Nuclear deformation in high-energy experiments: Status and prospects

by

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OUTLINE

- 1. Heavy-ion collisions, quark-gluon plasma, mean p_t and elliptic flow.

- 2. Initial-state fluctuations and Glauber Monte Carlo model, energy deposition.

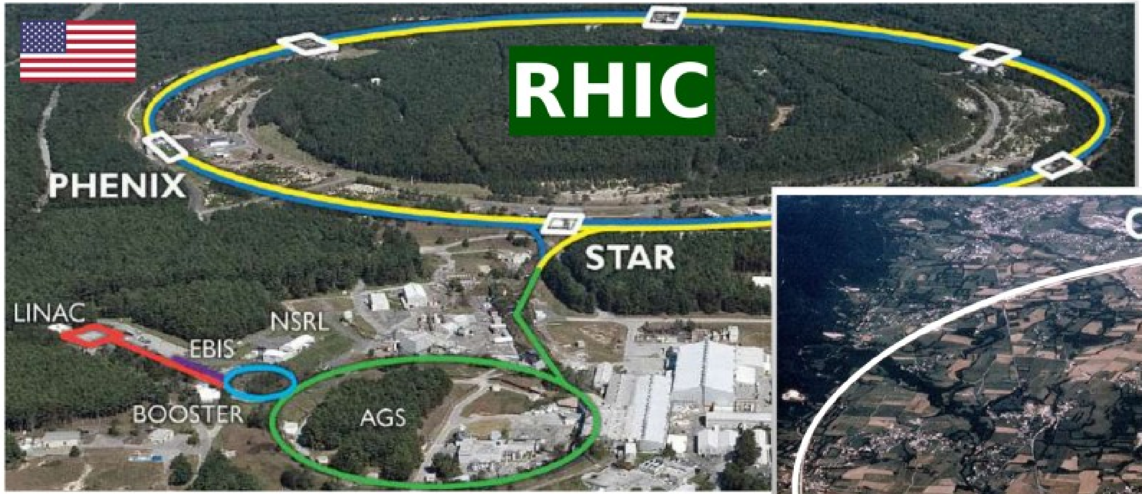
- 3. Heavy-ion collisions as a probe of collective correlations of nucleons.
  - Deformations (axial quadrupole).
  - Deformations (triaxial quadrupole).
  - Beayond-mean-field deformation (octupole).

- 3. Heavy-ion collisions and *ab-initio* nuclear structure theory.
  - Possibilities with O+O.
  - Science cases for ^{20}Ne+^{20}Ne.

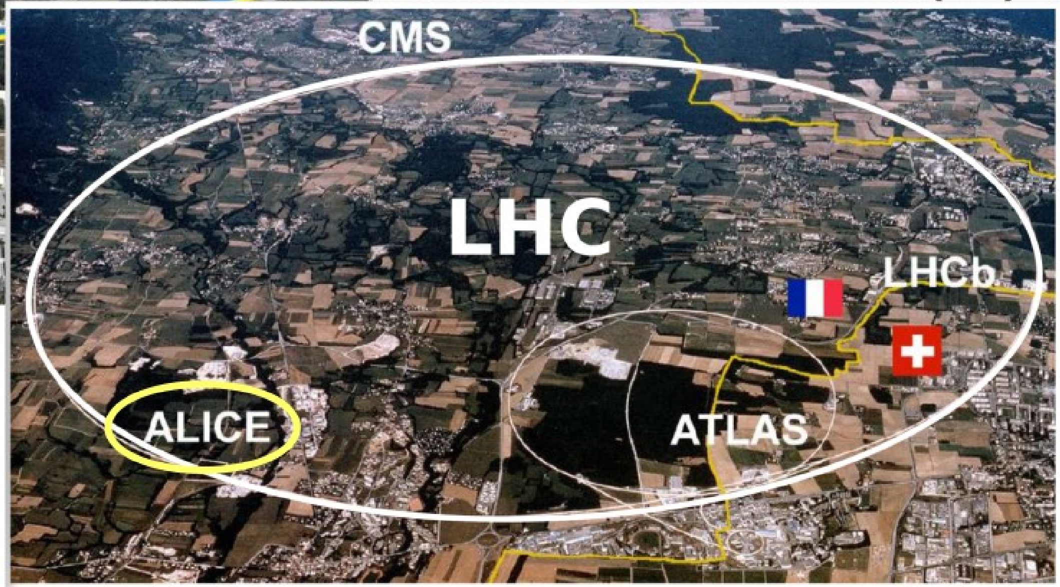
- Conclusion.

1. Heavy-ion collisions, quark-gluon plasma, mean p_t and elliptic flow.

Long Island (NY)



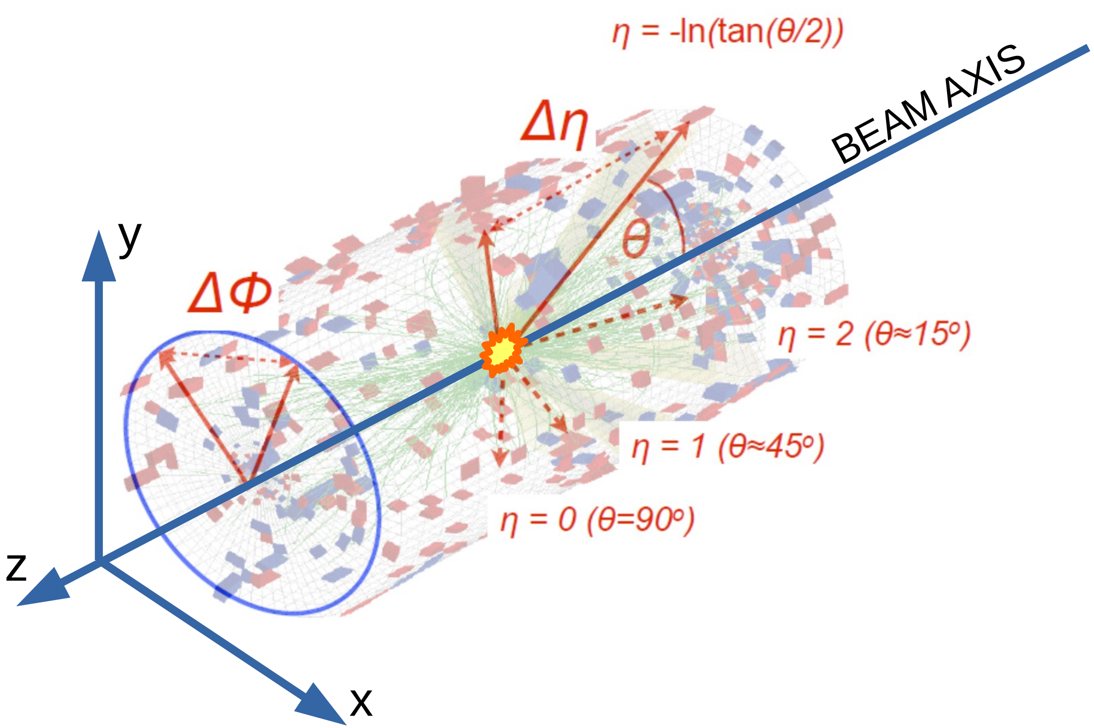
Geneva (CH)



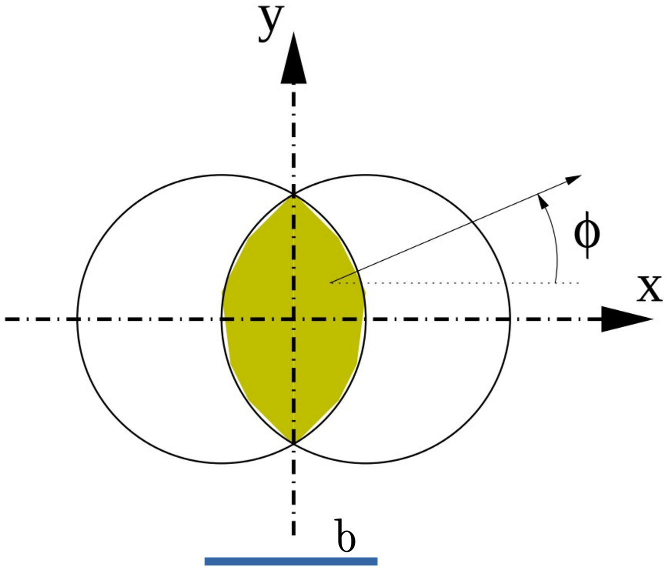
- Great experimental program of high-energy nuclear collisions.
  (~2k experimentalists involved)

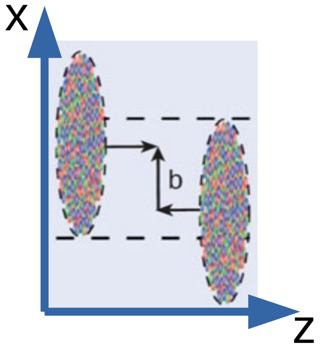
- Nuclei collided ~1 month/year @ LHC.
  RHIC is dedicated to nuclear collisions. (shutdown ~2026)

COLLISION GEOMETRY



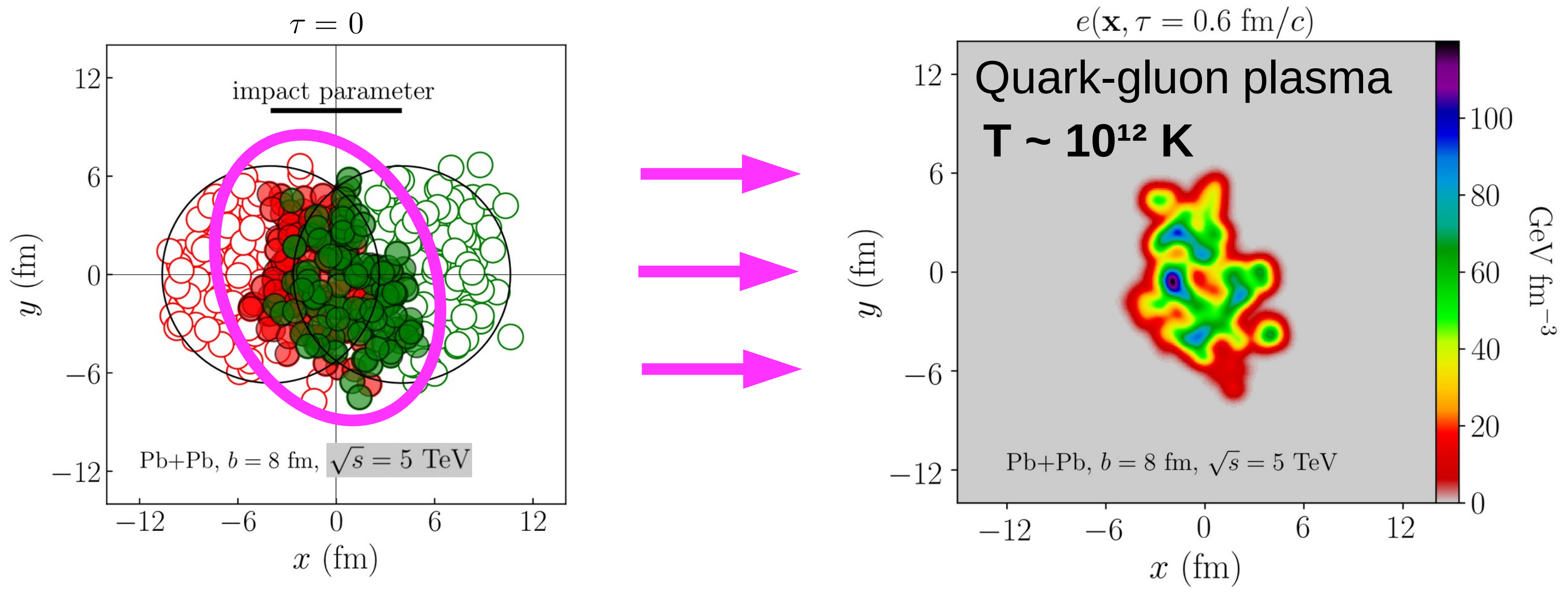
Plane transverse to the beam:





Nuclei are "pancakes" in the lab frame

REPRODUCING THE EARLY UNIVERSE IN THE LAB



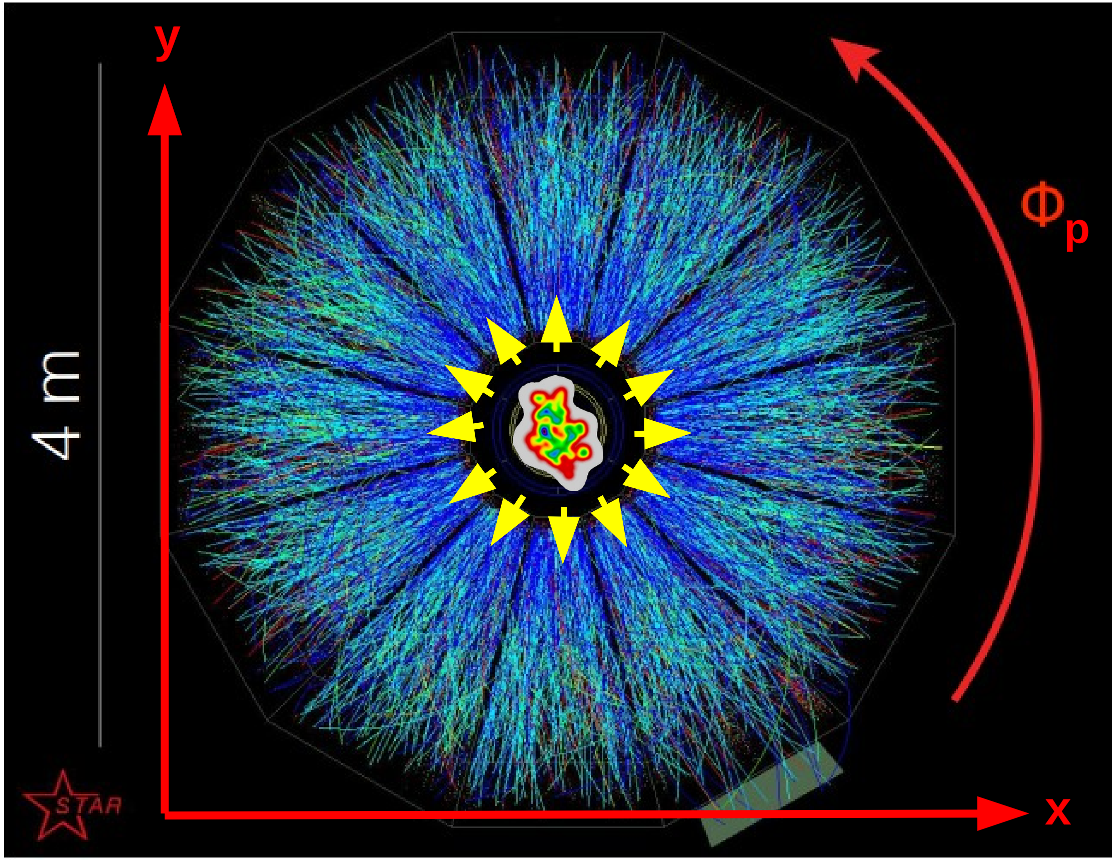
⟹ **Effective description: relativistic fluid.** [Romatschke & Romatschke, 1712.05815]

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$ + viscous corrections ($\eta/s, \zeta/s$, ...)

