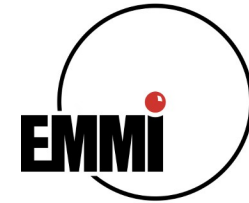
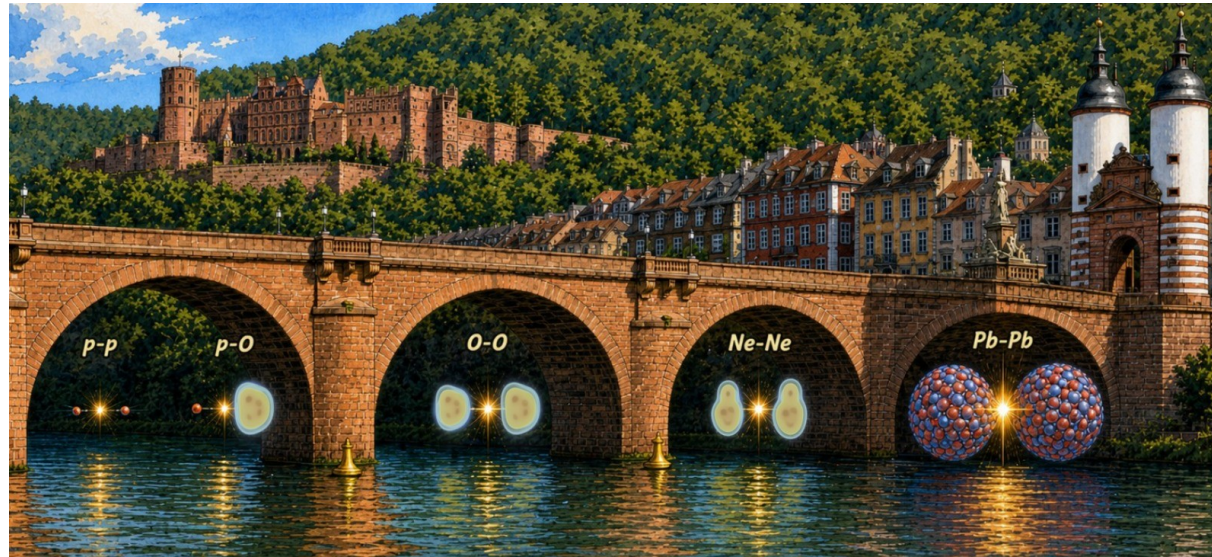


Nuclear structure in high-energy nuclear collisions – What is the deal?

