Effects of nuclear Deformation
in
Heavy Ion Collisions.

Peter FILIP

Institute of Physics, Slovak Academy of Sciences
Bratislava 845 11, Slovak Republic

Kent State University
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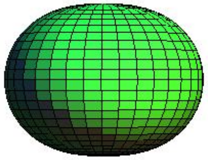
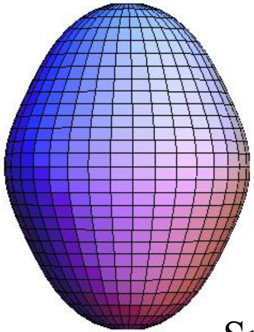




OUTLINE:

- Introduction to Nuclear Deformation

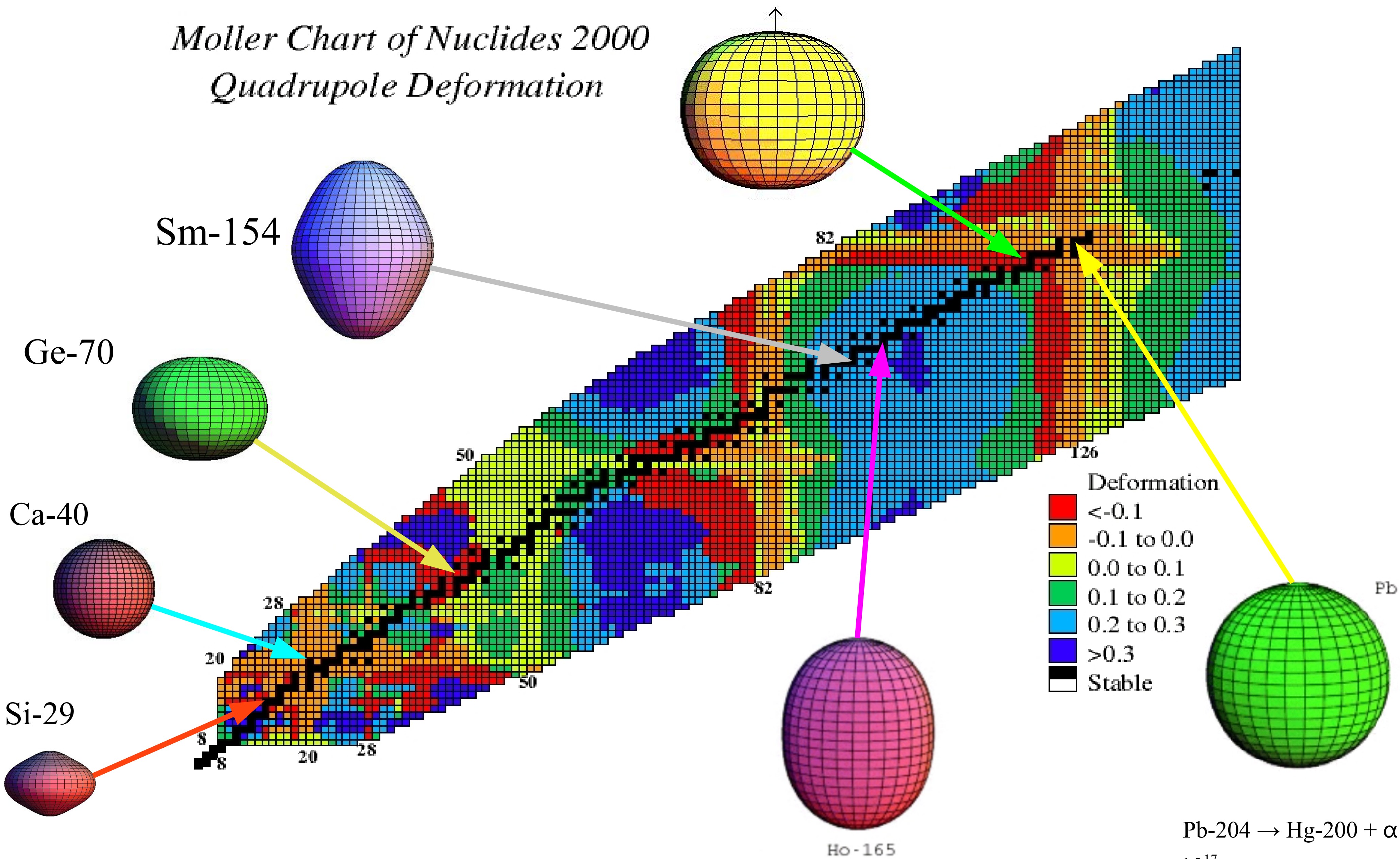
  → many interesting pieces, oblate, prolate...

- Collisions of deformed nuclei

  → eccentricity, elliptic flow, fluctuations....

- Conclusions...

Quadrupole deformation: Theoretical Calculation



Pb-204 → Hg-200 + α

10^{17} years

Woods-Saxon Density.

$$\rho_w(x,y,z) = \frac{\rho_o}{1 + e^{(r - R_o(1+\beta_2 Y_{20} + \beta_4 Y_{40}))/a}}$$

- Deformation parameters:

quadrupole: $\beta_2 \rightarrow$ $[3\cos^2(\theta) - 1] \approx Y_{20}$

octupole: $\beta_3 \rightarrow$ $[5\cos^3(\theta) - 3\cos(\theta)]$

higher order: $\beta_4 \rightarrow$ $[35\cos^4(\theta) - 30\cos^2(\theta) + 3] \approx Y_{40}$

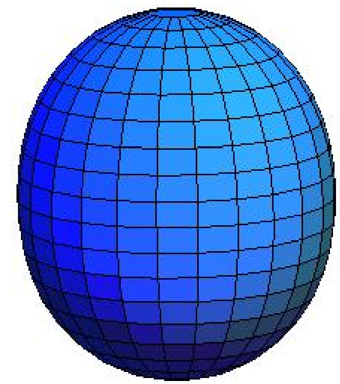
Highest order: $\beta_6 \rightarrow$ nucl-ex/0106023

- see old ref. Rev.Mod.Phys.30 pp.498-506 (1958)

Oblate/prolate shape: β_2

- $\beta_2 > 0 \rightarrow$ rugby-ball (prolate) shape.

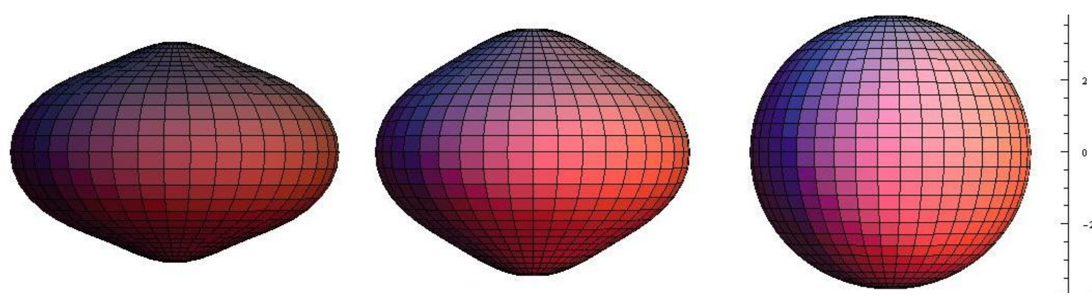
Ne-20, Cu-63, Sm, W, U..



Cu-63

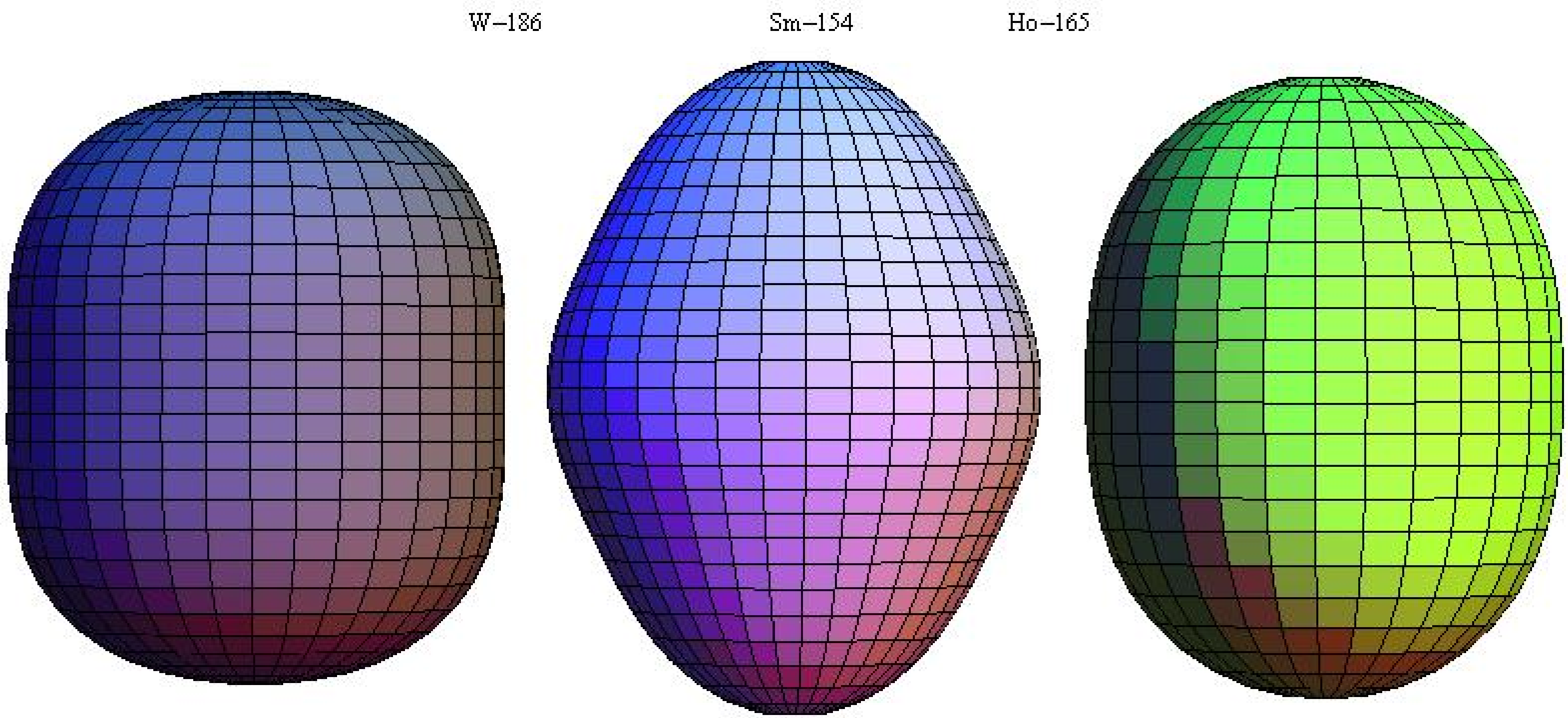
- $\beta_2 < 0 \rightarrow$ oblate (squeezed) shape: Si, As, Ge, Au