Equation of state from lattice QCD. Large number of DOF (~40): QGP.

[HotQCD collaboration, 1407.6387]

Main goals: understanding the initial condition and the transport properties.



All we see is particles.

Hydrodynamics describes the motion of the bulk of these particles, sitting at low momenta and following the collective expansion of the system.

$$\frac{d^2N}{dp_T d\phi} = \frac{dN}{dp_T}\left(1 + 2\sum_{n=0}^{\infty} v_n \cos(\phi - \Phi_n)\right)$$

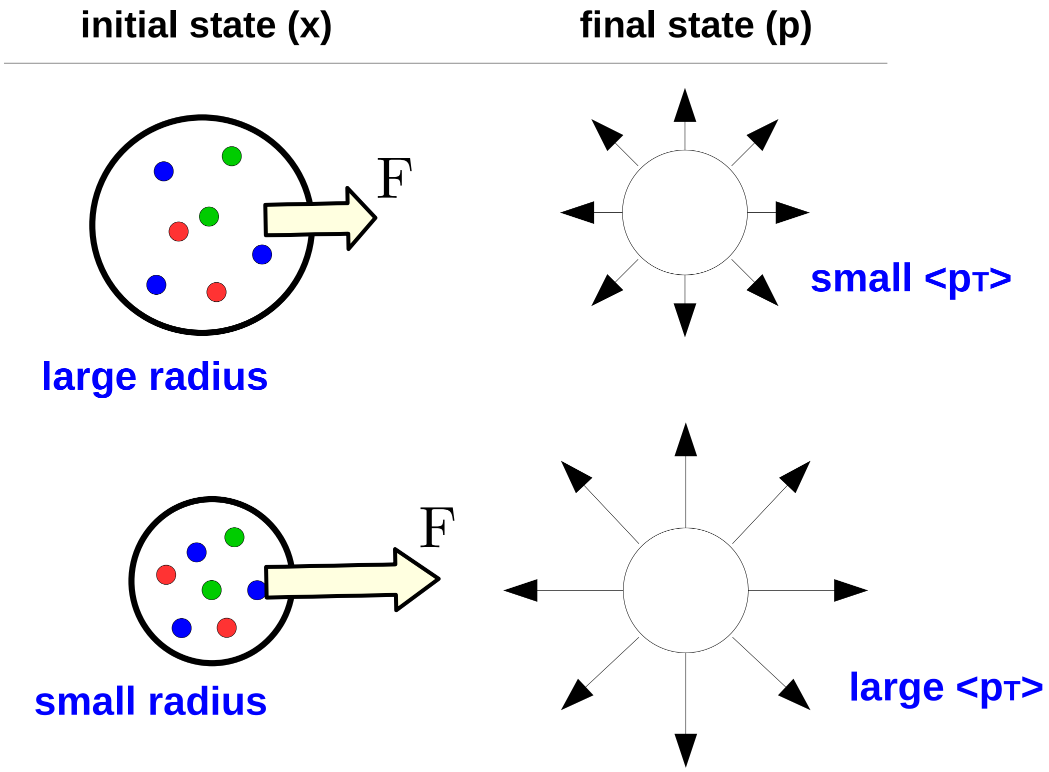
HOW EXPLOSIVE IS THE EXPANSION?

IS PARTICLE EMISSION ISOTROPIC IN AZIMUTH?

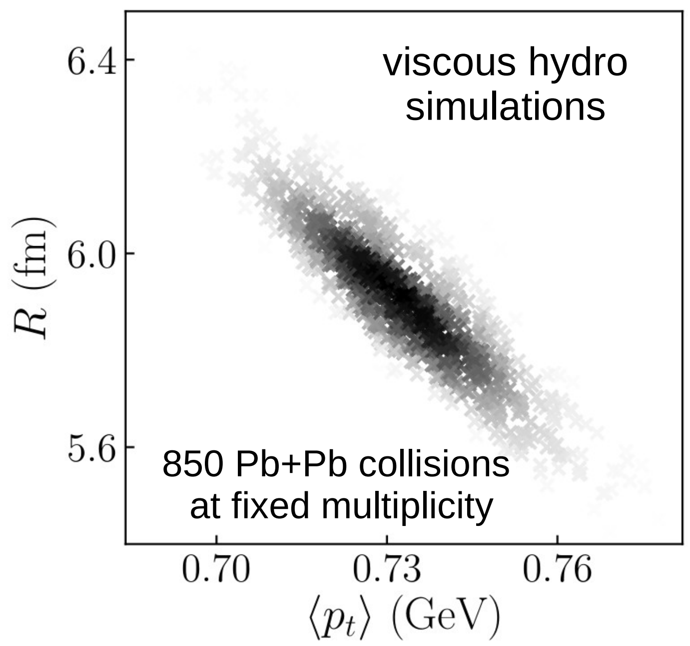
Consequence of hydrodynamics: EXPLOSIVENESS.

$$F = -\nabla P$$

For fixed particle number, the mean particle momentum is a measure of the volume of the QGP.



$$\langle p_{\mathrm{T}} \rangle = \frac{1}{N_{\mathrm{ch}}} \int dp_{\mathrm{T}}\ p_{\mathrm{T}} dN/dp_{\mathrm{T}}$$



Consequence of hydrodynamics: ANISOTROPY.

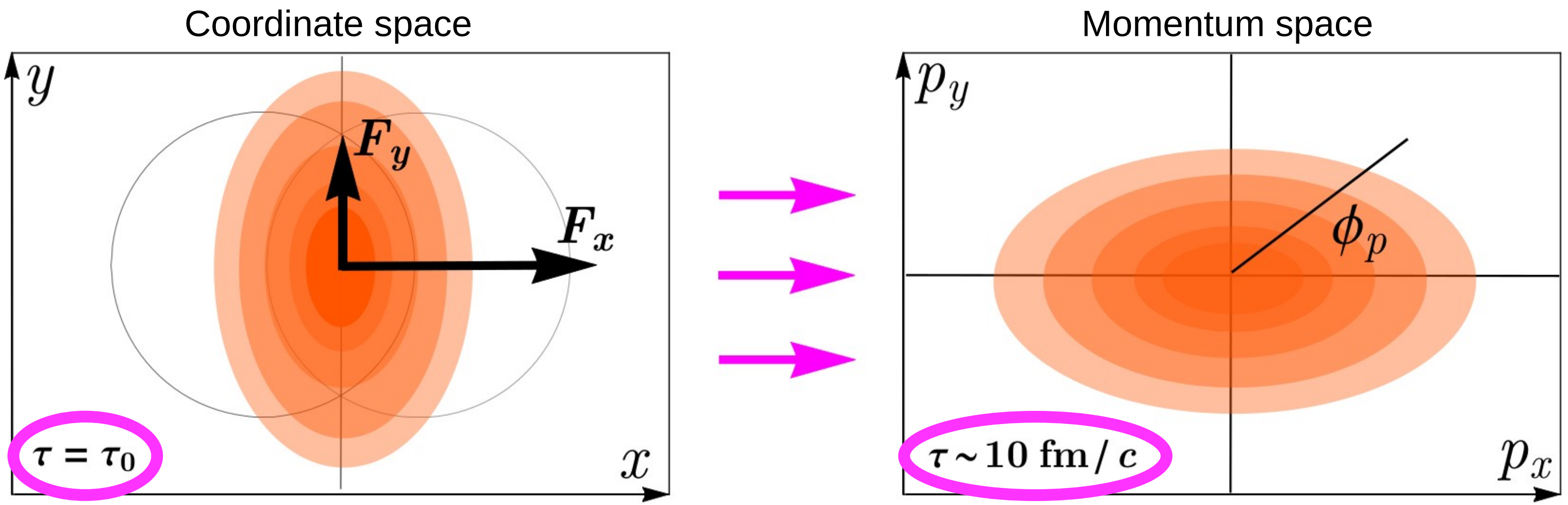
$$F = -\nabla P$$

Pressure-gradient force converts initial spatial asymmetry into final momentum asymmetry.

Harmonic spectrum as a consequence of initial spatial deformations.

$$\frac{d^2N}{dp_T d\phi} = \frac{dN}{dp_T}\left(1 + 2\sum_{n=0}^{\infty} v_n \cos(\phi - \Phi_n)\right)$$

for n=2, "elliptic flow" due to impact parameter



[Ollitrault, 1992]

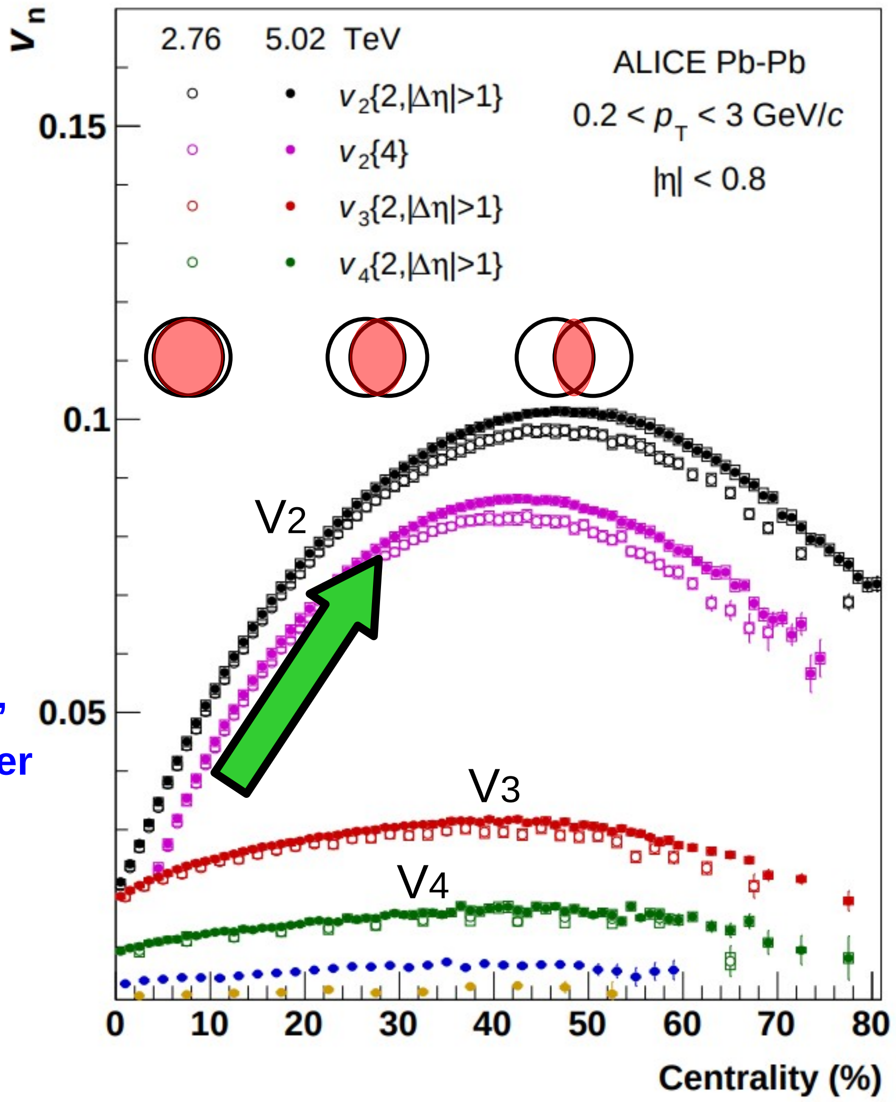
Recent measurements.

