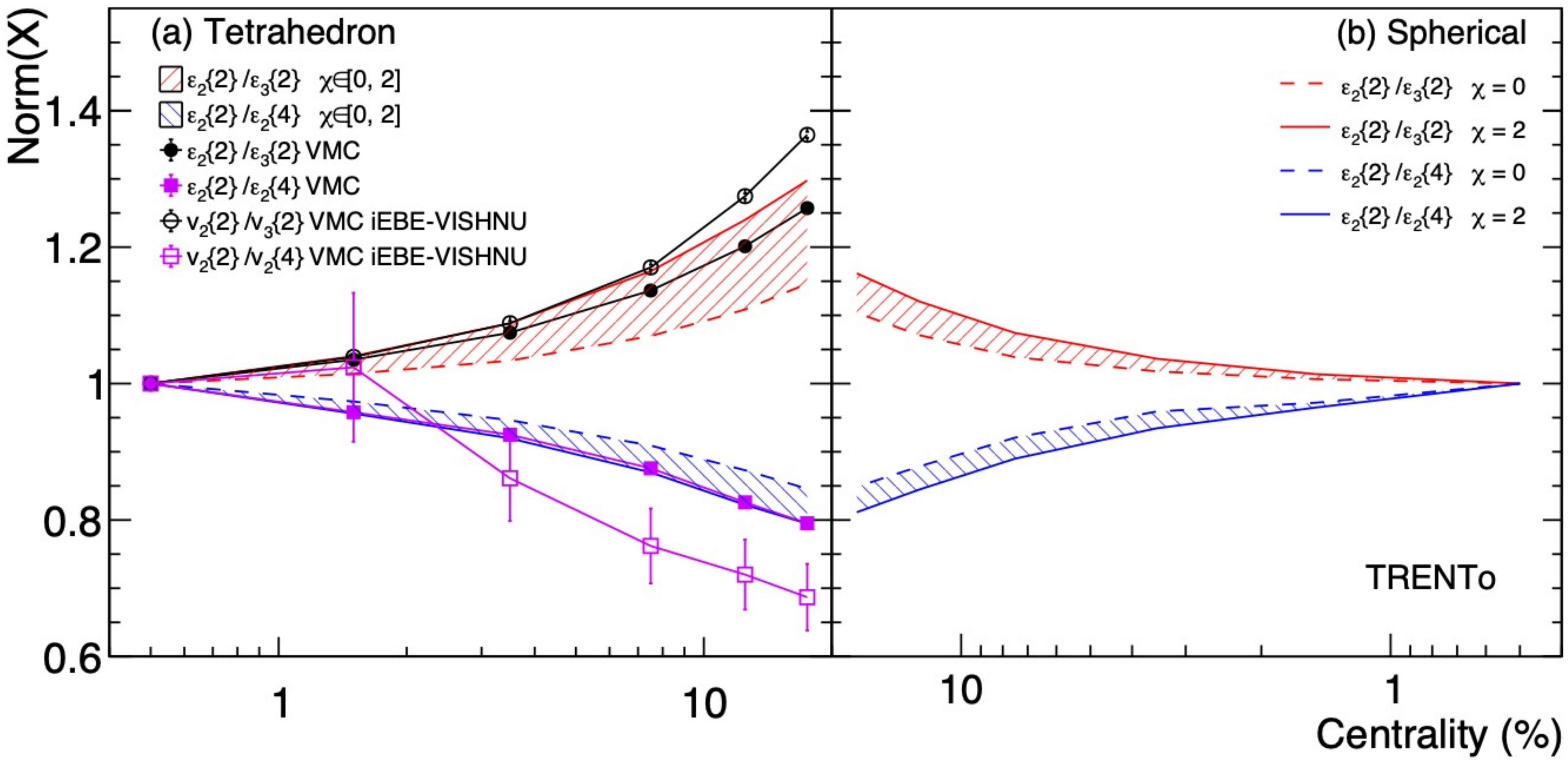
- 3pF as the baseline can NOT capture the NN correlations.
- Distinct differences are observed between VMC and NLEFT/PGCM.
- Central collision is prominent.

Data analysis is ongoing and will be presented in sQM.

