Probing the nuclear structure with relativistic heavy ion collisions

宋慧超

北京大学物理学院

原子核结构和高能核核碰撞前沿交叉研讨会

大连 2023年 8月1-5日

08/01/2023

Landscape of nuclear physics

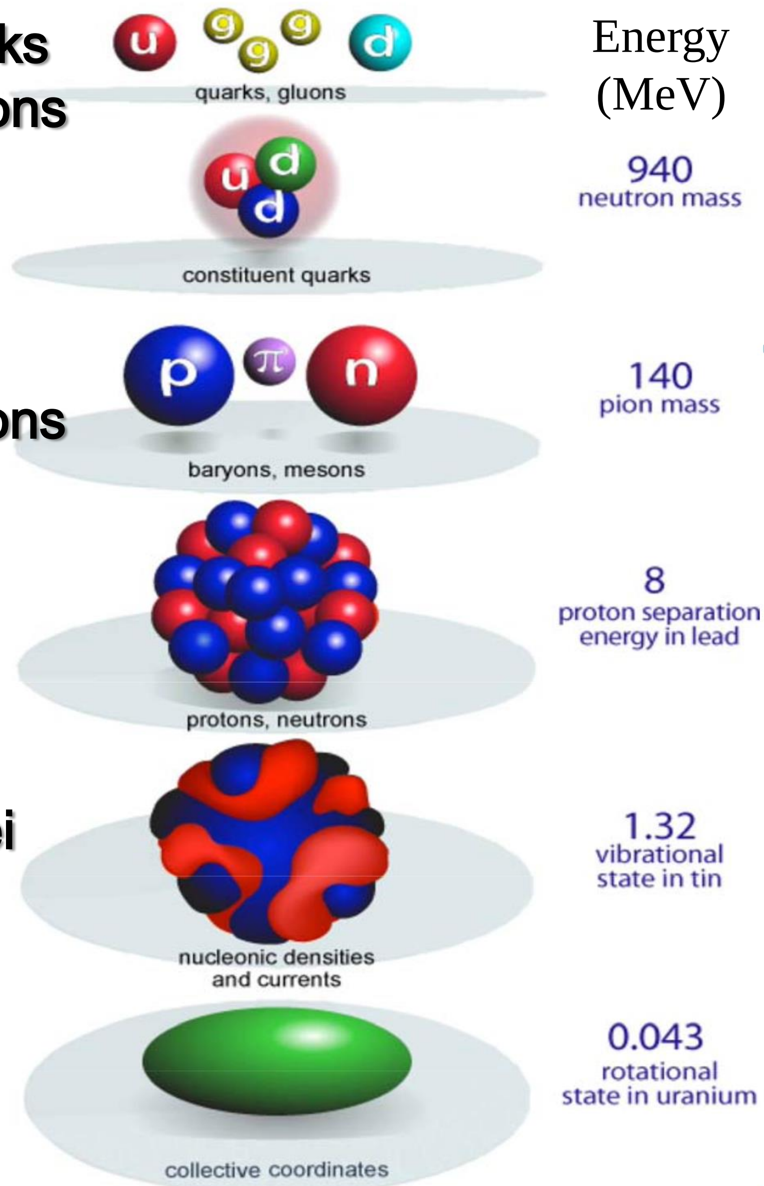
degrees of freedeom

Energy (MeV)

quarks & gluons

hadrons

nuclei



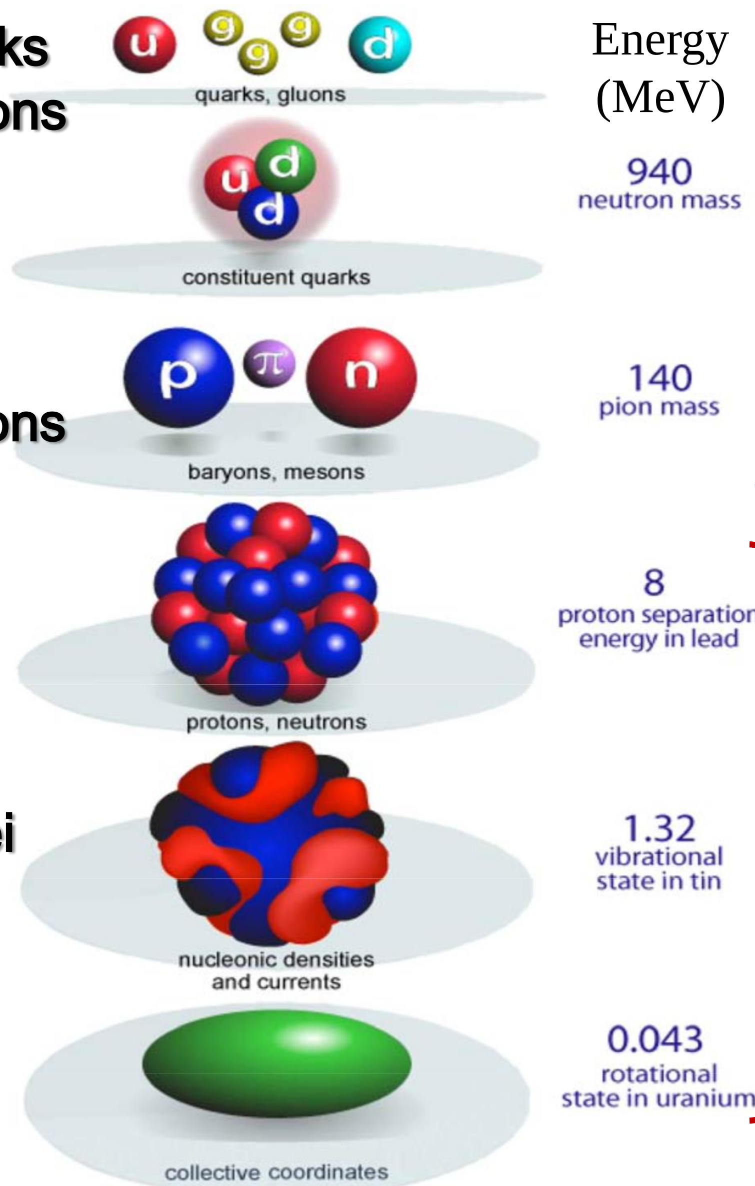
Landscape of nuclear physics

degrees of freedeom

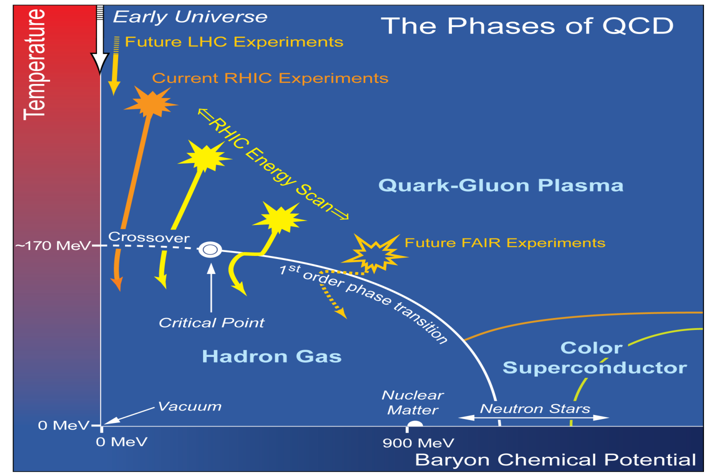
quarks & gluons

hadrons

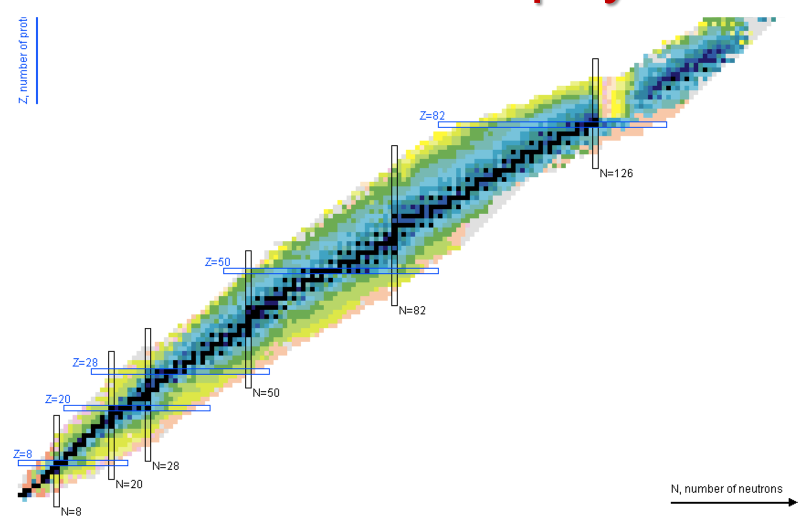
nuclei



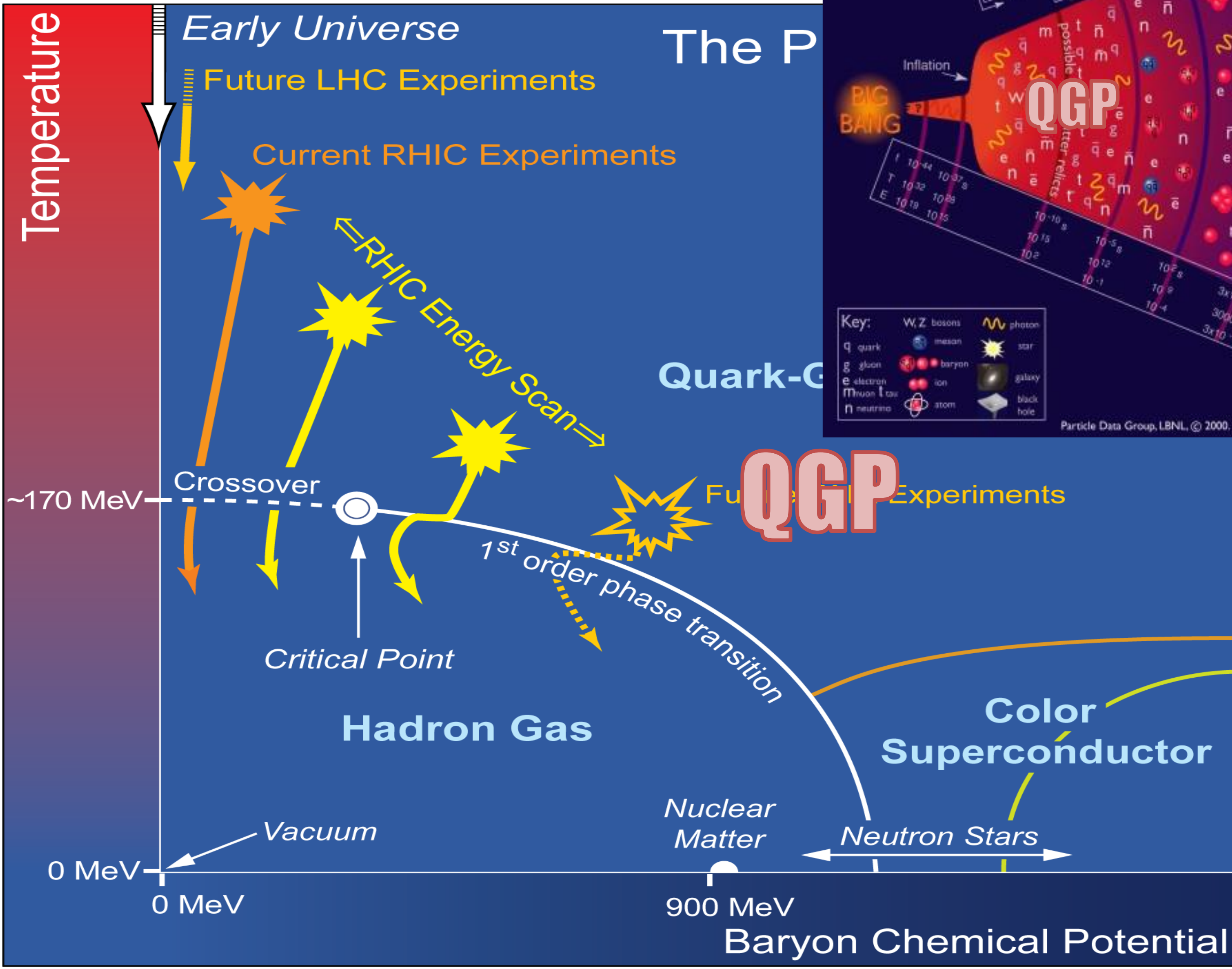
-intermediate and high energy nuclear physics

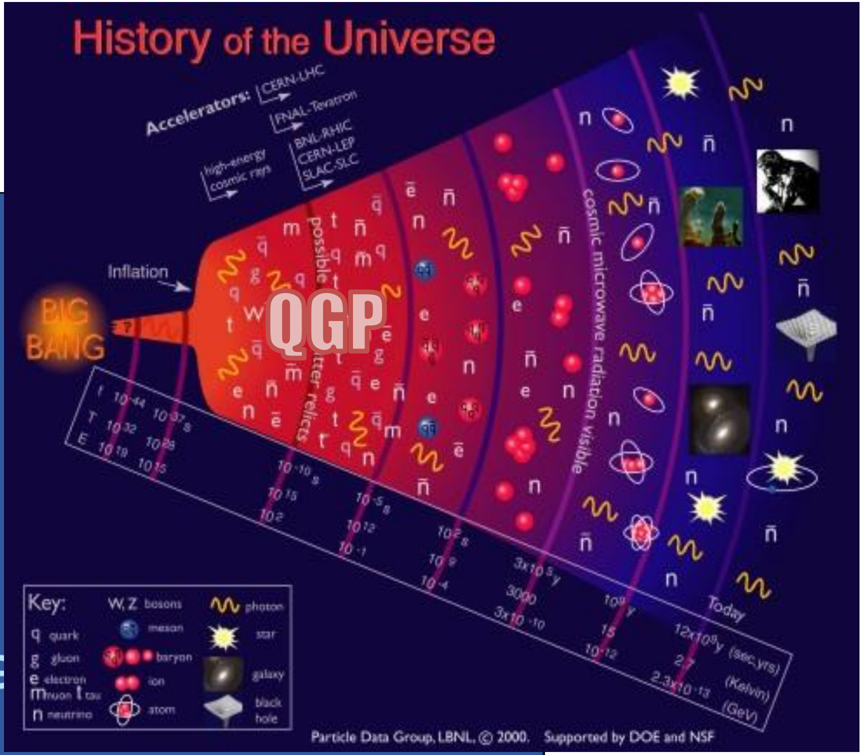


-nuclear structure physics

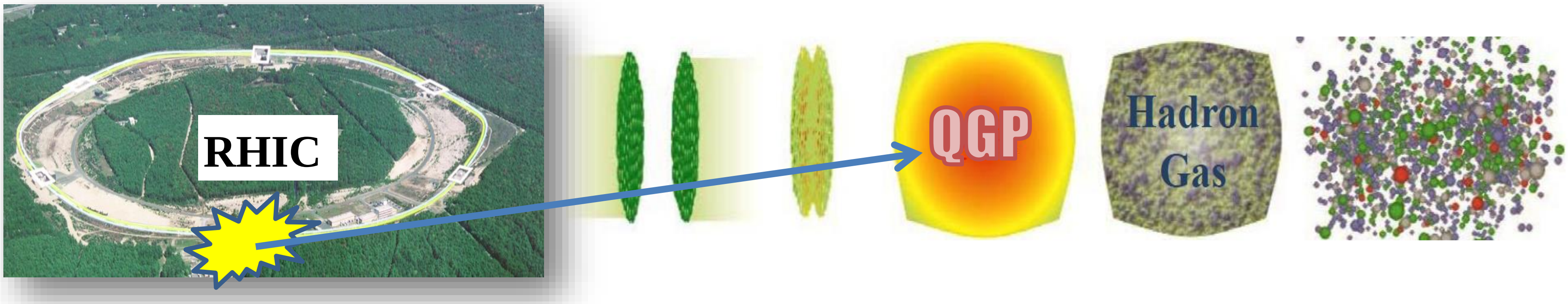


QCD phase diagram





Relativistic Heavy Ion Collisions



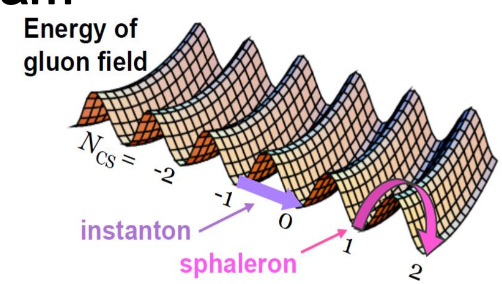
<u>Relativistic heavy ion collisions</u>

