Probing the nuclear structure with relativistic heavy ion collisions

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第十五届QCD相变与重离子碰撞研讨会

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12/18/2023

Landscape of nuclear physics

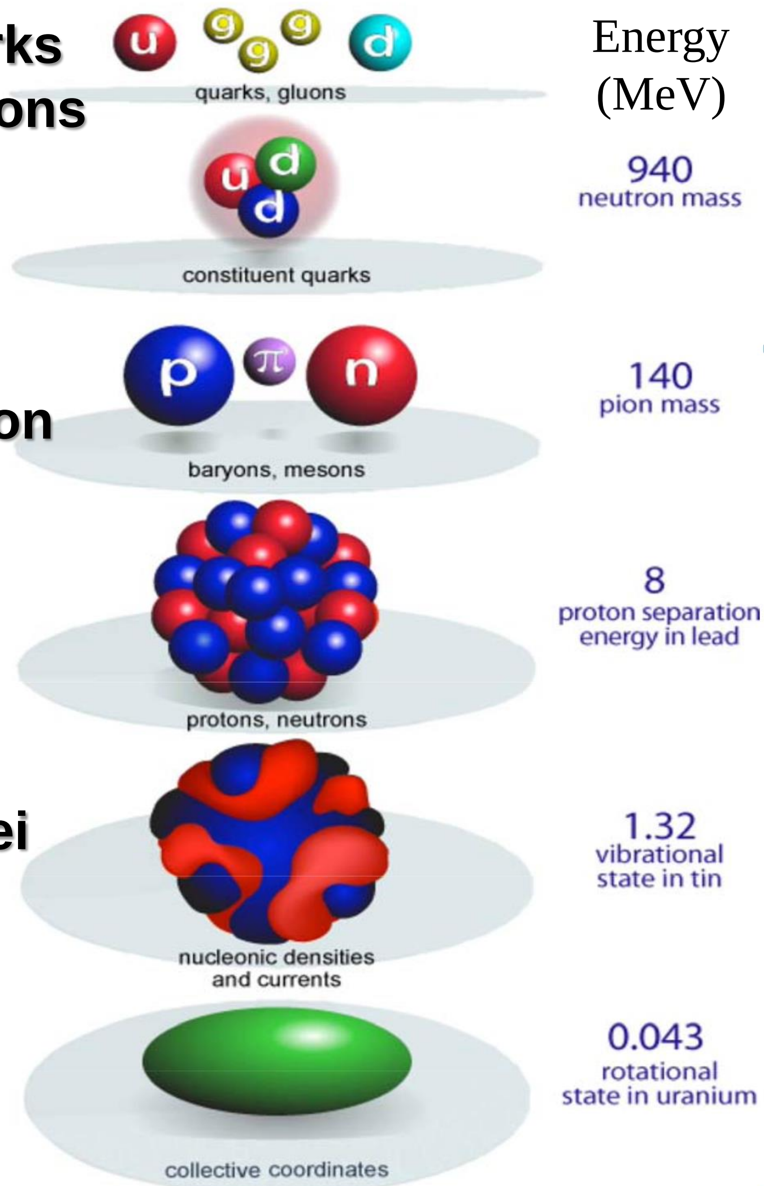
degrees of freedeom

quarks & gluons

hadron s

nuclei

Energy (MeV)



Landscape of nuclear physics

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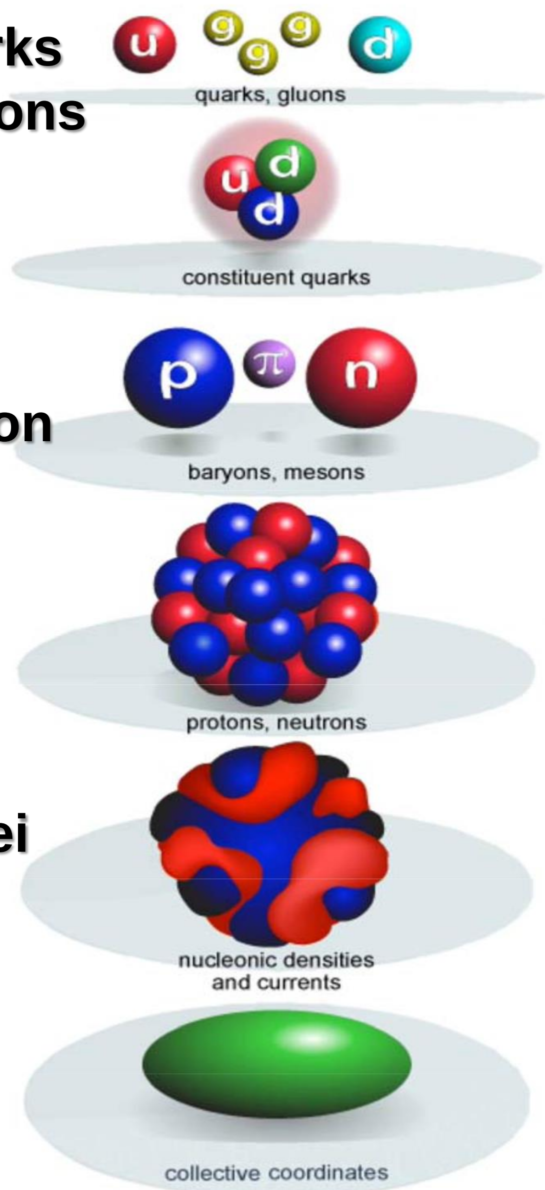


Energy (MeV)

940
neutron mass

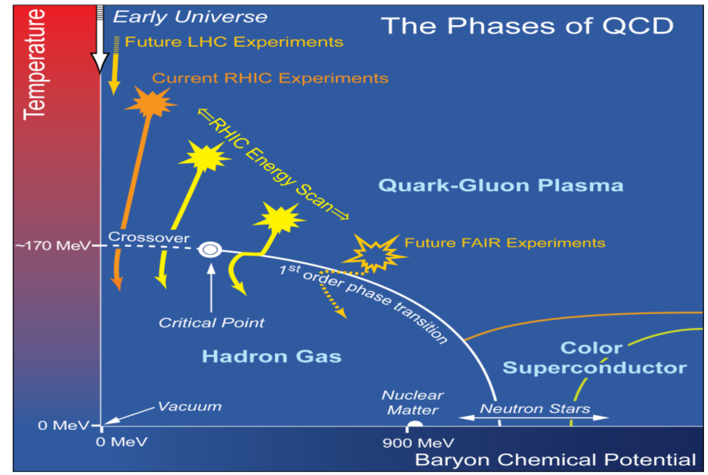
140
pion mass

8
proton separation energy in lead

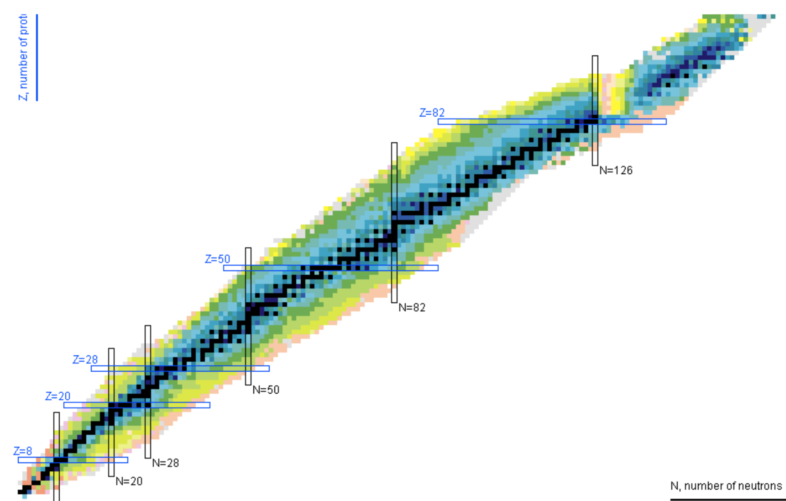
1.32
vibrational state in tin

0.043
rotational state in uranium

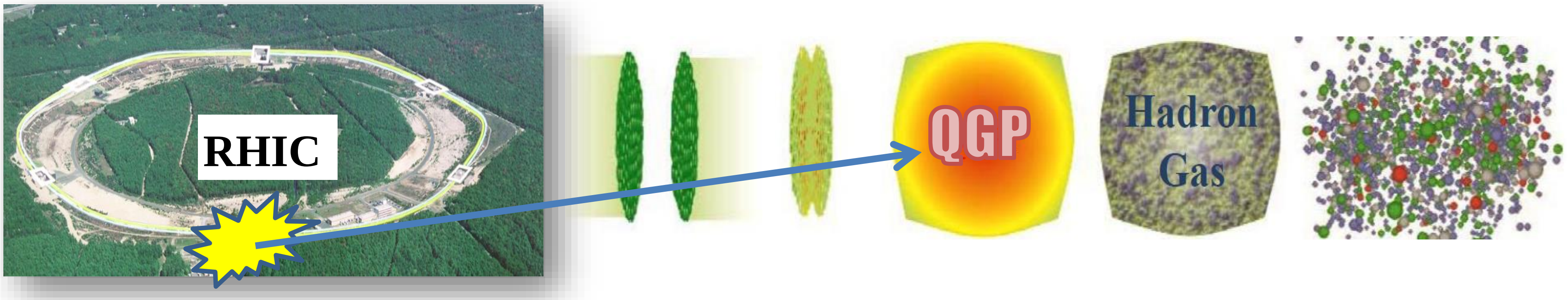
-intermediate and high energy nuclear physics