Si-28 Si-29 Si-30



$\beta_2 = -0.47$ $\beta_2 = -0.3$ $\beta_2 = 0.0$

Higher-order deformation: β_4



W-186 | Sm-154 | Ho-165

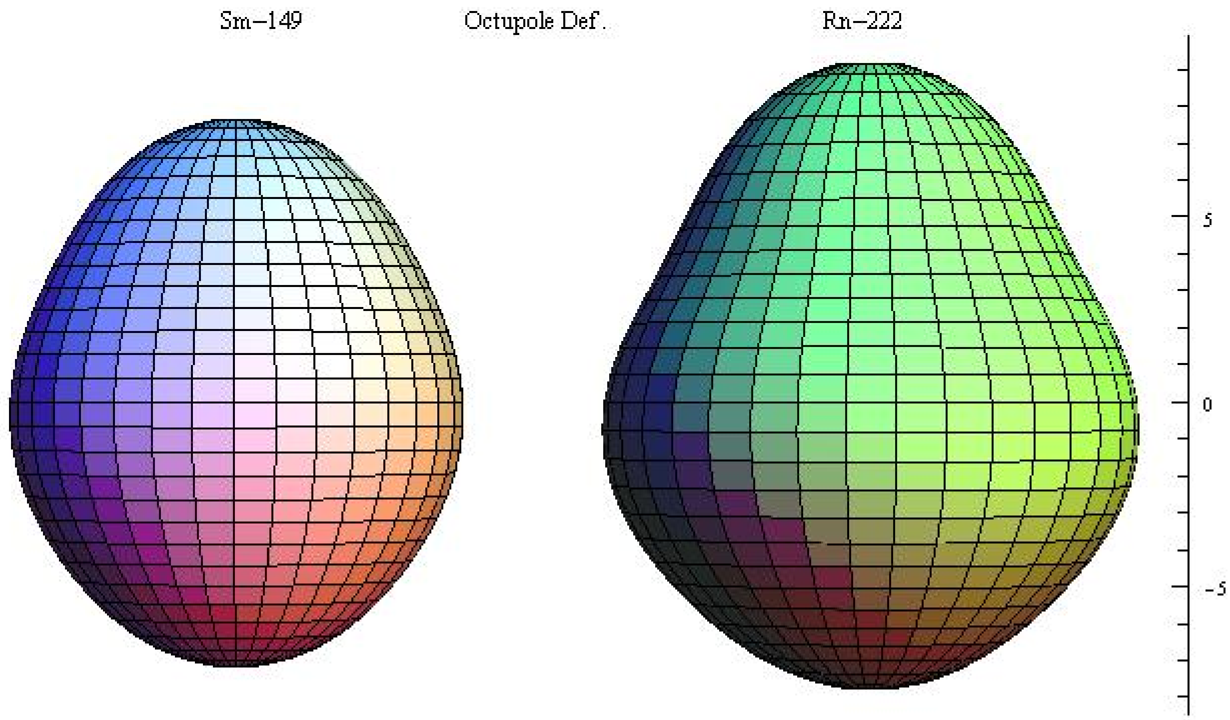
$\beta_4 = -0.1$ | $\beta_4 = +0.1$ | $\beta_4 = 0$

Octupole deformation: β_3

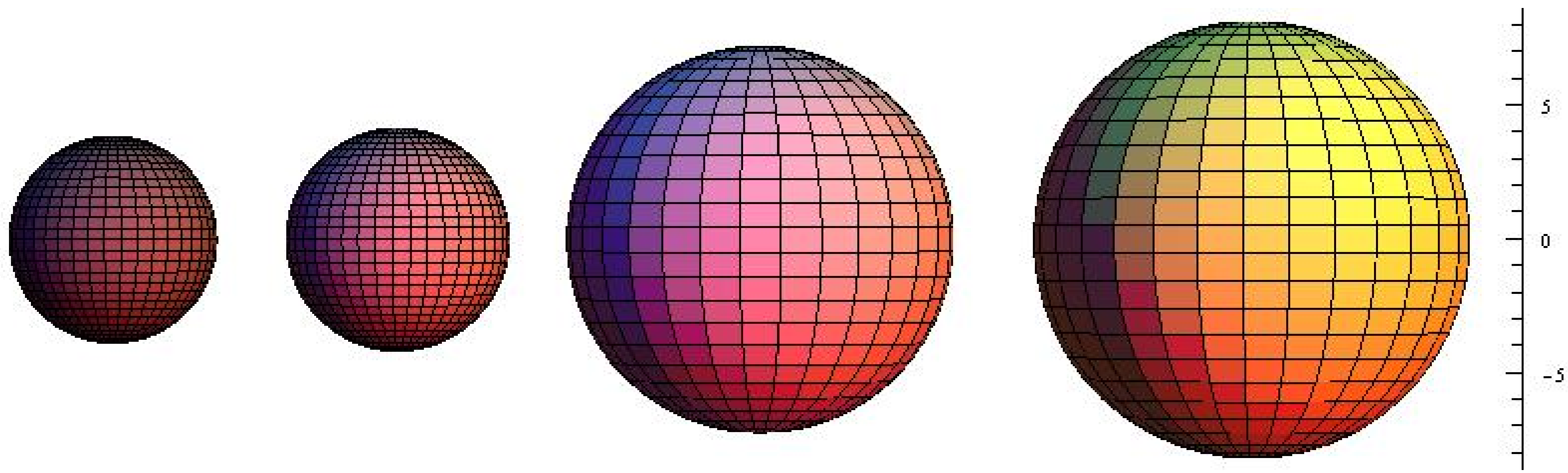
- Pear-shaped deformation

  → under investigation, unstable to α-decay
- Two candidates: Sm-149 and Rn-222

  (β_3= -0.05) (β_3= -0.13)



Size comparison.

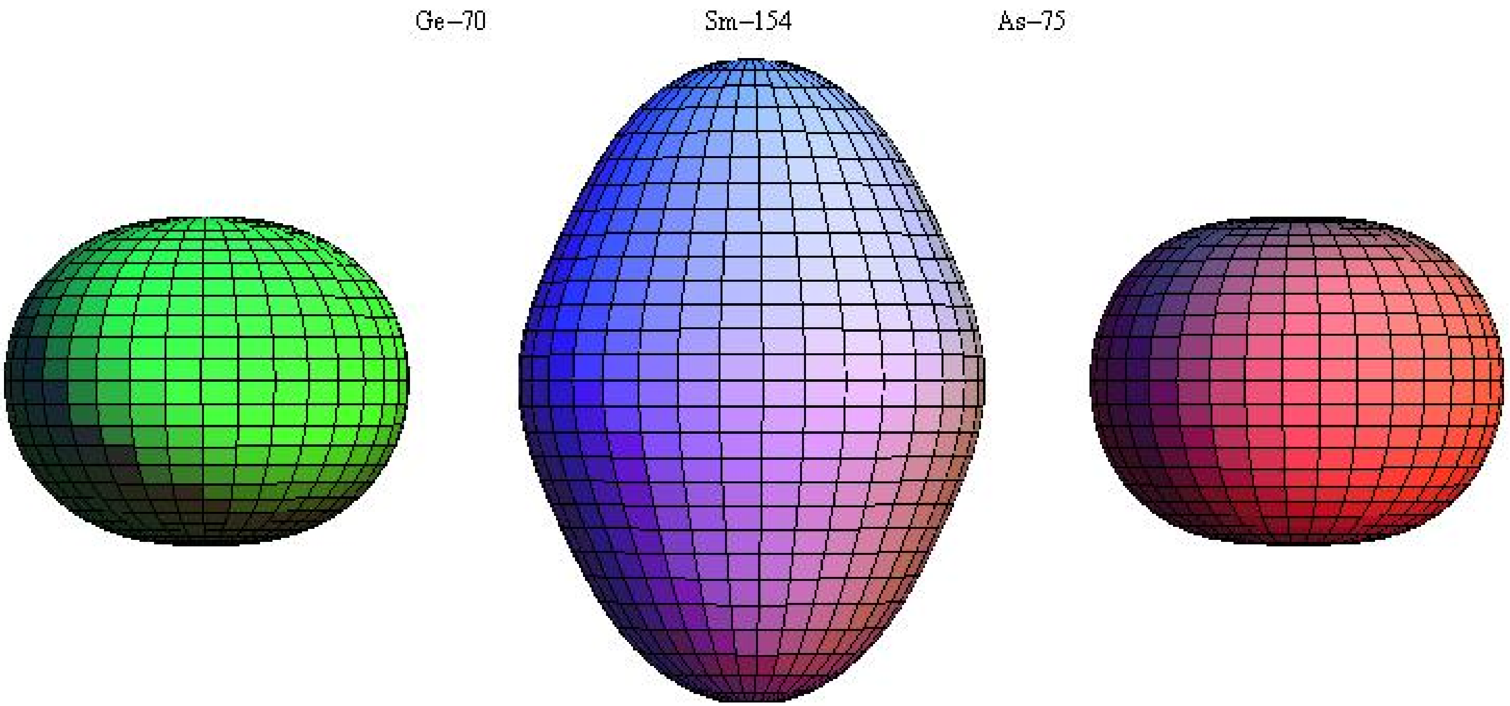


S-32 Ca-40 Pb-207 (118)-299

Spherical nuclei = closed shells of nucleon orbitals (magic numbers).

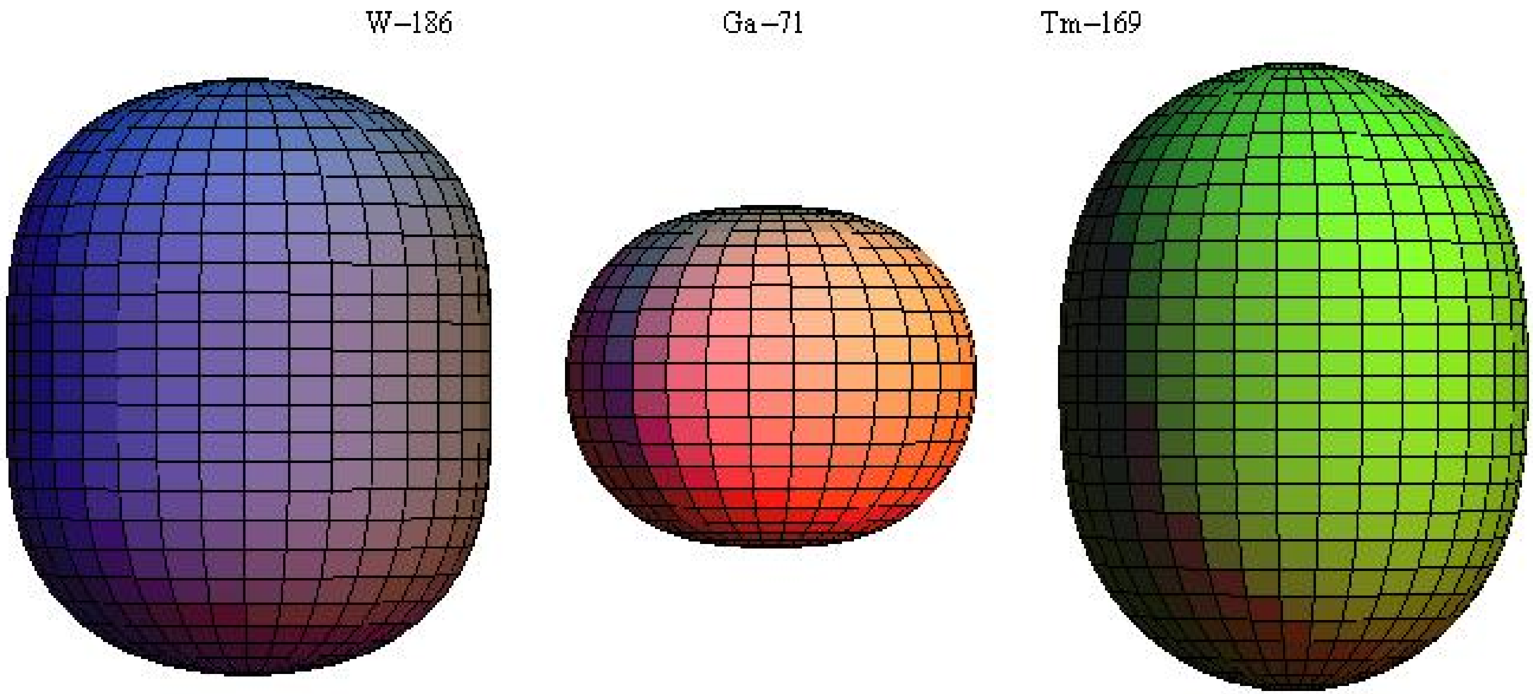
Radius increases as $A^{1/3}$ [assuming constant baryon density].

