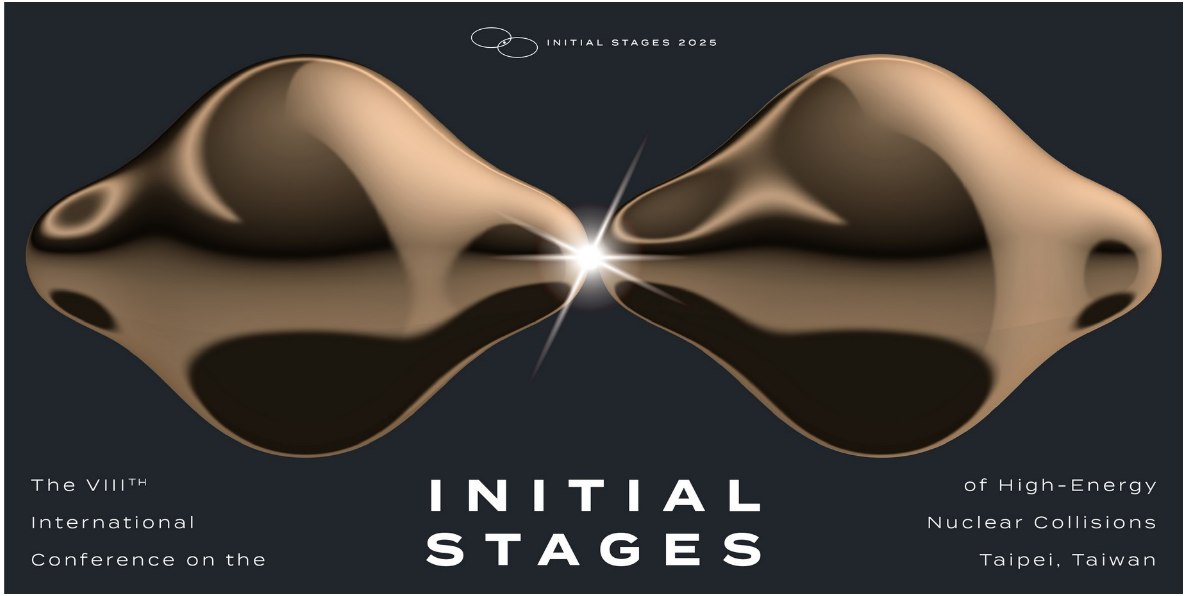
Emergent many-body dynamics at its limits: from ultracold atoms to high-energy collisions

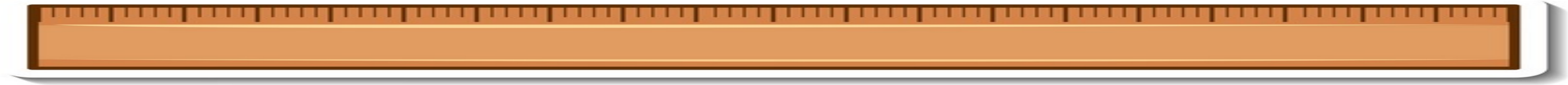
Giuliano Giacalone

September 12, 2025

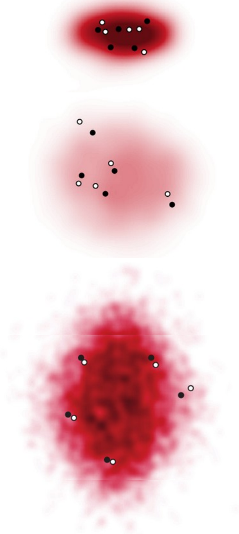


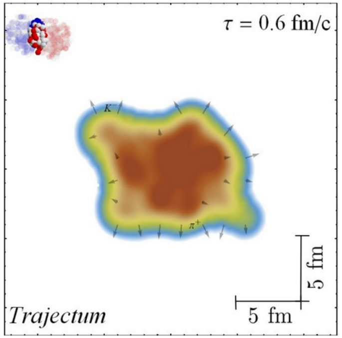
The physical world as an emergent phenomenon

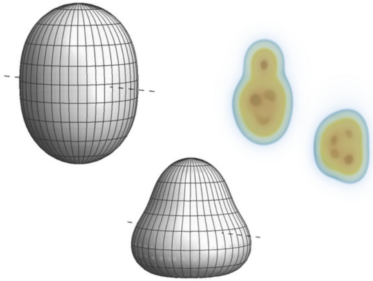
10^{15} m



10^{-15} m







More is different … 50 years later

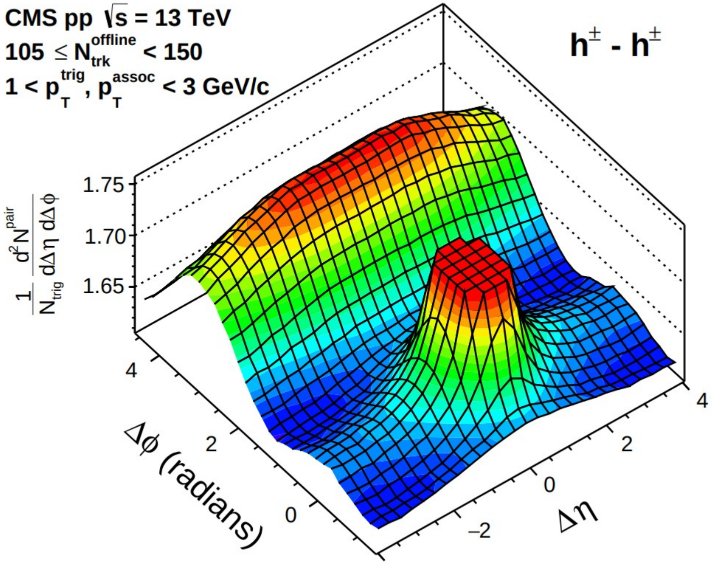
[P. W. Anderson, Science **177** (1972) 4047, 393-396]

Main point : We are able to dissect that statement and elucidate its meaning

What is the precise meaning of “more” ?

