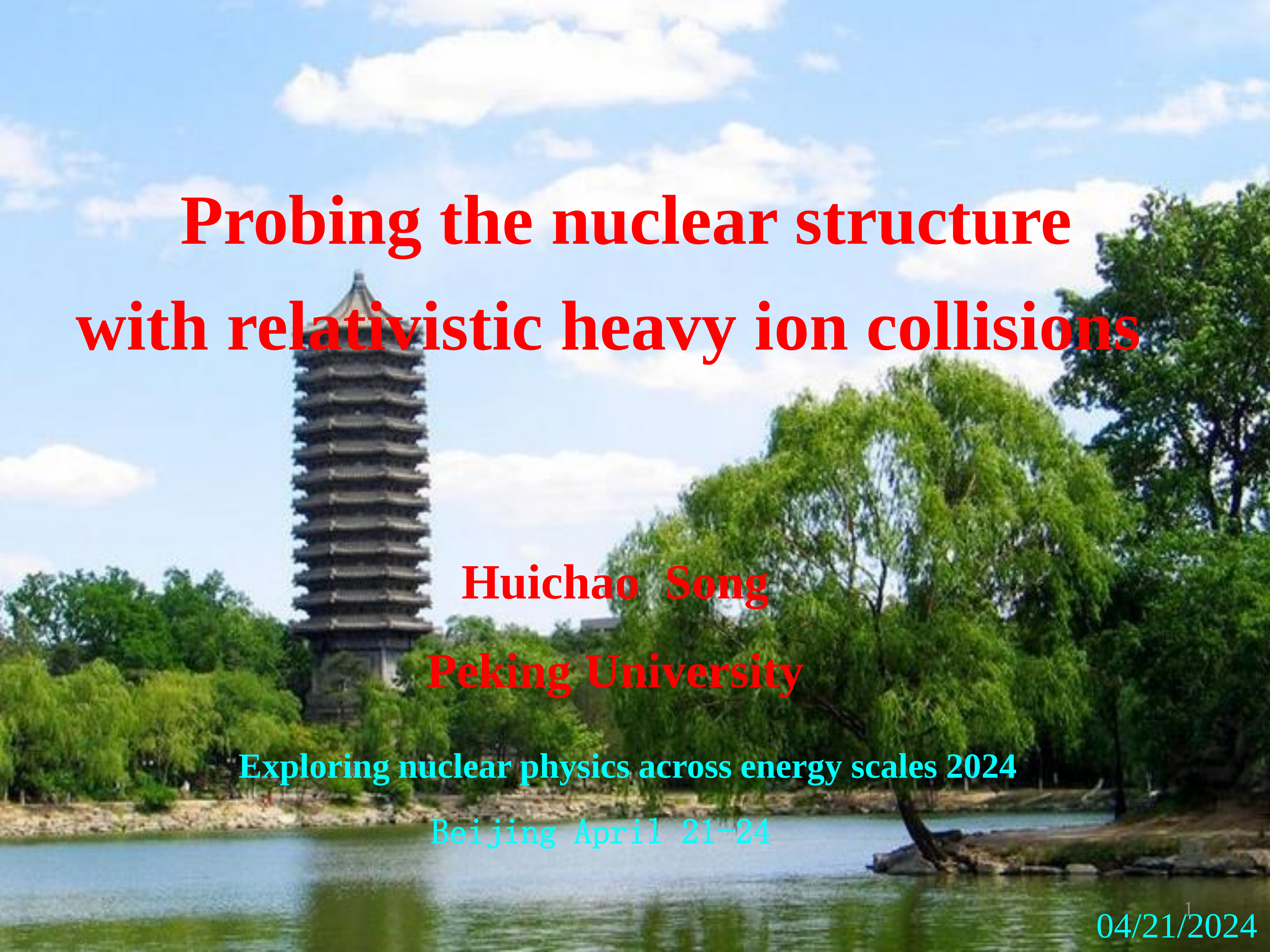


Probing the nuclear structure with relativistic heavy ion collisions

Huichao Song

Peking University

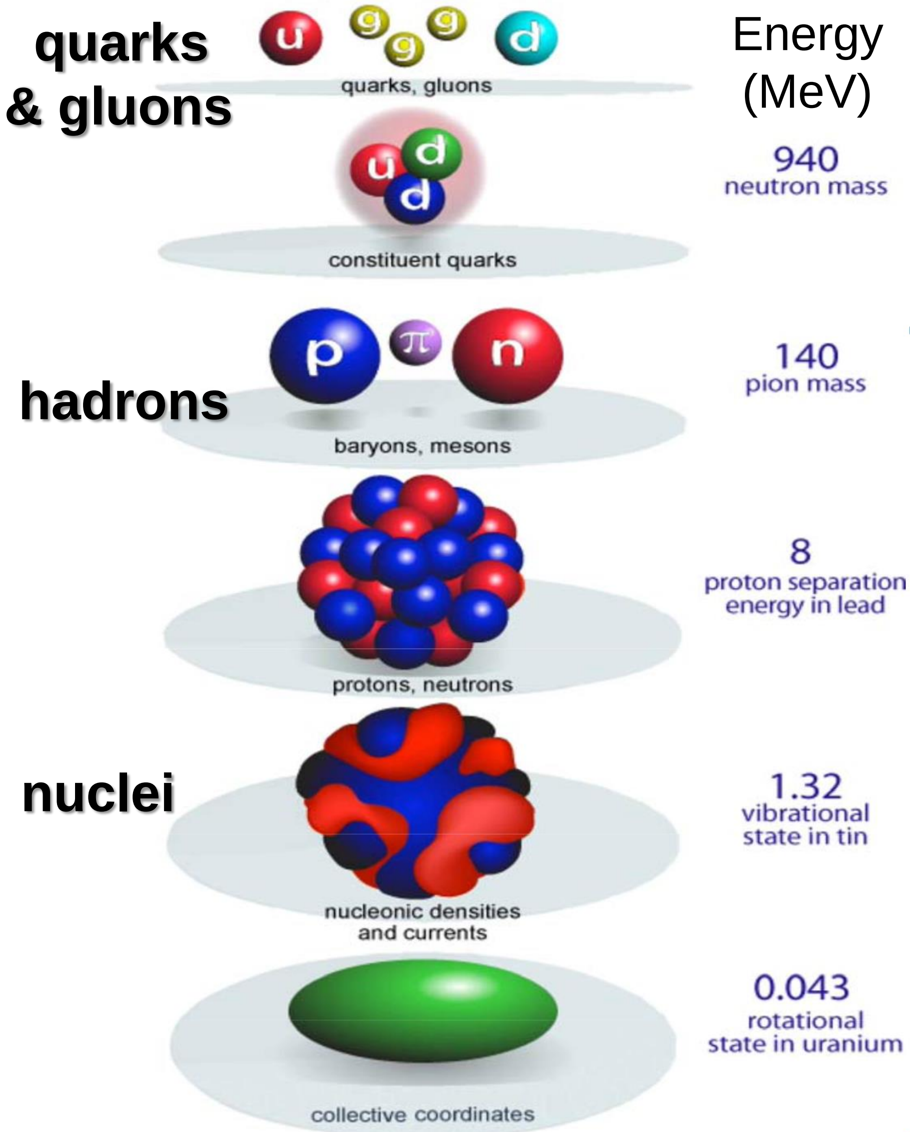
Exploring nuclear physics across energy scales 2024

Beijing April 21-24

04/21/2024

Landscape of nuclear physics

degrees of freedeom



Landscape of nuclear physics

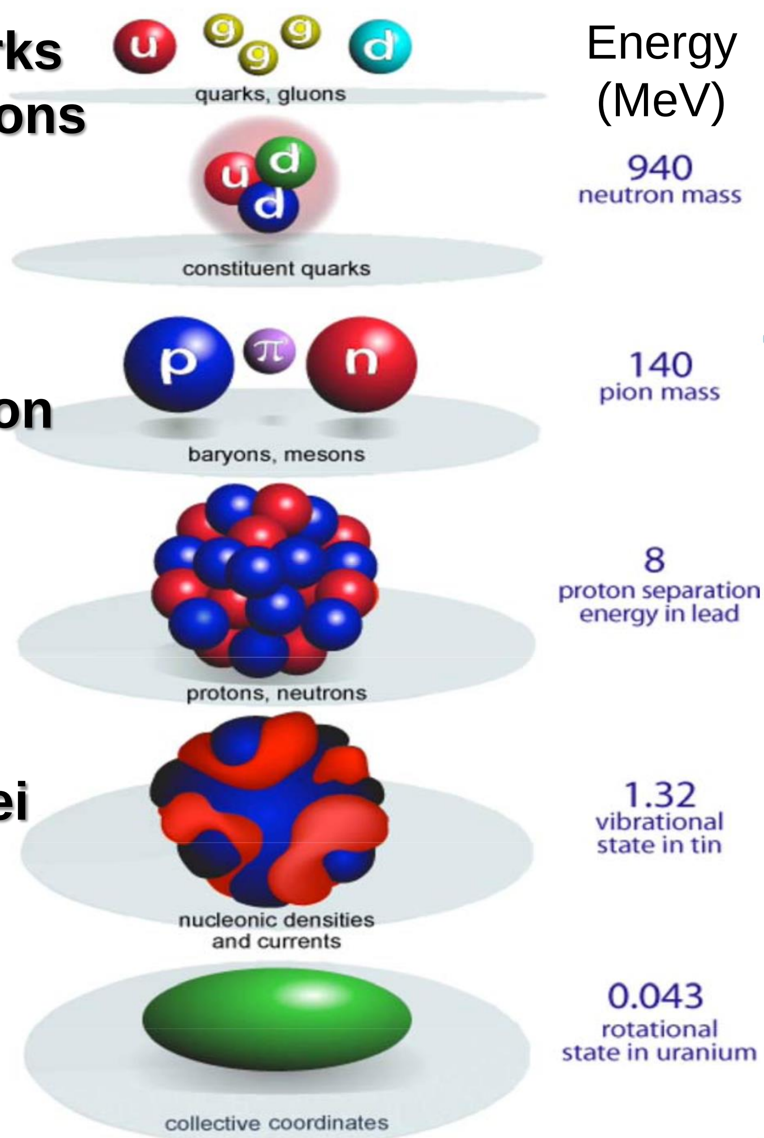
degrees of freedeom

quarks & gluons

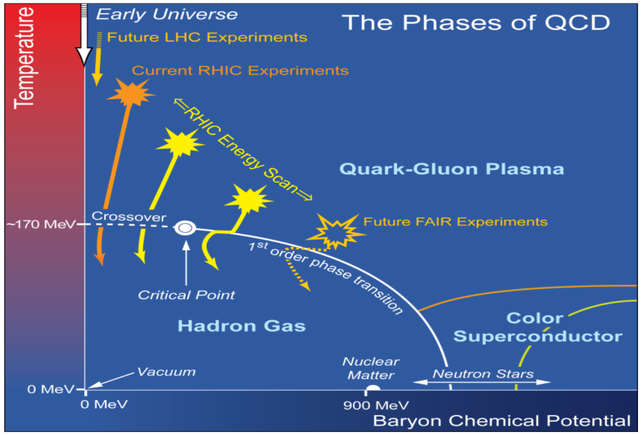
hadrons

nuclei

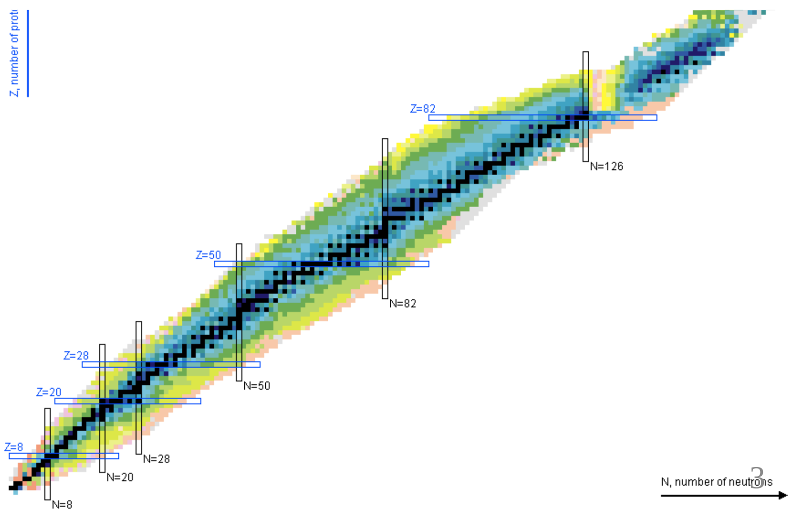
Energy (MeV)



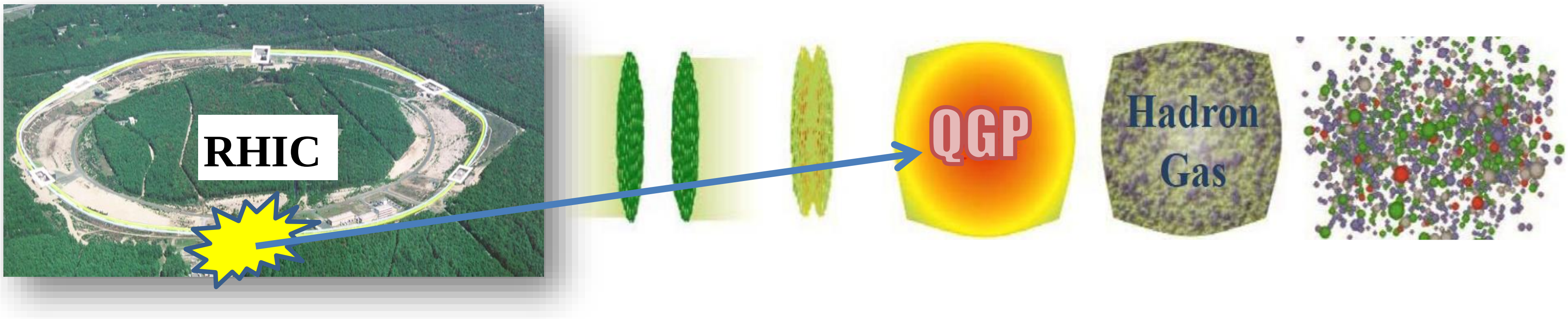
- intermediate and high energy nuclear physics



- nuclear structure

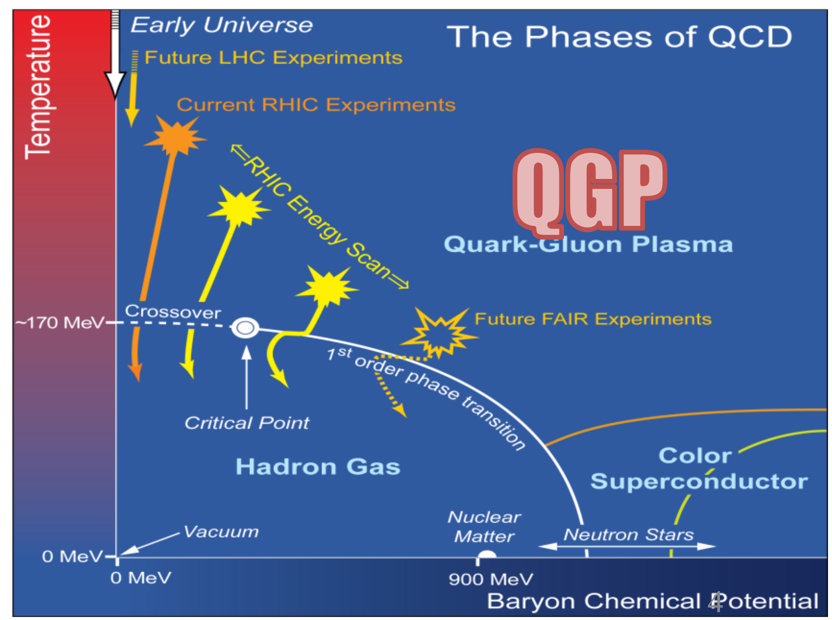


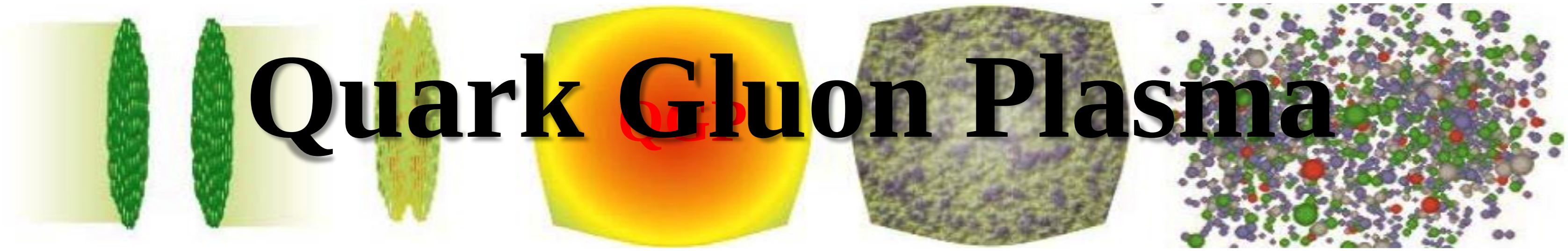
Relativistic Heavy Ion Collisions



<u>Relativistic heavy ion collisions</u>

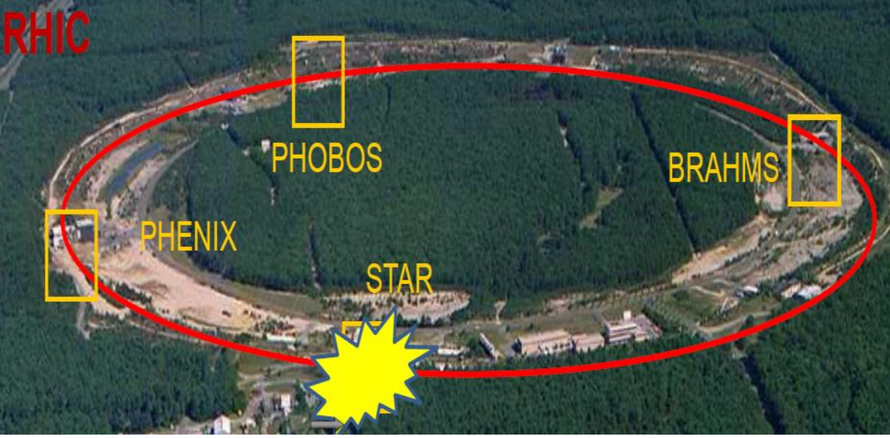
- **create and study QGP**
- **the QCD phase diagram**
- **the deconfinement & chiral phase transition**
- **the QCD vacuum**

