

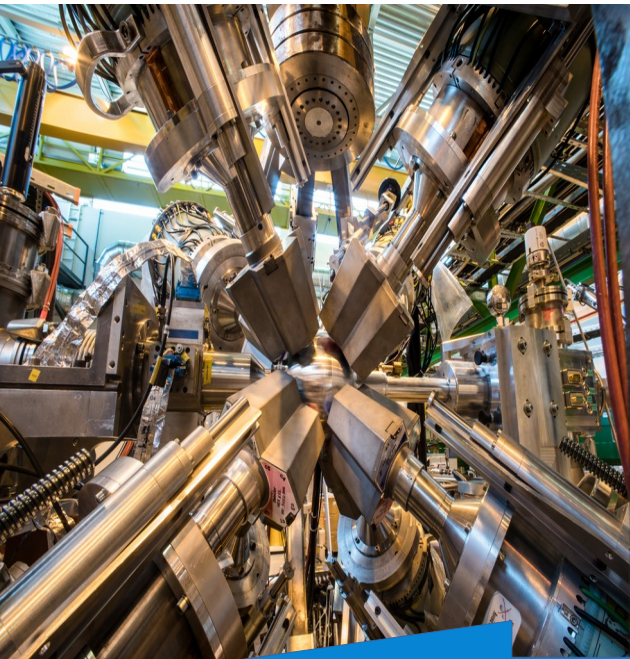


UNIVERSITY of the
WESTERN CAPE

Synergies with HIE-ISOLDE • Bridging Energy Scales @ CERN

Nico Orce @ EMMI Workshop • Light-ion collisions 2026

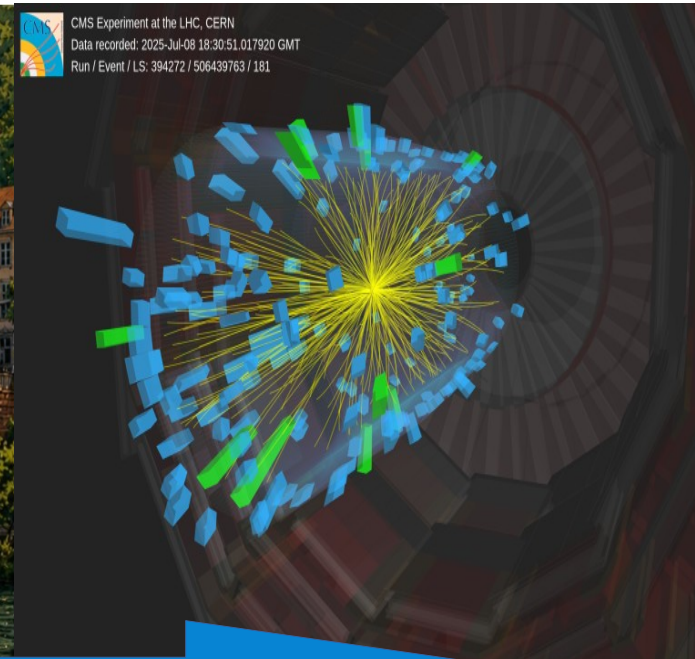
Kirchhoff Institute • Heidelberg University • 25.09.26



Low energy



ab initio



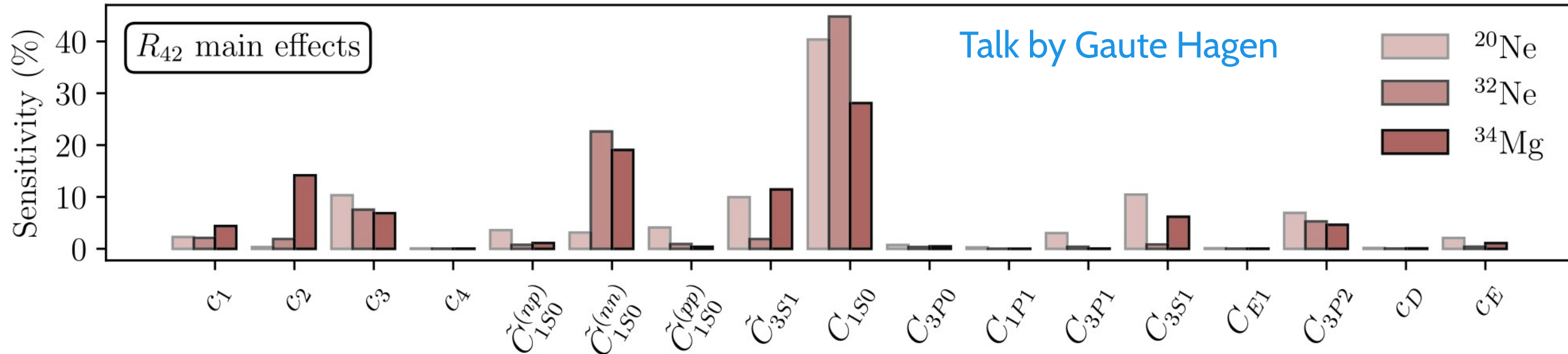
High energy

"More man-hours have been given to this problem (nuclear force) than to any other scientific question in the history of mankind."

Hans Bethe (Scientific American, 1953)

My take home: Linking deformation to nuclear forces

More than 50% of the deformation is driven by the S-wave contact part of the interaction



C_{150} (singlet) related to pairing (NN) → deformation

NOTE: the interaction between proton-proton and neutron-neutron brings in deformation through (two-body correlations allowed by Pauli blocking)

Strategic Opportunities, Synergies and International Context

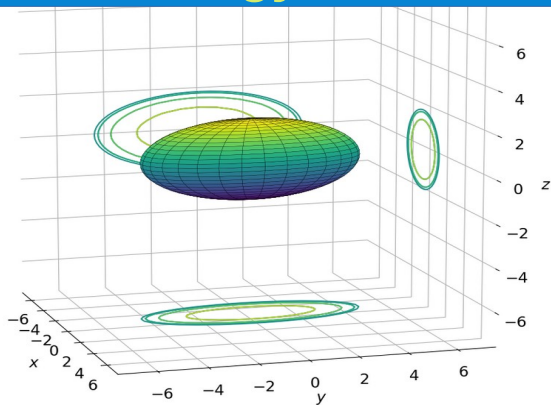
Synergies with relativistic collisions of stable light ions at the LHC should also be considered where relevant. For example, the study of nuclear shape at HIE-ISOLDE can guide ab-initio calculations of spatial distributions; this geometry before a relativistic collision influences collective particle flow and is crucial to the emergence of the quark-gluon plasma, potentially probing intrinsic deformation parameters, cluster formation and quantum fluctuations.

Nuclear deformation + two-body correlations (laser spectroscopy reorientation, rotational invariants,...)

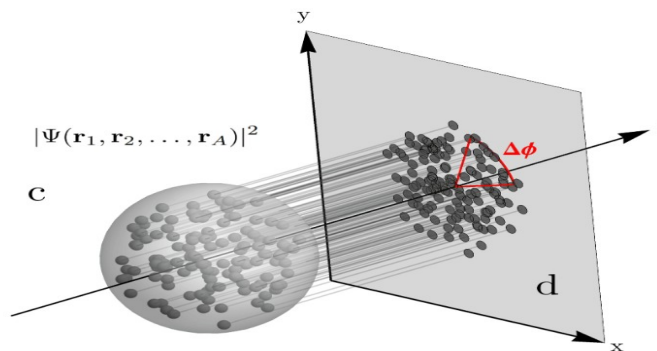
Fine tune NN, 3N forces
→ provide initial nucleon spatial configuration (pp, nn?)

LIC observables: QGP evolution, nuclear shapes, hydrodynamic flow,...

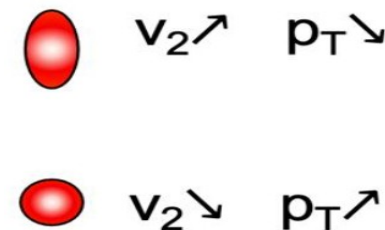
Low energy



ab initio



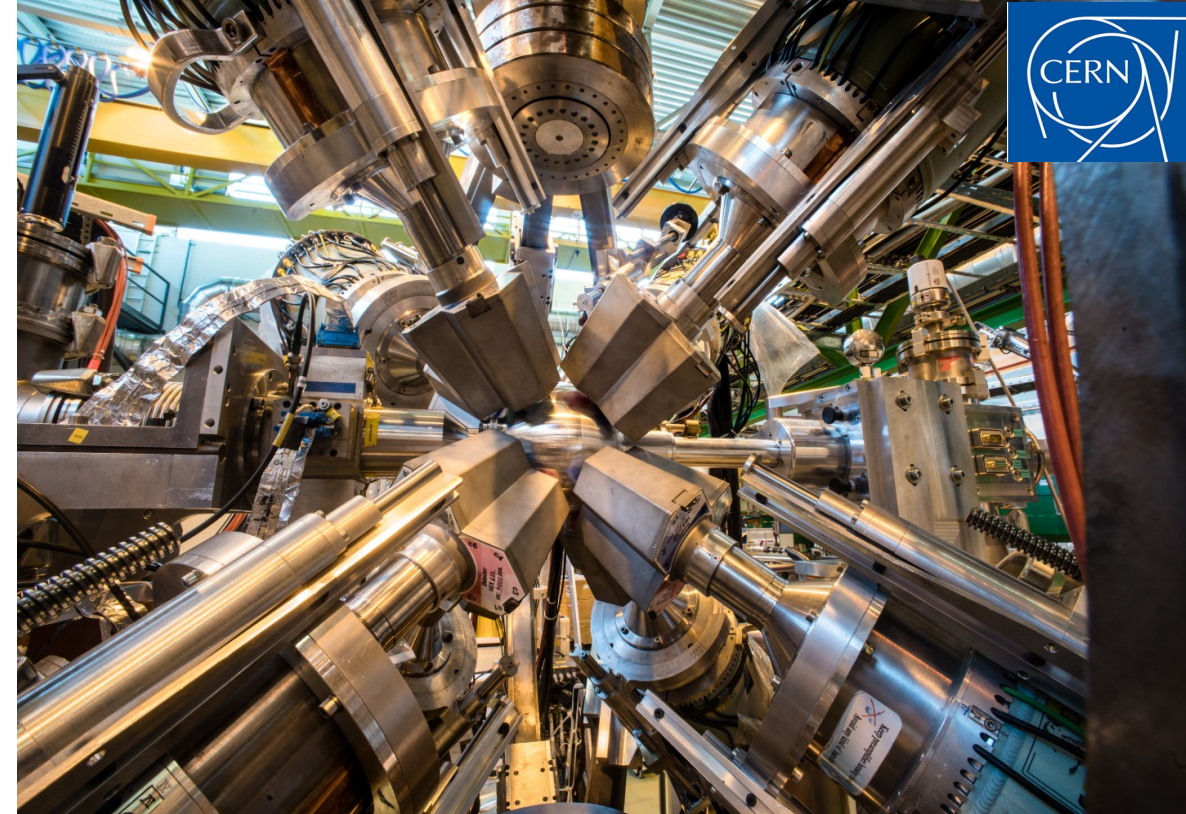
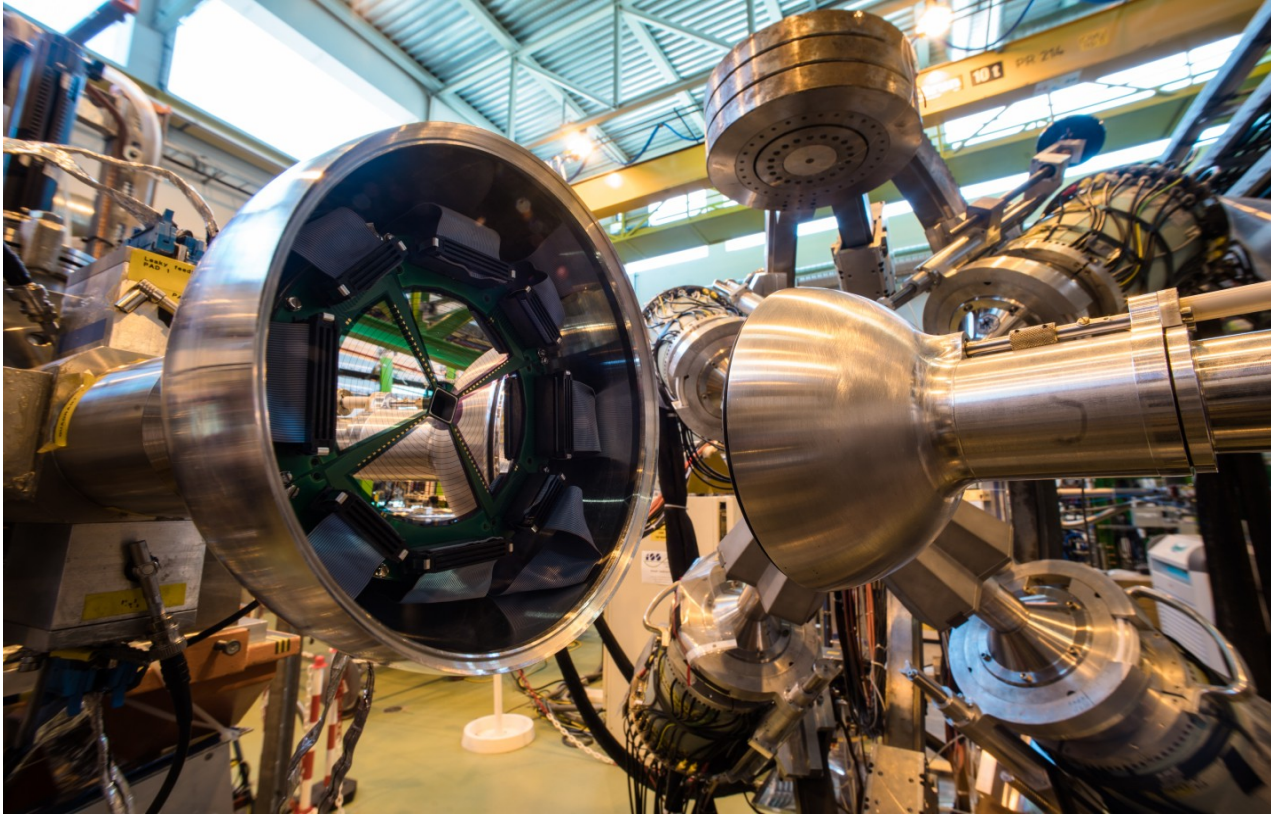
High energy



