Emergent phenomena in mesoscopic strongly-interacting matter

– from cold atoms, to atomic nuclei, to the quark-gluon plasma –

Giuliano Giacalone

CERN

EMMI Physics Day
July 16, 2024

EMMI

GSI

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Nuclear Physics Confronts Relativistic Collisions of Isobars

Heidelberg University, Germany, May 30 – June 3 & October 12 – 14, 2022

Organizers:
Giuliano Giacalone
Jiangyong Jia
Vittorio Somà
You Zhou

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Deciphering Many-Body Dynamics in Mesoscopic Quantum Gases

March 18-21, 2024
Heidelberg University, Germany

Organizers:
Tilman Enss (Heidelberg U.)
Giuliano Giacalone (Heidelberg U.)
Selim Jochim (Heidelberg U.)
Silvia Masciocchi (Heidelberg U. & GSI)
Aleksas Mazeliauskas (Heidelberg U.)

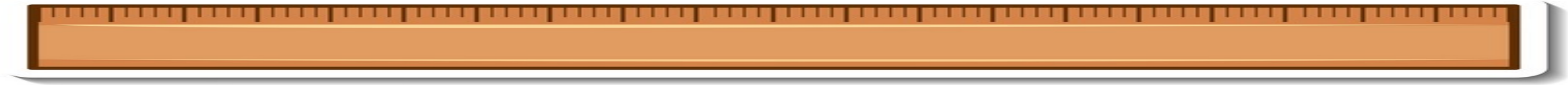
OUTLINE

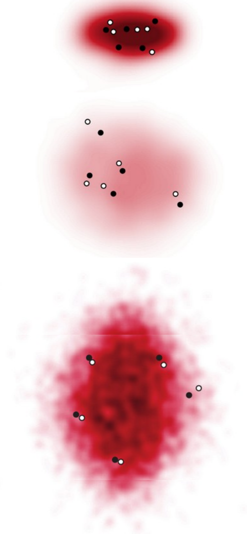
- **Effective descriptions of matter:** the “small system” question
- **Cold atoms**: observing collective behavior of few particles
- **Nuclear structure**: deformation and clustering in *ab initio* calculations
- **Small systems**: Precision tests of hydro paradigm with light ions

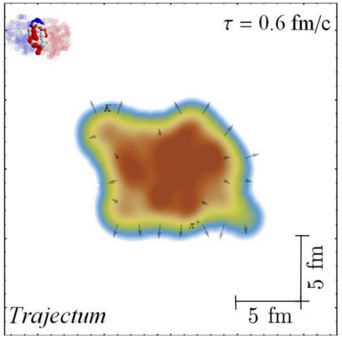
THE PHYSICAL WORLD AS AN EMERGENT PHENOMENON

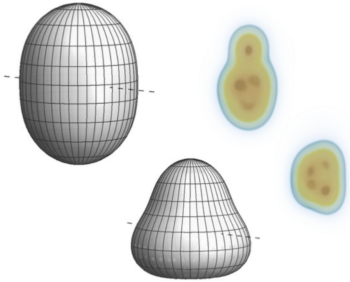
10^{15} m

10^{-15} m

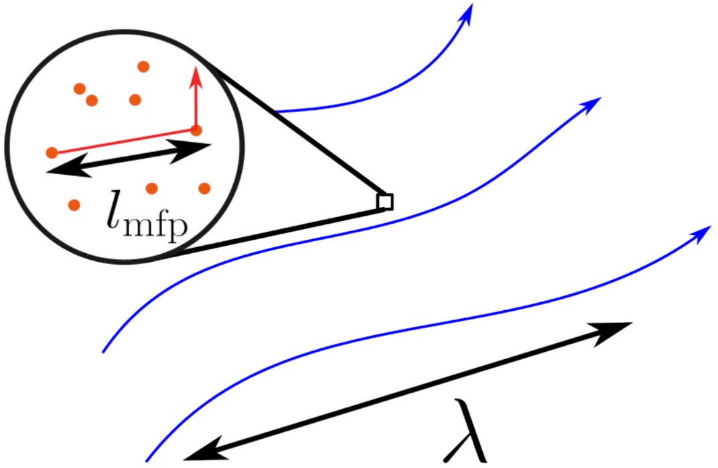








(COLLISIONAL) HYDRODYNAMICS



$$l_{\mathrm{mfp}} \ll \lambda$$

… from kinetic theory

The *pressure tensor* is defined as the fluctuation of the velocities of the ensemble from the mean velocity, i.e. as the 2-nd order moment:

$$\mathbf{P} = m \int (\mathbf{v} - \mathbf{v}_b)(\mathbf{v} - \mathbf{v}_b) f(\mathbf{v}) d^3 v$$

$$\mathbf{u}_\alpha = \langle \mathbf{v}_\alpha \rangle$$

Motion from conservation laws

$$\rho \left(\partial_t + \vec{u} \cdot \vec{\nabla} \right) \vec{u} = -\vec{\nabla} p + \eta \nabla^2 \vec{u}$$

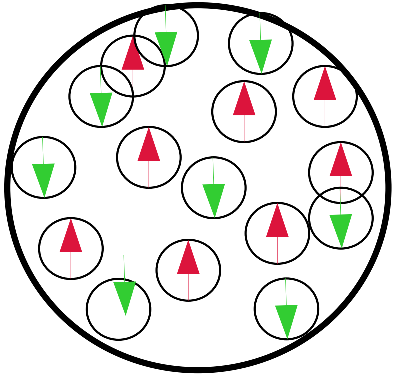
density pressure shear

[from any textbook, e.g. Landau-Lifshitz]

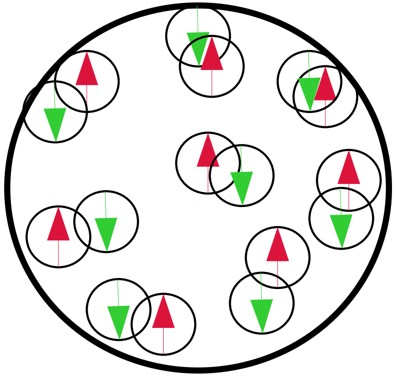
Large N, separation of scales (micro vs. macro), equilibrium, …

(SUPERFLUID) HYDRODYNAMICS

without interactions



with interactions



Condensate of molecules at T~0

molecule size << inter-molecule distance

Large system (N>>1), separation of scales ($n^{1/3}a \ll 1$)

condensate fluctuations

$$\boxed{\hat{\Psi}(r,t) = \Psi(r,t) + \cancel{\delta\hat{\Psi}(r,t)}}$$

$$\Psi = \sqrt{n}\, e^{iS(r,t)} \qquad \boxed{v_S = \frac{\hbar}{m}\nabla S}$$

$$\frac{\partial}{\partial t} n + \nabla(v_S n) = 0$$

$$m\frac{\partial}{\partial t} v_S + \nabla\left(\frac{1}{2} m v_S^2 + \mu(n) + V_{ext}\right) = 0$$

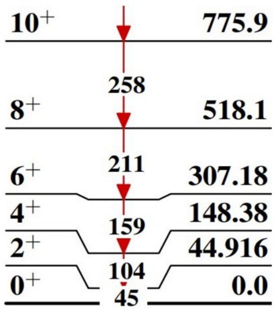
EOS

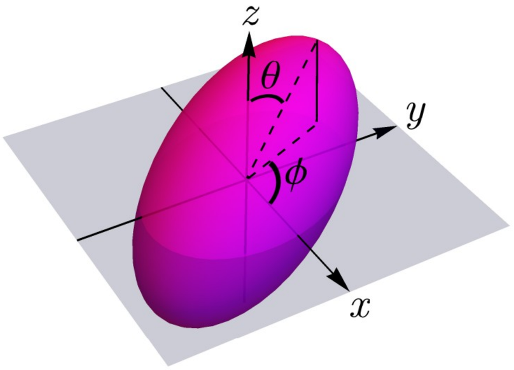
Hydrodynamic equations of superfluids (T=0)
Closed equations for n and v_S

[from S. Stringari, Lectures at Collège de France (2004/2005)]

Effective description of atomic nuclei: nuclear deformation

$^{238}_{92}\mathrm{U}$ **E = B J(J+1)**





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

$$P_1(\mathrm{r}_1) = \sum_{s,t}\int d^3\mathrm{r}_2\ldots d^3\mathrm{r}_A|\Psi_A(\mathrm{r}_1\ldots\mathrm{r}_A)|^2$$

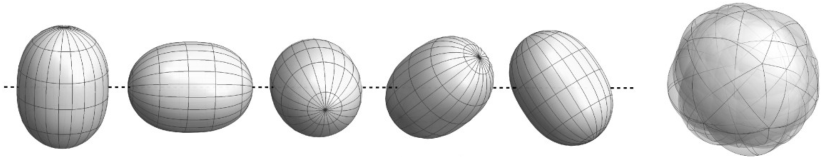
$$P_2(\mathrm{r}_1,\mathrm{r}_2) = \sum_{s,t}\int d^3\mathrm{r}_3\ldots d^3\mathrm{r}_A|\Psi_A(\mathrm{r}_1\ldots\mathrm{r}_A)|^2$$

...

Many-body physics from rotation of an intrinsic deformed density

$$P_1(\mathbf{r}_1) = \int_\Omega \rho_\Omega(\mathbf{r}_1)$$

EULER ANGLES



[STAR collaboration, arXiv:2401.06625]

$$P_2(\mathbf{r}_1,\mathbf{r}_2) = \int_\Omega \rho_\Omega(\mathbf{r}_1)\rho_\Omega(\mathbf{r}_2) \neq P_1(\mathbf{r}_1)P_1(\mathbf{r}_2)$$

DEFORMATION

...

