Imaging shapes of atomic nuclei in high-energy nuclear collisions at STAR experiment

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(for the STAR Collaboration)

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STAR 25 YEARS

QM 25

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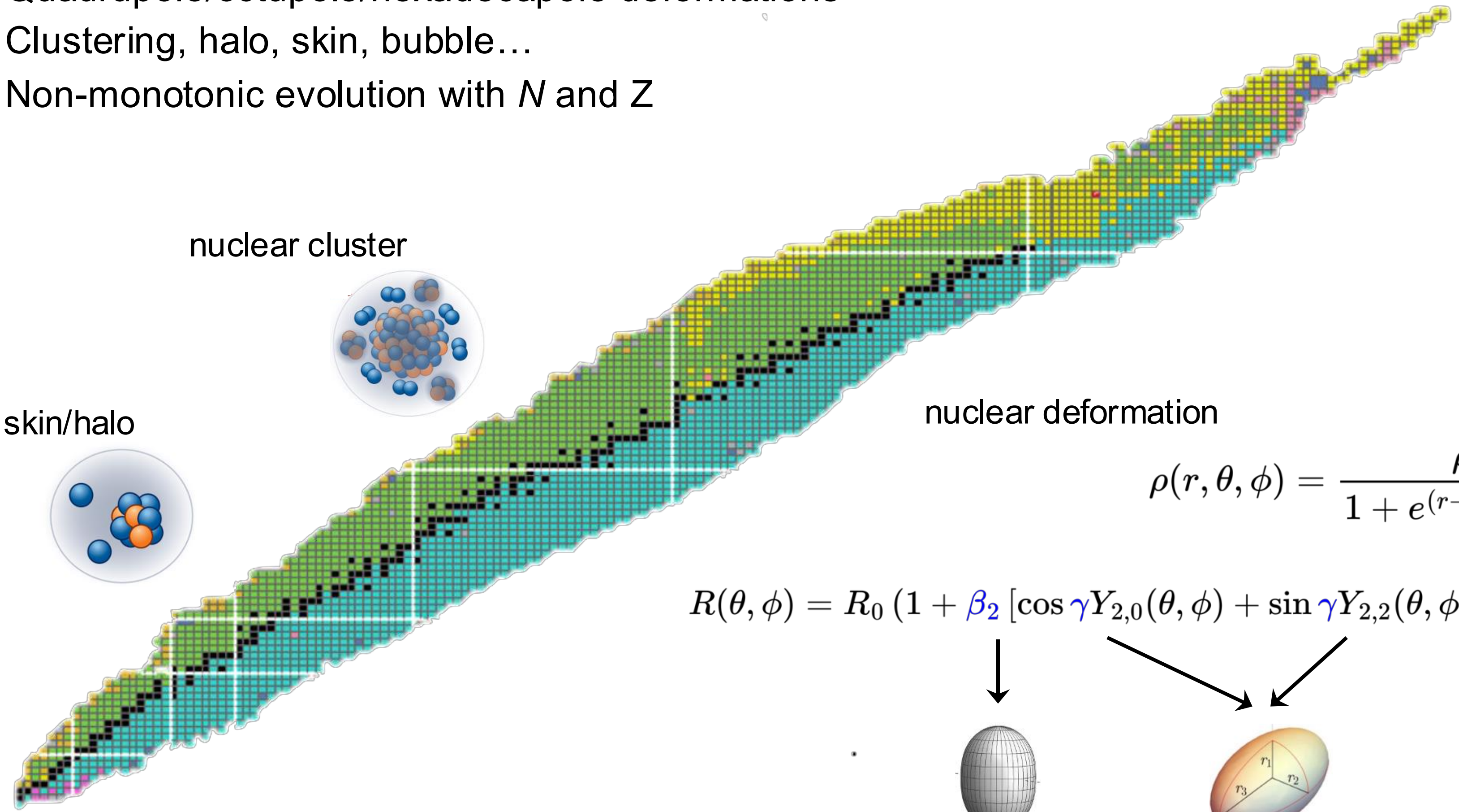
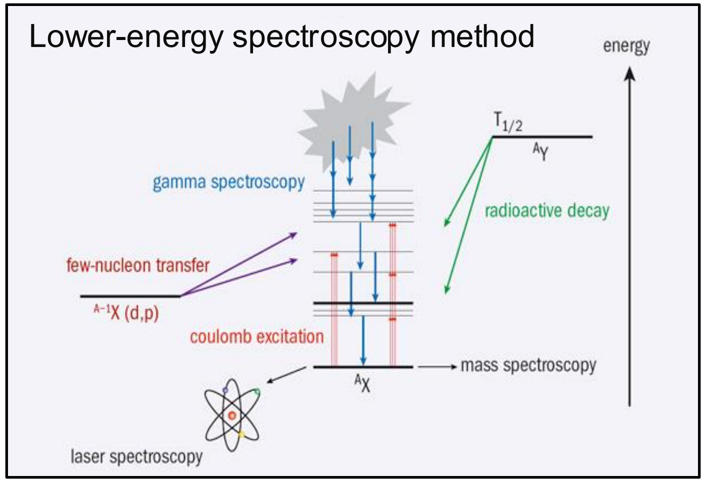
Fathom the fundamental structure of atomic nuclei

Emergent phenomena of the many-body quantum system

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





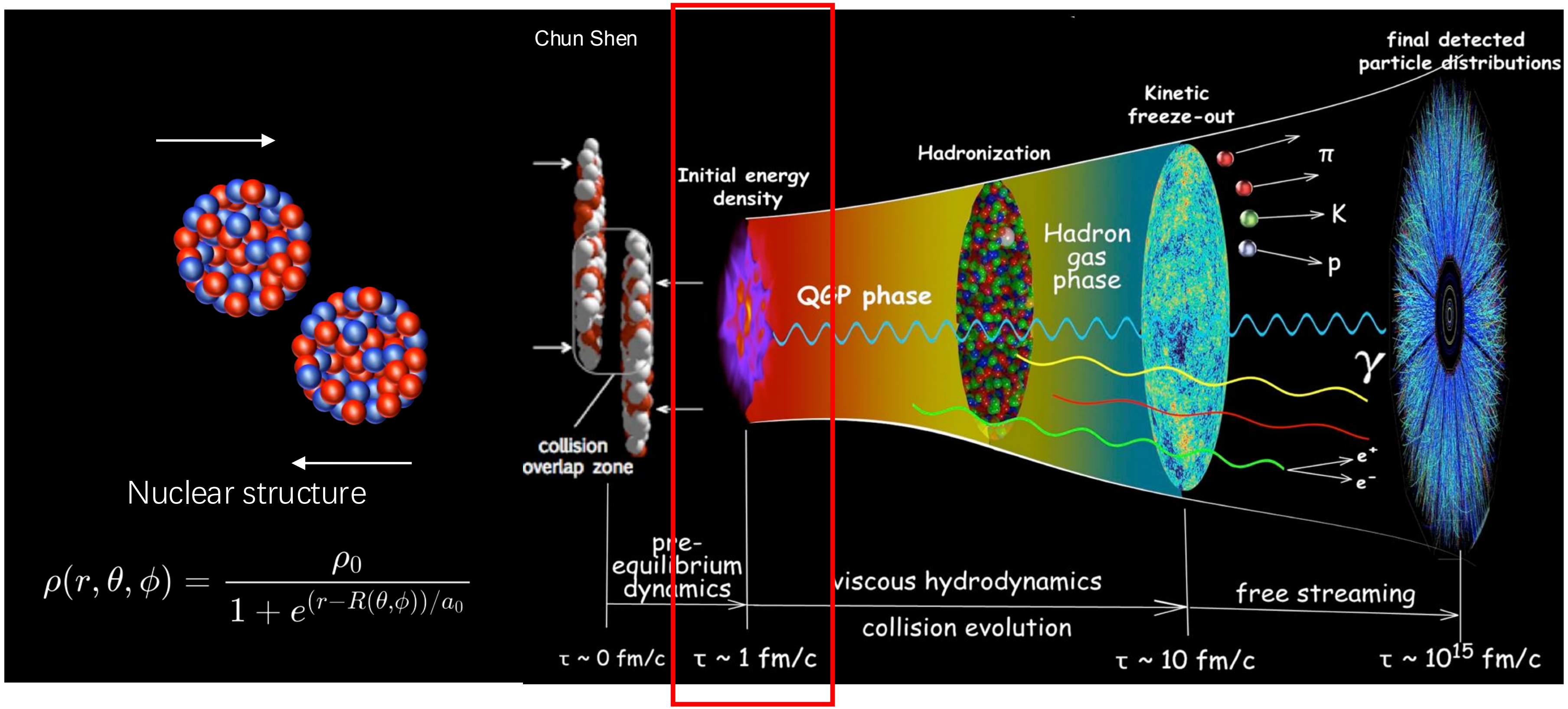
nuclear deformation

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

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

Understanding nuclear structure is crucial for nucleosynthesis, nuclear fission, and $(0\nu\beta\beta)$

Initial state constraints



Multiple stage /Complex dynamics

Different ways of depositing energy:

$$T \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{q/p}$$

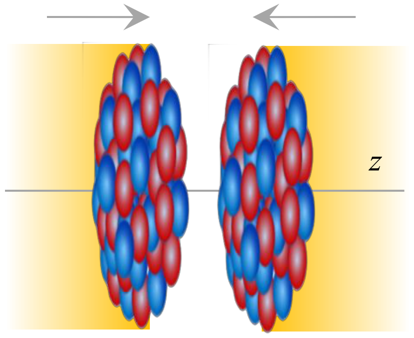
$$e(x,y) \sim \begin{cases} T_A + T_B & N_{\text{part}} - \text{ scaling}, p=1 \\ T_A T_B & N_{\text{coll}} - \text{ scaling}, p=0, q=2 \\ \sqrt{T_A T_B} & \text{Trento default}, p=0 \\ \min\{T_A, T_B\} & \text{KLN model}, p \sim -2/3 \\ T_A + T_B + \alpha T_A T_B & \text{two-component model,} \\ & \text{similar to quark-glauber model} \end{cases}$$