[ALICE collaboration, 1804.02944]

$$F = -\nabla P$$

$$\frac{d^2N}{dp_T d\phi} = \frac{dN}{dp_T}\left(1 + 2\sum_{n=0}^{\infty} v_n \cos(\phi - \Phi_n)\right)$$

for n=2, "elliptic flow" due to impact parameter

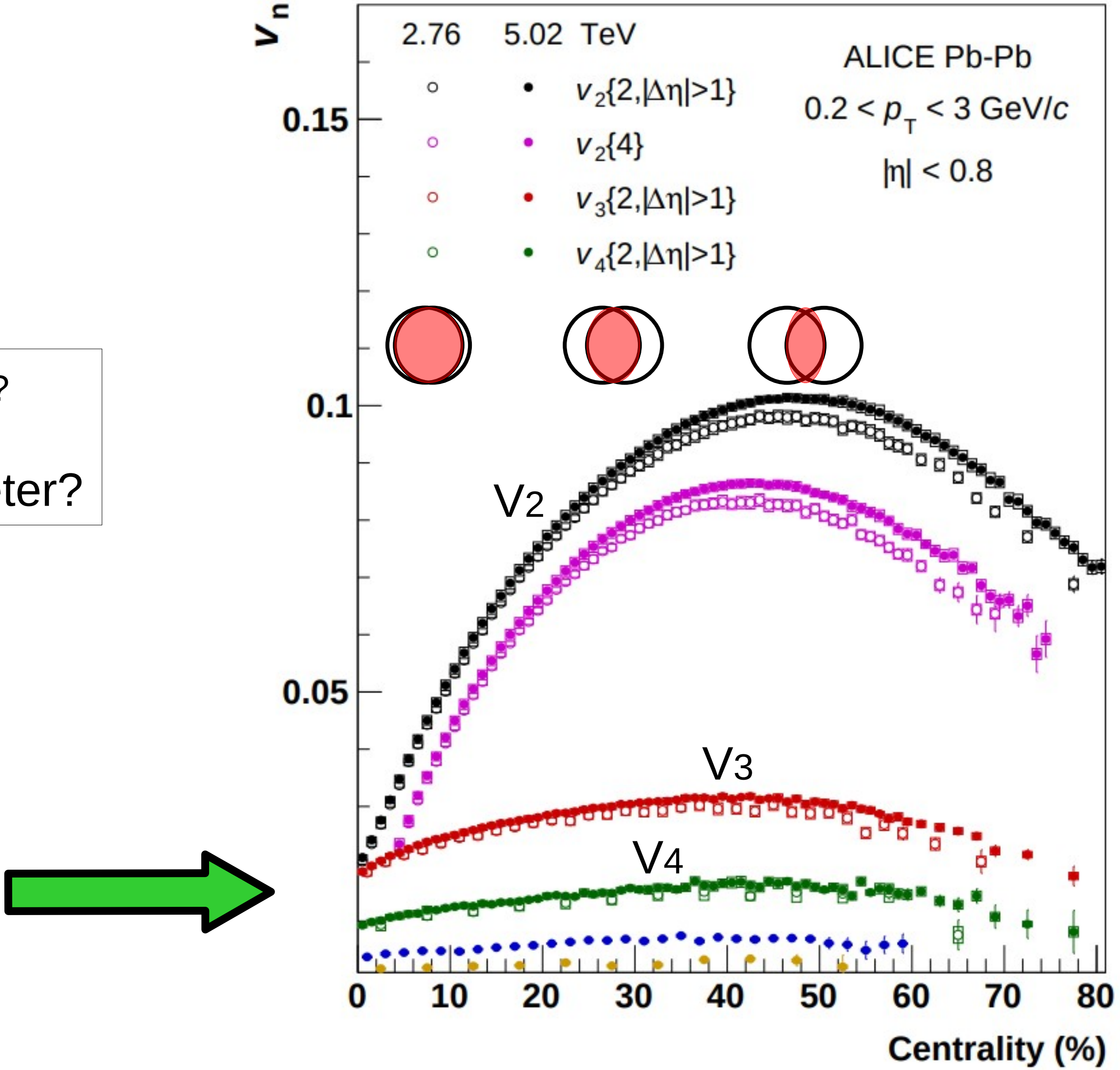


Strong enhancement of V_2 as the system becomes more elliptical. ✓

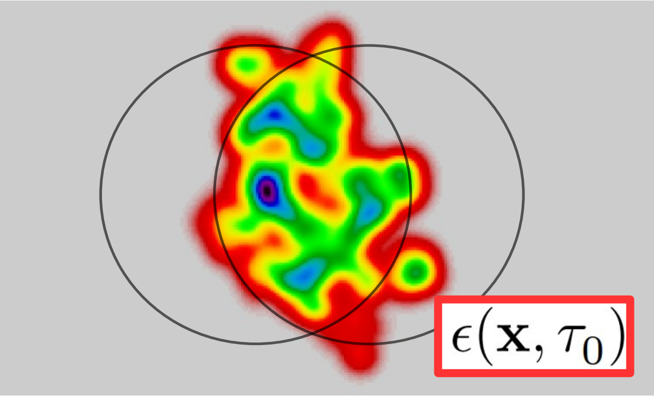
2. Initial-state fluctuations and Glauber Monte Carlo model, energy deposition.

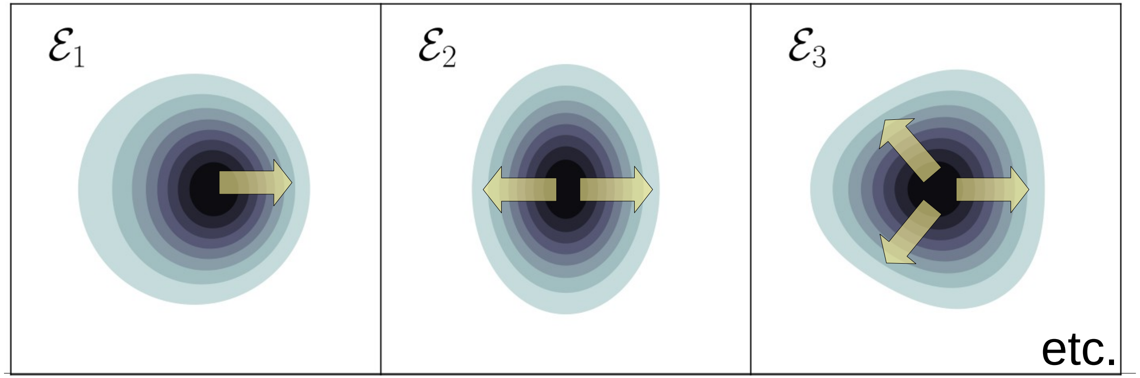
You may wonder, why V_3 and V_4?

Why $V_2 \neq 0$ at zero impact parameter?



QGP is not just a smooth elliptical object.
Hydrodynamics: flow harmonics via pressure gradients.





In QGP, all multi-pole moments of the density are nonzero.
They source the final-state momentum asymmetries.

$$\mathcal{E}_n = -\frac{\int r dr d\phi \; r^n e^{in\phi} \epsilon(r,\phi)}{\int r dr d\phi \; r^n \epsilon(r,\phi)} \quad \Rightarrow \quad V_n \propto \mathcal{E}_n$$

[Teaney, Yan, 1010.1876]

What is the origin of these fluctuations?

Notion of mean field. Independent nucleons in a potential created by strong interaction. Most of correlations left out.

FULL PROBLEM

$$H|\psi\rangle = E|\psi\rangle$$

INDEPENDENT PARTICLE PROBLEM

$$h_i|\phi_k^i\rangle = \varepsilon_k^i|\phi_k^i\rangle$$

$$h_i = \frac{p_i^2}{2m} + V(r_i)$$

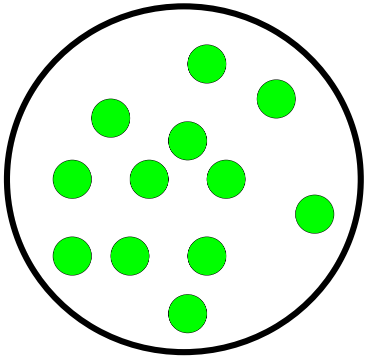
$$V(r_i) = -\frac{V_0}{1+\exp\left(\frac{r_i - R}{a}\right)}$$

Woods-Saxon

Nuclear state from variational equation with Ansatz of independent Fermions.

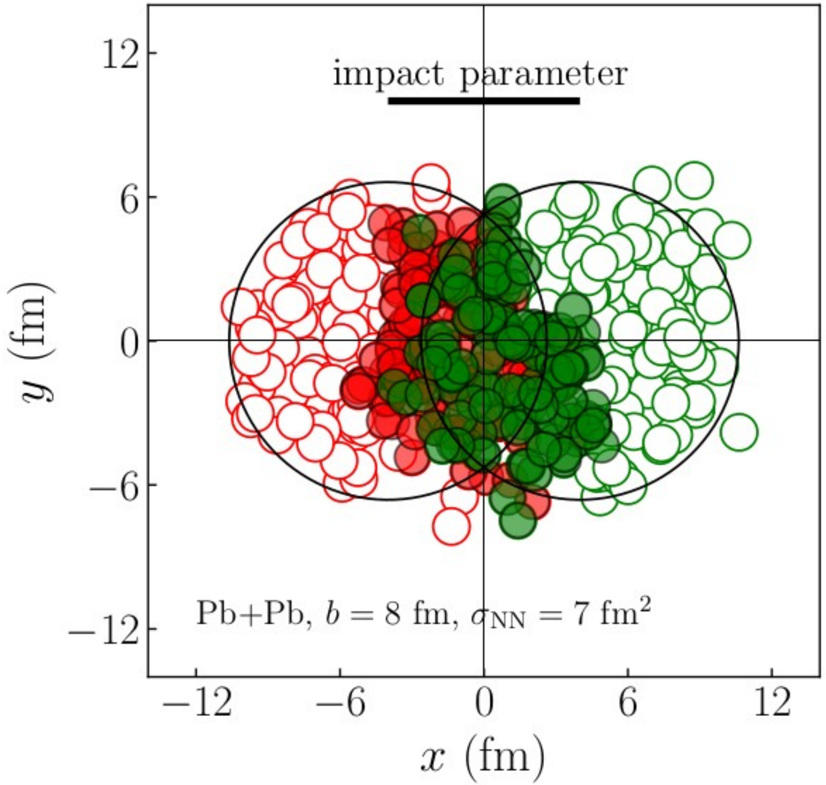
$$\delta \frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle} = 0$$

Slater determinant
(+ pairing)



Improved treatment: Potential generated from effective nucleon-nucleon interaction (Gogny force, Skyrme force, etc.), in "Energy Density Functional" theory.

First talk by Benjamin Bally



GLAUBER MODEL OF NUCLEAR COLLISIONS FOUNDATIONAL PRINCIPLES:

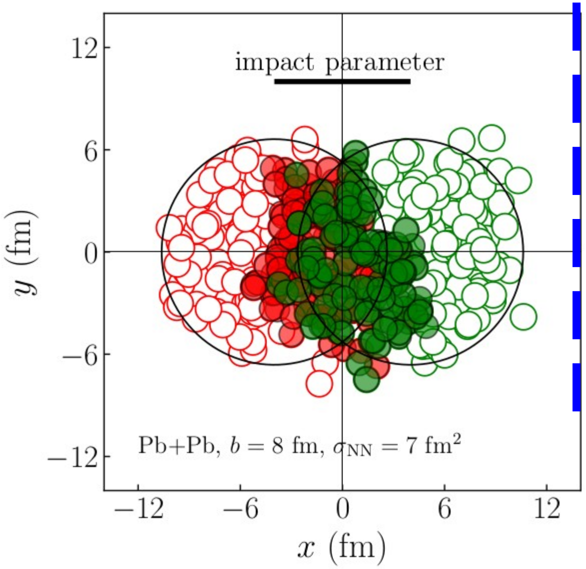
Nucleons independently sampled.
(System is in the ground state)
Interaction as a "quantum measurement".

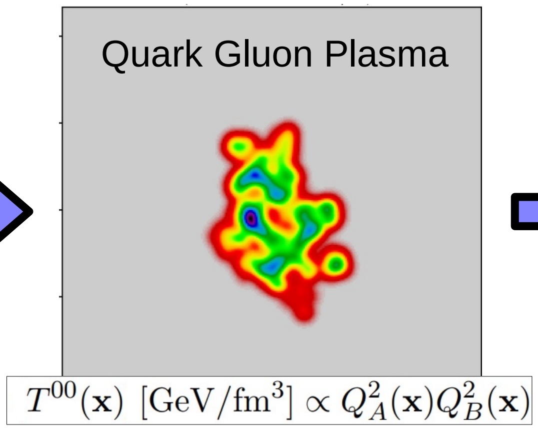
Notion of mean field justifies the Glauber Monte Carlo model!

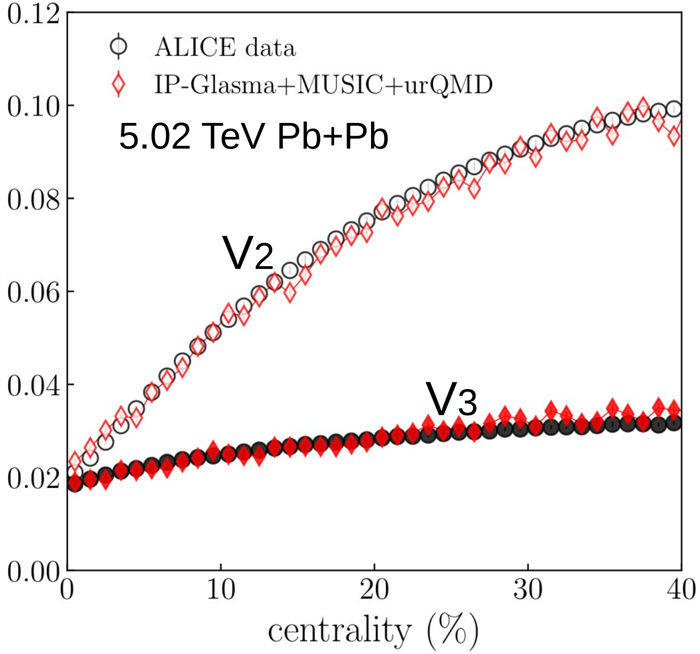
What next? Interaction and subsequent evolution do not yield fluctuations on large scales.

QUANTUM FLUCTUATIONS

"DETERMINISTIC" EVOLUTION







Standard model of heavy-ion collisions is greatly successful, and probably "correct".

Fluctuations on large scales (>1fm) come from nuclear structure.

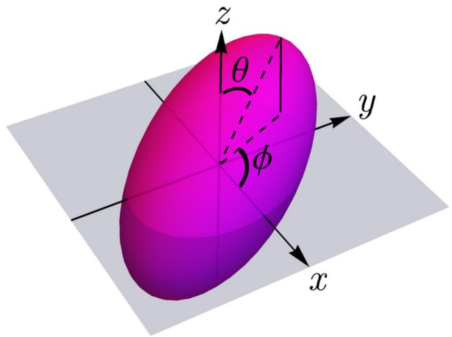
3. Heavy-ion collisions as a probe of collective correlations of nucleons.

All is well for 208Pb, but strong spatial correlations are typically present.

Data-driven approximation: “deformed” potential.
Intrinsic deformed shape (bag of nucleons) with random orientation.

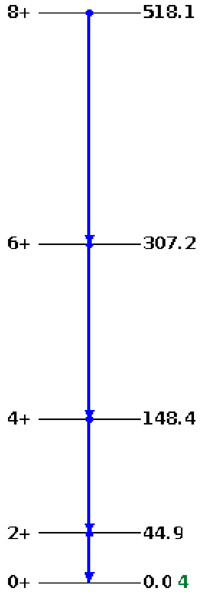
E = B J(J+1)

NB: ground state has J=0.



