THANKs

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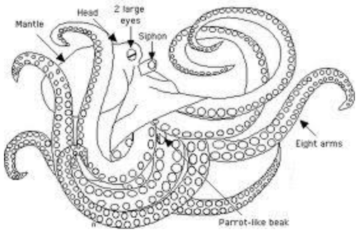
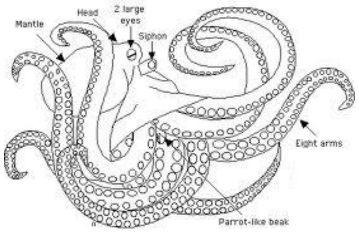


HQ organizers



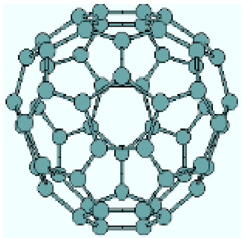
for

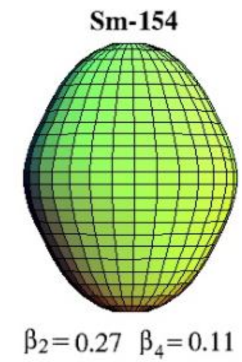
Invitation to attend Hot Quarks 2012

Initial state in RHIC

and

Ground-state properties of Nuclei

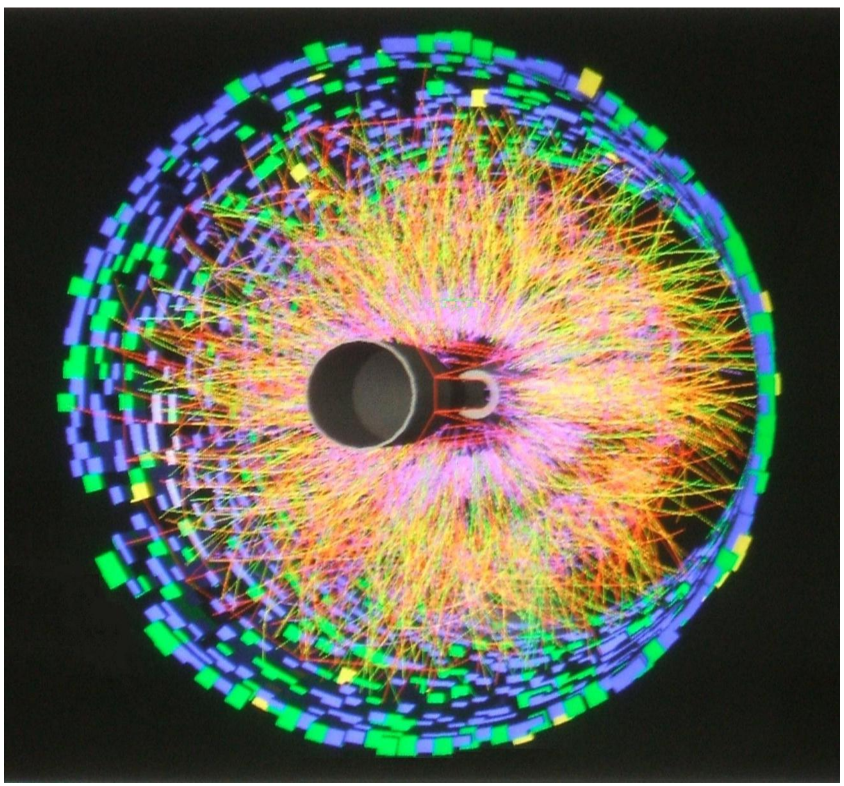




Peter Filip

(IP SAS, Bratislava)

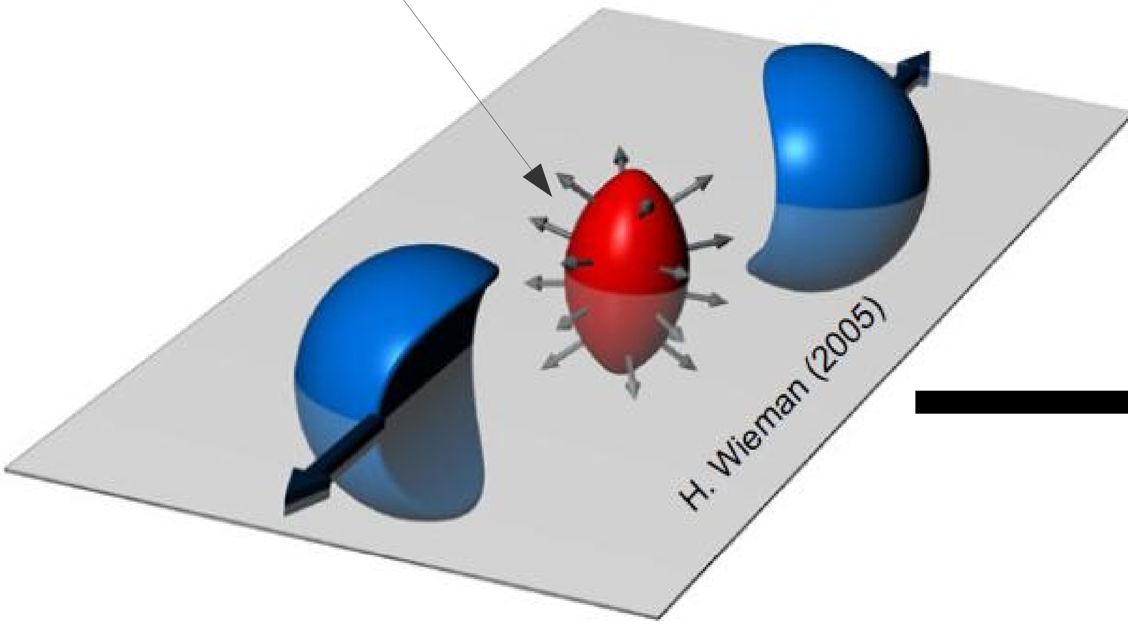
14-20. October, Hot Quarks 2012



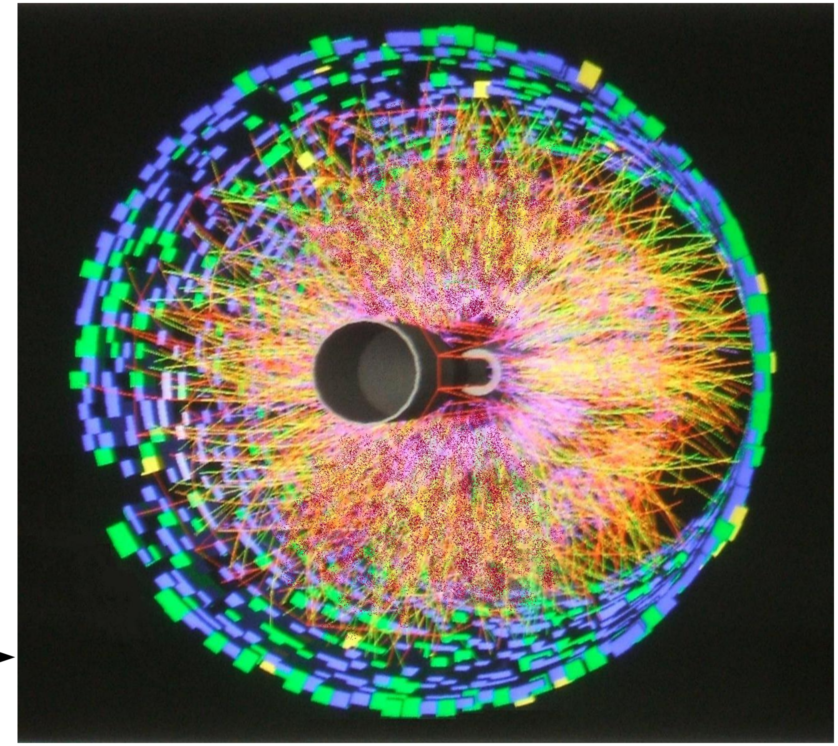
- Elliptic Flow
- Initial eccentricity
- Deformation effects
- GMC simulations
- Vibrations of nuclei
- Summary

Elliptic Flow: v_2

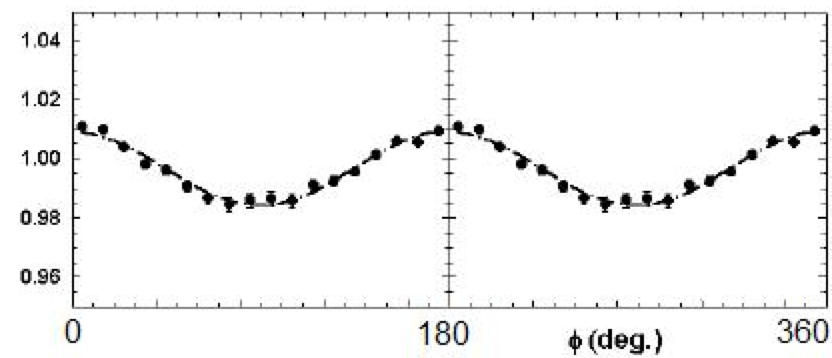
Initial state geometry



STAR plasma screen: Au+Au



Azimuthal asymmetry



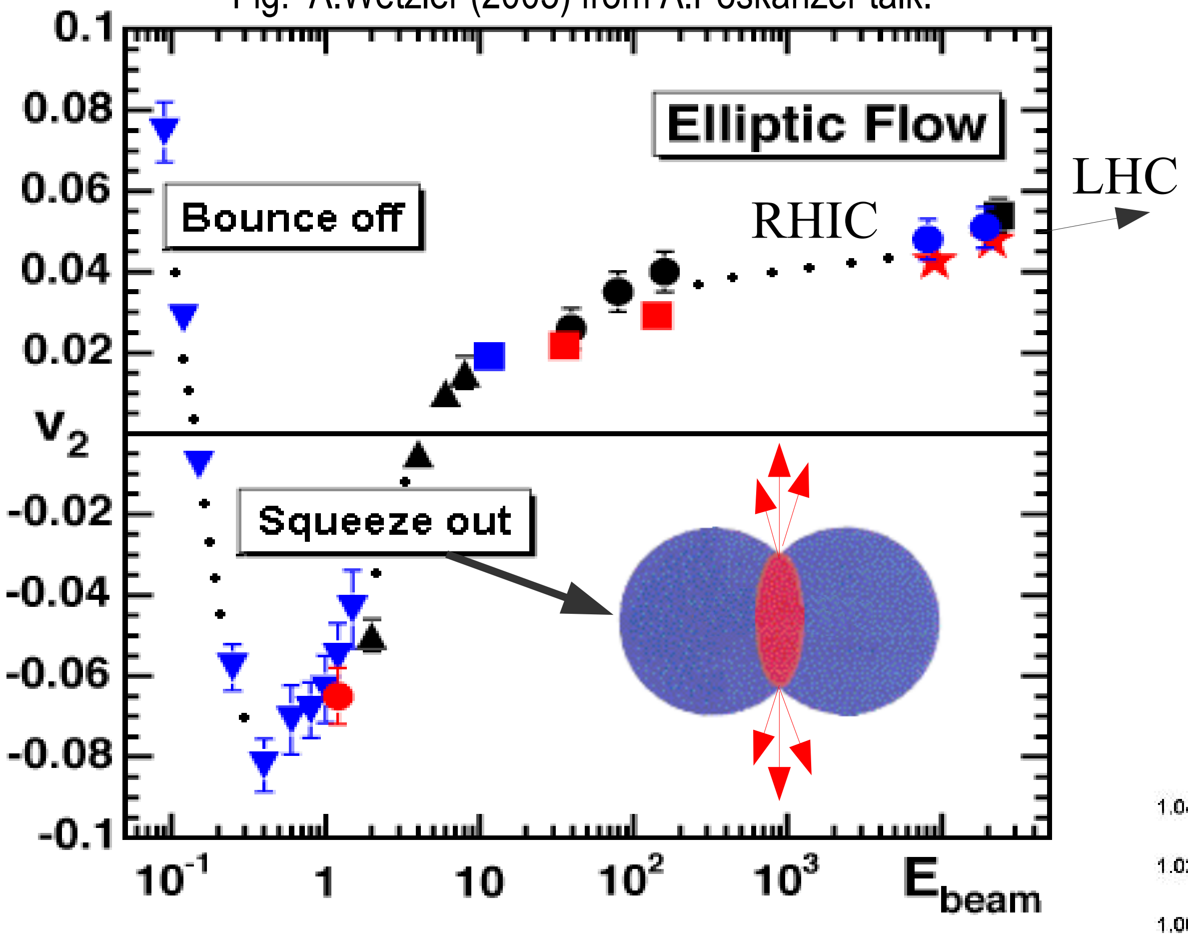
Asymmetry in Spatial distribution leads to

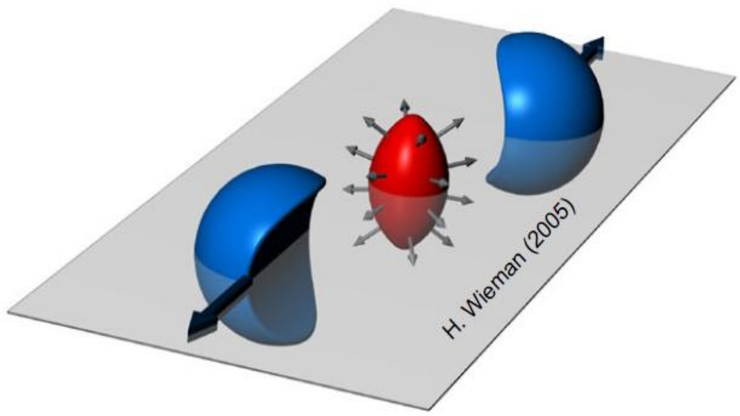
→ asymmetry in **Momentum** distribution

Asymmetry = v_2 depends on the COLLISION ENERGY

Elliptic Flow: v_2 energy dependence

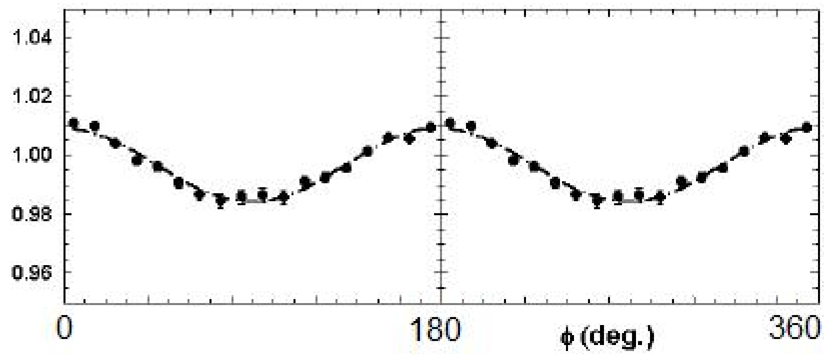
Fig: A.Wetzler (2005) from A.Poskanzer talk.