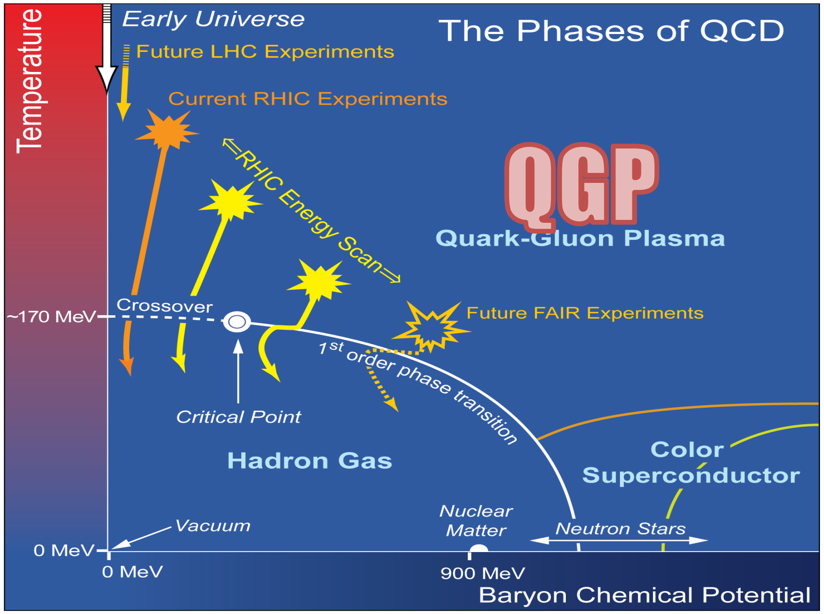
-the formation and properties of QGP,

-the deconfinement & chiral phase transition

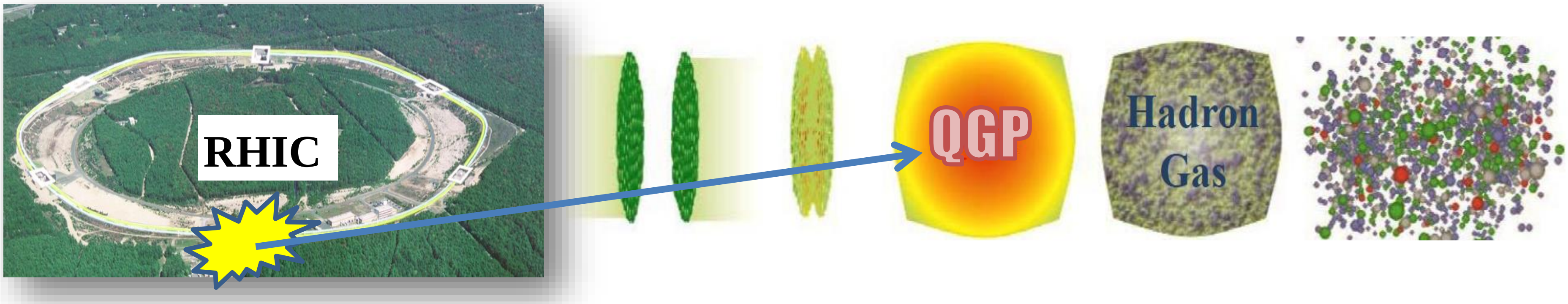
-the QCD phase diagram

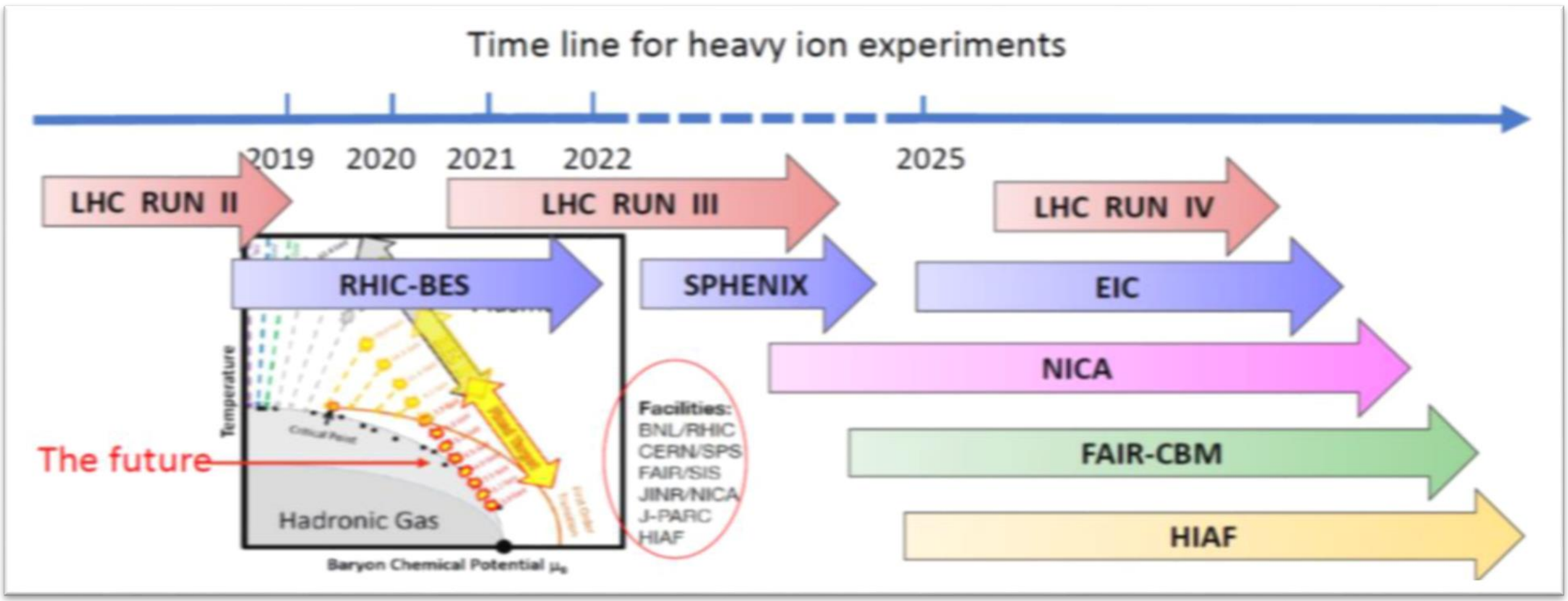
-the QCD vacuum





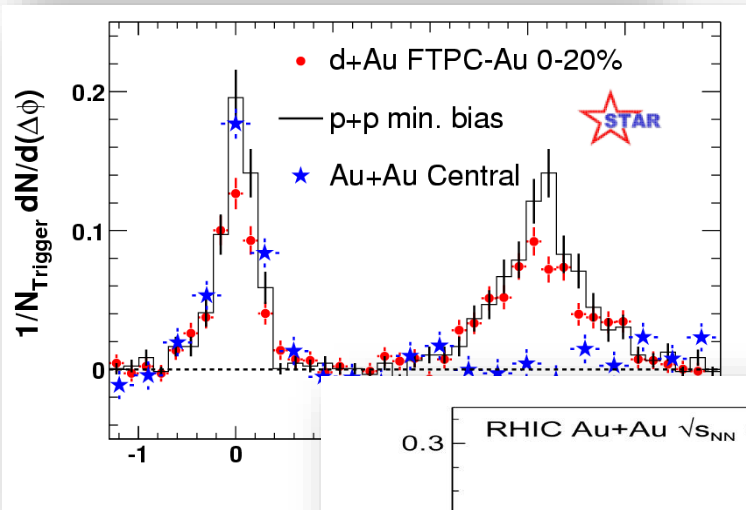
Relativistic Heavy Ion Collisions

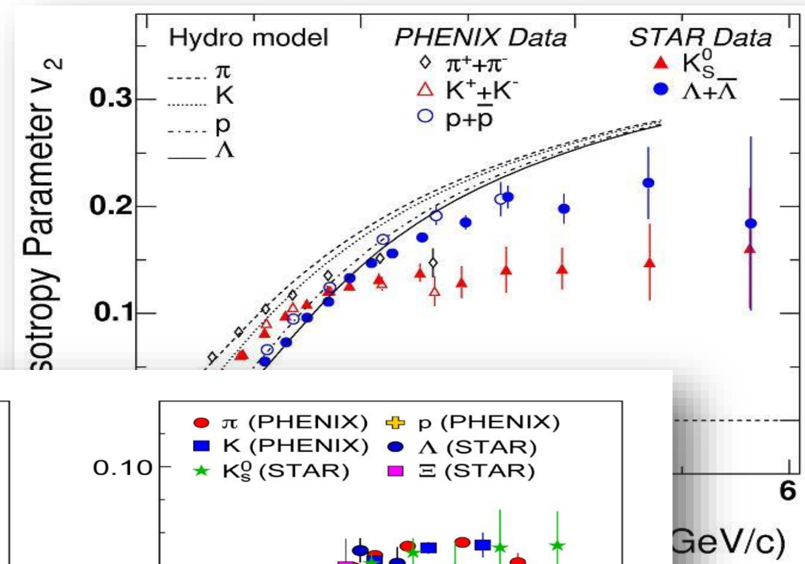


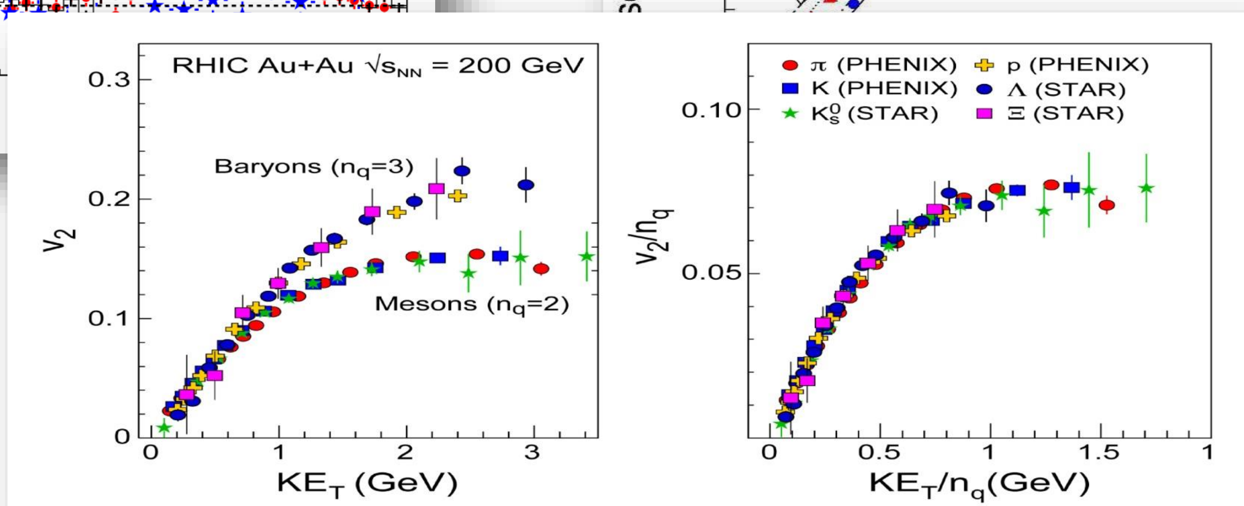


The formation of the QGP

The QGP have been created at RHIC & the LHC







QGP evolution -Viscous hydrodynamics

Conservation laws:

$$\partial_\mu T^{\mu\nu}(x) = 0 . \qquad \partial_\mu N_i^\mu(x) = 0 ,$$

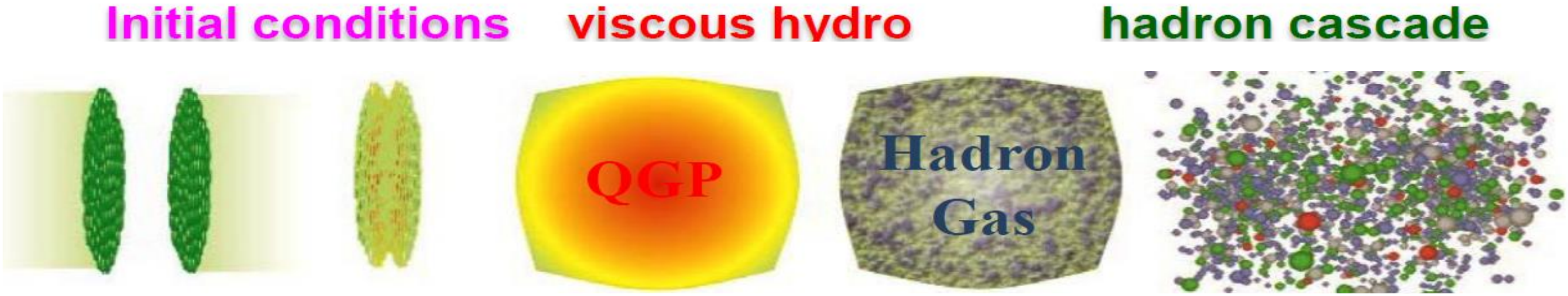
2nd order I-S equ:

$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta - l_{\Pi q}\nabla_\mu q^\mu + \Pi\zeta T\partial_\mu\left(\frac{\tau_\Pi u^\mu}{2\zeta T}\right)\right],$$

$$\Delta^\mu_\nu \dot{q}^\nu = -\frac{1}{\tau_q}\left[q_\mu + \lambda\frac{nT^2}{e+p}\nabla^\mu\frac{\nu}{T} + l_{q\pi}\nabla_\nu\pi^{\mu\nu} + l_{q\Pi}\nabla^\mu\Pi - \lambda T^2 q^\mu\partial_\mu\left(\frac{\tau_q u^\mu}{2\lambda T^2}\right)\right],$$

$$\Delta^{\mu\alpha}\Delta^{\nu\beta}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle} - l_{\pi q}\nabla^{\langle\mu}q^{\nu\rangle} + \pi_{\mu\nu}\eta T\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{2\eta T}\right)\right],$$

Input: “EOS” $\boldsymbol{\varepsilon = \varepsilon(p)}$ initial and final conditions



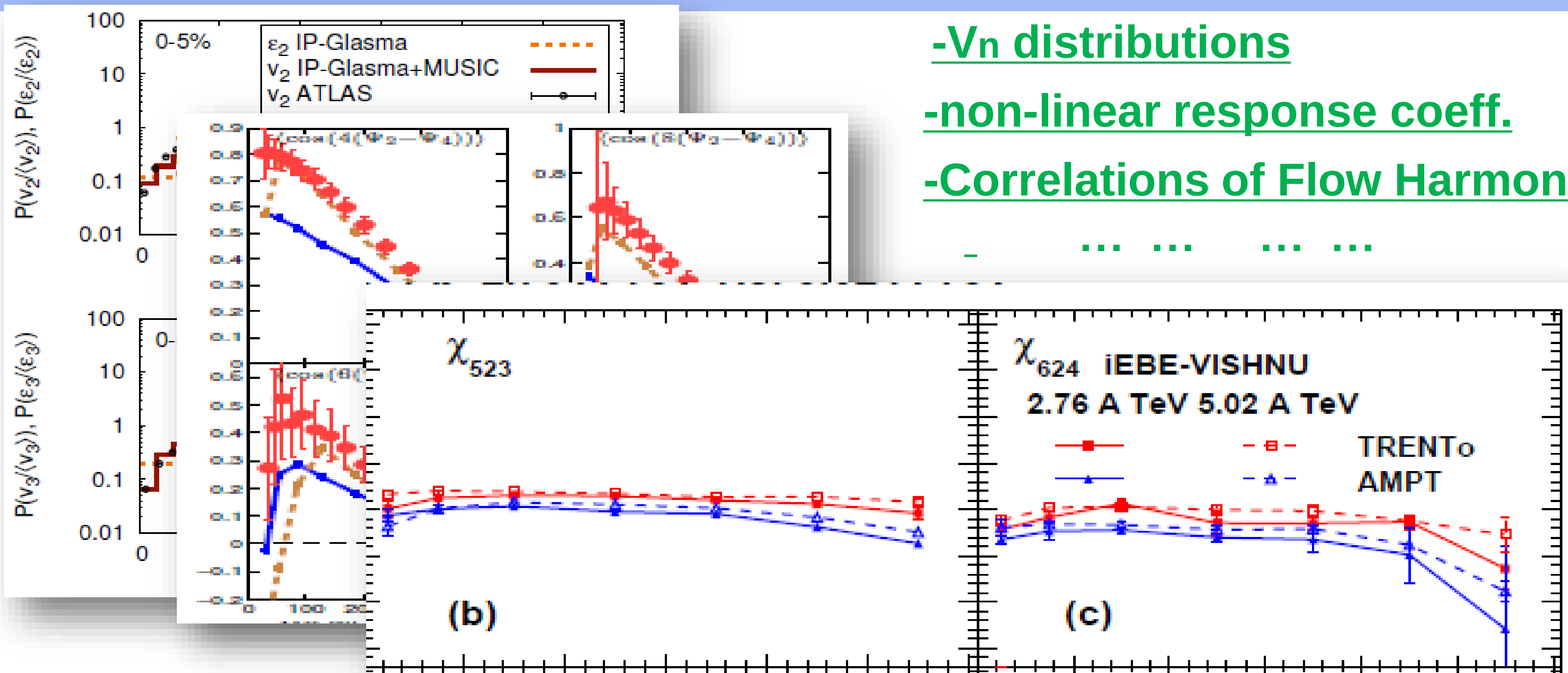
Predictions power of hydrodynamics

-Vn distributions

-non-linear response coeff.

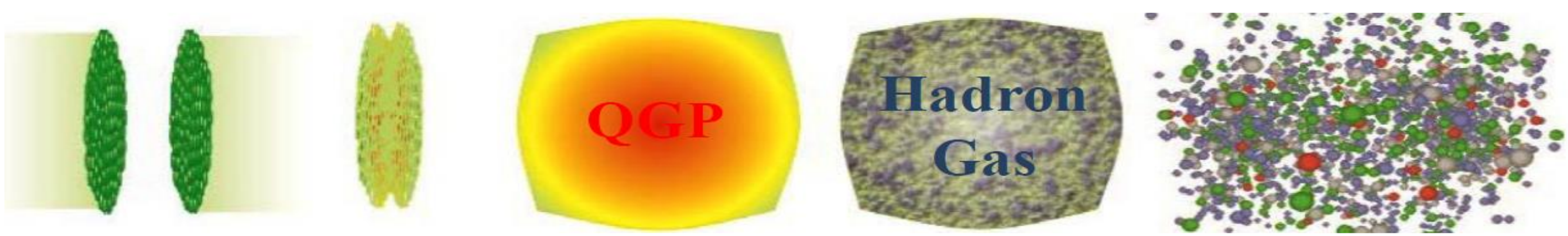
-Correlations of Flow Harmonics

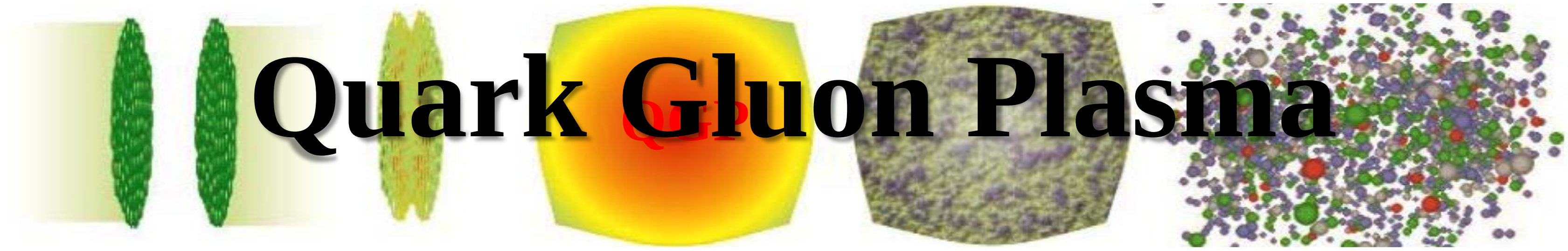
- … … … …



Well calibrated calculations

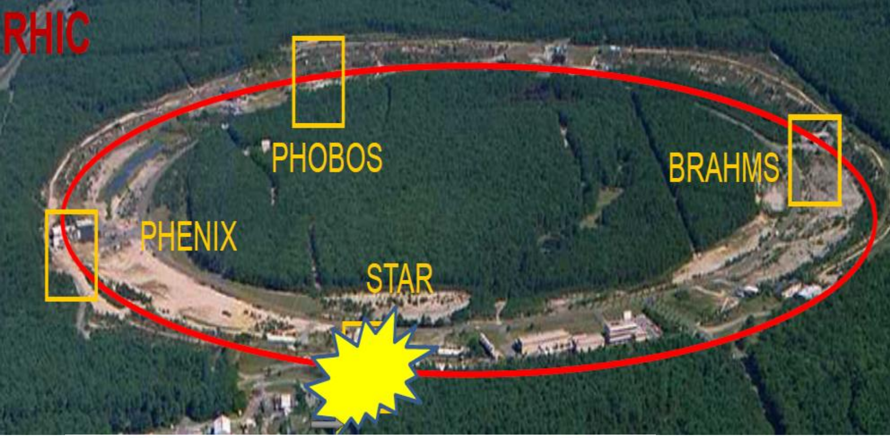
Initial conditions viscous hydro hadron cascade

