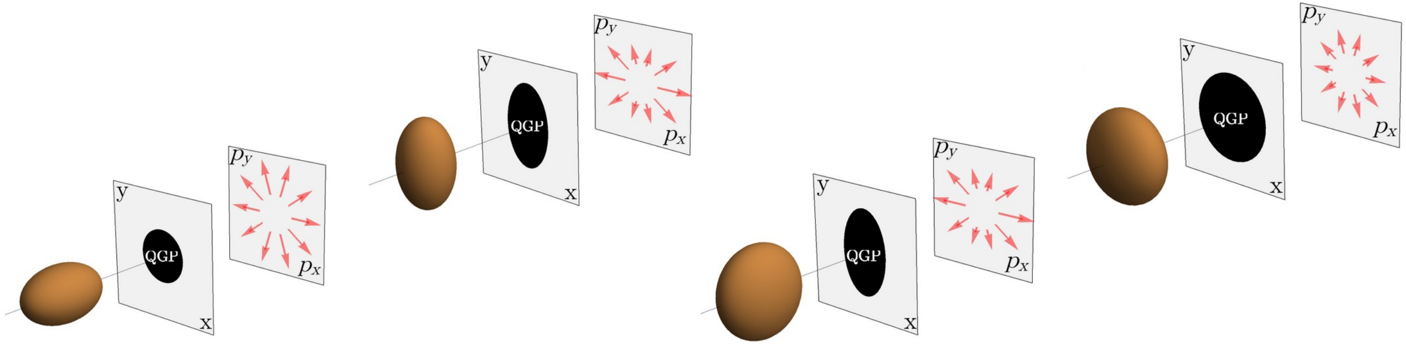
Imaging Nuclear Ground States with High-Energy Collisions

Giuliano Giacalone

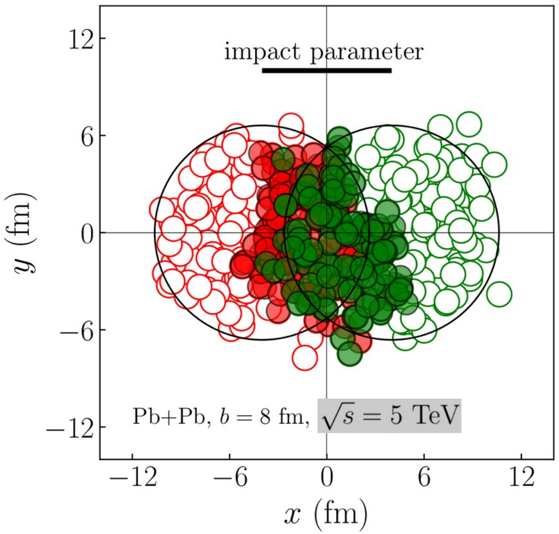
January 26, 2026

Exploring the quantum chromodynamics phase diagram: from hadrons and nuclei to matter under extreme conditions (HADNUCMAT)

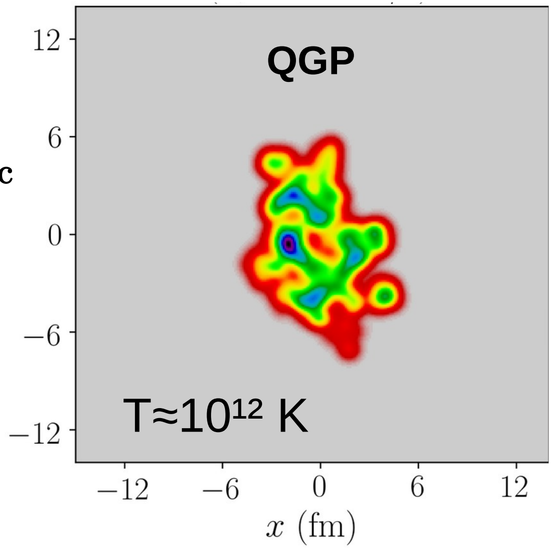
26–28 gen 2026
Facultat de Física, Universitat de Barcelona
Europe/Madrid fuso orario



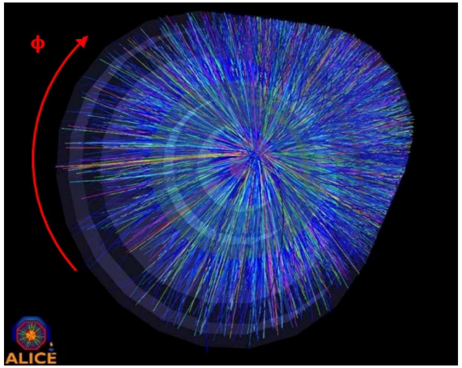
The perfect QCD fluid – 25 years later



≈ 1 fm/c



hydro



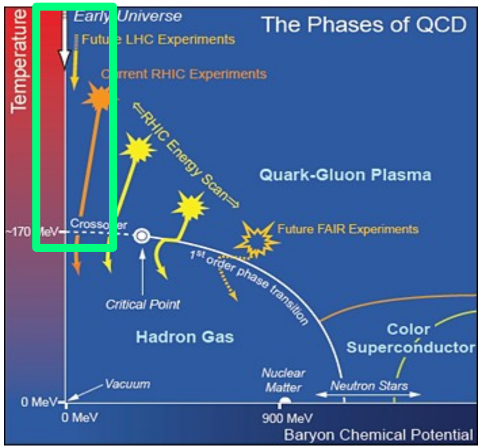
Relativistic fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$

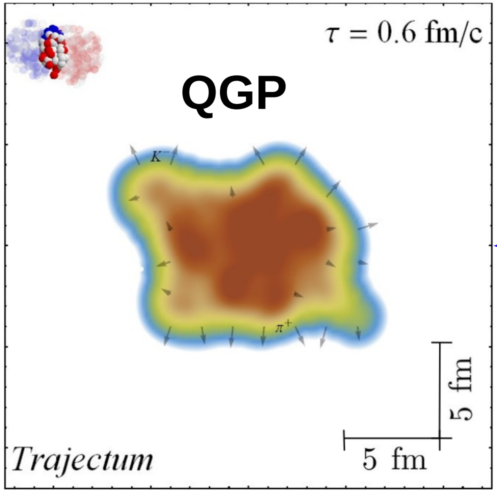
Equation of state from lattice QCD

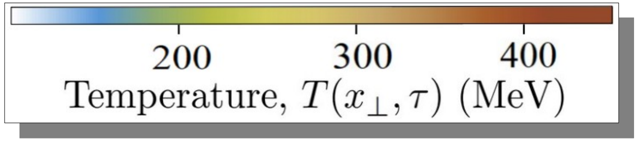
[HoTQCD collaboration, PRD **90** (2014) 094503]

Fluid is viscous (η/s **,** ζ/s **, …)**

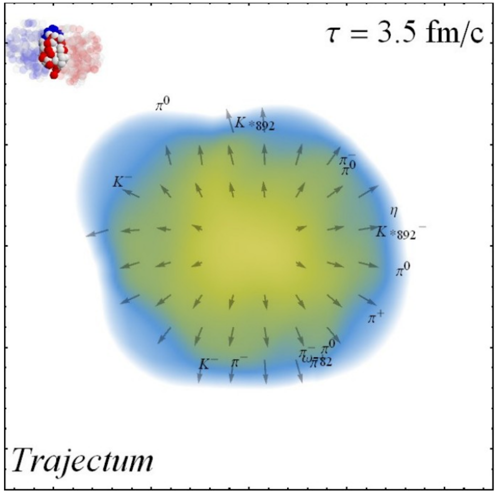
[Romatschke & Romatschke, arXiv:1712.05815]

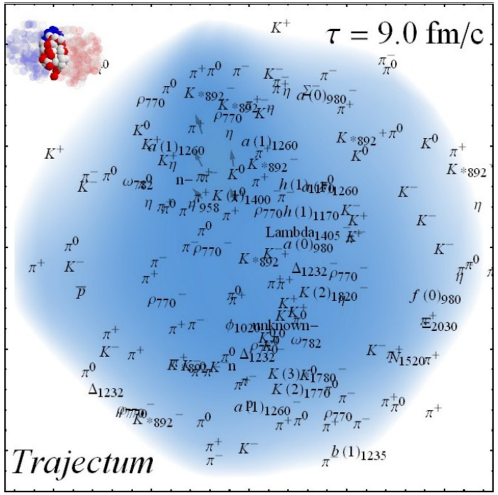


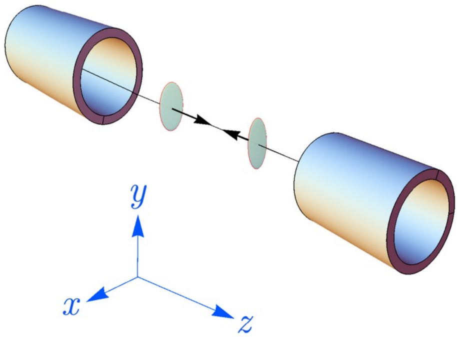




RECONSTRUCTING THE INITIAL STATE



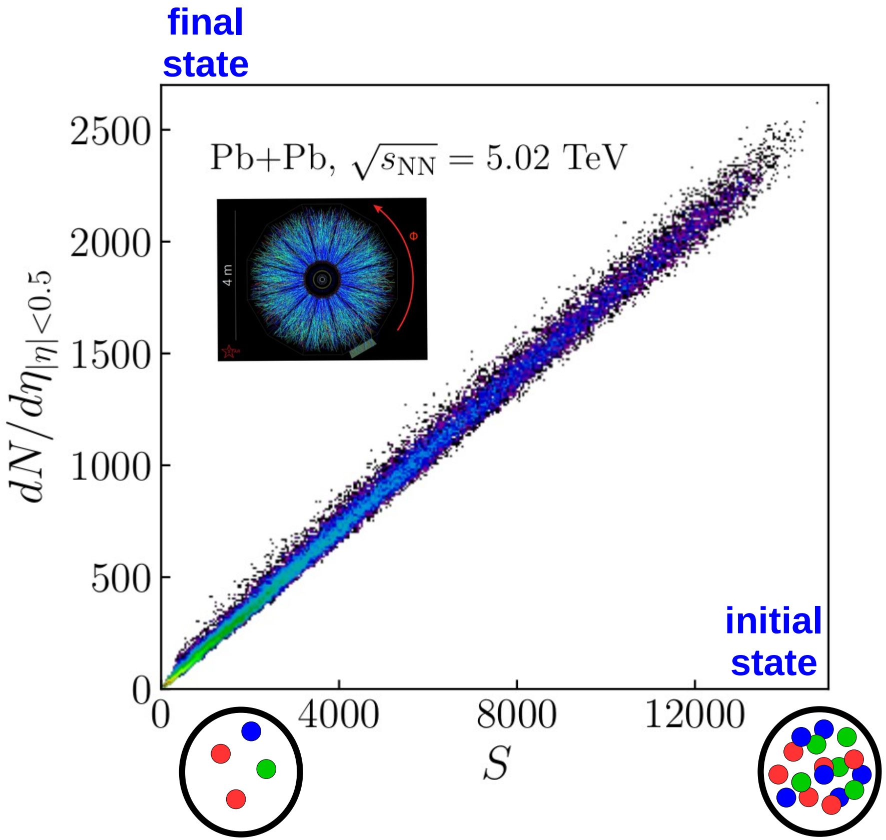


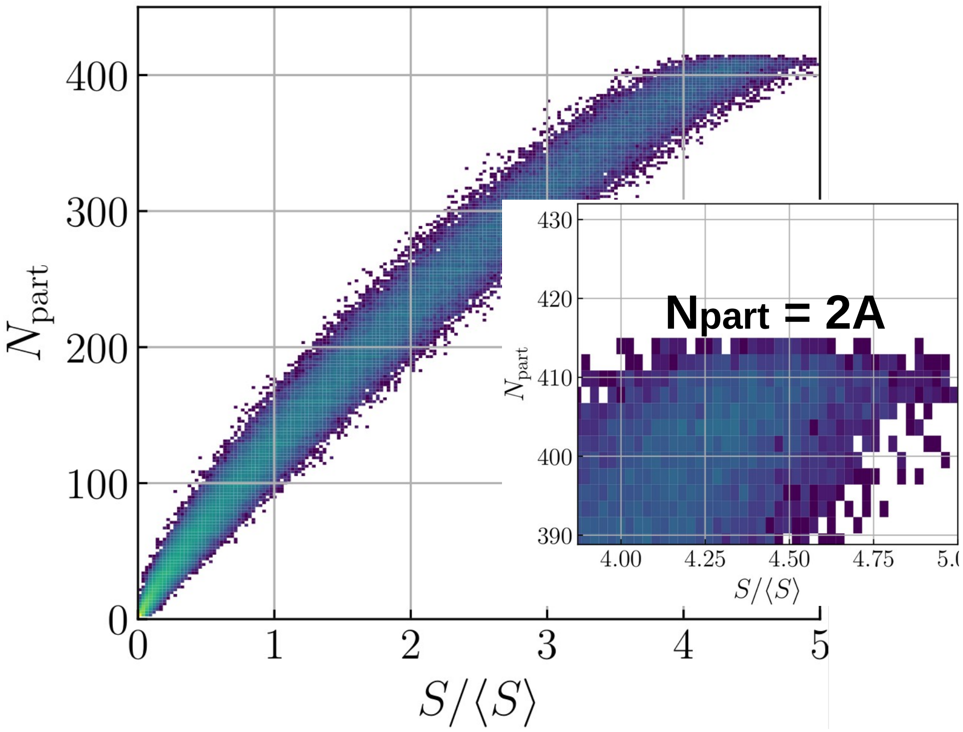


Understanding observables from thermo/hydrodynamic considerations

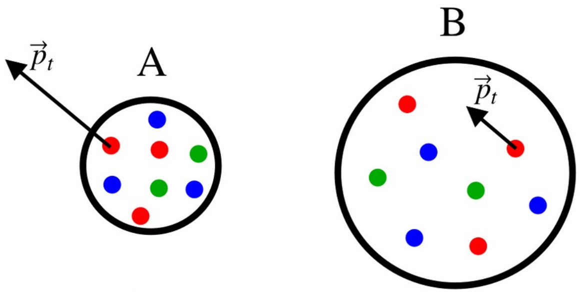
Ideal gas (high temperature) = entropy proportional to the particle number

Expansion is nearly isentropic = entropy is conserved ("ideal fluid")