-nuclear structure



Relativistic Heavy Ion Collisions



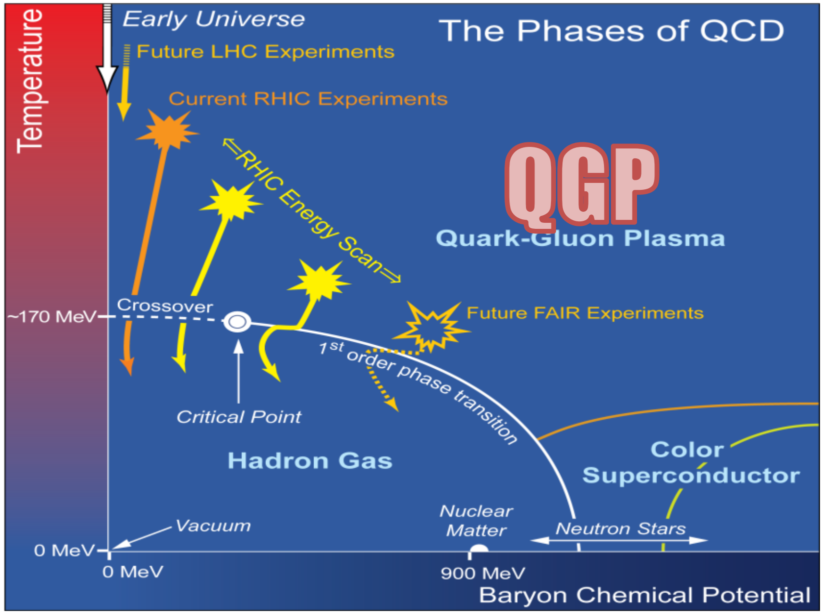
Relativistic heavy ion collisions

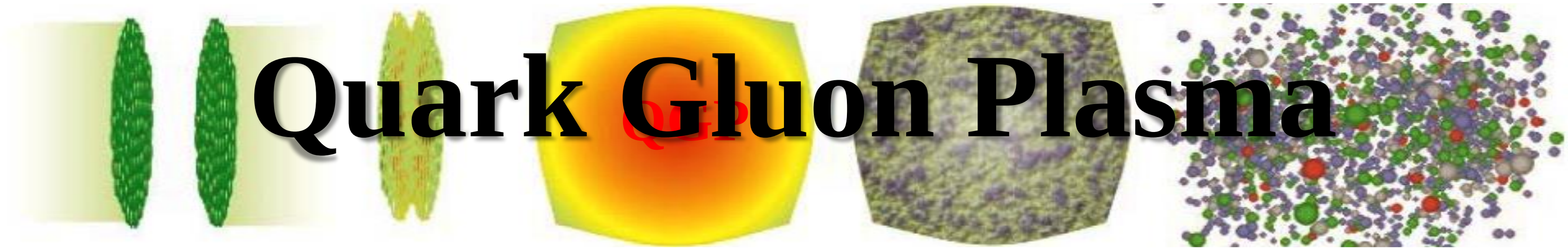
-create and study QGP

-the QCD phase diagram

-the deconfinement & chiral phase transition

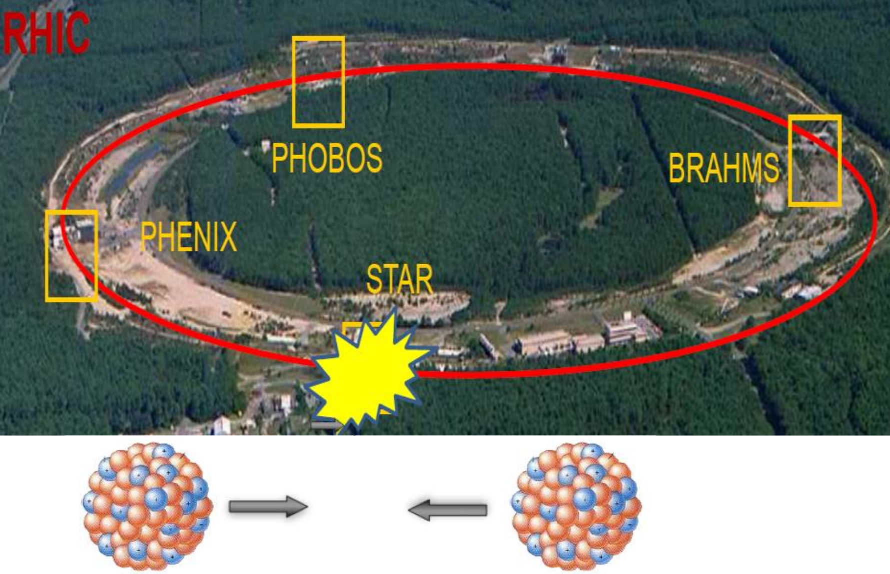
-the QCD vacuum

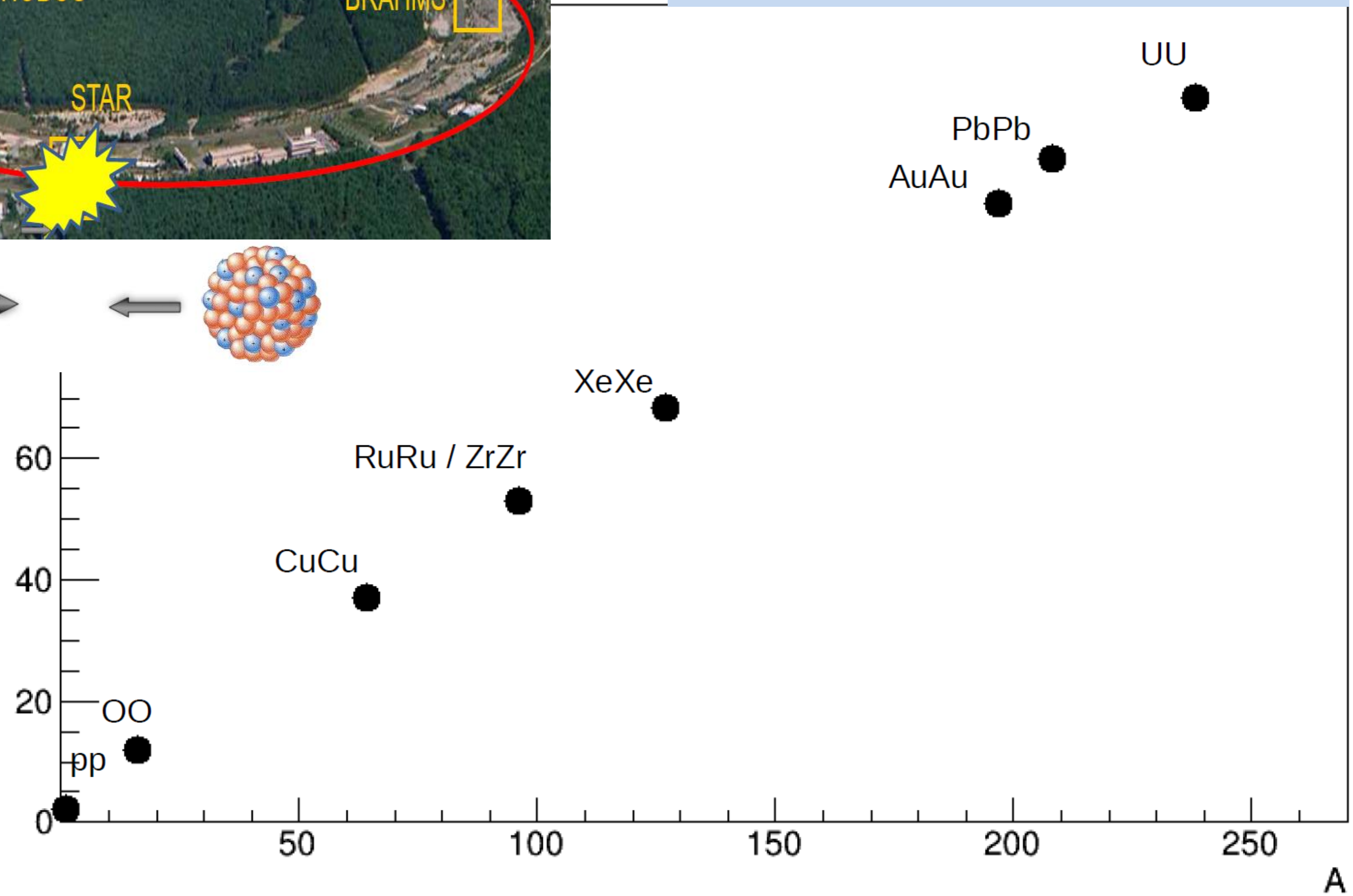




Hottest Matter on Earth

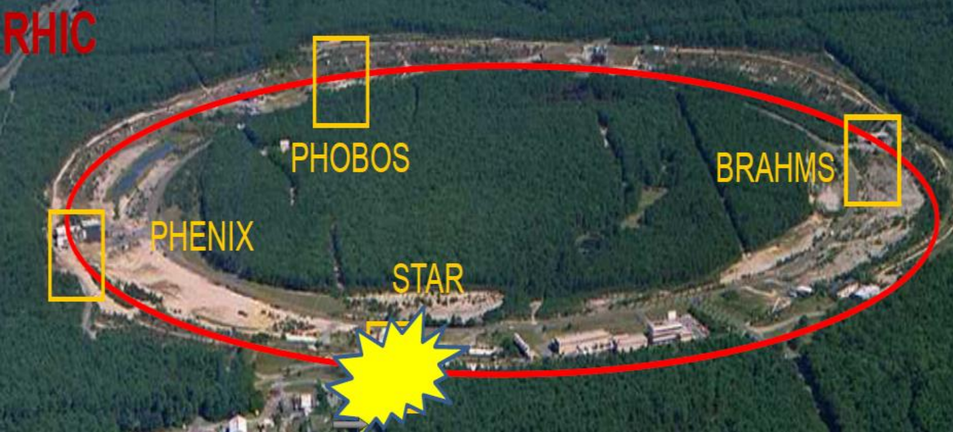
Rich A-A collisions at RHIC & the LHC

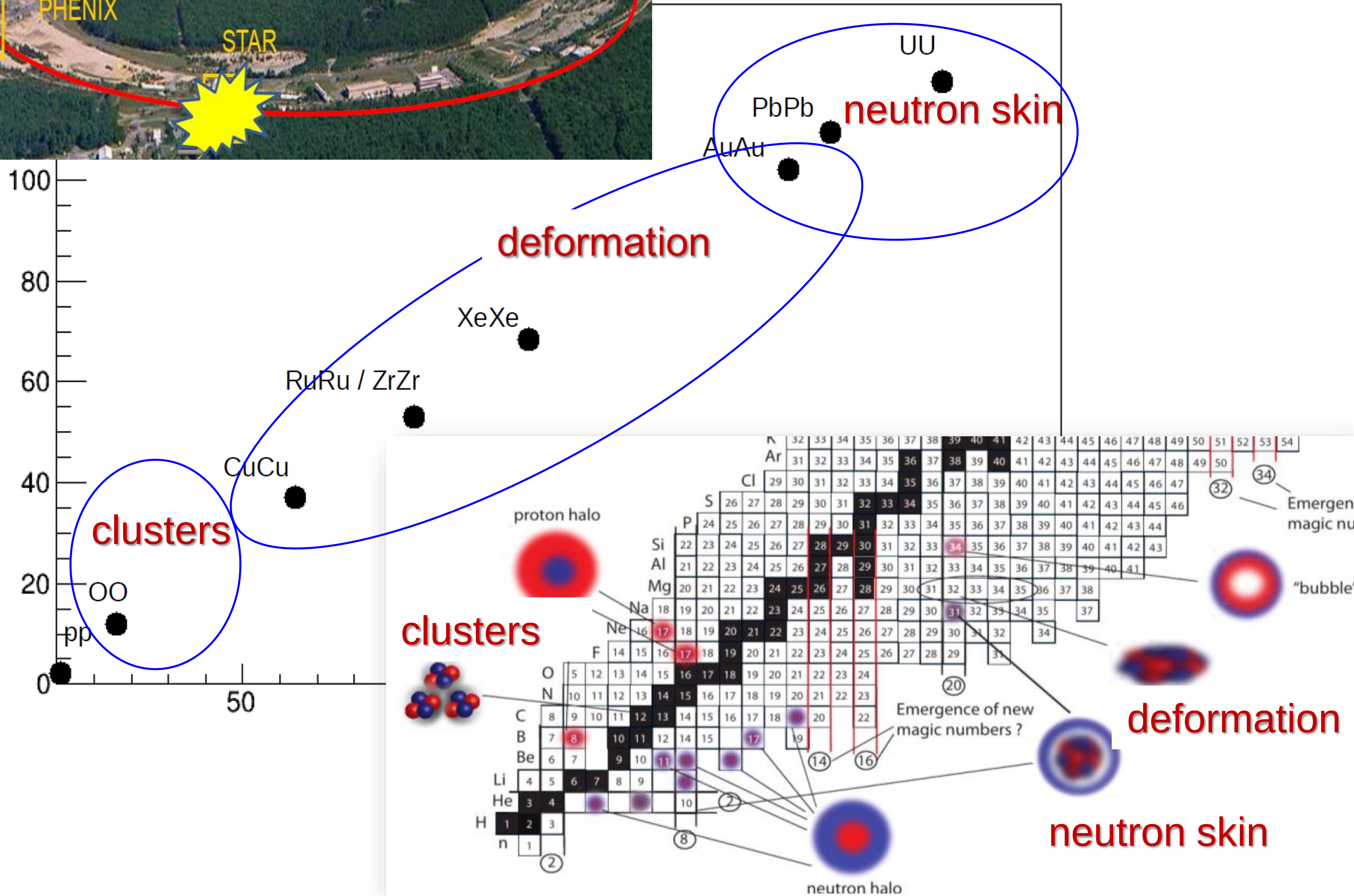




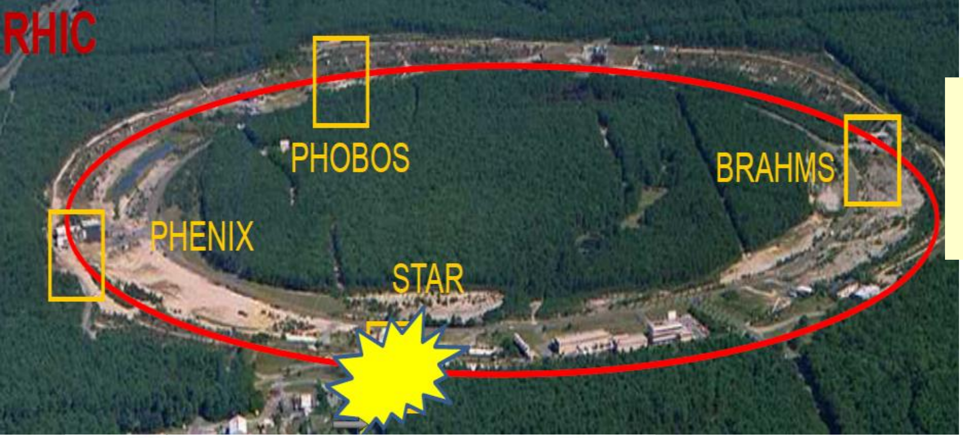
^{197}Au+^{197}Au、 ^{238}U+^{238}U、 ^{208}Pb+^{208}Pb、 ^{129}Xe+^{129}Xe、 ^{96}Zr+^{96}Zr、
^{96}Ru+^{96}Ru、 ^{64}Cu+^{64}Cu 、 ^{16}O+^{16}O 、 p+^{208}Pb、 p+p … …

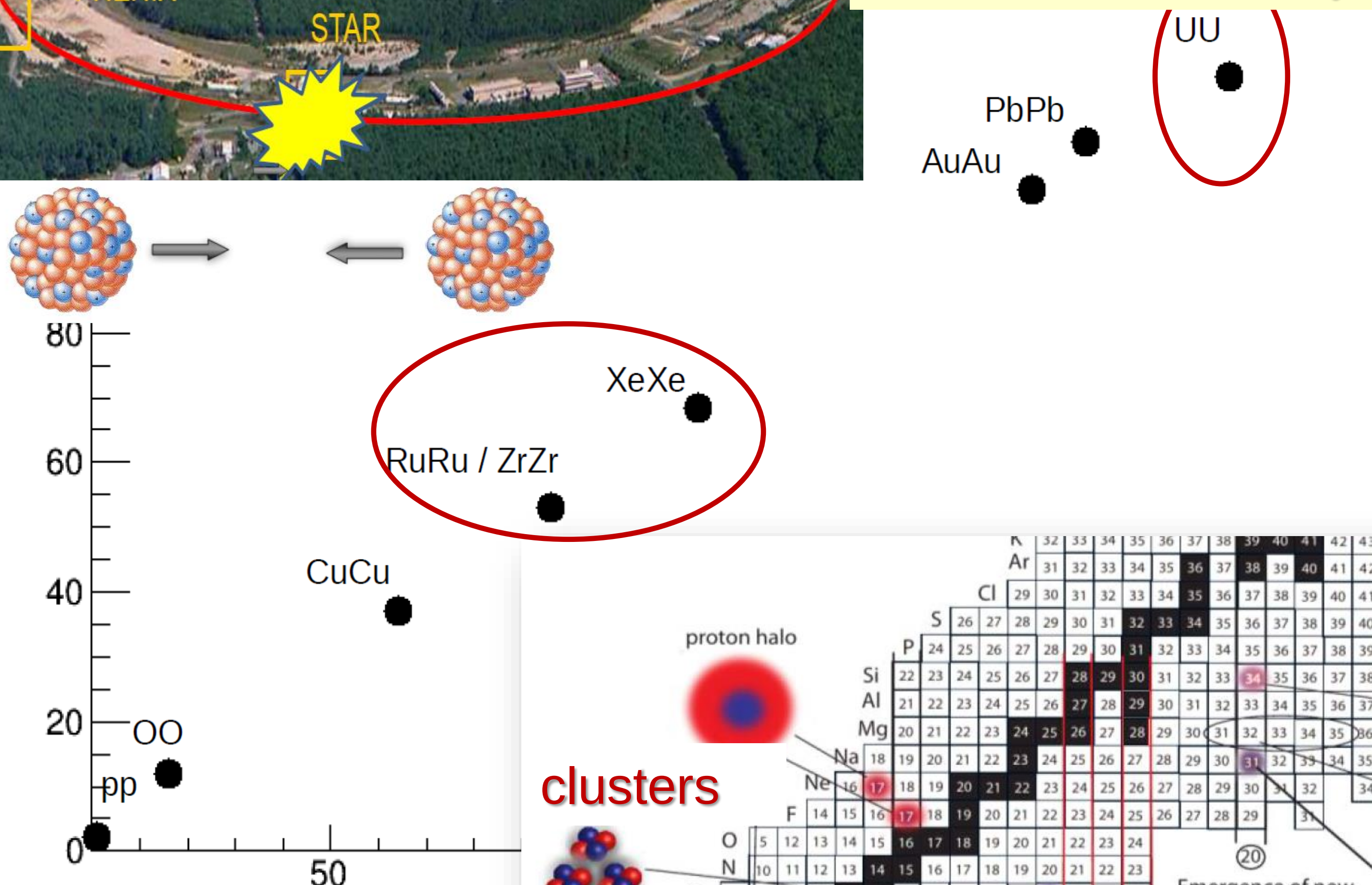
High energy nucleon nucleon collisions & nuclear structure

