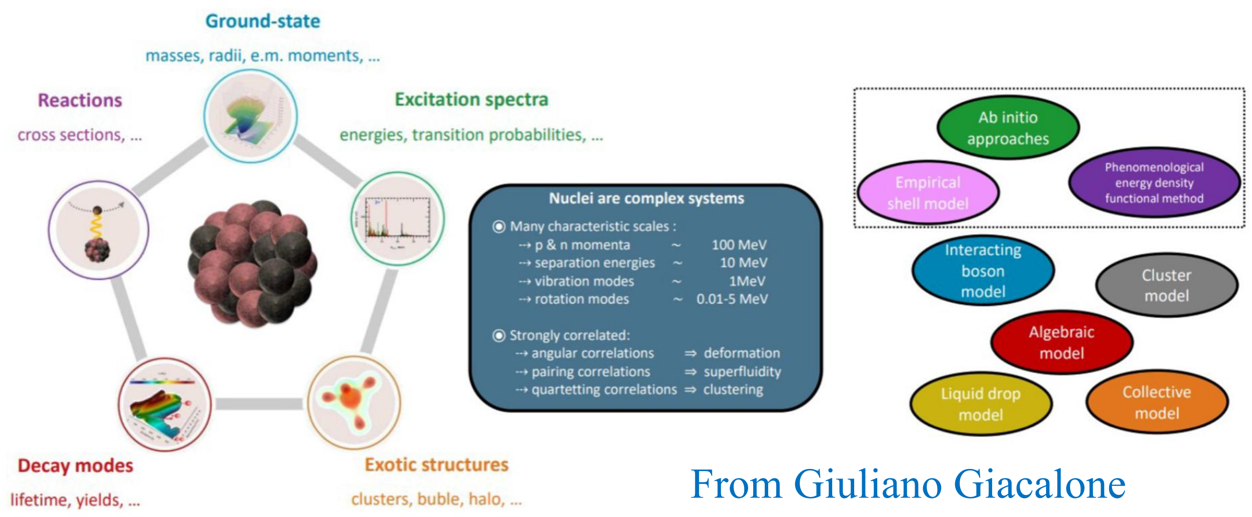
Zhiyong Lu
China Institute of Atomic Energy (CIAE)

In collaboration with: You Zhou, Emil Gorm Nielsen (NBI)

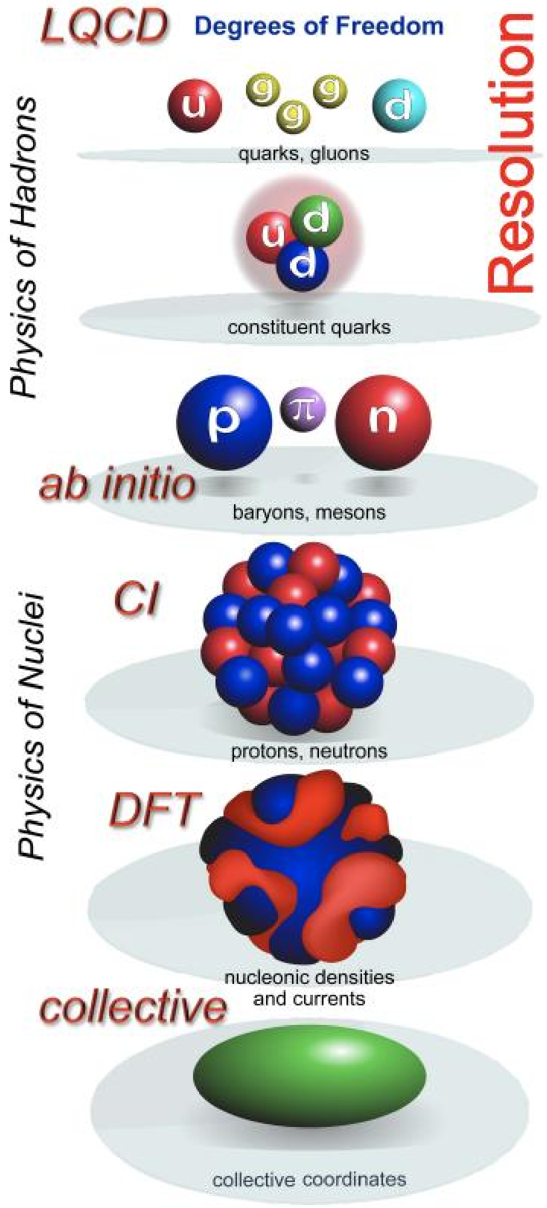
Nuclear structure at low energies

Atomic nuclei have rich phenomenology. Rooted in the strong nuclear force.
Nuclear structure is a very old field. Many different approaches.



From Giuliano Giacalone

- In low-energy nuclear physics, nuclei can be well described by many theoretical approaches at different resolution scales
- Nuclear many-body problem, when inspected at higher resolution, have a complicated structure of their own



Hot QCD
Cold QCD

Hadron-Nuclear interface

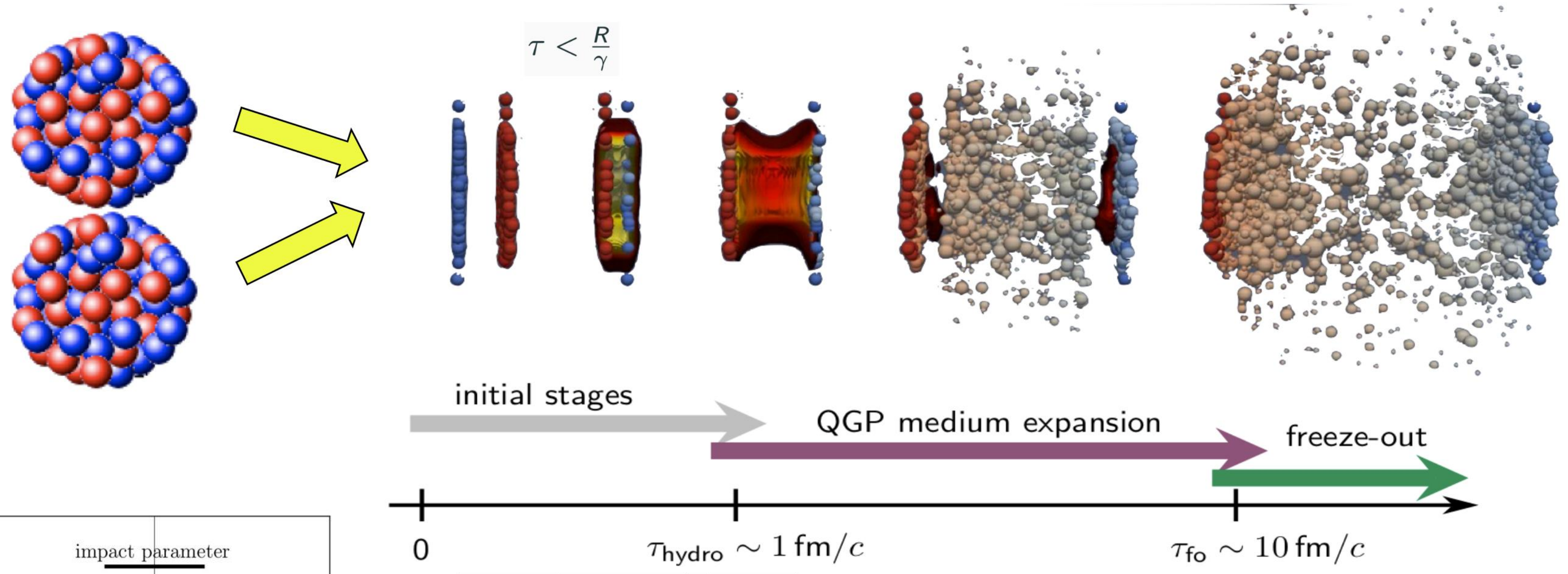
Nuclear structure
Nuclear reactions

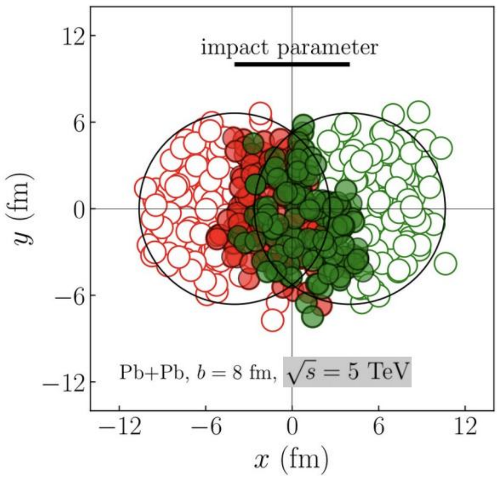
Nuclear astrophysics
New standard model

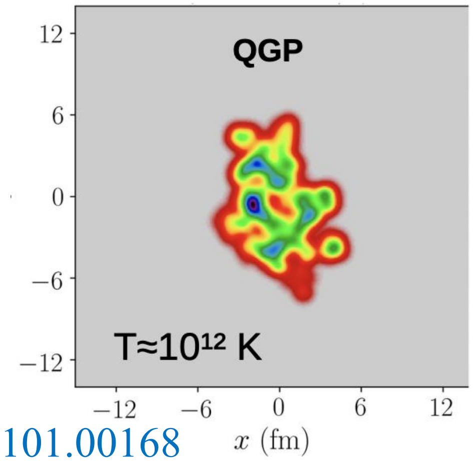
Applications of nuclear science

Witold Nazarewicz, JPG: NPP 43, 044002 (2016)

