Imaging the Collective Structure of Atomic Nuclei in High-Energy Nuclear Collisions from STAR

Chunjian Zhang
(for the STAR Collaboration)

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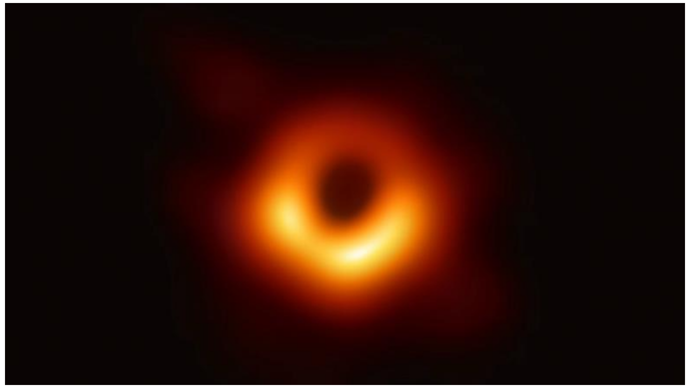
NN 2024
Supported by the U.S. DEPARTMENT OF ENERGY
The STAR experiment at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory
Stony Brook State University of New York
Fudan University 1905

The power of imaging

First-ever image of a black hole



MRI CT image

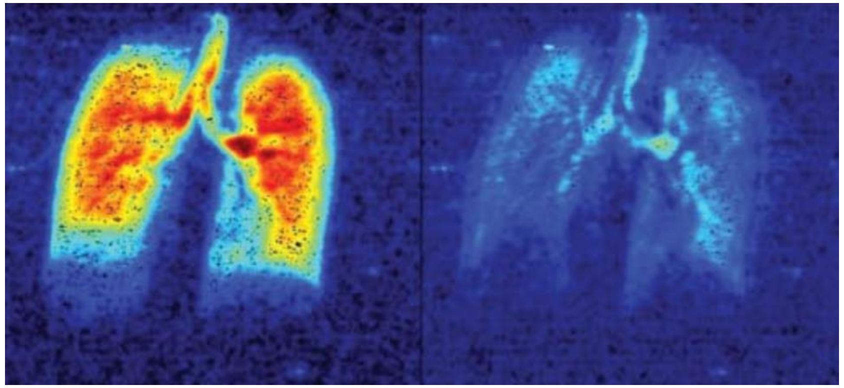
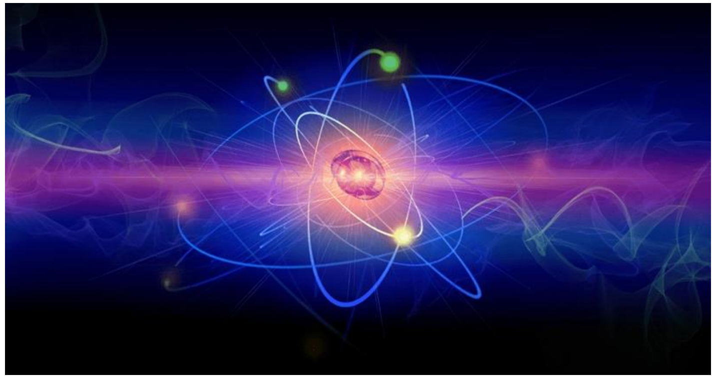


Image of electrons at attosecond

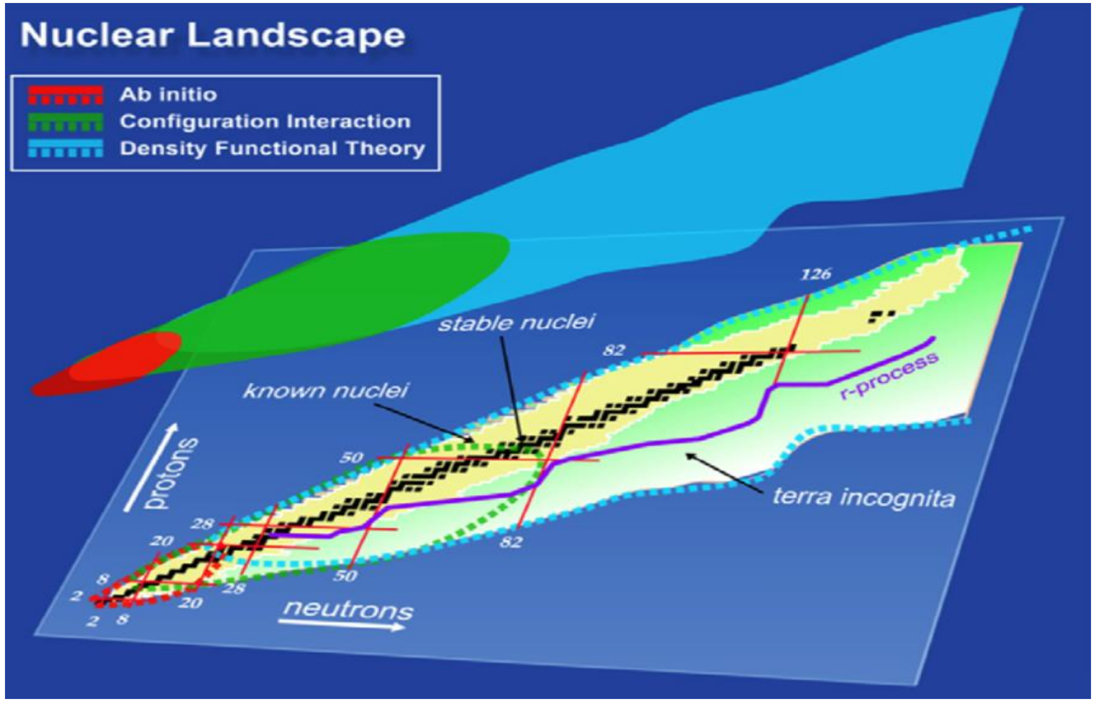


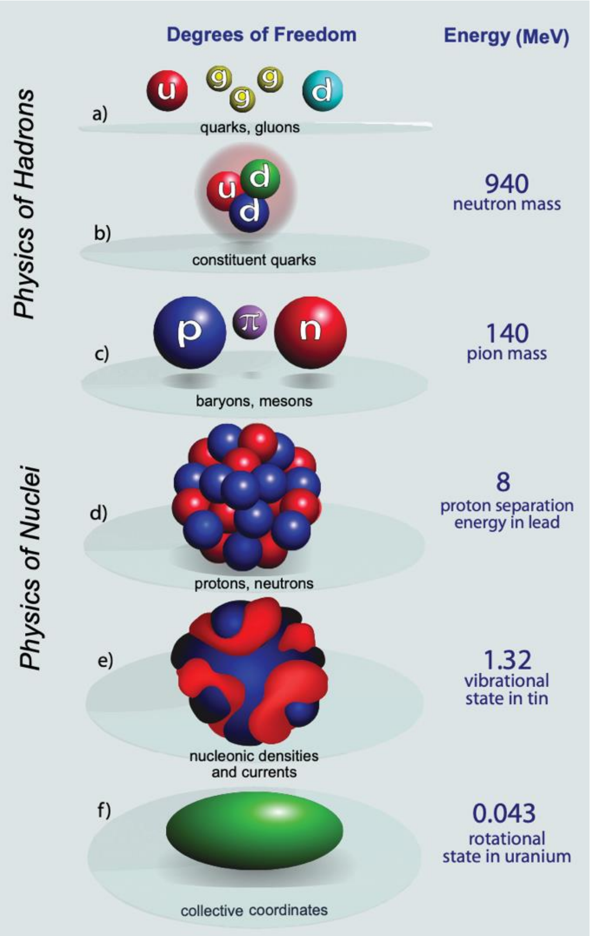
Astronomical scale → microscopic scale

Imaging: one of the scientific methods to understand nature!

