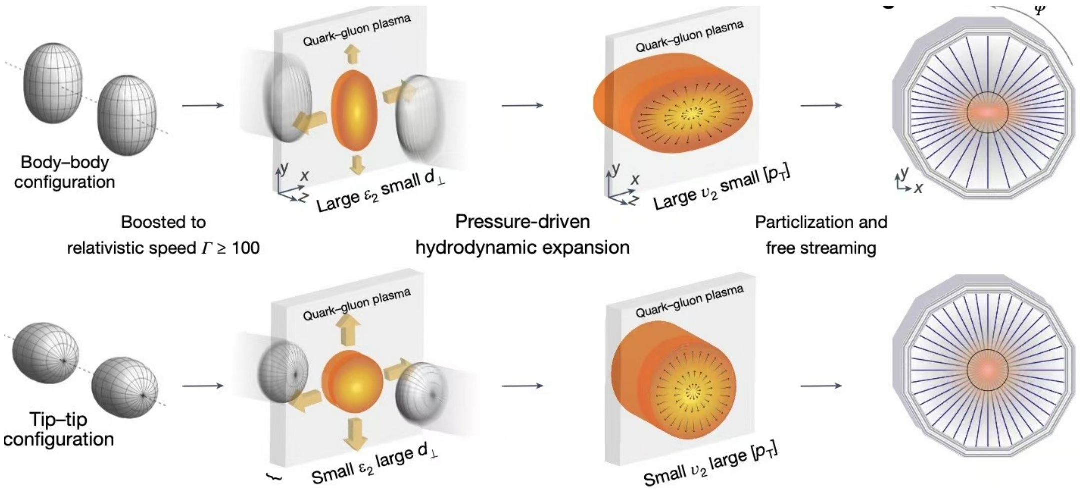
Essentials of nuclear imaging for high-energy colliders

Giuliano Giacalone

September 19, 2025



Nuclear physics across energy scales

Sep 18 – 21, 2025

Central China Center for Nuclear Theory
华中核理论中心

Spatial imaging – Frontier with ultra-cold atom gases

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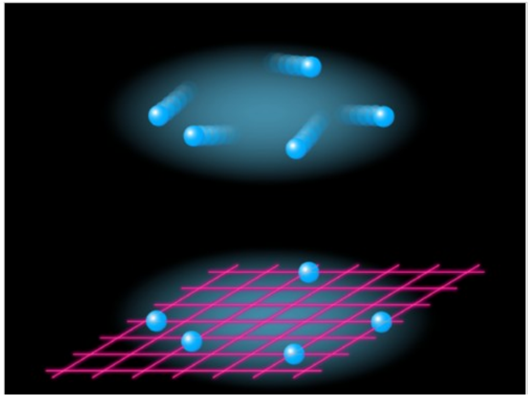
VIEWPOINT

A Glimpse at the Quantum Behavior of a Uniform Gas

Meera Parish
School of Physics and Astronomy, Monash University, Melbourne, Australia

May 5, 2025 • *Physics* 18, 89

An innovative way to image atoms in cold gases could provide deeper insights into the atoms’ quantum correlations.



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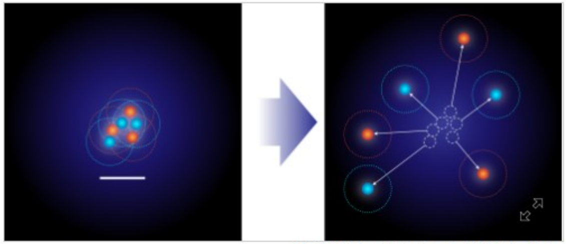
VIEWPOINT

Magnifying Atomic Images

Tarik Yefsah
French National Centre for Scientific Research (CNRS) and École Normale Supérieure, Paris, France

September 2, 2025 • *Physics* 18, 152

A new technique allows the imaging of an atomic system in which the interatomic spacing is smaller than the optical-resolution limit.



Massachusetts Institute of Technology

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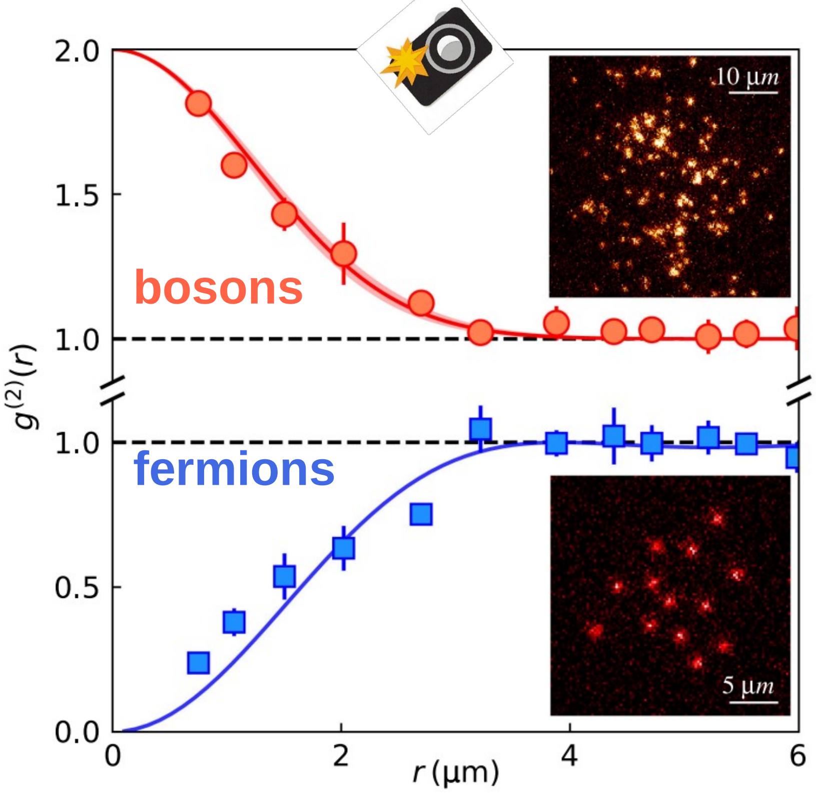
Many-body correlations of atoms – Snapshots of the ground-state wave function

