Coupling nuclear structure and the initial state of relativistic heavy-ion collisions

Benjamin Bally

EMMI Workshop - GSI, Darmstadt
10 November 2025

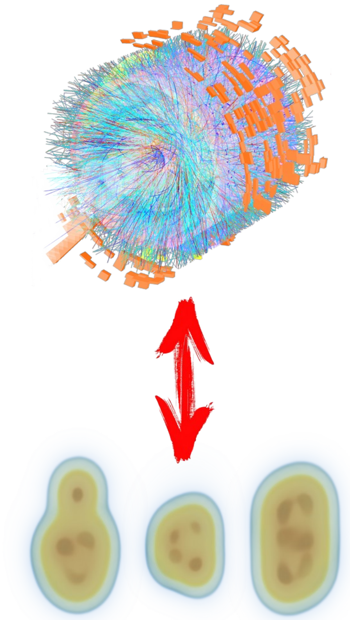
TECHNISCHE UNIVERSITÄT DARMSTADT

erc
DeformedNuclei
(A. Tichai)

Motivations

- Interface between low- and high-energy nuclear physics

relativistic nuclear collisions



structure of atomic nuclei

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- New and mutually beneficial possibilities

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  → Select nuclear species to collide

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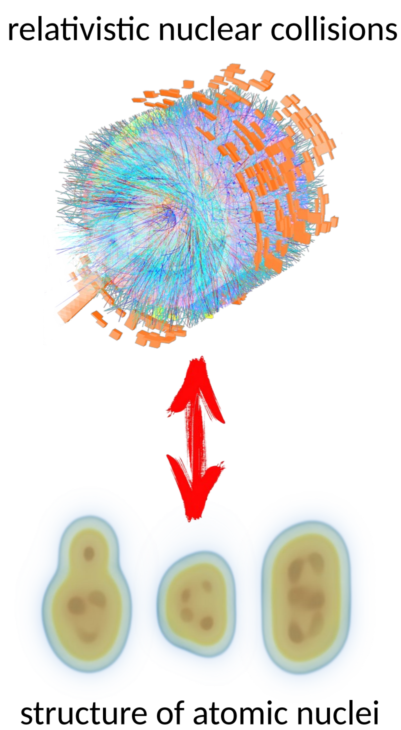

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- A lot of activity over the past few years

Giacalone, PRL 127, 242301 (2021)
Bally, PRL 128, 082301 (2022)
Jia, PRL 131, 022301 (2023)
Ryssens, PRL 130, 212302 (2023)

EMMI RRTF 2022 (Heidelberg)
INT Program 23-1a (Seattle)
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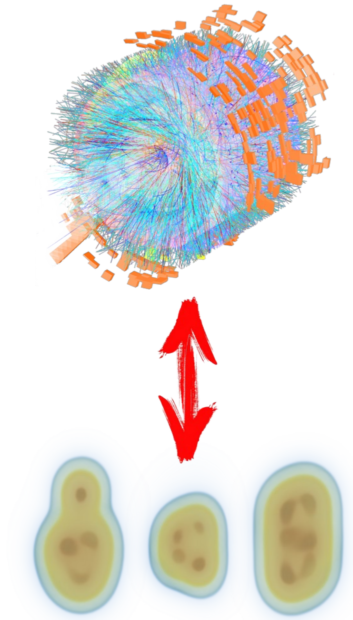

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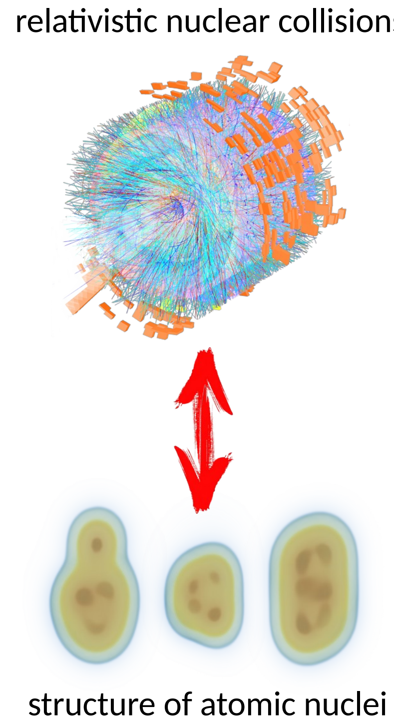
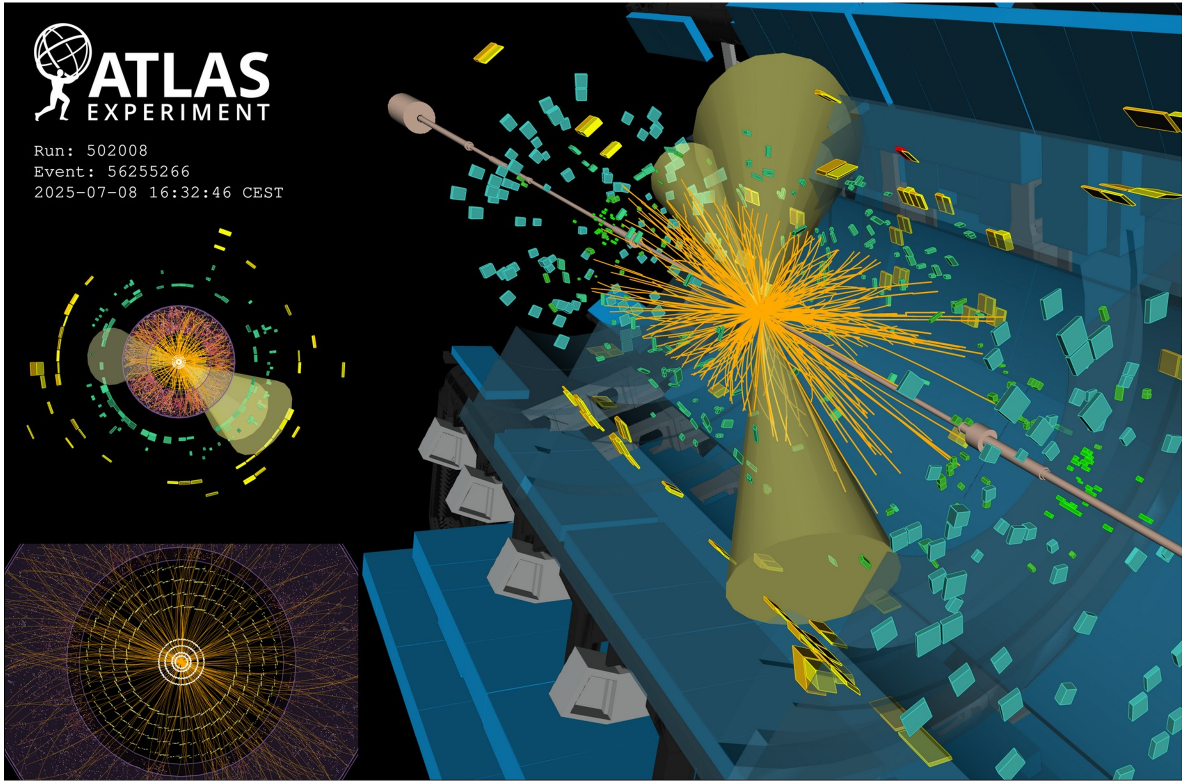
- Focus on high-energy and recent light-ions run at the LHC

  → Clear connection (hydro expansion, time scale of the collisions)

  → ^{16}O+^{16}O and ^{20}Ne+^{20}Ne collided in 2025 at the LHC



Breaking new ground: $^{20}Ne+^{20}Ne$ at the LHC!



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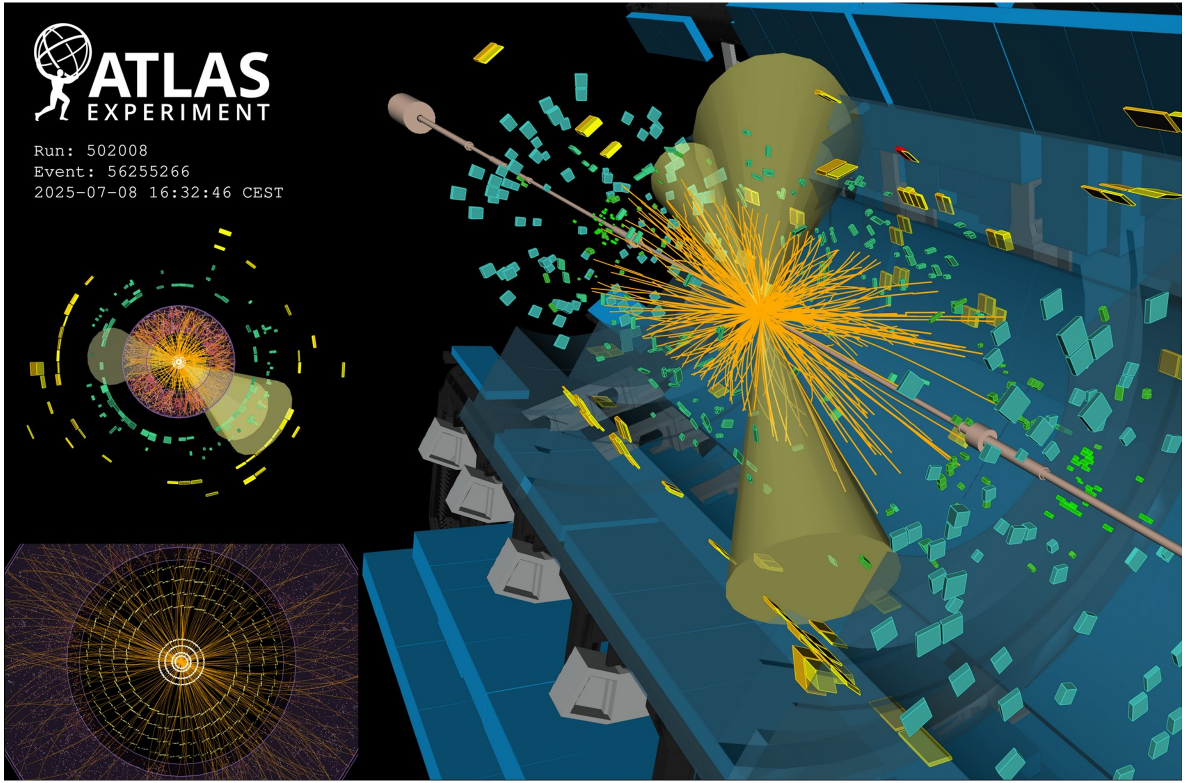
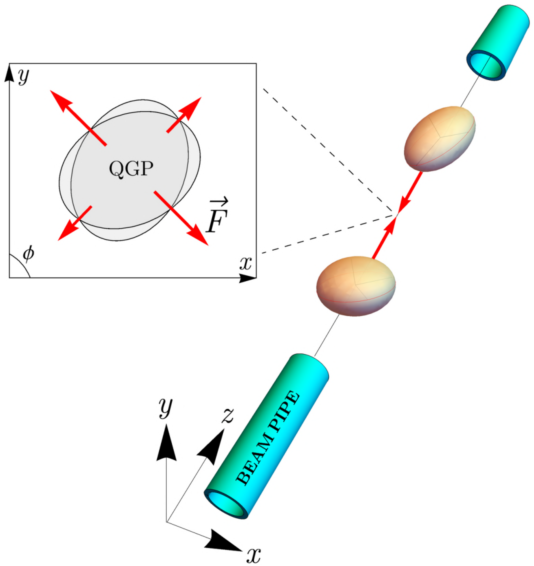