Asymmetry strength: v_2

$$dN/d\phi = (N/2\pi)[1+2v_2 \cos(2\phi)]$$

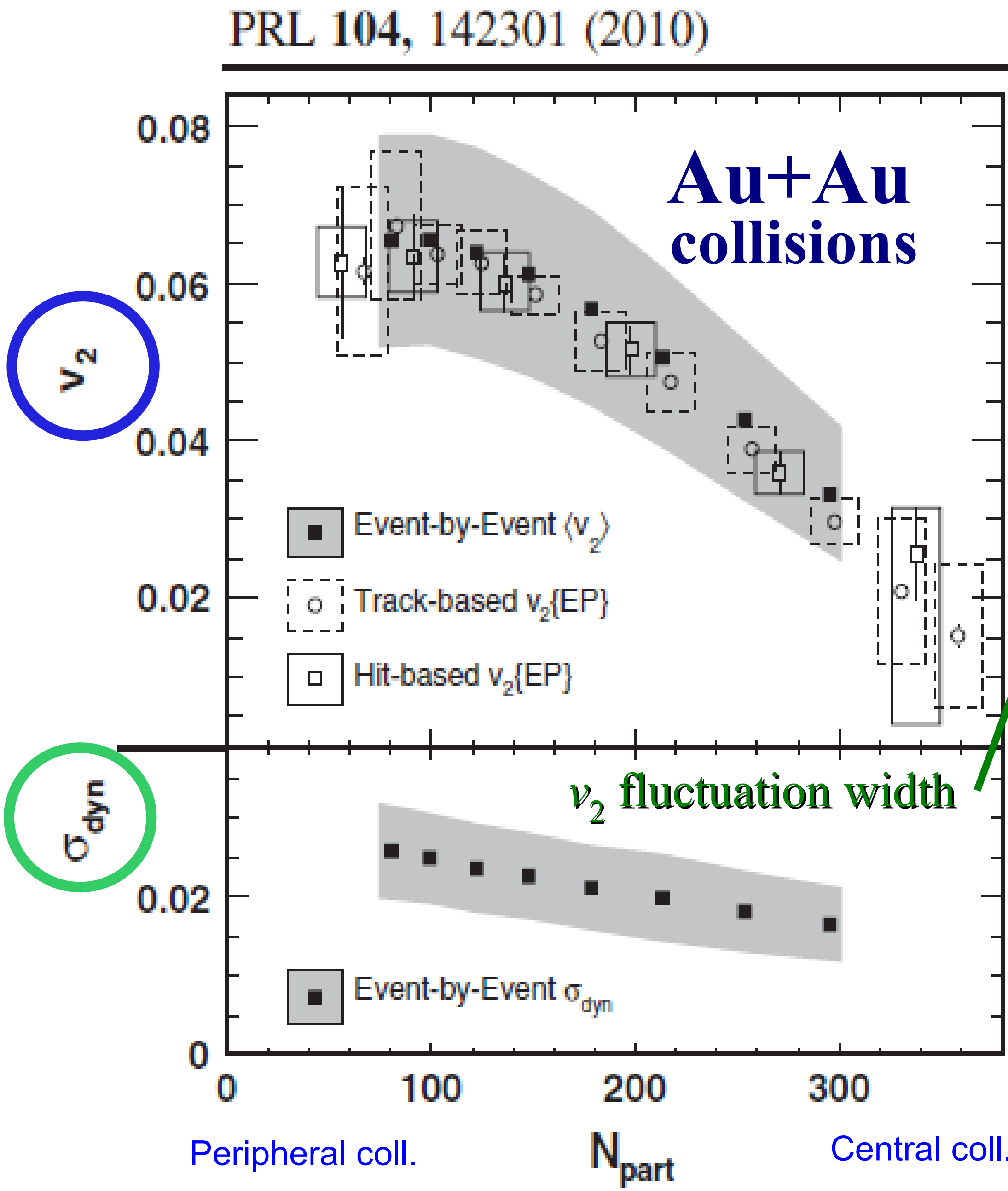


Azimuthal Momentum distribution

v_2: has **strength = magnitude** $\langle v_2 \rangle$

and **fluctuations**: σ_{v_2}

Elliptic flow v_2: magnitude & fluctuations



- We believe = assume:

  v_2 fluctuation

  comes from: the initial **eccentricity fluctuation** (at given N_{ch} or N_{part})

- Also **other possibilities:**

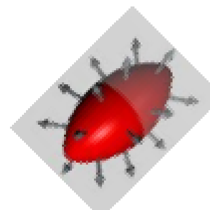
  - hydrodynamic instabilities during the expansion

<u>Elliptic Flow</u> → f (<u>CENTRALITY</u>)

from initial eccentricity **ε**:

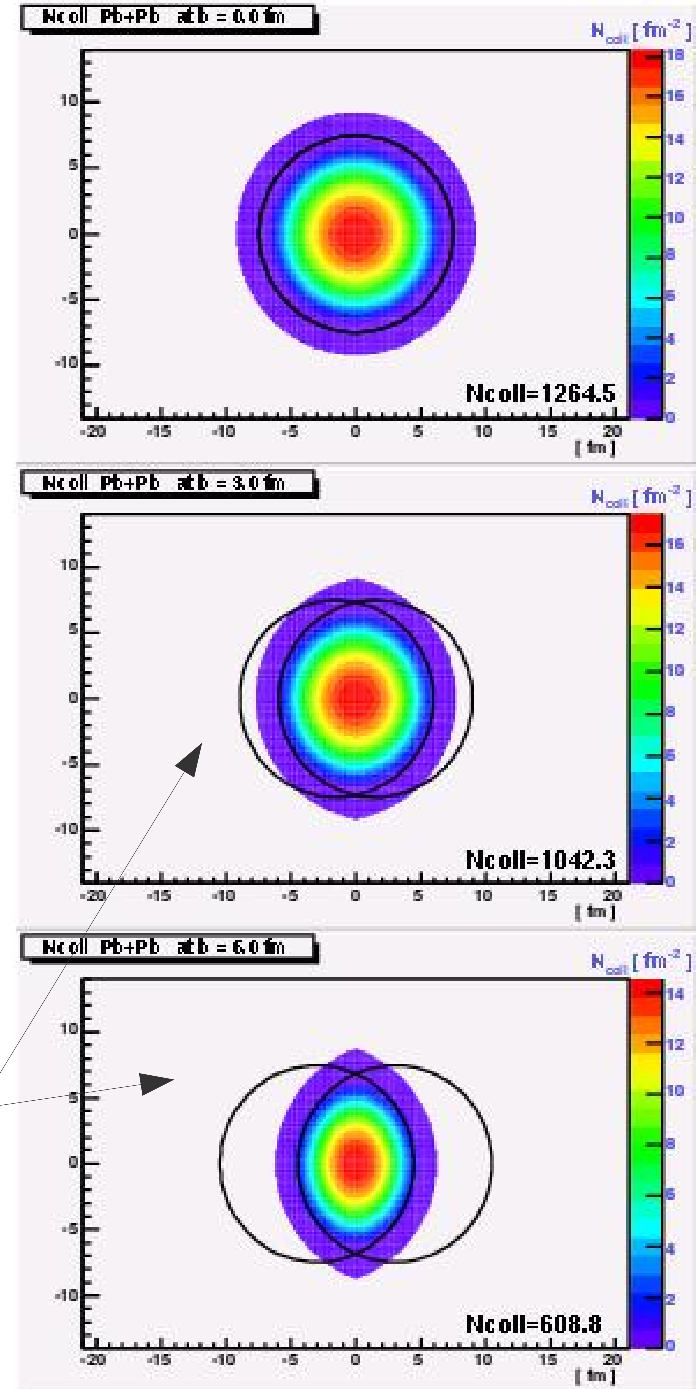
Rotation-ivariant formula

$$\varepsilon = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



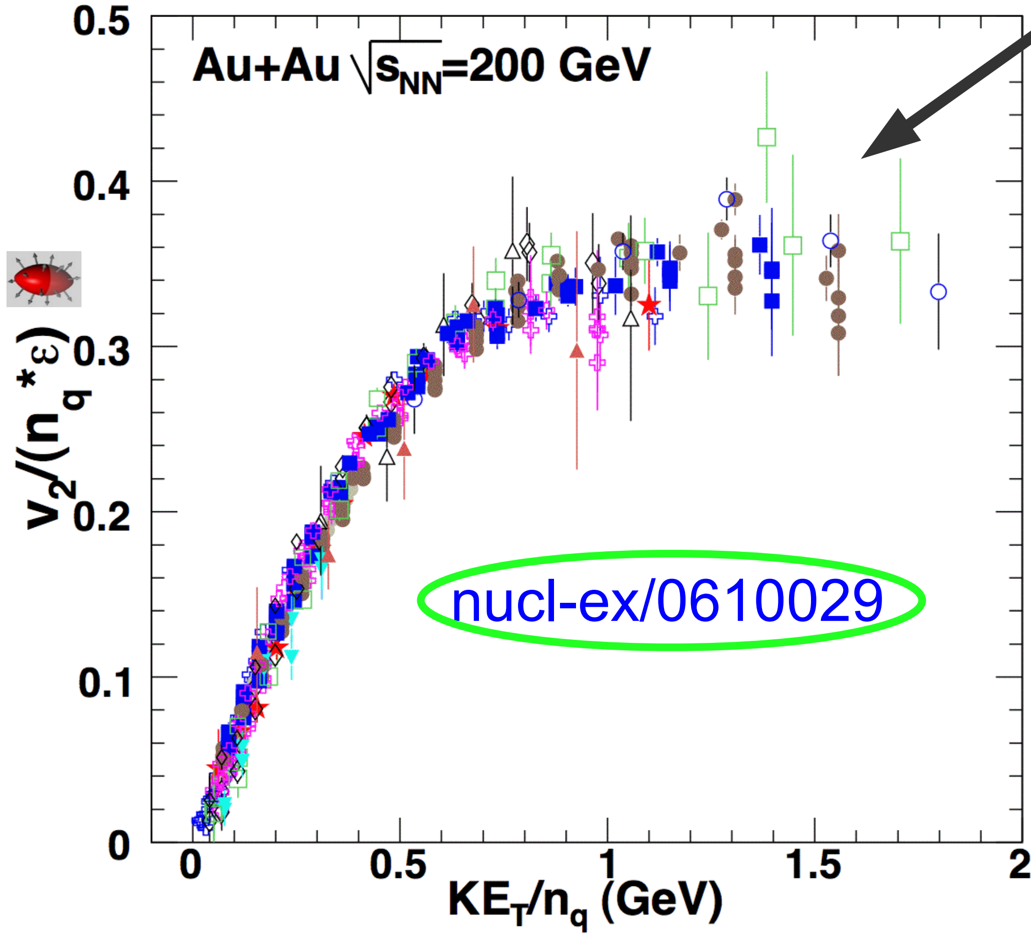
Hydrodynamics: $v_2 \approx 0.2 * \varepsilon$

- Eccentricity → larger in <u>non-central collisions</u>
- Elliptic flow → increases for non-central collisions



