SUMMARY

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

UNIVERSITÄT HEIDELBERG
ZUKUNFT
SEIT 1386

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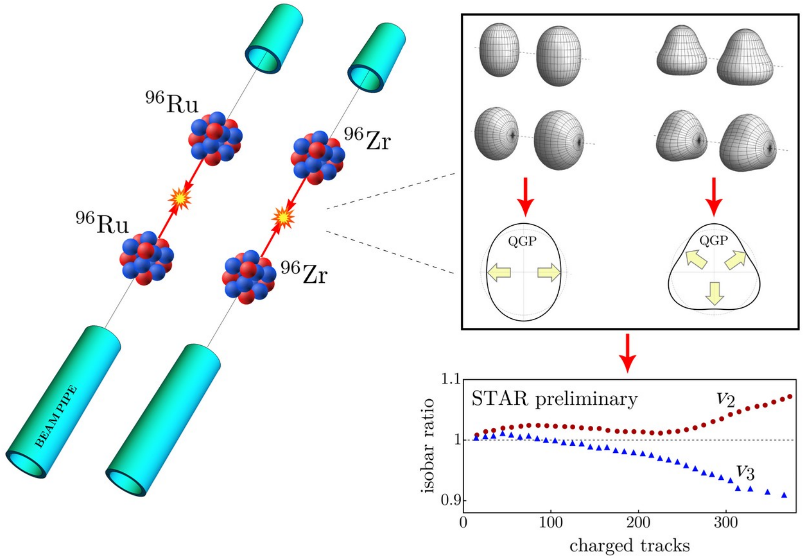
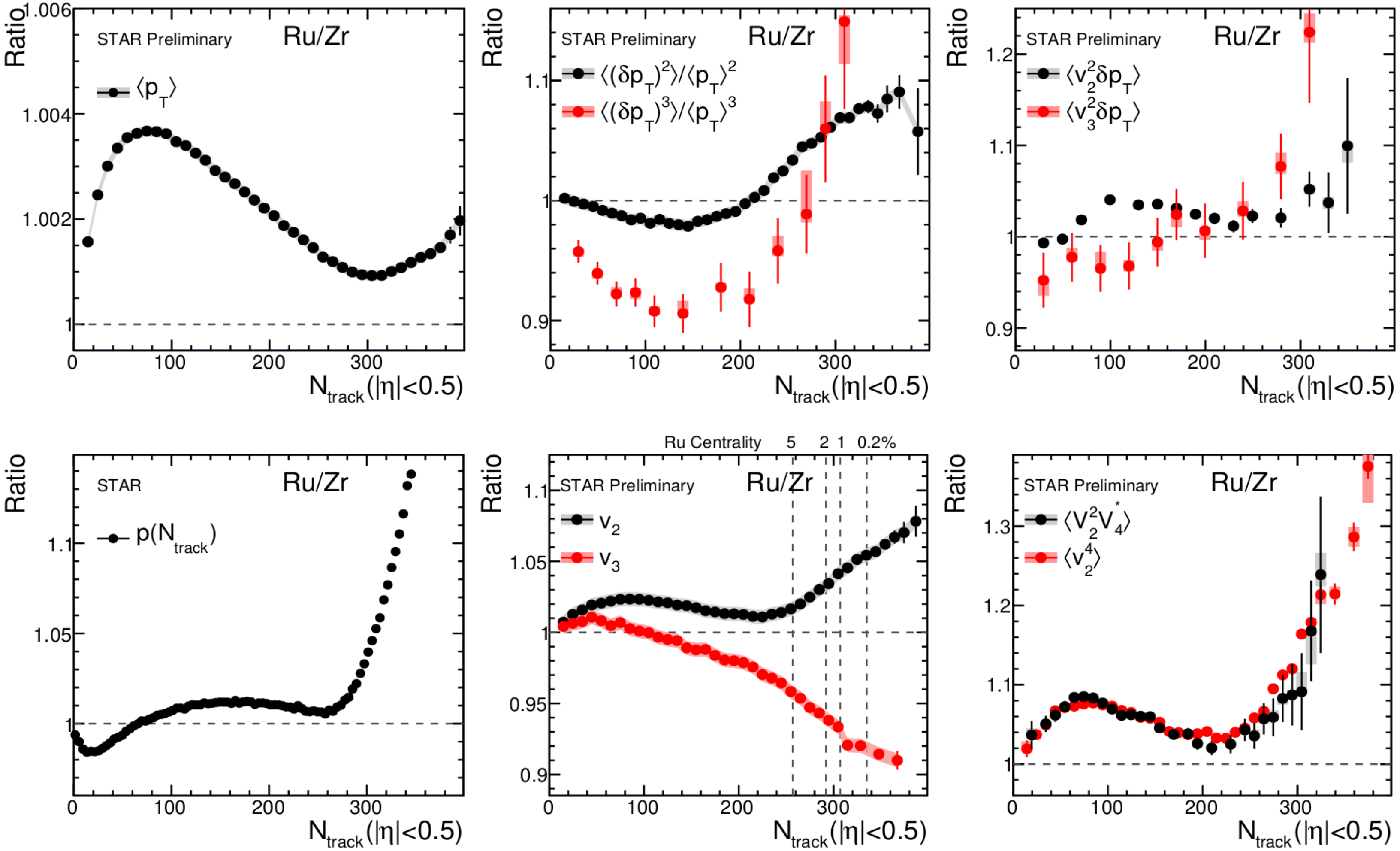


PHYSICS CASE



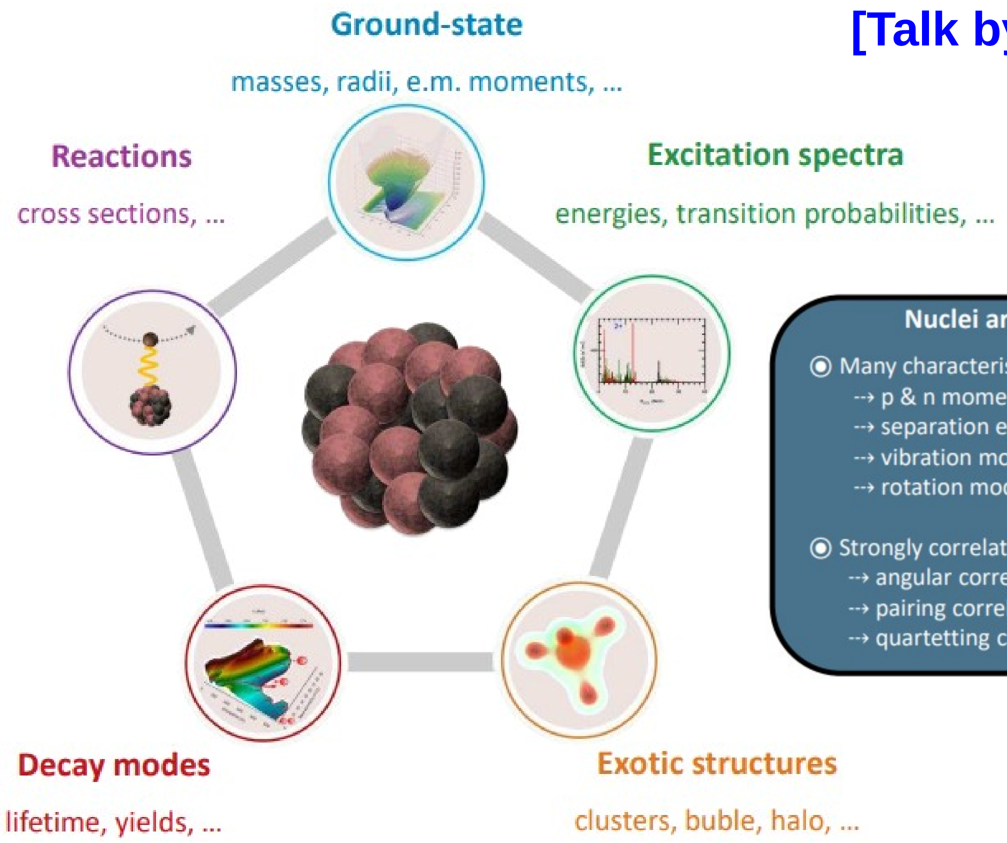
1. State-of-the-art frameworks to understand isobar collision results at RHIC.

2. Nuclear structure in heavy-ion collisions: Is it right/consistent with low-energy physics?

3. Considerations for the future: Optimal nuclei/isobars for colliders?

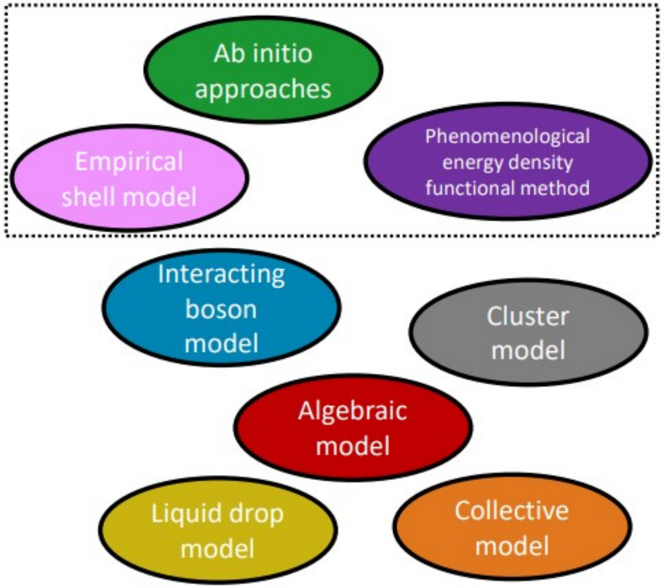
Atomic nuclei have rich phenomenology. Rooted in the strong nuclear force. Nuclear structure is a very old field. Many different approaches.

[Talk by Jean-Paul Ebran (CEA Bruyères-le-Châtel)]



Nuclei are complex systems

- Many characteristic scales :
  - --→ p & n momenta ~ 100 MeV
  - --→ separation energies ~ 10 MeV
  - --→ vibration modes ~ 1MeV
  - --→ rotation modes ~ 0.01-5 MeV
- Strongly correlated:
  - --→ angular correlations ⇒ deformation
  - --→ pairing correlations ⇒ superfluidity
  - --→ quartetting correlations ⇒ clustering



[for nuclear shell model see talk by Yusuke Tsunoda and Takaharu Otsuka (Tokyo U)]

PART I

The mean field and the Glauber Monte Carlo model

[Talk by Matt Luzum (São Paulo)]

[Talk by Luis Robledo (UAM Madrid)]

Notion of mean field. Mean free path in nuclear matter is large (~5fm).
Effectively, independent nucleons in a common potential (ideal gas). Problem is dramatically simplified.

$$H|\psi\rangle = E|\psi\rangle \longrightarrow \quad h_i|\phi_k^i\rangle = \varepsilon_k^i|\phi_k^i\rangle, \quad h_i = \frac{p_i^2}{2m} + V(r_i)$$

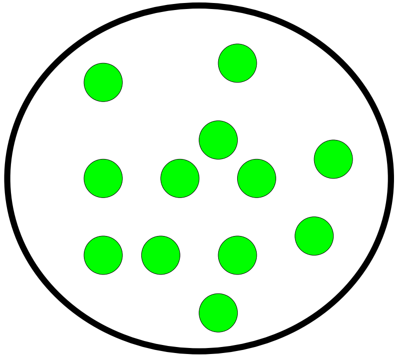
$$V(r_i) = -\frac{V_0}{1+\exp\left(\frac{r_i - R}{a}\right)}$$

Woods-Saxon

Variational approach is the way to go (Hartree-Fock). Ansatz of independent Fermions.