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



two-body correlation function

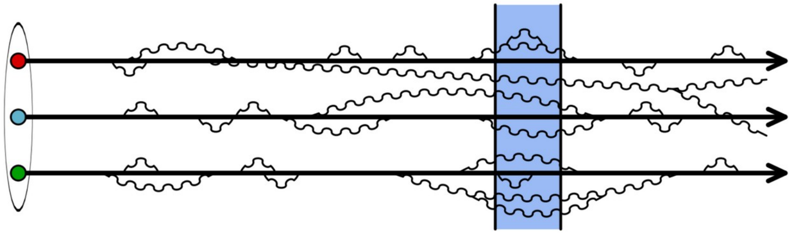
$$g_2(\mathbf{r}_1, \mathbf{r}_2) = \frac{\langle \psi^\dagger(\mathbf{r}_2)\psi^\dagger(\mathbf{r}_1)\psi(\mathbf{r}_1)\psi(\mathbf{r}_2)\rangle}{n^2}$$

[Yao et al., PRL **134** (2025) 18, 183402]

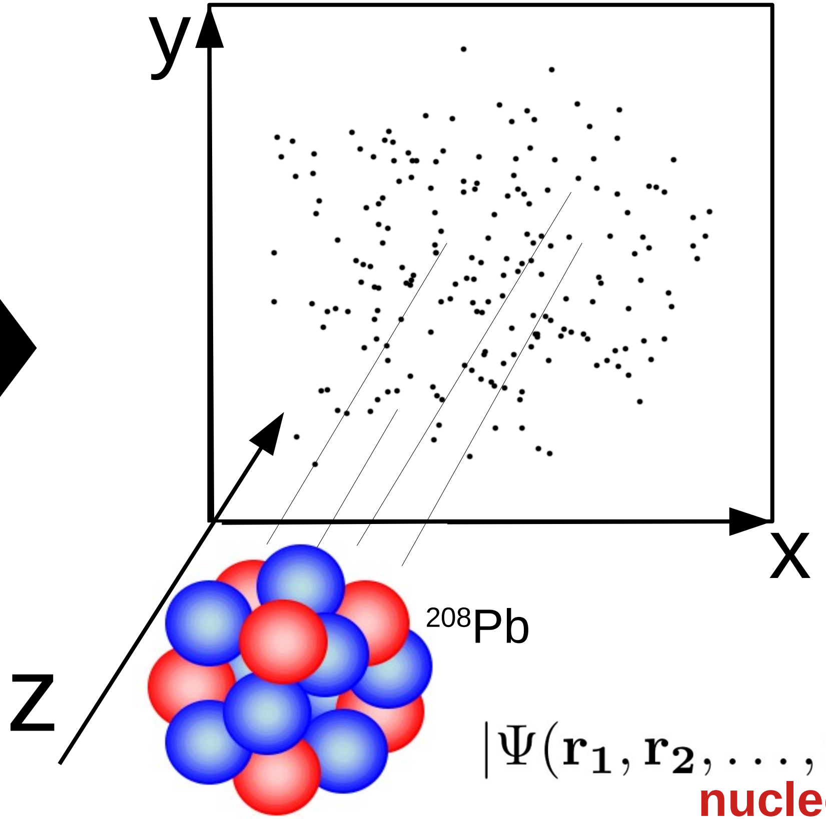
Can we image nuclear scales in the same way?