Fathom the fundamental structure of atomic nuclei

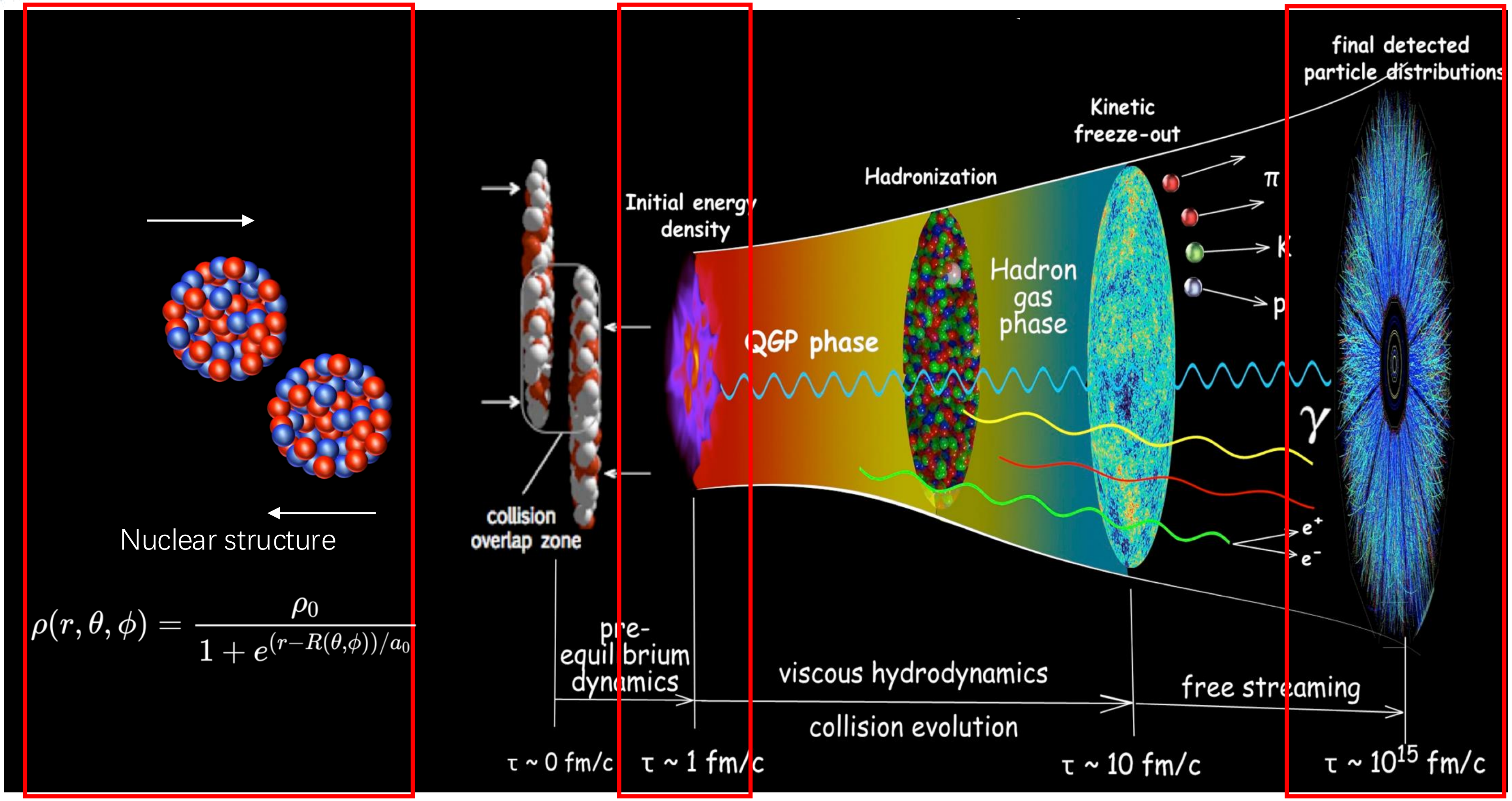
- Emergent phenomena of the many-body quantum system
  - Quadrupole/octupole/hexadecapole deformations
  - Clustering, halo, skin, bubble…
  - Non-monotonic evolution with *N* and Z





Understanding nuclear structure is crucial for nucleosynthesis, Nuclear fission, and neutrinoless double beta decay $(0\nu\beta\beta)$.