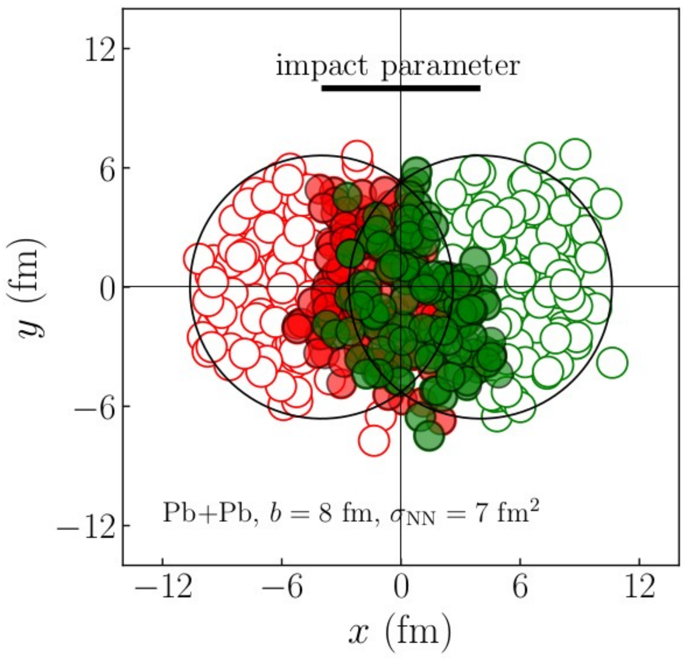
$$\delta \frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle} = 0$$

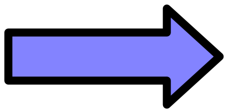
Slater determinant

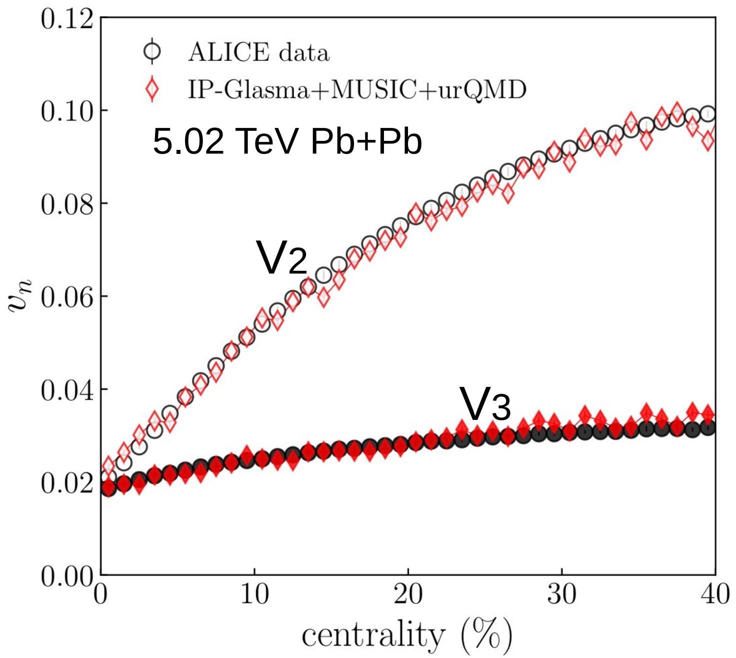


NB: more realistic treatment involves adding nucleon-nucleon interaction.
Framework is called “Energy Density Functional” theory. Phenomenological models.
(Gogny force, Skyrme force, Relativistic density functional, etc etc.)

Notion of mean field justifies the Glauber Monte Carlo model!





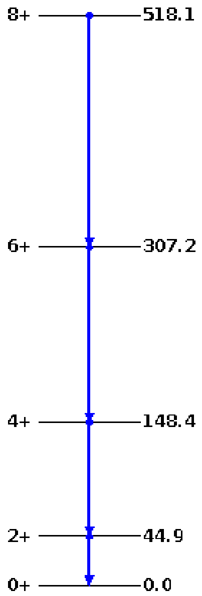


FOUNDATIONAL PRINCIPLES:

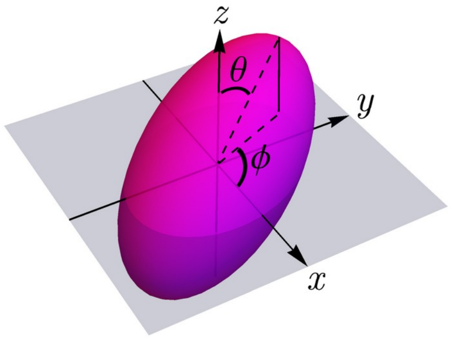
Nucleons independently sampled.
System is in the ground state.
Interaction as a "quantum measurement".

Nucleons in nuclei are strongly correlated. Fundamental phenomenon due to strong force. Emergent collective behavior(s).

E = B J(J+1)



Powerful approximation: “deformed” potential.
intrinsic deformed shape (nucleons) with random orientation.
NB: ground state has J=0.

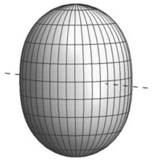
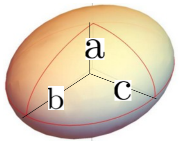


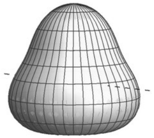
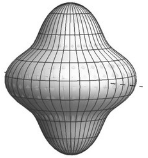
$^{238}_{92}\mathrm{U}$

https://www.nndc.bnl.gov/nudat3/

Generalize the Woods-Saxon profile to include intrinsic deformations:

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

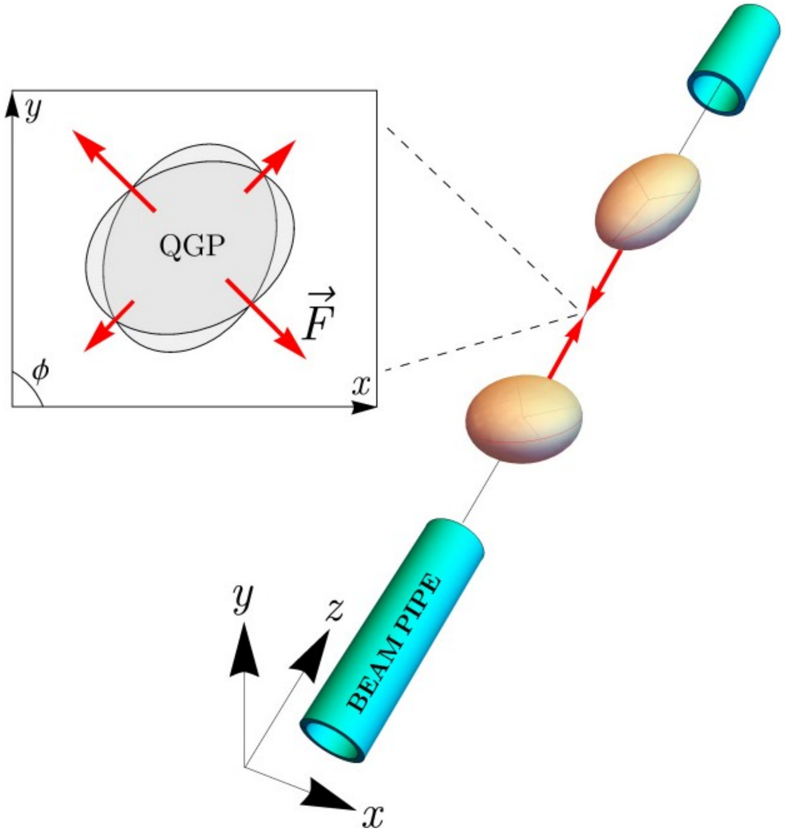
Intrinsic shapes are non-observable for direct measurements, but they leave their fingerprint on virtually all nuclear observables and phenomena

Michael Bender – RBRC Workshop Jan 2021

They will show up as well at high energy.

↓

THIS TALK!



Collide nuclei with intrinsic deformations.

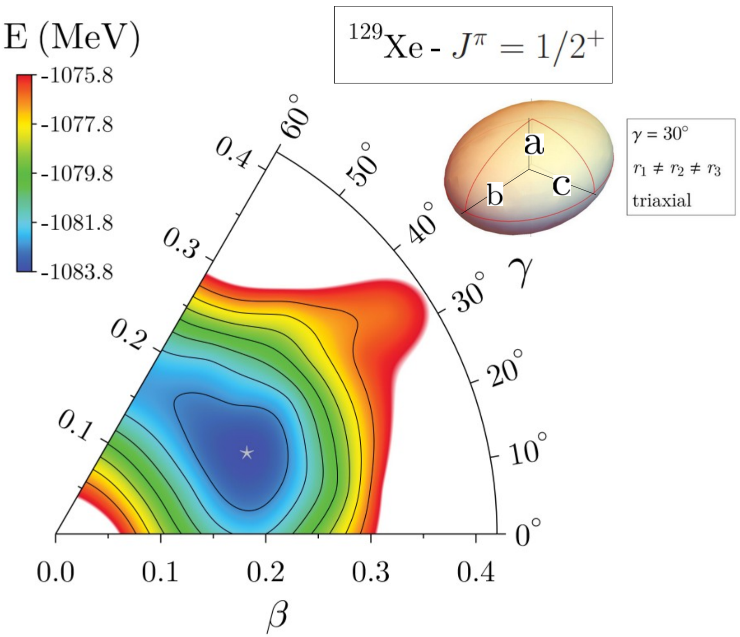
The configuration of nucleons is deformed and acquires a random orientation.

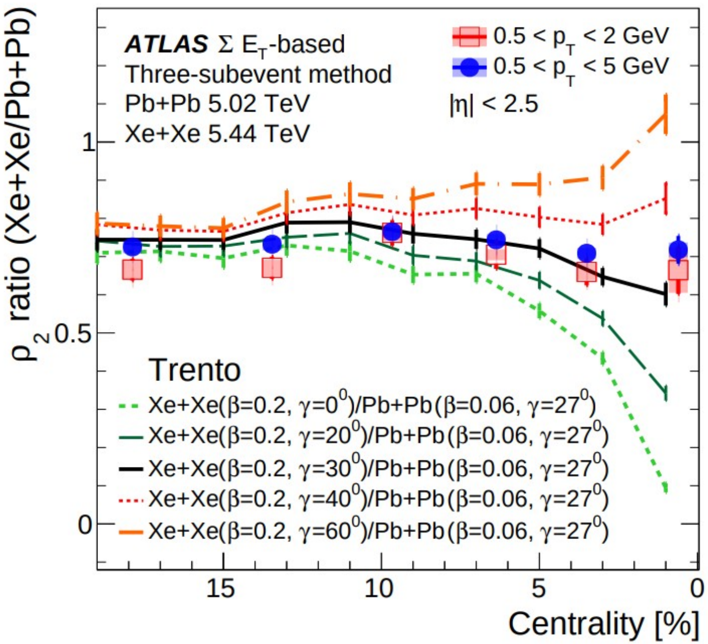
Allow for symmetry-breaking solutions for the "bag of nucleons".

$$\delta\left(\langle\Phi|H-\mu Q_2|\Phi\rangle\right)=0$$

e.g. quadrupole deformation

Example: Triaxial deformation of ^{129}Xe.