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

Use nuclear structure as extra lever-arm for initial condition

Collective flow-assisted nuclear structure imaging

nuclear structure



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

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

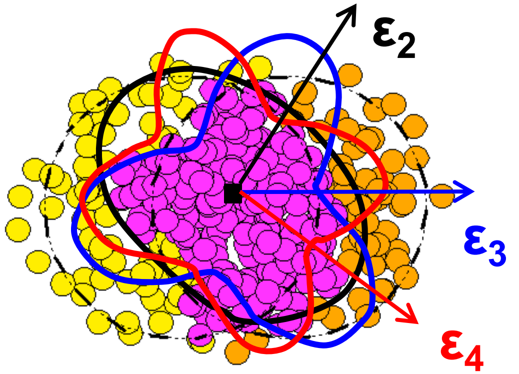
- β_2 → quadrupole deformation
- β_3 → octupole deformation
- γ → triaxiality
- a_0 → surface diffuseness
- R_0 → nuclear size

ab initio theory/shell model/DFT

imaging ←

?

initial conditions



$F = -\nabla P(\epsilon)$

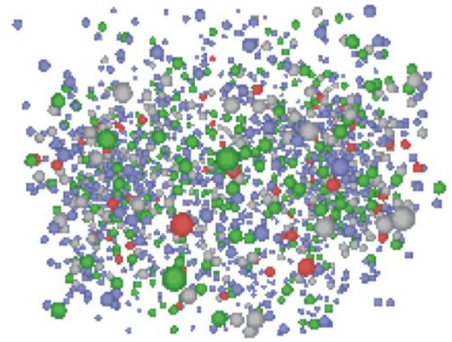
hydro-response →

initial size: $R_\perp^2 \propto \langle r_\perp^2 \rangle$

initial shape: $\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

R_0 a_0 β_n

final state



radial flow

anisotropic flow

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

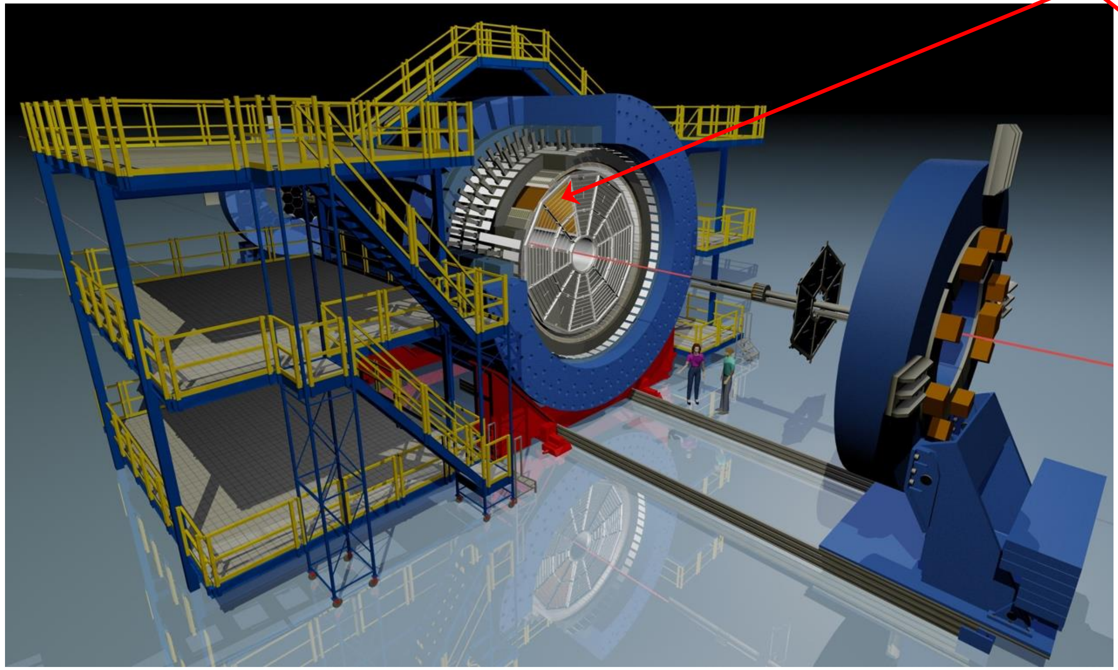
$N_{ch} \propto N_{part}$ $\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$ $V_n \propto \mathcal{E}_n$

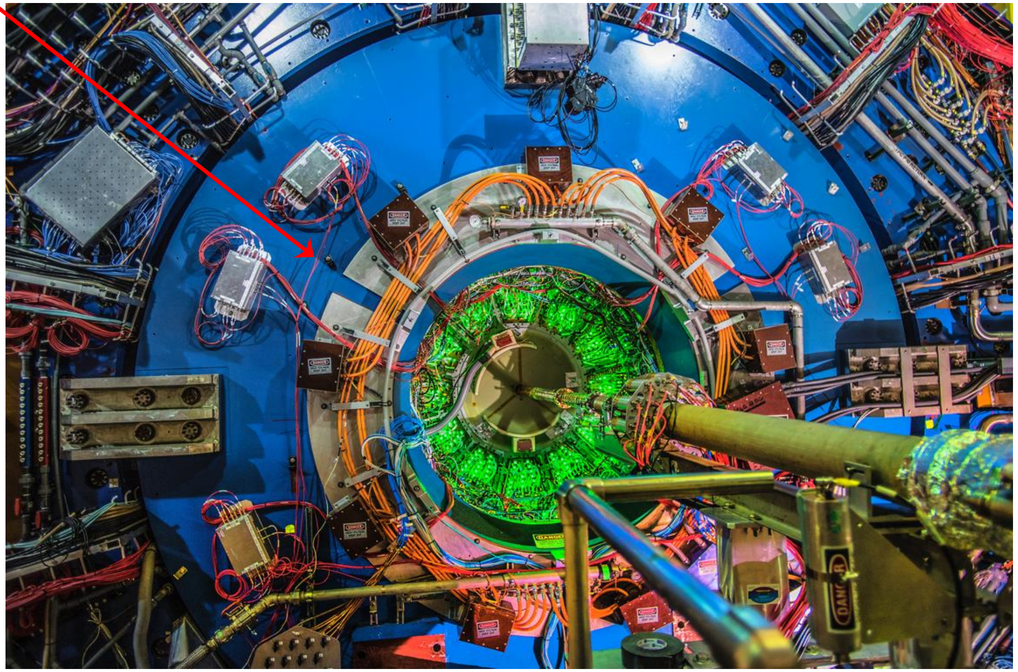
approximate linear response in each event

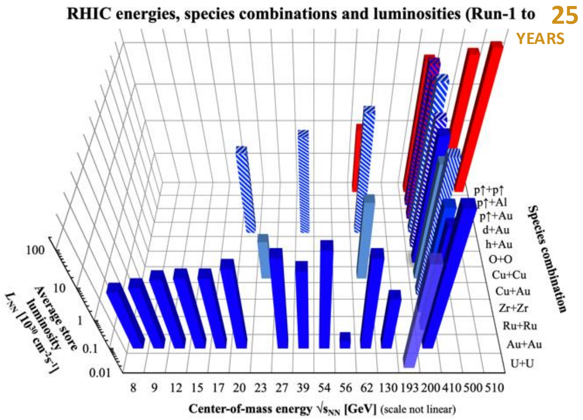
Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

STAR detector at BNL

Time Projection Chamber







STAR detector provides

1) Large/uniform acceptance, better centrality resolution

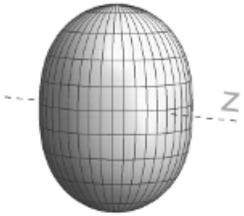
2) Sufficient statistics for emitted final-state hadrons

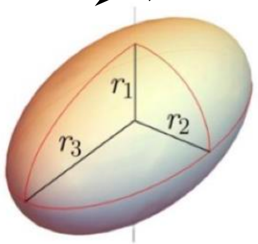
3) Different collision systems: U+U, Au+Au, Ru+Ru, Zr+Zr, …

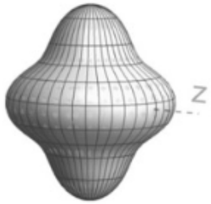
Nuclear structure in heavy ^{238}U nucleus