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

Heavy-ion collisions



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

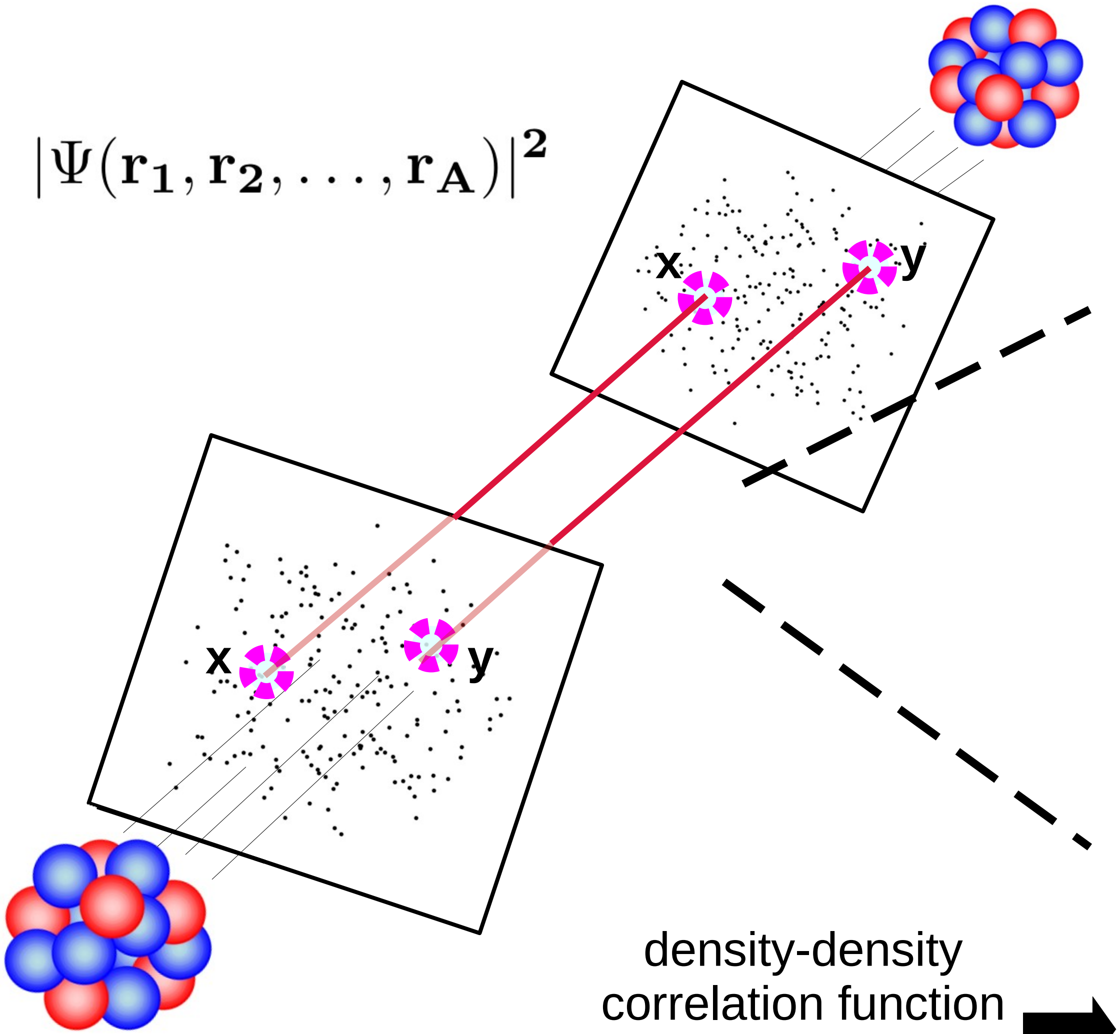


$$\left|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})\right|^2$$

nucleons

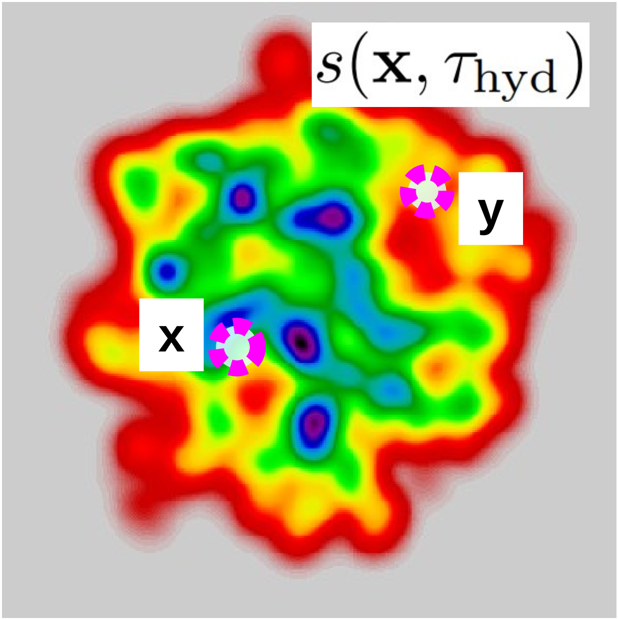
Instantaneous snapshot of the positions of the colliding nucleons

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



Interactions are highly local (Q~1 GeV)

Pre-equilibrium physics < 1 fm/c



density-density
correlation function
$\langle s(\mathbf{x}) s(\mathbf{y}) \rangle$

$|\mathbf{x} - \mathbf{y}| < 1/\Lambda$ high-energy physics

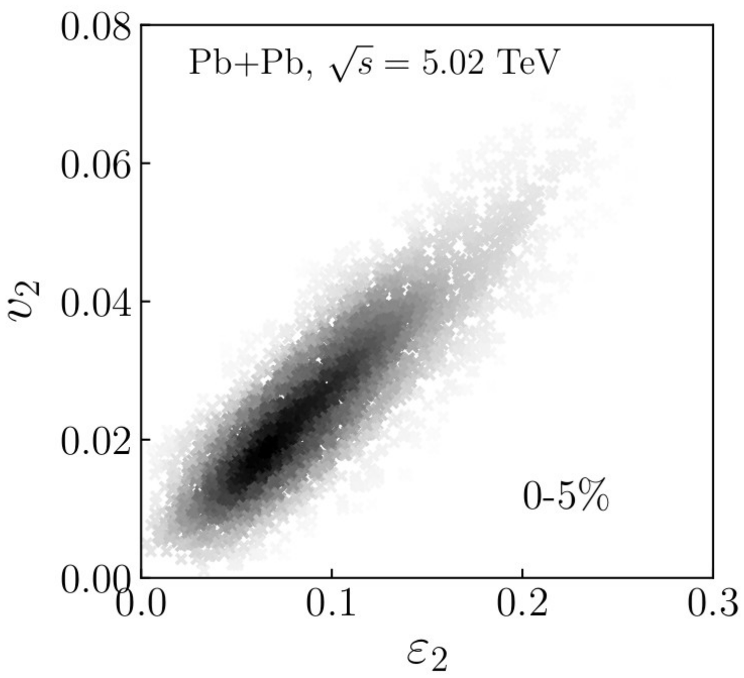
$|\mathbf{x} - \mathbf{y}| > 1/\Lambda$ low-energy physics

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

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

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

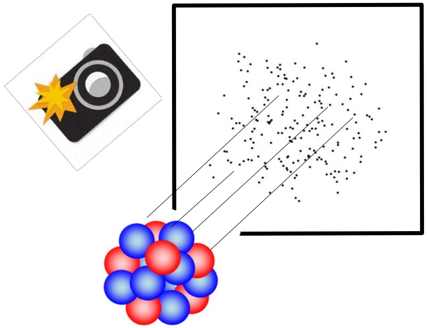
$$\mathcal{E}_n \equiv -\frac{\int_{\mathbf{x}} |\mathbf{x}|^n e^{in\phi_x} s(\mathbf{x})}{\int_{\mathbf{x}} |\mathbf{x}|^n s(\mathbf{x})}$$



Linearize in δs

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

Essential model of ultra-central collisions – density correlations



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

THICKNESS FUNCTION

ULTRA-CENTRAL ENTROPY

$$s(\mathbf{x}) \propto t(\mathbf{x})$$

N-POINT FUNCTIONS

$$\langle s(\mathbf{x}) \rangle \propto \langle t(\mathbf{x}) \rangle$$

$$\underline{\langle s(\mathbf{x}_1) s(\mathbf{x}_2) \rangle \propto \langle t(\mathbf{x}_1) t(\mathbf{x}_2) \rangle}$$