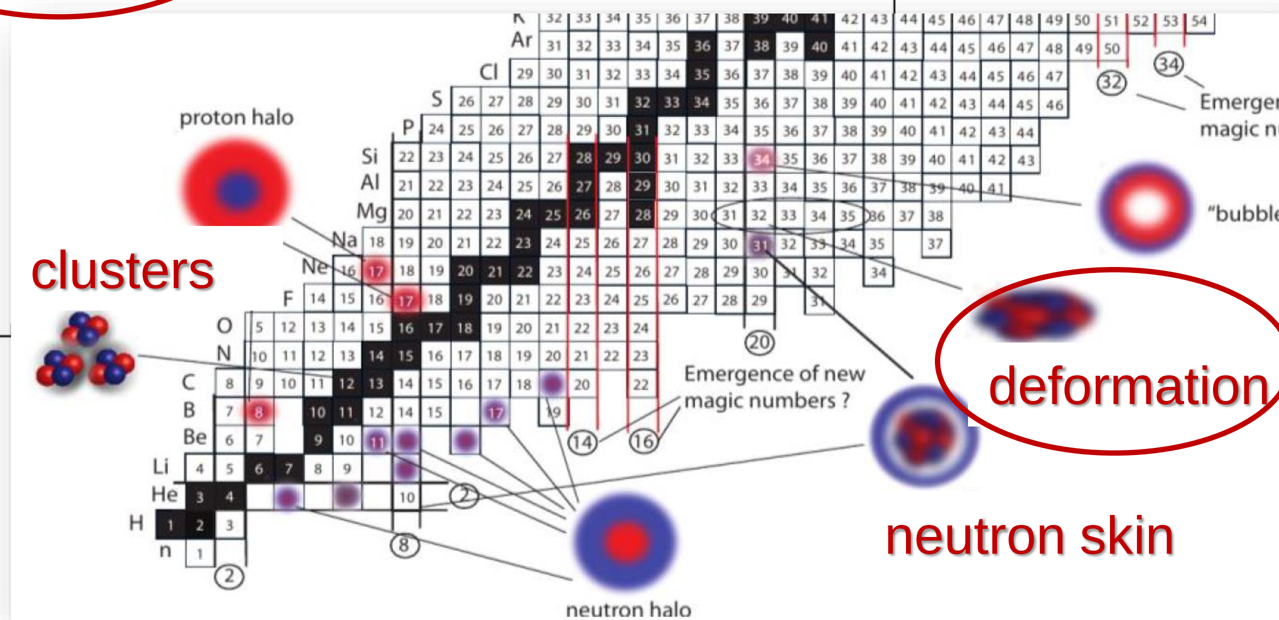


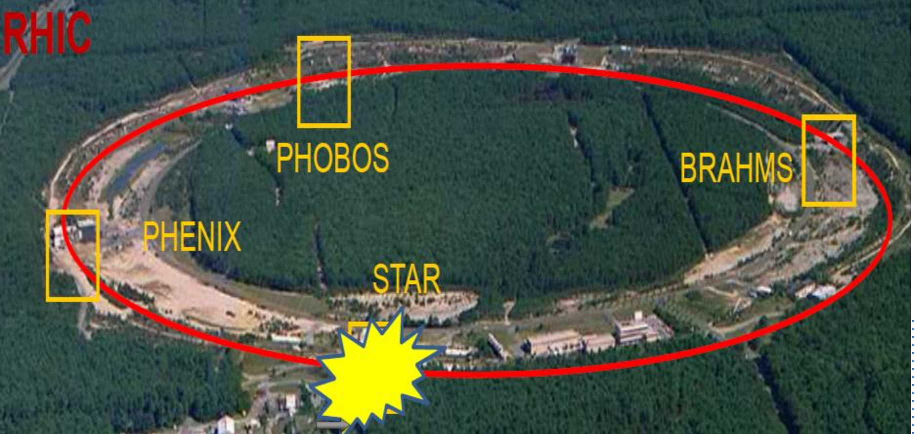


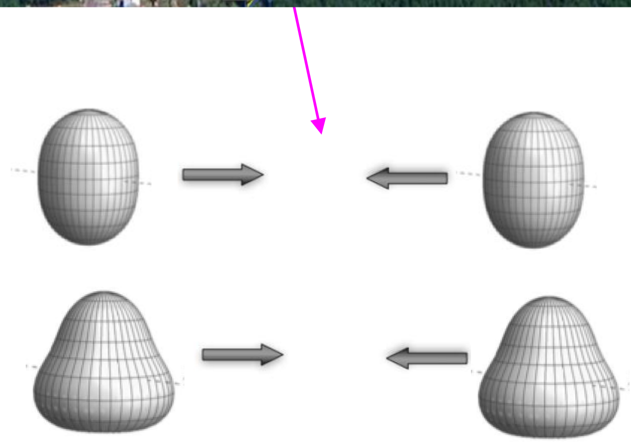
Probe the deformation of nuclei with relativistic heavy ion collisions







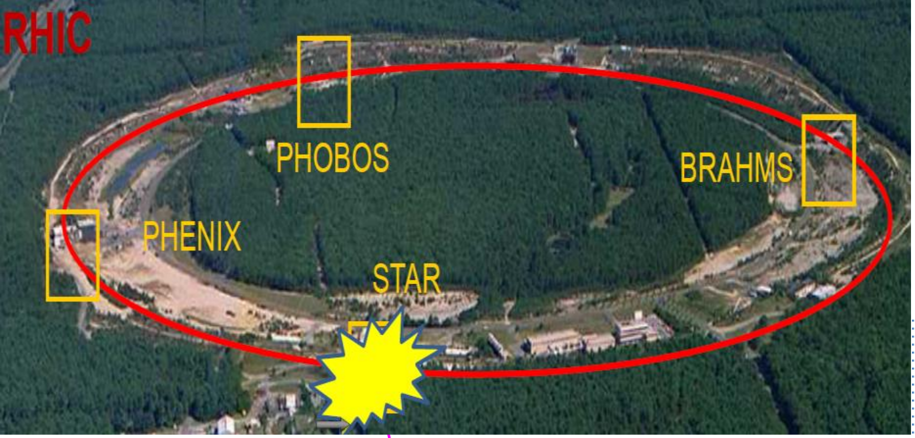




initial conditions:
(with deformations)

Probe the deformation of nuclei with relativistic heavy ion collisions

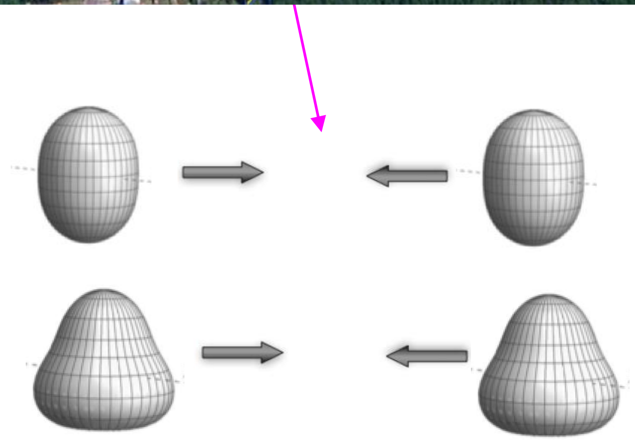
- Relativistic heavy collisions
  start from nuclei



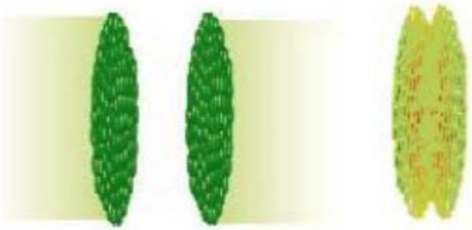
Probe the deformation of nuclei with relativistic heavy ion collisions

- Relativistic heavy collisions
  start from nuclei

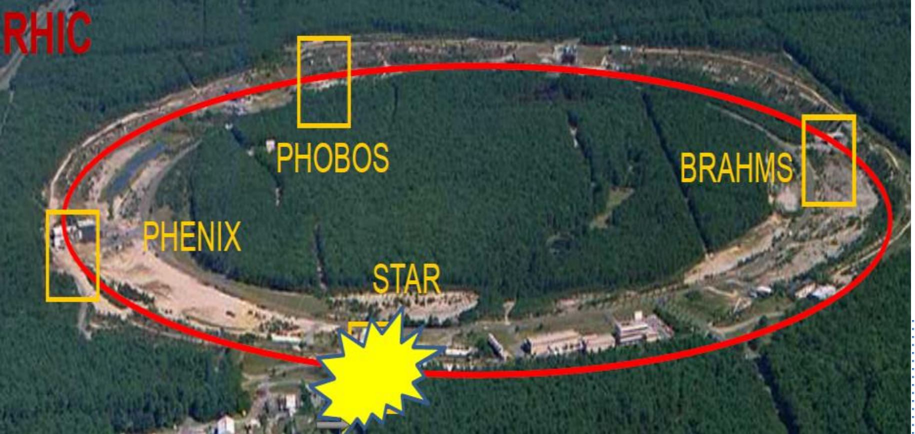
- Collision time < 10^{-24} s
  directly probe the ground state of nuclei



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

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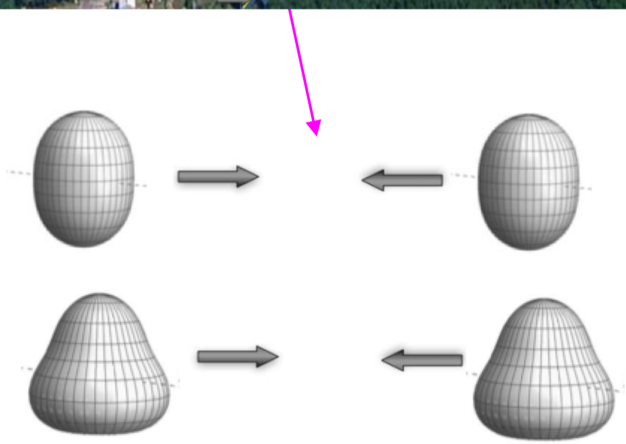
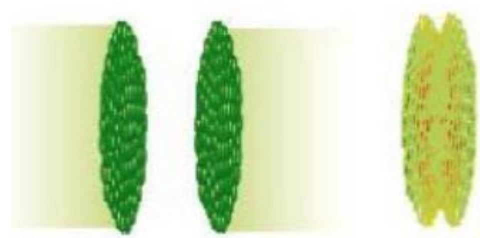
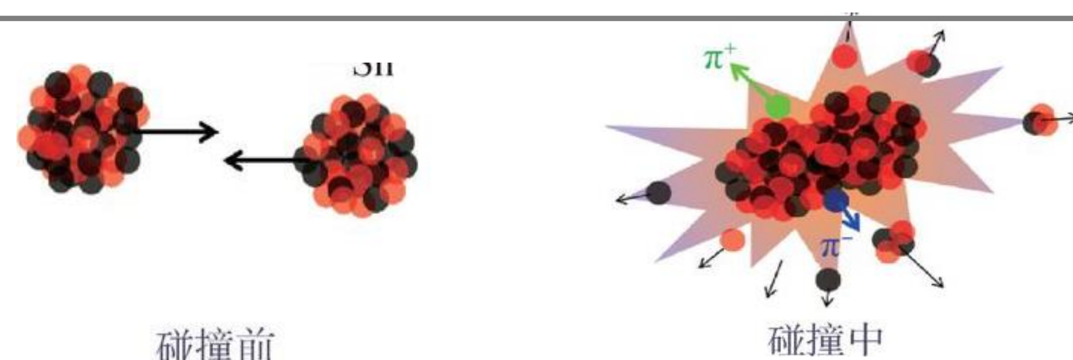


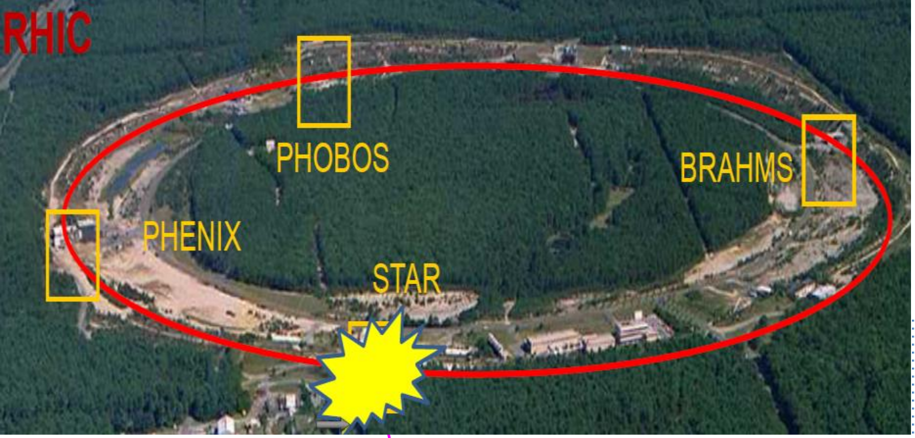
initial conditions: (with deformations)



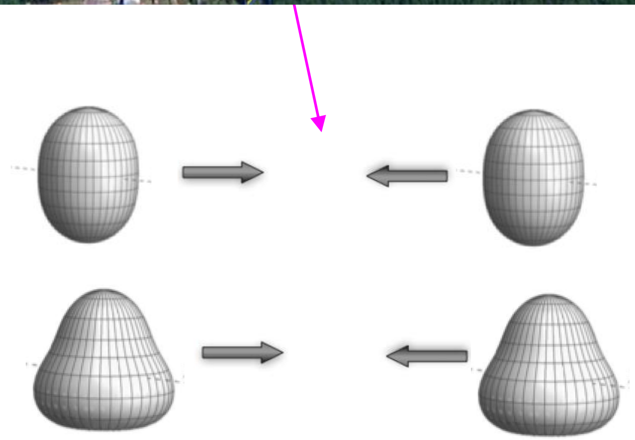
Collision time < 10^{-24} s

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





Probe the deformation of nuclei with relativistic heavy ion collisions



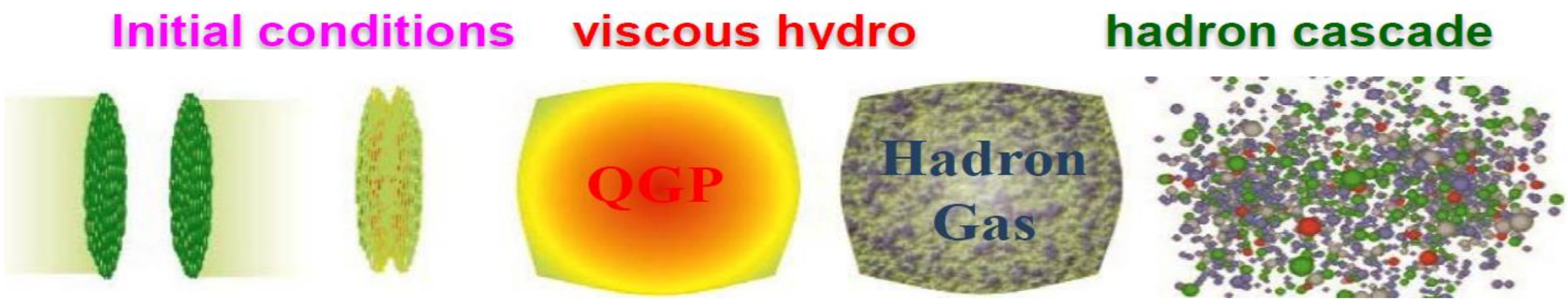
- Relativistic heavy collisions
  start from nuclei

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

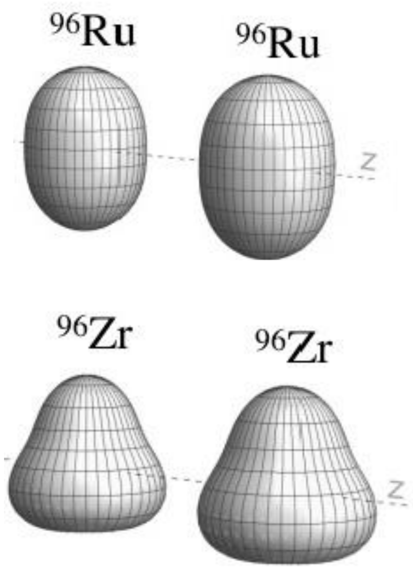
-Well calibrated calculations for QGP evolution; to focus on the initial state