Low-energy (safe) Coulomb-excitation measurements → reorientation effect

Spectroscopic quadrupole moments Q_s for $J \neq 0, 1/2$

$$Q_s(2_1^+) = \sqrt{\frac{16\pi}{5}} \frac{1}{\sqrt{2J+1}} \langle JJ20 | JJ \rangle \langle 2_1^+ || E2 || 2_1^+ \rangle = 0.75793 \langle 2_1^+ || E2 || 2_1^+ \rangle$$



The Miniball spectrometer @ HIE-ISOLDE

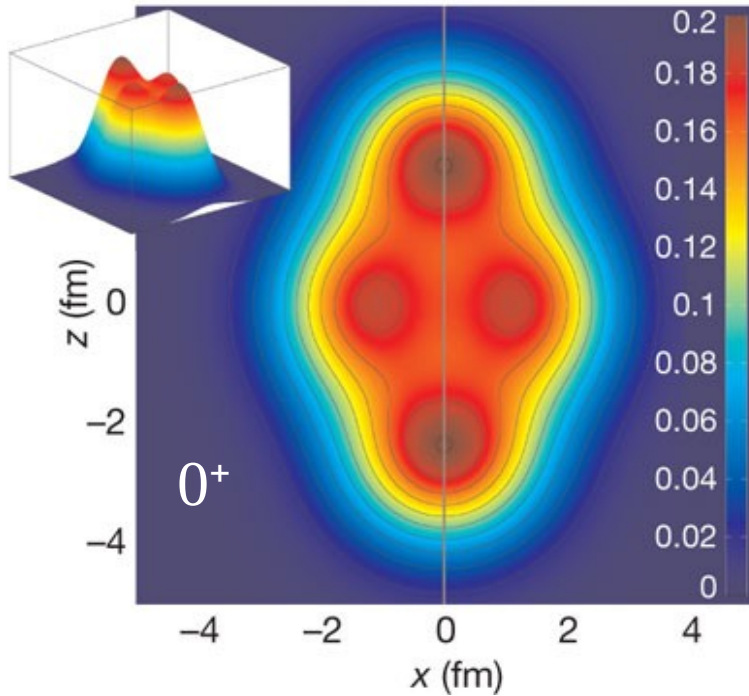
→ particle- γ coincidence measurements allows precise γ -ray spectroscopy N. Warr et al., EPJA (2013)

Alder & Winther, Electromagnetic excitation (1975), Häusser, Nuclear Spectroscopy and Reactions C (1974), Zielińska, Gaffney et al., EPJA (2016)

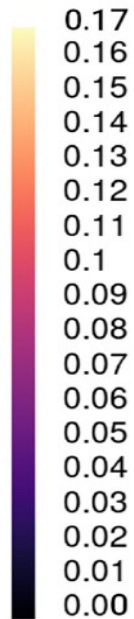
Similar intrinsic nucleon density of the ground and 2_1^+ states in ^{20}Ne

Bowling-pin shapes for both ground state and 2_1^+ state

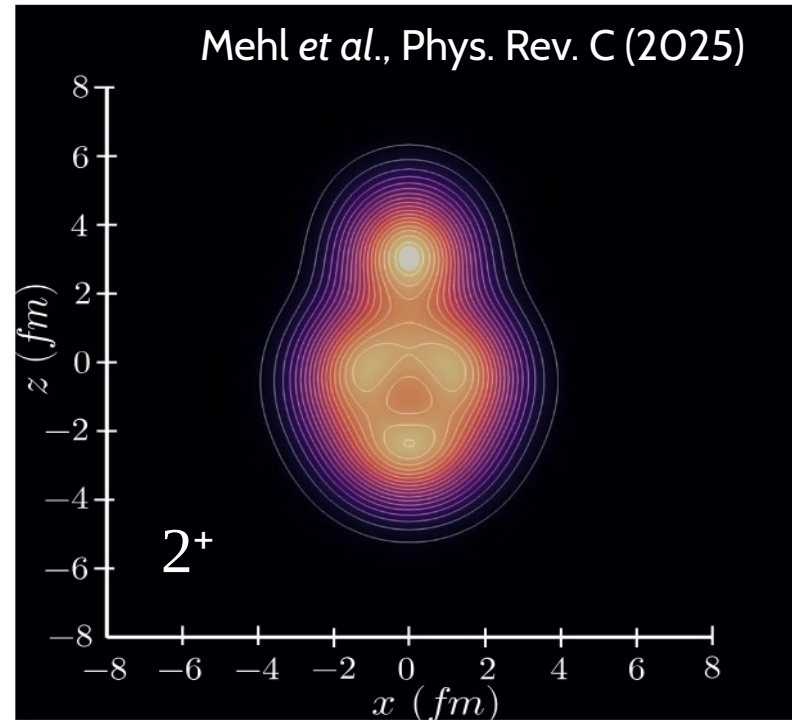
Ebran, Khan, Niksic & Vretenar, Nature (2012)



ρ (fm^{-3})

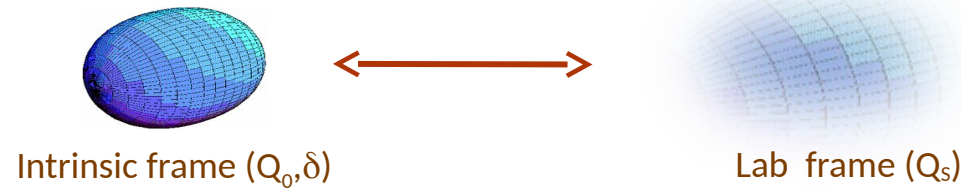


Mehl *et al.*, Phys. Rev. C (2025)

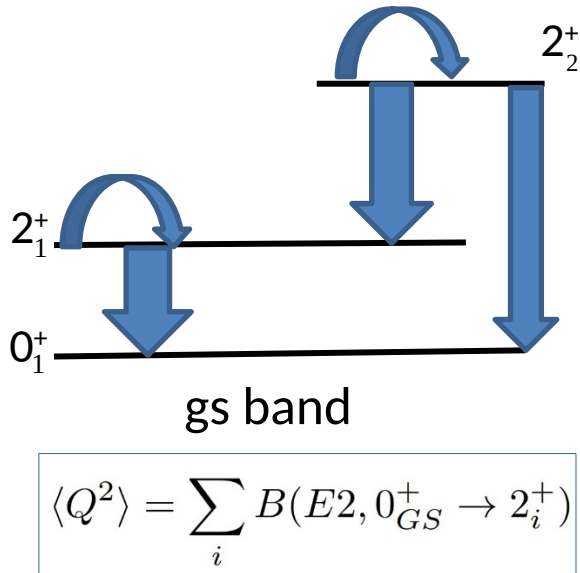


Fully microscopic description based on energy-density functionals (EDFs)
using **relativistic DD-ME2 (ground state) and DD-PC1 (first 2^+) functionals**.
Deep single-nucleon potentials favor more pronounced cluster structures (DD-ME2)

Rotational invariants or Kumar-Cline (KC) sum rules



Only model-independent measurement of quadrupole and triaxial (γ) deformations (~25 nuclei)
based on rotational invariants of zero-coupled products of E2 operator