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

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



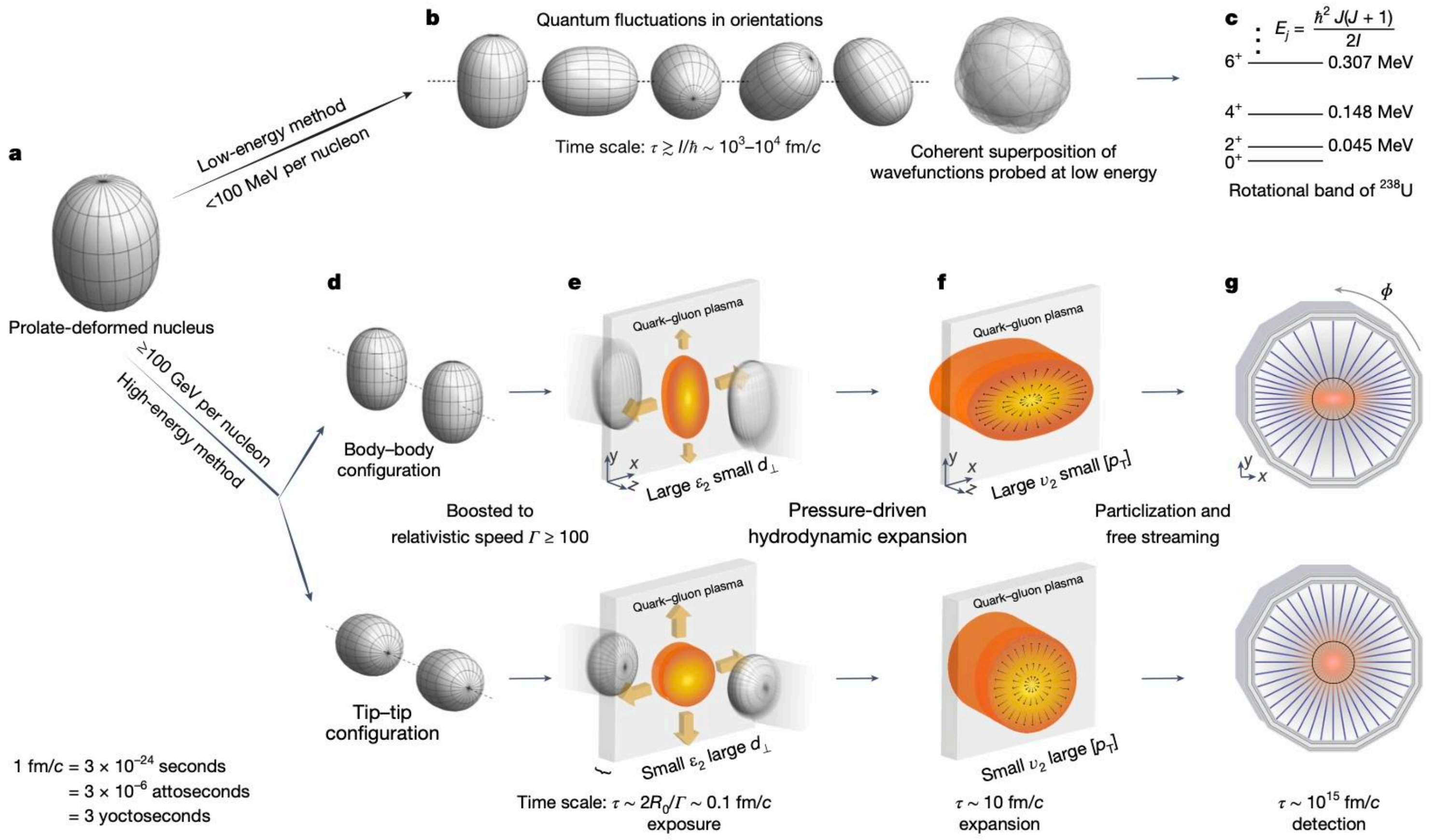




Imaging nuclear shape in high-energy snapshot as a novel way

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

  --Mainly inferred from non-invasive spectroscopy methods.



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

$v_2 \searrow$ $p_T \nearrow$

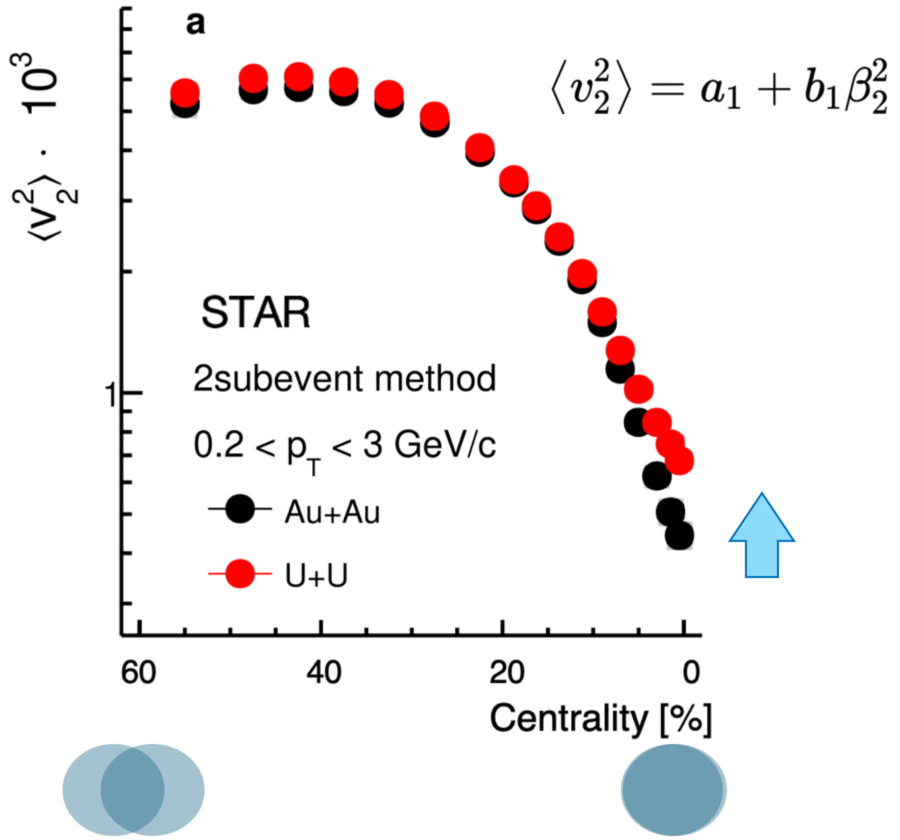
$$\langle v_2^2 \rangle = a_1 + b_1 \beta_2^2,$$
$$\langle (\delta p_T)^2 \rangle = a_2 + b_2 \beta_2^2,$$
$$\langle v_2^2 \delta p_T \rangle = a_3 - b_3 \beta_2^3 \cos(3\gamma).$$

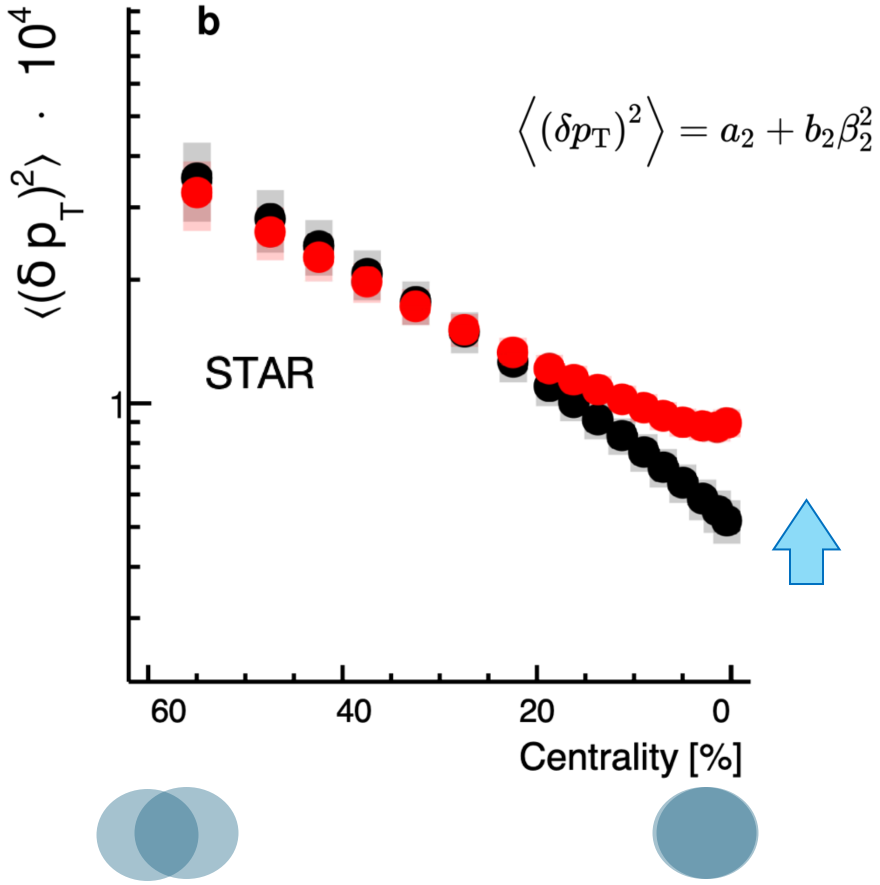
Shape-frozen like a snapshot during nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)

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

Evidence of deformation from system comparison

Two-body correlator:

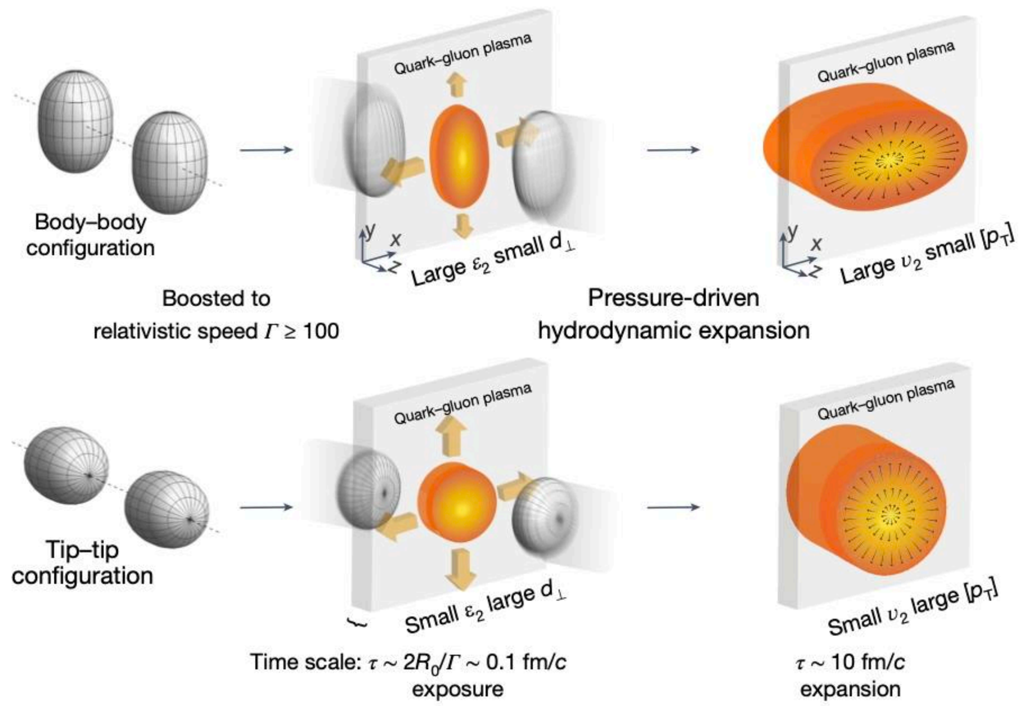




Elliptic flow and size fluctuation are enhanced by the nuclear deformation effect.

