Extraction of Ground-State Nuclear Deformations from Ultra-Relativistic Heavy-Ion Collisions

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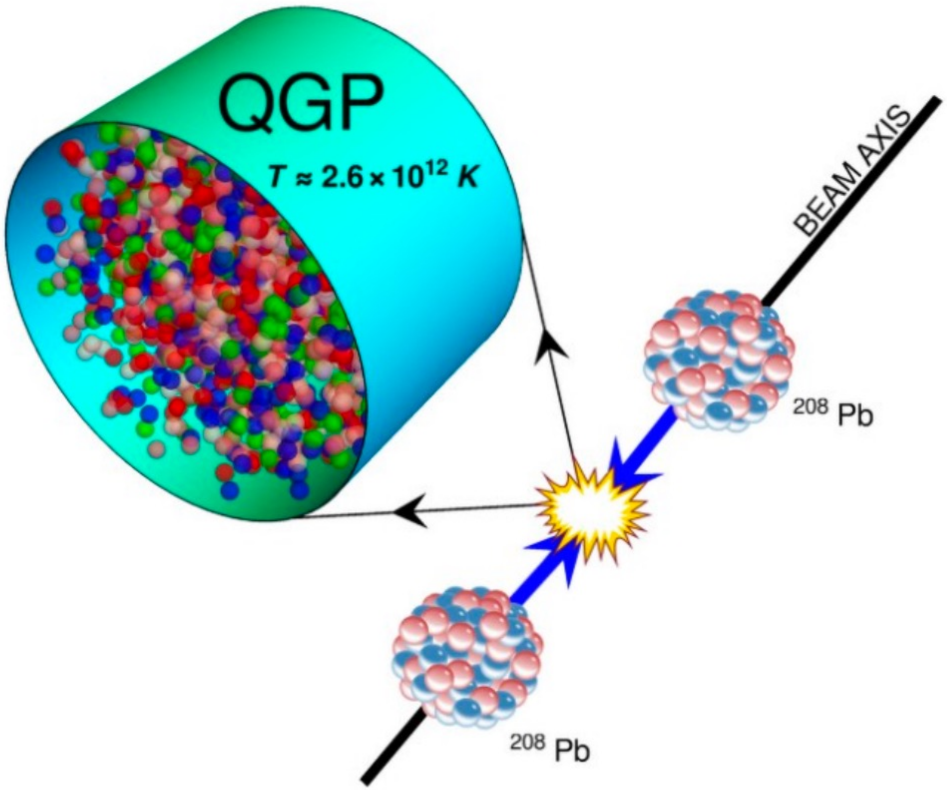
- arXiv:2507.05208v3

- Journal Club Presentation
- Nov.12, 2025

Heavy Ion Collisions – Somehow adhering to the“More is Different” paradigm in the context of high-energy physics **[P.W. Anderson, 1972]**

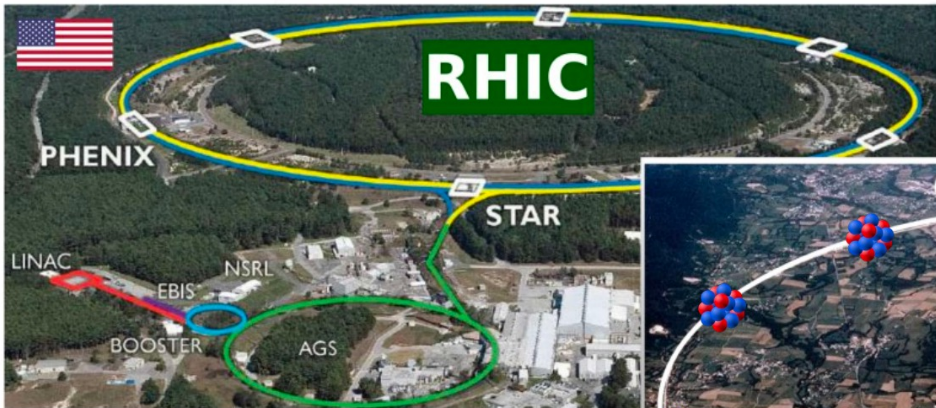
turn to a different direction; we should investigate some “bulk” phenomena by distributing high energy or high nucleon density over a relatively large volume. *The fact*

[T-D. Lee, 1974 link]

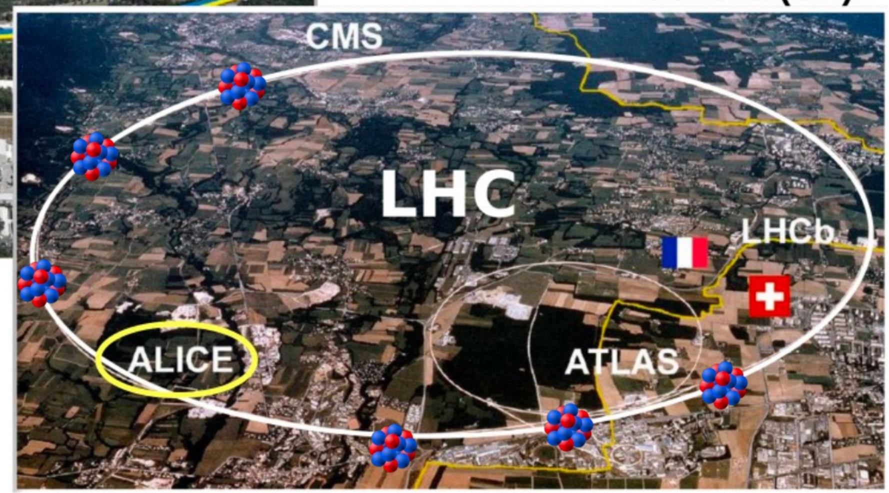


Ultra-relativistic heavy-ion collisions

Long Island (NY)



Geneva (CH)



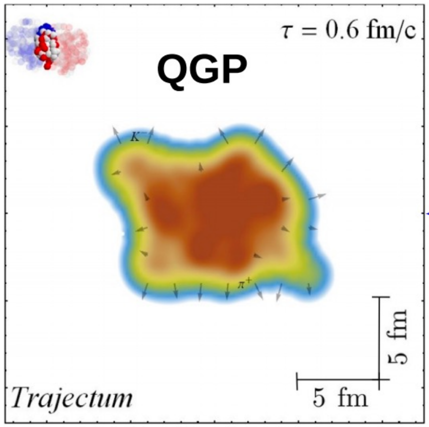
– From 2000 at Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC)

SHUT DOWN IN ~1 YEAR

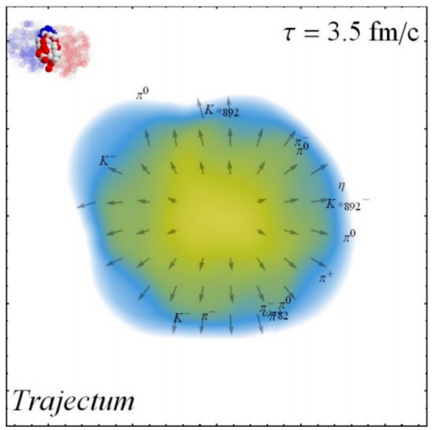
– Nuclear collisions about 1 month/year at the CERN Large Hadron Collider (LHC)

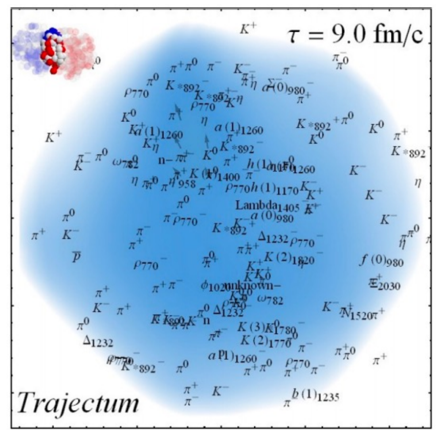
SHOULD KEEP COLLIDING NUCLEI FOR ~20 YEARS

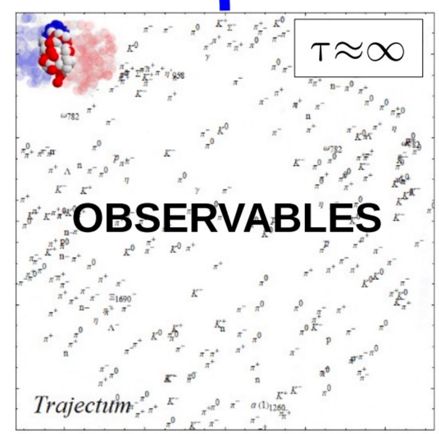
We only observe particles …
How do we infer properties / initial stages of the medium?

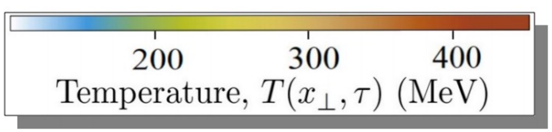


We need to model the process and calculate observables!