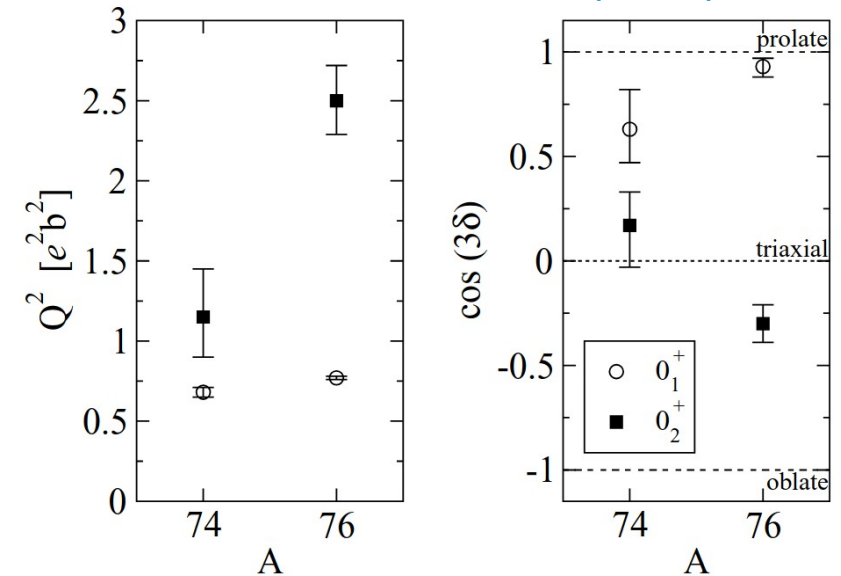


$$\begin{aligned} \langle Q^2 \rangle &= \sqrt{\frac{5}{2s+1}} \sum_r \langle s || E2 || r \rangle \langle r || E2 || s \rangle \begin{Bmatrix} 2 & 2 & 0 \\ s & s & r \end{Bmatrix} \\ \langle Q^3 \cos(3\delta) \rangle &= (-)^{s+1} \sqrt{\frac{175}{2(2s+1)}} \sum_{rt} (-)^r \\ &\times \langle s || E2 || t \rangle \langle t || E2 || r \rangle \langle r || E2 || s \rangle \\ &\times \begin{Bmatrix} 2 & 2 & 2 \\ r & s & t \end{Bmatrix} \begin{Bmatrix} 2 & 2 & 0 \\ s & s & r \end{Bmatrix}, \end{aligned}$$

Krishna Kumar, PRL (1972)

Douglas Cline, Ann. Rev. Nucl. Part. Sci. (1986)

Clement *et al.*, PRC (2007)



Problem: requires large number of E2 matrix elements connecting the state of interest
→ good for ground states though (even when 2_i states involved → $B(E2) \propto E_\gamma^{-5}$)

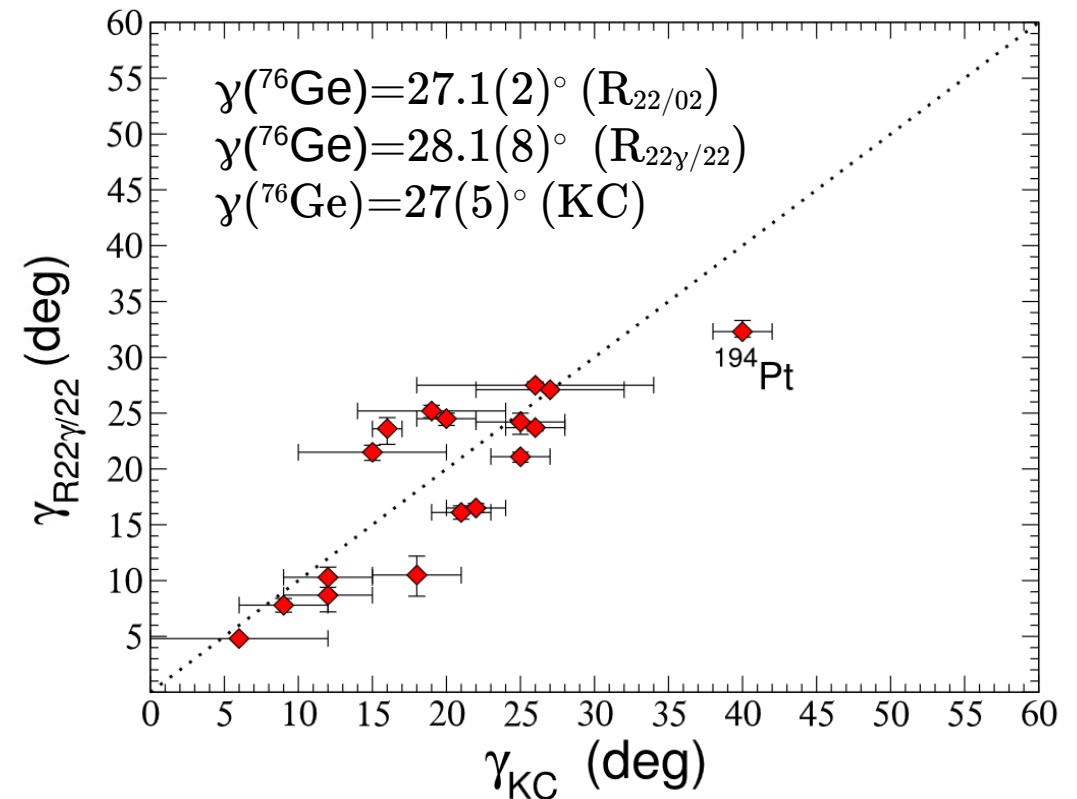
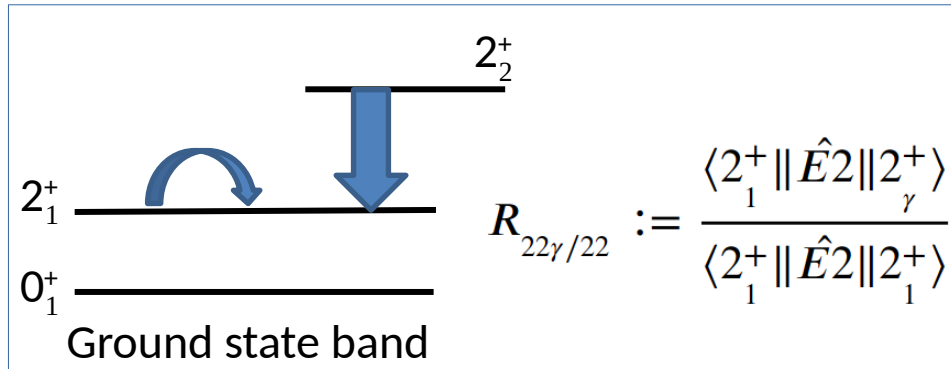
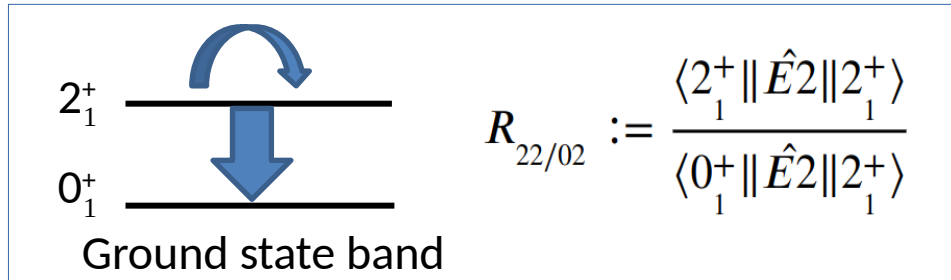
Synergy with HIE-ISOLDE: triaxiality of ^{76}Ge - ^{76}Se isobars

Empirical validation of the triaxial rotor model (stable triaxiality)

Lawrie & Orce, At. Data Nucl. Data Tables (2025)

$$\mathcal{H} = \frac{\hbar^2}{2\mathfrak{I}_1} \hat{I}_1^2 + \frac{\hbar^2}{2\mathfrak{I}_2} \hat{I}_2^2 + \frac{\hbar^2}{2\mathfrak{I}_3} \hat{I}_3^2$$

$$\Gamma(\gamma) = -\frac{1}{2} \cos^{-1} \left(\frac{\cos(4\gamma) + 2 \cos(2\gamma)}{\sqrt{9 - 8 \sin^2(3\gamma)}} \right)$$



Talks by Benjamin Bally + Dorian Frycz

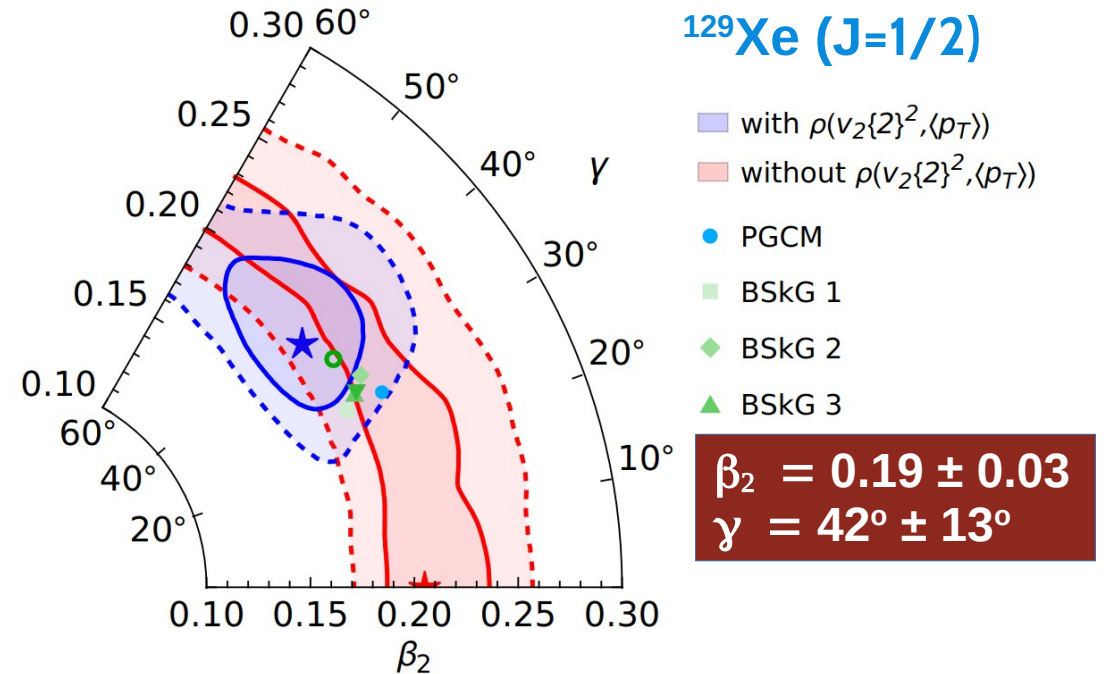
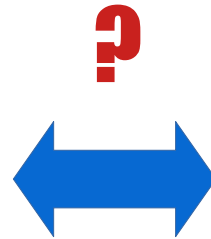
Similar results to KC sum rules and theory with only 2 ME!