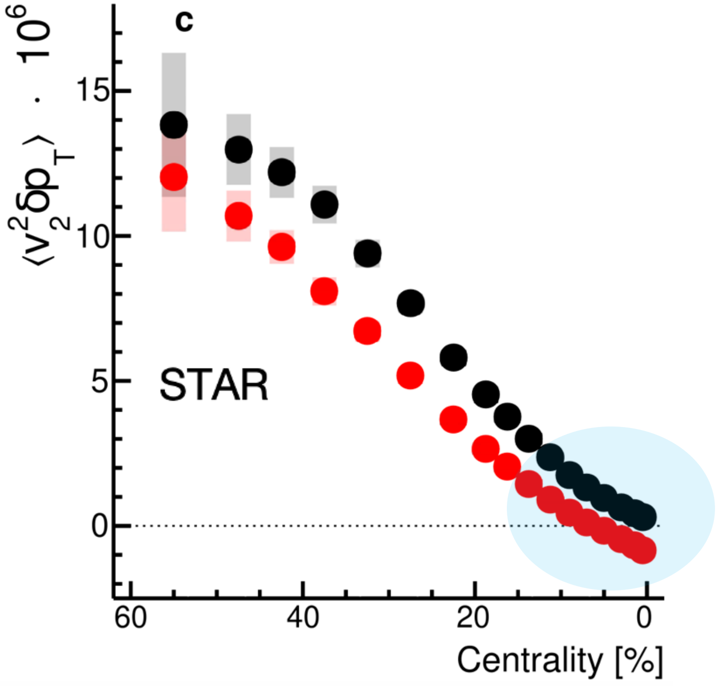
G. Giacalone, J. Jia, C. Zhang, PRL127, 242301(2021); J. Jia, PRC105, 014905(2022), PRC105, 044905(2022)

Reflecting the initial state from the nuclear geometry



v_2↗ p_T↘

v_2↘ p_T↗



Three-body correlator

$$\mathrm{cov}(v_n^2, [p_T]) \equiv \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j} (p_{T,k} - \langle\langle p_T \rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_{\mathrm{evt}}$$

$$[p_T] \equiv \frac{\sum_i w_i p_{T,i}}{\sum_i w_i}, \langle\langle p_T \rangle\rangle \equiv \langle [p_T] \rangle_{\mathrm{evt}}$$ w_i is track weight

- $\boldsymbol{\varepsilon}_2$ and R are influenced by the quadrupole deformation β_2
- $\langle p_T \rangle \sim 1/R$ and $v_2 \propto \boldsymbol{\varepsilon}_2$: $\left\langle \epsilon_n^2 \frac{1}{R} \right\rangle \rightarrow \left\langle v_n^2 \, p_T \right\rangle$

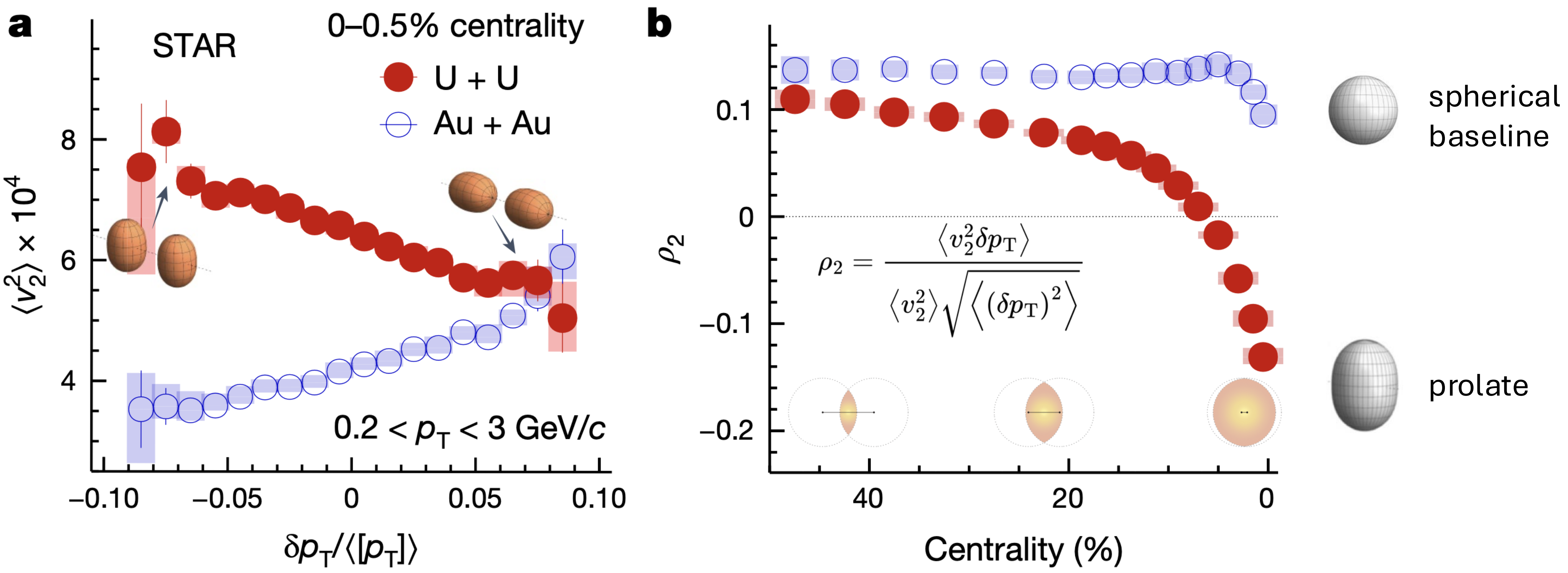
deformation contributes to anticorrelation between v_2 and $\langle p_T \rangle$