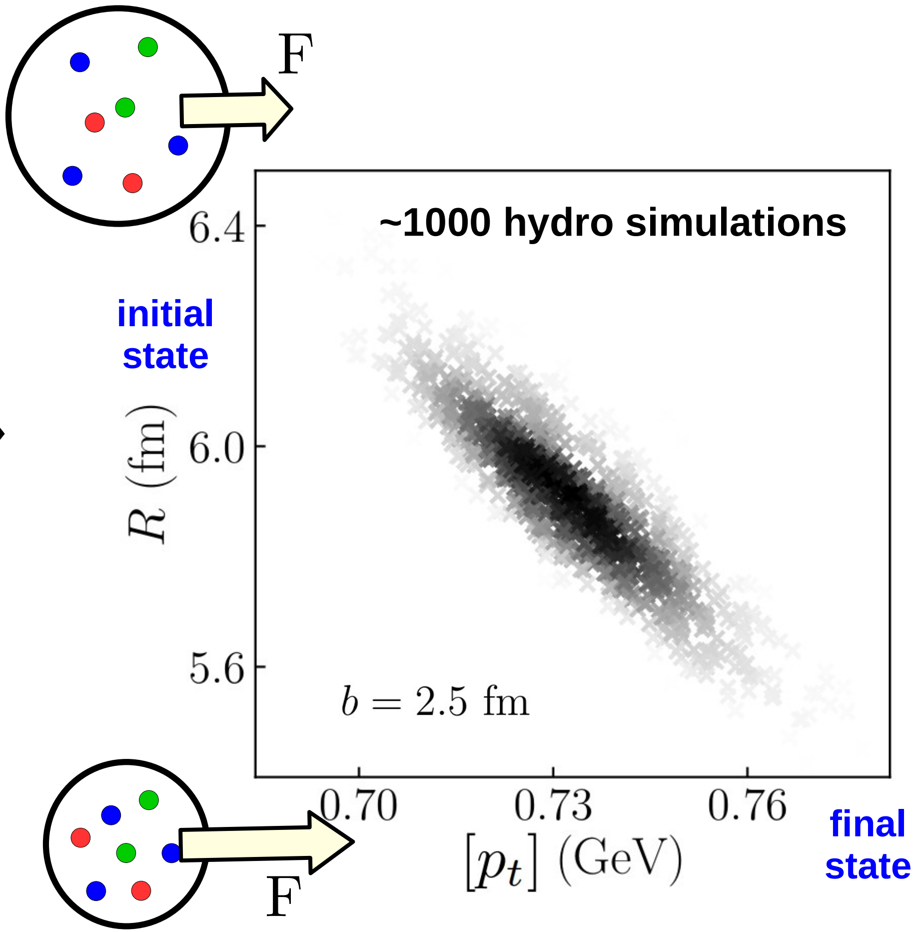
Understanding observables from thermo/hydrodynamic considerations



$$\begin{array}{c} S_A = S_B \\ R_A < R_B \end{array} \Longrightarrow T_A > T_B \Longrightarrow \langle p_t \rangle_A > \langle p_t \rangle_B$$

hydrodynamics: $F = -\nabla P$ → **1/R**

R = radius of the QGP

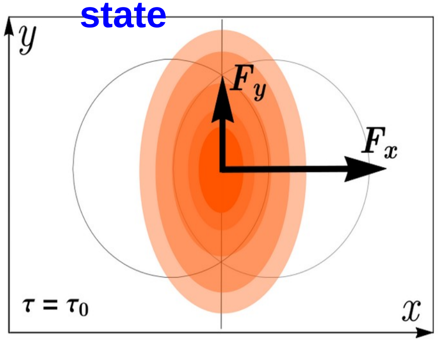


Average transverse momentum measures the initial size / gradients

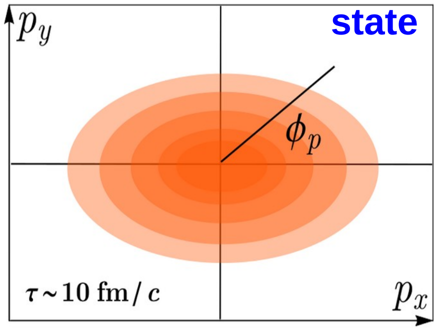
Understanding observables from thermo/hydrodynamic considerations

Denote by ε_2 the spatial ellipticity of the QGP

initial state



final state



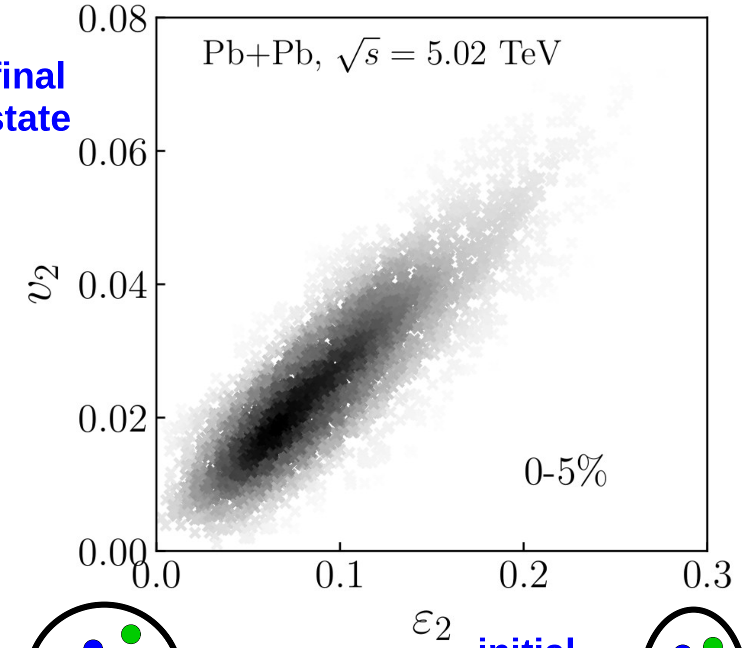
$$F = -\nabla P$$

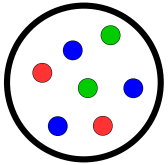
1/R

$$v_2 \propto \int_\phi e^{i2\phi} \frac{dN}{d\phi}$$

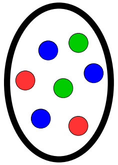
[Ollitrault, PRD **46** (1992) 229-245]
[Ollitrault, EPJA **59** (2023) 10]

final state



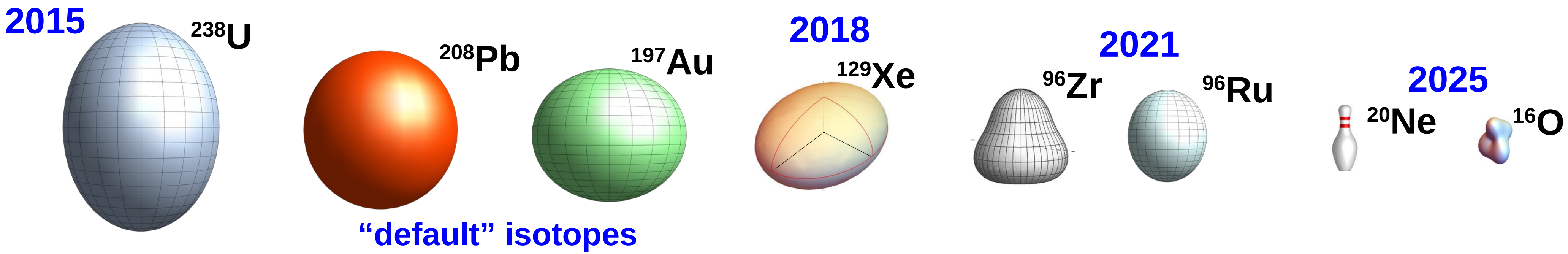


initial state



Elliptic flow measures the initial (elliptical) deformation

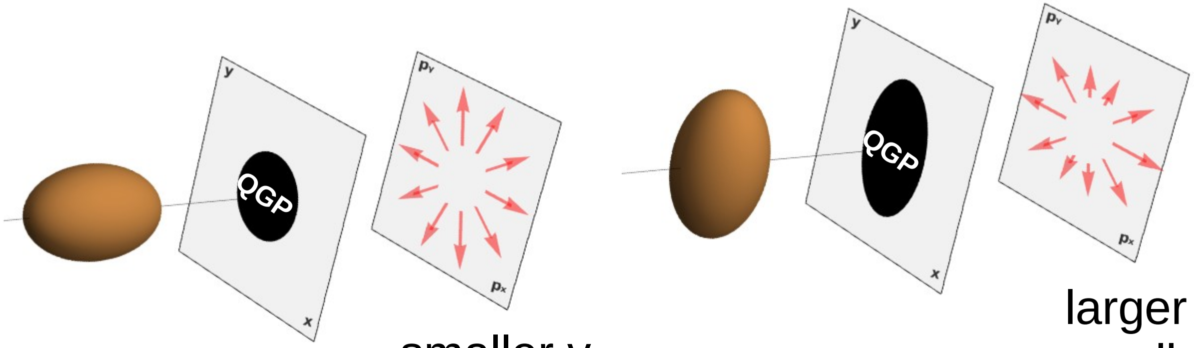
Many nuclei collided recently – Unprecedented opportunities



Classical pictures – Shapes as a source of anisotropic flow

$$F = -\nabla P$$

1/R

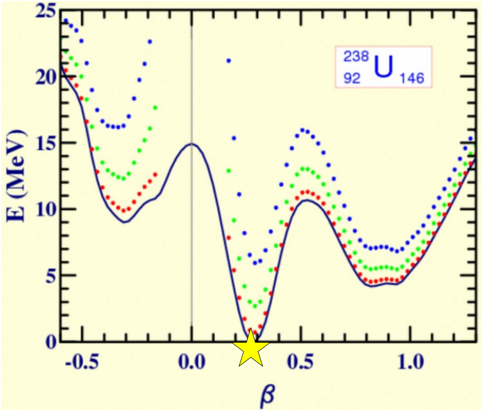


smaller v_2
larger $\langle p_T \rangle$

larger v_2
smaller $\langle p_T \rangle$

Input from energy density functional theory

– **Variational approach:** $\delta \frac{\langle \Phi | H | \Phi \rangle}{\langle \Phi | \Phi \rangle}$



$$\beta_{\ell m} \propto \left\langle Y_\ell^m(\theta,\phi)\; r^\ell \right\rangle$$

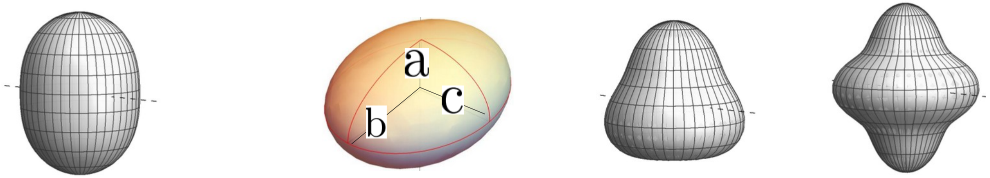
– **Intrinsic density at the relevant deformation:** $\rho(\mathbf{r}) = \sum_{s,t} \langle \Phi(\vec{\beta})|\; a^\dagger_{s,t}(\mathbf{r}) a_{s,t}(\mathbf{r}')\; |\Phi(\vec{\beta})\rangle \Big|_{\mathbf{r}=\mathbf{r}'}$

[Bally *et al.*, PRL **128** (2022) 8, 082301]
[Ryssens *et al.*, PRL **130** (2023) 21, 212302]

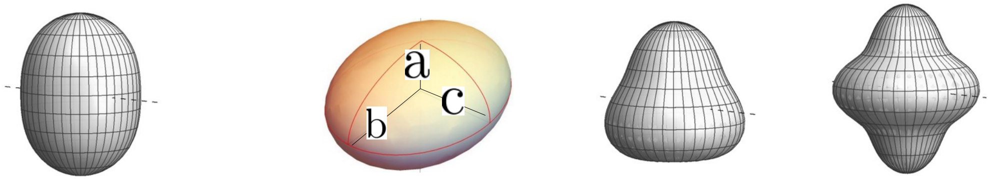
– **Find an appropriate parametrization of the intrinsic density:**

$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left([r-R(\theta,\phi)]/a\right)} \;,\quad R(\theta,\phi) = R_0\left[1+\beta_2\Big(\cos\gamma Y_{20}(\theta)+\sin\gamma Y_{22}(\theta,\phi)\Big)+\beta_3 Y_{30}(\theta)+\beta_4 Y_{40}(\theta)\right]$$

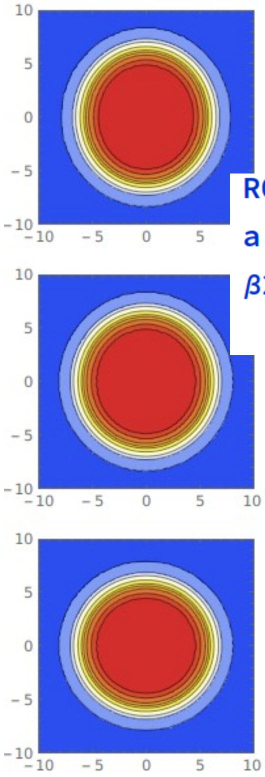
Woods-Saxon



$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left(\left[r-R(\theta,\phi)\right]/a\right)}\ , \quad R(\theta,\phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\theta)+\sin\gamma Y_{22}(\theta,\phi)\right)+\beta_3 Y_{30}(\theta)+\beta_4 Y_{40}(\theta)\right]$$

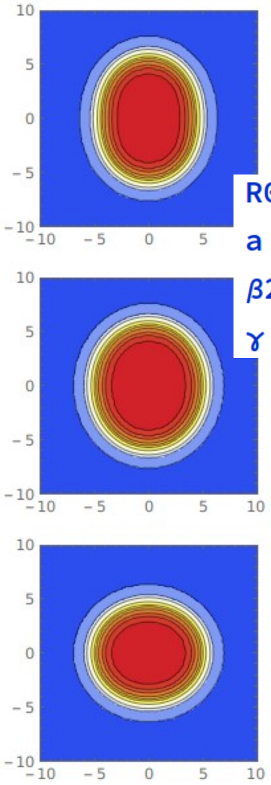


^{208}Pb



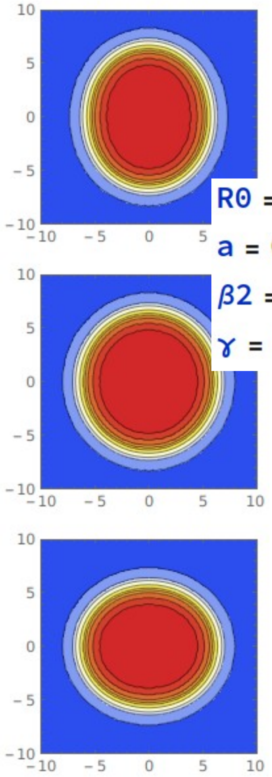
R0 = 6.64792;
a = 0.536756;
β2 = 0.062156;