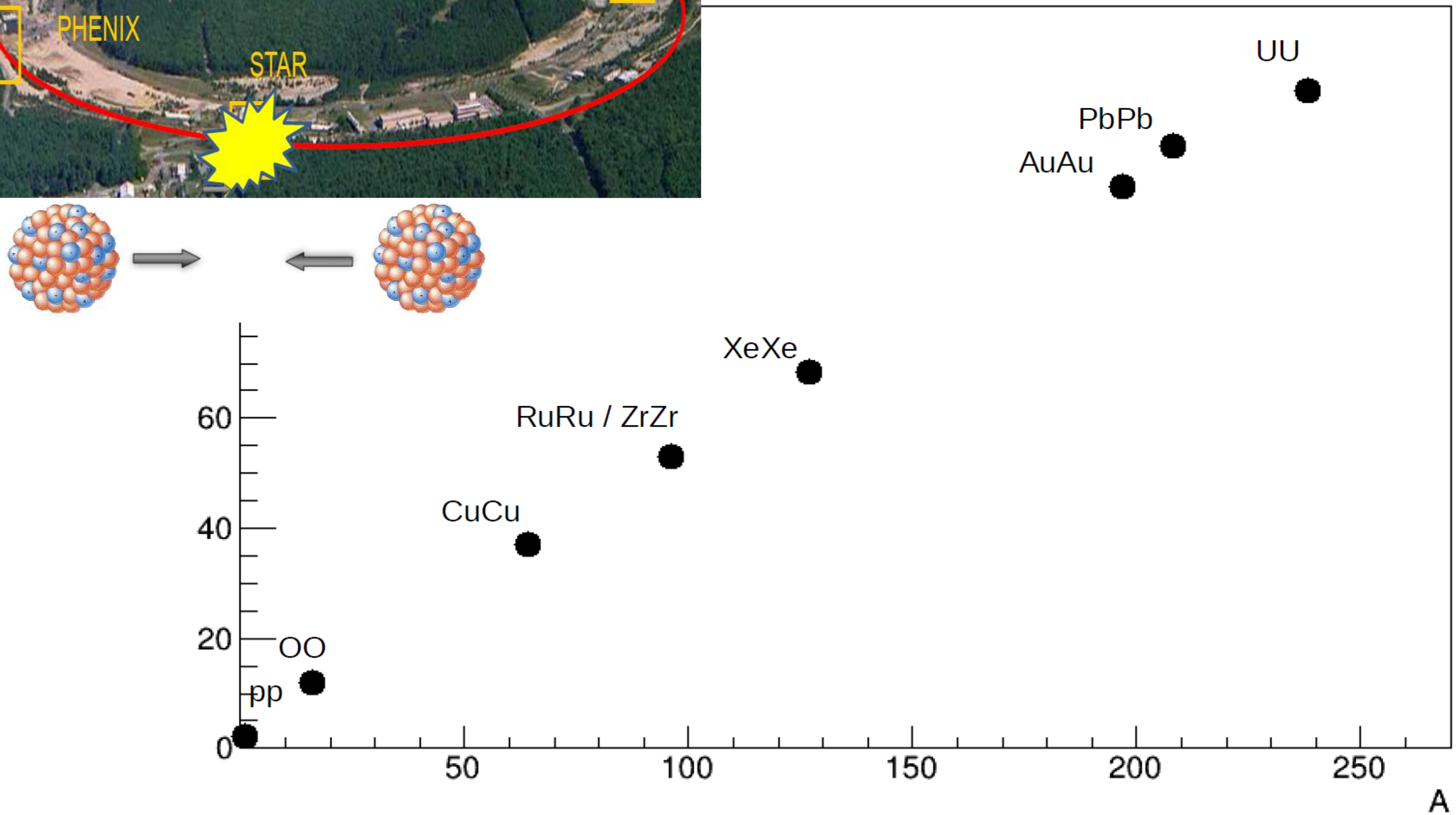




Hottest Matter on Earth

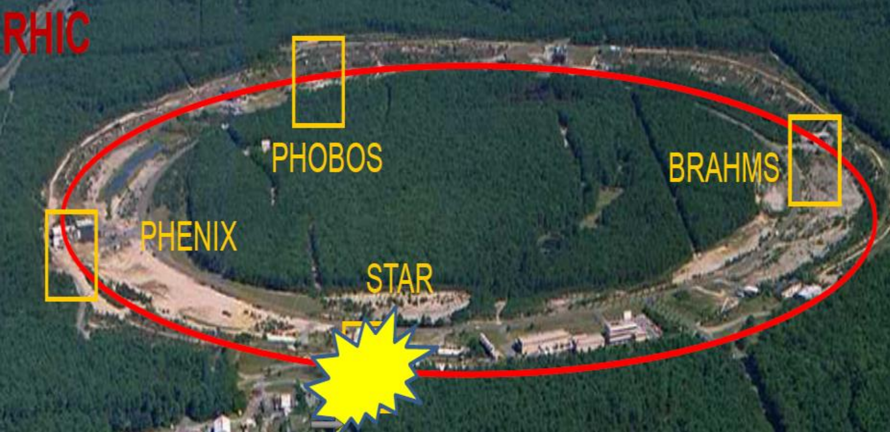
Rich A-A Collisions at RHIC & the LHC

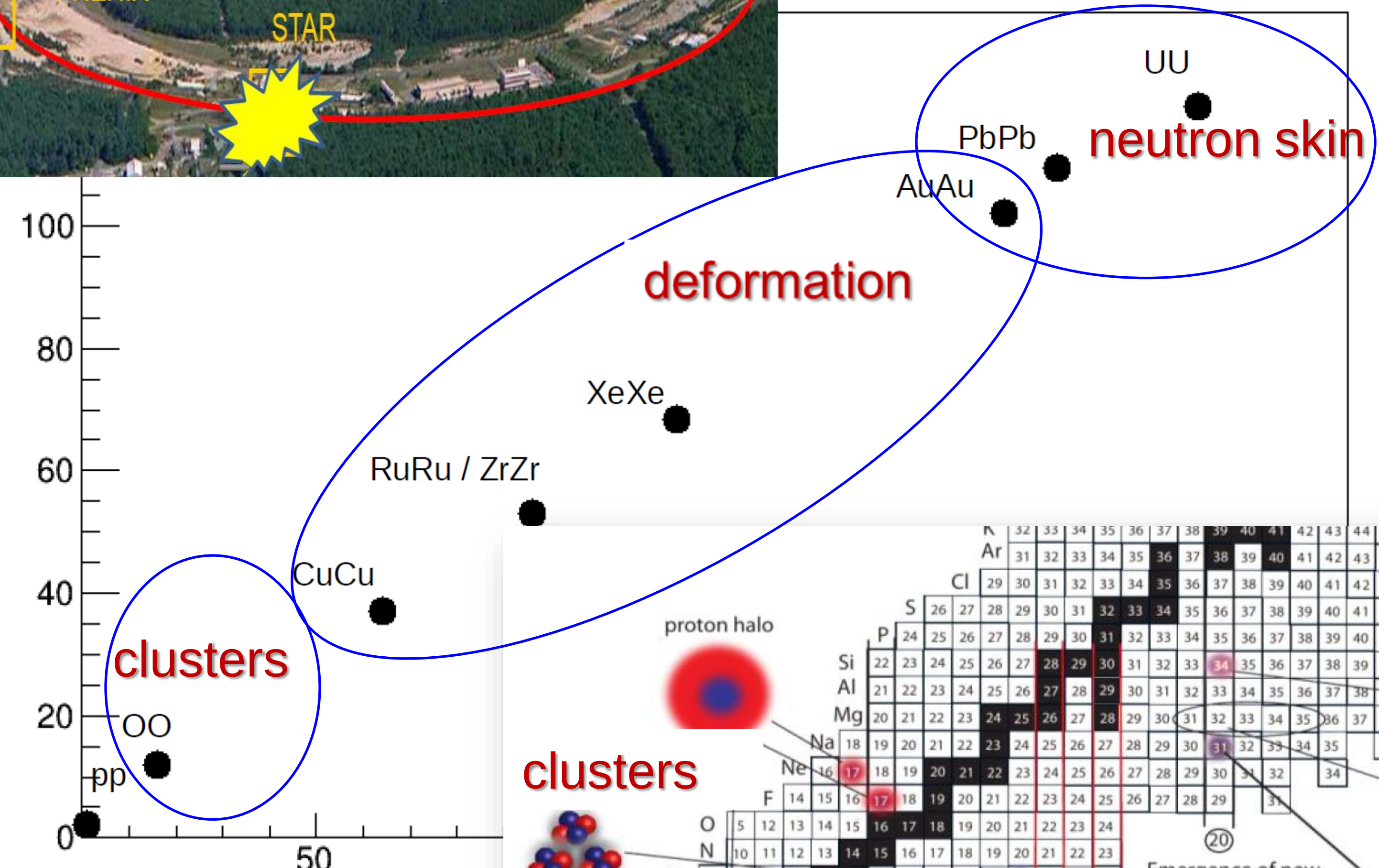


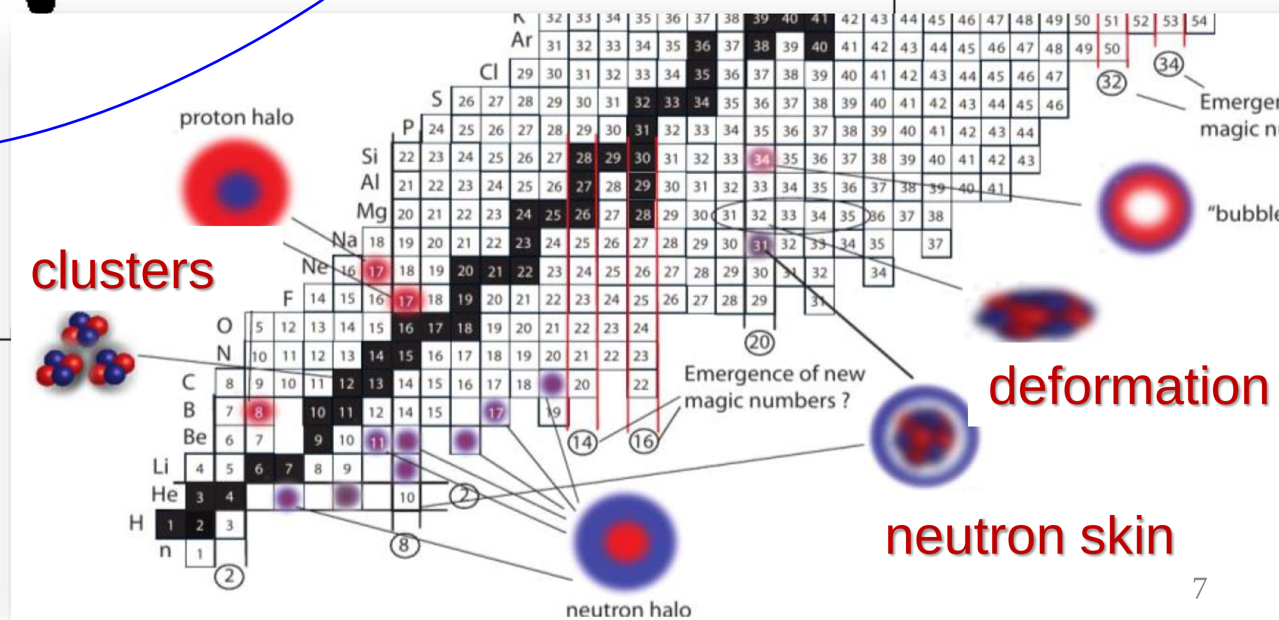


^{197}Au+^{197}Au、^{238}U+^{238}U、^{208}Pb+^{208}Pb、^{129}Xe+^{129}Xe、^{96}Zr+^{96}Zr、^{96}Ru+^{96}Ru、^{64}Cu+^{64}Cu 、^{16}O+^{16}O 、p+^{208}Pb、p+p ……

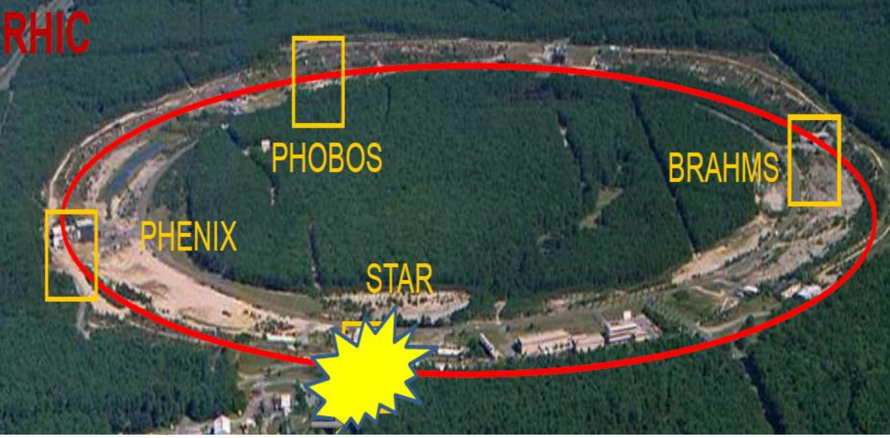
High energy nucleon nucleon collisions & nuclear structure

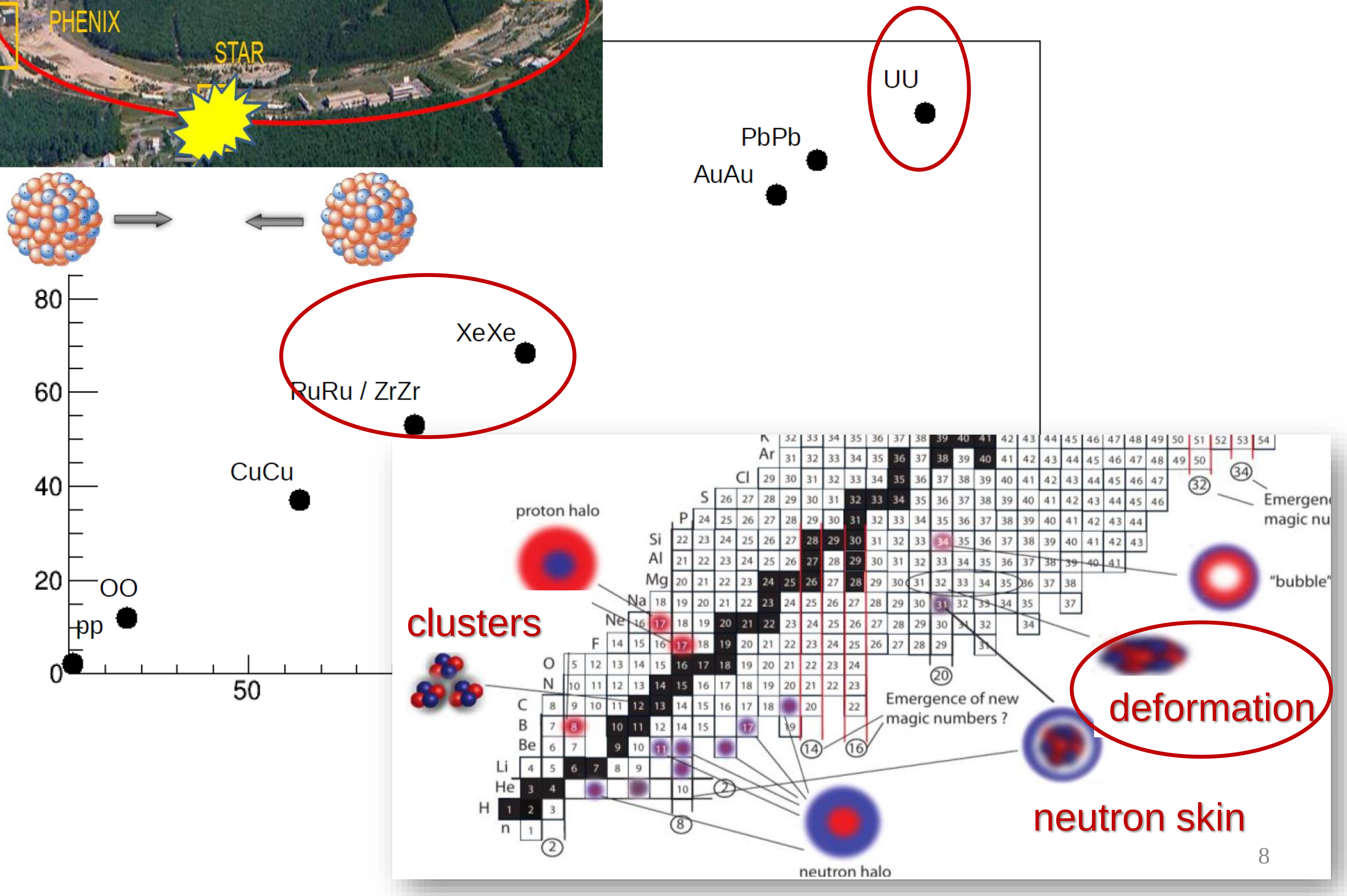




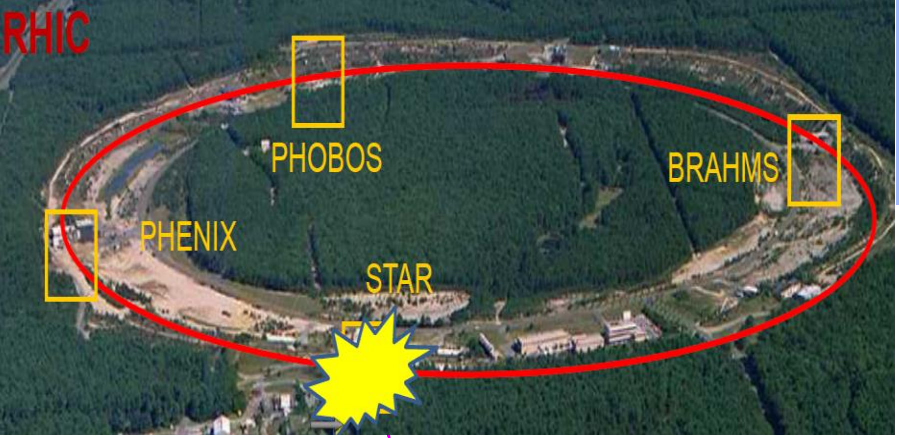


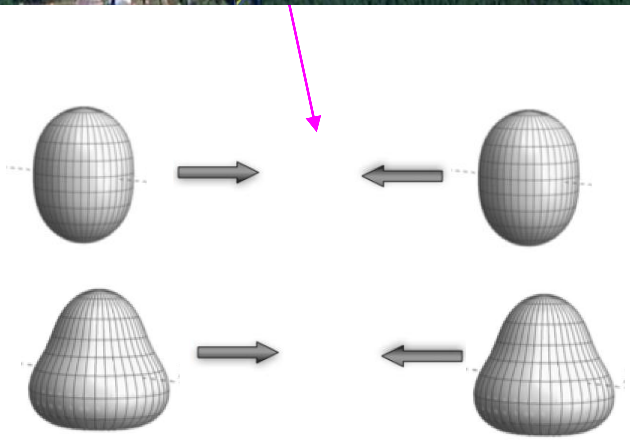
Probe the deformation of nuclei with relativistic heavy ion collisions





Probe the deformation of nuclei with relativistic heavy ion collisions

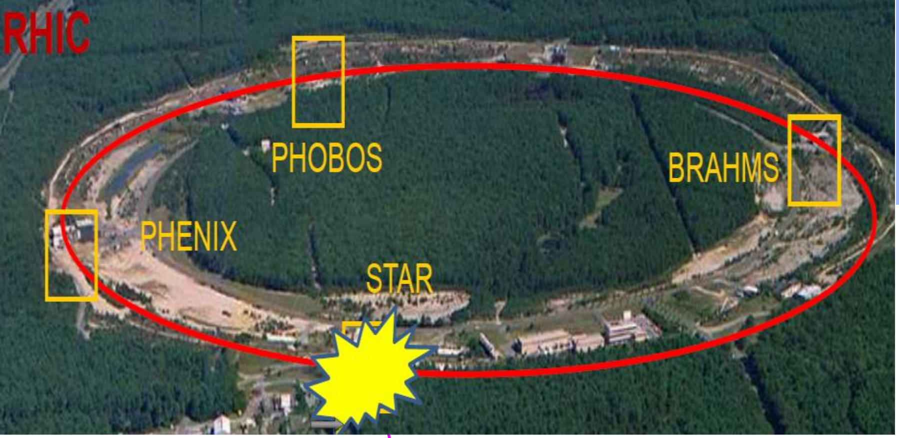




initial conditions:
(with deformations)

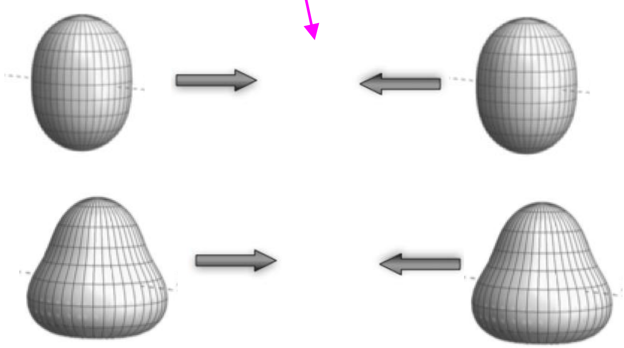
- Relativistic heavy collisions
  start from nuclei

Probe the deformation of nuclei with relativistic heavy ion collisions

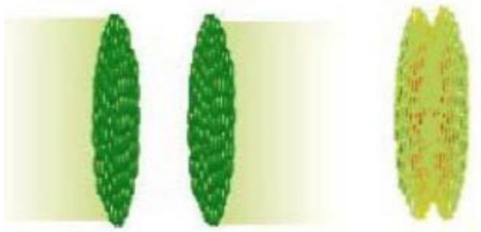


- Relativistic heavy collisions
  start from nuclei

-Collision time < 10^{-24} s
  directly probe the ground state of nuclei

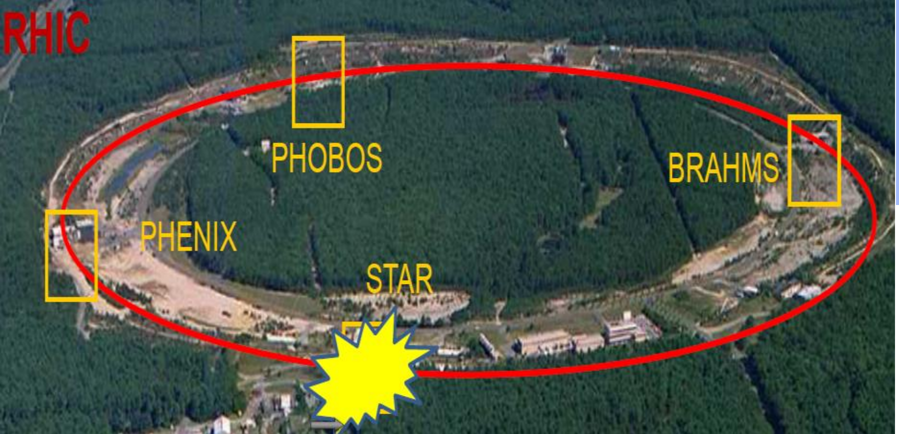


initial conditions:
(with deformations)



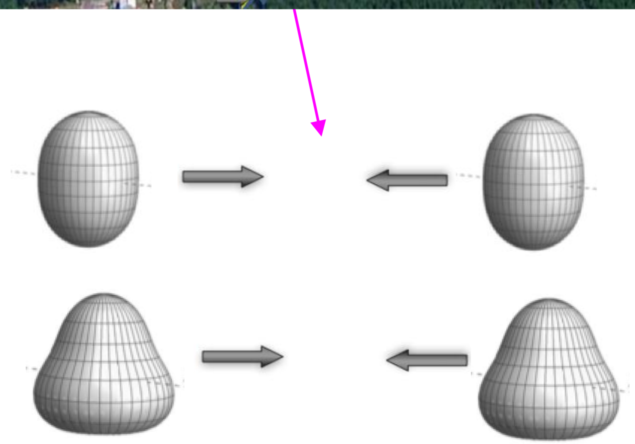
Collision time < 10^{-24} s

Probe the deformation of nuclei with relativistic heavy ion collisions

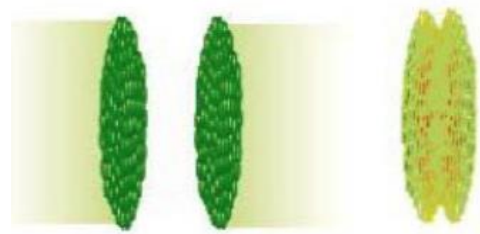


- Relativistic heavy collisions
  start from nuclei

-Collision time < 10^{-24} s
  directly probe the ground state of nuclei

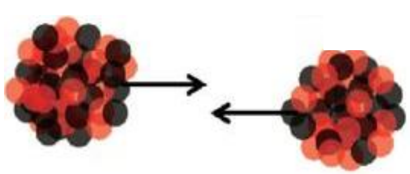


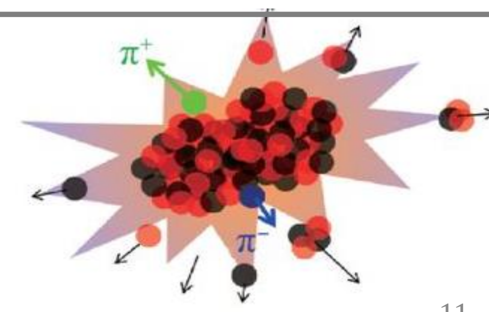
initial conditions:
(with deformations)