Sign-change in U+U in central collisions; Au+Au remains positive

P. Bozek, PRC93, 044908(2016)
G. Giacalone, PRL124, 202301(2020)

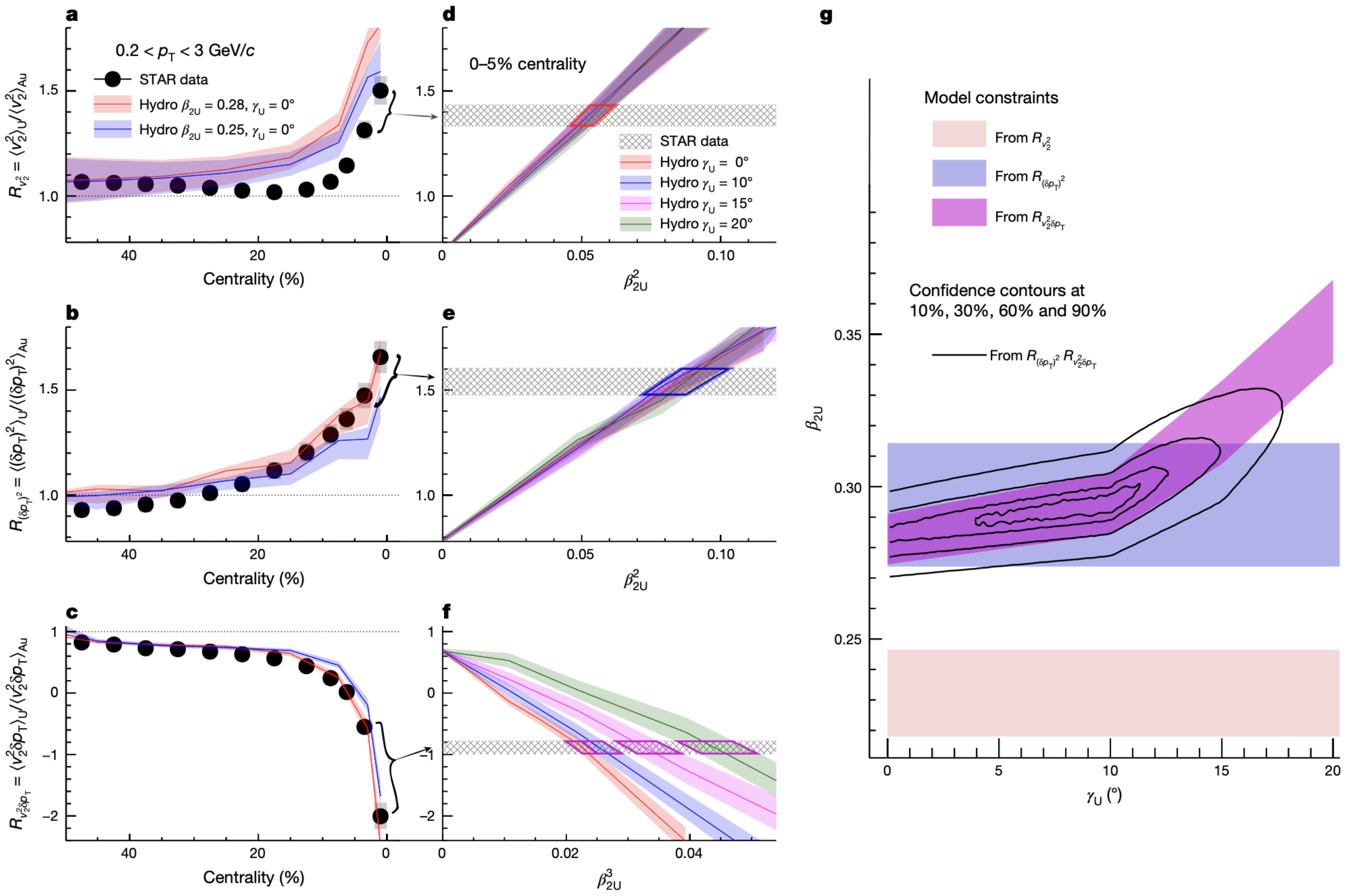
Impact of quadrupole deformation β_2

Seen directly by comparing $^{238}U+^{238}U$ with near-spherical $^{197}Au+^{197}Au$



Near-spherical → flat ρ_2 vs centrality
Strongly prolate → decreasing ρ_2 vs centrality

Imaging shape of the ground-state ^{238}U: β_2 and γ



Sufficient precision is achieved from ratios in ultra-central collisions

Relation confirmed from hydro

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

Constraints on β_2 and γ of ^{238}U simultaneously with data-hydro -comparison

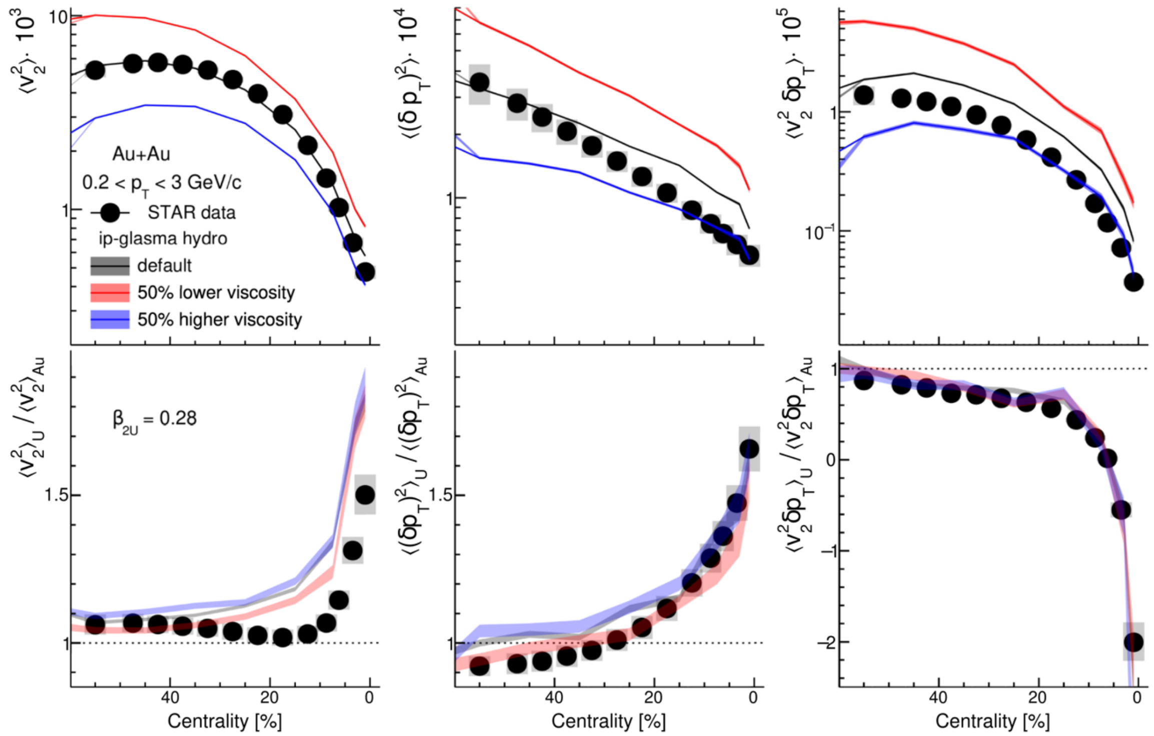
$$\beta_{2U} = 0.297 \pm 0.015$$
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

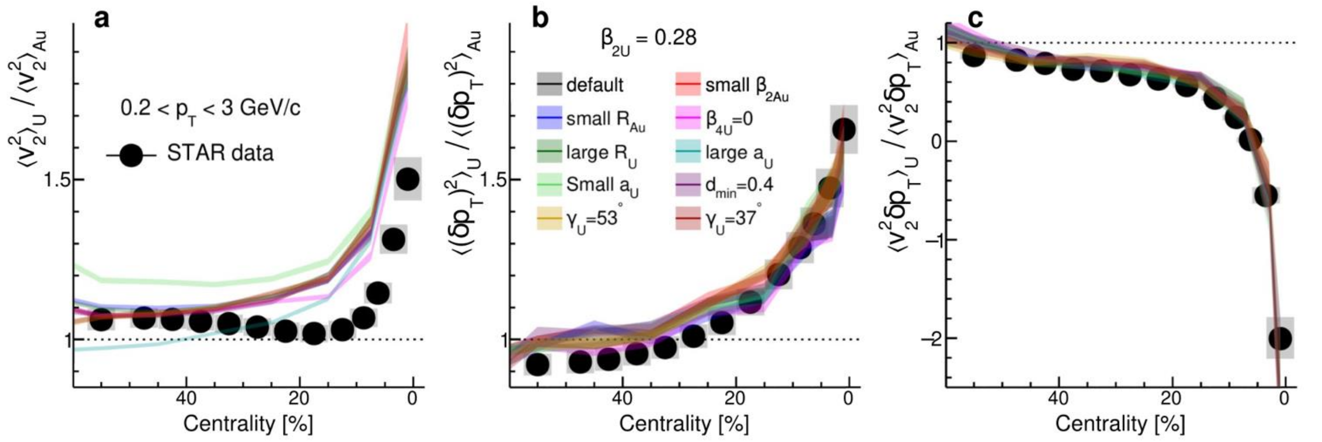
A large deformation with a slight deviation from axial symmetry in the nuclear ground-state

Viscosity, nuclear parameters, and model variations

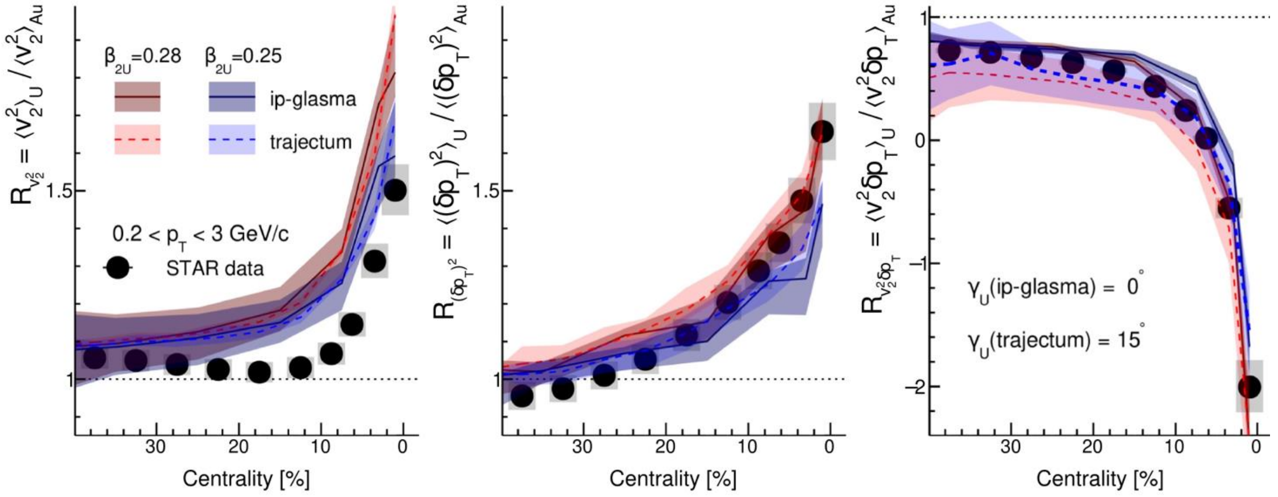
2) Effect from nuclear parameters are small, included as model systematics.

1) Taking the ratios cancels the viscosity effects.





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



Extracted β_2 and γ values are robust.