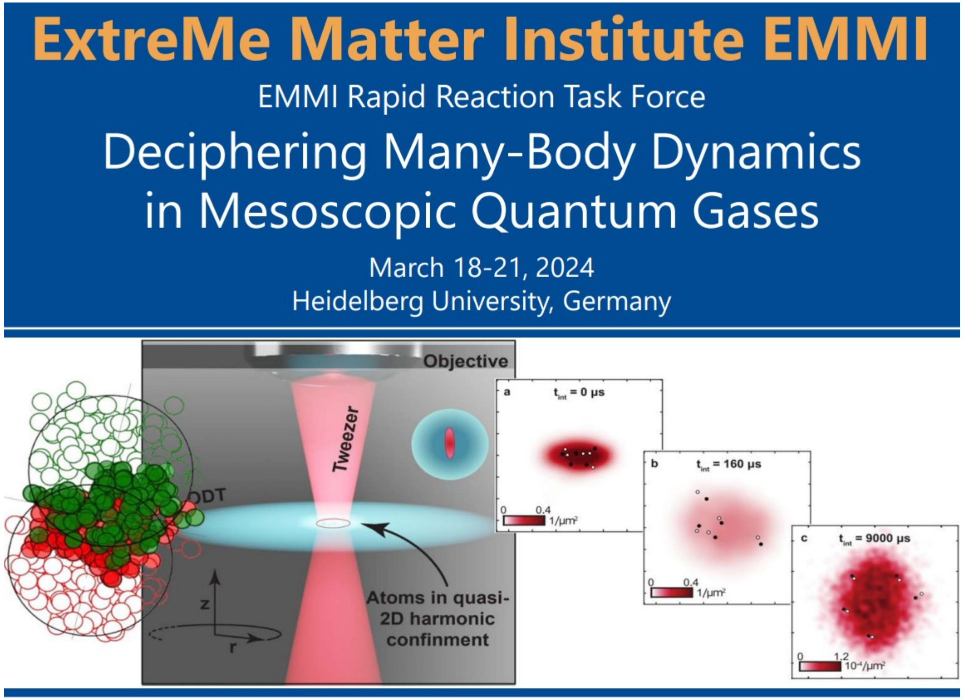
How does “few” become “more” ?

Why are p-p collisions “different” ?



arXiv:2509.05049

https://indico.gsi.de/event/19234/



Heavy Ions

Jurgen Berges
Jasmine Brewer
Stefan Floerchinger
Giuliano Giacalone
Silvia Masciocchi
Alice Ohlson
Aleksas Mazeliauskas
Thomas Schäfer
Ilya Selyuzhenkov
Derek Teaney
Raju Venugopalan

Cold atoms

Sandra Brandstetter
Georg Bruun
Tilman Enss
Keisuke Fujii
Maciej Galka
Qingze Guan
Carl Heintze
Lars Heyen
Selim Jochim
Jesper Levinsen
Philipp Lunt
Meera Parish
Nir Navon
Stephanie Reimann
Francesco Scazza
Joseph Thywissen
Yangqian Yan
Matteo Zaccanti
Torsten Zache

“… emerging area of research, which we believe holds the promise of establishing a new frontier within the discipline of physics as a whole”

… why these two fields ?

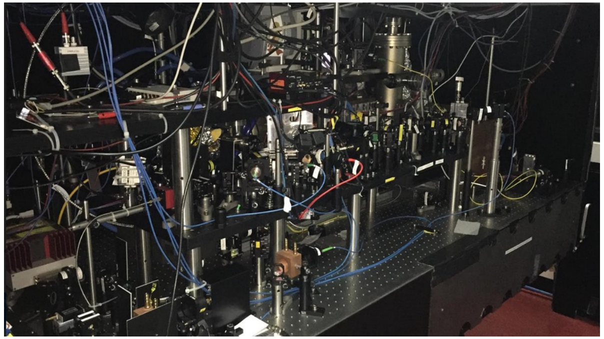
Ultracold atoms – Highly controllable quantum systems

particle number

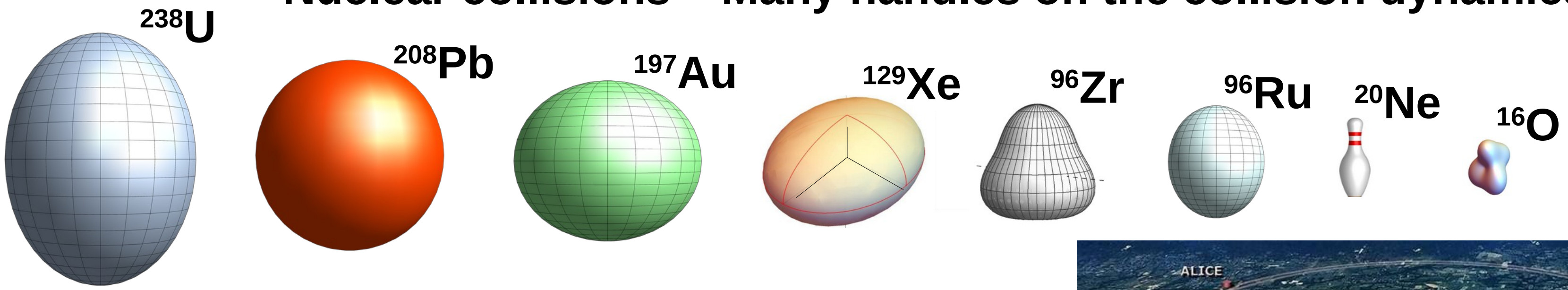
$$\mathcal{H} = -\sum_{i=1}^{N} \frac{\hbar^2}{2m} \boldsymbol{\nabla}_i^2 + \sum_{i<j} \frac{\hbar^2}{2m} g_0 \, \delta^{(d)} \left(\boldsymbol{r}_i - \boldsymbol{r}_j \right) + \sum_{i=1}^{N} \mathcal{V}_{\text{ext}} \left(\boldsymbol{r}_i \right)$$

interaction strength

geometry



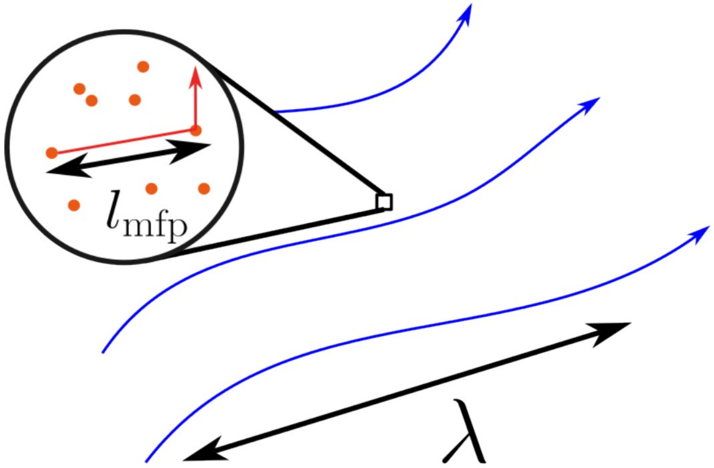
Nuclear collisions – Many handles on the collision dynamics