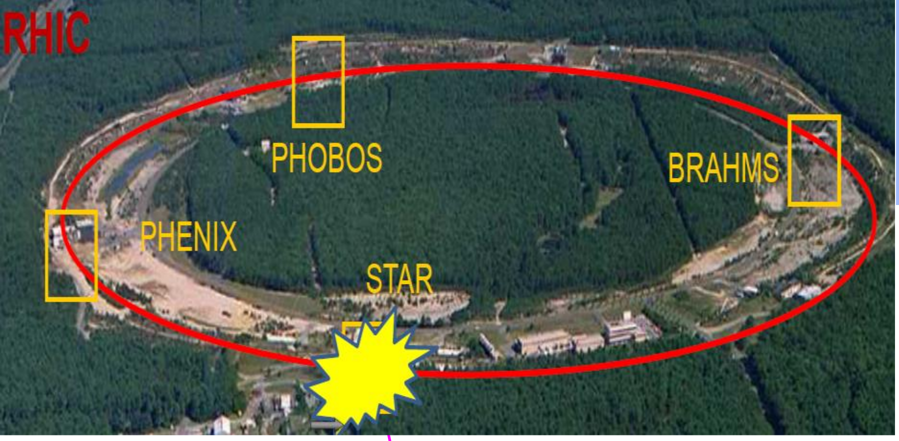


Collision time < 10^{-24} s

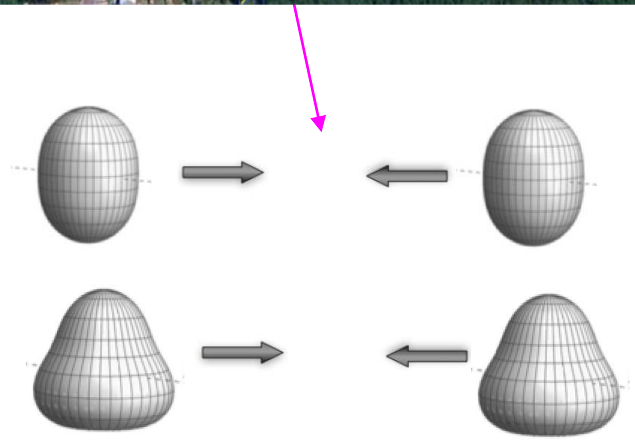
heavy ion collision at intermediate energies breaks up / excites nuclei during the collisions







Probe the deformation of nuclei with relativistic heavy ion collisions



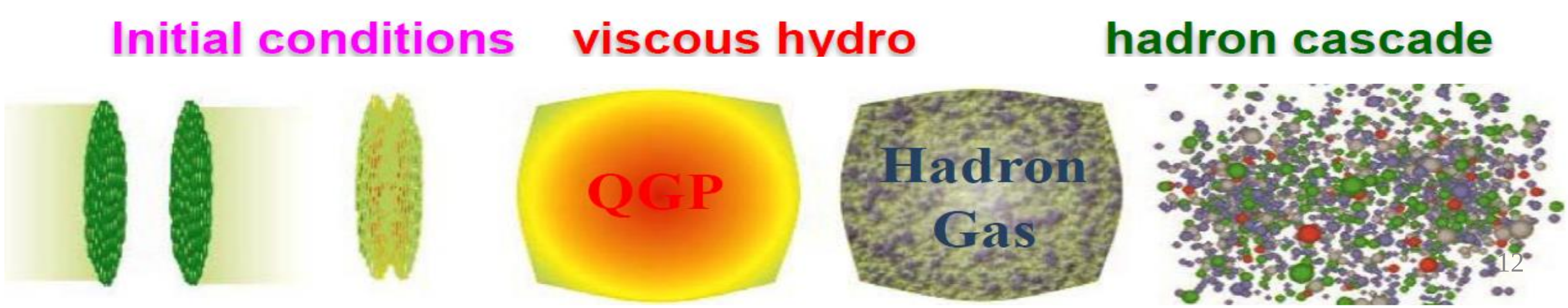
- Relativistic heavy collisions
  start from nuclei

-Collision time < 10^{-24} s
  directly probe the ground state of nuclei

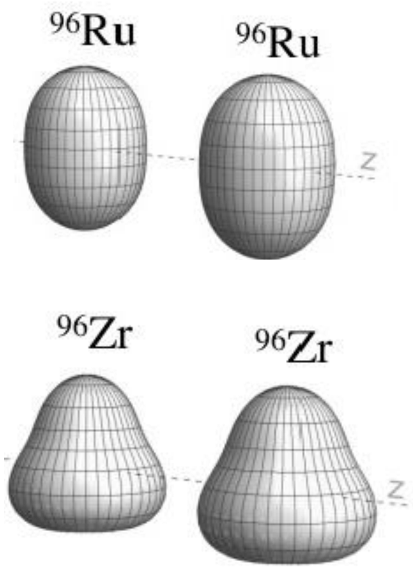
-Well calibrated calculations for QGP evolution; to focus on the initial state

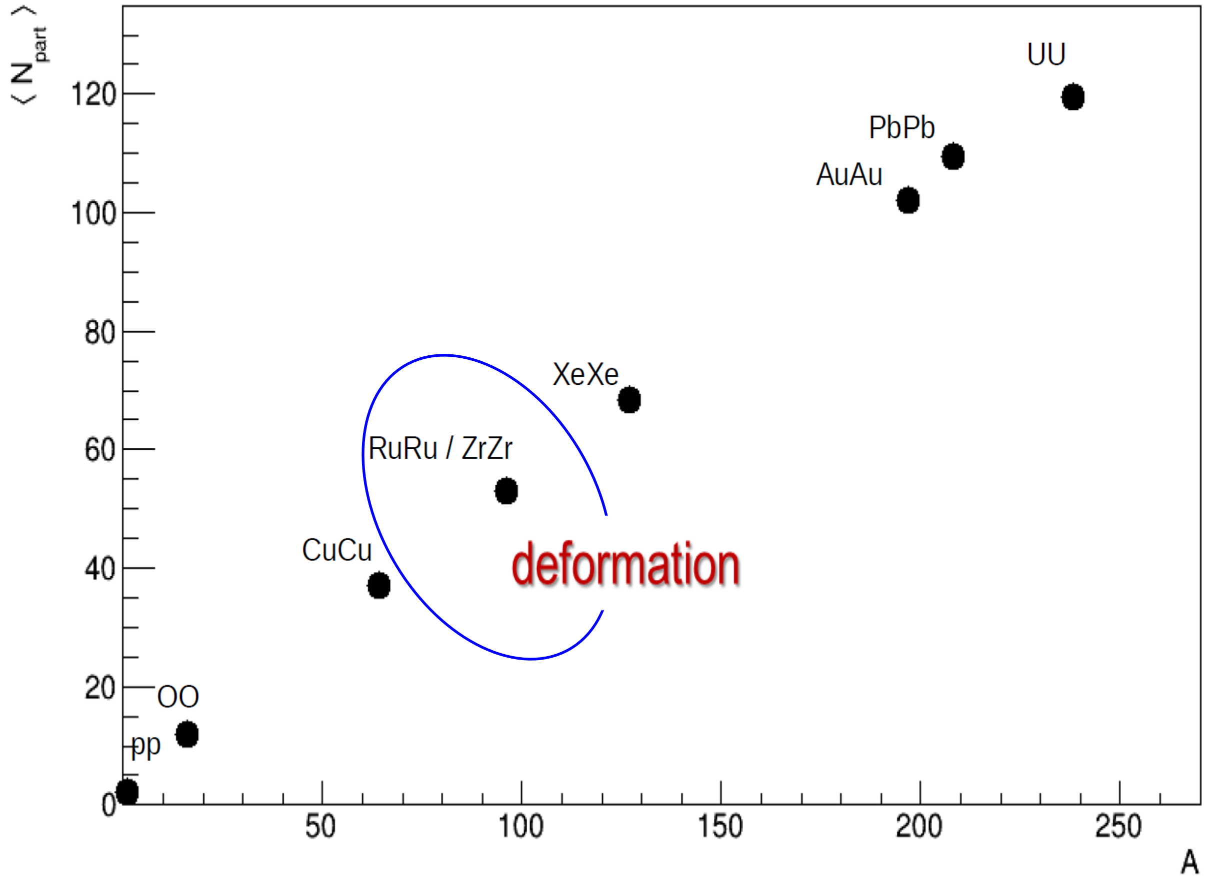
initial conditions:
(with deformations)

Well calibrated calculations

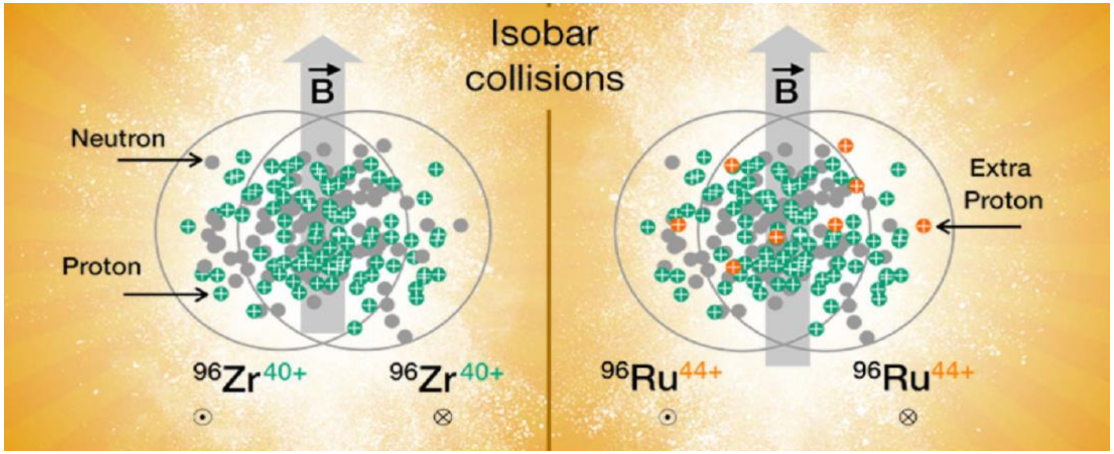


Study the deformation of ^{96}Ru and ^{96}Zr at RHIC isobar run





^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr Collisions @ RHIC isobar run



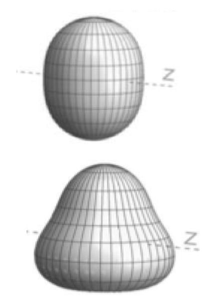
- To search the Chiral Magnetic Effect (CME)

- Obviously different early magnetic field for Ru+Ru and Zr+Zr collisions

Deformation of ^{96}Ru and ^{96}Zr

Conversion from B(En) to β_n via: $\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}}$, $\beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$

	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



ADNDT107,1 (2016) ADNDT80,35(2002)

Model calculation for Nuclear Deformation

General approach (DFT level)

Non-relativistic Schrodinger equation: Skyrme and Gogny DFT

Relativistic Dirac equation: covariant DFT (CDFT)

Range of interaction

Zero range - point coupling models in CDFT (no mesons)
- Skyrme DFT

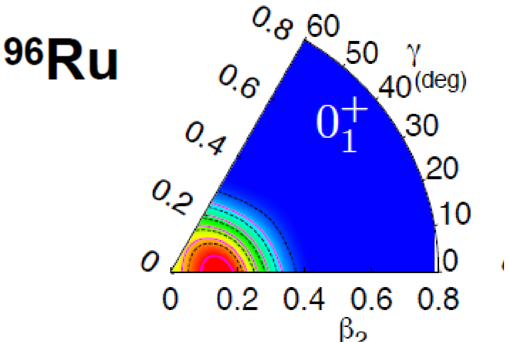
Finite range - meson exchange models in CDFT
- Gogny DFT

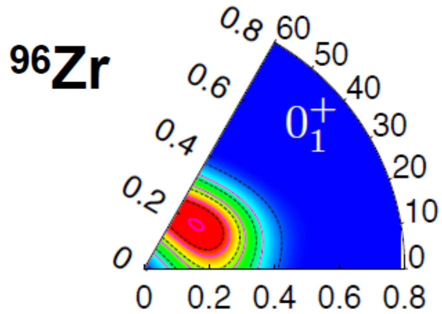
Effective density dependence

CDFT :
- explicit (DD-ME2, DD-PC1)
- non-linear (through the powers of mesons) (NL1, NL3*)

Skyrme and Gogny DFTs: different prescriptions for density dependence

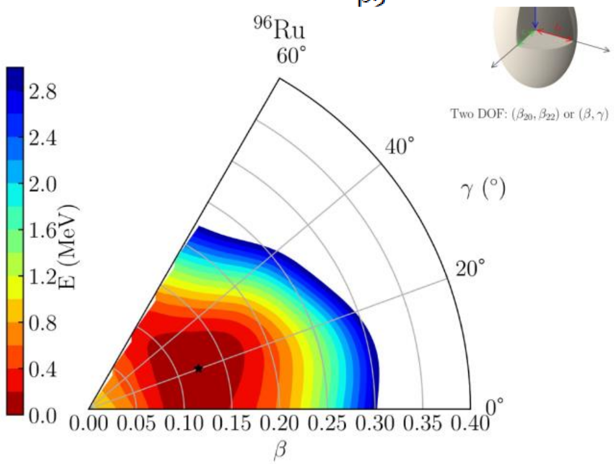
Deformation of ^{96}Ru & ^{96}Zr — DFT calculations

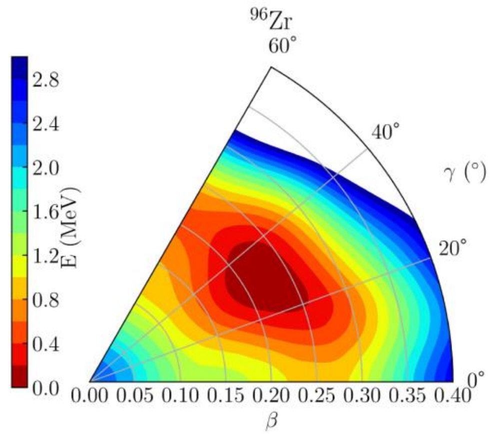




Gogny energy density functional |(Tiaxial)

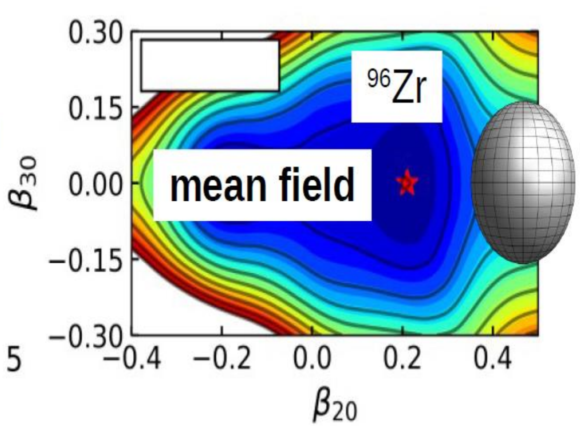
T R. Rodríguez EMMI RRTF 2022

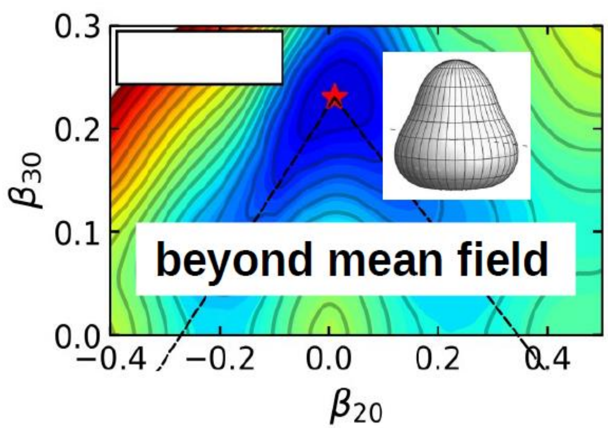




Skyrme EDF (with rotational correction)

W Ryssens EMMI RRTF 2022

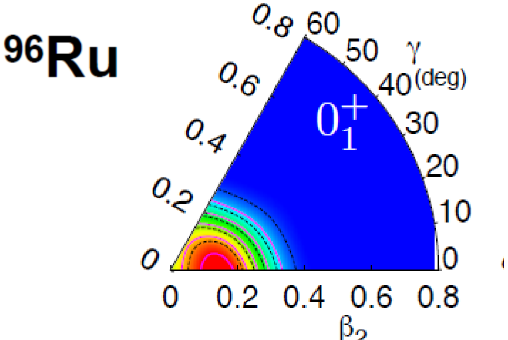


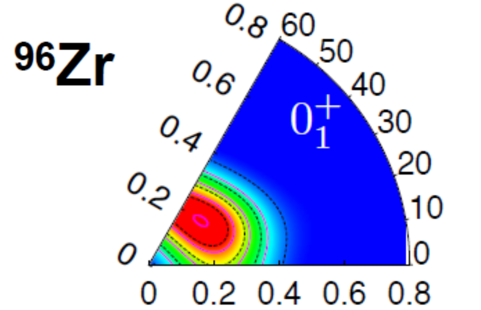


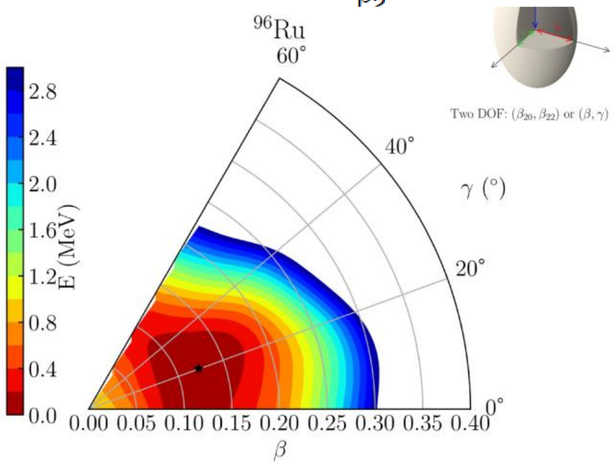
Beyond-mean-field correction is very important

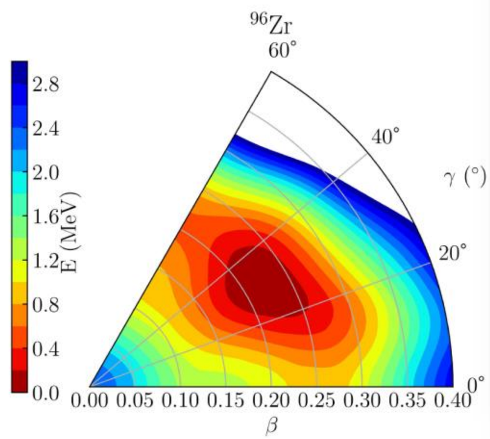
Rong, Lu, arXiv:2201.02114

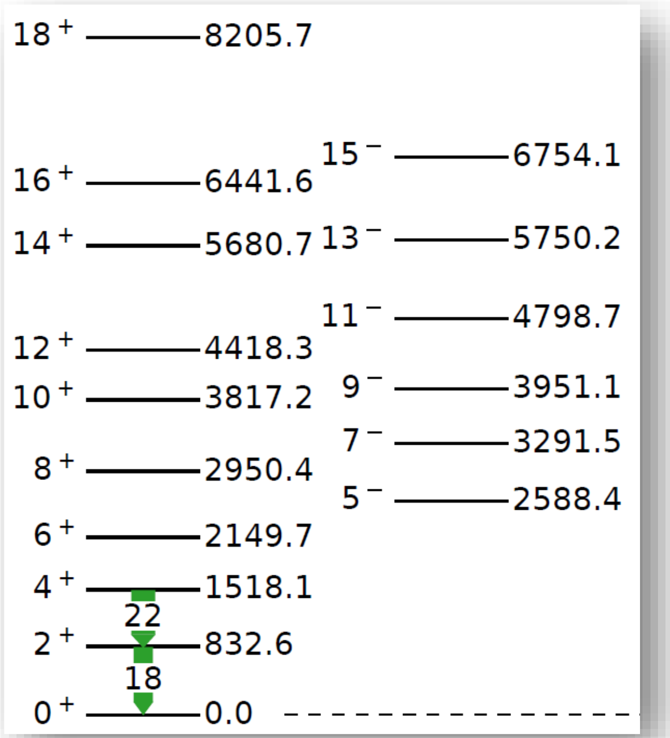
Deformation of ^{96}Ru & ^{96}Zr — personal comments