^{129}Xe



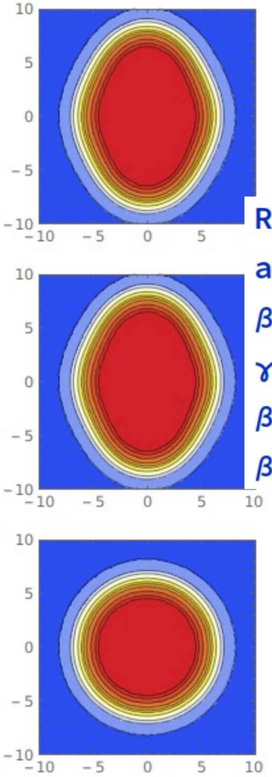
R0 = 5.60058;
a = 0.491644;
β2 = 0.206935;
γ = 27 / 180 Pi;

^{197}Au



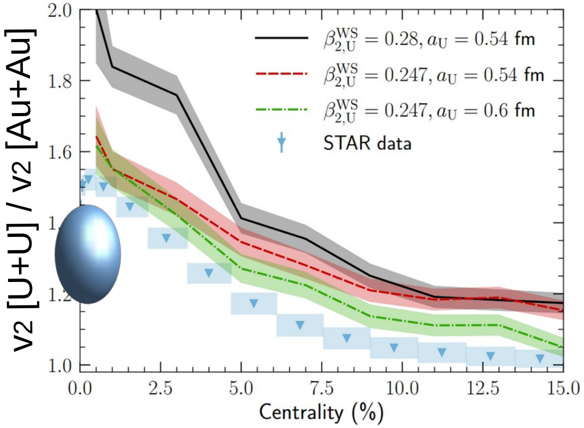
R0 = 6.56;
a = 0.48;
β2 = 0.135;
γ = 43 / 180 Pi;

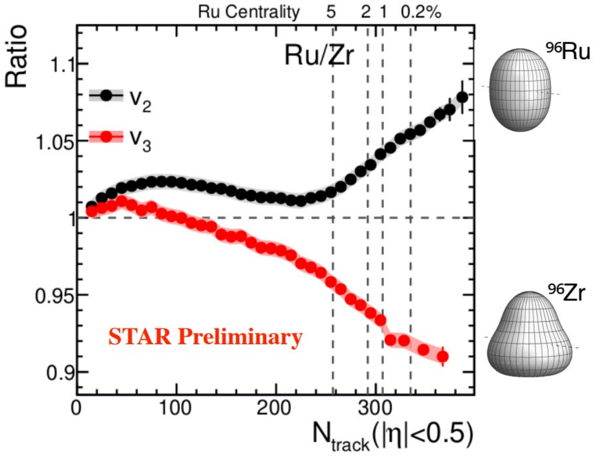
^{238}U

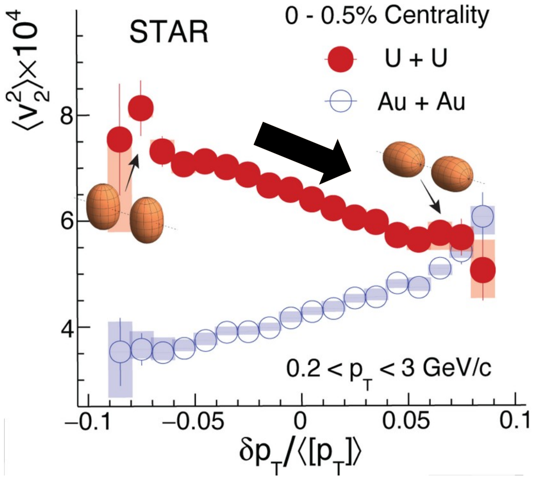


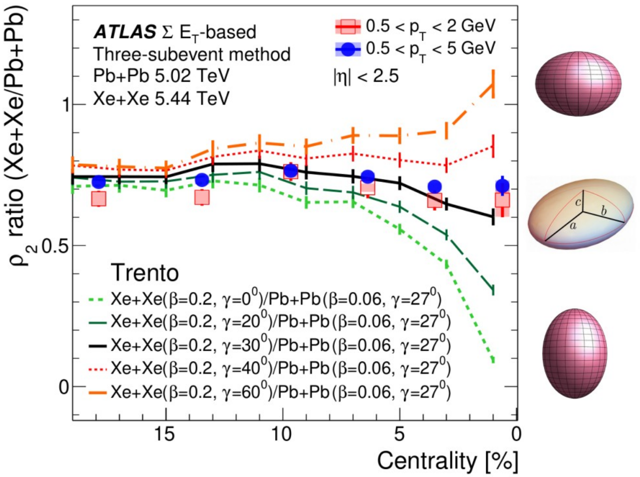
R0 = 7.068;
a = 0.538;
β2 = 0.247;
γ = 0;
β3 = 0;
β4 = 0.08;

“Anomalies” in results fully explained by nuclear shapes









[STAR collaboration, PRL **115**, no.22, 222301 (2015)]

[ALICE collaboration, PLB **784**, 82-95 (2018)]

[CMS collaboration, PRC **100**, no.4, 044902 (2019)]

[ATLAS collaboration, PRC **100**, no.4, 044902 (2019)]

[STAR collaboration, PRC **105**, no.1, 014901 (2022)]

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

[ATLAS collaboration, PRC **107**, no.5, 054910 (2023)]

[STAR collaboration, Nature **635**, no.8037, 67-72 (2024)]

[ATLAS collaboration, PRL **133** (2024) 25, 252301]

[ALICE collaboration, arXiv:2409.04343]

[STAR collaboration, arXiv:2506.17785]

[ATLAS collaboration, arXiv:2509.05171]

[ALICE collaboration, arXiv:2509.06428]

[CMS collaboration, arXiv:2510.02580]

…

Exploiting ^{20}Ne Isotopes for Precision Characterizations of Collectivity in Small Systems

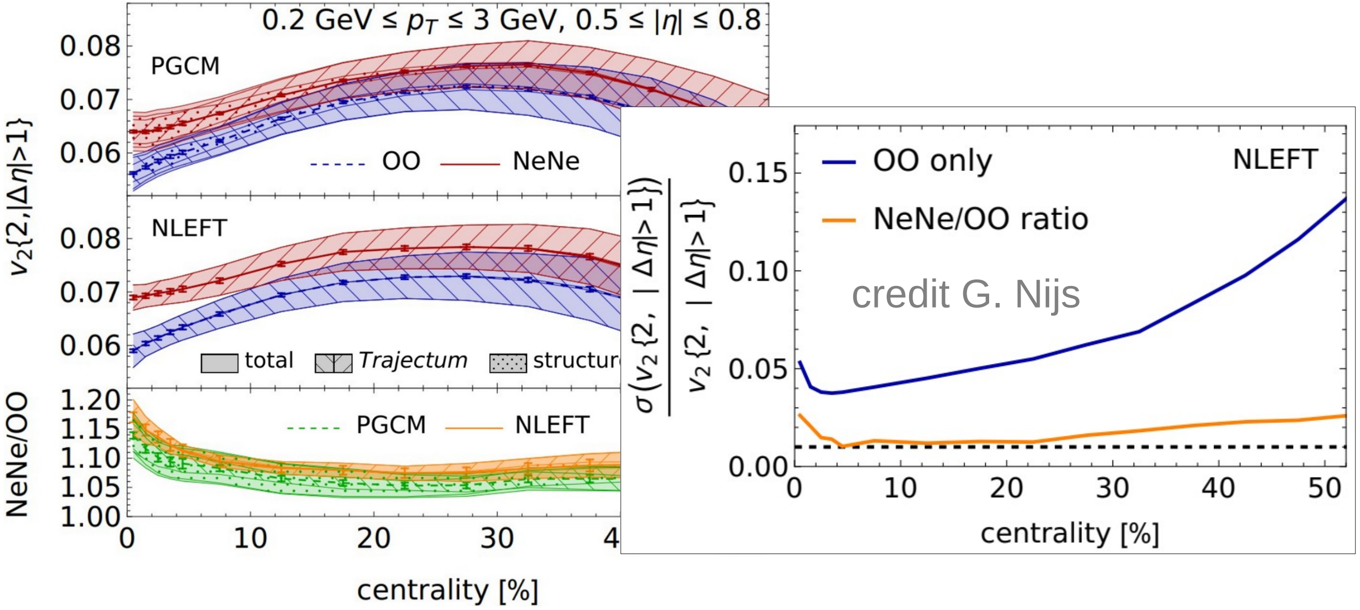
Giuliano Giacalone[1,*], Benjamin Bally[2], Govert Nijs[3], Shihang Shen[4], Thomas Duguet[5,6], Jean-Paul Ebran[7,8], Serdar Elhatisari[9,10], Mikael Frosini[11], Timo A. Lähde[12,13] *et al.*

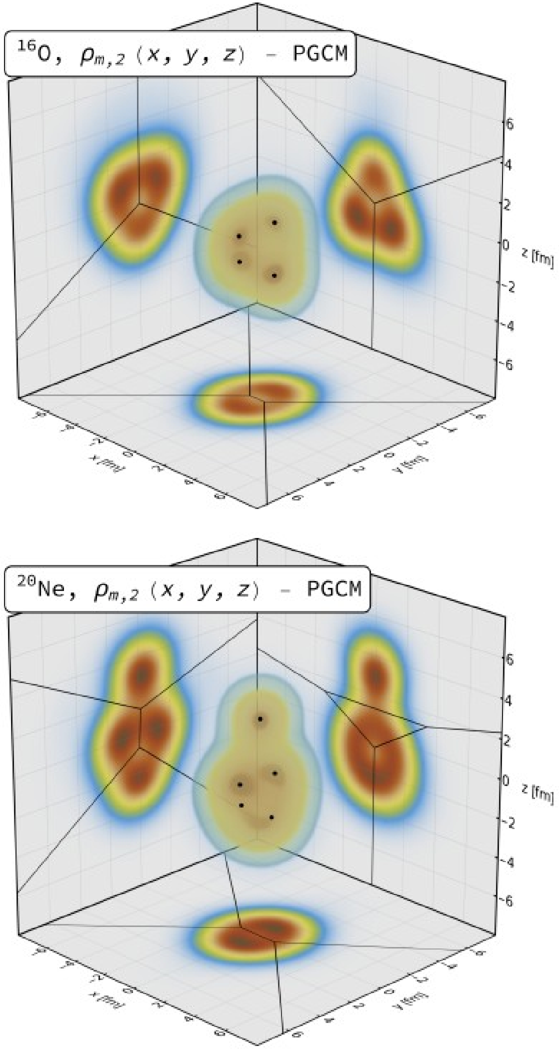
Hide

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]

