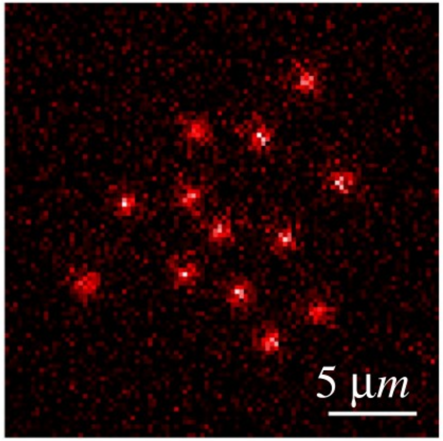
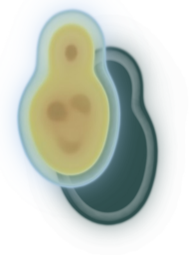
# Imaging atomic nuclei in high-energy collisions

Classical

Quantum

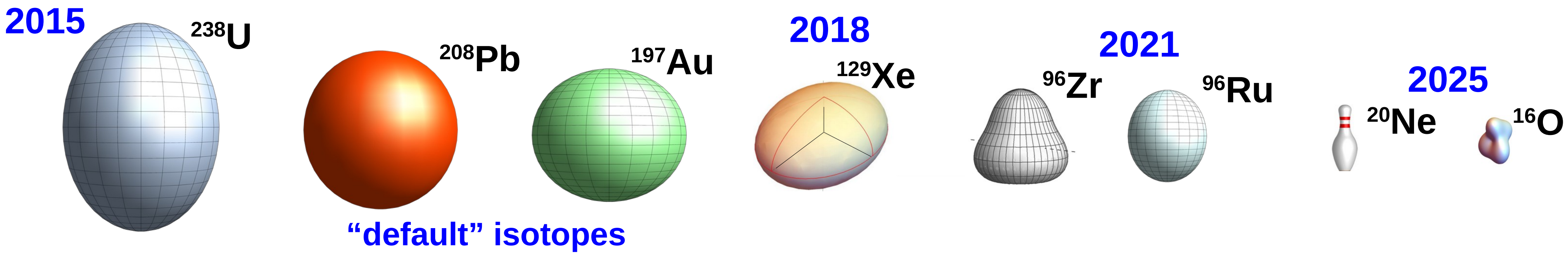


Topic 1 : Low-energy nuclear structure as a new “model uncertainty”

Topic 2 : A new experimental program in nuclear / collider research

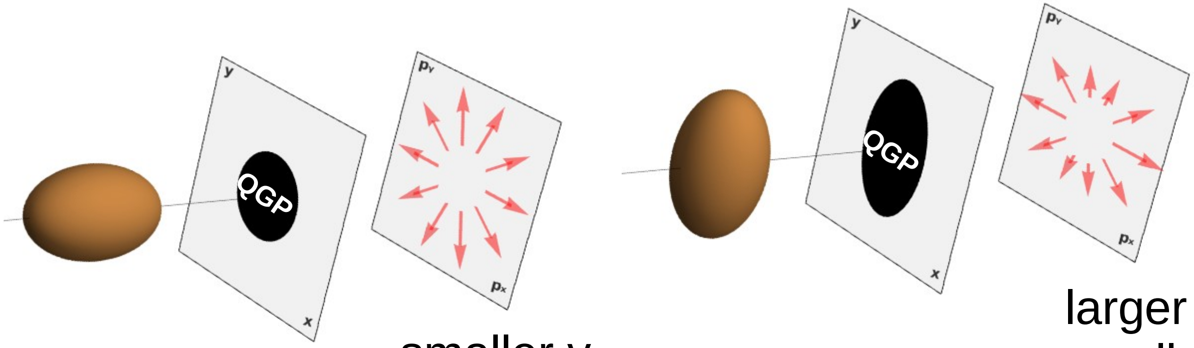
# TOPIC 1: Inevitable interface with nuclear structure – Many nuclei collided recently!




## Anomalies in the data – Shapes as a source of anisotropic flow

$$F = -\nabla P$$

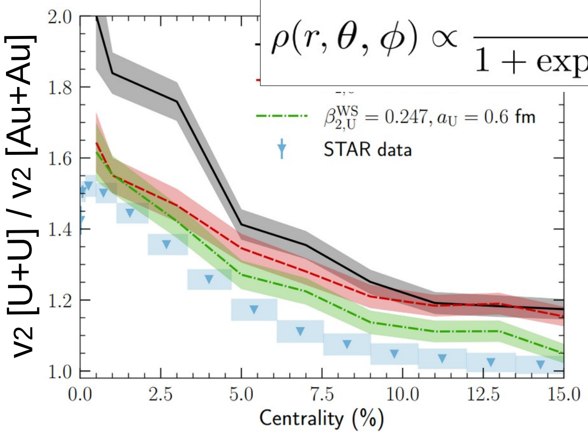
1/R

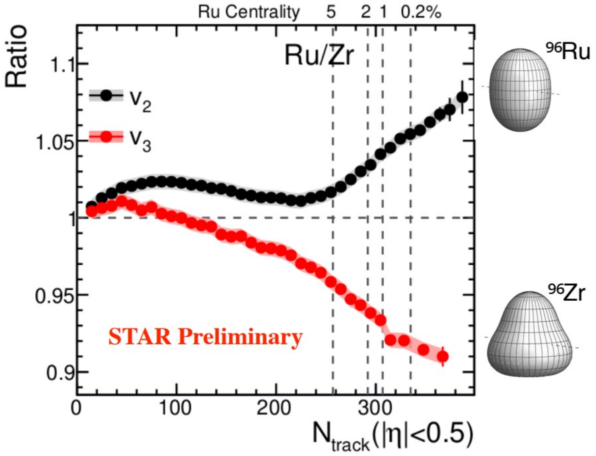



smaller $v_2$
larger $\langle p_T \rangle$

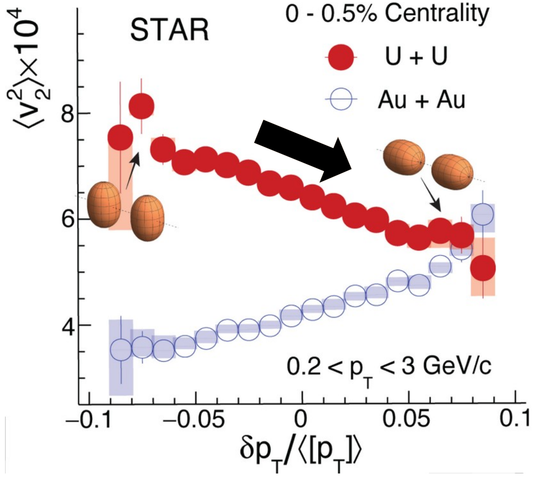
larger $v_2$
smaller $\langle p_T \rangle$