Giuliano Giacalone

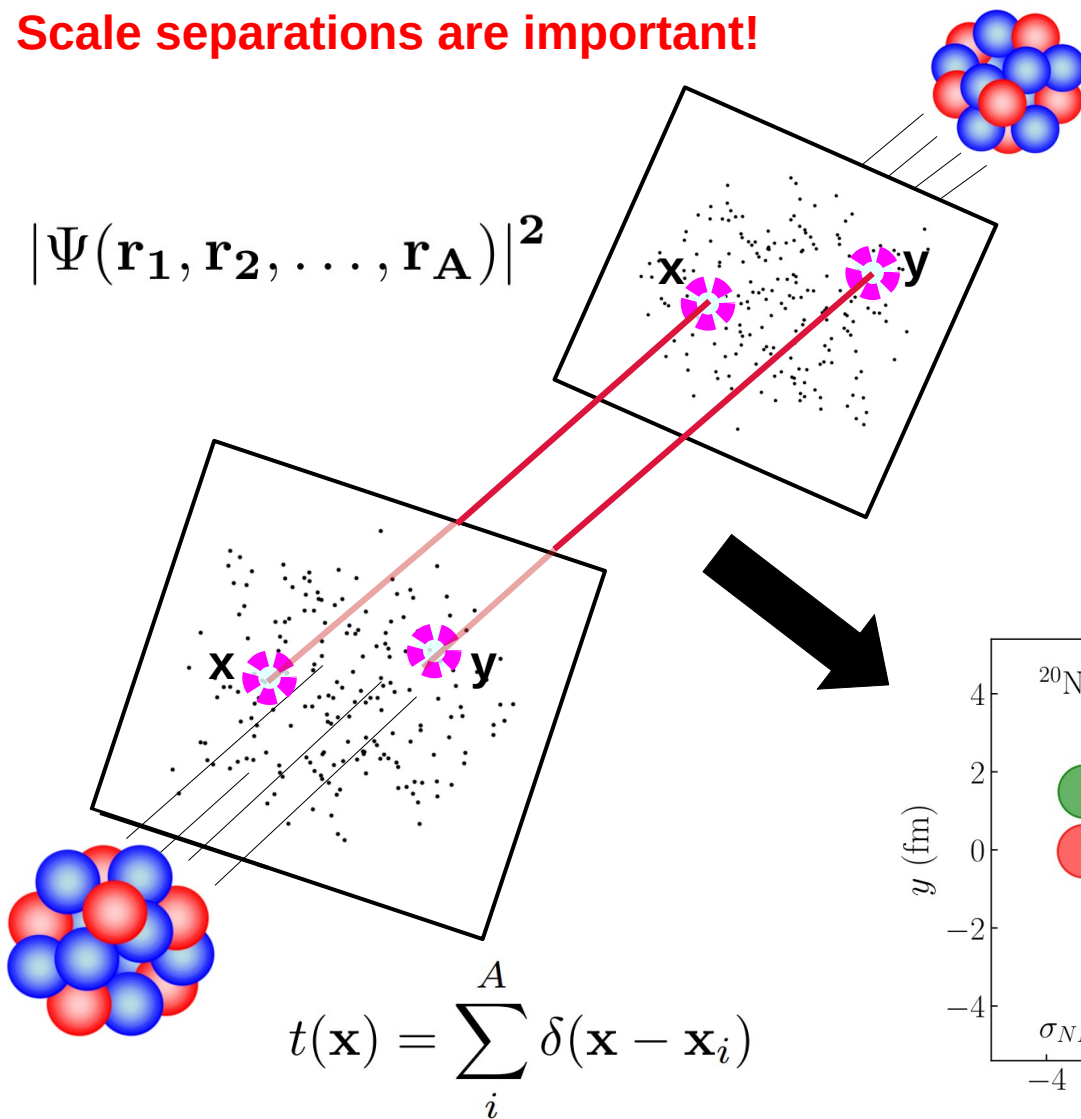


September 23, 2026



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SEIT 1386

Scale separations are important!



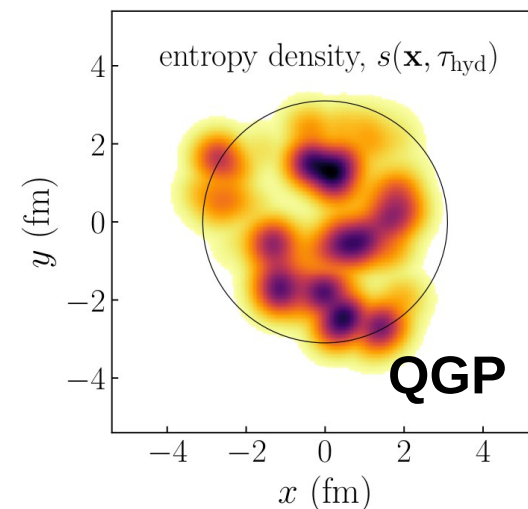
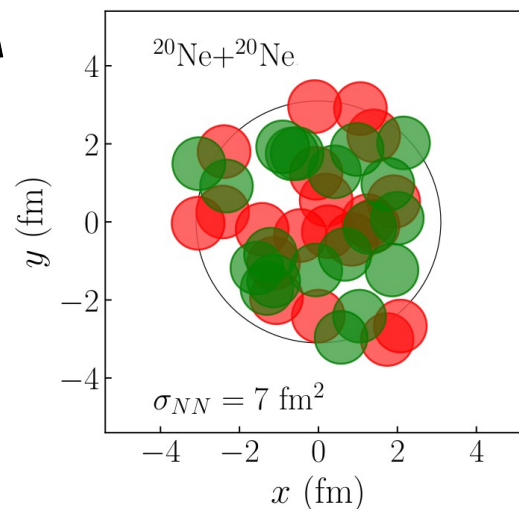
Ultra-central collisions

Time scale of scattering ~ 0.1 fm/c

Typical transverse kick $Q_s \sim 1$ GeV

Nucleon positions dictate large-scale structures in the QGP

Ground state properties



Elliptic flow by Ollitrault

P, Braun-Munzinger
memorandum on
U+U collisions

U+U data collected
released by STAR

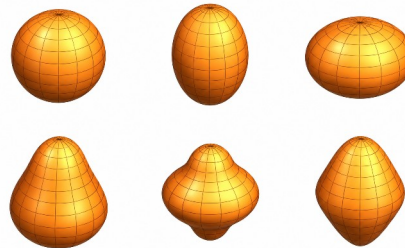
Modern era
Many-body correlations
Operators for flow observables
Light Ion Collisions
Ab initio Ne+Ne collisions

1992 **2000** **2005** **2012** **2015** **≈ 2020** **2025** → **Collider program of nuclear (QCD) many-body physics**