→ ^{20}Ne+^{20}Ne collided at the LHC on the 8th of July 2025!

→ Directly motivated by our predictions!

Giacalone, PRL 135, 012302 (2025)

Overview of relativistic nuclear collisions



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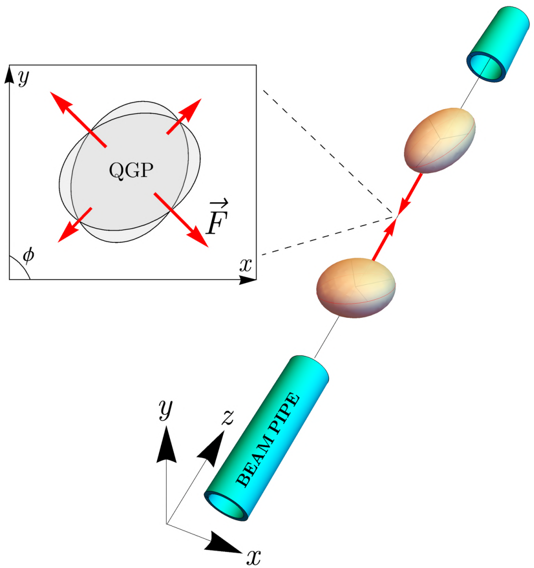

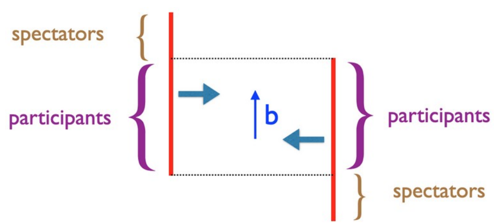

Ollitrault, EPJA 59, 236 (2023)

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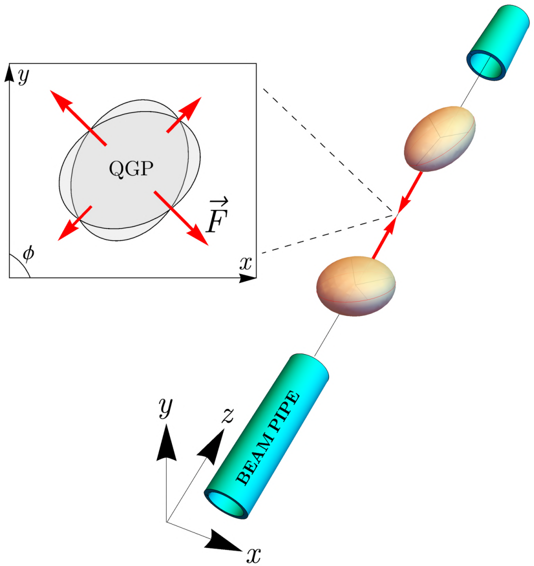

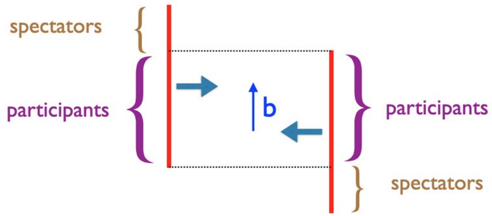

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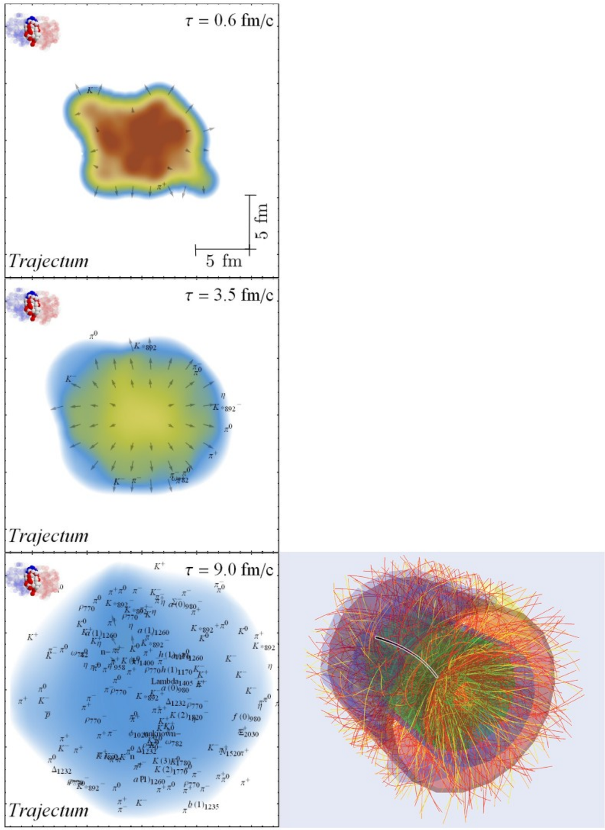

Giacalone, PRL 131, 202302 (2023)
ALICE collaboration

Emergent spatial arrangements of nuclei

- Protons and neutrons inside nuclei can adopt various spatial configurations

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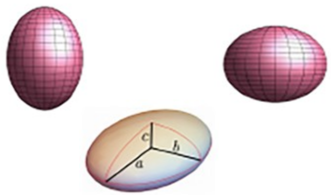
- Nuclear deformation (quadrupole, octupole, …)



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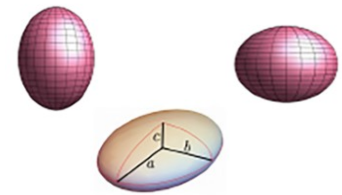
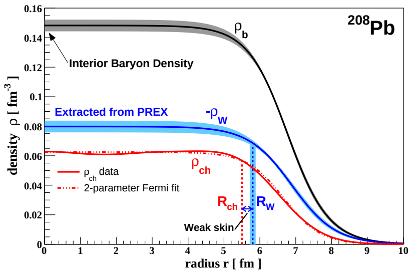


- Neutron-skin
  → directly connected to the EoS



Adhikari, PRL 126, 172502 (2021)

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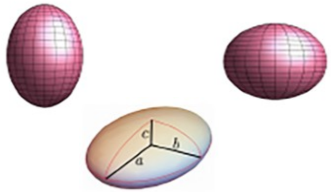

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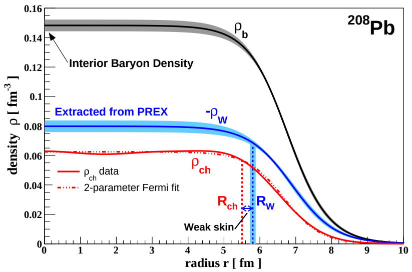

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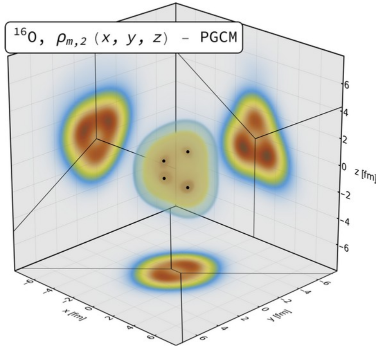
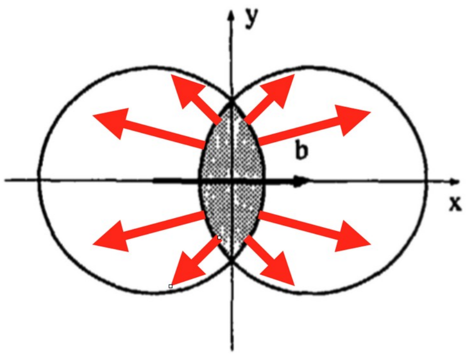
- Clustering (e.g. α-clusters)



Spatial anisotropy of initial conditions



Ollitrault, PRD 46, 229 (1992)
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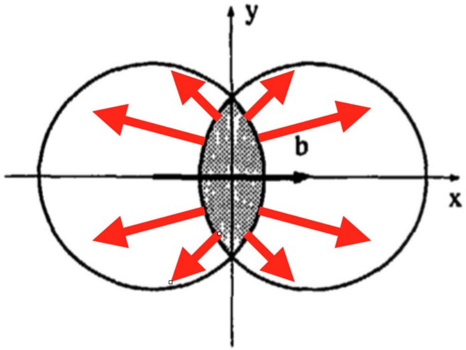