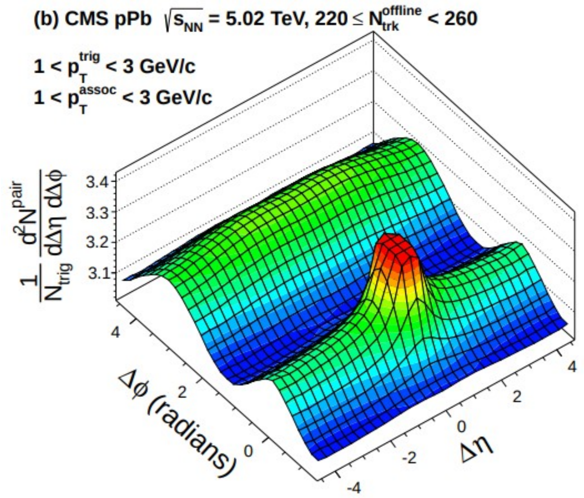
We have today the capabilities to unveil the mechanisms behind these phenomena

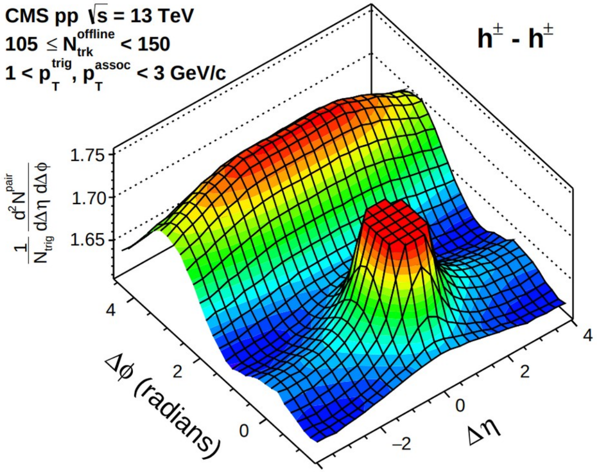
Probing boundaries of applicability and fundamental theory

Big trigger from LHC and RHIC – Small system collectivity

[Wiedemann, Groesse-Oetringhaus, arXiv:2407.7484]
[Noronha, Schenke, Shen, Zhao, arXiv:2401.09208]

Few dozen particles, breaking scale separations, out of equilibrium





[CMS collaboration, PLB **724** (2013) 213-240]
PLB **765** (2017) 193-220]

ultracold atoms

[Brandstetter *et al.*, arXiv:2308.09699]
(to appear in Nature Physics)

$$\mathcal{H} = -\sum_{i=1}^{N} \frac{\hbar^2}{2m} \nabla_i^2 + \sum_{i<j} \frac{\hbar^2}{2m} g_0 \delta^{(d)}(\boldsymbol{r}_i - \boldsymbol{r}_j) + \sum_{i=1}^{N} \mathcal{V}_{\text{ext}}(\boldsymbol{r}_i)$$

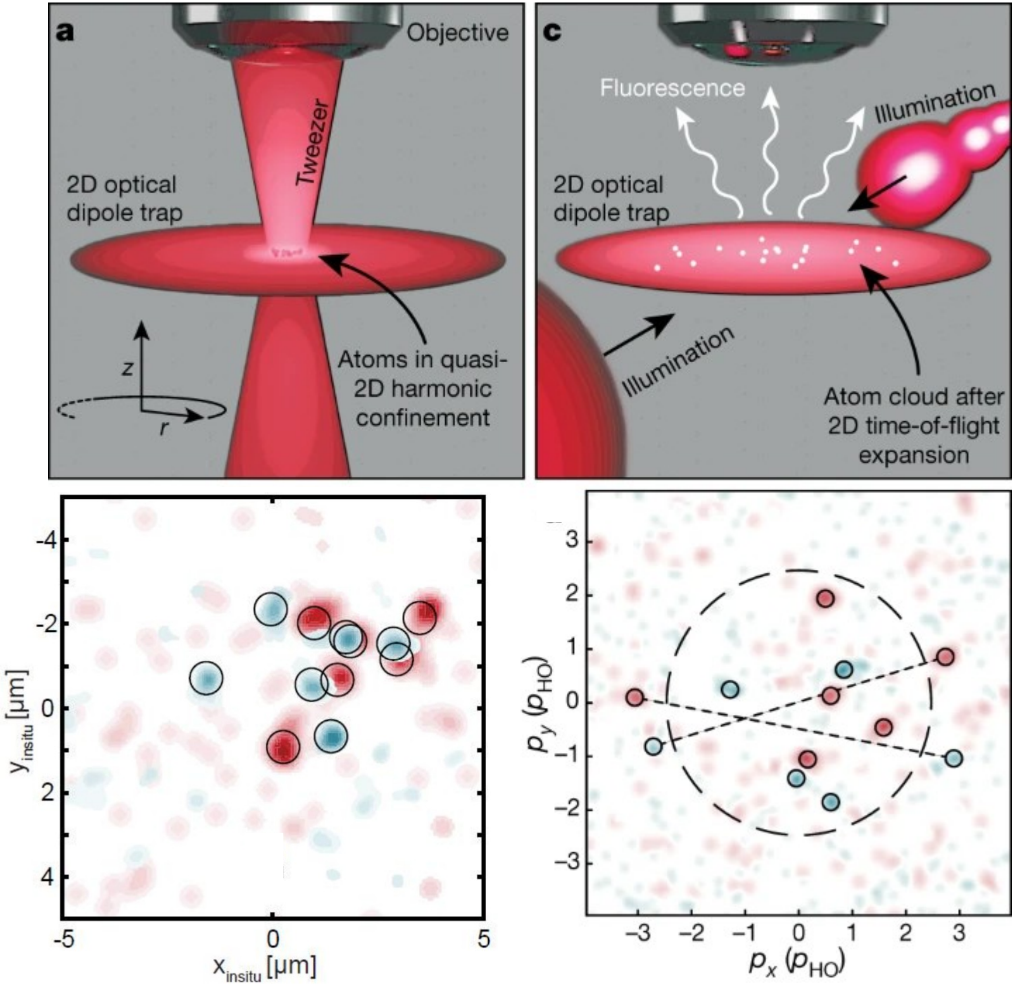
Jochim Lab @ Heidelberg University

Imaging of finite samples in “free space”

[see talk by S. Jochim at EMMI Physics Day ‘23]

The measurement can be carried out in either real or momentum space

[Holten *et al.*, Nature **606**, 287-291 (2022)]

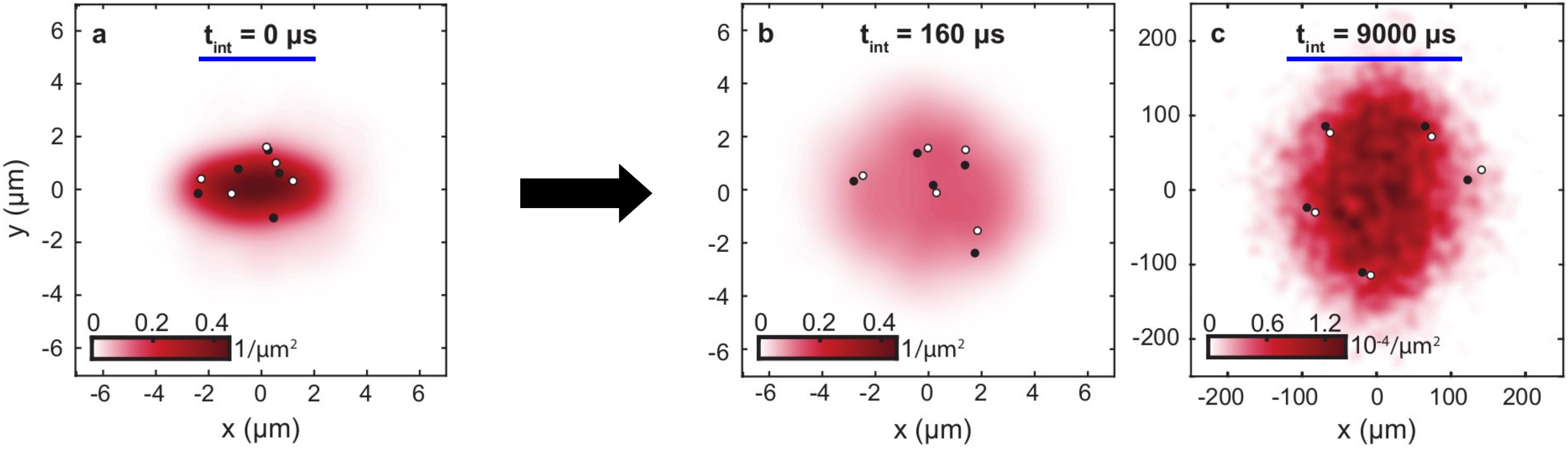


Proposal – Elliptic flow and the few-to-many-body transition

Flörchinger *et al.*, PRC **105** (2022) 4, 044908]

Phenomenon observed with only 10 atoms

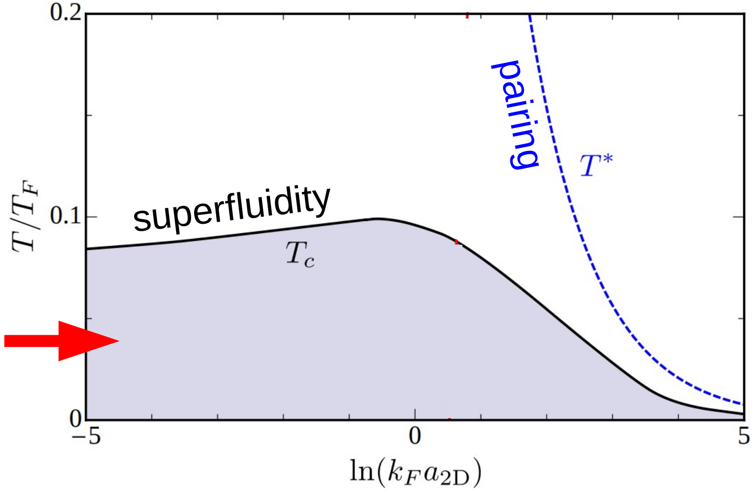
[Brandstetter *et al.*, arXiv:2308.09699]

