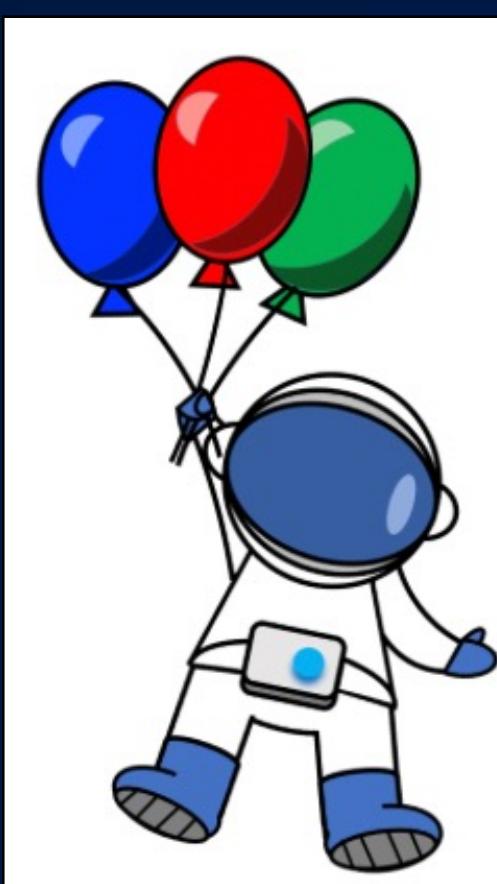




Shape Fluctuations of Atomic Nuclei: How Can Heavy Ion Collisions Probe it?

Aman Dimri, Somadutta Bhatta and Jiangyong Jia.
aman.dimri@stonybrook.edu, Stony Brook University



Introduction

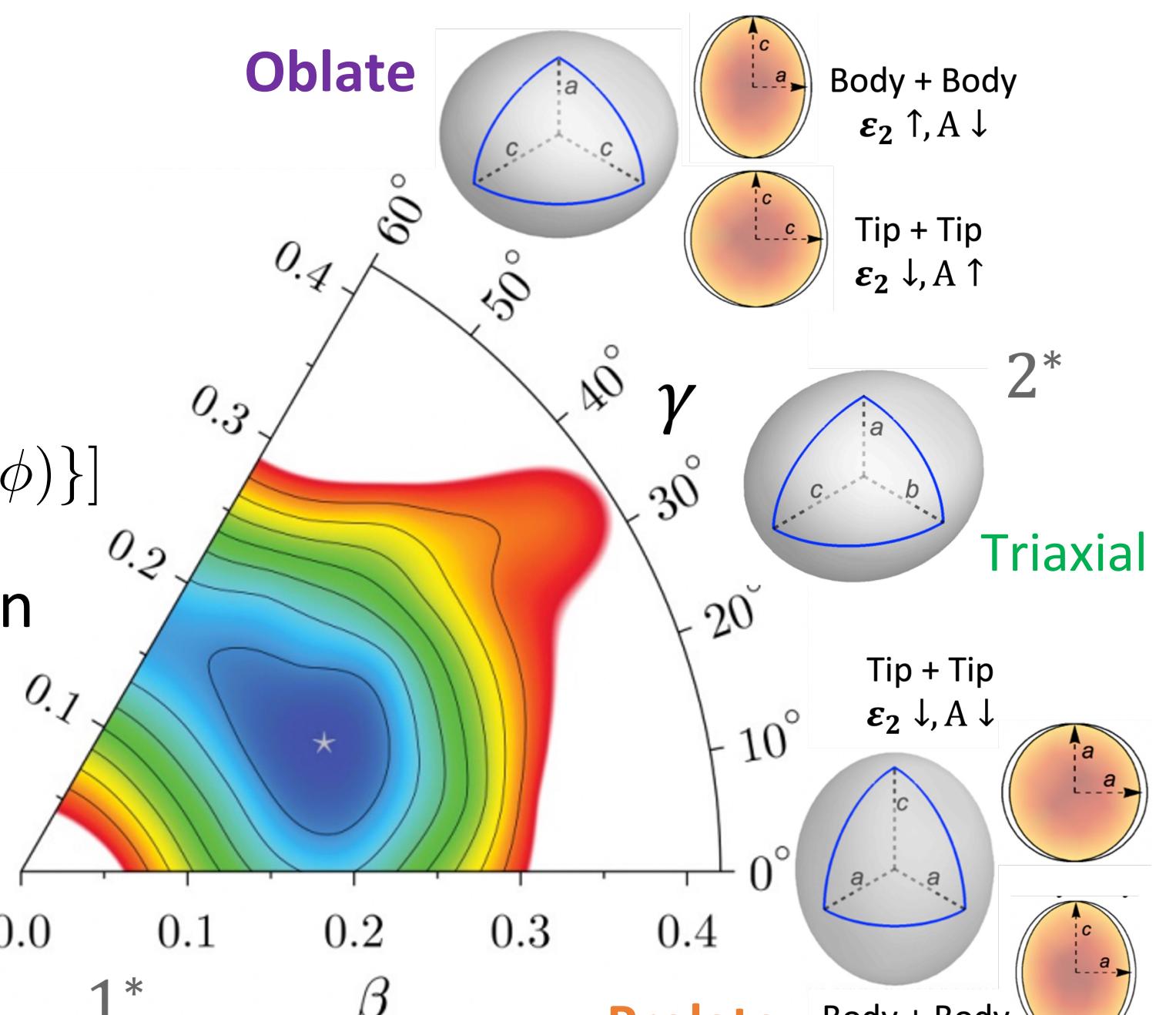
- Nuclear deformation and its fluctuations are ubiquitous phenomenon across nuclide chart.
- While deformed nuclei are well-studied, physics of shape fluctuations and shape co-existence is less explored.
- We investigate the impact of the shape fluctuations on flow observables in Heavy Ion (HI) collisions.