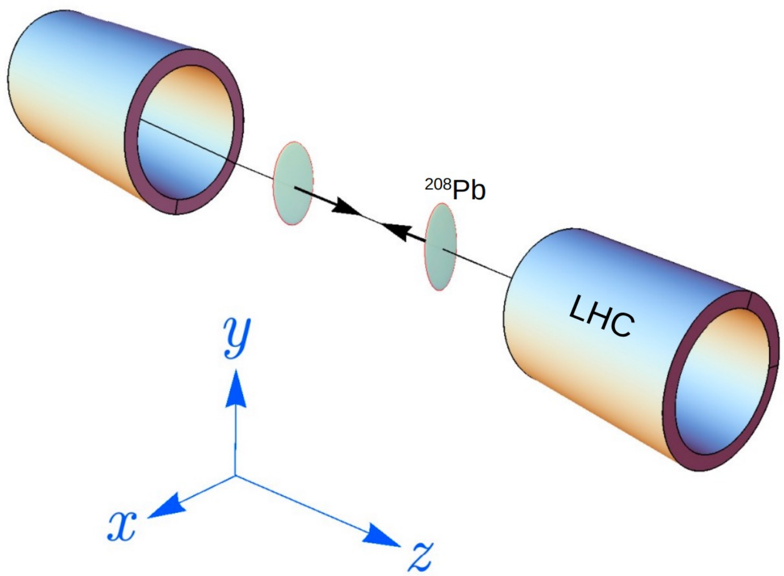




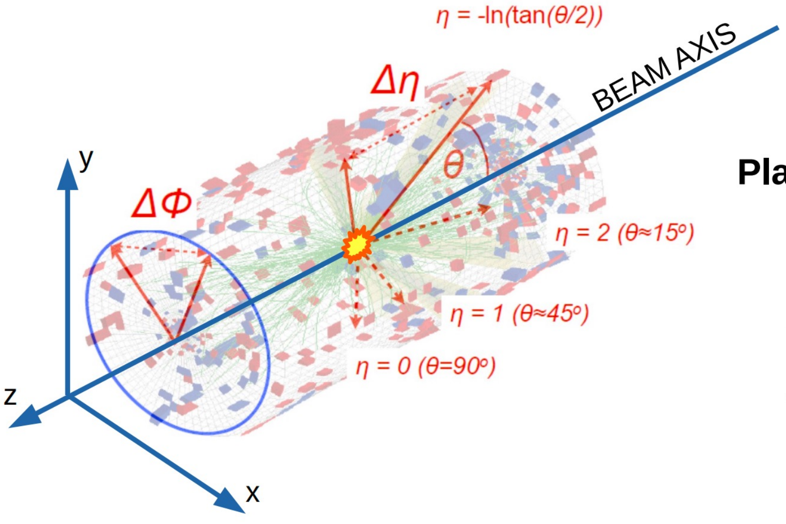


[e.g. Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]

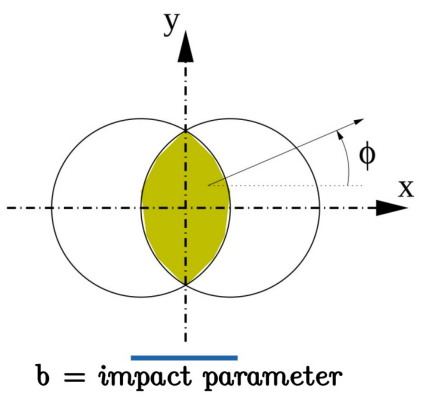
Modeling – Nuclei in the lab frame are squeezed in beam direction



Three-dimensional view



Plane transverse to the beam



Fundamental quantities in the soft sector

1 - event multiplicity

$$N = \int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t}$$

2 - anisotropic flow

$$V_n = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p}$$

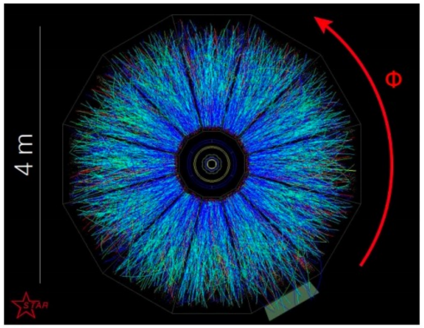
3 - average momentum

$$\langle p_t \rangle = \frac{1}{N}\int_{\mathbf{p}_t} p_t \frac{dN}{d^2\mathbf{p}_t}$$

Basics of QGP pheno: origin of these quantities

All of this elaborated further in my PhD thesis – arXiv:2101.00168

Understanding observables from thermo/hydrodynamic considerations



Construct observables from the final spectrum

SPECTRUM

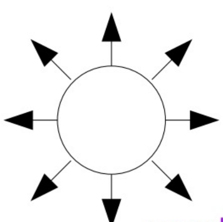
$$\frac{dN_{\rm ch}}{d\phi p_t dp_t}$$

CHARGED MULTIPLICITY

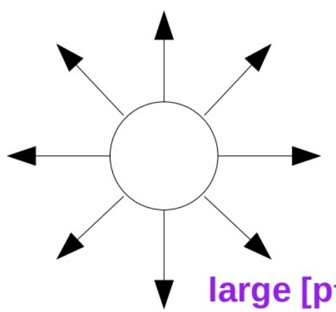
$$N_{\rm ch} = \int d\phi p_t dp_t \; \frac{dN_{\rm ch}}{d\phi p_t dp_t}$$

MEAN MOMENTUM

$$[p_t] = \frac{1}{N_{\rm ch}} \sum_{i=1}^{N_{\rm ch}} p_{t,i}$$



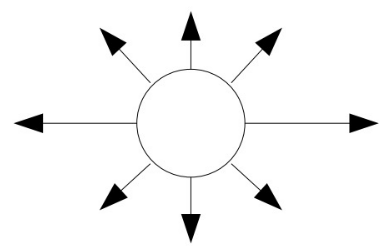
small [pT]



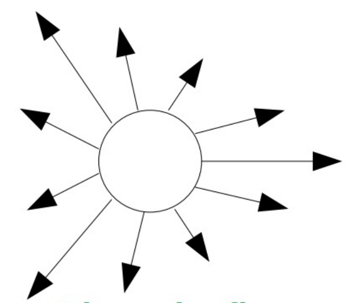
large [pT]

FOURIER HARMONICS

$$V_n = \frac{1}{N_{\rm ch}} \sum_{i=1}^{N_{\rm ch}} e^{-in\phi_i}$$



elliptic flow, v2



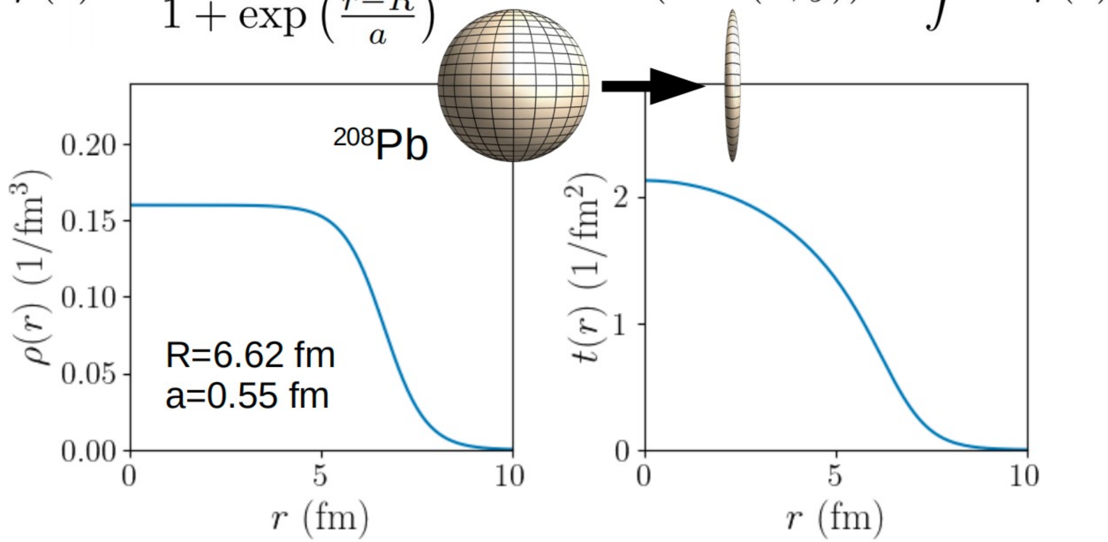
triangular flow, v3

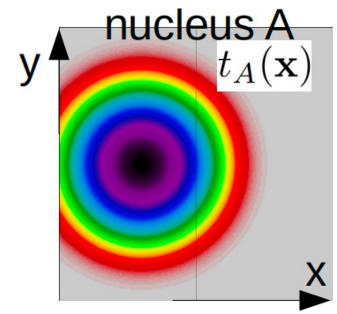
Exercise: Ellipticity of the energy density sources elliptic flow

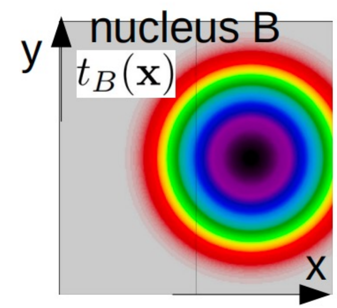
First contact with nuclear structure! Charge density of ^{208}Pb

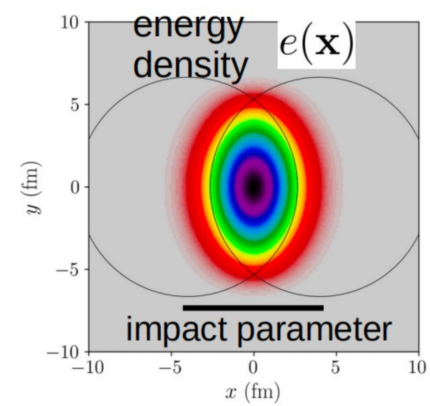
[de Vries *et al.*, Atom.Data Nucl.Data Tabl. 36 (1987) 495-536]

$$\rho(r) = \frac{\rho_0}{1+\exp\left(\frac{r-R}{a}\right)} \qquad t(\mathbf{r} \equiv (x,y)) = \int dz \; \rho(r)$$