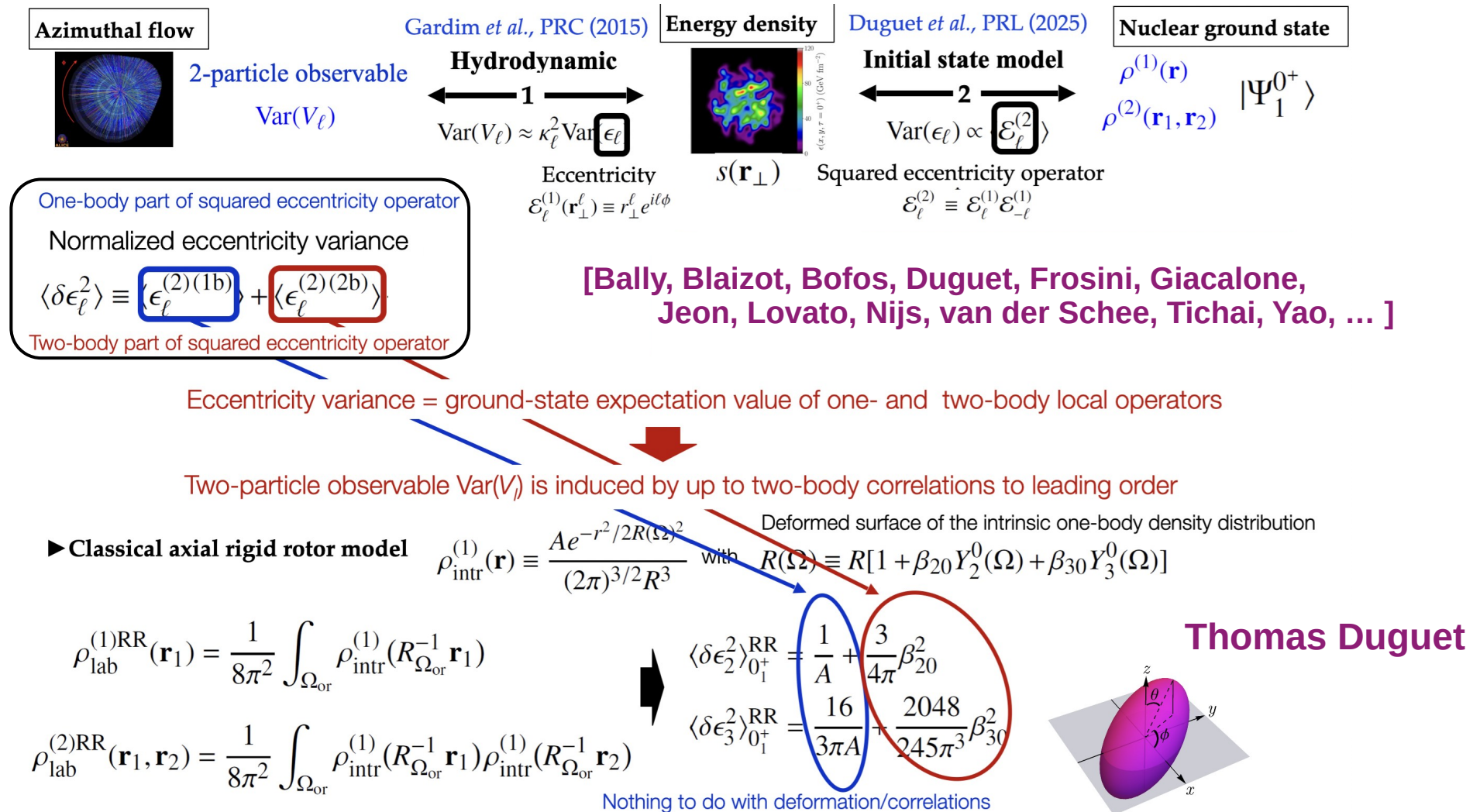
RHIC starts
some thoughts on
U+U collisions
(Shuryak, Gale,
Bao-An Li, Heinz ...)