Multi-stage collision dynamics in relativistic nuclear collisions

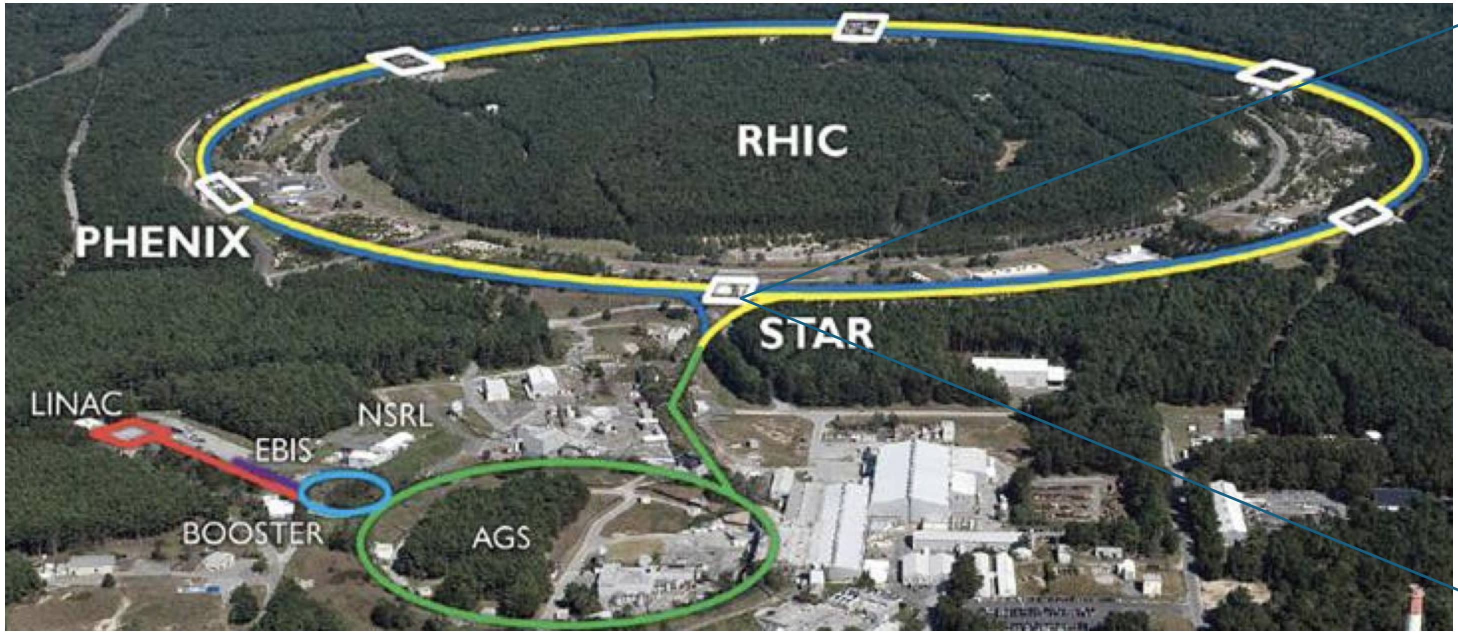


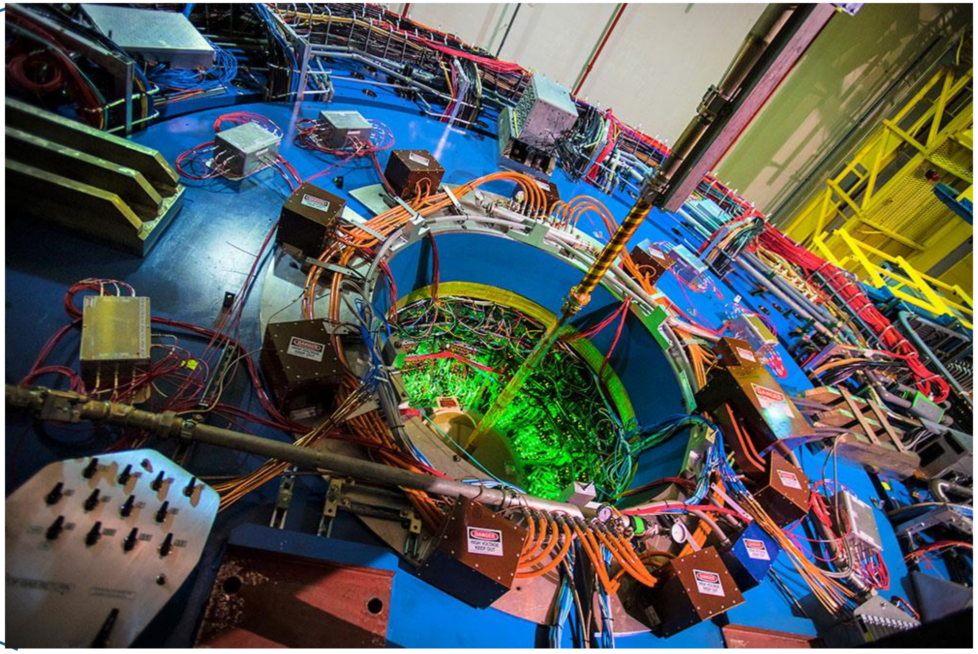
Multiple stage /Complex dynamics

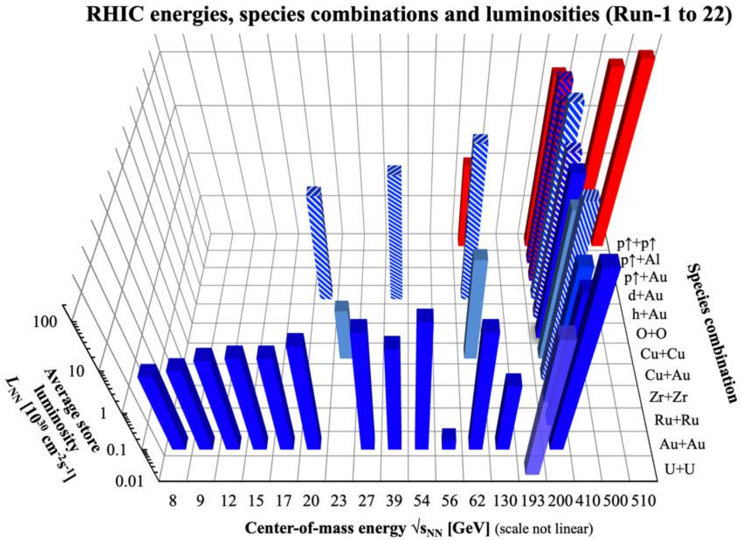
Hybrid multi-stage modeling with event-by-event fluctuations

- Constrain the initial condition by comparing nuclei with known structure properties.
- Reveal novel properties of nuclei by leveraging known hydrodynamic response.
- Study the unknown nuclear structure by heavy-ion collisions.

STAR detector at Brookhaven National Laboratory







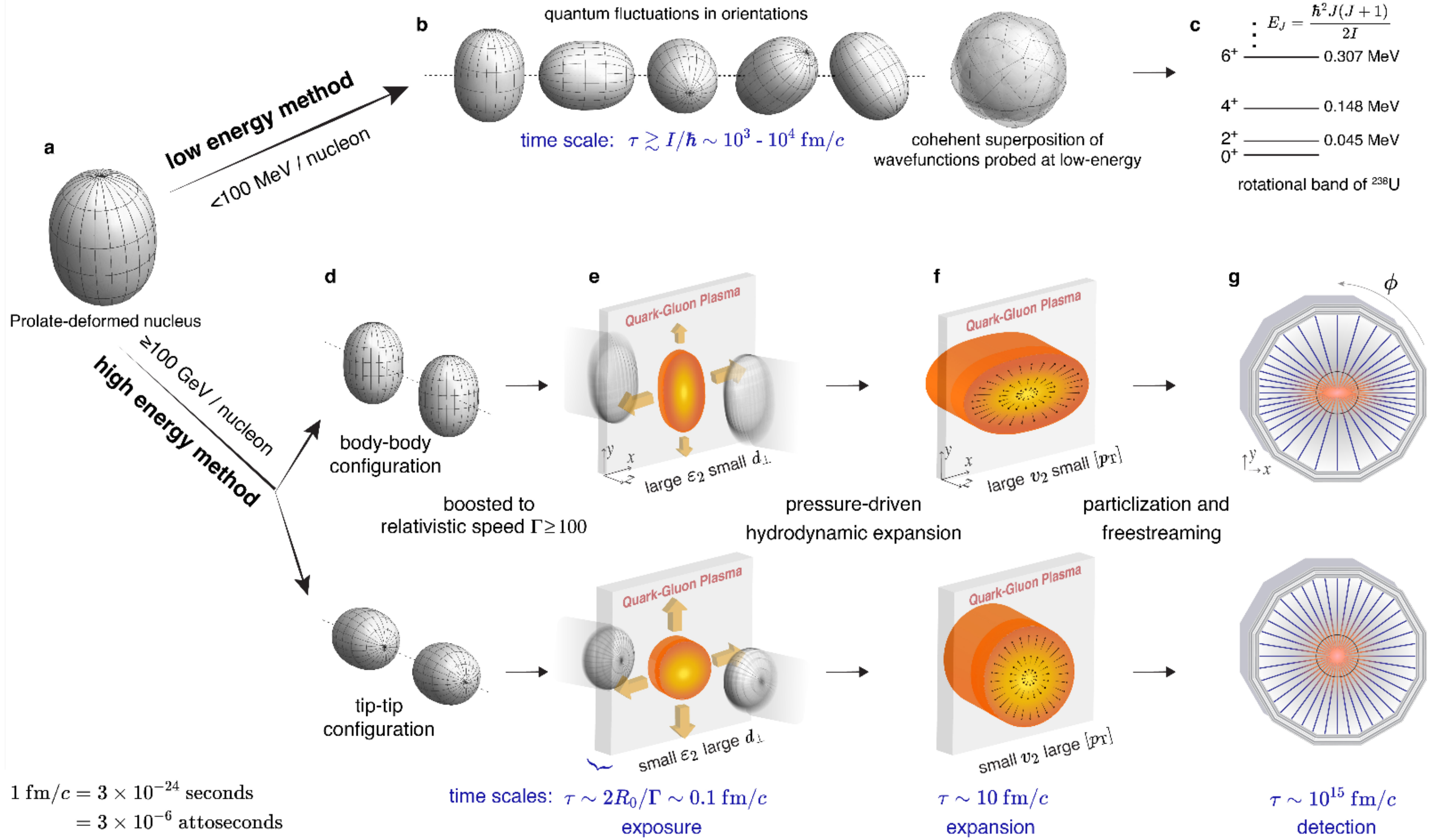
STAR detector provides

1) large, uniform acceptance at mid-rapidity
2) vast number of emitted final state hardons
3) capability to access nuclear structures in U+U, Ru+Ru, Zr+Zr, and O+O collisions…

Low-energy spectroscopy vs high-energy snapshot method

- Nuclear shape in intrinsic (body-fixed) frame not directly visible in the lab frame
  --Mainly inferred from non-invasive spectroscopy methods.