Energy density proportional to density of binary collisions:

$$e(\mathbf{x}) \propto t_A(\mathbf{x}) t_B(\mathbf{x}) \quad \text{(point-to-point product)}$$

Paradigm established around year 2005

[PHOBOS Collaboration, PRL **98** (2007) 242302]

The nucleus “prepared” for the collision is in fact a collection of points

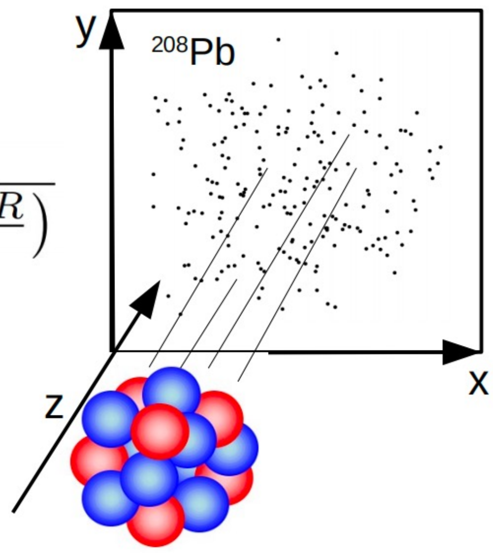
The relevant fluctuations are those of the positions of the nucleons that collide!

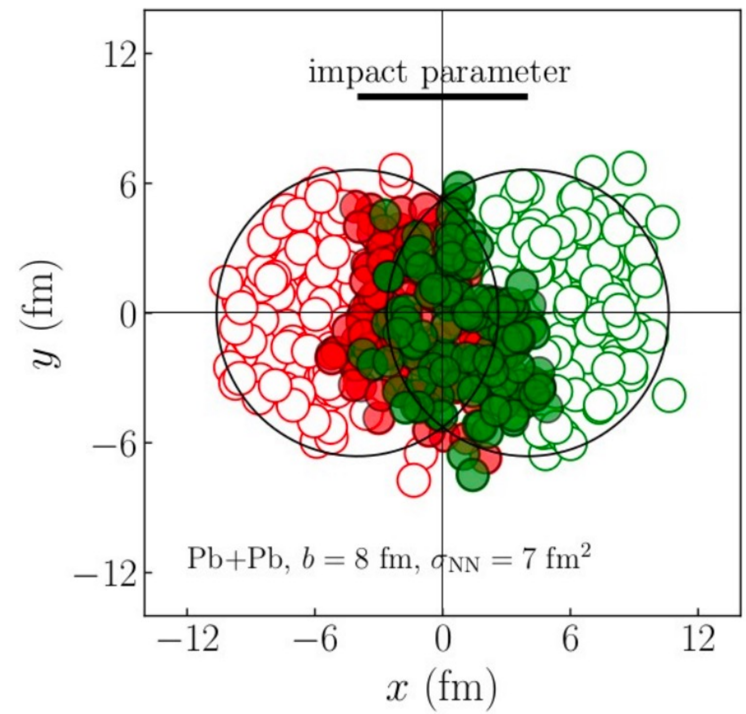
[Miller *et al.*, Ann.Rev.Nucl.Part.Sci. **57** (2007) 205-243]

[Alver, Roland, PRC **81** (2010) 054905]

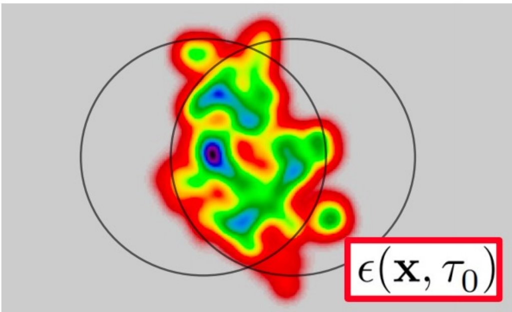
event-by-event sampling of nucleon centers

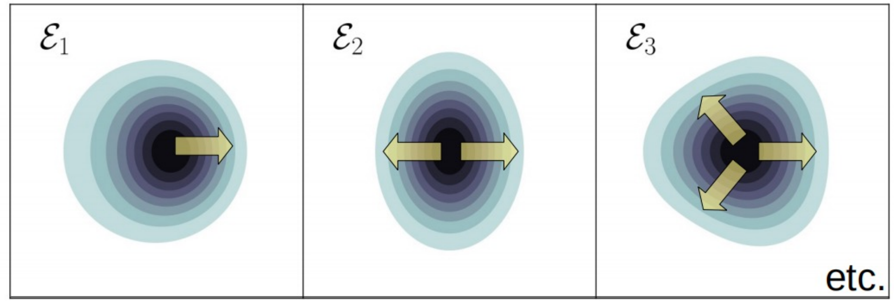
$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$





Consequence of fluctuations



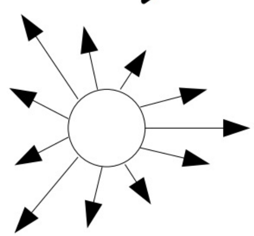


Multi-pole moments are nonzero:

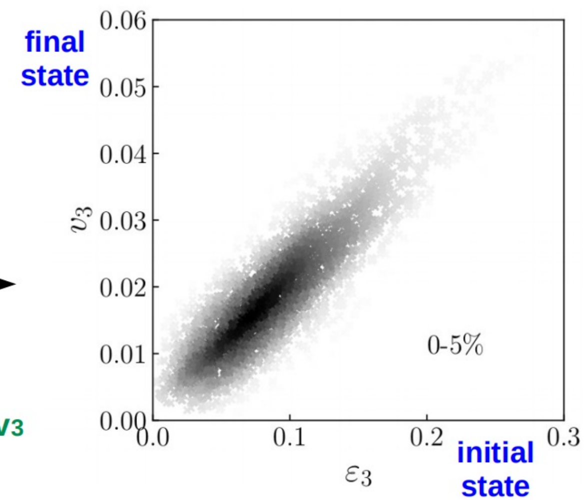
$$\mathcal{E}_n = -\frac{\int r dr d\phi \; r^n e^{in\phi} \epsilon(r,\phi)}{\int r dr d\phi \; r^n \epsilon(r,\phi)}$$

[Teaney, Yan, PRC **83** (2011) 064904]

n=3



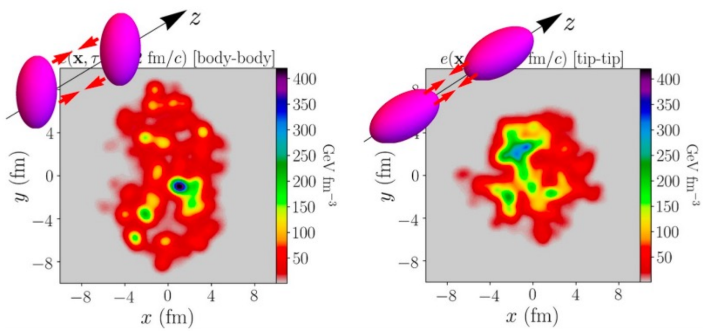
triangular flow, v_3



Proper modeling of the intrinsic density:

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

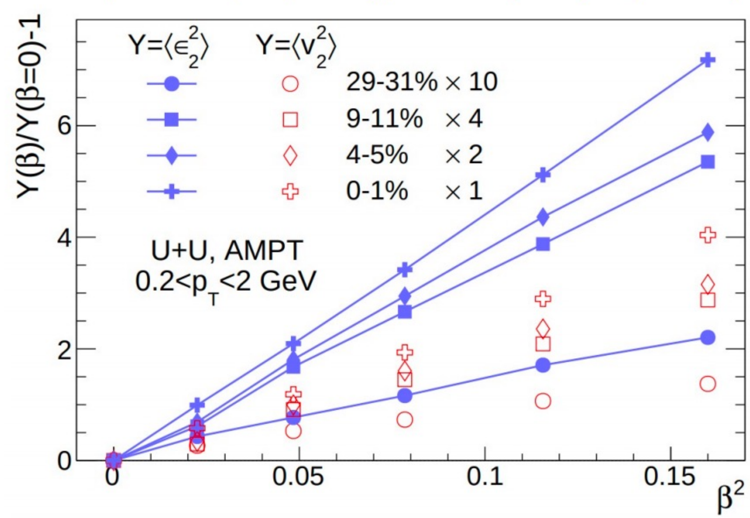
Impact of the two-body correlations (quadrupole deformation):



$$\left\langle v_2^2 \right\rangle = a + b\beta^2$$

$$\left\langle \varepsilon_2^2 \right\rangle = a' + b'\beta^2$$

[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]