PHOBOS
evidence of
initial-state
fluctuations

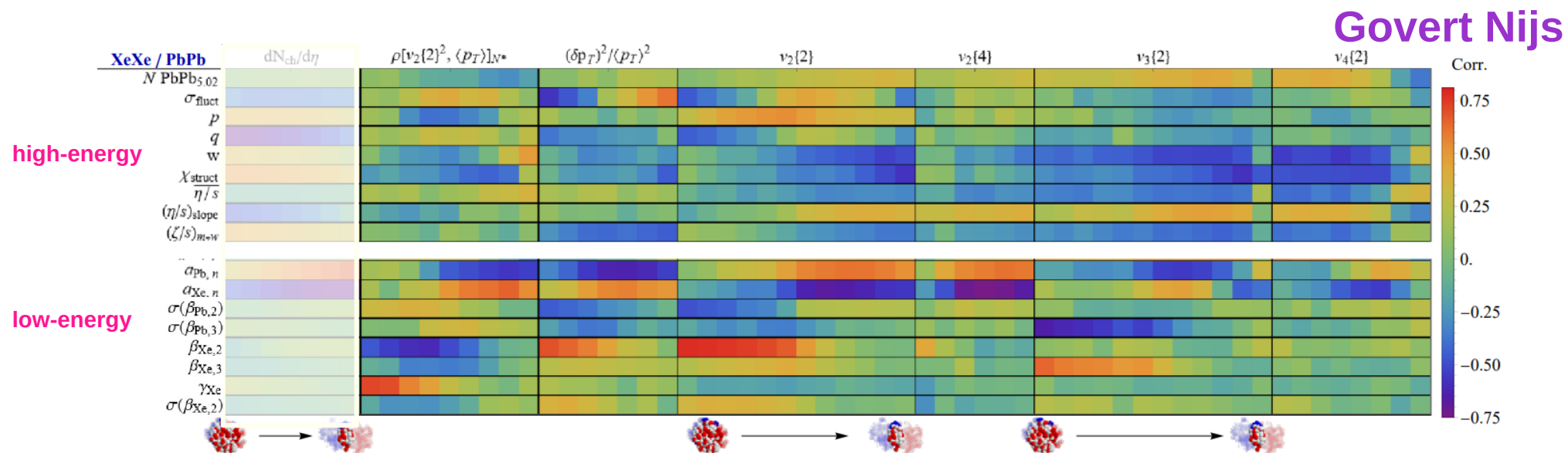
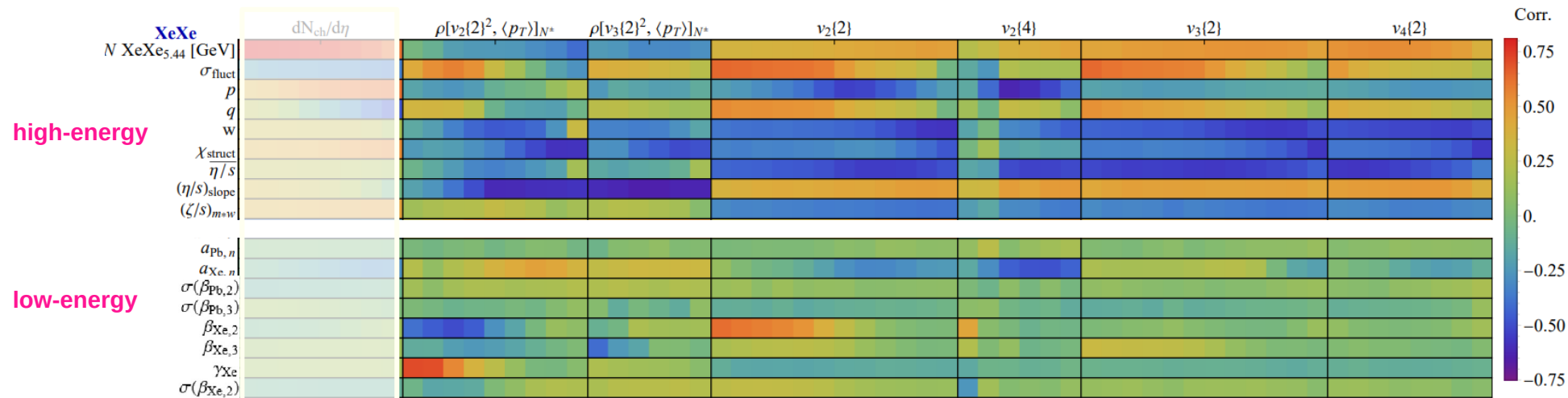
Classical era (shapes)
Xe-Xe collisions
 v_2 and $\langle p_T \rangle$ anti-correlated
Triaxiality
Isobar collisions
... ..



End of the classical age – Mean squared eccentricity and two-body correlations

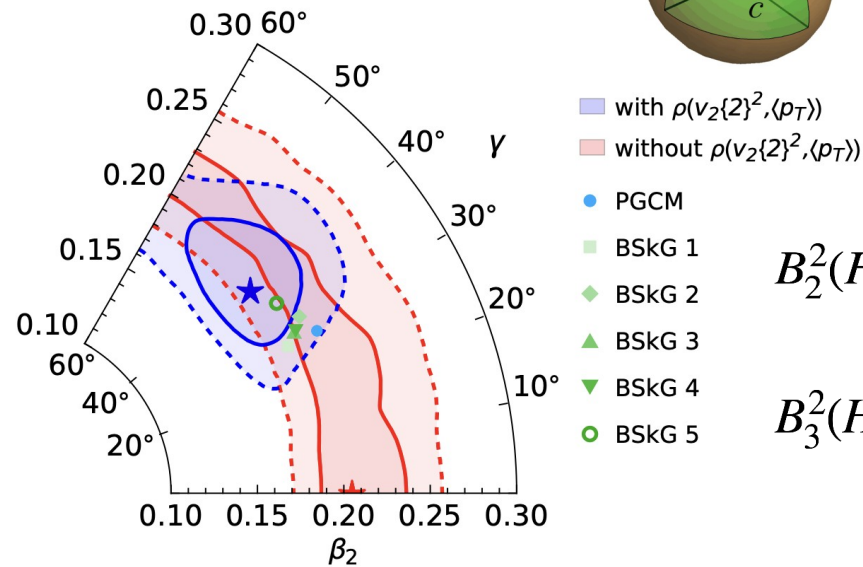


Extracting the shape of the rotor – Remarkable lifting of degeneracy in parameter space



What can we learn about the structure of nuclei from heavy-ion collisions?