Probing the tetrahedral α clusters in ^{16}O nucleus

Jin-Yu Hu, Hao-jie Xu, Xiaobao Wang, Shi Pu, *2507.01493*

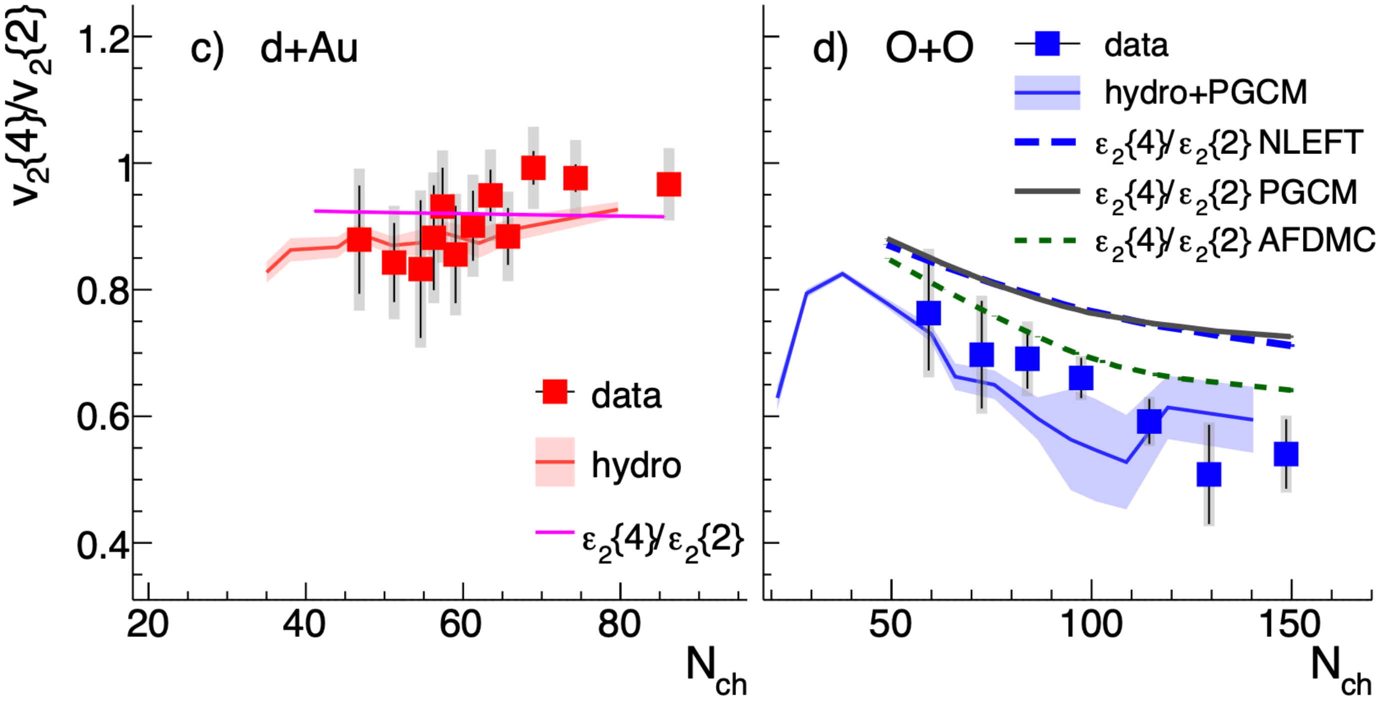
Compactness of cluster



Predictions for centrality-dependent trends are significantly sharper with tetrahedral deformation than with spherical symmetry.

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645*



S. Jahan, Roch, C. Shen, *2507. 11394*

NLEFT from Dean Lee*; PGCM from* Benjamin Bally

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

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

$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from three models:

AFDMC vs. EFT/PGCM has a visible difference.