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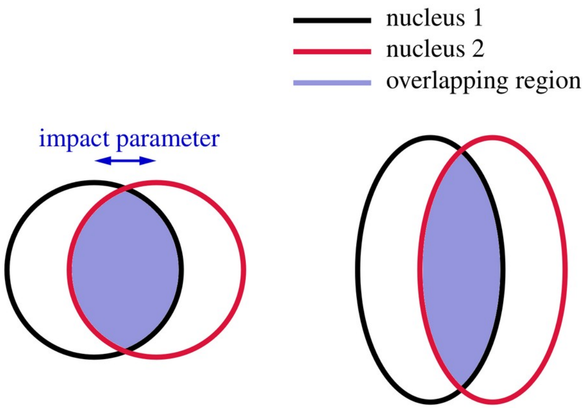

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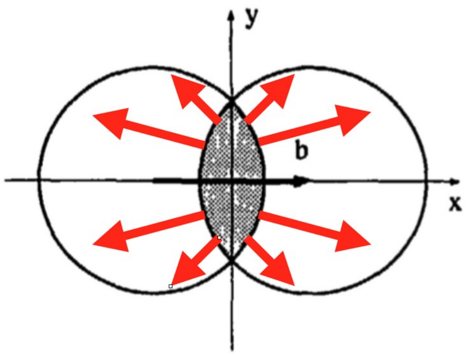

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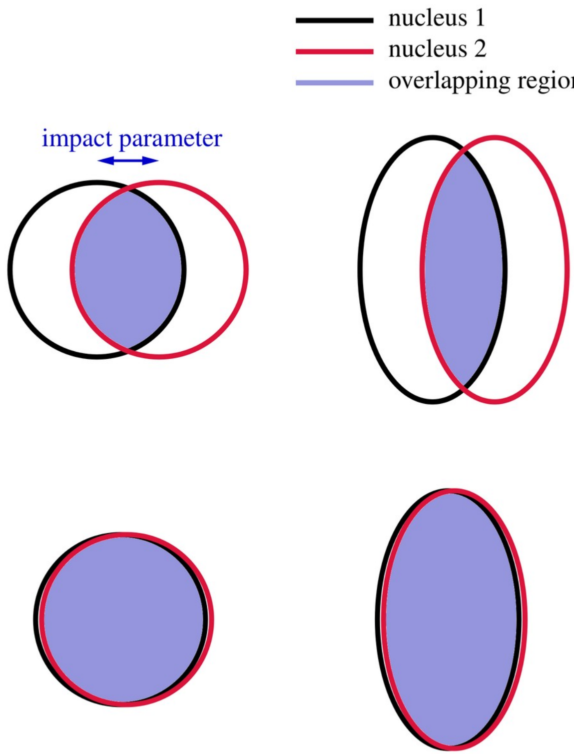

Nuclear arrangements → spatial anisotropies

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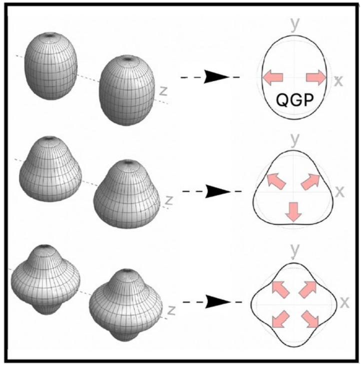

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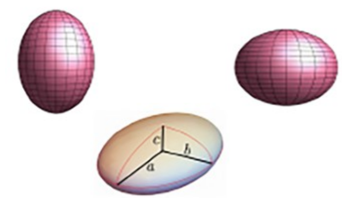

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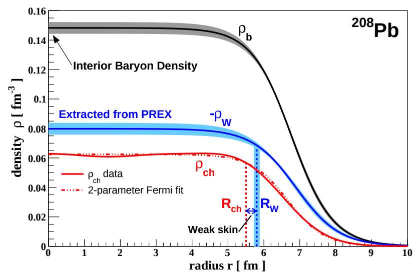

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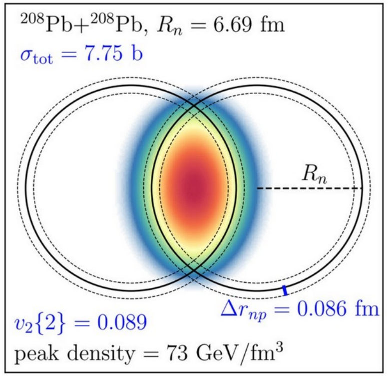

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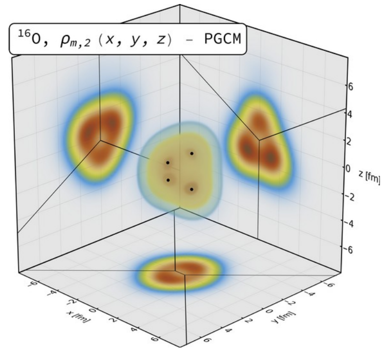

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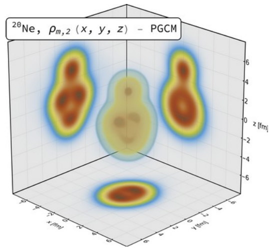
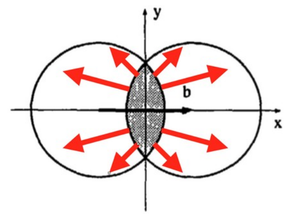
Connection between low- and high-energies



Spatial structure of nuclei



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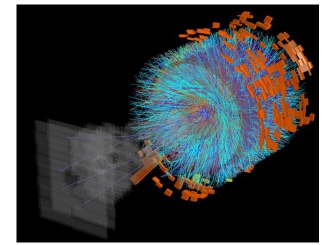

Final-state observables of collisions

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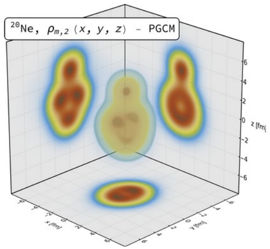

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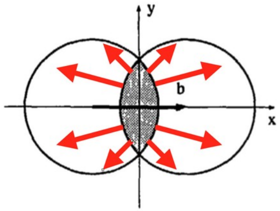

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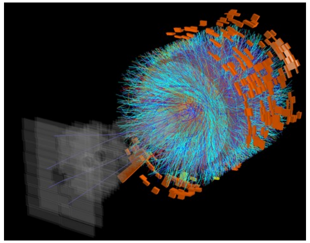

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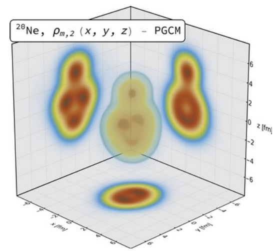

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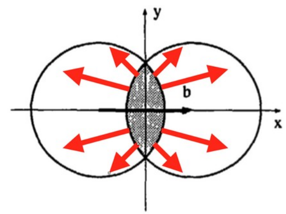

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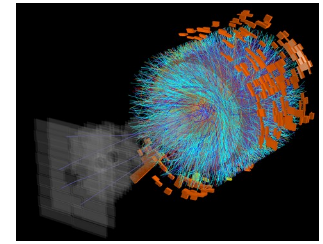

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Nuclear structure theory

Ab initio nuclear theory in a nutshell

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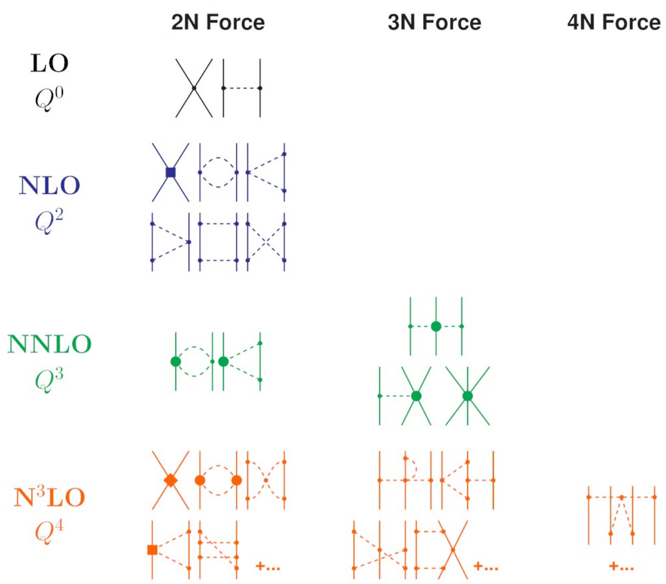

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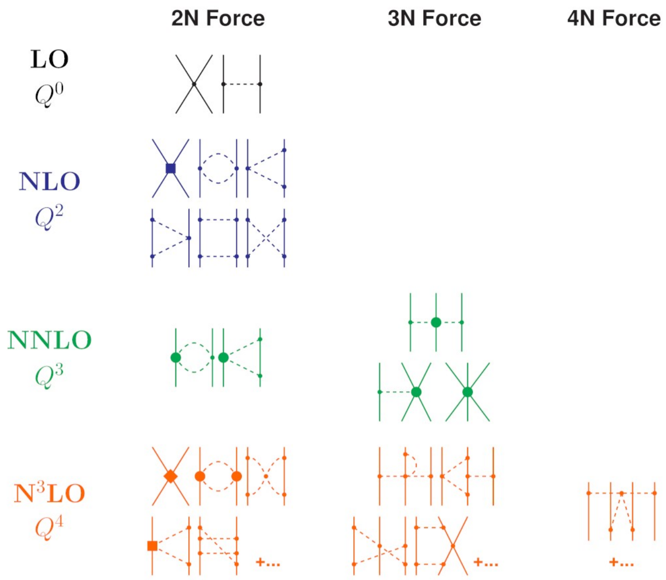