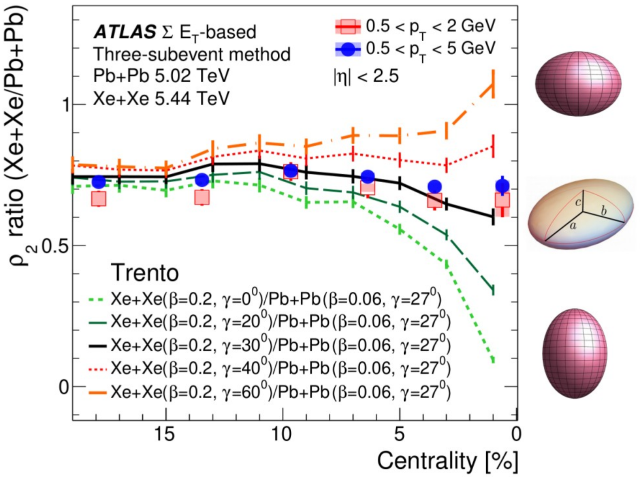
$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left([r-R(\theta,\phi)]/a\right)}\ ,\quad R(\theta,\phi)=R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\theta)+\sin\gamma Y_{22}(\theta,\phi)\right)+\beta_3 Y_{30}(\theta)+\beta_4 Y_{40}(\theta)\right]$$




# “classical interpretation”





[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]

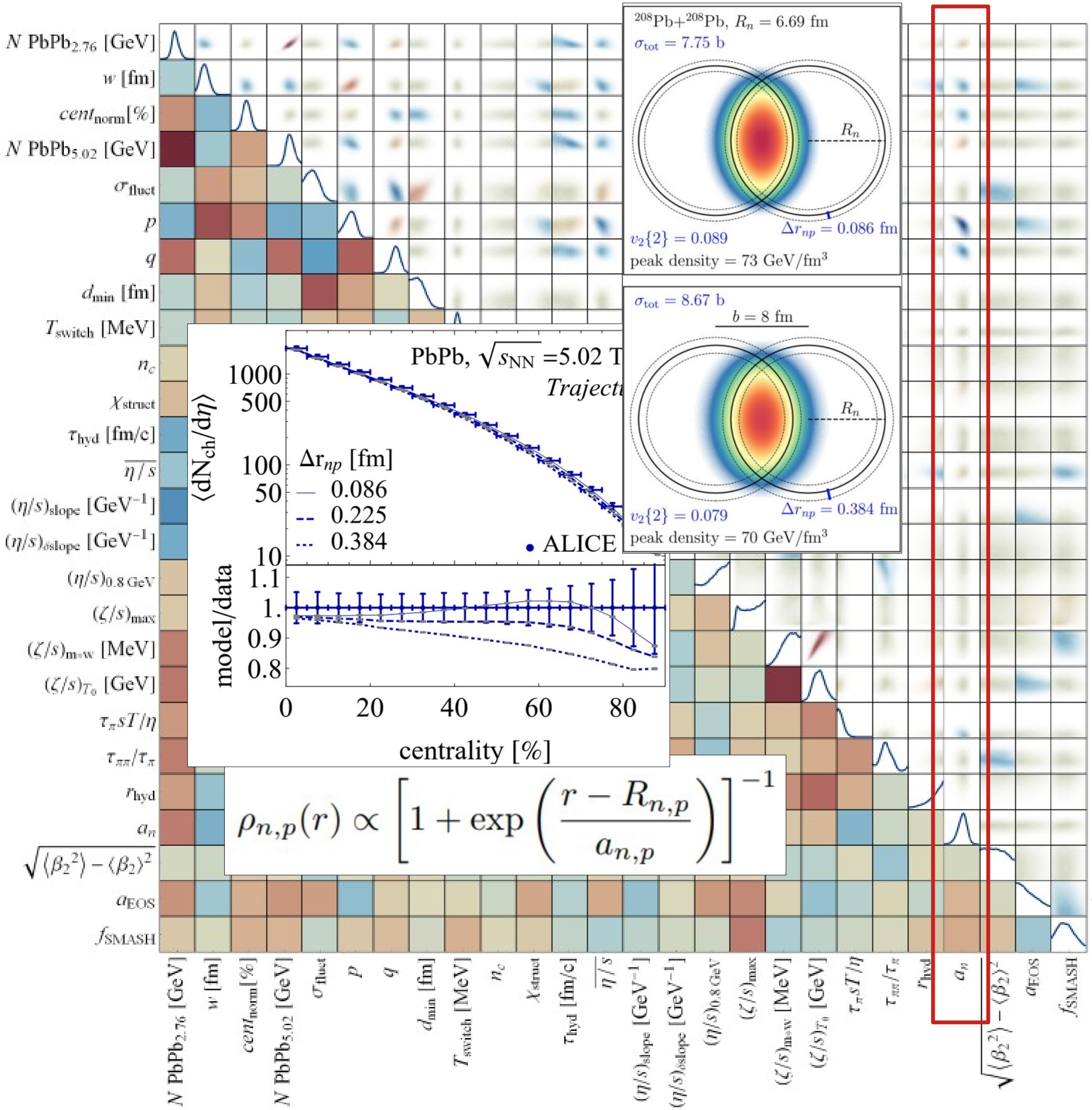
[STAR collaboration, arXiv:2506.17785]