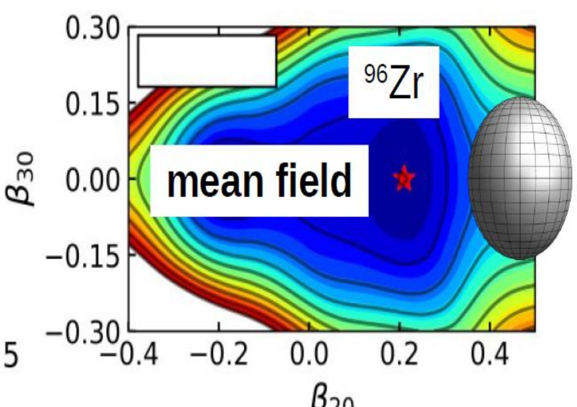


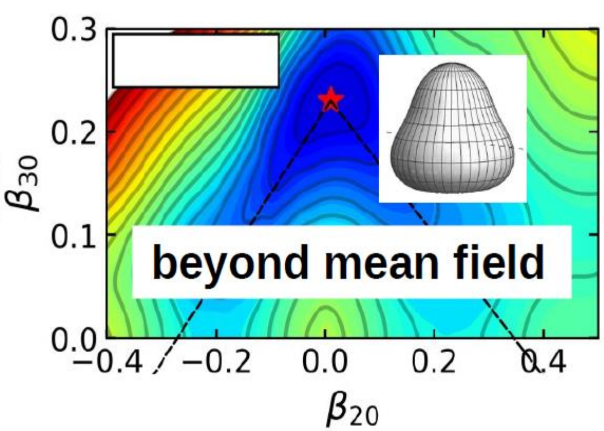






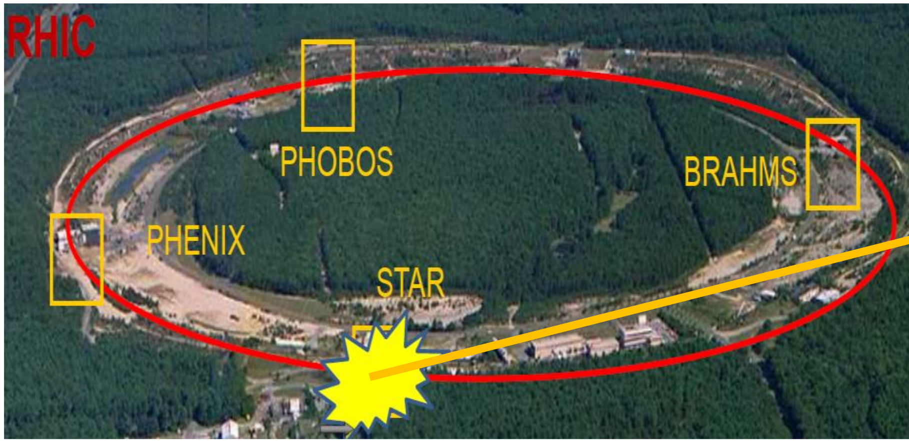


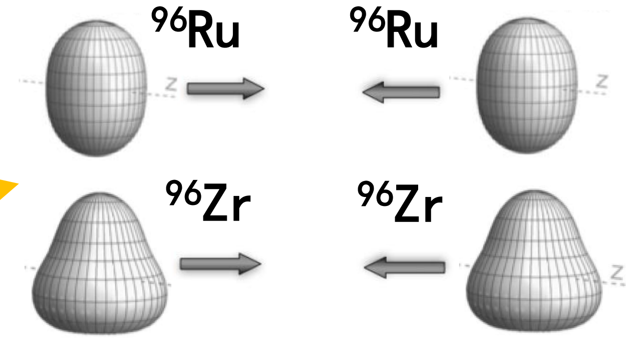




Nuclear structure physics obtain the deformation information from the spectrum with certain model calculations
(not directly image the deformation in position space)

Probe the deformation (mass distributions) of ^{96}Ru & ^{96}Zr

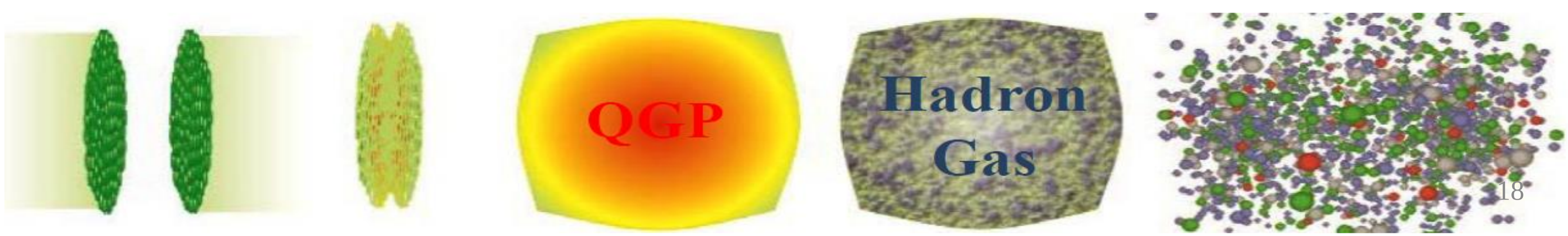




initial conditions:
(deformation / mass distributions)

Well calibrated calculations

Initial conditions **viscous hydro** **hadron cascade**



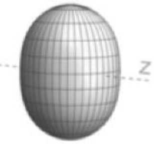
Hydrodynamic calculation with initially deformed nuclei

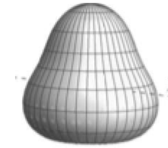
Initial conditions (TRENTO)

- Sample nucleon position in deformed nuclei with:

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

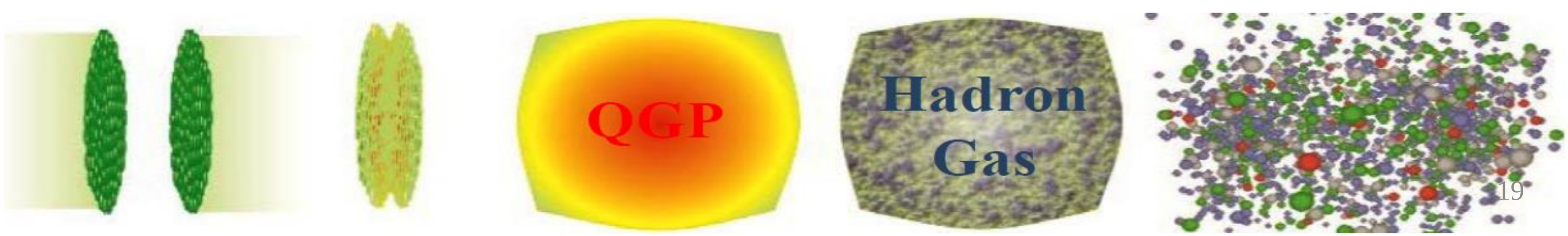
$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}] + \beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m} + \beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

Quadrupole: 

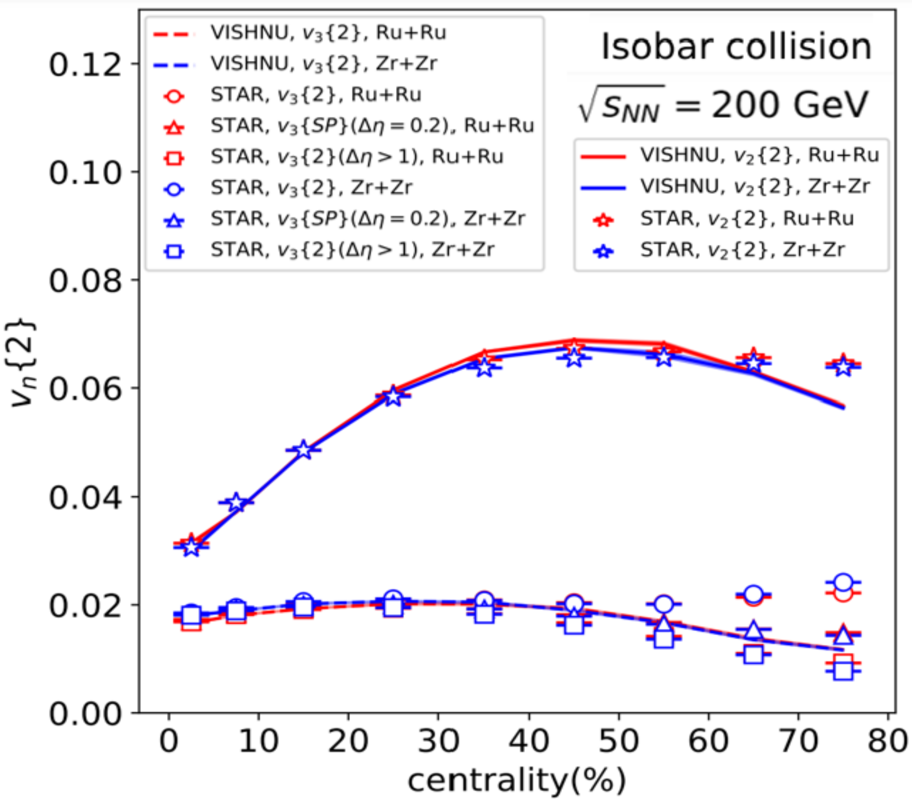
Octupole: 

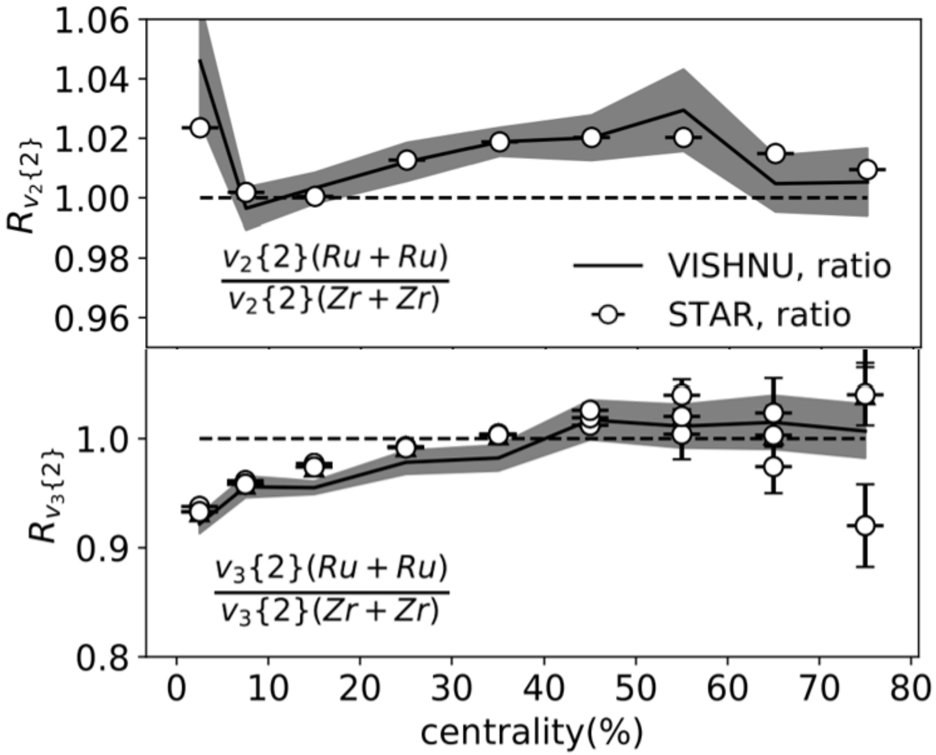
Well calibrated calculations

Initial conditions viscous hydro hadron cascade



V_2 and V_3 for Ru+Ru and Zr+Zr collisions



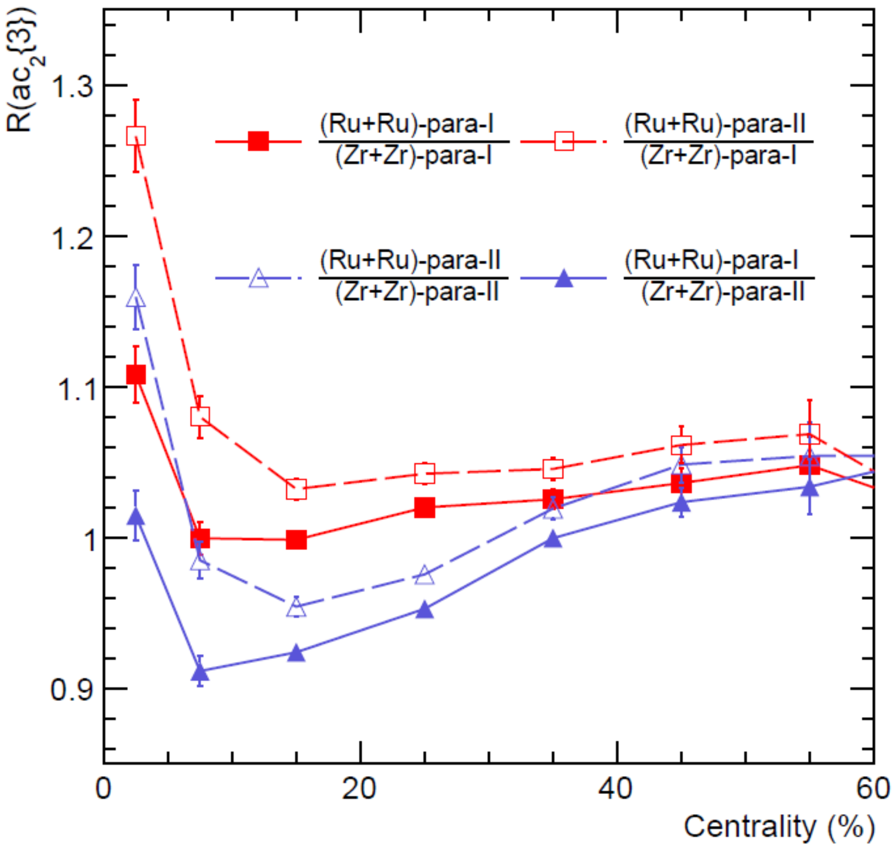


-With fine tuning parameters, iEBE-VISHNU fits V_2 & V_3 for Ru+Ru collisions

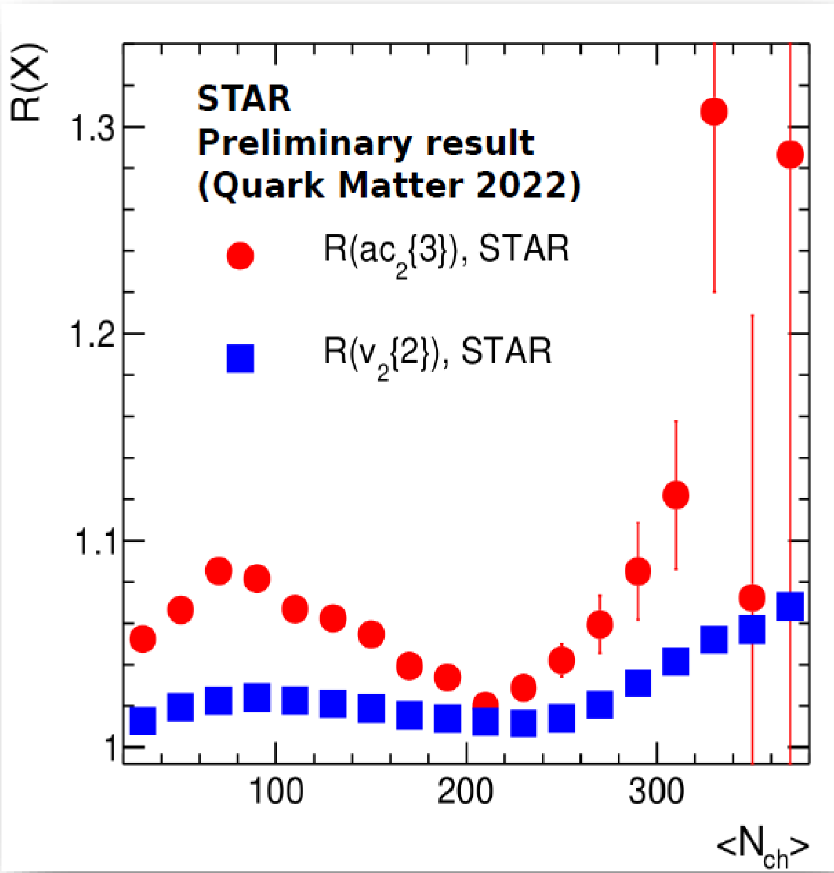
-Using β_2 β_3 in table1, it "predicts" V_2 & V_3 for Zr+Zr collisions & the related ratio -- (the data are roughly described).

"standard"	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

$ac_2\{3\}$for Ru+Ru and Zr+Zr collisions



$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle,$$



$ac_2\{3\}$ is sensitive to quadrupole and octupole deformations

S. Zhao, H. Xu, Y. Liu, H. Song. PLB2023, arXiv: 2204.02387

Probe the deformation of ^{96}Ru and ^{96}Zr

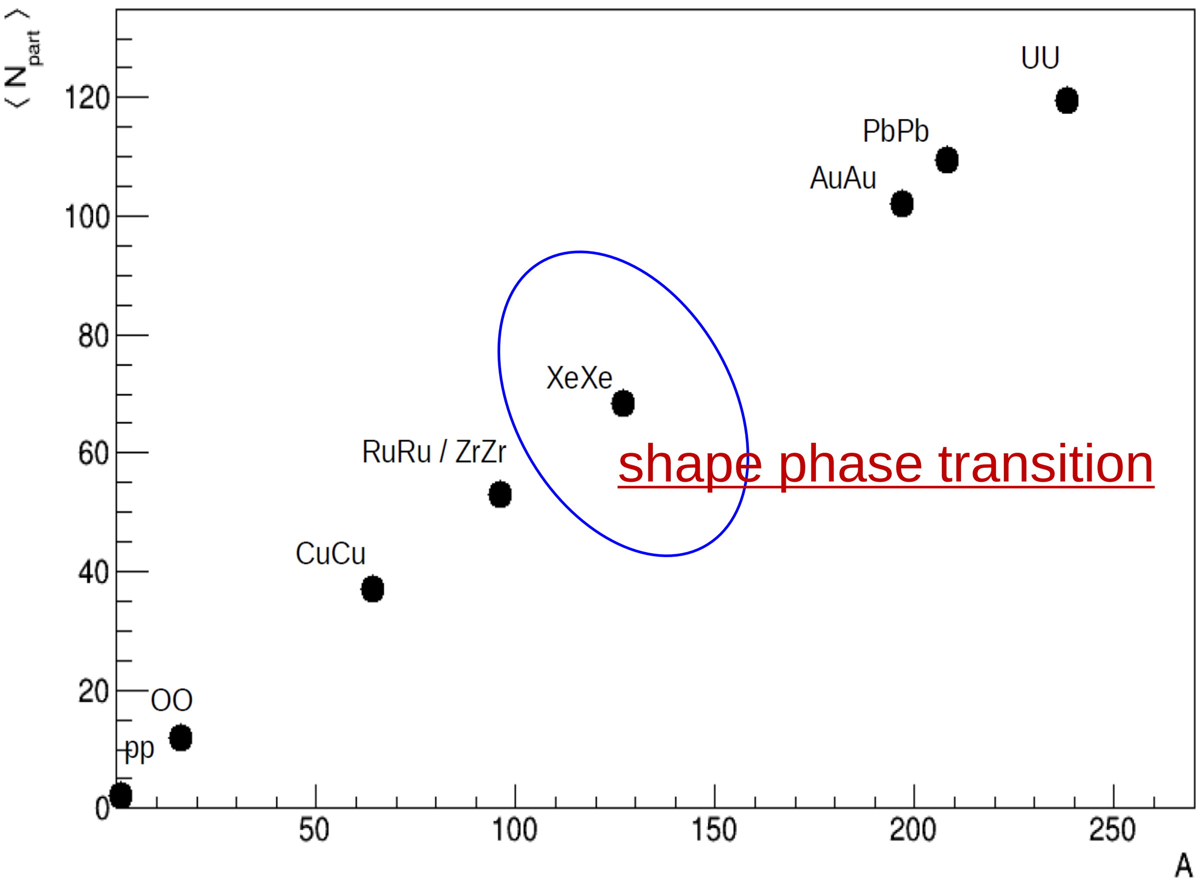
-- a short summary

-^{96}Ru and ^{96}Zr: two ideal nuclei for interdisciplinary research between relativistic heavy ion physics and nuclear structure

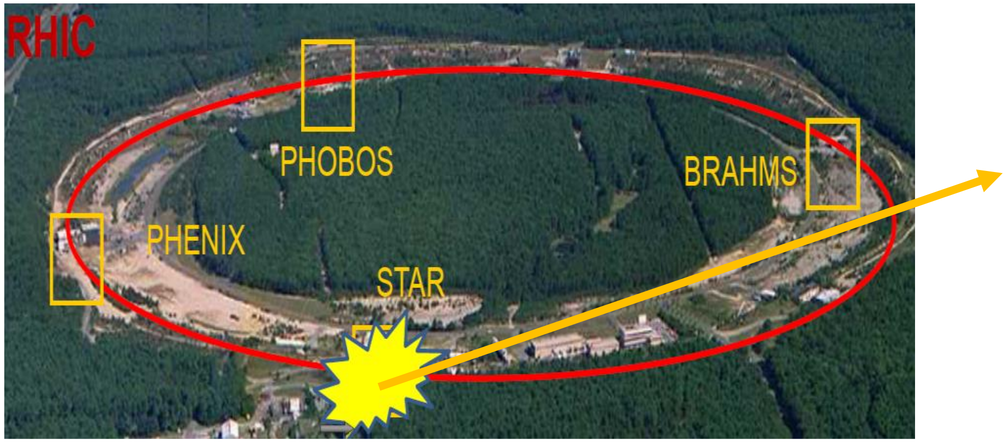
-isobar collisions provide rich and high statistical run data for various flow analysis, which could constrain the deformation of ^{96}Ru and ^{96}Zr from heavy ion physics side

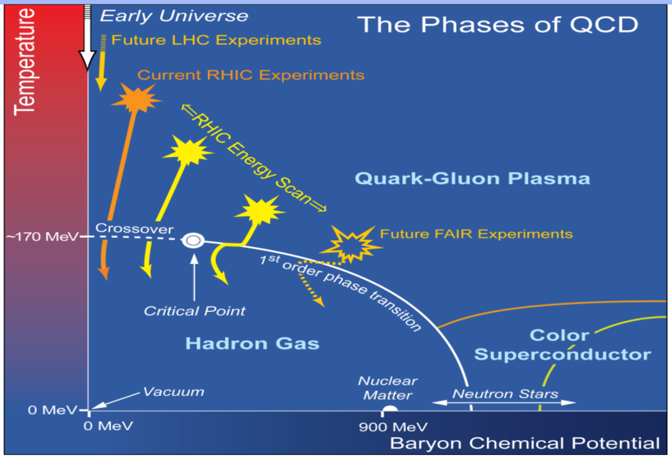
-Need more efforts to study the deformation of ^{96}Ru & ^{96}Zr from both experimental and theoretical sides in nuclear structure