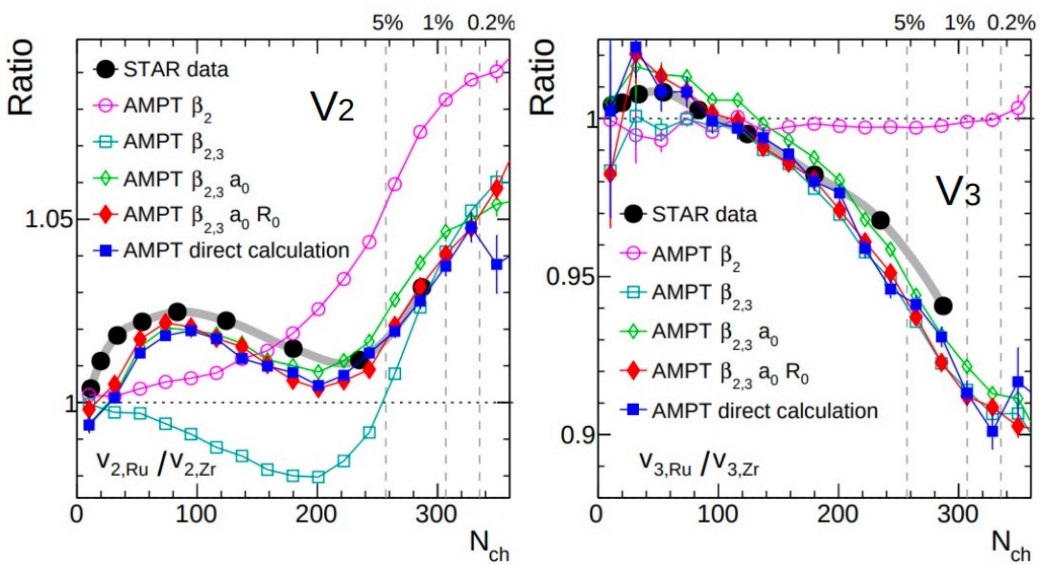


These ratios are determined by differences in the structure of the isobars

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

$$\frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1 \Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$$

[Zhang, Jia, PRL **128** (2022) 2, 022301]
[Zhang, Jia, PRC **107** (2023) 2, L021901]



$$\Delta\beta_n^2 = \beta_{n,\mathrm{Ru}}^2 - \beta_{n,\mathrm{Zr}}^2$$

Preferred values:

$$\beta_{2,\mathrm{Ru}} \simeq 0.16 \qquad \beta_{2,\mathrm{Zr}} \simeq 0$$

$$\beta_{3,\mathrm{Ru}} \simeq 0 \qquad \beta_{3,\mathrm{Zr}} \simeq 0.2$$

1. Motivation & Background

- UHIC at RHIC and LHC creates quark–gluon plasma (QGP).
- Flow anisotropies (v_2, v_3) reflect initial QGP geometry.
- Recent claims: UHIC can image nuclear shapes (e.g., STAR, Nature 2024).
- This paper critically evaluates those claims.

Article

Imaging shapes of atomic nuclei in high-energy nuclear collisions

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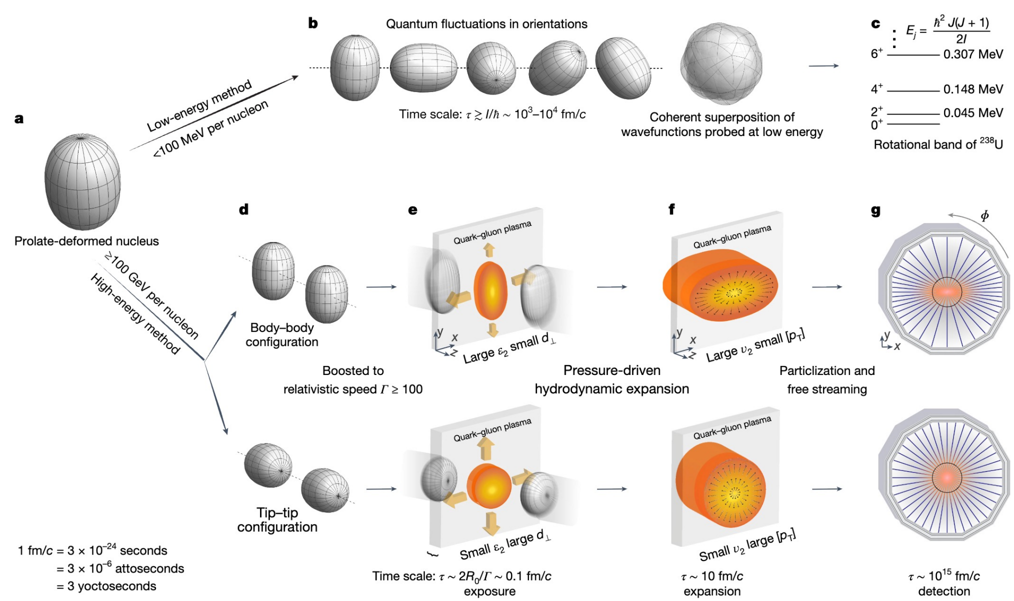
STAR Collaboration*✉

Atomic nuclei are self-organized, many-body quantum systems bound by strong nuclear forces within femtometre-scale space. These complex systems manifest a variety of shapes[1–3], traditionally explored using non-invasive spectroscopic techniques at low energies[4,5]. However, at these energies, their instantaneous shapes are obscured by long-timescale quantum fluctuations, making direct observation challenging. Here we introduce the collective-flow-assisted nuclear shape-imaging method, which images the nuclear global shape by colliding them at ultrarelativistic speeds and analysing the collective response of outgoing debris. This technique captures a collision-specific snapshot of the spatial matter distribution within the nuclei, which, through the hydrodynamic expansion, imprints patterns on the particle momentum distribution observed in detectors[6,7]. We benchmark this method in collisions of ground-state uranium-238 nuclei, known for their elongated, axial-symmetric shape. Our findings show a large deformation with a slight deviation from axial symmetry in the nuclear ground state, aligning broadly with previous low-energy experiments. This approach offers a new method for imaging nuclear shapes, enhances our understanding of the initial conditions in high-energy collisions and addresses the important issue of nuclear structure evolution across energy scales.



Nature | Vol 635 | 7 November 2024 | 67

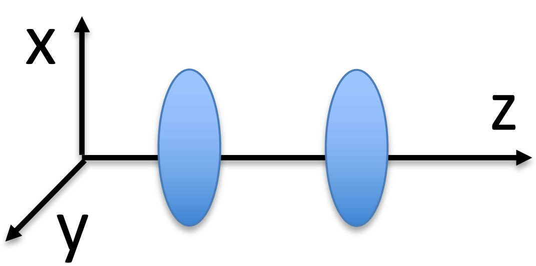
2. Central Question

- Can UHIC data reliably determine ground-state nuclear deformations?
- How does this compare to precision low-energy measurements?

The hydrodynamic expansion, reacting to ε2, results in particle anisotropy

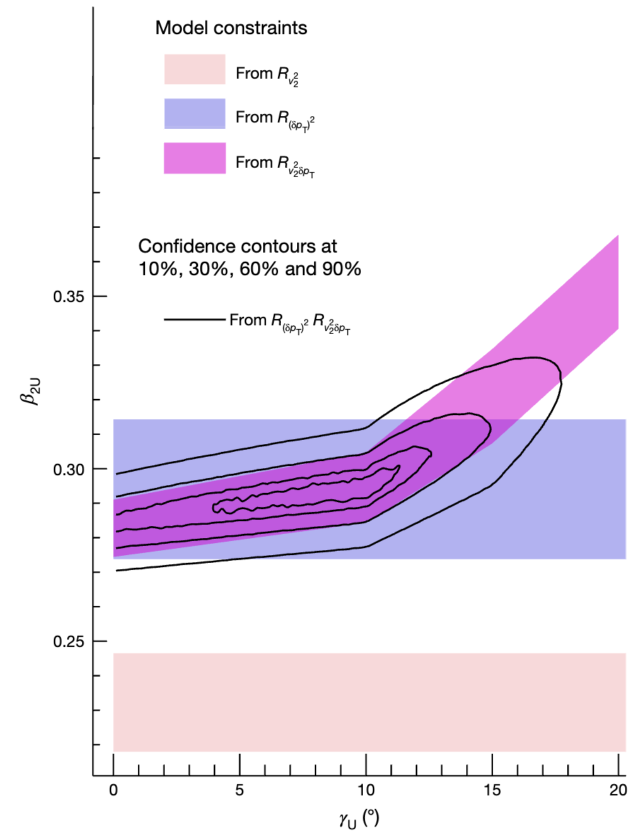
$$dN/d\phi \propto 1 + 2v_2\cos(2\phi)$$

$$\begin{aligned}\langle v_2^2\rangle &= a_1 + b_1\beta_2^2,\\ \langle(\delta p_T)^2\rangle &= a_2 + b_2\beta_2^2,\\ \langle v_2^2\delta p_T\rangle &= a_3 - b_3\beta_2^3\cos(3\gamma).\end{aligned}$$