Mean squared eccentricity of the density field

$$\langle v_n^2 \rangle \propto \langle \varepsilon_n^2 \rangle \propto \frac{1}{A} \int_{\mathbf{x}} \rho_\perp^{(1)}(\mathbf{x})(x^2+y^2)^n + \int_{\mathbf{x}_1,\mathbf{x}_2} \rho_\perp^{(2)}(\mathbf{x}_1,\mathbf{x}_2)\,(x_1 + i\,y_1)^n (x_2 - i\,y_2)^n$$

FINITE NUMBER OF NUCLEONS

TWO-BODY CORRELATIONS

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

Nuclear n-body densities

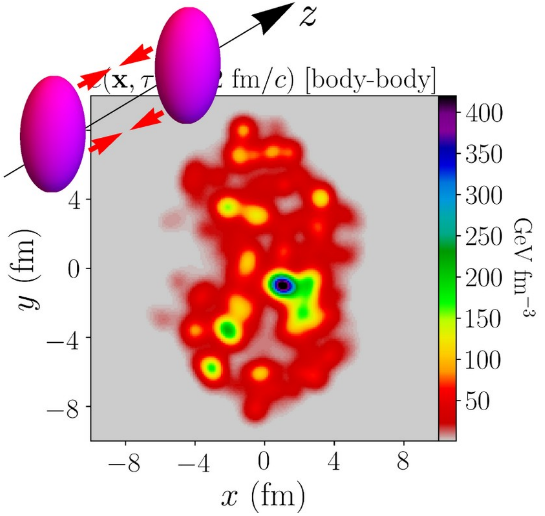
New operator in QM and new observable

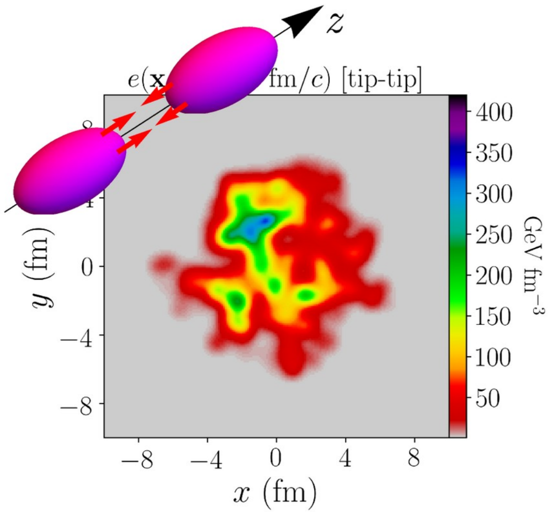
$$\hat{\mathcal{E}}_n(\mathbf{r}_1, \mathbf{r}_2) = (r_{1x} + i r_{1y})^n \, (r_{2x} - i r_{2y})^n$$
$$= r_1^n \, r_2^n \, e^{in(\phi_1 - \phi_2)}$$

[Duguet, Giacalone, Jeon, Tichai, 2504.02481]

Link to the classical rotor picture

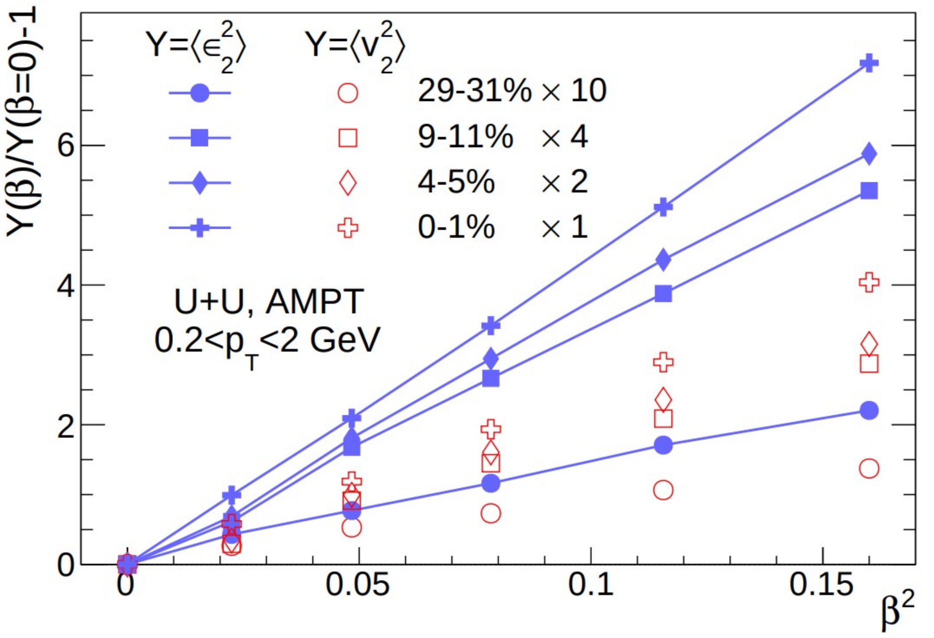
$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left(\left[r-R(\theta,\phi)\right]/a\right)} \;,\; R(\theta,\phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma}Y_{20}(\theta)+\sin\gamma Y_{22}(\theta,\phi)\right)+\underline{\beta_3}Y_{30}(\theta)+\underline{\beta_4}Y_{40}(\theta)\right]$$



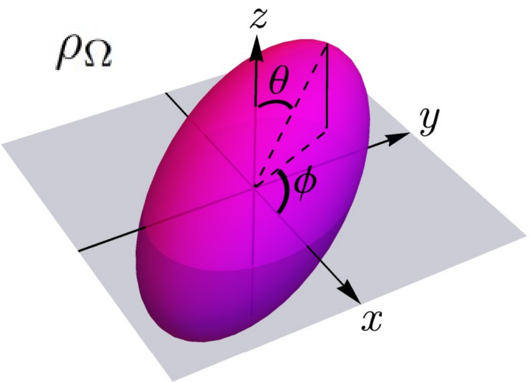


$$\langle v_n^2 \rangle = a_n + b_n \beta_n^2$$

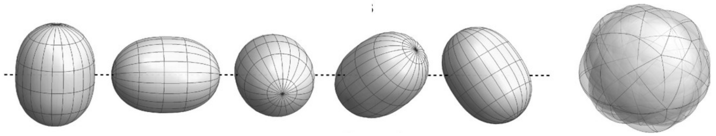
[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]