Phys. Rev. Lett. **135**, 012302 – **Published 2 July, 2025**

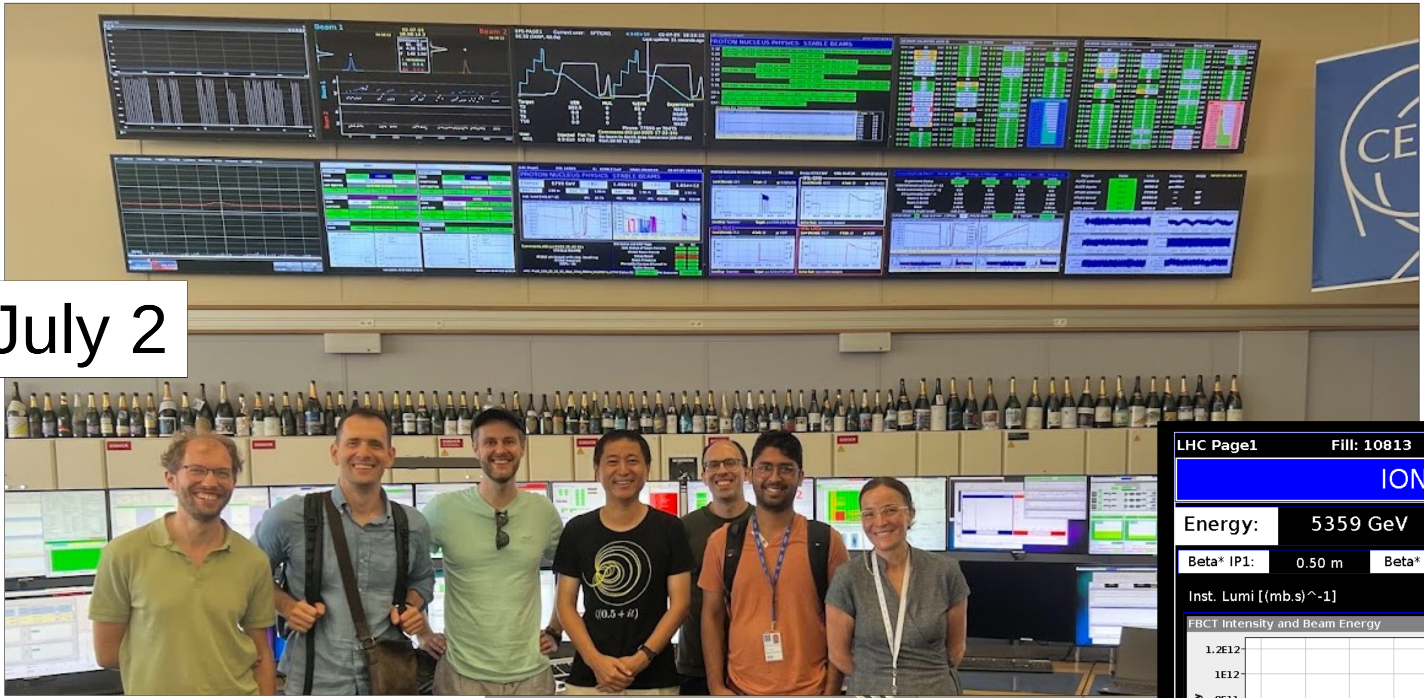
proposal for neon-20



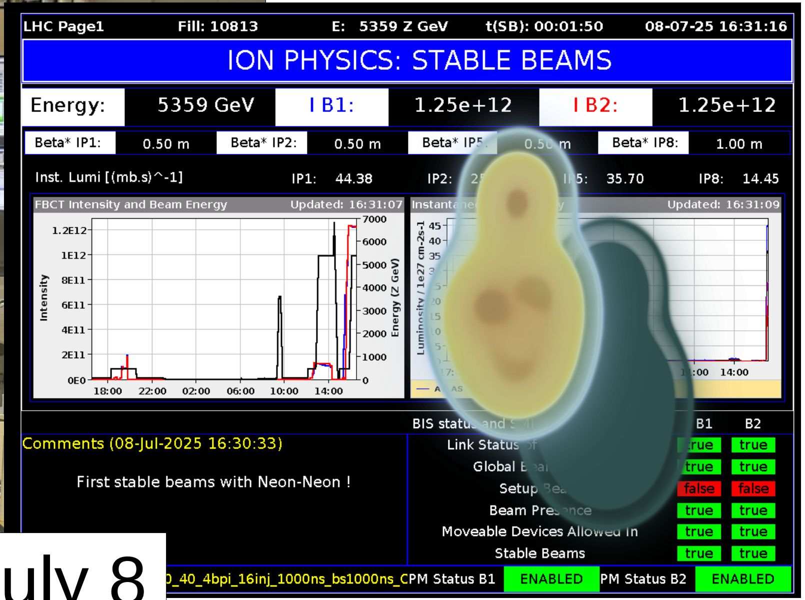


light-ion collisions

July 2



July 8



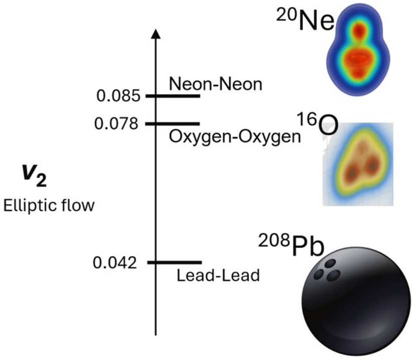
CERN Accelerating science

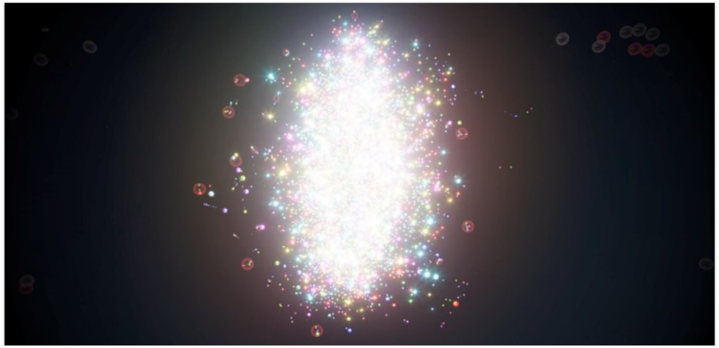
News › News › Topic: Physics

Shape-shifting collisions probe secrets of early Universe

The first high-energy collisions between light nuclei at the Large Hadron Collider confirm the unusual “bowling-pin” shape of neon nuclei and offer up a new tool to study the extreme state of matter produced in the aftermath of the Big Bang

18 SEPTEMBER, 2025



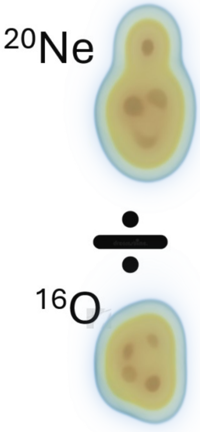


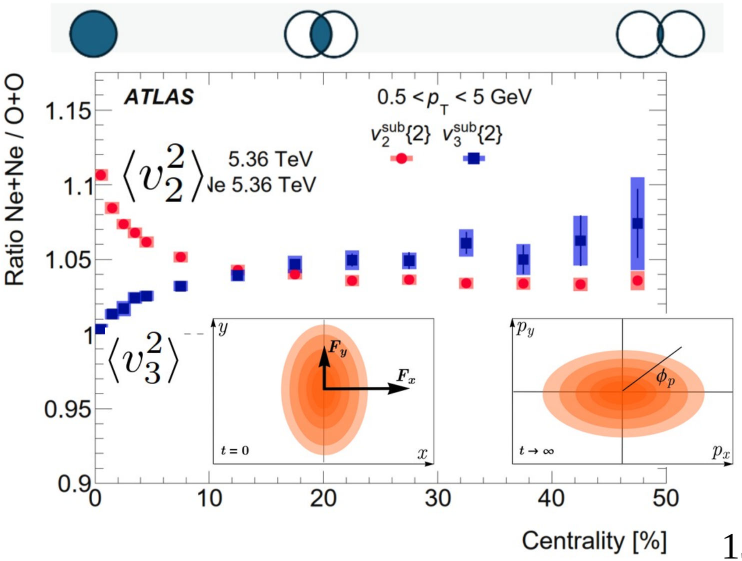
arXiv > nucl-ex > arXiv:2509.05171 **ATLAS**

arXiv > nucl-ex > arXiv:2509.06428 **ALICE**

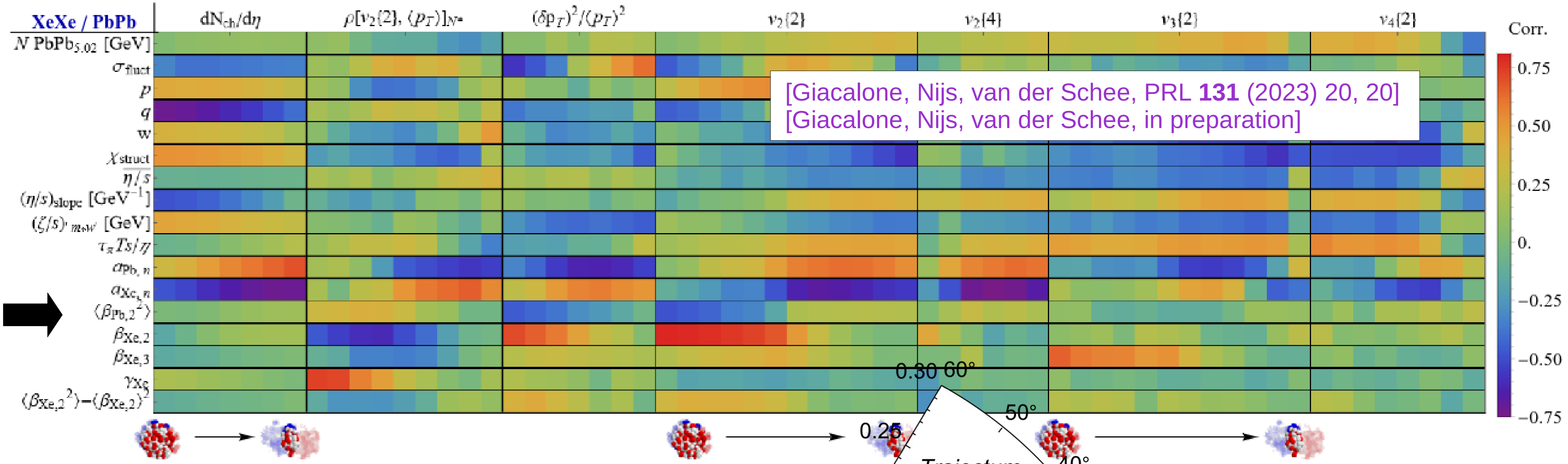
arXiv > nucl-ex > arXiv:2509.12399v1 **LHCb**

arXiv > nucl-ex > arXiv:2510.02580 **CMS**

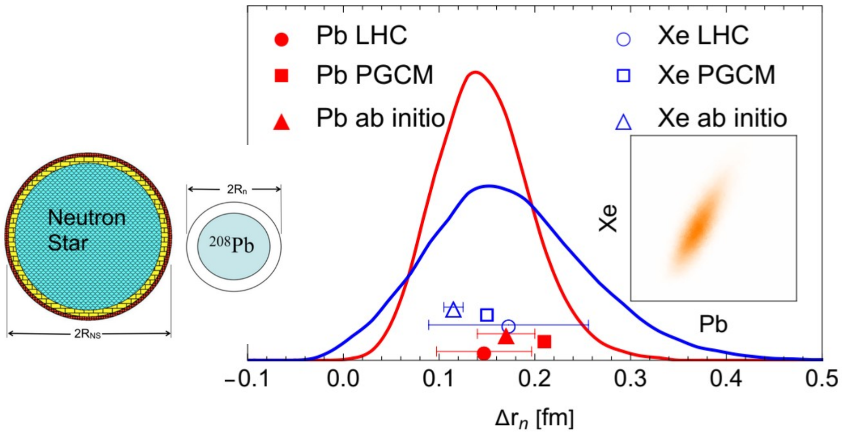


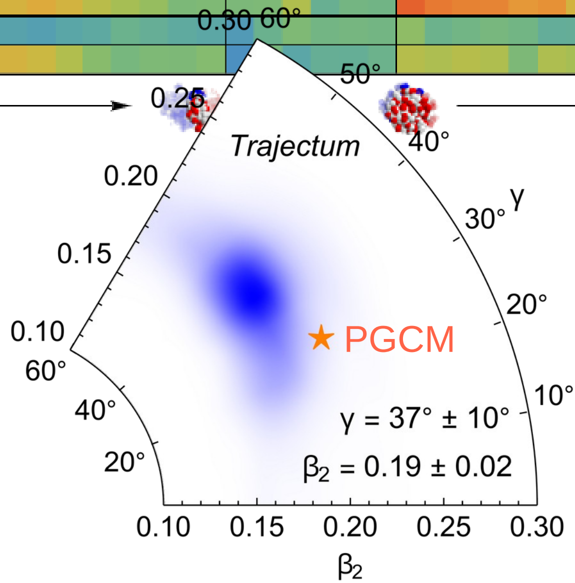


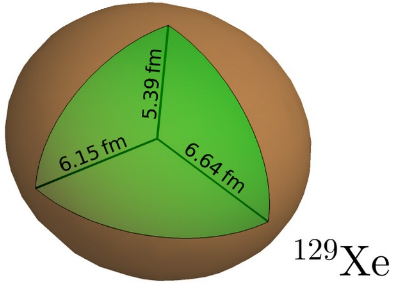
Nuclear structure becomes part of the problem and must be quantified



[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]
[Giacalone, Nijs, van der Schee, in preparation]





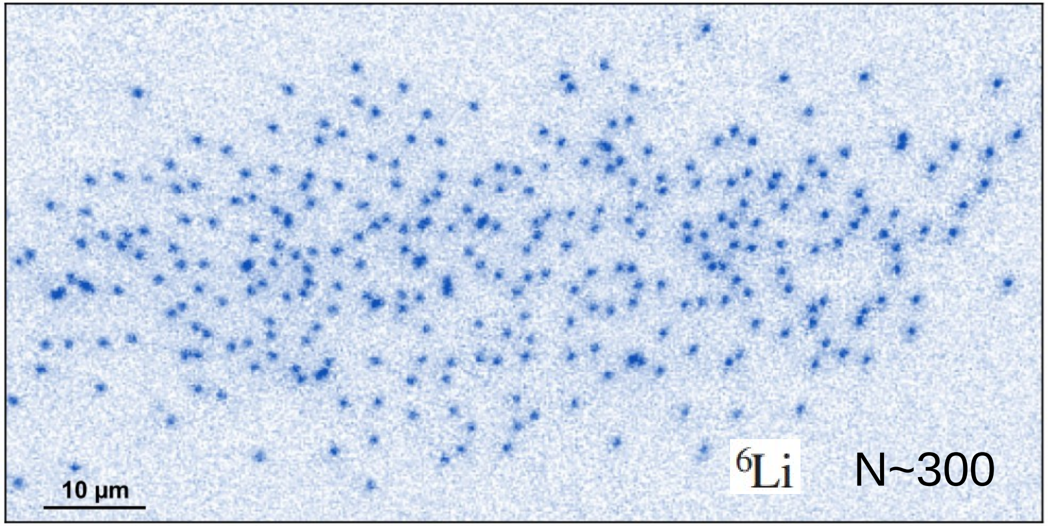


Beyond classical pictures – From shapes to many-body correlations

[with Bally, Blaizot, Duguet, Ekström, Hagen, Holt, Lee, Lovato, Miyagi, Tichai …]

Classical – One picture

Quantum – Statistical approach



FEATURED IN PHYSICS | EDITORS' SUGGESTION | ACCESS BY CERN LIBRARY

Quantum Gas Microscopy of Fermions in the Continuum

Tim de Jongh[1,*], Joris Verstraten[1,*], Maxime Dixmerias[1], Cyprien Daix[1], Bruno Peaudecerf[2], and Tarik Yefsah[1]

Notion of “imaging” rests on our capability of measuring correlation functions


FEATURED IN PHYSICS | EDITORS' SUGGESTION | ACCESS BY CERN LIBRARY

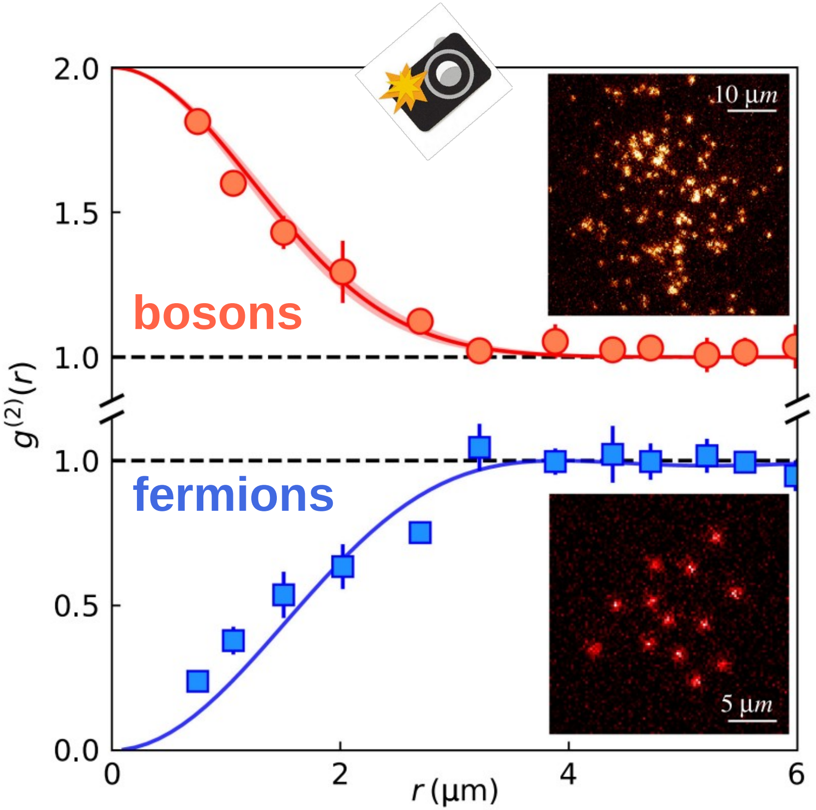
Measuring Pair Correlations in Bose and Fermi Gases via Atom-Resolved Microscopy

Ruixiao Yao, Sungjae Chi, Mingxuan Wang, Richard J. Fletcher, and Martin Zwierlein

$$|\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A)|^2_{\text{atoms}}$$

two-body density

$$g_2(\mathbf{r}_1, \mathbf{r}_2) = \frac{\langle \psi^\dagger(\mathbf{r}_2)\psi^\dagger(\mathbf{r}_1)\psi(\mathbf{r}_1)\psi(\mathbf{r}_2)\rangle}{n^2}$$

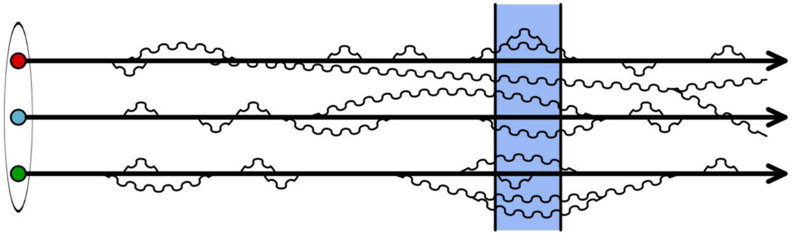


Can we image nuclear scales? (10^9 times smaller)

Can we take “snapshots” of nucleon positions?