KC intrinsic deformation vs snapshot with LICs

First nuclear shape measured (quantitatively) with LHC data using Bayesian analysis

Giuliano Giacalone, Govert Nijs, Wilke van der Schee @ <https://arxiv.org/abs/2606.03993>

$$\begin{aligned} \langle Q^2 \rangle &= \sqrt{\frac{5}{2s+1}} \sum_r \langle s || E2 || r \rangle \langle r || E2 || s \rangle \begin{Bmatrix} 2 & 2 & 0 \\ s & s & r \end{Bmatrix} \\ \langle Q^3 \cos(3\delta) \rangle &= (-)^{s+1} \sqrt{\frac{175}{2(2s+1)}} \sum_{rt} (-)^r \\ &\times \langle s || E2 || t \rangle \langle t || E2 || r \rangle \langle r || E2 || s \rangle \\ &\times \begin{Bmatrix} 2 & 2 & 2 \\ r & s & t \end{Bmatrix} \begin{Bmatrix} 2 & 2 & 0 \\ s & s & r \end{Bmatrix}, \end{aligned}$$



Evidence of the Triaxial Structure of ^{129}Xe at the Large Hadron Collider Phys. Rev. Lett. **128**, 082301 (2022)

Benjamin Bally¹, Michael Bender², Giuliano Giacalone³, and Vittorio Somà⁴

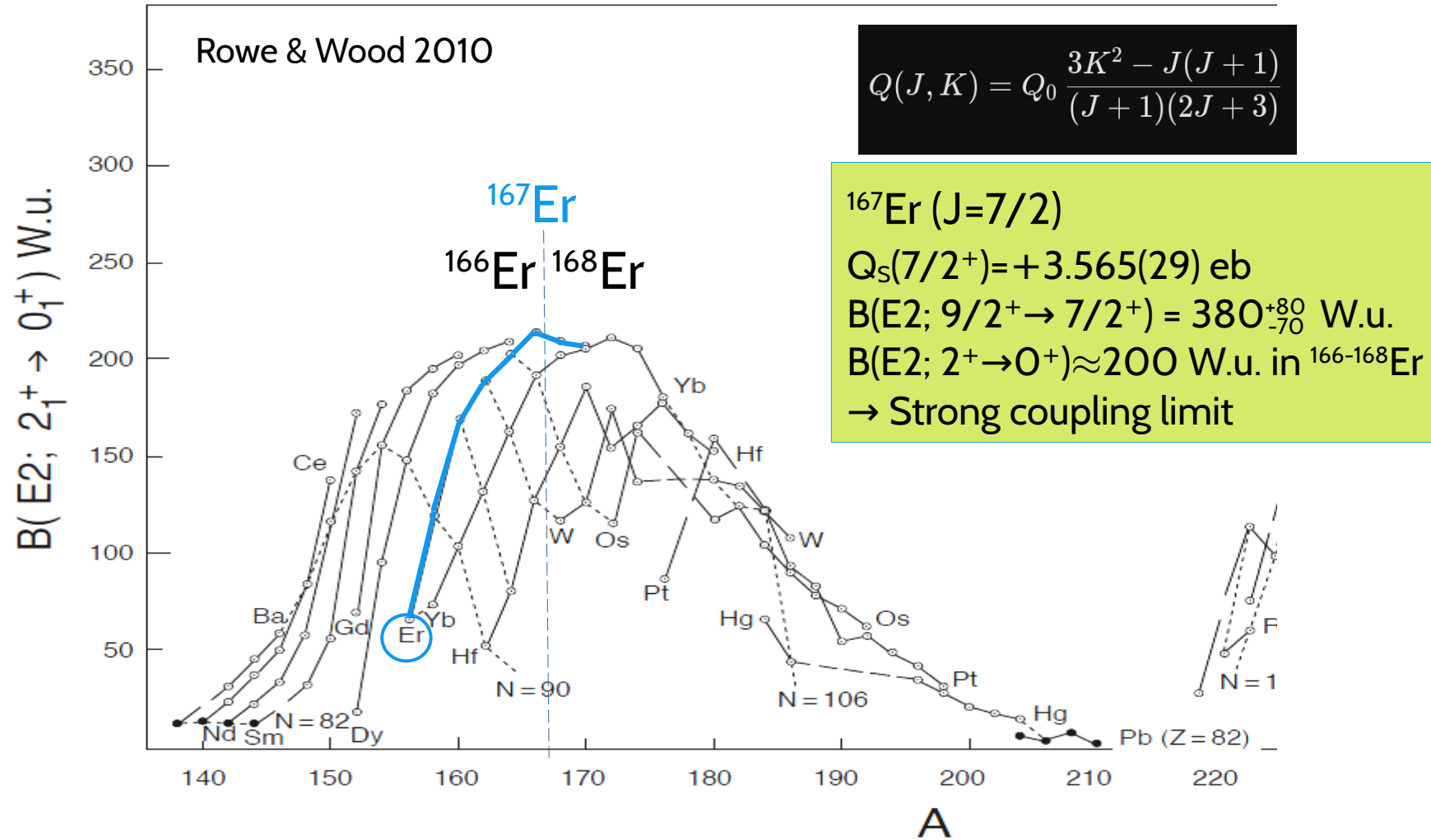
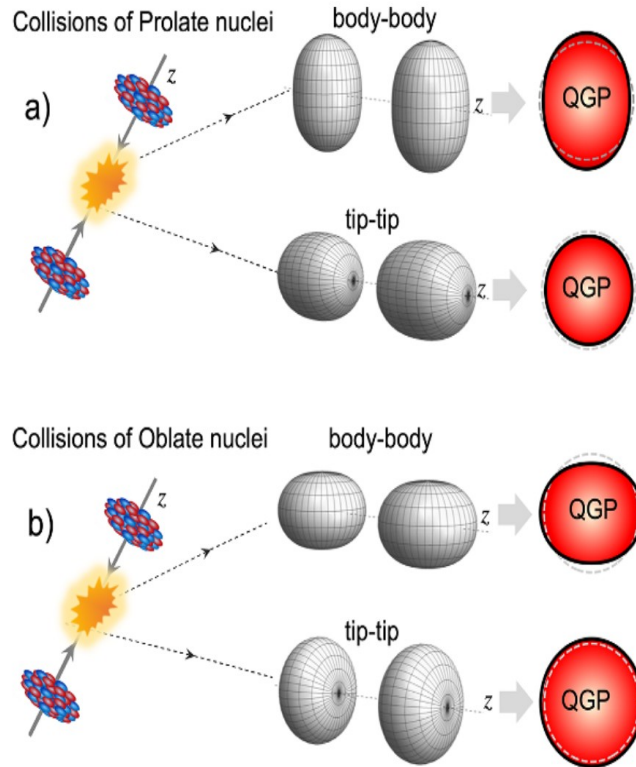
Shape-driving effects in the triaxial nucleus, ^{128}Xe

J. N. Orce^{1,2}, A. M. Bruce¹, A. Emmanouilidis¹, A. P. Byrne^{3,4}, G. D. Dracoulis³, T. Kibédi³, M. Caama El-Masri⁵, C. J. Pearson⁵ et al. Phys. Rev. C **74**, 034318 (2006)

ISOLDE: What about well-deformed nuclei with $J > 1/2$?

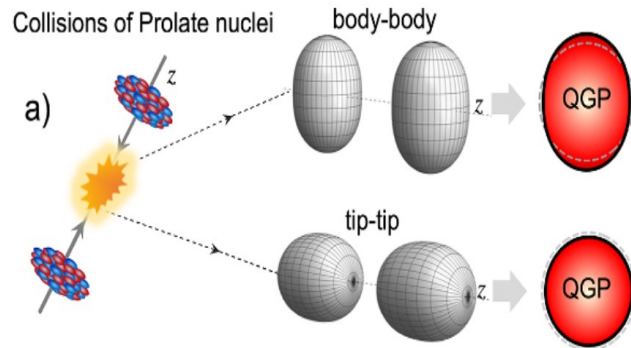
Proposed cases: ^{167}Er ($J=7/2$) or ^{163}Dy ($J=5/2$) → if possible, with polarized beams

Proof of principle with largest, very well-known collective systems (prolate)

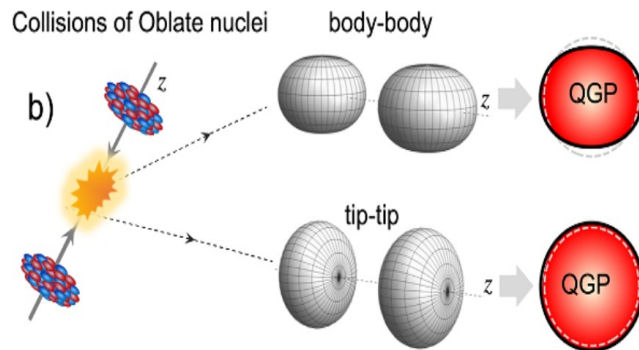


ISOLDE: What about well-deformed nuclei with $J > 1/2$?

Proposed cases: ^{167}Er ($J=7/2$) or ^{163}Dy ($J=5/2$) → if possible, with polarized beams



LIC: That would be of course great. We need to discuss a bit more, also with the low-energy folks, whether these non-zero quadrupole moments are interesting from a point of view of the collisions, where the focus is mainly on two- and higher-body operators.

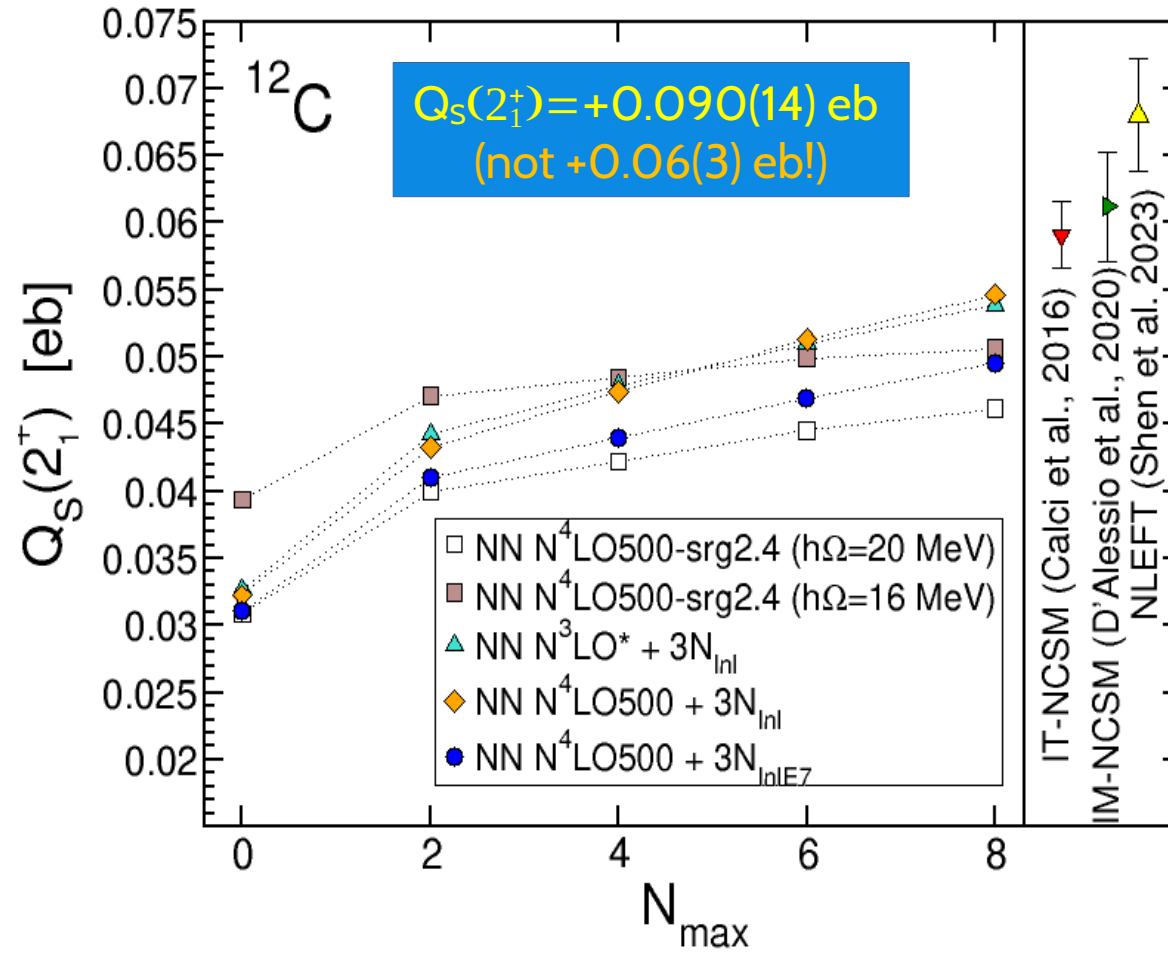


Luis Fraile (ISOLDE Spokesperson): ^{167}Er could be a nice deformed case, but not the easiest one from the point of view of production+extraction. Alternatively, $^{161,163}\text{Dy}$ both have $Q_S \sim +2.5$ eb, and has been done with RILIS