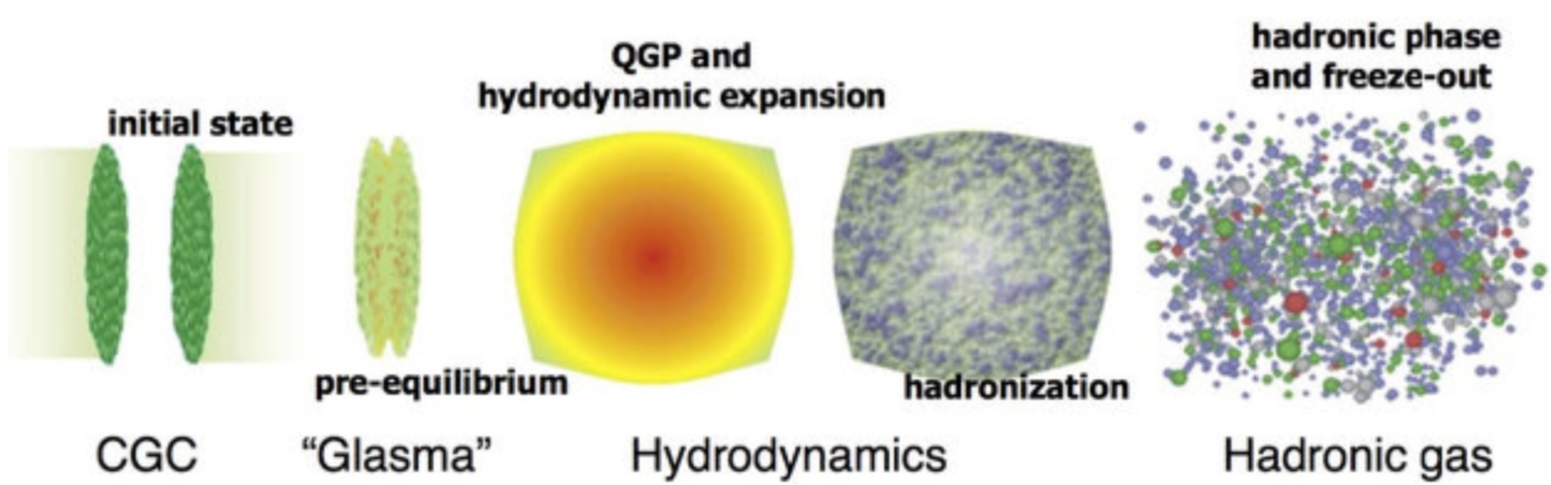
The initial shape of QGP is quantified by the **eccentricity** (偏心率) calculated from the nucleon distribution in the xy plane

$$\varepsilon_2 = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$$



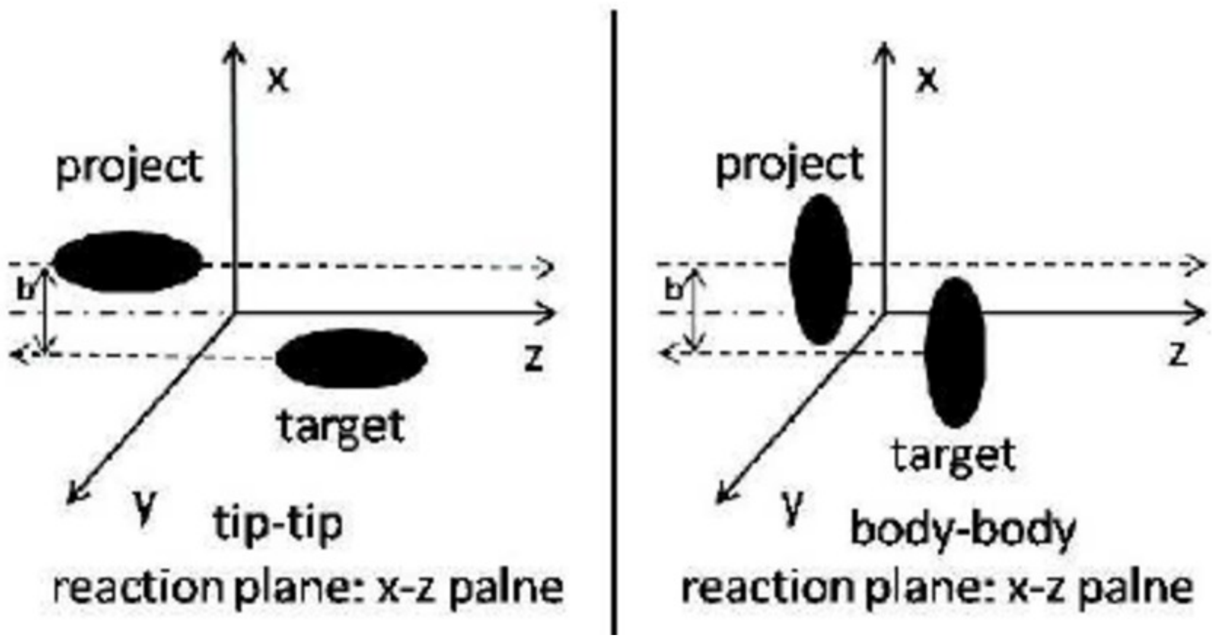
3. Key Argument Overview

- Ground states of even-even nuclei are rotationally invariant → spherical in lab frame.
- UHIC measures two-body correlations, not static multipole moments.
- “Instantaneous shapes” and “fluctuations” are not physical for stationary eigenstates.
- Low-energy data already provide precise deformation info.
- Uncertainty quantification (UQ) is essential for model validation.



4. Symmetry Breaking and Restoration

- Eigenstates of symmetry-conserving Hamiltonians are rotationally invariant.
- Deformation appears in symmetry-broken intrinsic wave functions.
- Shape measurement requires two-body densities, not one-body densities.
- Schematics like 'tip-tip' or 'body-body' are misleading mean-field images.

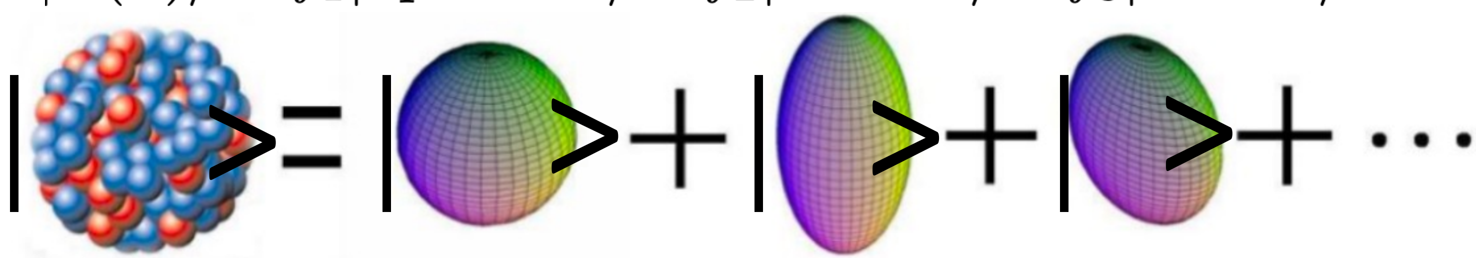


5. Static Shapes vs. Fluctuations

- No real-time fluctuations exist in stationary eigenstates.
- Dispersion arises from quantum uncertainties of observables.
- Symmetry-restored and beyond-mean-field methods describe static observables.
- UHIC references to long-timescale fluctuations are conceptually incorrect.

波函数叠加

$$|\Psi(J)\rangle = f_1|\mathrm{Spherical}\rangle + f_2|\mathrm{Prolate}\rangle + f_3|\mathrm{Oblate}\rangle + \cdots$$



$$= \frac{2I+1}{8\pi^2}\int d\Omega D^{I*}_{MK}(\Omega)\hat{R}(\Omega) \qquad |\Phi(\mathbf{q})\rangle$$

6. What We Already Know About Nuclear Deformation

- Quadrupole moments measured via μ-X rays, laser spectroscopy, e-scattering, Coulomb excitation.
- Databases provide 1% precision for many isotopes.
- Global surveys (FRDM, Gogny-HFB, CDFT) reproduce deformations.
- UHIC analyses sometimes overlook these established data.

7. Uncertainty Quantification (UQ)

- Model chain: nuclear structure → Glauber → hydrodynamics → hadronization.
- Each stage introduces model-dependent uncertainties.
- Unquantified discrepancies make UHIC-derived deformations unreliable.
- Example: Ref. [21] proposed UHIC probes of $0\nu\beta\beta$ NMEs, but lacked cross-validation with other data.

8. Conclusions

- Current UHIC 'shape imaging' is overstated and based on flawed assumptions.
- Proper interpretation requires two- or three-body densities and symmetry-aware modeling.
- Low-energy data provide stronger, validated constraints.
- UHIC’s strength lies in probing many-body correlations, not static shapes.

9. Discussion Points

- Are the authors too conservative or appropriately cautious?
- What observables could truly link UHIC data to intrinsic deformation?
- How can low-energy nuclear-structure knowledge improve UHIC analysis?
- Can Bayesian multi-fidelity models bridge UHIC and low-energy data?

10. Suggested Readings

- STAR Collaboration, Nature 635 (2024) 67
- Jia et al., Nucl. Sci. Tech. 35 (2024) 220
- Li et al., PRL 135 (2025) 022301
- Sheikh et al., J. Phys. G 48 (2021) 123001
- Nazarewicz & Ragnarsson, Handbook of Nuclear Properties (1996)

Abstract

The collective-flow-assisted nuclear shape-imaging method in ultra-relativistic heavy-ion collisions has recently been used to characterize nuclear collective states. In this paper, we assess the foundations of the shape-imaging technique employed in these studies. We argue that some current UHIC nuclear imaging techniques neglect fundamental aspects of spontaneous symmetry-breaking and symmetry-restoration in colliding ions and incorrectly infer one-body multipole moments from studies of nucleonic correlations. Therefore, the impact of this approach on nuclear structure research has been overstated. Conversely, efforts to incorporate existing knowledge on nuclear shapes into analysis pipelines can be beneficial for benchmarking tools and calibrating models used to extract information from ultra-relativistic heavy-ion experiments.