Probe the shape phase transition with Xe +Xe collisions



The Phase Transition





<u>Relativistic heavy ion collisions</u>

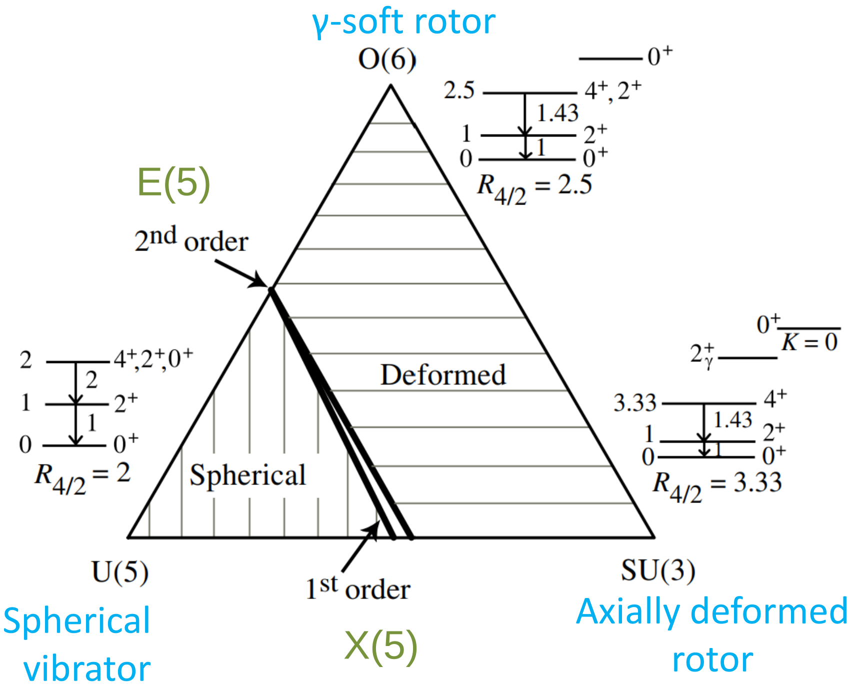
-mainly aim to explore QCD Phase Transition

-can also probe the shape phase transition of finite nuclei along certain isotope/ isotone chain

<u>^{129}Xe+^{129} Xe collision</u>

-explore the second-order shape phase transition occurring in the vicinity of $^{128-130}Xe$

The critical point symmetries



Shape phase transition for Xe isotopes

The shape phase transition:

-rapid structural change along certain isotope or isotone chains
-the dynamic interplay between the spherical-driving pairing interaction and the deformation-driving proton-neutron interaction

The shape phase transition for the Xe isotopes:

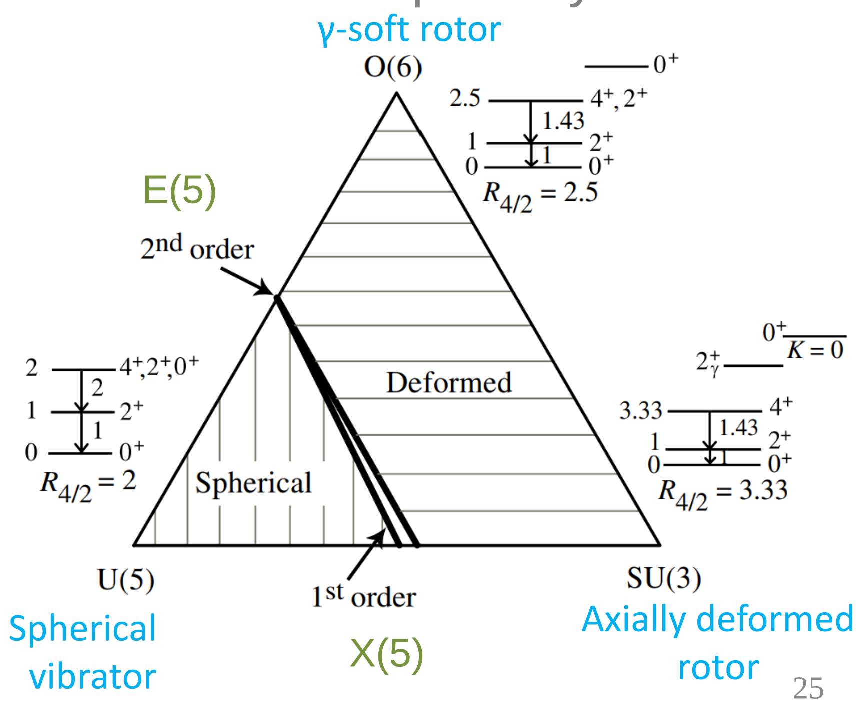
-Within the the framework of the interacting boson model (IBM), the Xe isotopes undergo a shape phase transition from a *γ*-soft rotor to a spherical vibrator

R. F. Casten, Nucl. Phys. A 439, 289 (1985). G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. A 348, 109 (1980). R. F. Casten and P. Von Brentano, Phys. Lett. B 152, 22 (1985).

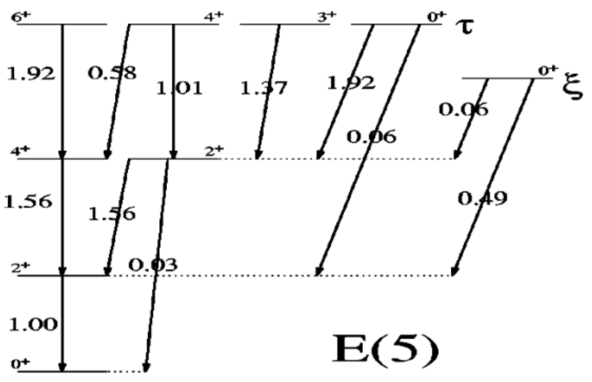
-the critical point is described by the *E*(5) symmetry, associated with a 2nd order phase transition

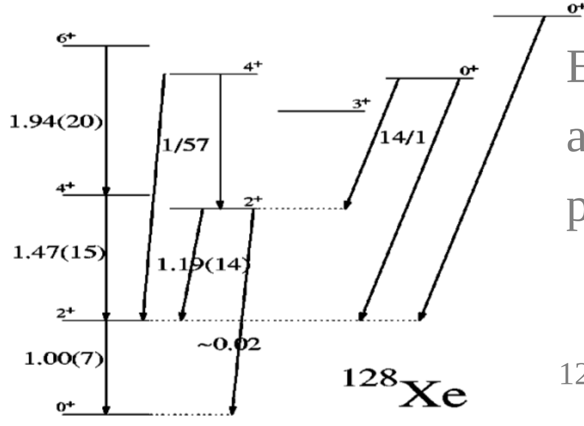
F. Iachello, Phys. Rev. Lett. 87, 052502 (2001).
F. Iachello, Phys. Rev. Lett. 85, 3580 (2000).

The critical point symmetries



Exp evidence of E(5) symmetry for ^{128}Xe

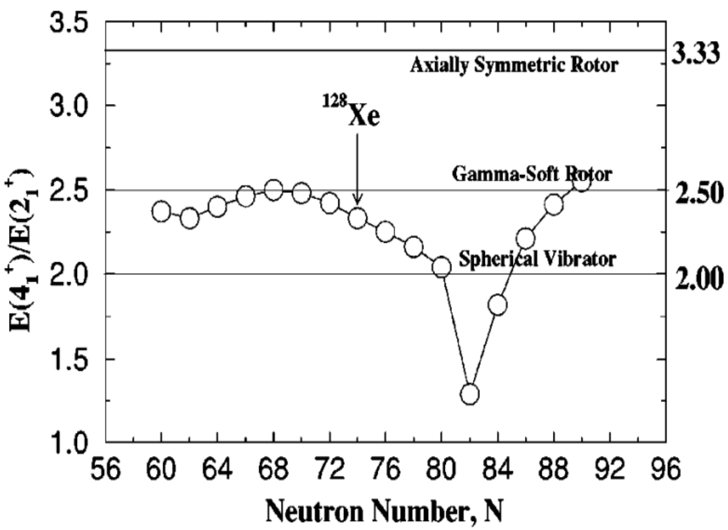




Energy spectroscopy: good agreement with E(5) prediction

Nucleus	$E(4_1^+)/E(2_1^+)$	$E(0_2^+)/E(2_1^+)$	$E(0_3^+)/E(2_1^+)$
^{128}Xe	2.33	3.57	4.24
^{130}Xe	2.25	(3.35)	(3.76)
^{132}Xe	2.16		
^{134}Xe	2.04		

^{128}Xe lies in between γ-soft rotor and spherical vibrator.



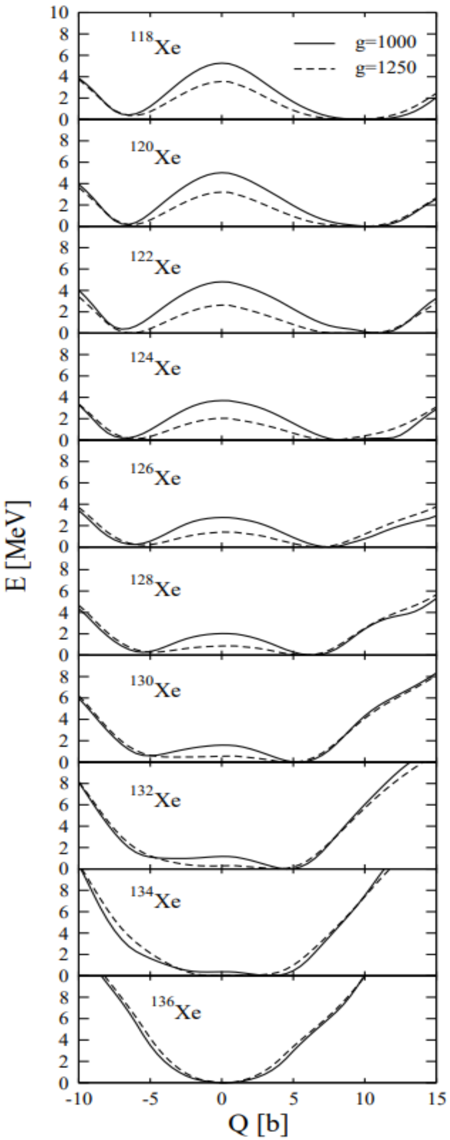
Evolution of $E(4_1^+)/E(2_1^+)$ ratio close to 2.2

Existence of two 0^+ states with $3<E(0_n^+)/E(2_1^+)<4$

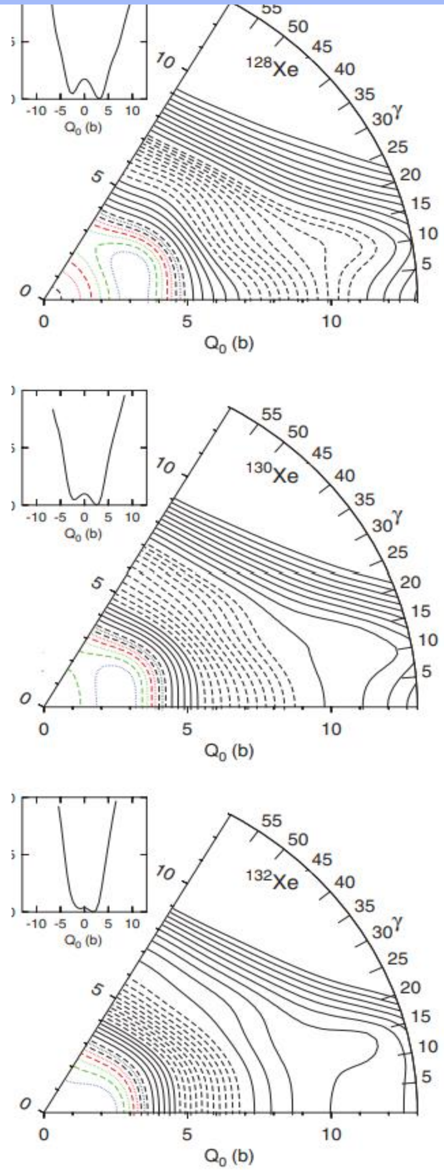
the measured energy spectroscopy of ^{128}Xe agrees well with the E(5) predic. (the normalized transition strengths, the branching ratios, the energy ratios between different energy levels

R. M. Clark, et. al. Phys. Rev. C 69, 064322 (2004)

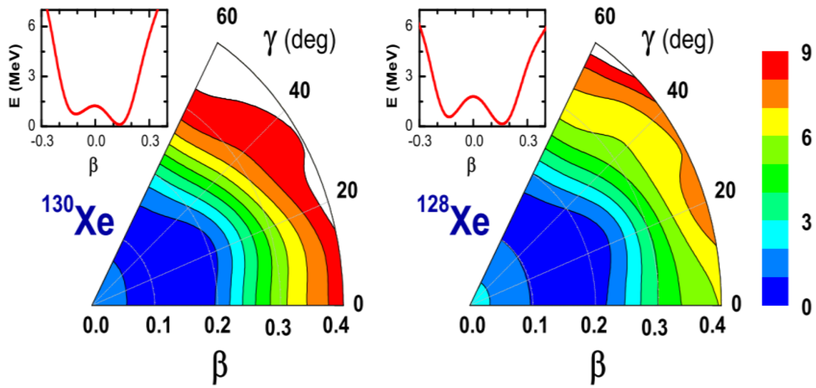
Theoretical predictions on E(5) symmetry near $^{128-130}$Xe



R. Rodriguez-Guzman, et. al. Phys. Rev. C 76, 064303 (2007)



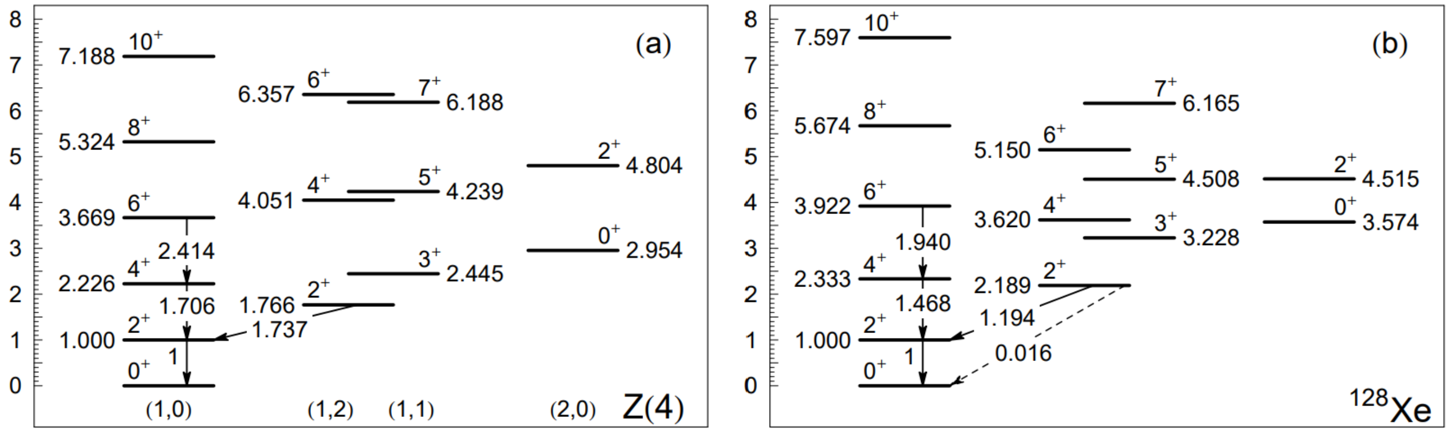
L.M.Robledo, et. al. Phys. Rev.C 78 (2008) 034314



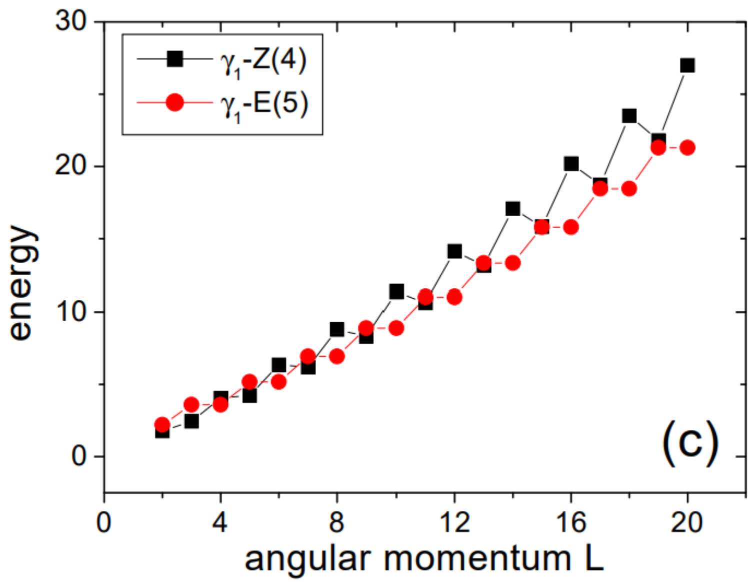
Z. P. Li, T. Niksic, D. Vretenar, and J. Meng (2010)

-Various theoretical calculations indicate a critical point of the second-order shape phase transition (E(5) symmetry) lies in the vicinity of $^{128-130}$Xe, associated with a γ-soft deformation

Z(4) or E(5) symmetry for $^{128-132}Xe$?



-Z(4) symmetry with a fixed γ at 30º can also describe the spectra and *B*(*E*2) rates for $^{128,130,132}Xe$



The mean difference between E(5) and Z(4) is the pair order of energy levels in the γ band.

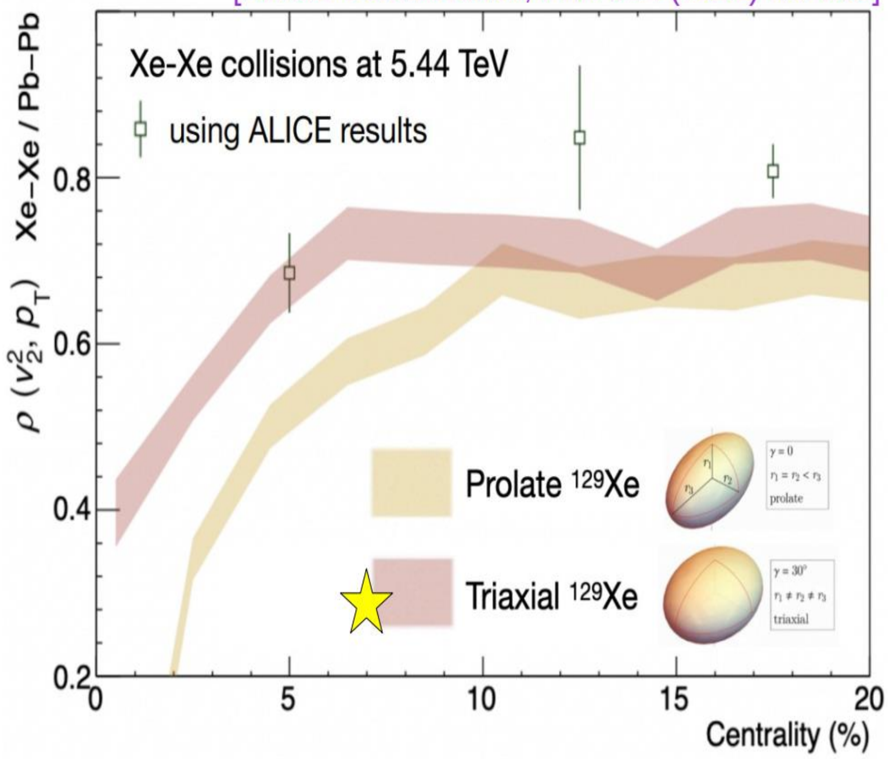
-It is hard to distinguish such E(5) and Z(4) symmetry in nuclear physics.