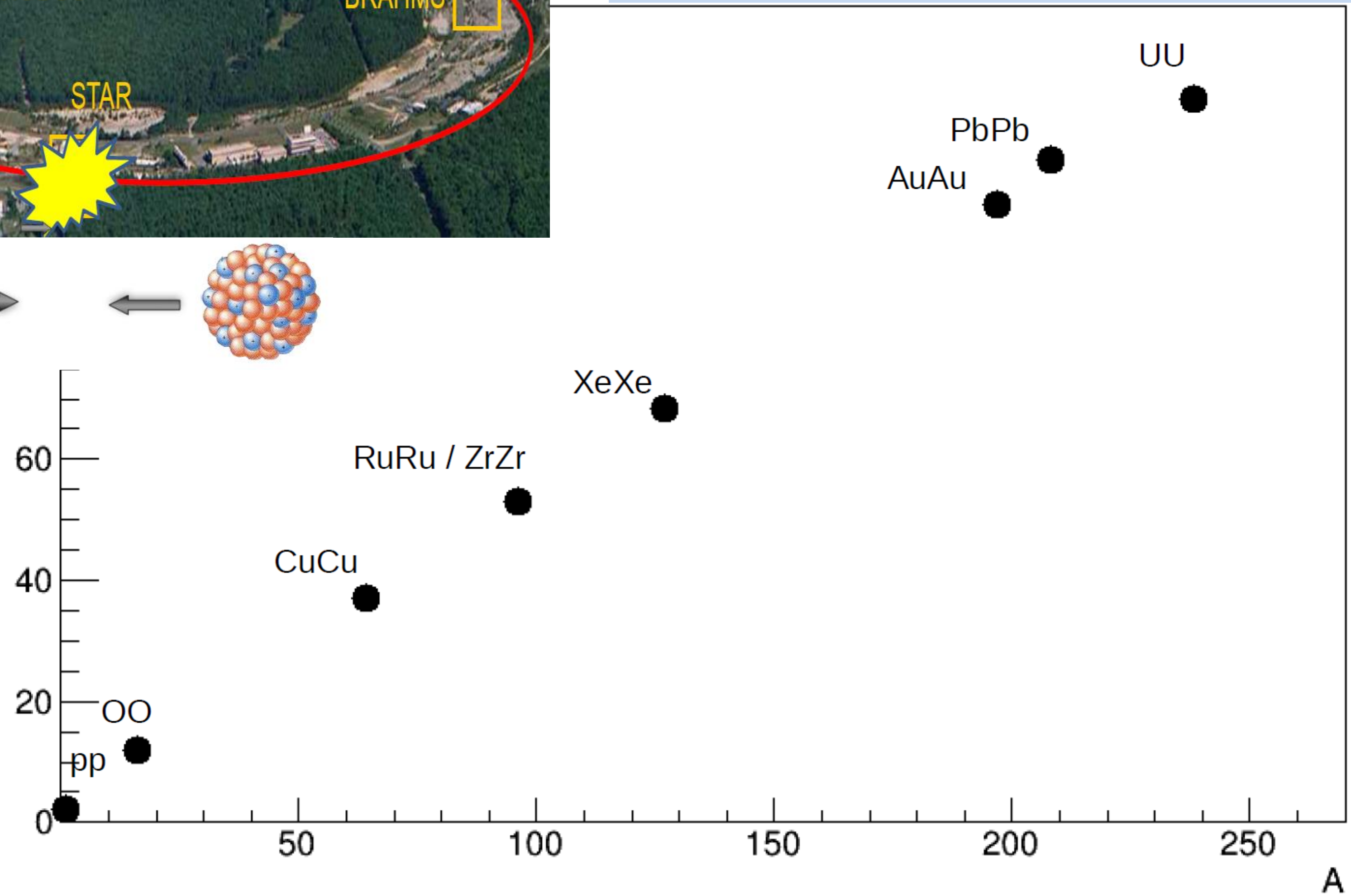




Hottest Matter on Earth

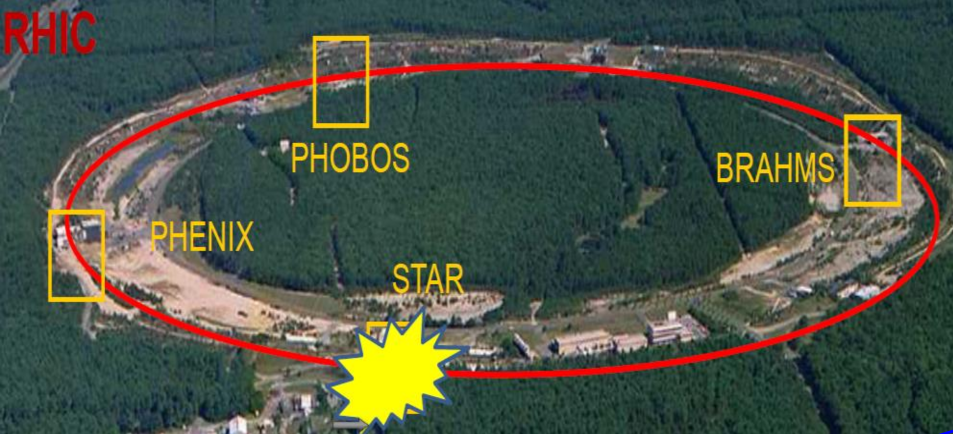
Rich collisions systems at RHIC & the LHC

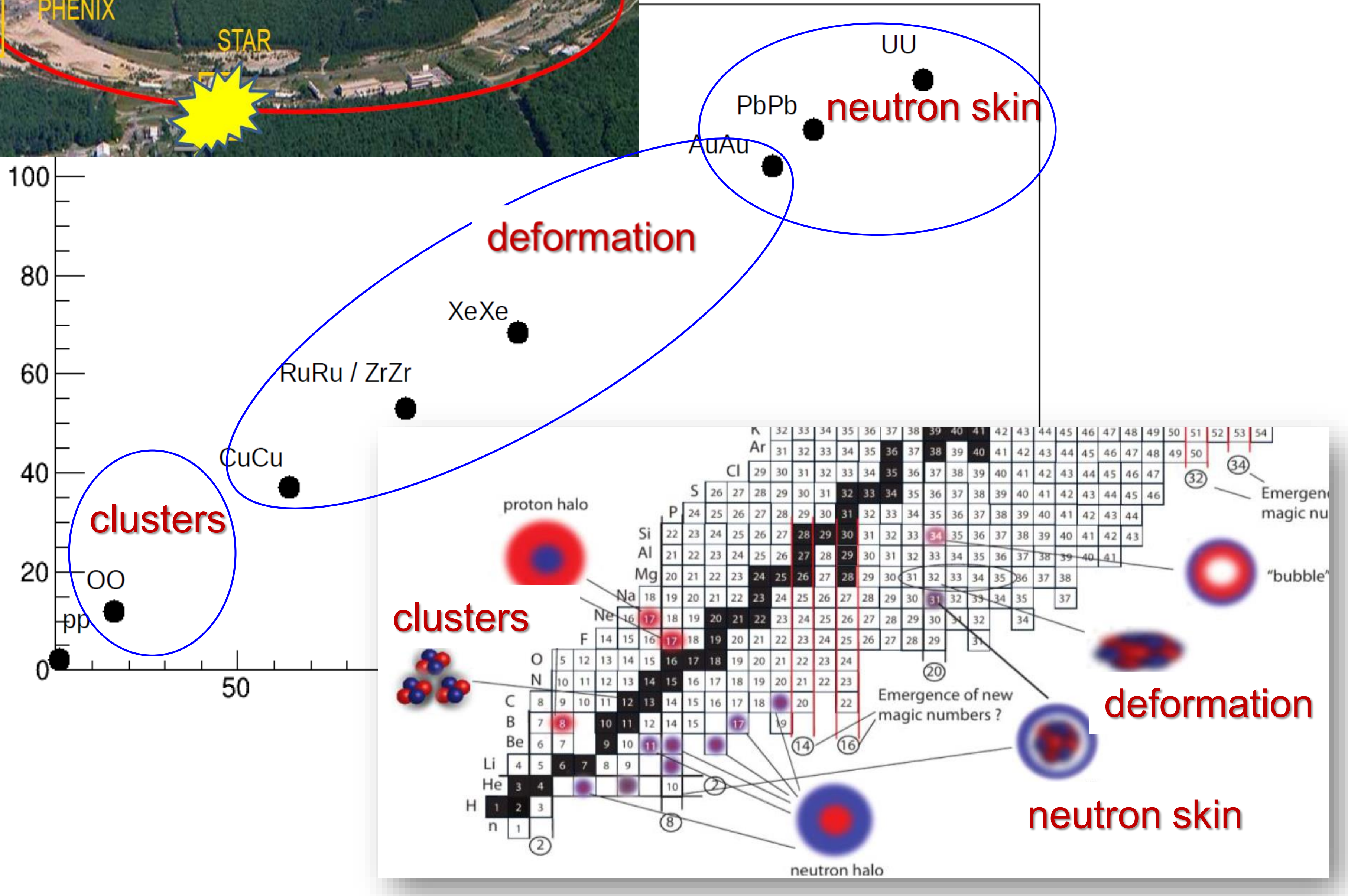




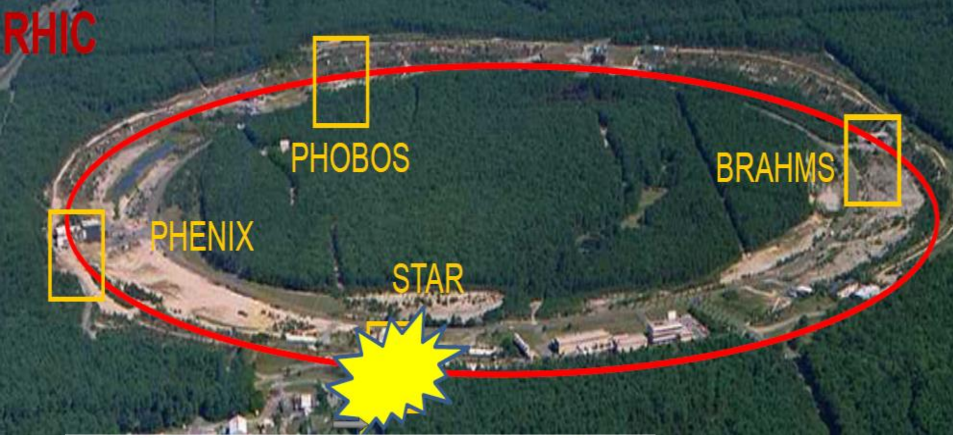
^{197}Au+^{197}Au、^{238}U+^{238}U、^{208}Pb+^{208}Pb、^{129}Xe+^{129}Xe、^{96}Zr+^{96}Zr、^{96}Ru+^{96}Ru、^{64}Cu+^{64}Cu 、 ^{16}O+^{16}O 、p+^{208}Pb、p+p … …

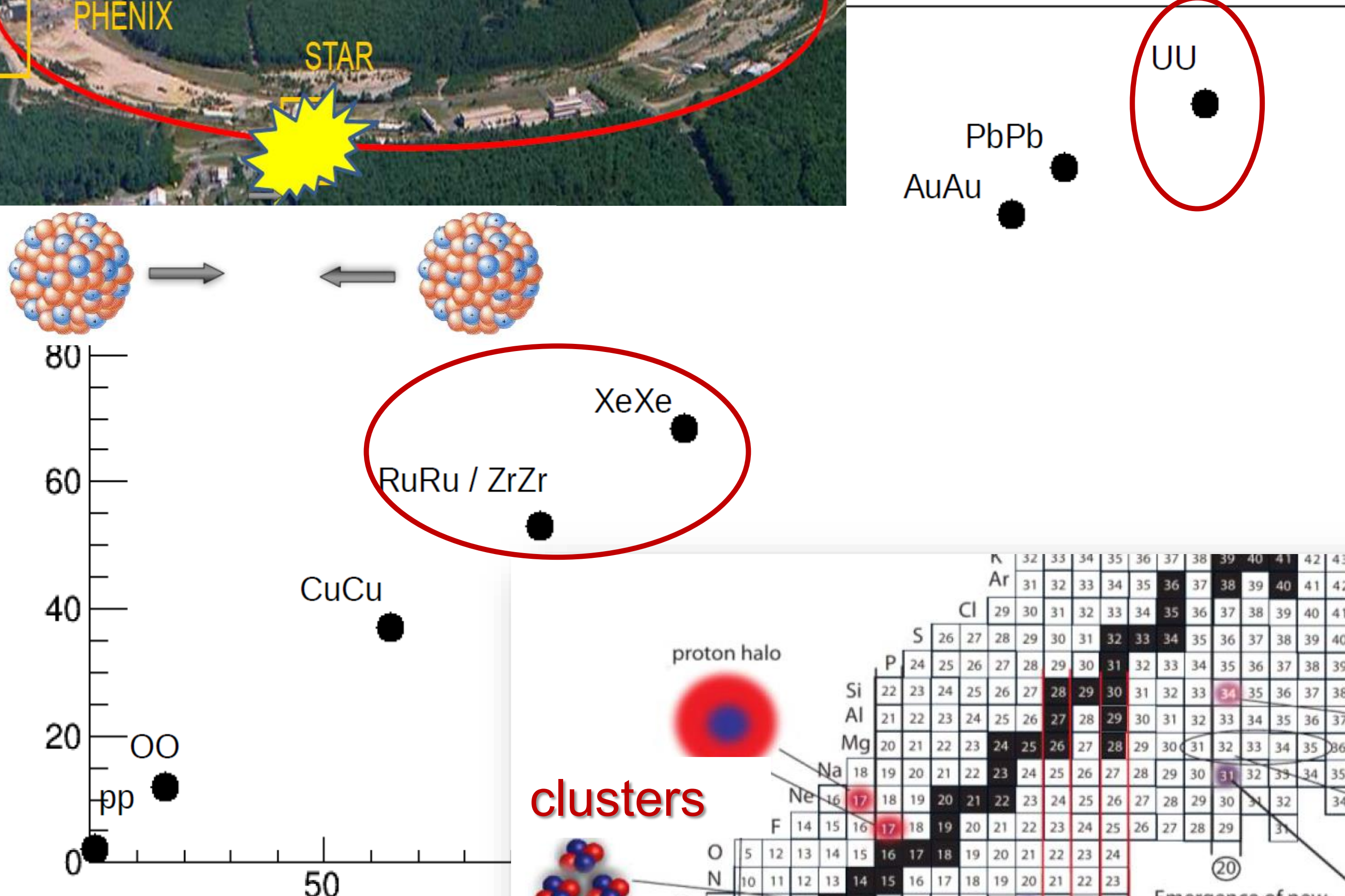
High energy nucleon nucleon collisions & nuclear structure

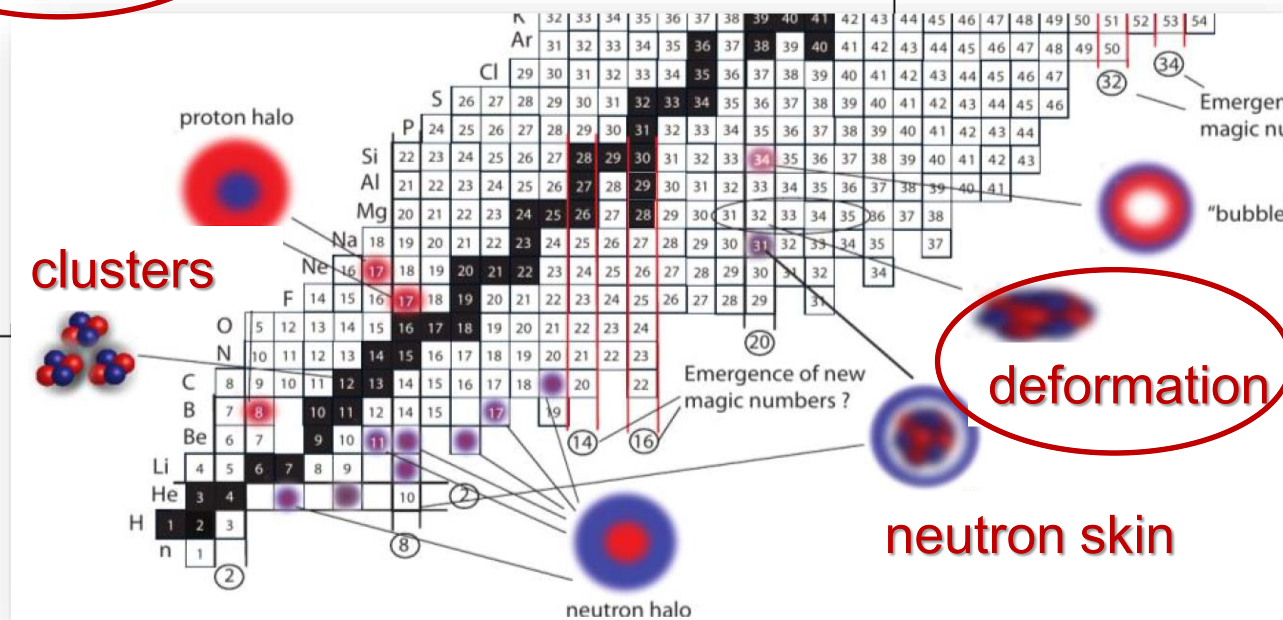


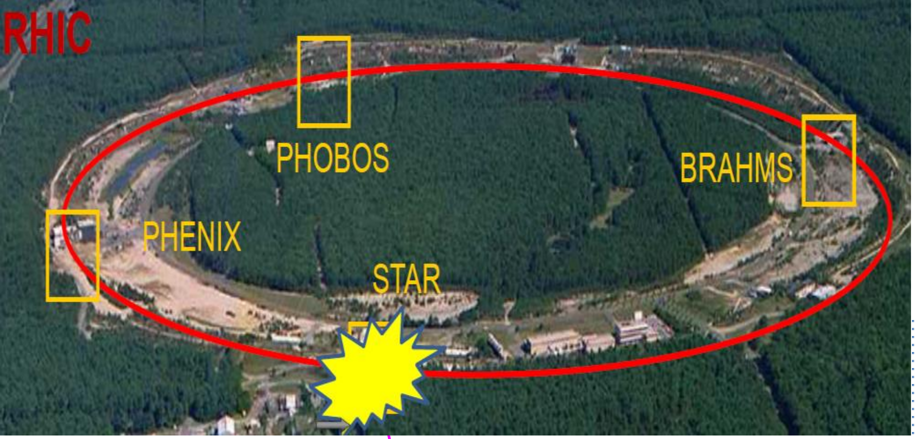


Relativistic heavy ion collision can directly probe the deformation of nuclei



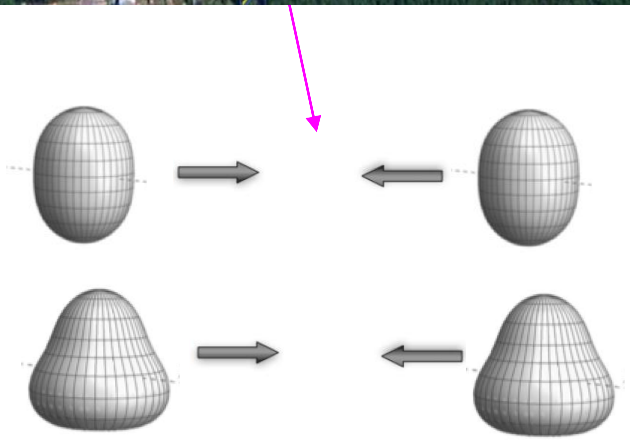




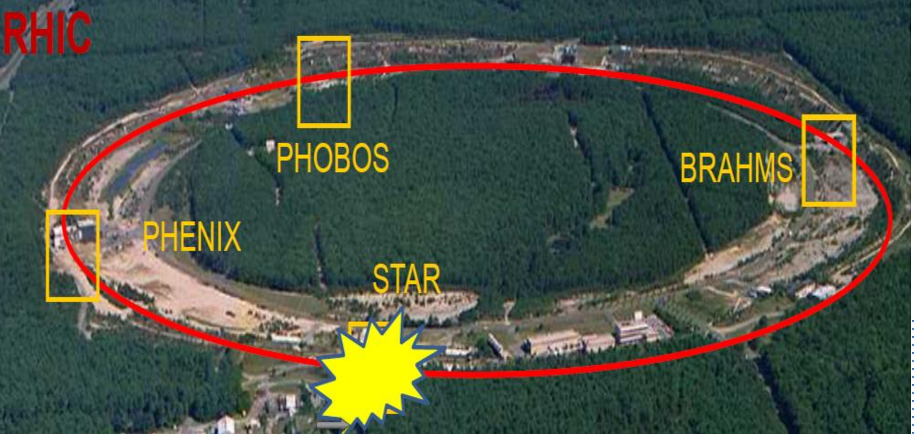


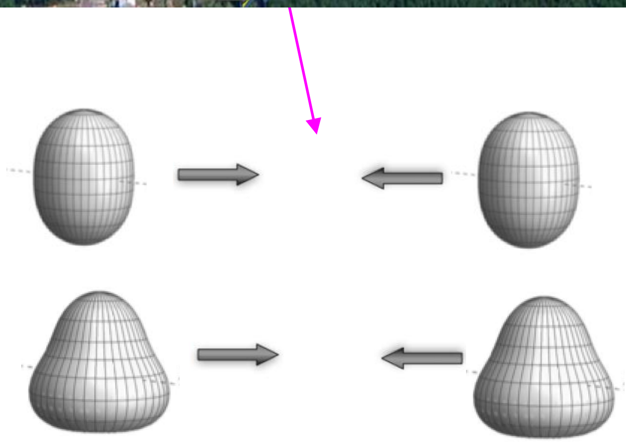
Relativistic heavy ion collision can directly probe the deformation of nuclei

- Relativistic heavy collisions start from nuclei



initial conditions:
(with deformations)



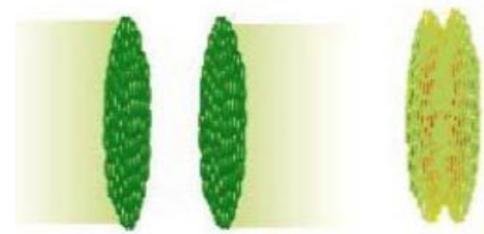


initial conditions:
(with deformations)