1. Motivation & Background

The shapes of nuclei colliding in ultra-relativistic heavy-ion collisions (UHIC) influence the geometry of the quark-gluon plasma (QGP) created, which, in turn, affects the momentum distribution of the particles produced [1–3]. The premise of the UHIC studies is rooted in the fact that the resulting anisotropic (hydrodynamic) expansion of the QGP [4] converts the initial spatial asymmetries into momentum anisotropies of the measured particles. A typical method of analyzing this flow consists in characterizing the azimuthal anisotropy by the Fourier coefficients ν_n of the flow [5]; the elliptic flow, ν_2, is sensitive to the ellipticity of the QGP, while the triangular one, ν_3, is sensitive to the triangularity, and so on.

By relating the flow anisotropies to the geometry of the QGP initial state, a shape-imaging method based on UHIC experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) has been suggested as a tool to study the geometrical shapes of the colliding nuclei [6–23]. In the present study, we examine the assumptions underlying the proposed shape-imaging technique in greater detail. In particular, we critically assess the claim in Ref. [17] that this approach "not only refines our understanding of the initial stages of the collisions but also turns high-energy nuclear experiments into a precision tool for imaging nuclear structures."

II. Symmetries: breaking and restoration

Let us first examine the symmetry aspects of self-bound many-body systems such as atomic nuclei. A fundamental theorem of quantum mechanics states that an eigenstate of a symmetry-conserving Hamiltonian must belong to a representation of the symmetry group. Therefore, the ground states of ^{238}U and ^{20}Ne, which a rotationally-invariant nuclear Hamiltonian governs, belong to the $J^\pi = 0^+$ representation, i.e., they are invariant under spatial orientation and reflections. In other words, they are perfectly spherical states in the beam's reference frame (or perfectly axial in the laboratory frame due to the huge relativistic contraction). Similarly, any ground or excited state with $J > 1/2$ [24, 25] for which the laboratory quadrupole moment is non-zero is covariant under spatial orientation (its rotation mixes the magnetic substates in a specific way). We focus on the $J^\pi = 0^+$ case for the following discussion, but note that all arguments apply to any of the others.

What is the shape, then, of the ^{238}U nucleus in its 0^+ ground state and how can it be measured? The answer to these questions is irrespective of whether we use UHIC, electron scattering, or Coulomb excitation. A concept that addresses this properly is spontaneous symmetry breaking – an essential notion ubiquitous across all the various domains of physics. As exposed by Anderson in his seminal article [26], it encompasses finite systems (such as molecules or nuclei), very large systems (like crystals), and infinite systems (such as quantum fields). It does not contradict the aforementioned fundamental theorem of quantum mechanics; on the contrary, it allows us to understand what it means to measure the shape of a quantum object.

A false friend in this understanding is an intuition that allows one to picture the deformed ^{238}U nucleus as a rotating and vibrating classical object, with corresponding time scales inferred from the energies of the quantum rotational and vibrational states [10, 12, 16–18]. This is a misleading picture – the 0^+ ground state of ^{238}U studied in the experiments is a stationary eigenstate; it does not rotate or vibrate, it does not change with time, and, thus, no instantaneous snapshot of the shape can be taken, no matter the time scale of the experiment performed.

A proper quantum-mechanical intuition that helps to understand the shape of the ^{238}U 0^+ ground state is a model of a spontaneously symmetry-broken deformed wave function. This is not the wave function that reaches the detector in the UHIC experiment. However, this deformed wave function can be used to build *an intuitive model* of the ^{238}U 0^+ ground state by constructing a linear combination of wave functions differently oriented in space and having different shapes, that is, by restoring the symmetry [27]. This model of the 0^+ ground state is still time-independent; it does not rotate or vibrate. Most importantly, one must remember that in this model state, the wave functions of different orientations and shapes are mixed, not their squares or density distributions, as shown in diagrams like the tip-tip or body-body configurations of Ref. [18]. Recently, this aspect has been further explored quantitatively in Ref. [28].

As is the case for any other quantum-mechanical wave function, a *single* experiment, when properly designed, may project the wave function on a given value of its "position" (its orientation and shape). However, a series of several identical experiments will give *different* values of positions. In particular, for the 0^+ ^{238}U ground state, all the different possible orientations will come out with equal probabilities, and the information on the shape will be inaccessible. Indeed, it must be so, as the shape of the 0^+ state is spherical.

A similar discussion can be made about the "bowling pin" schematics of Refs. [19, 20] symbolizing a pear-shaped nucleus, ^{20}Ne. Indeed, in the laboratory system, the $J^\pi = 0^+$ ground-state wave function of ^{20}Ne is perfectly spherical and reflection-symmetric, i.e., it does not point in a specific direction.

So, how then can one measure the shape of a spontaneously symmetry-broken state of ^{238}U or ^{20}Ne? One cannot. The reason is simple: such a stationary state does not exist in nature and, therefore, is unavailable for experimentation. In quantum mechanical modeling, the deformed symmetry-broken state is a wave packet, a coherent superposition of states with different angular momenta. A possible experimental situation where

such a state might briefly appear is in a heavy-ion fusion-evaporation reaction, where two ions fuse and rotate together at very high angular momentum. However, immediately after the first de-excitation photon is detected in a γ-ray detector, the wave packet collapses into a high-angular-momentum eigenstate, which then emits a series of $E2$ photons and rapidly relaxes to the 0^+ ground state. In conclusion, the broken-symmetry states are not the ones examined in the UHIC experiments.

At this point, we are ready to discuss what is measured in the UHIC experiments. The key point is that one does not measure one-body nuclear moments in these events. Instead, through event reconstruction, the positions of individual nucleons are identified based on measurements of outgoing particles. Multiple identical collisions then provide access to different quantum probability distributions. In short, every UHIC takes a snapshot of the spatial positions of the nucleons, not a snapshot of nuclear rotations or vibrations. In analogy, this can be related to Coulomb explosion experiments, which yield geometrical images of individual molecules [29, 30].

Any measurement of the probability distribution to find one nucleon at any given position in space maps the (exact) one-body density of the nucleus. It is equal to the modulus squared of the (exact) many-body wave function, which depends on the coordinates of A particles, integrated over $A-1$ coordinates. The one-body density of any 0^+ state is spherical. To determine the shape, one must use the concept of conditional probability [31], that is, the probability of finding one nucleon at a specific position in space under the condition that another nucleon occupies another position in space. Such a conditional probability is related to the (exact) two-body density (the integral of the exact wave function's modulus squared over $A-2$ coordinates). It has an axial shape because it must be symmetric to rotations about the line defining the position of the first point in question, and it can provide the density map in the plane spanned by the positions of both points. In this way, the axial shape of a 0^+ state can, in principle, be determined. Therefore, if the UHIC measurements can extract such conditional probabilities, the axial deformation can also be assessed in a 0^+ state. However, the one-body densities, as used in Refs. [13–15], are insufficient for that purpose.

Examples of earlier theoretical analyses, involving two-particle correlations, can be found in, e.g., Refs. [27, 31, 32], where the mean-field, symmetry-breaking, and symmetry-restored solutions are compared with the exact solutions of the problem, with many aspects of the arguments mentioned above explicitly presented. It is only recently that the nuclear UHIC modelers realized the importance of the many-body nuclear density for determining nucleons' position distributions Refs. [33–35], and practical calculations of correlated samplings of nucleon positions were carried out in only one case study [19].

The two-particle densities from UHIC imaging must be compared to those from modeled wave functions. However, this method for experimentally determining nuclear multipole moments is indirect because the values heavily depend on the model, and the impact of this dependence on uncertainty estimates remains unknown. As a result, they are not competitive with other methods that have been used so far, see Sec. IV.

In summary, ultra-relativistic collisions take place in the *laboratory frame*. Since ^{238}U is spherical in its $J = 0$ ground state and angular momentum is conserved, a deformed collision image is impossible, based on physics principles, regardless of the collision mechanism. (Likewise, a direct laboratory-system measurement of the electric dipole moment of the ammonia molecule in its ground state is impossible as the molecule has good parity [26].)

In other words, in the beam's coordinate system, the heavy ion *impinging on target* is described by a rotationally-invariant many-body wave function that depends on the coordinates of the nucleons, not just on the nucleon densities oriented in space. It is *following the collision event* that the wave function collapses into one symmetry-breaking component, characterized by the nucleons' positions (planar image of the wave function in the coordinate representation). Hence, to extract the initial QGP configuration, a simple one-body picture of the deformed nuclear density is insufficient.

III. Static shapes and dynamic shape fluctuations

Publications by the STAR collaboration [16, 18] introduce the notion of “instantaneous shapes” and “long-timescale quantum fluctuations, making direct observation challenging.” It is claimed that “Nuclear shapes, even in ground states, are not fixed. They exhibit zero-point quantum fluctuations involving various collective and nucleonic degrees of freedom at different timescales. These fluctuations superimpose on each other in the laboratory frame” [16].

We wish to point out that there are no quantum fluctuations in any eigenstate of any quantum system. The shape of a projectile/target nucleus entering the collision does not fluctuate; there is no time-dependence involved, and, thus, there is no timescale. One should not confuse the model of a collective rotational or vibrational state, described as a time-dependent Slater determinant, with the reality of a quantum state that is accessible in an experiment. Similarly, one should not confuse dynamical fluctuations with the quantum uncertainty of an observable. An observable, the quantum quadrupole moment operator, defines the nuclear shape. The nuclear ground state is not an eigenstate of the quadrupole operator; therefore, any measurement of the quadrupole operator in the nuclear ground state must lead to the standard quantum dispersion of the results. Such dispersion is not related to any collective motion.