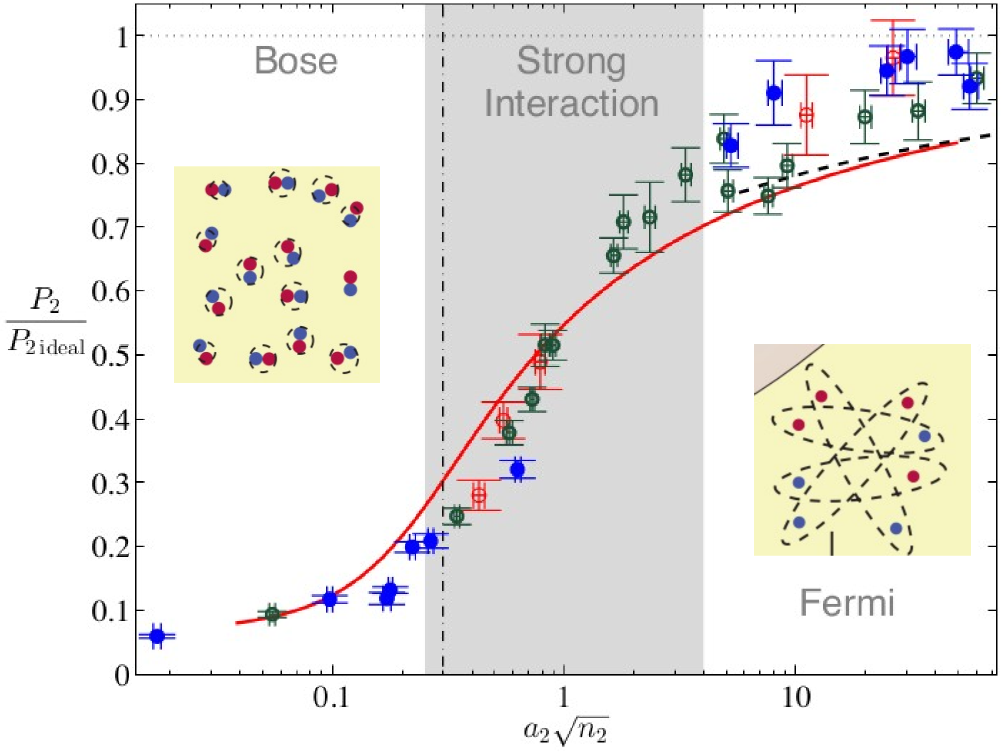


"textbook" criteria not fulfilled (e.g. large quantum 1/N fluctuations)

Is it hydrodynamics? Many-body limit of superfluid in 2D

[Levinsen, Parish, arXiv:1408.2737]





Continuity and Euler equations (ideal fluid)

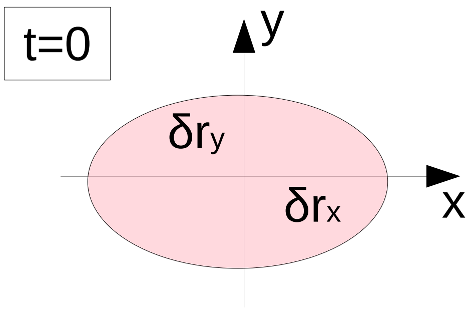
$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0$$

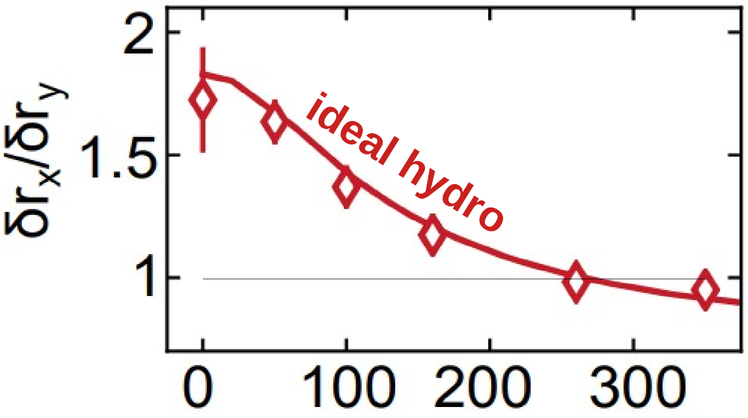
$$\rho(\partial_t + \mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla P$$

$$P_{\mathrm{ideal}} = \frac{\pi \hbar^2}{2M} n^2$$

Mass of ^{6}Li

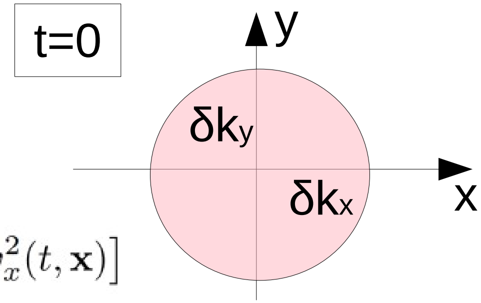
real space

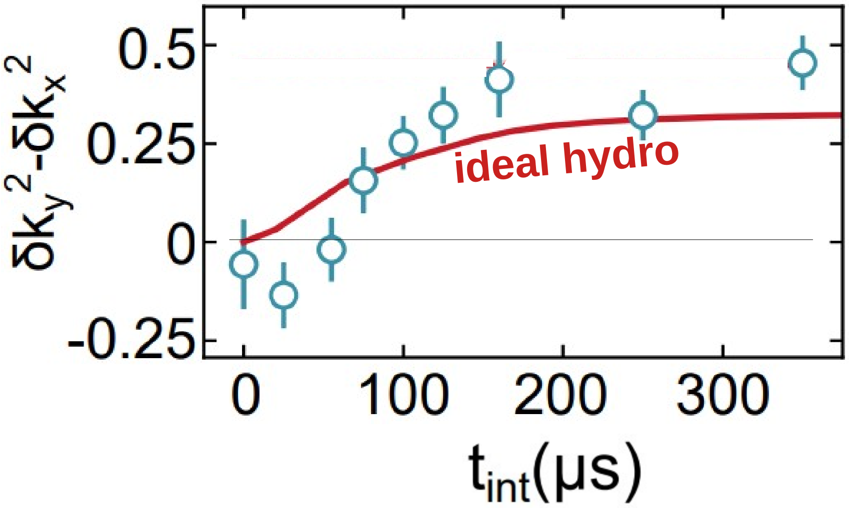




momentum space

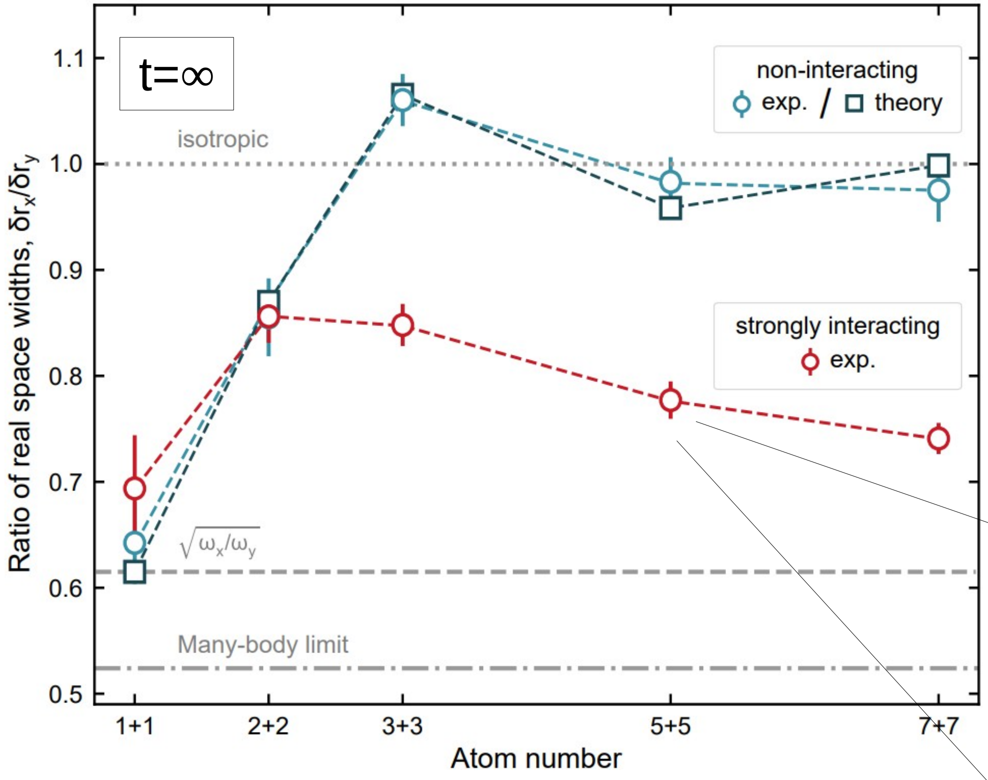
$$\frac{m}{2N}\int_{\mathbf{x}} \rho(t,\mathbf{x})\left[v_y^2(t,\mathbf{x}) - v_x^2(t,\mathbf{x})\right]$$





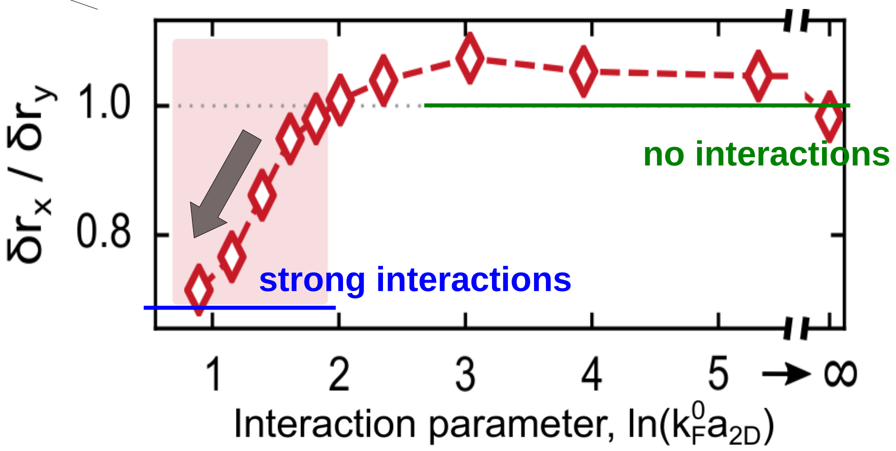
NB: hydro does not describe well individual δr_{xy} , δk_{xy} … More work in progress

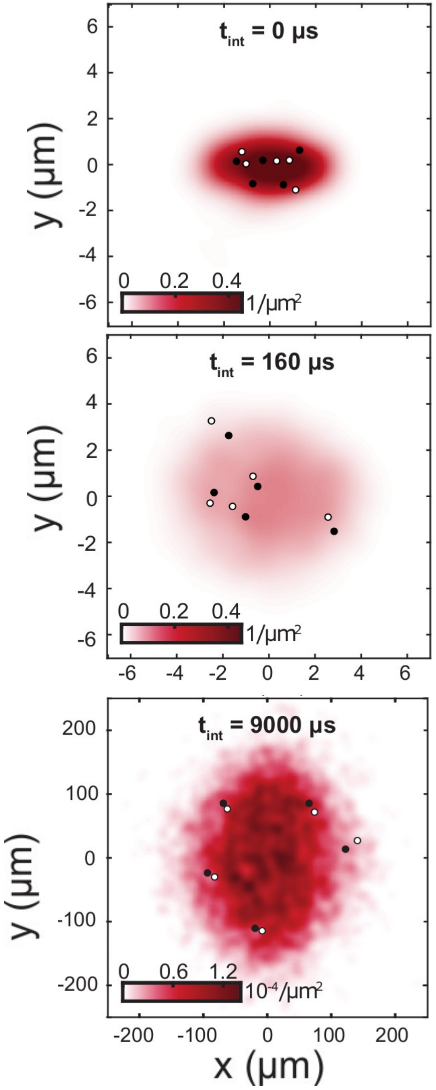
Emergence of elliptic flow as a function of particle number and interaction strength