Elliptic flow at *RHIC*: partonic expansion

NCQ scaling



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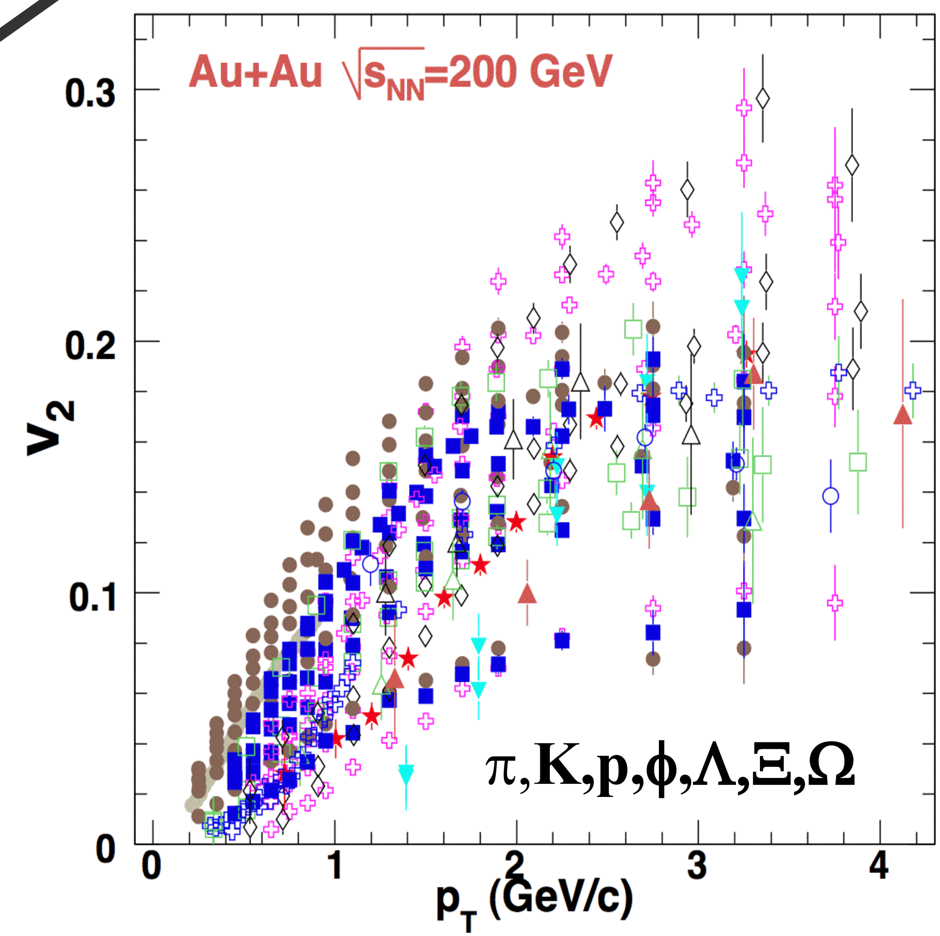


Very nice !

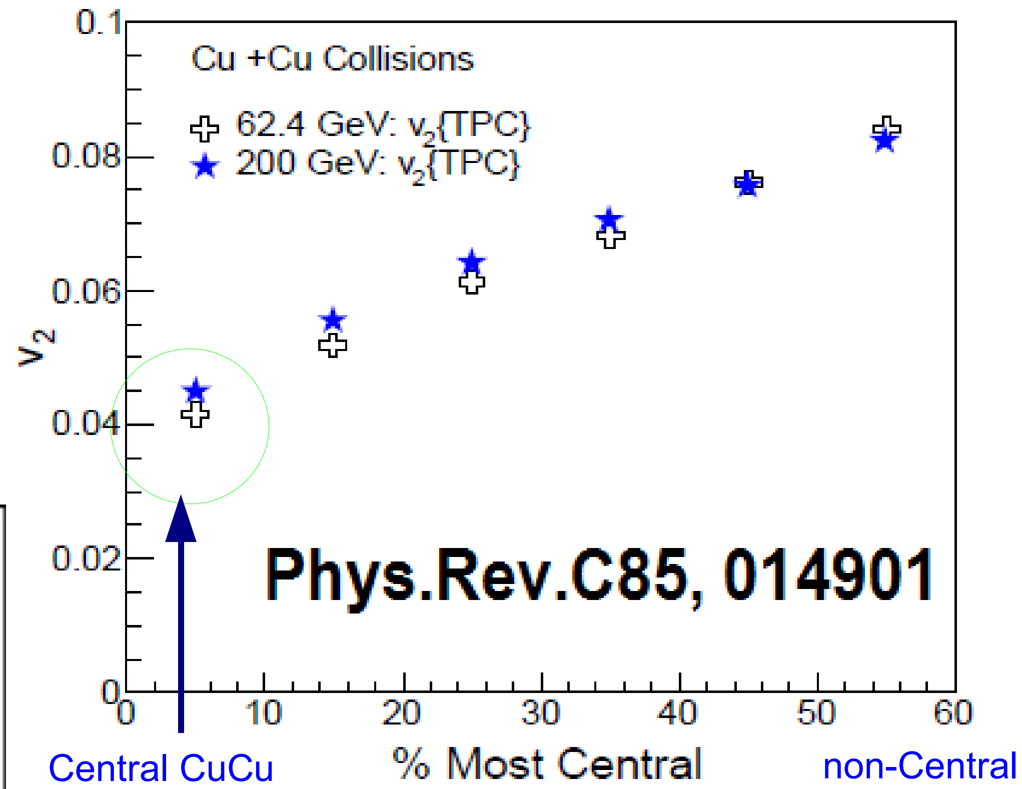
However: Cu+Cu →

Elliptic flow v_2 strength in Cu+Cu

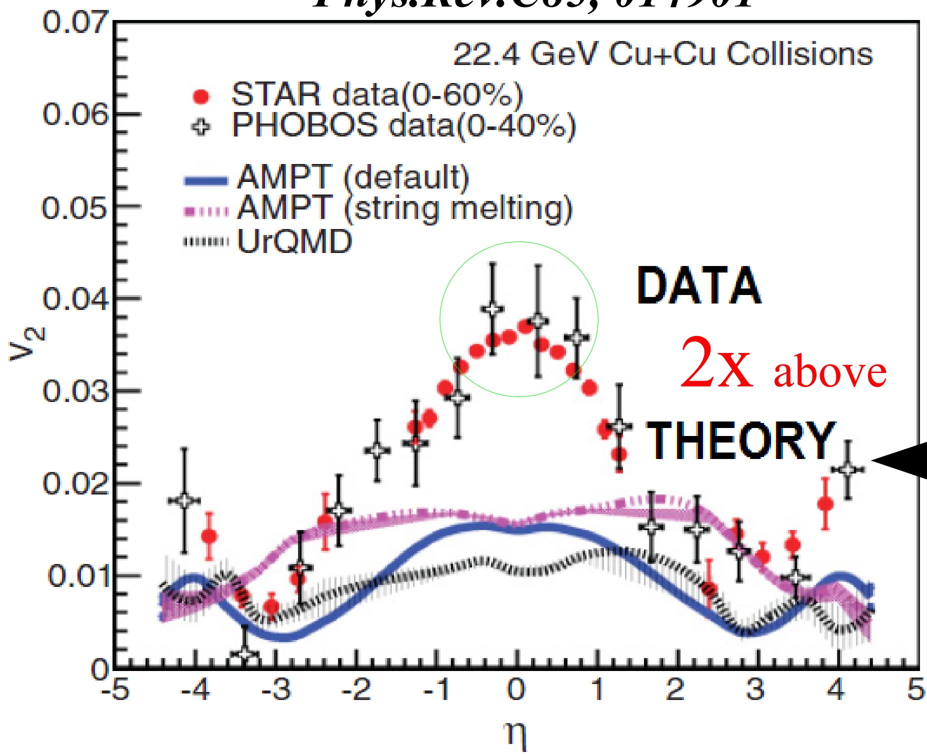
- v_2 strength = $< v_2 >$

  → average v_2 value

  (pseudorapidity: η)



Phys.Rev.C85, 014901



v_2 __strength__ in Cu+Cu

(RHIC at 22.4 GeV/n)

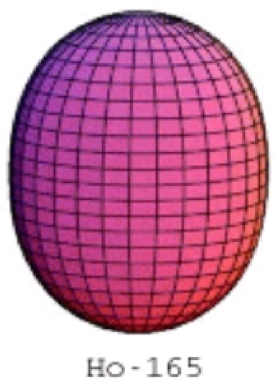
is not understood ...

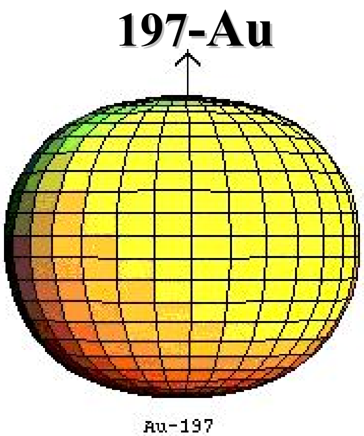
In this talk we discuss why:

Geometry of Initial-state

(eccentricity $\boldsymbol{\varepsilon}_2$, $\boldsymbol{\varepsilon}_3$, $\boldsymbol{\varepsilon}_4$ ...)

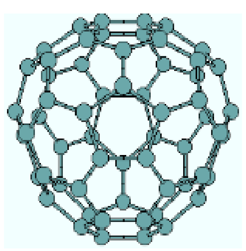
is influenced by



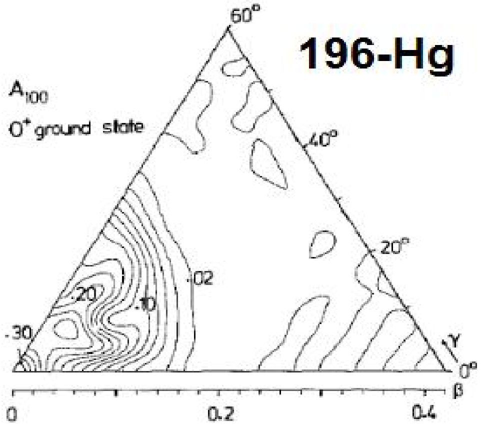


Ground-state **deformation**

Phys.Rev.C80 (2009)