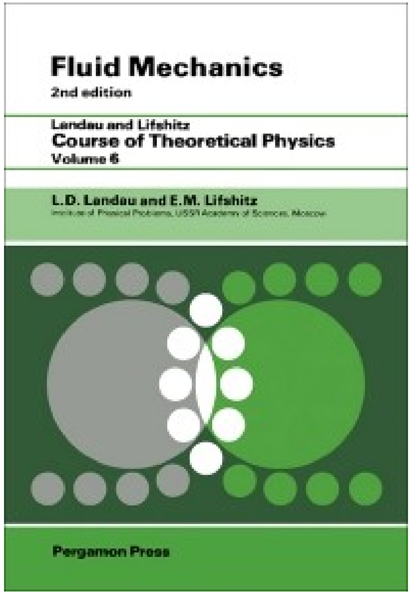
multiplicity, rapidity, collision energy …

Example for heavy ions : Collisional hydrodynamics (T>0)

Large N, separation of scales, equilibrium, …



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



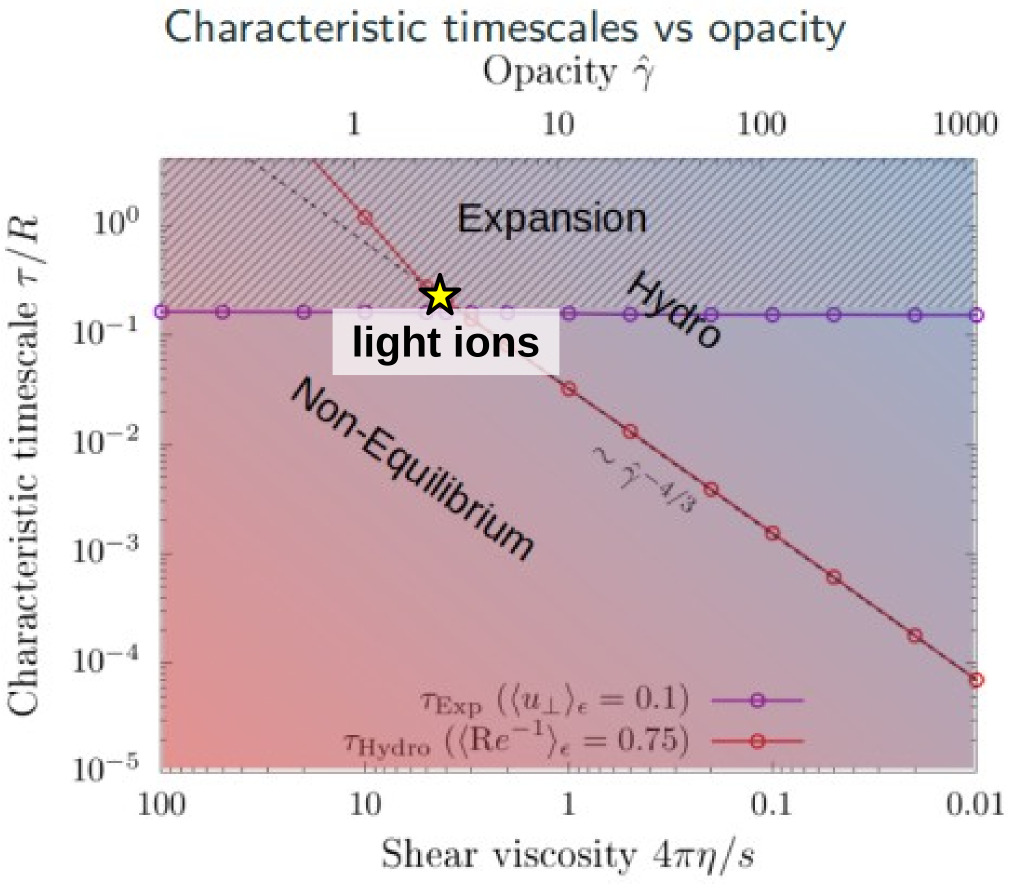
$$\rho \left(\partial_t + \vec{u} \cdot \vec{\nabla} \right) \vec{u} = -\vec{\nabla} p + \eta \nabla^2 \vec{u}$$

density pressure shear

$$\mathrm{Kn} \equiv \frac{\eta}{\rho\, v} \frac{1}{R} \ll 1$$

Breaking textbook criteria – Since 2018

[Kurkela, Wiedemann, Wu, EPJC **79** (2019) 11, 965]



Boltzmann eq. in relaxation time approximation (RTA)

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

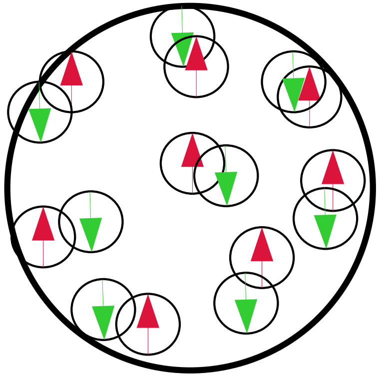
Detailed numerical solutions to assess hydro applicability