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

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

G. Giacalone et al., *PRL135, 012302 (2025), PRL134, 082301 (2025)*

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

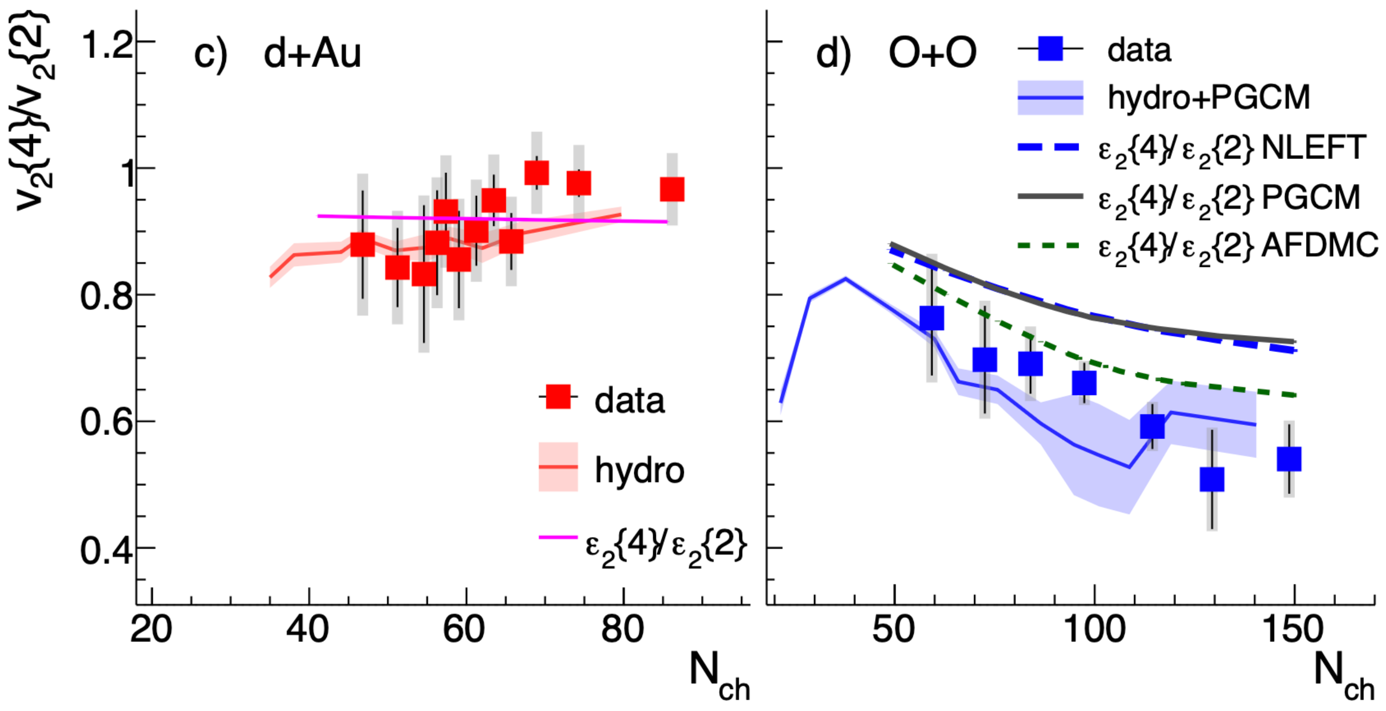
STAR, PRL 130, 242301 (2023)

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

d+Au is flat; Large enhancement in O+O with continuous decrease

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645*



S. Jahan, Roch, C. Shen, *2507. 11394*   *NLEFT from* Dean Lee*; PGCM from* Benjamin Bally

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***ε_2*{4} /*ε_2*{2} from three models:**

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Geometric scan elucidates nuclear tomography and strong nuclear force?