Nuclear structure at high energies







G.Giacalone, PhD Thesis, arXiv: 2101.00168

Final-state particle correlations
Mean p_T

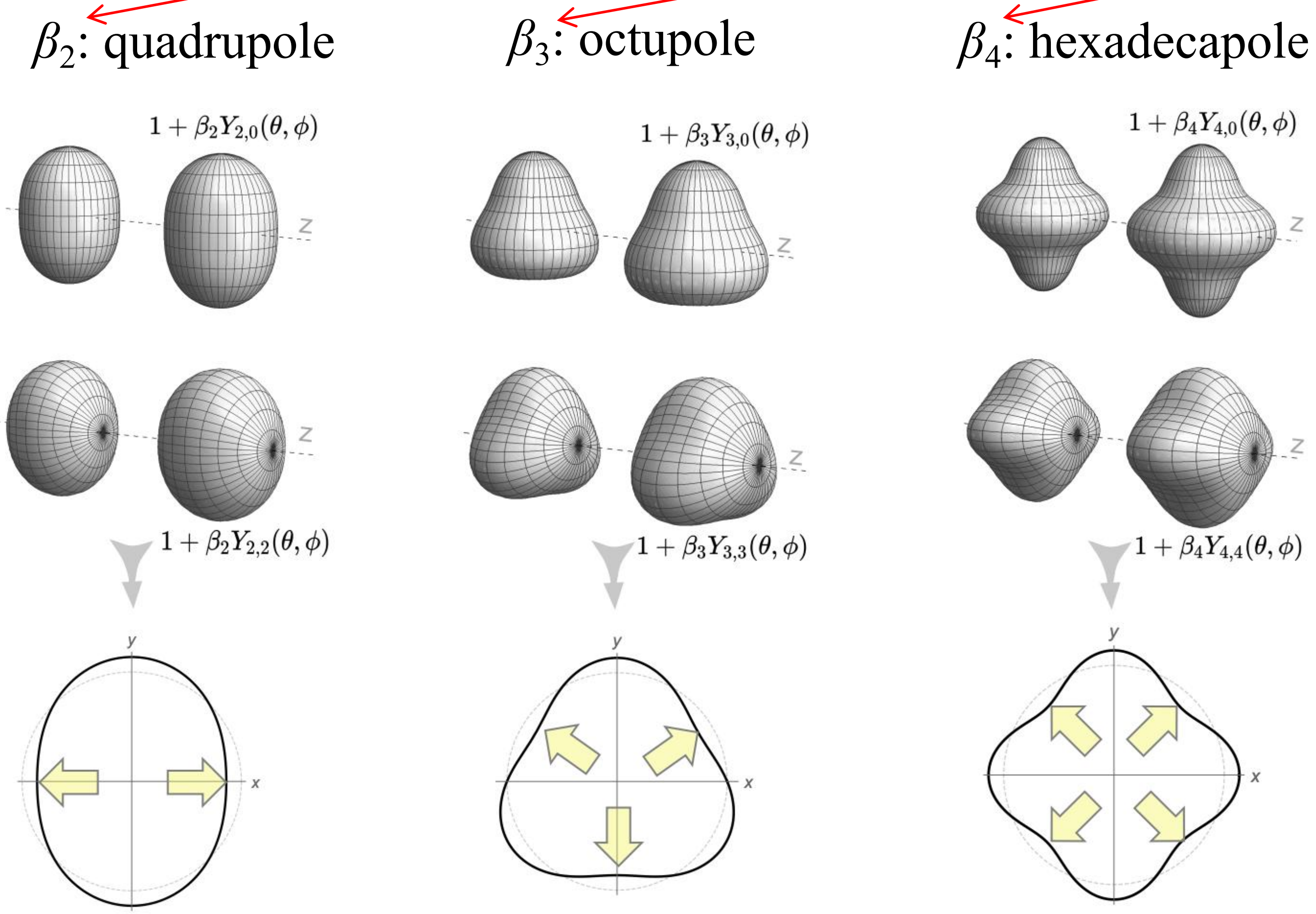
ALICE, PLB 784 (2018) 82-95
ALICE, ALICE-PUBLIC-2018-003
ATLAS, PRC 107 (2023) 5, 054910
ALICE, arXiv: 2409.04343
STAR, Nature 635, 67–72 (2024)
etc

Nucleon density profile in Woods-Saxon form

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

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

Deformation



J.Jia, PRC 105 (2022) 1, 014905

Nucleon density profile in Woods-Saxon form

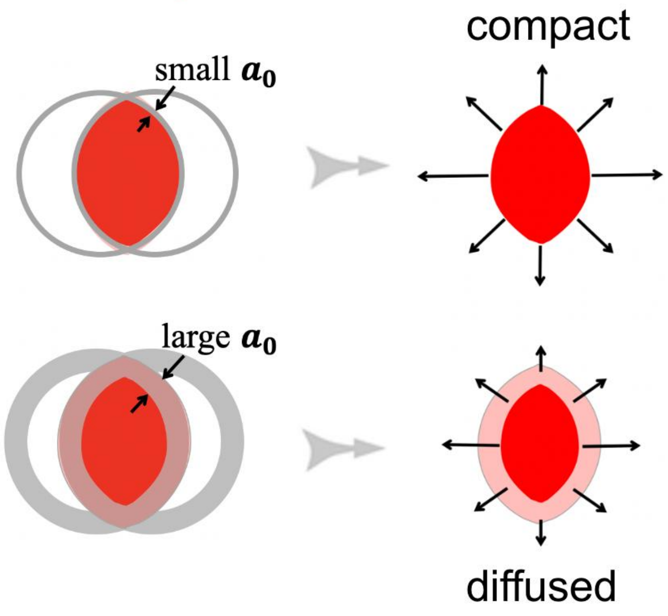
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

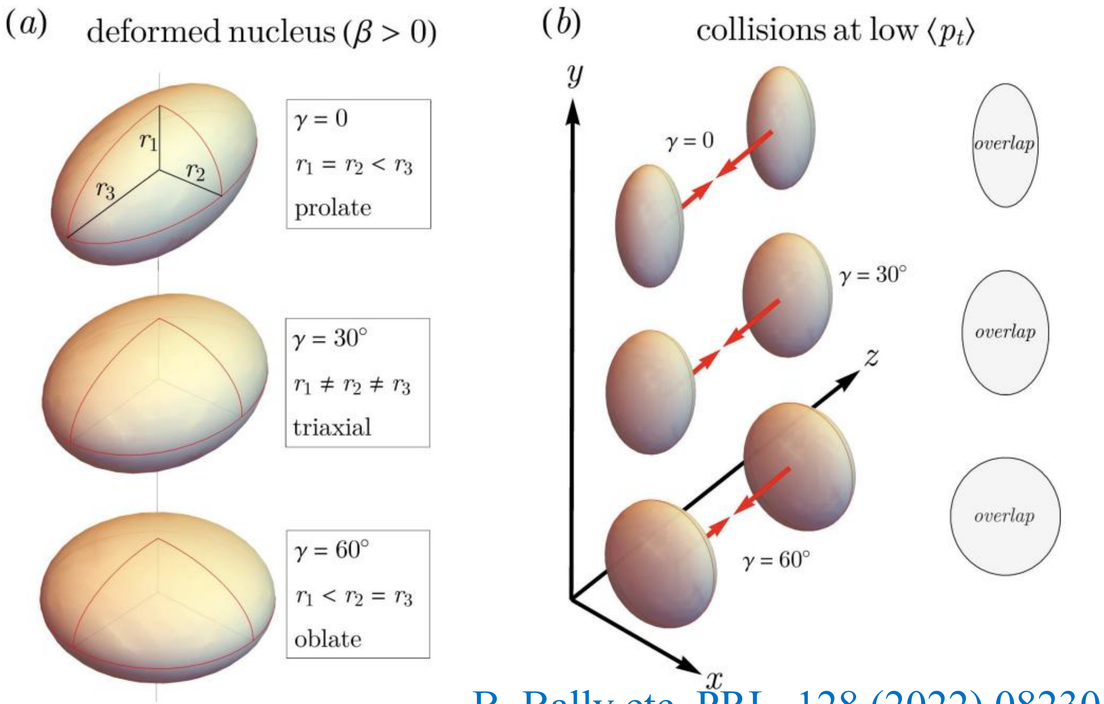
a_0: nuclear diffuseness

γ: traxiality parameter

Radial profile:



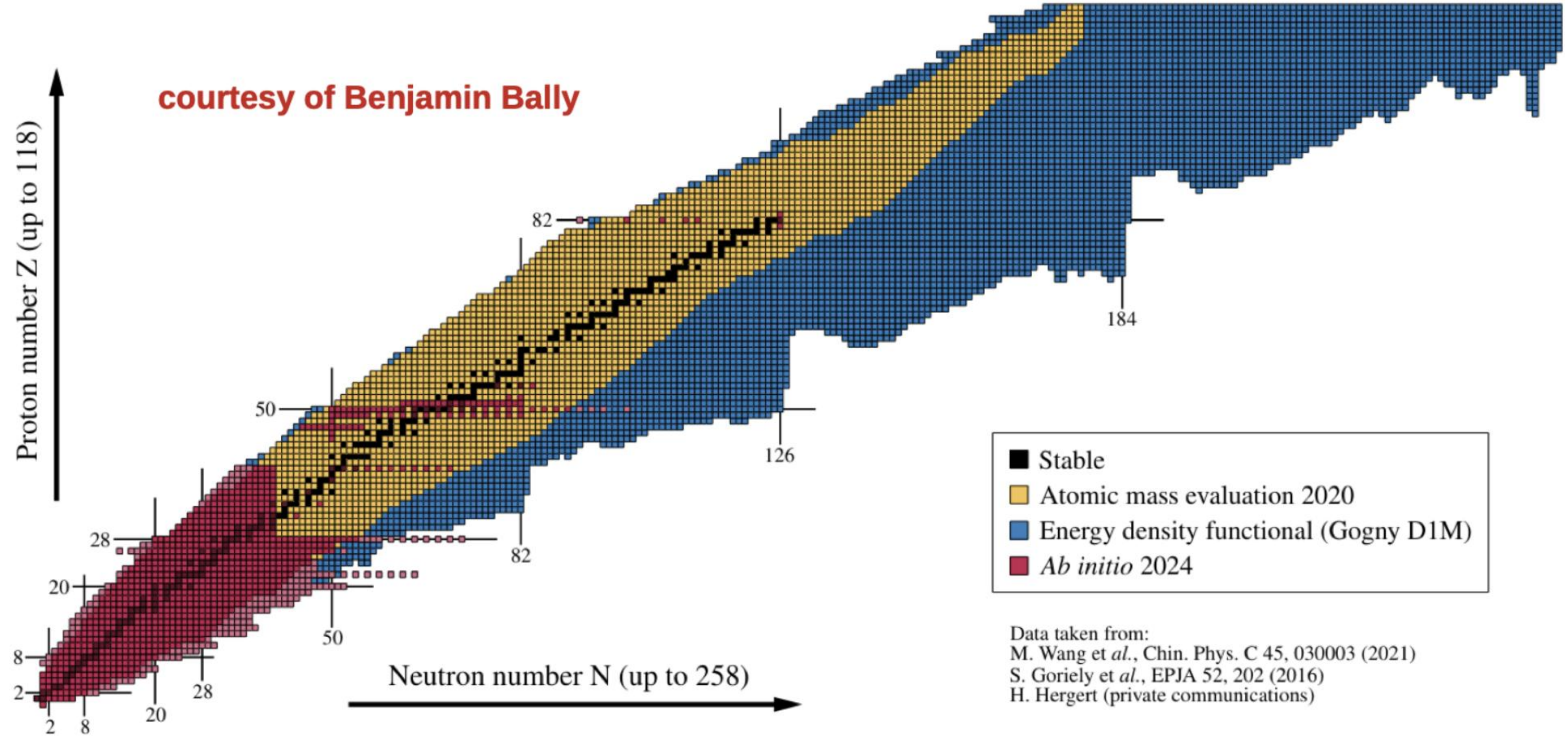
From Jiangyong Jia's slides



B. Bally etc, PRL. 128 (2022) 082301

Analogy to γ, $\alpha_{3,m}$ and $\alpha_{4,m}$ describe the inequality of axes and satisfy the normalization condition

Nuclear structure from *ab-initio*



Talk on Tuesday

Baseline calculations for oxygen and neon isotopes *Adam Takacs*
4/3-006 - TH Conference Room, CERN 10:50 - 11:15

Talks on Wednesday

Nuclear wave functions for HIC: ab initio PGCM *Benjamin Bally*
4/3-006 - TH Conference Room, CERN 11:15 - 11:40

Nuclear wave functions for HIC: Nuclear Lattice EFT *Bingnan Lu*
4/3-006 - TH Conference Room, CERN 11:40 - 12:05

Nuclear wave functions for HIC: ab initio NCSM *Takaharu Otsuka*
4/3-006 - TH Conference Room, CERN 12:05 - 12:30

TH Colloquium: Advances in many-body theory and applications to heavy-ion collisions *Dean Lee*
500/1-001 - Main Auditorium, CERN 14:00 - 15:00

Ab initio: describe atomic nucleus by solving multi-nucleon correlations

- Modern *ab-initio* methods have successfully described light nuclei with A ≤ 50
- Important inputs for all light-ion collisions and possible applications for heavy-ion

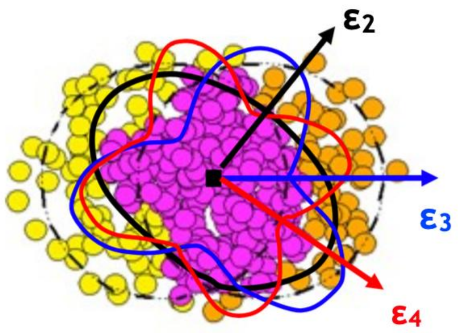
Experiment tools: Anisotropic flow and $[p_T]$

Figure made by You Zhou

G. Giacalone, PRC 102 (2020) 2, 024901

Initial state

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n\rangle}$$



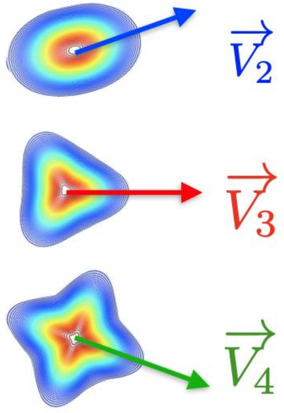
anisotropic spatial distribution

System expansion ⟹

Final state

$$\vec{V_n} = v_n\, e^{in\Psi_n}$$

anisotropic momentum distributions

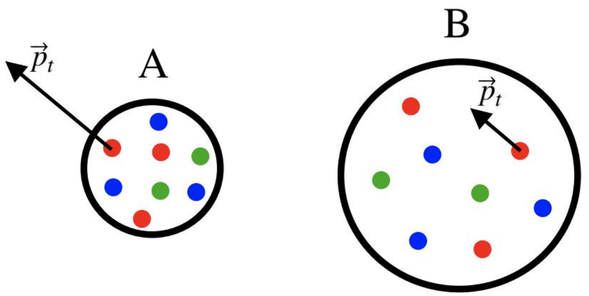


$$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, ..., \Phi_m, \Phi_n, \Phi_k, ...) \Longrightarrow P(v_m, v_n, v_k, ..., \Psi_m, \Psi_n, \Psi_k, ...)$$

Experimental tools

How does v_n fluctuate	How does ψ_n fluctuate	How do v_n and v_m correlate	How do ψ_n and ψ_m correlate
$P(v_n)$	$P(\Psi_n)$	$P(v_m, v_n, v_k, ...)$	$P(\Psi_m, \Psi_n, \Psi_k, ...)$

initial shape and shape fluctuations



$S_A = S_B$, $R_A < R_B$ $\Longrightarrow$ $T_A > T_B$ $\Longrightarrow$ $\langle p_t\rangle_A > \langle p_t\rangle_B$

↓

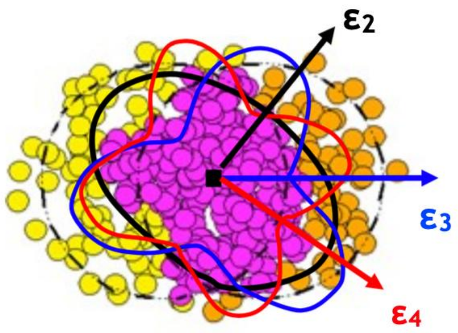
$\langle p_T\rangle$ and its fluctuations

initial size and size fluctuations

Experiment tools: Anisotropic flow and $[p_T]$

Figure made by You Zhou

Initial state $\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$

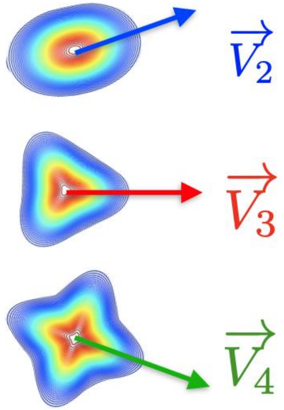


anisotropic spatial distribution

System expansion

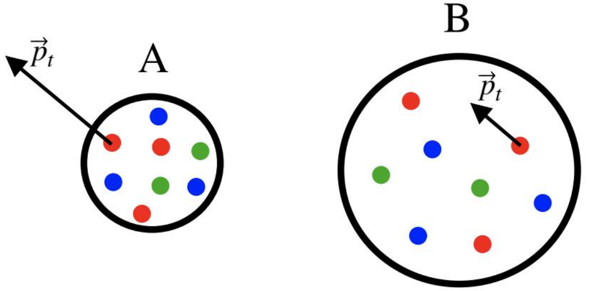
Final state $\vec{V}_n = v_n e^{in\Psi_n}$

anisotropic momentum distributions



$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, ..., \Phi_m, \Phi_n, \Phi_k, ...)$ ⇒ $P(v_m, v_n, v_k, ..., \Psi_m, \Psi_n, \Psi_k, ...)$

G. Giacalone, PRC 102 (2020) 2, 024901



$S_A = S_B$, $R_A < R_B$ $\Longrightarrow$ $T_A > T_B$ $\Longrightarrow$ $\langle p_t \rangle_A > \langle p_t \rangle_B$

Experimental tools

- How does v_n fluctuate — $P(v_n)$
- How does ψ_n fluctuate — $P(\Psi_n)$
- How do v_n and v_m correlate — $P(v_m, v_n, v_k, ...)$
- How do ψ_n and ψ_m correlate — $P(\Psi_m, \Psi_n, \Psi_k, ...)$
- $<p_T>$ and its fluctuations

v_n^2–$<p_T>$ correlations

Considering $v_n \propto \varepsilon_n$, $[p_T] \propto E_0$

$$\rho(v_n^2, [p_\mathrm{T}]) = \rho(\varepsilon_n^2, [E_0])$$

final-state model calculation

Initial-state model estimation

P. Bozek, PRC 93, 044908 (2016)
G. Giacalone etc, PRC 103, 024909 (2021)

Ion possibilities at the LHC

- ^{129}Xe–^{129}Xe@5.44 TeV
- ^{208}Pb–^{208}Pb@5.02, 5.36 TeV

LHCb SMOG2 (talk by Giacomo Graziani on Wednesday):