Note: Lots of ^{179}Au ($J=3/2$) data, but not well deformed
Also lots of well-deformed ^{238}U data, but $J=0$

High-statistics measurement of $Q_S(2^+)$ in $^{12}\text{C}_1$ (benchmark nucleus for ab initio) @ MLL with 10^{11} ions/s
 Major issue: *ab initio* calculations can't reproduce the large quadrupole moment in ^{12}C

Ngwetsheni, Orce, Navratil *et al.*, <https://arxiv.org/abs/2506.03236>

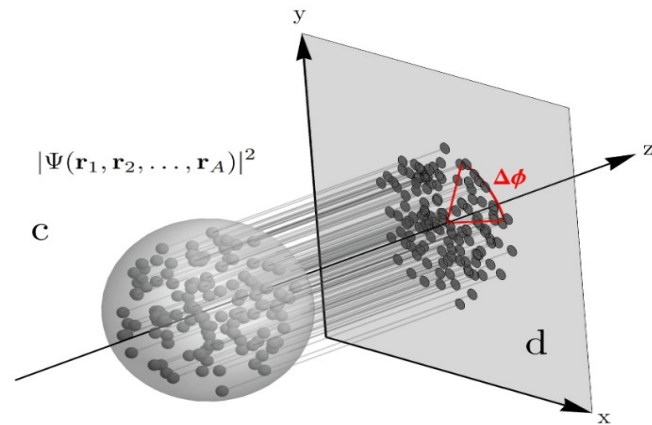


Quoted value is the weighted average from our work + Vermeer et al., PLB (1983), Raju, Orce, PLB (2018), Saiz-Lomas, Petri, PLB (2023), D'Alessio et al. PRC (2020)

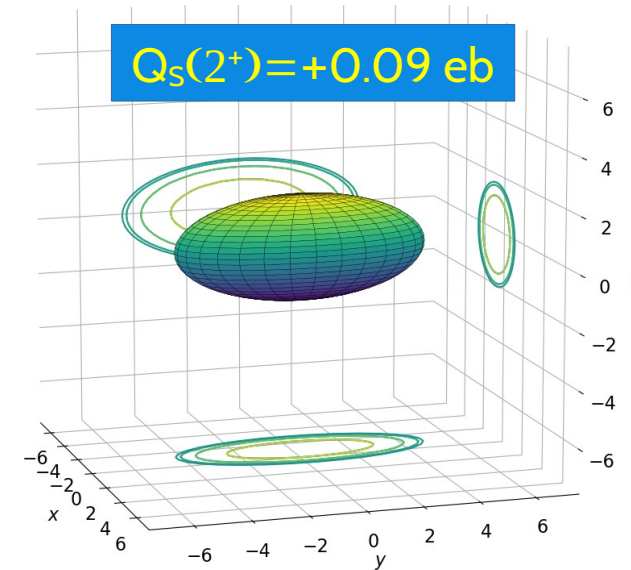
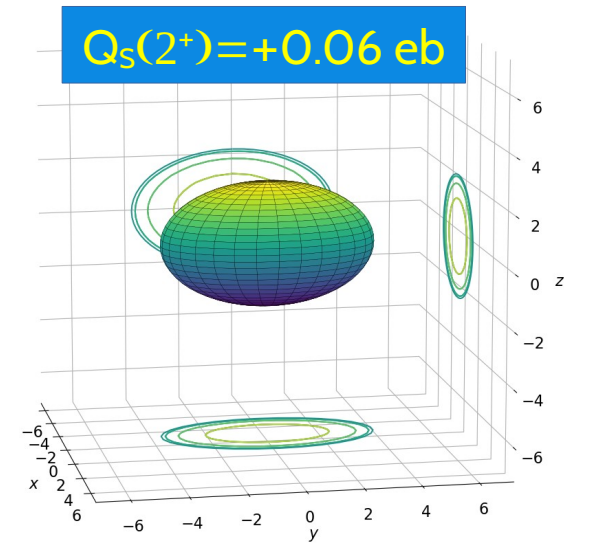
High-statistics measurement of $Q_S(2^+)$ in ^{12}C (benchmark nucleus for ab initio) @ MLL with 10^{11} ions/s

Major issue: *ab initio* calculations can't reproduce the large quadrupole moment in ^{12}C

How precise do you need to know the nucleon spatial configurations before QGP formation?



$$Q_0 = \left(\frac{16\pi}{5}\right)^{1/2} \frac{3}{4\pi} ZeR^2\beta$$

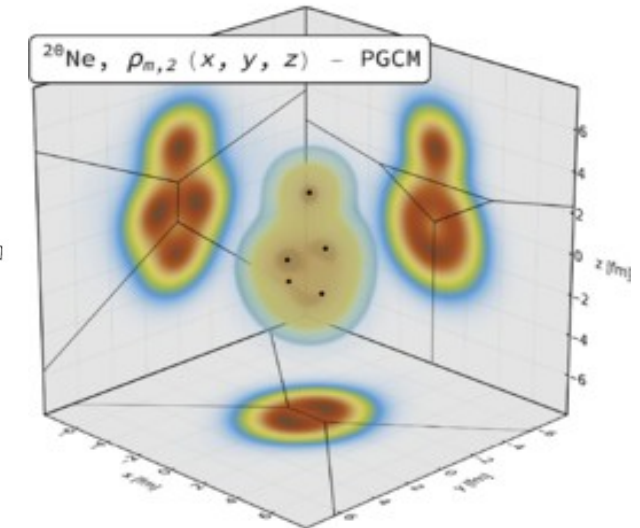
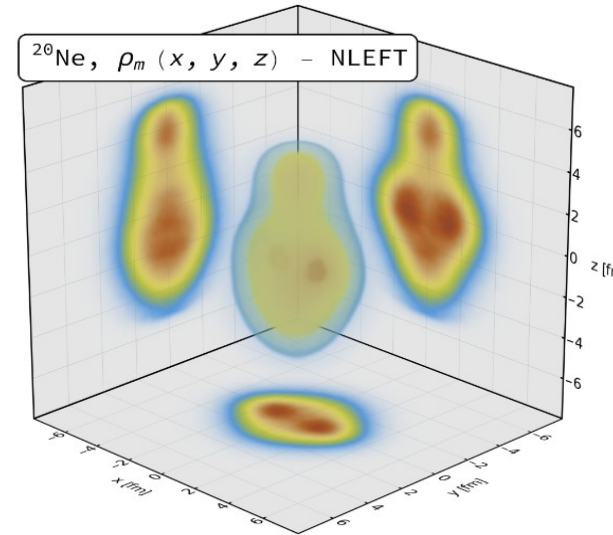
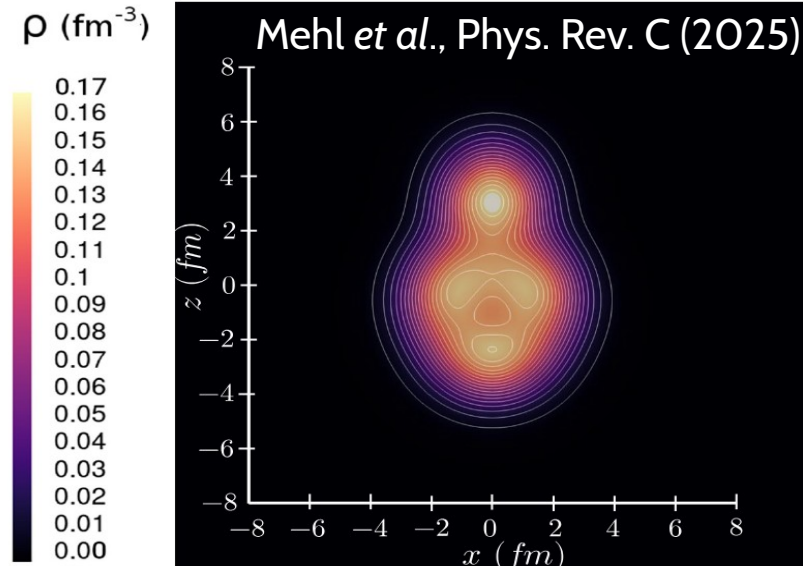


First Coulomb-excitation measurements using ^{20}Ne beams at safe incident energies @ iThemba LABS

Nico Orce @ Light Ion Collisions @ the LHC · CERN Workshop · Dec 2025

$$Q_s(2_1^+) = -0.22(2) \text{ eb}$$

Giacalone et al., PRL (2025)



NLEFT finally reproduce the large $Q_s(2^+)$ value in ^{20}Ne when considering α cluster correlations in the NN interaction, $Q_s(2^+) = -0.25(1)(1) \text{ eb}$
→ Looking forward to Dean Lee's new NLEFT calculations in ^{12}C !

Tetrahedral or octupole symmetry of ^{16}O

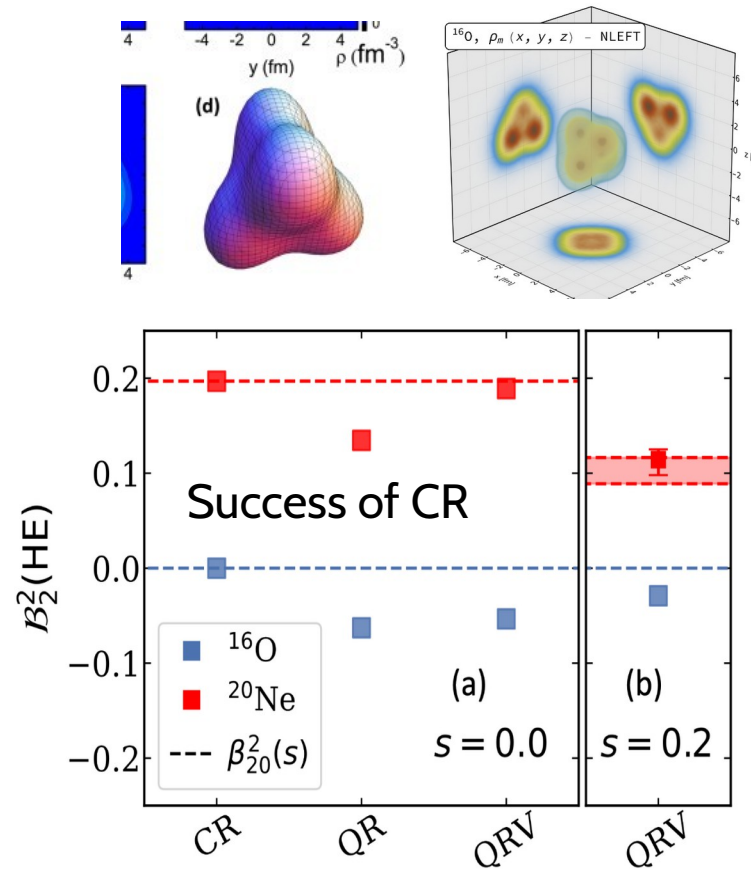
$$Q_0 = \left(\frac{16\pi}{5} B(E2; 0_1^+ \rightarrow 2_1^+) \right)^{1/2}$$