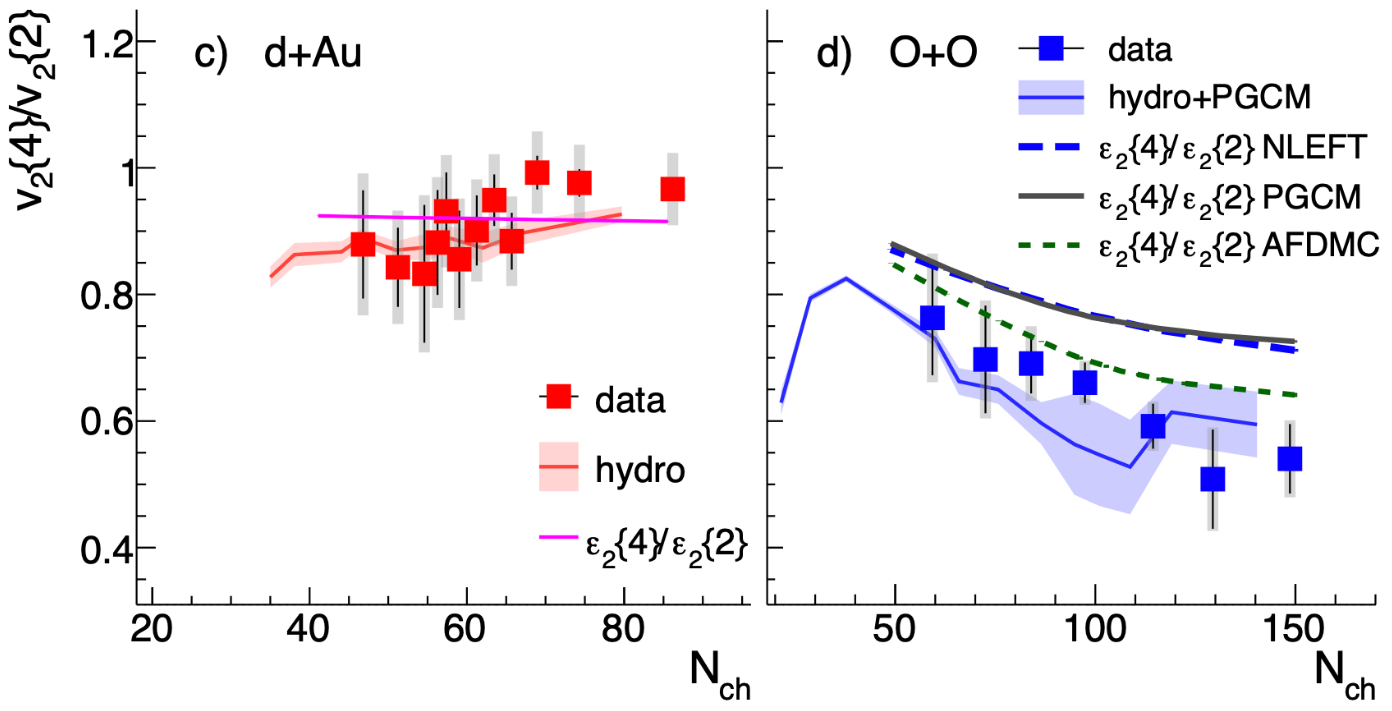
data & high-energy model & low-energy inputs

More results will be presented in sQM.

d+Au is flat; Large enhancement in O+O with continuous decrease

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645*



S. Jahan, Roch, C. Shen, *2507. 11394* *NLEFT from* Dean Lee*; PGCM from* Benjamin Bally

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$\varepsilon_2\{4\}$ /$\varepsilon_2\{2\}$ from three models:

AFDMC vs. EFT/PGCM has a visible difference.

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

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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?

data & high-energy model & low-energy inputs

More results will be presented in sQM.

Interesting measurements from LHC O+O/Ne+Ne

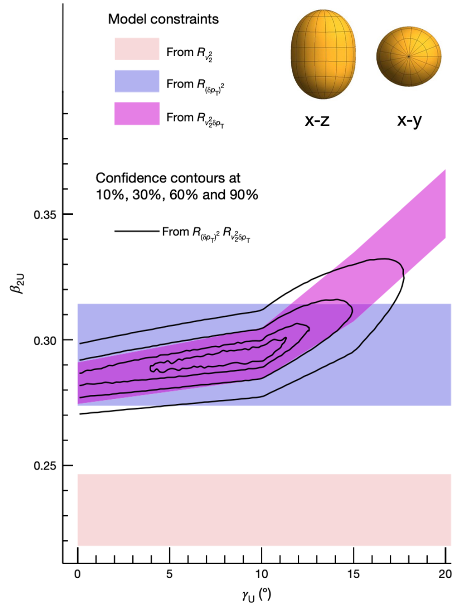
New avenue: shape imaging method for light ions

d+Au is flat; Large enhancement in O+O with continuous decrease

IV. Conclusions and Outlooks

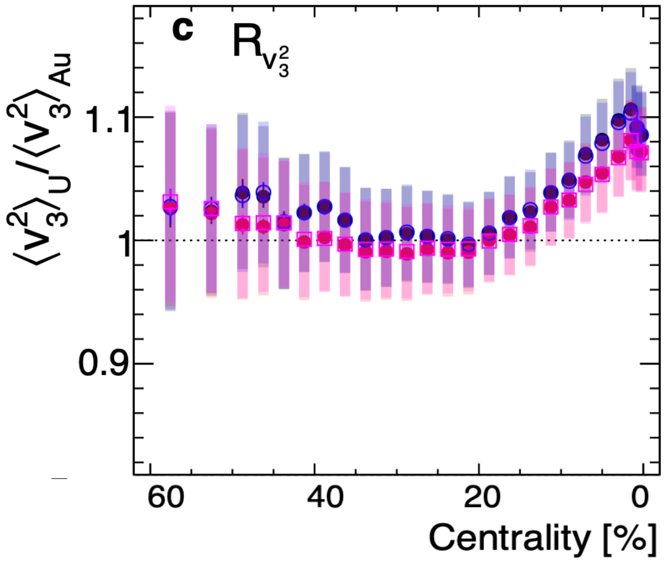
1. The signatures of nuclear structure in nuclear collisions are ubiquitous:

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



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

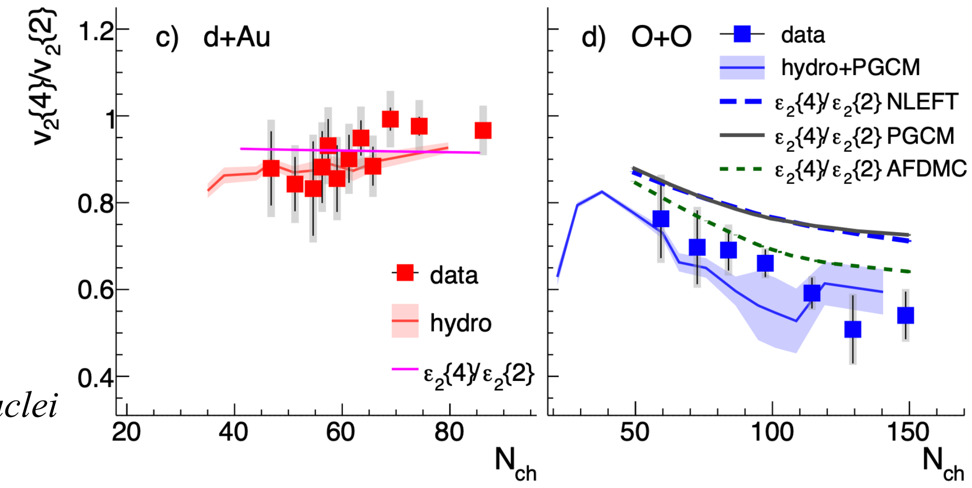
STAR, *Rep. Prog. Phys.* **88,** 108601 (2025)



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

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

STAR, *2510.19645*



NN correlations is remarkable

2. Many potentially interesting works to study

→ Rigid and soft β_n and γ (shape fluctuations/coexistence)

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

→ TeV-GeV facilities, LHC and HIAF

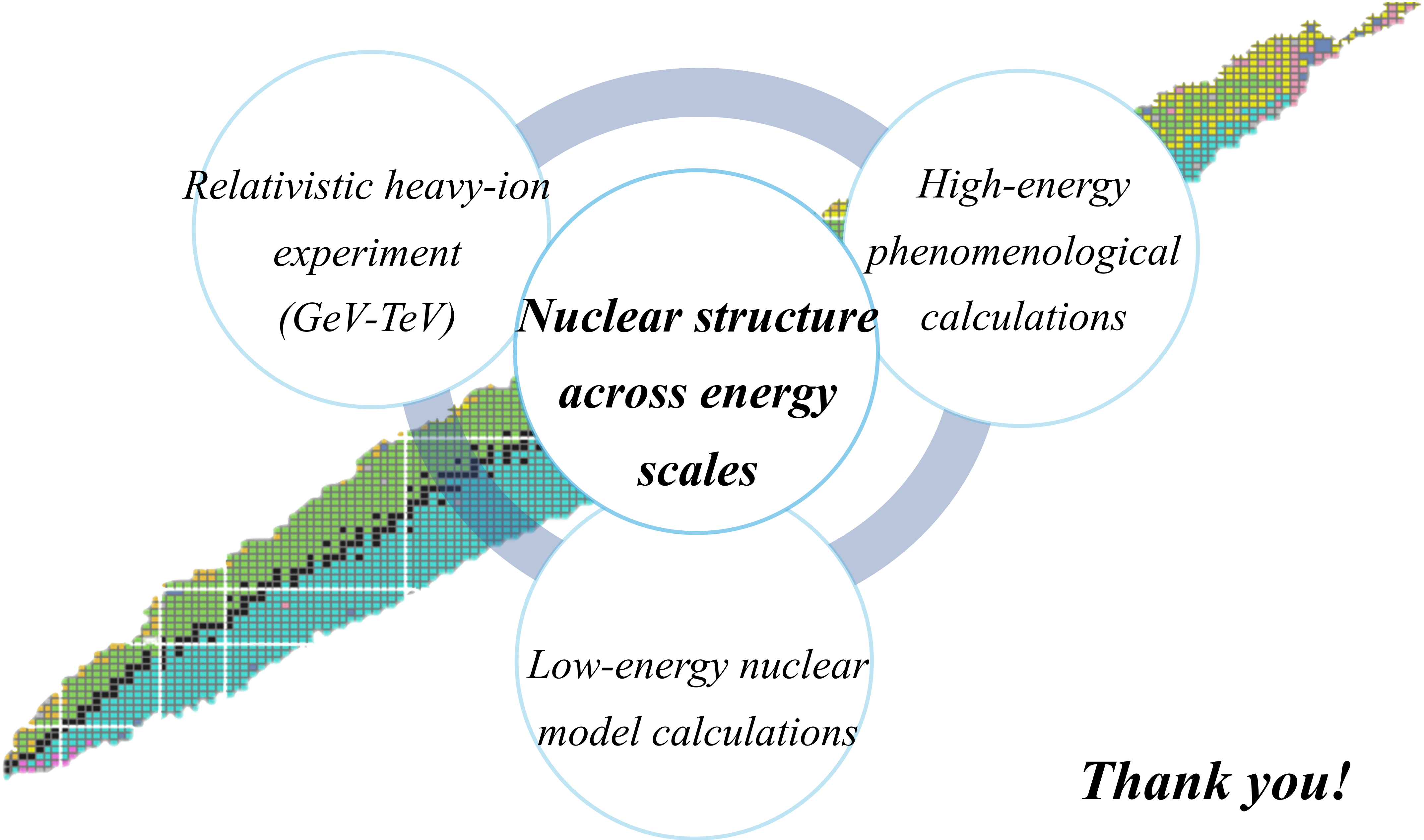
→ Neutron skin & symmetry energy constraints