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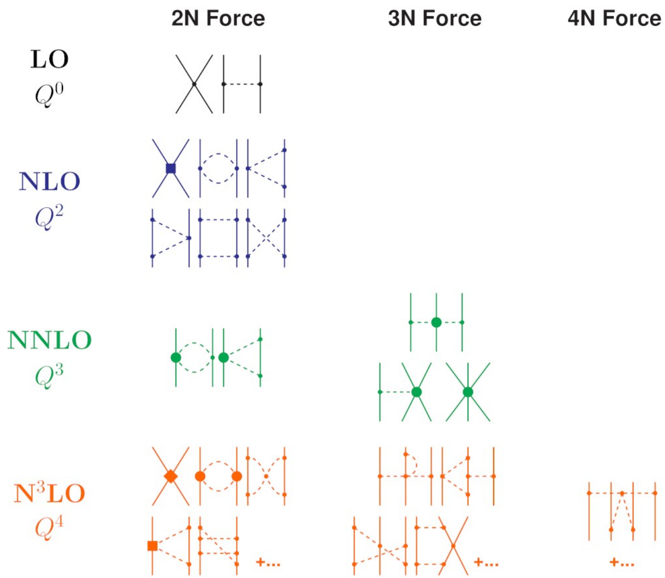
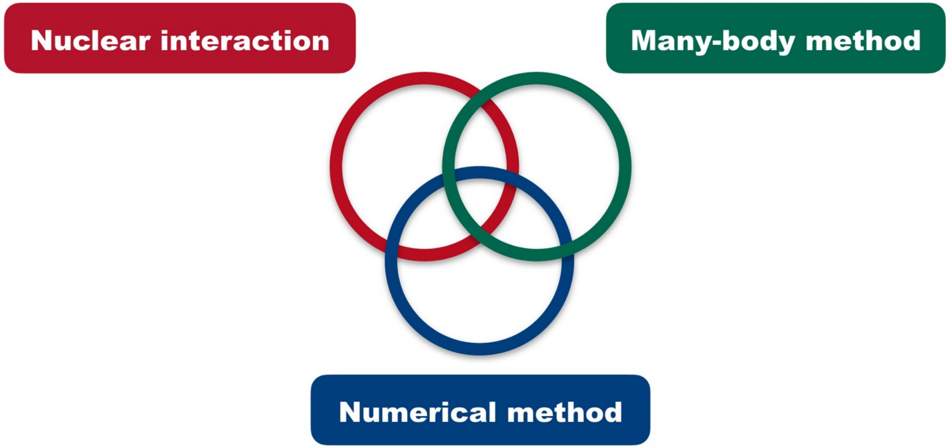
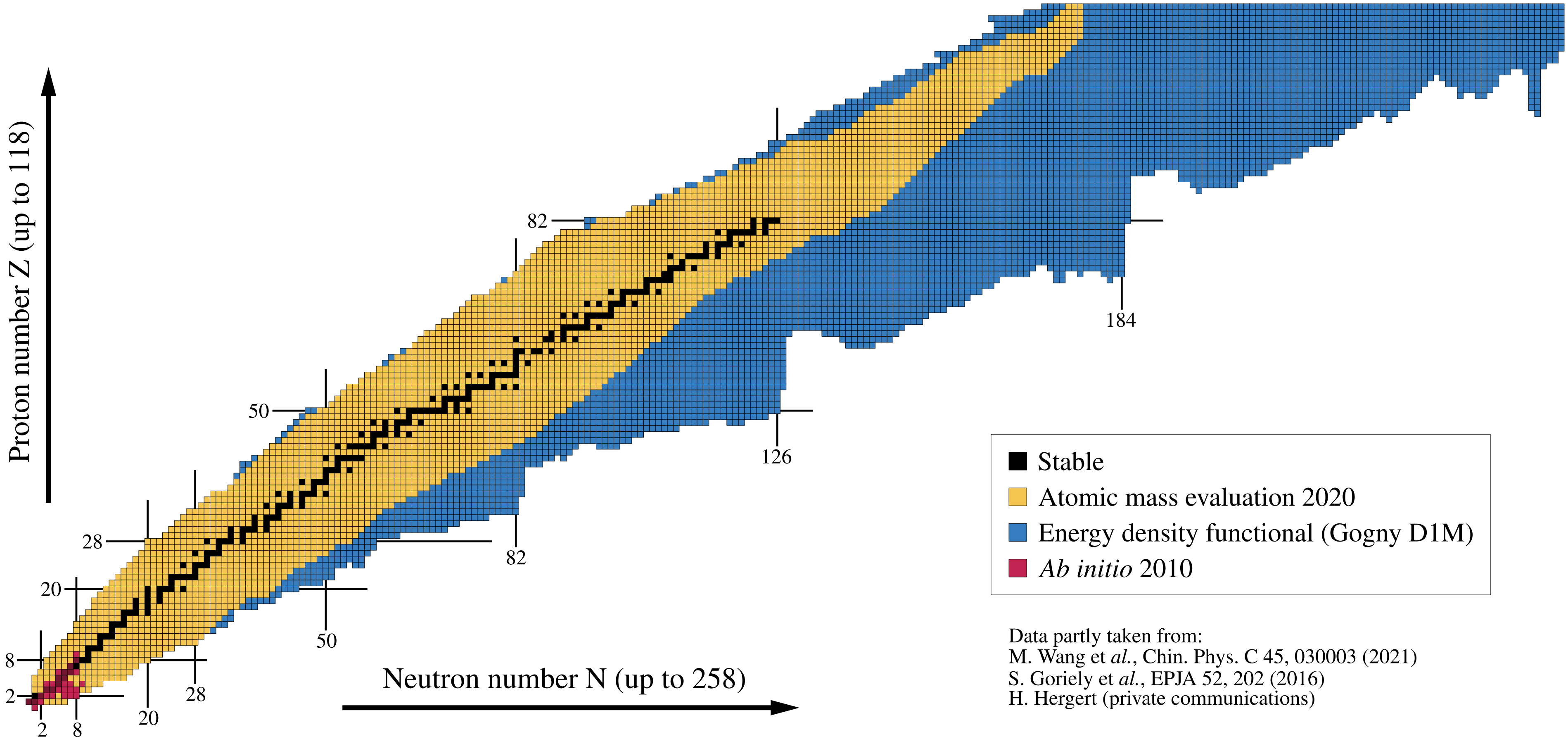




Courtesy of P. Arthuis

Reach of *ab initio* nuclear theory (2010)



Data partly taken from:
M. Wang et *al.*, Chin. Phys. C 45, 030003 (2021)
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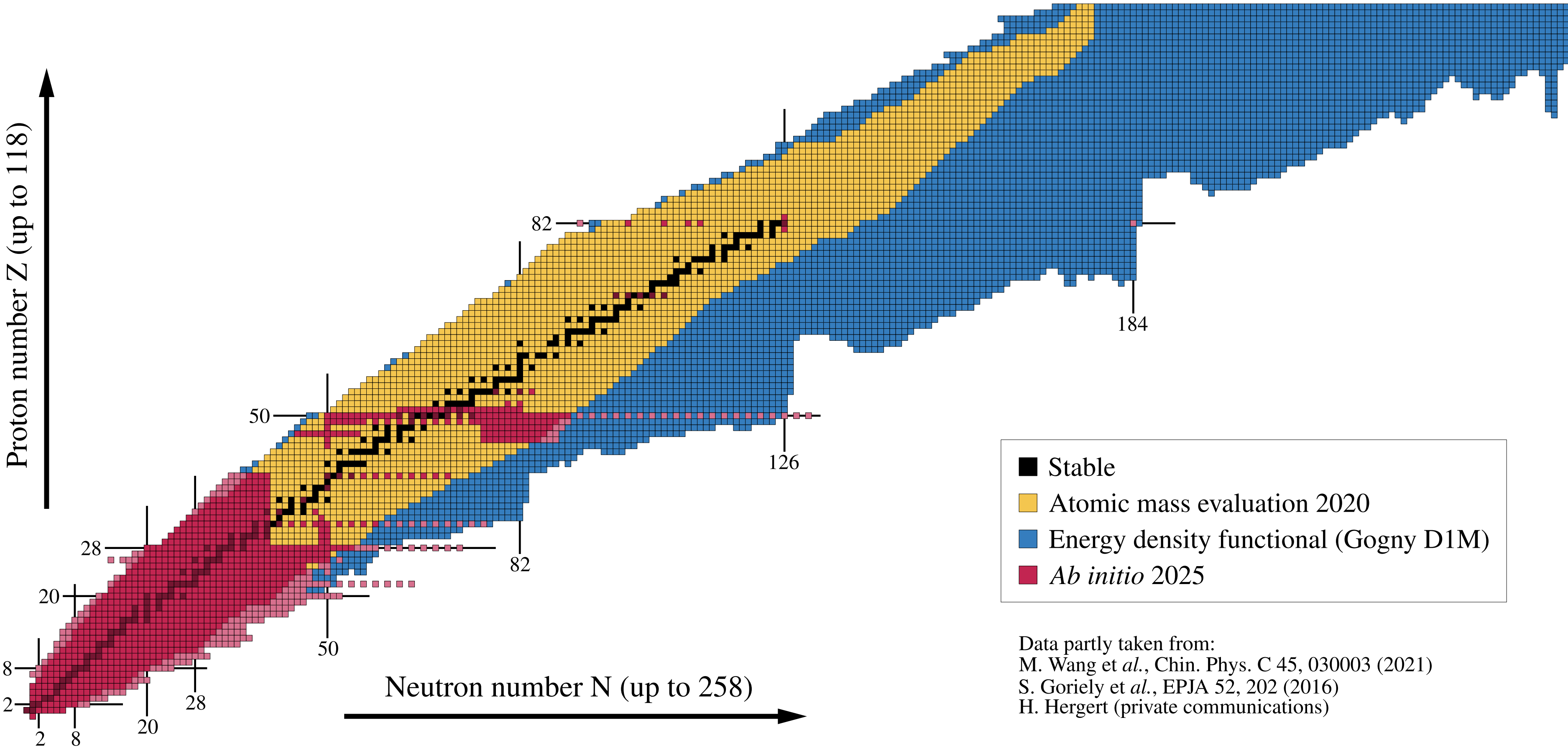