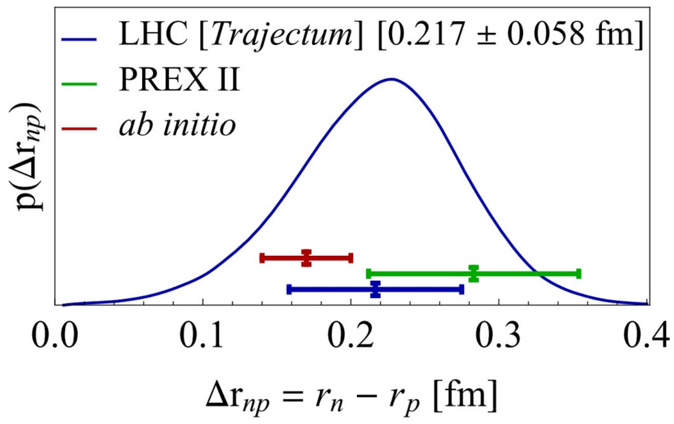
[ATLAS collaboration, arXiv:2509.05171]

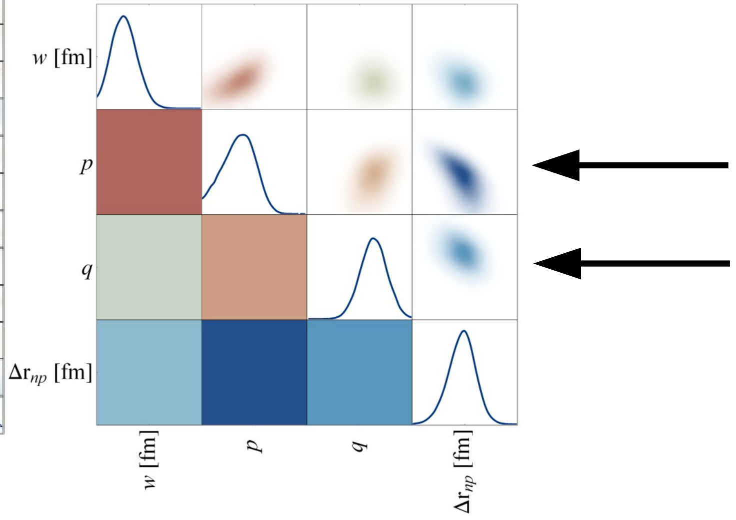
[ALICE collaboration, arXiv:2509.06428]

[CMS collaboration, arXiv:2510.02580]

# Bayesian analysis of $^{208}$Pb neutron skin



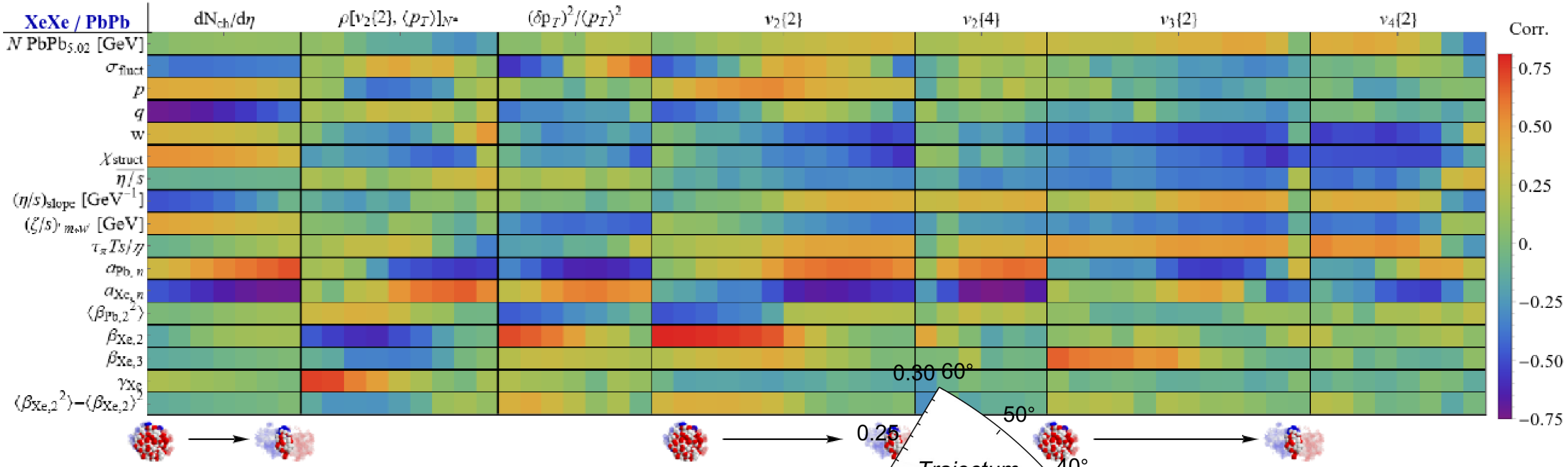



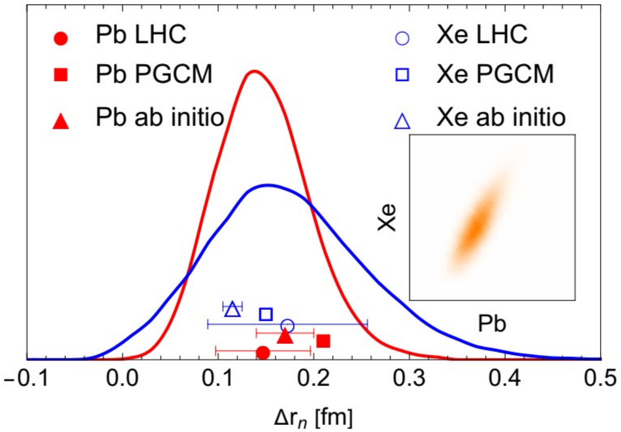



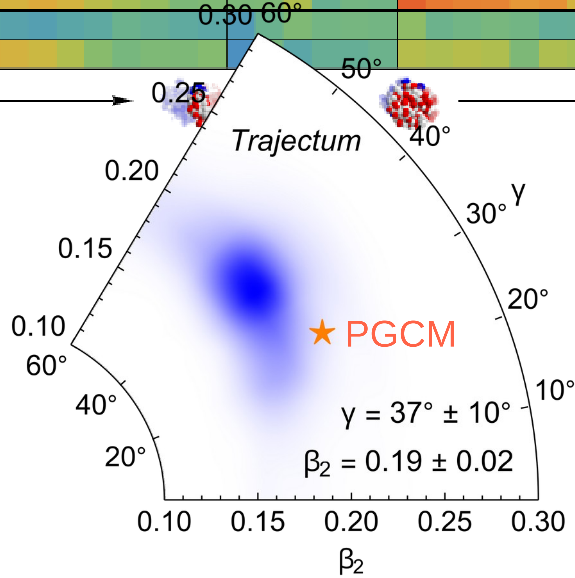

[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]