■ high-energy approach



- Probes protons + neutrons
- Expectation directly in the ground state
- Higher-order correlators are straightforward
- Octupole and quadrupole on equal footing

^{129}Xe [Giacalone, Nijs, van der Schee, 2606.03993]

$$B_2^2(HE) \frac{\langle \mathcal{E}_2 \mathcal{E}_{-2} \rangle_2}{\langle R_2 \rangle_1^2} \equiv \frac{\langle r_{1\perp}^2 r_{2\perp}^2 e^{i2(\phi_1 - \phi_2)} \rangle_2}{\langle r_{1\perp}^2 \rangle_1^2} = 0.0131(1)_{\text{stat}}(19)_{\text{syst}}$$

$$B_3^2(HE) \frac{\langle \mathcal{E}_2 \mathcal{E}_{-2} \rangle_2}{\langle R_2 \rangle_1^2} \equiv \frac{\langle r_{1\perp}^3 r_{2\perp}^3 e^{i3(\phi_1 - \phi_2)} \rangle_2}{\langle r_{1\perp}^3 \rangle_1^2} = 0.0043(1)_{\text{stat}}(26)_{\text{syst}}$$

$$\frac{\langle R_2 \mathcal{E}_2 \mathcal{E}_{-2} \rangle_3}{\langle R_2 \rangle_1^3} - \frac{\langle \mathcal{E}_2 \mathcal{E}_{-2} \rangle_2}{\langle R_2 \rangle_1^2} = 0.01(1)_{\text{stat}}(30)_{\text{syst}} \times 10^{-3}$$

Q: How to generalize (correlated) sampling of nucleons beyond the rotor model?
 How to implement Pauli, collective, dynamical correlations (and beyond)?
 Could also fit directly low-energy constants for some frameworks (Matt Luzum)

■ low-energy approach

$$\langle Q^2 \rangle = \sum_i B(E2, 0_{GS}^+ \rightarrow 2_i^+)$$

- Probes protons
- Many levels needed
- Higher-order correlators (e.g. triaxiality) increase complexity
- Study of octupole correlations?

Toward an EFT for correlation functions in the soft sector (long due...)

$$\langle F_{n,\text{ev}} F_{n,\text{ev}}^* \rangle_{\text{ev}} = |g_{n0}|^2 \underbrace{\int d^2\mathbf{x}_1 d^2\mathbf{x}_2 r_1^n r_2^n e^{in(\varphi_1 - \varphi_2)}}_{\text{mean squared eccentricity}} \underbrace{\langle \delta e_{\text{ev}}(\mathbf{x}_1) \delta e_{\text{ev}}(\mathbf{x}_2) \rangle_{\text{ev}}}_{\text{leading response}} + \mathcal{O}[(\delta e_{\text{ev}})^3, r^{2n+2}(\delta e_{\text{ev}})^2]$$

mean squared anisotropy

Q: are these corrections ordered?



energy deposition relates energy density ($\tau=0^+$) to nuclear density (thickness)

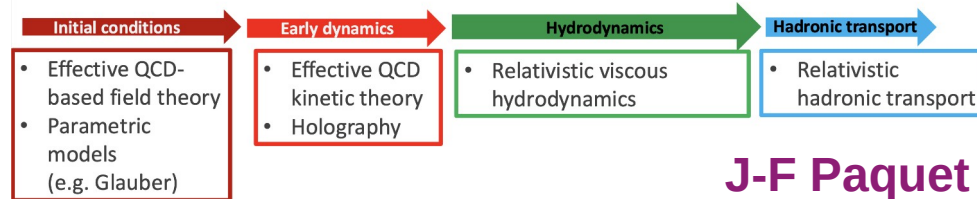
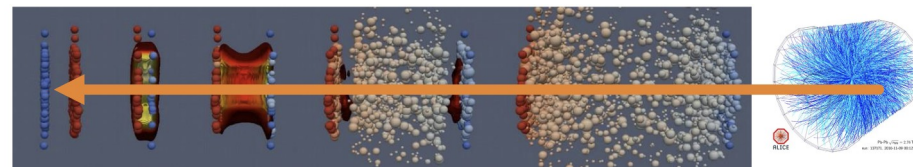
$$\langle \delta e_{\text{ev}}(\mathbf{x}_1) \delta e_{\text{ev}}(\mathbf{x}_2) \rangle_{\text{ev}} = F(|\mathbf{x}_1|, |\mathbf{x}_2|) \langle \delta t_{\text{ev}}(\mathbf{x}_1) \delta t_{\text{ev}}(\mathbf{x}_2) \rangle_{\text{ev}} + \mathcal{O}(\delta t^4) \quad \hat{t}(\mathbf{x}) = \sum_{i=1}^A \delta(\mathbf{x} - \hat{\mathbf{x}}_i)$$

