# New Data on Wobbling Motion for A≈130 Mass Region

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# Outline

# Nuclear Deformation

## Nuclear shapes

Most generally described in terms of the **nuclear radius**:

$$R(\theta,\varphi) = R_0 \left( 1 + \sum_{\lambda=0}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu} Y_{\lambda}^{\mu}(\theta,\varphi) \right)$$

## Quadrupole deformations $\lambda = 2$

- Most relevant modes are the **quadrupole vibrations** $\lambda = 2 \Longrightarrow$ *Play a crucial role in the rotational spectra of nuclei:*
- $\alpha_{2\mu}$ reduced to only two *deformation parameters*: $\beta_2$ (**eccentricity**) and $\gamma$ (**triaxiality**) (*Bohr and Mottelson, 1969*).

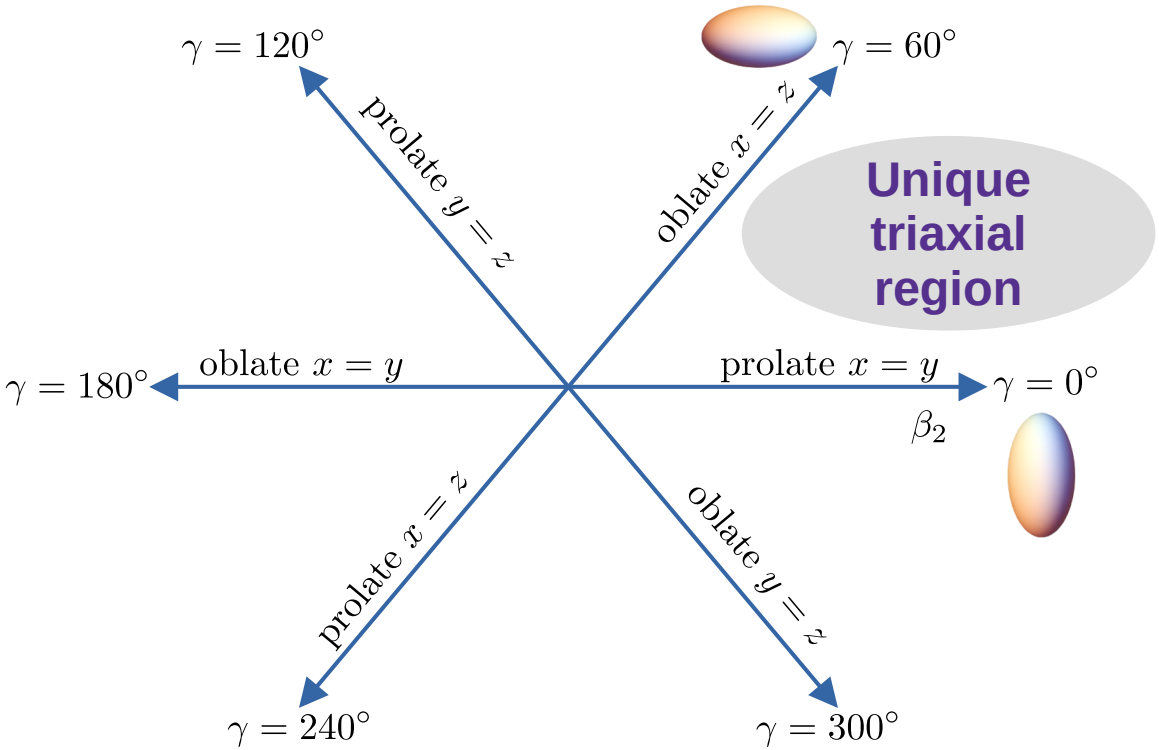
# Axial shapes

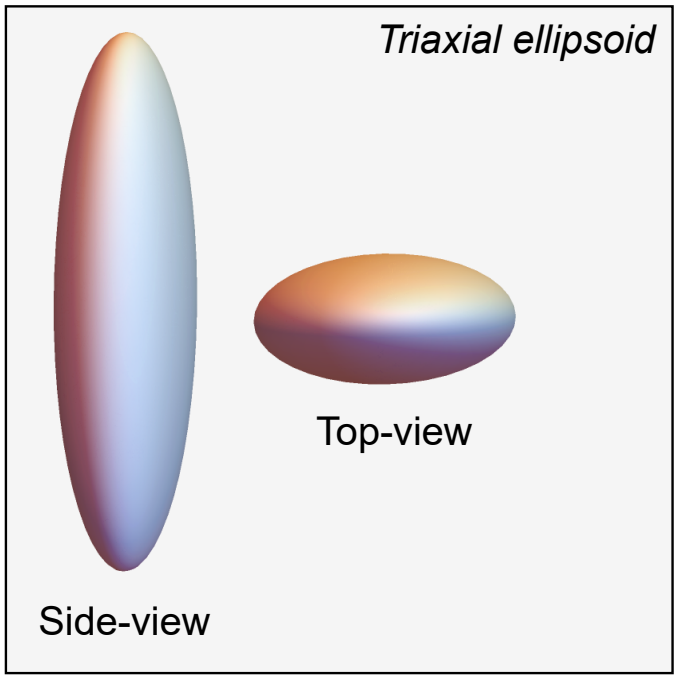
- Most of the nuclei are either **spherical** or **axially symmetric** in their ground-state.
- Nuclear moments of inertia $\mathcal{I}_{1,2,3}$: only two are equal.

Figure: **spherical:** $\beta_2 = 0$ **prolate:** $\beta_2 > 0$ **oblate:** $\beta_2 < 0$. ($\gamma = 0°$).

# Non-axial shapes

- The triaxiality parameter $\gamma \neq 0°$: departure from axial symmetry.
- Moments of inertia: $\mathcal{I}_1 \neq \mathcal{I}_2 \neq \mathcal{I}_3$.