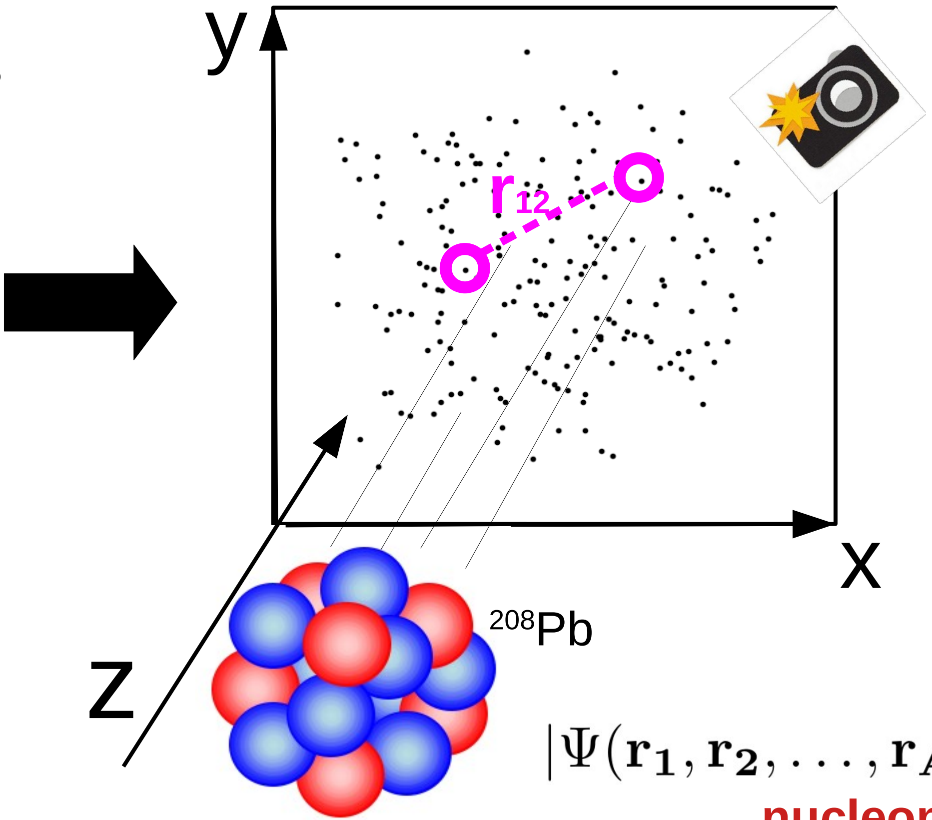
Separation of scales – Billions of high-resolution snapshots

High-energy collisions as imaging tools



[Gelis, IJMPE **24** (2015) 10, 1530008]

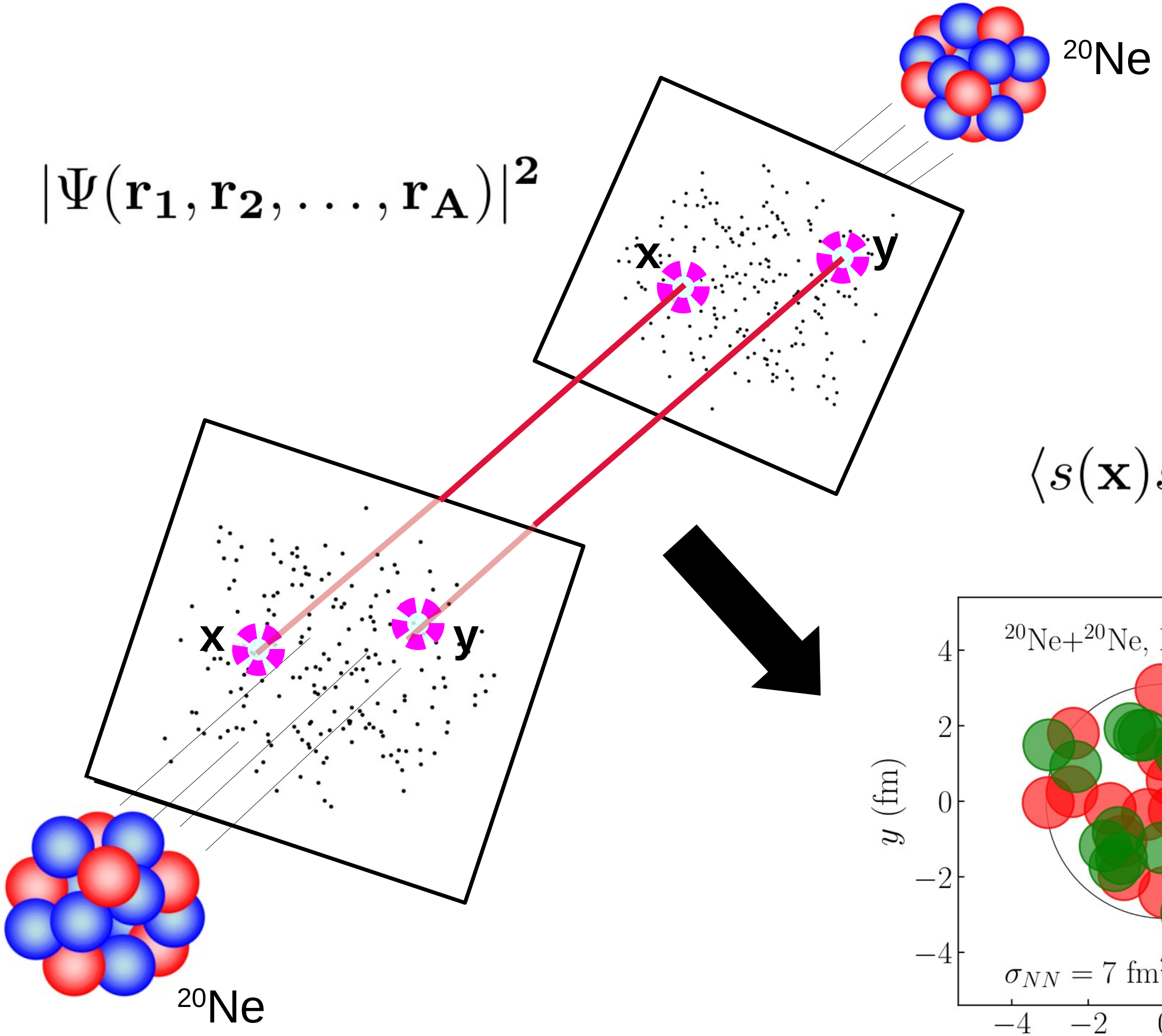
$$t(\mathbf{x}) = \sum_{i}^{A} \delta(\mathbf{x} - \mathbf{x}_i)$$



$$|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})|^2$$

nucleons

$$\left|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})\right|^2$$

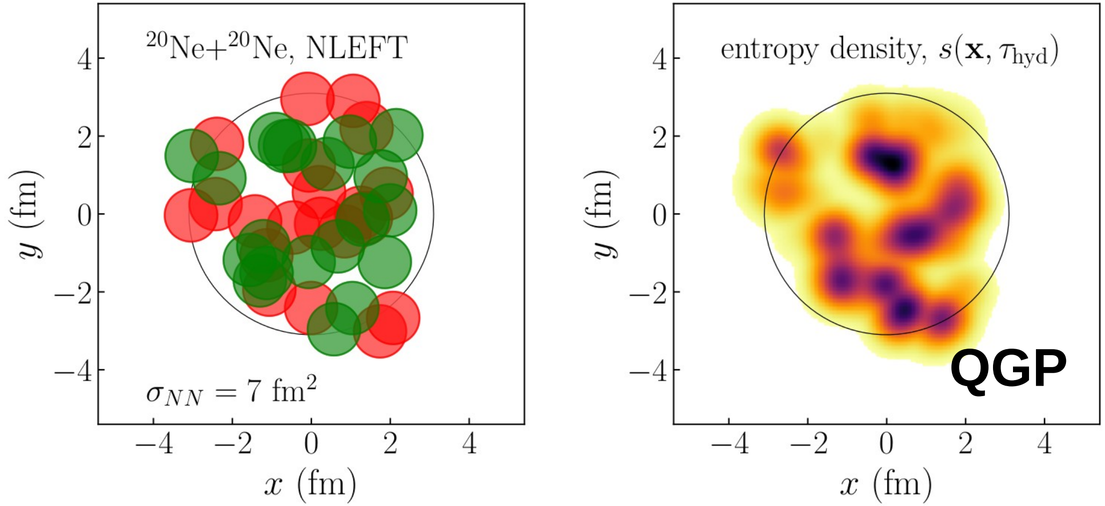


Ultra-central collisions (all nucleons involved)

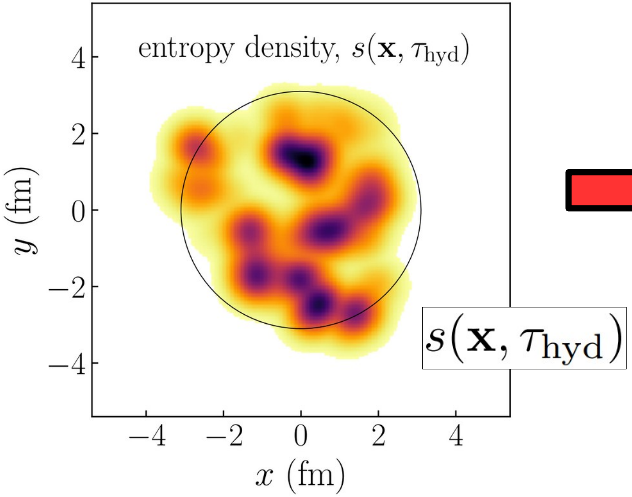
Large-scale structures from incoming nuclei !

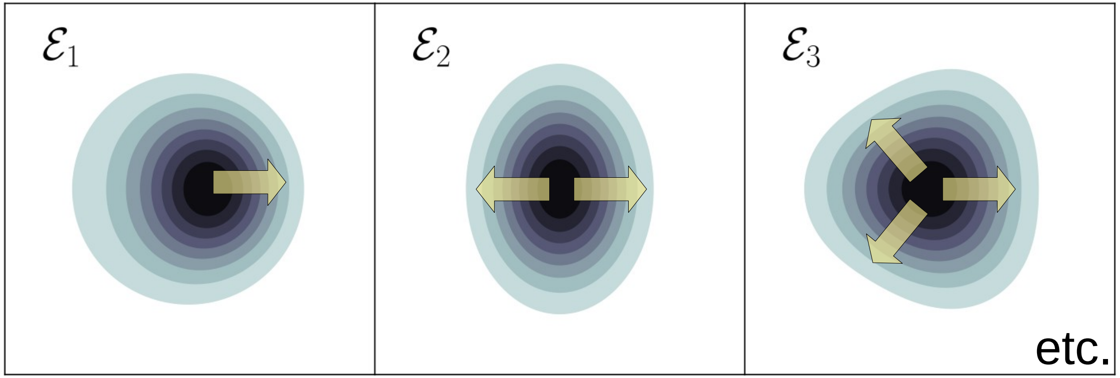
$$\langle s(\mathbf{x}) s(\mathbf{y}) \rangle \qquad |\mathbf{x} - \mathbf{y}| > 1/\Lambda_{\text{GeV}}$$

→ low-energy physics!