Final state is isotropic

Final state is elliptical

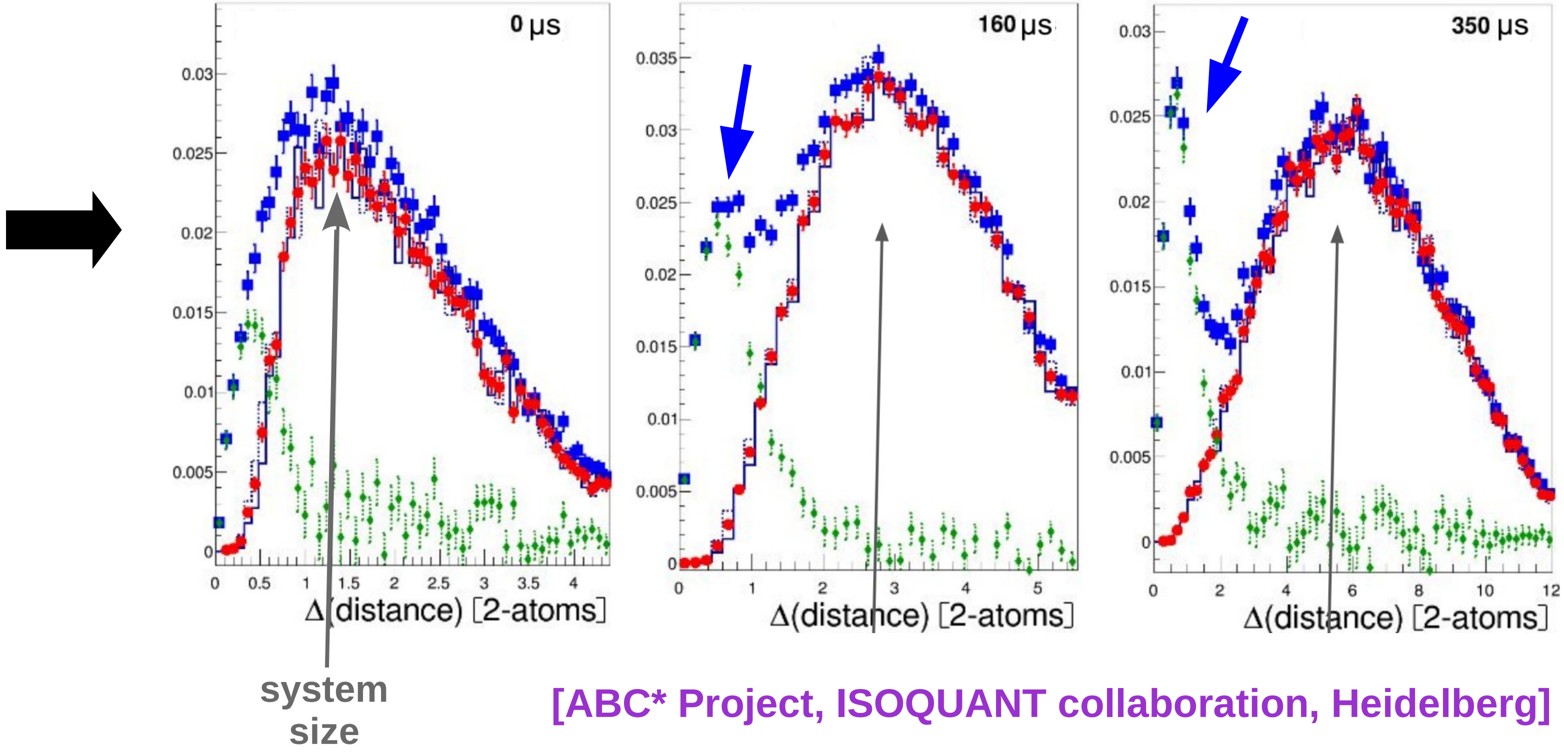




Role of two-body correlations for collectivity

Pair formation is resolved as density decreases

Red = mixed events, **Blue** = up-down correlations



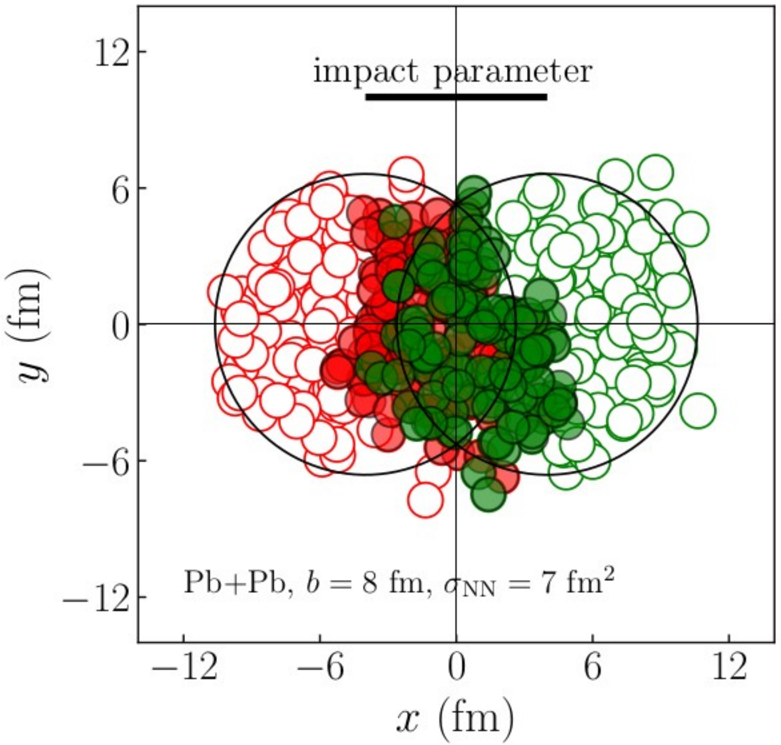
[ABC* Project, ISOQUANT collaboration, Heidelberg]

nuclear structure

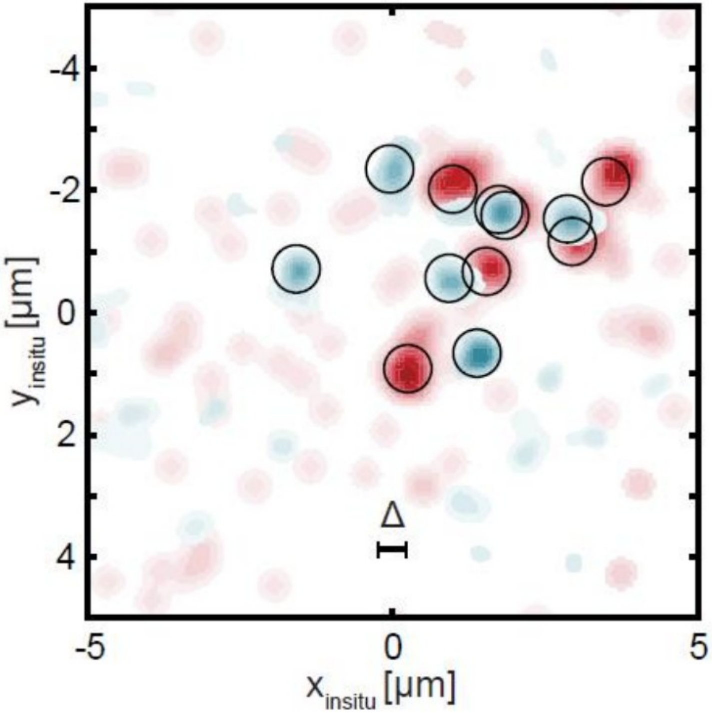
[Giacalone *et al.*, arXiv:2402.05995, arXiv:2405.20210]

High-energy collisions – Snapshots of atomic nuclei

[Miller *et al.*, Ann.Rev.Nucl.Part.Sci. **57** (2007) 205-243]