- ^{208}Pb–X(^{16}O, ^{20}Ne, ^{40}Ar, etc)

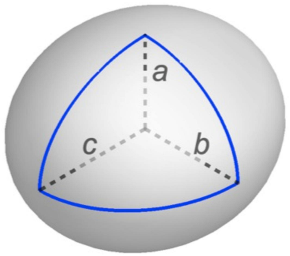
SMOG2: Status, species available, prospects for collectivity studies	*Giacomo Graziani*
4/3-006 - TH Conference Room, CERN	10:50 - 11:15

New possibilities in the future:

- ^{16}O–^{16}O (planned in 2025)
- ^{20}Ne–^{20}Ne
- ^{40}Ca–^{40}Ca
- ^{48}Ca–^{48}Ca

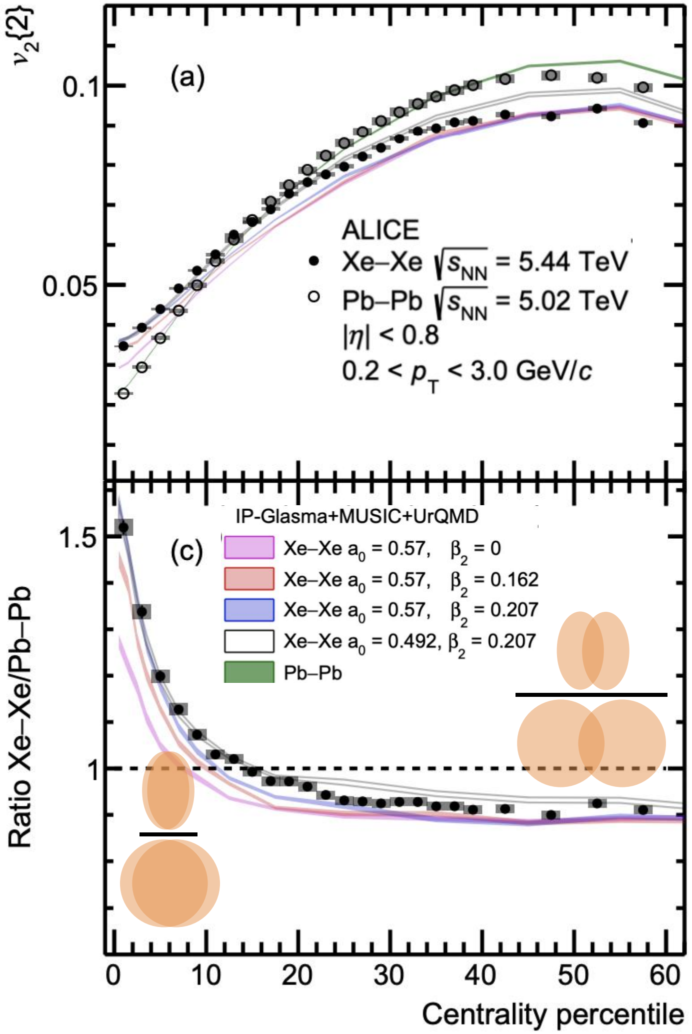
^{129}Xe nucleus: deformed and triaxial shape

^{129}Xe: $\beta_2 \approx 0.18$

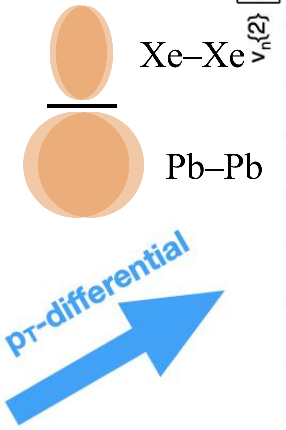


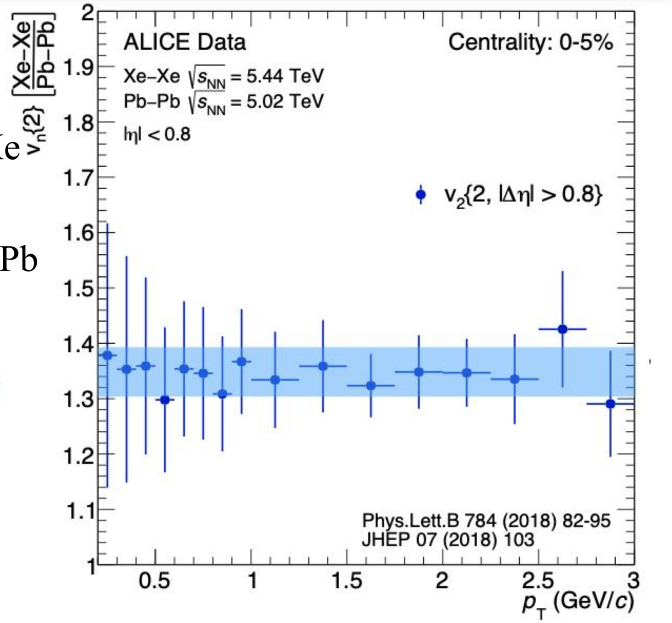
ALICE-PUBLIC-2018-003
Figure from B. Bally etc, PRL. 128 (2022) 082301

- Anisotropic flow shows promising sensitivity to β_2 in Xe–Xe/Pb–Pb, while final-state effects are largely cancelled out.
  - Z. Lu etc, EPJA 59 (2023) 11, 279
  - H. Song etc, arxiv: 2403.07441
  - C. Shen etc, arxiv: 2409.19064
- LHC measurements provide unique constrains on the value of β_2
  - ATLAS, PRC 107 (2023) 054910
  - ALICE, arxiv: 2409.04343

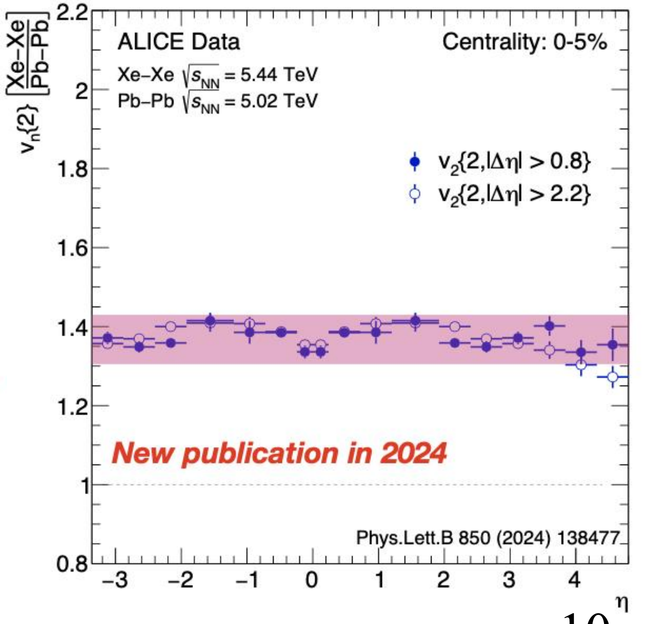


ALICE, arxiv: 2409.04343
systematic investigations on
11 flow-related observables





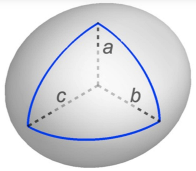
In 0~5% centrality



^{129}Xe nucleus: deformed and triaxial shape

^{129}Xe: $\beta_2 \approx 0.18$, $\gamma \approx 30^\circ$

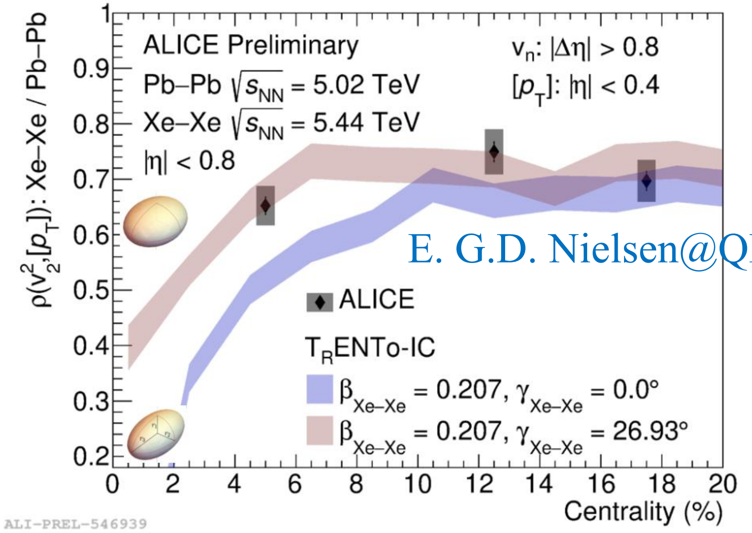
ALICE-PUBLIC-2018-003
B. Bally etc, PRL. 128 (2022) 082301



$a \neq b \neq c$

- Pearson correlation between v_n and $[p_T]$ serves as an essential probe to triaxial shape

  B. Bally etc, PRL. 128 (2022) 082301
  J. Jia etc, PRC 105 (2022) 4, 044905
  J. Jia etc, Phys.Rev.C 105 (2022) 1, 014906