$$\langle F_{n,\text{ev}} F_{n,\text{ev}}^* \rangle_{\text{ev}} = |g_{n0}|^2 \underbrace{\langle \hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_n^\dagger \rangle_{\Psi}}_{\text{leading response}} + \mathcal{O}(r^2 \hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_n^\dagger) + \mathcal{O}(\hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_{m+n}^\dagger) + \dots$$

mean squared anisotropy

multipole operator correlator

Assigning values to the expansion coefficients



Multipole operator

$$\hat{\mathcal{Q}}_n = \sum_i^A r_i^n e^{in\phi_i}$$

[Barata, Giacalone, 2609.18754]

J-F Paquet

Toward an EFT for correlation functions in the soft sector (long due...)

$$\langle F_{n,\text{ev}} F_{n,\text{ev}}^* \rangle_{\text{ev}} = |g_{n0}|^2 \underbrace{\int d^2\mathbf{x}_1 d^2\mathbf{x}_2 r_1^n r_2^n e^{in(\varphi_1 - \varphi_2)}}_{\text{mean squared eccentricity}} \underbrace{\langle \delta e_{\text{ev}}(\mathbf{x}_1) \delta e_{\text{ev}}(\mathbf{x}_2) \rangle_{\text{ev}}}_{\text{leading response}} + \mathcal{O}[(\delta e_{\text{ev}})^3, r^{2n+2}(\delta e_{\text{ev}})^2]$$

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$$\langle F_{n,\text{ev}} F_{n,\text{ev}}^* \rangle_{\text{ev}} = |g_{n0}|^2 \underbrace{\langle \hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_n^\dagger \rangle_\Psi}_{\text{leading response}} + \mathcal{O}(r^2 \hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_n^\dagger) + \mathcal{O}(\hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_{m+n}^\dagger) + \dots$$