# Wobbling Motion

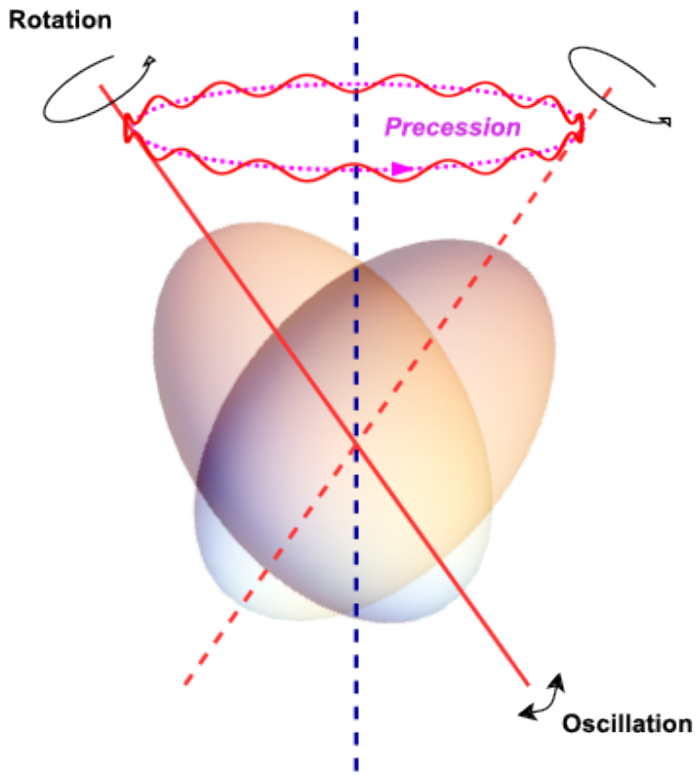
$\gamma \neq 0°$

↓

MOI anisotropy

↓

*main rotation* around $\mathcal{J}_{\text{max}}$ is disturbed by the other two axes



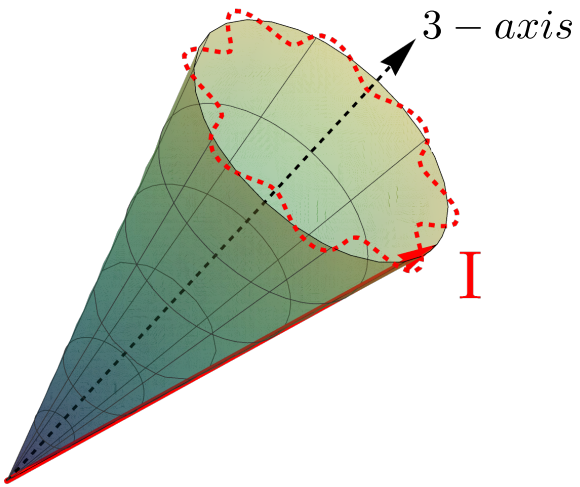

## Wobbling Effect

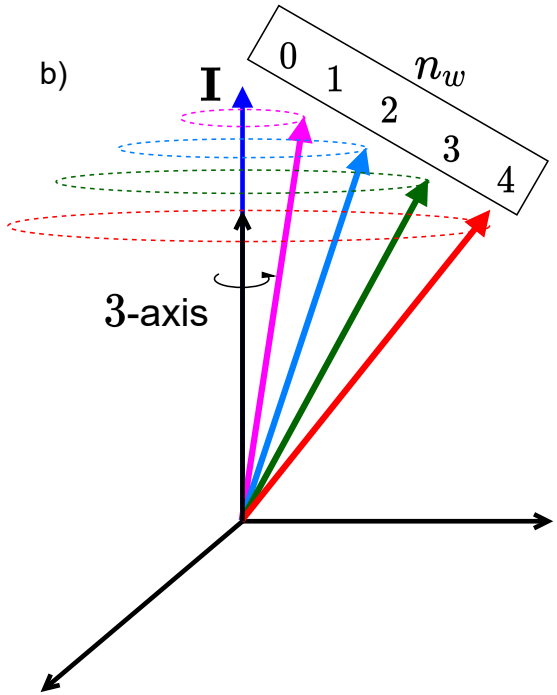
- The **total angular momentum** of the nucleus **precesses** and **oscillates** around $\mathcal{J}_{\text{max}}$.

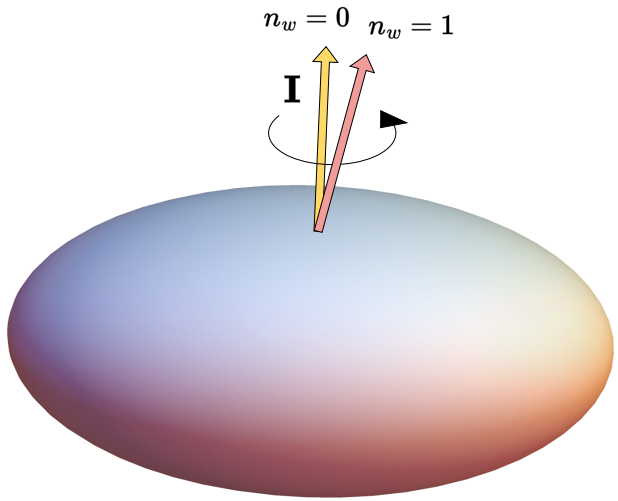
# Wobbling Motion

## Harmonic oscillation

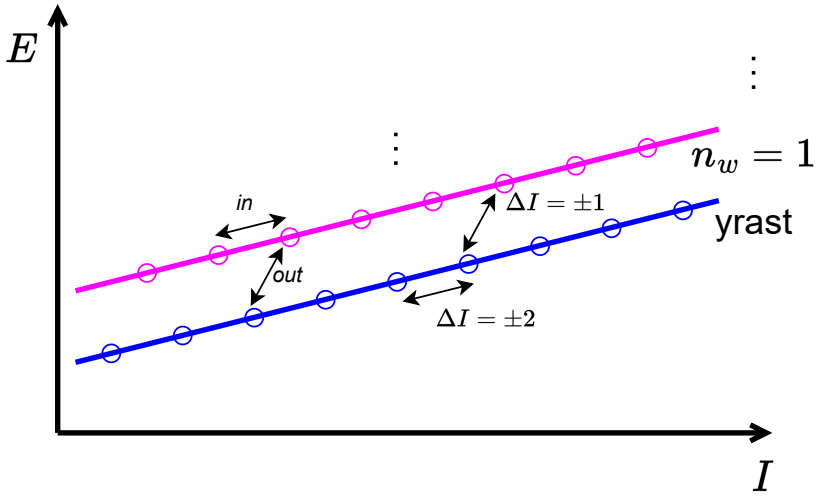
- Precession of **I** is affected by **rotational frequency** and/or **tilting**
- Tilting only by "specific" amount $\rightarrow$ **harmonic character** $\rightarrow$ **wobbling phonon**: $n_w = 0, 1, 2, \ldots$.