D. Bonatsos, D. Lenis, D. Petrellis, P. A. Terziev, and I. Yigitoglu, Phys. Lett. B 621, 102 (2005),

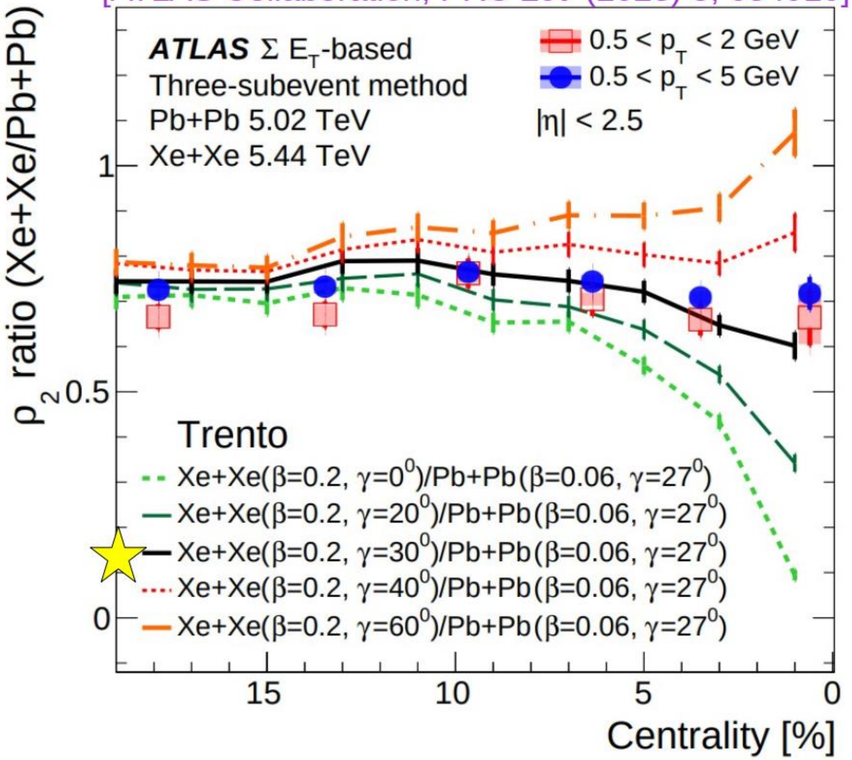
Probing triaxial deformation of ^{129}Xe with ^{129}Xe+^{129}Xe collisions

B. Bally, M. Bender, G. Giacalone, V. Somà, Phys. Rev. Lett. 128 (8) (2022) 082301

[ALICE Collaboration, PLB **834** (2022) 137393]



[ATLAS Collaboration, PRC **107** (2023) 5, 054910]



Distinguish triaxial and γ-soft deformation of ^{129}Xe with ^{129}Xe+^{129}Xe collisions

explore the possible 2nd order phase transition of Xe isotopes

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th]

Hydro initial condi. with triaxial or γ-soft deformation

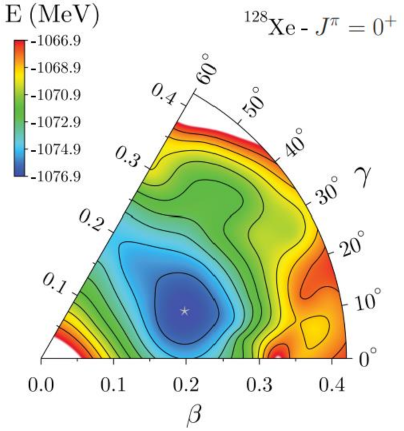
S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th

Initial conditions (TRENTO)

- Sample nucleon position in deformed nuclei with:

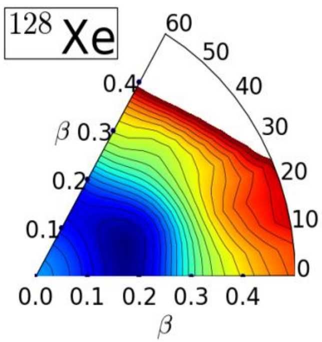
$$\rho(r,\theta,\phi)=\frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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



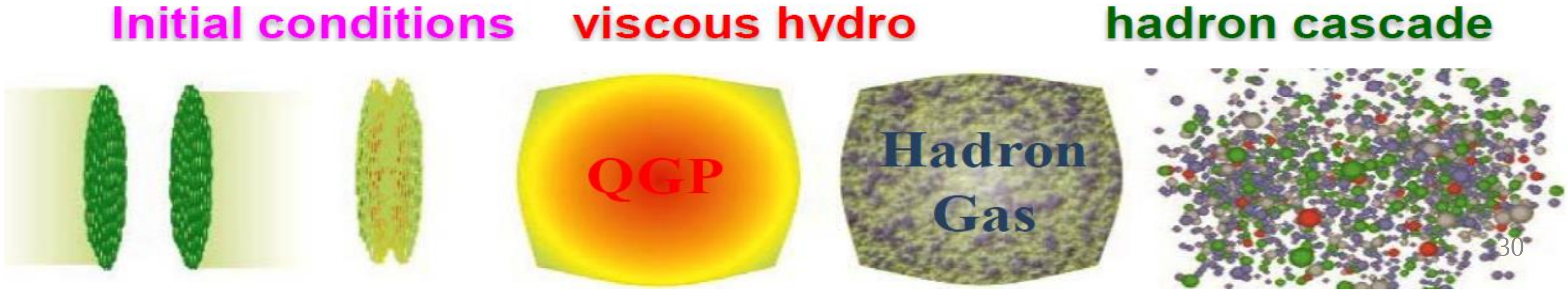
Rigid triaxial deformation (γ=30º)

Bally et. al. Eur.Phys.J. A 58 (2022) 9, 187,

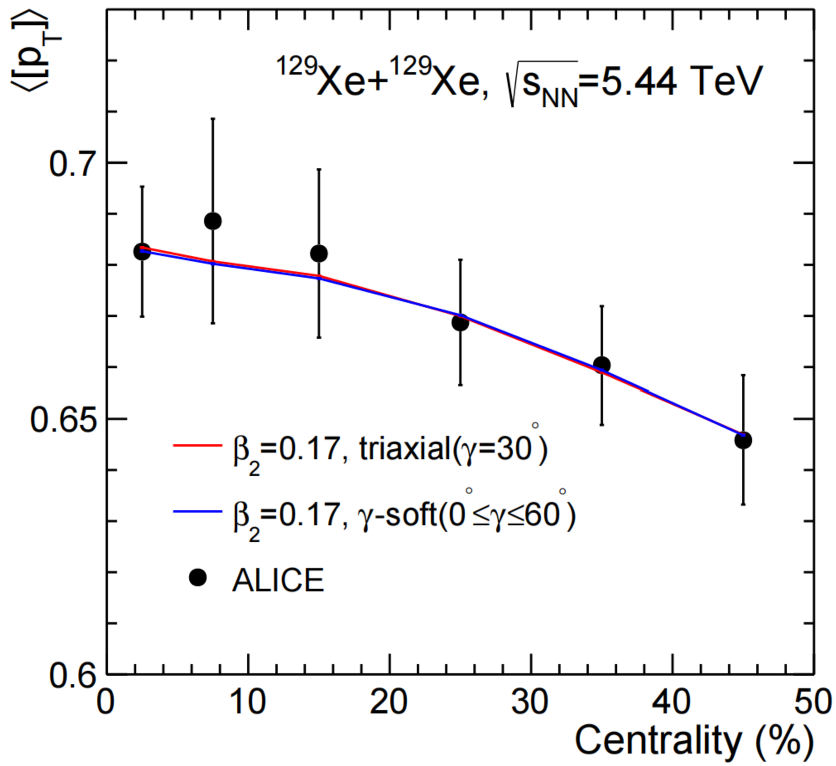


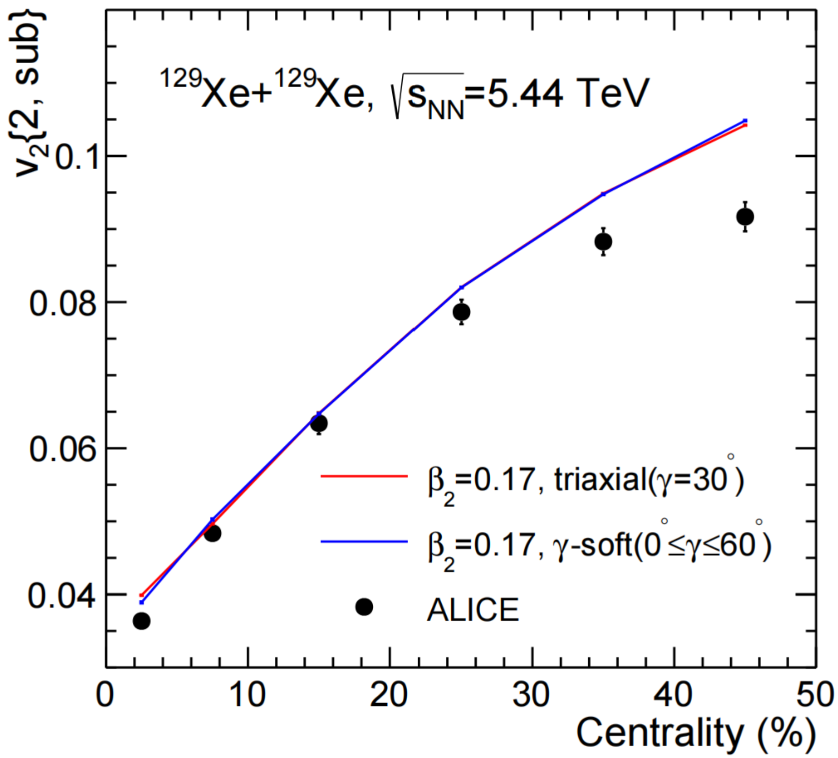
γ-soft (flat distribution in 0≤γ≤60º)

Z. P. Li, et. al. Phys. Rev. C 81, 034316 (2010),



mean P_T & v2

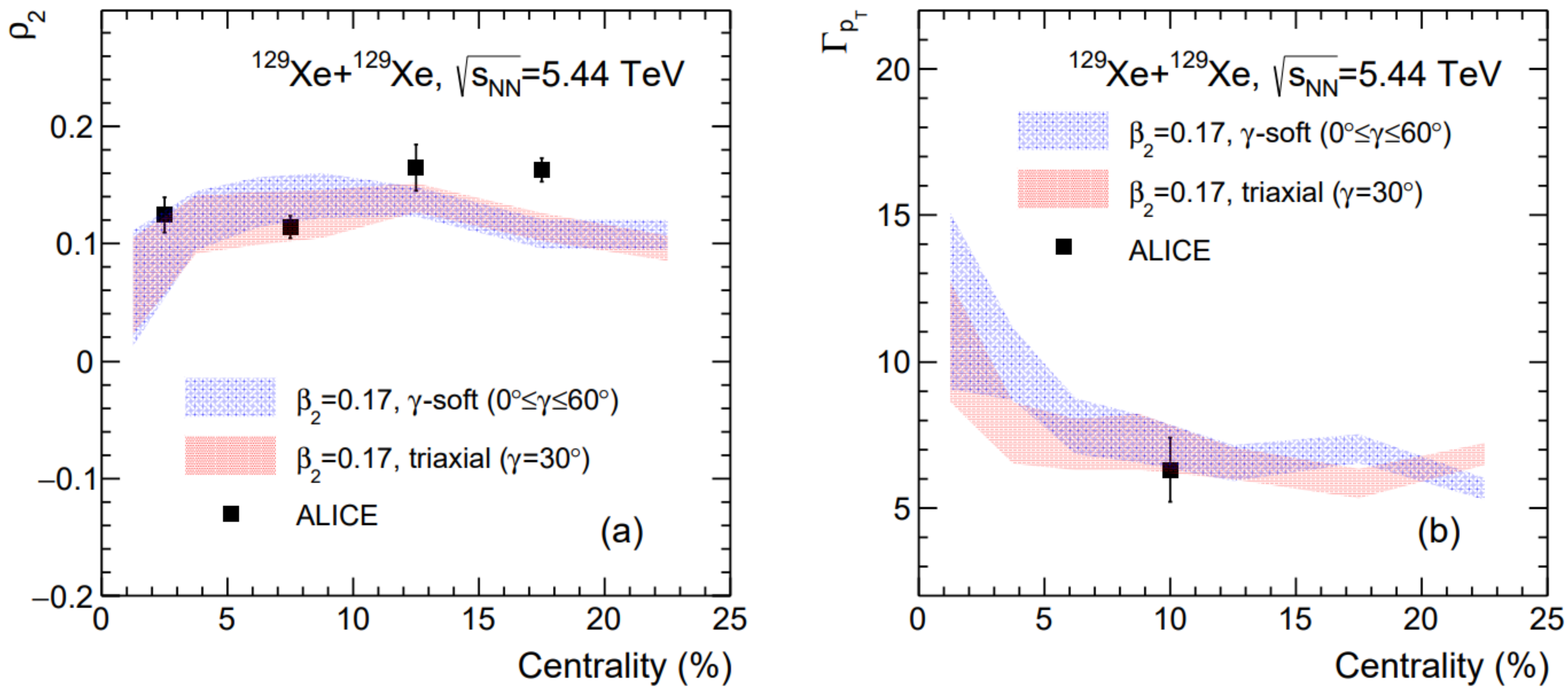




-With the parameters obtained from previous Bayesian analysis (Pb+Pb coll), our iEBE-VISHNU, with rigid triaxial or γ-soft deformation of ^{129}Xe, can describe most of the bulk observables in Xe+Xe collisions

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th], private note

3-particle correlation



$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}.$$

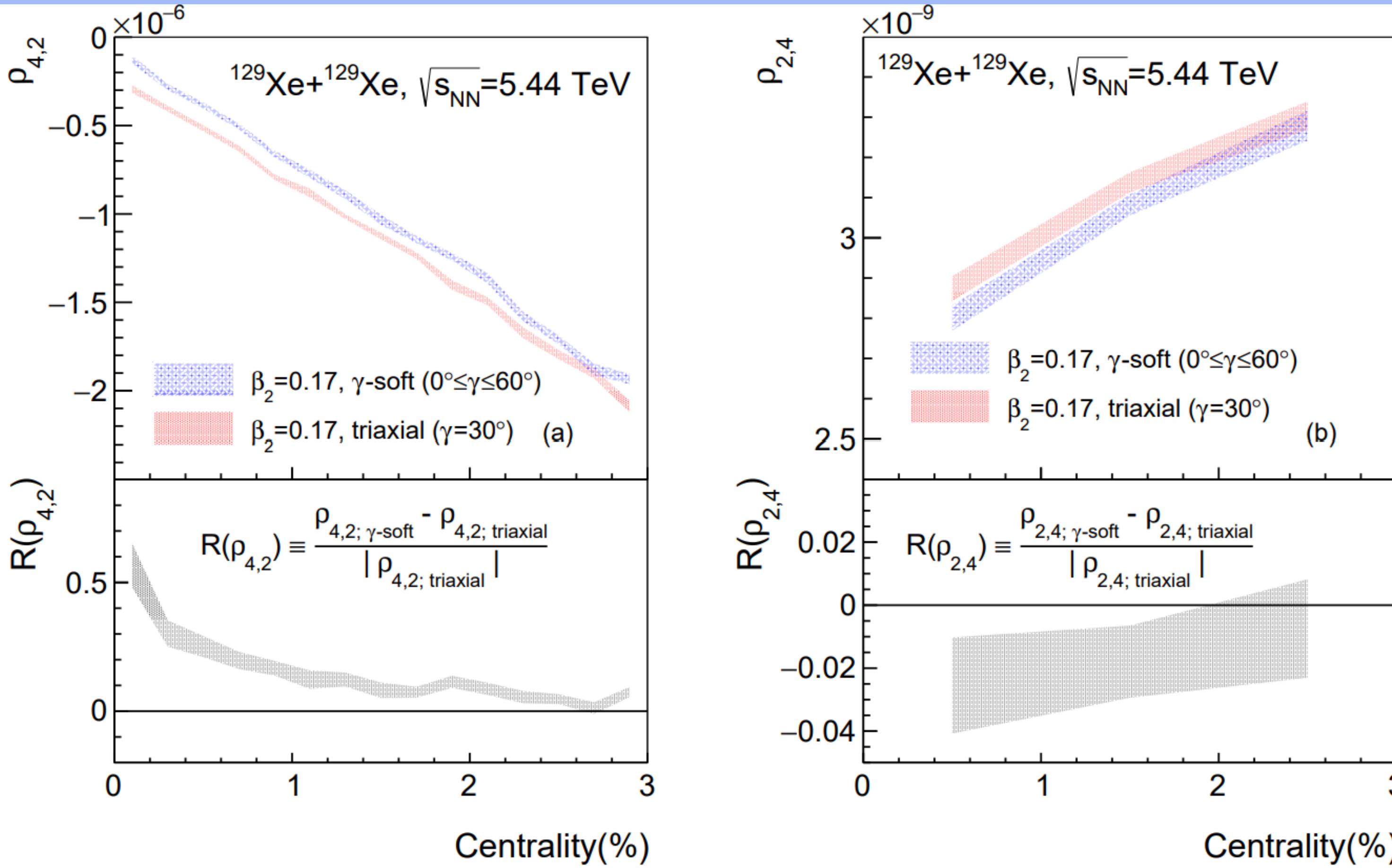
$$\Gamma_{p_T} = \frac{\langle \delta p_{T,i}\delta p_{T,j}\delta p_{T,k}\rangle\langle [p_T]\rangle}{\langle \delta p_{T,i}\delta p_{T,j}\rangle^2},$$

-Our calculations with rigid triaxial or γ-soft deformation of ^{129}Xe can describe the measured ρ_2 and Γ_{pT} equally well.

$\rho_2, \Gamma_{p_T} \propto \beta_2^3 \cos(3\gamma)$ insensitive to triaxial deformation γ=30º and γ-soft 0≤γ≤60º

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th]

6-particle correlations



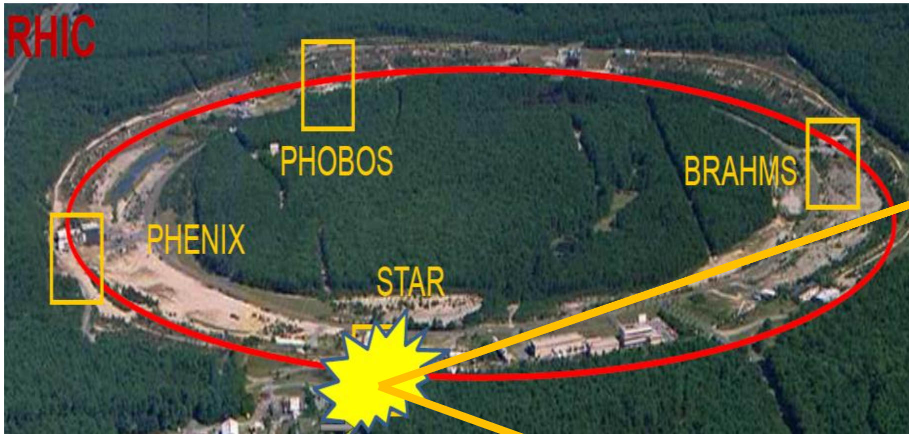
$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \right)_c \qquad \rho_{2,4} \equiv \left(\frac{\langle \varepsilon_2^2 \delta d_\perp^4 \rangle}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \right)_c \qquad \langle \cos(6\gamma) \rangle$$

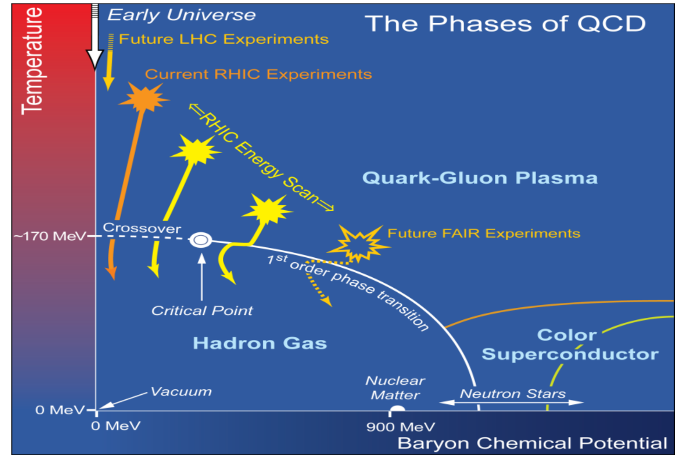
The γ-soft deformation of ^{129}Xe lead to a clear enhancement of 6-particle correlations $\rho_{4,2}$ in ultra-central Xe+Xe collisions

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th]

Exploring the Shape Phase Transision along Xe isotopes

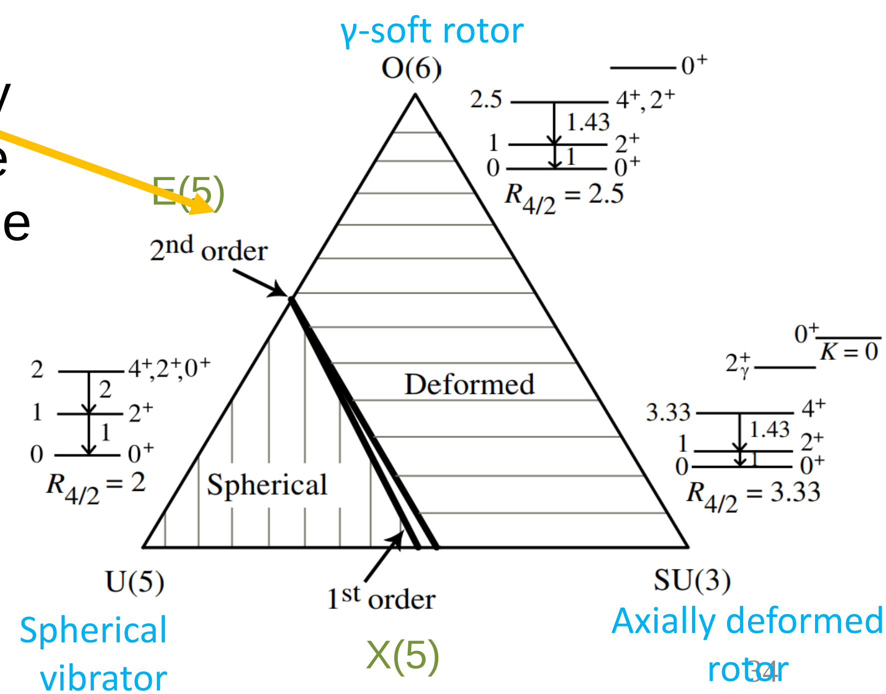
-- a short summary



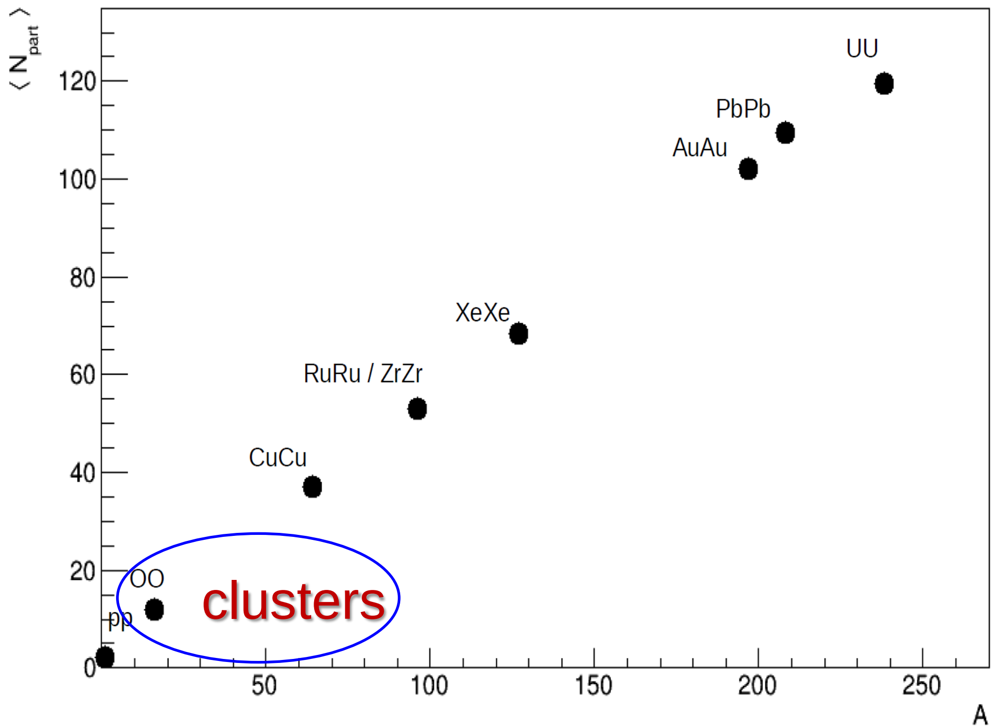


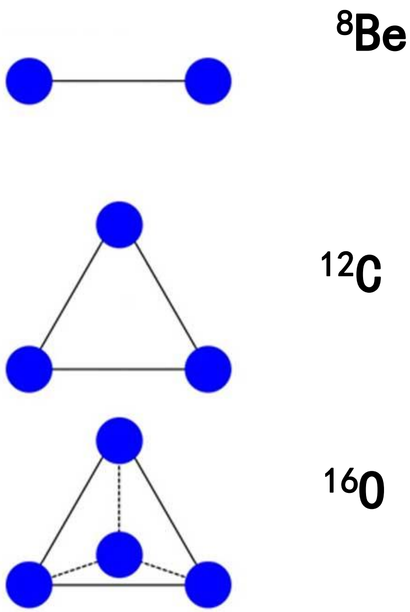
In nuclear structure physics, it is generally believe Xe isotope chain experience a the second-order shape phase transition in the vicinity of $^{128\text{-}130}$Xe.