Another way to probe deformation

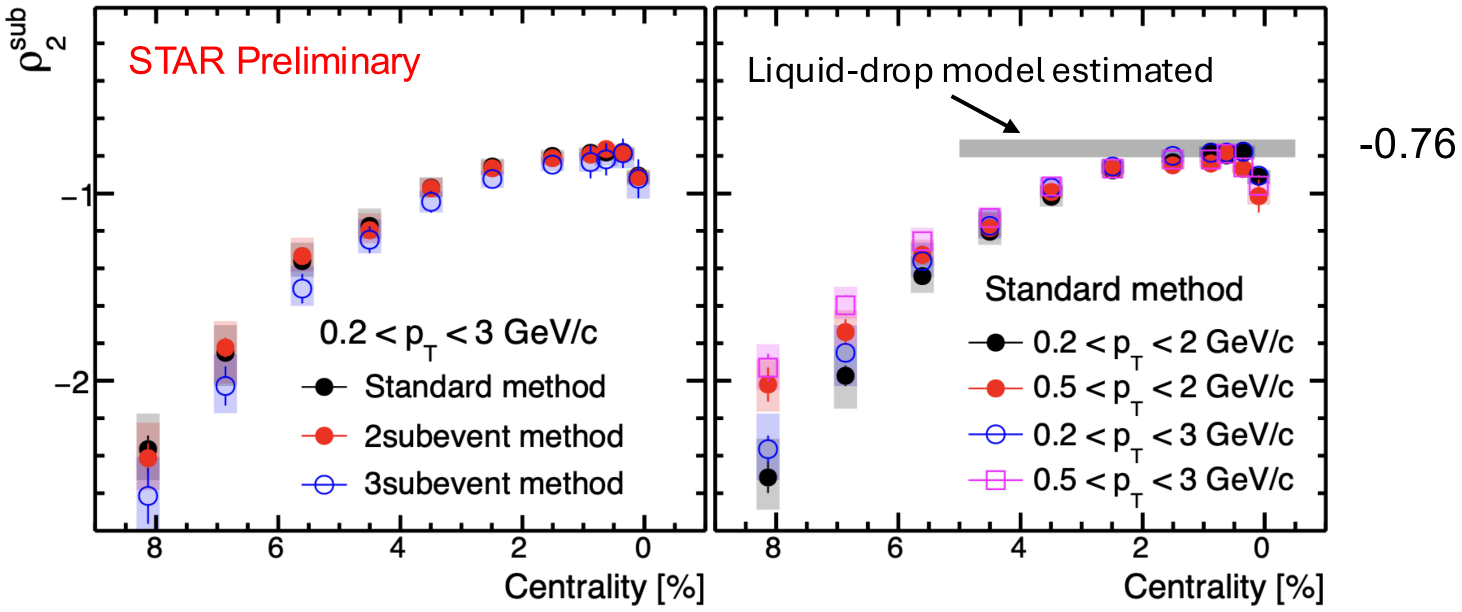
$$\langle v_2^2 \delta p_T \rangle \approx a - b\cos(3\gamma)\beta_2^3 \qquad \langle v_2^2 \rangle \approx a_2 + b_2\beta_2^2 \qquad \left\langle (\delta p_T)^2 \right\rangle \approx a_0 + b_0\beta_2^2$$

new

Removing “a” terms by subtracting the system A (U+U) and B (Au+Au)

$$\rho_2^{\mathrm{sub}} = \frac{\langle v_2^2\delta p_T\rangle_U - \langle v_2^2\delta p_T\rangle_{Au}}{\left(\langle v_2^2\rangle_U - \langle v_2^2\rangle_{Au}\right)\sqrt{\left\langle(\delta p_T)^2\right\rangle_U - \left\langle(\delta p_T)^2\right\rangle_{Au}}} \approx -\frac{b_3\left(\cos(3\gamma_U)\beta_{2U}^3 - \cos(3\gamma_{Au})\beta_{2Au}^3\right)}{b_1\sqrt{b_2}\left(\beta_{2U}^2 - \beta_{2Au}^2\right)^{3/2}} \overset{\beta_{2Au}\to 0}{=} -\frac{b_3}{b_1\sqrt{b_2}}\cos(3\gamma_U)$$

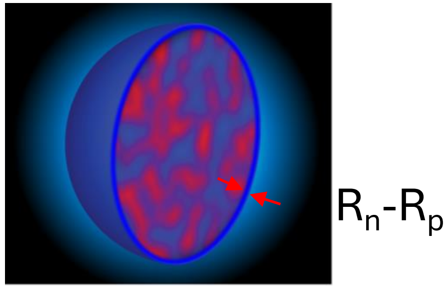
expected to work well in central region



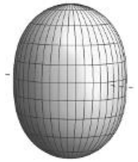
Independent of different methods and p_T selections

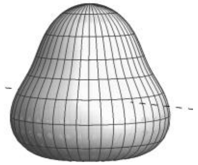
Nuclear structure in isobaric ^{96}Ru and ^{96}Zr nuclei

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



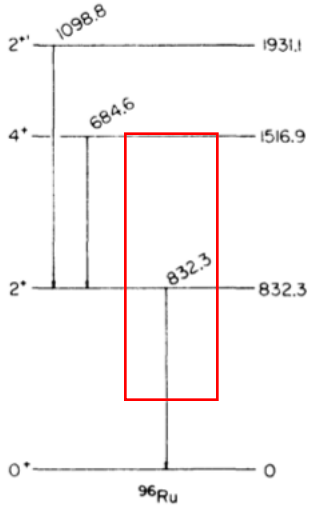
$$R(\theta,\phi) = R_0\left(1+\beta_2\left[\cos\gamma Y_{2,0}(\theta,\phi)+\sin\gamma Y_{2,2}(\theta,\phi)\right]+\beta_3 Y_{3,0}(\theta,\phi)+\beta_4 Y_{4,0}(\theta,\phi)\right)$$





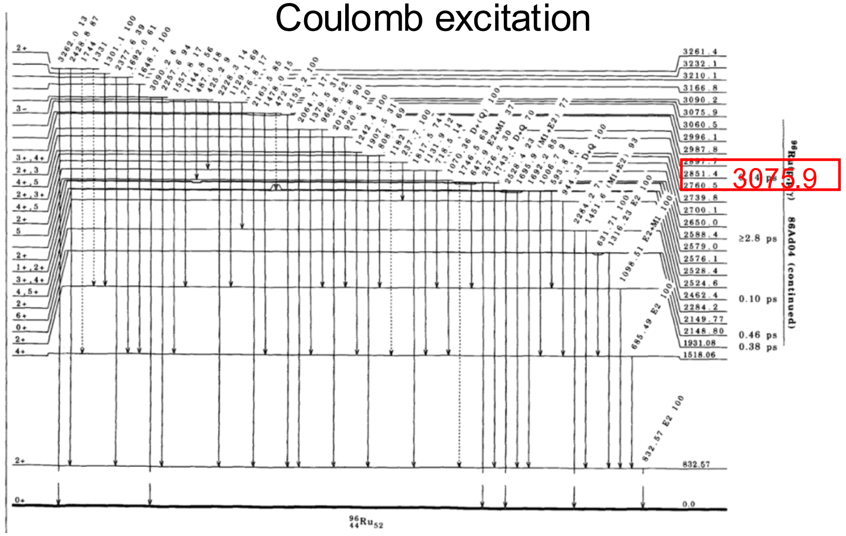
Low-energy experimental measurements on ^{96}Ru and ^{96}Zr

^{96}Ru



S. Landsberger et al. PRC21, 588(1980)

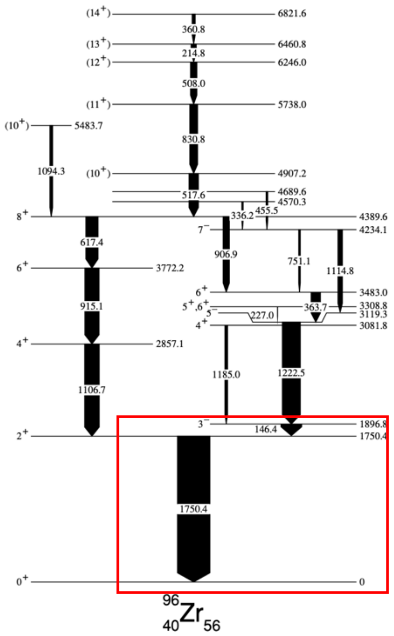
Coulomb excitation

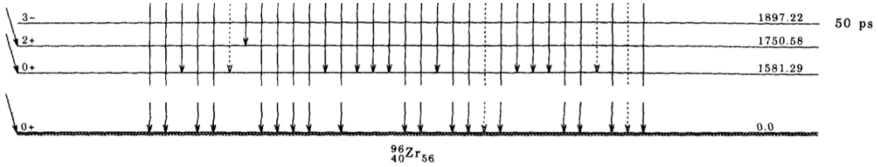


P. L.K, NDS68, 165(1993)

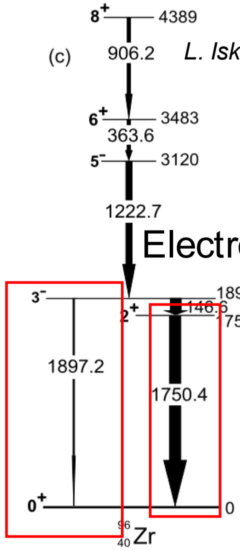
D. Pantelica et al., PRC72, 024304(2005)

^{96}Zr



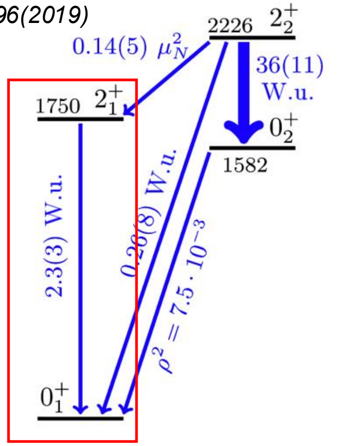


P. L.K, NDS68, 165(1993)



L. Iskra et al., PLB788, 396(2019)

Electron scattering



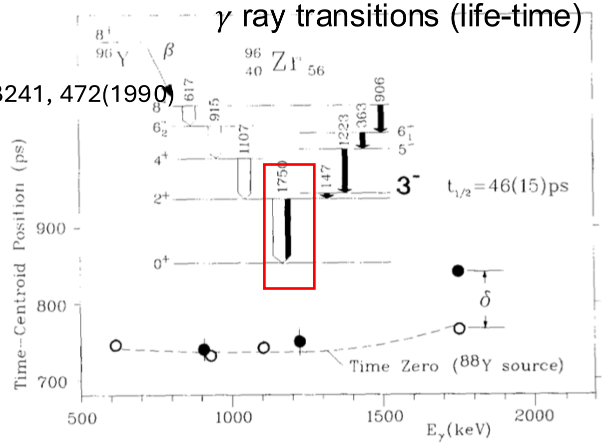
C. Kremer et al., PRL117, 172503(2016)

large $\beta_{2,\mathrm{Ru}}$, larger $\beta_{3,\mathrm{Zr}}$ with large uncertainties.