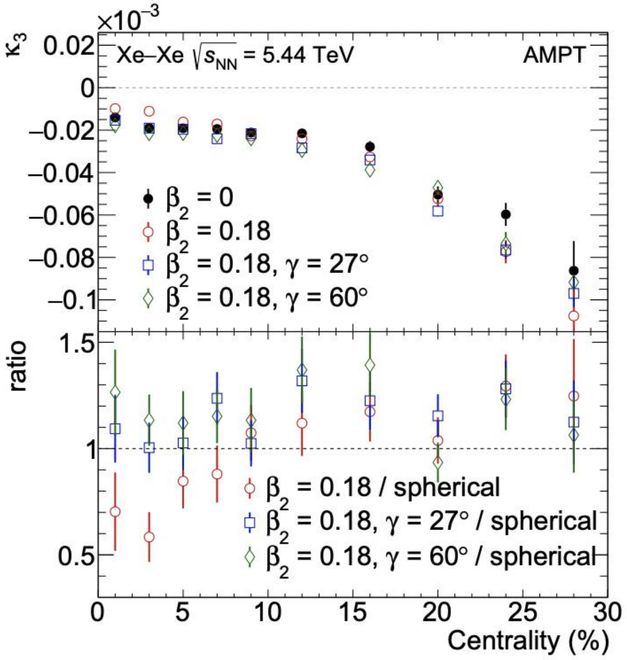


E. G.D. Nielsen@QM2023

$$\rho(v_n^2,[p_t]) = \frac{\langle \delta v_n^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}},$$

Similar results confirmed by ATLAS
ATLAS, PRC 107 (2023) 054910

- New proposal of multi-particle $[p_T]$ correlations
- Third order $[p_T]$ cumulant κ_3 shows strong dependence on γ in most central collisions



$$\kappa_m = \langle [p_T^{(m)}] \rangle - \sum_{k=1}^{m-1} \binom{m-1}{k-1} \langle [p_T^{(m-k)}] \rangle \kappa_k .$$

Final state cumulant	Initial state cumulant	Liquid-drop model
κ_2	$\left\langle \left(\frac{\delta d_\perp}{d_\perp}\right)^2 \right\rangle$	$\frac{1}{32\pi}\langle \beta_2^2 \rangle$
κ_3	$\left\langle \left(\frac{\delta d_\perp}{d_\perp}\right)^3 \right\rangle$	$\frac{\sqrt{5}}{896\pi^{3/2}}\langle \cos(3\gamma)\beta_2^3 \rangle$

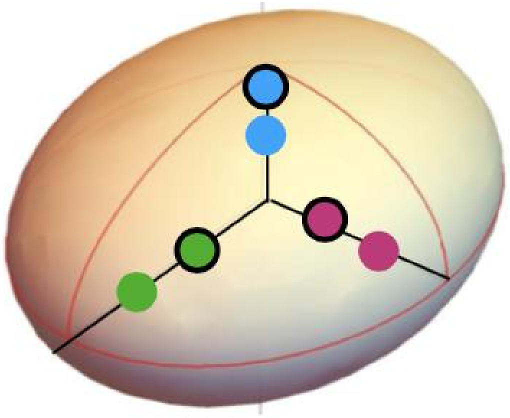
E. G.D. Nielsen etc., EPJA 60 (2024) 38

^{129}Xe nucleus: γ-soft structure

S. Zhao etc, PRL 133 (2024) 192301

Exploring the Nuclear Shape Phase Transition in Ultra-Relativistic ^{129}Xe+^{129}Xe Collisions at the LHC

Shujun Zhao,[1] Hao-jie Xu,[2,3] You Zhou,[4] Yu-Xin Liu,[1,5,6] and Huichao Song[1,5,6]



$\gamma = 30°$

$r_1 \neq r_2 \neq r_3$

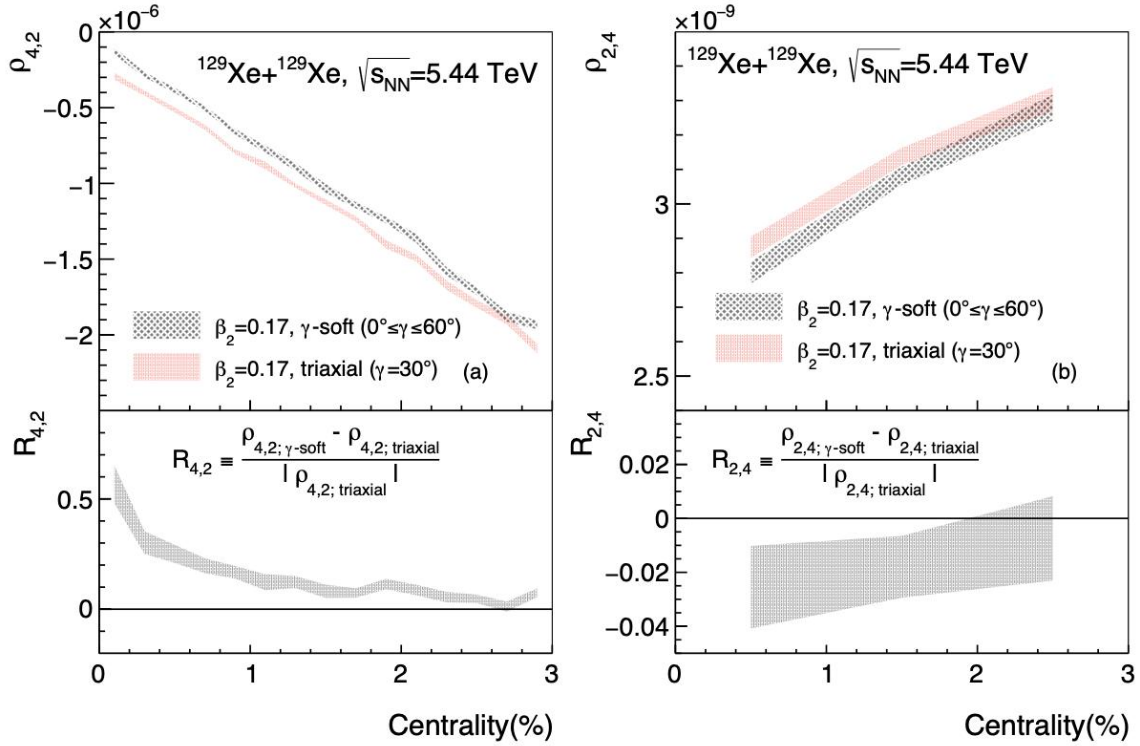
triaxial

- Study the nuclear shape phase transition in ^{129}Xe
- γ is the relation between r_1, r_2 and r_3; To probe γ fluctuations, we need 6-particle correlations

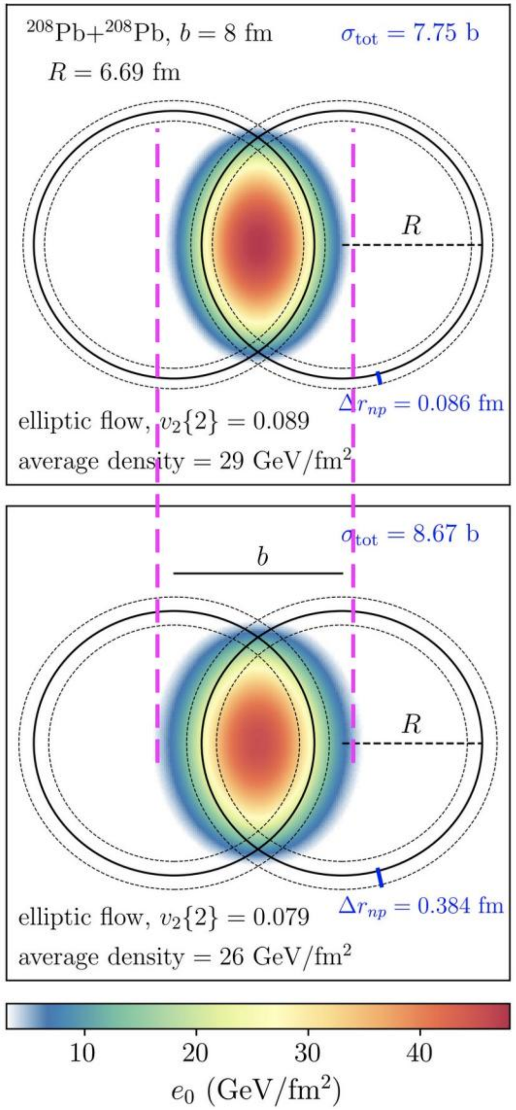
$$\rho_{4,2} \equiv \left(\frac{\langle\varepsilon_2^4 \delta d_\perp^2\rangle}{\langle\varepsilon_2^4\rangle\langle d_\perp\rangle^2}\right)_c \equiv \frac{1}{\langle\varepsilon_2^4\rangle\langle d_\perp\rangle^2}\left[\langle\varepsilon_2^4\delta d_\perp^2\rangle + 4\langle\varepsilon_2^2\rangle^2\langle\delta d_\perp^2\rangle - \langle\varepsilon_2^4\rangle\langle\delta d_\perp^2\rangle - 4\langle\varepsilon_2^2\rangle\langle\varepsilon_2^2\delta d_\perp^2\rangle - 4\langle\varepsilon_2^2\delta d_\perp\rangle^2\right]$$

$$\rho_{2,4} \equiv \left(\frac{\langle\varepsilon_2^2 \delta d_\perp^4\rangle}{\langle\varepsilon_2^2\rangle\langle d_\perp\rangle^4}\right)_c \equiv \frac{1}{\langle\varepsilon_2^2\rangle\langle d_\perp\rangle^4}\left[\langle\varepsilon_2^2\delta d_\perp^4\rangle - 6\langle\varepsilon_2^2\delta d_\perp^2\rangle\langle\delta d_\perp^2\rangle - 4\langle\varepsilon_2^2\delta d_\perp\rangle\langle\delta d_\perp^3\rangle - \langle\varepsilon_2^2\rangle\langle\delta d_\perp^4\rangle + 6\langle\varepsilon_2^2\rangle\left(\langle\delta d_\perp^2\rangle\right)\right].$$

- Newly proposed 6-particle correlations allow to differentiate triaxial (fixed γ = 30°) and γ-soft (fluctuating γ) structures.
- Difference in $\rho_{4,2}$ can reach 50% in the ultra-central collisions.