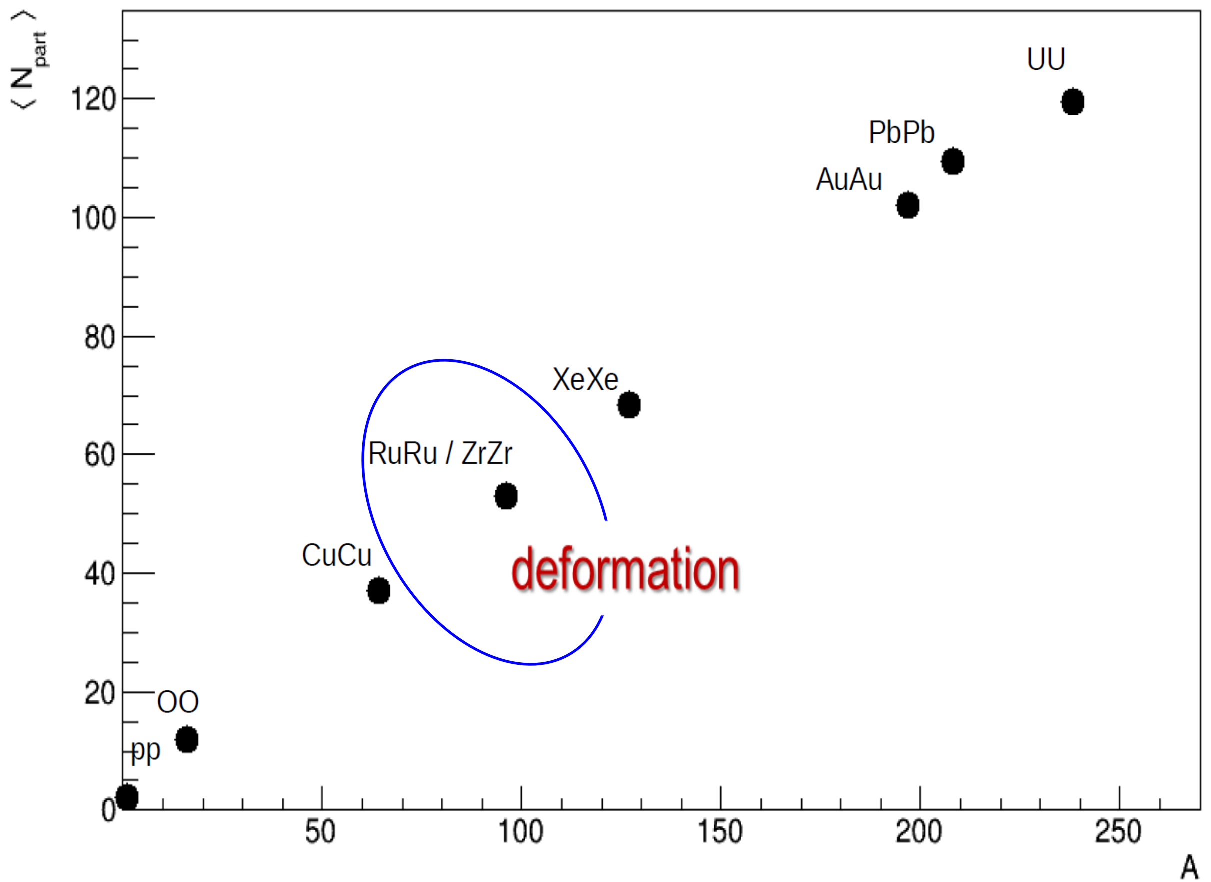
initial conditions:
(with deformations)

Well calibrated calculations

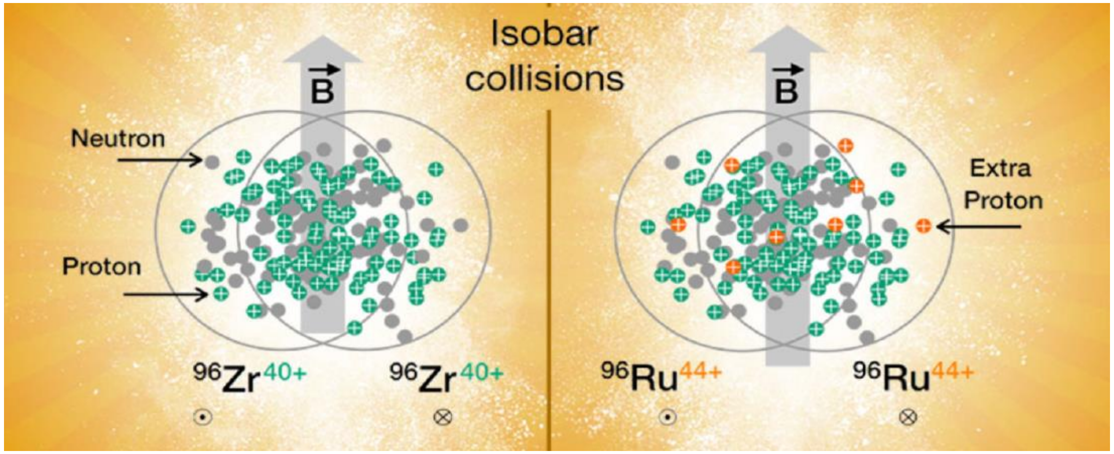


Study the deformation of ^{96}Ru and ^{96}Zr at RHIC isobar run





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



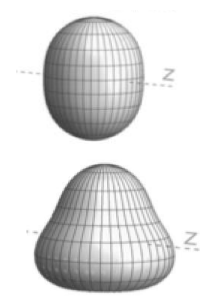
-to search the Chiral Magnetic Effect (CME)

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

	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

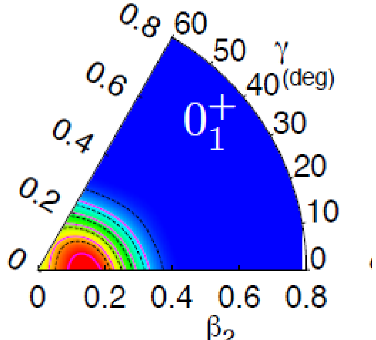
Effective density dependence

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

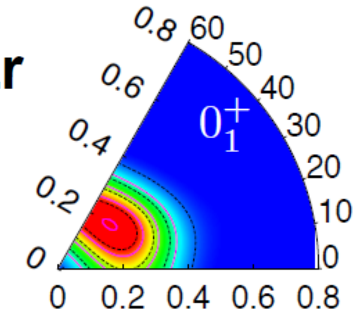
Skyrme and Gogny DFTs: different prescriptions for density dependence

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

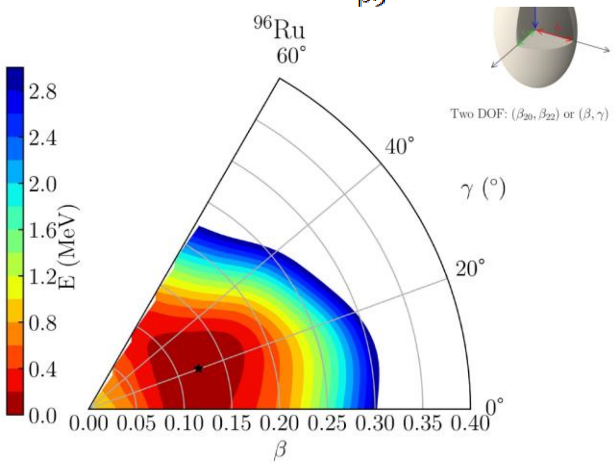
^{96}Ru

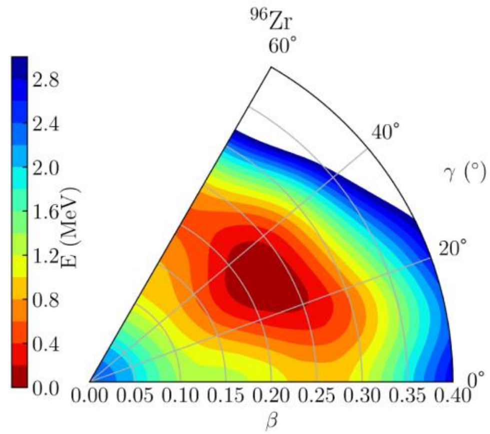


^{96}Zr



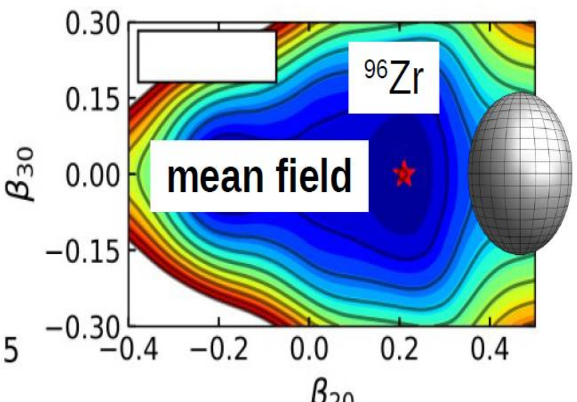
Gogny energy density functional |(Tiaxial) T R. Rodríguez EMMI RRTF 2022

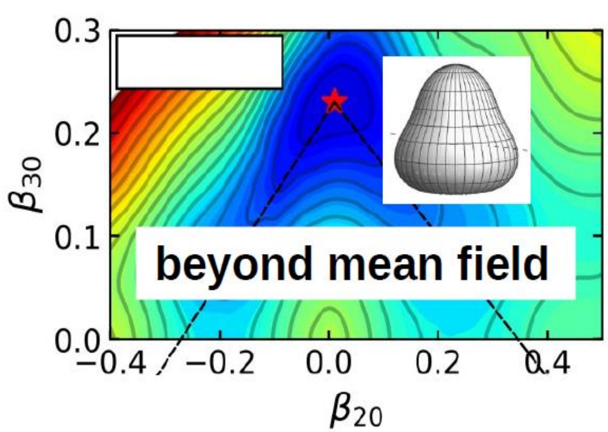




Skyrme EDF (with rotational correction)

W Ryssens EMMI RRTF 2022



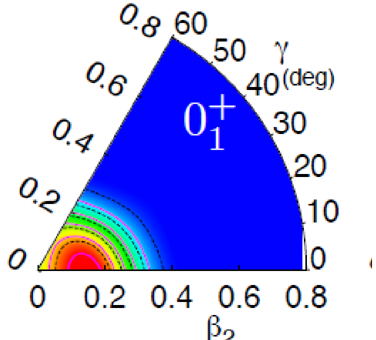


Beyond-mean-field correction is very important

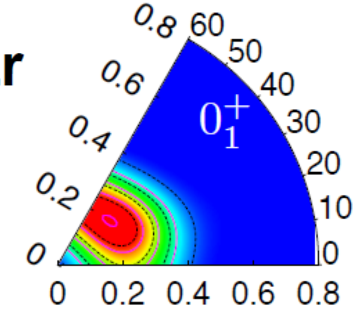
Rong, Lu, arXiv:2201.02114

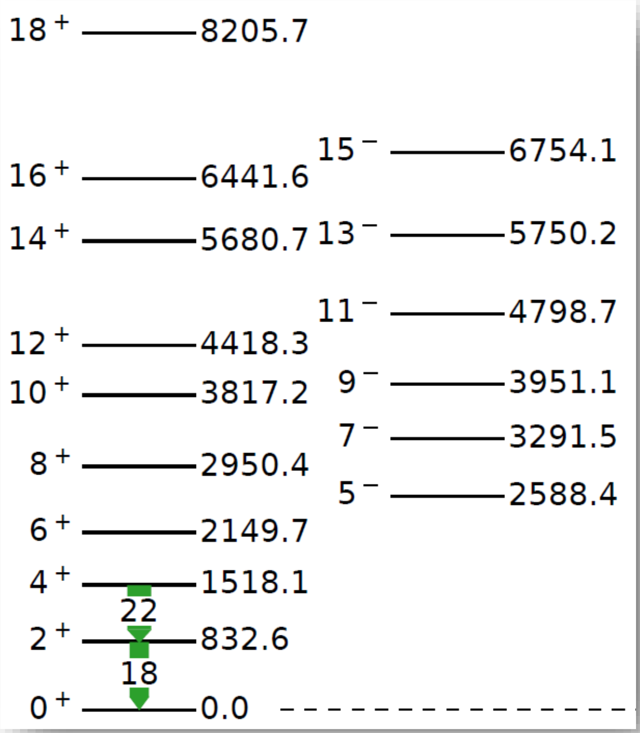
Deformation of ^{96}Ru &^{96}Zr – personal comments

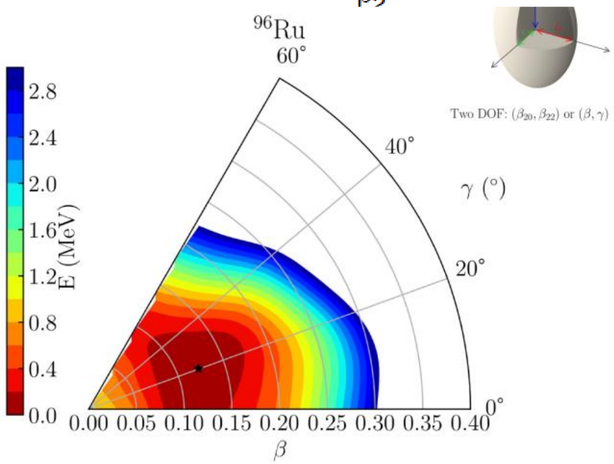
^{96}Ru

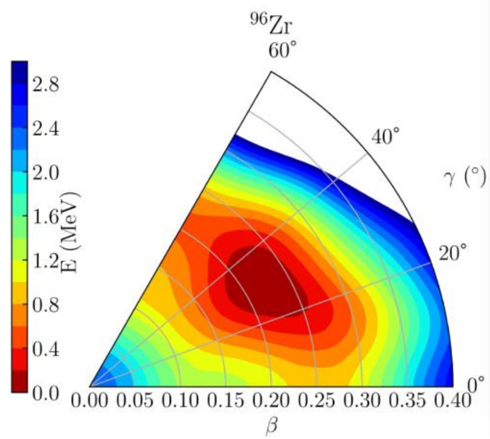


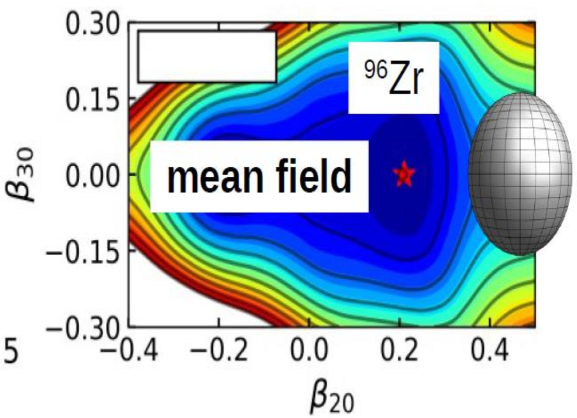
^{96}Zr

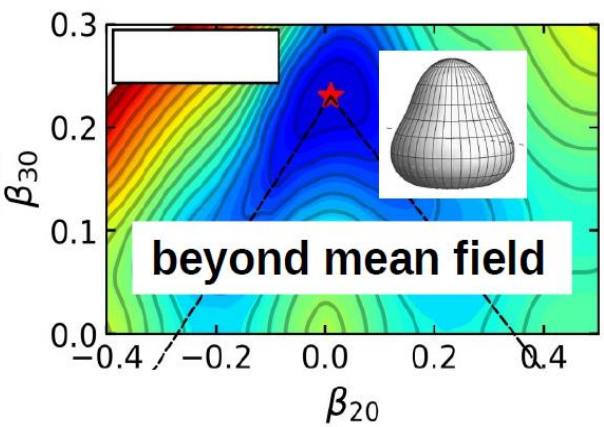






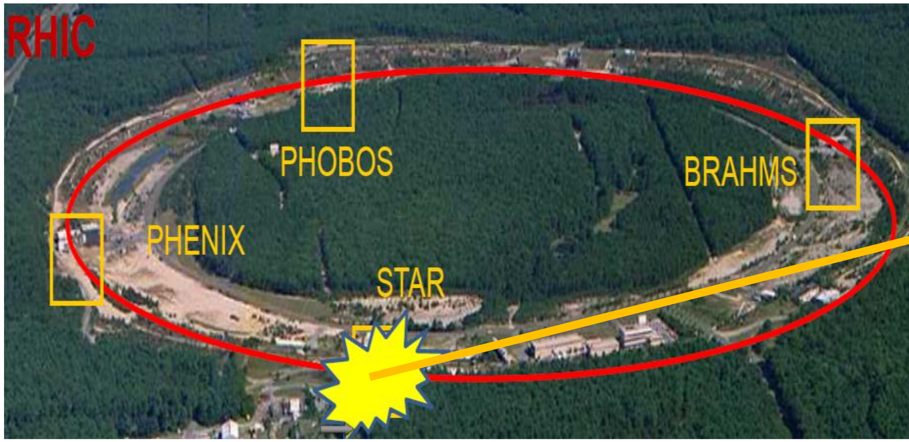


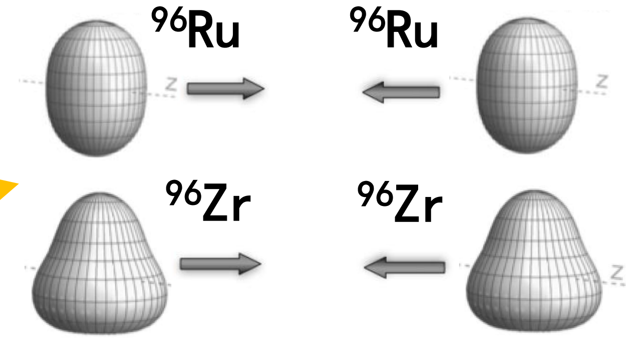




Nuclear structure physics obtain the deformation information from the spectrum with certain model calculations (not directly image the deformation in position space)