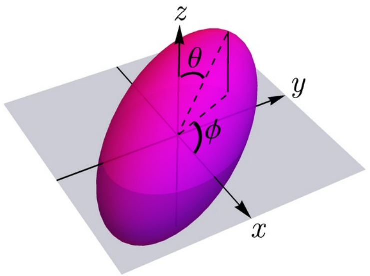




What can low-energy nuclear experiments do for deformations?

GSI

Rotational model



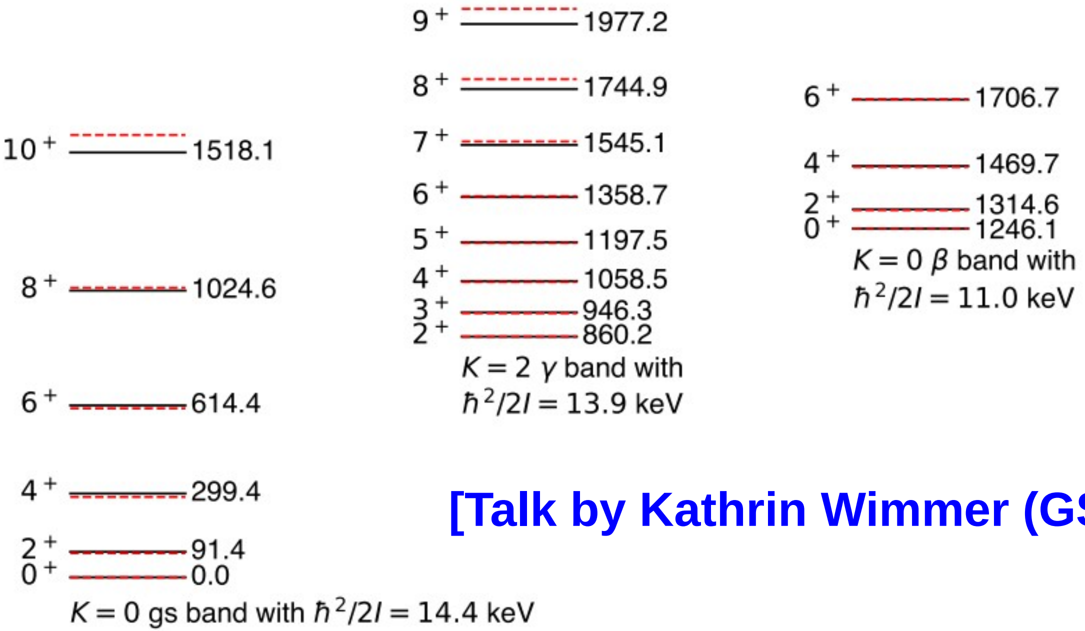
- measuring β or γ is not possible
- need to use nuclear models to estimate the deformation from the data
- rotational model:

$$E(J) = \frac{\hbar^2}{2I}\left(J(J+1) + K(K+1)\right)$$

- with moment of inertia for an ellipsoid (rigid, first order)

$$I_{\text{rigid}} = \frac{2}{5} AMR_0^2 (1 + 0.31\beta)$$

- increasing deformation β $\rightarrow$ smaller energy spacing
- assumption: constant I along band
- superposition of vibrational excitations below the pairing gap

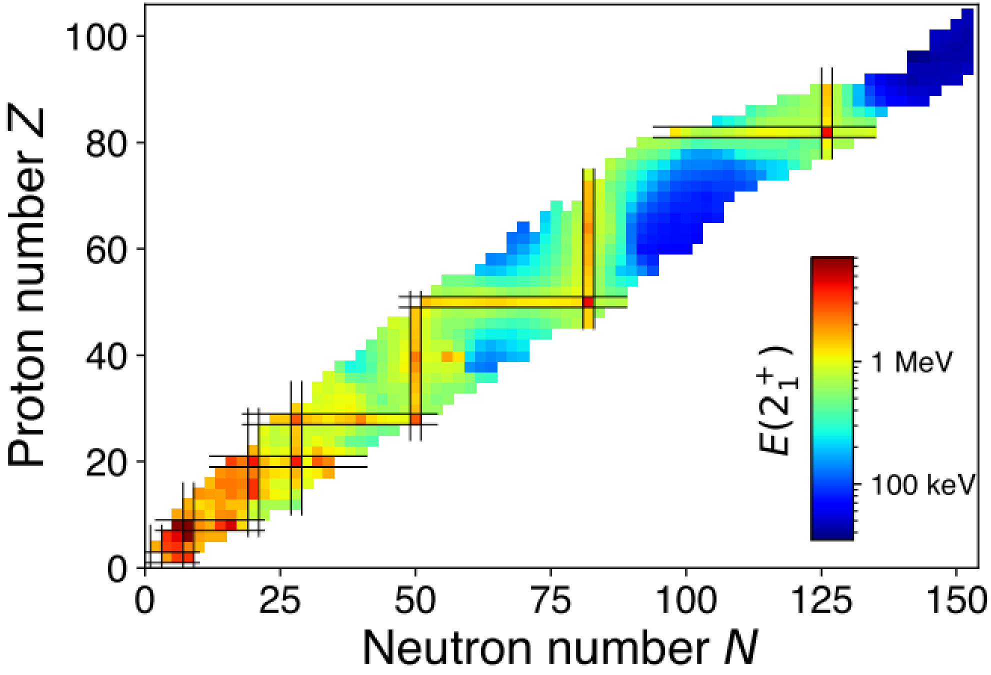


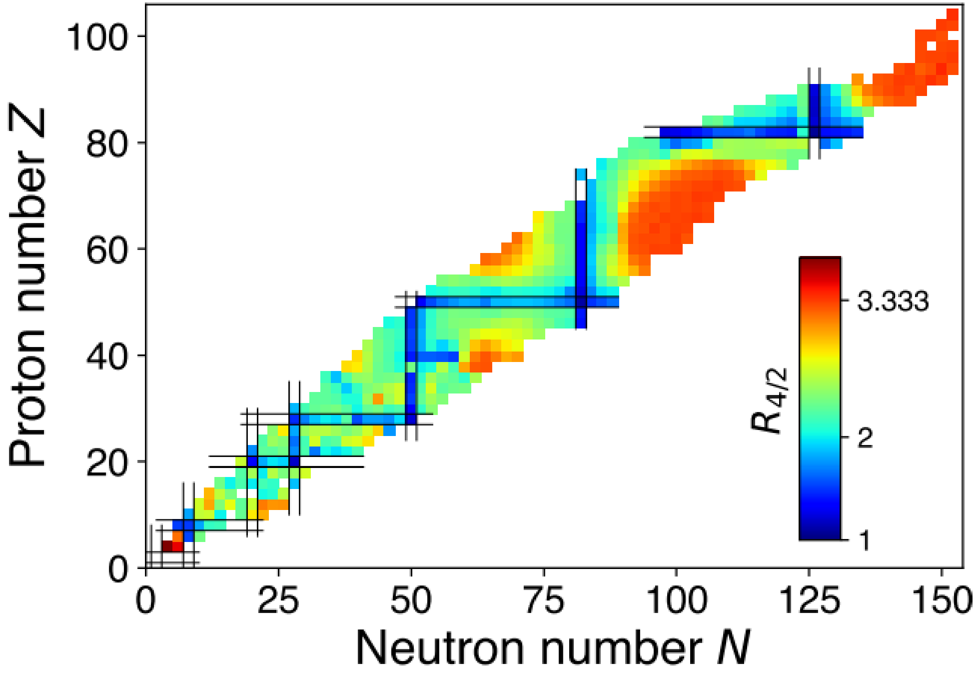
[Talk by Kathrin Wimmer (GSI)]

Under several approximations, degree of collectivity is inferred in experiments

- spectroscopy of first few excited states
- low $E(2_1^+)$ indicates collective nature
- energy ratio $R_{4/2} = \frac{E(4_1^+)}{E(2_1^+)}$, for vibrational $R_{4/2} = 2$, for rotational $R_{4/2} = 3.333$

[Talk by Kathrin Wimmer (GSI)]





- assuming axial symmetry, deformation can be extracted from $B(E2)$ values

$$B(\Pi\lambda) = \frac{|\langle I_f || \Pi\lambda || I_i \rangle|}{2I_i + 1} \qquad \beta_2 = \frac{4\pi}{3eZR^2}\sqrt{B(E2;\, 0_1^+ \to 2_1^+)}$$

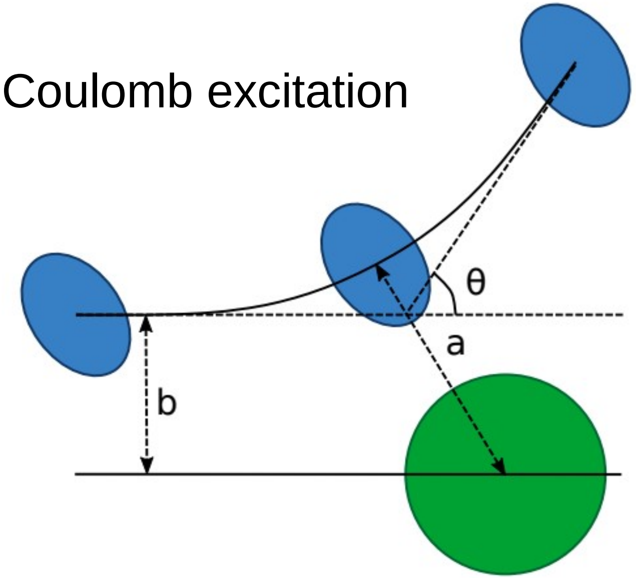
- $\beta = 0.3$ for well-deformed rare-earth and super-heavy nuclei
- at Coulomb barrier energies, longer interaction times allow for multi-step processes
  $\rightarrow$ excitation of 4^+, 2_2^+, 0_2^+, etc states

$$\left(\frac{d\sigma}{d\Omega}\right)_{i\to f} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Ruth}} |a_{i\to f}|^2$$