Classical rotor picture – Correlations from symmetry restoration



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



EULER ANGLES

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

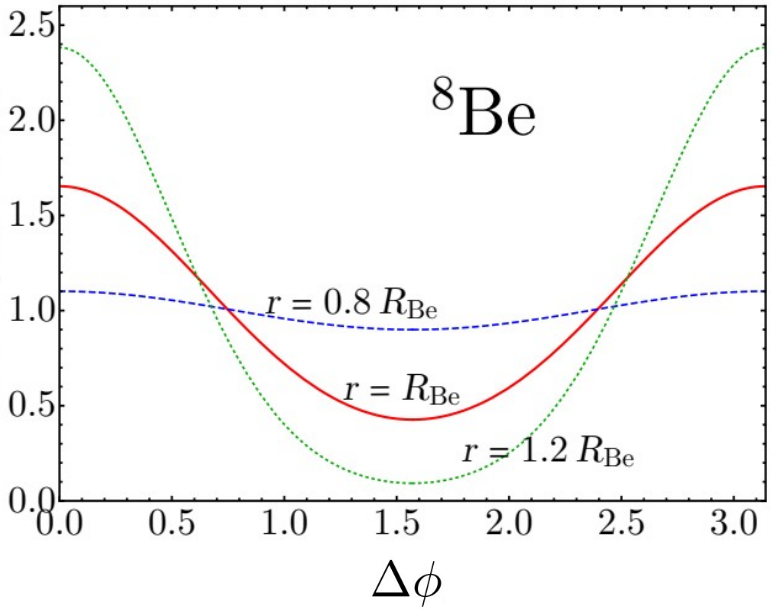
DEFORMATION

Generic considerations – Deformation

$$\rho_\perp^{(2)}(\mathbf{r}_1, \mathbf{r}_2) \propto \beta_2^2\, r_1^2\, r_2^2\, \cos(2\Delta\phi)$$

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

[Blaizot, Giacalone, 2504.15421]



Understanding effects of deformations in the rotor model

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

With $\rho_\perp^{(2)}(\mathbf{r}_1, \mathbf{r}_2) \propto \beta_n^2 \, r_1^n \, r_2^n \cos(n\Delta\phi)$

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

$$\langle \hat{\mathcal{E}}_n \rangle$$

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

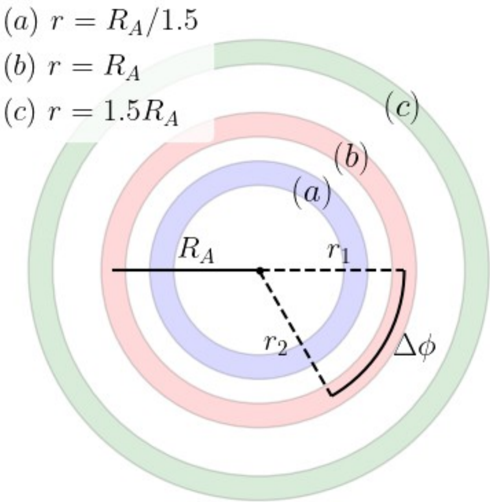
The new observable measures the (squared) deformation of the classical rotor

$$\langle \hat{\mathcal{E}}_2 \rangle \propto \beta_2^2 \qquad \langle \hat{\mathcal{E}}_3 \rangle \propto \beta_3^2$$

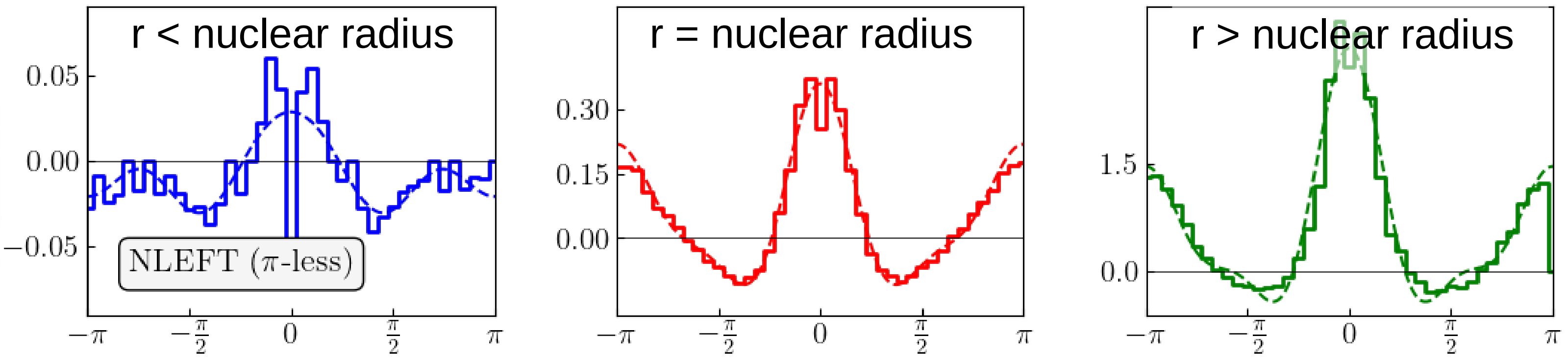
Going *ab initio* – The azimuthal structure of the projected two-body density

Quadrupole modulation in *ab initio* computation for J=0 state ^{20}Ne !!!