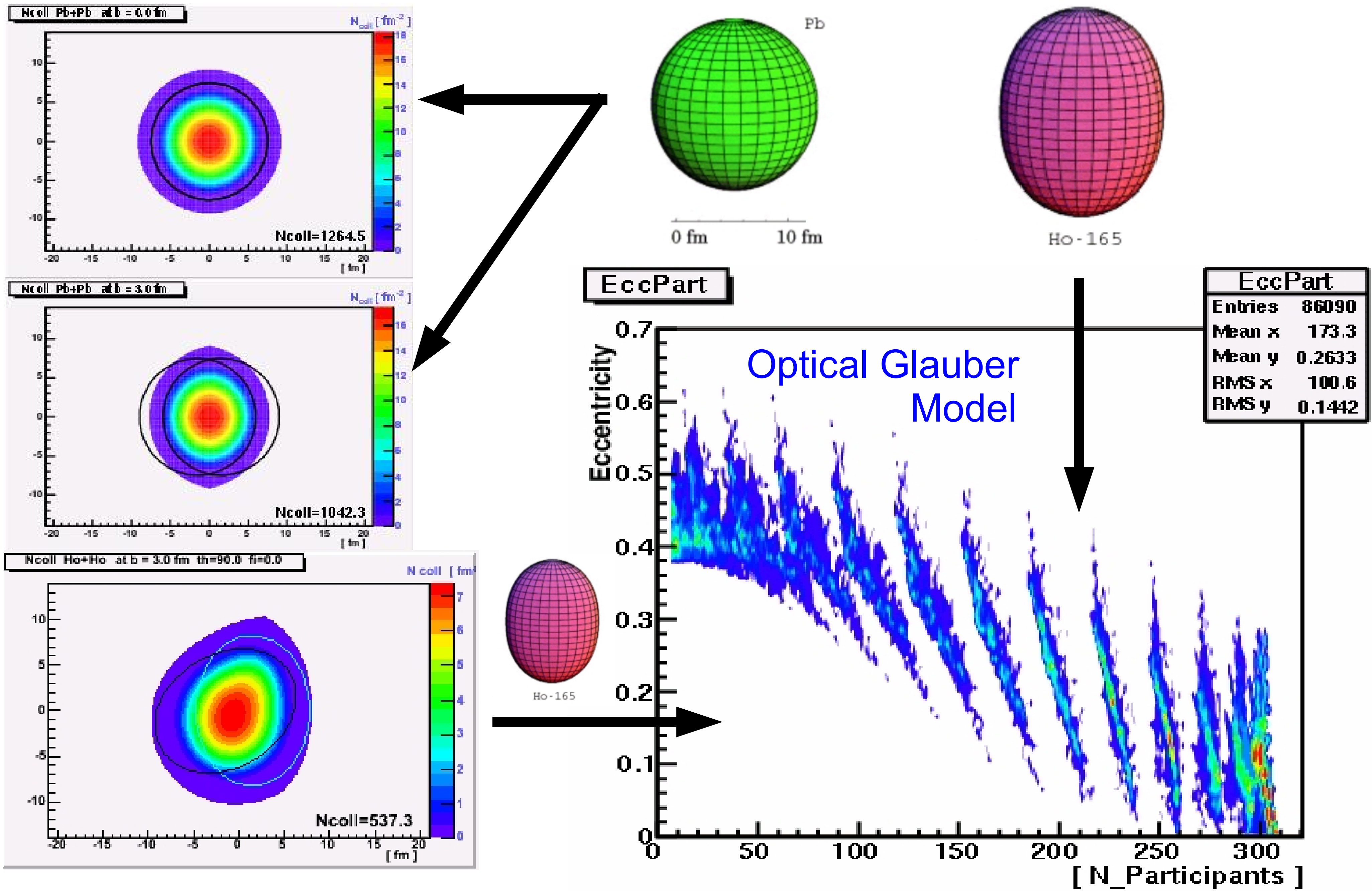


Shape **Vibration**

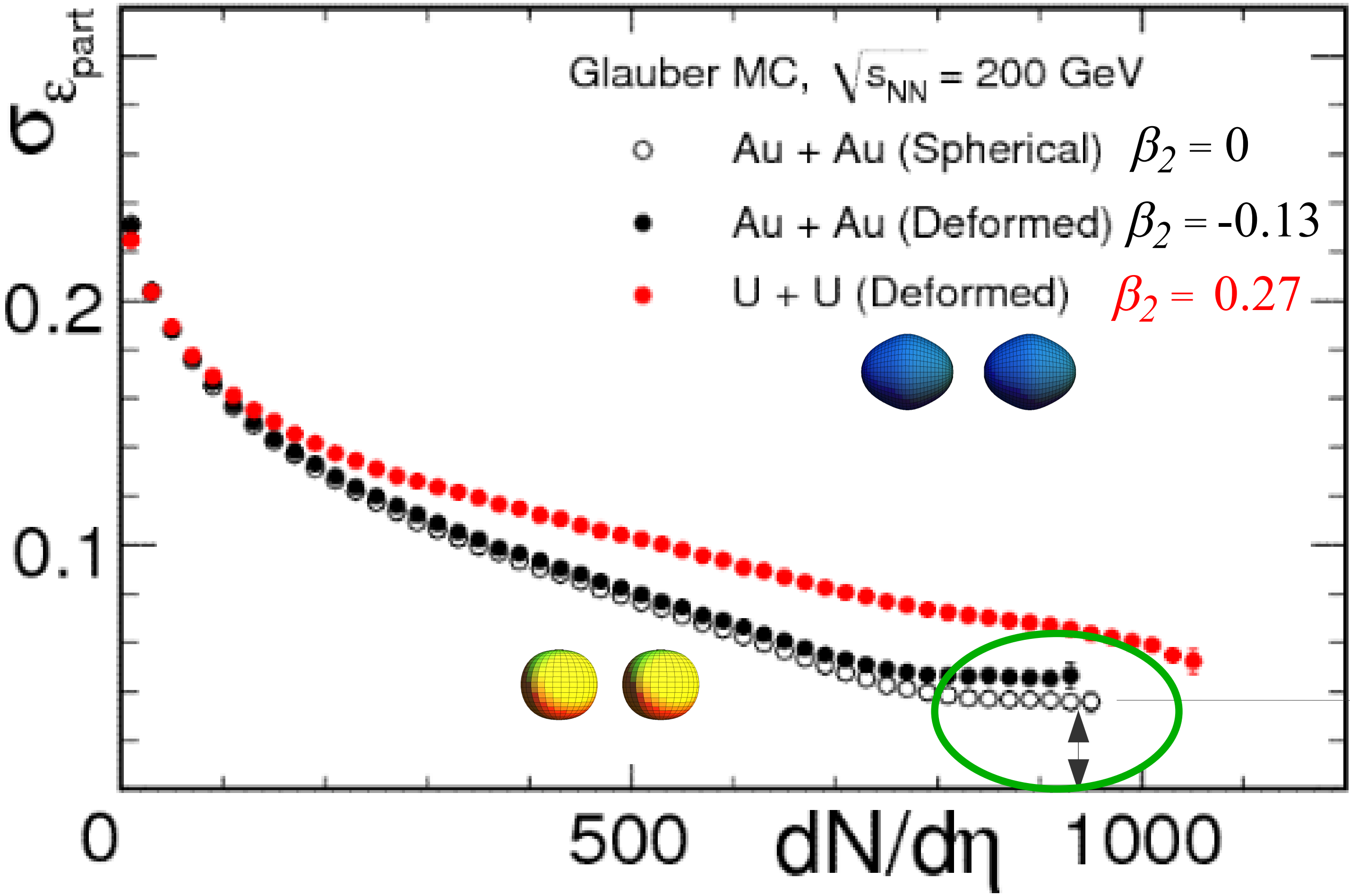


(to publish in 2013)

Deformation → affects Eccentricity fluctuations



Deformation of nuclei in MC Glauber:
→ **increased** Eccentricity **<u>fluctuations</u>**



$$\sigma_\varepsilon = \sqrt{\sigma^2_{\beta_2} + \tilde{\sigma}^2_\varepsilon}$$

due to deformation

standard fluctuation

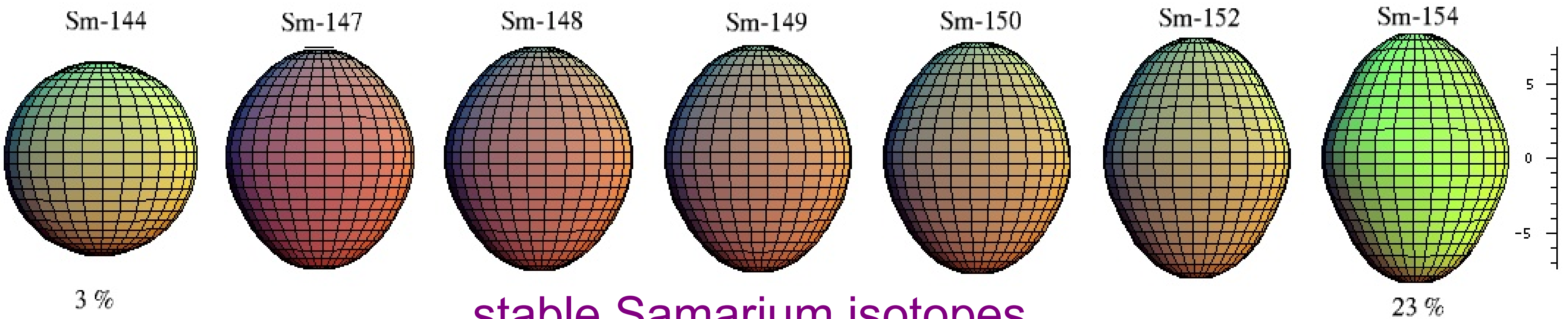
Phys.Rev.C80, 054903: Deformation influences σ_{v_2} (fluctuation of v_2)

Experimental test: does deformation (β_2) of nuclei

in Heavy Ion Collisions

→ have influence on <u>elliptic flow phenomenon</u> ?

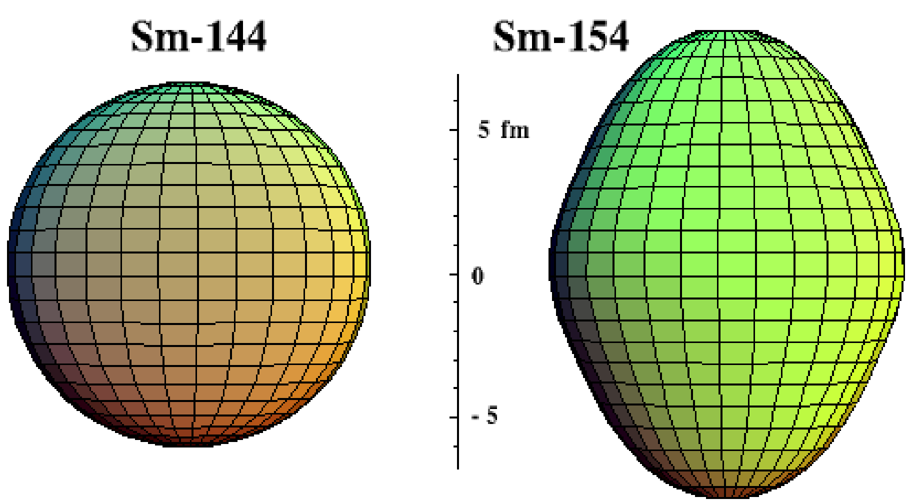
Sm+Sm collisions



stable Samarium isotopes

Comparing v_2 fluctuations:

→ for spherical & deformed ***Sm+Sm*** *collisions*



$\beta_2, \beta_4 = 0$

$\beta_2 = 0.27,\ \beta_4 = 0.11$

$$\sigma_\varepsilon = \sqrt{\sigma^2_{\beta_2} + \tilde{\sigma}^2_\varepsilon}$$

due to deformation

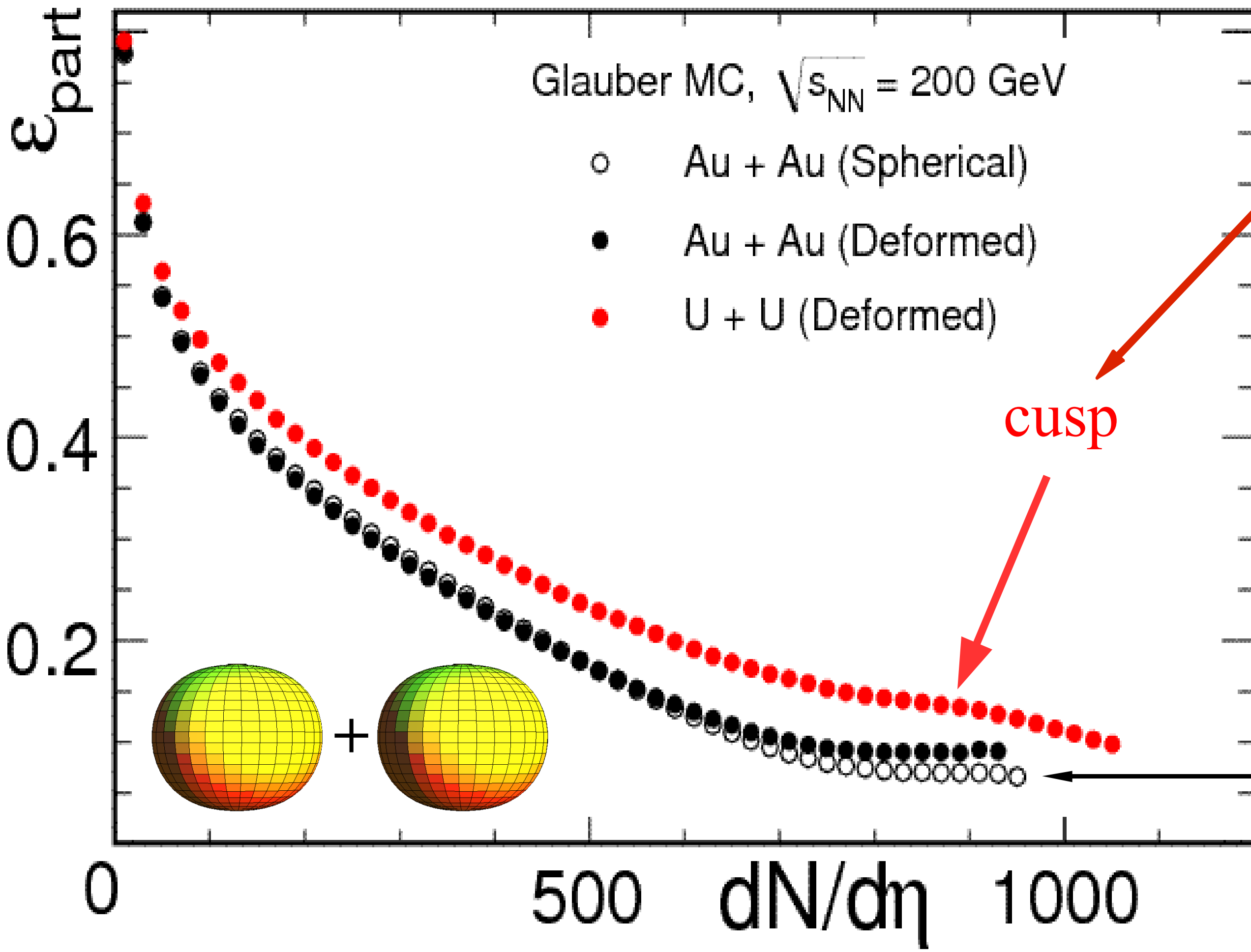
all other fluctuations

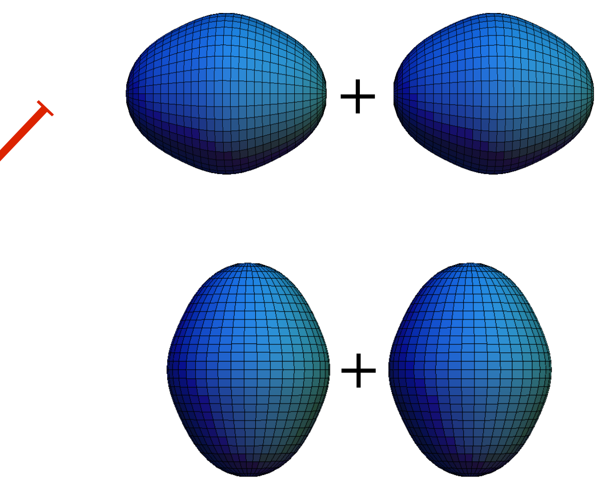
Let's compare also v_2 strength !

why ? → **v_2 cusp** prediction:

Average $<\boldsymbol{\varepsilon}>$ in MC Glauber:

cusp $\longrightarrow$ self-orientation effect in central UU coll.