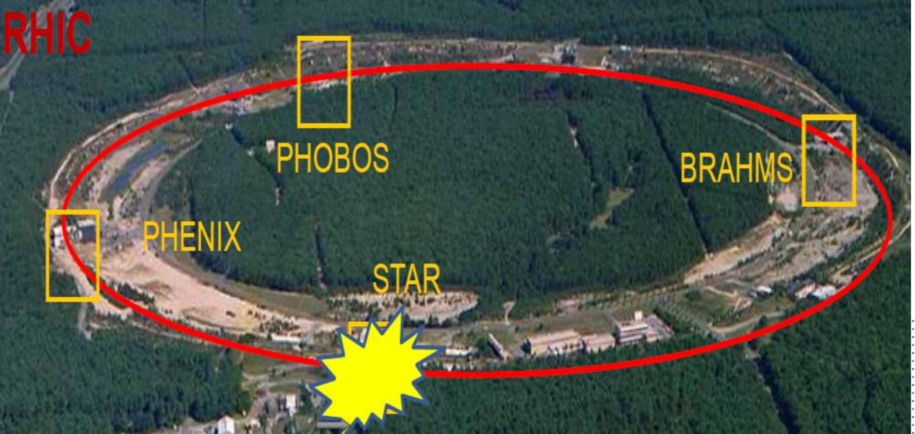
Relativistic heavy ion collision can directly probe the deformation of nuclei

- Relativistic heavy collisions
  start from nuclei

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



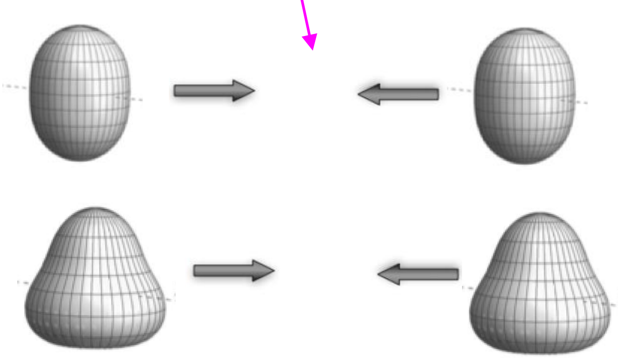
Collision time < 10^{-24} s



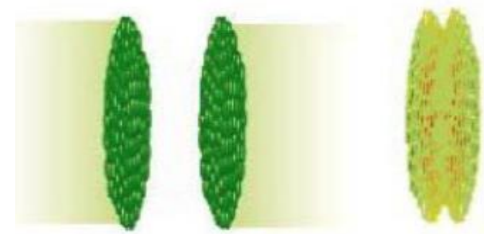
Relativistic heavy ion collision can directly probe the deformation of nuclei

- Relativistic heavy collisions start from nuclei

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

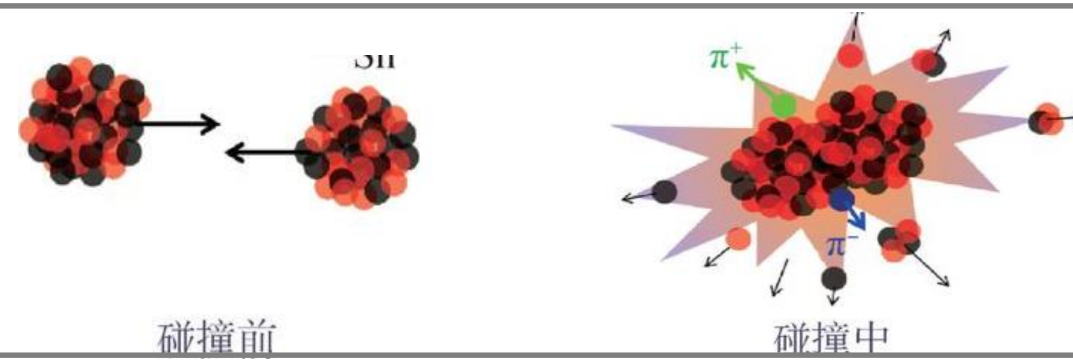


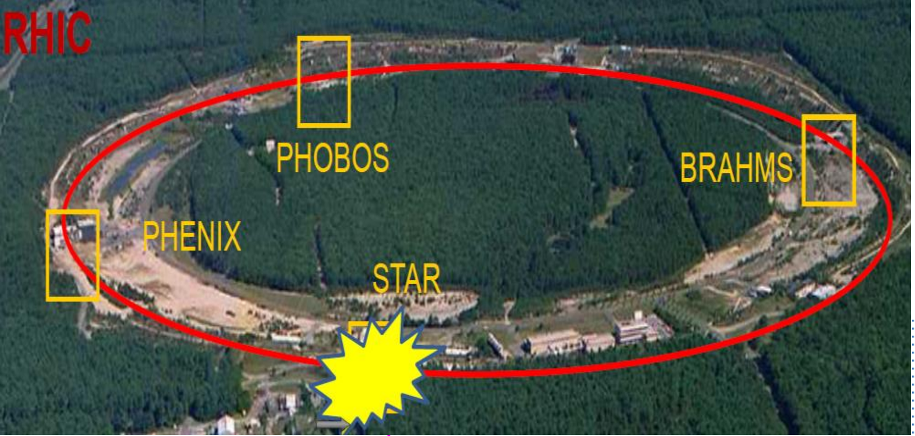
initial conditions: (with deformations)



Collision time < 10^{-24} s

heavy ion collision at intermediate energies excites nuclei during the collision



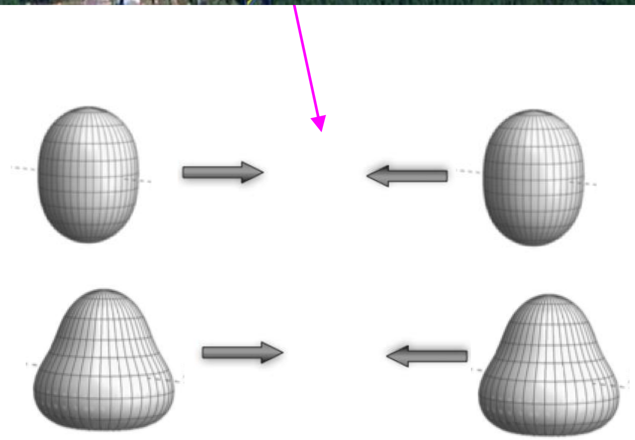


Relativistic heavy ion collision can directly probe the deformation of nuclei

- Relativistic heavy collisions
  start from nuclei

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

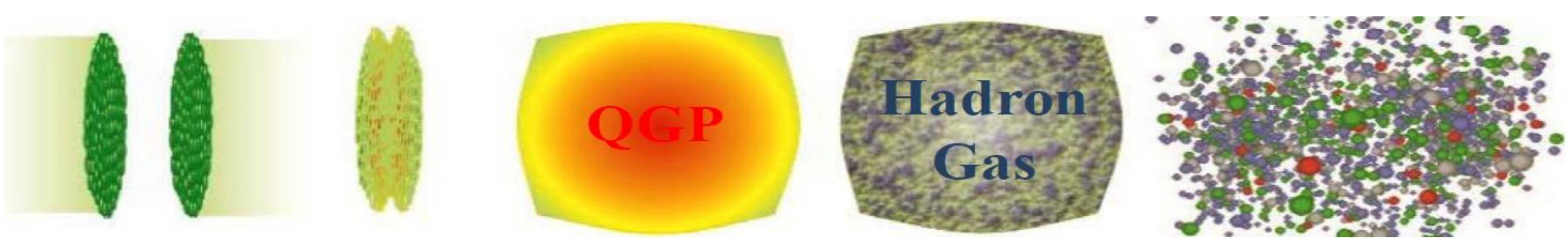
-Well calibrated calculations
  to focus on the initial state effects from the succeeding evolution



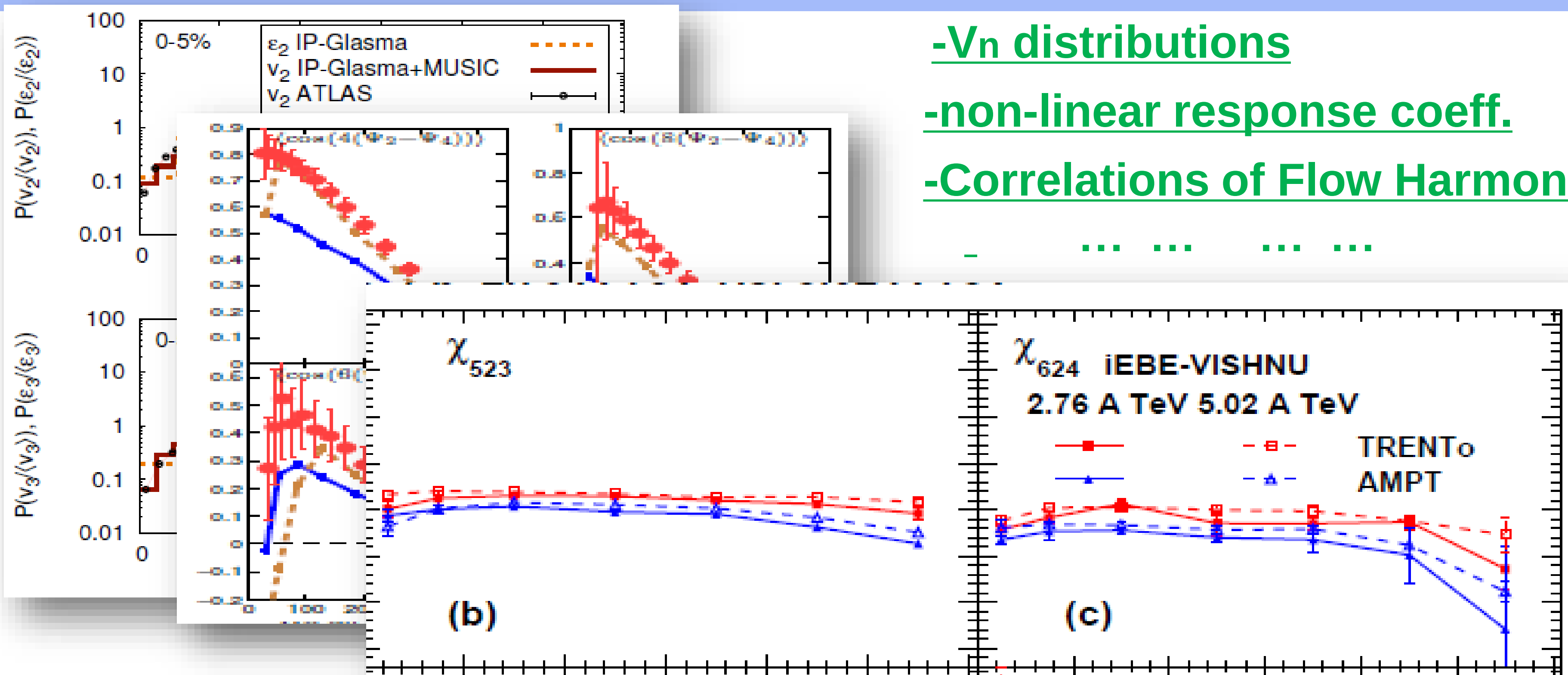
initial conditions:
(with deformations)

Well calibrated calculations

Initial conditions   viscous hydro   hadron cascade



Predictions power of hydrodynamics



-Vn distributions

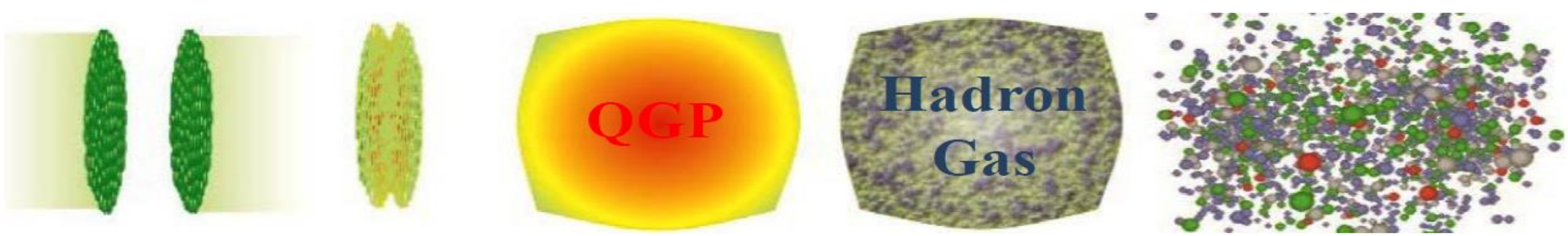
-non-linear response coeff.

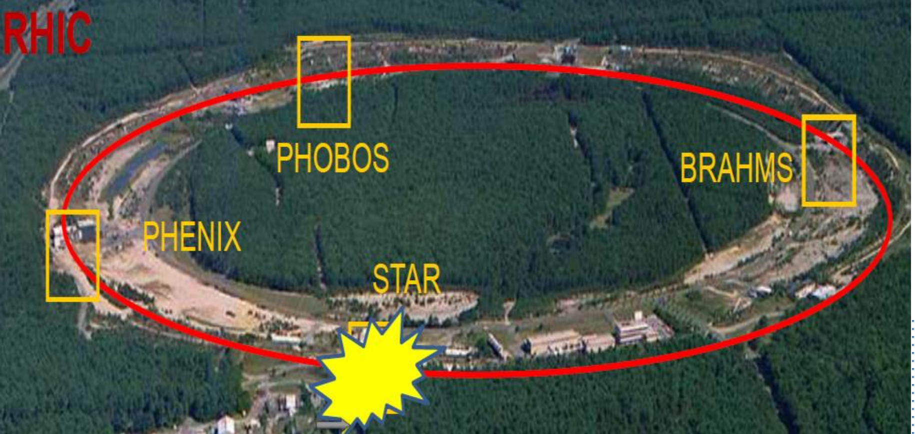
-Correlations of Flow Harmonics

- … … … …

Well calibrated calculations

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



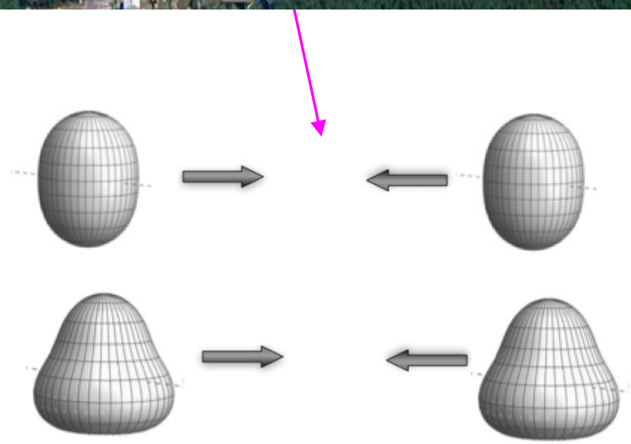


Relativistic heavy ion collision can directly probe the deformation of nuclei

- Relativistic heavy collisions
  start from nuclei

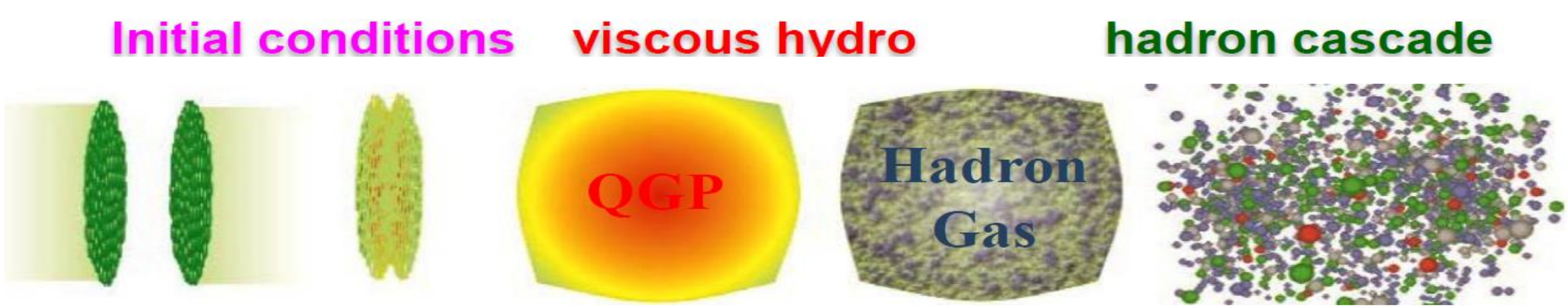
-Collision time < 10^{-24} s
  directly probe the ground state of nuclei

-Well calibrated calculations
  to focus on the initial state effects from the succeeding evolution

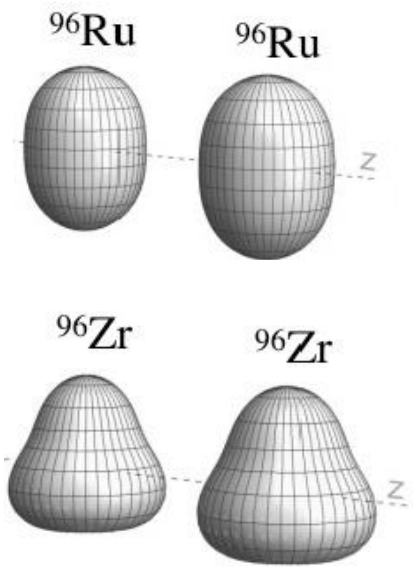


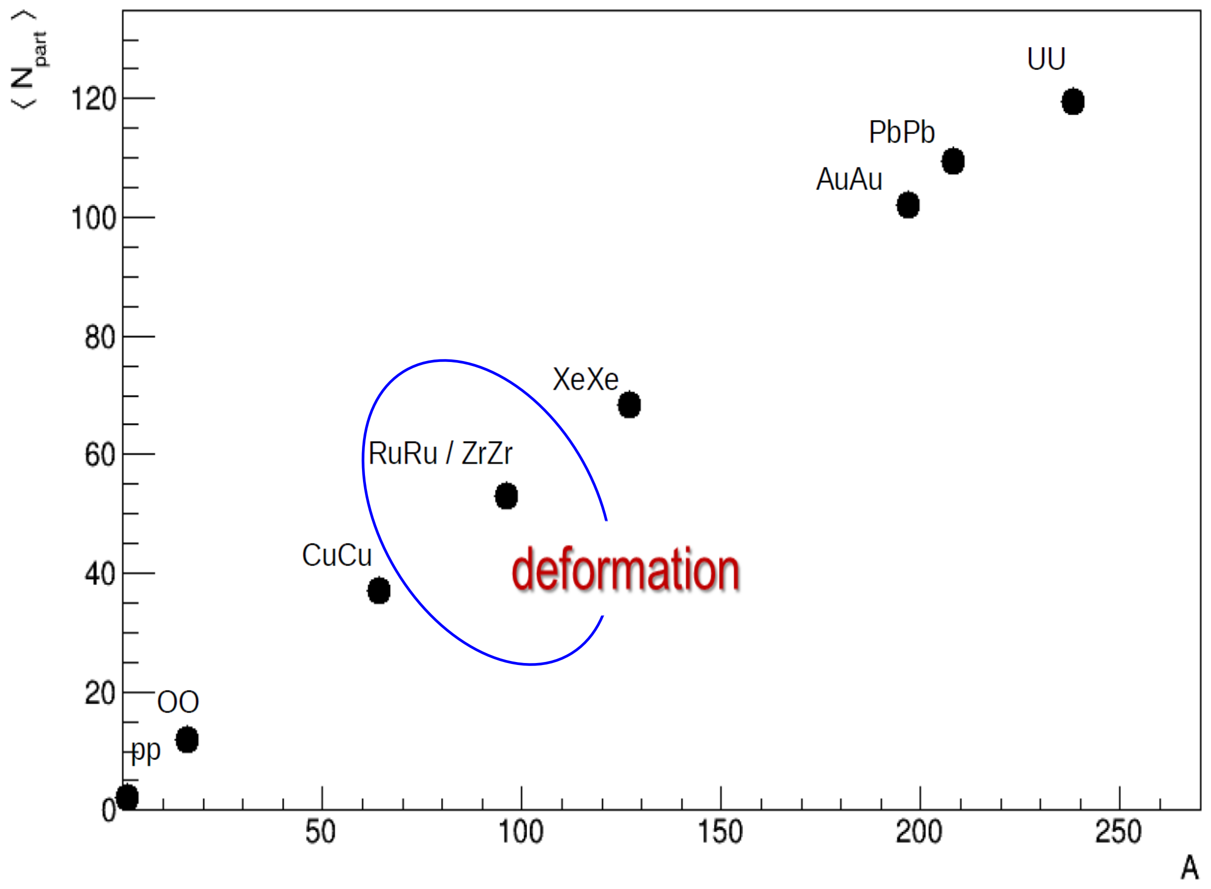
initial conditions:
(with deformations)