Relevance of density-density correlations for experiments – Leading order picture





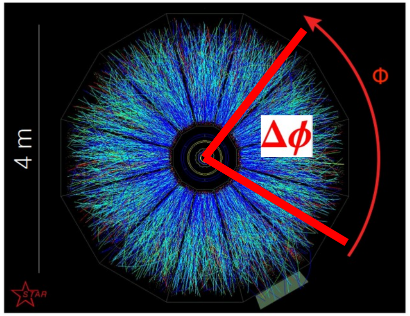
$$s(\mathbf{x}) = \langle s(\mathbf{x}) \rangle + \delta s(\mathbf{x})$$

$$\varepsilon_n \equiv - \frac{\int_{\mathbf{x}} |\mathbf{x}|^n e^{in\phi_x} s(\mathbf{x})}{\int_{\mathbf{x}} |\mathbf{x}|^n s(\mathbf{x})} \Rightarrow V_n \propto \mathcal{E}_n$$

[Blaizot, Broniowski, Ollitrault PLB **738** (2014) 166-171]

Linearize in δs

$$\langle v_n^2 \rangle \propto \langle \varepsilon_n^2 \rangle = \frac{\int_{\mathbf{x},\mathbf{y}} |\mathbf{x}|^n \; |\mathbf{y}|^n \; e^{in(\phi_x - \phi_y)} \langle s(\mathbf{x}) s(\mathbf{y}) \rangle}{\left(\int_{\mathbf{x}} |\mathbf{x}|^n \; \langle s(\mathbf{x}) \rangle \right)^2}$$

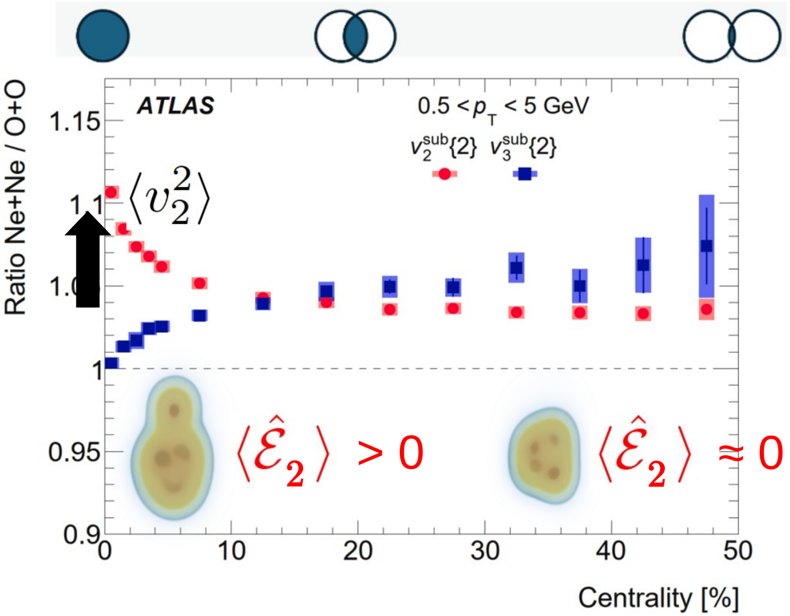


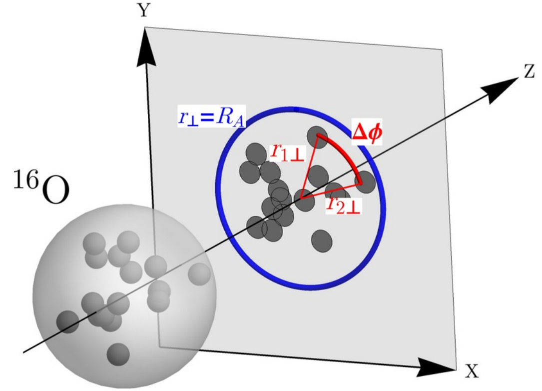
FINAL STATE TWO-PARTICLE CORRELATION

$$\langle v_n^2 \rangle = \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle_{\text{events}}$$

TWO-BODY NUCLEAR CORRELATIONS

$$\int_{\mathbf{r}_1, \mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2)\, r_{1\perp}^n\, r_{2\perp}^n\, e^{in(\phi_1 - \phi_2)}$$





$$\rho^{(n)}(\mathbf{r}_1, \ldots, \mathbf{r}_n) \equiv \int_{\mathbf{r}_{n+1}, \ldots, \mathbf{r}_A} |\Psi(\mathbf{r}_1, \ldots, \mathbf{r}_A)|^2$$

New two-body operators

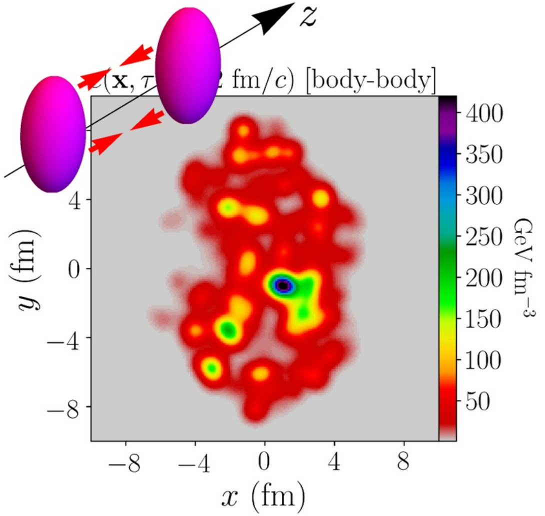
$$\left\langle \begin{aligned} \varepsilon_n(\mathbf{r}_1)\, \varepsilon_{-n}(\mathbf{r}_2) &= r_{1\perp}^n\, r_{2\perp}^n\, e^{in(\phi_1 - \phi_2)} \\ &= r_1^n Y_n^n(\Omega_1)\, r_2^n Y_n^{-n}(\Omega_2) \end{aligned} \right\rangle_\Psi$$

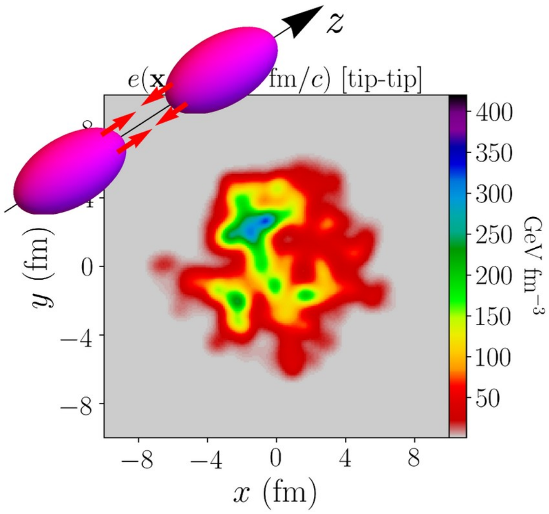
$Q_{n,n}$ $Q_{n,-n}$

[Duguet, Giacalone, Jeon, Tichai, PRL **135** (2025) 18, 182301]

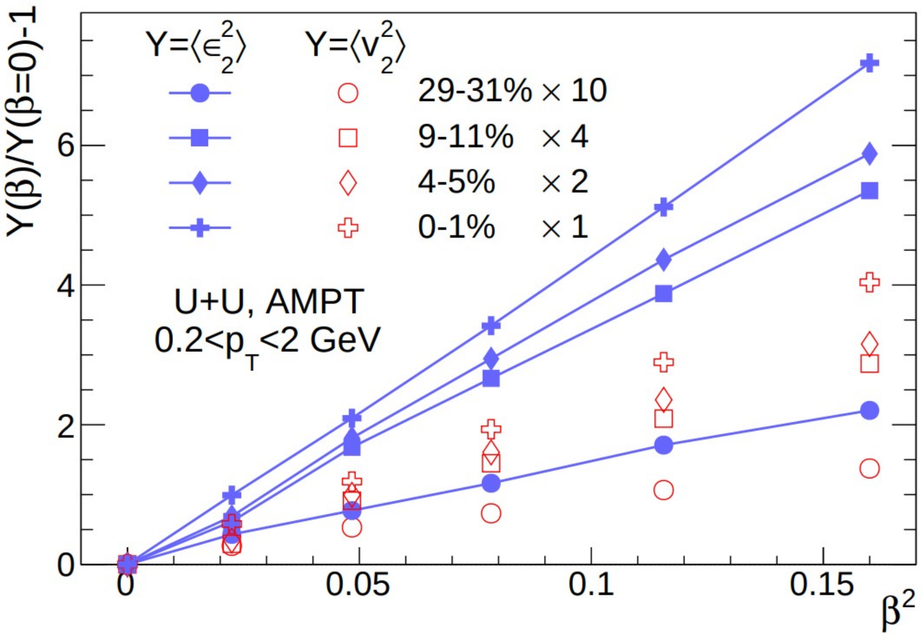
Link to the classical rotor picture

$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left(\left[r-R(\theta,\phi)\right]/a\right)} \ , \quad R(\theta,\phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\theta)+\sin\gamma Y_{22}(\theta,\phi)\right)+\beta_3 Y_{30}(\theta)+\beta_4 Y_{40}(\theta)\right]$$



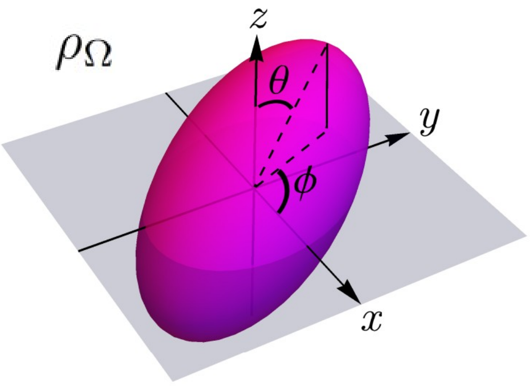


[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]

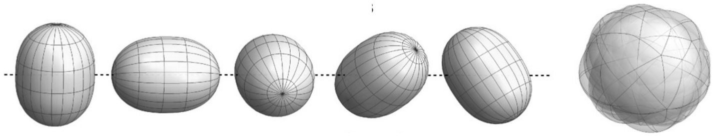


$$\langle v_n^2\rangle = a_n + b_n\beta_n^2$$

Classical rotor picture – Correlations from symmetry restoration



$$\rho^{(1)}(\mathbf{r}_1) = \int_\Omega \rho_\Omega(\mathbf{r}_1)$$



EULER ANGLES

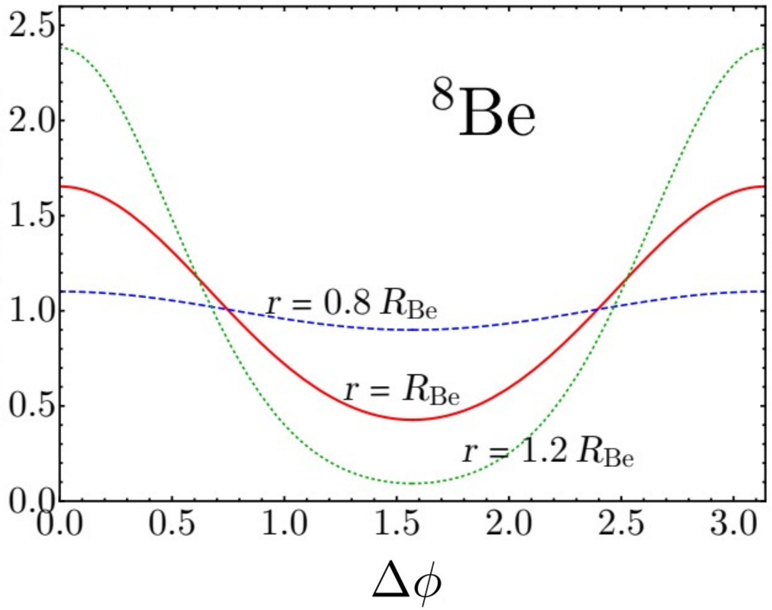
$$\rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2) = \int_\Omega \rho_\Omega(\mathbf{r}_1)\rho_\Omega(\mathbf{r}_2) \neq \rho^{(1)}(\mathbf{r}_1)\rho^{(1)}(\mathbf{r}_2)$$

DEFORMATION

Generic considerations – Deformation

$$\rho_\perp^{(2)}(\mathbf{r}_1, \mathbf{r}_2) \propto \beta_2^2 \, r_{1\perp}^n \, r_{2\perp}^n \, \cos(n\Delta\phi)$$

$\mathbf{r}_1 = (r_1, \phi_1)$ $\mathbf{r}_2 = (r_2, \phi_2)$ $\Delta\phi = \phi_1 - \phi_2$



[Blaizot, Giacalone, EPJA **61** (2025) 9, 220]

Understanding effects of deformations in the rotor model

$$\langle v_n^2 \rangle = a_n + b_n \beta_n^2$$

With $\rho_{\perp}^{(2)}(\mathbf{r}_1, \mathbf{r}_2) \propto \beta_n^2 \, r_{1\perp}^n \, r_{2\perp}^n \, \cos(n\Delta\phi)$

$$\propto \quad \langle \varepsilon_n^2 \rangle = \frac{1}{2A} \frac{1}{\left(\int_{\mathbf{r}_1} \rho^{(1)}(\mathbf{r}_1) r_{1\perp}^n \right)^2} \left[\int_{\mathbf{r}_1} \rho^{(1)}(\mathbf{r}_1) r_{1\perp}^{2n} \right.$$

$\langle \varepsilon_n^2 \rangle^{1b}$

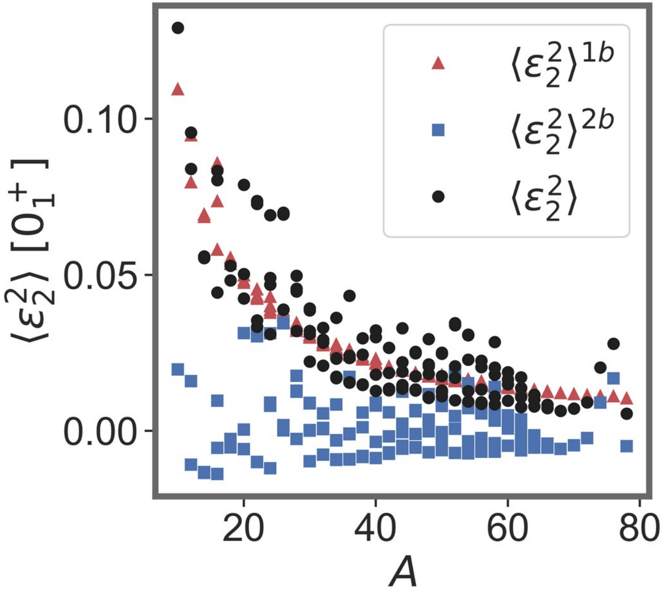
$\langle \varepsilon_n^2 \rangle^{2b}$

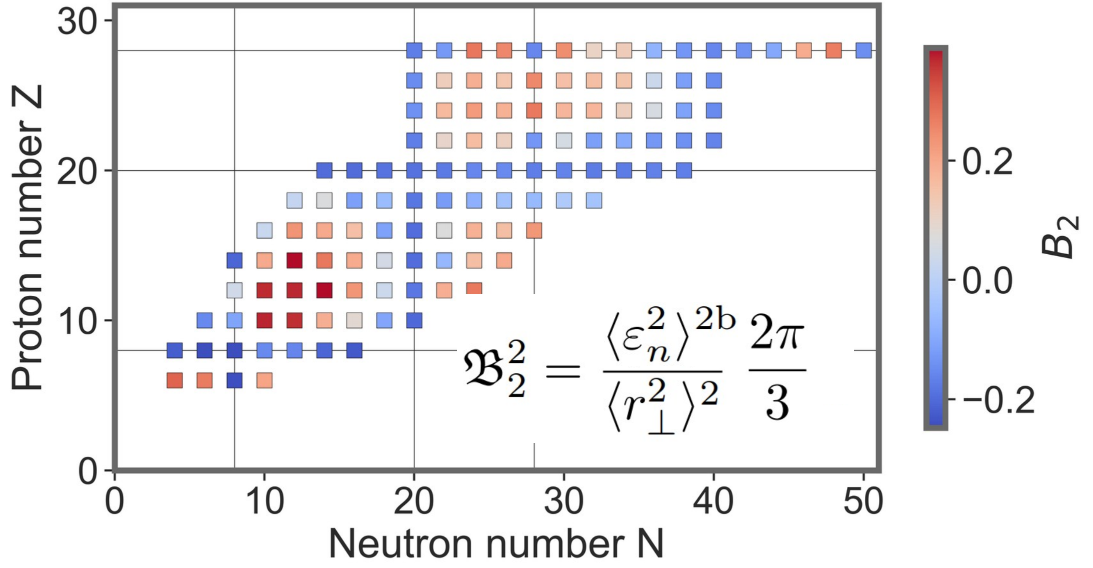
$$\left. + \int_{\mathbf{r}_1, \mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2)(r_{1x} + ir_{1y})^n (r_{2x} - ir_{2y})^n \right]$$