The effects describing the dispersion of static observables in the ground states of nuclei are well understood in nuclear structure. They are adequately accounted for by symmetry restoration after mixing the symmetry-broken states [43, 44]. Although they often go by the name of the "vibrational" corrections or "fluctuations" (quadrupole, octupole, pairing, etc.), they model the stationary nuclear states. Such an approach to modeling UHIC results is in its infancy, see, e.g., [13, 20, 21]. Still, it is a proper avenue to take, provided it is used to determine two-body densities and not only the multipole moments.

While a theoretical jargon exists pertaining to static deformations (related to symmetry-breaking deformed mean-field solutions) and dynamical zero-point effects, or fluctuations (representing the dynamical beyond-mean-field corrections), the corresponding many-body wave functions are always stationary. Likewise, the jargon referring to the "intrinsic" reference frame is unhelpful in this context; it is better to use the proper quantum-mechanical notion of a symmetry-broken state.

V. Uncertainty quantification

Uncertainty quantification is at the heart of any pipeline connecting models that span disparate scales. By quantifying the models' discrepancies and deficiencies, one can construct a rigorous statistical framework that provides a means to transfer information both forwards and backwards within this multiscale (or multifidelity) modeling framework. In the context of the current work, the forward direction involves propagating uncertainties from quantified nuclear models through to final-state observables in UHIC. The natural next step is then to have information flowing in the other direction in the pipeline. This provides an opportunity to solve the inverse problem and perform statistical inference on shapes and other correlated observables accessible within the chosen nuclear structure model. Both steps represent exciting developments and are examples of the confluence of advances in theoretical modeling, experimental analyses, and computational statistics and data science in modern nuclear physics.

It is also essential to acknowledge the fact that any conclusion drawn in such an analysis is inherently model-dependent. The experimental data, on an event-by-event basis, undoubtedly encode intricate details about the correlated nuclear system. Decoding this information, however, necessitates a sophisticated theoretical modeling framework that translates UHIC observations into quantitative measures of nuclear deformation. This framework typically involves several interconnected stages, each with its own set of assumptions and uncertainties.

Centrality, for instance, in heavy-ion collisions is typically determined by measuring the number of charged particles produced in the collision and then comparing this number to a Monte Carlo Glauber calculation or another similar framework [94–97]. This approach, while widely used, has certain limitations. The accuracy of centrality determination relies on the validity of the chosen model, which has inherent assumptions about the nucleon-nucleon interactions and the density distribution of nucleons within the nucleus. Additionally, the efficiency of detecting charged particles and the methods used to distinguish between particles originating from the collision and those from secondary decays can introduce uncertainties. The subsequent hydrodynamic evolution of the QGP is another example, as it relies on equations of state and transport coefficients that are not fully constrained by experimental data, and even then, there are multiple competing models to propagate the QGP after formation [98]. In addition to this hydrodynamical flow, there are also nonflow correlations that must be corrected for and that add further model-based uncertainties to the analysis pipeline [99]. The recent debate [100, 101] underscores the importance of these nonflow contributions, specifically in the context of nuclear shape extraction. Finally, the process of hadronization, whereby the QGP converts back into hadrons, introduces further uncertainties related to the fragmentation, clusterization, and subsequent decay of these particles [102, 103].

The complexity and non-uniqueness of this modeling framework raise concerns regarding the robustness and reproducibility of results drawn from the method. Different research groups, employing subtly different implementations of the same underlying stages, could potentially arrive at different conclusions regarding the extracted deformations of the colliding system. These discrepancies can arise from variations in the specific data sets considered in the fit, the choice of initial conditions, the details of the hydrodynamic evolution, the treatment of hadronization, and other factors. While this model dependence has not been investigated in detail for shape extraction, model discrepancy studies have been performed for UHIC-related quantities in Ref. [104], and the impact on the Bayesian inference was found to be significant.

Finally, it is worth discussing the required properties and fidelity of the nuclear structure models to be useful in this pipeline. At a minimum, one should consider 'reasonable' models of nuclei. A convenient definition in this case would be any model that allows one to simultaneously describe (and predict) observables in low-energy nuclear structure to a reasonable accuracy. For the forward direction in the pipeline, this would also ideally involve quantified models that have been calibrated to a wide class of nuclear observables and have been validated on the class of observables that are of most interest in any particular study. The uncertainties of the initial state should then be propagated through the pipeline, from the hydro phase of the QGP to the hadronization phase. This already provides an excellent anchor point for UHIC studies to ensure that the nuclear structure input is well validated, providing further confidence in any UQ efforts for the UHIC simulation pipeline itself.

For the reverse direction, the core question is "are the constraints and resulting uncertainties sufficient to distinguish between models used to predict the initial state?". If the discussed pipeline is rather coarsely constraining, then one should only expect differences to arise from large-scale, bulk changes in the nucleus. For models meeting the reasonableness criteria above, these bulk properties are likely to be very similar. Furthermore, employing any nuclear structure models for inference on nuclear properties of any sort *requires* quantified Hamiltonians and detailed model discrepancy studies to validate those models on nuclear deformations and to render any conclusions statistically significant. This is equally true for any model of nuclear structure, including *ab initio* models. While this discussion has focused on nuclear shapes, this is a core point for the extraction of any properties of nuclei. For example, the investigation in Ref. [21] suggests UHIC experiments as a novel probe of matrix elements central to the search for neutrinoless double-beta decay, although without considering the constraining potential of those UHIC observables in the context of other available nuclear structure observables (see, e.g., Ref . [105] for a multitude of factors impacting matrix elements for neutrinoless double-beta decay). More fundamentally, one needs to demonstrate the suitability of the structure model itself for such studies by showing that, when considering data from other sources, the results are not in conflict with well-known nuclear properties.

VI. Conclusions

"Extraordinary claims require extraordinary evidence" [106]. The purpose of this paper is to shed light on the collective-flow-assisted nuclear shape imaging employed in the analysis of data from UHIC, and to assess the claims of high relevance of these experiments to nuclear structure research. While there is little doubt that the proper treatment of the geometries of colliding heavy ions is essential for the characterization of the initial QGP configuration and, hence, the extraction of fundamental properties of QGP from UHIC, we believe that the proposed nuclear shape-imaging method is based on several flawed assumptions and, hence, its usefulness as a "discovery tool for exploring nuclear structure" [16] has been overstated.

First, the modeling of the initial QGP state formed following the heavy-ion collision involves the description of the relative position identification of the individual nucleons. To this end, the information contained in the one-body nucleonic density, as presented in the majority of papers dealing with nuclear imaging from UHIC, is insufficient. The proper tool for this imaging of the nucleon's position distributions is the two-body density (to map axial distributions) or the three-body one (to map triaxial shapes). The schematics depicting the deformed orientations of nuclei are misleading, as even-even nuclei, such as ^{238}U or ^{20}Ne, have isotropic ground-state wave functions in the laboratory system. In this context, the recently proposed approaches in Refs. [19, 28, 33–35], based on the many-body wave function, hold promise.

Second, the notions of "instantaneous shapes," "long-timescale quantum fluctuations," and "zero-point quantum fluctuations involving various collective and nucleonic degrees of freedom at different timescales" [16] make little physical sense as the many-body wave function of the colliding ion is stationary.

Third, rich databases exist of shape deformations measured in low-energy experiments, as well as of theoretical deformations computed within nuclear mean-field theory. The data on stable nuclei are particularly rich and seem more than sufficient to inform models of the initial QGP state.

Fourth, the existing precise information on nuclear shapes should be utilized by nuclear UHIC imaging practitioners to validate analysis techniques and control model uncertainties and discrepancies. Currently, a comprehensive and combined uncertainty quantification analysis of UHIC data has not been carried out because of the lack of a consistent methodology for propagating uncertainties from nuclear models through to final-state observables, and with propagating uncertainties backwards in the pipeline.

In summary, we find that the current use of UHIC to image low-energy nuclear structure – namely, nuclear deformations – is prone to many flaws of interpretation and precision. Nuclear one-body electric moments for stable or long-lived nuclei are well understood and have been studied extensively over many years using a wide range of techniques, both direct and indirect. This is still a very active area of research, as many detailed challenges remain in low-energy experiment and theory. The UHIC measurements do not directly contribute to this field of study because they provide many-body correlations in the laboratory frame. As proposed in this work, there is potential for using the measured many-body correlations by the UHIC nuclear imaging to examine multipole collectivity from an entirely new perspective. This could open up a fascinating new research avenue.

The modeling dependence, large uncertainties, and limited isotopic reach of UHIC-based studies pose significant challenges and hinder the method's ability to meaningfully add to the existing corpus of data on nuclear shapes. On the other hand, the existing systematic nuclear structure measurements and calculations provide strong constraints for the modeling of the initial state of UHIC and a firm baseline for future studies of QGP formation and flow. With that being said, a compelling feature of UHIC analyses is that they explicitly probe many-body correlations in the nucleus. Focusing on this aspect, rather than shapes, represents a strength of the approach worth playing to.