- Nuclear geometry parametrized by Woods-Saxon distribution in HI:

$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{(r-R(\theta,\phi))}{a}}}$$

$$R(\theta, \phi) = R_0 [1 + \beta \{ \cos \gamma Y_{20}(\theta, \phi) + \sin \gamma Y_{22}(\theta, \phi) \}]$$

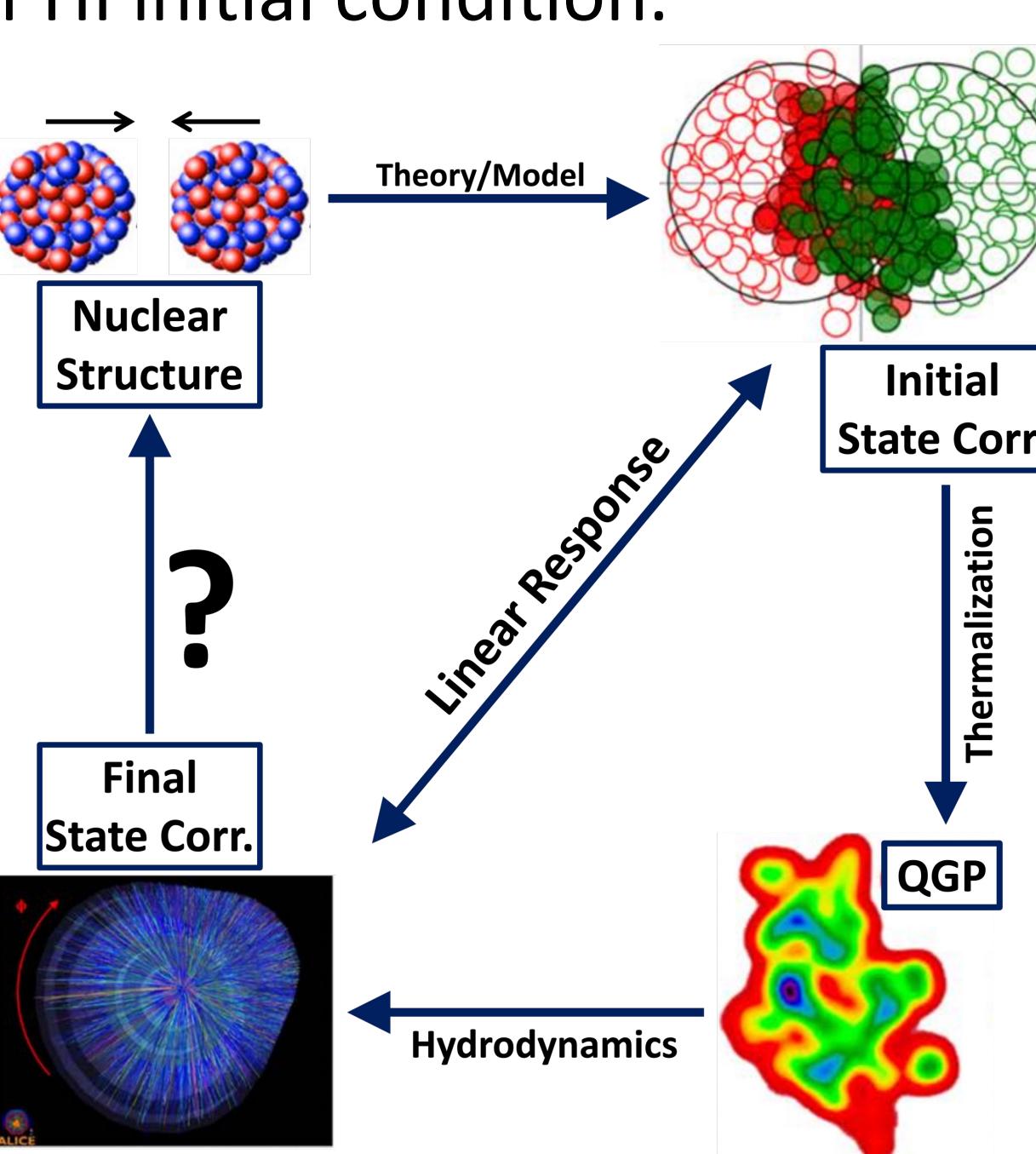
β, γ : parameters for quadrupole deformation