Well calibrated calculations

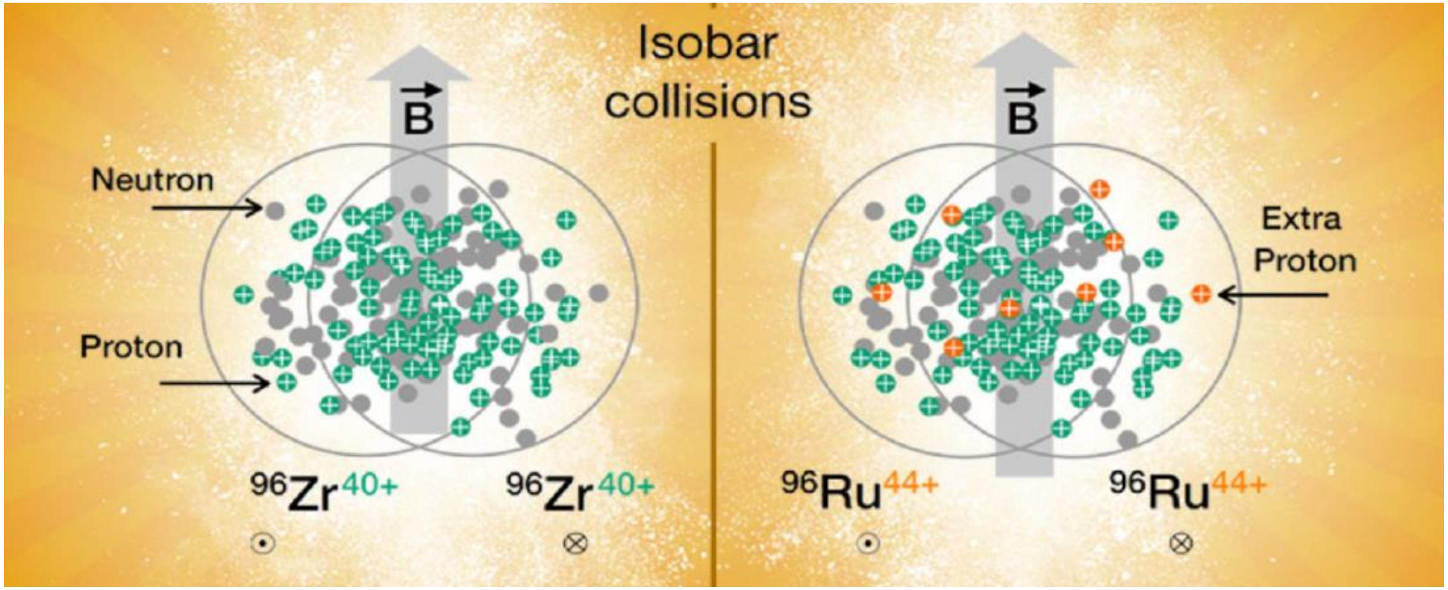


Probe the deformation of ^{96}Ru and ^{96}Zr at RHIC isobar run



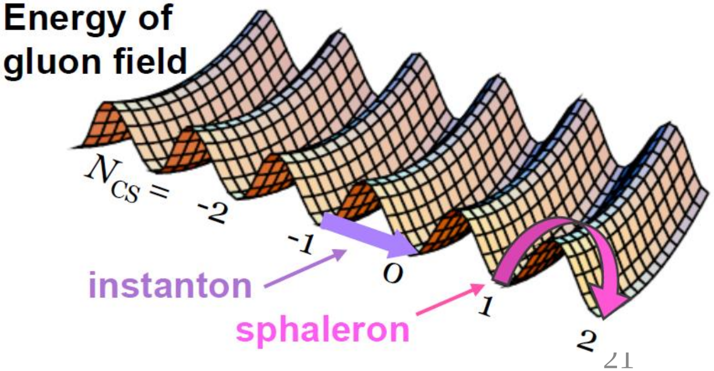


$^{96}Ru+^{96}Ru$ and $^{96}Zr+^{96}Zr$ Collisions @ RHIC isobar run

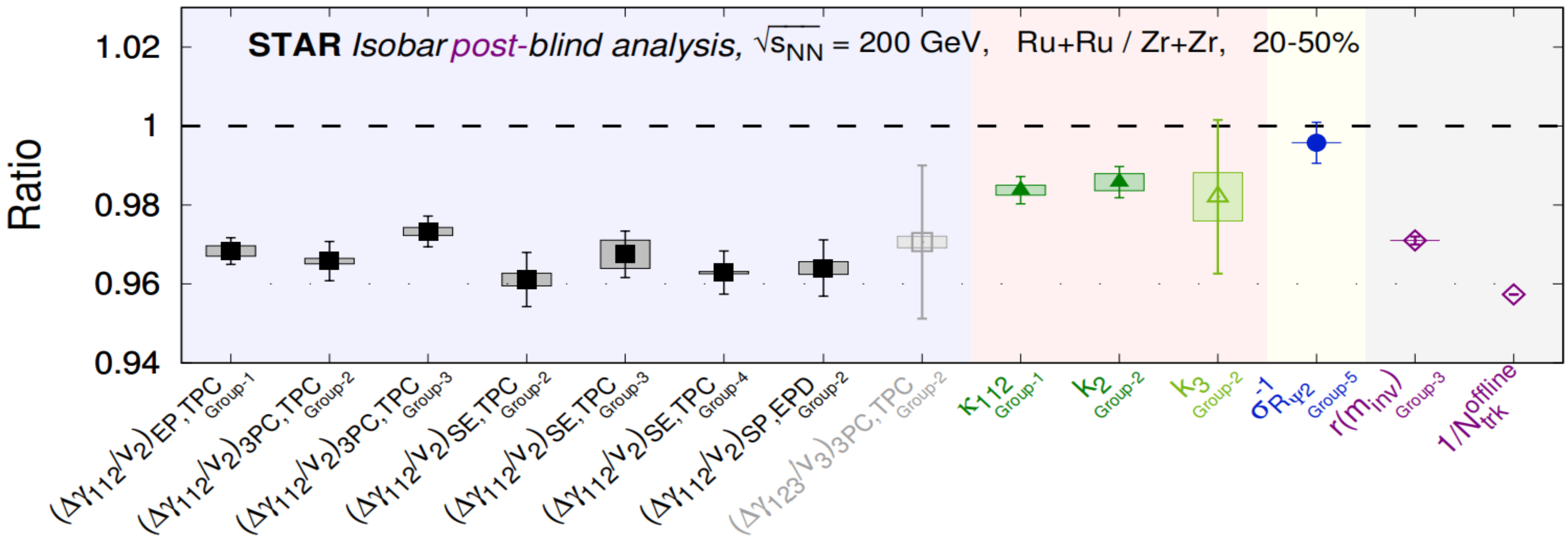


-to search the Chiral Magnetic Effect (CME) and probe nontrivial structure of the QCD vacuum

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



Search CME with Isobar collisions



STAR Collaboration. arXiv: 2109.00131 [nucl-ex]

between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

-Observed differences in both multiplicity and v2 imply that CME background are different for ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr Collisions at matching centralities

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

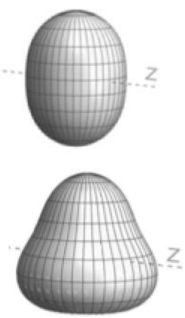
PHYSICAL REVIEW C VOLUME 42, NUMBER 3 SEPTEMBER 1990

Strong octupole and dipole collectivity in ^{96}Zr: Indication for octupole instability in the $A=100$ mass region

^{96}Zr has very large octupole deformation from $B(E3; 0_1^+ \rightarrow 3_1^-)$

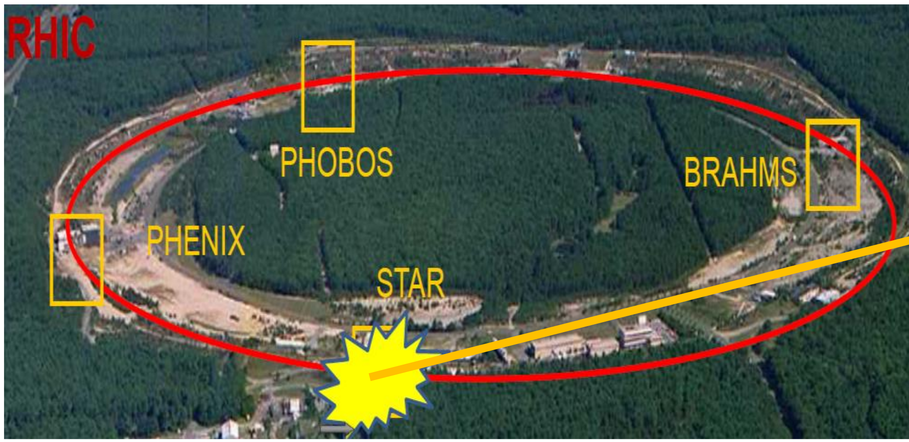
Conversion from B(En) to β_n via: $\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}}$, $\beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$

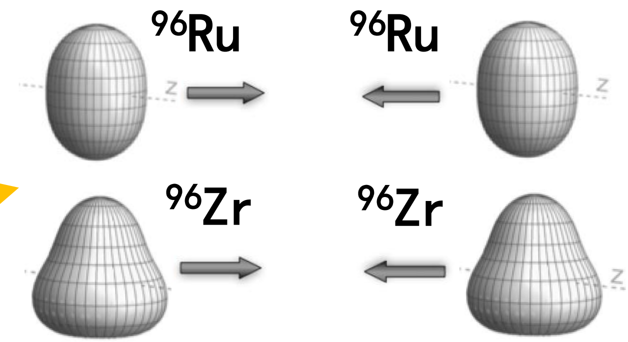
	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90



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

Isobar collisions to probe the deformation of ^{96}Ru & ^{96}Zr

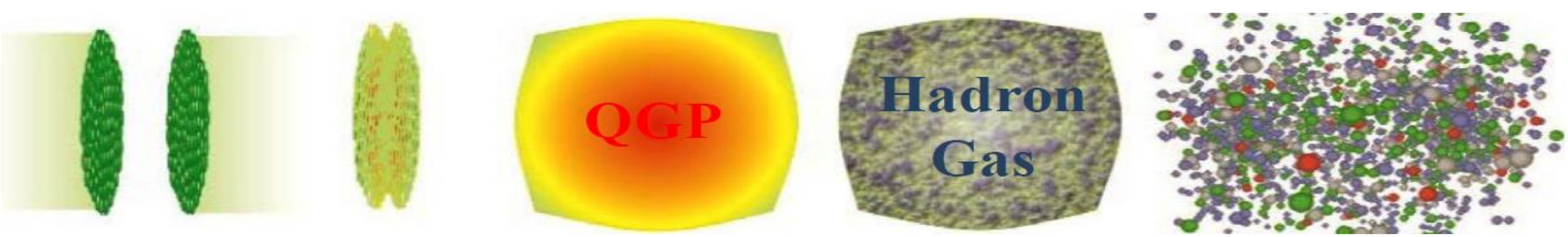




initial conditions:
(with deformation)

Well calibrated calculations

Initial conditions   viscous hydro   hadron cascade

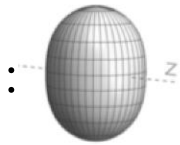


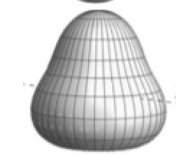
Hydrodynamic calculation with initially deformed nuclei

Initial conditions (TRENTO)

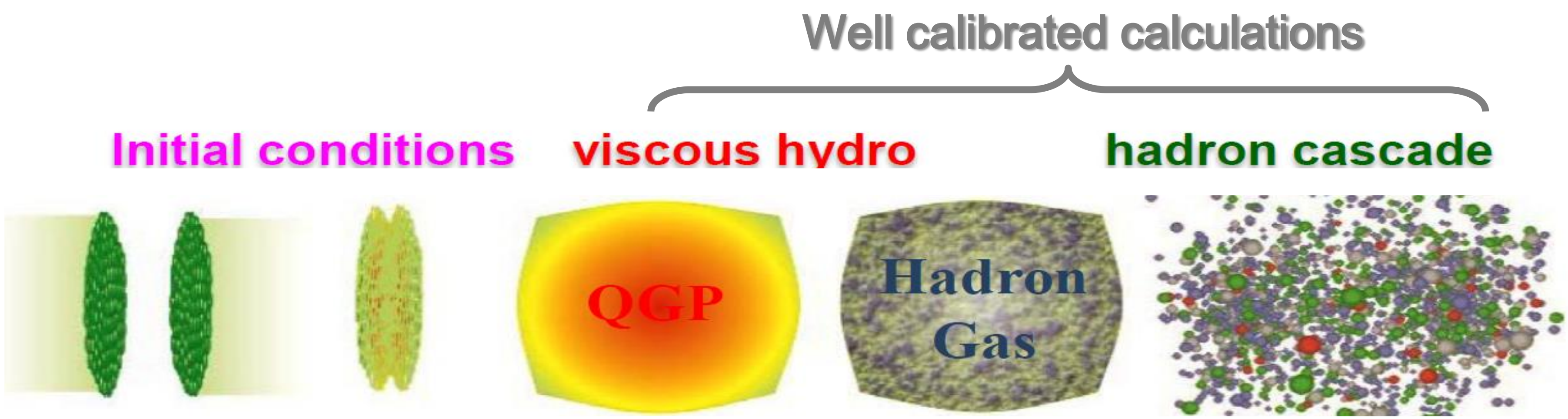
-Sample nucleon position in deformed nuclei with:

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

Quadrupole: 

Octupole: 

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



Hydrodynamic calculation with initially deformed nuclei

Initial conditions (TRENTO)

-Sample nucleon position in deformed nuclei with:

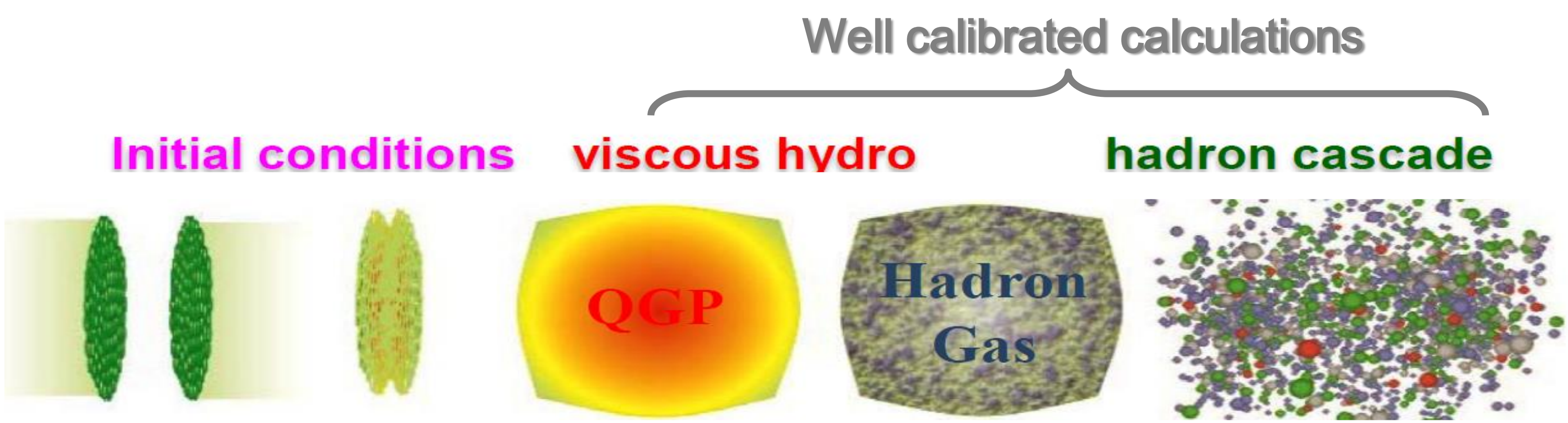
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

	β_2	β_3	R_0	a
Ru-para-I	0.12	0.00	5.093	0.487
Ru-para-II	0.16	0.00	5.093	0.471
Zr-para-I	0.00	0.16	5.021	0.524
Zr-para-II	0.00	0.20	5.021	0.517

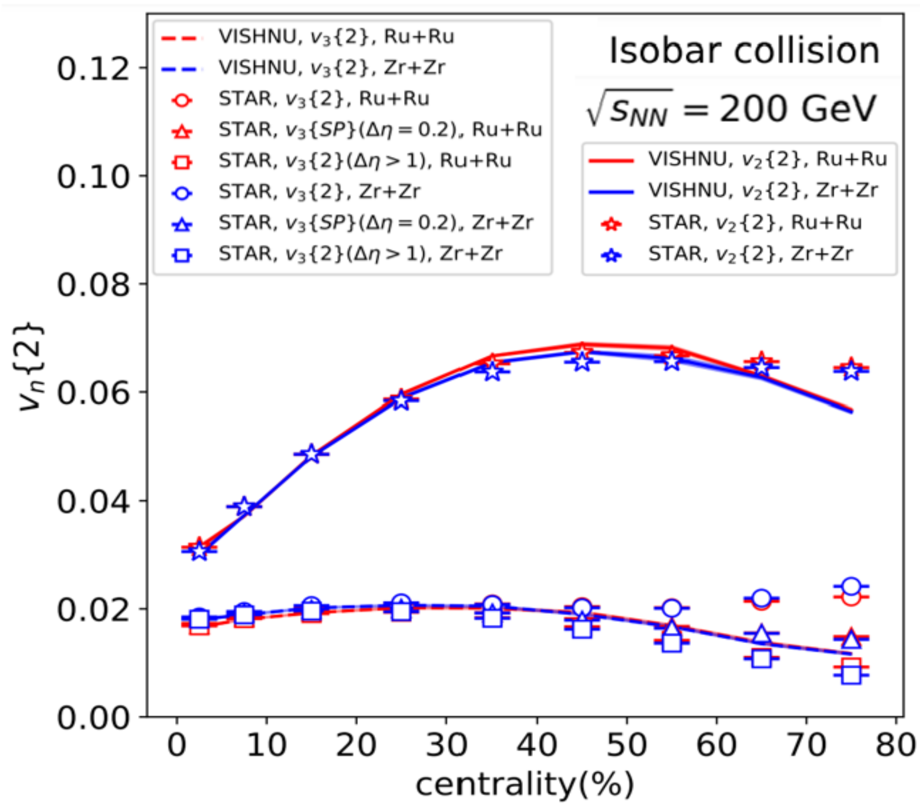
Parameters are refer to:

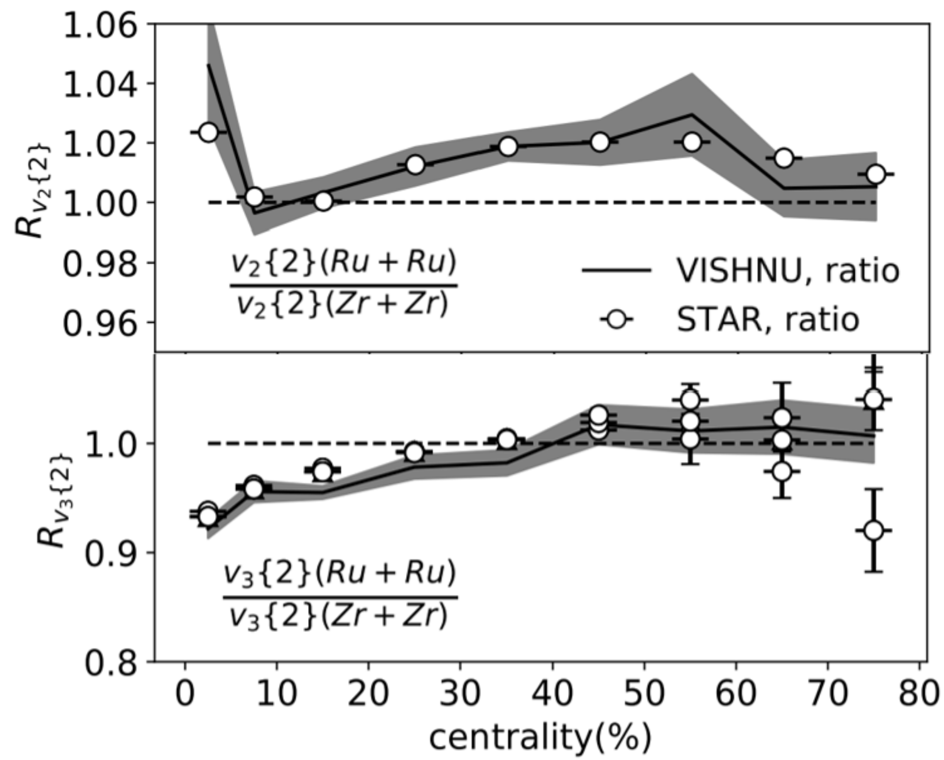
G. Fricke, et al. Atom. Data Nucl. Data Tabl. 60, 177 (1995).B. Pritychenko, et al. Atom. Data Nucl. Data Tabl. 107, 1 (2016).T Kib´edi and R. H Spear, Atom. Data Nucl. Data Tabl. 80, 35 (2002).