20% difference in ε manitude

(affecting extracted viscosity)

MC Glauber simulation: Phys.Rev.C80, 054903: $\boldsymbol{\varepsilon}$ (CUSP) $\longrightarrow$ $\boldsymbol{v_2}$ (CUSP)

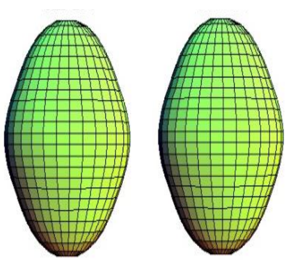
Self-orientation CUSP effect:

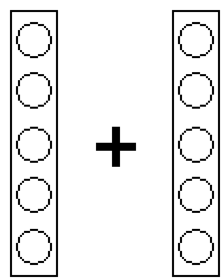
- Comes from the high N_{ch} multiplicity (and ZDC) cut

more NN collisions $\rightarrow$ max N_{ch} $\rightarrow$ orientation

Extreme deformation

example:

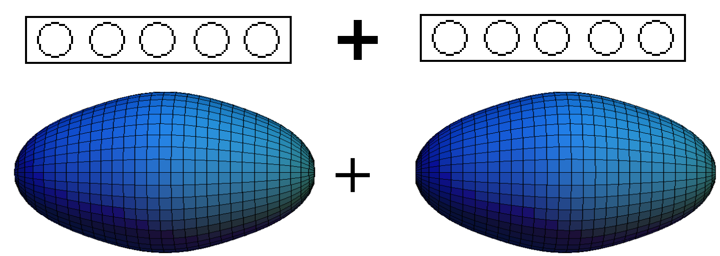




NN coll. = 5

N part. = 10

Binary n-n collisions sensitivity to orientation



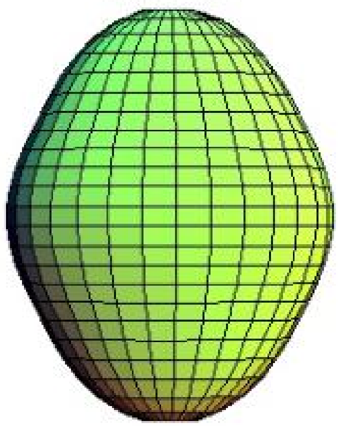
NN coll. = 25

N part. = 10

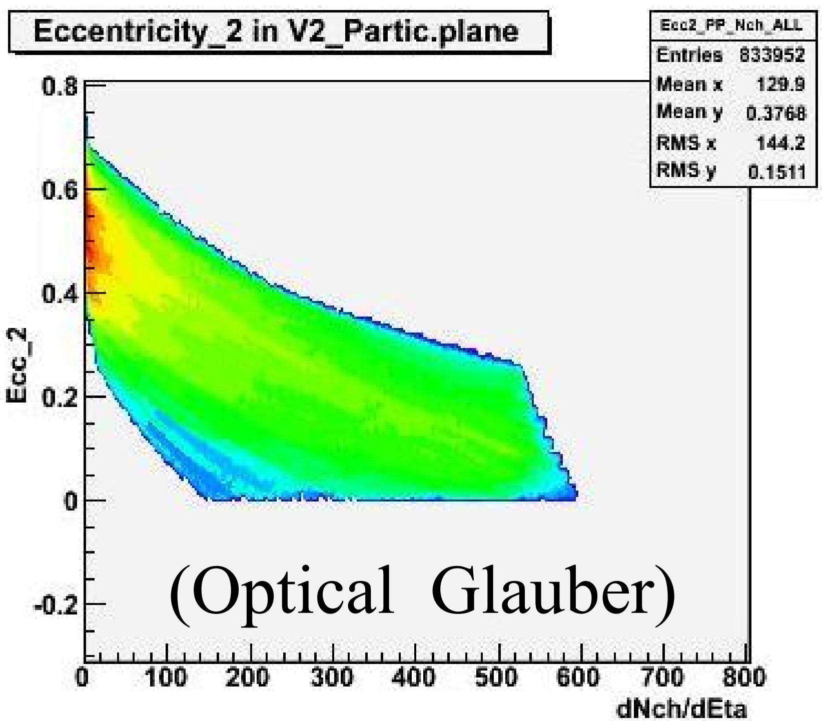
$$dN_{\mathrm{ch}}/d\eta = (1-x)\cdot n_{pp}\frac{N_{\mathrm{part}}}{2} + x\cdot n_{pp}\,N_{\mathrm{coll}}$$

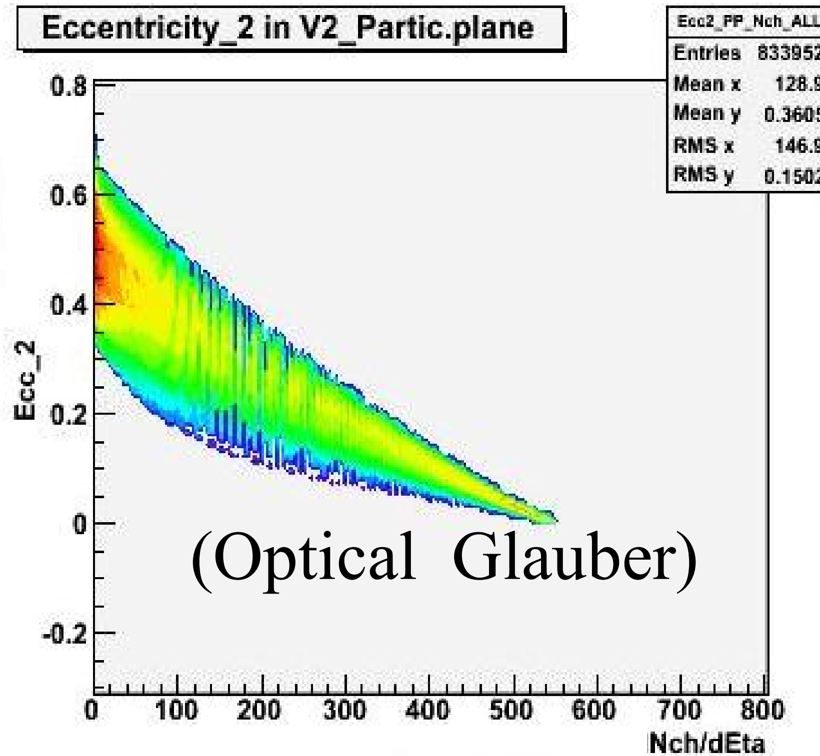
Opt-GM simulation of Eccentricity Sm+Sm

Sm-154

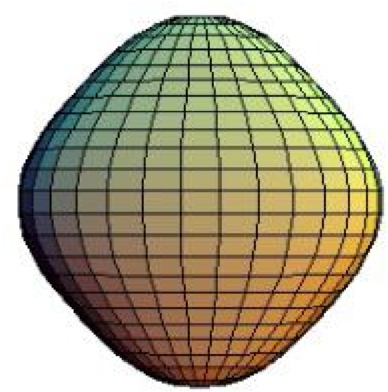


$\beta_2 = 0.27 \quad \beta_4 = 0.11$





$\beta_4 = 0.11$



$\beta_2 = 0.0$

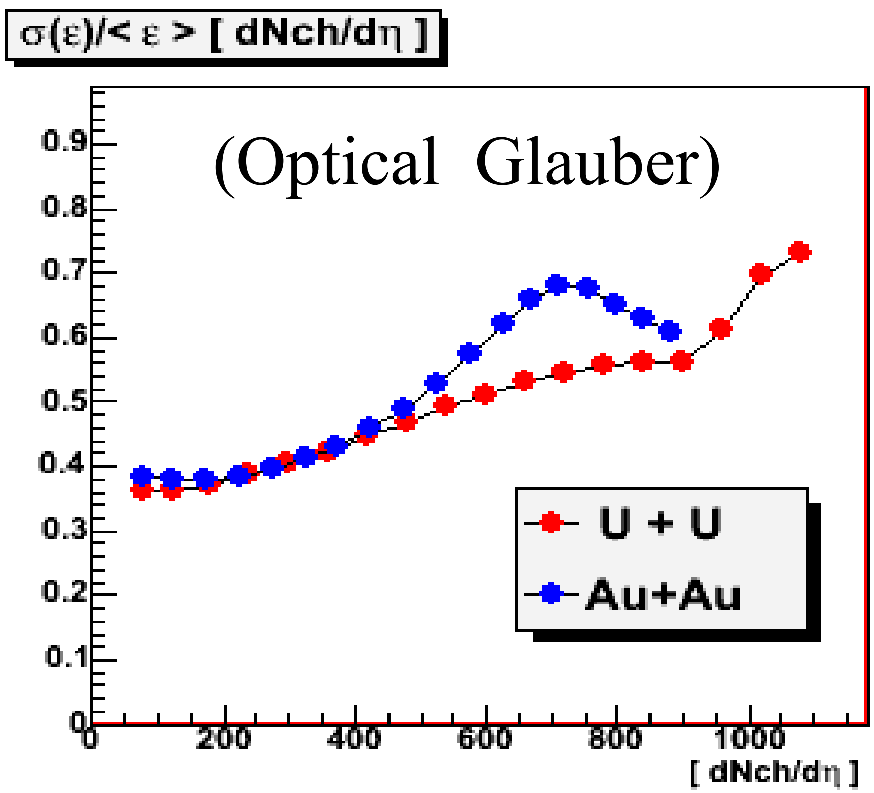
Combined deformation effect:

$\sigma_{v_2} / v_2 \; [\, N_{ch} \,]$

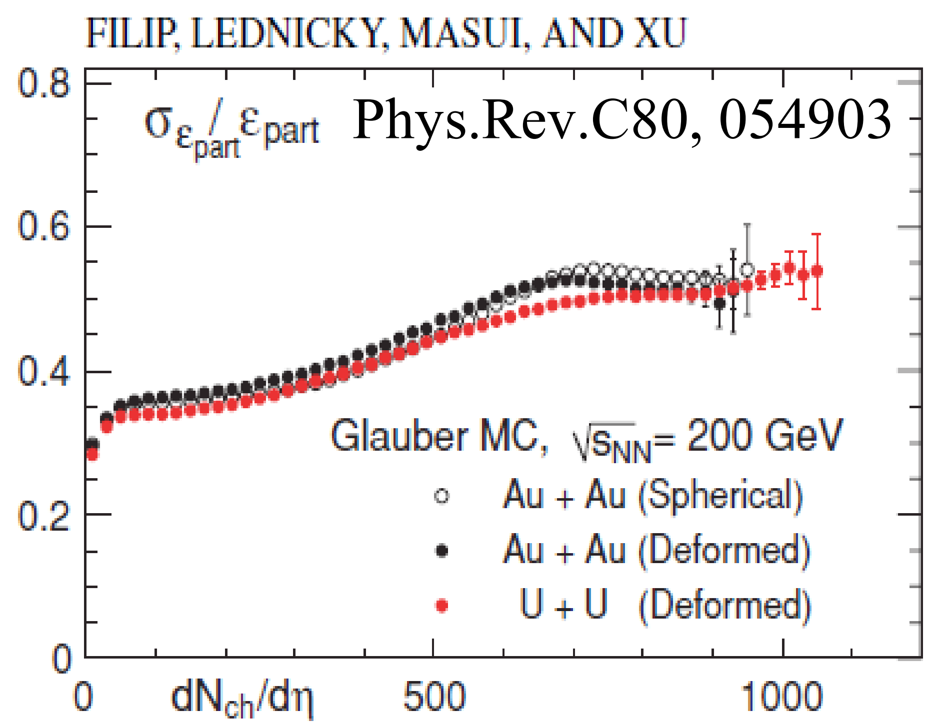
Assuming hydrodynamical expansion:

$\rightarrow \quad \sigma_{v_2}/v_2 \;\approx\; \sigma_{\varepsilon} \,/\, <\varepsilon>$

→ may be sensitive to deformation of nuclei



Optical Glauber Model



Full MC Glauber simulation

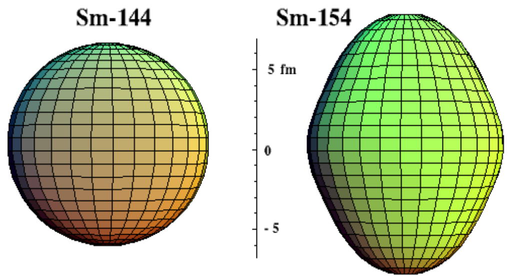
Summary I

- **Deformation** of nuclei

  → can influence initial eccentricity (elliptic flow)