“snapshot” of nucleon positions

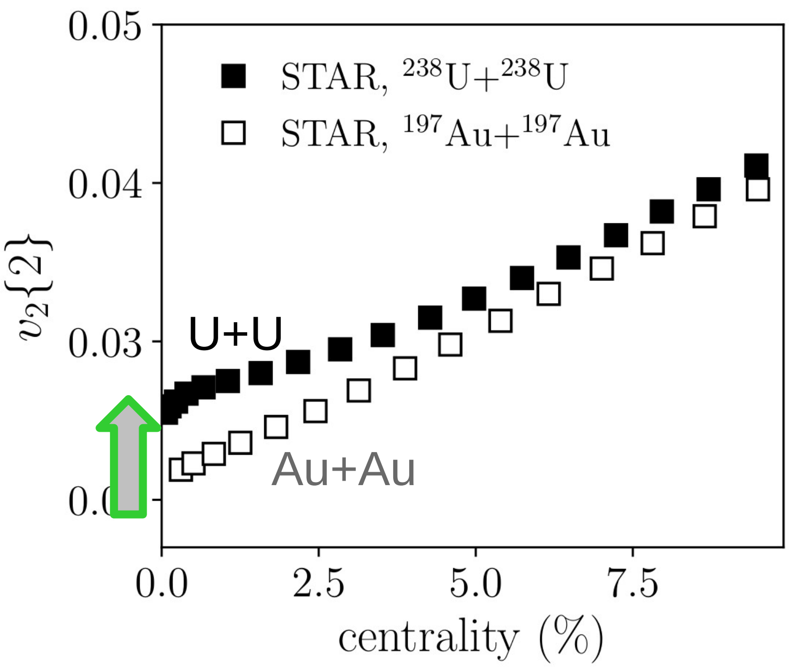


collapsed wave function of 10 Li atoms

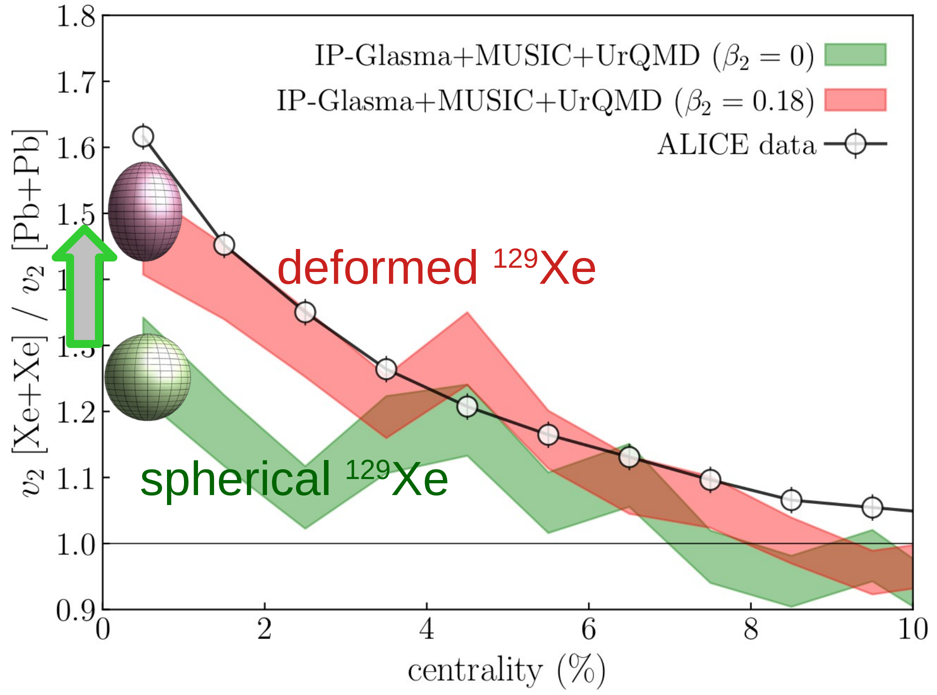
Heavy-ion collisions probe details of the ground state: $|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})|^2$

[Giacalone, EPJA **59** (2023) 12, 297]

Impact of two-body correlations (deformation) on the elliptic flow



[STAR Collaboration, PRL **115** (2015) 22, 222301]
[STAR Collaboration, arXiv:2401.06625]



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

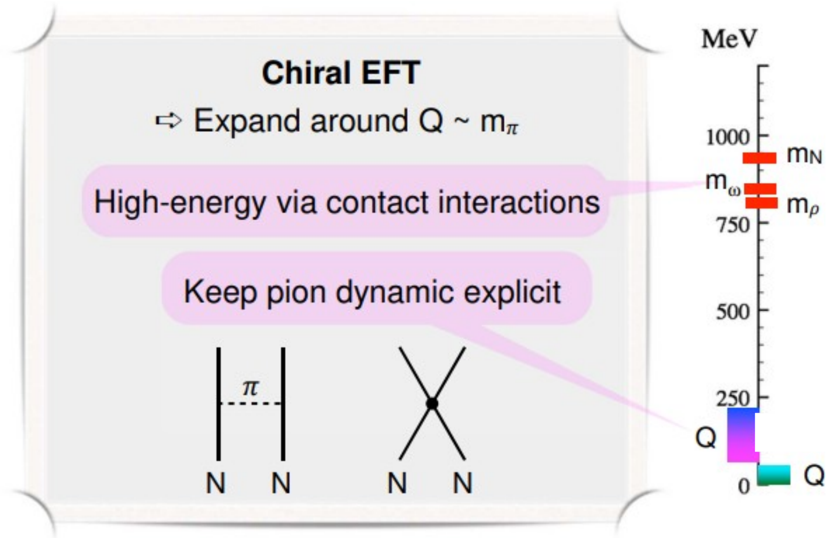
First-principles understanding of nuclear structure?

[upcoming talk by A. Tichai]

Effective field theory of low-energy QCD

[Epelbaum, Hammer, Meissner, RMP **81** (2009) 1773-1825]

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



– theory of nucleons and pions

– consistent with symmetries of QCD

– nucleon-nucleon interaction encoded in low-energy constants (from lattice QCD or data)

– terms can be ordered $m_\pi / m_{\mathrm{QCD}} \ll 1$

… many-body methods to solve the Schrödinger equation $H|\Psi_k^A\rangle = E_k^A|\Psi_k^A\rangle$

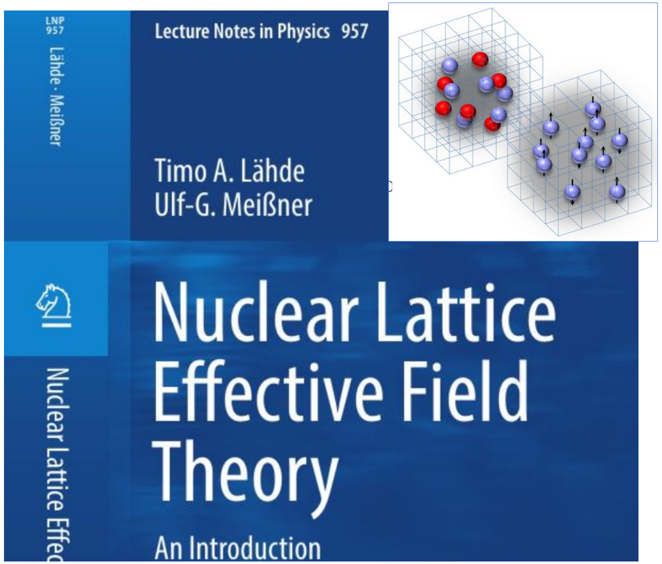
Collaborations

– Nuclear Lattice Effective Field Theory (NLEFT)

MC solution of Schrödinger equation on a lattice (LO Hamiltonian)

≈ 15 000 ground-state configurations available

[BN Lu *et al.*, PLB **797** (2019) 134863]
[Summerfield *et al.*, PRC **104** (2021) 4, L041901]



Nucleons sampled directly from A-body wave function!

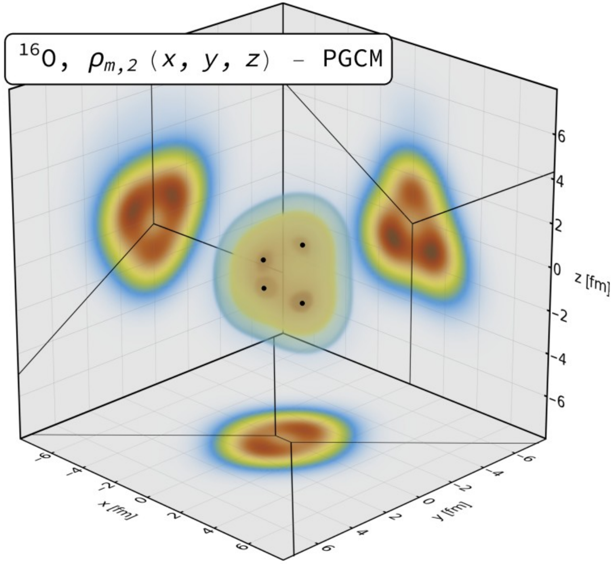
– *ab initio* Projected Generator Coordinate Method (PGCM)

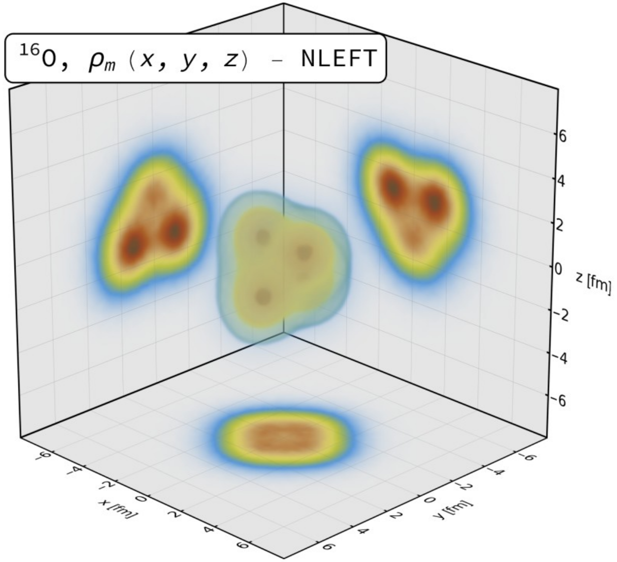
Wave function from variational calculation
(akin to energy density functional theory)
N^3LO interactions developed in Darmstadt

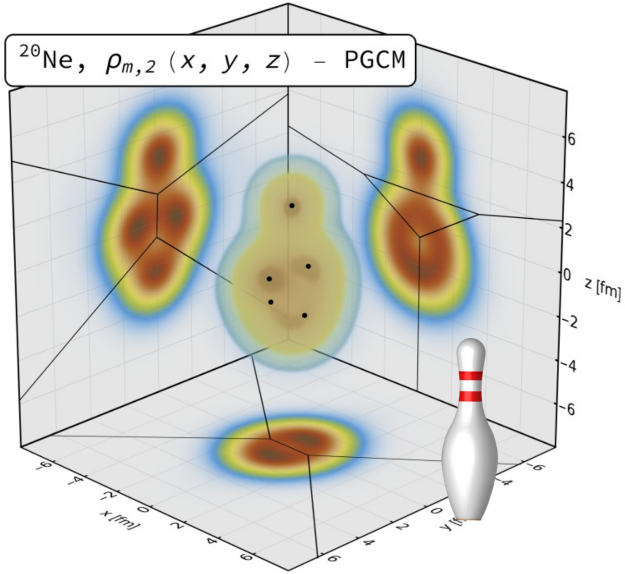
$$\delta \frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle} = 0$$

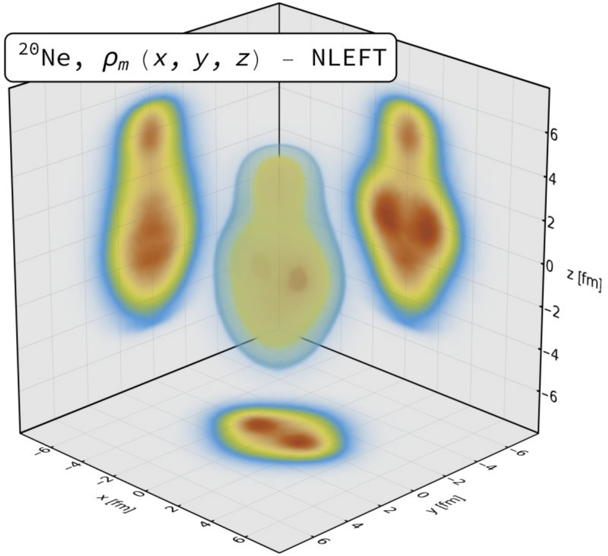
[Frosini *et al.*, EPJA **58** (2022) 4, 62
EPJA **58** (2022) 4, 63
EPJA **58** (2022) 4, 64]