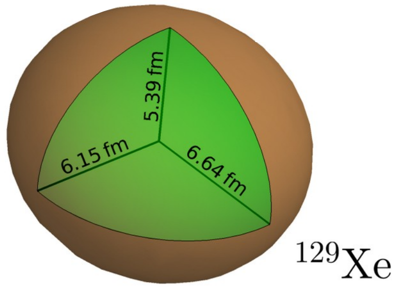
# Bayesian analysis of $^{129}$Xe effective shape

[Giacalone, Nijs, van der Schee, in preparation]



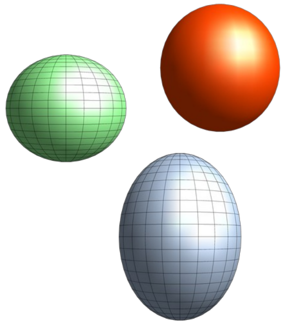



# Dealing with nuclear structure in the multi-system Bayesian era

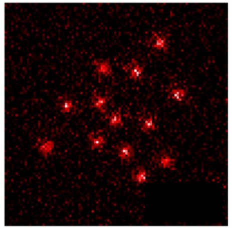
**Old paradigm:** Take one-body charge density of nucleus X from a 1987 paper and sample nucleons … makes little sense, we see many-body correlations (a.k.a. deformations) in data!
**Issue:** Deformation/skin parameters (e.g. Woods-Saxon) needed in HIC cannot really be taken from low-energy measurements!

**Strategy #1 – Keep a deformed one-body picture add related WS parameters to Bayesian fits.** No interest in parameters themselves: use shapes to capture "realistic" initial-state effects and get QCD information
(Caveat: extracted shape parameters should still make some sense)

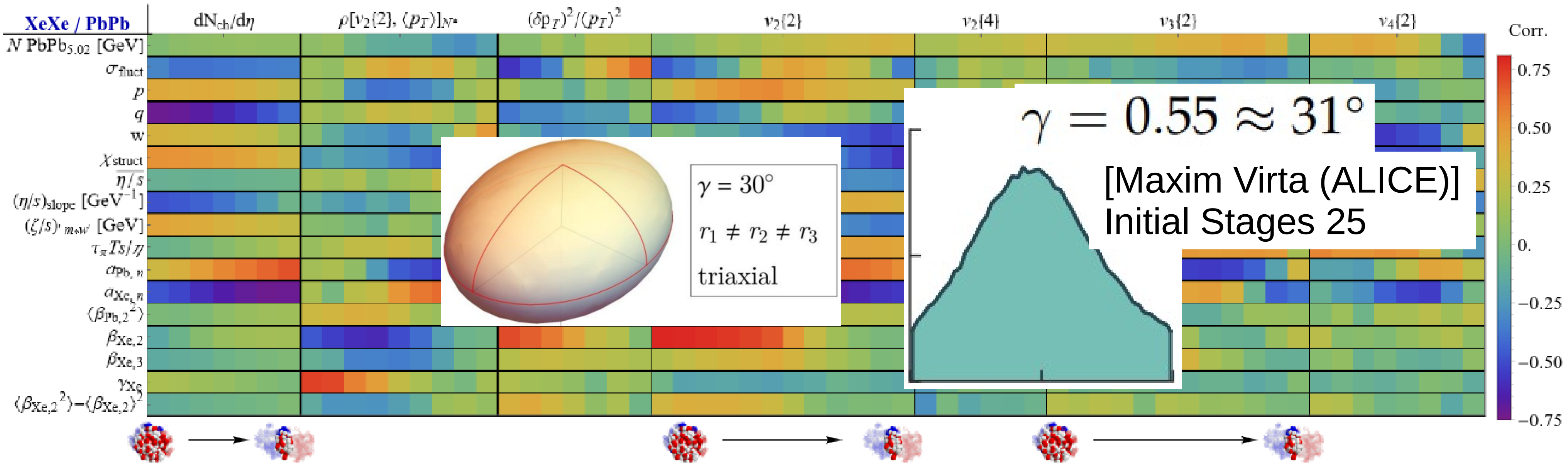


**Strategy #2 – Take one nuclear input/model as "truth" and do fits**
NB: Woods-Saxon parametrizations not viable, and subtleties with sampling of PGCM [e.g. analysis by Weiyao Ke: 2509.09549]
**Possibility:** Nuclear Lattice EFT with chiral EFT interactions
(Caveat: some uncertainty quantification still needed)

$|\psi|^2$



# TOPIC 2: Impressive sensitivity to many-body properties of nuclei




**What do we learn?**

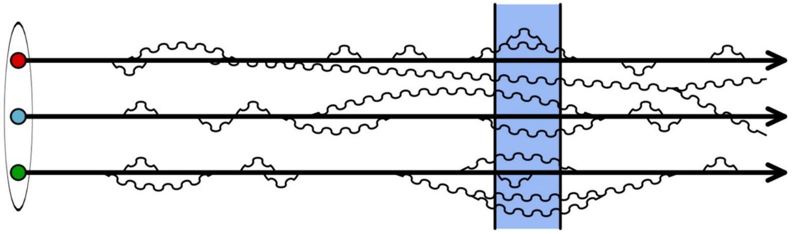
… compelling feature of UHIC analyses is that they explicitly probe many-body correlations in the nucleus. Focusing on this aspect, rather than shapes, represents a strength of the approach worth playing to.