The new observable measures the (squared) deformation of the classical rotor

$$\langle \varepsilon_2^2 \rangle^{2b} \propto \beta_2^2 \qquad \langle \varepsilon_3^2 \rangle^{2b} \propto \beta_3^2$$

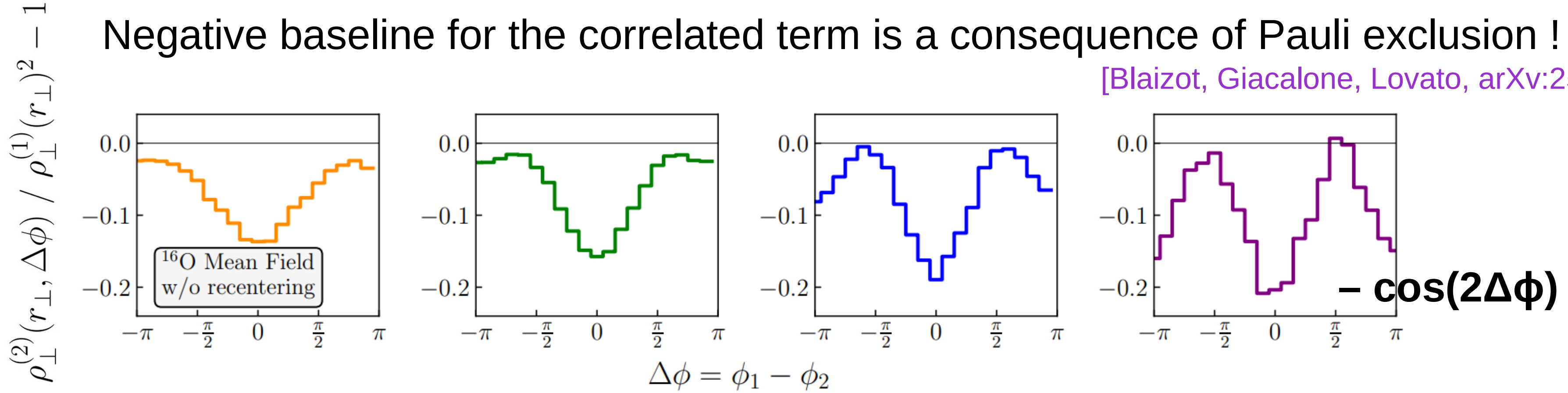
PHFB calculations (quantum rotor) [S. Bofos, B. Bally, T. Duguet and M. Frosini, unpublished]





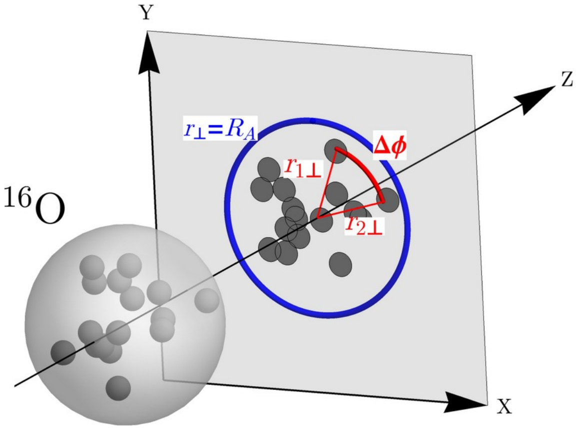
Negative baseline for the correlated term is a consequence of Pauli exclusion !

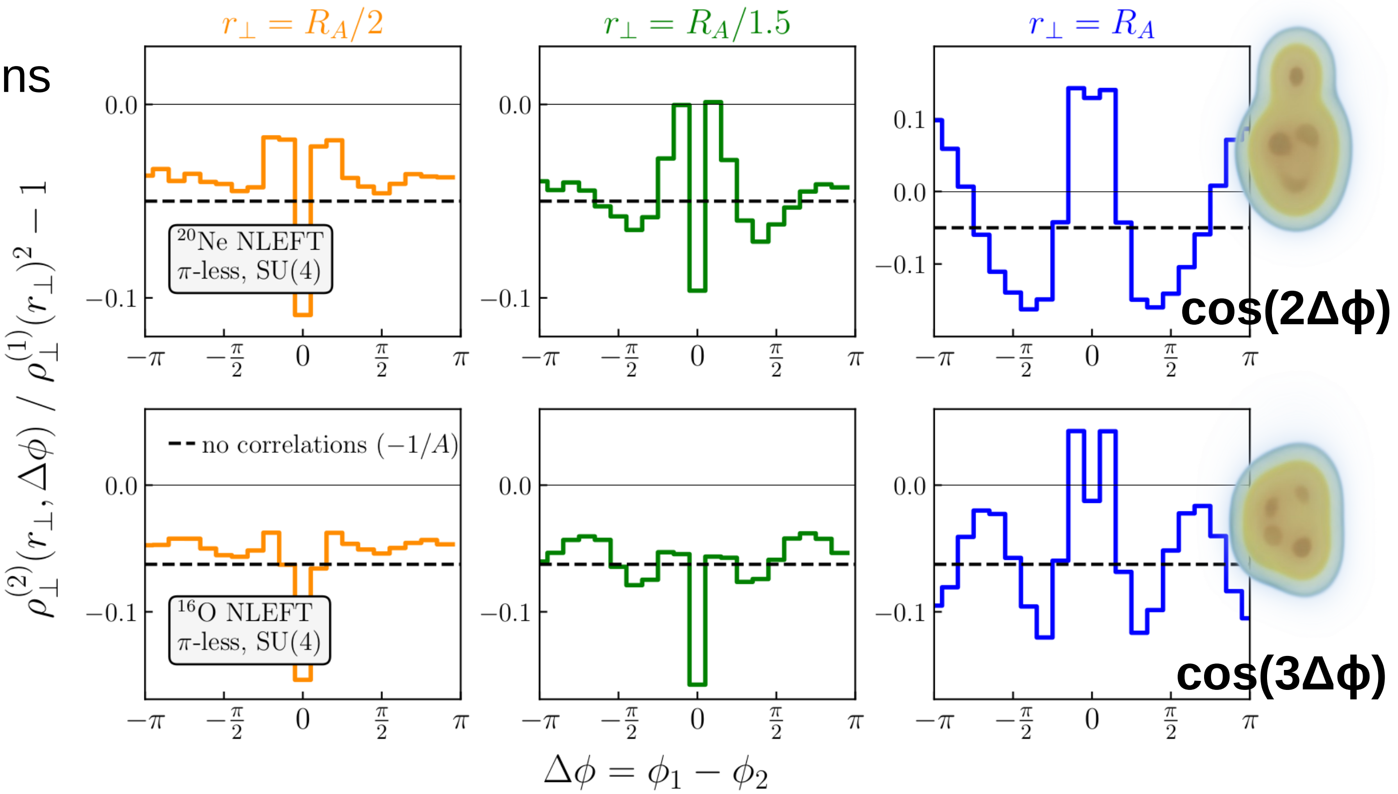
[Blaizot, Giacalone, Lovato, arXv:2512.18926]



New paradigm for describing nuclei … what do we mean with "deformation" ?

ab-initio calculations





Amplitude of modulations is measured at colliders via flow coefficients

SUMMARY

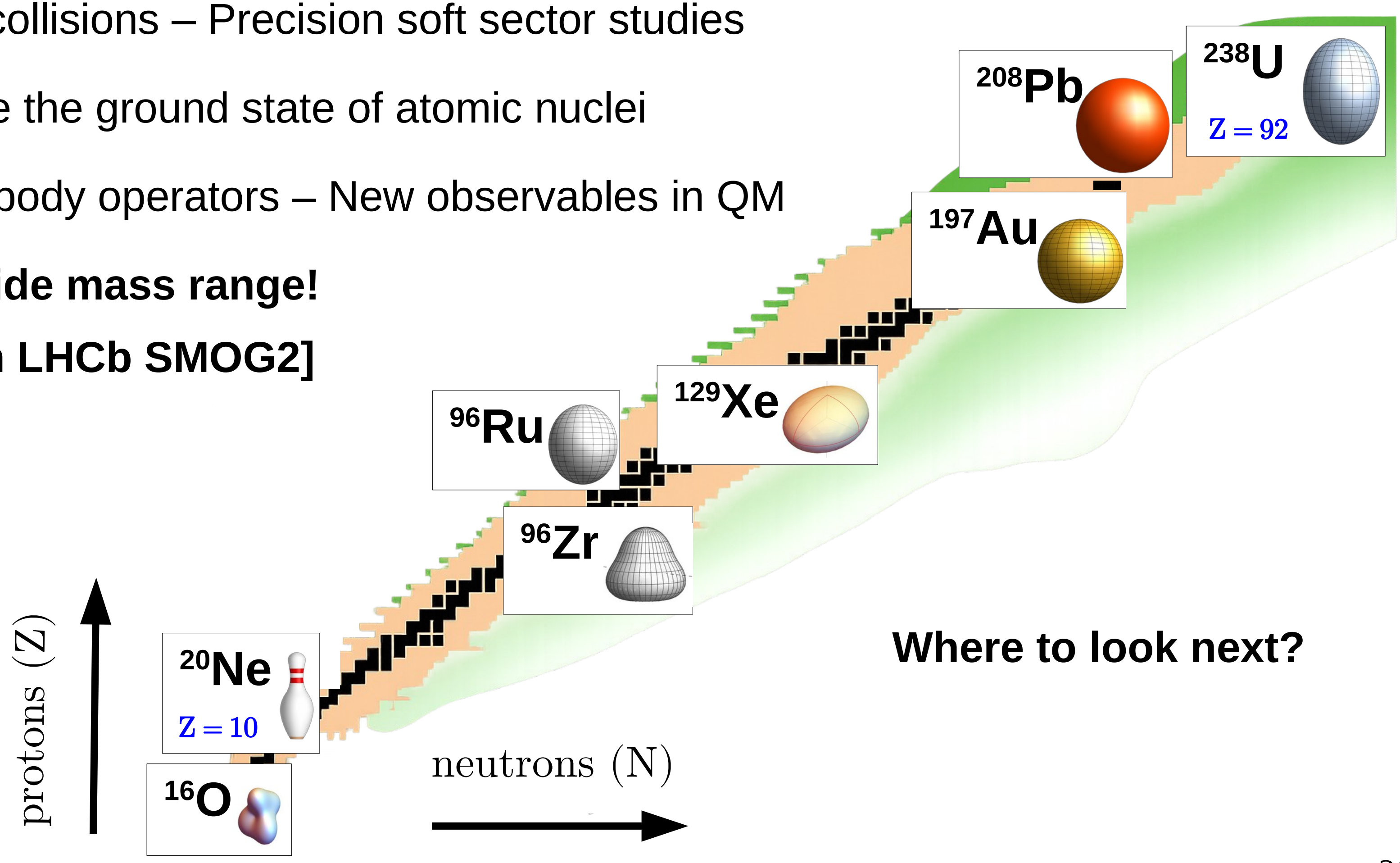
25 years of heavy-ion collisions – Precision soft sector studies

A new method to image the ground state of atomic nuclei

From shapes to many-body operators – New observables in QM

8 species across a wide mass range!

[+ much coming from LHCb SMOG2]



Where to look next?

Outlook – Low energy EFTs of QCD

Input from heavy-ion collisions!

$$\varepsilon_n(\mathbf{r}_1)\,\varepsilon_{-n}(\mathbf{r}_2) = r_{1\perp}^n\, r_{2\perp}^n\, e^{in(\phi_1-\phi_2)}$$

CC computations

chiral EFT

$$H\psi_n = E_n\psi_n$$

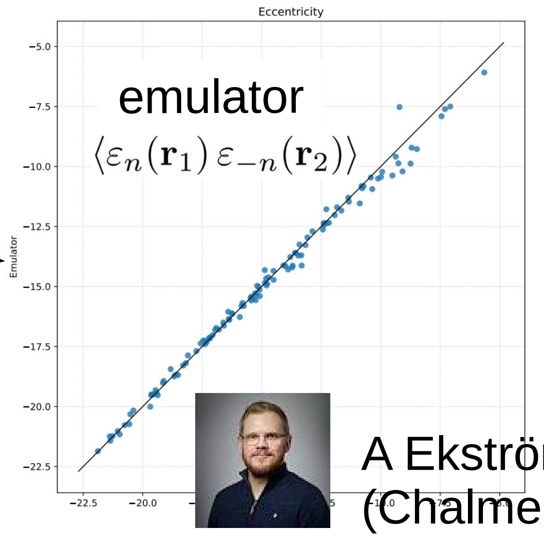
$$\langle\varepsilon_n(\mathbf{r}_1)\,\varepsilon_{-n}(\mathbf{r}_2)\rangle$$

G Hagen (ORNL)

$$\sum_{pq}\bar{\epsilon}_{pq}^{(n)} c_p^\dagger c_q + \frac{1}{4}\sum_{pqrs}\bar{\epsilon}_{pqrs}^{(n)} c_p^\dagger c_q^\dagger c_s c_r$$

A Tichai (TU Darmsadt)

T Miyagi (Tsukuba)