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

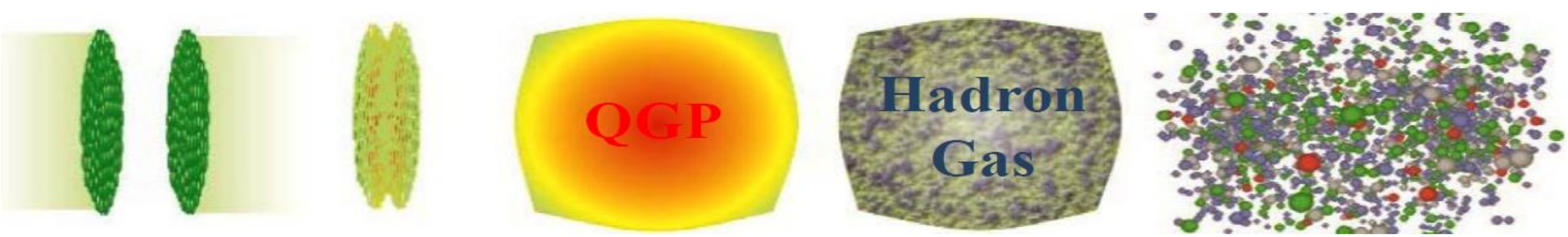




initial conditions:
(deformation / mass distributions)

Well calibrated calculations

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

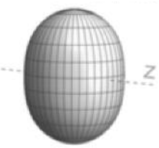


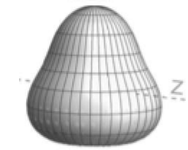
Hydrodynamic calculation with initially deformed nuclei

Initial conditions (TRENTO)

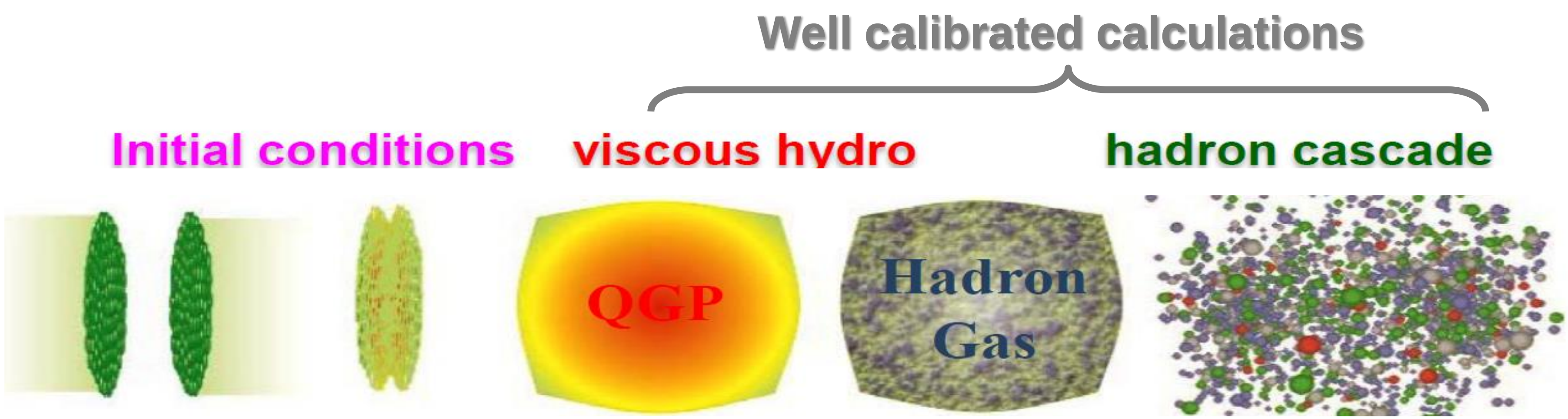
-Sample nucleon position in deformed nuclei with:

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

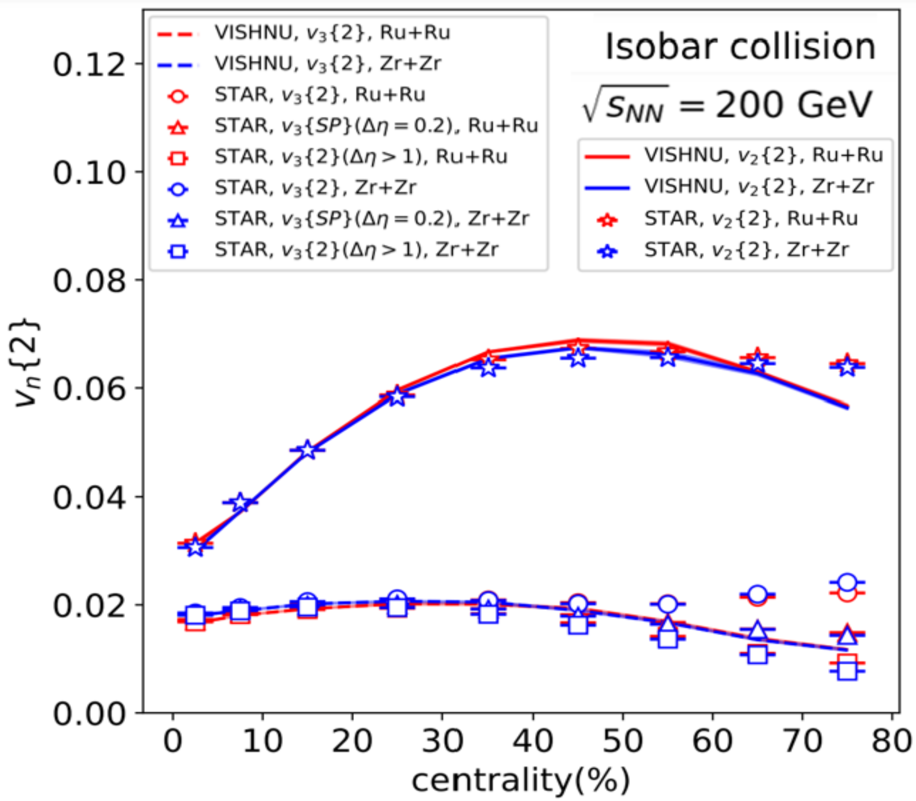
Quadrupole: 

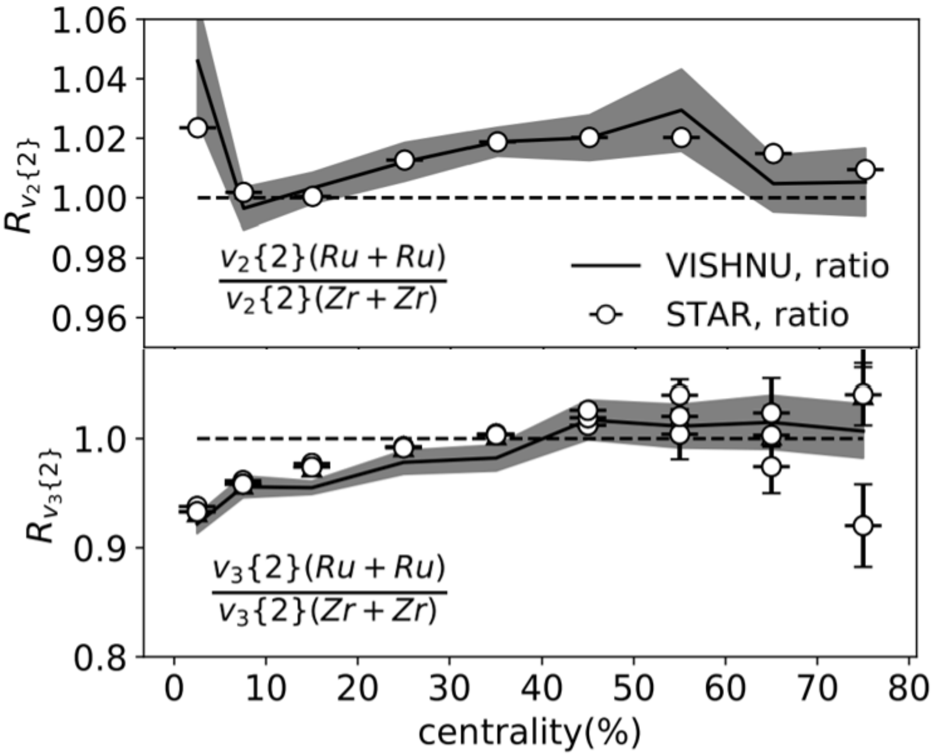
Octupole: 

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



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



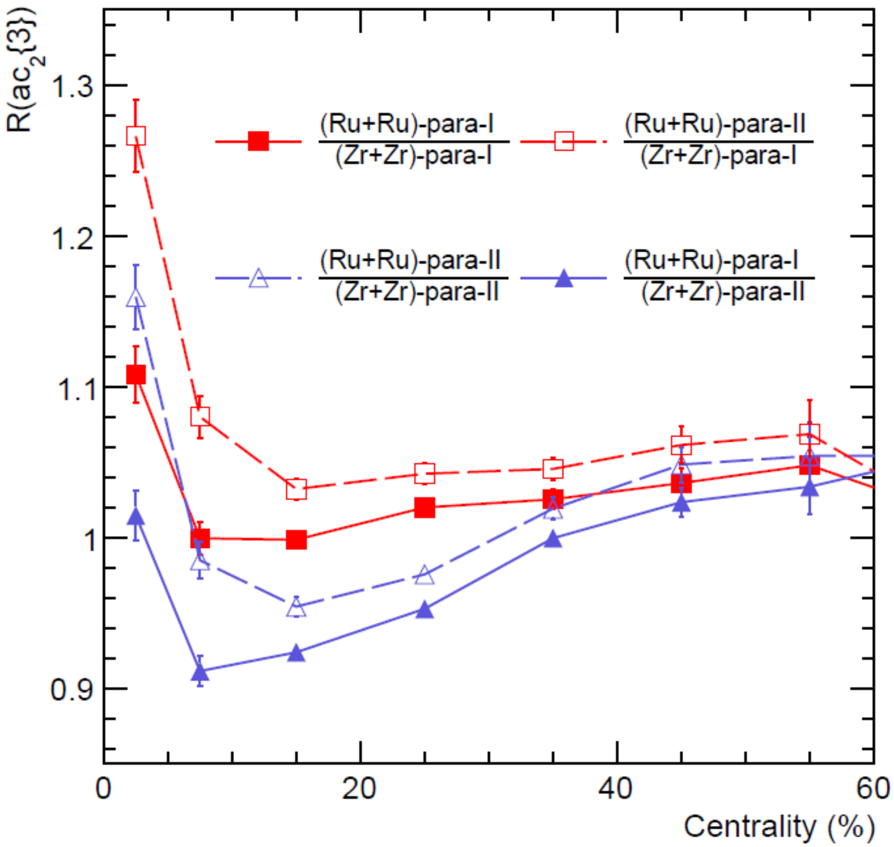


-With fine tuning parameters, iEBE-VISHNU fits V_2 & V_3 for Ru+Ru collisions

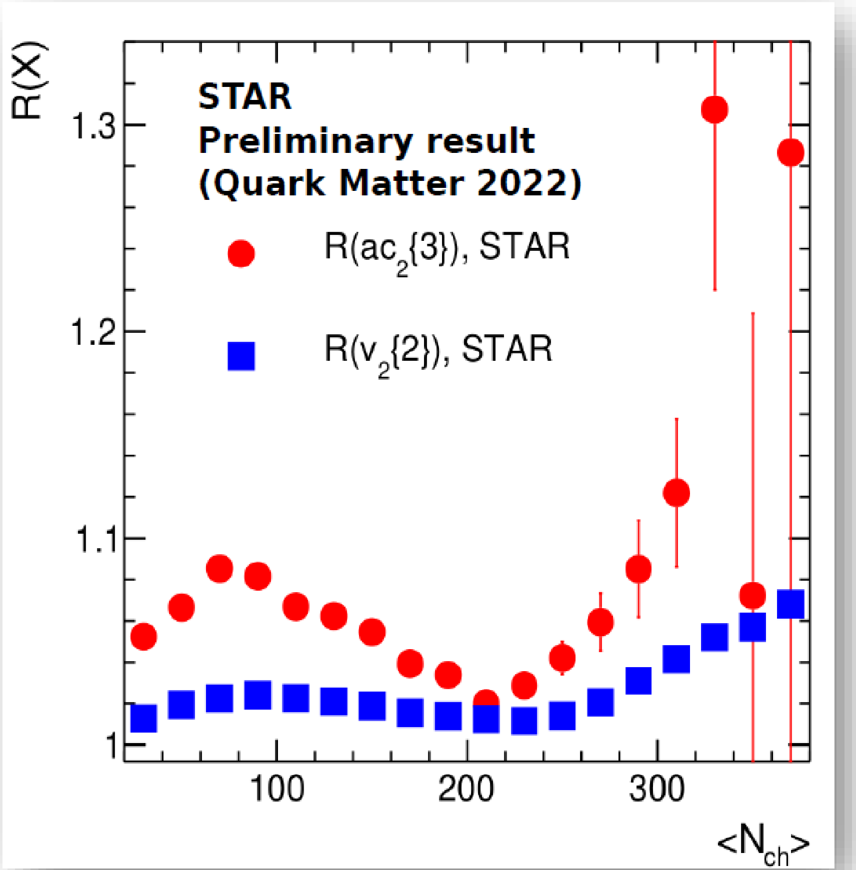
-Using β_2 β_3 in table1, it "predicts" V_2 & V_3 for Zr+Zr collisions & the related ratio -- (the data are roughly described).