Low-energy experiments
can't measure the shape of
 ^{16}O shape directly:

3^- state @ 6.1 MeV

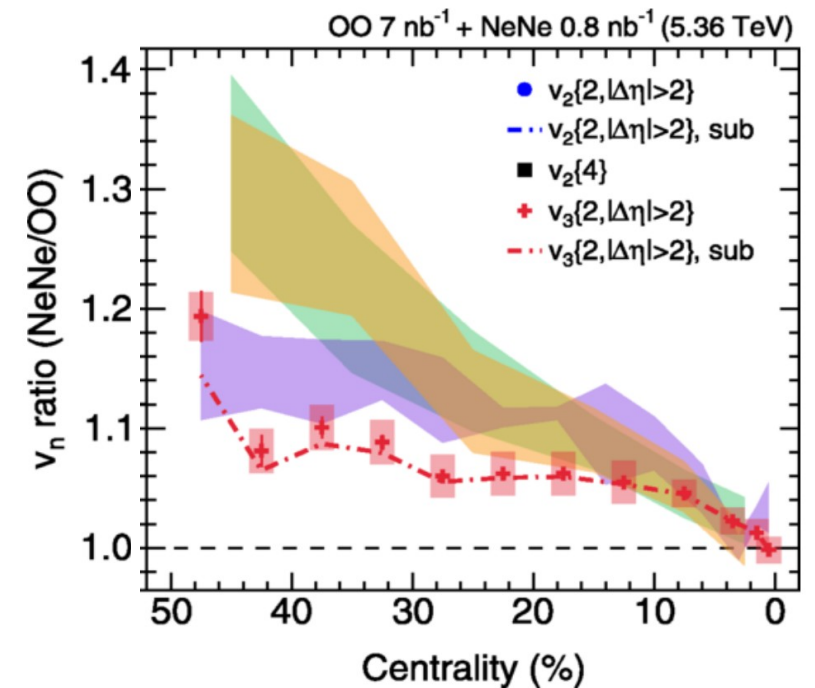
2^+ state @ 6.9 MeV

$\xi = (t_{\text{collision}}/t_{\text{nuclear}}) \gg 1$
(adiabatic)



Duguet's talk (Ding et al. @ 2608.22699)
Wang et al., PLB (2019)
Giacalone et al., PRL (2025)

^{16}O is more octupole deformed than
 ^{20}Ne (already octupole deformed!)



Low energy

ab initio

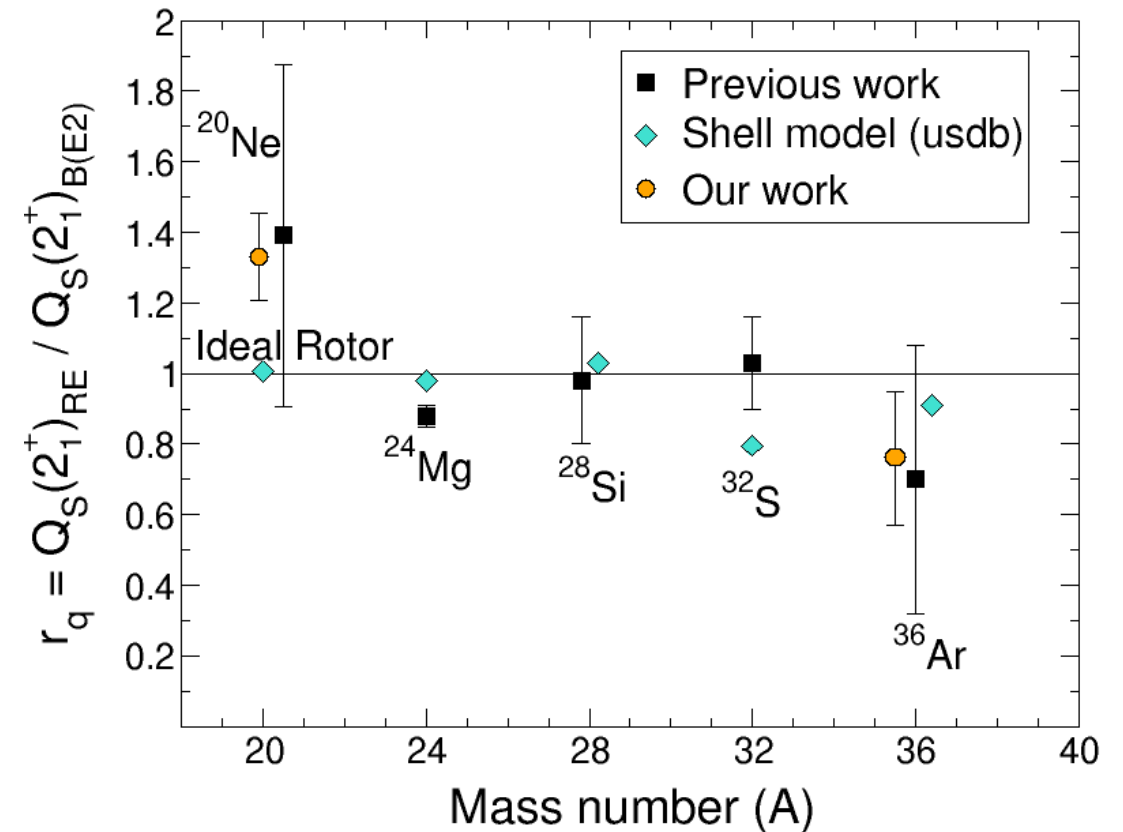
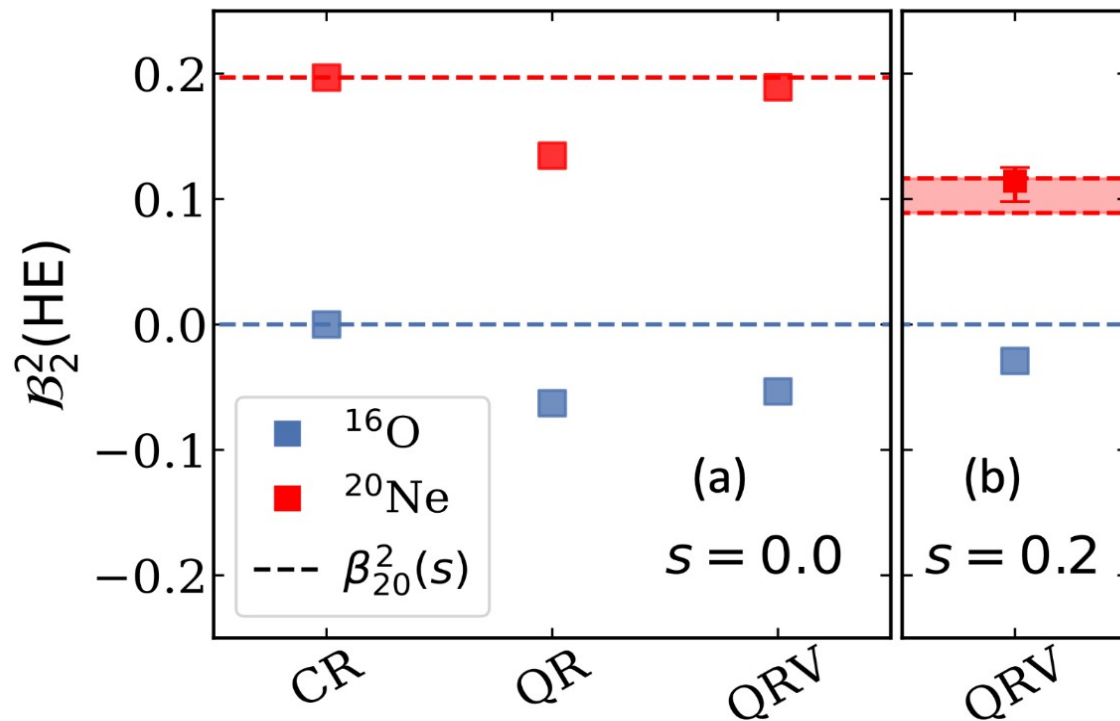
High energy

Classical vs Quantum Rotor in ^{16}O and ^{20}Ne (clusters)

Test of CR $\rightarrow$ deviations from r_q values

$$Q_0 = \left(\frac{16\pi}{5} B(E2; 0_1^+ \rightarrow 2_1^+) \right)^{1/2}$$

$$Q_s(2_1^+) = \frac{3K^2 - J(J+1)}{(2J+3)(J+1)} Q_0 = -2/7 Q_0$$

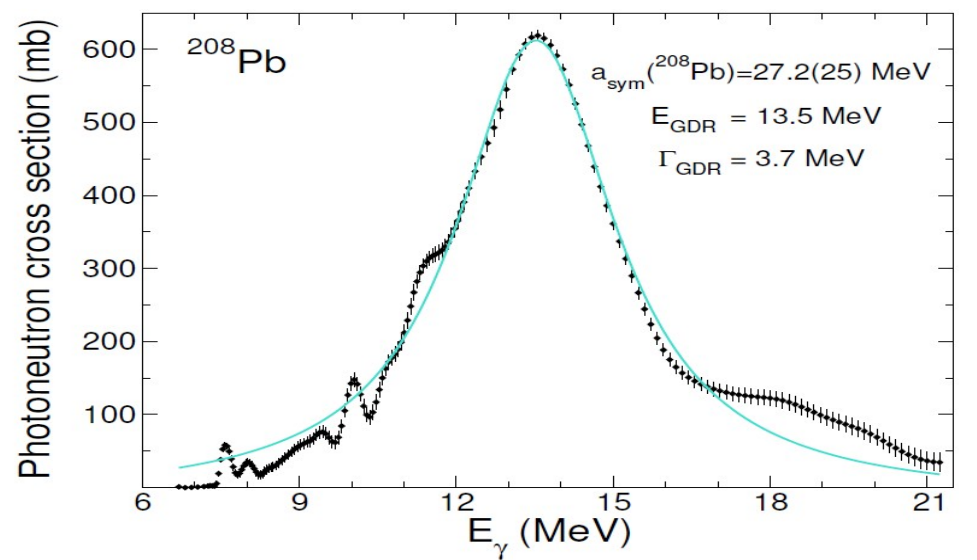
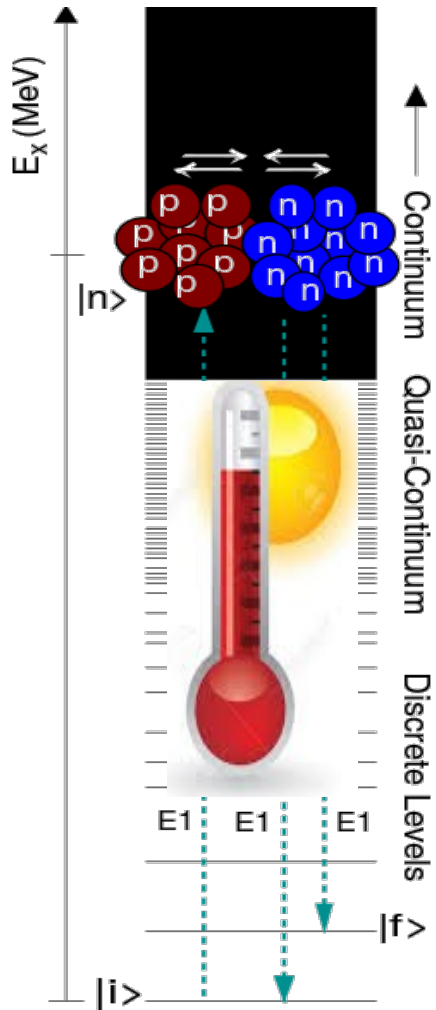