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

Talk by Clemens Werthmann

Talk by Aleksi Kurkela

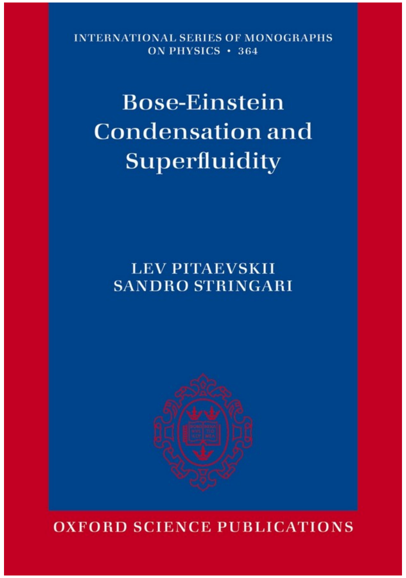
Example for cold atoms : Superfluid hydrodynamics (T~0)



large system of bosons $N \gg 1$

separation of scales $na_s^3 \ll 1$

molecule size << inter-molecule distance



Gross-Pitaevskii equation $\hat{\Psi}(r,t) = \Psi(r,t) + \cancel{\delta\hat{\Psi}(r,t)}$

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V_{\text{ext}}(\mathbf{r}) + g|\Psi|^2\right)\Psi$$

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

ideal (superfluid) hydrodynamics

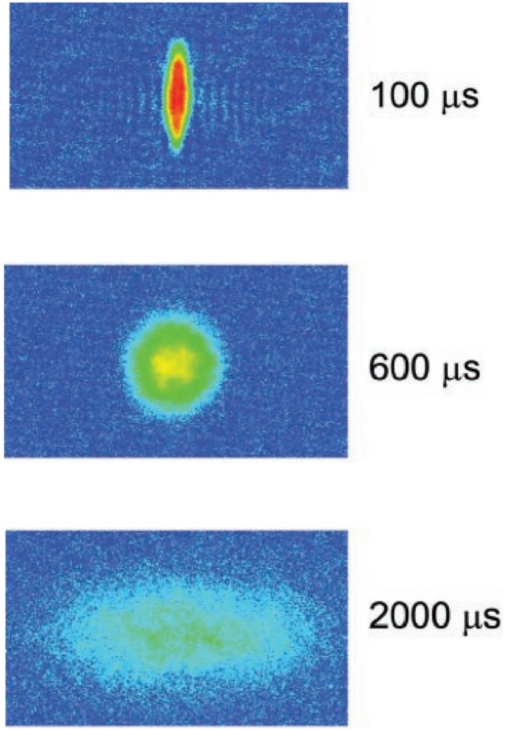
$$\frac{\partial}{\partial t}n + \nabla(v_S n) = 0$$

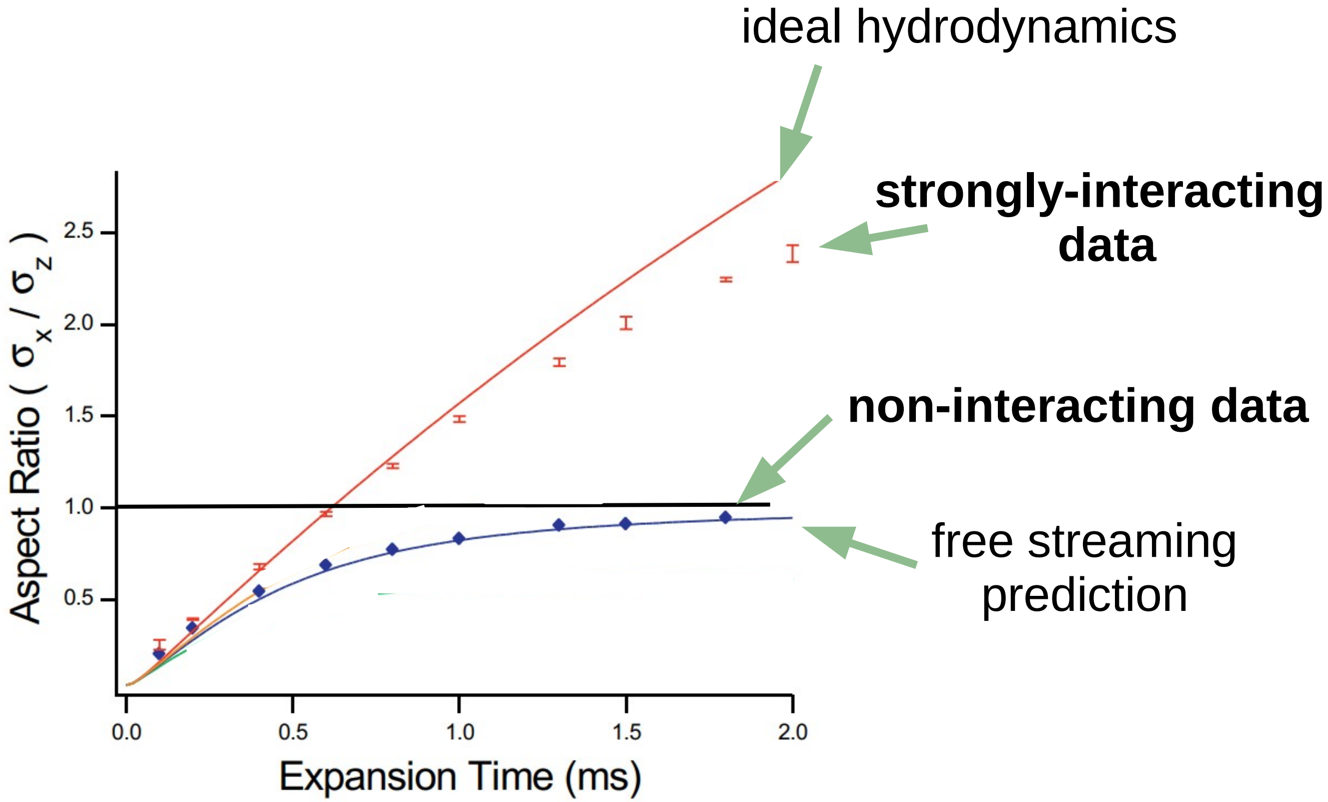
$$m\frac{\partial}{\partial t}v_S + \nabla\left(\frac{1}{2}mv_S^2 + \mu(n) + V_{ext}\right) = 0$$

Bits of history …

Control of geometry and interactions – Elliptic flow to probe superfluid hydrodynamics

[O'Hara et al., Science **298** (2002) 2179-2182]
[Menotti, Pedri, Stringari, PRL **89**, 250402 (2002)]