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

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

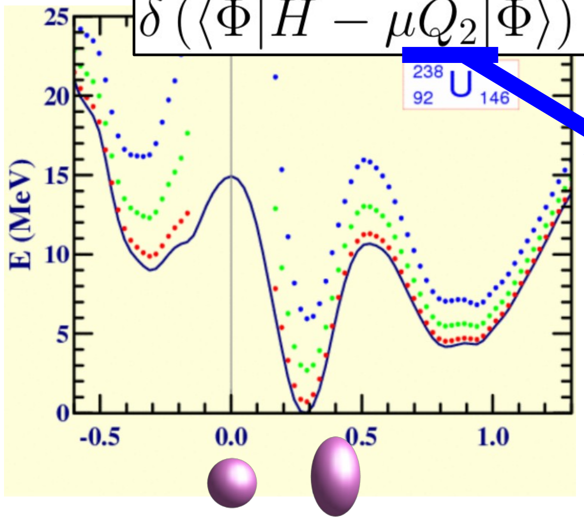


Look for solution of variational equation as a function of the deformation of the intrinsic shape.

↓

Most of ground states have some quadrupole deformation.

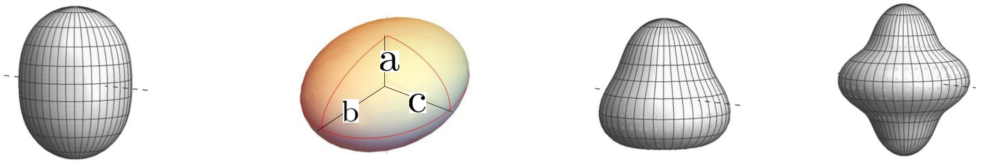
$$\delta\left(\langle\Phi|H-\mu Q_2|\Phi\rangle\right)=0$$



Quadrupole moment of the bag of nucleons

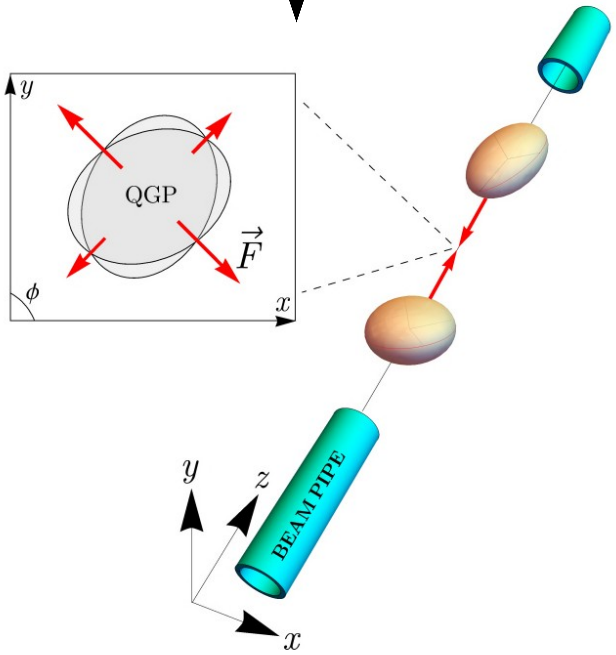
Generalize the Woods-Saxon profile to include intrinsic deformations:

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



Spatial correlations will show up at high energy.

THIS TALK!

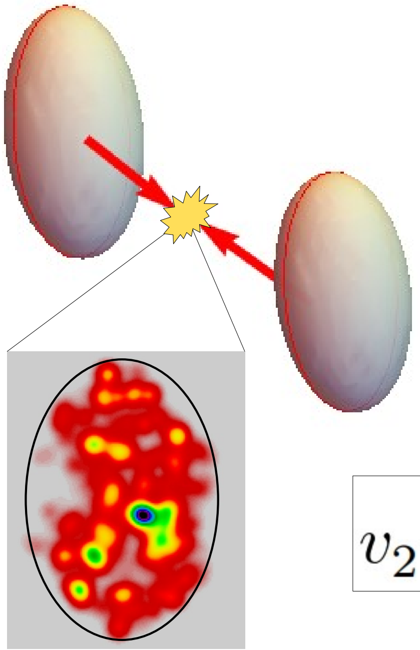


Collide nuclei with intrinsic deformations.

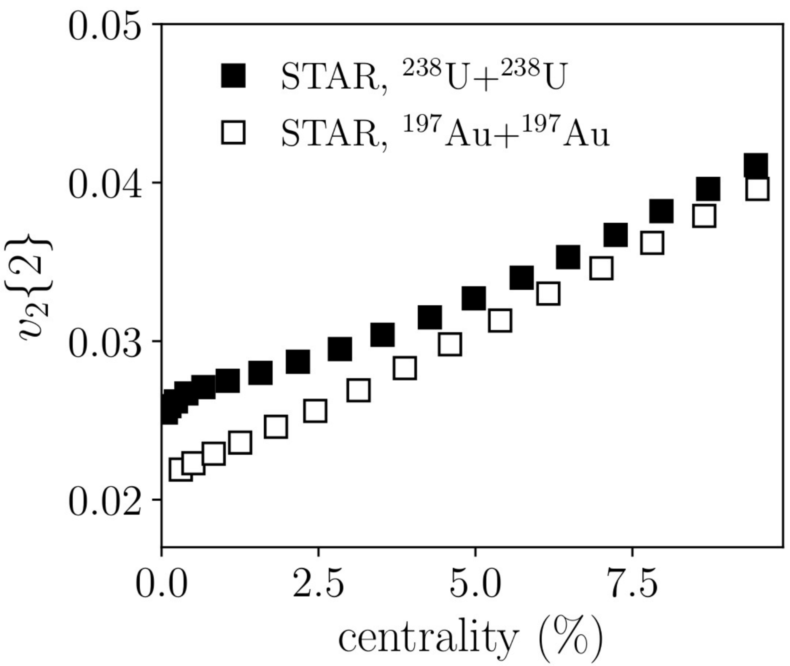
The configuration of nucleons is deformed and acquires a random orientation.

MODEL-INDEPENDENT SIGNATURES

In the limit of fully-overlapping nuclei, contamination of side-on-side collisions leads larger fluctuations of elliptic flow



$$v_2\{2\}^2 = a_2 + b_2\beta_2^2$$

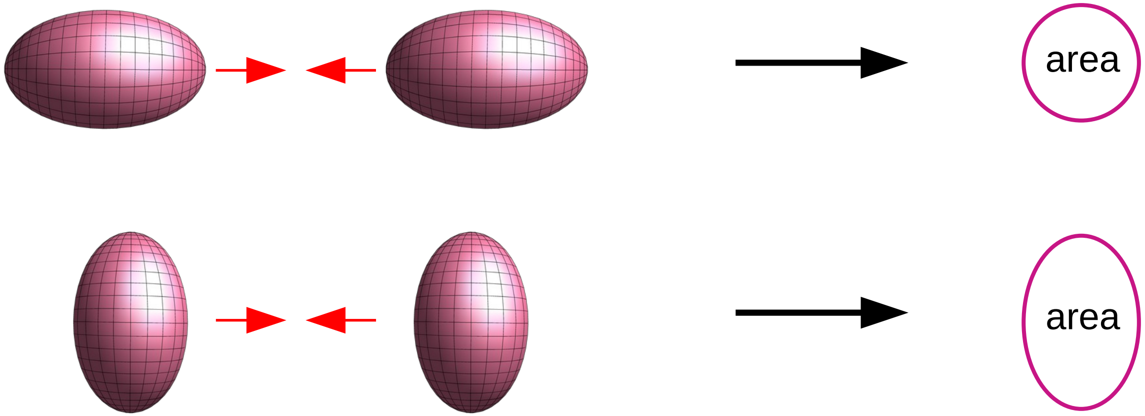


Important: coefficient a_2 is larger in Au-Au (~1/A). Larger deformation of ^{238}U explains data.

A new “classical phenomenon”. What if we select events with a large overlap area?

tip-tip

body-body



small v_2
small area
large $<p_t>$

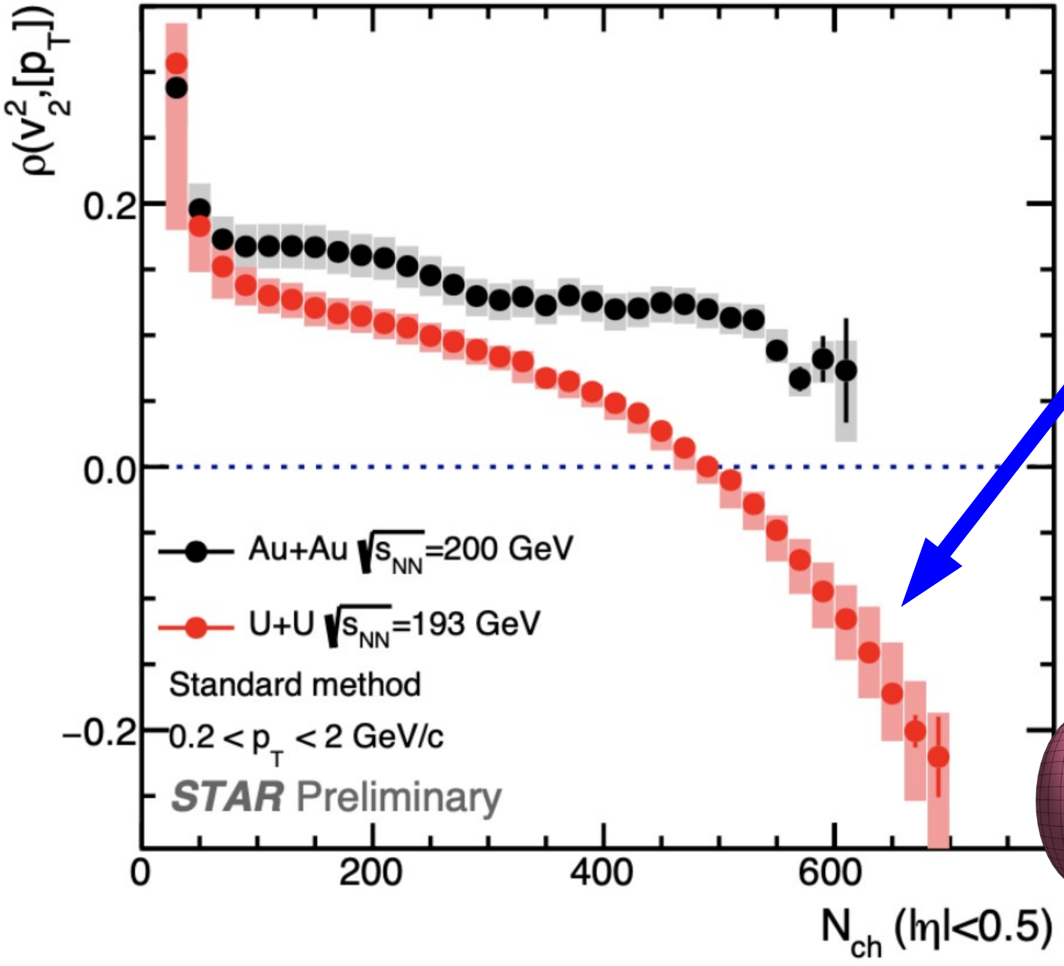
large v_2
large area
small $<p_t>$

Area of overlap to control the relative orientation of the colliding ions.

Measure correlation of v_2 and $<p_T>$ in fully-overlapping events. It is negative.

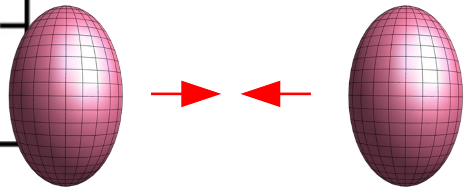
$$\rho_2 \equiv \rho(v_2^2, [p_t]) = \frac{\langle \delta v_2^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}} \longrightarrow \boxed{\rho_2 < 0}$$

MODEL-INDEPENDENT SIGNATURES



IT GOES NEGATIVE

Correlation between shape and size of the QGP provides the best sensitivity to deformation in colliding ions.

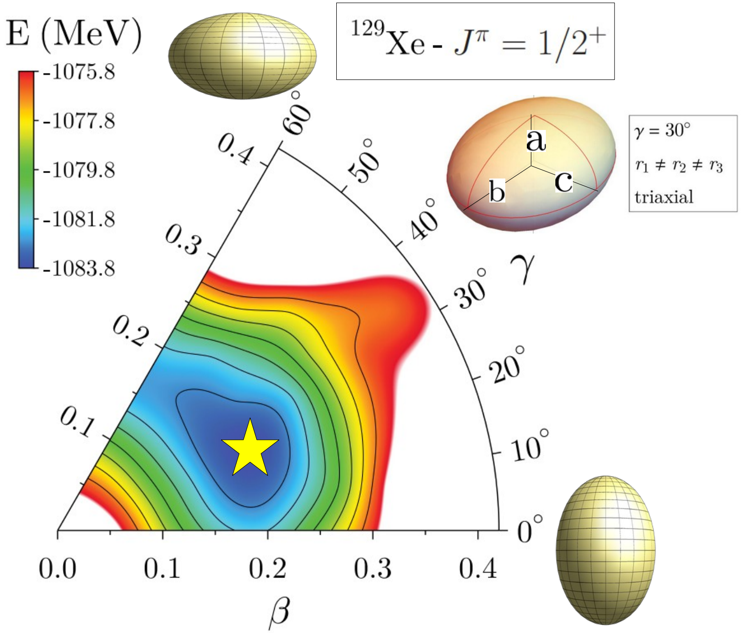


The observable probes as well the triaxiality (simple geometric arguments).
It has a leading dependence on γ.