[Blaizot, Giacalone, Lovato, in progress]



$$\rho_\perp^{(2)}(r\ ,r\ ,\Delta\phi)\Big/\rho_\perp^{(1)}\rho_\perp^{(1)}$$

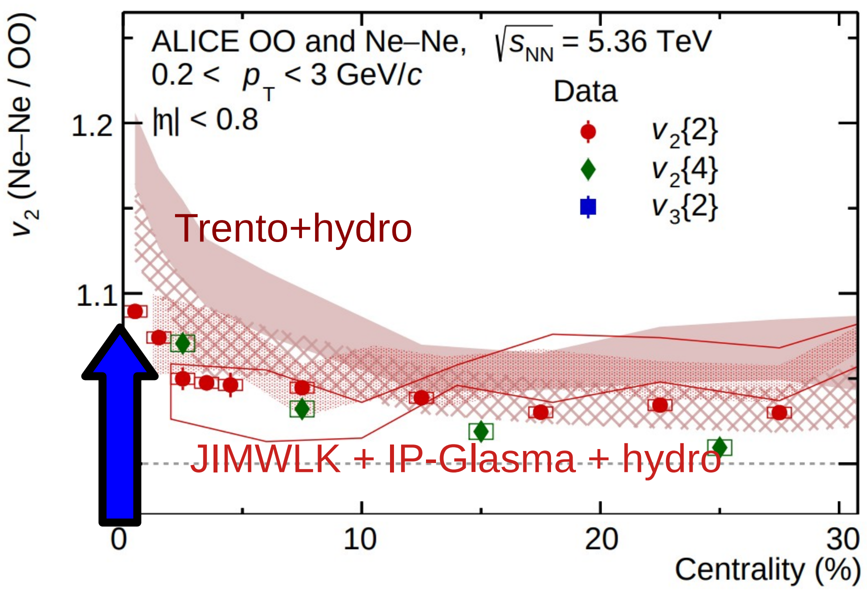


$$\Delta\phi = \phi_1 - \phi_2$$

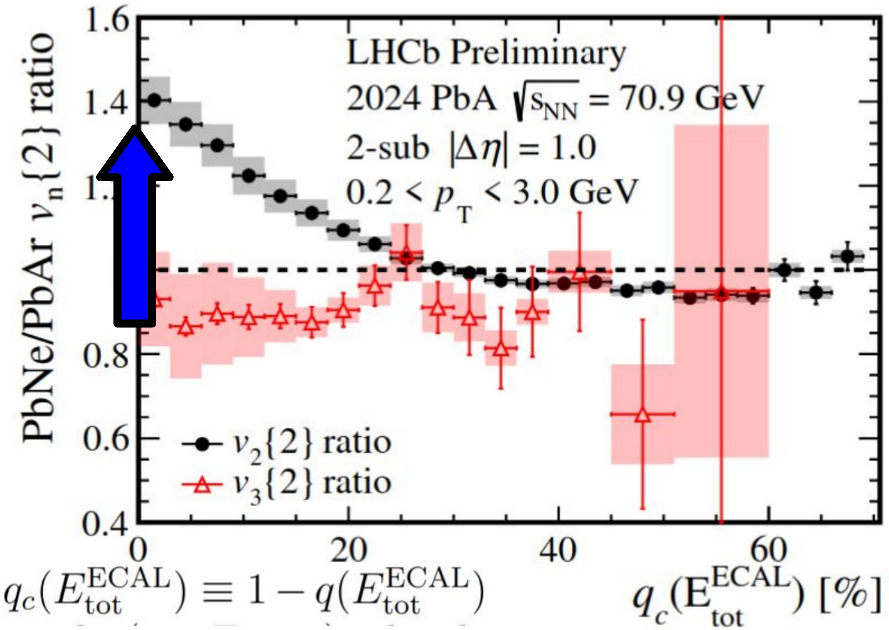
Ground-state expectation $\langle \Psi_0 | \hat{\mathcal{E}}_2 | \Psi_0 \rangle$ **measures the amplitude of modulation**

Modern pictures of emergent collective behavior in nuclear ground states

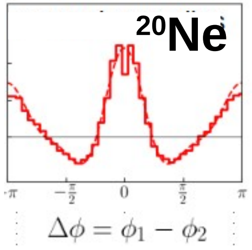
[ALICE Collaboration, 2509.06428]



[LHCb collaboration, Initial Stages 25]



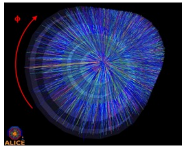
Upward correction from the ground-state expectation $\langle \Psi_0 | \hat{\mathcal{E}}_2 | \Psi_0 \rangle$

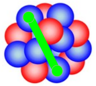


Neon has stronger angular correlations than oxygen / argon

IP-Glasma+hydro shows different trend from Trento+Hydro … interplay with small-x effects?

Prospects – A new window onto the many-body structure of nuclei

Observables 

Many-body operators 

this talk

$$\langle V_n V_n^* \rangle \quad \longleftrightarrow \quad \int_{\mathbf{x}_1,\mathbf{x}_2} |\mathbf{x}_1|^n \, |\mathbf{x}_2|^n \, e^{in(\phi_{\mathbf{x}_1}-\phi_{\mathbf{x}_2})} \, \rho_\perp^{(2)}(\mathbf{x}_1,\mathbf{x}_2)$$

$$\langle V_n V_n^* \, [p_T] \rangle \qquad \int_{\mathbf{x}_1,\mathbf{x}_2} |\mathbf{x}_1|^m \, |\mathbf{x}_2|^n \, \rho_\perp^{(2)}(\mathbf{x}_1,\mathbf{x}_2)$$

much more to come…

$$\int_{\mathbf{x}_1,\mathbf{x}_2} |\mathbf{x}_1|^{2n} |\mathbf{x}_2|^n \, e^{in(\phi_1-\phi_2)} \, \rho_\perp^{(2)}(\mathbf{x}_1,\mathbf{x}_2)$$

$$\langle V_n V_n \, V_n^* V_n^* \rangle \qquad \int_{\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3} |\mathbf{x}_1|^n |\mathbf{x}_2|^n |\mathbf{x}_3|^n \, e^{in(\phi_2-\phi_3)} \, \rho_\perp^{(3)}(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3)$$

$$\langle V_n V_n^* \, V_m V_m^* \rangle \qquad \int_{\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3,\mathbf{x}_4} |\mathbf{x}_1|^n |\mathbf{x}_2|^n |\mathbf{x}_3|^n |\mathbf{x}_4|^n \, e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \, \rho_\perp^{(4)}(\mathbf{x}_1,\mathbf{x}_2,\mathbf{x}_3,\mathbf{x}_4)$$

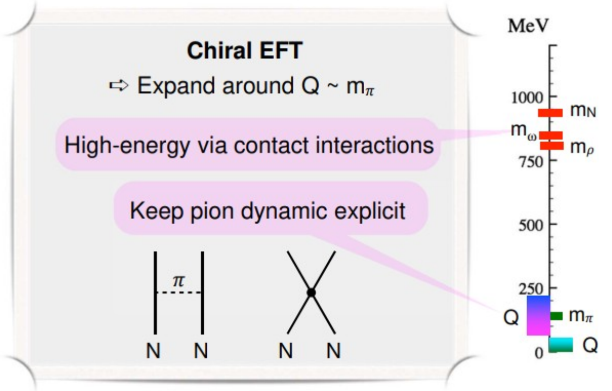
...　　　　　　...