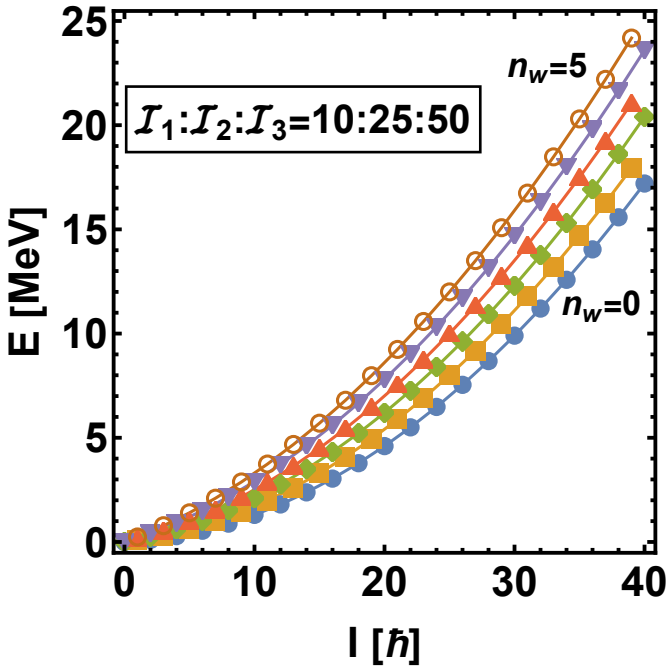


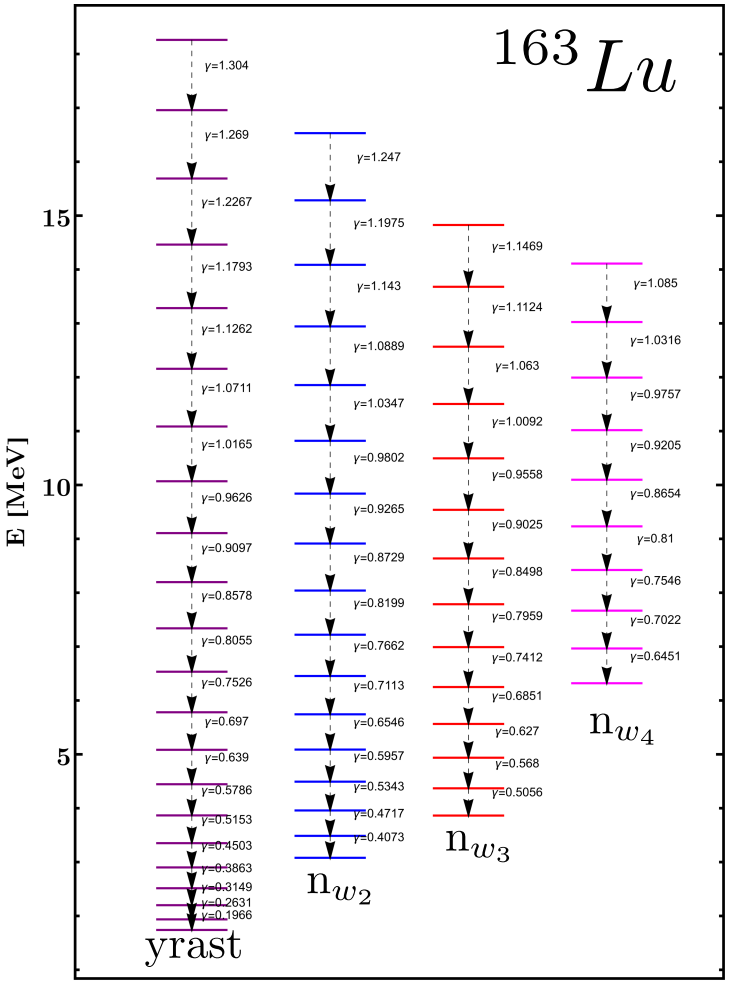



# Wobbling Motion II



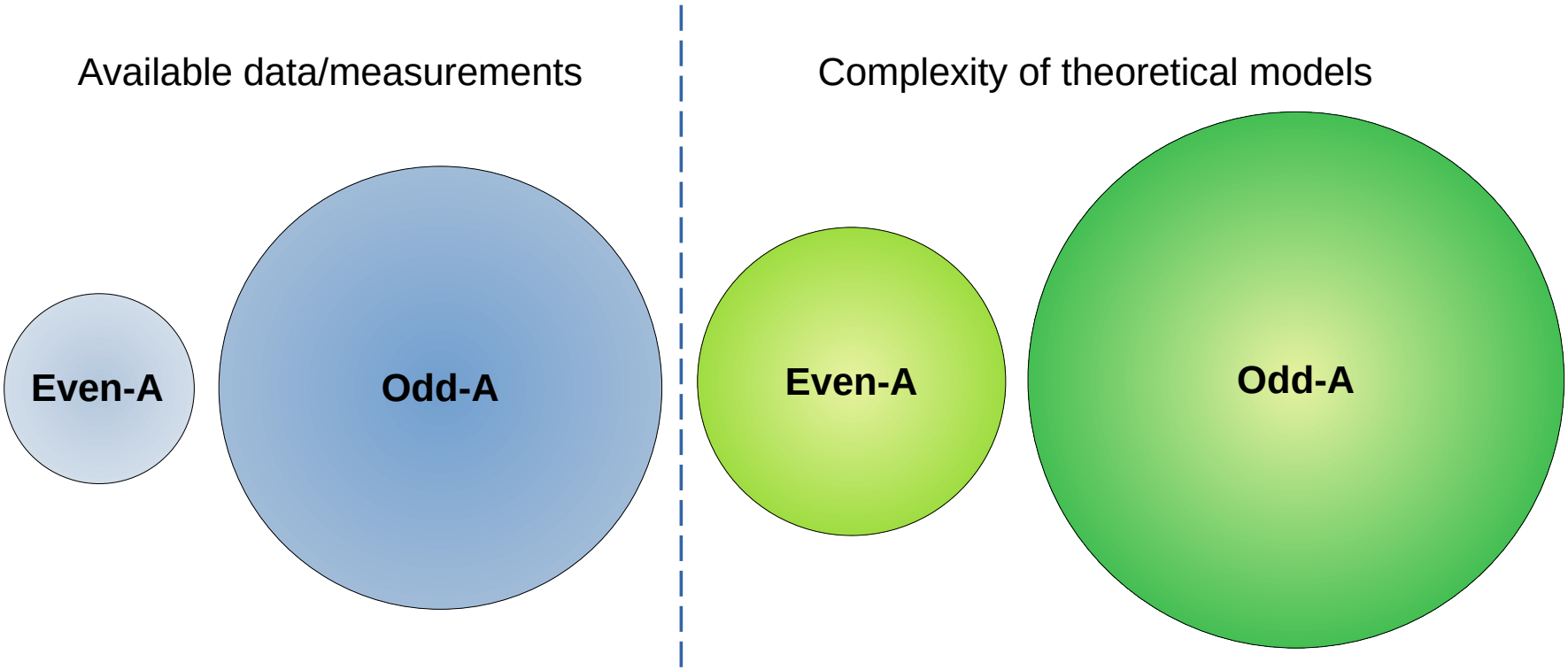




*R. Poenaru, 2023.*

# Even-$A$ vs. Odd-$A$ Picture

- Predicted for even-$A$ nuclei more than 50 years ago.
- First experimental evidence: $^{163}$Lu (*Ødegård, 2001*).
- Current mass-regions for wobblers: $A \approx [130, 160, 180]$.



# $A \approx 100$

**Excitation energies** vs. **Wobbling Energies**:

$$E_{\mathrm{wob}}(I_{\mathrm{even}}) = E_{I,n} - E_{I,0} \ ,$$

$$E_{\mathrm{wob}}(I_{\mathrm{odd}}) = E_{I,n} - \frac{1}{2}\left(E_{I-1,0} + E_{I+1,0}\right)$$