- multipole expansion

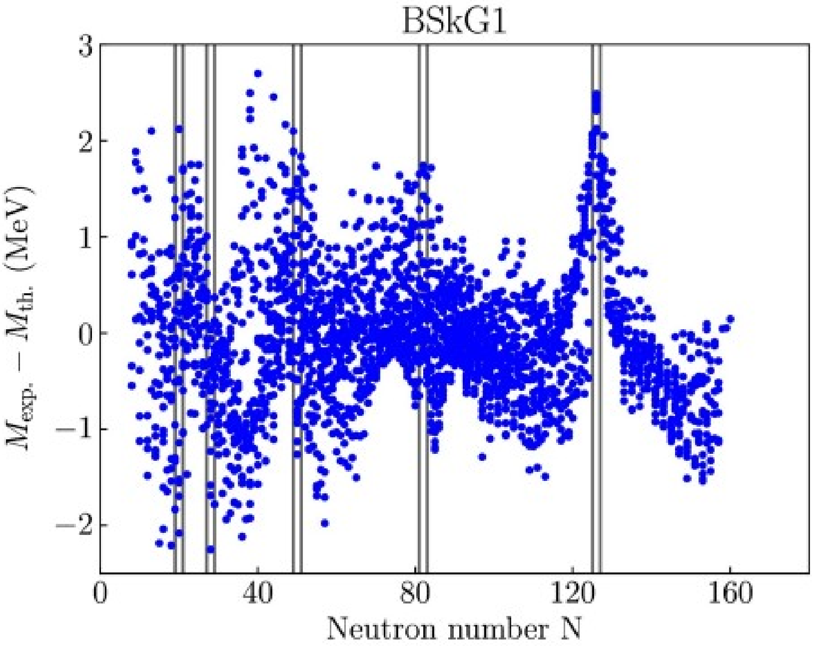
$$\sigma(\pi\lambda)_{i\to f} \propto B(\pi\lambda;\, I_i \to I_f)$$

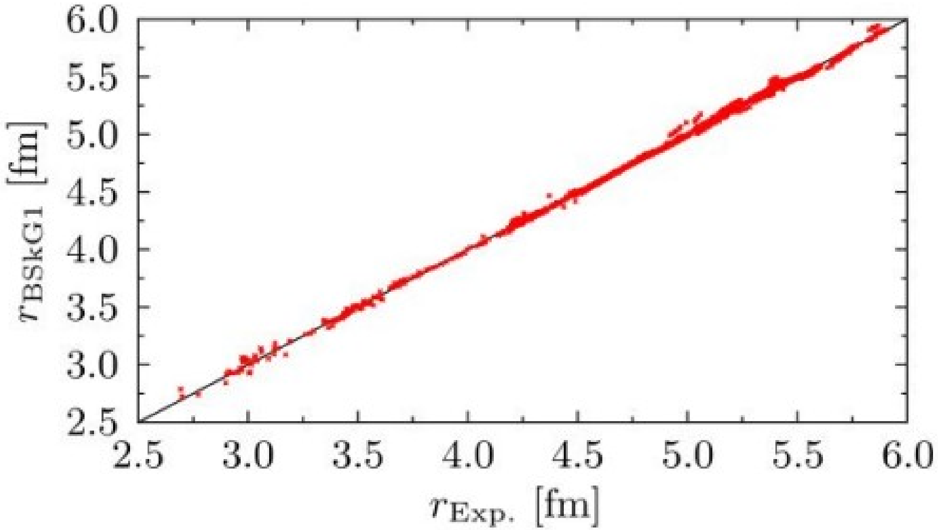
Coulomb excitation



[Talk by Kathrin Wimmer (GSI)]

Nuclear models aim at an accurate description of masses and radii.
Basic features with little influence from complicated many-nucleon correlations.





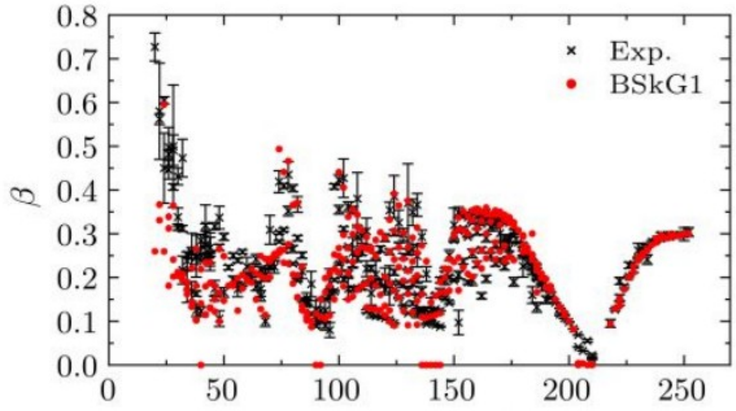
[Talk by Wouter Ryssens (Brussels)]

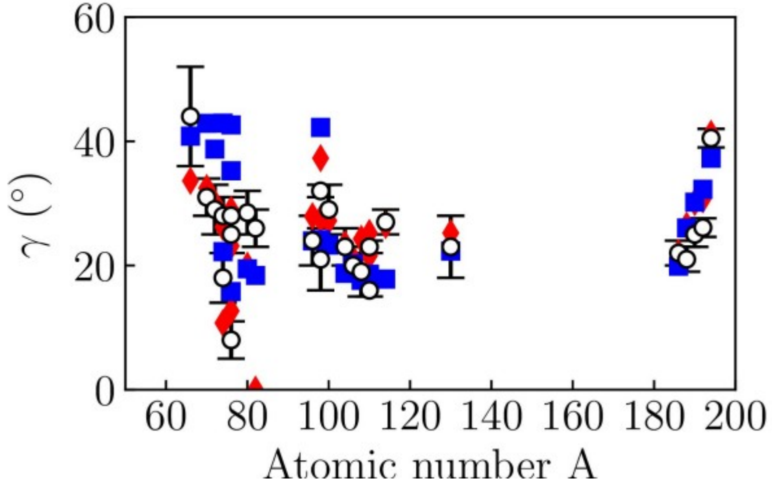
For deformations, no interest in precise fits.
(except for large well-deformed ions)

Mostly an experimental issue. In general, there are no real probes of multi-nucleon correlations.
Huge model dependence.

Knowledge of deformations mostly come from theoretical results fitted to other data.

[Talk by Wouter Ryssens (Brussels)]





PART II

Going beyond the mean field with heavy-ion collisions

Symmetry-breaking solutions

- Mean-field calculations: $\delta\langle\Phi(q_i)|\hat{H}|\Phi(q_i)\rangle = 0$
  $|\Phi(q_i)\rangle \equiv$ Product states (simple wave functions)
- Symmetry-unrestricted MF calculations favor "deformed" solutions
- Examples: pairing, quadrupole and octupole deformations, ...
- Problem: deformed solutions break the symmetries of $\hat{H}$

$$|\Phi(q_i)\rangle = \sum_{NZJM\pi} \sum_{\epsilon} c_{\epsilon}^{NZJM\pi} |\Psi_{\epsilon}^{NZJM\pi}(q_i)\rangle$$

$\Rightarrow$ unphysical in nuclei

Physical symmetry	Group	Quant. numb.	Correlations
Particle-number inv.	$U(1)_Z \times U(1)_N$	N, Z	Pairing, Finite temp.
Rotational inv.	$SU(2)_A$	J, M_J	Deformation (any)
Parity inv.	Z_{2A}	π	Deformation (odd)
Translational inv.	T_A^3	$\vec{P}$	Localization
Isospin	$SU(2)_A$	T, M_T	Pairing n-p

[Talk by Benjamin Bally (Paris-Saclay)]

- Nuclear wave functions wave functions: Generator Coordinate Method (GCM) ansatz

$$|\Psi_\sigma^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} P_{MK}^J P^N P^Z P^\pi |\Phi(q)\rangle$$

$\Gamma \equiv (JMNZ\pi)$

weights

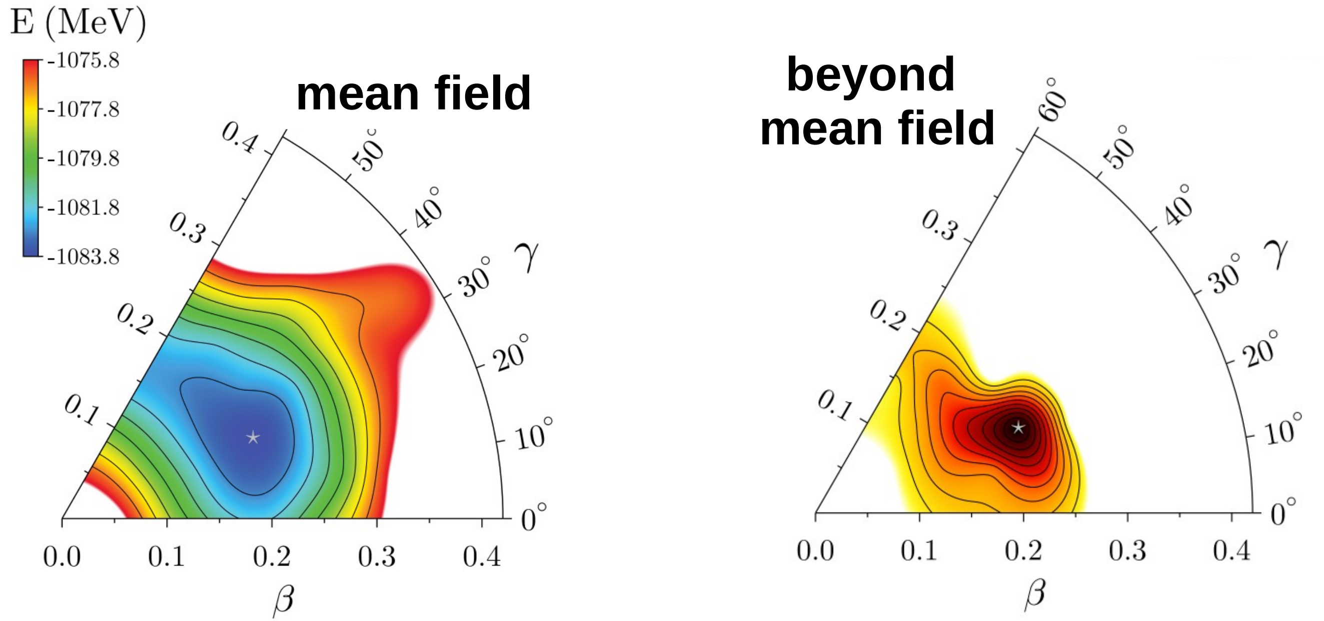
"basis" states

Symmetry restoration via projections&mixing

Importance of a given deformation

Contains corrections (correlations) **beyond the mean field Ansatz.**

Symmetry restoration has small impact on <u>129Xe</u>

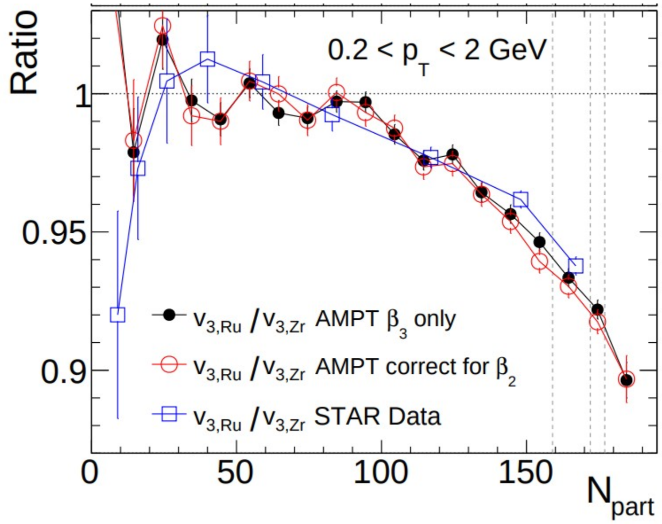


[Talk by Tomás Rodriguez (UAM Madrid)]

Not the case for octupole deformations!