[Gale, Giacalone, Jeon, Kakekaspan, in progress]
[Mehrabpour, Giacalone, Luzum, in progress]

Prospects – A new window onto the nuclear force?

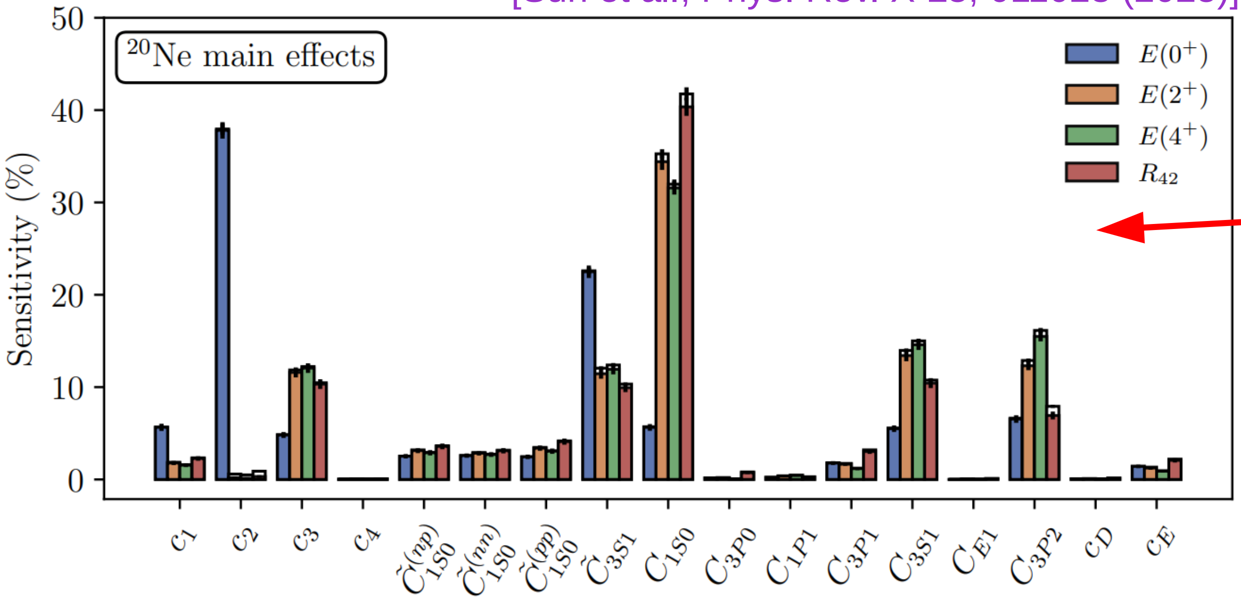
$$\mathcal{H} = \sum_i \mathcal{T}_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

[Hammer, König, van Kolck, RMP **92** (2020) 2, 025004]
[Piarulli, Tews, Front.in Phys. **7** (2020) 245]



17 low-energy constants at N2LO – What determines the “shape” of ^{20}Ne?

[Sun et al., Phys. Rev. X **15**, 011028 (2025)]



How about anisotropic flow?

?

$\langle \hat{\mathcal{E}}_n \rangle$

[work in progress with A. Ekström, G. Hagen, T. Miyagi, A. Tichai]

Some results for ^{16}O !!

[work in progress with A. Ekström, G. Hagen, T. Miyagi, A. Tichai]

mean field results (Pauli exclusion only)

$$\langle\hat{\mathcal{E}}_2\rangle\ [\text{Lovato}] = -0.766\ \text{fm}^4$$

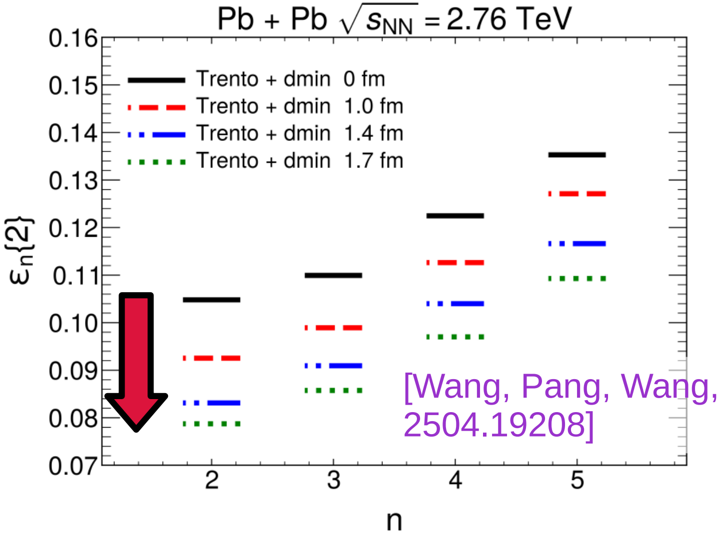
$$\langle\hat{\mathcal{E}}_2\rangle\ [\text{Regnier}] = -0.679\ \text{fm}^4$$

$$\langle\hat{\mathcal{E}}_2\rangle\ [\text{Miyagi} + \text{Tichai}] = -0.700\ \text{fm}^4$$