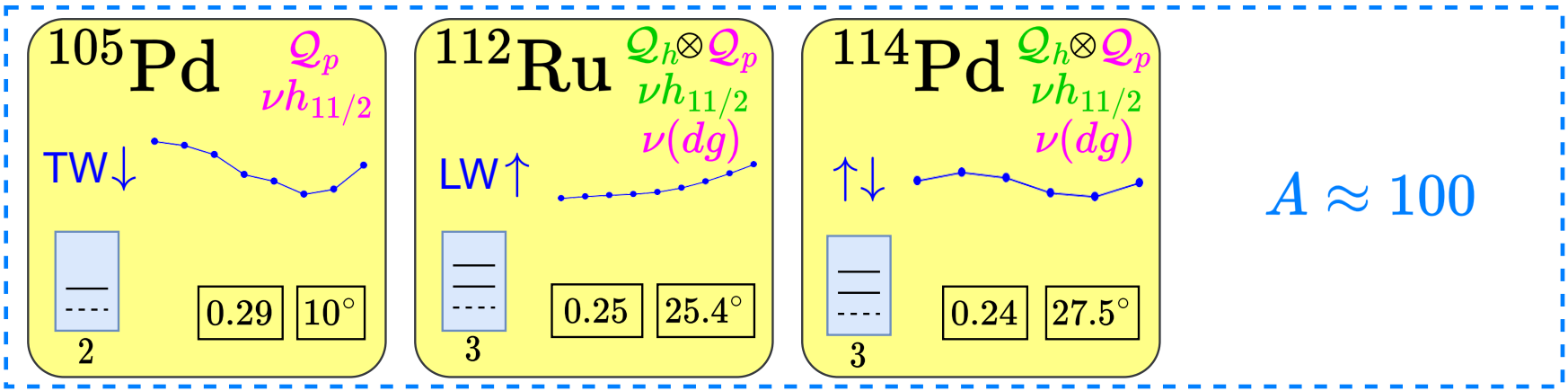



Figure: *Experimentally confirmed wobblers, R Poenaru, 2023.*

# $A \approx 130$

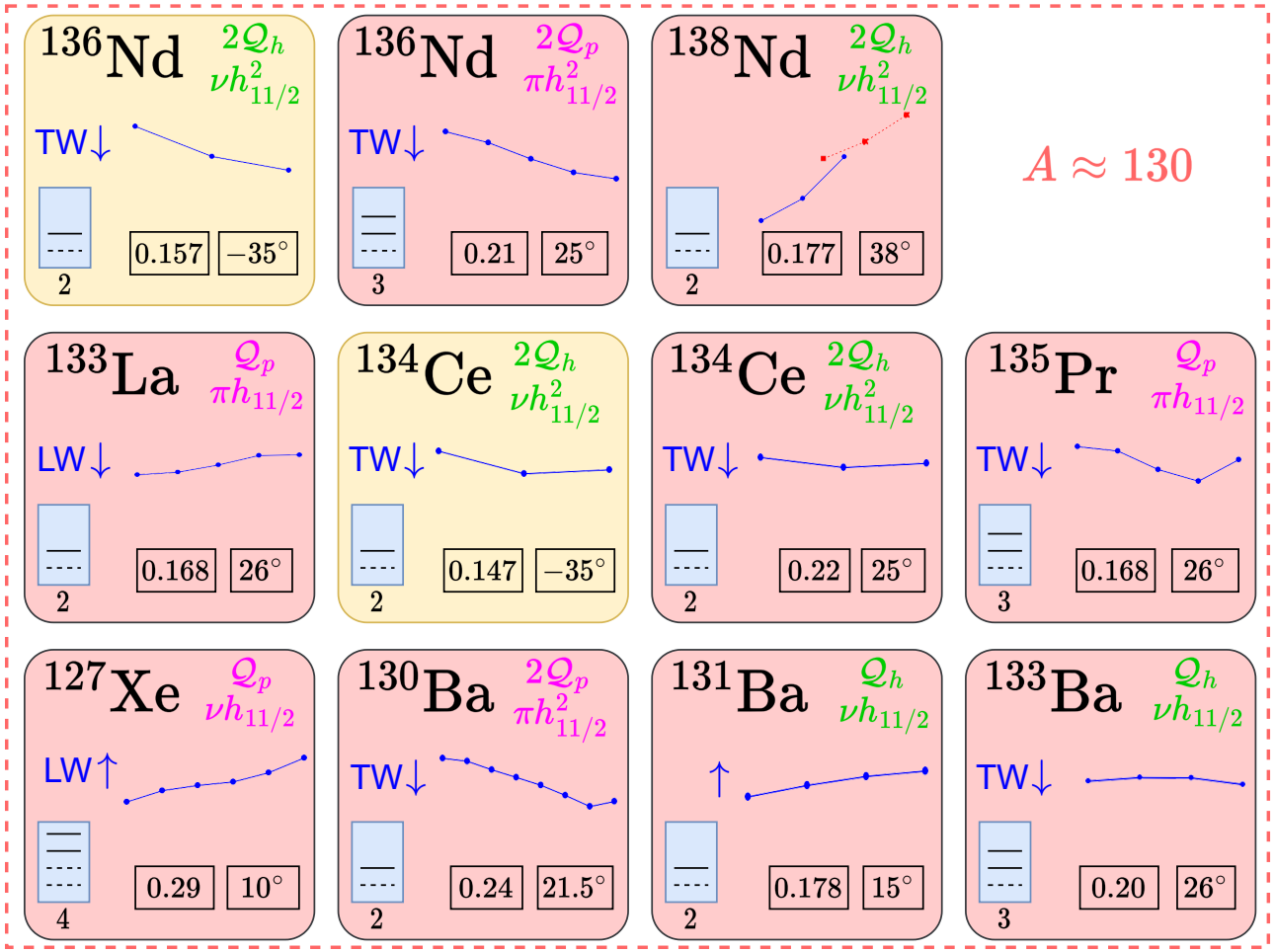