Provides a deformed density motivated by chiral EFT









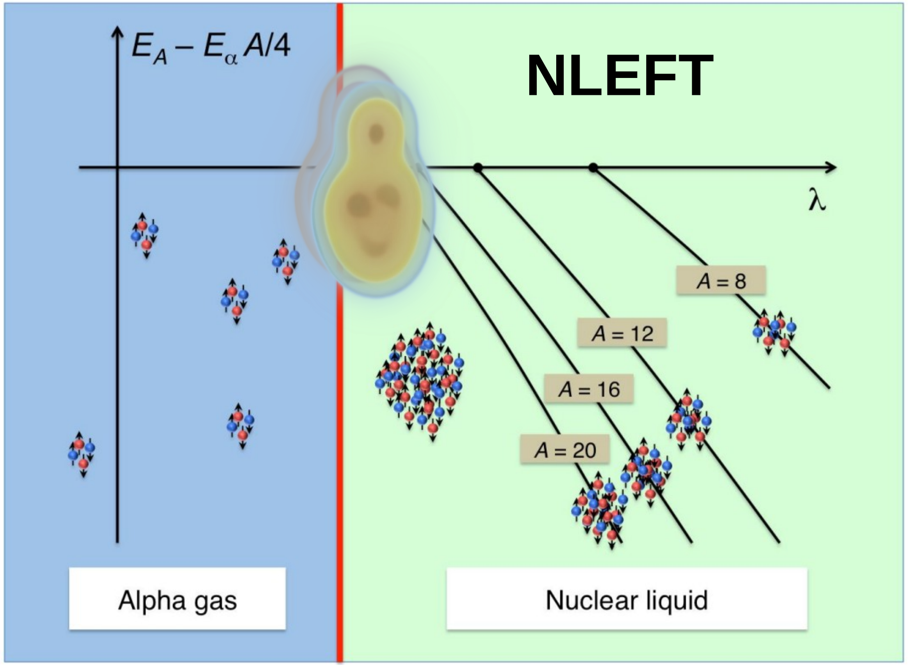
arXiv:2402.05995

Ancillary files (details):

- NLEFT_dmin_0.5fm_negativeweights_Ne.h5
- NLEFT_dmin_0.5fm_negativeweights_O.h5
- NLEFT_dmin_0.5fm_positiveweights_Ne.h5
- NLEFT_dmin_0.5fm_positiveweights_O.h5
- PGCM_clustered_dmin0_Ne.h5
- PGCM_clustered_dmin0_O.h5
- PGCM_uniform_dmin0_Ne.h5
- PGCM_uniform_dmin0_O.h5

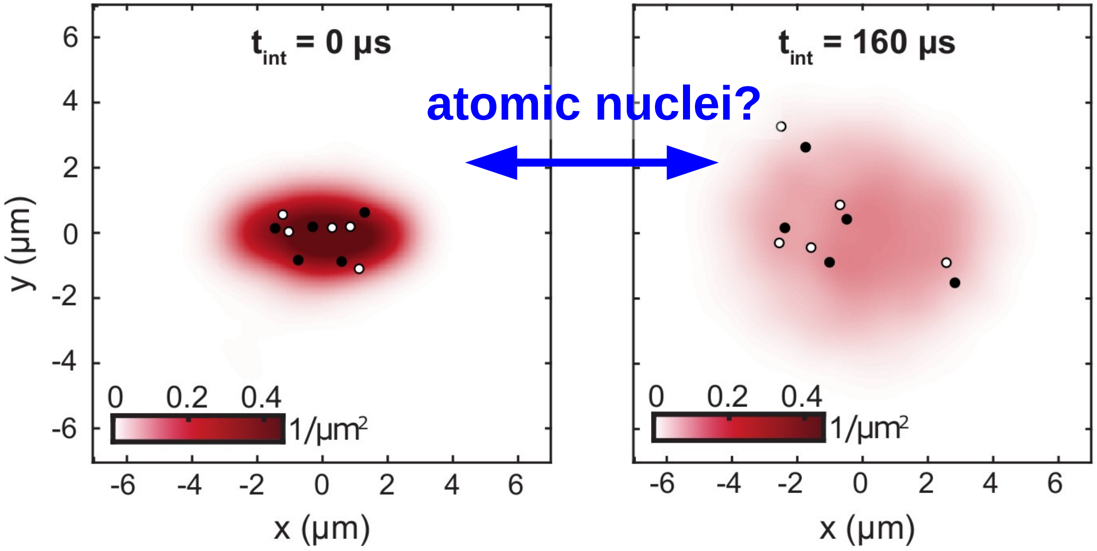
Atomic nuclei at the transition – alpha gas vs. strongly-correlated liquid

Importance of α-α interactions? Interplay of shape and clustering?



[Elhatisari *et al.*, PRL **117** (2016) 13, 132501]

5 clusters in 5(↑)+5(↓) cold fermions



[Brandstetter *et al.*, arXiv:2308.09699]

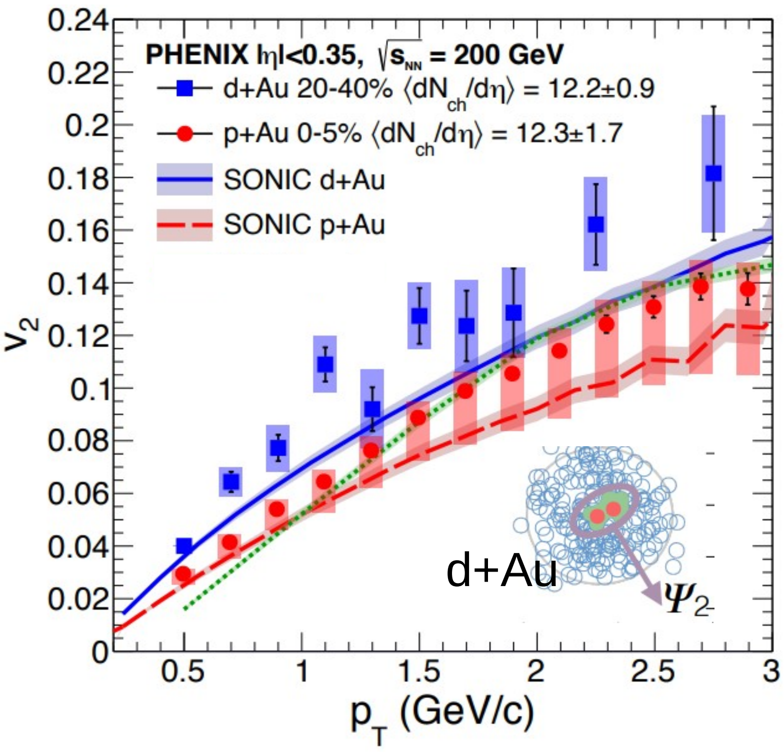
Emergence from parameters of the χEFT interaction?

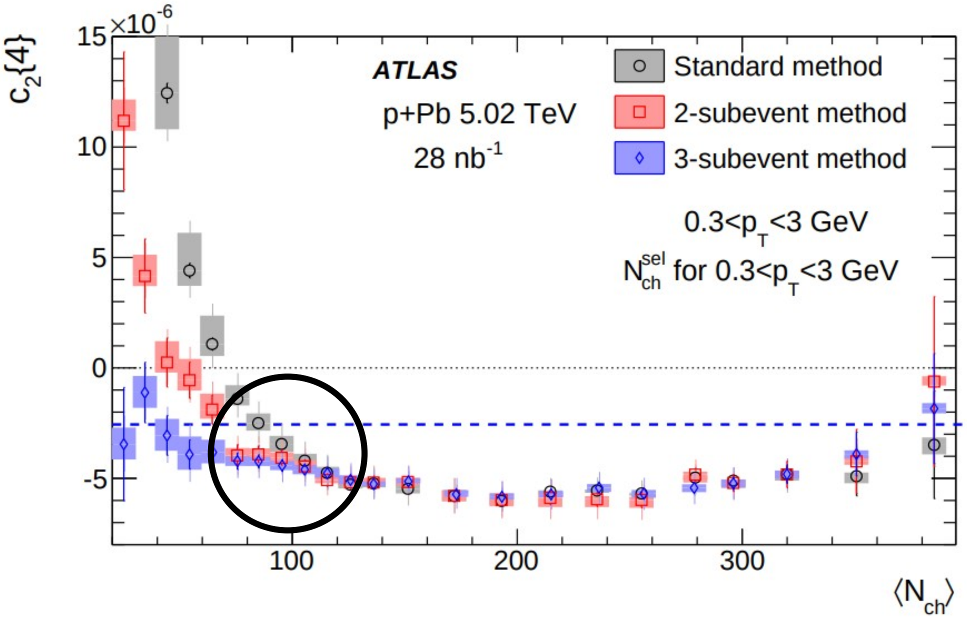
[Ekström *et al.*, arXiv:2305.06955]
[ZH Sun *et al.*, arXiv:2404.00058]

small systems

[Giacalone *et al.*, arXiv:2402.05995, arXiv:2405.20210]