Deformation entirely as a beyond mean field effect.

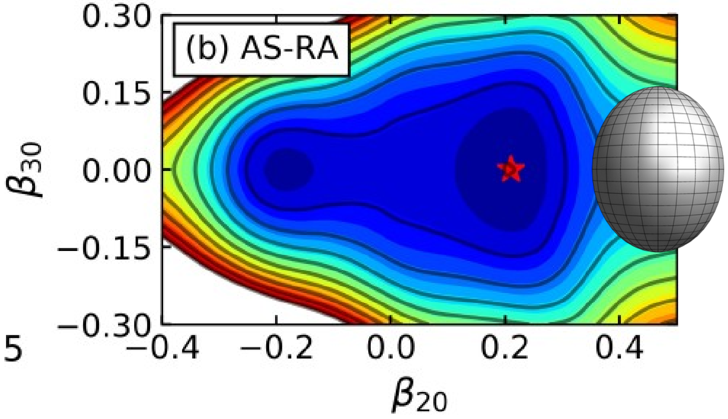
Experimental consequences?



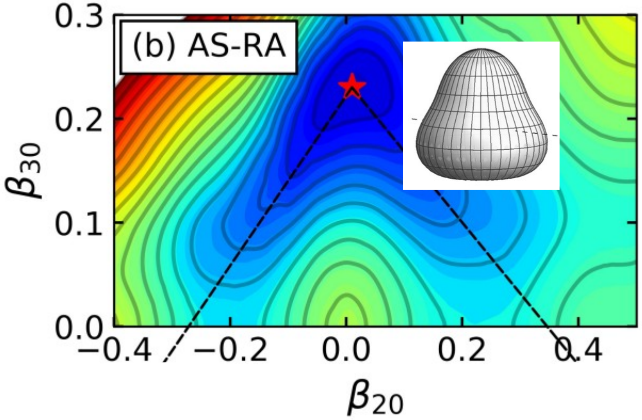
^{96}Zr

[from 2201.02114]

mean field



beyond mean field



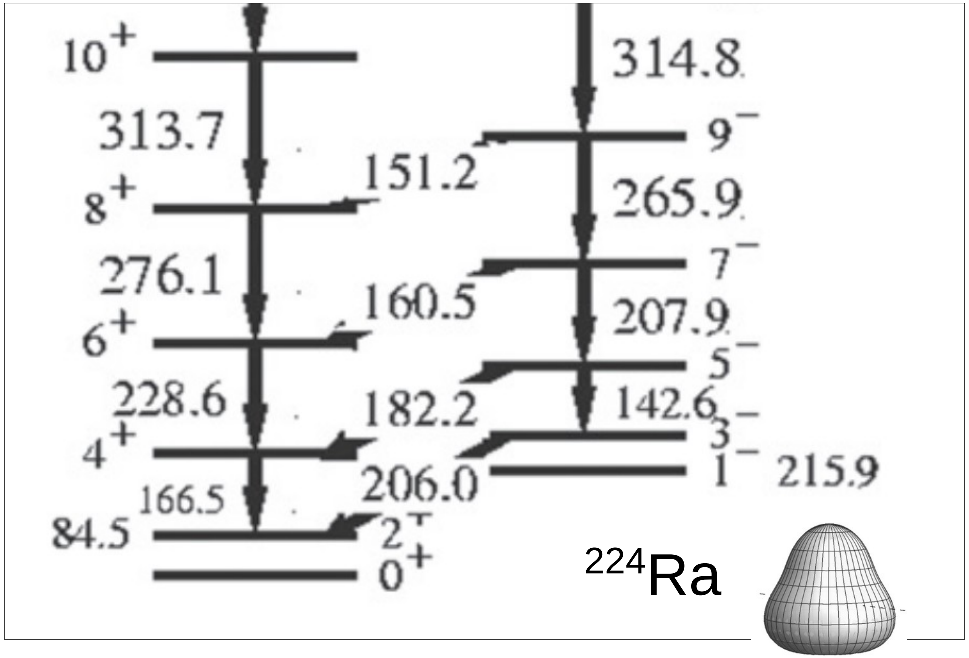
Clean signature of octupole deformations is spectrum of interleaved negative and positive parity states.

Observed for only a few heavy nuclei. Theory agrees with this.

‘Dynamical’ octupole deformation does not show up in data.

Heavy-ion collisions are fully sensitive to all such correlations.

Static octupole deformation

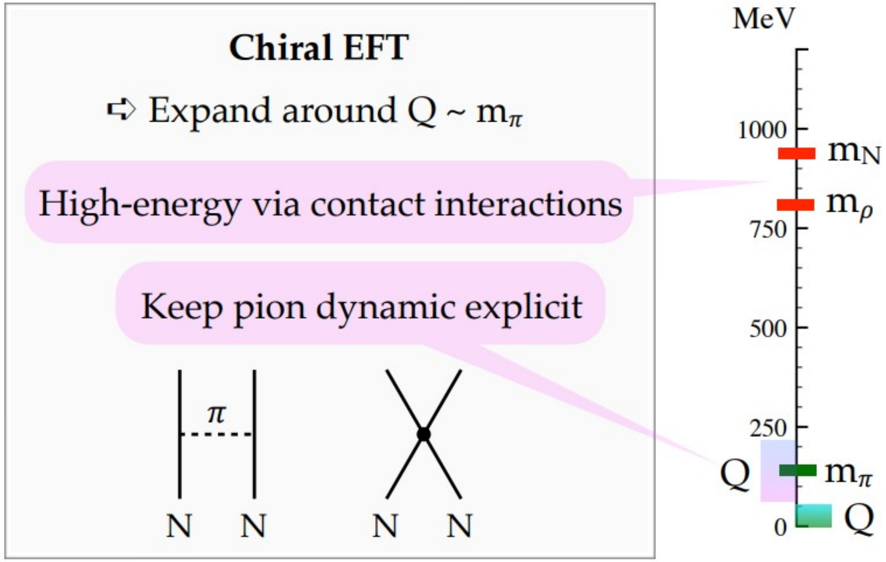


[Talk by Anatoli Afanasjev (Mississippi)]

PART III

Ab-initio approaches in nuclear physics across scales

End of 90's, new paradigm in nuclear structure.
Constructing the nuclear force from an effective theory of low-energy QCD.



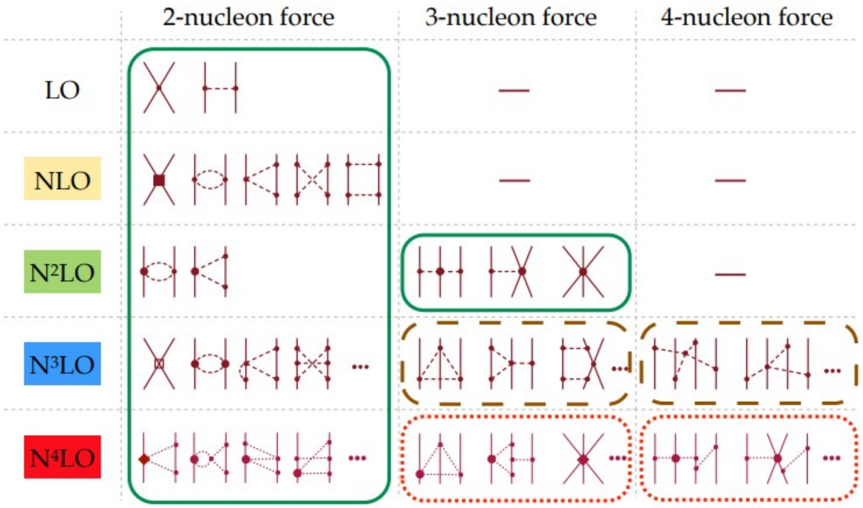


Fig. 19. Diagrams appearing in the first five orders of chiral EFT derived within Weinberg power counting. Dashed lines and dots represent pion exchanges contact interactions respectively. Sectors contoured with a green solid line have been formally derived and are routinely implemented in nuclear structure calculations. Sectors contoured with a brown dashed line have been formally derived but are not yet routinely implemented in nuclear structure calculations. Sectors contoured with a red dotted line have not been formally derived yet.

[Talk by Vittorio Somà (Paris-Saclay)]

Application in the variational framework.
Mean-field calculation with ab-initio interaction.

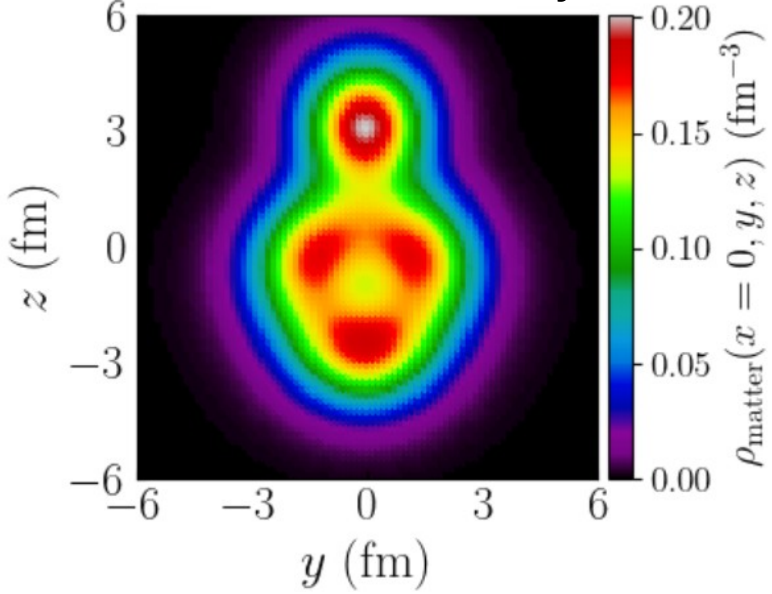
$$\delta \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} = 0$$

Hamiltonian from effective theory of low-energy QCD

Application to the strongly-correlated neon-20.