Figure: *Experimentally confirmed wobblers, R Poenaru, 2023.*

# $A \approx 160$

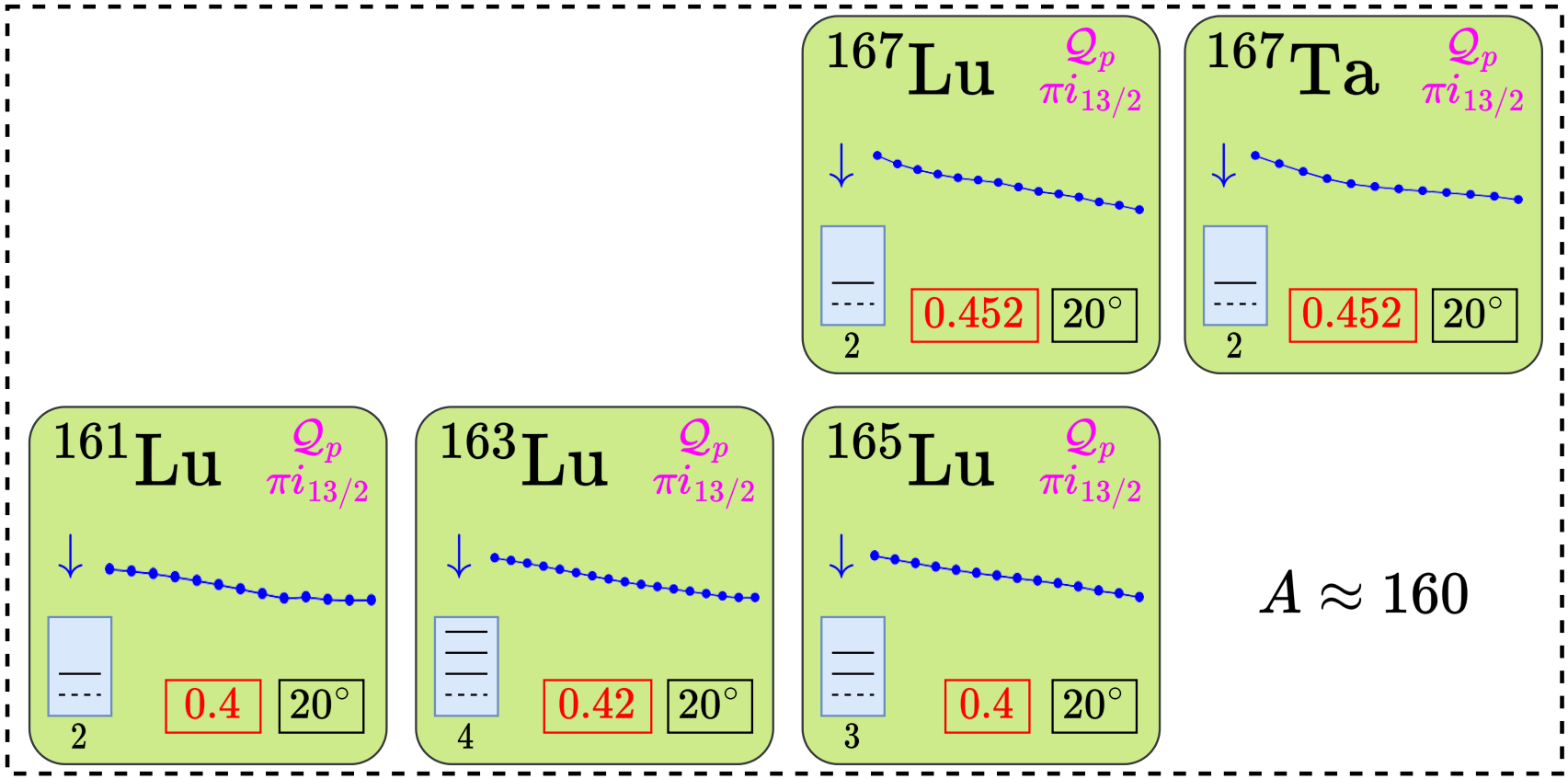