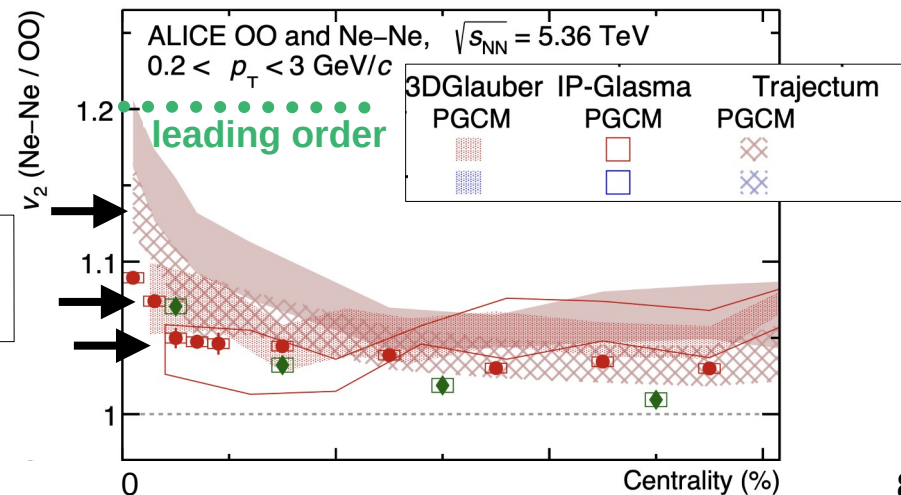
mean squared anisotropy

multipole operator correlator

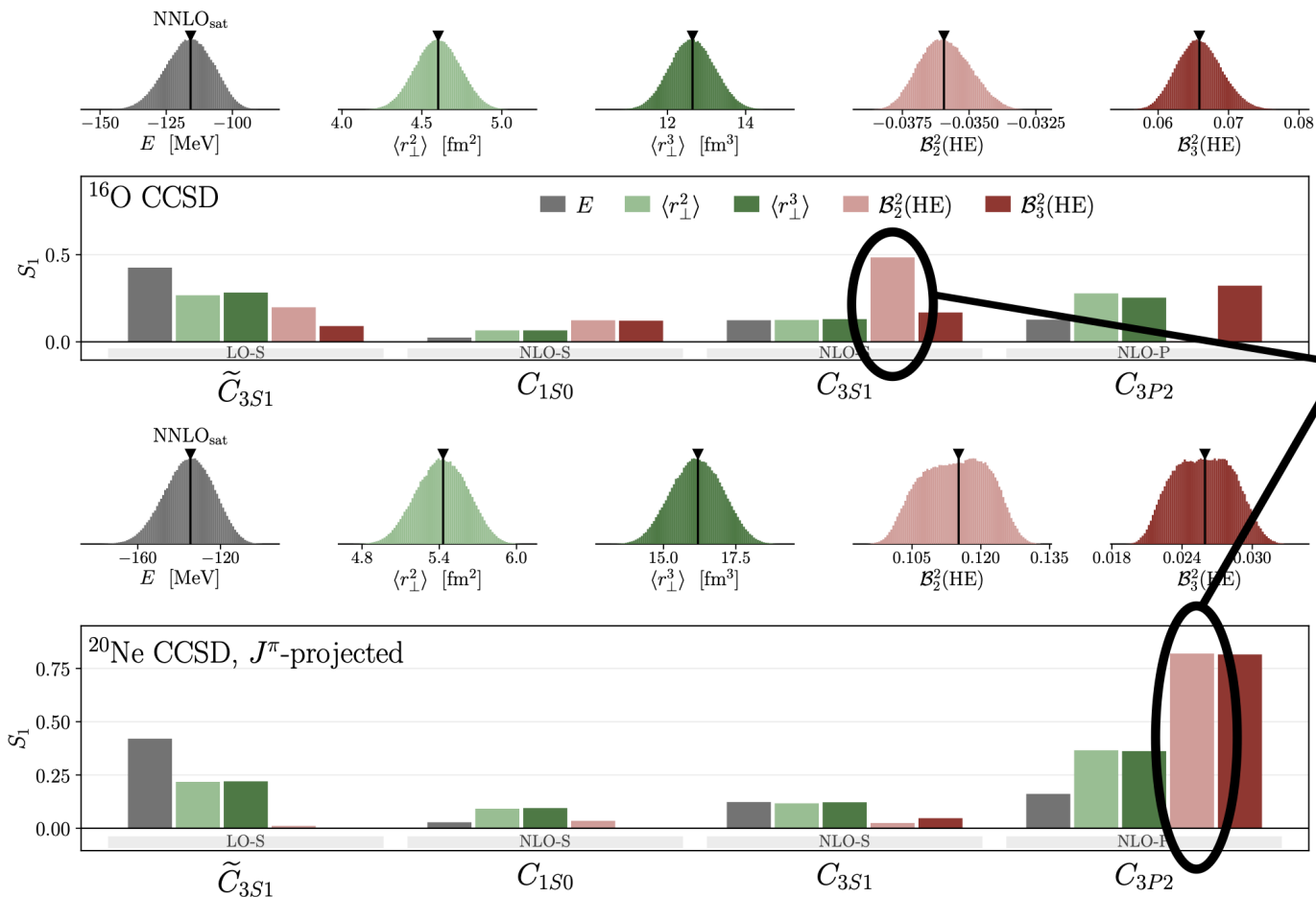
Multipole operator

$$\hat{\mathcal{Q}}_n = \sum_i^A r_i^n e^{in\phi_i}$$

same leading order different coefficients



Prospect #1 – Unveiling the nuclear force through multi-particle correlations



- **Energy:** LO $^3S_1$ sets the scale of binding in both nuclei.
- **Radius:** Similar LO/NLO-S and NLO-P wave sensitivities in both nuclei.

Quadrupolar (B_2^2) shape:

- ¹⁶O NLO $^3S_1$ 49% + LO $^3S_1$ 20%
- ²⁰Ne NLO $^3P_2$ 82%

guesstimate: need to know $B_2^2(\text{HE})$ to $\lesssim 5 - 10\%$ total uncertainty for it to inform chiral Hamiltonians

Andreas Ekström

NB. Complementary to the effort of determining hadron interactions from femtoscopy

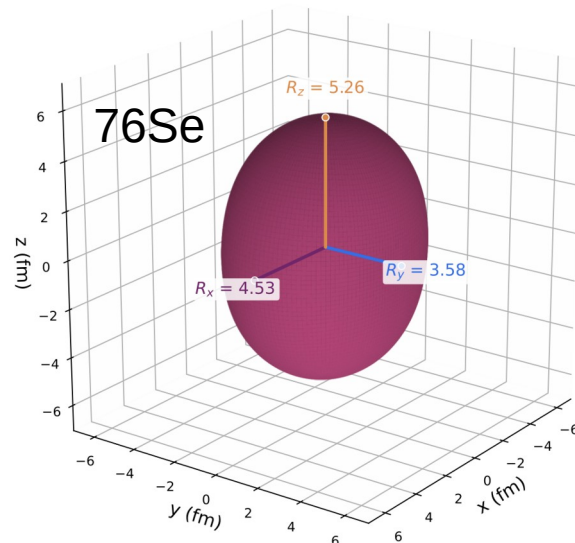
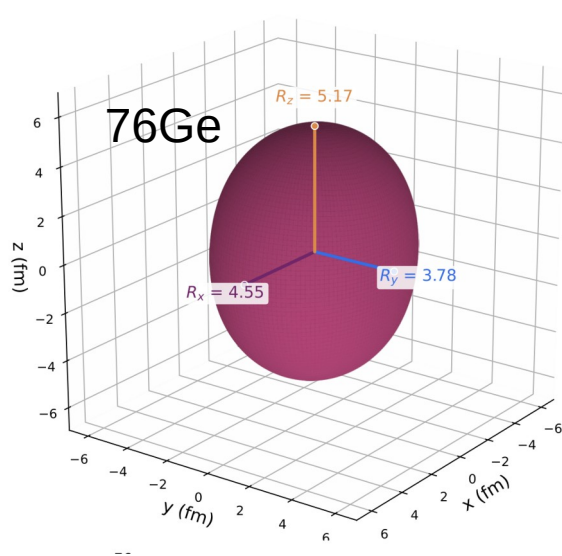
Prospect #2 – Nuclear matrix elements for neutrinoless double beta decay