- Comparing v_2 in $({}^{144}Sm+{}^{144}Sm)$ and $({}^{154}Sm+{}^{154}Sm)$

  → suggested for: LHC



$\beta_2,\beta_4=0$ $\beta_2=0.27,\ \beta_4=0.11$

- **Cusp in v_2 (Nch) expected** for **$^{154}Sm+^{154}Sm$** and ***U+U***

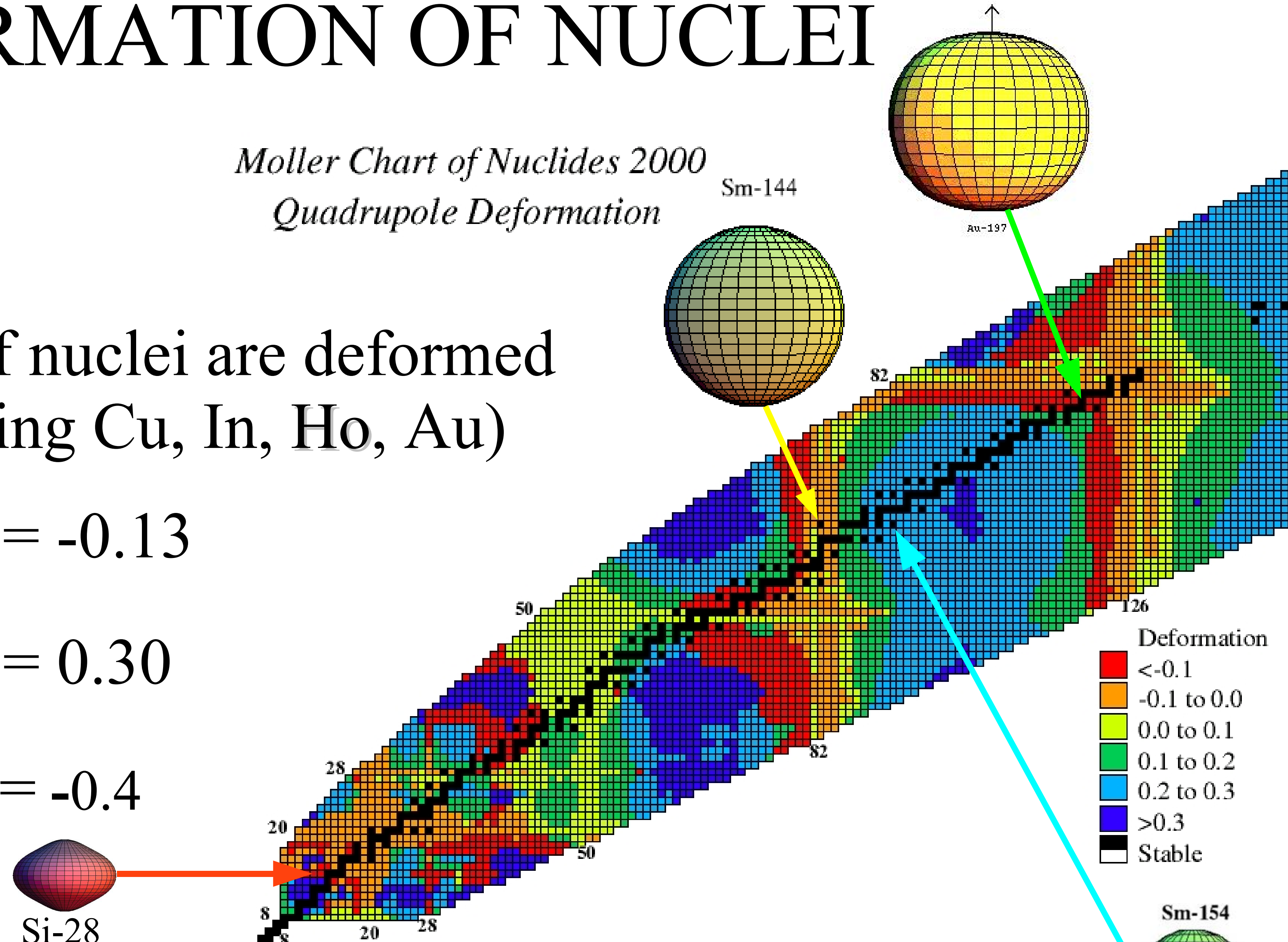
  in ultra-central collisions → **to be observed.**

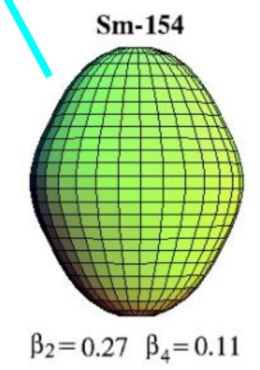
DEFORMATION OF NUCLEI

- Most of nuclei are deformed (including Cu, In, Ho, Au)
- **Au:** β_2 = -0.13

  Ho: β_2 = 0.30

  Si^{28}: β_2 = -0.4





- <u>Nd,Sm,Ho,Si</u> collisions at LHC/RHIC/SPS

  → can improve understanding of the Elliptic flow.

Other <u>initial-state</u> influence ?

→ <u>GROUND-STATE nuclear Vibration</u> (GSV)

- **What is it ? (Zero-Point-Shape-Vibration)**

  → present in deformed nuclei ?

  → present also in spherical nuclei ?

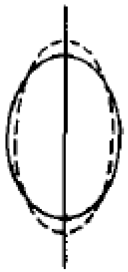
  → **Is it stronger or weaker for light nuclei ?**

- **Does it really exist ?**

  → has anybody observed Ground-State <u>vibration</u> ?

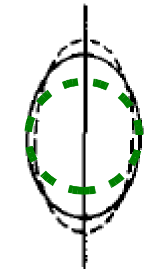
  (in molecular physics ? and μ–cF ?)

- **Should we include it in MC simulations of HIC ?**



β-vibration

Bohr and Mottelson on ZPV
Nuclear Structure II



β-vibration

Occurrence of shape oscillations

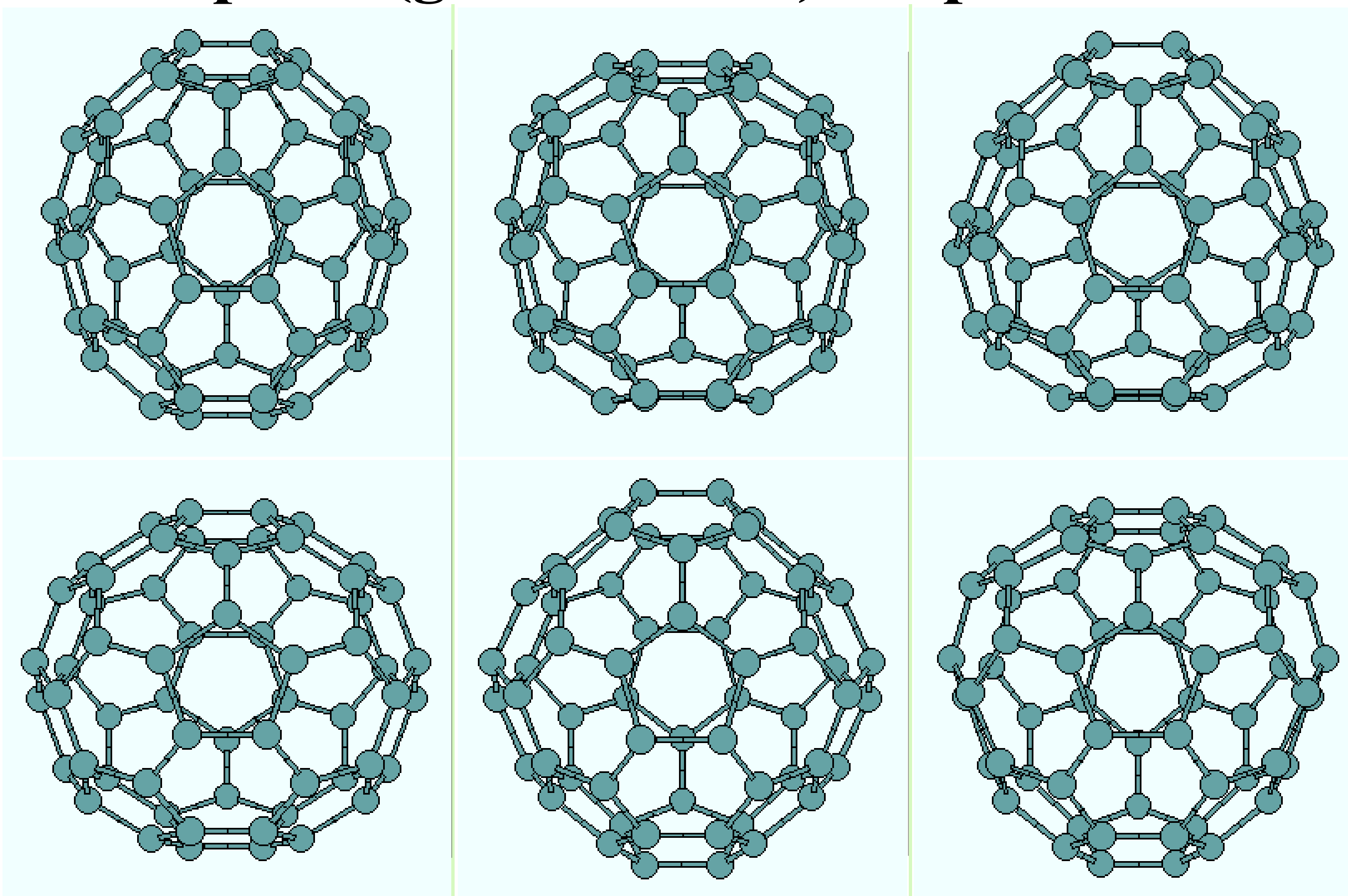
The study of the low-energy spectra of the even-even nuclei has revealed the systematic occurrence of $I\pi = 2+$ and $3-$ states with properties suggesting a vibrational interpretation. The collective character of the excitations is implied by the large transition probabilities and by the fact that the properties vary rather smoothly with N and Z. The systematics of the excitation energies of the $2+$ and $3-$ modes are shown in Fig. 2-17a, b, Vol. I, pp. 196–197, and Fig. 6-40, p. 560, respectively. The transition probabilities are an order of magnitude larger than the single-particle unit, and if interpreted as shape oscillations, as in Eq. (6-65), correspond to zero-point amplitudes β_2 and β_3 typically of order 0.2 (see Fig. 4-5)

→ nuclei do oscilate = vibrate in the ground state

→ **amplitudes comparable to static deformation** β_2

Molecular Physics: C_{60}

Zero-point (ground-state) <u>shape vibration</u>



Quadrupole vibration: β_2 Hexa-decapole vibration: β_4 Octupole vibration: β_3

From → J.Ménendez and J.Page:"Vibrational spectroscopy of C_{60}" **Nuclei can vibrate similarly!**

Bohr and Mottelson on ZP Vibration

Nuclear Structure II

The vibrational wave functions $\varphi_n(\alpha)$ have the form

$$\varphi_n(\alpha)=(2\pi)^{-1/4}(2^n n!\alpha_0)^{-1/2}H_n\left(2^{-1/2}\frac{\alpha}{\alpha_0}\right)\boxed{\exp\left\{-\frac{1}{4}\frac{\alpha^2}{\alpha_0^2}\right\}} \qquad (6\text{-}14)$$

where H_n is the nth Hermite polynomial $(H_0(x)=1,\ H_1(x)=2x)$

while $\boxed{\alpha_0 \text{ is the zero-point amplitude}}$

$$\alpha_0 \equiv \langle n=0|\alpha^2|n=0\rangle^{1/2}=\left(\frac{\hbar}{2D\omega}\right)^{1/2}$$

← depends on Nucleus

→ Zero-point vibration = Quantum effect !

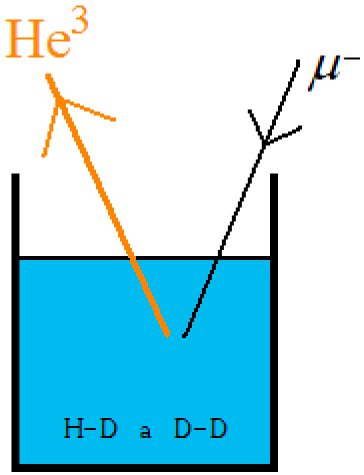
→ well known from Molecular physics: C_{60} and $\mu^- F$

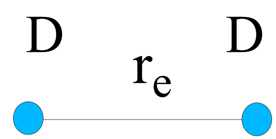
Mollecular Ground-state VIBRATION important in: μCF

μ^-CatalyzedFusion

(1956)

Berkeley





200x smaller

→ vibrating...