Shape comparison I.



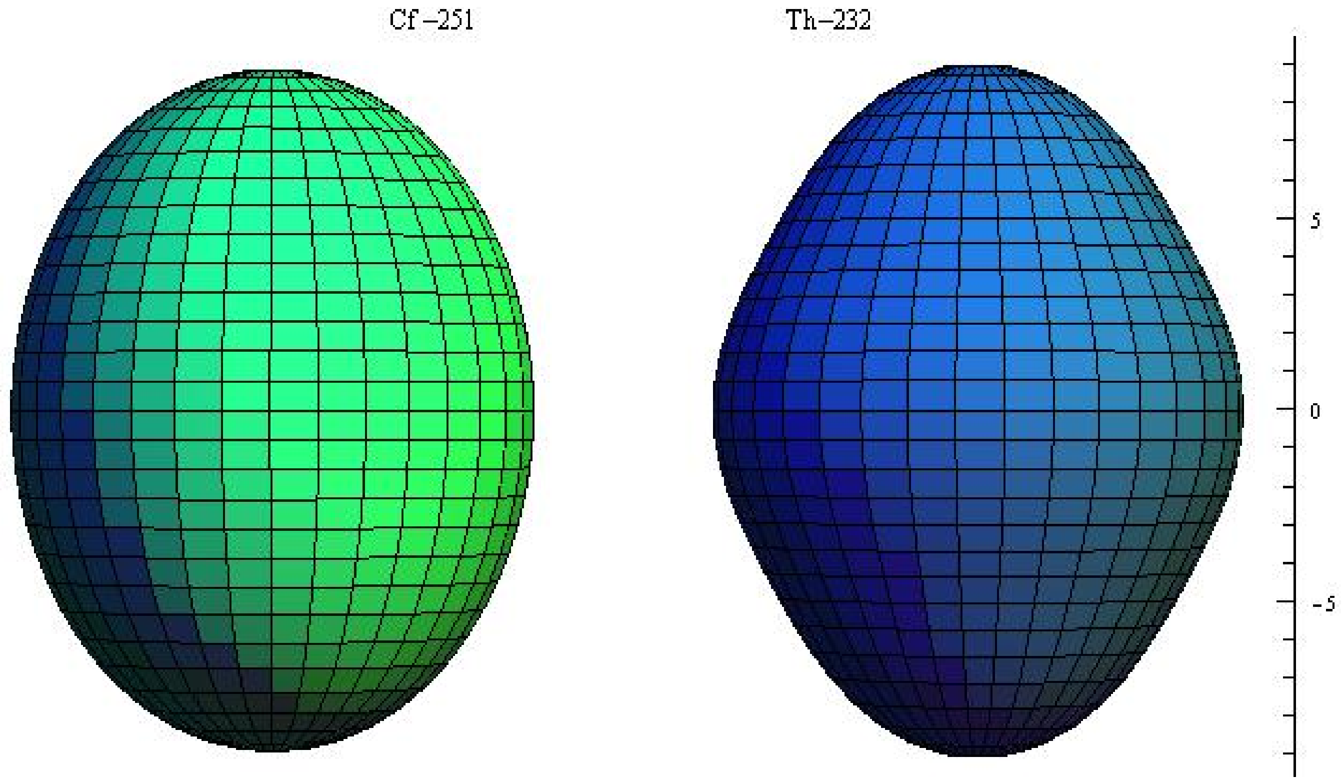
Ge-70 Sm-154 As-75

Shape comparison II.



W-186 Ga-71 Tm-169

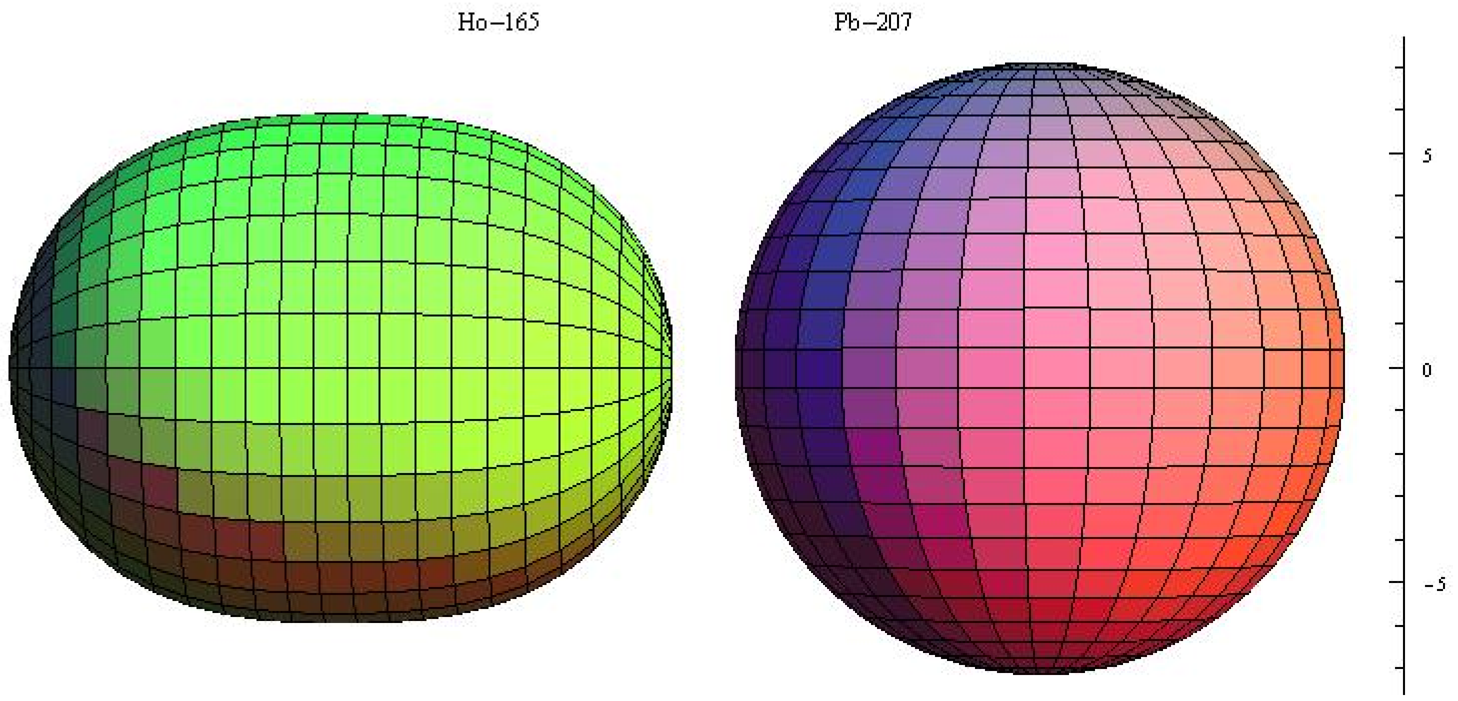
Other Pictures I.



Cf-251 and Th-232

[Cf-251 in RHIC = 89800 Years half-life at 100GeV/n; for 10^{13} / beam ≈ 1 decay/6s]

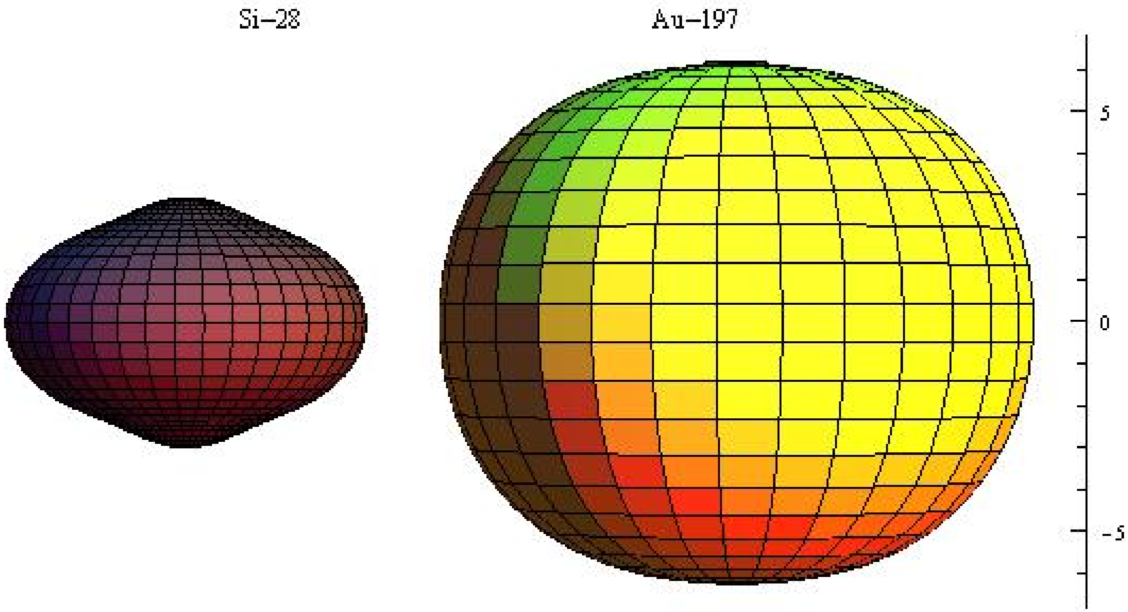
Other Pictures II.