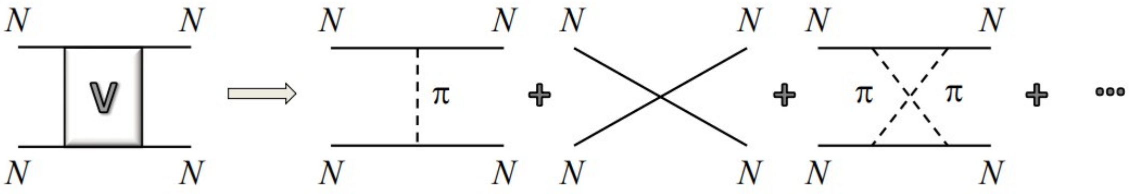
^{20}Ne

Point-nucleon density

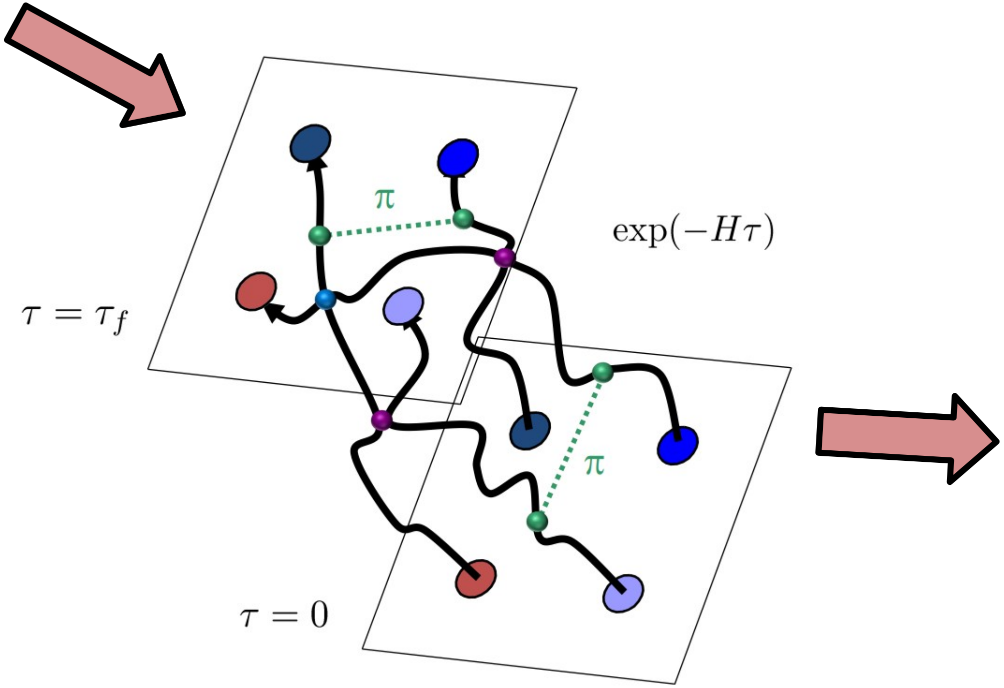


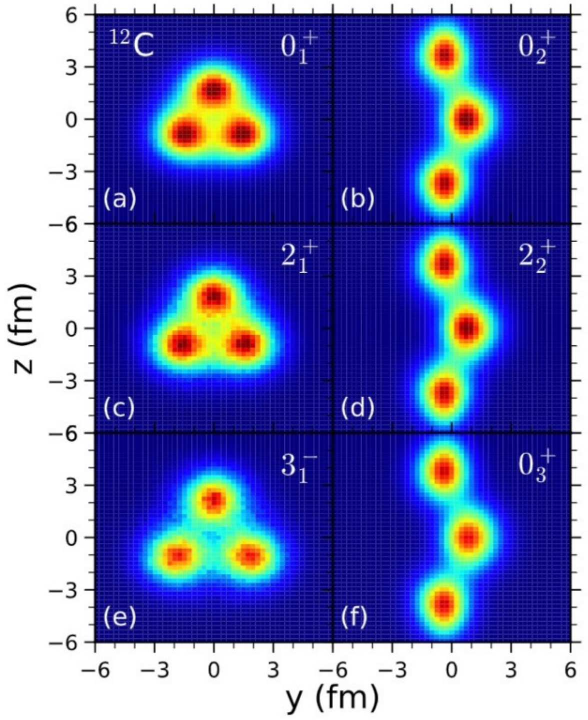
[Talk by Benjamin Bally (Paris-Saclay)]

Fully-correlated nucleon configurations with no notion of ‘deformation’.
Chiral effective field theory on a lattice. In a sense, lattice low-energy-QCD.



Nuclear Lattice Effective Field Theory (NLEFT)



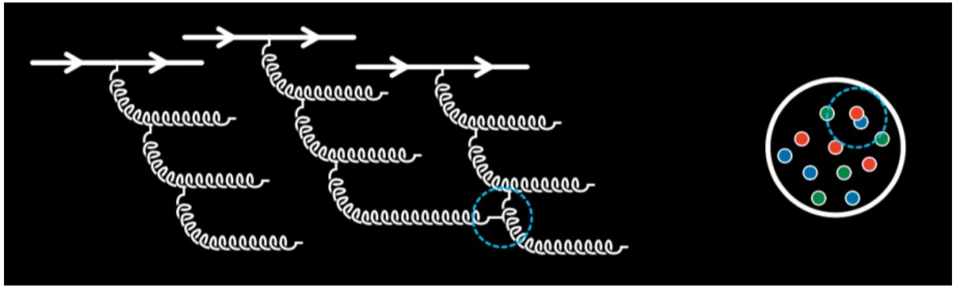


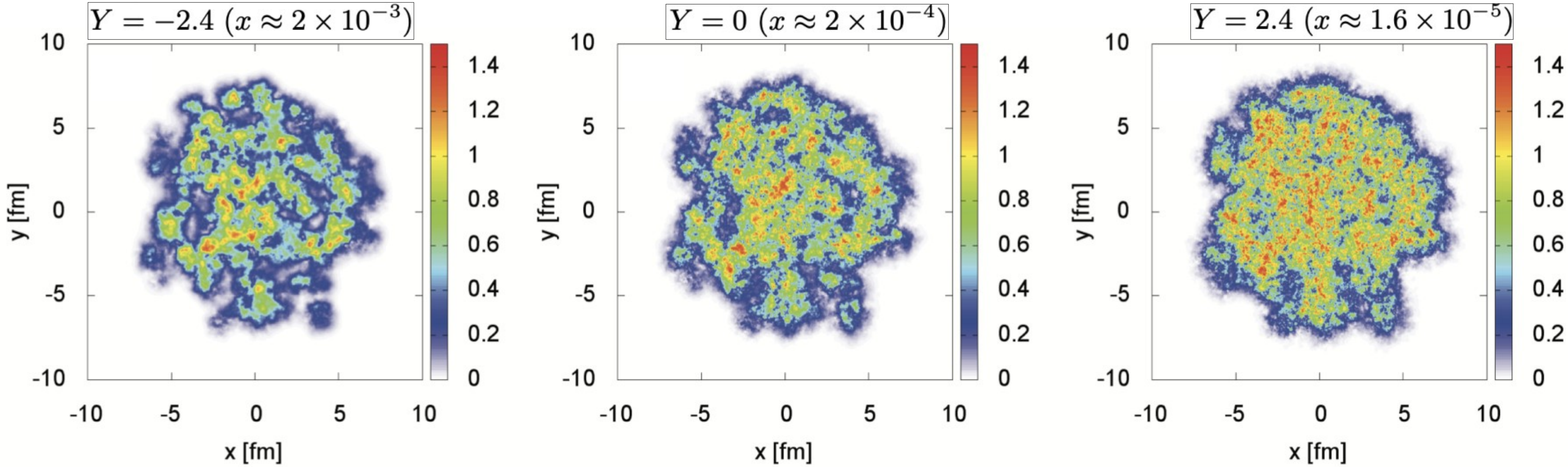
[Talk by Dean Lee (FRIB)]

Large-x and small-x dynamics are completely de-coupled.

Role of small-x evolution on global nuclear geometry?

[Talk by Bjoern Schenke (BNL)]

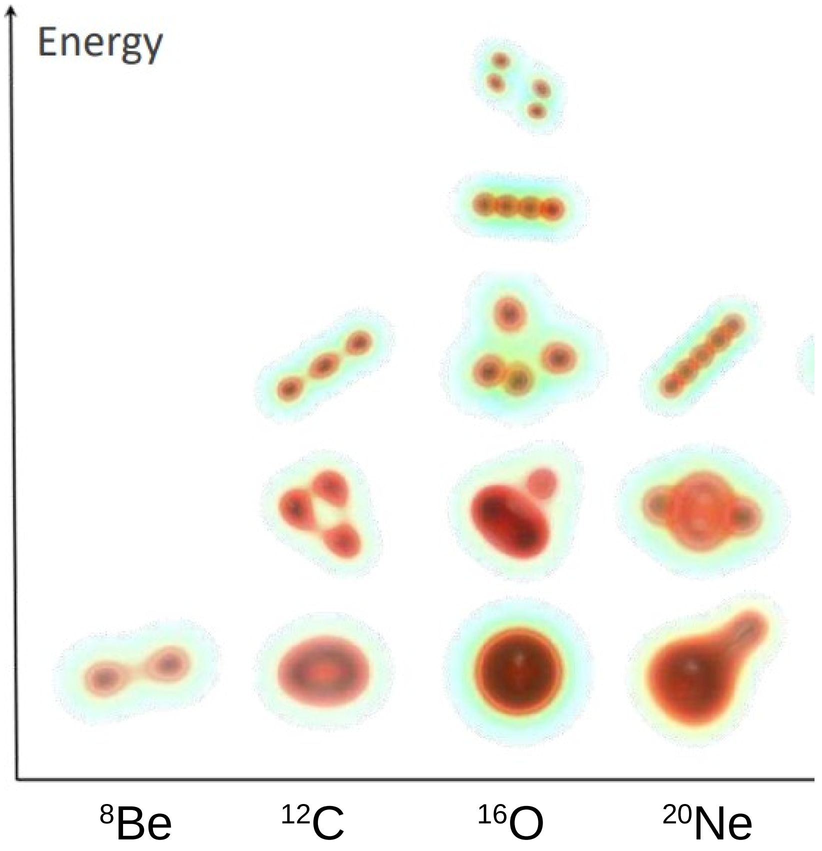




Highly clustered structures emerge in high-energy excited states.