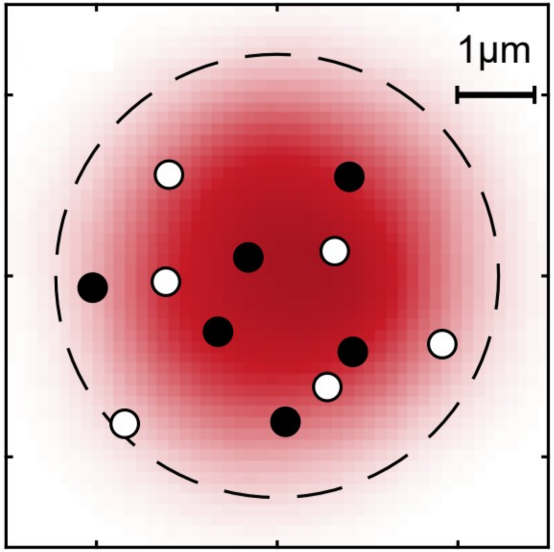


Jochim Lab @ Heidelberg University – Control of particle numbers down to one atom!

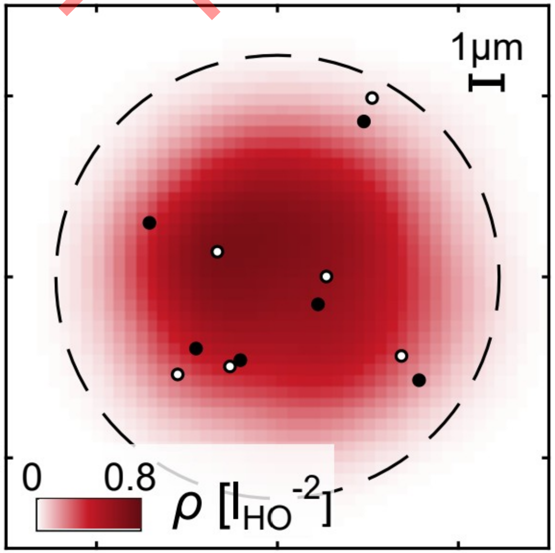
[Serwane *et al.*, Science **332** (2011) 6027]

Breaking textbook criteria – One by one

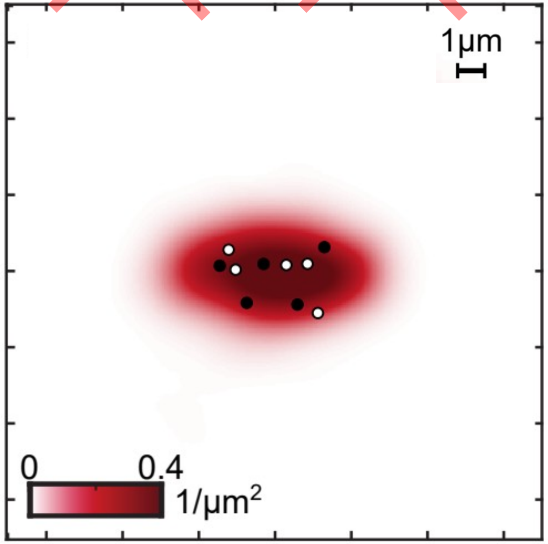
No interactions



~~N>>1~~ $a^3n<<1$



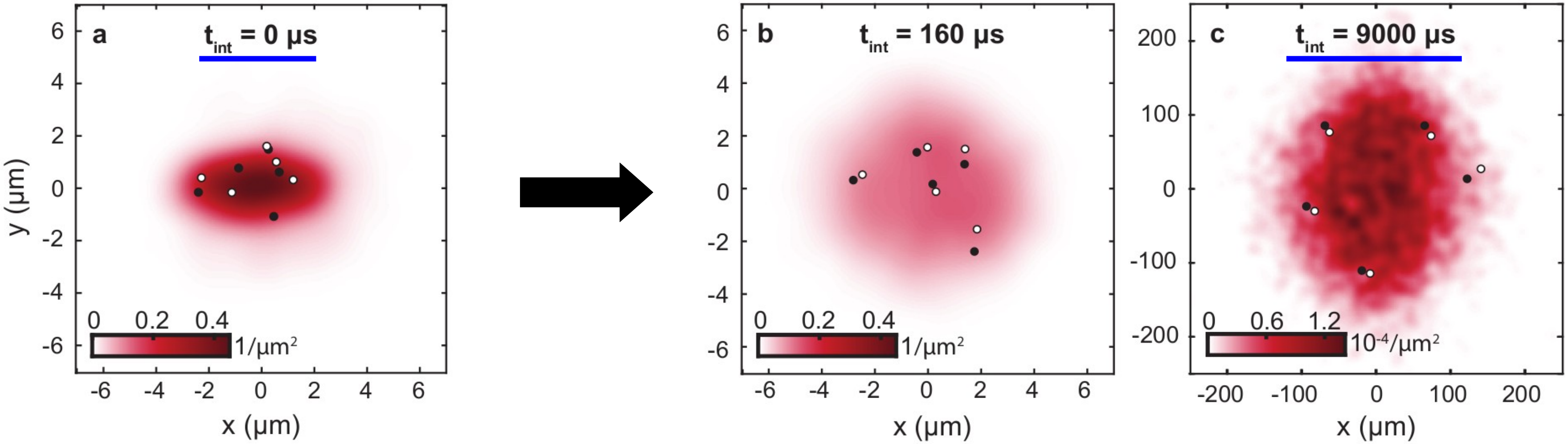
~~N>>1~~ ~~$a^3n<<1$~~



? ? ?