STAR, 2401.06625



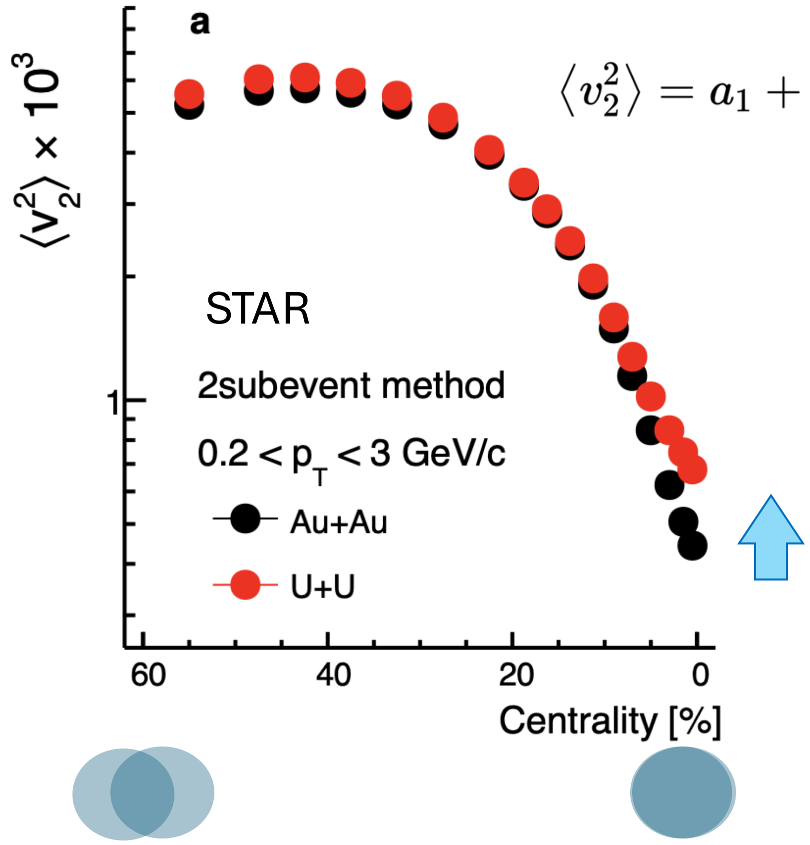
Energy/time scales

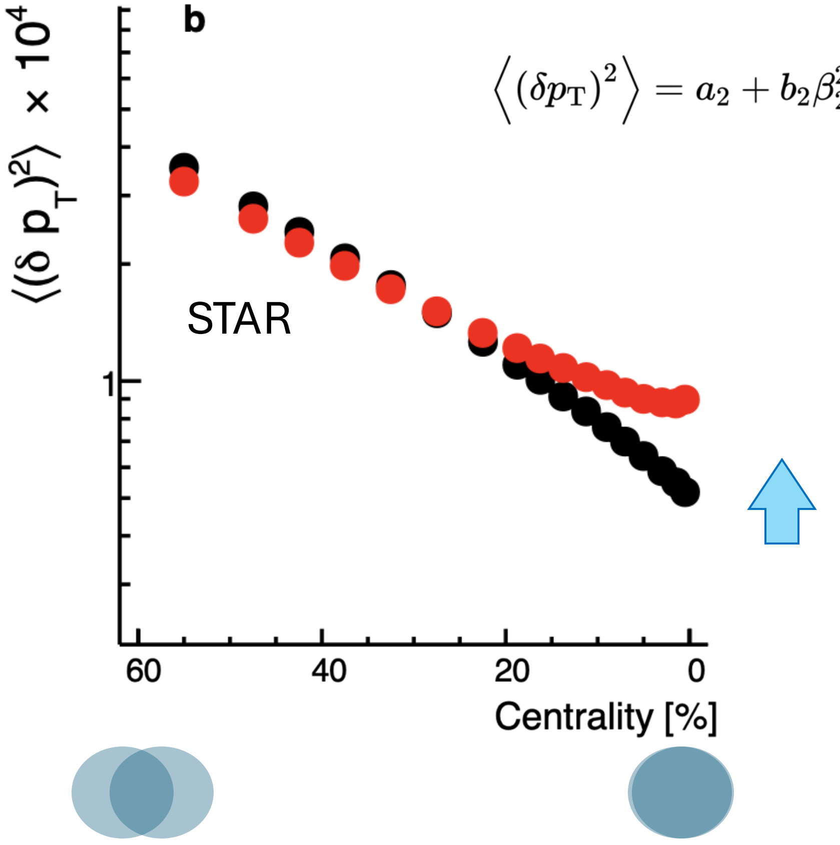
- Shape-frozen like snapshot in nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)
  --probe entire mass distribution in the intrinsic frame via multi-point correlations.

Evidence of deformation from system comparison

STAR, 2401.06625

Two particle correlator:

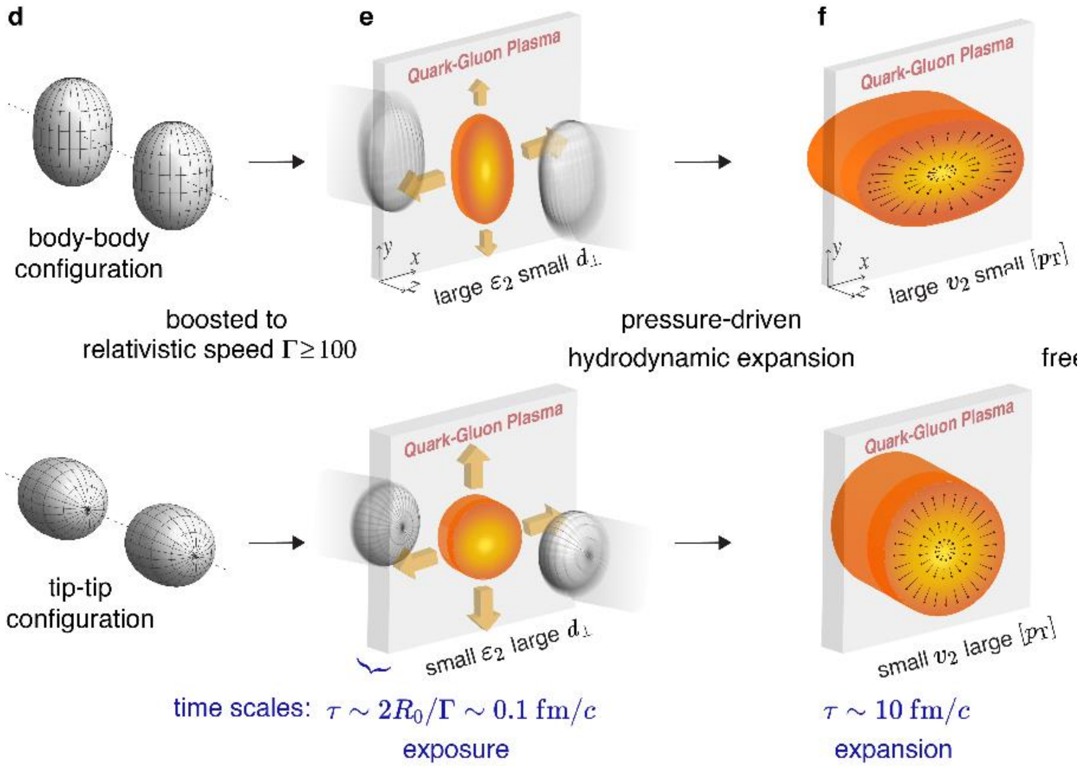


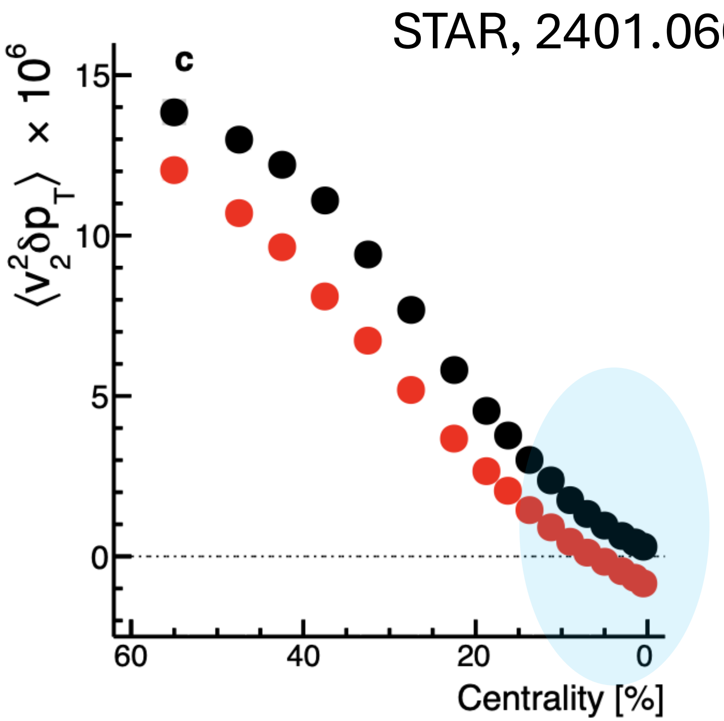


Elliptic flow and size fluctuation are enhanced by the nuclear deformation effect.