observation

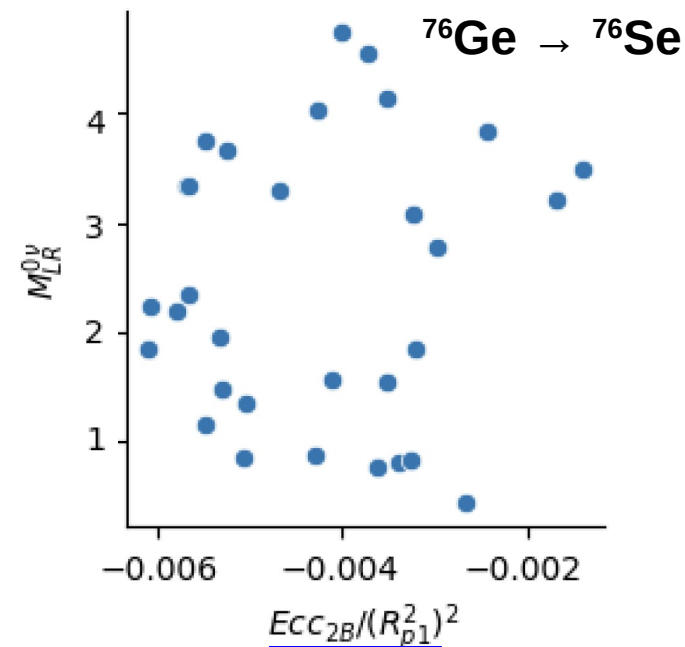
$$1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2$$

BSM

nuclear
structure

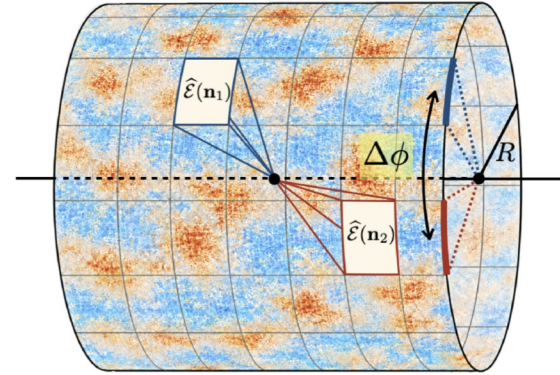
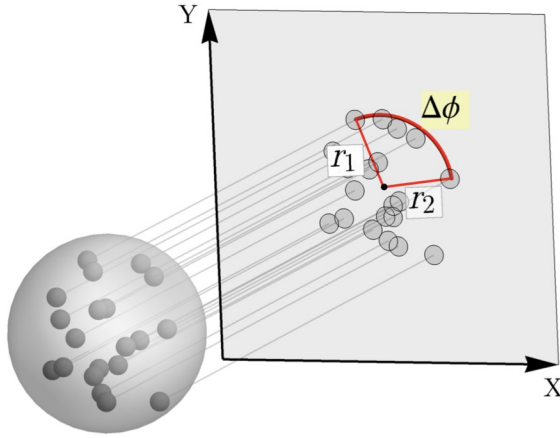


first *ab initio* results!
(spherical nuclei only)



Strong motivation for studying ^{76}Ge and ^{76}Se at a collider

Prospect #3 – EFT in terms of energy-energy correlators? More natural language



[Barata, Giacalone, 2609.18754]

Azimuthal nuclear correlation

$$\int \langle \delta t(\mathbf{r}_1) \delta t(\mathbf{r}_2) \rangle_{\text{ev}} r_1^n r_2^n e^{in\Delta\phi} + \dots$$

$$\propto \langle \hat{\mathcal{Q}}_n \hat{\mathcal{Q}}_n^\dagger \rangle_\Psi + \dots$$

future ?

Azimuthal detector correlation

$$\langle F_{n,\text{ev}} F_{n,\text{ev}}^* \rangle_{\text{ev}} \propto$$

$$\int \langle \delta \mathcal{E}_{\text{ev}}(\mathbf{n}_1) \delta \mathcal{E}_{\text{ev}}(\mathbf{n}_2) \rangle e^{in\Delta\phi}$$

Q: Can we formulate the flow vs. non-flow separation within an EFT language?

Q: Shall we get rid of the notion of 'centrality' and work only with Npart=2A? With ZDCs?