Tantalizing hydrodynamic signals in low-multiplicity collisions





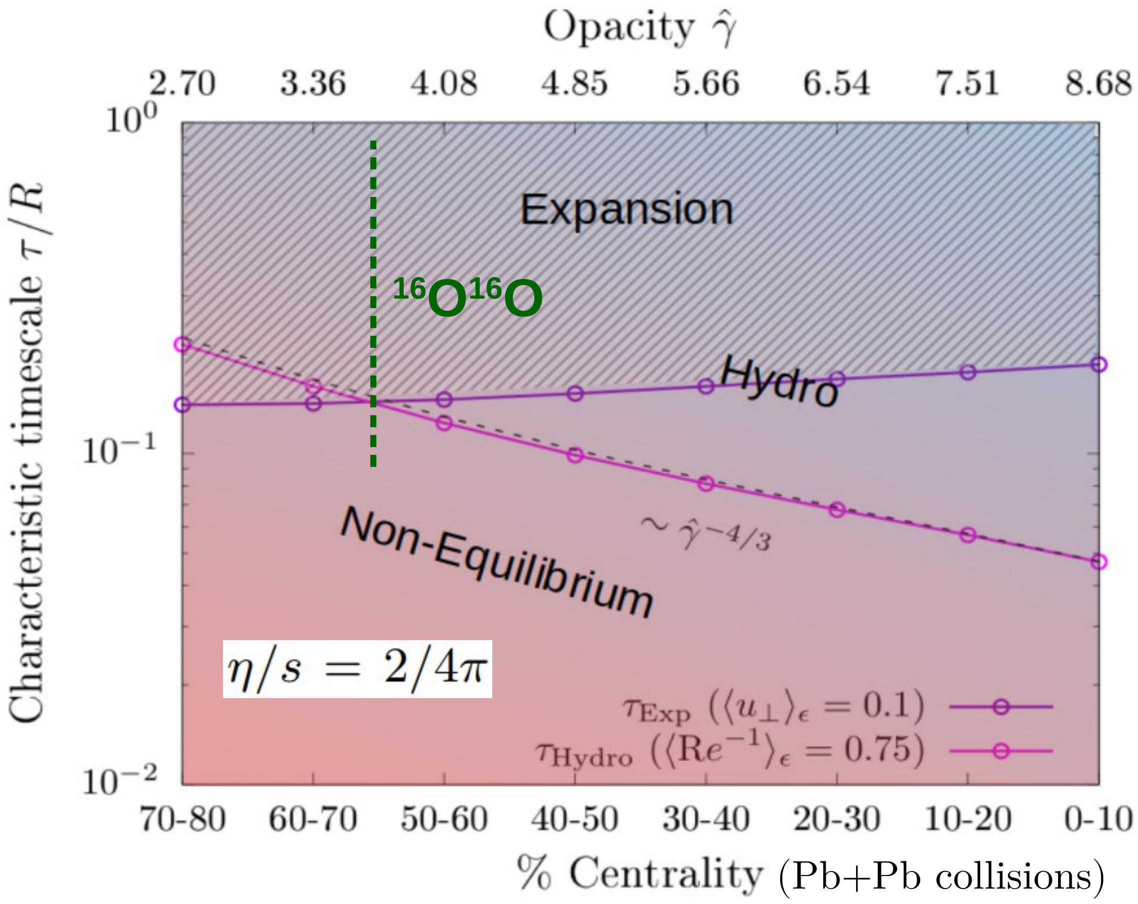
$$v_2\{2\}_{d^{197}\mathrm{Au}} > v_2\{2\}_{p^{197}\mathrm{Au}}$$

Genuine 4-particle correlation in p-Pb down to dNch/dη ~ 50

[ATLAS Collaboration, PRC **97** (2018) 2, 024904]

[PHENIX Collaboration, Nature Phys. **15** (2019) 3, 214-220]
[STAR collaboration, PRL **130** (2023) 242301]

Robust criteria to establish applicability of hydrodynamics



Boltzmann eq. in relaxation time approximation (RTA)

$$p^\mu \partial_\mu f(x,p) = -\frac{u^\mu(x) p_\mu}{\tau_R(x)} \left[f(x,p) - f_{\rm eq}(x,p)\right]$$

Opacity parameter

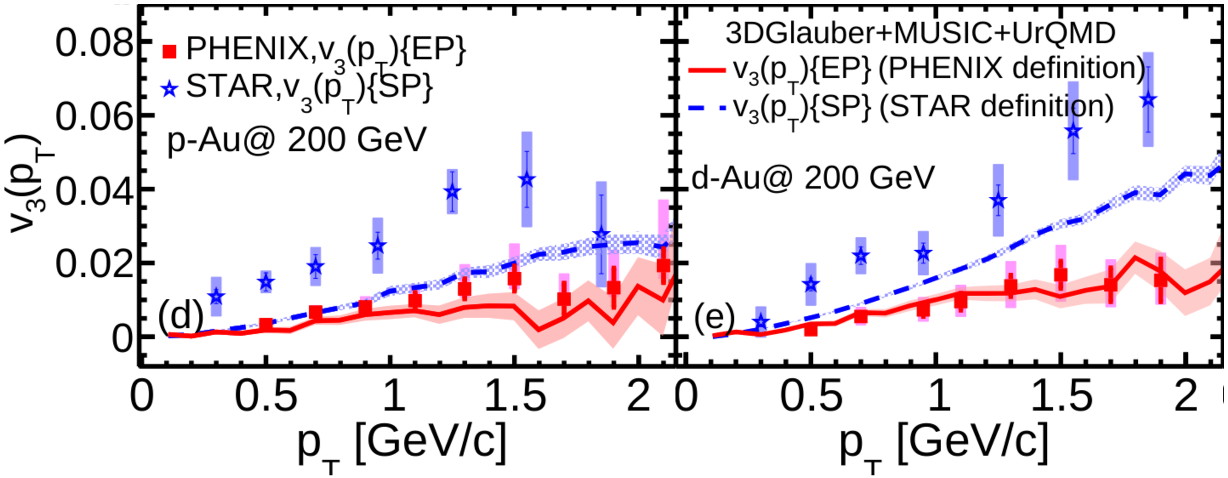
$$\hat{\gamma} = \frac{1}{5\eta/s} \left(\frac{R}{\pi a} \frac{dE_\perp^0}{d\eta} \right)^{1/4}$$

[Ambrus, Schlichting, Werthmann, PRL **130** (2023) 15, 152301]

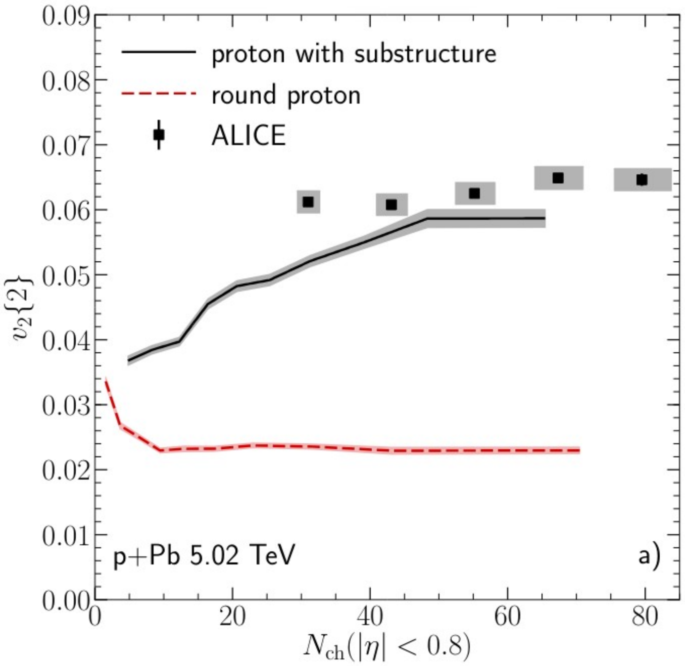
But can we draw robust conclusions from data?

Theory systematics for these systems are huge

Full 3D modeling + sub-nucleon structure are essential



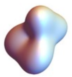
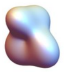
[Zhao, Ryu, Shen, Schenke, PRC **107** (2023) 1, 014904]



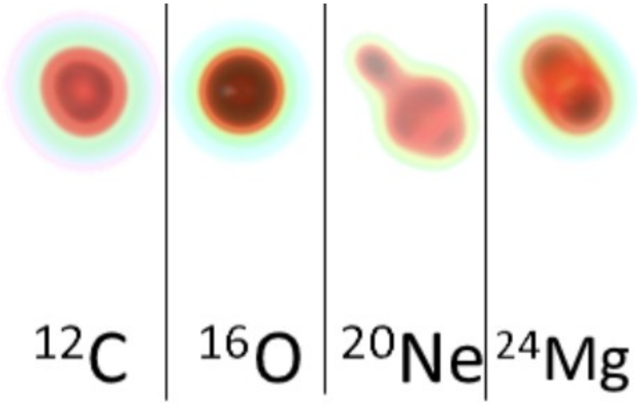
[Schenke, RPP **84** (2021) 8, 082301]

Quantitative understanding of data seems out of reach

Exploiting *ab initio* knowledge of light-nuclei geometries

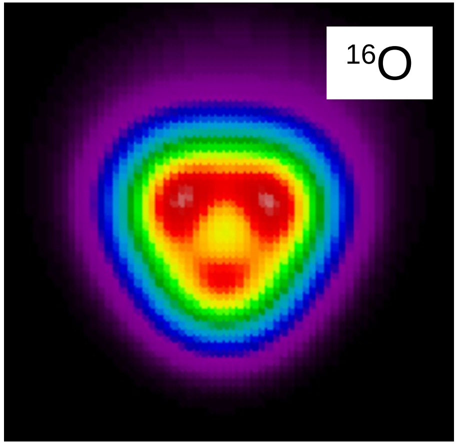
^{16}O  +  ^{16}O vs. ^{20}Ne  +  ^{20}Ne

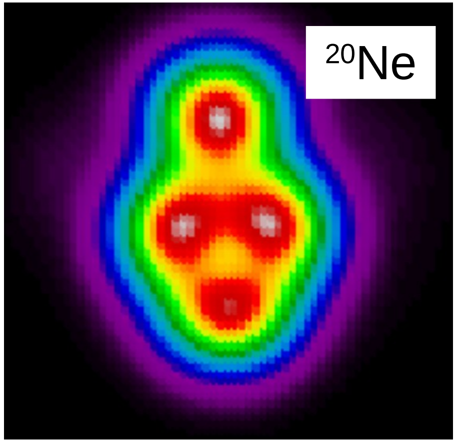
Studying hydro response, reducing theory systematics



[Ebran *et al.*, PRC **90** (2014) 5, 054329]

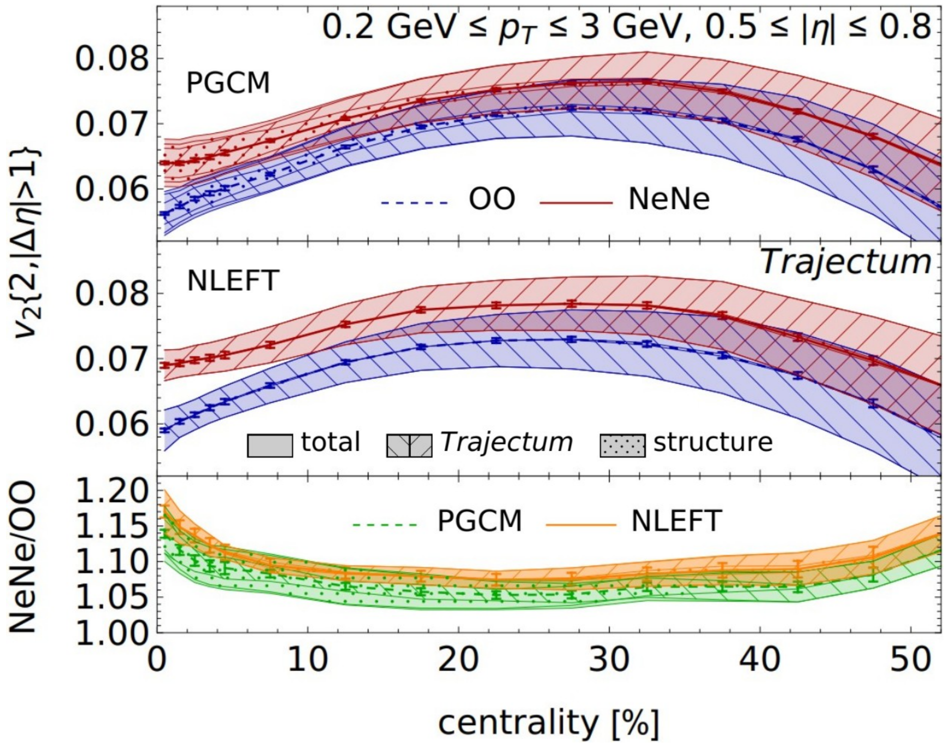
[B. Bally, *ab initio* PGCM]