Formulas are confirmed by 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





particle correlator

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

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

w_i is track weight

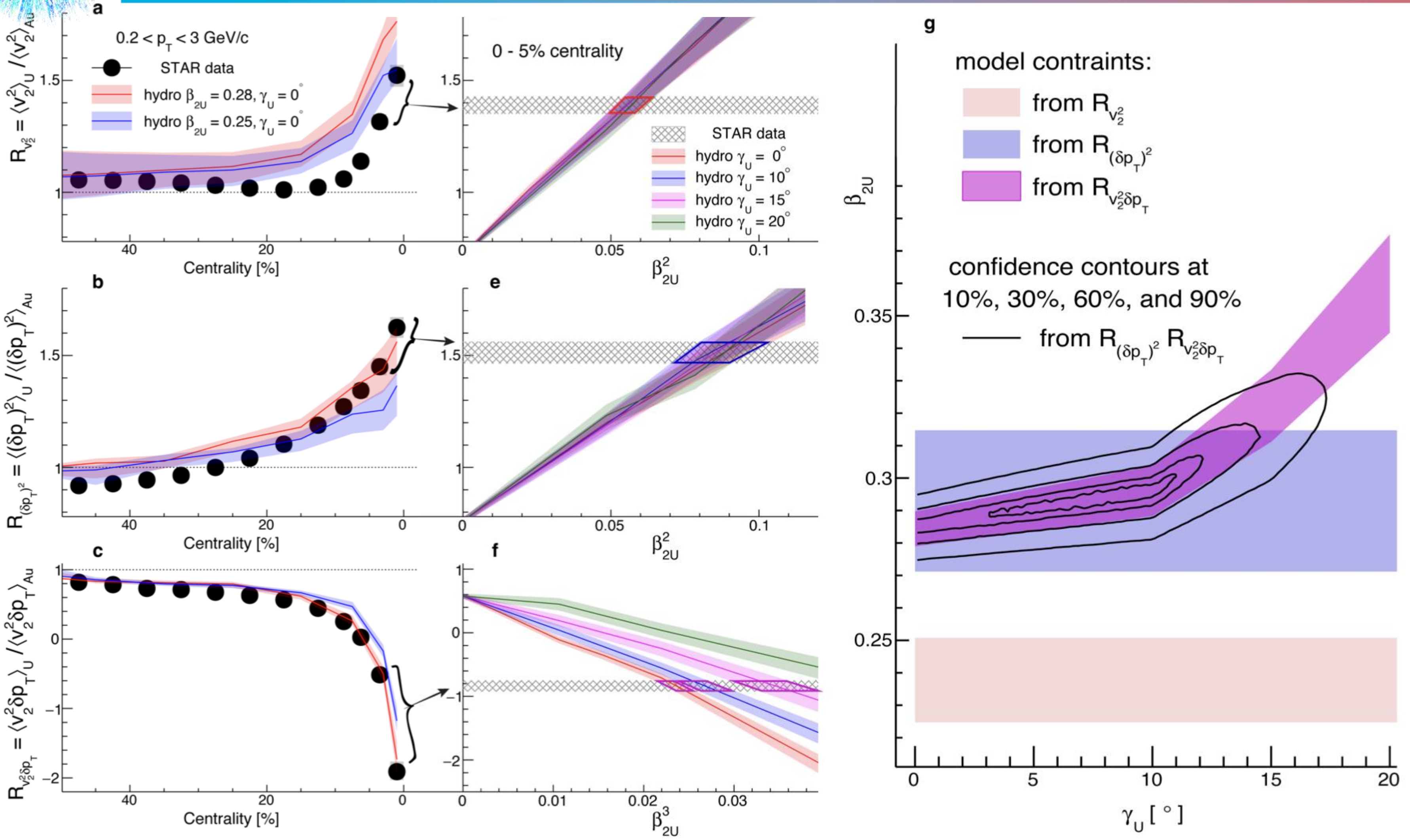
- $\boldsymbol{\varepsilon}_2$ and R are influenced by the quadrupole deformation β_2
- $\langle p_T \rangle \sim 1/R$ and $v_2 \propto \boldsymbol{\varepsilon}_2$: $\left\langle \epsilon_n^2 \frac{1}{R} \right\rangle \rightarrow \left\langle v_n^2\, p_T \right\rangle$

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)

Extracting shape of ^{238}U: quadrupole deformation and triaxiality



STAR, 2401.06625

Achieves a better description of ratios in UCC region

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

Constraints on β_2 of ^{238}U from data comparison with hydro

$$\beta_{2\mathrm{U}} = 0.297 \pm 0.013$$

$$\gamma_U = 8.6^\circ \pm 4.8^\circ$$

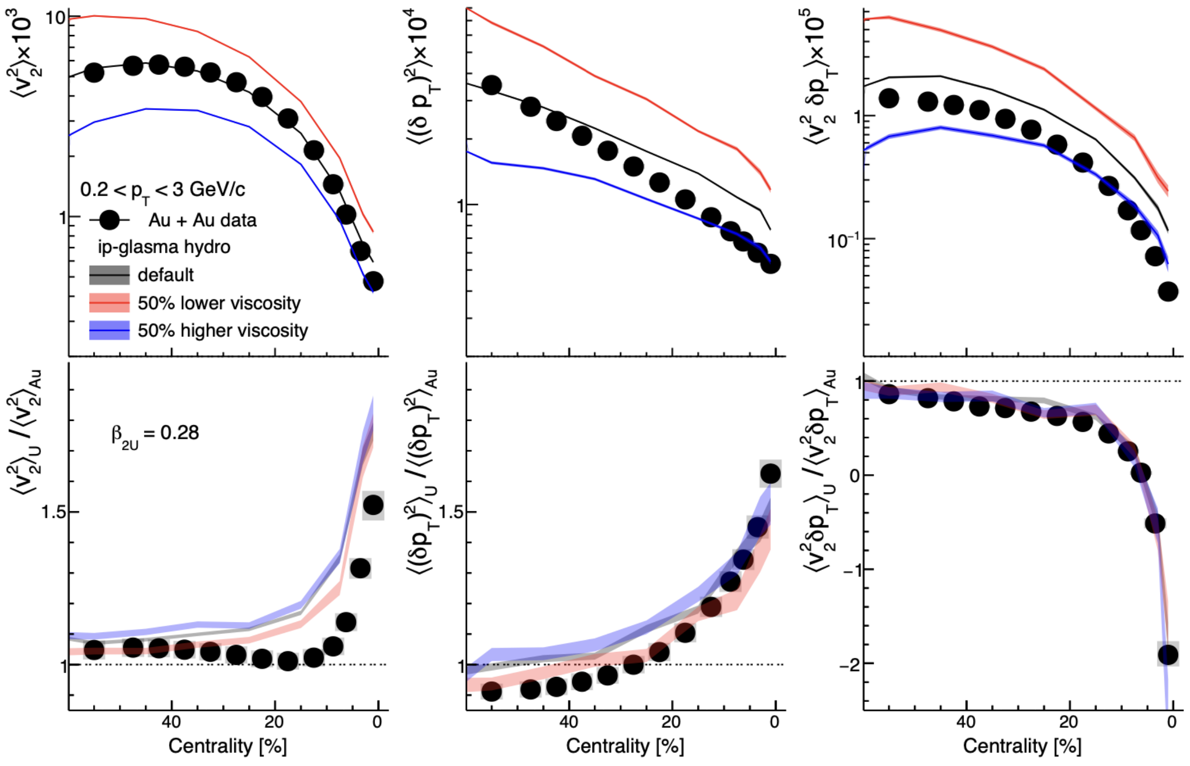
Understanding the nuclear deformation in the shorter time scales.

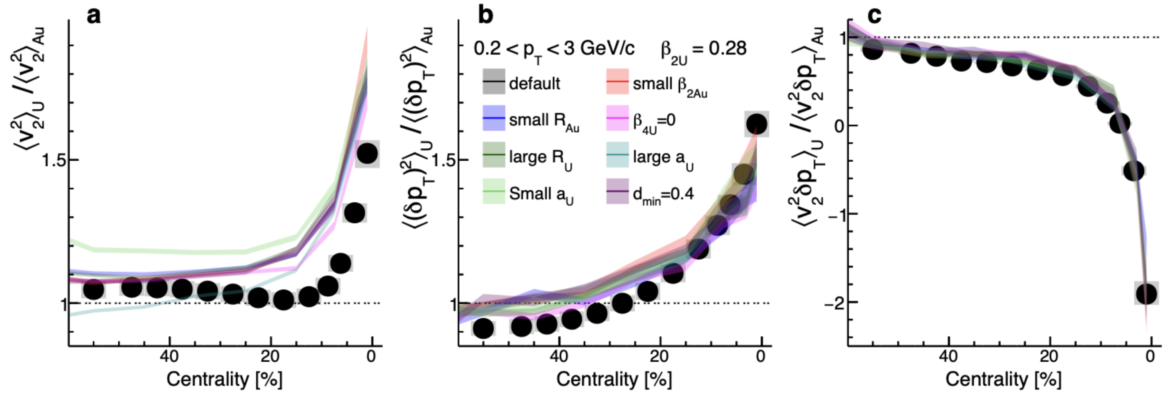
The heavy-ion collisions could also quantify the shape of ^{238}U as a novel tool.