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

ac{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{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

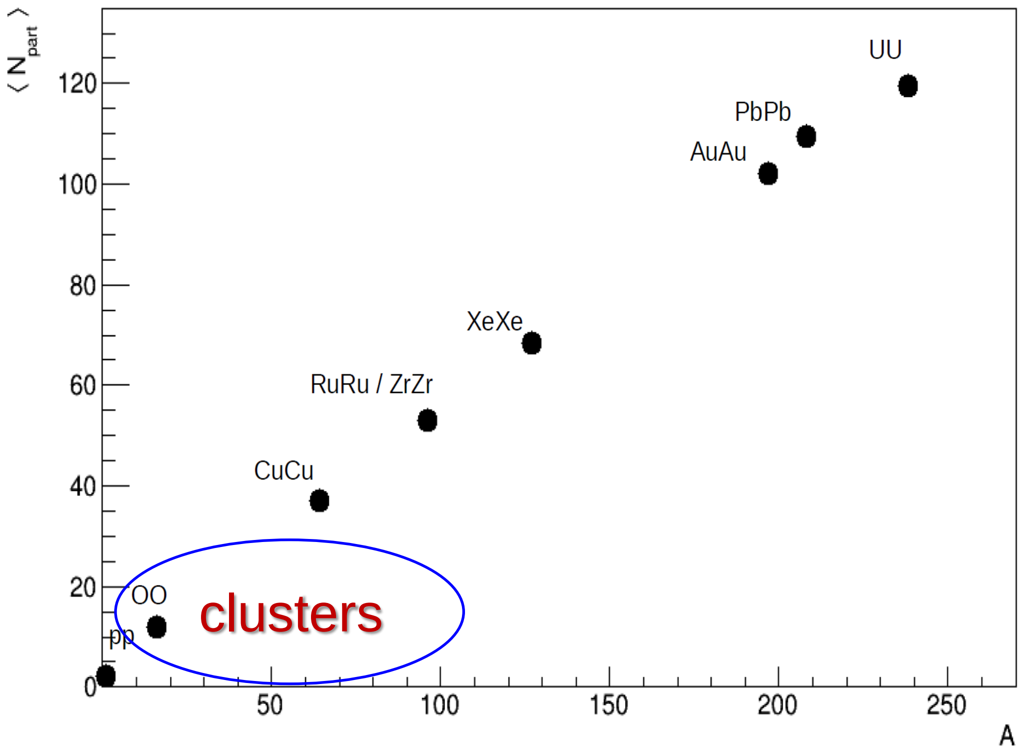
-- a short summary

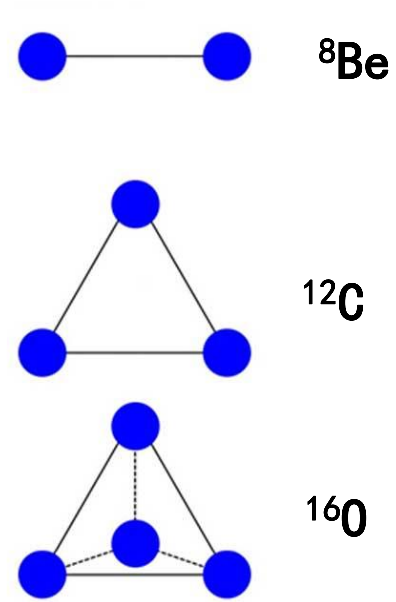
-^{96}Ru and ^{96}Zr: two ideal nuclei for interdisciplinary research between relativistic heavy ion physics and nuclear structure

-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

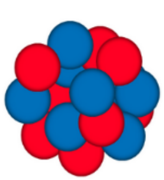
Probe the α-cluster of ^{16}O at RHIC and the LHC



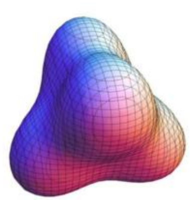


^{16}O+^{16}O collisions and p+^{16}O collisions originally aim to study the possible formation of the QGP in small systems

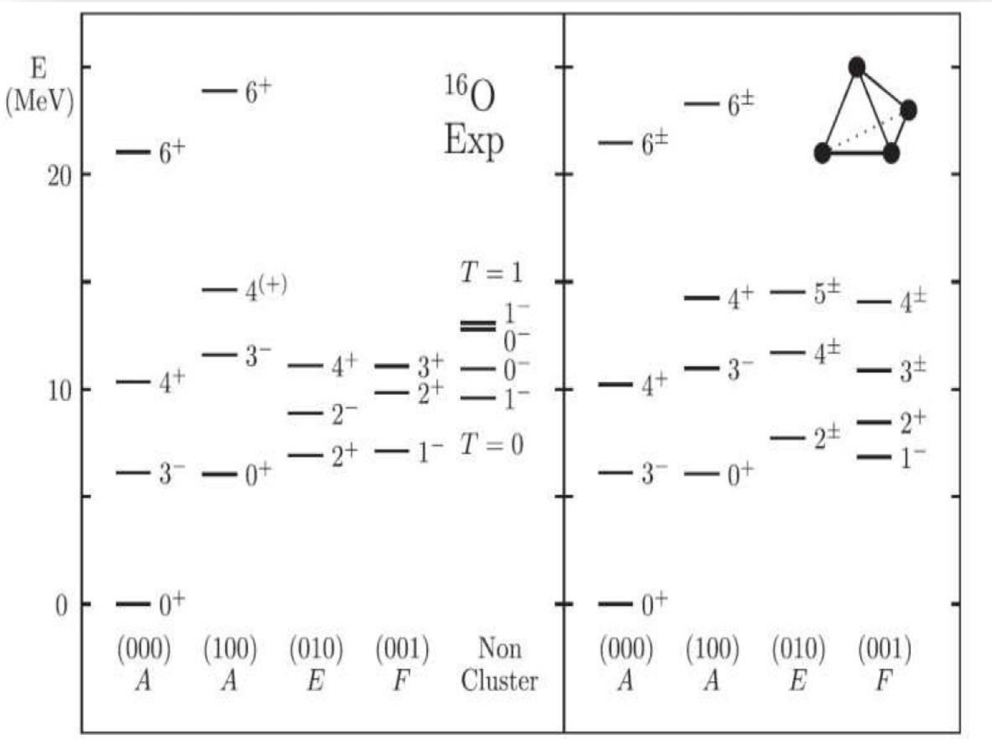
^{16}O



^{16}O



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

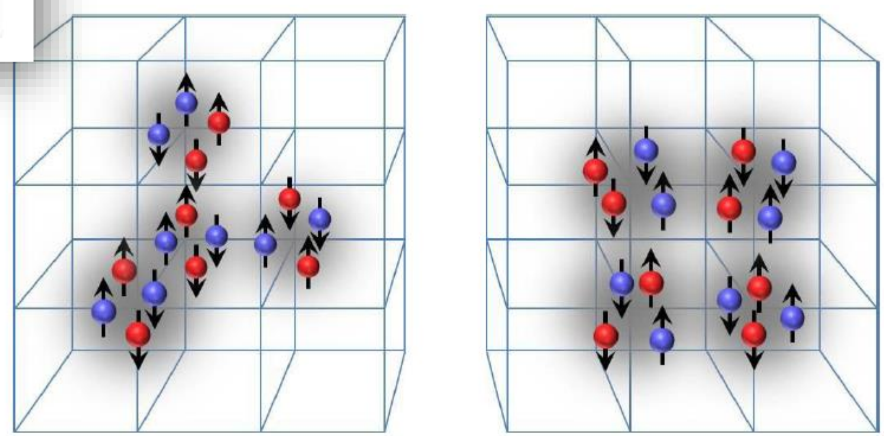


-ACM calculations show that the low-lying states of 16O can be described as rotation-vibration of a 4α cluster with tetrahedral symmetry.

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)

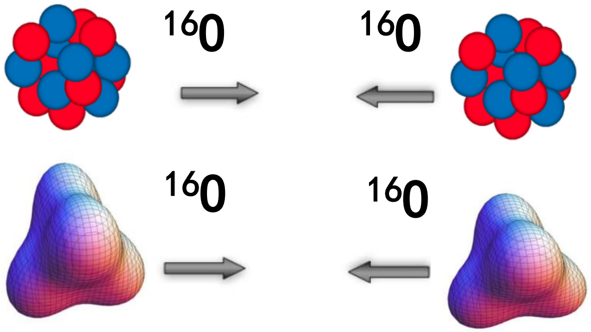


(a) Initial state “A”, 8 equivalent orientations.

(b) Initial states “B” and “C”, 3 equivalent orientations.

Nuclear structure physics infer the α-cluster configuration of ^{16}O from the measured spectrum

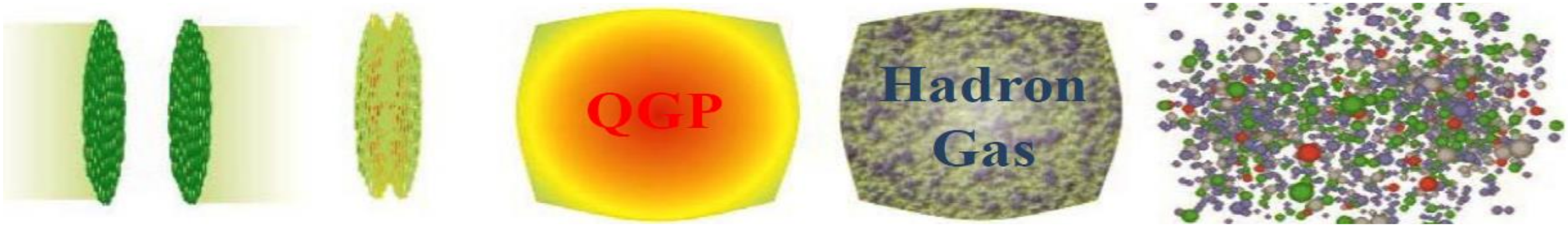
Relativistic heavy ion collision to probe the structure of ^{16}O



initial conditions:
(with or without α-cluster)

Well calibrated calculations

Initial conditions viscous hydro hadron cascade

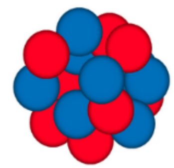


Hydrodynamic calculation w/wo clustering

Initial conditions (TRENTO)

-Woods-Saxon:

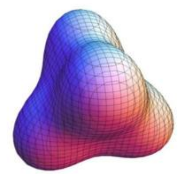
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r-R(\theta,\phi))/a_0}}$$



Spherical shape

-Alpha-Cluster:

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

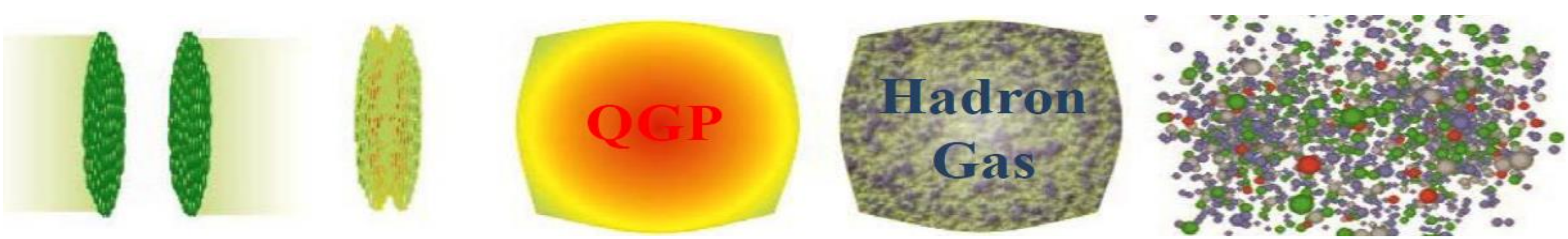


tetrahedral alpha clusters

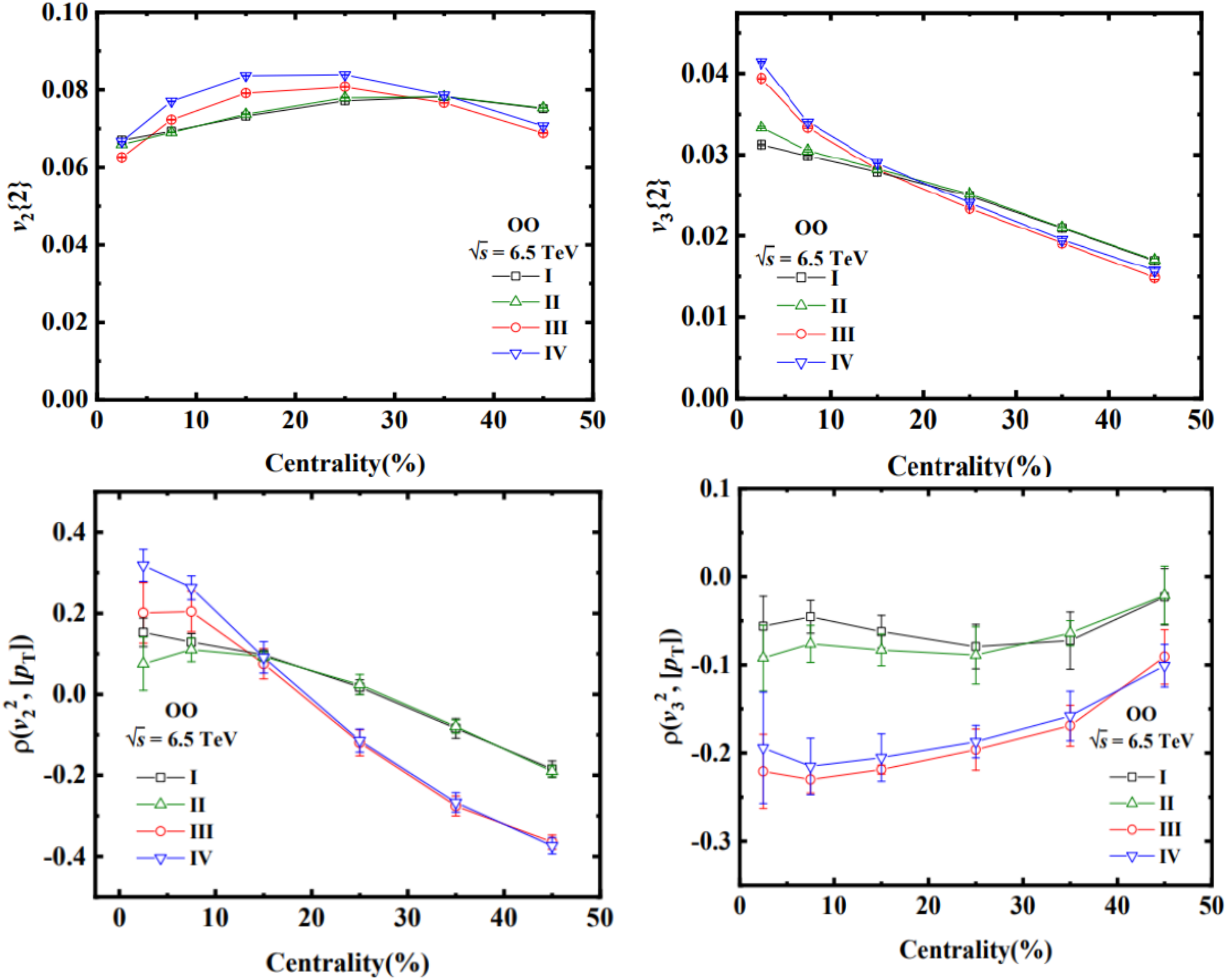
	distribution	l	r_α
I	Woods–Saxon		
II	alpha cluster	2.8	2.0
III	alpha cluster	3.2	1.1
IV	alpha cluster	3.42	1.1