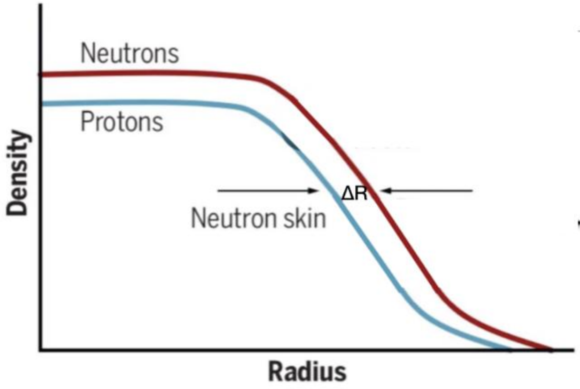


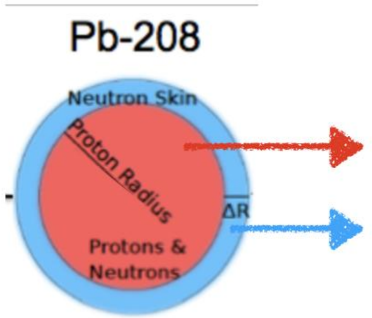
^{208}Pb nucleus: neutron skin



G. Giacalone etc, PRL 131 (2023) 20, 202302

Figure from You Zhou





$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left([r-R(\Theta,\Phi)]/a\right)}$$

$$\rho_p(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left([r_p-R_p(\Theta,\Phi)]/a_p\right)}$$

$$\rho_n(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left([r_n-R_n(\Theta,\Phi)]/a_n\right)}$$

a_p = 0.448 fm,
R_p = 6.680 fm,
r_p = 5.436 fm,
R_n = 6.690 fm

Large neutron skin → Large Initial size → Smaller $[p_T]$ & stronger $[p_T]$ fluctuations

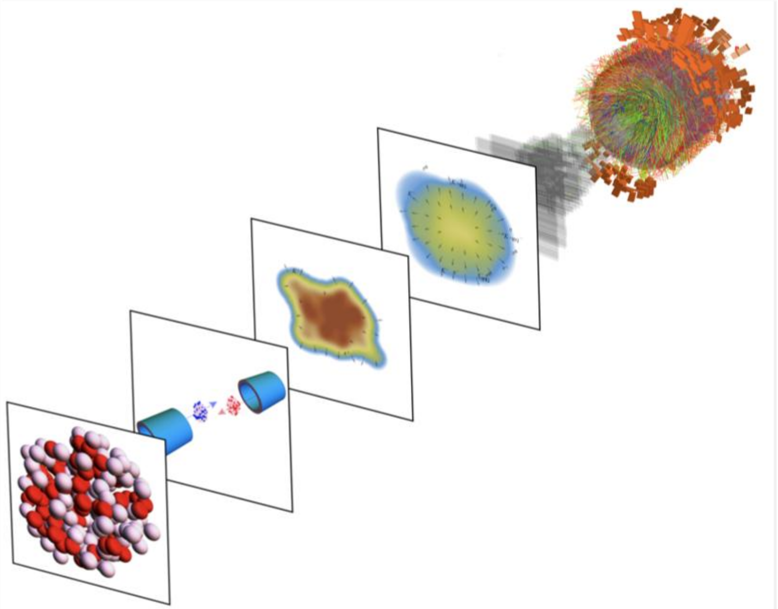
Large Initial size → Weaker flow fluctuations

^{208}Pb nucleus: neutron skin

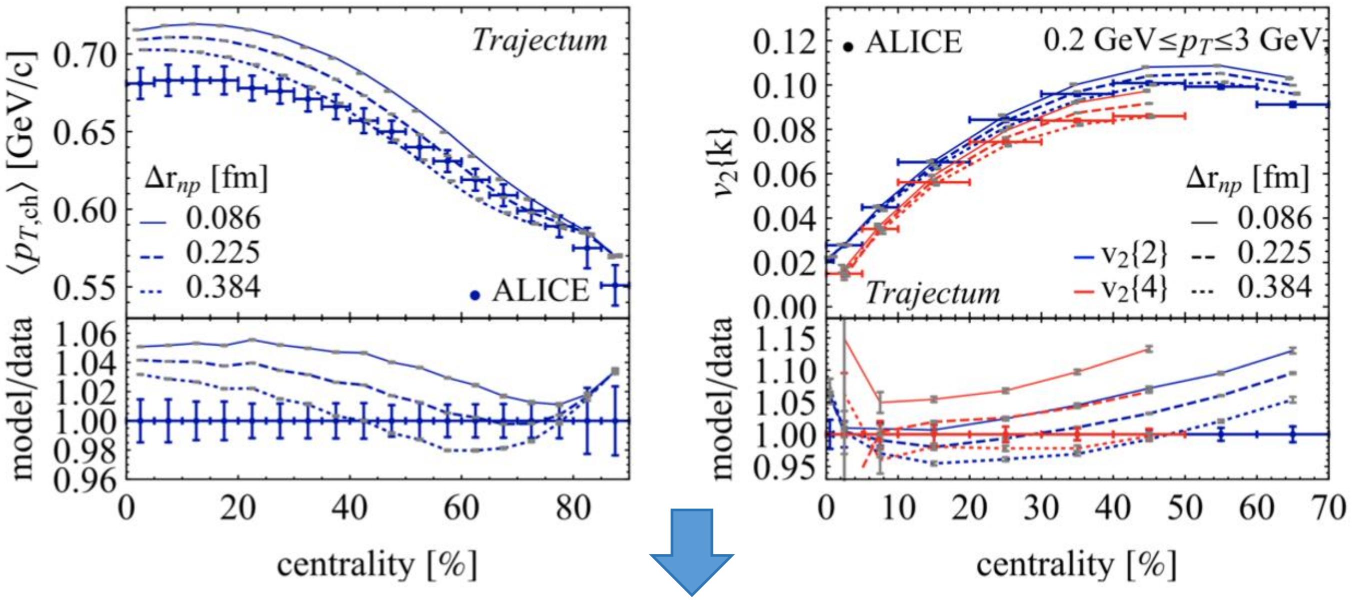
Thick-skinned: Using heavy-ion collisions at the LHC, scientists determine the thickness of neutron "skin" in lead-208 nuclei

This is the first measurement of the neutron skin of lead-208 using exchanges predominantly involving gluons and it can provide insight into the structure of nuclei and neutron stars

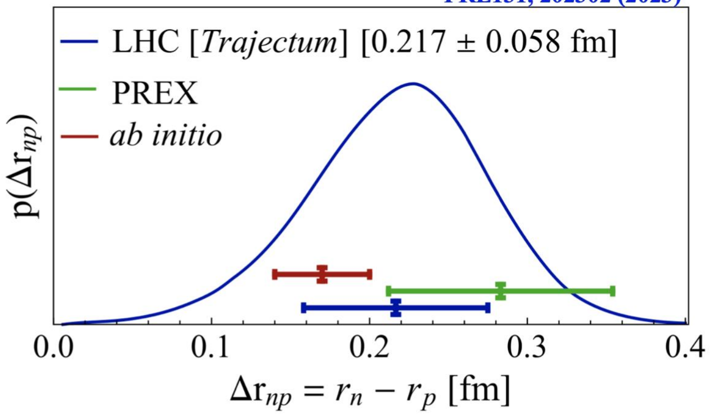
15 NOVEMBER, 2023 | By Naomi Dinmore



CERN News



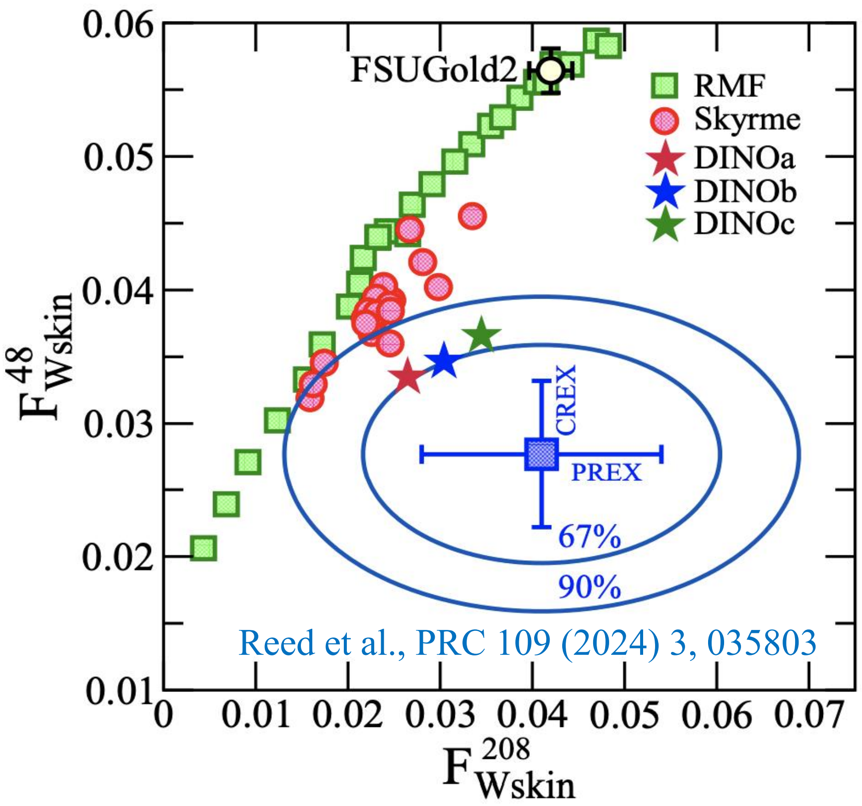
PRL131, 202302 (2023)