CATALYSIS OF NUCLEAR REACTION

J. D. JACKSON

Princeton University

$(p+d+\mu^-) \longrightarrow$ He^3

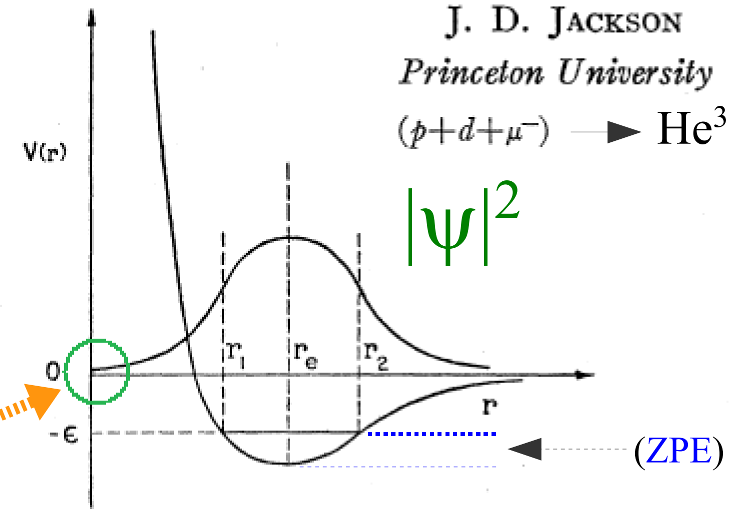


FIG. 1. Nuclear potential energy curve in μ-mesonic hydrogen molecule, and ground-state vibrational wave function for the

$$\boxed{\Psi_{\text{vib}}(x) = (\alpha/\pi)^{\frac{1}{4}} \exp\left[-\tfrac{1}{2}\alpha(x-x_0)^2\right]}$$

μ^- meson serves as a *catalyst*

The reaction rate $T \sim 2.5 \times 10^{-6}$ sec can be written

$$1/T = A\,|\Psi(0)|^2$$

where reaction constant is $A \sim 10^{-22}$ cm³/sec

$\Psi(0)$ is value of wave function at zero separation

PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

Catalysis of Nuclear Reactions between Hydrogen Isotopes by μ^- Mesons

J. D. JACKSON*
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received January 10, 1957; revised manuscript received February 4, 1957)

We observe:

Ground-state Vibration of H_2

is needed to understand

the yield of Fusion reaction: $\mu^- + p + D \rightarrow He^3$

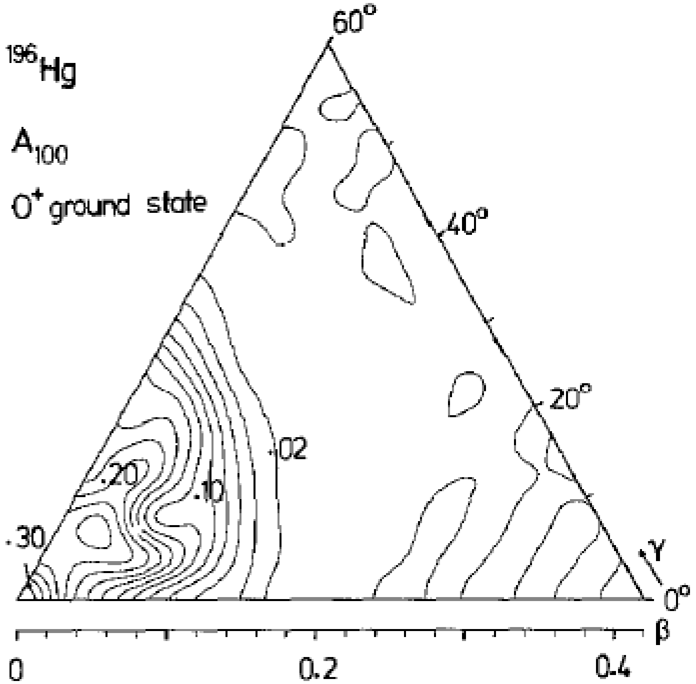
Shape-Vibration of deformed nuclei: $\rightarrow \beta_2$, β_3

is *probably* needed to understand

$\rightarrow$ ***Elliptic flow***

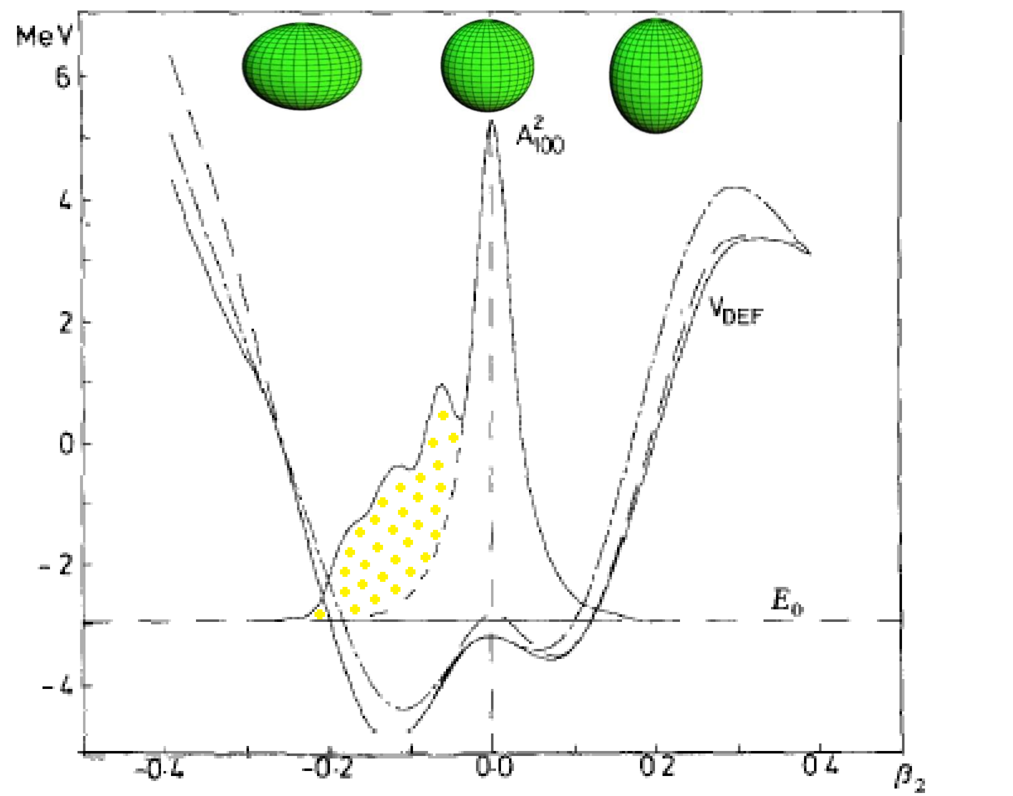
in central Au+Au, U+U collisons (also Cu+Cu ?)

Ground-state wave function: ^{196}Hg



Contour plot of the ground-state wave function $A_{100}(\beta,\gamma)$ for ^{196}Hg. Remark the pronounced maximum of the wave function for $\beta = 0$. The ground-state energy relative to the deformation potential V_{def} (fig. 2) is $E_0 = -2.959$ MeV and the rms values are $\beta_{rms} = 0.126$ and $\gamma_{rms} = 38°$.

Nucl.Phys.A403 (1983) p.263



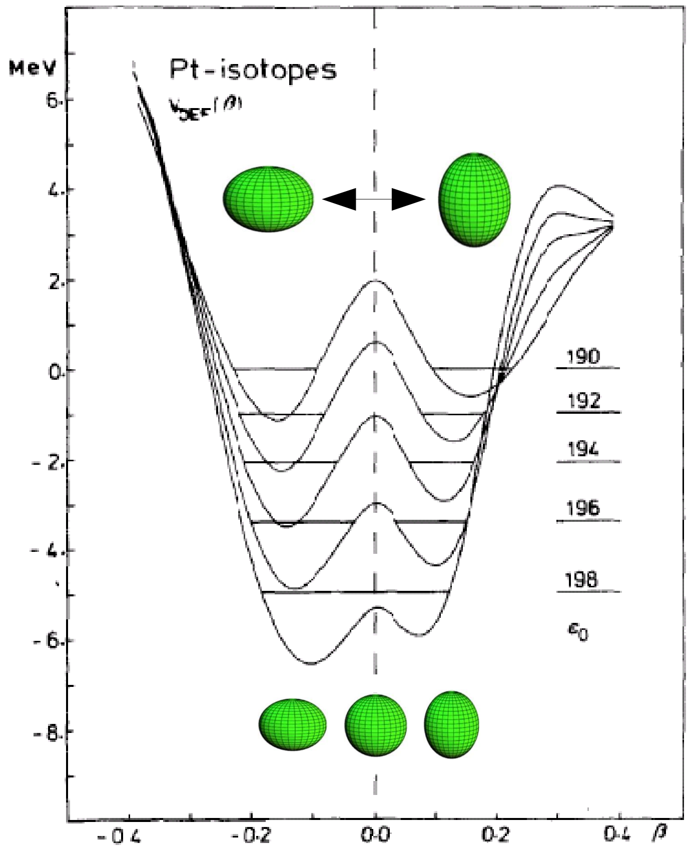
deformation energy V_{def} for different values of the hexadecapole parameter $\beta_4 = 0.0$, $\beta_4 = -0.036$, $\beta_4 = \beta_{4\,min}$). ground-state wave function A^2_{100} is also shown E_0 is ground-state energy

Fluctuating β_2 parameter !!! ($\langle\beta_2\rangle = -0.13$)

→ ^{197}Au similar behavior: $\langle\beta_2\rangle = -0.13$ (P-hole in ^{198}Hg).

Ground state of **Pt, Hg** isotopes

Nucl.Phys.A403 (1983) p.289



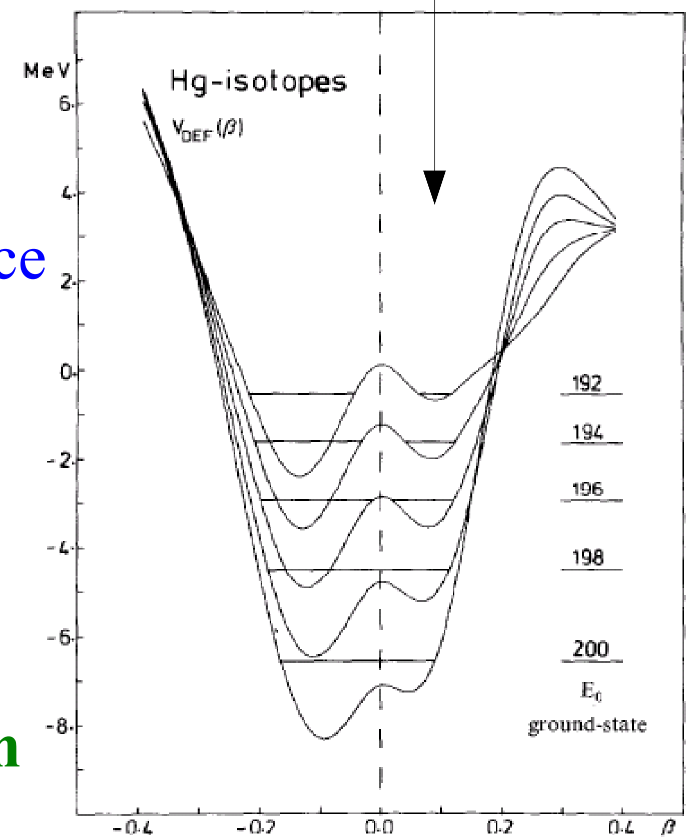
V_{DEF} for the platinum isotopes ^{190,192,194,196,198}Pt.

shape

coexistence

shape vibration

Th. J. Köppel et al. / Even-mass Hg, Pt 289

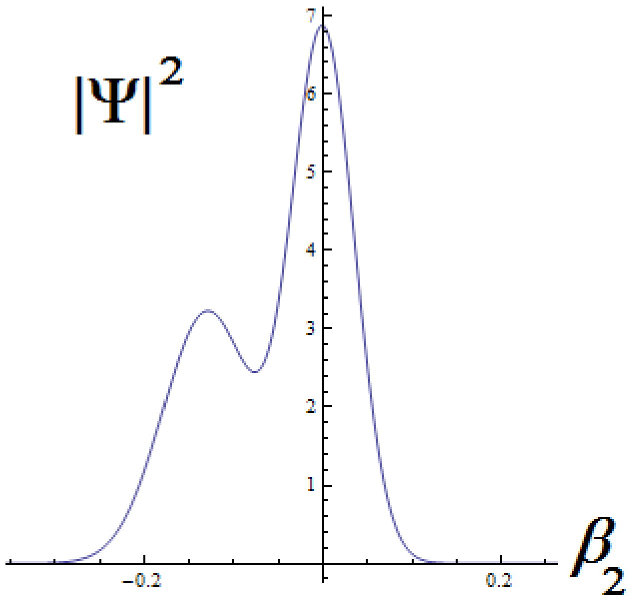


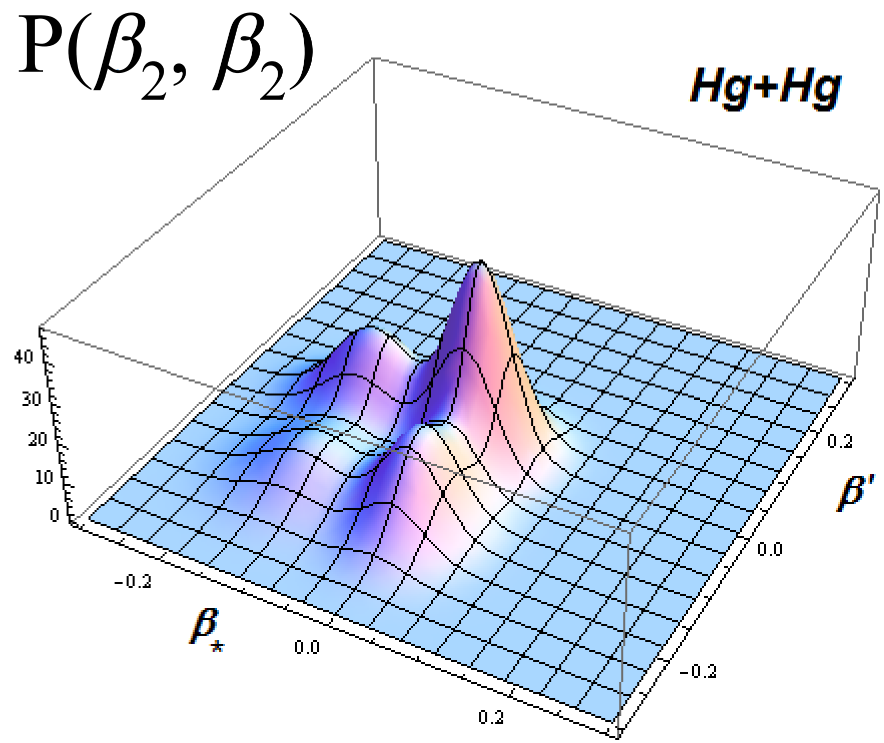
deformation energies for mercury isotopes ^{192,194,196,198,200}Hg