Duguet's talk (Ding et al., @ <https://arxiv.org/abs/2608.22699>)

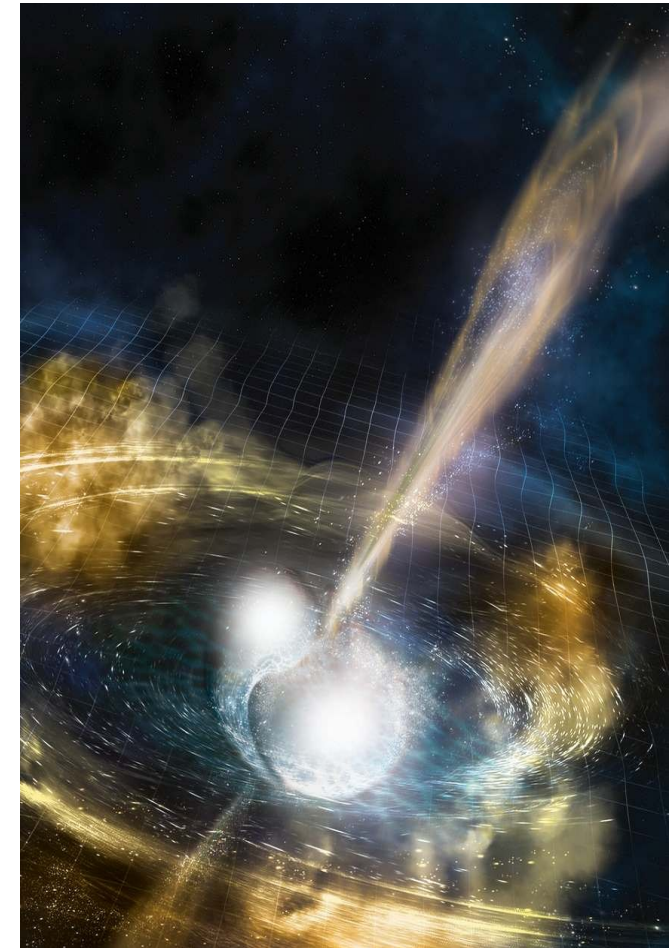
Mehl, Orce et al. PRC (2025)
Orce et al., PRC (2021)

How do we explore nuclear matter @ different temperatures?

Using Giant Dipole Resonances (GDRs) built on ground and excited states as spectroscopic probes
(our nuclear thermometer)



GDR is a collective mode where all protons in the nucleus oscillate out of phase against all neutrons, driven by an electric dipole excitation.



Experimentally: an enhanced symmetry energy at neutron-capture temperatures (kT vs $E_x \sim aT^2$) in neutron star mergers $\rightarrow$ reduced binding energy $\rightarrow$ shifts the neutron drip line towards the line of stability $\rightarrow$ no exotic r-process network $\rightarrow$ universality of element abundances

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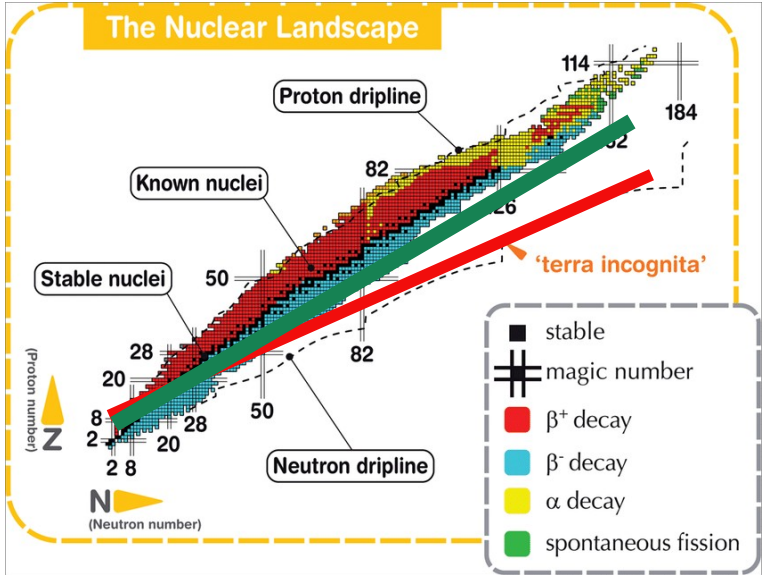
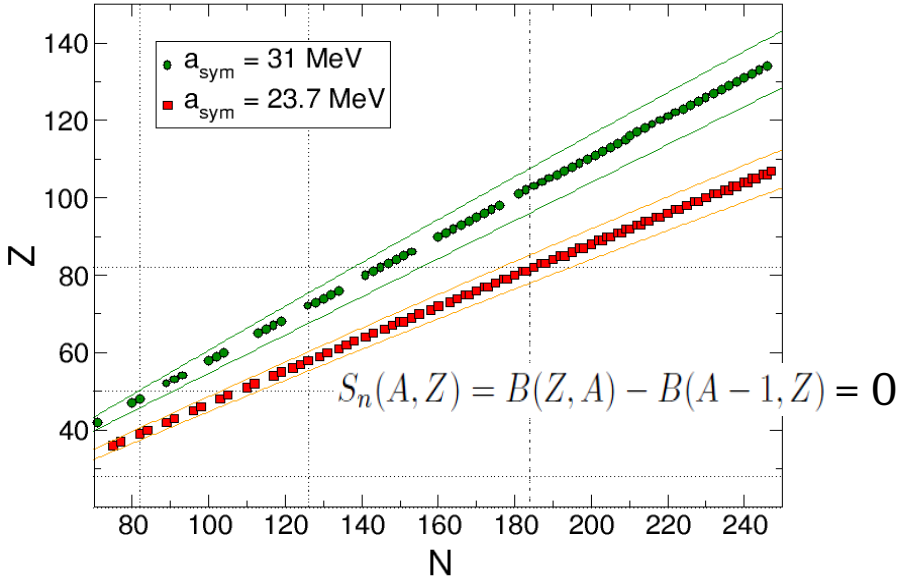
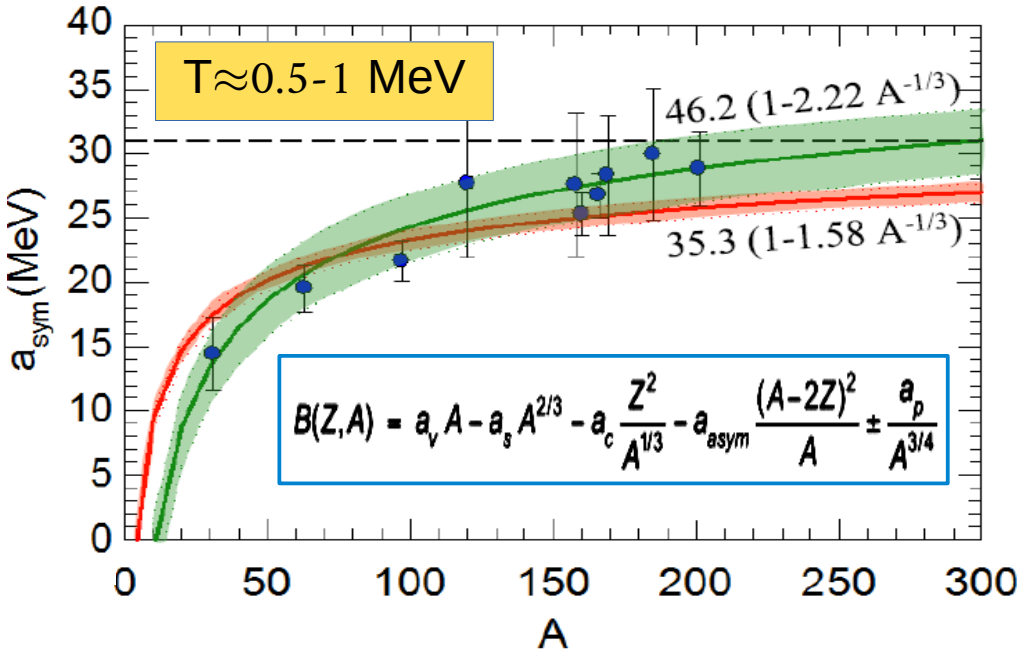
JOURNAL ARTICLE

Enhanced symmetry energy may bear universality of r-process abundances FREE

José Nicolás Orce ✉, Balam Dey ✉, Cebo Ngwetsheni, Srijit Bhattacharya, Deepak Pandit ✉, Brenden Lesch, Andile Zulu

Monthly Notices of the Royal Astronomical Society, Volume 525, Issue 4, November 2023, Pages 6249–6256, <https://doi.org/10.1093/mnras/stad2539>

Published: 04 September 2023 Article history ▾



Theoretically: supported by smaller dipole polarizability for the first excitation of nuclei (1 $\hbar\omega$ shell model calculations)

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Stellar processes driven by the rise of nuclear collectivity

Regular Article – Experimental Physics | [Open access](#) | Published: 08 October 2025

Volume 61, article number 228 (2025) | [Cite this article](#)

[José Nicolás Orce](#)

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Physica Scripta

PAPER • OPEN ACCESS

Universality of r-process elemental abundances: a well-regulated conspiracy of astrophysical and nuclear properties