Figure: *Experimentally confirmed wobblers, R Poenaru, 2023.*

# $A \approx 180$

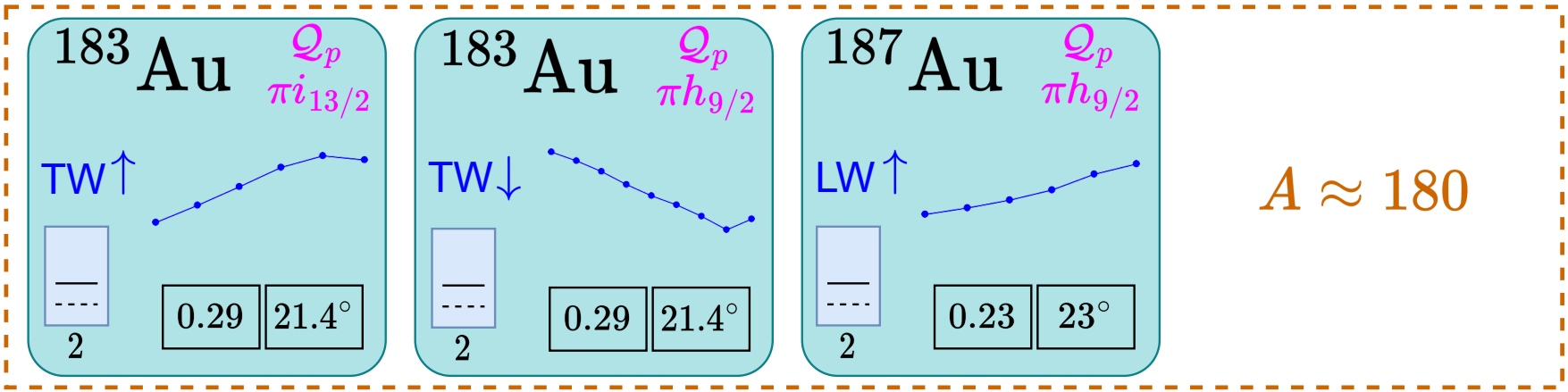
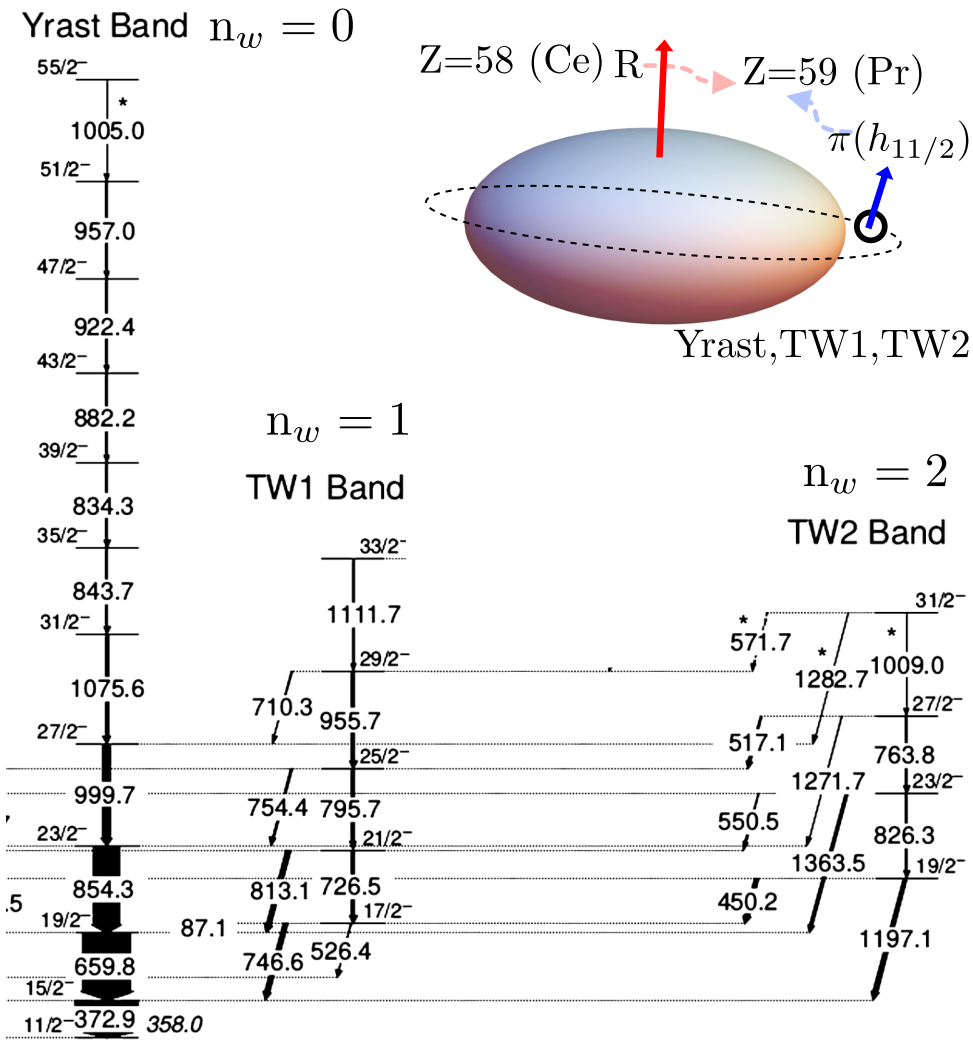