Extracting shape of ^{238}U: robust and remarkable in central

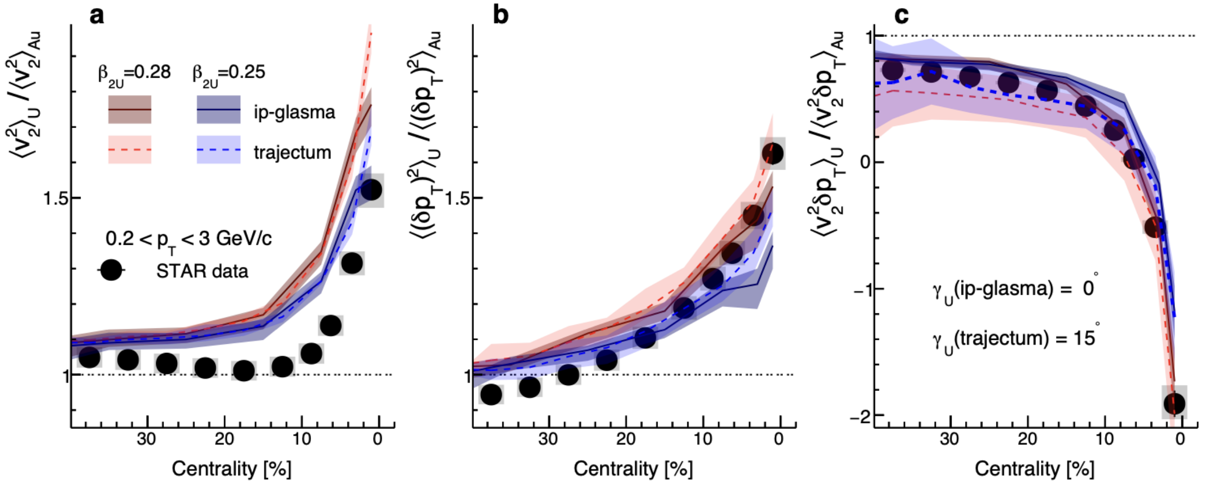
Effect from nuclear parameters are smaller and also included as model systematics.

Ratios cancel the viscosity effects.





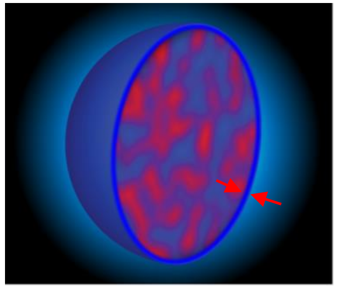
Other hydrodynamics model (Trajectum) also shows rather consistent extractions even if it was not tuned to RHIC data.



Model systematics sources are included in the experimental paper.

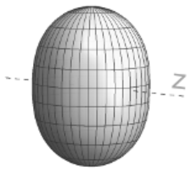
Nuclear structure in isobaric ^{96}Ru and ^{96}Zr nuclei

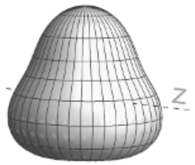
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r - R(\theta,\phi))/a_0}}$$



R_n-R_p

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





Lower energies experimental measurement

$$\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}} \qquad \beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$$

	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.

Pear-shaped nuclei enable new-physics searches?

US Long Range Plan 2023

Sidebar 6.2 Radioisotope harvesting at FRIB for fundamental physics

The Facility for Rare Isotope Beams (FRIB) will yield the discovery of new, exotic isotopes and the measurement of reaction rates for nuclear astrophysics, and will produce radioactive isotopes that can be used for a broad range of applications, including medicine, biology, and fundamental physics.

Converting waste to wealth
Radioisotopes at FRIB are produced via fragmentation when accelerated ion beams interact with a thin target. Several isotopes, including those previously unobserved, across the entire periodic table will be produced in practical quantities for the first time in the water beam dump at the FRIB accelerator. The Isotope Harvesting Project provides a new opportunity to collect these isotopes, greatly enhancing their yield and real-time availability to enable a broad spectrum of research across multiple scientific disciplines. Isotopes will be extracted from the beam dump and chemically purified using radiochemistry techniques in a process called harvesting. Harvesting operates commensally, therefore providing additional opportunities for science.

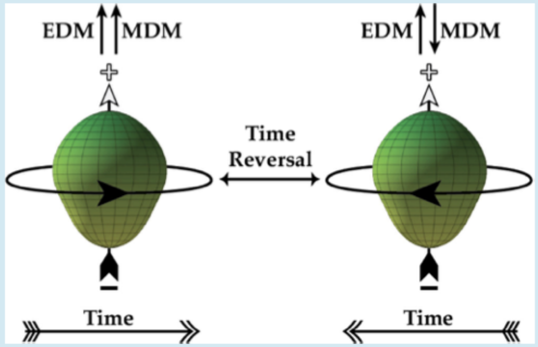


Figure 1. A pear-shaped nucleus spins counterclockwise or clockwise, depending on the direction of time. [S47]

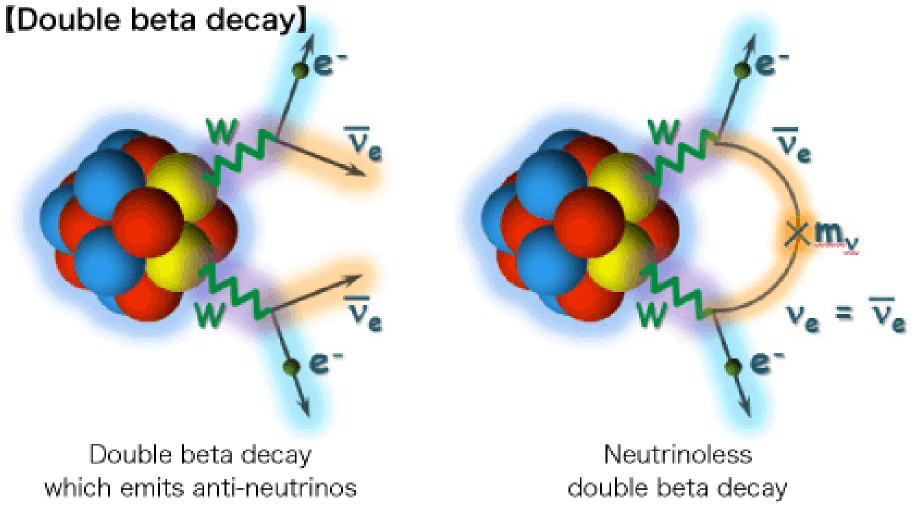
Pear-shaped nuclei enable new-physics searches
With uranium-238 ion beams, these methods can produce heavy, pear-shaped nuclei that can be used to search for violations of fundamental symmetries that would signal new forces in nature. For example, a nonzero permanent electric dipole moment (EDM) would break parity and time-reversal symmetries. Figure 1 shows a pear-shaped nucleus spinning under applied electric and magnetic fields. Its magnetic dipole moment (MDM) is nonzero, and if its EDM is also nonzero, then its spin-precession rate changes if the direction of time is reversed. Heavy, pear-shaped nuclei can greatly amplify the sensitivity to a nonzero EDM and complement neutron EDM studies. Pear-shaped isotopes such as radium-225 and protactinium-229 will be produced in abundance at FRIB, and their EDM effects can be further enhanced by using them to form polar molecules, which can then be probed using cutting-edge laser techniques. The unique sensitivity of these experiments opens otherwise inaccessible windows on new physics.

EDMs are very small and difficult to measure.

Higher sensitivity via Schiff nuclear moments in heavy nuclei

-> Octupole deformation enhancements

Hunt for the no neutrinos



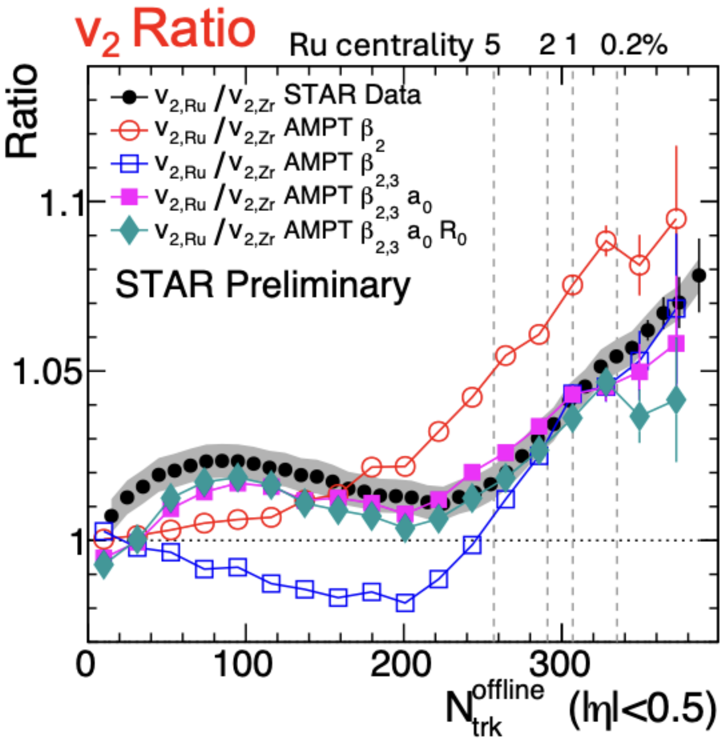
Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta}\rangle$ (eV)	Experiment	Reference
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV	(157)
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA	(158)
	> 1.9	$< 0.24 - 0.52$	MAJORANA DEMONSTRATOR	(159)
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	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)