Ho-165 → ← Pb-207

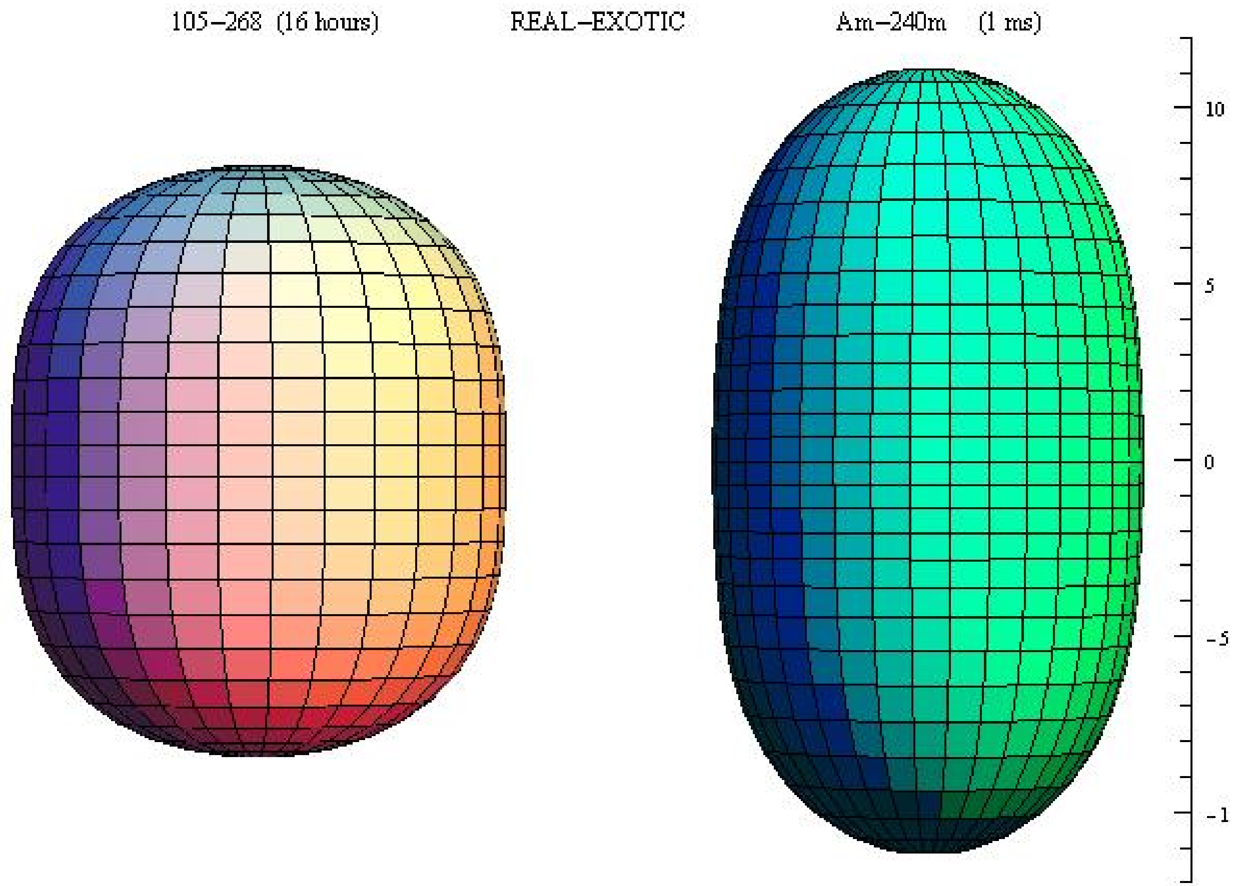
(long-polarized)

Other Pictures III.



Si-28 $\rightarrow$ $\leftarrow$ Au-197
(AGS)

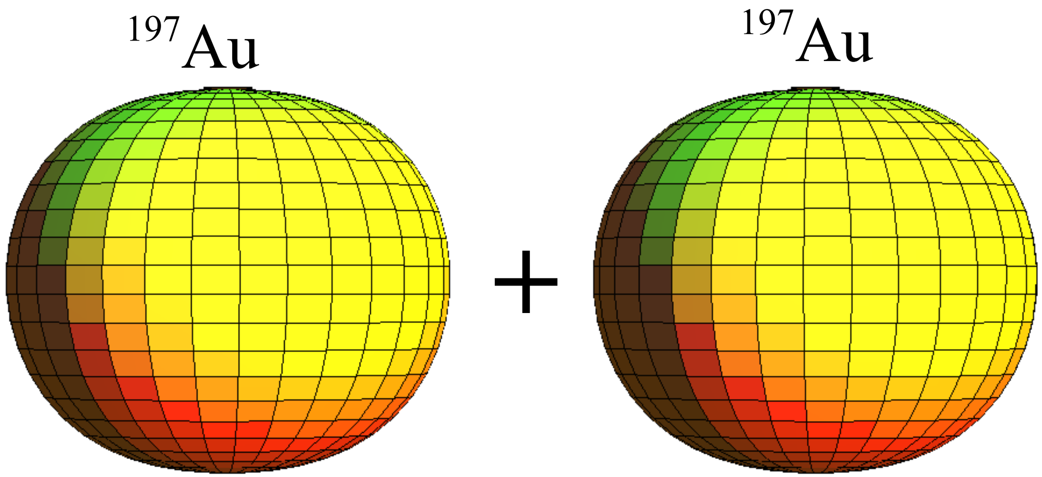
EXOTICS.



Dubnium(105)-268 (16hours) Americium(95)-240m (1ms)

Reality: RHIC Au+Au 200GeV/n

3-protons, 8-neutrons
below 2x-magic Pb.



oblate shape[1]

β_2 = - 0.13

spin: 3/2
stable, 100%
Natural isotope

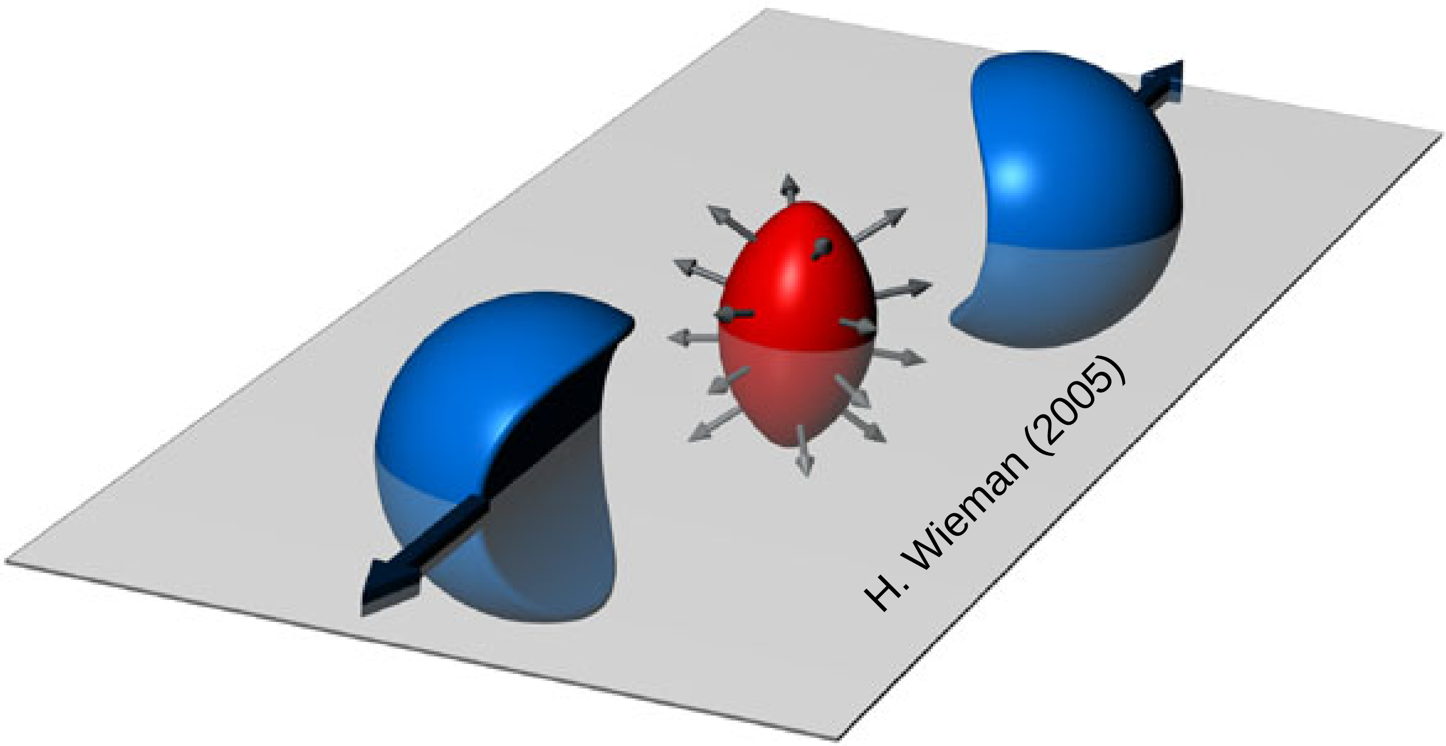
Au-197 nucleus Deformation ?

Yes: has quadrupole moment Q=0.59 barn [Phys.Rev.A73(2006)022510]
Prediction β_2: [1] P.Moller et al. At. Data Nucl. Data Tables 59 (1995) 185.
Experiment: [2] C.Nair et al. (Giant Dipole Resonance ^{197}Au) arXiv:08114746.

Other deformed nuclei at RHIC ? Yes: Cu-63 & U-238.

Elliptic flow at RHIC energies:

→ origin: the initial spatial asymmetry.



For deformed nuclei → initial eccentricity is affected !!!

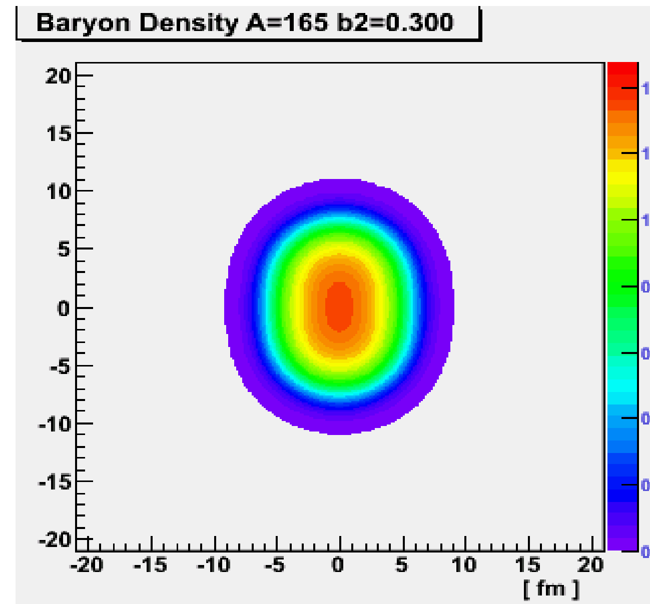
→ elliptic flow is affected.