Figure: *Experimentally confirmed wobblers, R Poenaru, 2023.*

# Wobbling Motion in $^{135}$Pr

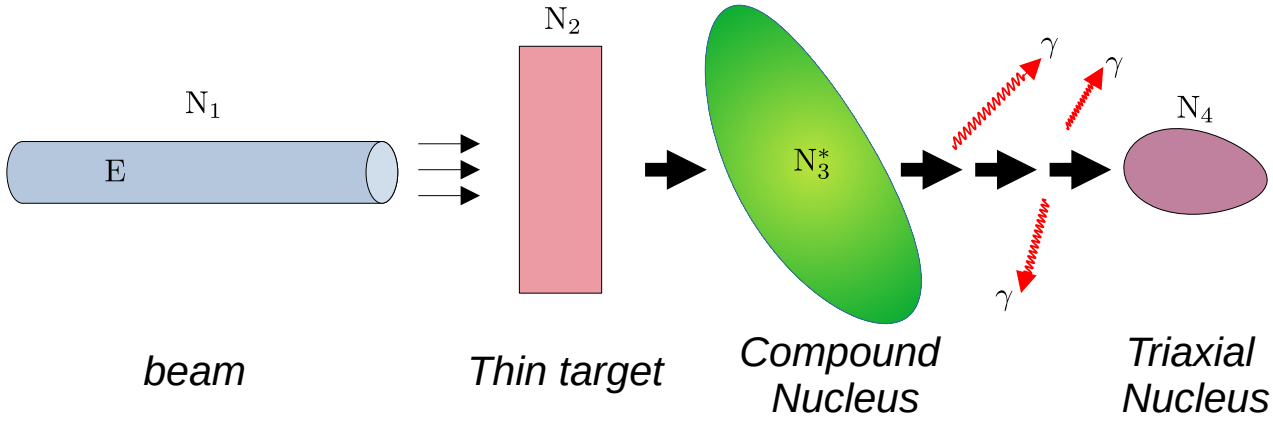
## What we know so far

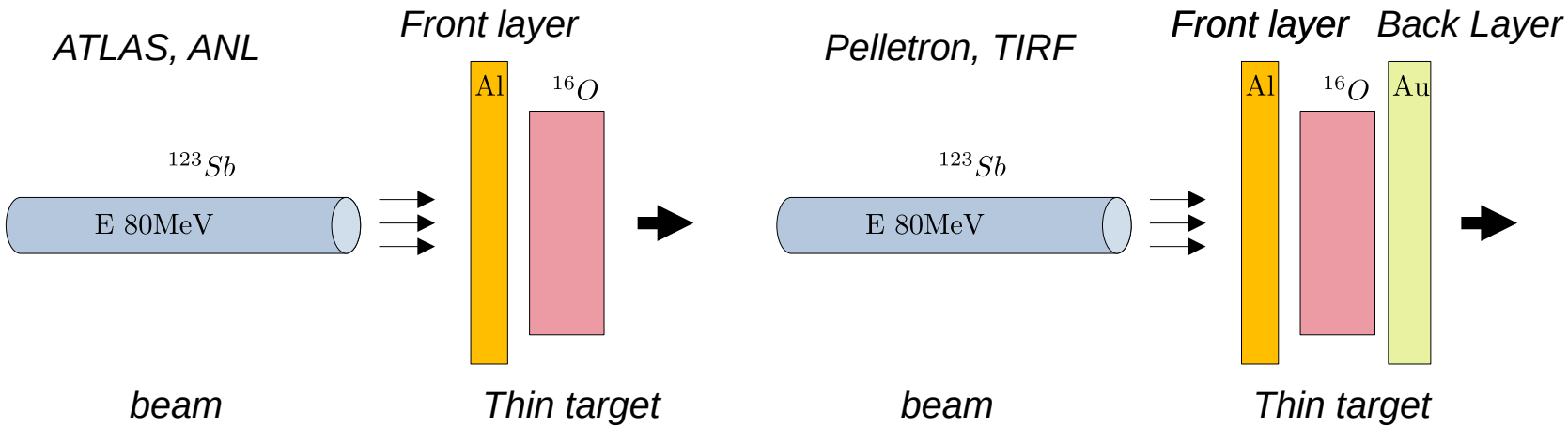
- Two-wobbling phonon bands were measured (*Matta et. al. 2015 + Sensharma et. al. 2019*)
- Exp. measurements: Fusion-Evaporation reactions: $^{123}\mathrm{Sb}\left(^{16}\mathrm{O}, 4n\right)^{135}\mathrm{Pr}$
- **1st round:** ATLAS, ANL (USA), **2nd round:** Pelletron-TIFR, Mumbai.



# Fusion Evaporation Reactions

**Fusion-evaporation reactions**: Long-lived + enhanced deformation



# Theoretical Frameowork

## New Boson Method

- A rotor Hamiltonian was used to describe the wobbling spectrum of $^{135}$Pr
- $\hat{H}_{\text{rot}} = \sum_{k=1,2,3} A_k \left(\hat{I}_k - \hat{j}_k\right)^2$
- The eigenvalues were obtained via a special algebra of the angular momentum operators $\hat{I}_{\pm,0}$.
- Using a set of Dyson-like boson operators for the angular momentum representation.

# Results for $^{135}$Pr

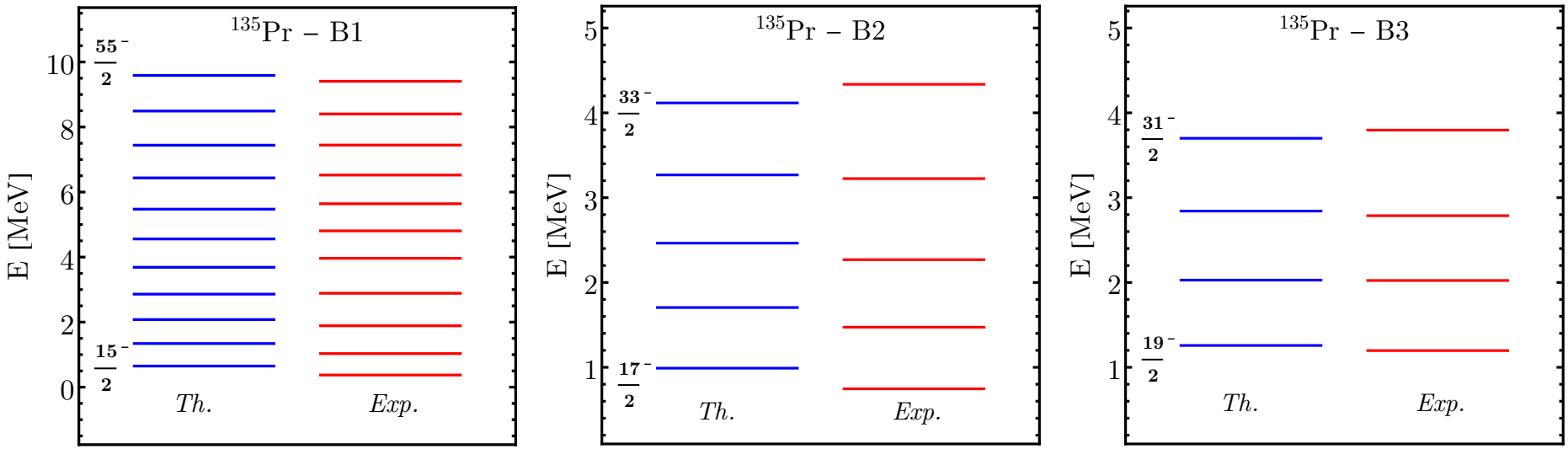



Figure: The excitation energies in $^{135}$Pr. Exp data: *Sensharma, 2019*.

| $\mathcal{I}_1$ | $\mathcal{I}_2$ | $\mathcal{I}_3$ | $\theta$ [degrees] | N.o. states | RMS [MeV] |
|---|---|---|---|---|---|
| 91 | 9 | 51 | −119 | 20 | 0.174 |

A.A. Raduta, C.M. Raduta, **R Poenaru**, Journal of Physics G 48, 2020.