[Dobaczewski *et al.*, PRR **7** (2025) 4, 043159]

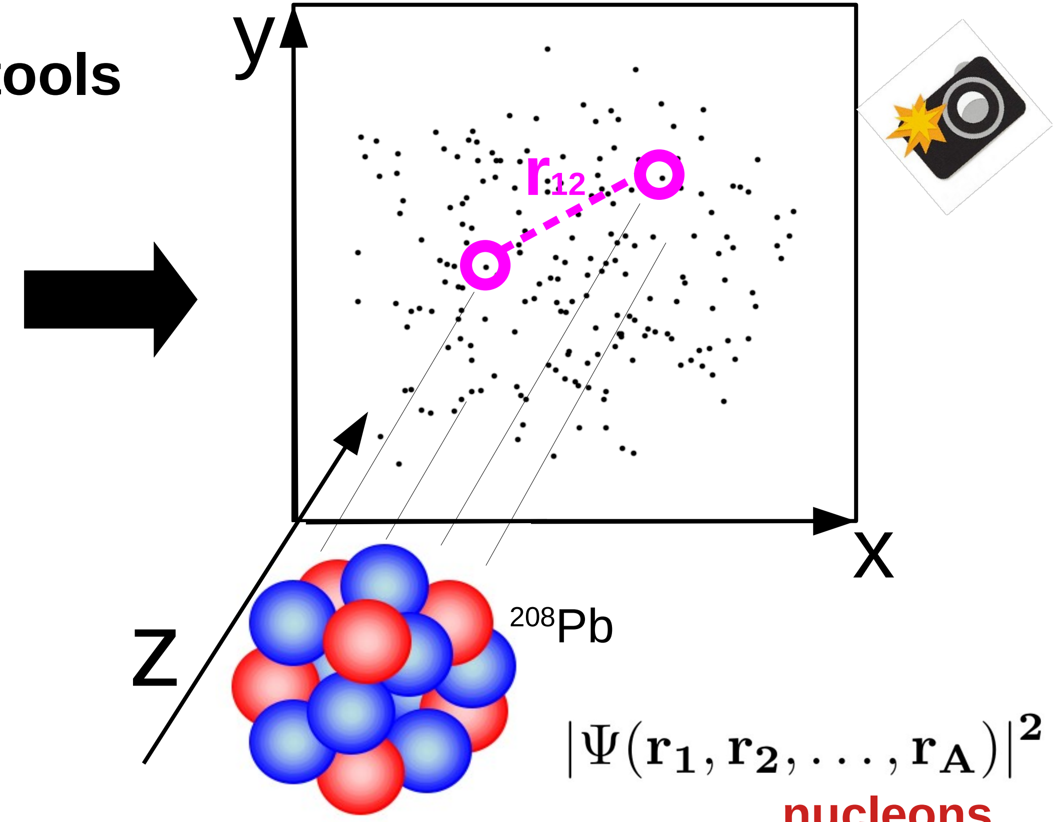
# Unique separation of scales – A billion high-resolution snapshots

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

## High-energy collisions as imaging tools



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




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

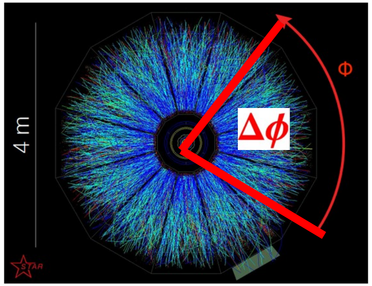
## Correlations of nucleon positions?

**FINAL STATE TWO-PARTICLE CORRELATION**

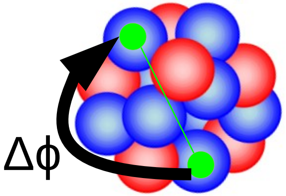
$$\langle v_n^2 \rangle = \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle_{\text{events}}$$

**TWO-BODY NUCLEAR CORRELATIONS**

$$\underbrace{\int_{\mathbf{r}_1, \mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2) \; r_{1\perp}^n \; r_{2\perp}^n \; e^{in(\phi_1 - \phi_2)}}_{\langle \hat{\mathcal{E}}_n \rangle}$$




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

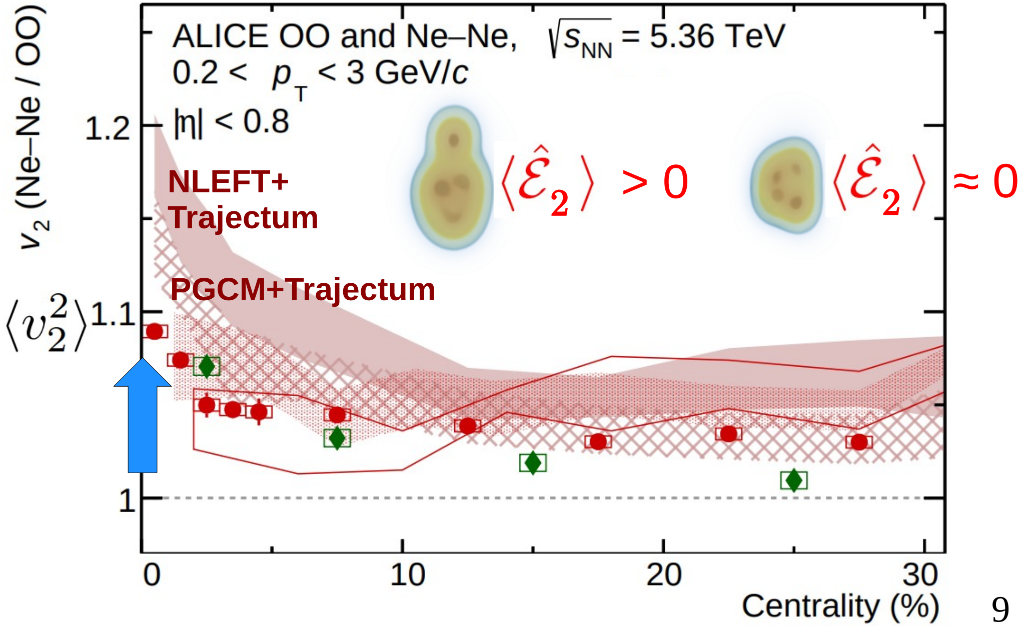



[Duguet, Giacalone, Jeon, Tichai, PRL **135** (2025) 18, 182301]