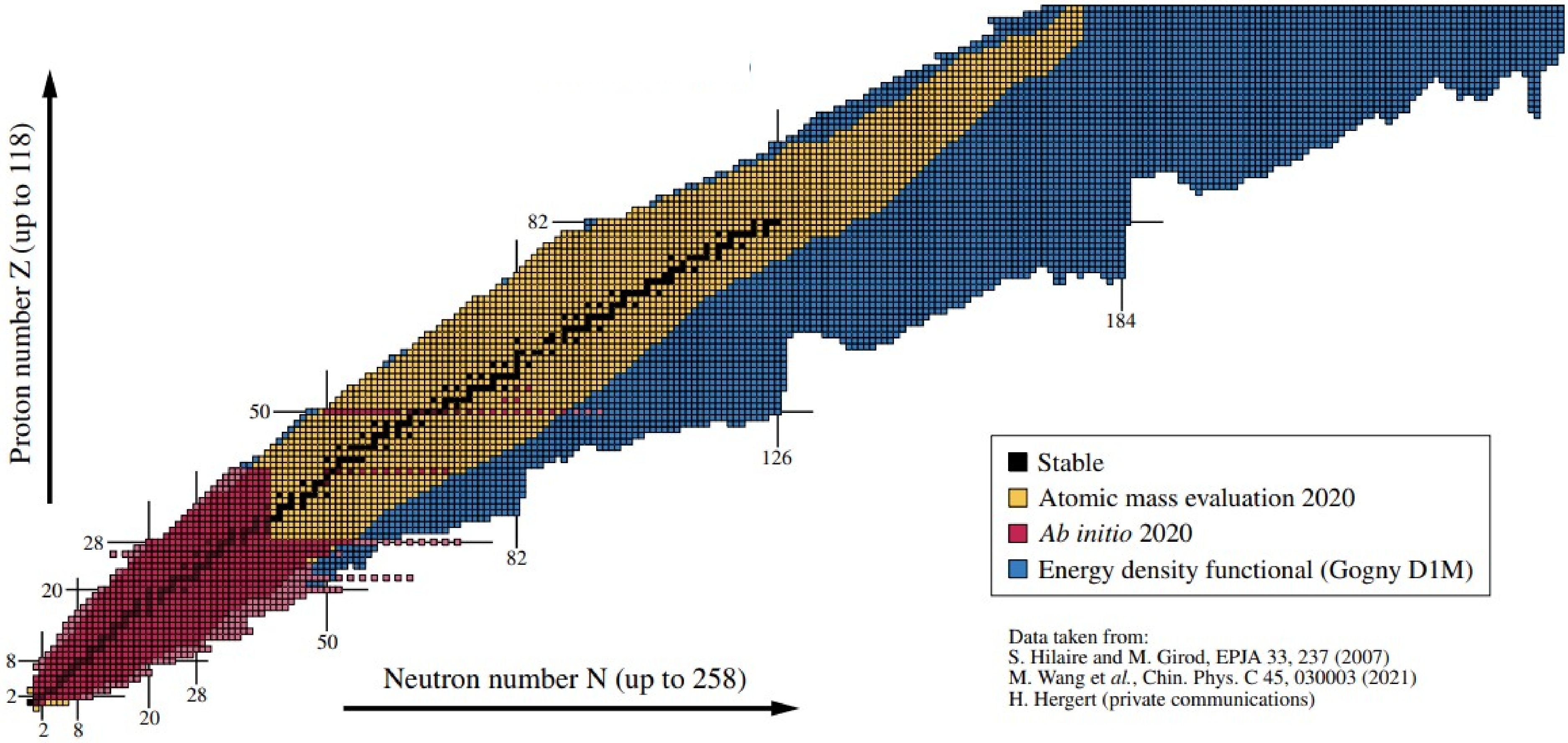
Ground states are weakly correlated, with the exception of neon-20 (for A>10).

Oxygen-16 is a very good baseline of weakly correlated system.



[Talk by Jean-Paul Ebran (CEA Bruyères-le-Châtel)]

Substantial progress with ab-initio descriptions. Large nuclei achievable in next decade. Heavy-ion collisions are natural way to use/test them.



[Talk by Benjamin Bally (Paris-Saclay)]

PART IV

Science cases for collider runs

[Discussion summary at:
https://indico.gsi.de/event/14430/contributions/64193/]

SUMMARY OF OUR DISCUSSION

On June 1st, 2022, the Task Force met to discuss the physics opportunities offered by potential future collider runs with new nuclear species. A window to perform collisions with new ions may be opened in future, in particular at the Large Hadron Collider (LHC). The Task Force has, thus, worked on the identification of nuclear species that would maximize the scientific outcome of such runs. More precisely, one could select nuclear species that, besides permitting to address some targeted issues of the high-energy nuclear physics program, would in addition permit to:

- Exploit the known low-energy structure of the colliding ions to access more efficiently the targeted high-energy features;
- Allow us to to extract some important information about the structure of the colliding ions that would complement the effort of low-energy experiments;
- Reveal features of the low-energy structure of the colliding ions that are not accessible via conventional nuclear structure experiments, and that would have a significant impact on low-energy nuclear structure models.

The discussion lead to the identification of three science cases that may readily lead to break-through observations via relativistic collision experiments. They involve nuclides belonging, respectively, to the mass regions $A \sim 20$, $A \sim 40$, and $A \sim 150$.

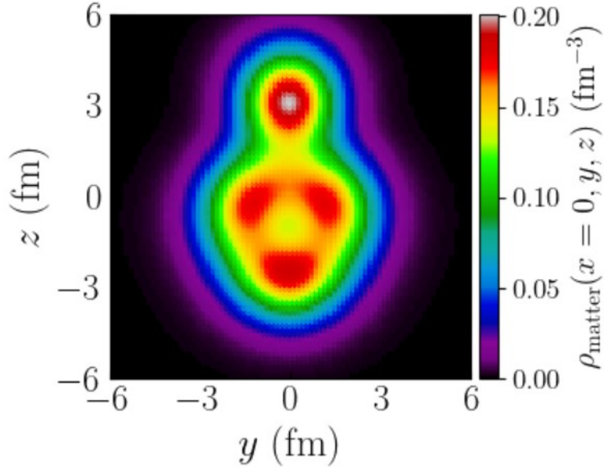
I will discuss only two of them

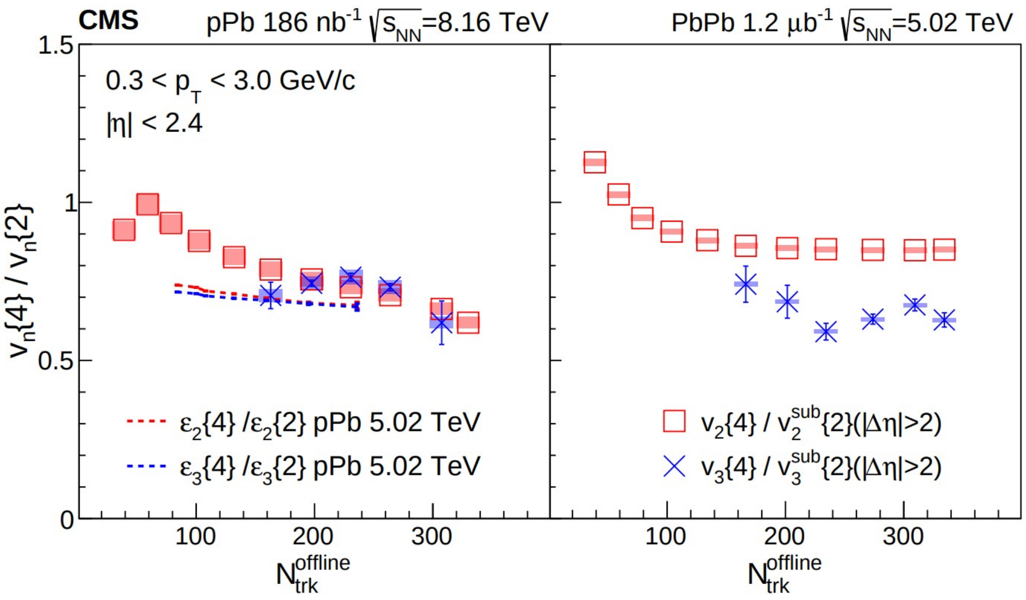
1. Stress-testing small-system collectivity with ^{20}Ne

Q: what evidence we have that flow in small systems has a geometric origin?

^{20}Ne

Point-nucleon density



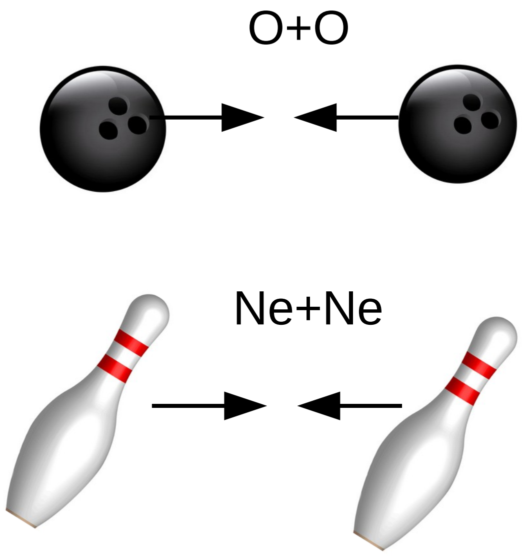


Not much.

Mostly $v_2\{4\}$ difference with Pb-Pb.

Can we use O+O and Ne+Ne to observe ‘very strong’ purely-geometric effects at dN/dy~100?

Yes.



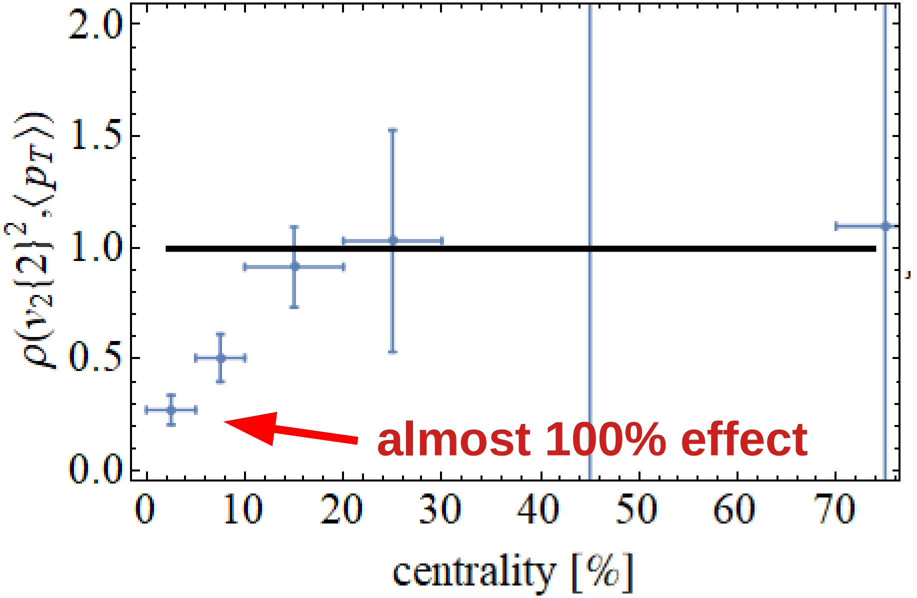
Final word on geometric origin of flow.

NB: There is no other way to get such a clean signature!

NB: Basic flow of O+O collisions will be very hard to understand without an ‘isobar’.

Trajectum framework

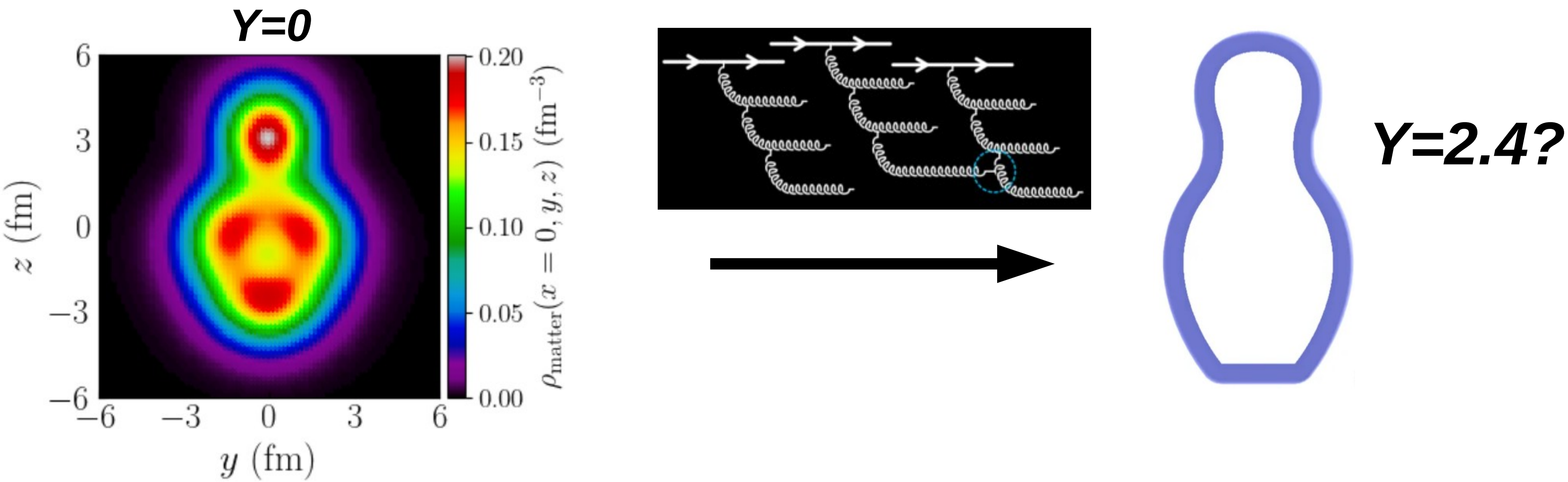
Ratio 16O+16O / 20Ne+20Ne



Longitudinal structure and beam-energy dependence.