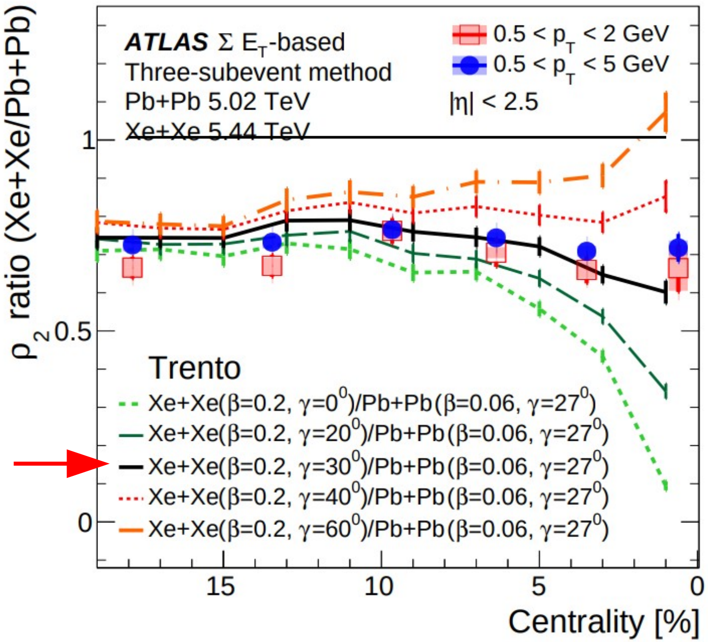
$$\rho_2 \propto -\cos(3\gamma)\beta_2^3$$

[Jia, 2109.00604]

Example: Triaxial deformation of ^{129}Xe. Observe deviation from ^{208}Pb+^{208}Pb baseline.



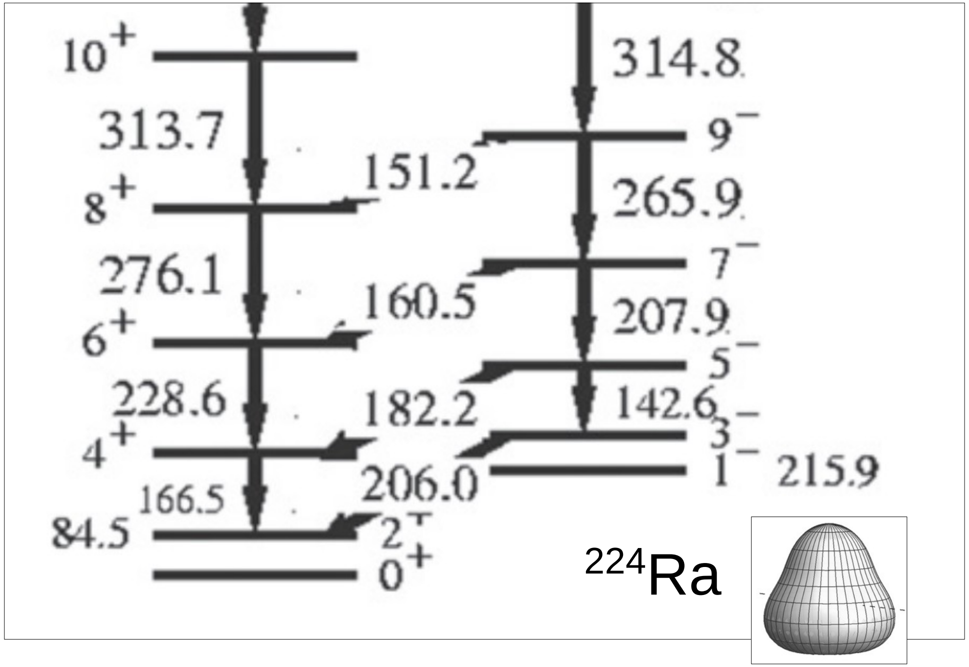
[Bally et al., PRL **128** (2022) 8, 082301]



CONSISTENCY ACROSS ENERGY SCALES

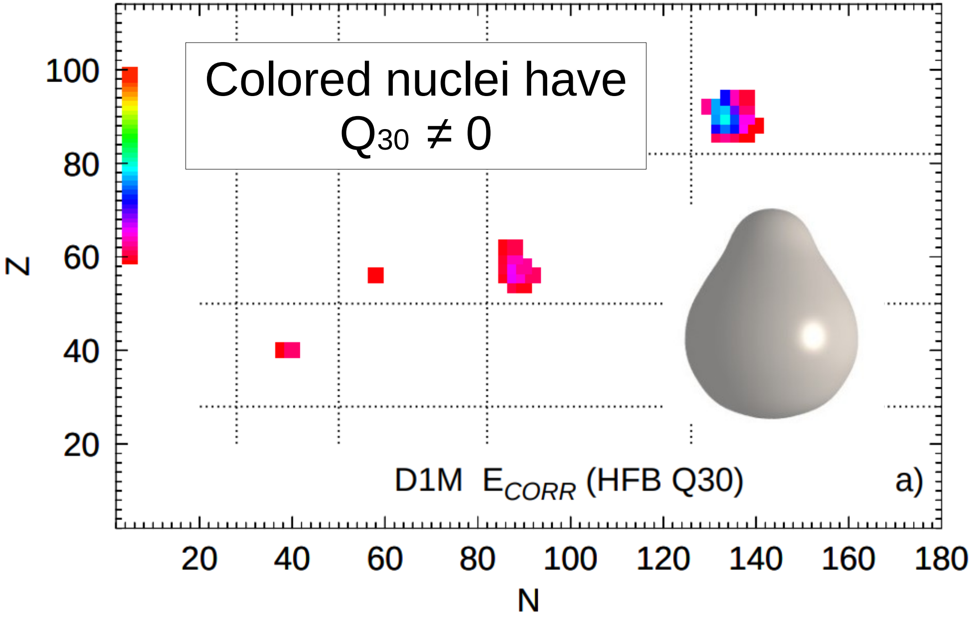
One step further. What about the octupole deformation?

Manifestation of “static” (mean-field) octupole deformation in low-energy experiments.



But this is almost never observed …

… in agreement with nuclear models

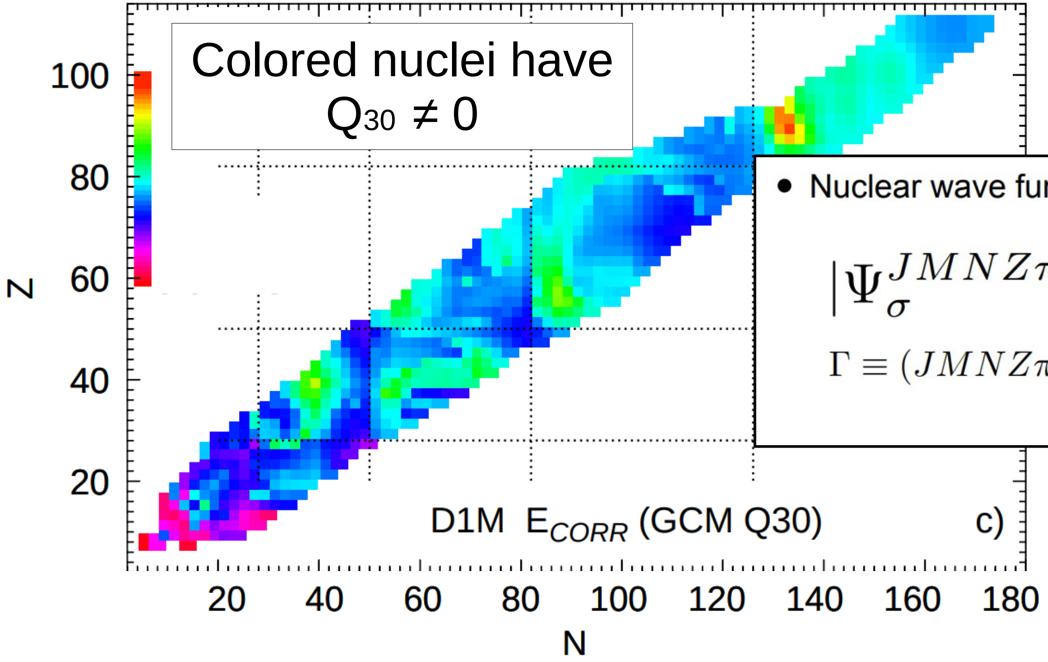


[Bertsch, Robledo, J. Phys. G **42** (2015) 5, 055109]

In short: no evidence of “permanent” octupole deformations.

However (!), all nuclei are octupole-deformed when correlations “beyond mean field” are taken into account. **They are associated with the <u>restoration of broken symmetries.</u>**

even ^{238}U is spherical!



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

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

$$\Gamma \equiv (JMNZ\pi)$$

MIXING — **PROJECTION** — **DEFORMED MF STATE**

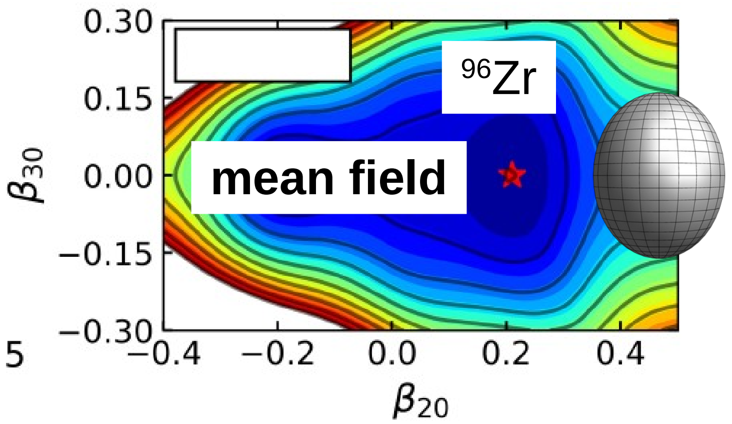
[Bertsch, Robledo, J. Phys. G **42** (2015) 5, 055109]

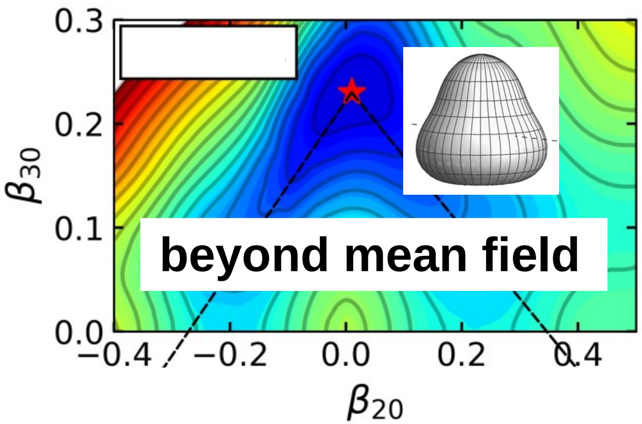
The resulting weights $f_{\sigma;qK}^{JMNZ\pi}$ will determine what deformed states are important in the final wave function. Octupole deformations appear in this way.

<u>**Important:** These “dynamical” deformations can not be determined in low-energy experiments.</u>

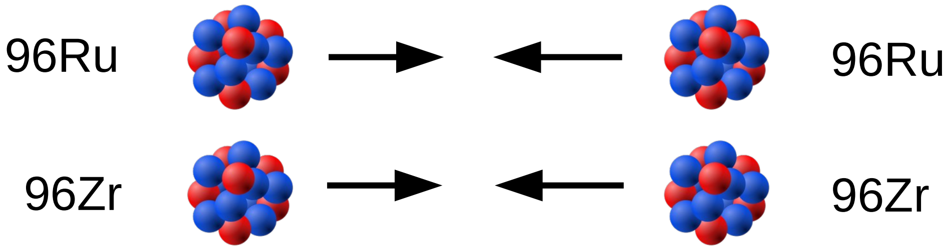
Beyond-mean-field correction is very important for 96Zr.

[Rong, Lu, arXiv:2201.02114]





Much potential from "isobar collisions" performed a BNL RHIC.



If X and Y are isobars:

Ratios of observables is unity?

$$\frac{\mathcal{O}_{\mathrm{X+X}}}{\mathcal{O}_{\mathrm{Y+Y}}} \stackrel{?}{=} 1$$

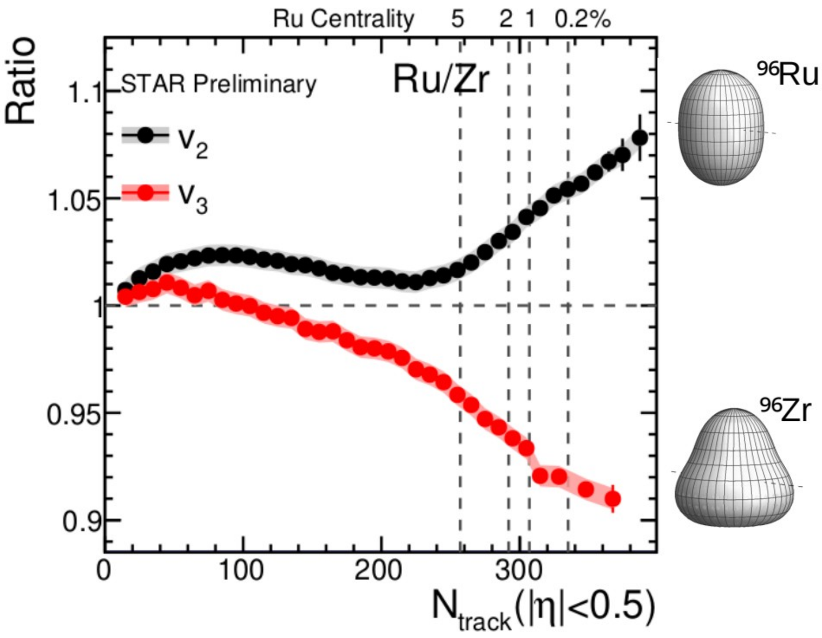
Departure from unity from nuclear structure.

Breakthrough by the STAR Collaboration.

[STAR Collaboration, Phys. Rev. C **105** (2022) 1, 014901]

Heavy-ion collisions probe all spatial correlations of nucleons in the wave function.

“Static” or “dynamical” octupole deformations are the same, they will show up in the same way, and will be detected with the same methods.



Can low-energy nuclear theory even predict such effect?