Well calibrated calculations

Initial conditions viscous hydro hadron cascade

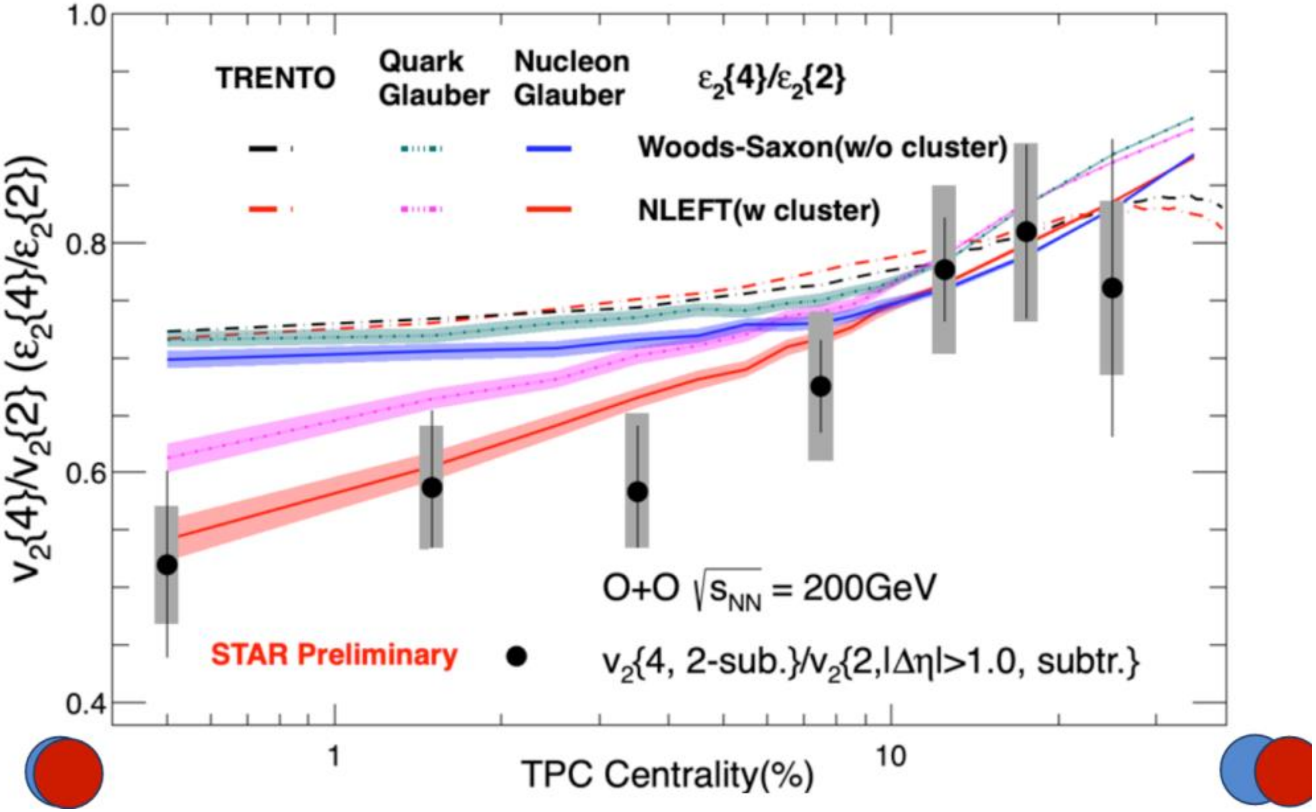


Sensitive observables for α-clustering



Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song. Paper in preparation.
Please also refer to the work from Y G Ma's groups

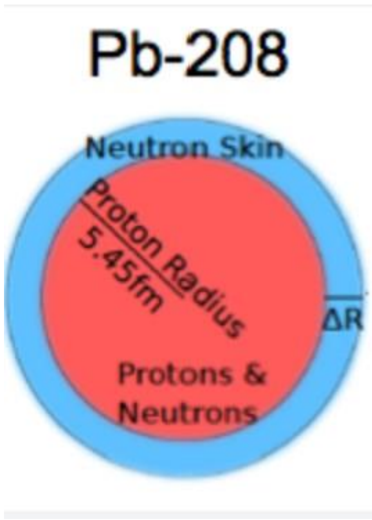
Measurement from $^{16}O+^{16}O$ collisions

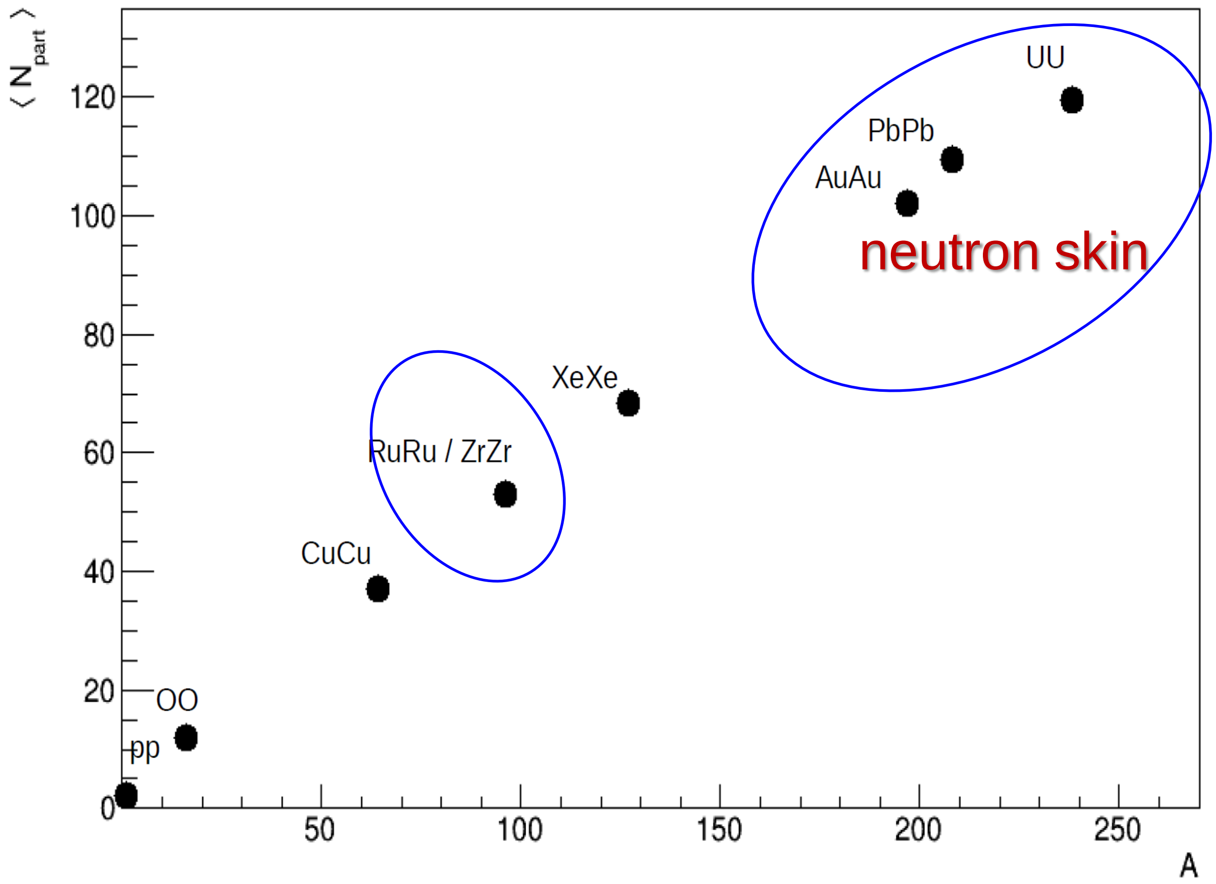


-$v_2\{4\}/v_2\{2\}$: enhanced fluctuations in ultra-central collisions

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

Probe neutron skin at RHIC and the LHC





Neutron Skin & neutron star

EOS of nuclear matter

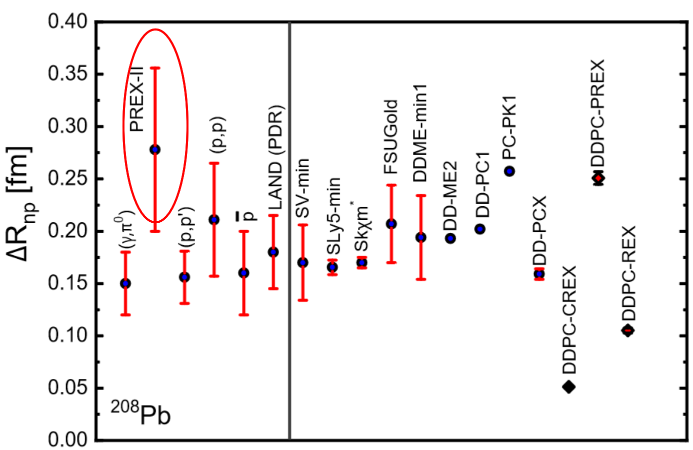
$$\epsilon(\rho,\alpha) = [\epsilon_{SNM}(\rho_0) + S(\rho_0)\alpha^2)] + \alpha^2 L \frac{\rho-\rho_0}{3\rho_0} + \frac{1}{2}(K_0 + \alpha^2 K_{sym})(\frac{\rho-\rho_0}{3\rho_0})^2$$

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

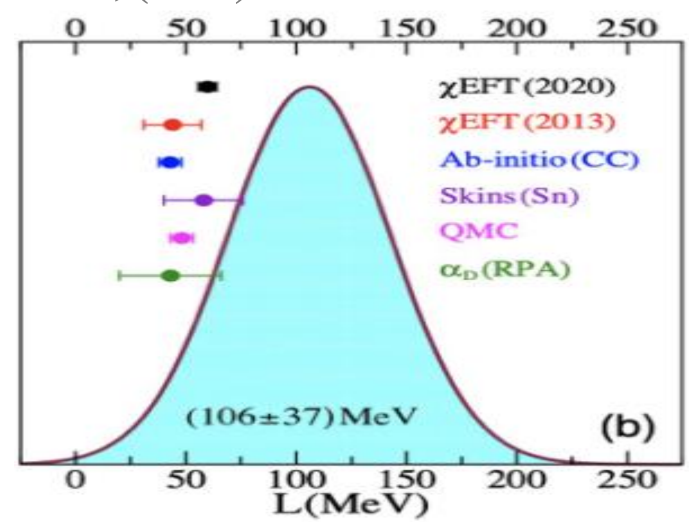
Probe the Neutron Skin at low energy nuclear physics

Parity-Violating Electron Scattering in Jefferson Lab

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

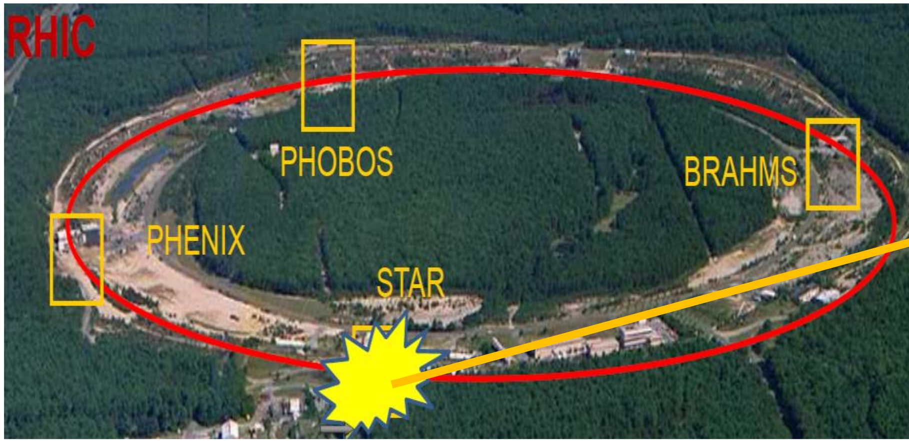


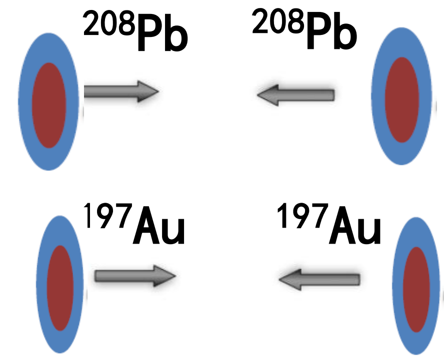
arXiv:2206.06527 Esra Yüksel and Nils Paar



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

Relativistic heavy ion collision to probe the neutron skin

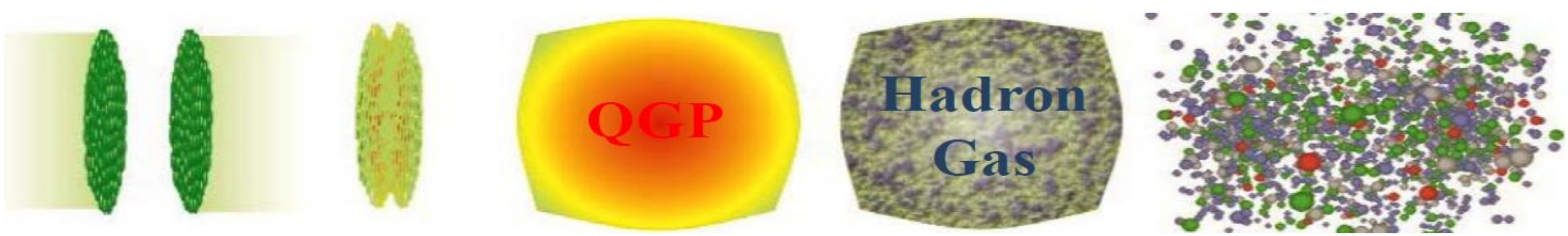




initial conditions:
(with neutron skin)