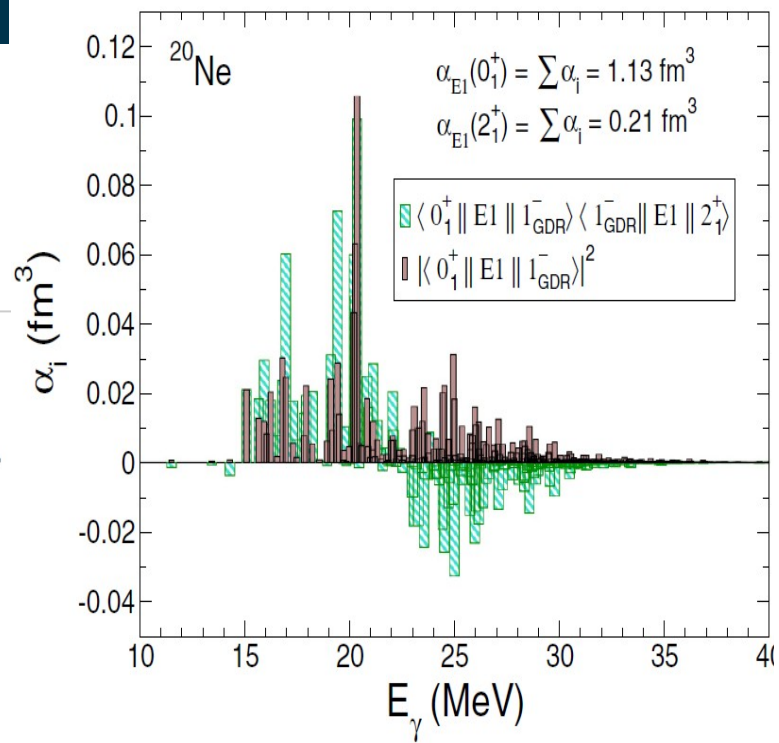
Article metrics

833 Total downloads

José Nicolás Orce*

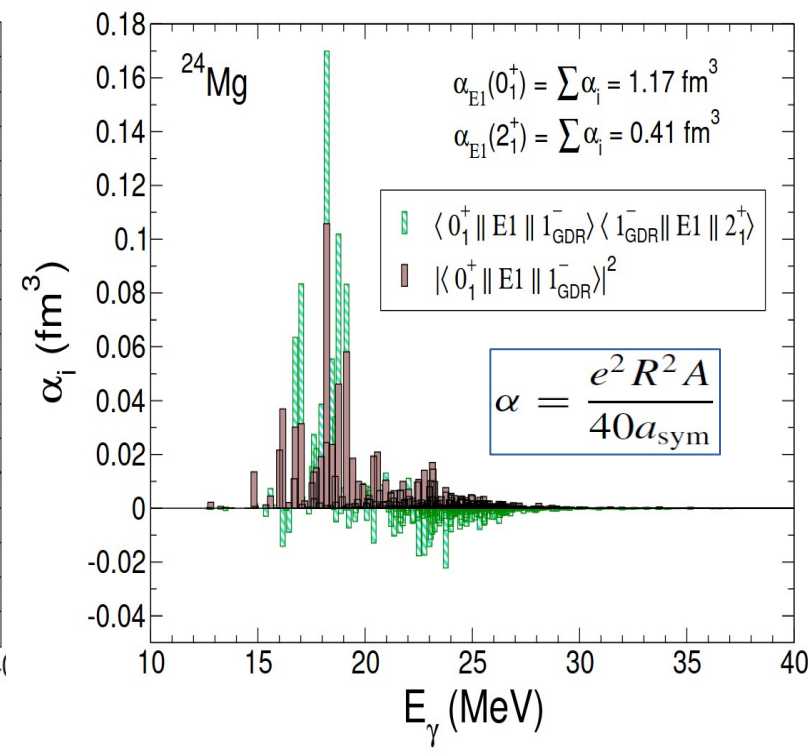
Ground state

$$\alpha_{E1} = \frac{2e^2}{2J_i + 1} \sum_n \frac{|\langle i || \hat{E}1 || n \rangle|^2}{E_n - E_i} = \frac{9\hbar c}{8\pi^3} \sigma_{-2}$$



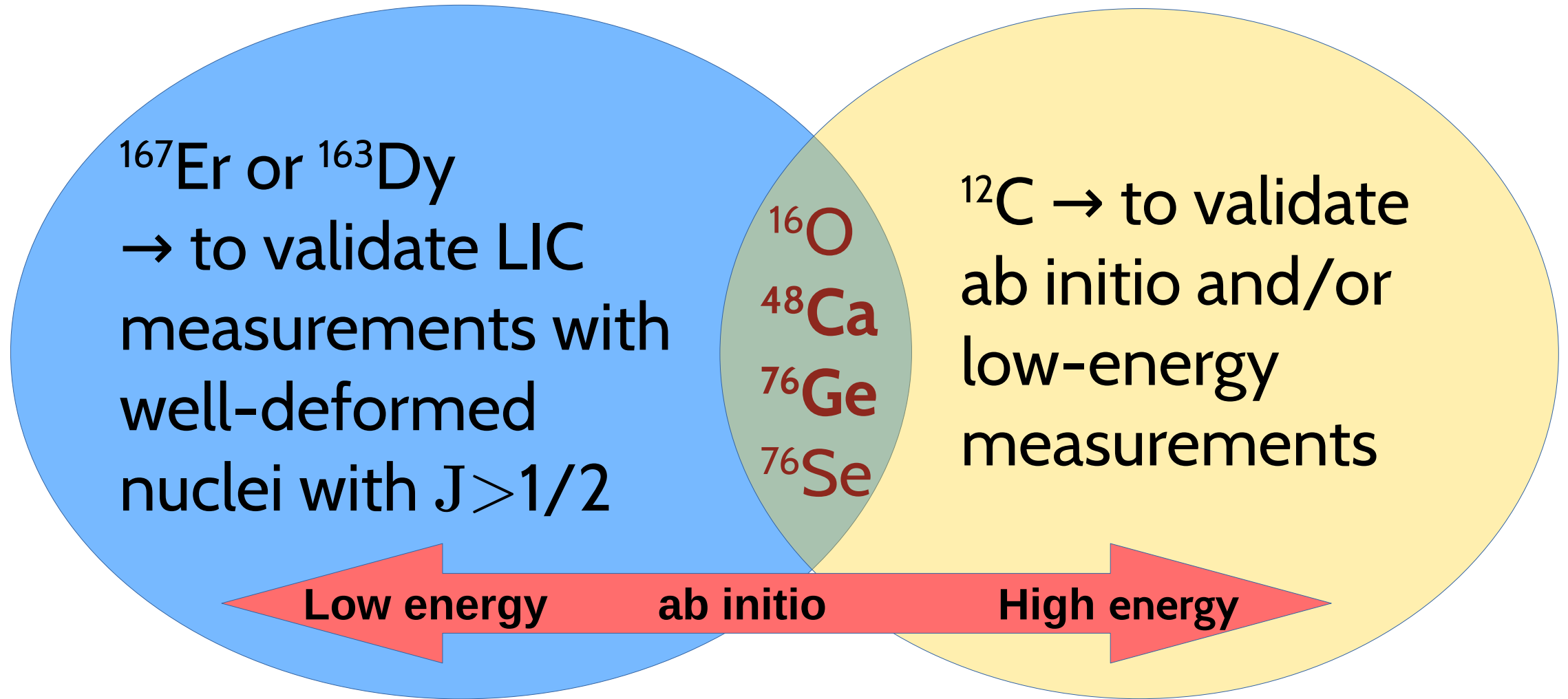
First excitation

$$\alpha_{E1} = 1.11 \frac{ZA^{2/3}}{\langle i || \hat{E}2 || f \rangle} \sum_{J_n, \Delta T} \frac{\mathcal{S}(E1)}{W(\lambda_{in} \lambda_{nf} J_i J_f, \lambda J_n)},$$
$$\sigma_{-2} = 0.155 \frac{ZA^{2/3}}{\langle i || \hat{E}2 || f \rangle} \sum_{J_n, \Delta T} \frac{\mathcal{S}(E1)}{W(\lambda_{in} \lambda_{nf} J_i J_f, \lambda J_n)}$$



Not only for these light nuclei, but for any → expect a stronger effect in light and neutron-rich nuclei (e.g., ⁴⁸Ca and ⁷⁶Ge!) → **New idea for LIC & HIE-ISOLDE: Studying shapes of ground vs first excitation**

Suggestions



Thank You!!

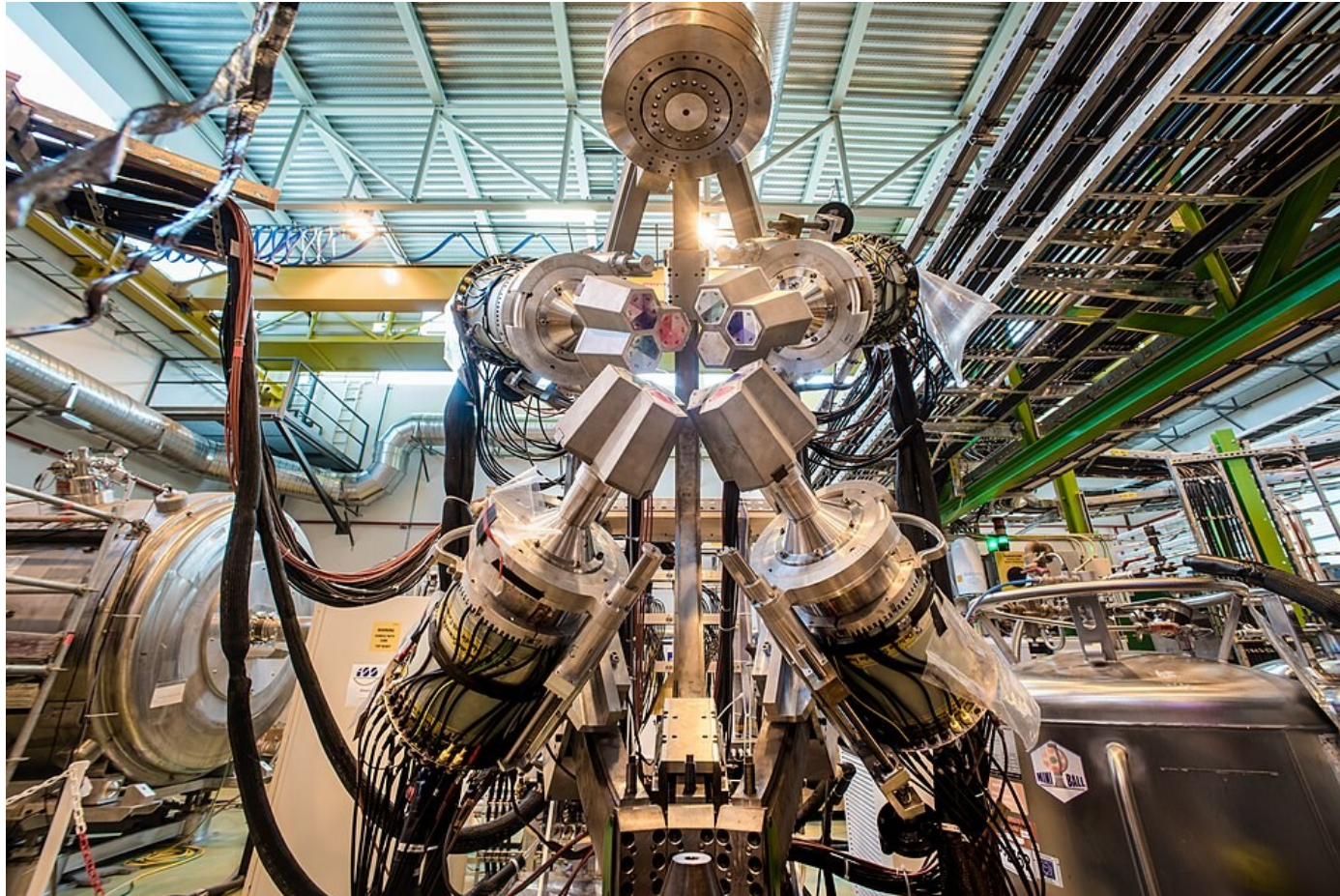
Acknowledgments: physics, feedback & discussions with Reyes Alemany Fernández, Giuliano Giacalone, Luis Fraile, Cole Faraday, Will Horowitz, Elena Lawrie, Craig Mehl, Thomas Duguet, Mikael Frosini, Alex Brown, Petr Navratil, Petar Marevic, Cebo Ngwetsheni, Liam Gaffney, J.-P. Ebran, David Jenkins, Nikita Bernier, Tomás Rodríguez, Georgi Georgiev, Sean Freeman, Joakim Cederkall other colleagues and students @ the HIE-ISOLDE collaboration



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