**New <u>many-body</u> operators**

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

**Neon has stronger angular (quadrupole) correlations than oxygen**



# What do we learn? – Understanding the nuclear force

# [at least what I find most interesting]

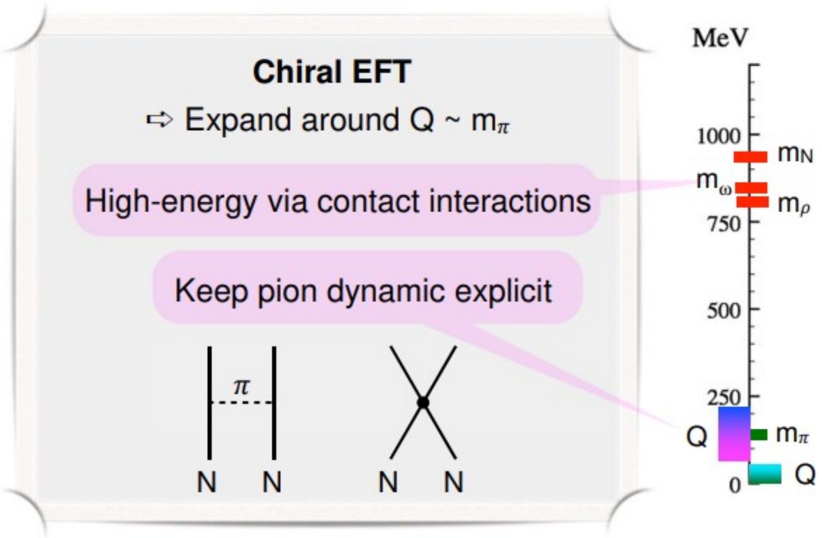
[Weinberg, PLB **251** (1990) 288-292,
NPB **363** (1991) 3-18]

**Modern paradigm of nuclear forces**

**Effective field theory of low-energy QCD**

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

$$m_\pi / m_{\mathrm{QCD}} \ll 1$$




r-process nucleosynthesis, neutron star EOS and mergers,
neutrinoless double β decay, direct DM searches, …

[Hammer, König, van Kolck, RMP **92** (2020) 2, 025004]
[Epelbaum, Hammer, Meissner, RMP **81** (2009) 1773-1825]

## Example of pipeline

## Input from heavy-ion collisions!

$$\hat{\mathcal{E}}_n(\mathbf{r}_1, \mathbf{r}_2) = r_{1\perp}^n \; r_{2\perp}^n \; e^{in(\phi_1 - \phi_2)}$$

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

A Tichai (TU Darmsadt)

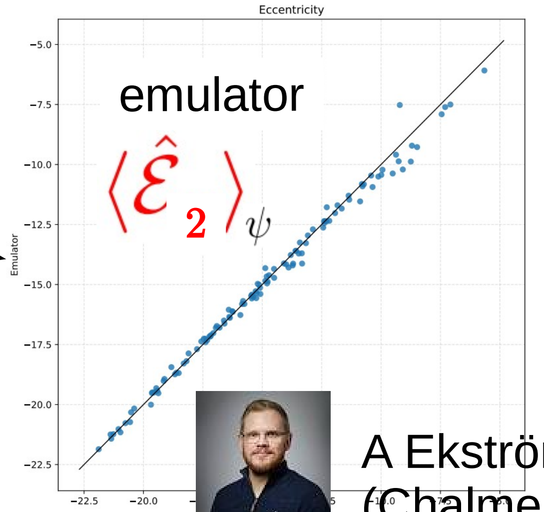
T Miyagi (Tsukuba)

CC computations

$$H\psi_n = E_n \psi_n$$

$$\langle \hat{\mathcal{E}}_2 \rangle_\psi$$


G Hagen (ORNL)

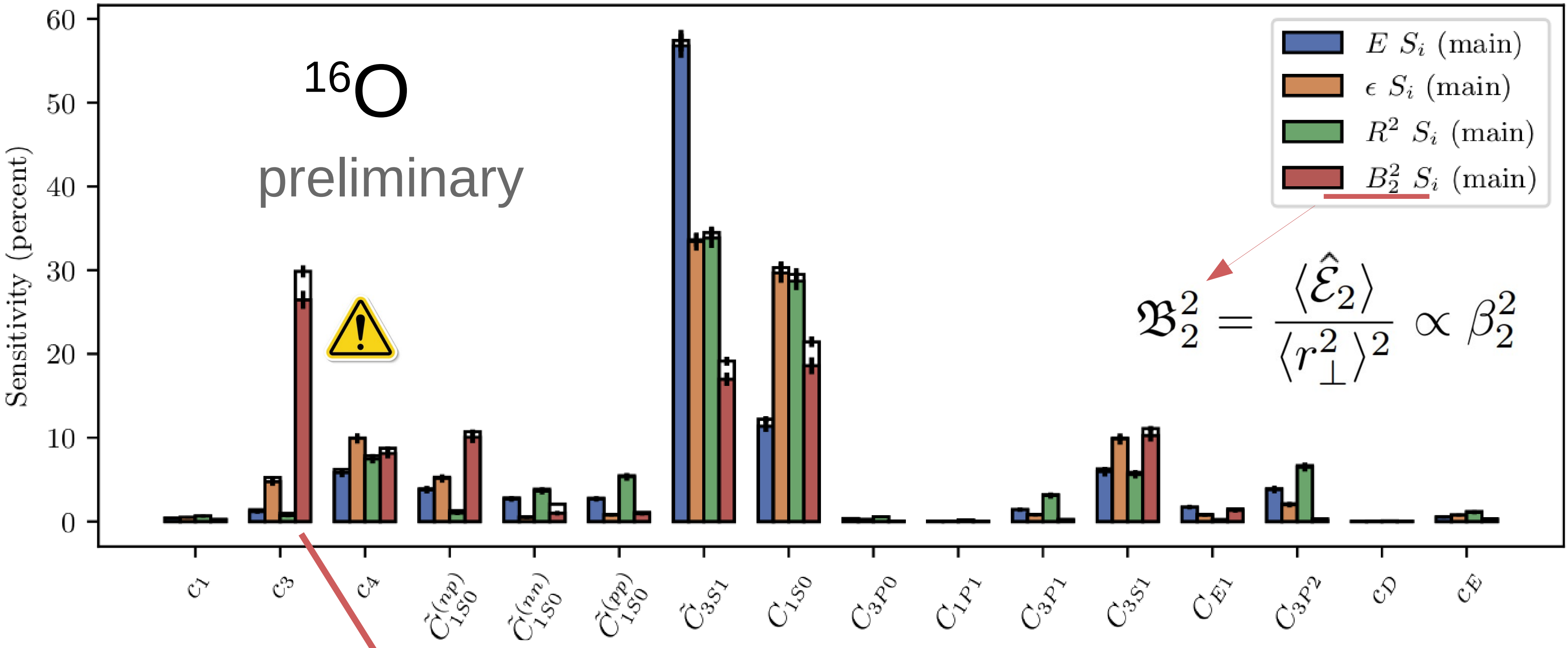



emulator

$$\langle \hat{\mathcal{E}}_2 \rangle_\psi$$

A Ekström (Chalmers, SE)