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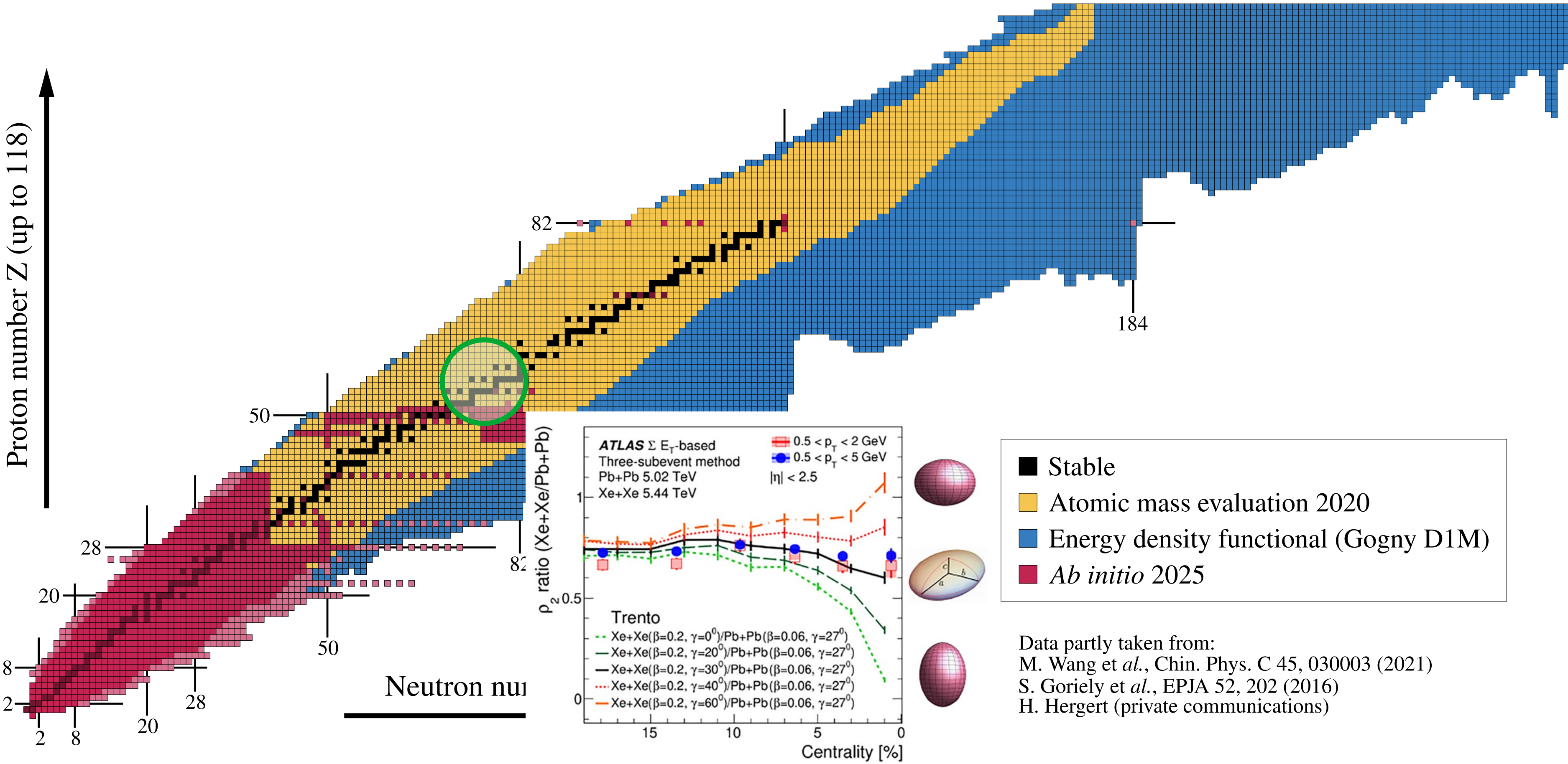
Also contributions from density functionals



Importance of triaxiliay in ^{129}Xe
Bally, PRL 128, 082301 (2022)

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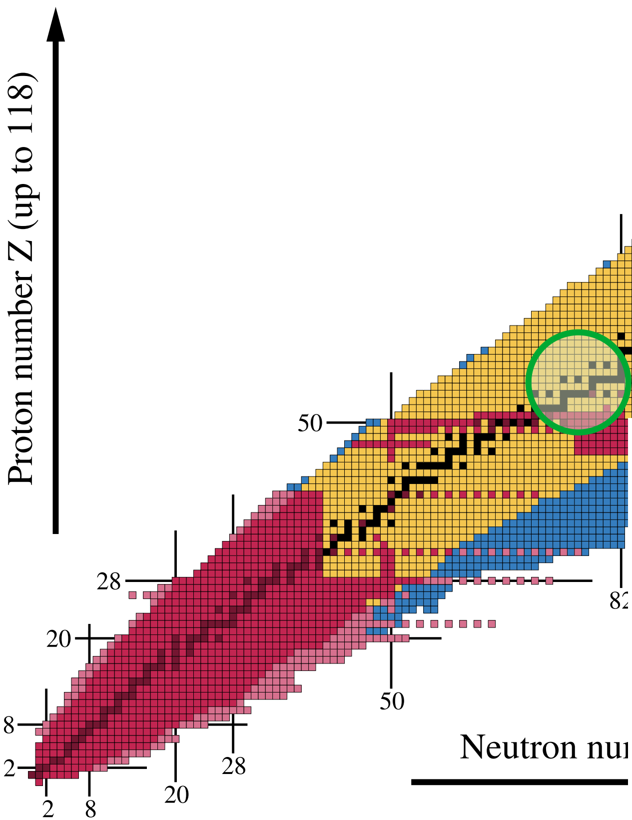
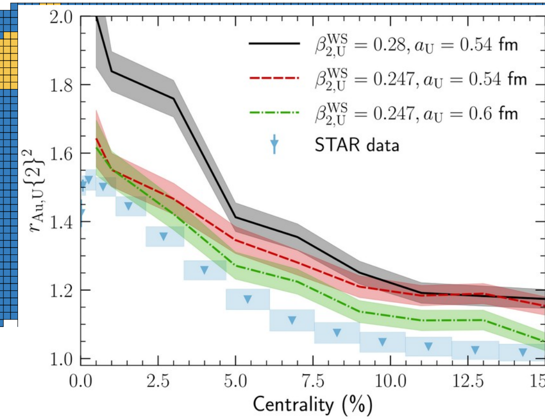
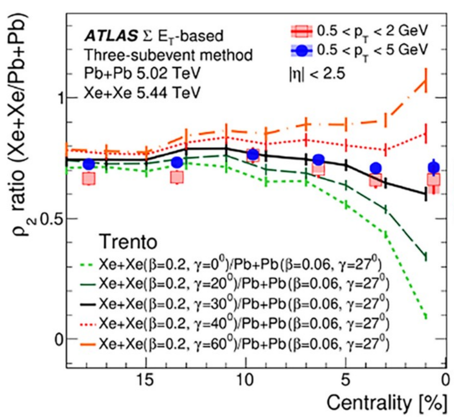
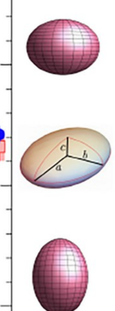




Importance of hexadecapole in ^{238}U

Ryssens, PRL 130, 212302 (2023)