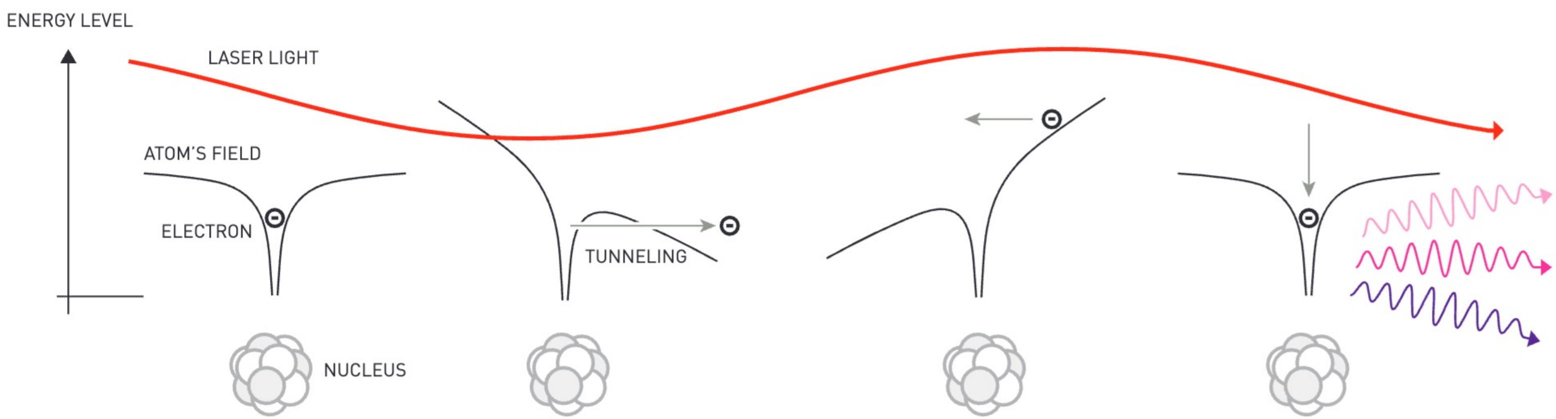
The 2023 Nobel Prize in Physics has been awarded to Pierre Agostini, Ferenc Krausz and Anne L'Huillier "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter".

If scientists got to pick a superpower, many physicists and chemists would want to be able to directly watch electrons moving around atoms, molecules and condensed-matter systems. The generation of attosecond light pulses, which was awarded this year's Nobel Prize in Physics, has brought science closer to this goal than ever before.

Credit: © Nobel Prize Outreach, Ill. Niklas Elmehed

Laser light interacts with atoms in a gas

Experiments that created overtones in laser light led to the discovery of the mechansim that causes them. How does it work?



1 An electron that is bound to an atom's nucleus cannot normally leave its atom; it does not have enough energy to lift itself out of the well created by the atom's electrical field.

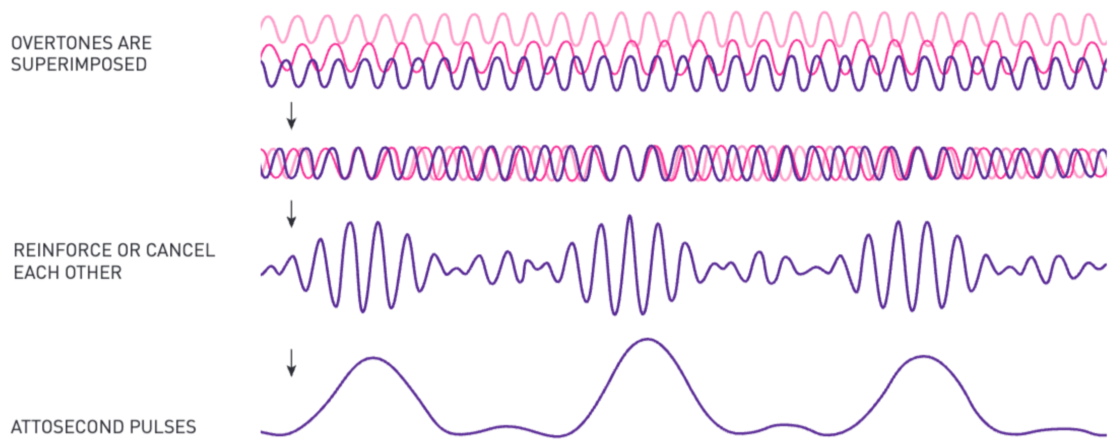
2 The atom's field is distorted when it is affected by the laser pulse. When the electron is only held by a narrow barrier, quantum mechanics allow it to tunnel out and escape.

3 The free electron is still affected by the laser field and gains some extra energy. When the field turns and changes direction, the electron is pulled back in the direction it came from.

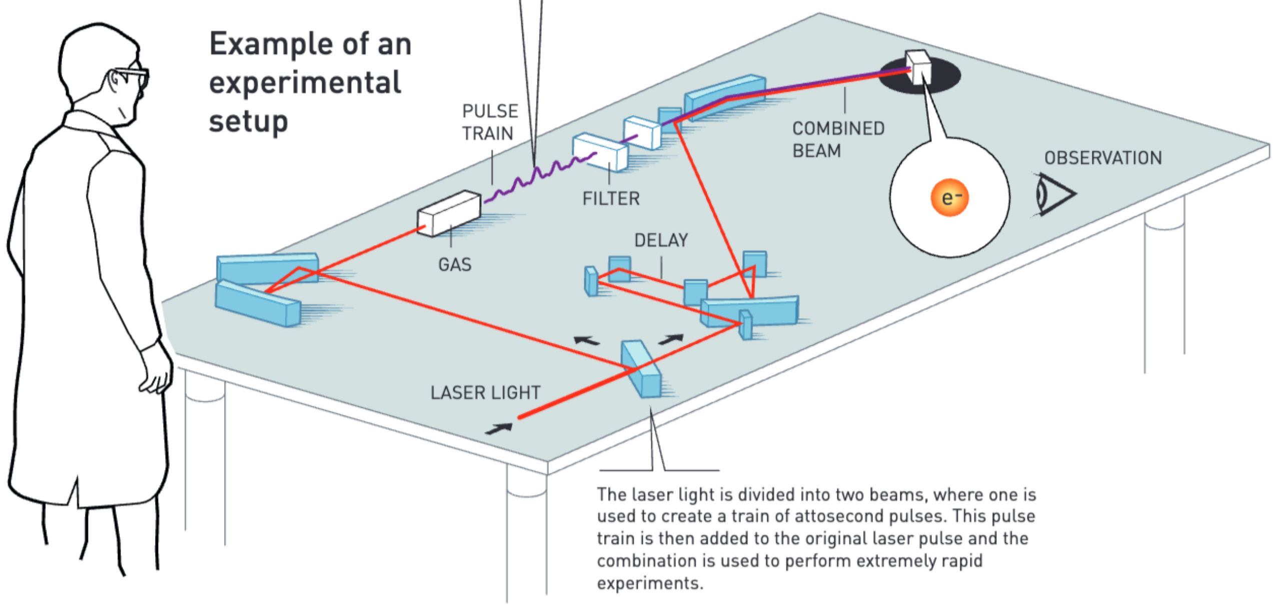
4 To reattach to the atom's nucleus, the electron must rid itself of the extra energy it gained during its journey. This is emitted as an ultraviolet flash, the wavelength of which is linked to that of the laser field, and differs depending on how far the electron moved.

The world of electrons is explored with the shortest of light pulses

When laser light is transmitted through a gas, ultraviolet overtones arise from the atoms in the gas. In the right conditions, these overtones may be in phase. When their cycles coincide, concentrated attosecond pulses are formed.



Example of an experimental setup



The laser light is divided into two beams, where one is used to create a train of attosecond pulses. This pulse train is then added to the original laser pulse and the combination is used to perform extremely rapid experiments.

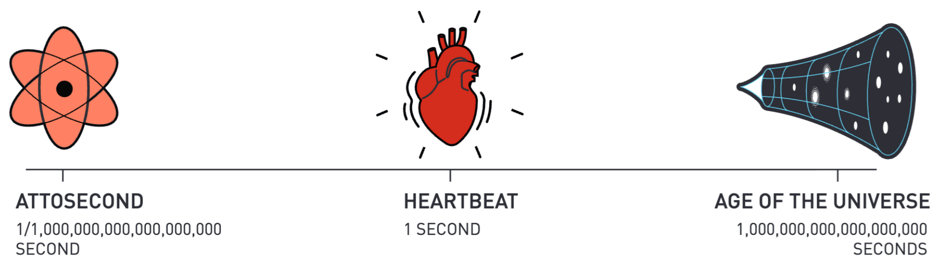
Electrons' movements have become accessible

Attosecond pulses make it possible to measure the time it takes for an electron to be tugged away from an atom, and to examine how the time this takes depends on how tightly the electron is bound to the atom's nucleus. It is possible to reconstruct how the distribution of electrons oscillates from side to side or place to place in molecules and materials; previously their position could only be measured as an average.

Attosecond pulses can be used to test the internal processes of matter, and to identify different events. These pulses have been used to explore the detailed physics of atoms and molecules, and they have potential applications in areas from electronics to medicine.

For example, attosecond pulses can be used to push molecules, which emit a measurable signal. The signal from the molecules has a special structure, a type of fingerprint that reveals what molecule it is, and the possible applications of this include medical diagnostics.

The attosecond (10^{-18} s), also known as a quintillionth of a second, is the timescale of atomic events. In Niels Bohr's 1913 model of a hydrogen atom, it takes about **150 attoseconds for an electron to orbit the proton**.



Electrons' movements in atoms and molecules are so rapid that they are measured in attoseconds. An attosecond is to one second as one second is to the age of the universe.