Criteria for applicability of many-body description fail

Yet ... Observed inversion of the initial anisotropy



nature physics

Article https://doi.org/10.1038/s41567-024-02705-8

Emergent interaction-driven elliptic flow of few fermionic atoms

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Accepted: 10 October 2024

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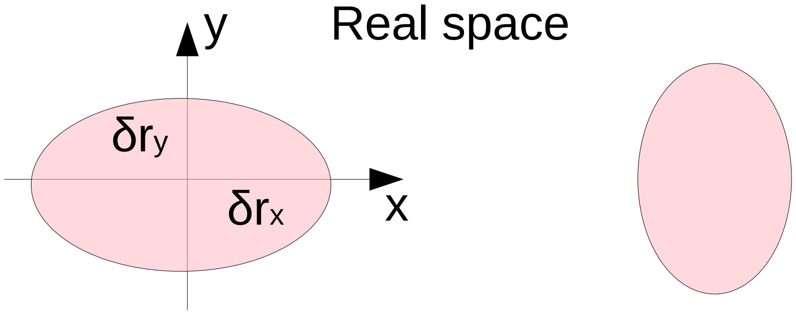
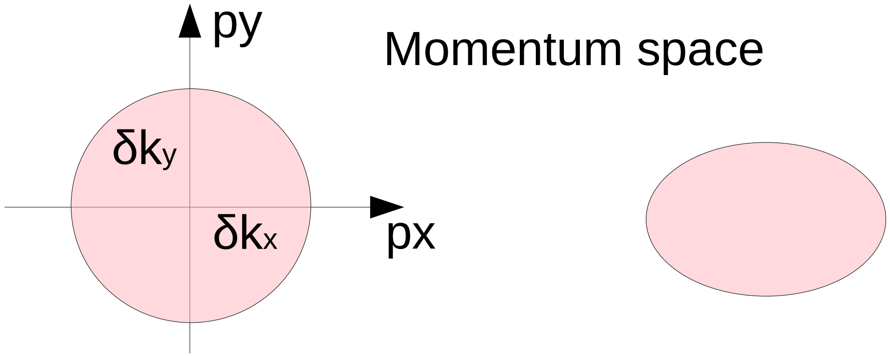
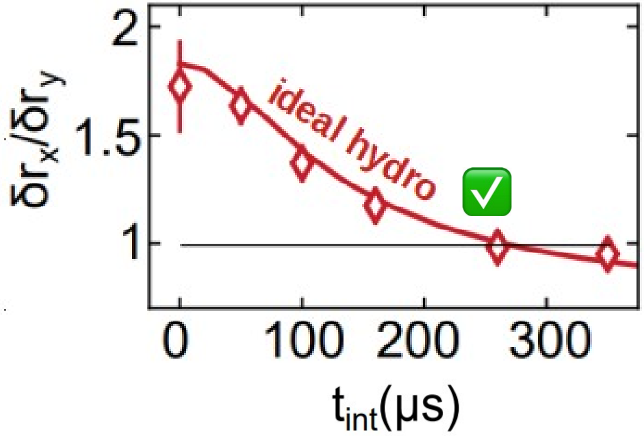
Sandra Brandstetter[1,6], Philipp Lunt[1,6], Carl Heintze[1], Giuliano Giacalone[2], Lars H. Heyen[2], Maciej Gałka[1], Keerthan Subramanian[1], Marvin Holten[1,4], Philipp M. Preiss[1,5], Stefan Floerchinger[3] & Selim Jochim[1]

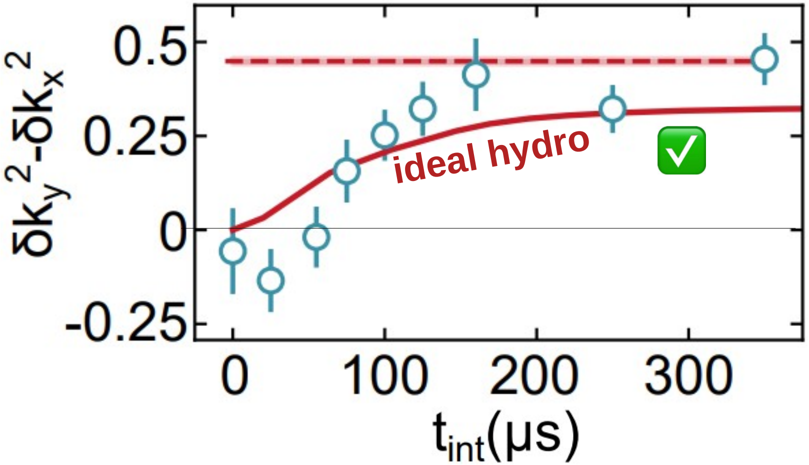
… fluid of 10 atoms !?

Ideal hydro model based on the many-body gas (EOS, N>>1)









Bonus : Tails of the trapped density nicely captured by Gross-Pitaevskii framework

[Floerchinger, Giacalone, Heyen, PRC **112** (2025) 1, 014003]

10 is "different" !?

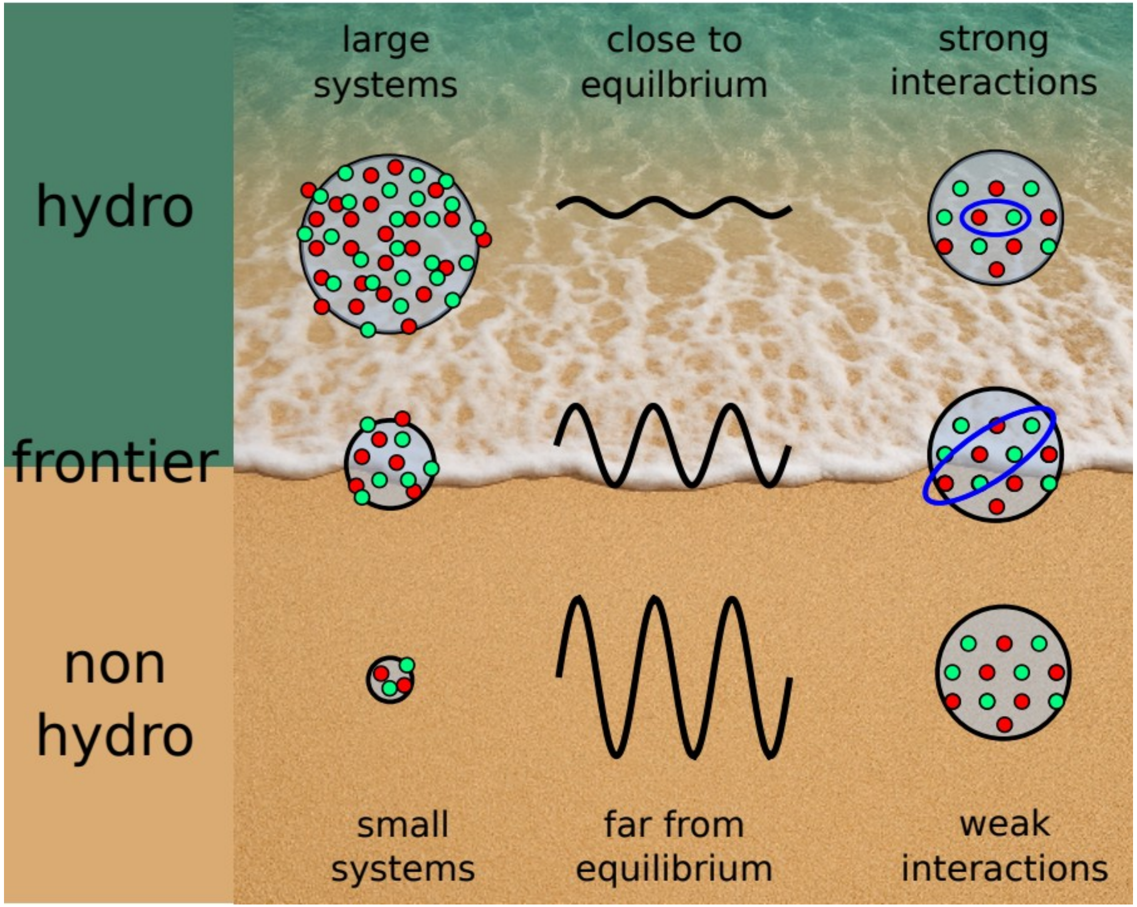
More prospects [from arXiv:2509.05049] – ideas welcome!