Relativistic heavy ion collisions (such as ^{129}Xe+^{129}Xe) can not only study the QCD phase transition, but also explore such shape phase transition of finite nuclei

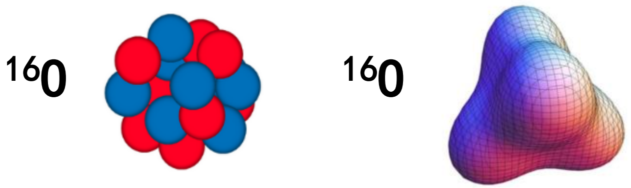


Probe the α-cluster of ^{16}O at RHIC and the LHC

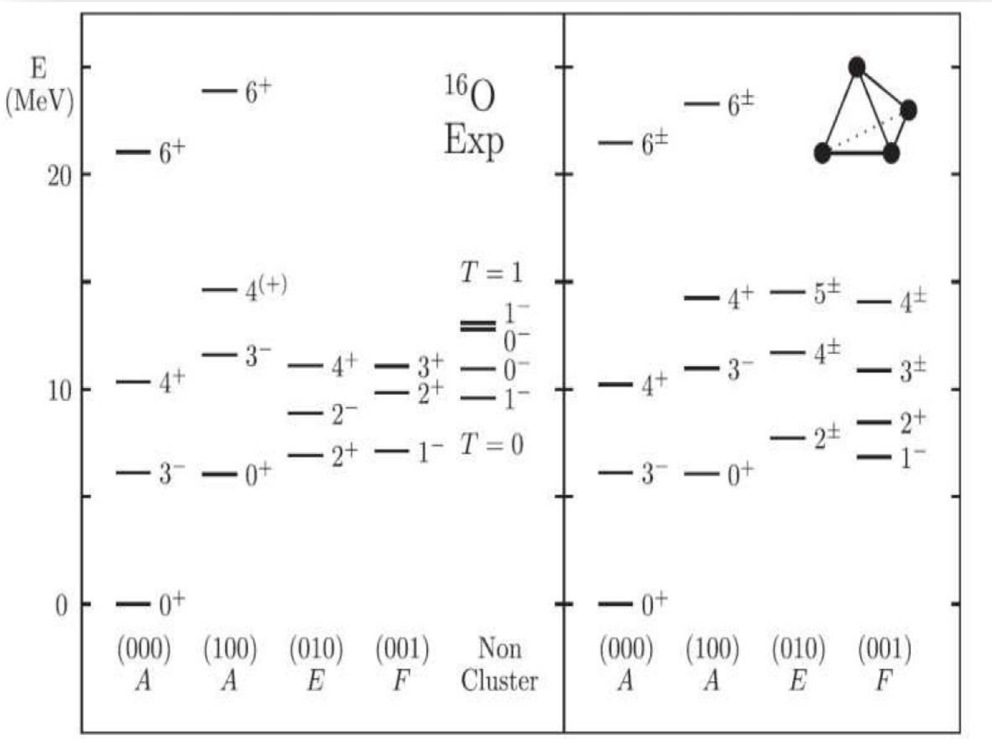




^{16}O+^{16}O collisions and p+^{16}O collisions originally aim to study the possible formation of the QGP in small systems



α-cluster of ^{16}O from nuclear structure

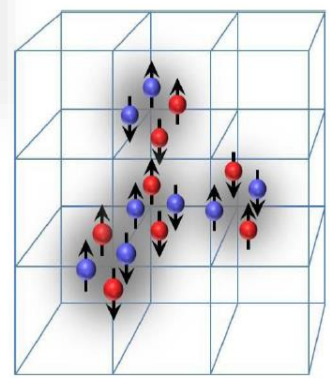


-ACM calculations show that the low-lying states of ^{16}O can be described as rotation-vibration of a 4α cluster with tetrahedral symmetry.

R.Bijker and F.Iachello, Phys. Rev. Lett. 112, no.15, 152501 (2014)

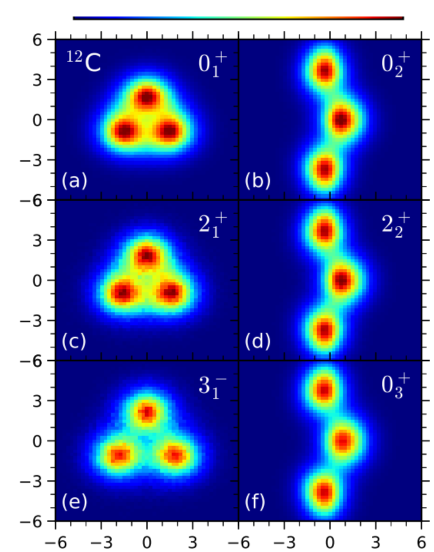
-ab initio lattice calculations demonstrate the nucleons are arranged in a tetrahedral alpha clusters in the ground state

E. Epelbaum, et al Phys. Rev. Lett.112, no.10, 102501 (2014)



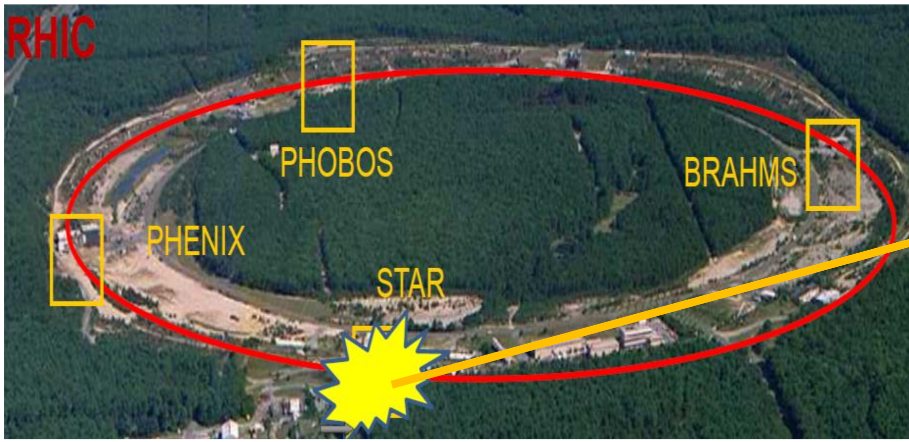
(a) Initial state "A", 8 equivalent orientations.

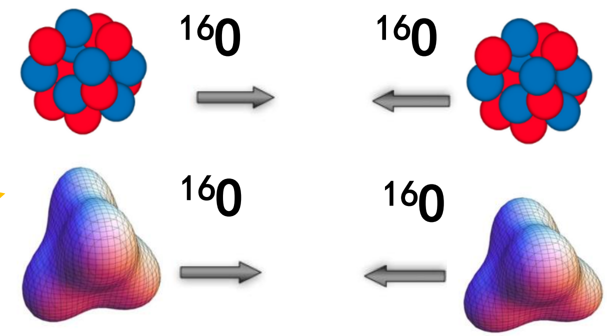
Recent NLEFT calculations for light nuclei: Intrinsic shape composed of alpha clusters



Shen, Elhatisari, Lahde, Lee, Lu, UGM, Nature Commun. **14** (2023) 2777
Dee Lee talk, today

Relativistic heavy ion collision to probe the structure of ^{16}O

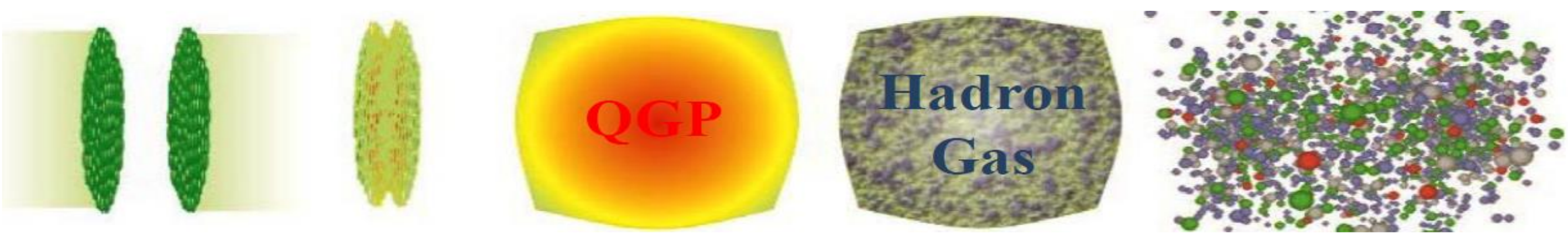




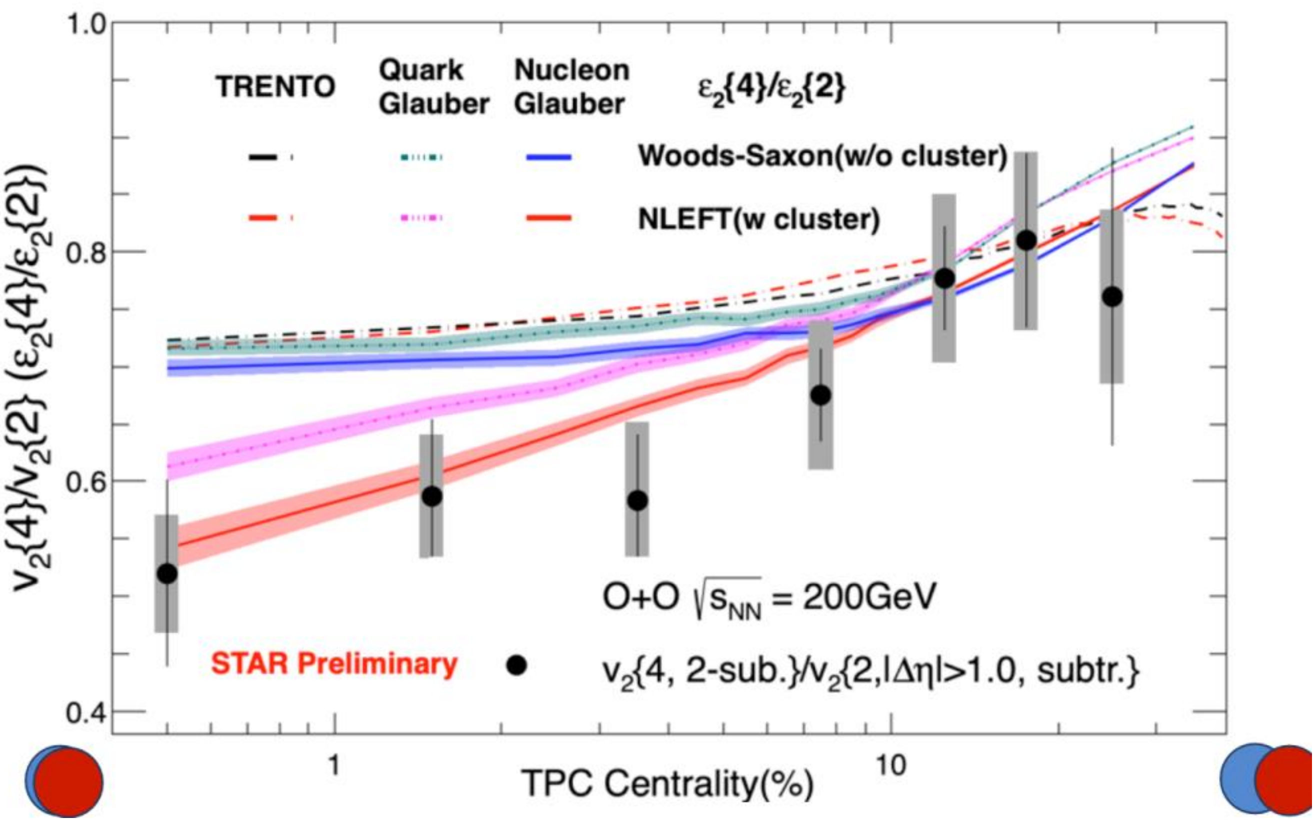
initial conditions:
(with or without α-cluster)

Well calibrated calculations

Initial conditions **viscous hydro** **hadron cascade**



Measurement from $^{16}O+^{16}O$ collisions



- $v_2\{4\}/v_2\{2\}$: enhanced fluctuations in ultra-central collisions

heavy ion collision data hint alpha-clustering in ^{16}O

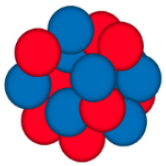
Hydrodynamic calculation w/wo clustering

Initial conditions (TRENTO)

Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song. arXiv: 2401.15723 [nucl-th].

-Woods-Saxon:

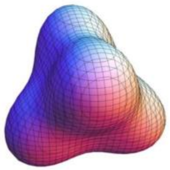
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$



Spherical shape

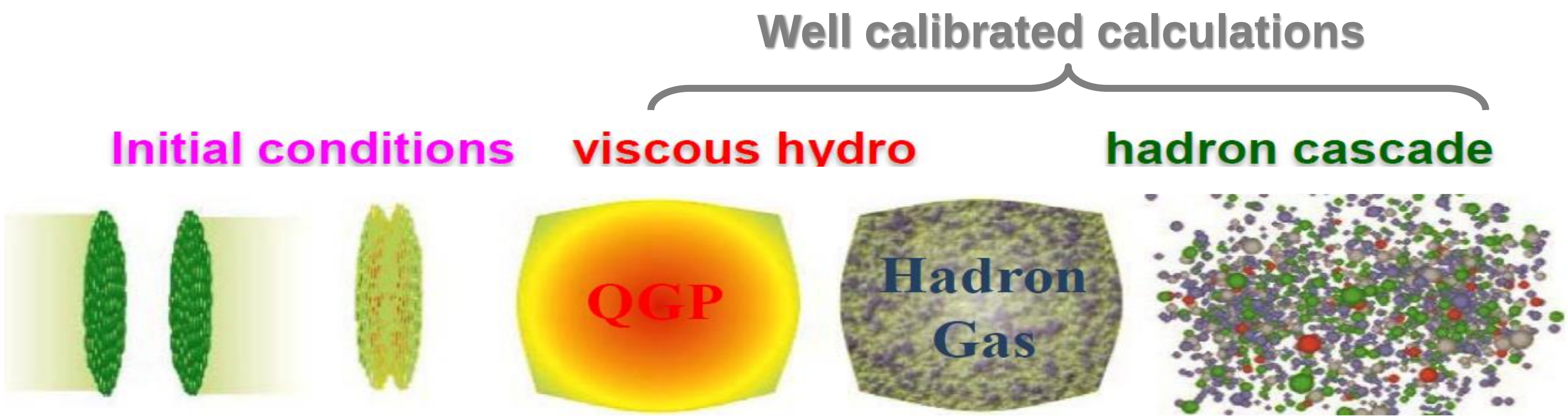
-Alpha-Cluster:

$$f_i(\mathbf{r}) = A\exp\left[-\frac{3(\mathbf{r}-\mathbf{r}_i)^2}{2{r_\alpha}^2}\right]$$

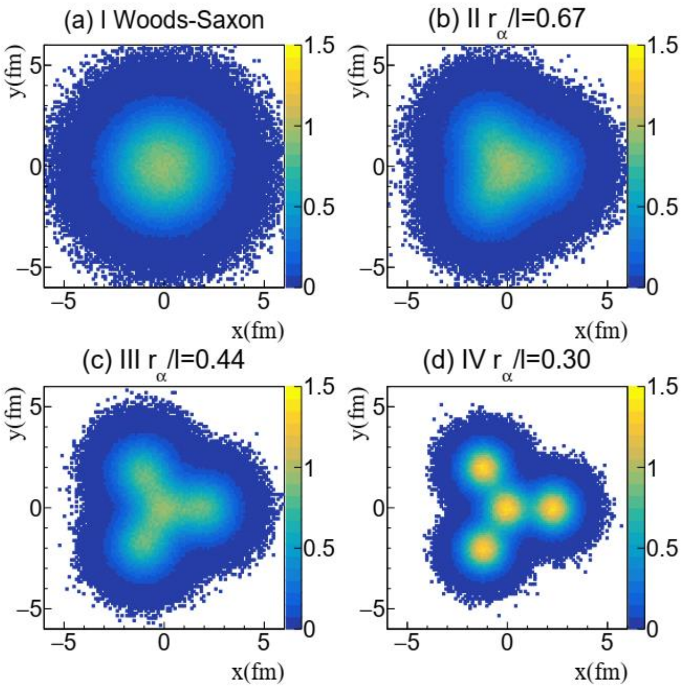


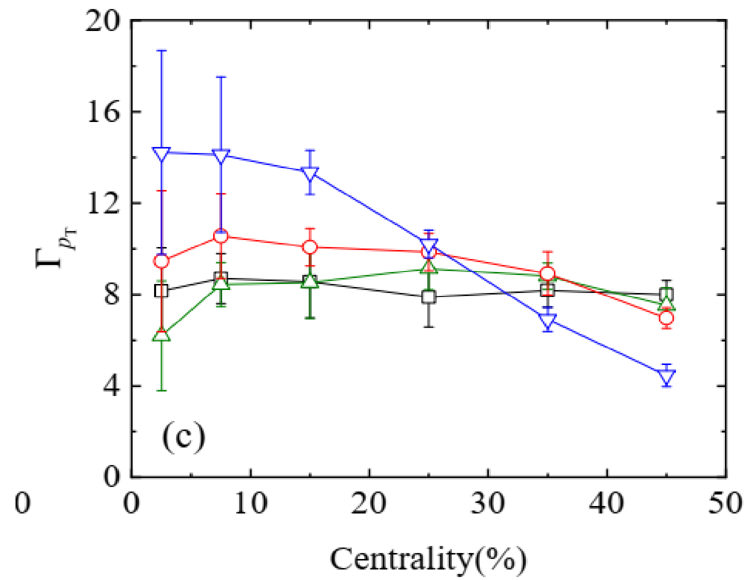
tetrahedral alpha clusters

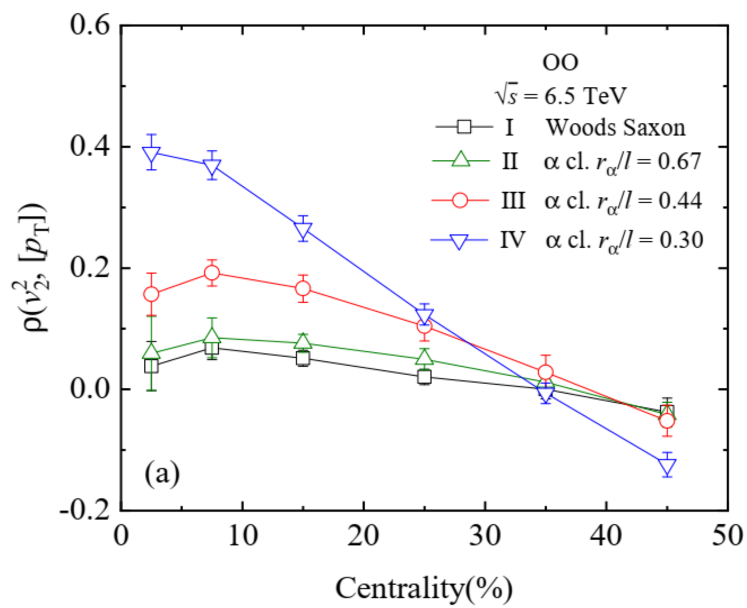
	distribution	l	r_α	r_α/l
I	Woods–Saxon			
II	α cluster	3.0	2.0	0.67
III	α cluster	3.6	1.6	0.44
IV	α cluster	4.0	1.2	0.30