(H. Xu, et al., Phys. Lett. B 819, 136453 (2021)J. Jia, et al. arXiv: 2111.15559 [nucl-th])



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



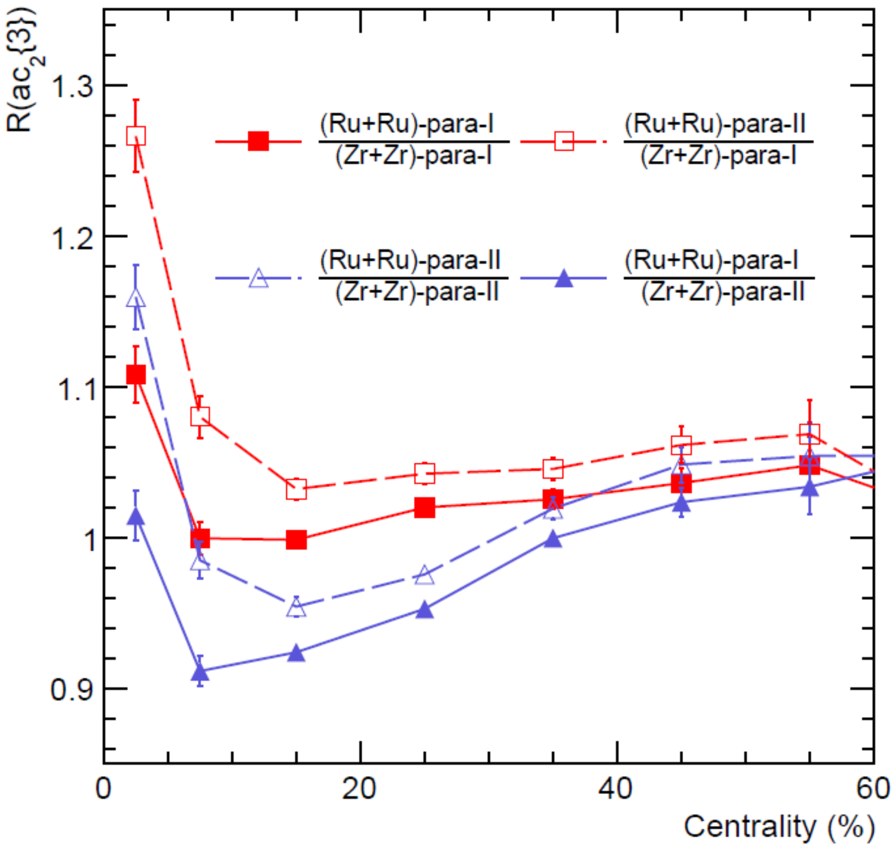


-With fine tuning parameters, iEBE-VISHNU fits V_2 & V_3 for Ru+Ru collisions

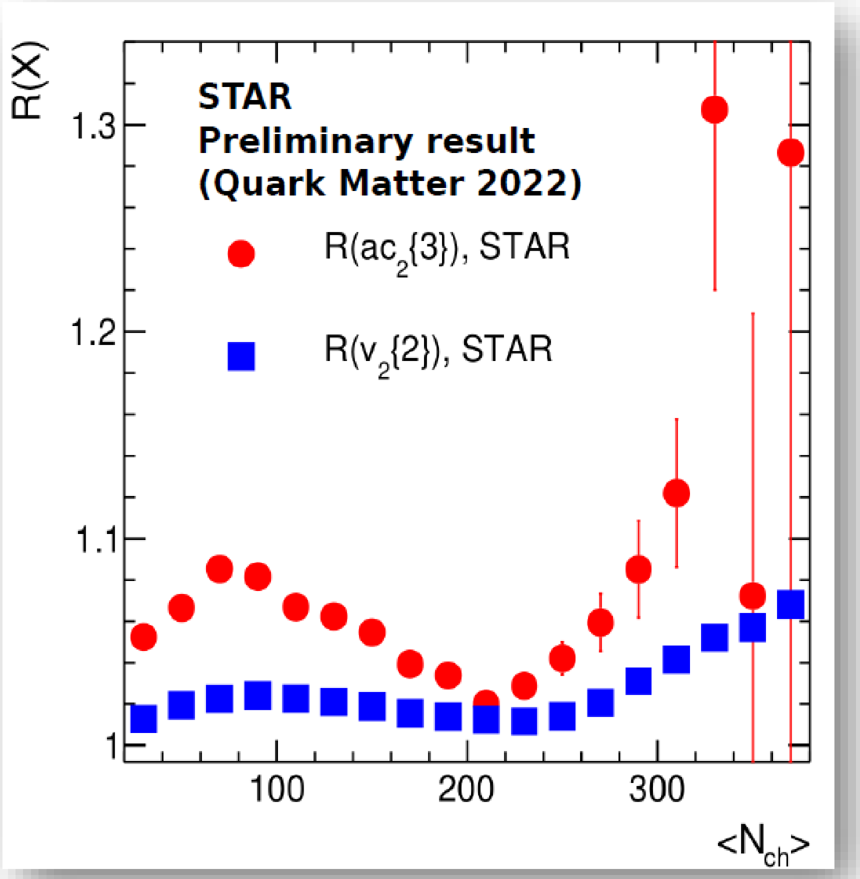
-Using β_2 β_3 in table1, it "predicts" V_2 & V_3 for Zr+Zr collisions & the related ratio -- (the data are roughly described).

"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

Study the deformation of ^{96}Ru and ^{96}Zr in Nuclear Structure

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

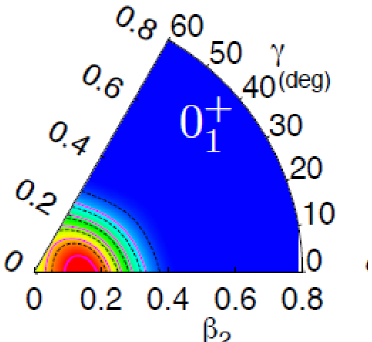
CDFT :
- explicit (DD-ME2, DD-PC1)
- non-linear (through the powers of mesons) (NL1, NL3*)

Skyrme and Gogny DFTs: different prescriptions for density dependence

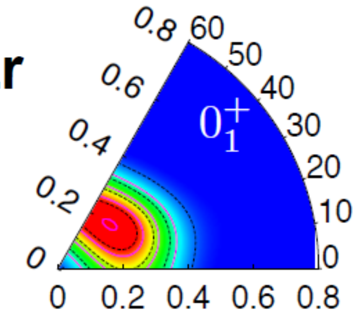
-Model dependent calculations, which results is more reliable?

Deformation of ^{96}Ru & ^{96}Zr – re-evaluation and updates

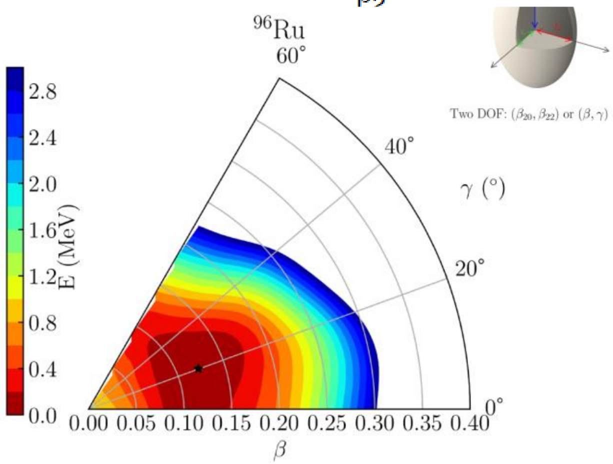
^{96}**Ru**

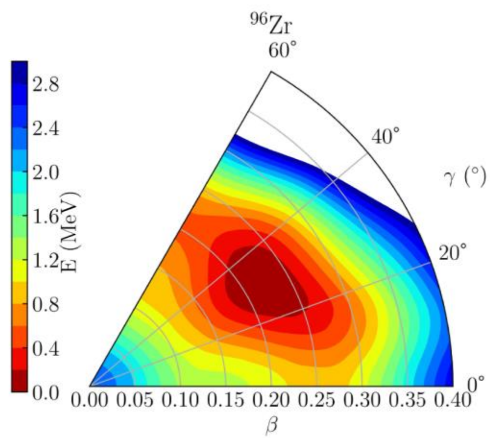


^{96}**Zr**



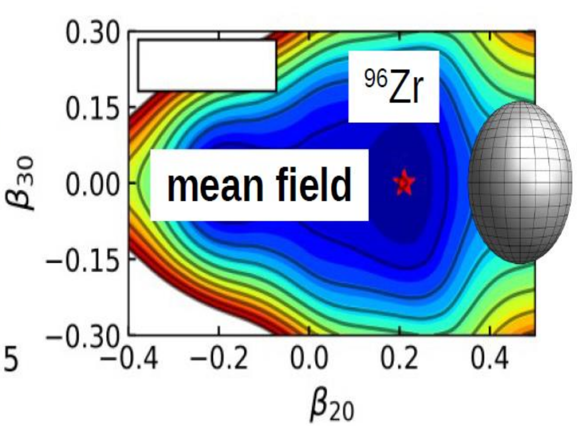
Gogny energy density functional |(Tiaxial) T R. Rodríguez EMMI RRTF 2022

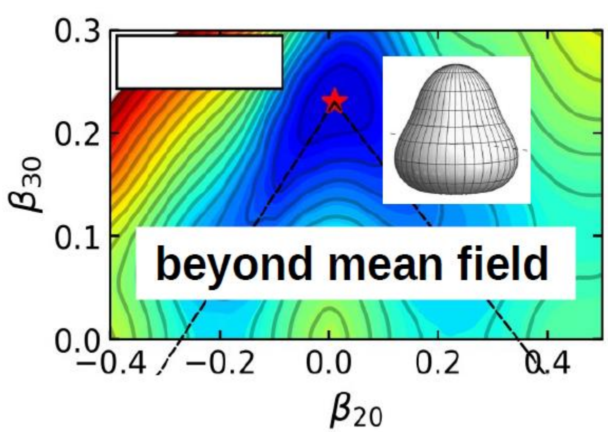




Skyrme EDF (with rotational correction)

W Ryssens EMMI RRTF 2022



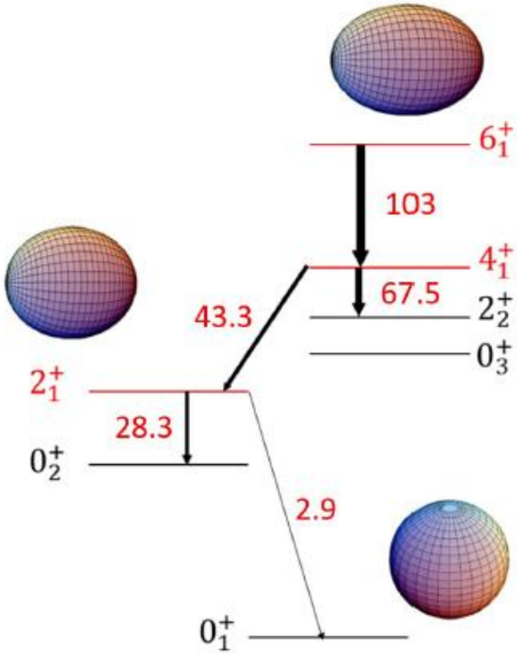


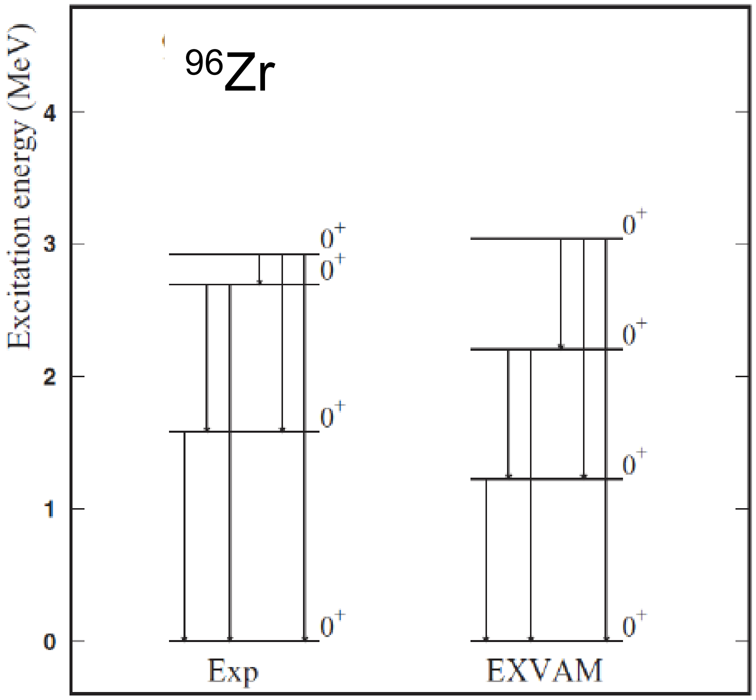
Beyond-mean-field correction is very important

Rong, Lu, arXiv:2201.02114

Deformation of ^{96}Zr – shape coexistence

^{98}Zr: triple shape coexistence
ground state = spherical





Phys.Rev. Lett. 121, 192501 (2018)

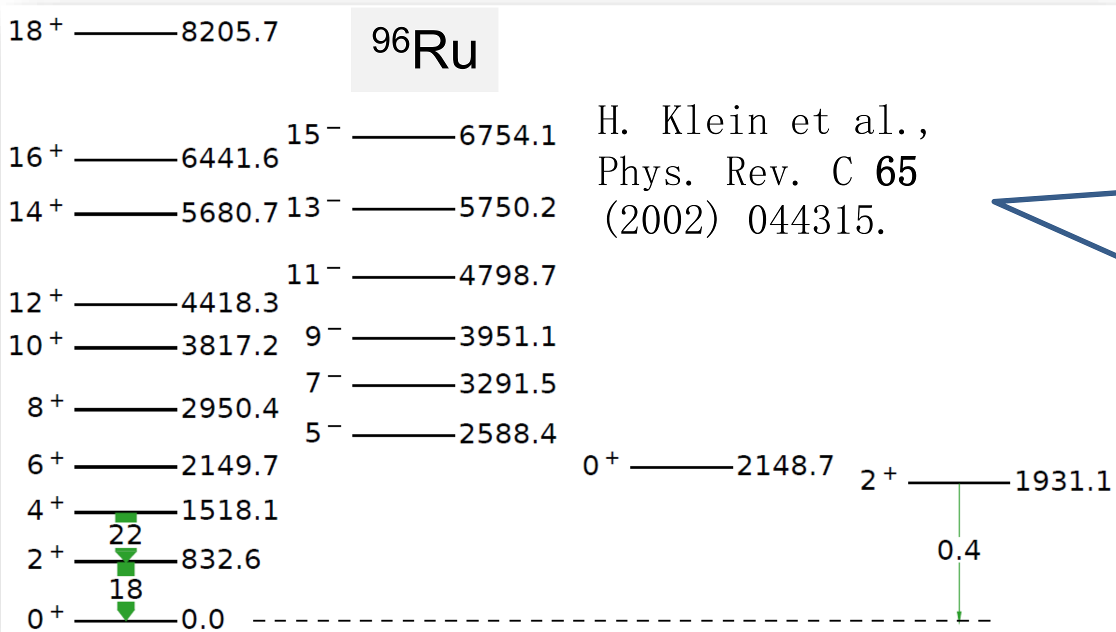
Also refer to T.Togashi, Quantum Phase Transition in the Shape of Zr isotopes," Phys. Rev. Lett. 117, no.17, 172502 (2016)

TABLE I. The structure of the wave functions for the lowest four 0^+ states of ^{96}Zr.

$I[\hbar]$	Spherical	Prolate	Oblate
0_1^+	94%	1%	4%
0_2^+	19%	45%	35%
0_3^+	30%	54%	15%
0_4^+	36%	16%	47%

A. Petrovici et al PRC101, 024307 (2020)

Properties of ^{96}Ru and ^{96}Zr – experimental measurements

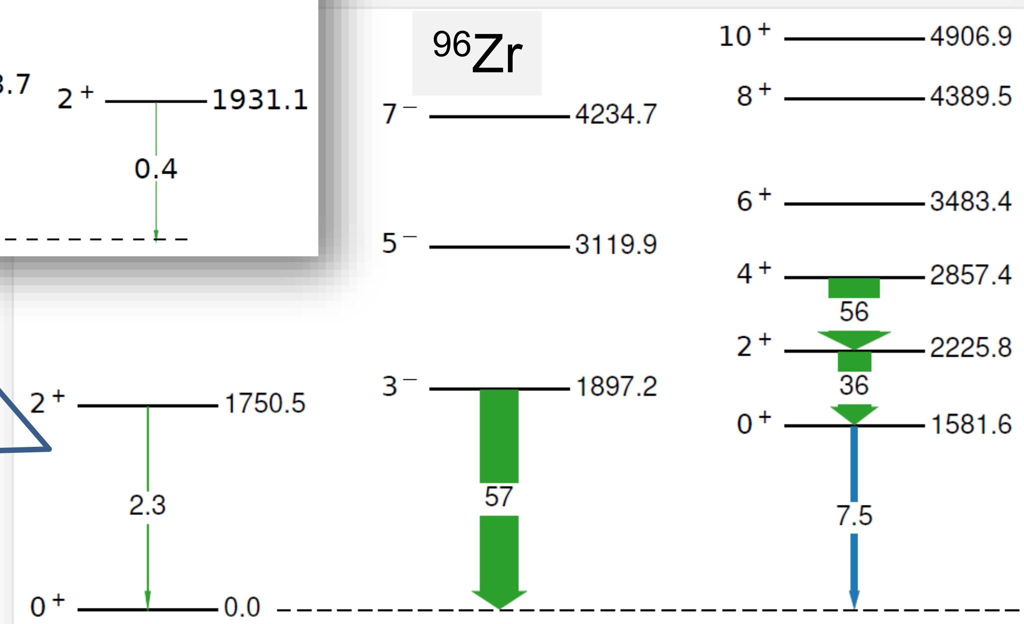


H. Klein et al., Phys. Rev. C **65** (2002) 044315.

$B(E2;\, 0_1^+ \rightarrow 2_1^+) = 18.2$ W.u.

$\beta_2 = 0.154$

moderately deformed ground state band



G. Kumbartzki et al., Phys. Lett. B **562** 193 (2003)

$B(E2;\, 0_1^+ \rightarrow 2_1^+) = 2.3(3)$ W.u.