IMPORTANT: neon-20 is a strongly-correlated system (highly-deformed and clustered).
Big question: do these correlations survive when beam energy/rapidity increases?

Will the small-x evolution “melt” the bowling pin?



1 - FOCAL upgrade of ALICE. “Dilute-dense” Ne+Ne, one at small x, one at large x.

2 – 20Ne is available in SMOG system of LHCb. Collider = fixed target means we have Collisions at sqrt(s)=7000 GeV and sqrt(s)=70 GeV at the same time! Factor 100!

OUTCOME: Unique window onto the role of quarks and gluons (QCD) for collective structure.

2. Measuring the neutron skin of ^{48}Ca

Astrophysics-motivated. Equation of state of nuclear matter:

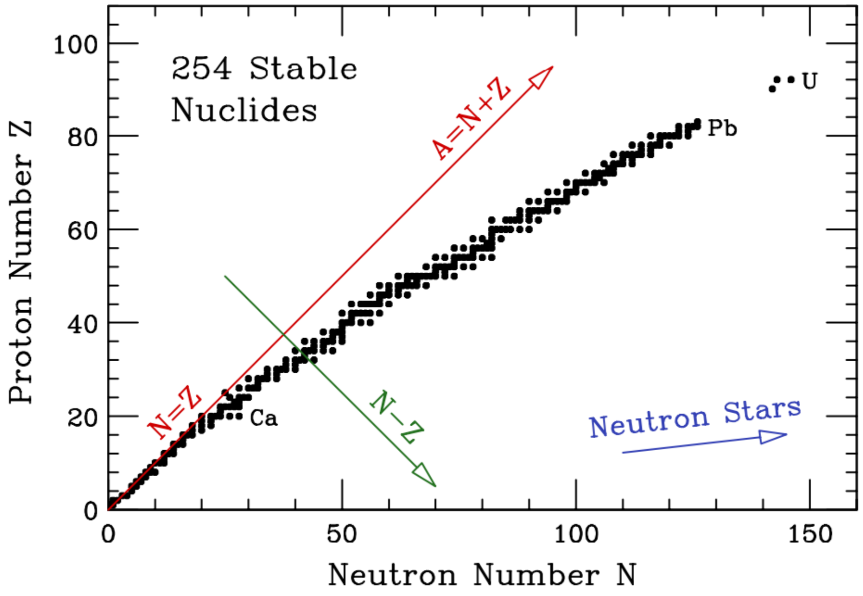
$$\frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + \mathcal{O}(\ldots^4)$$

symmetric matter (a)symmetry energy $\rho = \rho_n + \rho_p$

Symmetry energy is usually Taylor expanded around saturation density

$$S(\rho) = S(\rho_0) + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \ldots$$

[From P. Danielewicz, RBRC Workshop Jan 2022]

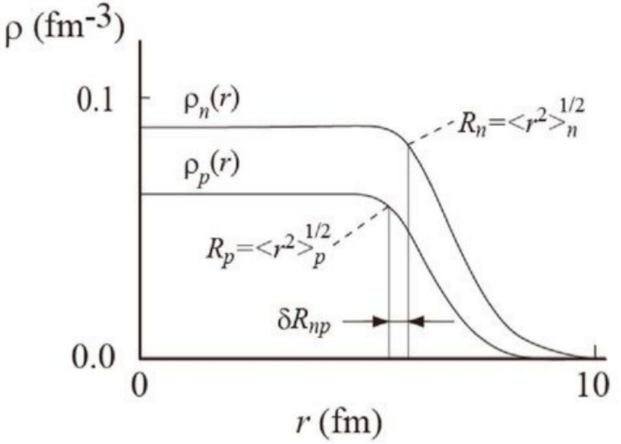


Symmetry energy is about the ‘cost’ of making system more neutron rich at a given density.

Slope parameter, L, determines the stiffness of the EoS.

Determines structure of neutron rich systems, from nuclei to neutron stars.

The neutron skin in atomic nuclei, Δr_{np}, is proportional to the slope L of symmetry energy.



Accurate measurement of Δr_{np} of ^{208}Pb from neutral weak form factor at JLab (PREX-II experiment):

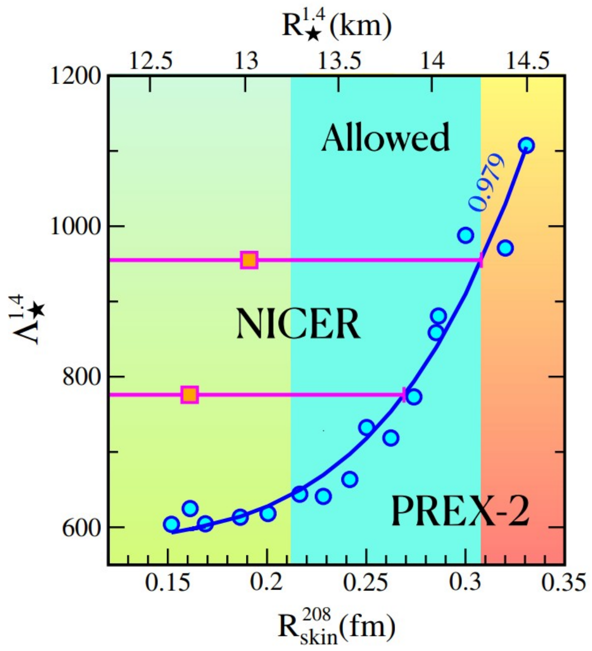
$$\Delta r_{np} = 0.283 \pm 0.071 \text{ fm}$$

$$L = (106 \pm 37) \text{ MeV}$$

[PREX-II experiment, PRL **126** (2021) 17, 172502]

Stiffer EoS than expected.

[Reed et al., PRL **126** (2021) 17, 172503]
[Fattoyev et al., PRL **120** (2018) 17, 172702]



From GW170817

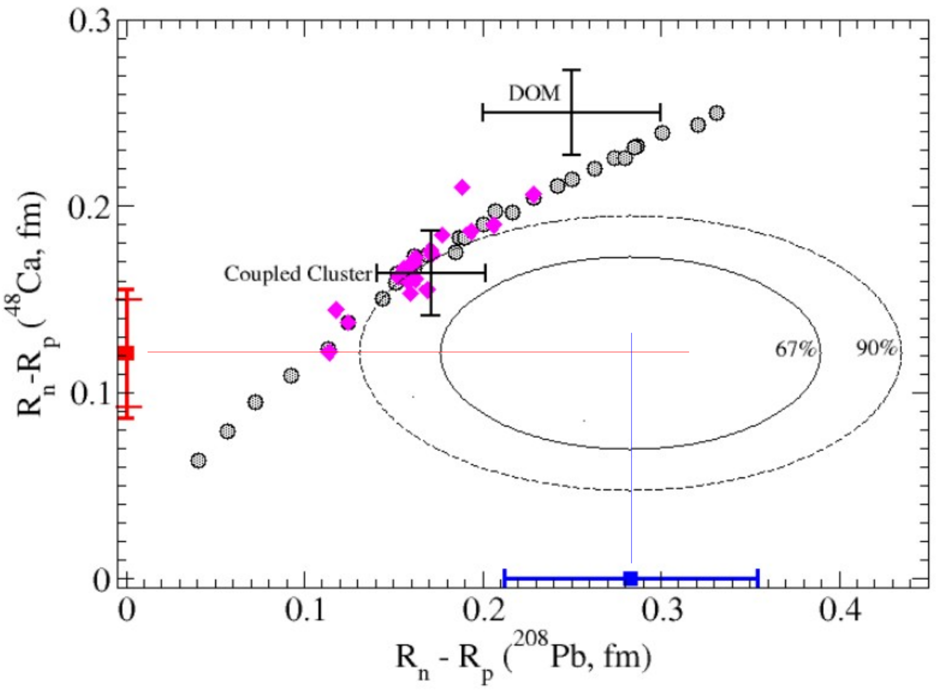
of $\Lambda_{1.4} \lesssim 580$ [44], we eagerly await the next generation of terrestrial experiments and astronomical observations to verify whether the tension remains. If so, the softening of the EOS at intermediate densities, together with the subsequent stiffening at high densities required to support massive neutron stars, may be indicative of a phase transition in the stellar core [42].

Another dedicated experiment at JLab. C-REX experiment for neutron skin of Calcium-48.

We can easily access the difference in neutron skin between two 'isobars'.

$$\delta_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}$$

$$\delta_{\rm np}(^{48}{\rm Ca}) - \delta_{\rm np}(^{40}{\rm Ca}) \simeq \delta_{\rm np}(^{48}{\rm Ca})$$



https://arxiv.org/pdf/2205.11593.pdf

$\longrightarrow$ **Collisions to perform:** $^{40}{\rm Ca}+^{40}{\rm Ca}$, $^{48}{\rm Ca}+^{48}{\rm Ca}$

CONCLUSION

- Reaching precision in flow analyses of heavy-ion collisions implies dealing with nuclear structure.
- Nuclei are strongly-correlated systems and there is a rich phenomenology of multi-nucleon correlations, i.e., deformations. They naturally show up in high-energy collisions.
- Low-energy experiments can not really probe correlations in as much detail as heavy-ion collisions. The observed octupole deformation of 96Zr could not be predicted on the basis of low-energy data.
- We understand Xe+Xe data from low-energy theory. We do not understand yet Zr+Zr. **EMMI Task Force will shed light on this.**
- **Frontier of nuclear structure: ab-initio descriptions motivated by QCD. Heavy-ion collisions are the natural environment to test/exploit their predictions.**
- **There is a strong scientific case for colliding 20Ne. Ideally at LHC Run4.**
- **Bonus:** We know how to isolate the impact of neutron distributions. High-energy collisions can contribute to understanding the EOS of nuclear matter. **Determination of 208Pb and 48Ca skins from high-energy data.**
- **In summary, a whole program of studies of emergent phenomena in nuclei with heavy-ion collisions.**

THANK YOU!
(and stay tuned)

Intersection of nuclear structure and high-energy nuclear collisions

Jan 23rd - Feb 24th 2023

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