Sensitive observables for α-clustering



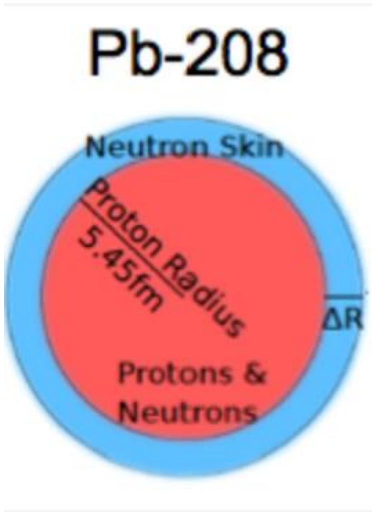


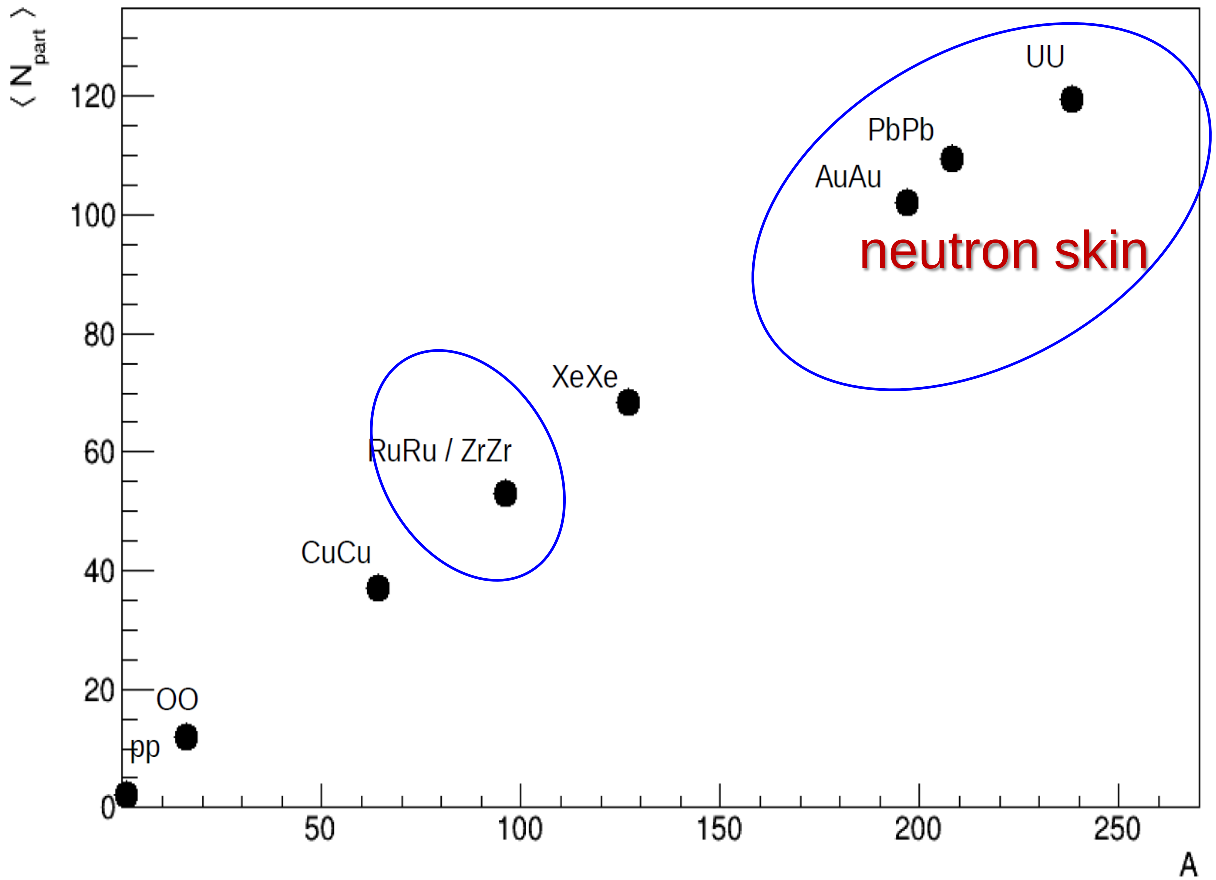


Several observables, such as the correlator Γ the $v_n - p_T$ correlations in ^{16}O+^{16}O collisions are sensitive to the compactness of the *α* cluster in the colliding nuclei, which can be used to constrain the detailed configurations of ^{16}O in the future.

Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song. arXiv: 2401.15723 [nucl-th].

Probe neutron skin at RHIC and the LHC





Neutron skin & neutron star

EOS of nuclear matter

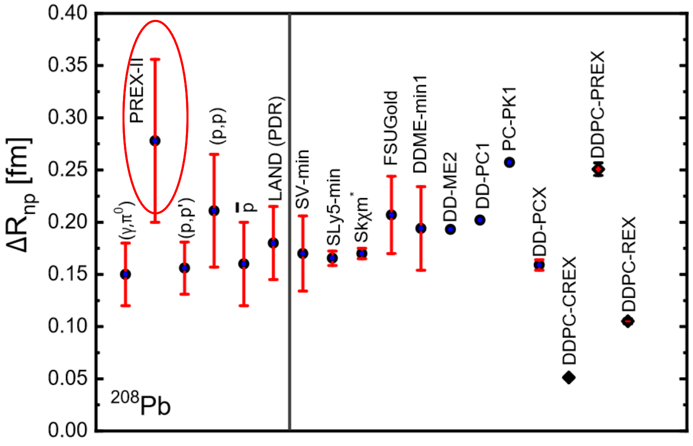
$$\epsilon(\rho,\alpha) = [\epsilon_{SNM}(\rho_0) + S(\rho_0)\alpha^2)] + \alpha^2 L \frac{\rho-\rho_0}{3\rho_0} + \frac{1}{2}(K_0 + \alpha^2 K_{sym})(\frac{\rho-\rho_0}{3\rho_0})^2$$

L: the first order term in EOS; symmetry energy; Large L thick neutron skin

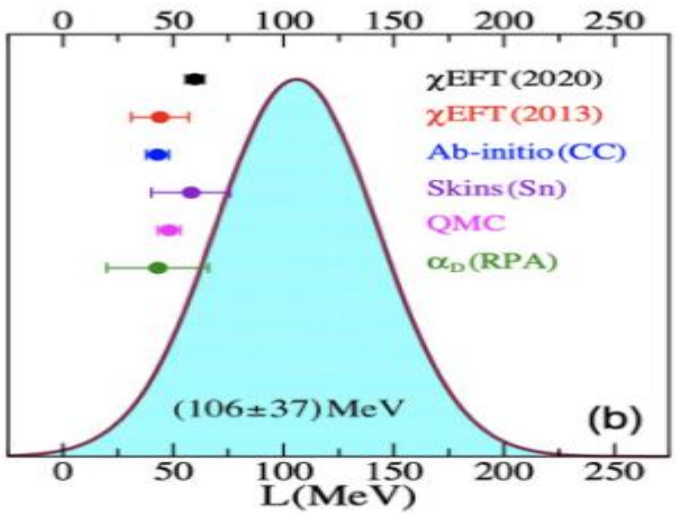
Probe the Neutron Skin at low energy nuclear physics

Parity-Violating Electron Scattering in Jefferson Lab

$R^{208}_{skin} = 0.278^{+0.078}_{-0.078} fm$ Phys. Rev. Lett. 126, 172502, (2021)

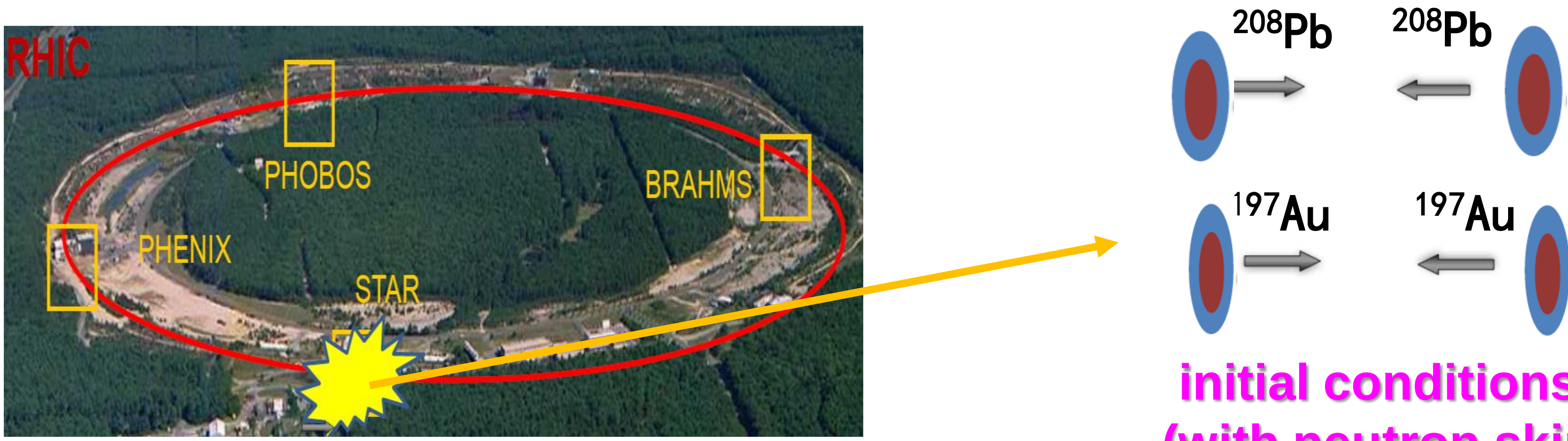


arXiv:2206.06527 Esra Yüksel and Nils Paar



Phys. Rev. Lett. 126, 172502 D. Adhikari et al

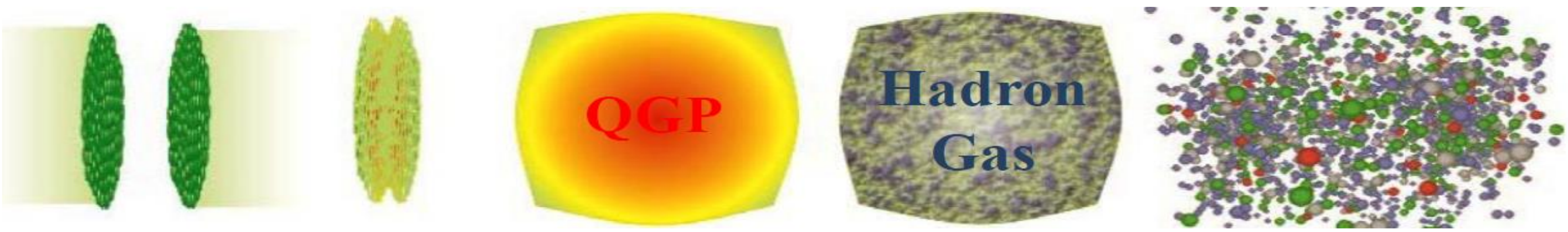
Relativistic heavy ion collision to probe the neutron skin



initial conditions:
(with neutron skin)

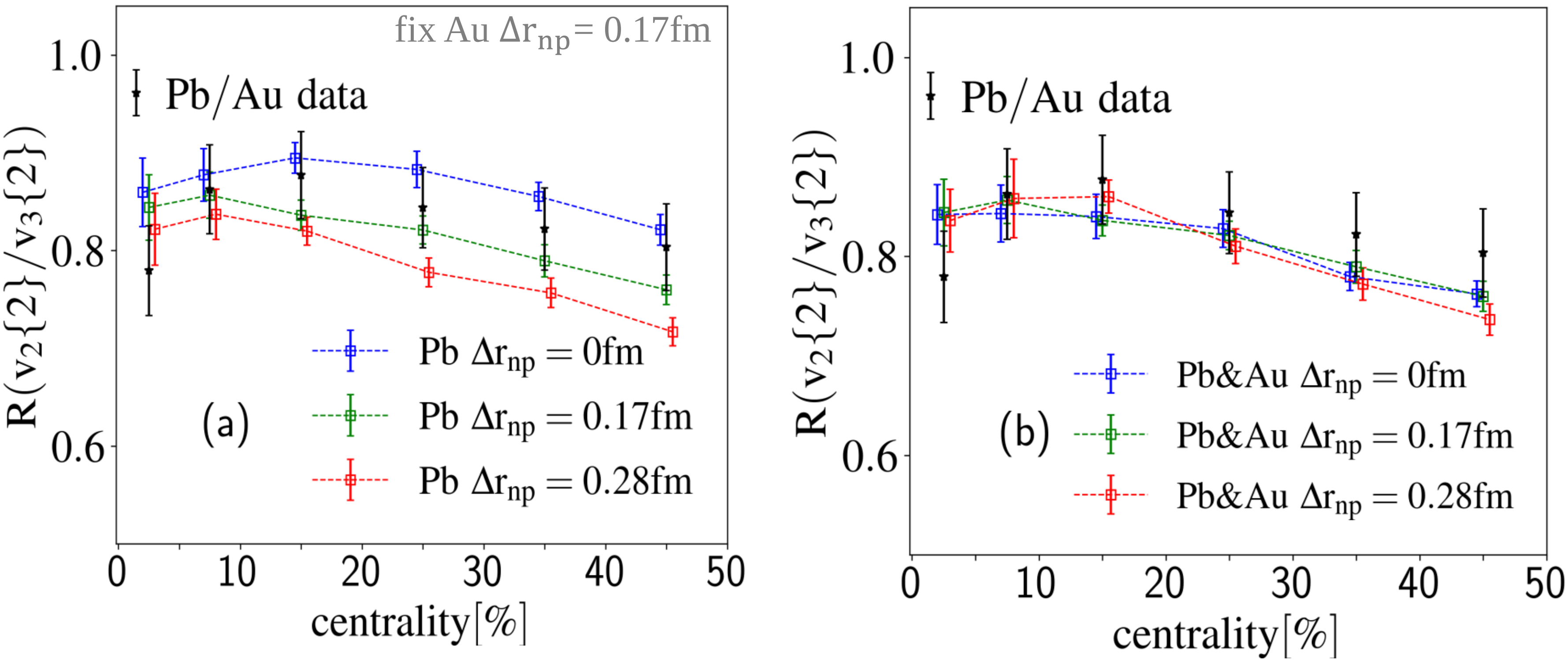
Well calibrated calculations

Initial conditions **viscous hydro** **hadron cascade**



Probing the neutron skin of ^{197}Au and ^{208}Pb

<u>semi-isobaric double ratio</u>

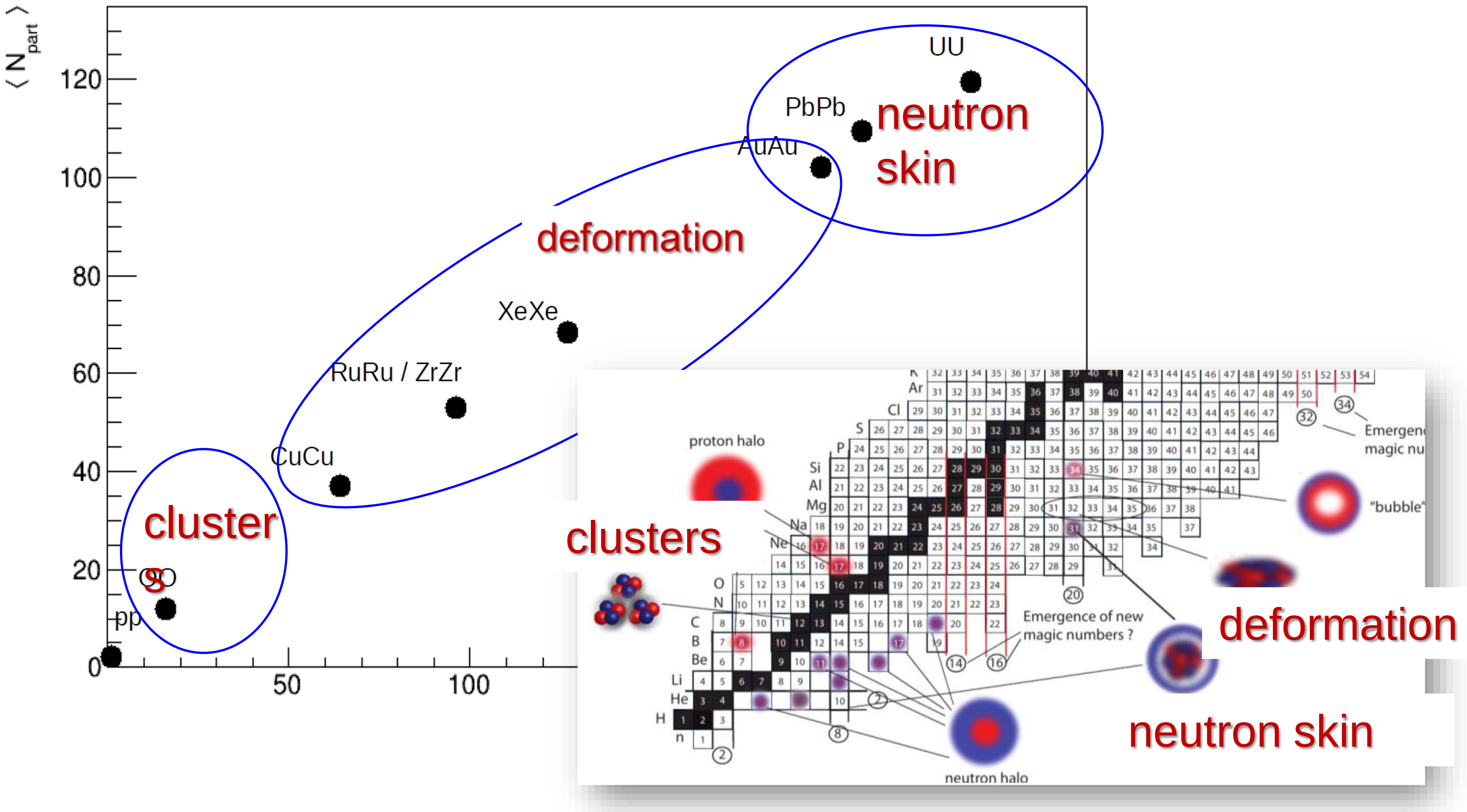


A scaling behavior was found in double ratio of $v_2\{2\}/v_3\{2\}$ when Au and Pb have the neutron skins of the same size,

The measured flow harmonics at various centrality suggest Au and Pb have similar neutron skin

Q. Liu, H. Xu and H. Song. Phys.Rev.C 109 (2024) 3, 034912.

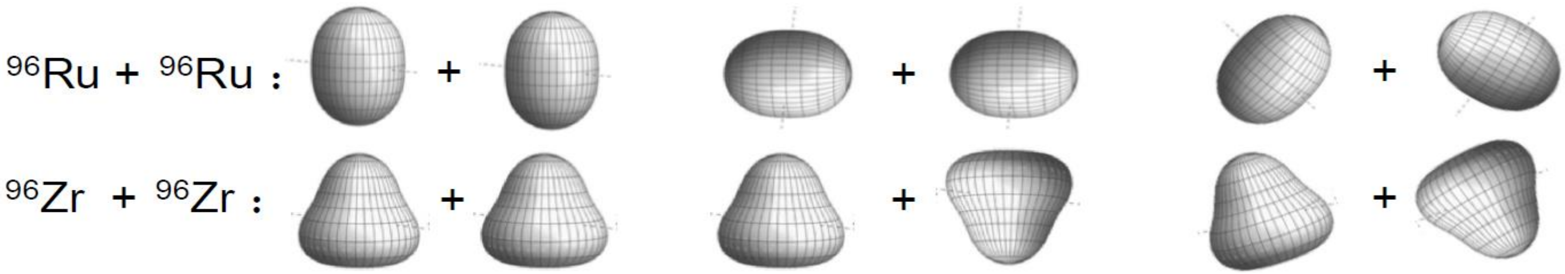
Summary

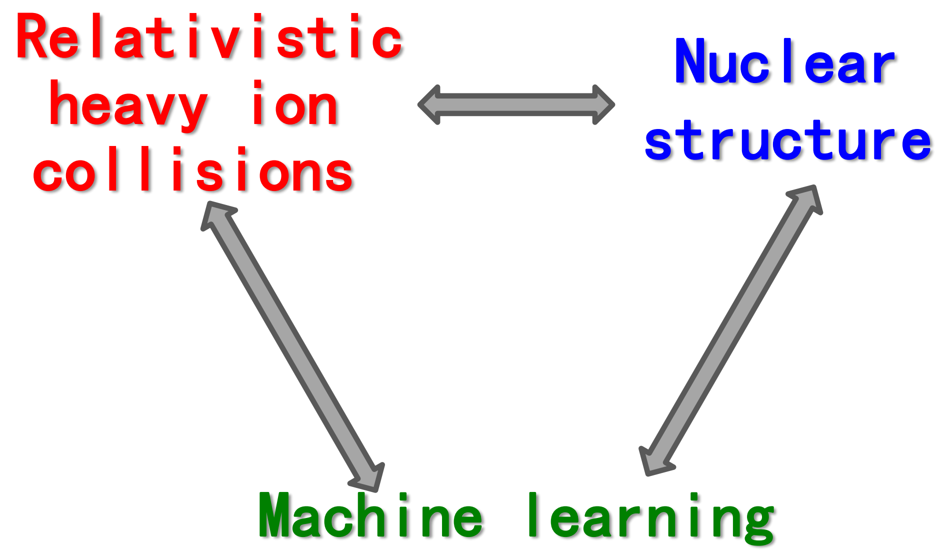


Relativistic heavy ion collisions have already provide rich collision systems to study various aspects in nuclear structure, there are lots of things to explore !

- Nuclear structure: deformation, cluster, neutron skin; shape coexistence, γ-soft (shape phase transition)

-Rich configurations for QGP initial conditions





Weiyao Ke talk on April 23 Long-Gang Pang talk during the program

Backup