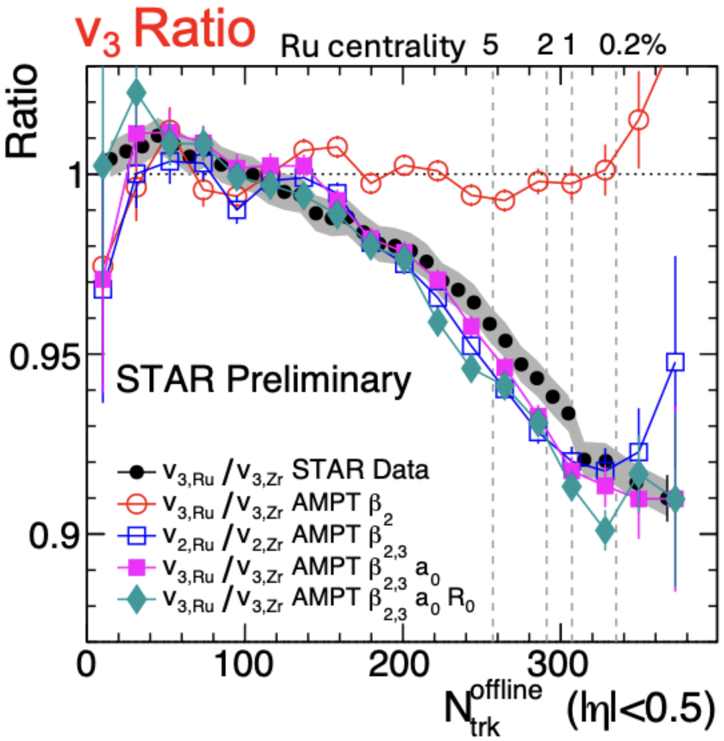
^{96}Zr with high-case rate, strong neutrino mass limiting ability

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

Rev.Mod.Phys.91, 015001(2019); Rep.Prog.Phys.80, 046301(2017); Ann.Rev.Nucl.Part.Sci.69, 219(2019)

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



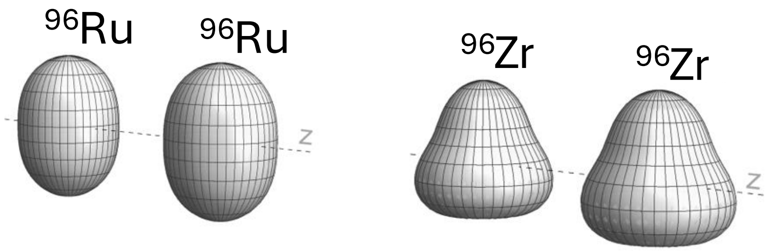


$\beta_{2\mathrm{Ru}} \sim 0.16$ increase v_2, no influence on v_3 ratio

$\beta_{3\mathrm{Zr}} \sim 0.2$ 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.



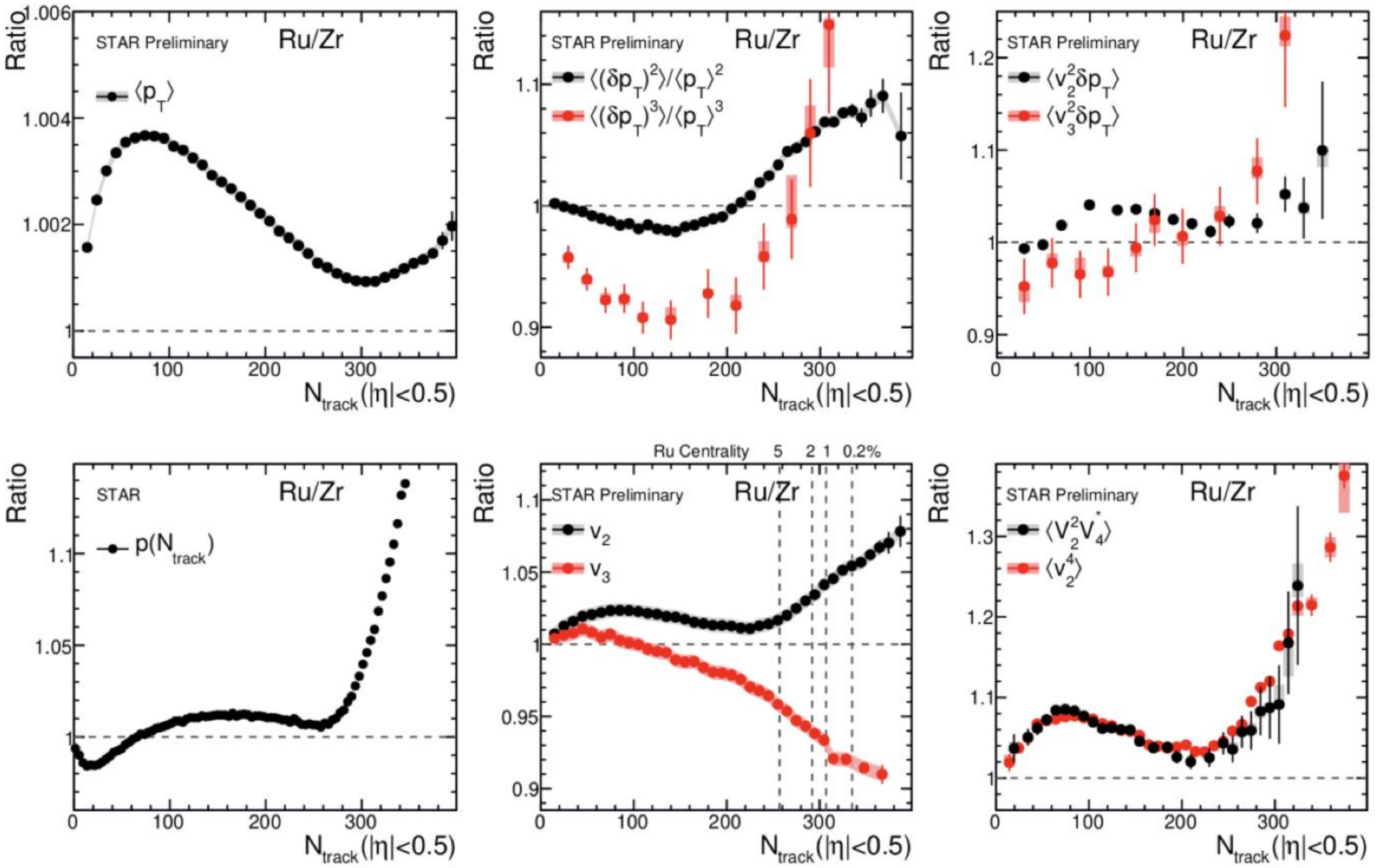
Species	β_2	β_3	a_0	R_0
Ru	0.162	0	0.46 fm	5.09 fm
Zr	0.06	0.20	0.52 fm	5.02 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

- 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

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

C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia and C. Zhang, PRC107, L021901(2023); J. Jia, G. Giacalone, C. Zhang, PRL131, 022301(2023)

Nuclear structure influences everywhere in various observables



Conclusions and Outlooks

1. The signatures of nuclear structure in heavy-ion collisions are everywhere, robust and reliable:

   ---constrain quadrupole deformations and observe triaxiality shape in ^{238}U

$$\beta_{2\mathrm{U}} = 0.297 \pm 0.013 \qquad \gamma_U = 8.6^\circ \pm 4.8^\circ$$

   ---observe large octupole deformation in ^{96}Zr and neutron skin thickness difference between ^{96}Zr and ^{96}Ru

Species	β_2	β_3	a_0	R_0
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Zr	0.06	0.20	0.52 fm	5.02 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

2. Decoding the nuclear structure utilizing many bulk tools via vast final state hadrons.

3. As a novel tool to unveil nuclear structure, high-energy collisions could help further understand fundamental structure in odd- or even-nuclei, and better treat QGP initial conditions.

4. Heavy ion collisions open the interdisciplinary connection between low- and high-energy.

   ---High-order nuclear deformations, rigid and soft triaxiality, NN correlations in light nuclei…

Expect more collaborations for understanding the nature of the shape of atomic nuclei!