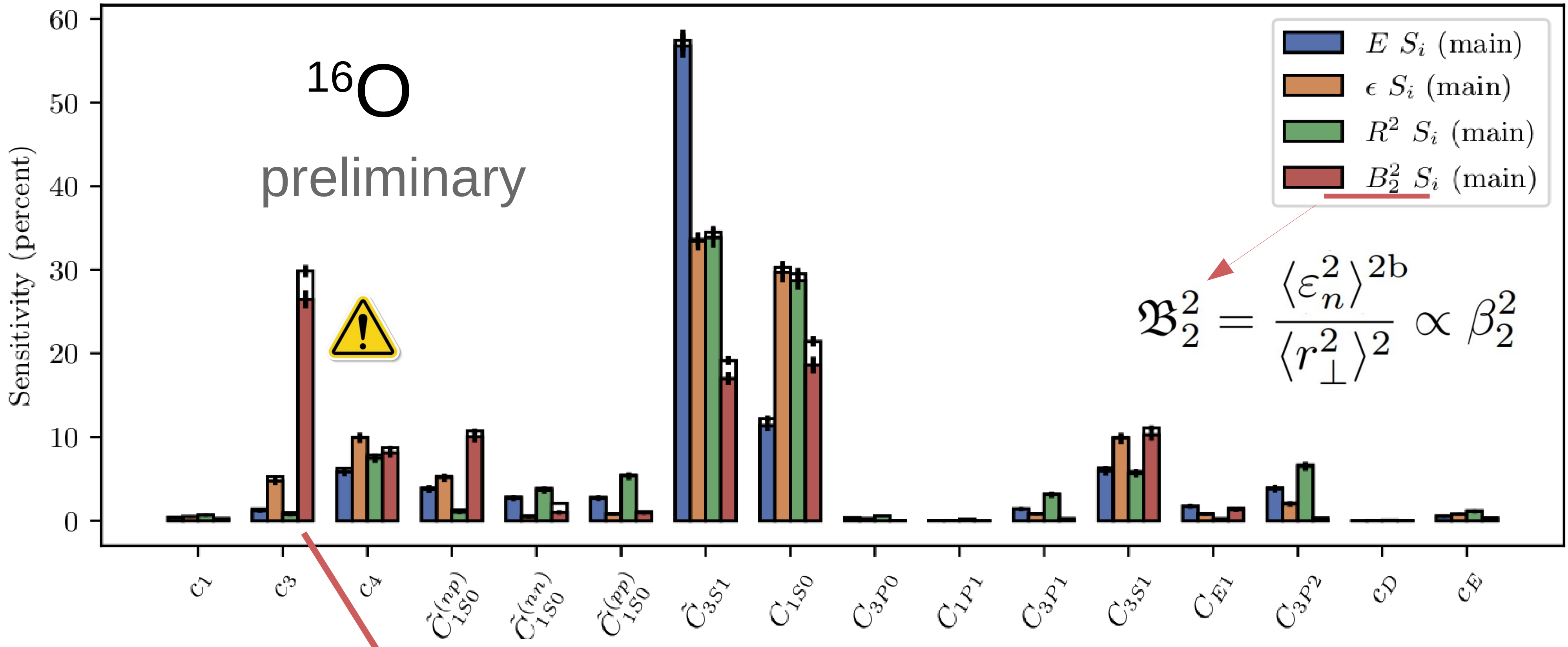


emulator

$$\langle\varepsilon_n(\mathbf{r}_1)\,\varepsilon_{-n}(\mathbf{r}_2)\rangle$$

A Ekström (Chalmers)

Δ-full chiral EFT expansion at N2LO – 17 low-energy constants



$$\mathfrak{B}_2^2 = \frac{\langle \varepsilon_n^2 \rangle^{2b}}{\langle r_\perp^2 \rangle^2} \propto \beta_2^2$$

NNLO
$(Q/\Lambda_\chi)^3$

New many-body observables and sensitivities to explore parameter space of the EFT of QCD

Tip of the iceberg …

Outlook – Multi-messenger probes ?

nature communications

Explore content ⌄ About the journal ⌄ Publish with us ⌄

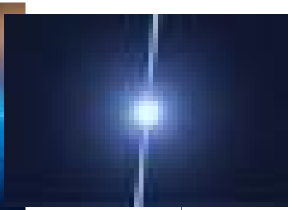
nature > nature communications > articles > article

Article | Open access | Published: 06 November 2025

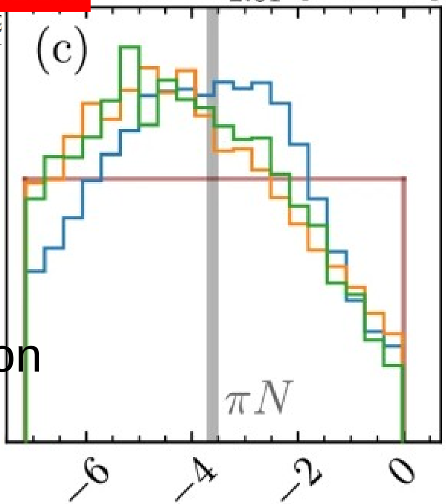
Inferring three-nucleon couplings from multi-messenger neutron-star observations

Rahul Somasundaram, Isak Svensson, Soumi De, Andrew E. Deneris, Yannick Dietz, Philippe Landry, Achim Schwenk & Ingo Tews

Nature Communications **16**, Article number: 981

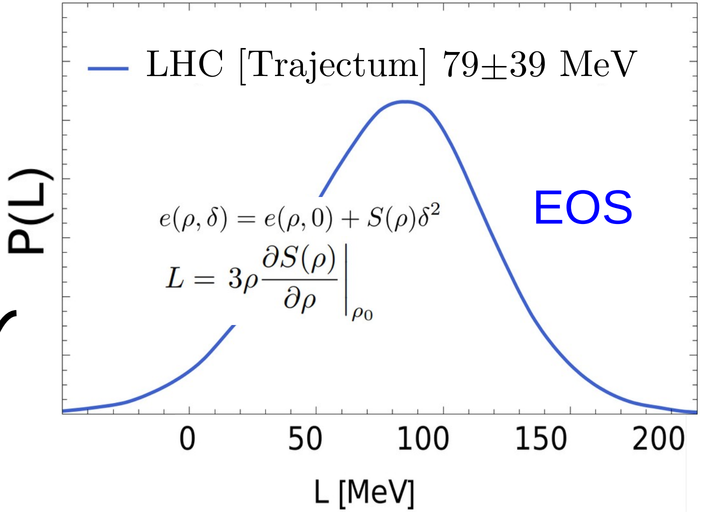


$c_3 = -4.14^{+3.20}_{-2.61}$ [GeV^{-1}]



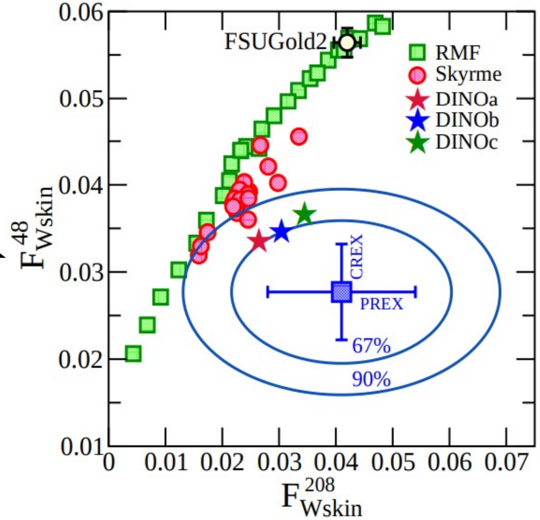
posterior distribution

[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]

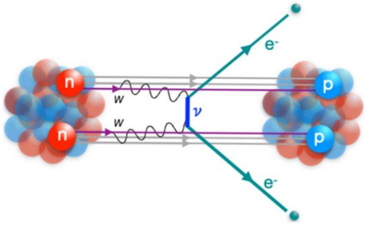


collide ^{48}Ca ?

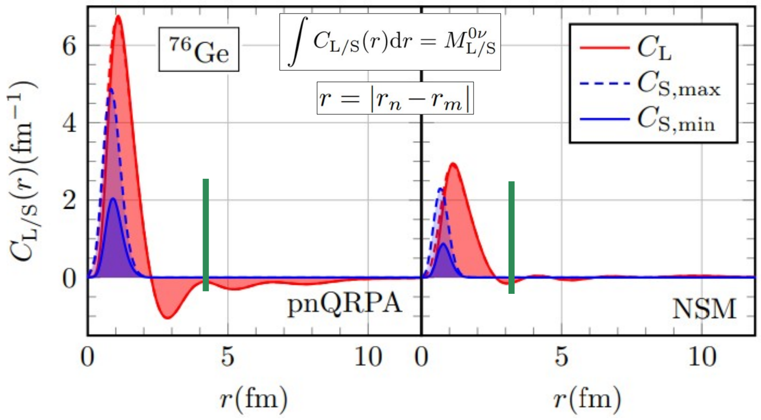
[Reed *et al.*, PRC **109** (2024) 3, 035803]



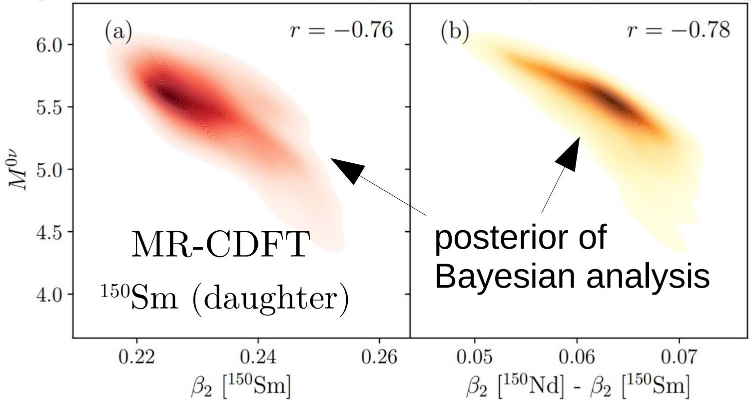
Outlook – NMEs of 0νββ decay and ground-state two-body properties

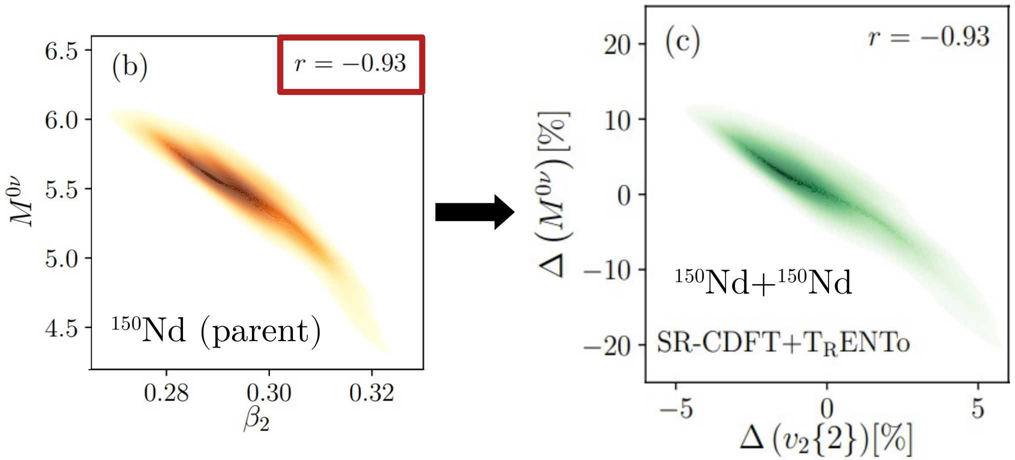


[Jokiniemi, Soriano, Menéndez, PLB **823** (2021) 136720]



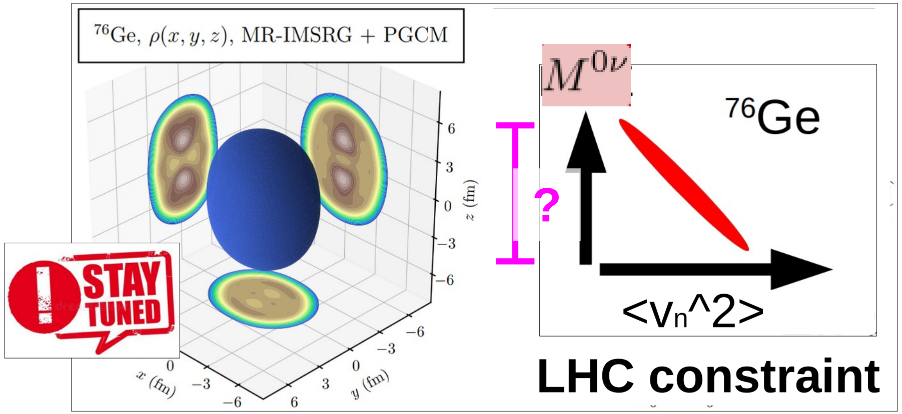
[Li, Giacalone, Yao, Zhang, PRL **135** (2025) 2, 022301]





Correlation of NME with new operators ?

[Giacalone, Holt, *et al.* … in progress]



Intersection of nuclear structure and high-energy nuclear collisions 2026

Apr 13 – 24, 2026
Yukawa Institute for Theoretical Physics
Asia/Tokyo timezone

- Overview
- Registration
- Participant List

Overview

The purpose of this workshop is to review recent progress at the interface between the physics of low-energy nuclear structure and high-energy nuclear collisions, and to explore future directions in this rapidly developing interdisciplinary field. We will bring together theorists and experimentalists from both communities to foster mutual understanding and initiate collaborations.

The workshop will be held in Yukawa Institute for Theoretical Physics, Kyoto University. (Access map)

Schedule

- **1st week (Apr. 13-17): Discussion week**
  1~2 seminars per day and discussions
- **2nd week (Apr. 20-24): Workshop week**
  4~10 talks, including 1~2 seminars, per day, and discussions

Invited Speakers

- Thomas Duguet (CEA Saclay)
- Reyes Alemany Fernandez (CERN)
- Wataru Horiuchi (Osaka Metropolitan U.)
- Weiyao Ke (CCNU)
- Takayuki Miyagi (Tsukuba)
- Oscar Garcia Montero (Santiago)
- Koichi Murase (RCNP)
- Shunji Nishimura (RIKEN)
- Björn Schenke (BNL)
- Daisuke Suzuki (Tokyo)
- Kenichi Yoshida (RCNP)
- Chunjian Zhang (Fudan U.)
- Shujun Zhao (Sophia U.)
- Pengwei Zhao (Peking U.)
- You Zhou (NBI Copenhagen)

Organizers

Giuliano Giacalone (CERN), Kouichi Hagino (Kyoto U.), Tetsufumi Hirano (Sophia U.), Jiangyong Jia (Stony Brook U.), Masaaki Kimura (RIKEN), Masakiyo Kitazawa (YITP, Kyoto), Huichao Song (Peking U.), Jiangming Yao (Sun Yat-sen U.)

https://indico.yukawa.kyoto-u.ac.jp/event/75/