Optical Glauber Model*

- Using Deformed Woods-Saxon density:

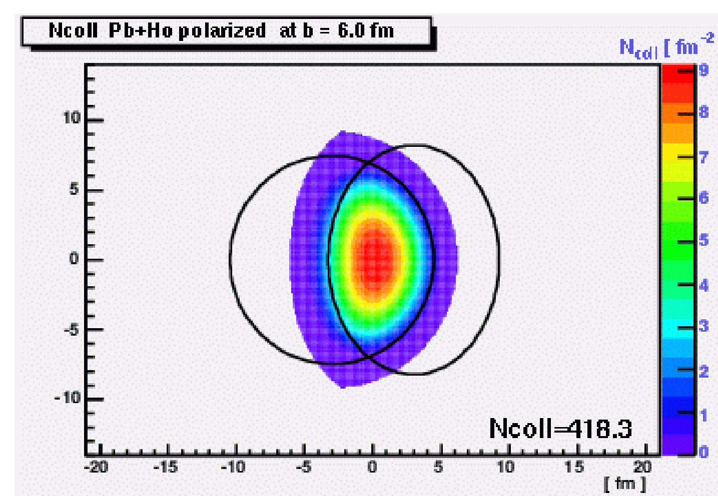
$$\rho_w(x,y,z) = \frac{\rho_o}{1 + e^{(r - R_o(1+\beta_2 Y_{20} + \beta_4 Y_{40}))/a}}$$

- Projections [θ,φ] in transversal plane →



- From the overlap of colliding nuclei:
  - Baryon density
  - N_{part}: participant density $\rho_{\rm part}(x,y)$
  - N_{coll}: $\rho_{\rm coll}(x,y)$ binary collisions density
- Obtain eccentricity

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

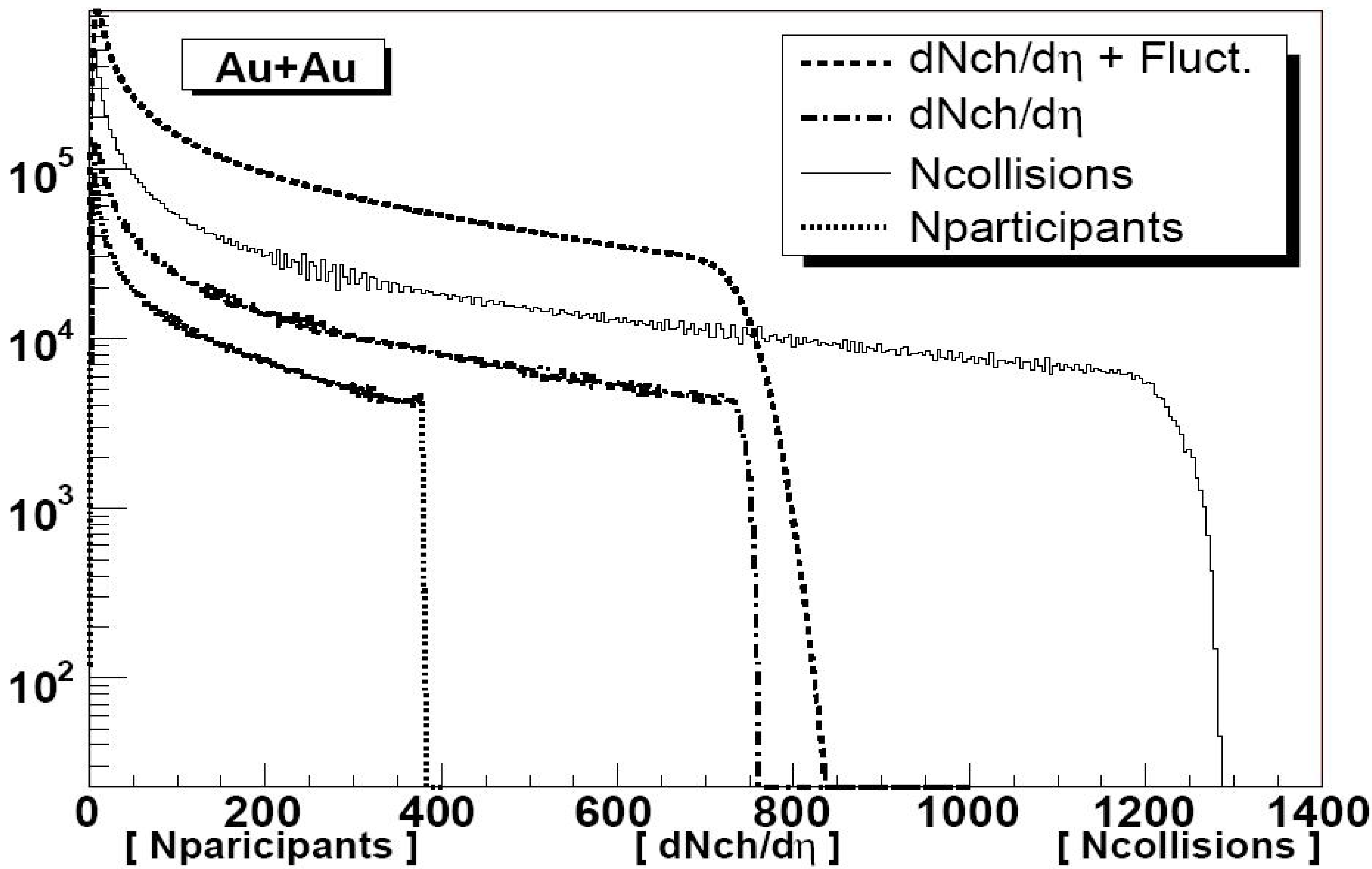


- Multiplicity:

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

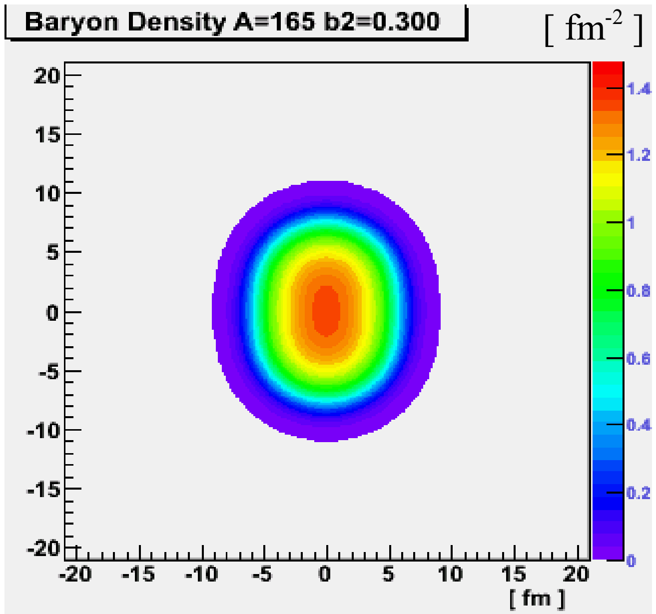
* Phys. of Atom. Nucl. 71 (2008) 1609

Distributions N_{part}, N_{coll}, N_{ch} from Opt.GM



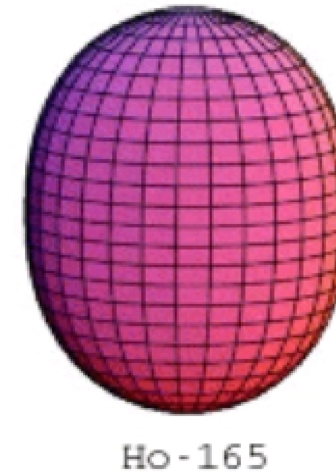
Two-component $dN_{ch}/d\eta$: Phys.Lett.B507(2001)121; $\boldsymbol{n_{pp}} = 2.29$ and $\boldsymbol{x} = 0.13$

Eccentricity in collisions of prolate nuclei.

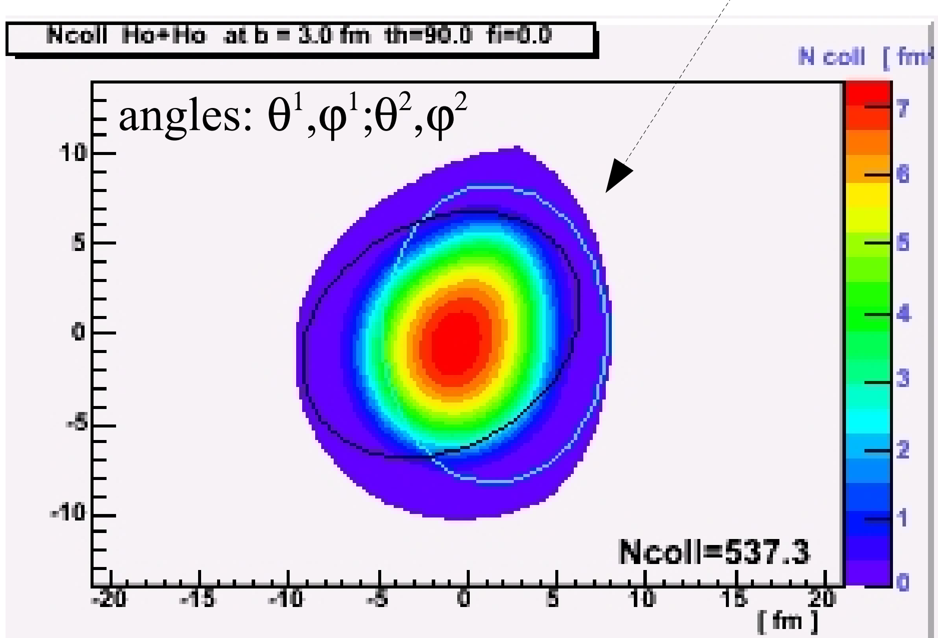


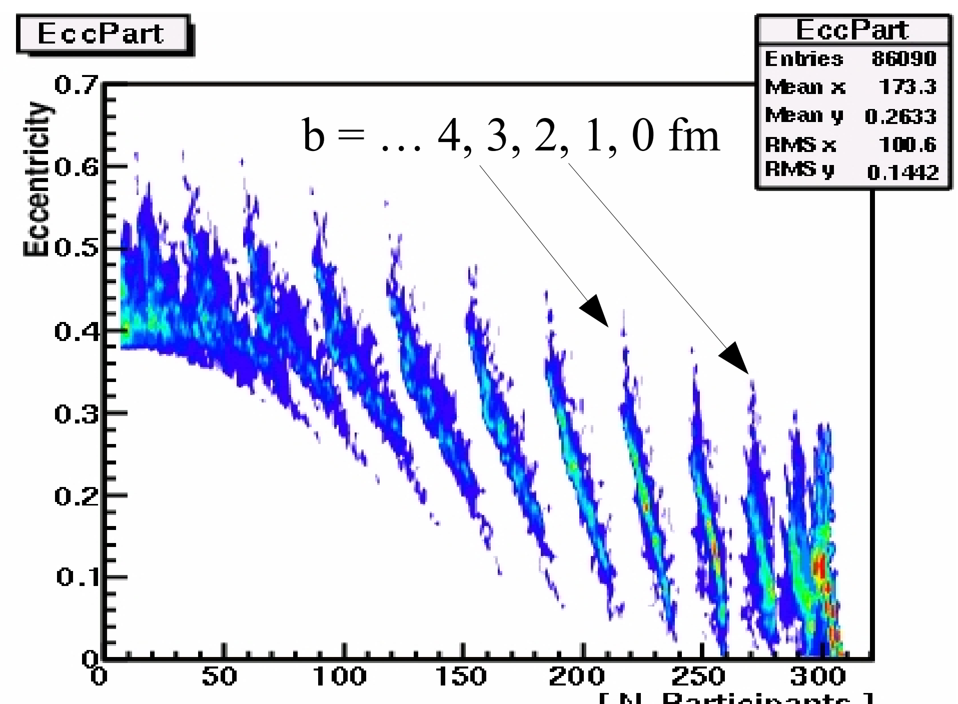
- Ho-165 ($\beta_2 = +0.3$)