# New experiments

*Article*

## Wobbling Motion in Nuclei

**B.F. Lv [1,2,3] and C. M. Petrache [3,*]**

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2 School of Nuclear Science and Technology, University of Chinese Academy of Science, Beijing 100049, People's Republic of China
3 Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
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Figure: 26th of April, 2023, *Cited our work from JPG.*

- Performed new measurements on the $\gamma$ rays emitted during the fusion-evaporation reactions. $^{100}\mathrm{Mo}\,(40\mathrm{Ar}, 1p4n)^{135}\,\mathrm{Pr}$ ($E_{\mathrm{beam}} = 152$ MeV)
- University of Jyväskylä, Finland, JUROGAM II spectrometer.

# Key factors

There are some *key values* that can point out a **wobbling character** of a nucleus.

- Mixing ratios ($|\delta| > 1$)
- Reduced transition probabilities (mostly E2)
- Quadrupole moments ($\uparrow$)

## Contradicting values

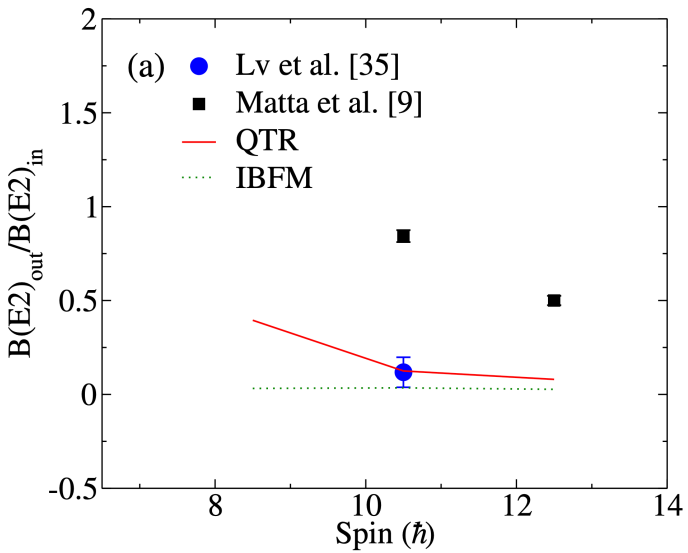
Lv et. al. obtained different experimental values, pointing **against wobbling character**.

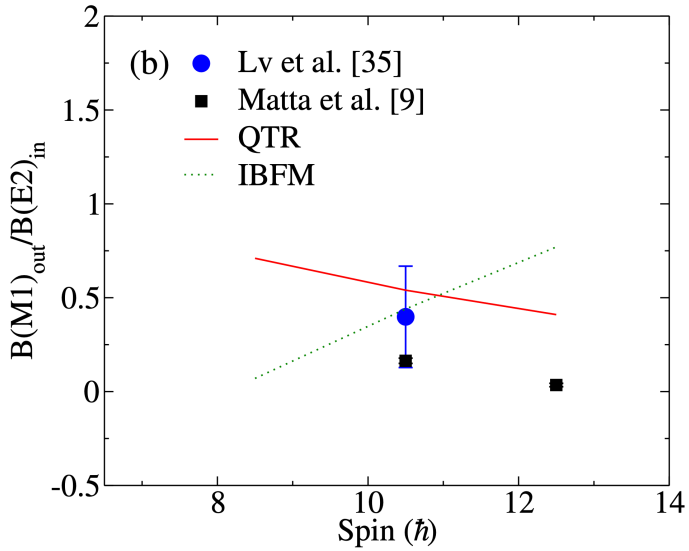
- small mixing ratios
- smaller branching ratios
- ...

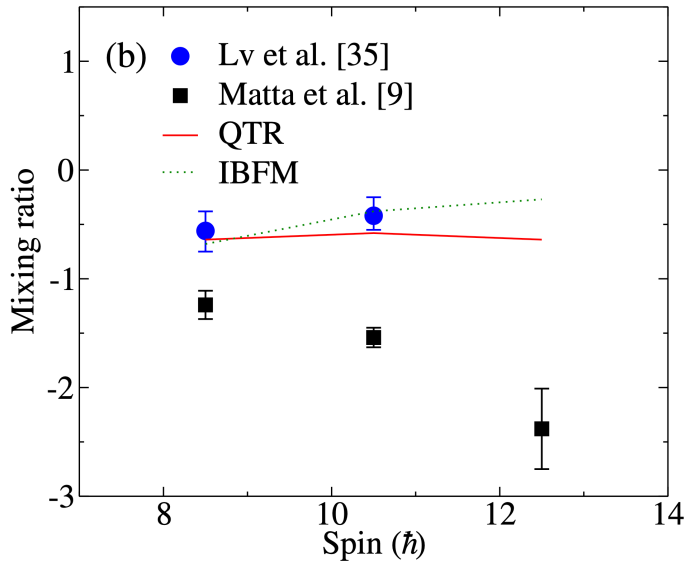
# Moments of inertia

- Values obtained by Matta et. al.: $\mathcal{I}_{1,2,3} = 19, 8, 3\ \hbar^2\text{MeV}^{-1}$.
  $\epsilon = 0.16$, $\gamma = 26^\circ$.
- Values obtained by Sensharma et. al.: $\mathcal{I}_{1,2,3} = 7.4, 5.6, 1.8\ \hbar^2\text{MeV}^{-1}$.
  $\epsilon = 0.16$, $\gamma = 26^\circ$.
- Values obtained by Raduta et. al.: $\mathcal{I}_{1,2,3} = 91, 9, 51\ \hbar^2\text{MeV}^{-1}$.
  Quadrupole deformations not needed.

# New experimental data



# Conclusions

- Disagreement between the experimental measurements for an odd-mass nucleus.
- First work pointing out contradictory behavior of $^{135}$Pr in terms of collective excitations
- The smaller values of mixing ratios and branching ratios show that the three triaxial bands in the isotope are at normal deformation, show collective nature, but no wobbling.

**Future perspectives**: Re-calibrate the existing theoretical interpretation of the triaxial nature of the wobblers near $A \approx 130$ mass region.

Thank you for your attention!