- Potential Energy Surface of many nuclei have broad minima → strong shape fluctuations.
- Precise determination of nuclear shape is important :
 - Precise constraining of HI QGP initial condition and its properties
 - Influence rates of important nuclear reactions in nuclear astrophysics
 - For determining nuclear-matrix-element for search of $0\nu\beta\beta$

Challenge to separate average shape from Shape Fluctuations in Low-Energy Spectroscopic method.

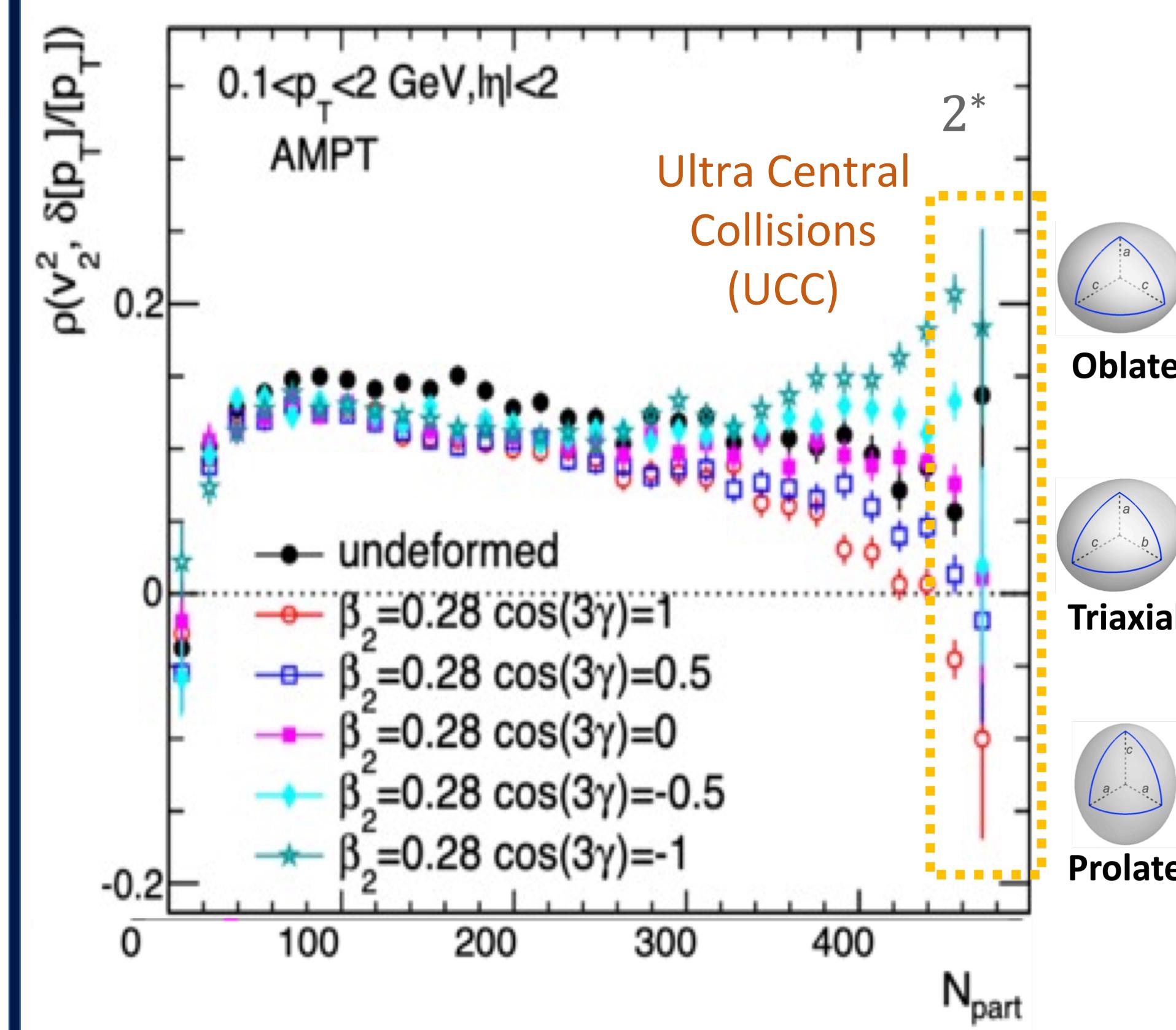
- Multi-particle correlations are new tools to constrain nuclear structure properties.
- Elliptic flow (v_2) & radial flow ($[p_T]$) sensitive to the shape & size of HI initial condition.