$$\varepsilon_{\text{part}} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

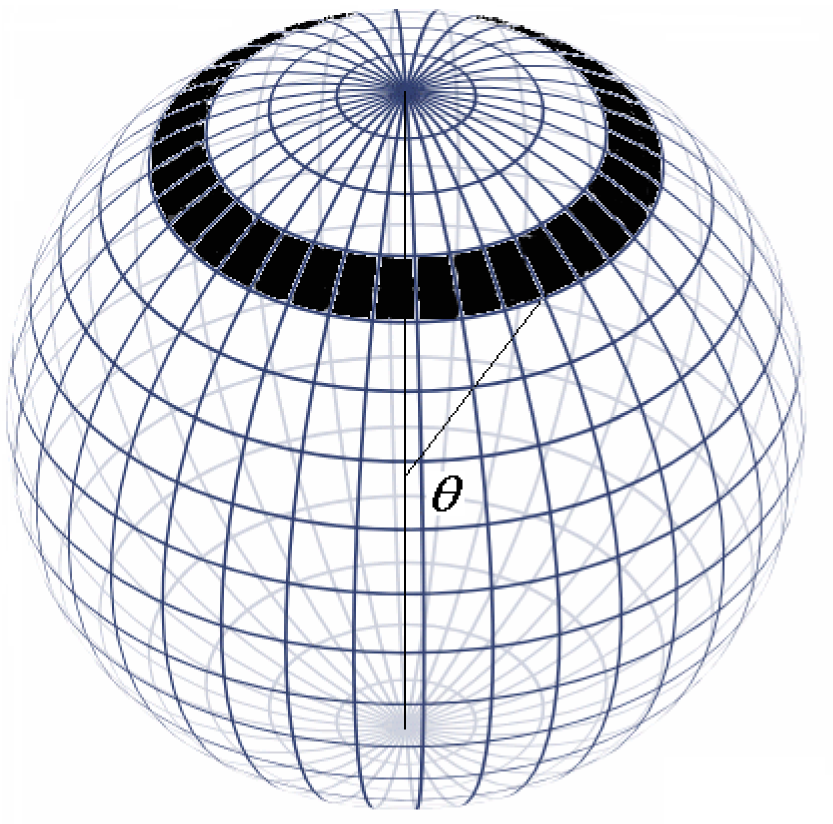


- Pear-shaped overlaps !
- Fluctuations $\varepsilon[\theta^1,\varphi^1;\theta^2,\varphi^2]$ at given [b]





Technical detail: Random orientation of nucleus.



Random orientation:
= random distribution of points where main axis (spin) crosses the surface of the sphere.

<u>Probability is proportional to the area.</u>

Area dS corresponding to $d\theta d\varphi$ is:

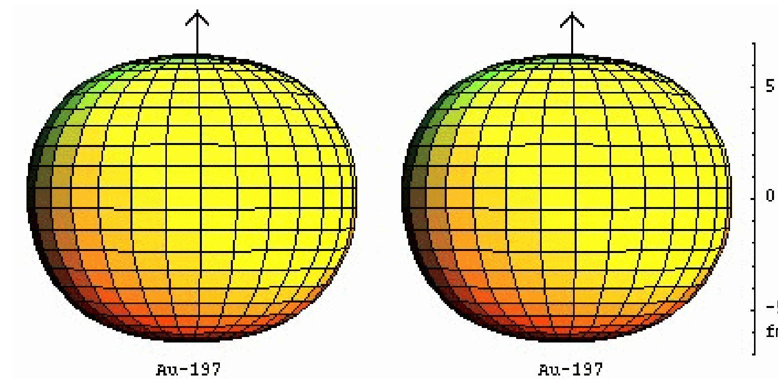
$$dS = R \sin(\theta)\, d\theta d\varphi$$

→ $P(\theta) = \sin(\theta)/2$ (normalized to 1.)
→ $P(\varphi) = \text{const.}$ (random φ angle)

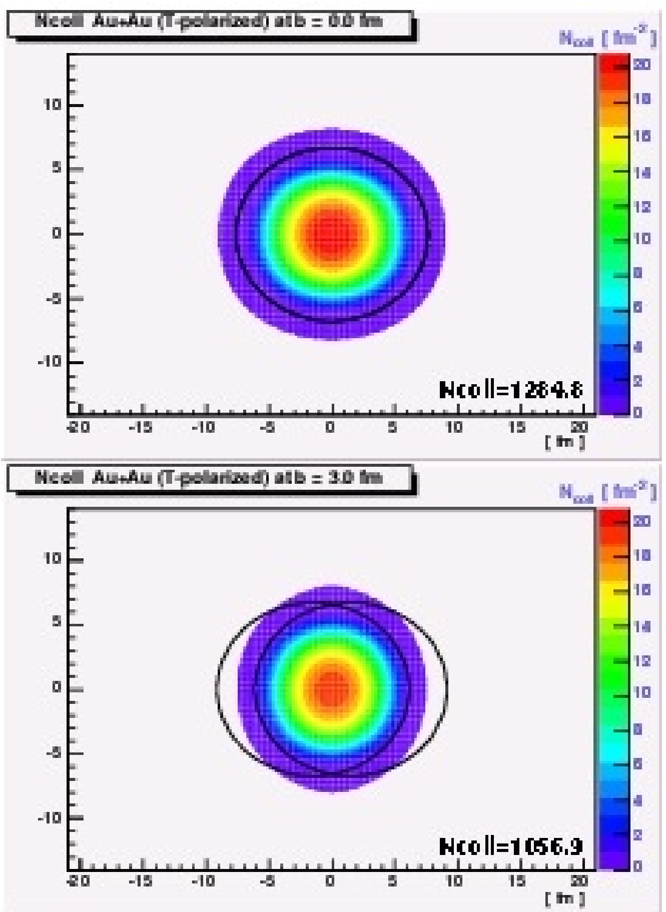
→ angle θ is not random.
Random orientation means random φ, and sin(θ) distributed θ angle.

Eccentricity in collisions of oblate nuclei.

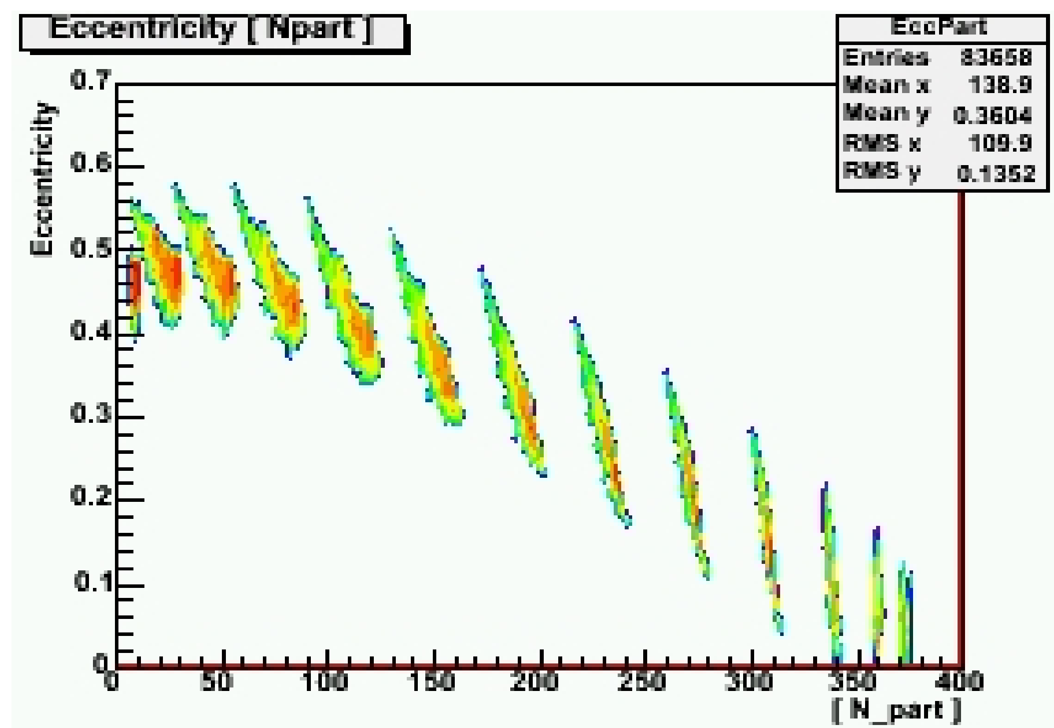
- Au-197 (predicted β_2 = -0.13)



Zero eccentricity at b=3fm and non-zero ε for b=0fm



Eccentricity fluctuates again !



OBSERVATION:

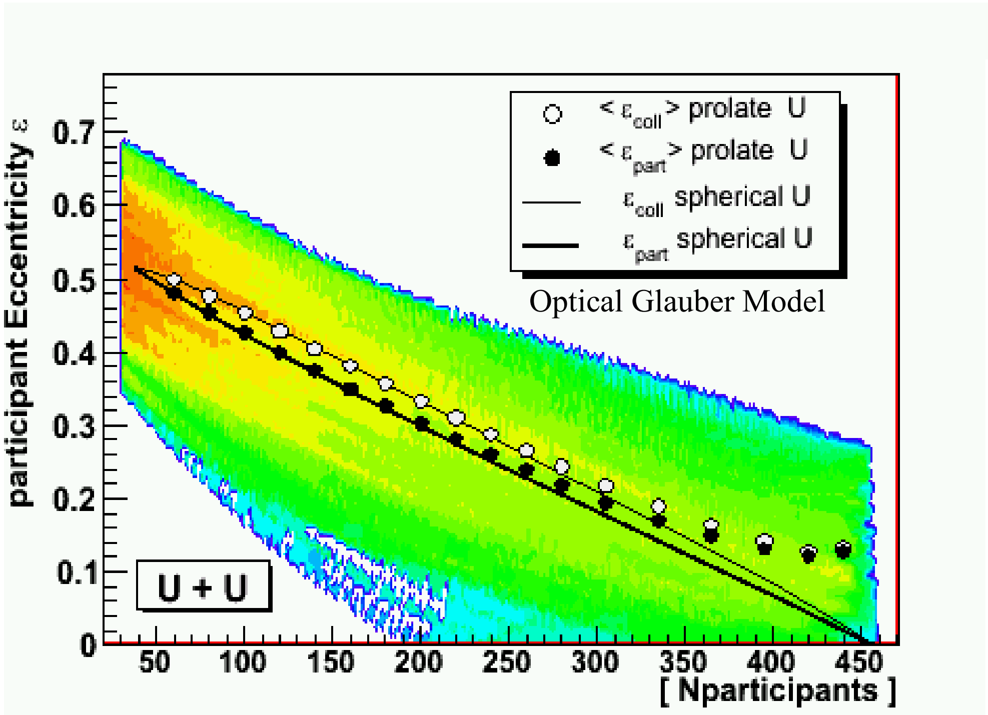
Deformation of nuclear shape

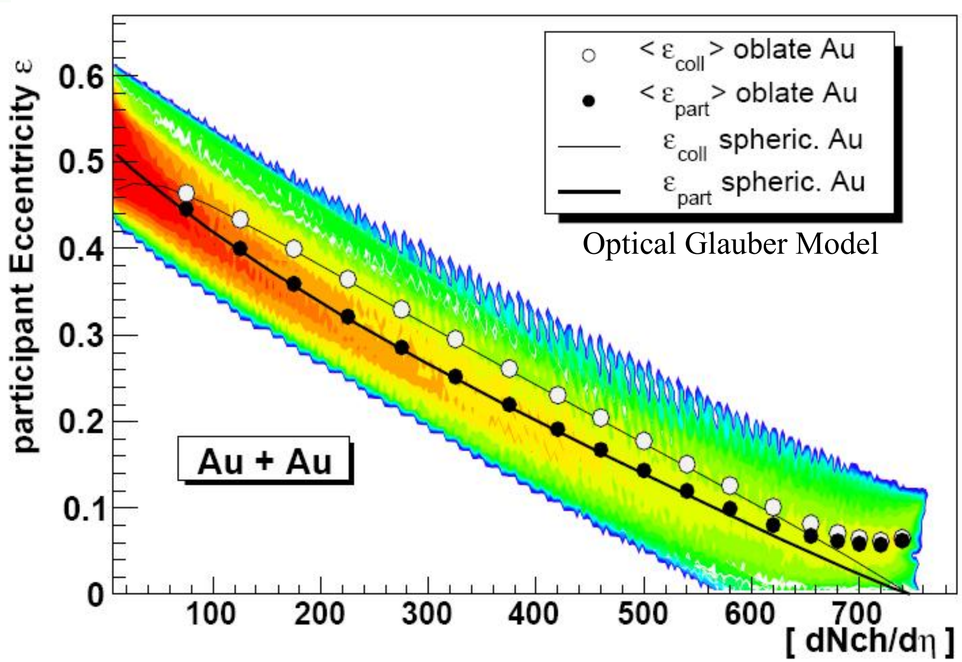
increases

$\varepsilon \rightarrow v_2$ = Elliptic flow **fluctuations**.

(at given fixed collision centrality).

What happens with < ε > due to deformation in UU & AuAu ?





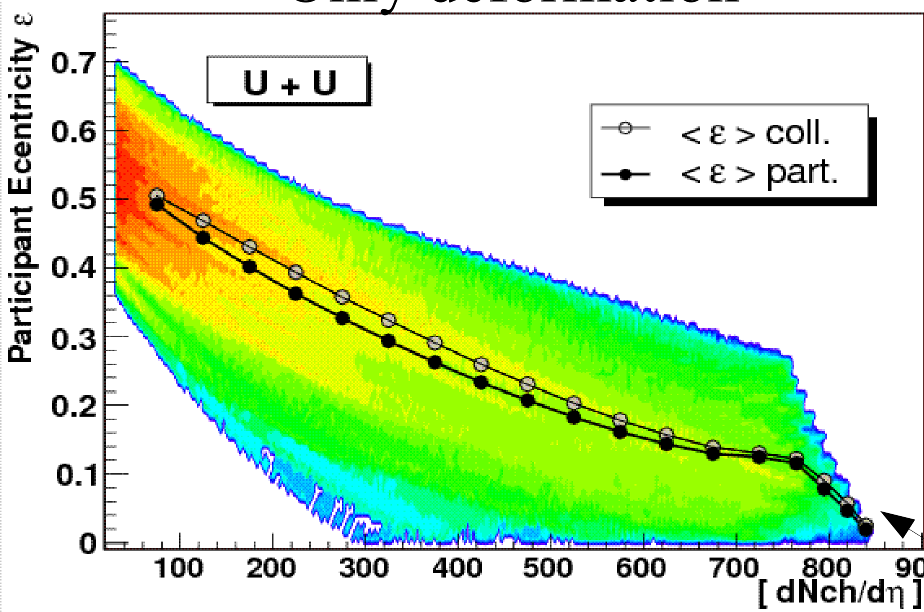
- In noncentral collisions < ε > stays unchanged

→ central coll: Increased < ε > due to deformation.

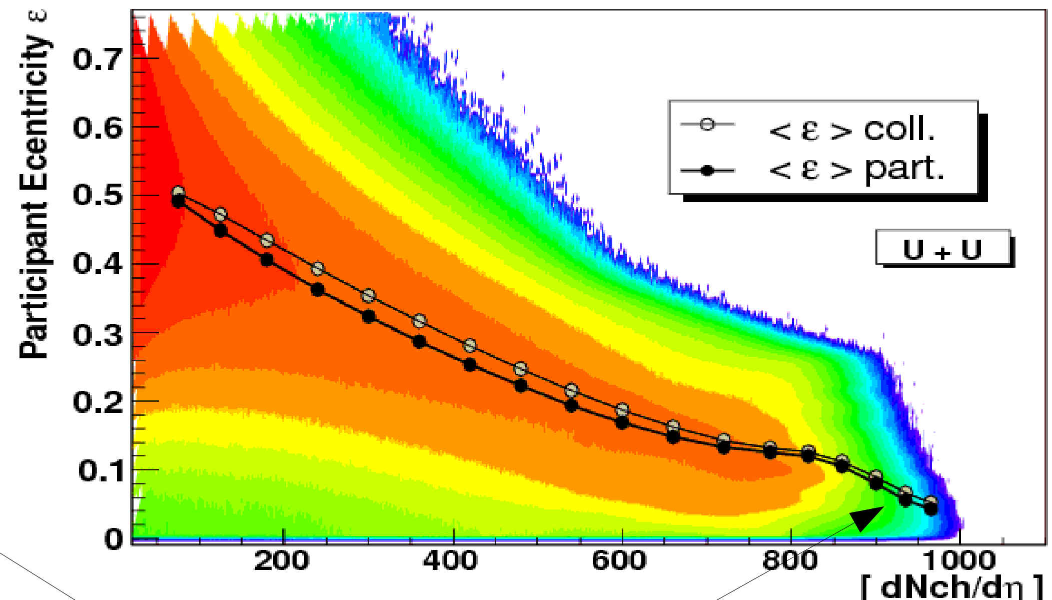
+ addtionally, deformation increases eccentricity fluctuations.

UU collisions from Opt.GM: dNch/dη

Only deformation

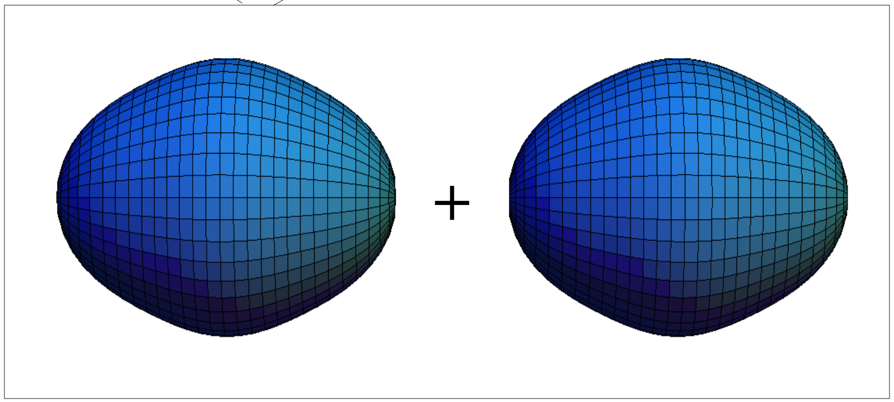


Deformation + FLUCT

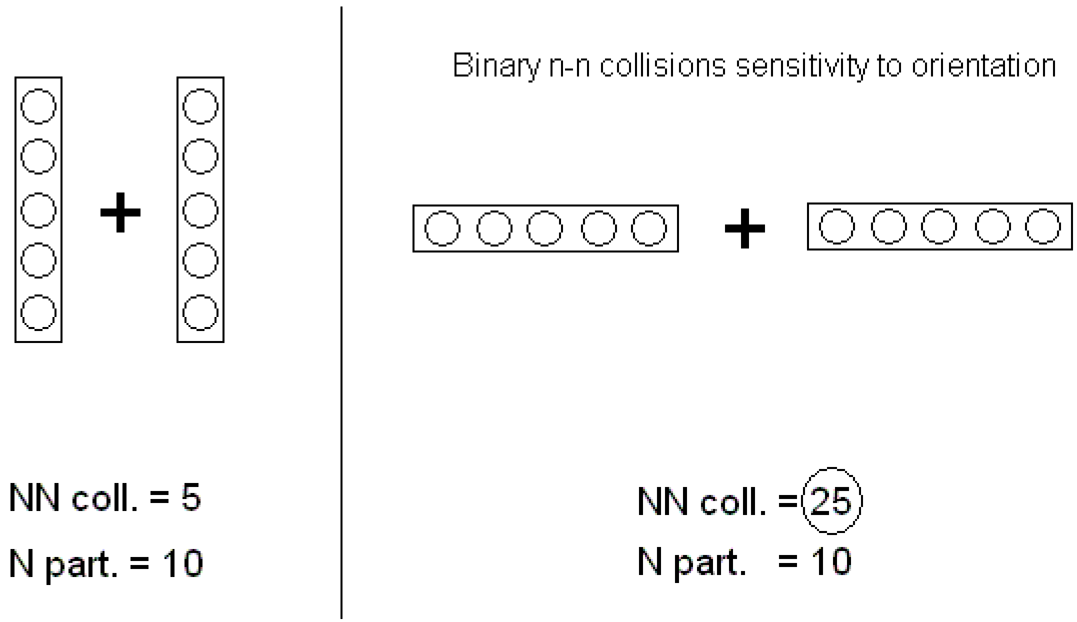


→ Cusp in $<\varepsilon>$ for very-central collisions (large $dN_{ch}/d\eta$).

Highest multiplicity: $dN_{ch}/d\eta$
is observed
for longitudinaly polarized,
central b=0 fm collisions.
→ eccentricity cusp ←



Why (dNch/dη) sensitive to oriention ?



→ dNch/dη depends on orientation due to NN_{coll}

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

N_{part} is **not** sensitive to orientation v_2 [Npart] not interesting.

→ Study: $\mathbf{v_2}$ [dNch/dη] (in central collisons) !