We can play with

- Initial geometry/size
- Interaction strength
- Number of atoms
- Perturbations

We can measure

- Response/relaxation
- Two- and multi-particle correlations
- Transport/EOS



Much activity on the “equilibrium front” … hydrodynamic attractors

New platform operational in Huzhou for studying thermal gas across opacities

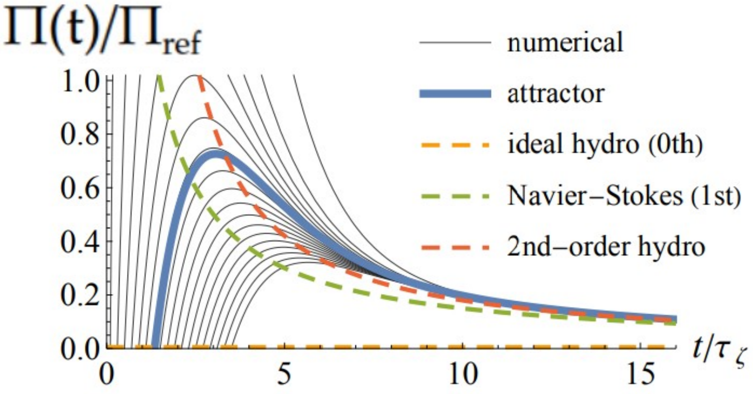
[Li *et al.*, arXiv:2405.02847] **Talk by Fuqiang Wang**

Protocol to look for attractor in cold gases

[Fuii, Enss, PRL **133** (2024) 17, 173402]

Seeing cyclic attractor behavior

[Mazeliauskas, Enss, arXiv:2501.19240]



Talk by Clemens Werthmann

Far-from-equilibrium dynamics in thermal near-unitary gas

[Werthmann, Heller, arXiv:2507.02838]

Ultracold atom setup ideally suited for experimental discovery of the attractor

Frontier with ultra-cold atom gases – Spatial imaging

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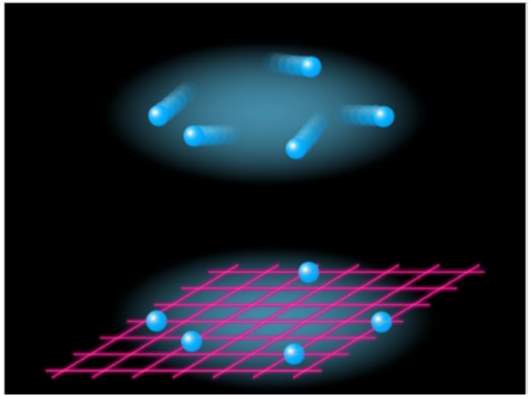
VIEWPOINT

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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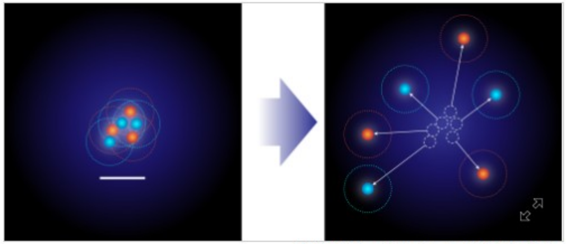
VIEWPOINT

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

Laboratoire Kastler Brossel

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UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

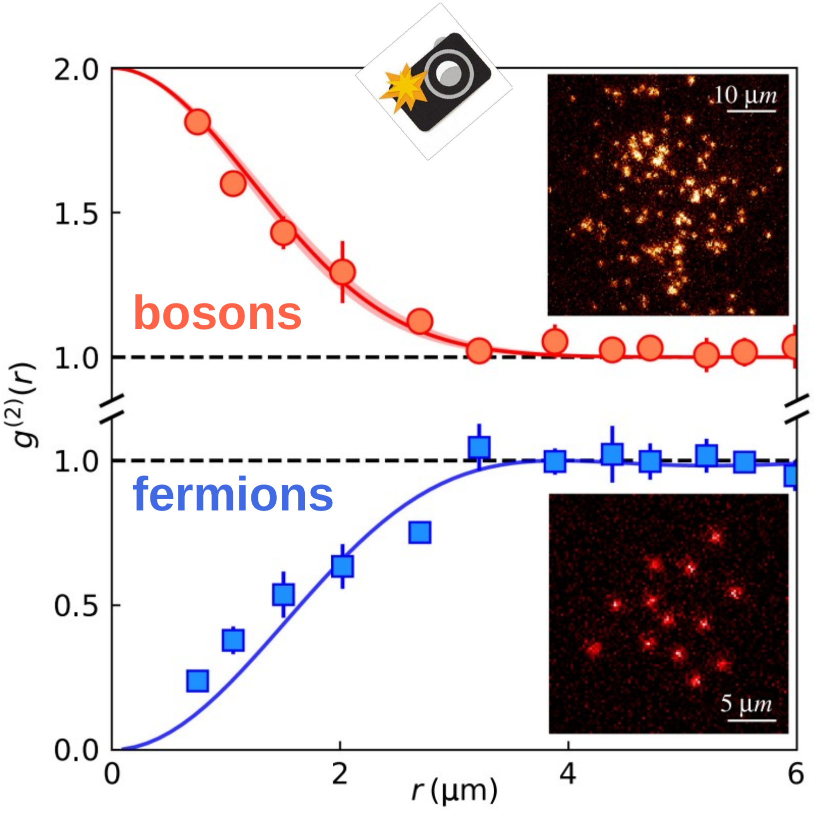
Many-body correlations of atoms – Snapshots of the ground-state wave function