3. Heavy-ion collisions and *ab-initio* nuclear structure theory.

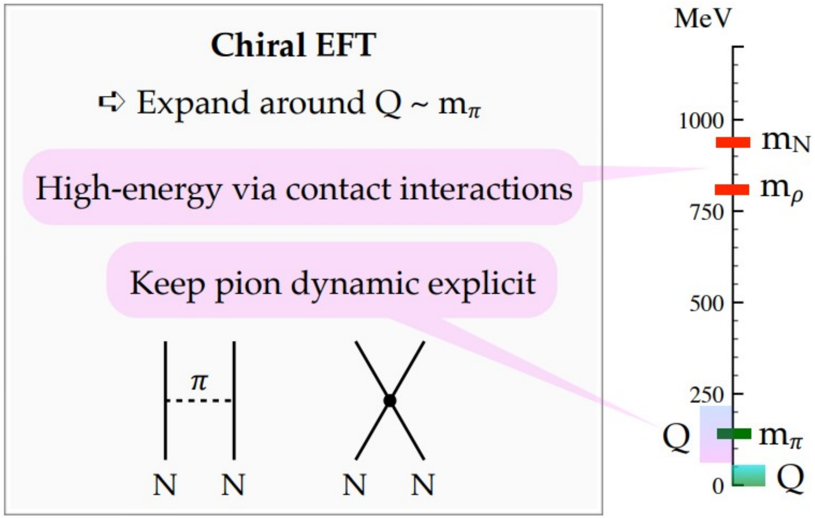
Idea: Solving directly the Schrödinger equation (without an Ansatz for the wave function).

$$\boxed{H}|\psi\rangle = E|\psi\rangle$$

[Somà, Eur. Phys. J. Plus 133 (2018) 10, 434]

TWO-FOLD PROBLEM – (1/2) THE INTERACTION.

Effective theory of low-energy QCD,
“chiral effective field theory”.



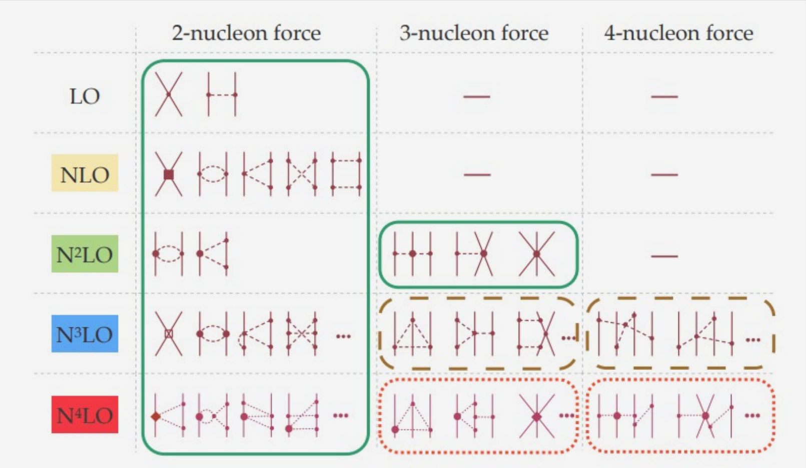


Fig. 19. Diagrams appearing in the first five orders of chiral EFT derived within Weinberg power counting. Dashed lines and dots represent pion exchanges contact interactions respectively. Sectors contoured with a green solid line have been formally derived and are routinely implemented in nuclear structure 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.

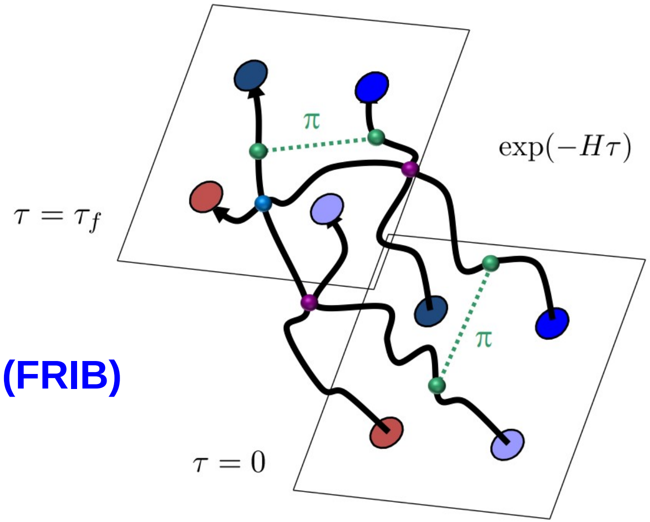
Idea: Solving directly the Schrödinger equation (without an Ansatz for the wave function).

$$H|\psi\rangle = E|\psi\rangle$$

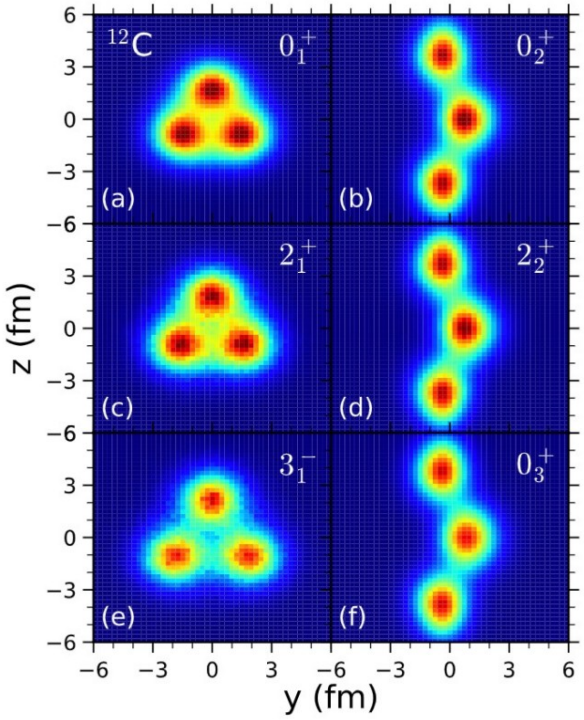
TWO-FOLD PROBLEM – (2/2) SOLVING THE EQUATION.

[Shen *et al.*, arXiv:2202.13596]

Example: Nuclear Lattice Effective Field Theory (NLEFT)



from Dean Lee (FRIB)

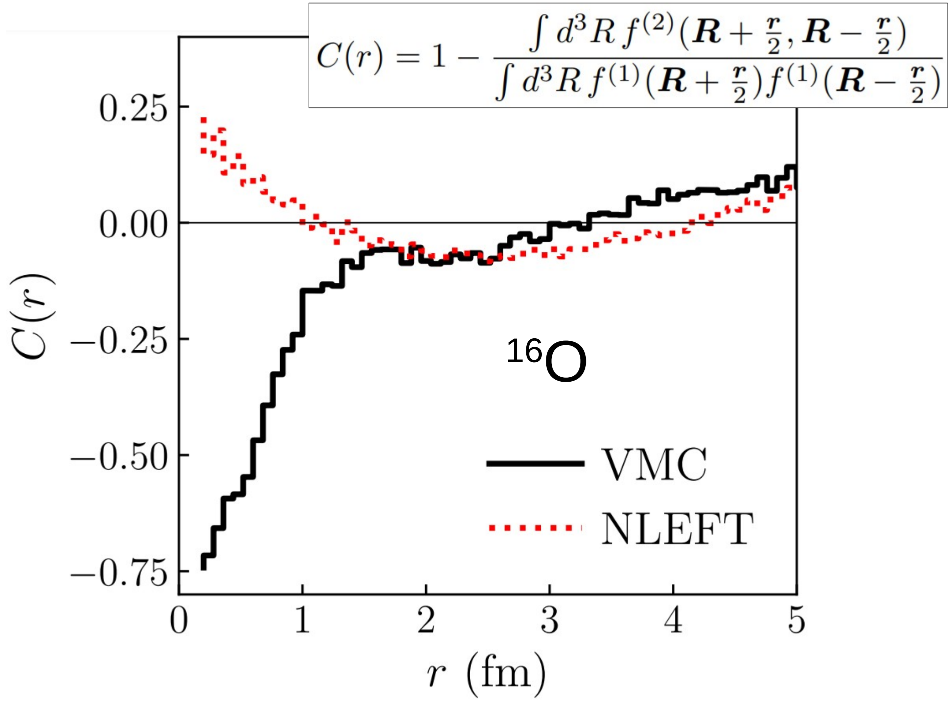


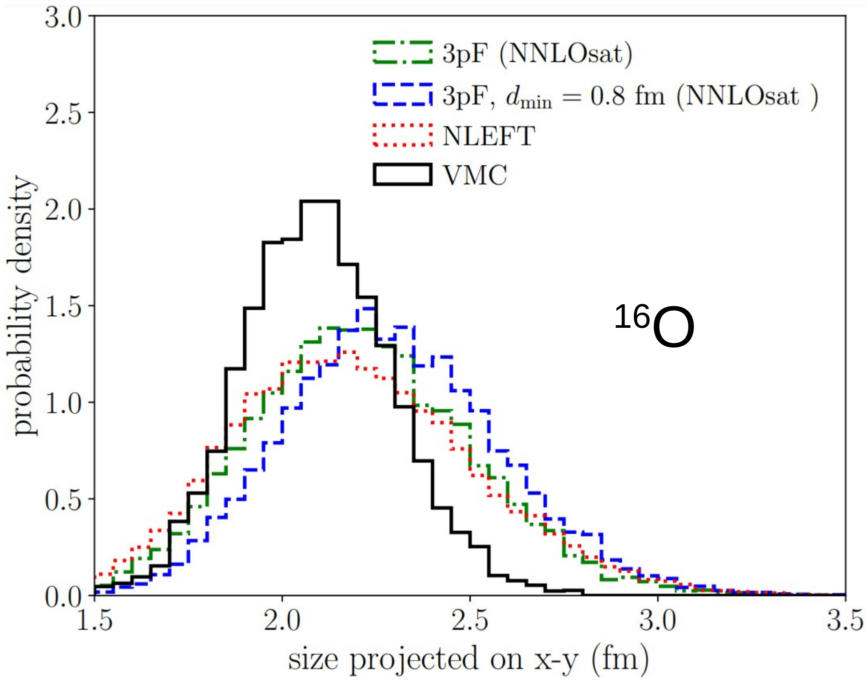
We have ~10 000 samples of fully-correlated nucleons in oxygen-16 nuclei from:

- Nuclear Lattice Field Theory (NLEFT, simple interaction, pion-less EFT)
- Variational Monte Carlo method (VMC, better interaction, AV18 + UIX)

[Londardoni *et al.*, Phys. Rev. C 96 (2017) 2, 024326]

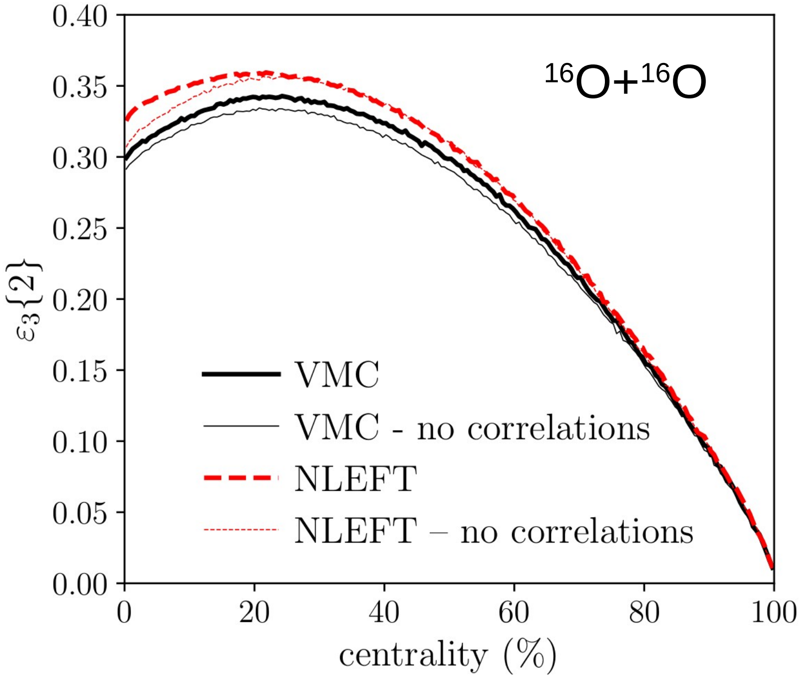
Short- and large-scale physics seem very different. Details of nucleon positions matter!

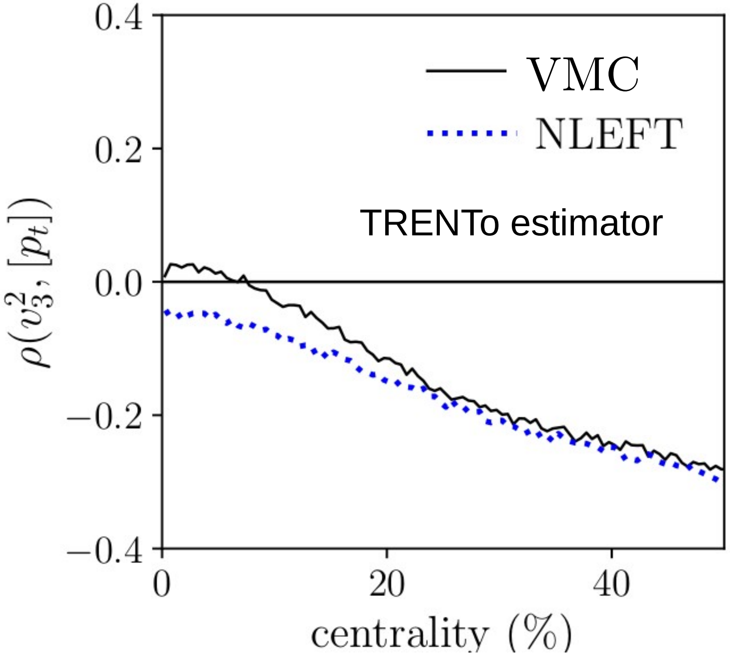




Detailed analysis of fluctuations and correlations reveals effects akin to octupole deformation. Only visible in the NLEFT calculation, not the VMC one.