Glauber Monte Carlo Simulation*

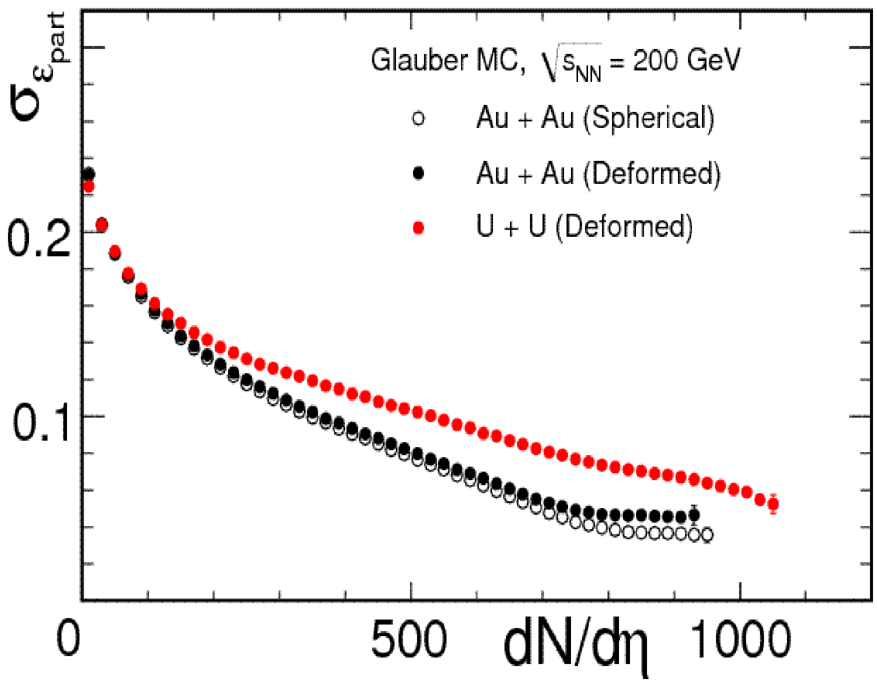
[*] QM09 poster (LBNL + JINR)

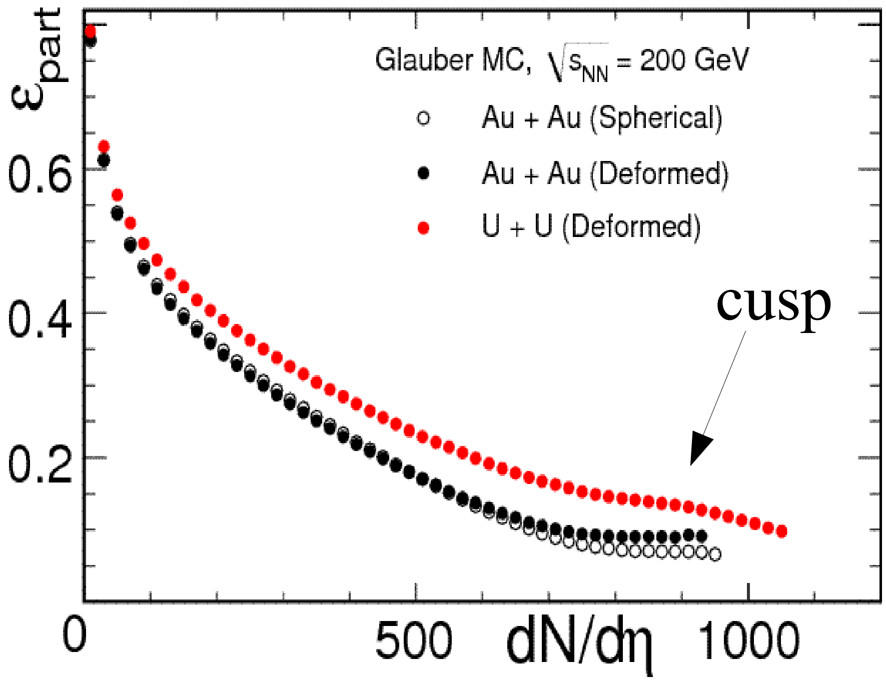

Quark Matter 2009

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

→ finite number of interacting nucleons: $\tilde{\sigma}_\varepsilon$

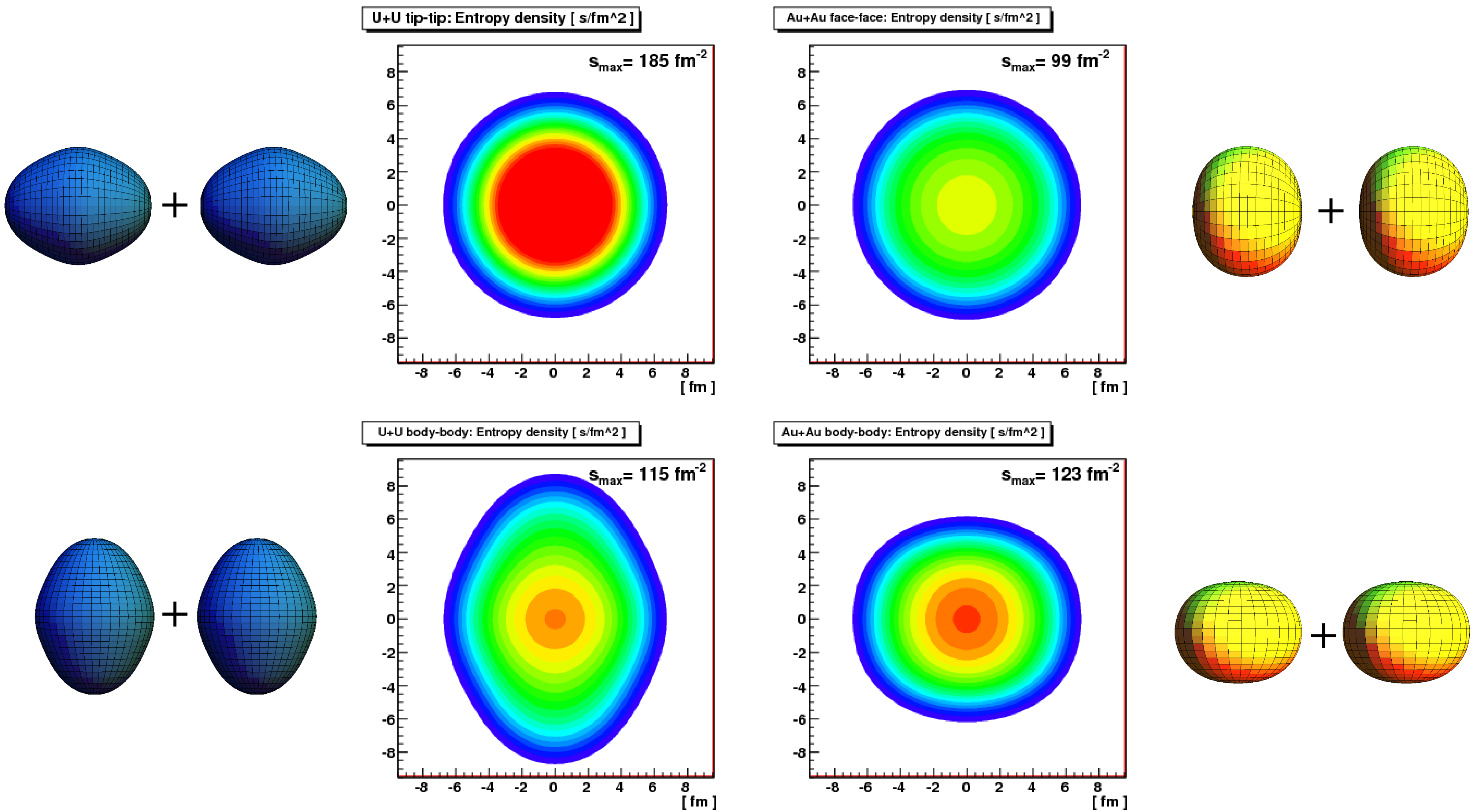
→ ground-state deformation of coll. nuclei: σ_{β_2}





Effects predicted by Optical Glauber Model → confirmed.

Comparison of Entropy Density in Au+Au vs. U+U



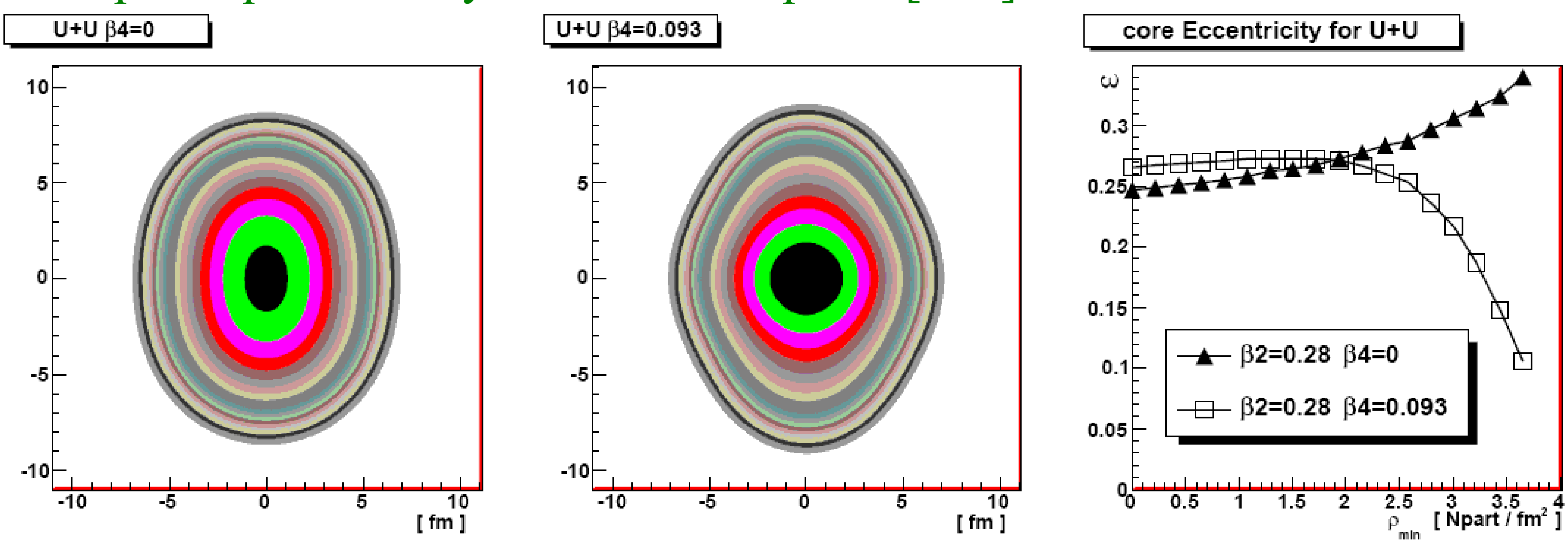
Entropy density: $\rho_s(x,y) = \kappa_s[\alpha\,\rho_{\mathrm{part}}(x,y) + (1-\alpha)\rho_{\mathrm{coll}}(x,y)]$

PRC72(2005) page 037901.

β_4 deformation Parameter for ^{238}U

- Moller et al. [1] prediction for ^{238}U is: $\beta_4 = +\,0.093$
  → spatial distribution of nucleons is modified
  → participant eccentricity is modified
  → final v_2 strength can be modified ! [hydro calc. needed].

U+U participant density in transversal plane [fm^{-2}].



[1] Moller et al. At. Data Nucl. Data Tables 59, 185 (1995)

Polarization of ^{238}U beam ? No way.

Spin of $^{238}U = 0^+$

Magnetic moment $\mu = 0$

Quadrupole moment: unknown.

→ consider ^{238}U beam unpolarized.

CONCLUSIONS:

- **Nuclei collided at AGS/SPS/RHIC are deformed:**
  → Si-28, Cu-63, In-115, Au-197, (U).

- **Elliptic flow is affected in deformed nuclei collisions:**
  → eccentricity: $< \varepsilon >$ increased in Au+Au central
  + cusp for Ho+Ho and U+U predicted
  → fluctuations: $\sigma(\varepsilon)$ increased !

- β_4 deform. parameter for ^{238}U is important !

- **Study of deformation effects is needed to understand properties of partonic matter created at RHIC.**