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- Atomic mass evaluation 2020
- Energy density functional (Gogny D1M)
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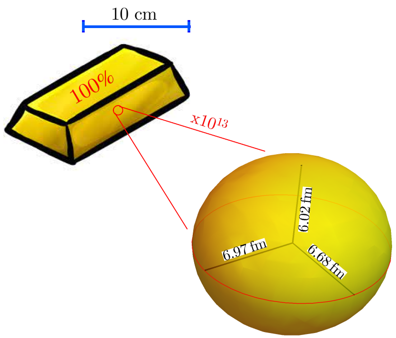
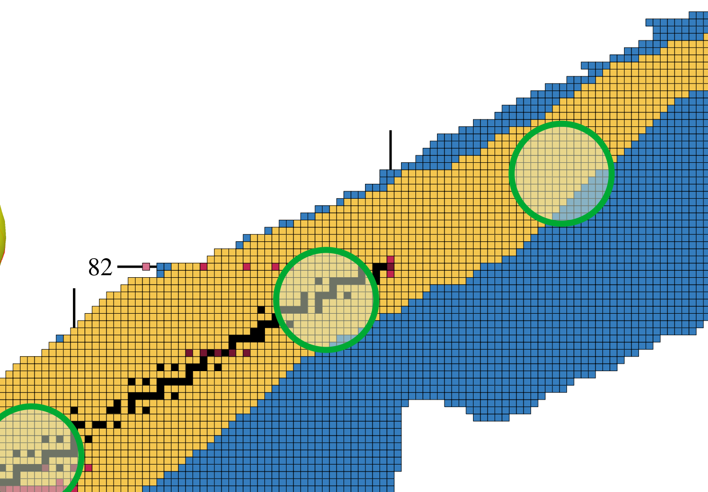
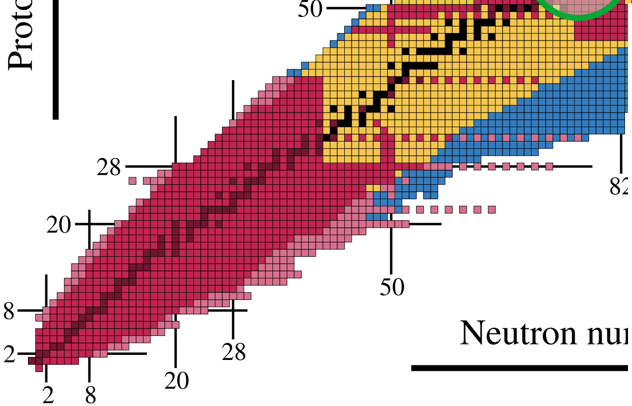
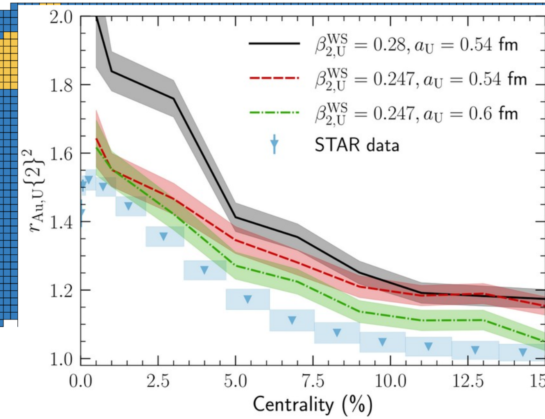


The shape of gold (^{197}Au)
Bally, EPJA 59, 58 (2023)



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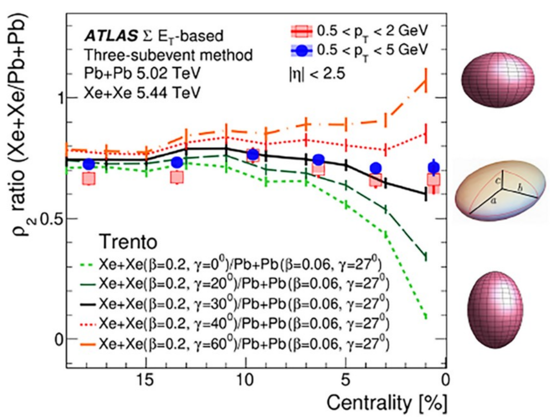

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Application to OO and NeNe collisions @LHC

PHYSICAL REVIEW LETTERS **135,** 012302 (2025)

Exploiting ^{20}Ne Isotopes for Precision Characterizations of Collectivity in Small Systems

Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]

- Large collaboration of theorists from heavy-ion collisions and nuclear structure

Application to OO and NeNe collisions @LHC

PHYSICAL REVIEW LETTERS **135**, 012302 (2025)

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- Perform state-of-the-art calculations with quantitative predictions

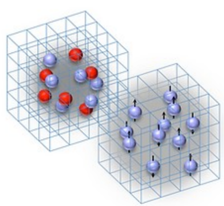
Tools and workflow

EFT → Nuclear structure → Relativistic Hydro → Hadron transport → PRL

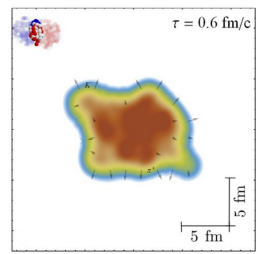
Chiral EFT
N3LO

PGCM

Pionless EFT
LO



NLEFT



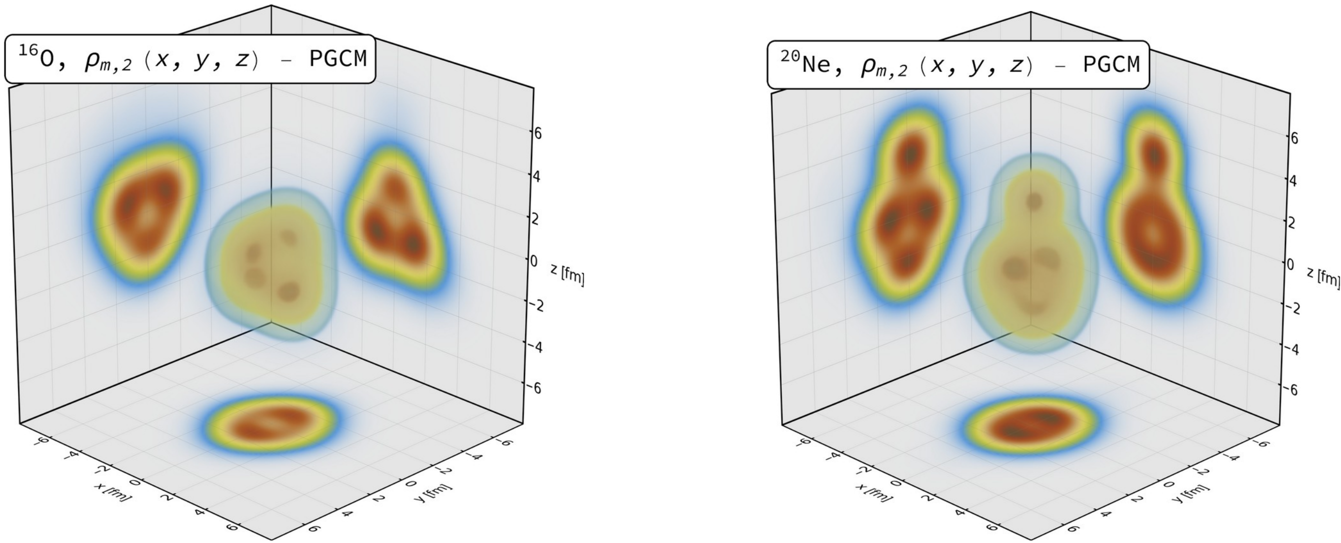
Trajectum

smash

PRL 135, 012302

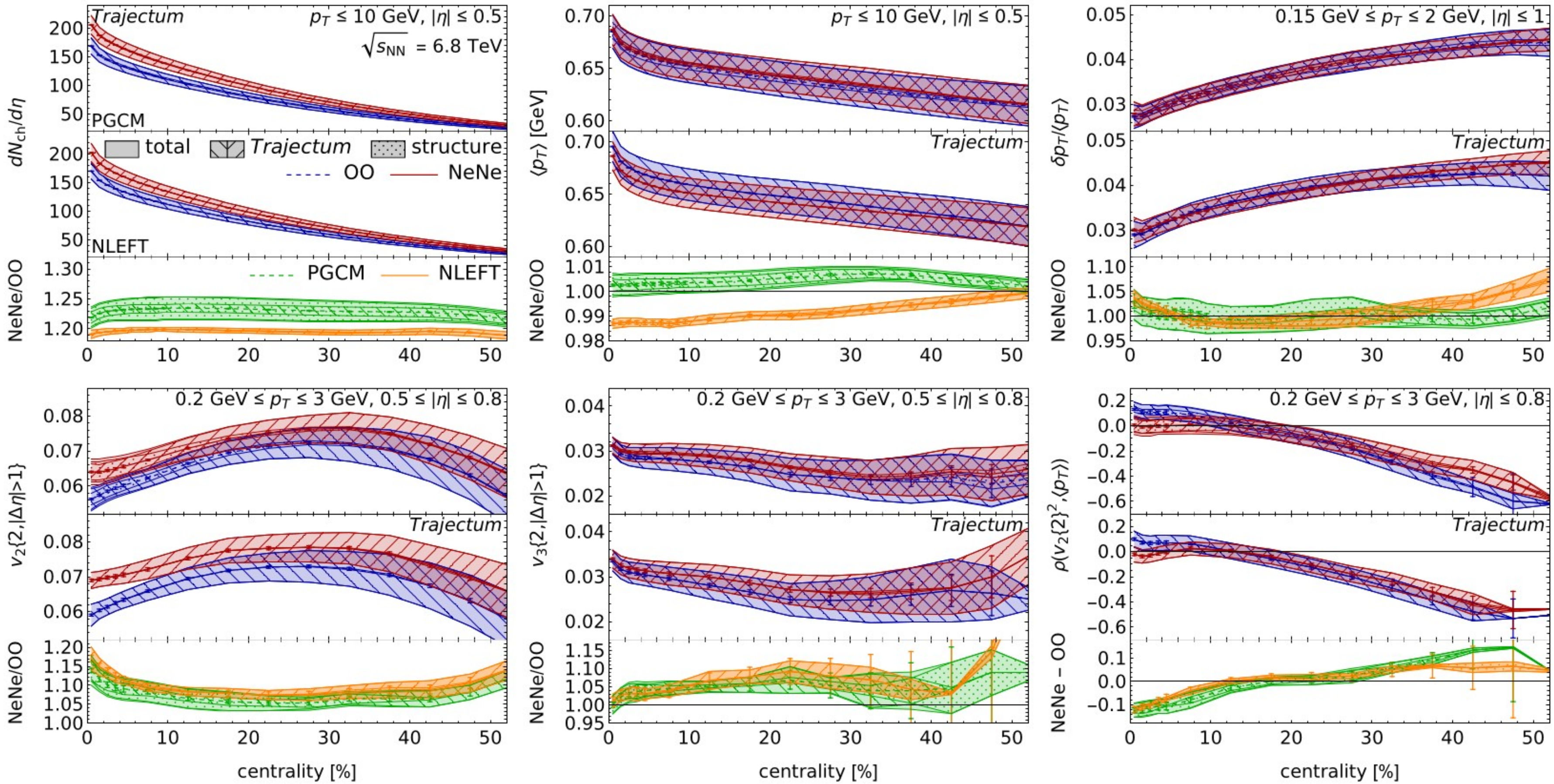
TAURUS: https://github.com/project-taurus
Trajectum: https://sites.google.com/view/govertnijs/trajectum
SMASH: https://github.com/smash-transport/smash