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

→ Other tools, i.e. UPC, AI-assistant work

STAR, *Science Advances 9, abq3903 (2023); Shuo Lin, Jin-Yu Hu, Hao-Jie Xu, Shi Pu, Qun Wang, PRD 111, 074020 (2024); ....*

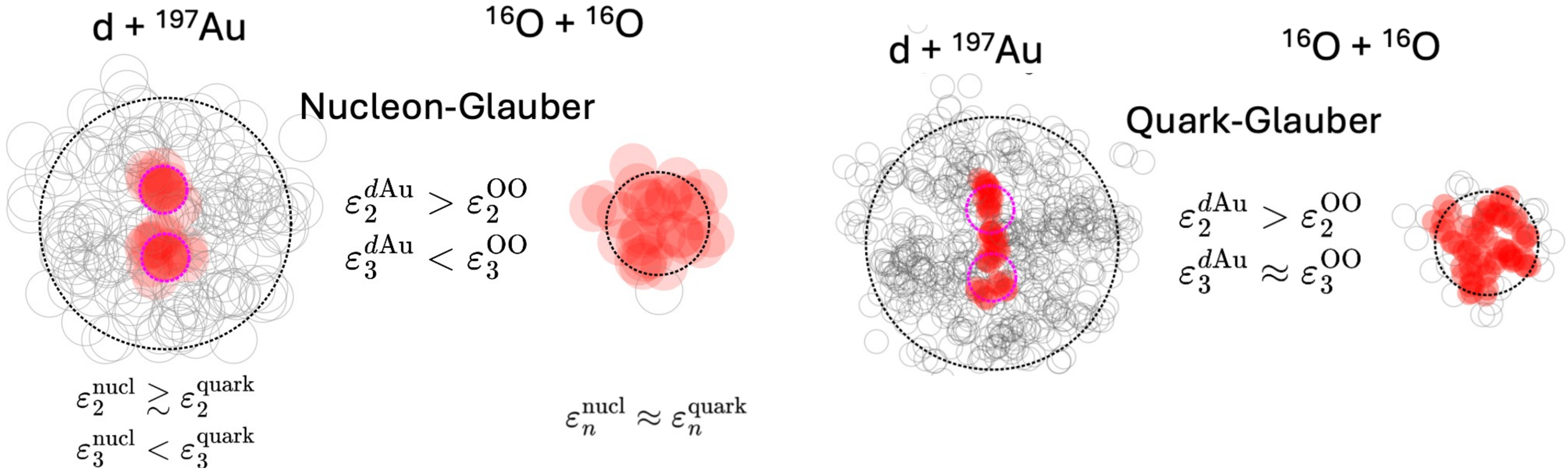
IV. Conclusions and Outlooks



Thank you!

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645*



Nucleon-Glauber and quark-Glauber yield different triangular v_3