The past and future workshops

EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 1/2)

https://indico.gsi.de/event/14430/

30 May 2022 to 3 June 2022
Heidelberg University
Europe/Berlin timezone

2022, Heidelberg

- Overview
- Registration
- Participant List
- Timetable

Support
emmi-office@gsi.de

EMMI Rapid Reaction Task Force (RRTF)

"Nuclear physics confronts relativistic collisions of isobars"

High-energy collisions of the A=96 isobars ^{96}Zr and ^{96}Ru have been performed in 2018 at the Relativistic Heavy Ion Collider (RHIC) as a means to probe effects of local parity violation in the strong sector, that would manifest as deviations from unity in the ratio of observables taken between ^{96}Zr+^{96}Zr and ^{96}Ru+^{96}Ru collisions. Recently released measurements of such ratios reveal deviations from unity. However, such observations are primarily caused by the two collided isobars having different radial profiles and intrinsic deformations. To make progress in understanding RHIC data, we will gather nuclear physicists across the energy spectrum to answer the following question. Does the combined effort of state of-the-art low-energy nuclear structure physics and high-energy heavy-ion physics allow us to understand the observations made in isobar collisions at RHIC?

EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 2/2)

https://indico.gsi.de/event/15627/

12-14 October 2022
Heidelberg University
Europe/Berlin timezone

- Overview
- Registration
- Participant List
- Timetable

Support
emmi-office@gsi.de

EMMI Rapid Reaction Task Force (RRTF)

"Nuclear physics confronts relativistic collisions of isobars"

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Jiangyong Jia
(Stony Brook & BNL)

INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023

2023, Seattle

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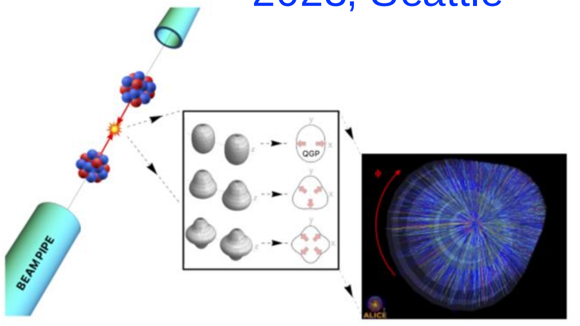

High-energy heavy-ion collisions producing a quark gluon plasma whose energy density profile reflects the collective structure of the colliding ions

- TALK SLIDES AND VIDEOS
- PARTICIPANT LIST
- HIGH-RESOLUTION IMAGES
- EXIT SURVEY
- INT YOUTUBE CHANNEL

https://www.int.washington.edu/programs-and-workshops/23-1a

Exploring nuclear physics across energy scales 2024: intersection between nuclear structure and high energy nuclear collisions

Apr 15 – 27, 2024
Asia/Shanghai timezone

2024, Beijing

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- Meal and food
- Visa to China
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Huichaosong@pku.edu...

Introduction: Recently, it has been realized that relativistic heavy ion collisions could provide new approaches to study some fundamental properties of atomic nuclei. It is therefore timely to gather scientists from both the low-energy and high-energy nuclear physics communities to discuss the recent progress and future perspective in this research direction. The two-week program+workshop on "Exploring Nuclear Physics across Energy Scales" emphasizes the intersection between nuclear structure and high-energy nuclear collisions, with a focus on the following questions: How does the low-energy structure of nuclei manifest in high-energy collisions? How do the observations made at colliders complement our knowledge of nuclear structure? During the program days (April 15-19, April 24-27, 2024) the two invited speakers each day are expected to give a one-hour seminar with sufficient time for discussions. The embedded workshop (April 21-23, 2024) will be 3 days with 25-30 invited talks and 3 short discussion sections.

The scientific program includes the following topics, which emphasises the intersections between nuclear structure and high-energy collisions.

- Manifestation of nuclear deformations across energy scales
- Neutron skin determinations and applications
- Many-body correlations and clustering in light nuclei
- Bayesian analysis for high-energy collisions and nuclear structure
- Role of nuclear structure in low- and intermediate-energy collisions
- Connection to Ultra-peripheral Collisions (UPCs) and the future Electron-Ion Collider (EIC)
- Opportunities with colliding new species at future high-energy experiments

Program: 10:00-11:00 am 2:30-3:30 pm April 15-19, April 24-27, 2024

Workshop: 9:00-12:00 am 2:00-6:00 pm April 21-23, 2024

Note: Due to the limited hotel reservations in Zhongguan Yuan, we have shifted the 3-day workshop from April 20-22 to April 21-23. April 20 is now the registration day for the workshop and the free excursion day for the program.

Video and picture files are available on Baiduyun,

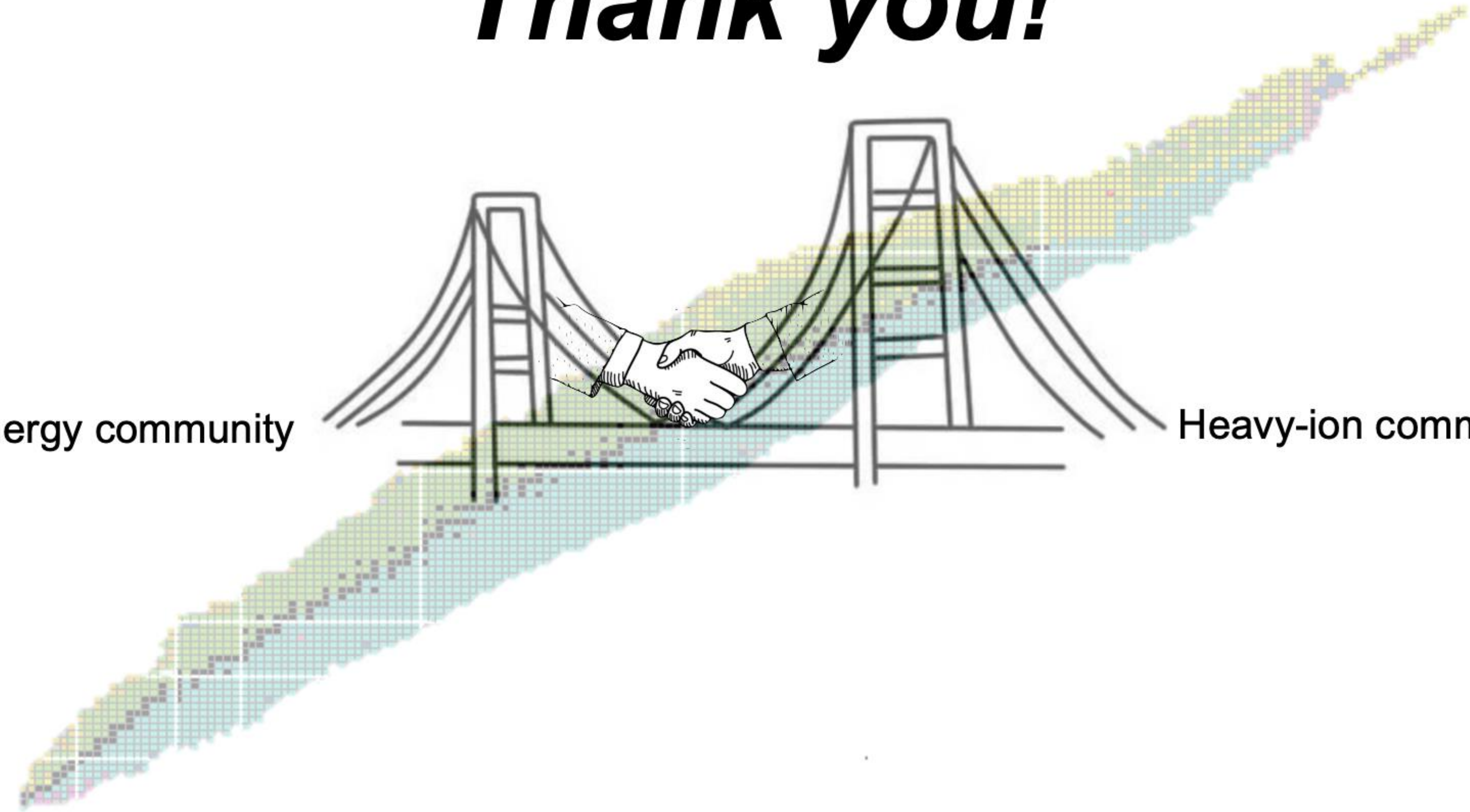
Link: https://pan.baidu.com/s/1aHzRtSH0a6h_R6W3tQAkPg

Extraction Code: 3j9r

https://indico.ihep.ac.cn/event/20877/

Continue the efforts to further explore nuclear physics in high-energy collisions.

Thank you!



Low energy community

Heavy-ion community

Snapshot imaging = tracing the intrinsic nuclear structure?

“…figuring out a pocket watch by smashing two together and observing the flying debris”

— Richard Feynman

Short-time scale imaging could see detailed shapes?