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




$$\mathfrak{B}_2^2 = \frac{\langle \hat{\mathcal{E}}_2 \rangle}{\langle r_\perp^2 \rangle^2} \propto \beta_2^2$$

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

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

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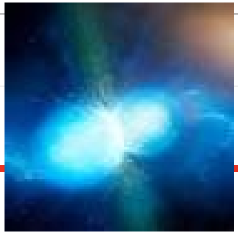
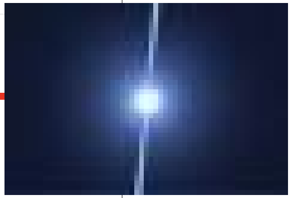
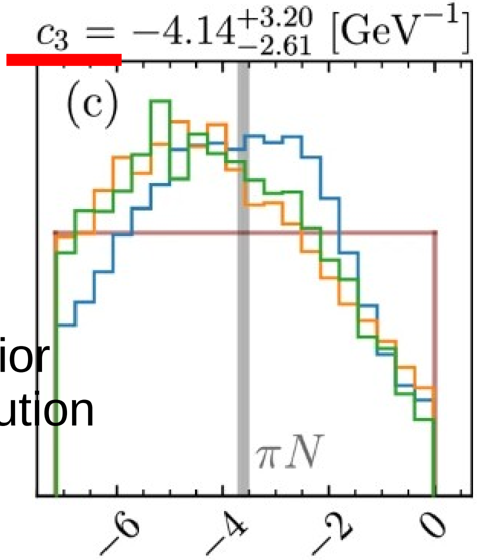
# Inferring three-nucleon couplings from multi-messenger neutron-star observations

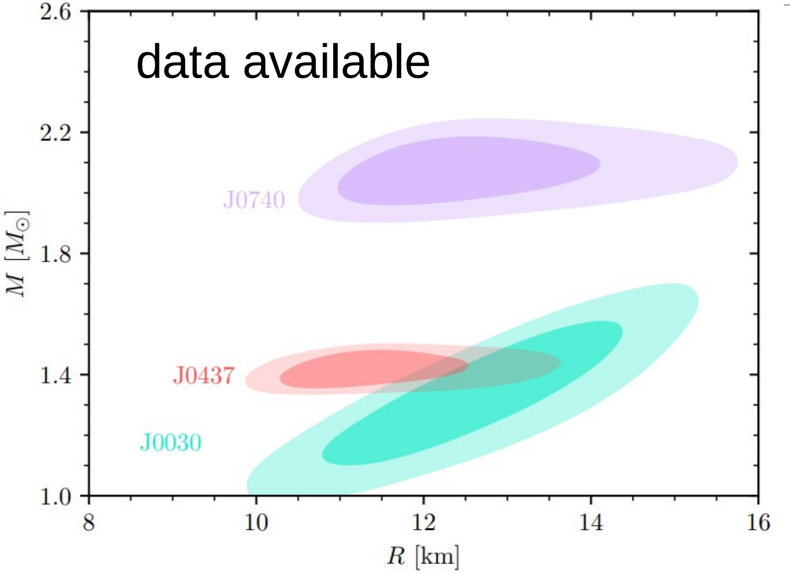
Rahul Somasundaram, Isak Svensson, Soumi De, Andrew E. Deneris, Yannick Dietz, Philippe Landry, Achim Schwenk & Ingo Tews



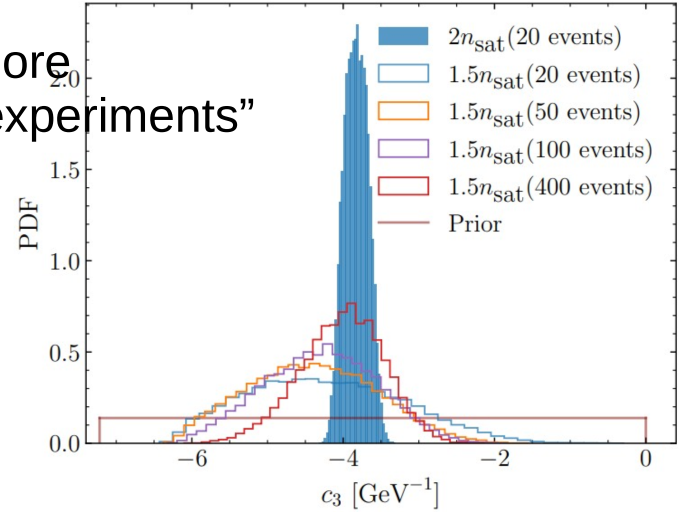





posterior distribution




data available




more "experiments"

# Correlated sampling methods – How to deliver new information on nuclei?

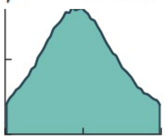
## 1 – The shape approach

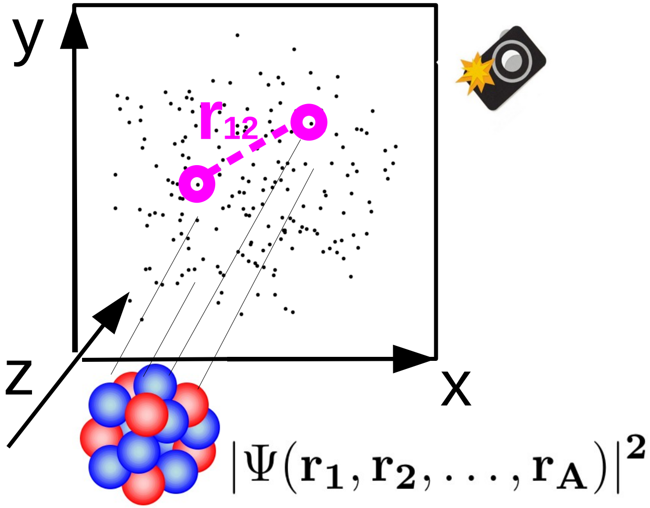
Use deformations/diffuseness as “intermediaries”
Return results in terms of **observables** [more to come]

$$\beta_2, \gamma,\ \beta_3,\ \ldots \longrightarrow \int_{\mathbf{r}_1,\mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1,\mathbf{r}_2)\hat{\mathcal{E}}_n(\mathbf{r}_1,\mathbf{r}_2)$$