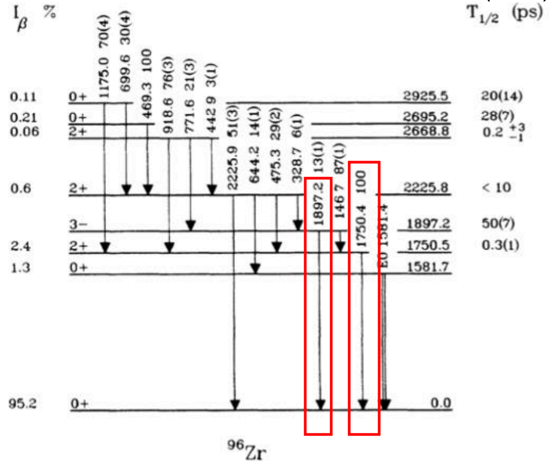
	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90

Evidence of static octupole moments at low energies is rather sparse.

γ ray transitions (life-time)



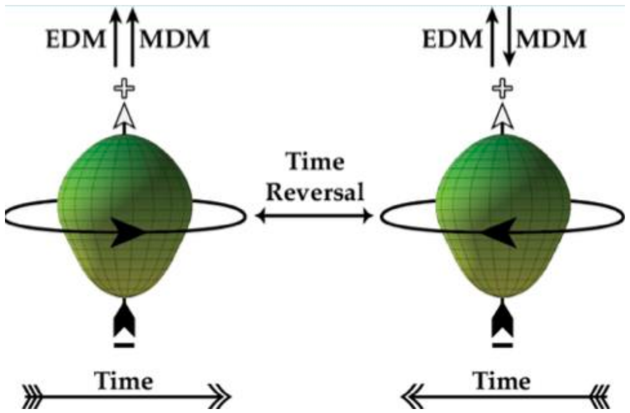
H. Ohm et. al.,PLB241, 472(1990)



H. Mach et. al., PRC42R, 811(1990)

Pear-shaped nuclei enable new-physics searches?

EDMs search



A pear-shaped nucleus spins counterclockwise or clockwise, depending on the direction of time.

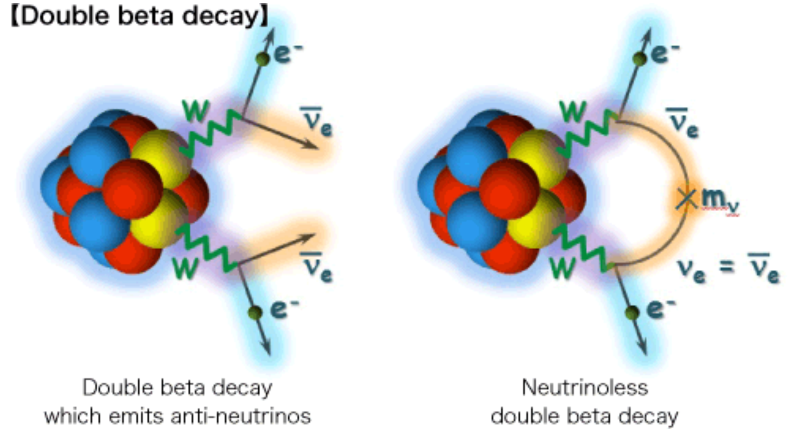
EDMs are very small and difficult to measure.

Higher sensitivity via Schiff nuclear moments in heavy nuclei

Octupole deformation enable EDMs search

Nature 497, 199 (2013); Rev. Mod. Phys. 91, 015001 (2019); Rep. Prog. Phys. 80, 046301 (2017); Ann. Rev. Nucl. Part. Sci. 69, 219 (2019); The 2023 Long-rang plan for nuclear physics

Neutrinoless double beta decay



Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment	Reference
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV	(157)
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA	(158)
	> 1.9	$< 0.24 - 0.52$	MAJORANA DEMONSTRATOR	(159)
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	NEMO-3	(160)
^{96}Zr	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3	(161)
^{100}Mo	$> 1.1 \times 10^{-1}$	$< 0.33 - 0.62$	NEMO-3	(162)
^{116}Cd	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3	(163)
^{128}Te	$> 1.1 \times 10^{-2}$	—	—	(164)
^{130}Te	> 1.5	$< 0.11 - 0.52$	CUORE	(124)
^{136}Xe	> 10.7	$< 0.061 - 0.165$	KamLAND-Zen	(165)
	> 1.8	$< 0.15 - 0.40$	EXO-200	(166)
^{150}Nd	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3	(167)

^{96}Zr with high-case rate, **strong neutrino mass limiting ability**

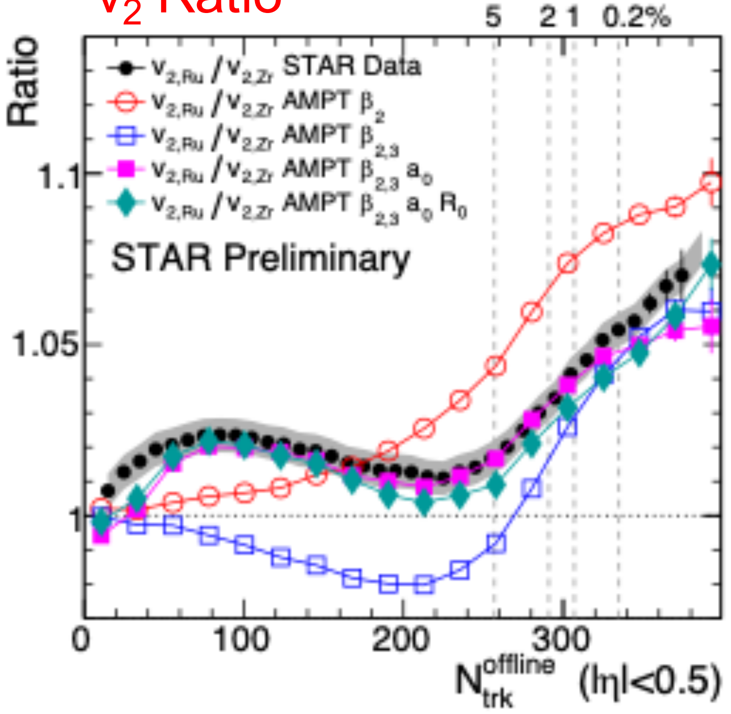
$$T^{0\nu}_{1/2} = \left(G |\mathcal{M}|^2 \langle m_{\beta\beta} \rangle^2 \right)^{-1} \simeq 10^{27-28} \left(\frac{0.01\text{eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \text{y}$$

Nuclear matrix element

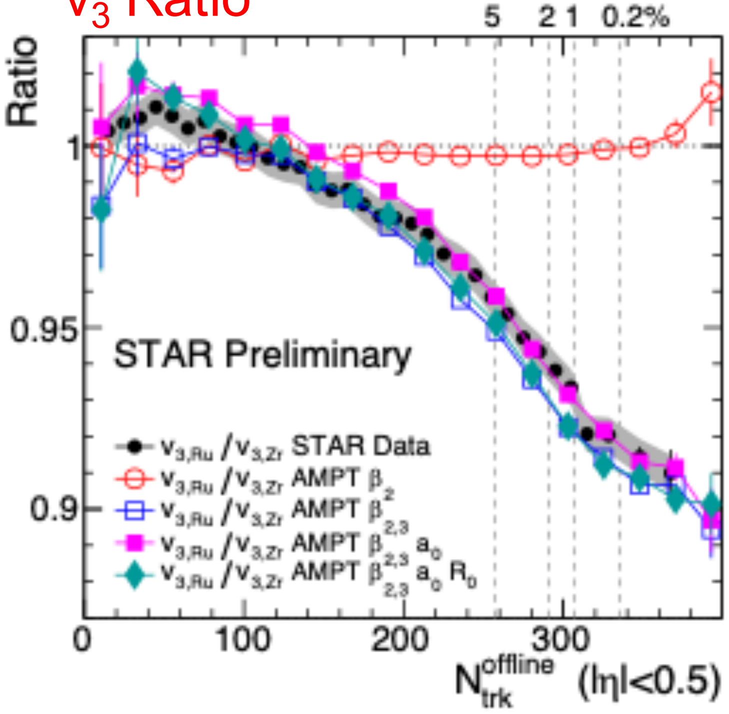
Y. Li, X. Zhang, G. Giacalone, J. Yao, arXiv:2502.08027