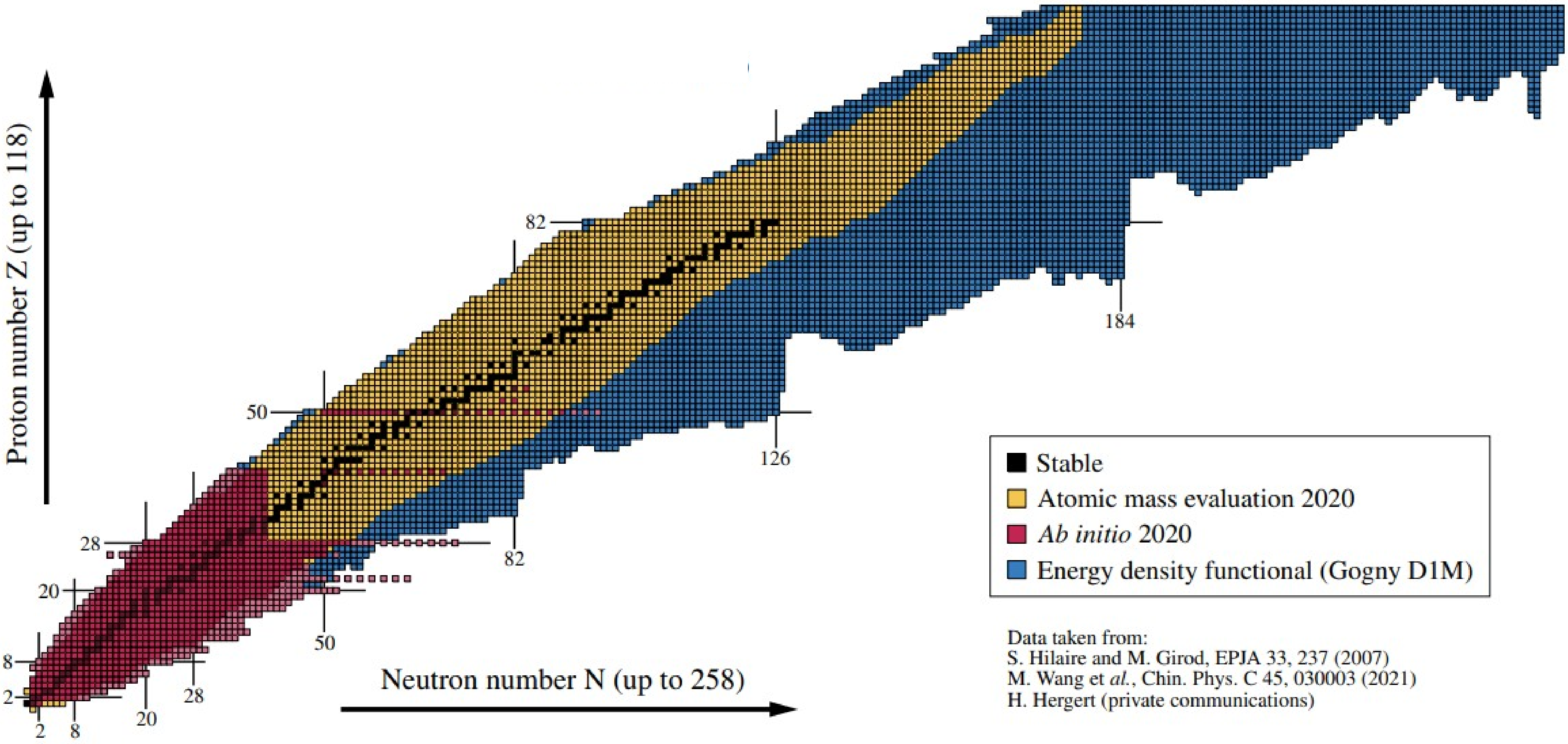
Clear impact on high-energy observables in hydrodynamic model. What about low-energy data?





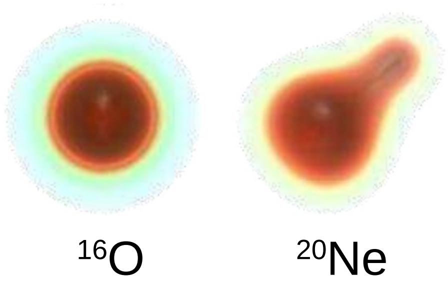
[G. Giacalone, G. Nijs, W. van der Schee, work in preparation]

Prospect: Large nuclei achievable in next decade.
Any use for high-energy nuclear studies, or vice versa?



from Benjamin Bally (Paris-Saclay)

A good case: Studies with strongly-correlated nuclei. Great example is ^{20}Ne.



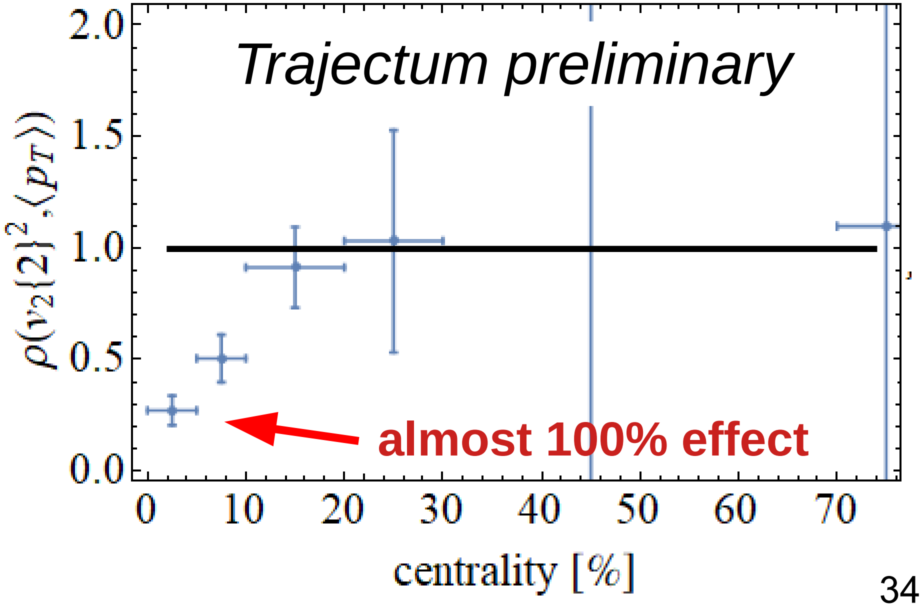
Strong geometry effects in a small system.

Extreme structure to test hydrodynamic response.

⇕

Nucleus amenable to *ab-initio* description.

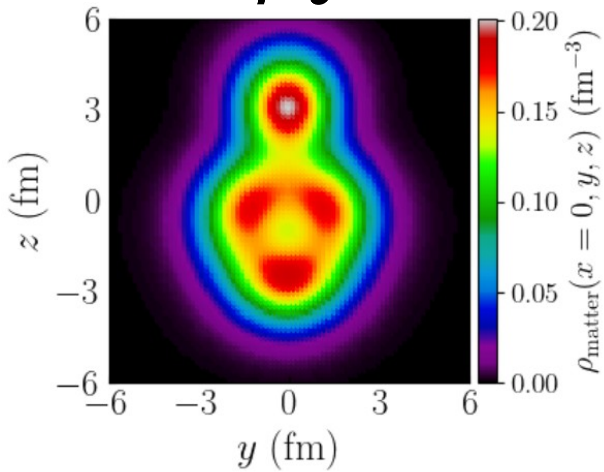
Ratio ^{20}Ne+^{20}Ne / ^{16}O+^{16}O

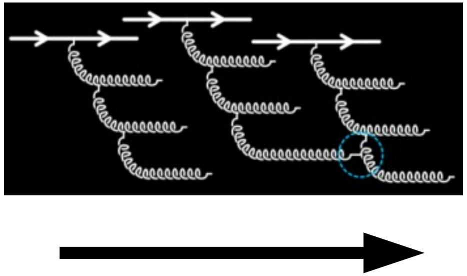


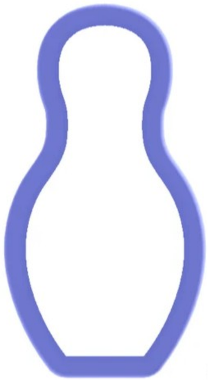
Longitudinal structure and beam-energy dependence.

Neon-20 is a strongly-correlated system (highly-deformed and clustered).
Do these correlations survive when beam energy/rapidity increases?

Y=0







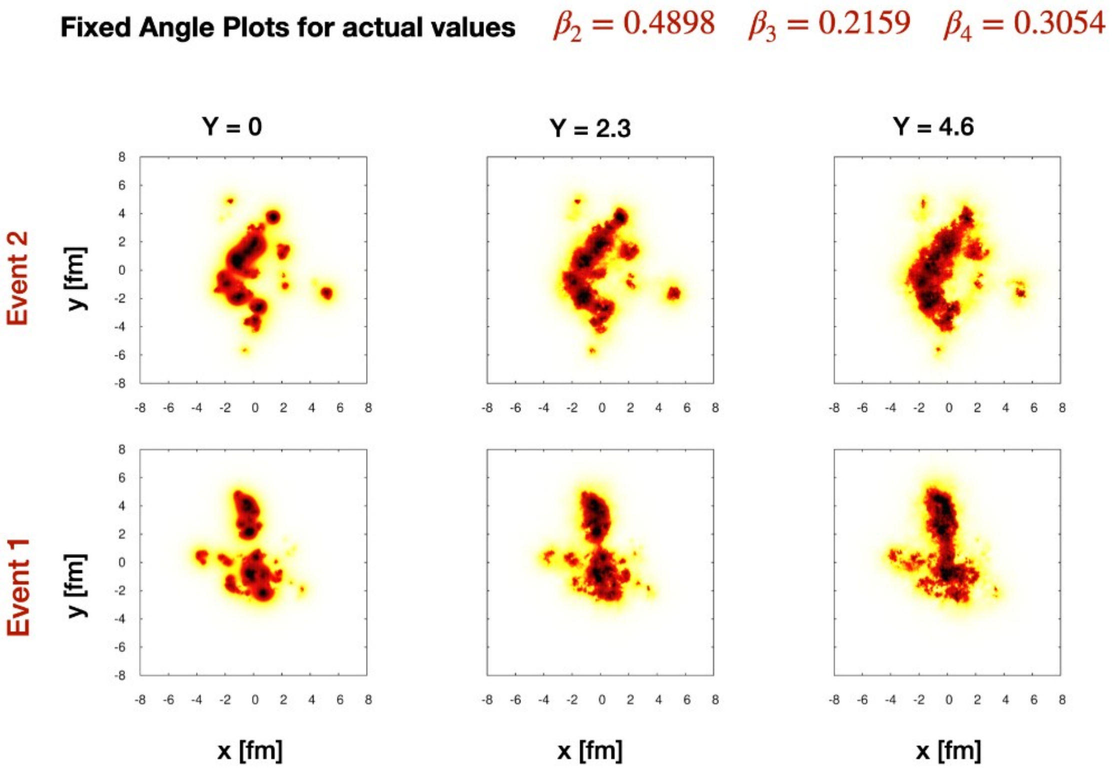
Y=2.4?

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

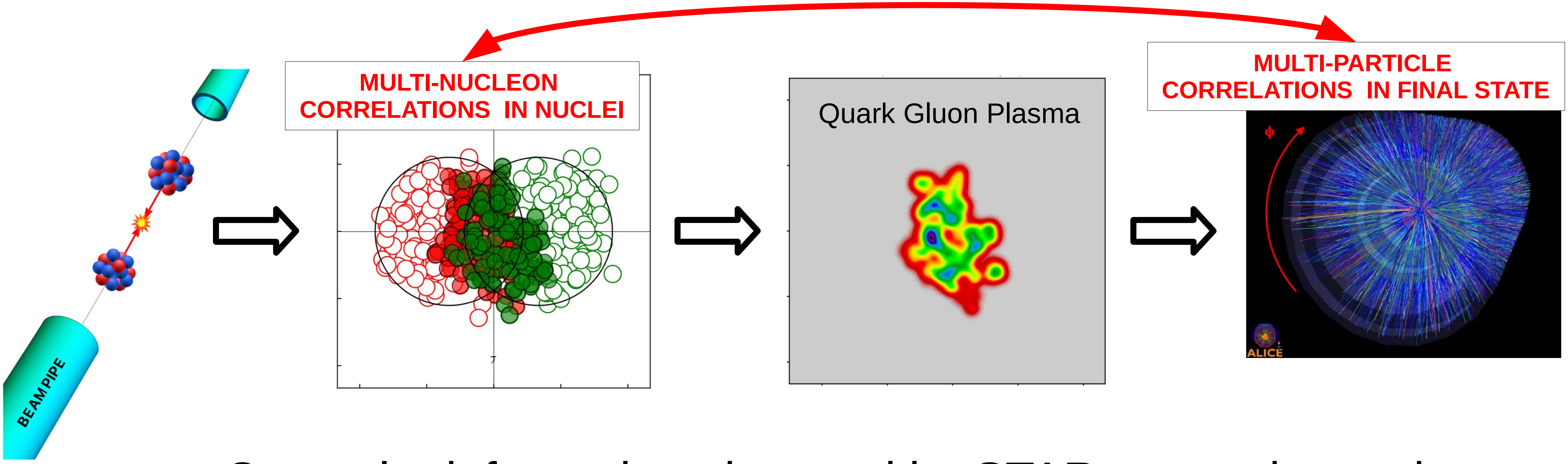
Window onto the role of quarks and gluons (QCD) for collective nuclear structure.

Deformation input from *ab-initio* Projected Generator Coordinate Method.
Evolution towards small Borken x within color glass condensate theory.



My hope: the octupole deformation will be significantly reduced…

CONCLUSION



- Octupole deformation observed by STAR proves heavy-ion collisions can effectively access all spatial correlations in nuclei. Possibly the best probe of such correlations.
- Unique synergy between heavy-ion output and *ab-initio* nuclear theory. Exciting research direction.

THANK YOU!
(and stay tuned)

Intersection of nuclear structure and high-energy nuclear collisions

Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

Organizers:
Giuliano Giacalone (Heidelberg)
Jiangyong Jia (Stony Brook & BNL)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Jaki Noronha-Hostler (Urbana-Champaign)
Fuqiang Wang (Purdue)

Backup: Neutron skin physics with heavy-ion collisions.

Heavy-ion collisions probe neutron distributions in nuclei. How to exploit this?