- Average value $\beta_2 = -0.13$ (theory estimate: from HFB)

Exact situation with ^{197}**Au** → unknown ! (ask experts)

Collisions of deformed vibrating nuclei:



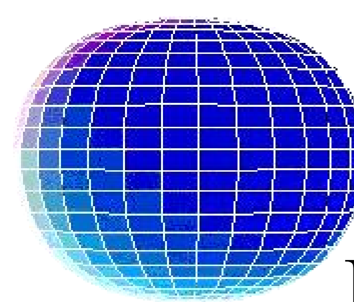


- Shape probability for colliding Hg+Hg:

  → spherical + spherical (40%)

  → spherical + deformed (45%)

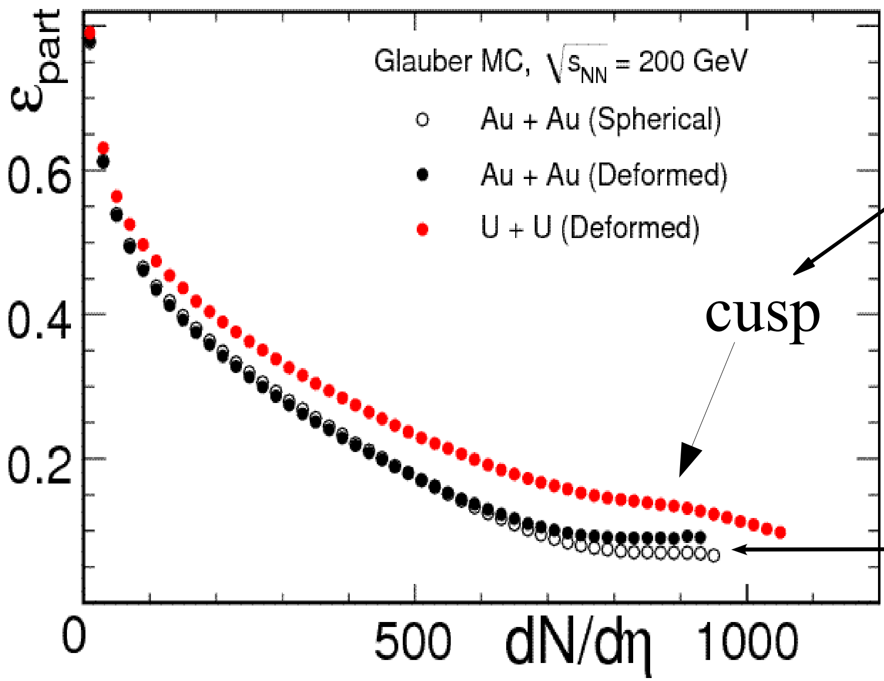
  → deformed + deformed (15%)

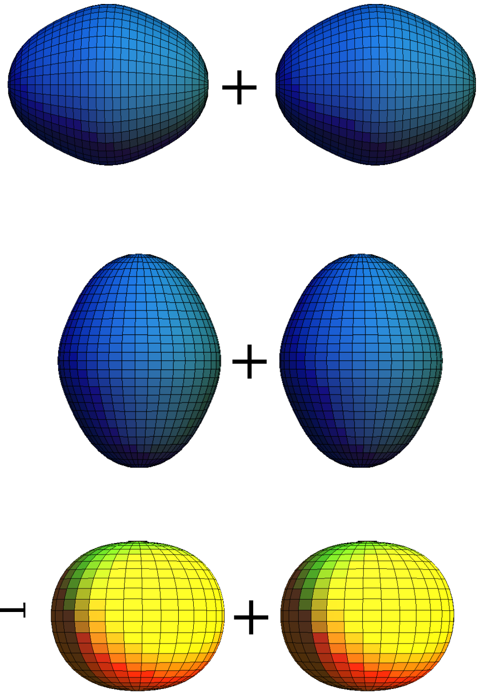


Hg^{196}

ZPVibration of deformed nuclei in RHIC

→ affecting self-orientation (CUSP) effect in central UU ?
→ **influencing AuAu eccentricity ?**



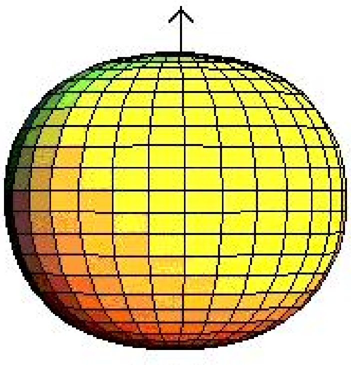


- in Phys.Rev.C80, 054903 (β_2,β_3 vibrations were neglected)

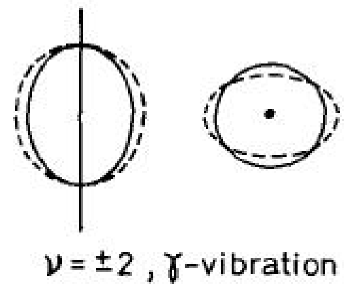
→ need to be studied to obtain a correct < initial state >

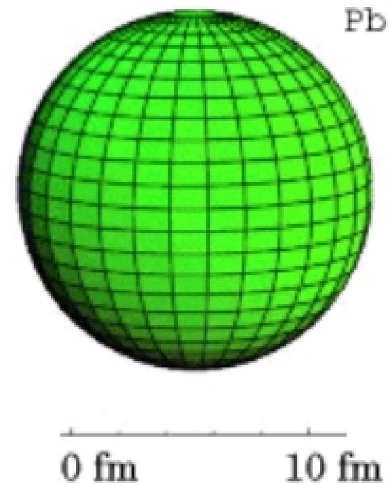
Au,U (RHIC,GSI) & Pb, In (SPS,LHC)

→ possible shape vibrations...



How large they are ?





SHOULD WE INCLUDE (? Cu+Cu ?)

SHAPE VIBRATION

into Elliptic Flow (eccentricity) SIMULATIONS ?

→ Does it affect v_2 physics at RHIC / LHC ?

Frequency of ZP vibrations:

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

- For molecules: $f_{zpv} \approx 10^{12\text{-}13}$ Hz (microwave)
- For Nuclei $E_{ZPE} \approx 2$ MeV

$$f_{ZPV} \approx 5 * 10^{20}\ \text{Hz}$$

- Compared to fast RHIC initial overlap time:

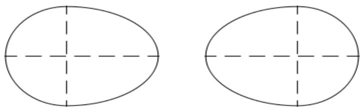
$$2*10^{-23}\ \text{s} = T_{init} \approx \text{max } 6\ \text{fm/c}$$

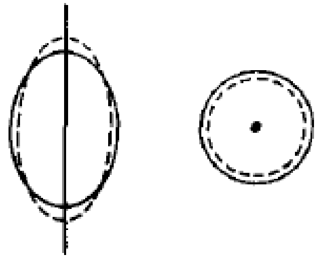
- Collisions happen in **frozen** vibrational state

Summary II

- Quadrupole β_2 (octupole β_3, axial γ) vibration

  → expected in Ground state

  β_3 vibrations in U: 



$\nu = 0$, β-vibration
$\delta R \propto (3\cos^2\Theta - 1)\cos\omega t$

- Large amplitudes $|\beta - \beta_o| \approx 0.1$ (possible)

  → **Influencing v_2 CUSP EFFECT in Ultra-Central Collisions**

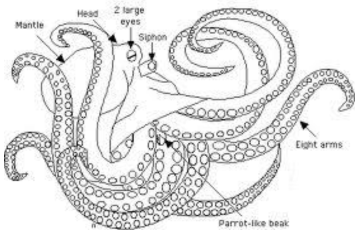
- Vibration is <u>frozen</u> during A+A interaction

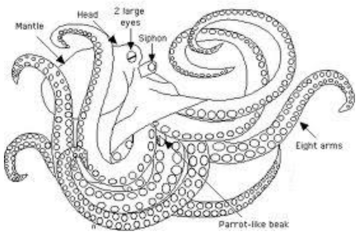
  larger β_2 , β_3 , β_4 possible, MC-Glauber simulation is needed.

THANK YOU

for

Your kind ATTENTION





Vibrational properties of Nuclei

(comparing B(E2) transition probability with Q_o)

→ some nuclei **Vibrate**: Ca, Fe, Ni, Zn, Ge, Kr, Sr, Pd, Cd, **Sn**

→ some nuclei do Not vibrate: Zr, Nd, Sm, Gd, Dy, Er, **W**, Os

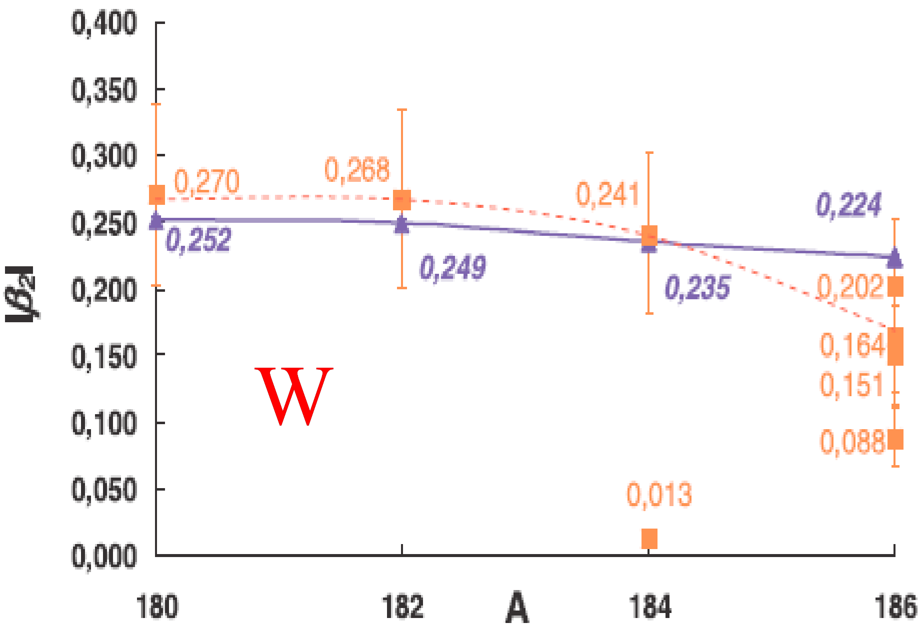


Fig. 1. Comparison of $|\beta_2|$ values obtained from B(E2) ↑ data (blue triangles, solid line) and from Q data (red squares, dotted line) for W

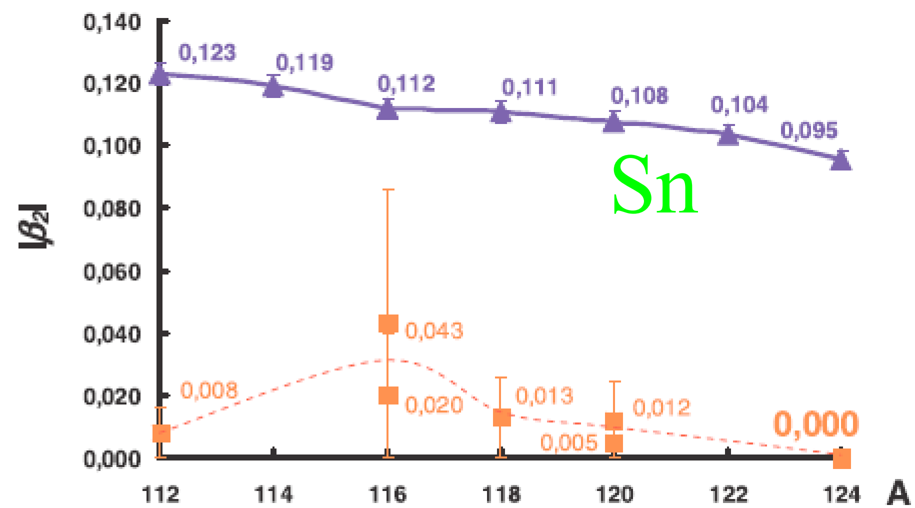


Fig. 2. Comparison of $|\beta_2|$ values obtained from B(E2) ↑ data and from Q data for Sn ("group 2"). ^{124}Sn case ($|\beta_2|_Q = 0$) is indicated

<u>Publication</u>: Phys.Rev. C 81 (2010) 014303.

and also **"...Quadrupole deformation of nucleus and its surface <u>dynamic vibrations</u>"**

International Conf. on Nuclear Data for Science and Technology 2007 (DOI: 10.1051/ndata:07103)