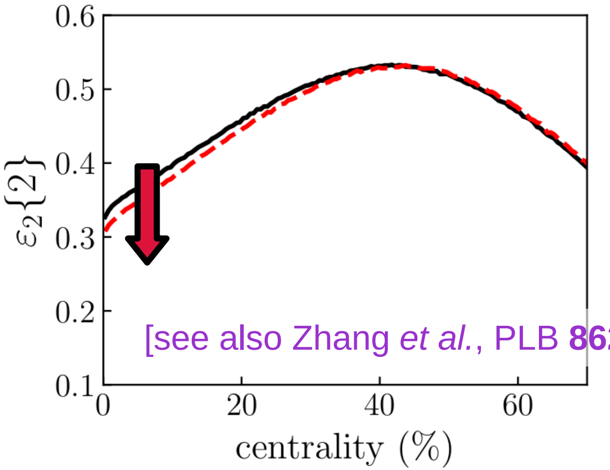
With interactions (IMSRG)

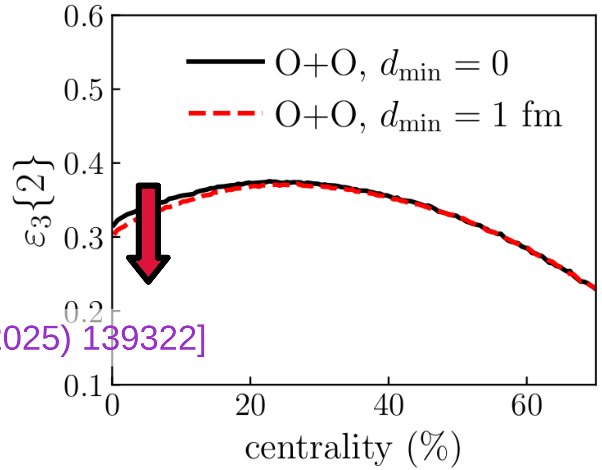
$$\langle\hat{\mathcal{E}}_2\rangle\ [\text{Miyagi} + \text{Tichai}] = -0.269\ \text{fm}^4$$

Negative sign consistent with observation that “repulsion” lowers anisotropies



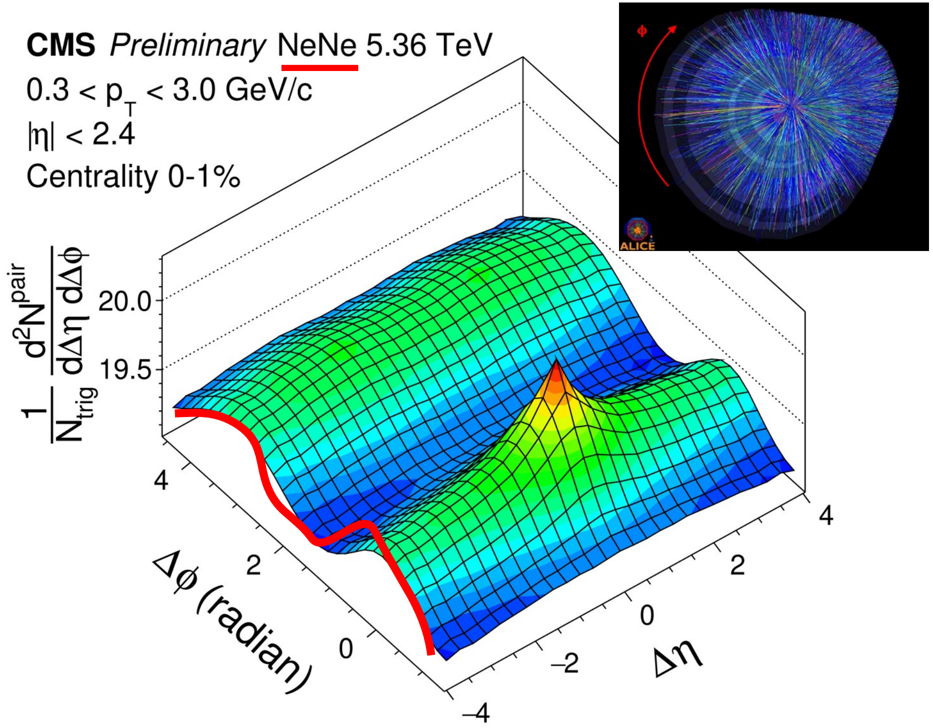
[Wang, Pang, Wang, 2504.19208]

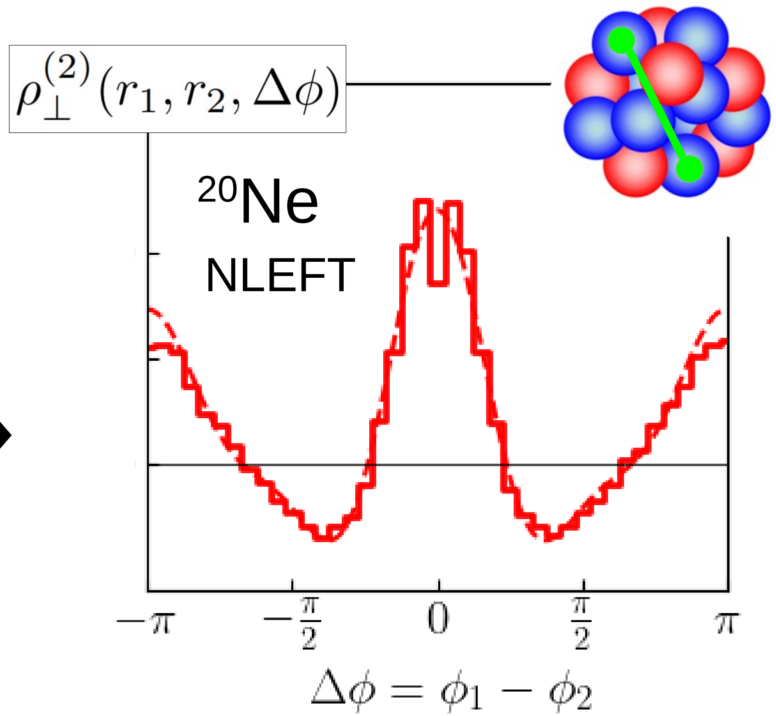




[see also Zhang *et al.*, PLB **862** (2025) 139322]

25 years later … Seeing the many-body structure of nuclear ground states





Implications for nuclear forces in chiral EFT? Connection to QCD?

Implications for 0νββ matrix elements, Schiff moments, … other ideas?

[collaboration with *ab initio* nuclear structure community]

谢谢