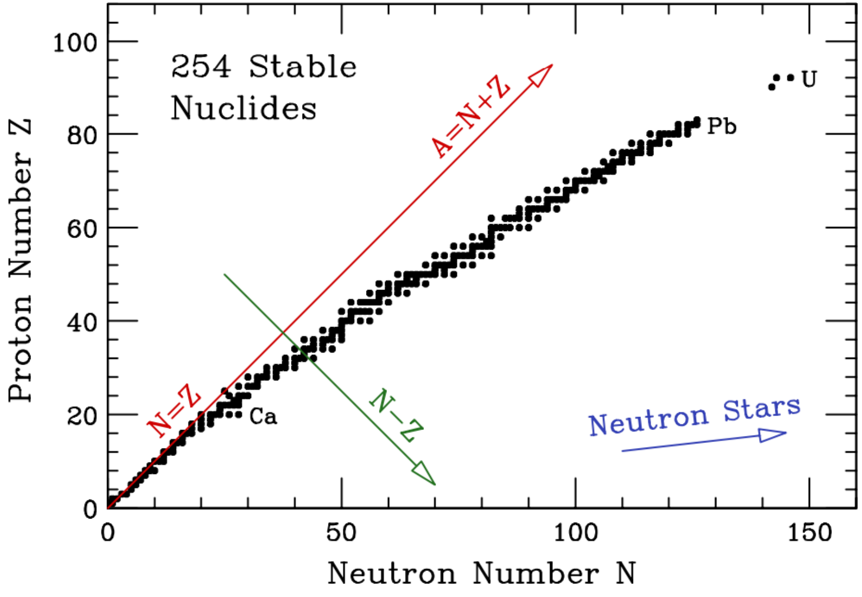
Major motivation from neutron star physics. Equation of state of nuclear matter:

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

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

Symmetry energy usually Taylor expanded around saturation density:

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

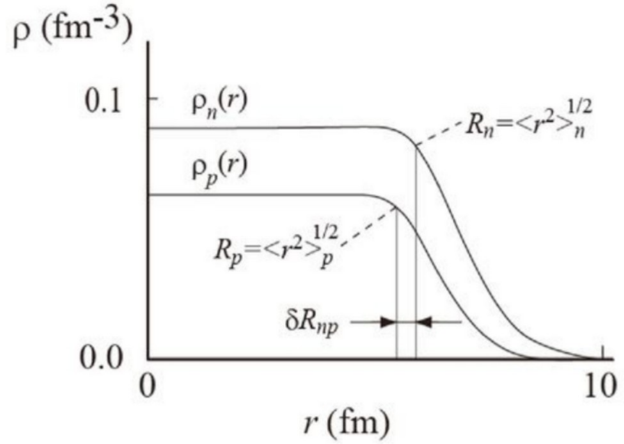


[From P. Danielewicz (MSU)]

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.

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):

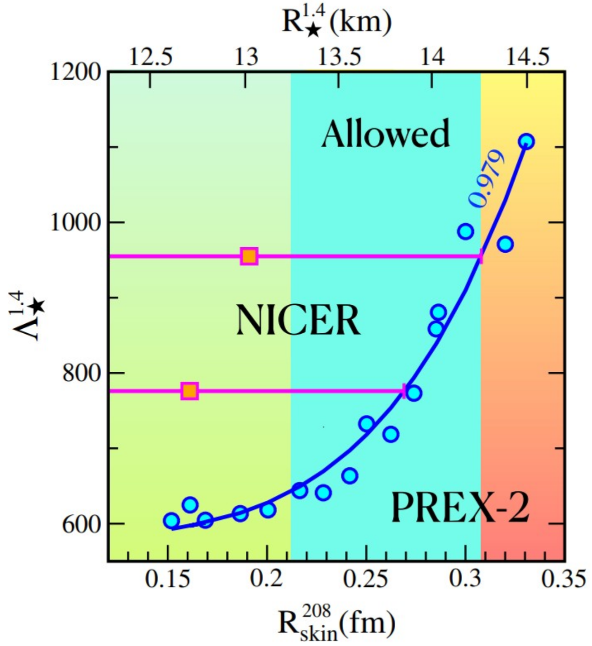
$$\Delta r_{np} = 0.283 \pm 0.071 \text{ fm}$$

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

[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]

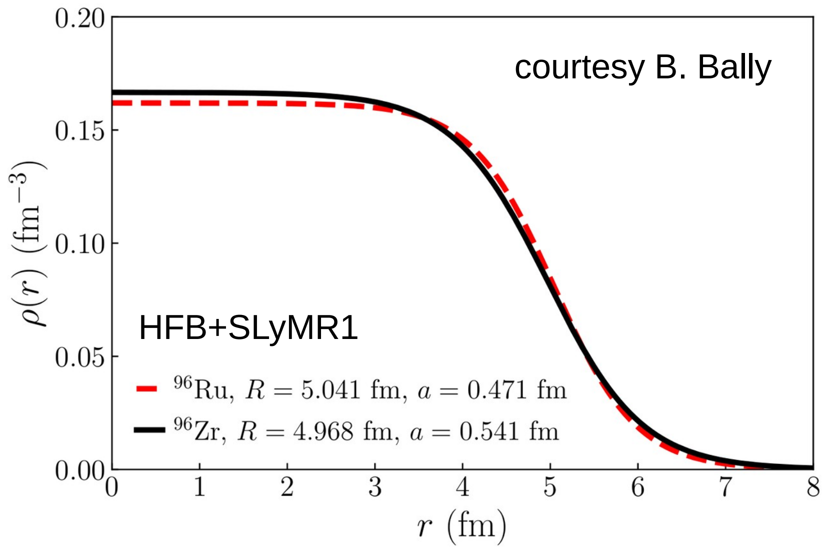


From GW170817

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].

Can we contribute to this effort at RHIC?

Possibilities from isobars. Accessing neutrons.

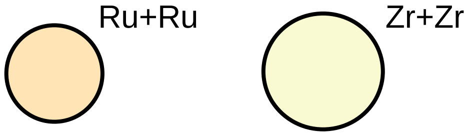


Radial profile parameters:

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r - R}{a}\right)}$$

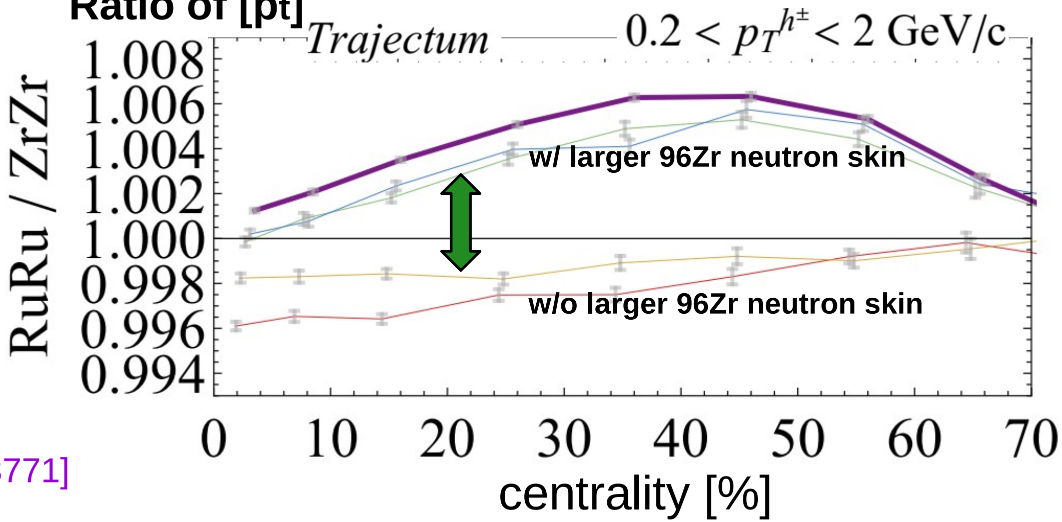
- 96Zr, more diffuse **due to larger N**.
- 96Ru, sharper surface.

Due to the smaller neutron halo,
Ru+Ru systems are more compact.

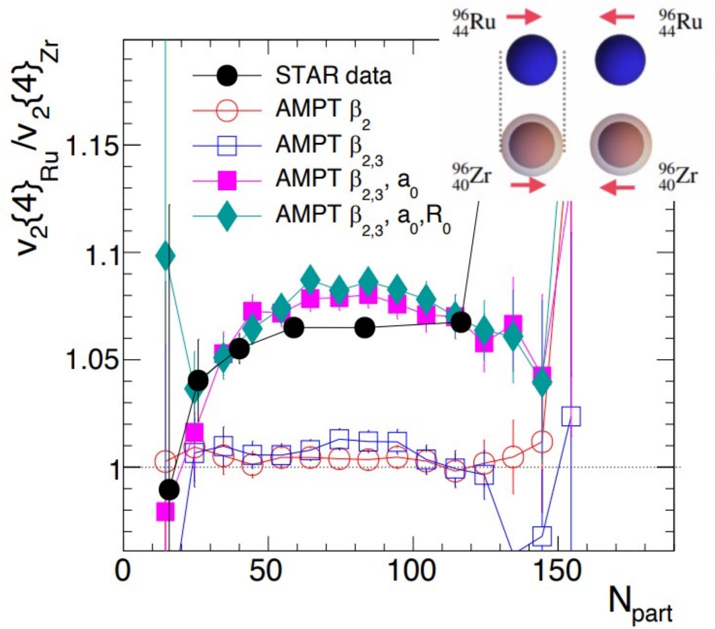


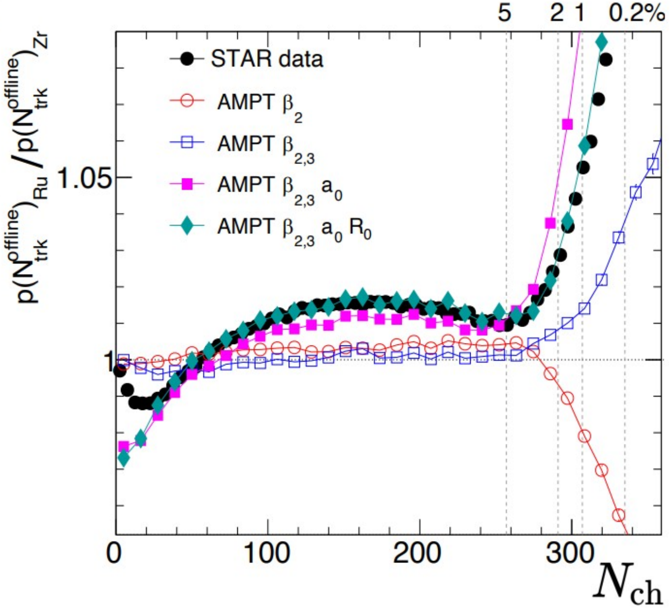
Effect on radial flow, i.e.,
mean transverse momentum, [pt].

Ratio of [pt]



[Nijs, van der Schee, arXiv:2112.13771]
[Xu, et al., 2111.14812]





Impact on specific observables has been isolated.

[Xu et al., 2103.05595]
[Jia, Giacalone, Zhang, 2206.10449]

– [pt], the average transverse momentum.

– v2{4}, the average ellipticity in the reaction plane.

– P(Nch), the probability distribution of multiplicity.

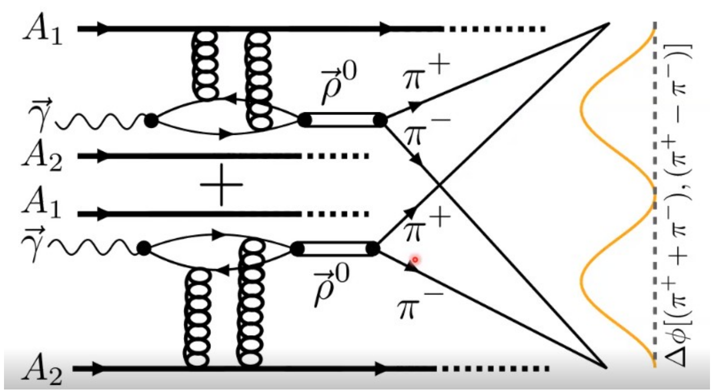
Access to neutron skin difference

$$\Delta(\Delta r_{np}) = \Delta r_{np,\mathrm{Ru}} - \Delta r_{np,\mathrm{Zr}}$$

[Jia, Zhang, 2111.15559]

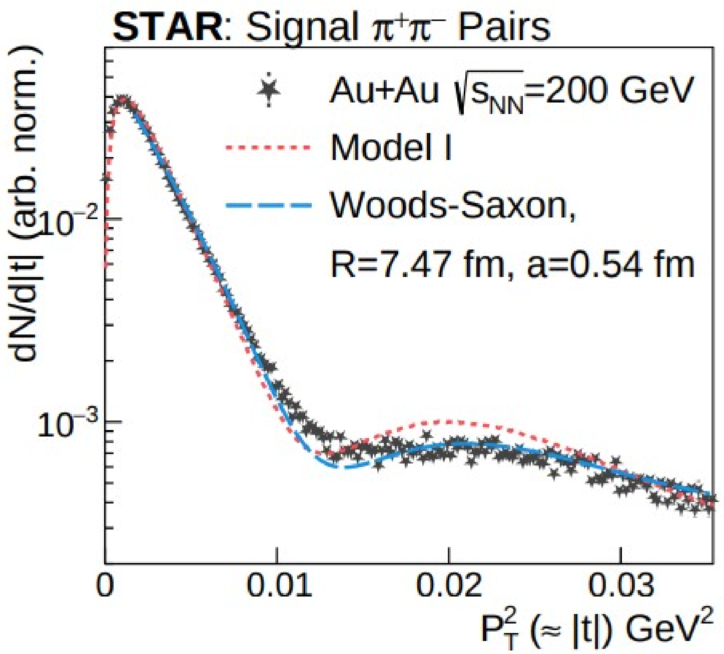
New method developed by STAR in photo-nuclear processes (UPC).

[STAR Collaboration, arXiv:2204.01625]



$$f(t) = A_c |\mathcal{F}[\rho_A(r; R, a)](|t|)|^2 + \frac{A_i/Q_0^2}{(1 + |t|/Q_0^2)^2}$$

FT of gluon density (Woods-Saxon)



UNCERTAINTY AS GOOD AS OR BETTER THAN PREX-II

neutron skin: $0.17 \pm 0.03(\text{stat.}) \pm 0.08(\text{syst.})$ fm for ^{197}Au

Very good consistence with low-energy experimental and theoretical results.