Spatial structure of ^{16}O and ^{20}Ne

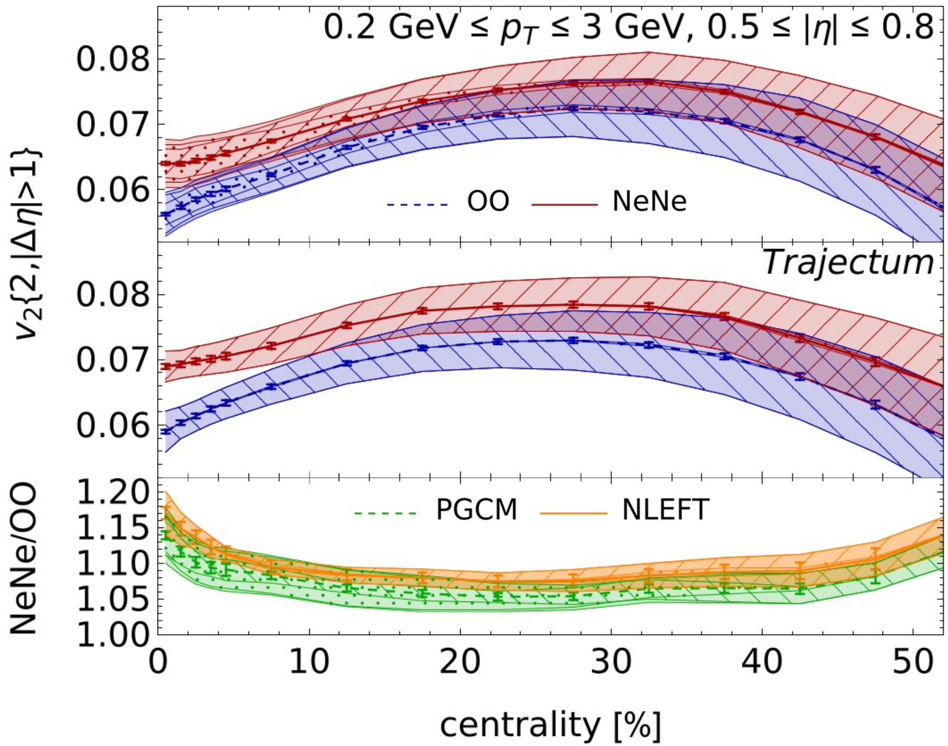


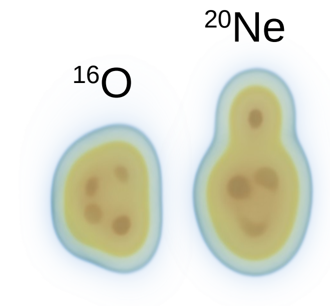
- Effective one-body densities associated with the PGCM calculations
- $^{16}O \rightarrow$ tetrahedron of 4 α-clusters
- $^{20}Ne \rightarrow {}^{16}O + \alpha$ *"Bowling Pin"*

Predictions for $^{16}O+^{16}O$ and $^{20}Ne+^{20}Ne$



Focus on the elliptic flow

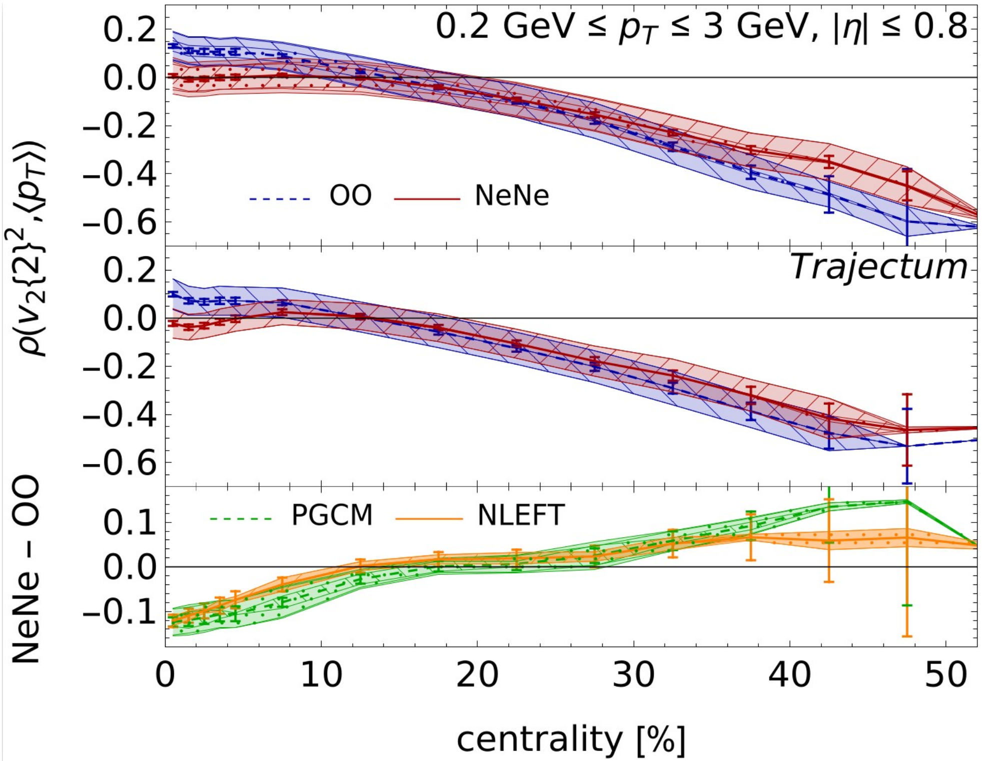


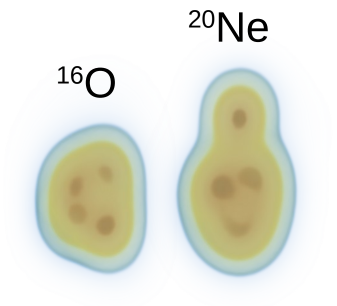


$$\frac{v_2\{2\}_{\rm NeNe}}{v_2\{2\}_{\rm OO}} = \begin{cases} 1.174(8)_{\rm stat}(31)^{Traj}_{\rm syst}(4)^{\rm str}_{\rm syst} & \text{(NLEFT)}, \\ 1.139(6)_{\rm stat}(27)^{Traj}_{\rm syst}(28)^{\rm str}_{\rm syst} & \text{(PGCM)}, \end{cases}$$

- Ratio > 1 in very central collisions → consistent with large deformation of ^{20}Ne
- Predictions consistent between PGCM and NLEFT

Focus on the correlation ρ(v{2},<p$_t$>)

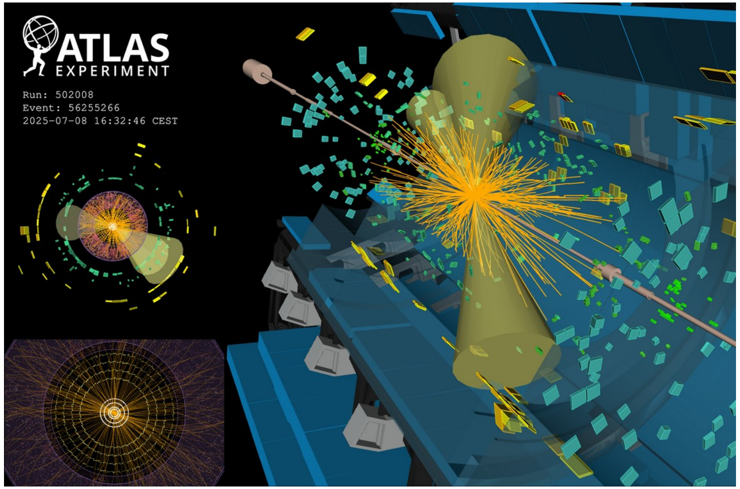


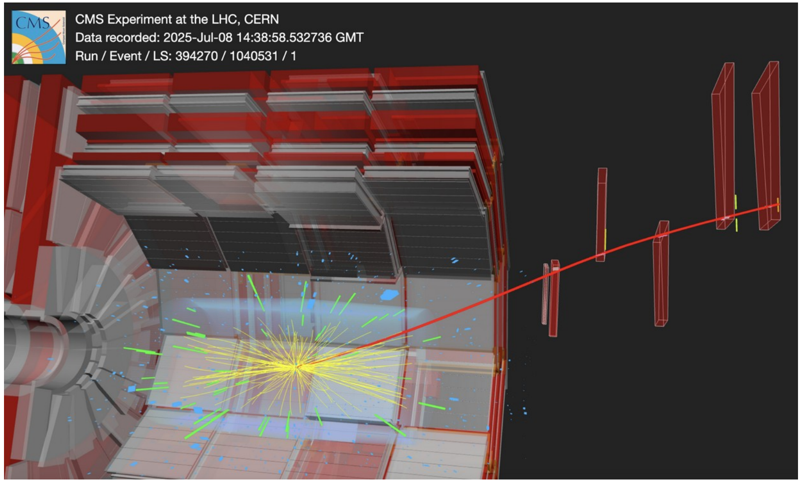


$$\rho(v_2^2, \langle p_t \rangle) = \frac{\langle \delta v_2^2 \delta \langle p_t \rangle \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta \langle p_t \rangle)^2 \rangle}}$$

- Suppression of ρ due to the large deformation of ^{20}Ne: $\rho_{\mathrm{Ne+Ne}} - \rho_{\mathrm{O+O}} \propto \left(\beta^3_{2,{}^{16}\mathrm{O}} - \beta^3_{2,{}^{20}\mathrm{Ne}}\right)$

First results from the LHC!