Previous Studies

HI observables are directly influenced by nuclear shapes, to leading order:

- $\langle \varepsilon_2^2 \rangle \propto \langle v_2^2 \rangle \sim c'_0 + c'_1 \beta^2$
- $\langle \varepsilon_2^2 \frac{\delta d_\perp}{d_\perp} \rangle \propto \langle v_2^2 \frac{\delta [p_T]}{[p_T]} \rangle \sim a'_0 + a'_1 \cos(3\gamma) \beta^3$



HI Collisions can work as a Nuclear Shape Imaging Tool!

HI observables can constrain both β and γ deformation parameters

Effect of Shape Fluctuations on Initial State Heavy-Ion Observables

How to separate the average shape from shape fluctuations?

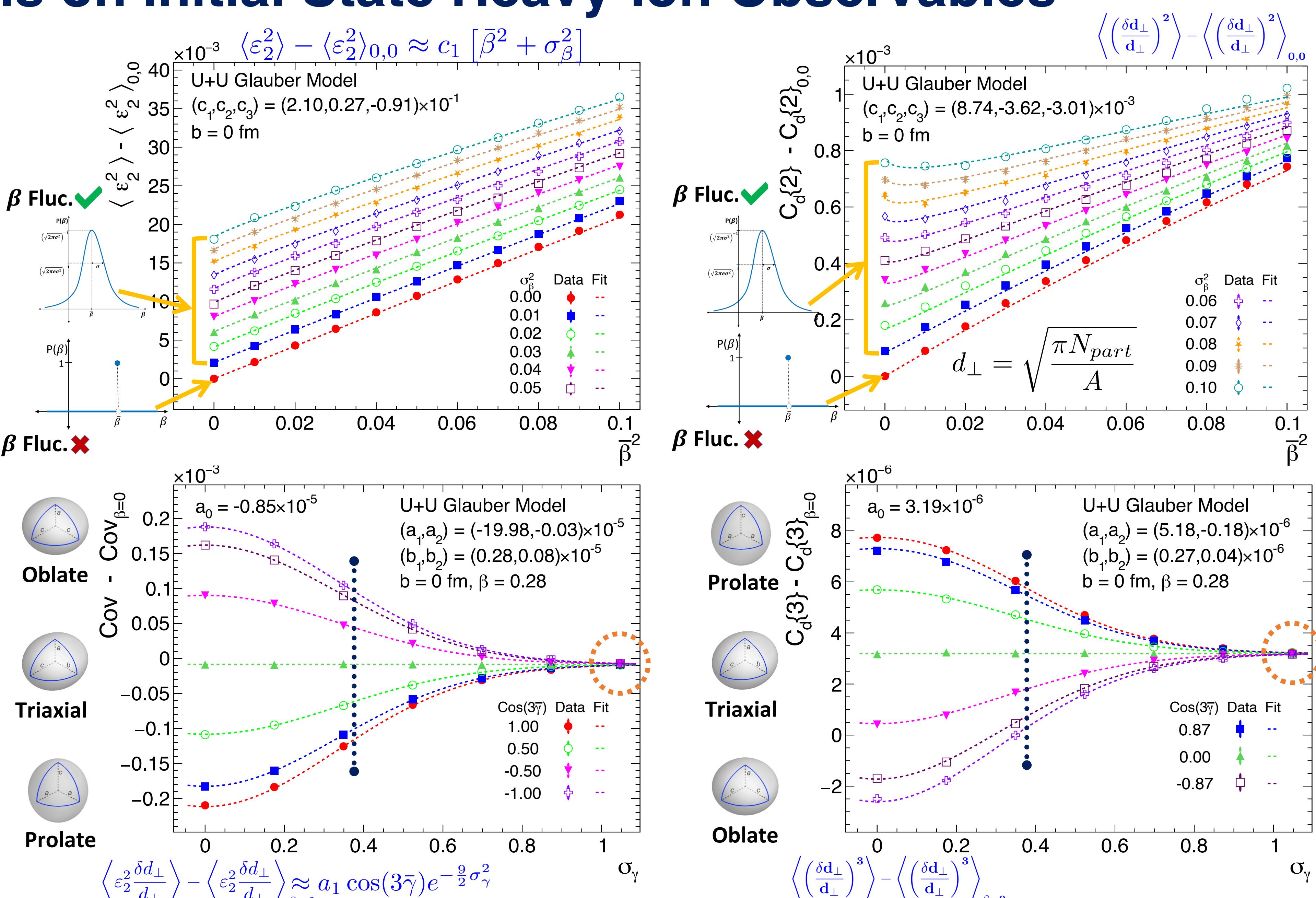
Investigated by simulating UCC via Glauber Model, allowing shape parameters to fluctuate following a Gaussian distribution.

Expectation:

$$\begin{aligned} \text{For } \beta \text{ fluctuations} & \quad \langle \varepsilon_2^2 \rangle - \langle \varepsilon_2^2 \rangle_{\beta=0}, \\ & \quad \left\langle \left(\frac{\delta d_\perp}{d_\perp} \right)^2 \right\rangle - \left\langle \left(\frac{\delta d_\perp}{d_\perp} \right)^2 \right\rangle_{\beta=0} \\ & = c_1 \langle \beta^2 \rangle + c_2 \langle \beta^3 \cos(3\gamma) \rangle + c_3 \langle \beta^4 \rangle \\ \text{For } \gamma \text{ fluctuations} & \quad \langle O \rangle = a_0 + \sum_{n=1}^{\infty} [a_n \cos(3n\bar{\gamma}) + b_n \sin(3n\bar{\gamma})] e^{-\frac{9n^2\sigma_\gamma^2}{2}} \\ & \approx a_0 + a_1 \cos(3\bar{\gamma}) e^{-\frac{9\sigma_\gamma^2}{2}} \end{aligned}$$