- Extracted neutron skin [0.217 ± 0.058(theo.) fm] agrees with PREX II measurements [0.278 ± 0.078(exp.) ± 0.012(theo.) fm]

PREX, PRL 126 (2021) 17, 172502

^{40}Ca and ^{48}Ca nucleus: neutron skin

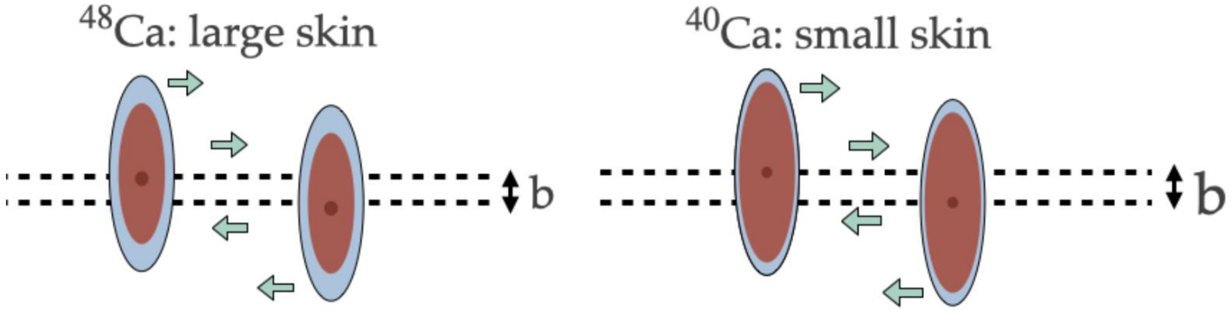


- Discrepancy between PREX and CREX results for ^{48}Ca

CREX collaboration, PRL 129 (2022) 4, 042501
P. Reinhard etc, PRL 127 (2021) 23, 232501 and PRL 129 (2022) 23, 232501

No model has been able to simultaneously reproduce within 1σ the PREX and CREX results.

- ^{40}Ca: 20 protons + 20 neutrons ➡ near zero neutron skin, enable precision extraction of ^{48}Ca skin

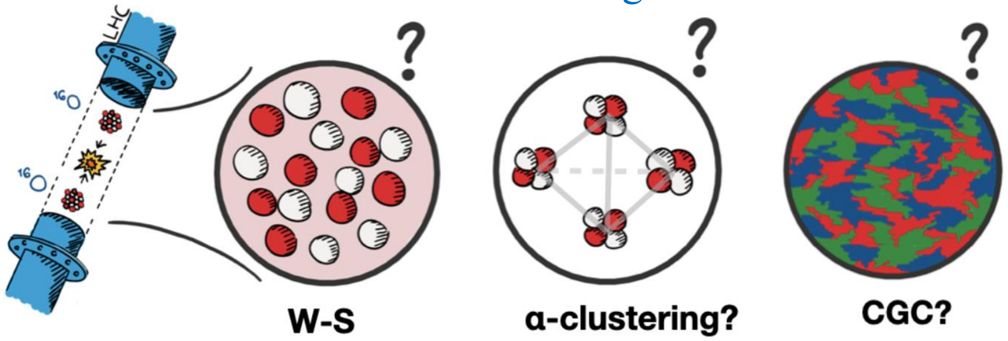


- The precise measurement at the LHC can provide a strong pin on this problem
- Isobars runs operated in RHIC-STAR have been proved they are precision tools to nuclear structure
- The best opportunity to measure neutron skin at the LHC