CMS: arXiv:2510.02580

ATLAS: arXiv:2509.05171

ALICE: arXiv:2509.06428

LHCb: LHCb-CONF-2025-001

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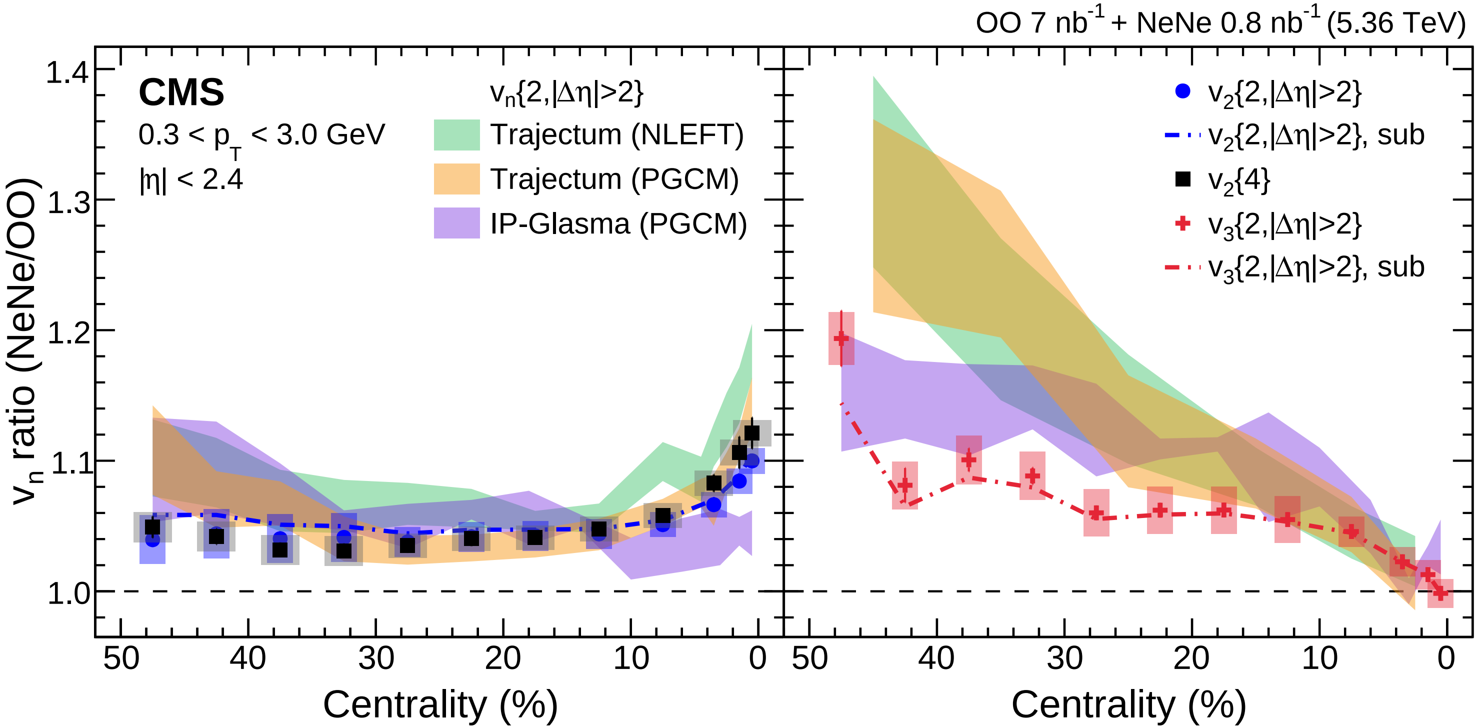
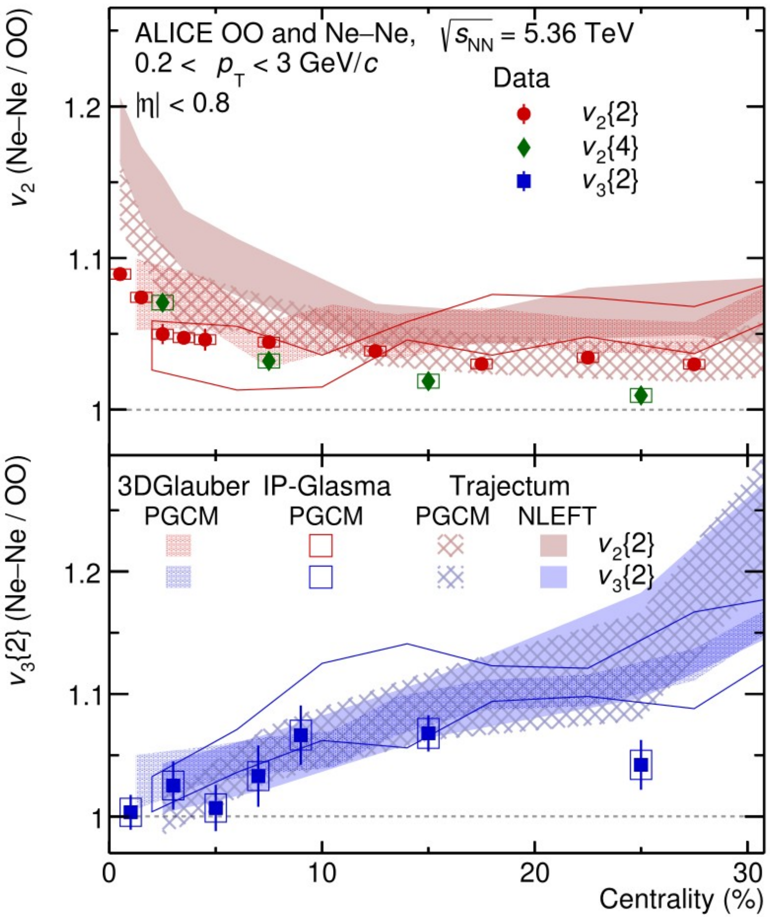
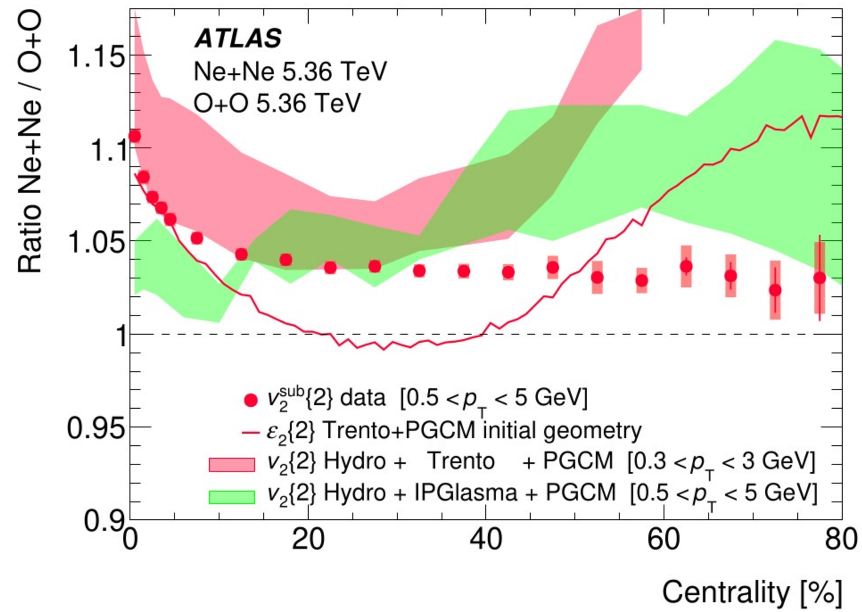


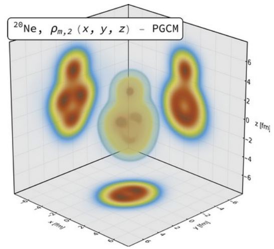
- **Excellent agreement in very central collisions!**

First results from the LHC!

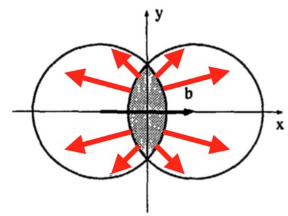




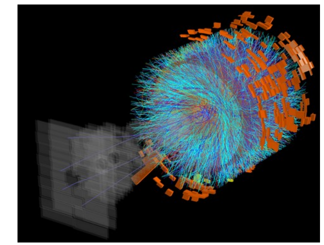
Conclusion



Spatial structure of nuclei



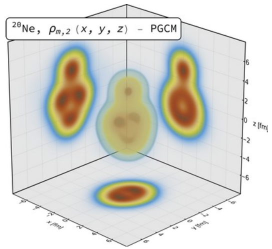
Initial conditions of collisions



Final-state observables of collisions

- Spatial structure of nuclei impacts relativistic collisions
  → initial geometry of collisions
  → effects visible on final-state observables (e.g., flow)

Conclusion



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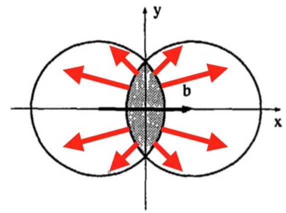

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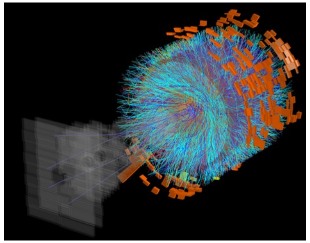

Final-state observables of collisions

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  → initial geometry of collisions
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- Collaboration between low- and high-energy nuclear theorists has great potential!
  → use nuclear-structure theory to determine the initial geometry
  → motivated ^{20}Ne+^{20}Ne run at the LHC!