$\beta = 0.062(3)$

$$\beta_3 = \frac{4\pi}{3eZR^3}\sqrt{B(E2;\, 0_1^+ \rightarrow 3_1^-)}$$

$\beta_3 \sim 0.25$

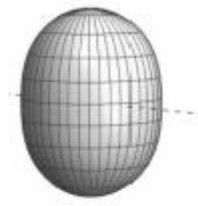
- only one measurement for $B(E2;\, 0_1^+ \rightarrow 2_1^+)$ but compilations also cite a publication for 1965 “Coulomb Excitation of the First 2^+ Levels of ^{90}Zr and ^{96}Zr” with an almost two times larger $B(E2)$

S. Raman et al., At. Data Nucl. Data Tables **78** (2001) 1, Y. P. Gangrskii, I. K. Lemberg, Yadern. Fiz. **1** (1965) 1025.

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

-- a short summary

^{96}Ru



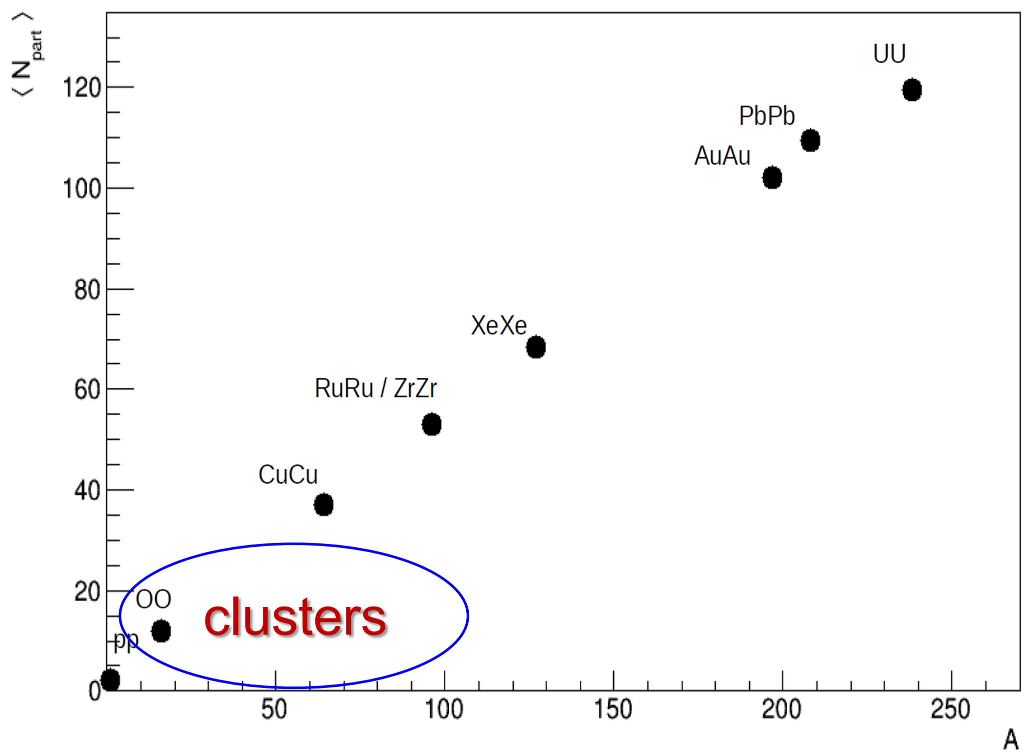
^{96}Zr

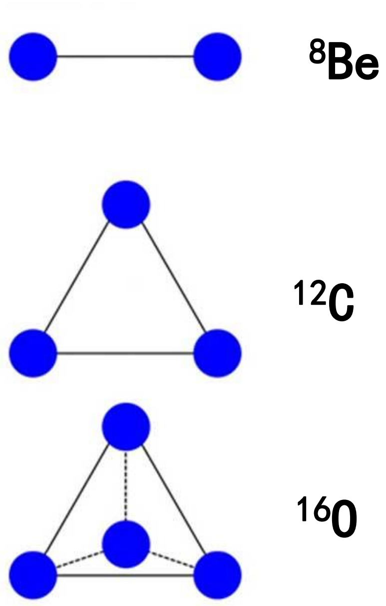
-^{96}Ru and ^{96}Zr: two ideal nuclei for interdisciplinary research between relativistic heavy ion phyiscs and nuclear structure

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

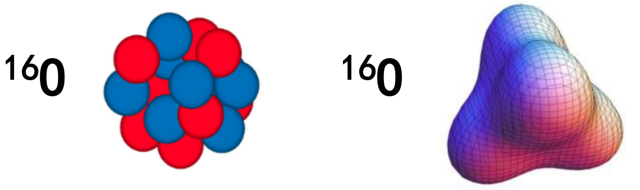
-Need more efforts to study the deformation of ^{96}Ru & ^{96}Zr from both experimental and theoretical sides in nuclear structure

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

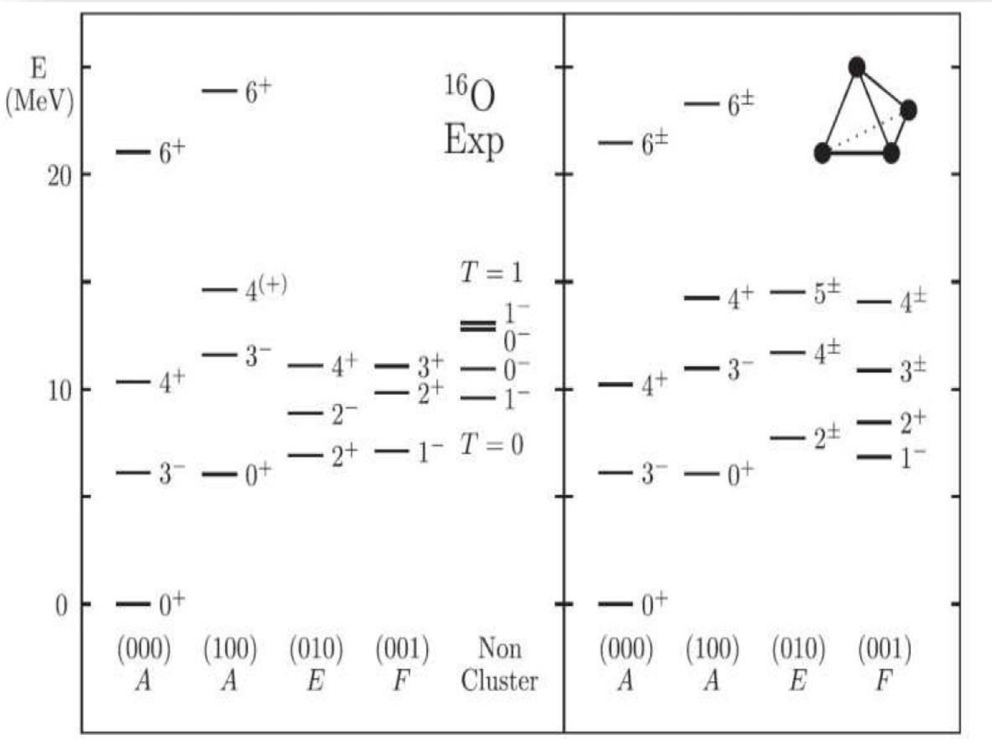




$^{16}O+^{16}O$ collisions and $p+^{16}O$ collisions originally aim to study the possible formation of QGP in small systems



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

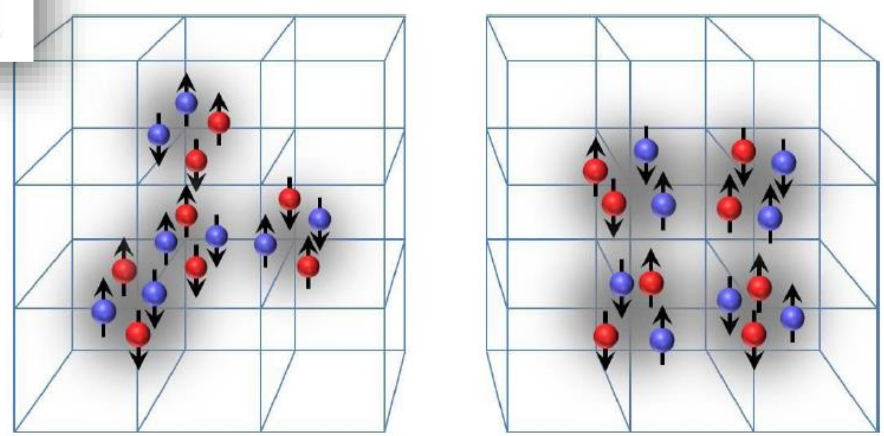


-ACM calculations show that the low-lying states of 16O can be described as rotation-vibration of a 4α cluster with tetrahedral symmetry.

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)

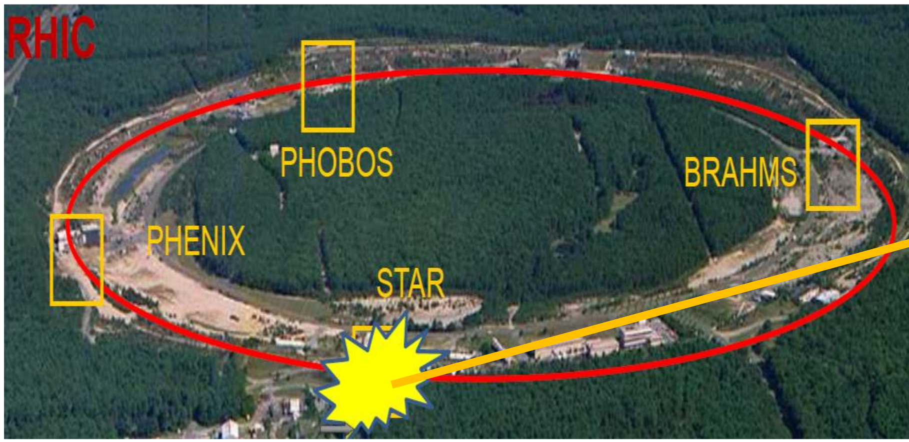


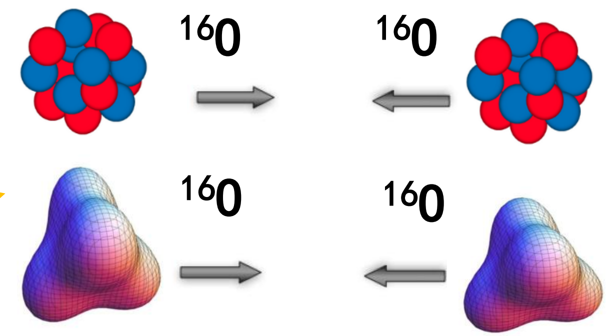
(a) Initial state “A”, 8 equivalent orientations.

(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

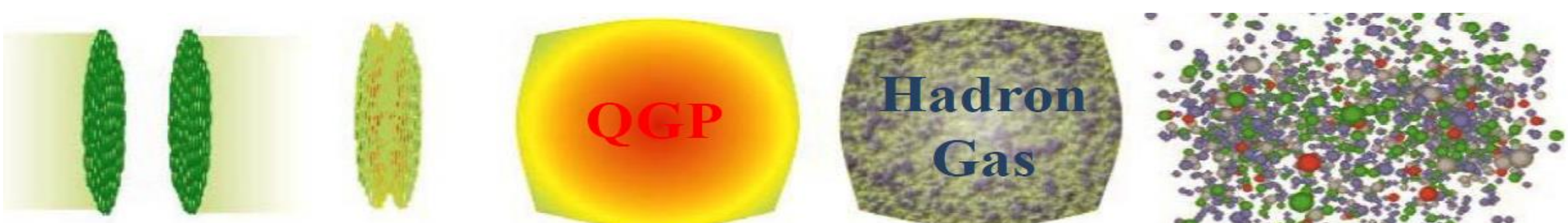




initial conditions:
(with or without α-cluster)

Well calibrated calculations

Initial conditions   viscous hydro   hadron cascade

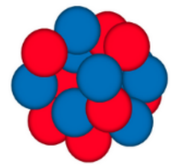


Hydrodynamic calculation w/wo clustering

Initial conditions (TRENTO)

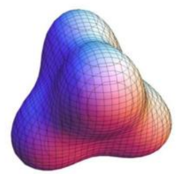
-Woods-Saxon:

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



-Alpha-Cluster:

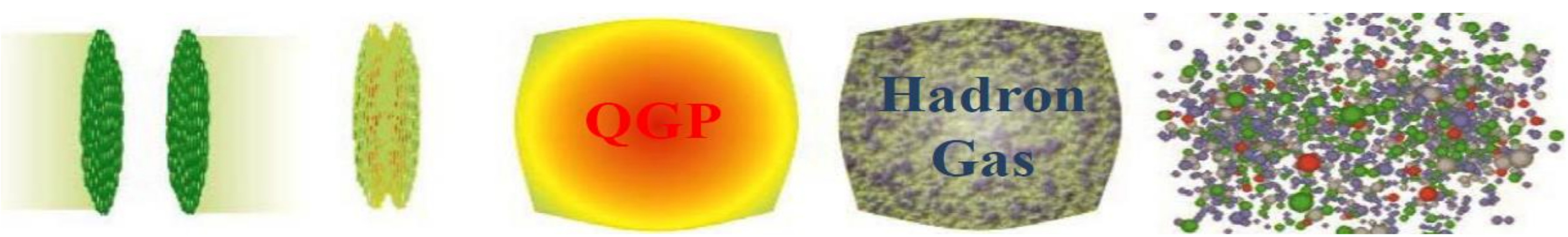
$$f_i(\mathbf{r}) = A\exp\left[-\frac{3(\mathbf{r}-\mathbf{r}_i)^2}{2{r_\alpha}^2}\right]$$



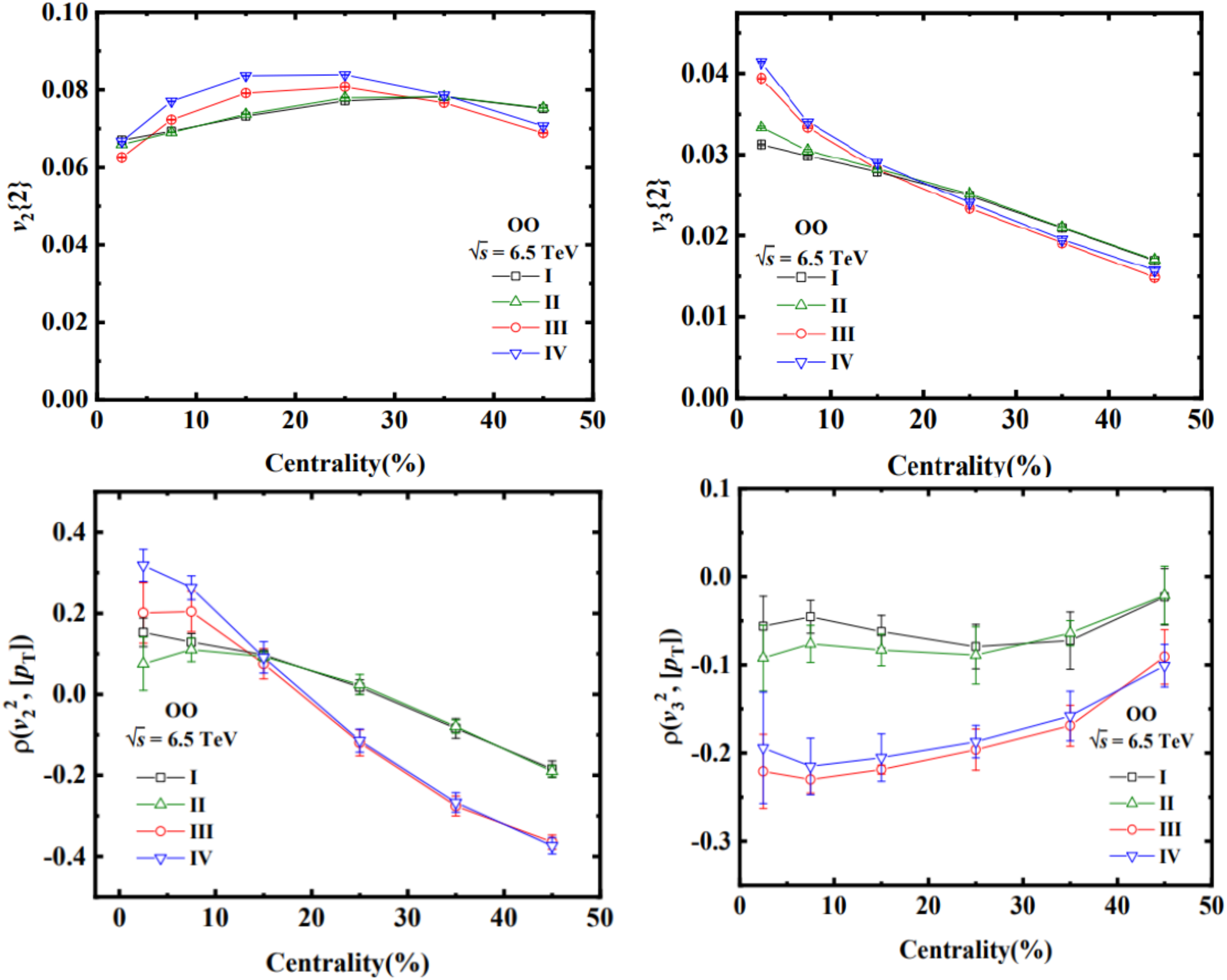
	distribution	l	r_α
I	Woods–Saxon		
II	alpha cluster	2.8	2.0
III	alpha cluster	3.2	1.1
IV	alpha cluster	3.42	1.1