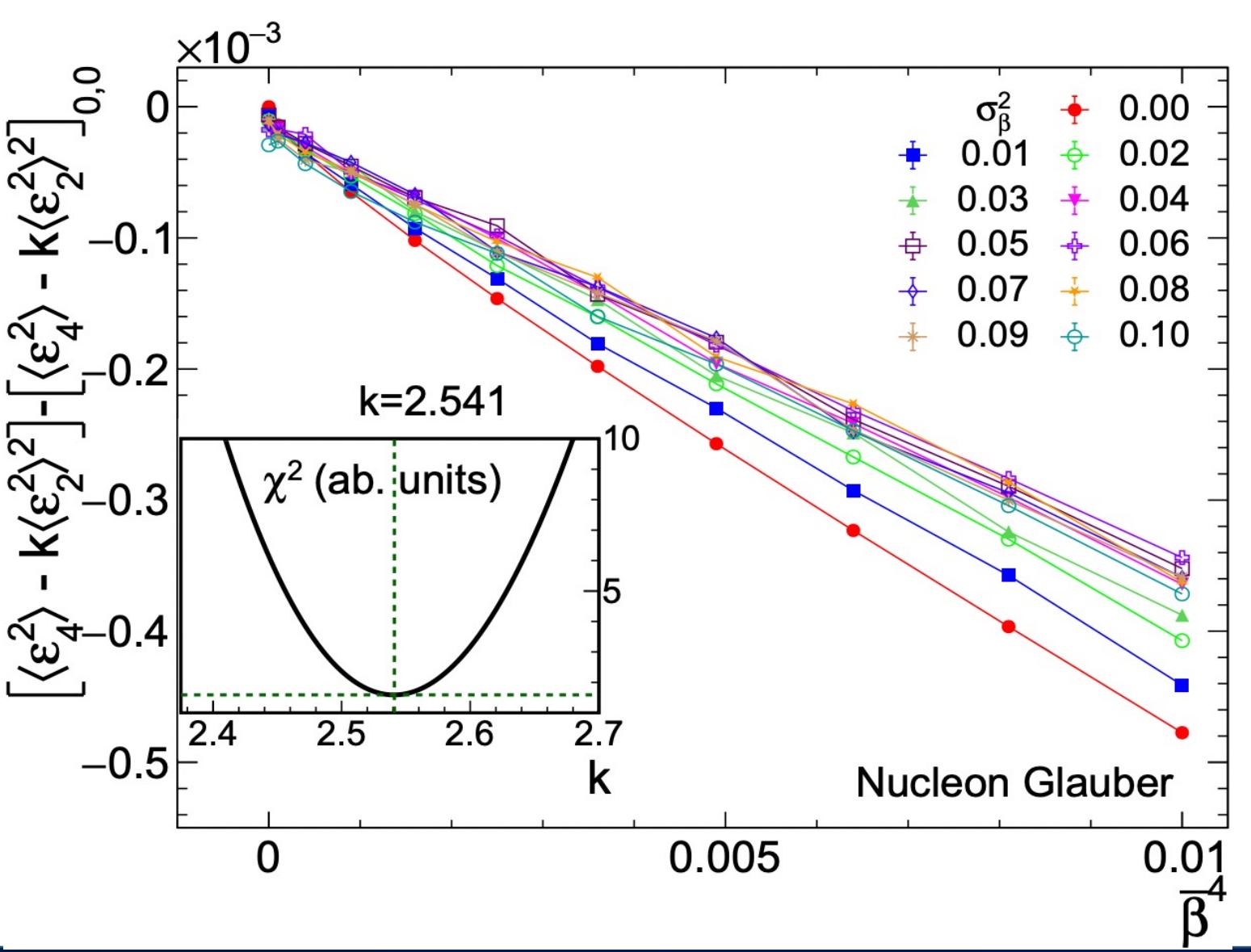
Observations:

- Fluctuation in β enhances the deformation signal.
- Fluctuation in γ exponentially decays the triaxial signal.



Variations in β give equivalent linear contributions from both mean and fluctuations.

Large γ fluctuations → Observables fail to distinguish between prolate and oblate nuclei. Difficult to resolve γ soft vs rigid triaxial nuclei.



Extracting the mean and variance of β, γ fluctuations:

- Appropriately combine higher order correlations $\longrightarrow f(\bar{\beta}, \sigma_\beta; k) = \langle \varepsilon_2^4 \rangle - k \langle \varepsilon_2^2 \rangle^2$
- At $k=2.5$, $f(\bar{\beta}, \sigma_\beta; k) - f(\bar{\beta}, 0; k) \propto \bar{\beta}^4$. Determines $\bar{\beta}$ with a precision of 7% in the Glauber model.

Combine higher-order multi-particle correlations to constrain the mean and variance!!

$$\langle \varepsilon_2^4 \rangle - k \langle \varepsilon_2^2 \rangle^2 \sim \langle \beta^4 \rangle - k' \langle \beta^2 \rangle^2 \sim C \bar{\beta}^4$$

Conclusions

- Fluctuations in β polynomially enhance the deformation signal while having equal contributions from mean and variance.
- Fluctuations in γ exponentially decay the triaxial signal. In the large γ fluctuation limit, HI observables lose their ability to discriminate between prolate and oblate nuclear shapes.
- Higher-order multi-particle correlations can be combined to constrain the mean and variance of β and γ fluctuations.

References *

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