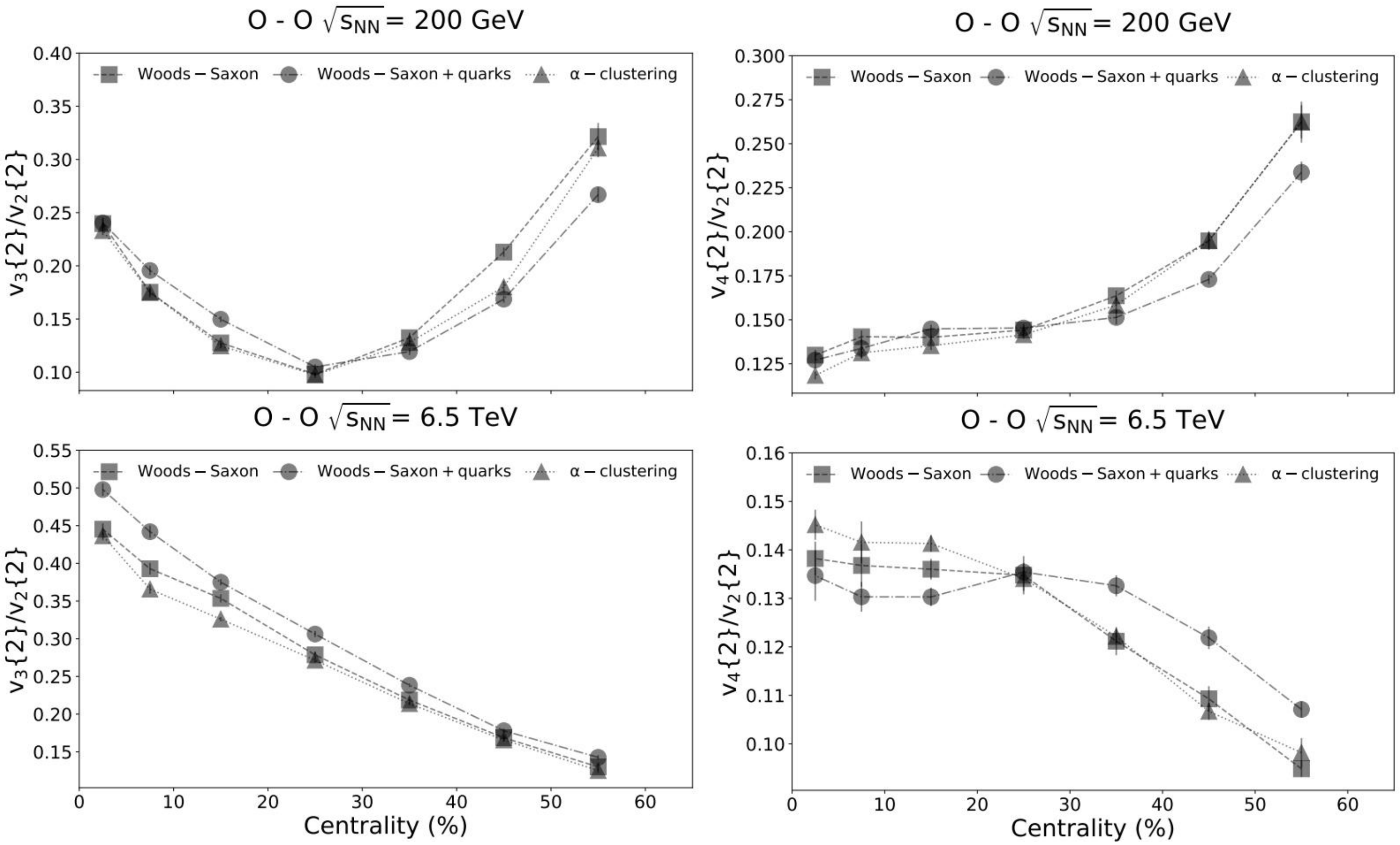
^{16}O nucleus: α-cluster

LHC Plan: $\sqrt{s_{NN}}$ = 7 TeV ~0.5 /nb, within 1-week period in 2025

Figure from You Zhou



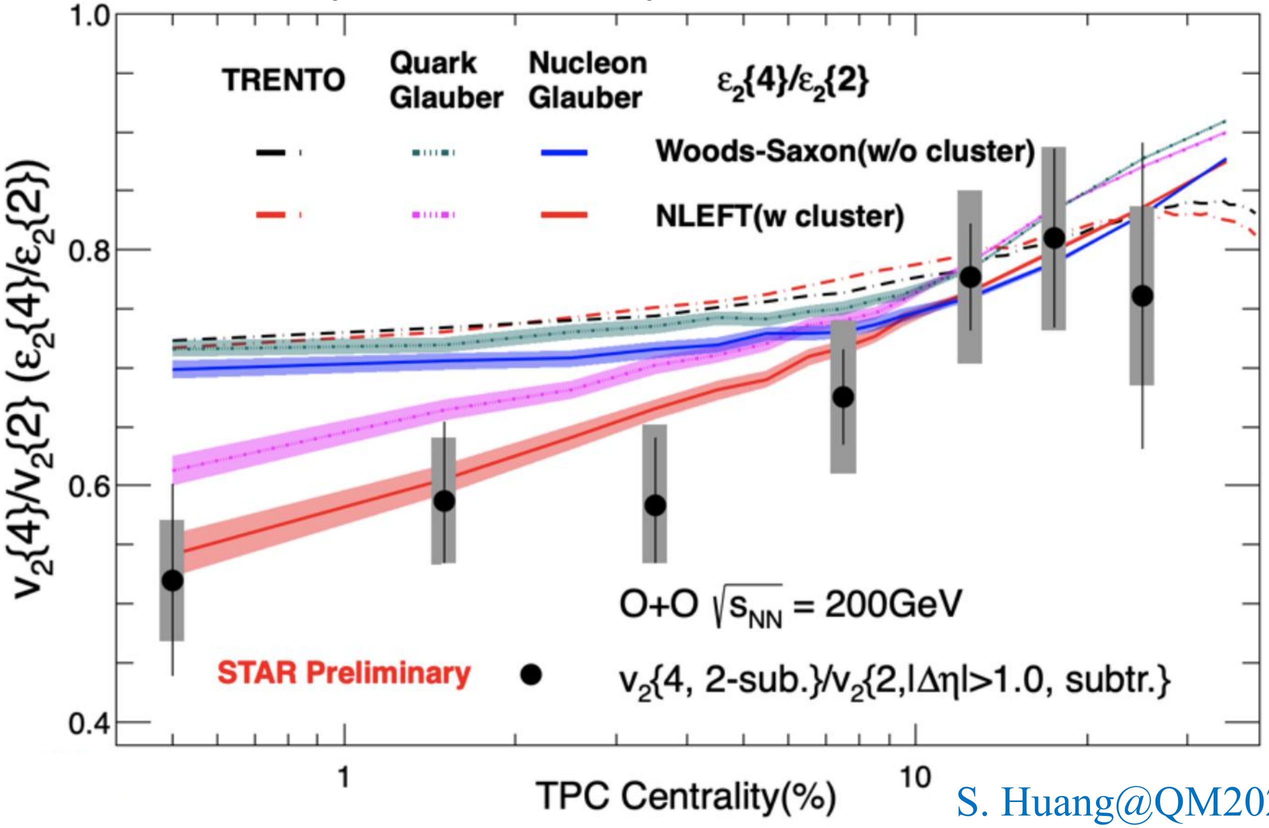
- α-structure may exist, but large fluctuations due to small system size
- ratios of harmonics (e.g. $v_3\{2\}/v_2\{2\}$ and $v_4\{2\}/v_2\{2\}$) and ratios of multi-particles (e.g. $v_2\{4\}/v_2\{2\}$) are able to find the evidence of α-cluster
- LHC energies has better distinguishability



N. Summerfield etc, PRC 104, 041901 (2021)

^{16}O nucleus: α-cluster

Preliminary ^{16}O–^{16}O by the STAR collaboration



S. Huang@QM2023

- $v_2\{4\}/v_2\{2\}$ with nucleon Glauber + NLEFT agrees with STAR measurement
- Calculations (except TRENTO) shows strong influences by the existence of α-cluster

Many theorerical predictions has already been performed for ^{16}O–^{16}O at RHIC and LHC energies.

Y. Wang etc, PRC 109 (2024) 5, L051904

Exploring the compactness of α cluster in ^{16}O nuclei with relativistic ^{16}O+^{16}O collisions

Yuanyuan Wang,[1] Shujun Zhao,[1] Boxing Cao,[1] Hao-jie Xu,[2,3,*] and Huichao Song[1,4,5,†]

G. Giacalone etc, arXiv: 2402.05995

The unexpected uses of a bowling pin: exploiting ^{20}Ne isotopes for precision characterizations of collectivity in small systems

Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]

C. Zhang etc, arXiv: 2404.08385

***Ab-initio* nucleon-nucleon correlations and their impact on high energy ^{16}O+^{16}O collisions**

Chunjian Zhang,[1,2,3,*] Jinhui Chen,[1,2,†] Giuliano Giacalone,[4,‡] Shengli Huang,[3,§] Jiangyong Jia,[3,5,¶] and Yu-Gang Ma[1,2,**]

X. Zhao etc, arXiv:2404.09780

Nuclear cluster structure effect in ^{16}O+^{16}O collisions at the top RHIC energy

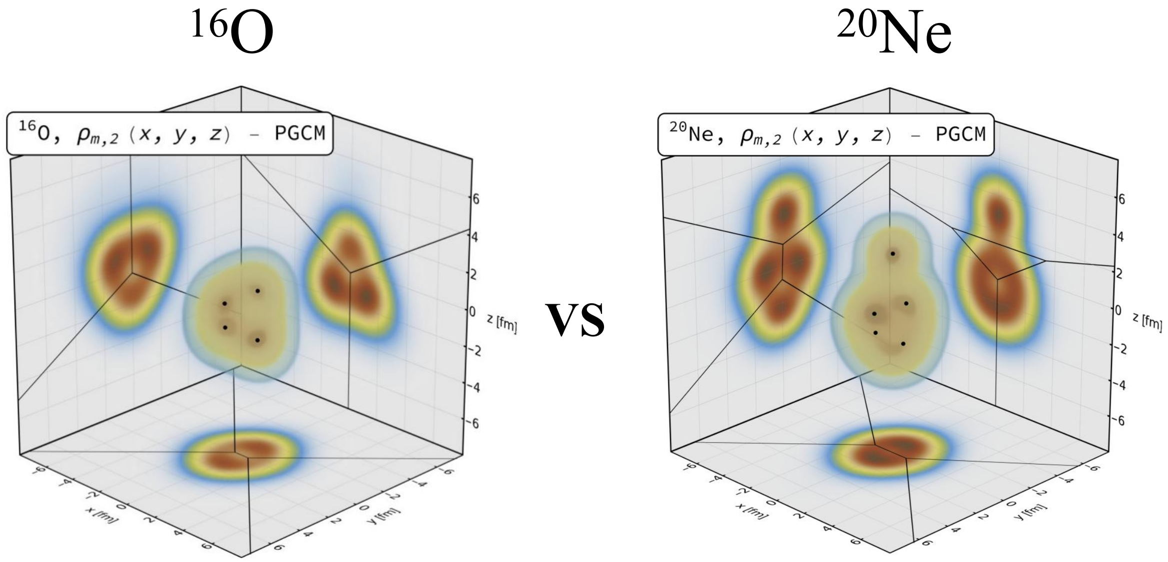
Xin-Li Zhao,[1,2,3] Guo-Liang Ma,[2,3,*] You Zhou,[4,†] Zi-Wei Lin,[5] and Chao Zhang[6]

^{20}Ne nucleus: α-cluster, bowling pin shape

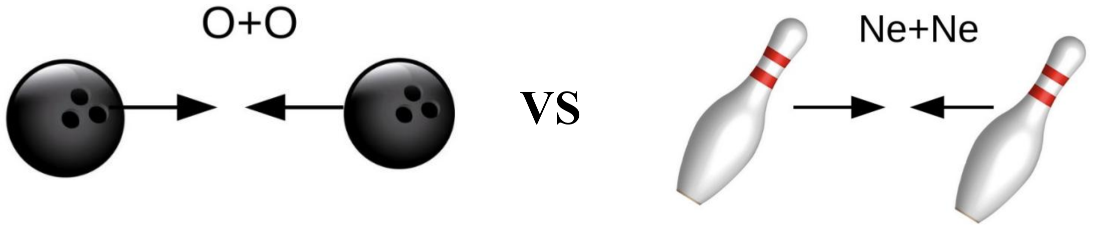
- The drawback of light-ion collisions: nuclear shape effect is only a small correction compared to large density fluctuations.

- ^{16}O–^{16}O vs ^{20}Ne–^{20}Ne where ^{20}Ne has a shape like ^{16}O+α
- Uncertainties are largely cancelled in the ratios of two system with similar mass

- Well understood light ions structure serve as important inputs for initial-state geometry
  - ➡ Is there a QGP in small system?
  - ➡ Perfect opportunity to tune theory



G. Giacalone etc, arXiv: 2402.05995



$$\frac{v_2\{2\}_{\mathrm{NeNe}}}{v_2\{2\}_{\mathrm{OO}}} = \begin{cases} 1.170(8)_{\mathrm{stat.}}(30)^{Traj.}_{\mathrm{syst.}}(0)^{\mathrm{str.}}_{\mathrm{syst.}} & \text{(NLEFT)}, \\ 1.139(6)_{\mathrm{stat.}}(27)^{Traj.}_{\mathrm{syst.}}(28)^{\mathrm{str.}}_{\mathrm{syst.}} & \text{(PGCM)}, \end{cases}$$

Summary

- The NS studies at the high energies are complementary to low energies: description of NS through the entire energy scale from MeV to TeV

- Operated runs at the LHC (Xe–Xe, Pb–Pb) already provides valuable inputs into the NS
- The knowledge of NS benefits the physics in the central collisions

- Planned ^{16}O–^{16}O run is expected to confirm whether ^{16}O has α-cluster structure
- Ratios of ^{16}O–^{16}O and ^{20}Ne–^{20}Ne cancel most of uncertainties and final-state effect
  ➡ Well understood NS inputs help to understand the puzzles in small system

- ^{40}Ca–^{40}Ca and ^{48}Ca–^{48}Ca runs will slove the puzzle of discrepancy between PREX and CREX. The best opportunity to measure neutron skin at the LHC