Well calibrated calculations

Initial conditions viscous hydro hadron cascade

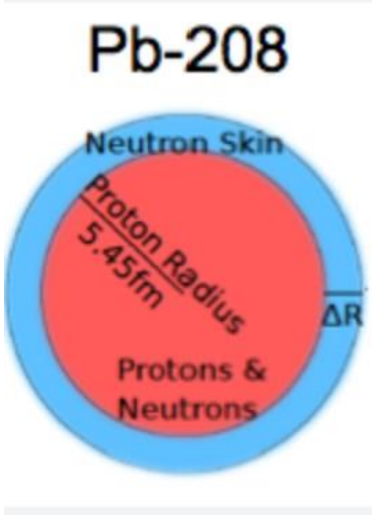


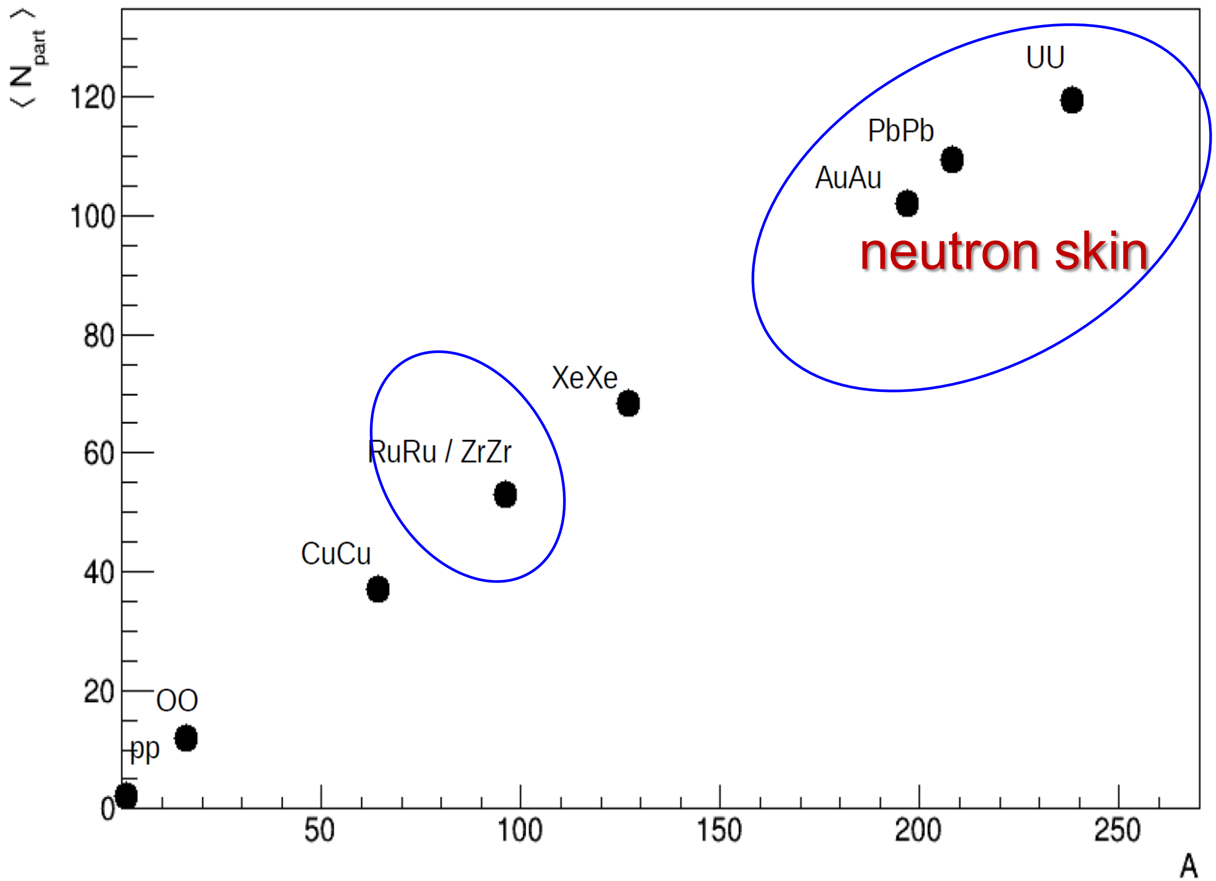
Sensitive observables for α-clustering



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

Probe neutron skin at RHIC and the LHC





Neutron Skin & neutron star

EOS of nuclear matter

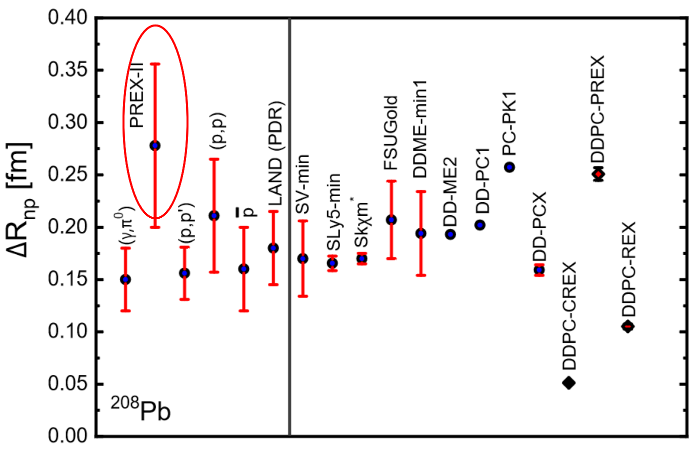
$$\epsilon(\rho,\alpha) = [\epsilon_{SNM}(\rho_0) + S(\rho_0)\alpha^2)] + \alpha^2 L\frac{\rho-\rho_0}{3\rho_0} + \frac{1}{2}(K_0 + \alpha^2 K_{sym})(\frac{\rho-\rho_0}{3\rho_0})^2$$

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

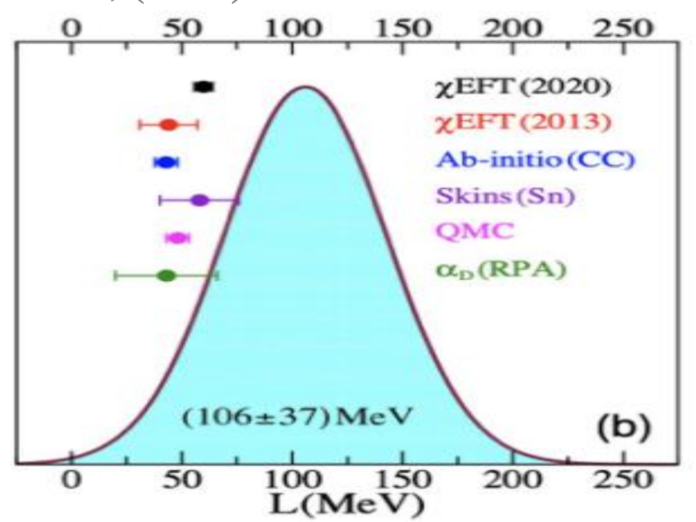
Probe the Neutron Skin at low energy nuclear physics

Parity-Violating Electron Scattering in Jefferson Lab

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



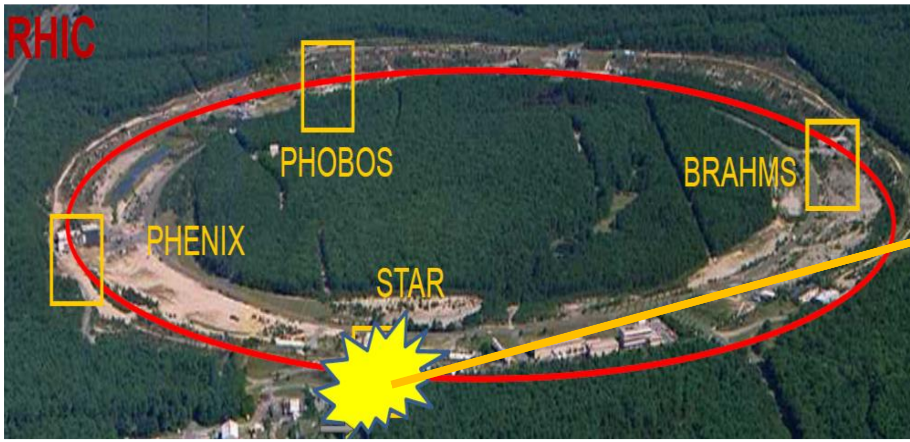
arXiv:2206.06527 Esra Yüksel and Nils Paar

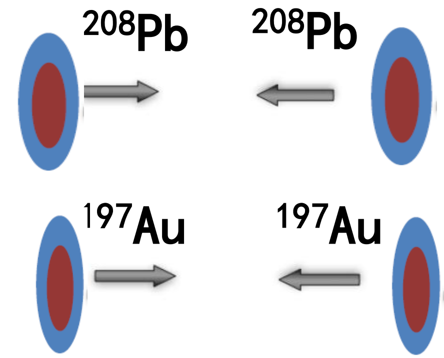


Phys. Rev. Lett. 126, 172502 D. Adhikari et al

Please also refer to Jinlong Zhang' talk on Aug.4

Relativistic heavy ion collision to probe the neutron skin

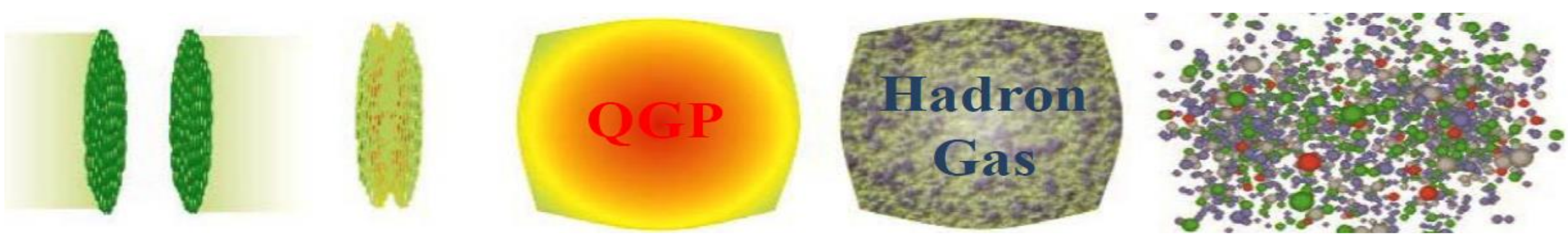




initial conditions:
(with neutron skin)

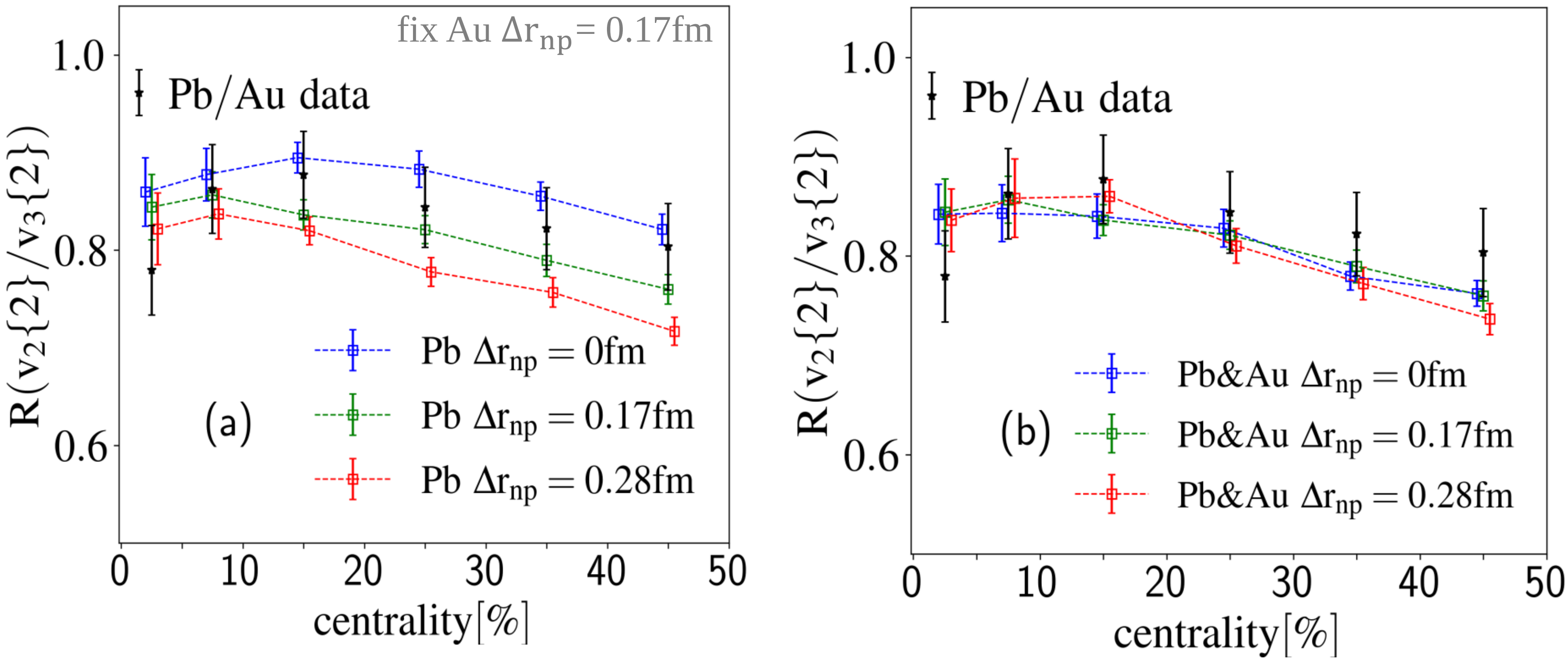
Well calibrated calculations

Initial conditions   viscous hydro   hadron cascade



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

semi-isobaric double ratio

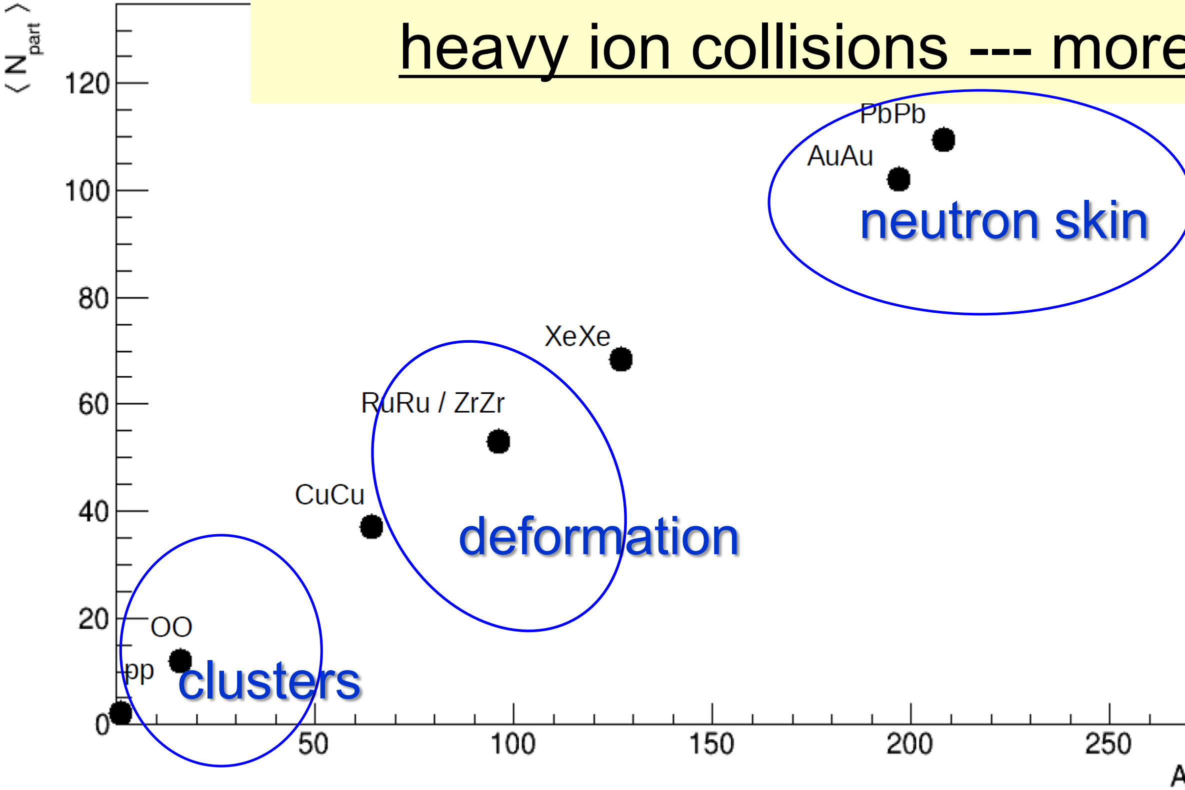


A scaling behavior was found in double ratio when Au and Pb have neutron skins of the same size, which suggest Au and Pb have similar neutron skin.

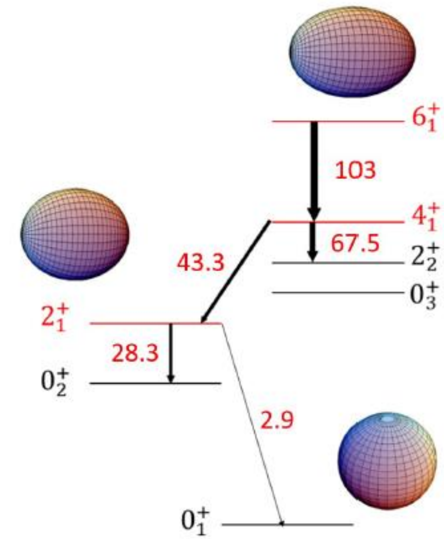
Q. Liu, H. Xu and H. Song. Paper in preparation.

Please also refer to H Xu' talk on Aug.4

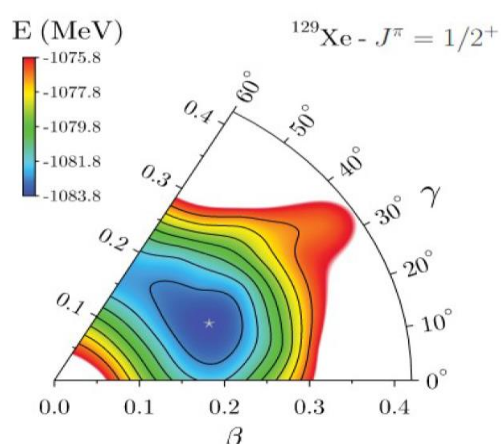
Probing the nuclear structure with relativistic heavy ion collisions --- more to explore

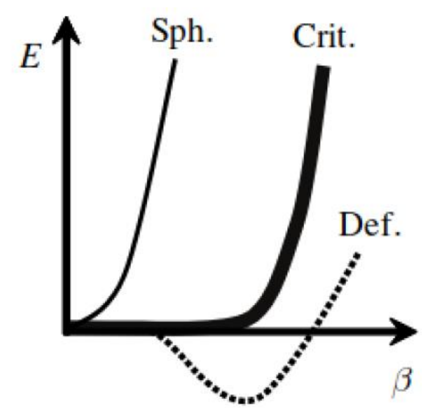


^{96}Zr: shape coexistence



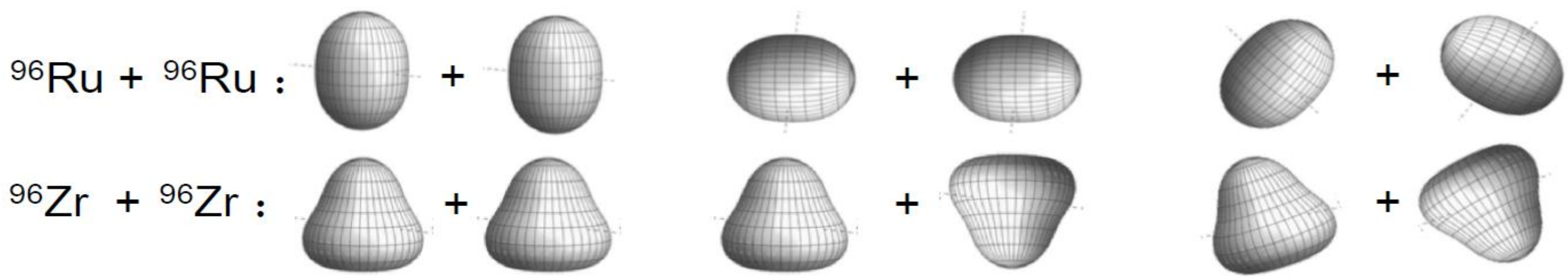
^{129}Xe: γ soft shape phase transiton

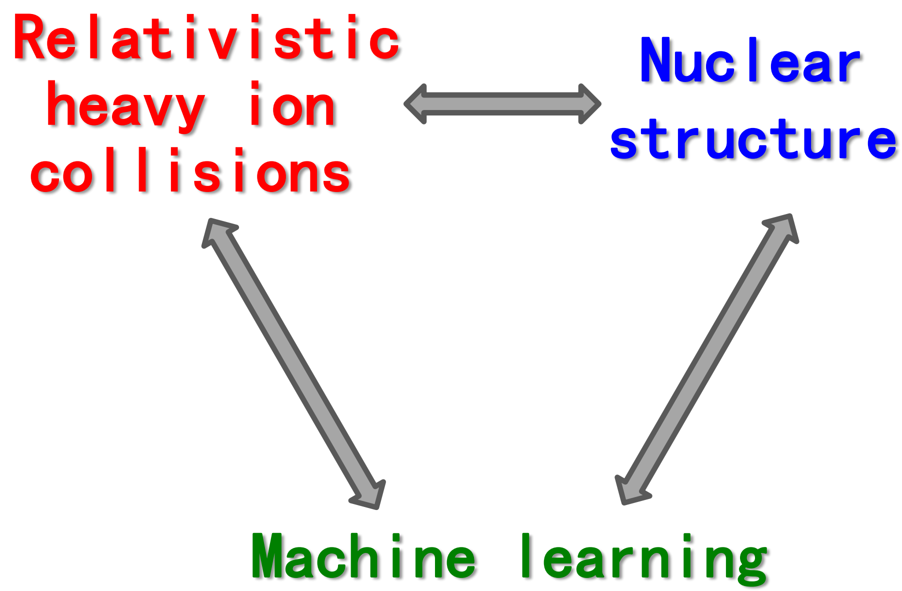




-Rich nuclear structure: deformation, cluster, neutron skin; shape coexistence, γ-soft (shape phase transition)

-Rich configurations for QGP initial conditions





Please also refer to L Pang talk today

Summary and Outlook

-Sensitive observables have been found to probe the deformation of ^{96}Ru & ^{96}Zr, cluster of ^{16}O, neutron skin of ^{208}Pb & ^{96}Au, respectively

-More observables are needed to study the deformation, cluster and neutron skin of various colliding nuclei

-Machine learning and Bayesian analysis are needed to precisely extract the information of nuclear structure in heavy ion collisions