Study correlations with final-state observables
(and with modeling of short-scale QCD effects)

$\gamma = 0.55 \approx 31°$






## 2 – Systematic inference of LECs of chiral EFT

Obtain nucleon positions from A-body (or reduced) densities (NLEFT, QMC, …)
Promote LECs to parameters to infer in global Bayesian analyses
<u>Do we have the technology to do this?</u> [feedback to QGP program]

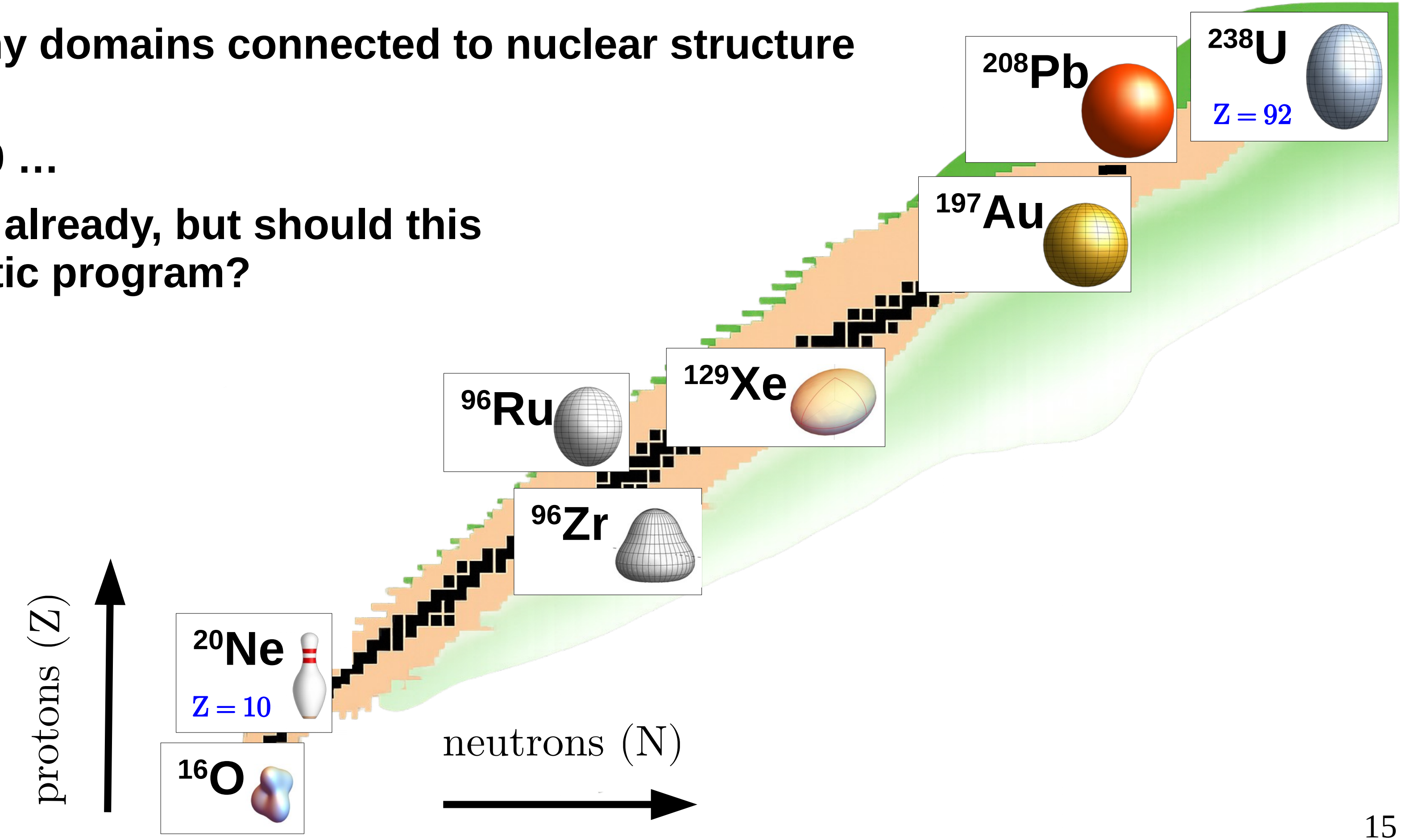
New approach to many-body properties of nuclei through ground-state correlations

New window onto EFTs of low-energy QCD

----> impact on many domains connected to nuclear structure

8 species out of ~250 …

… lot of information already, but should this turn into a systematic program?



# School

## Frontiers in Nuclear and Hadronic Physics 2026

**Feb 16, 2026 - Feb 28, 2026**

**Apply** (deadline: Dec 18, 2025 )

**Abstract**

The current edition of the school is devoted to the study of the hot/dense matter produced in relativistic heavy-ion collisions or present in the core of compact starts, focusing on its equation of state, on its approach to thermalization, on the signatures arising from the structure of the colliding nuclei and on the hard probes of its transport properties

**Topics**

L. Apolinario (LIP Lisbon): *Jet Physics in ultra-relativistic collisions*

N. Brambilla (Tech. Univ. of Munich): *Non-Relativistic EFT and Lattice QCD for Heavy Flavor Dynamics*

G. Giacalone (CERN, Geneva): *Nuclear Structure studies through ultra-relativistic collisions*

S. Schlichting (Bielefeld Univ.): *Hydrodynamics and Kinetic Theory: Attractors and Thermalization*

A. Vuorinen (Helsinki Univ.): *Dense matter equation-of-state from colliders to neutron stars*

**Organizers**

Alessandro Bacchetta (Pavia U.), Andrea Beraudo (INFN, Torino), Ignazio Bombaci (Pisa U.), Maria Colonna (INFN-LNS), Luigi Coraggio (INFN, Napoli), Vincenzo Greco (Catania U.), Elena Santopinto (INFN, Genova), Enrico Vigezzi (INFN, Milano)

**Local organizer**

Andrea Beraudo, Vincenzo Greco

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