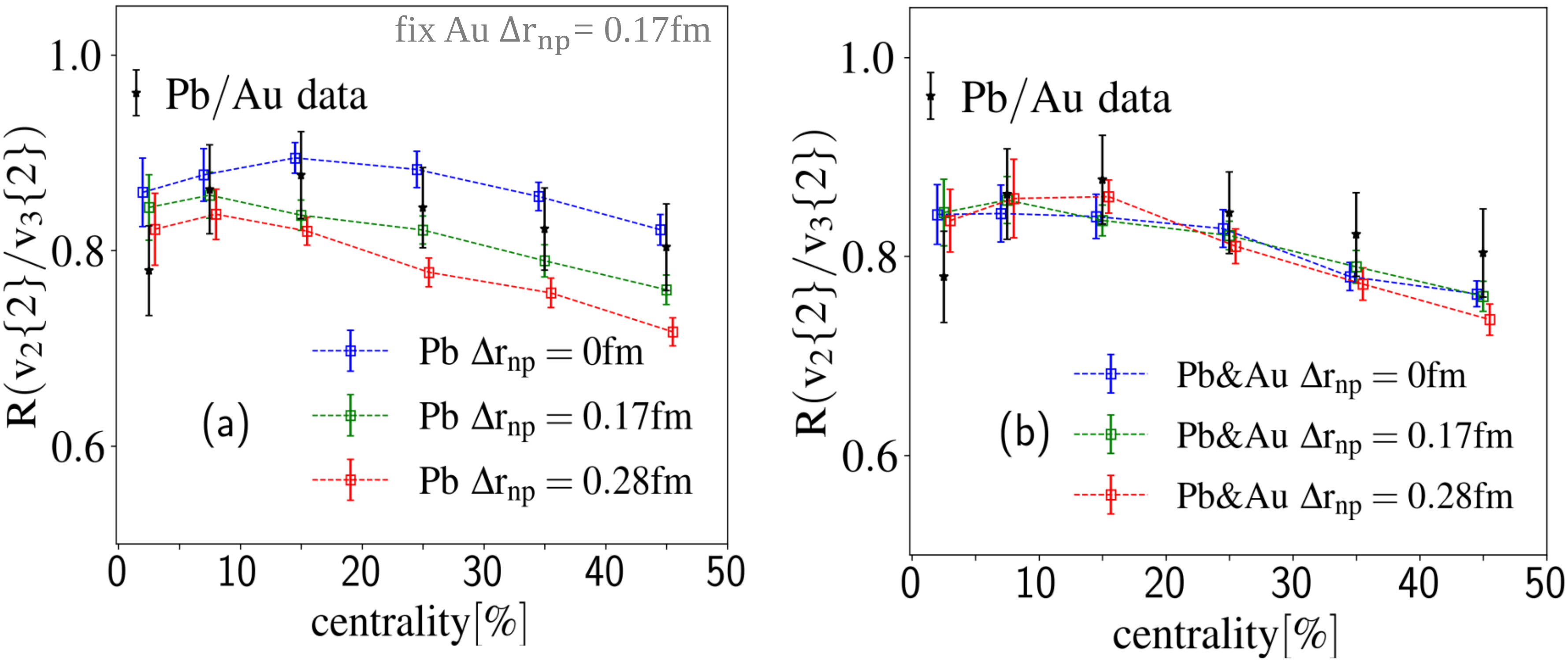
Well calibrated calculations

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



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

semi-isobaric double ratio

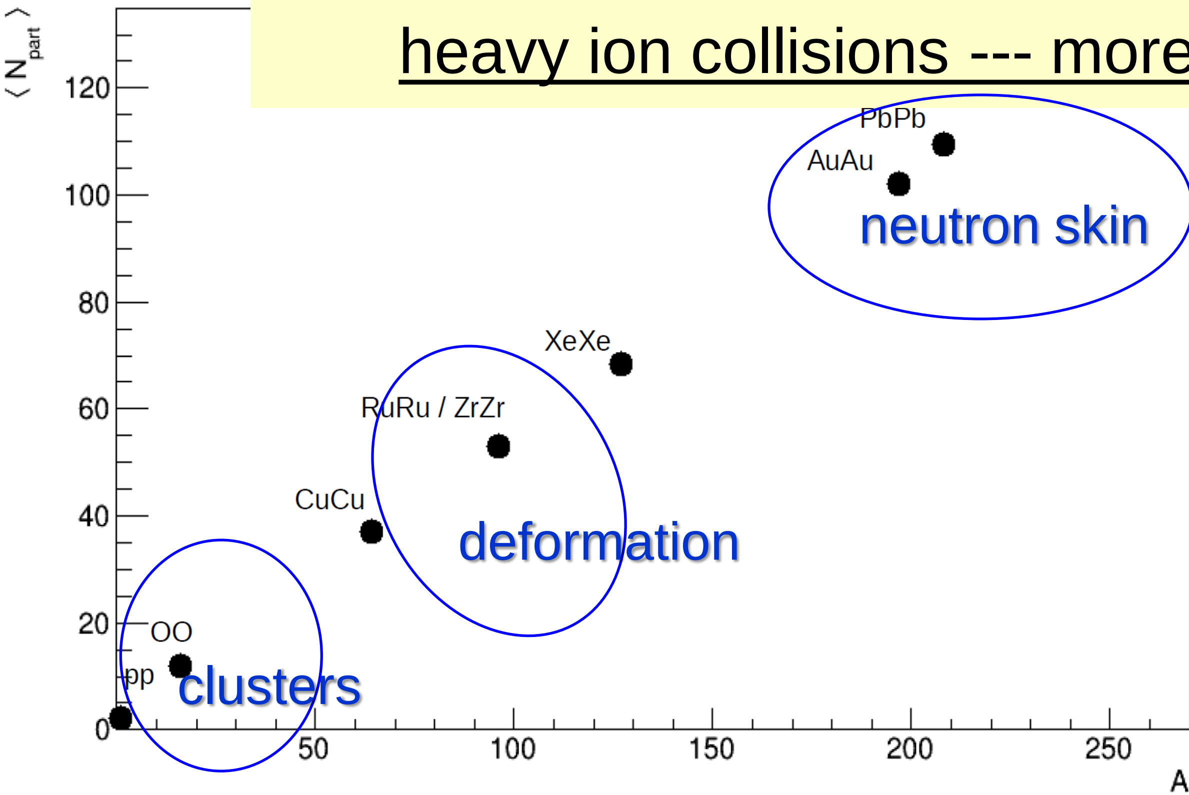


A scaling behavior was found in double ratio of $v_2\{2\}/v_3\{2\}$ when Au and Pb have the neutron skins of the same size,

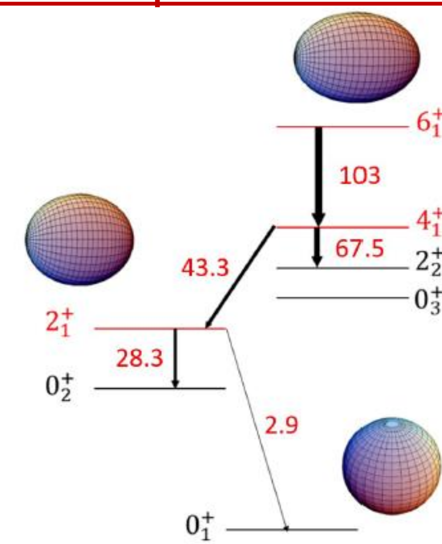
The measured flow harmonics at various centrality suggest Au and Pb have similar neutron skin

Q. Liu, H. Xu and H. Song. arXiv:2311.01747.

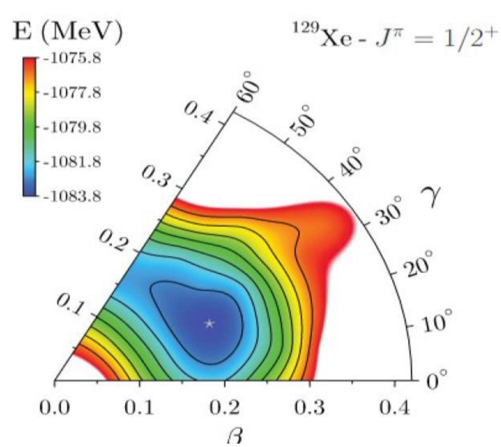
Probing the nuclear structure with relativistic heavy ion collisions --- more to explore

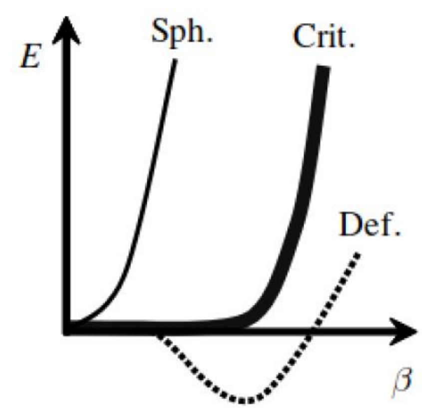


^{96}Zr: shape coexistence



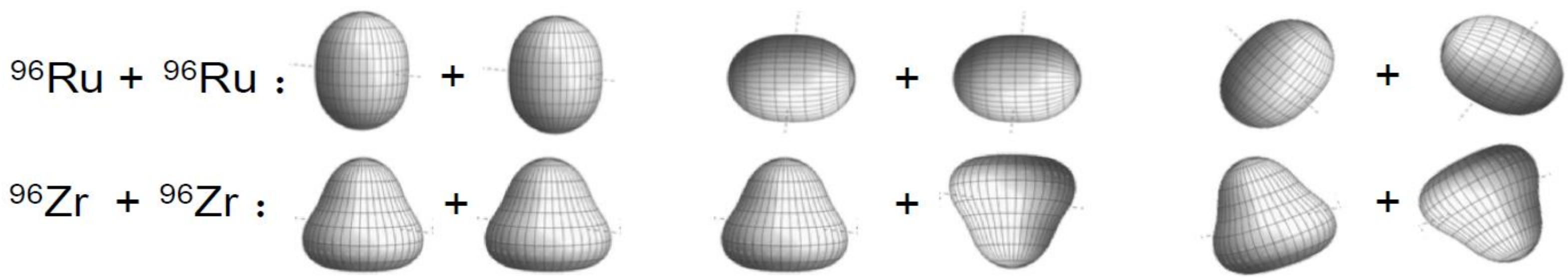
^{129}Xe: γ soft
shape phase transiton

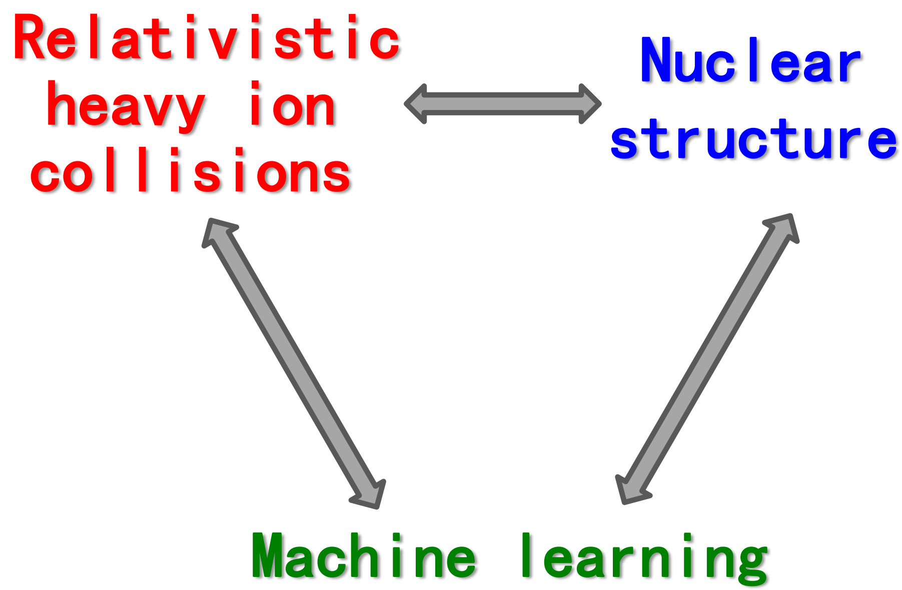




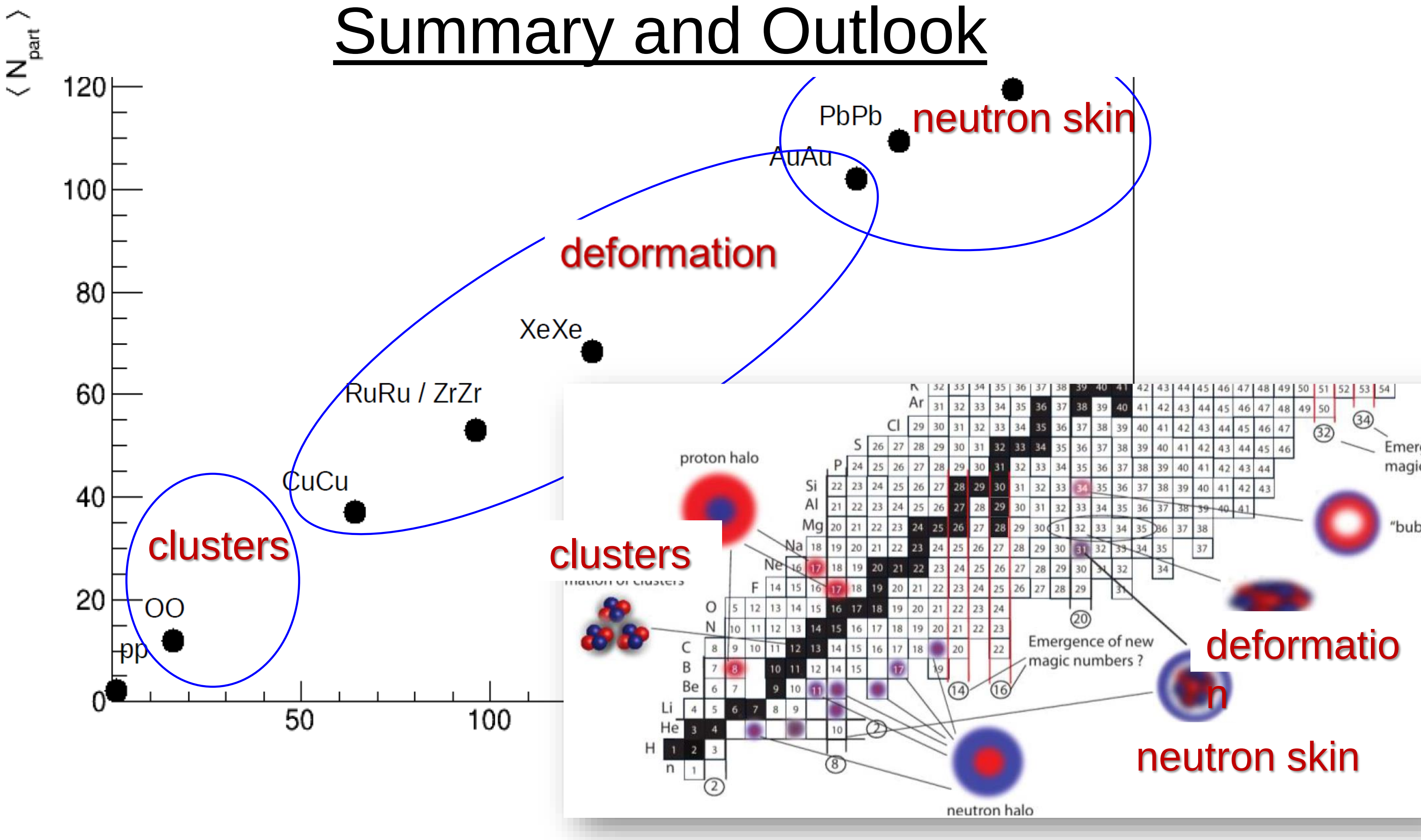
-Nuclear structure: deformation, cluster, neutron skin; shape coexistence, γ-soft (shape phase transition)

-Rich configurations for QGP initial conditions



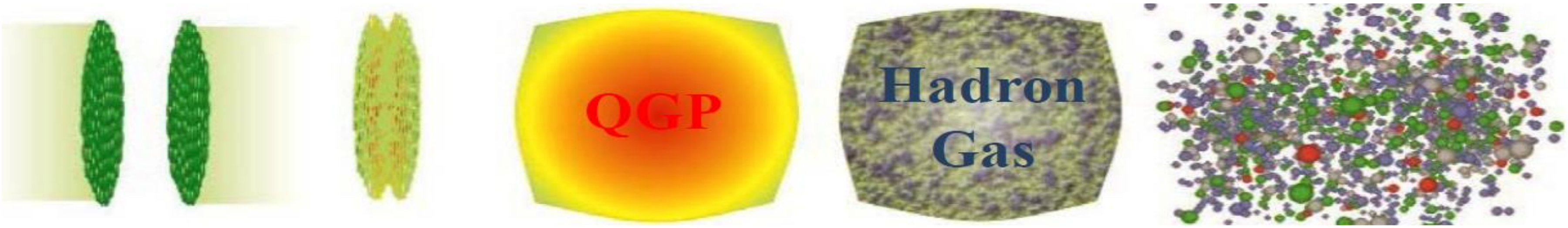


Summary and Outlook



Relativistic heavy ion collisions have already provide rich collision systems to study various aspects in nuclear structure. Even we focus on these several colliding nuclei, there are lots of things to explore !

Summary and Outlook



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

-Over the past 40 years
- -the concept of QGP was proposed
- -the accelerators was built
- -the QGP was discovered
- -the properties of the QGP are being explored

-Put more efforts on initial conditions (nuclear structure aspects)
- -high energy nuclear physics: necessary for a precisely study QGP
- -low energy nuclear physics: new insights for nuclear structure

The future is bright !

Exploring nuclear physics across energy scales
Program + workshop Beijing April 15-28 2024

Program: CCAST April 15-18, 23-28, 2024
seminars + discussions each day
Workshop: CHEP, Peking U. April 19-22, 2024

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高能物理研究中心
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Sectaries:

Lvlv (Peking U)
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Chunxia Zhao(ITP,CAS)
Email: lvlv@pku.edu.cn

CCAST Building

Discussion area

Meeting room

Visitor offices

Exploring nuclear physics across energy scales

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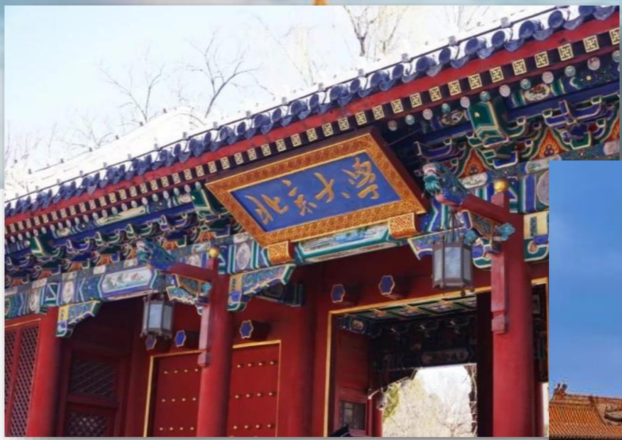

Welcome to Beijing in coming April next year!