Towards quantitative theory-to-data comparisons for small systems

[Giacalone *et al.*, arXiv:2402.05995]



- *Trajectum* systematic uncertainty contains contributions from:
  - Uncertainties in parameters.
  - Extrapolation to zero grid spacing.
- PGCM systematic uncertainty contains contributions from:
  - Sampling method: how to convert a density into a configuration.
  - Constraint application: order of operations in the PGCM computation.
- NLEFT systematic uncertainty contains contributions from:
  - Resolution of ambiguities from periodicity of the lattice.

courtesy of Govert Nijs

Quantitative hydrodynamic predictions (dN/dη ≈ 150)

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

Future runs / prospects ?

COLLIDER

- ^{16}O + ^{16}O **(run 3)**
- proton + ^{16}O **(run 3)**
- ^{20}Ne + ^{20}Ne **(?)**
- ^{10}B + ^{10}B, ^{24}Mg + ^{24}Mg **(run 4?)**

FIXED-TARGET @ LHCb

- ^{208}Pb + ^{20}Ne , ^{16}O , ^{14}N , ^{40}Ar ...
- proton + ^{20}Ne , ^{16}O , ^{14}N , ^{40}Ar ...

NuPECC Long Range Plan 2024
For European Nuclear Physics

Physics aims.

Particle production and QCD dynamics from small to larger systems. High-precision studies of rare probes are mandatory, to address outstanding open questions on the existence of a QGP in small collision systems. Example studies include the comparison of heavy-quark and quarkonium flow in small and large systems and the searches for thermal radiation and partonic energy loss, an outstanding puzzle

CONCLUSIONS

- **Theoretical and experimental breakthroughs –** We explore the fundamental mechanisms behind emergent properties of matter.

- **Cold atoms –** Hydro behavior with only ~10 strongly-interacting fermions. Production of molecules has been revealed directly for the first time. Comparisons with ideal hydrodynamic results point to the smallest superfluid.

- **Nuclear structure –** Studying emergence of clustering and deformations from fundamental theory. New results for ^{16}O and ^{20}Ne. Connection with cold atoms? Interplay between heavy-ion collisions and nuclear interactions?

- **Small systems –** Challenging applicability of a hydrodynamic description. Progress towards quantitative understanding should leverage light-nuclei geometries in future experiments. Unprecedented constraints on the nature of the observed dynamics.

This 1-week TH Institute will bring together theorists, experimentalists and accelerator physicists to assess our current understanding of small system collectivity and to discuss perspectives for how this understanding could be developed further in an interplay between advanced theoretical modelling and future experiments with light-ion beams.

Dedicated sessions will include

- Experimental overviews
- Collectivity in small systems
- Nuclear PDFs in light ions
- Nuclear structure of light ions
- Hard probes in small systems
- Cosmic rays and forward physics

Light ion collisions at the LHC

11–15 nov 2024
CERN
Europe/Zurich fuso orario

Inizio 11 nov 2024, 09:30
Finisce 15 nov 2024, 12:30
Europe/Zurich

CERN
4/3-006 - TH Conference Room
Vai alla mappa

Giuliano Giacalone
Govert Hugo Nijs
Huichao Song
Jing Wang
Qipeng Hu
Reyes Alemany Fernandez
Saverio Mariani
Urs Wiedemann
Wilke Van Der Schee
You Zhou

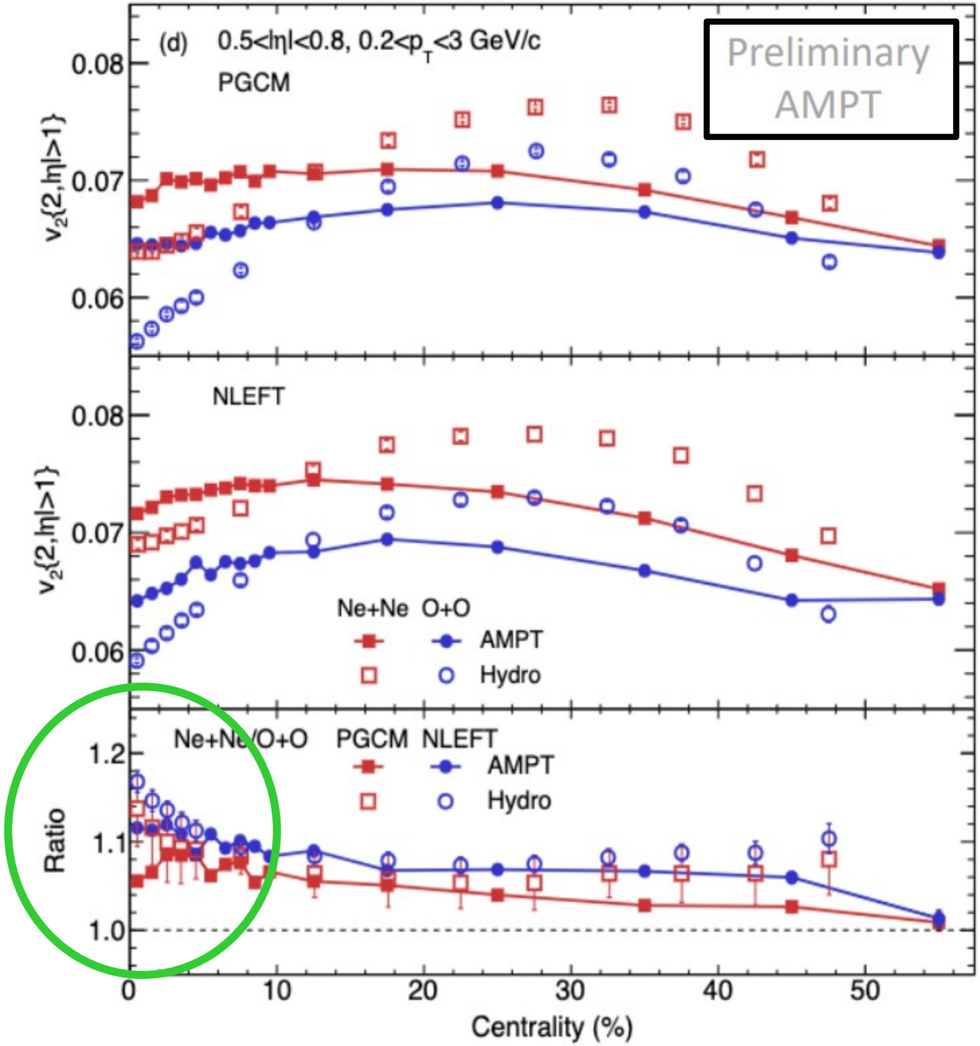
https://indico.cern.ch/event/1425712/

BACKUP

Preliminary results from transport (by Xin-Li Zhao [USST, Shanghai])

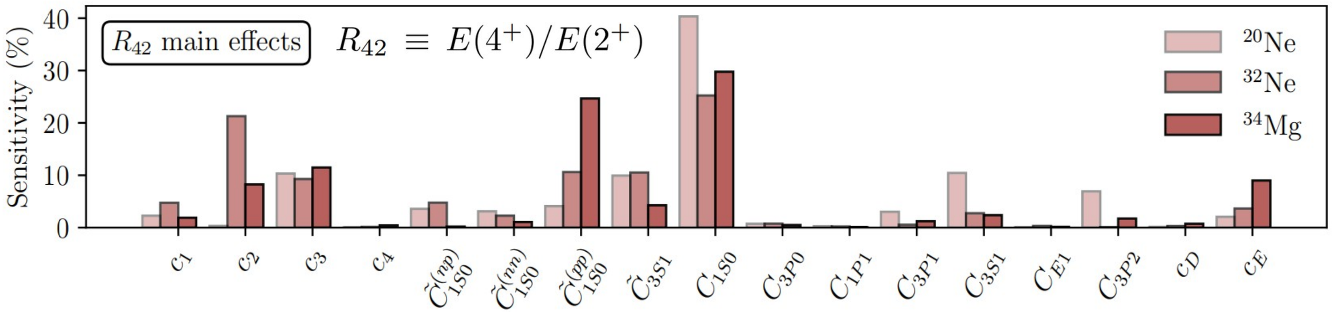
Difference between AMPT and hydro seems significant in the central region

Pinning down nature of collectivity



Unveiling emergent features of nuclei from first principles

Δ-full chiral EFT with 17 low-energy constants – What drives the deformation of ^{20}Ne?



[Ekström *et al.*, arXiv:2305.06955]
[ZH Sun *et al.*, arXiv:2404.00058]

Systematic input for high-energy collisions from LO Hamiltonian

$$H_{\mathrm{SU}(4)} = H_{\mathrm{free}} + \frac{1}{2!} C_2 \sum_{\mathbf{n}} \tilde{\rho}(\mathbf{n})^2 + \frac{1}{3!} C_3 \sum_{\mathbf{n}} \tilde{\rho}(\mathbf{n})^3$$

$$\tilde{\rho}(\mathbf{n}) = \sum_i \tilde{a}_i^\dagger(\mathbf{n})\tilde{a}_i(\mathbf{n}) + s_L \sum_{|\mathbf{n}'-\mathbf{n}|=1} \sum_i \tilde{a}_i^\dagger(\mathbf{n}')\tilde{a}_i(\mathbf{n}')$$

$$\tilde{a}_i(\mathbf{n}) = a_i(\mathbf{n}) + s_{NL} \sum_{|\mathbf{n}'-\mathbf{n}|=1} a_i(\mathbf{n}')$$

lattice coordinates $\boldsymbol{n} = (n_x, n_y, n_z)$