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

two-body correlation function

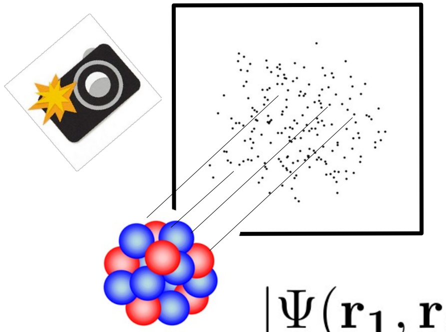
$$g_2(\mathbf{r}_1,\mathbf{r}_2)=\frac{\langle\psi^\dagger(\mathbf{r}_2)\psi^\dagger(\mathbf{r}_1)\psi(\mathbf{r}_1)\psi(\mathbf{r}_2)\rangle}{n^2}$$

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



Connection with nuclear physics?

Imaging nuclear ground states at colliders – Same strategy



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

THICKNESS FUNCTION

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

ULTRA-CENTRAL ENTROPY

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

Mean squared eccentricity

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

FINITE NUMBER OF NUCLEONS

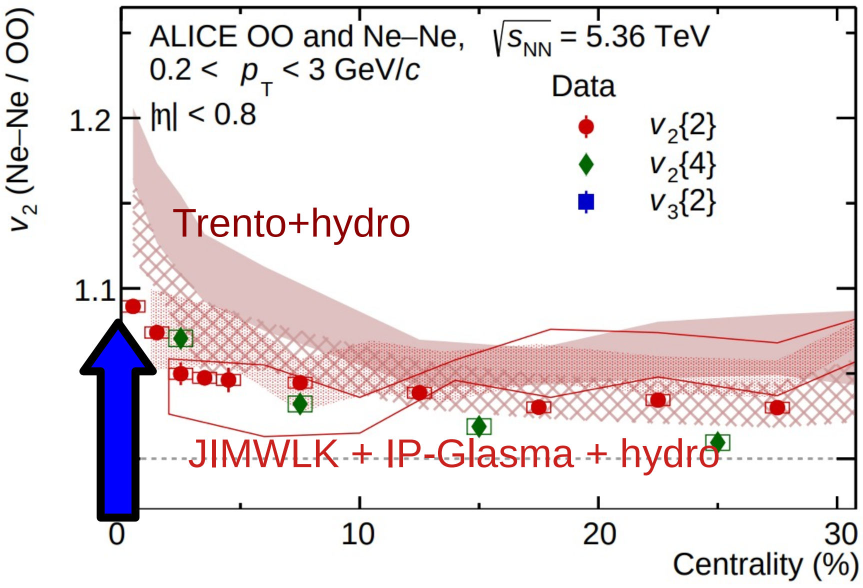
TWO-BODY CORRELATIONS

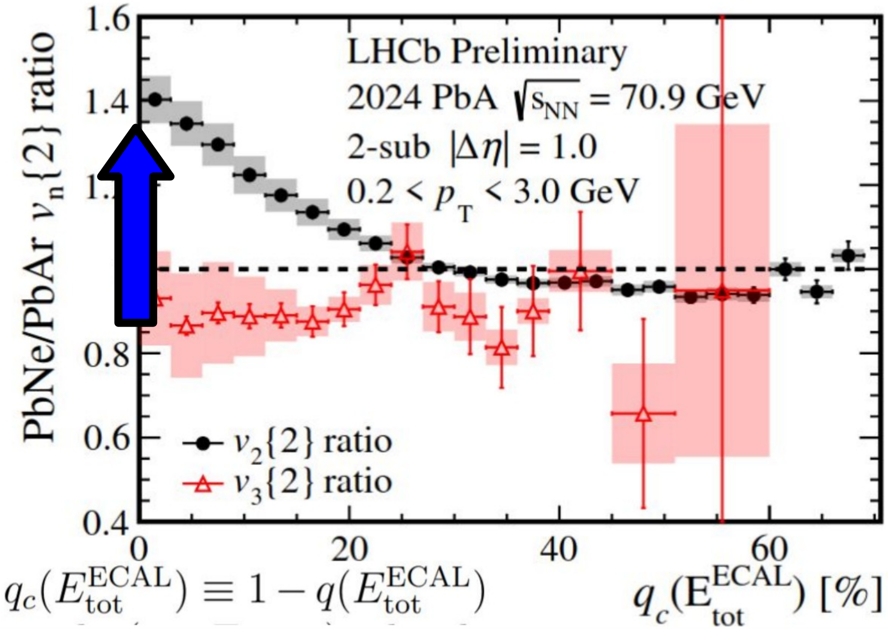
New "eccentricity operator" for many-body quantum systems

$$\hat{\mathcal{E}}_n(\mathbf{x}_1, \mathbf{x}_2) = (x_1 + iy_1)^n\,(x_2 - iy_2)^n$$

[Duguet, Giacalone, Jeon, Tichai, arXiv:2504.02481]

Highlights from ALICE and LHCb at this conference





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

Neon has stronger angular correlations than oxygen (e.g. deformation)

Implications for nuclear forces in chiral EFT? Interplay with QCD effects?

[work in progress with *ab initio* nuclear structure community]

Conclusion

Fully controllable quantum systems are available (particle number, interactions, geometry)

Understanding emergence – Re-examining textbook criteria, new language/interpretation

Heavy/Light ions (or?) and ultracold atoms at the forefront of these developments!