Nuclear structure via collectivity v_n ratio $\frac{\mathcal{O}_{^{96}\mathrm{Ru}}+\mathcal{O}_{^{96}\mathrm{Ru}}}{\mathcal{O}_{^{96}\mathrm{Zr}}+\mathcal{O}_{^{96}\mathrm{Zr}}} \stackrel{?}{=} 1$

v_2 Ratio



v_3 Ratio

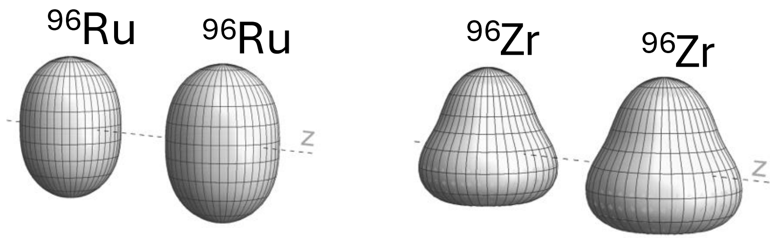


β_{2Ru} ~ 0.16 increase v_2, no influence on v_3 ratio

β_{3Zr} ~ 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

Radius ΔR_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 different N_{ch} regions

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

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

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

C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, G. Giacalone, C. Zhang, PRL131, 022301(2023)

Conclusions and Outlooks

1. **Intersection of nuclear structure and hot QCD across energy scales:**

   → better control variation of the QGP initial conditions

   → a novel way to unveil nuclear structure across energy scales

2. **The signatures of nuclear structure in nuclear collisions are ubiquitous:**

   → constrain β_2 and observe γ shape in ground-state ^{238}U: $\beta_{2\mathrm{U}} = 0.297 \pm 0.015 \quad \gamma_U = 8.5^\circ \pm 4.8^\circ$

   → observe large β_3 in ^{96}Zr, a_0 difference between isobaric ^{96}Zr and ^{96}Ru

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

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

3. **Many potential applications from large to small heavy-ion collision systems :**

   → high-order β_3 and β_4 nuclear deformations
   → rigid and soft γ (shape fluctuations/coexistence)
   → neutron skin
   → nuclear cluster in light nuclei (i.e.^{16}O and ^{20}Ne) at RHIC and the LHC
   → neutrinoless double-beta decay

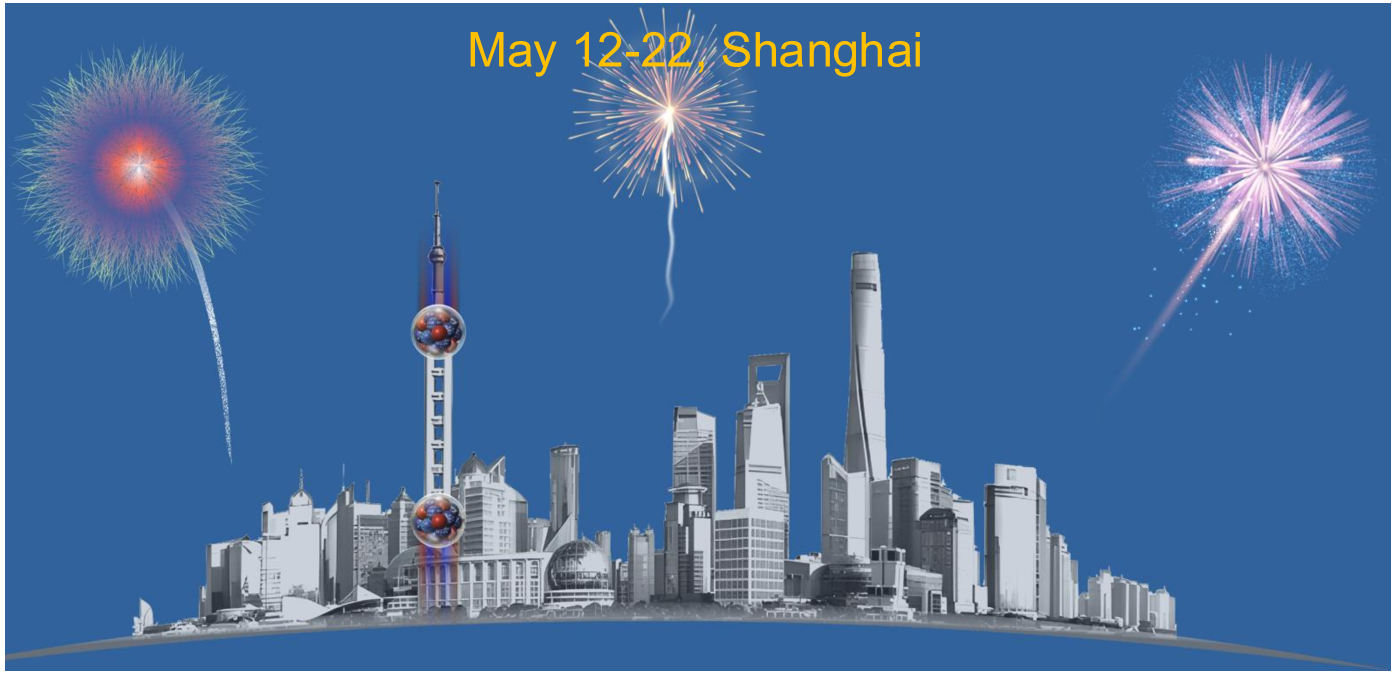
Plenary talk by You Zhou
April 11, 10:00 AM

The past activities and nearest workshop in Shanghai

Recently organized activities from 2022:

- RBRC workshop Jan 2022, link
- EMMI Taskforce May&Oct 2022, link
- ESNT workshop Sep 2022, link
- INT program Jan-Feb 2023, link
- Dalian workshop Aug 2023, link
- Beijing workshop April 2024, link
- CERN workshop Nov 2024, link

Nuclear structure physics across the energy spectrum 2025, link



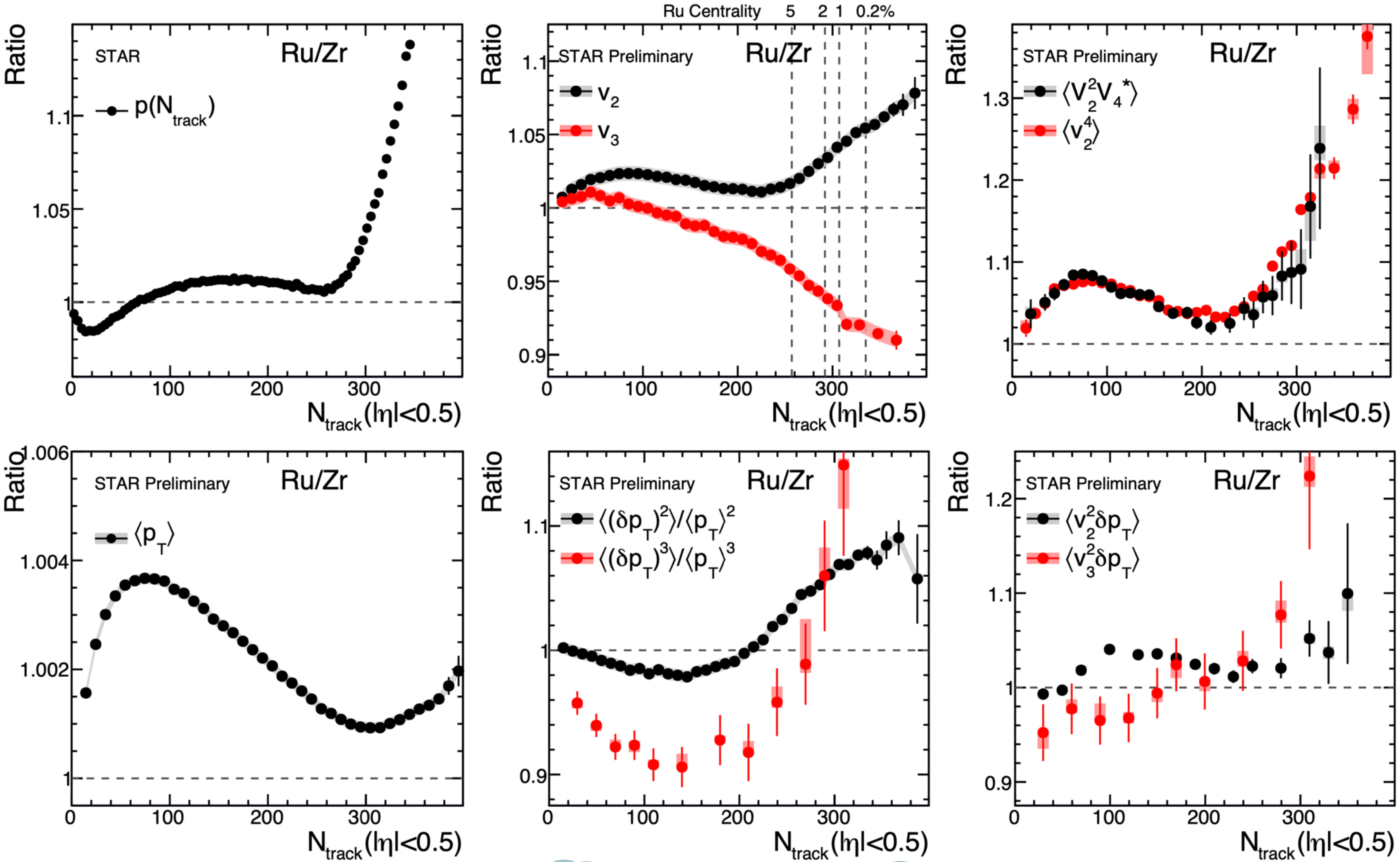
Continue the efforts to further constrain QGP initial conditions and nuclear structure across energy scales.

Thank You

Backup

Nuclear structure is inherent of heavy-ion probes

one-body distribution | two-body correlations | three-body correlations



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Smashing uranium-238 ions together proves to be a reliable way of imaging their nuclei. High-energy collision experiments reveal nuclear shapes that are strongly elongated and have no symmetry around their longest axis.

By Magda Zielińska & Paul E. Garrett

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By Benjamin Thompson & Emily Bates