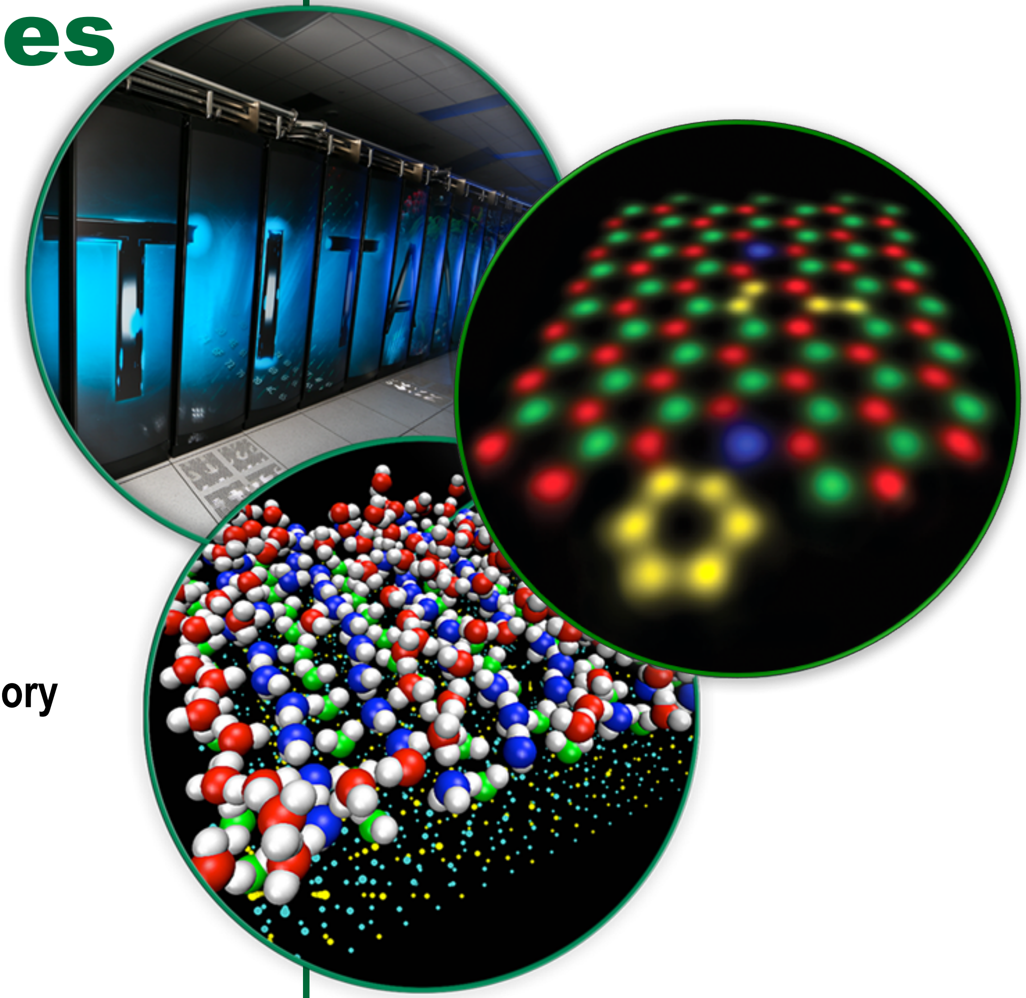
Triaxiality in Neutron-Rich Mo-Ru Isotopes from Coulomb Excitation



James Mitchell Allmond
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SSNET’17 – Gif sur Yvette, France

U.S. DEPARTMENT OF
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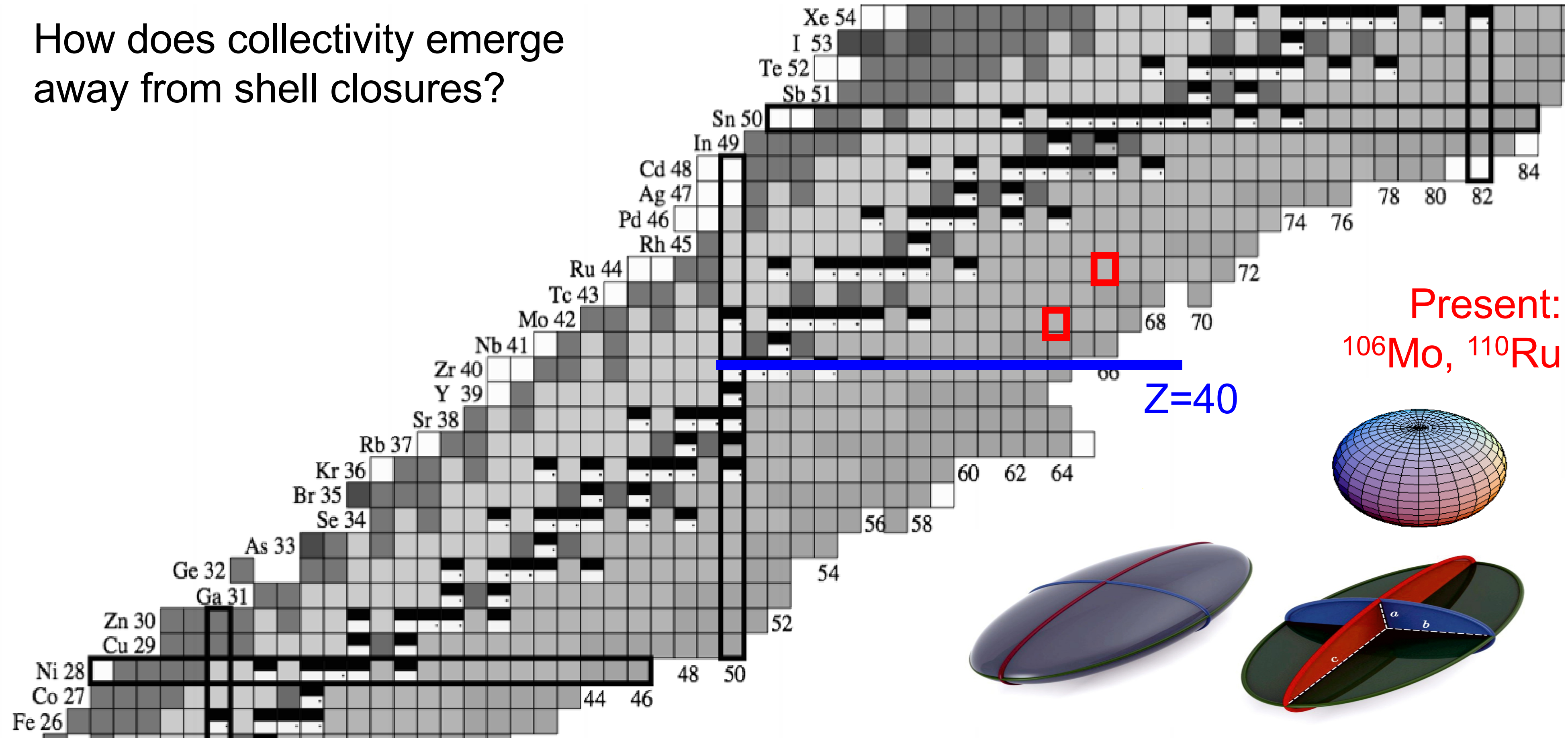
Coulex of Radioactive Mo-Ru

first coulomb excitation study of reaccelerated refractory elements

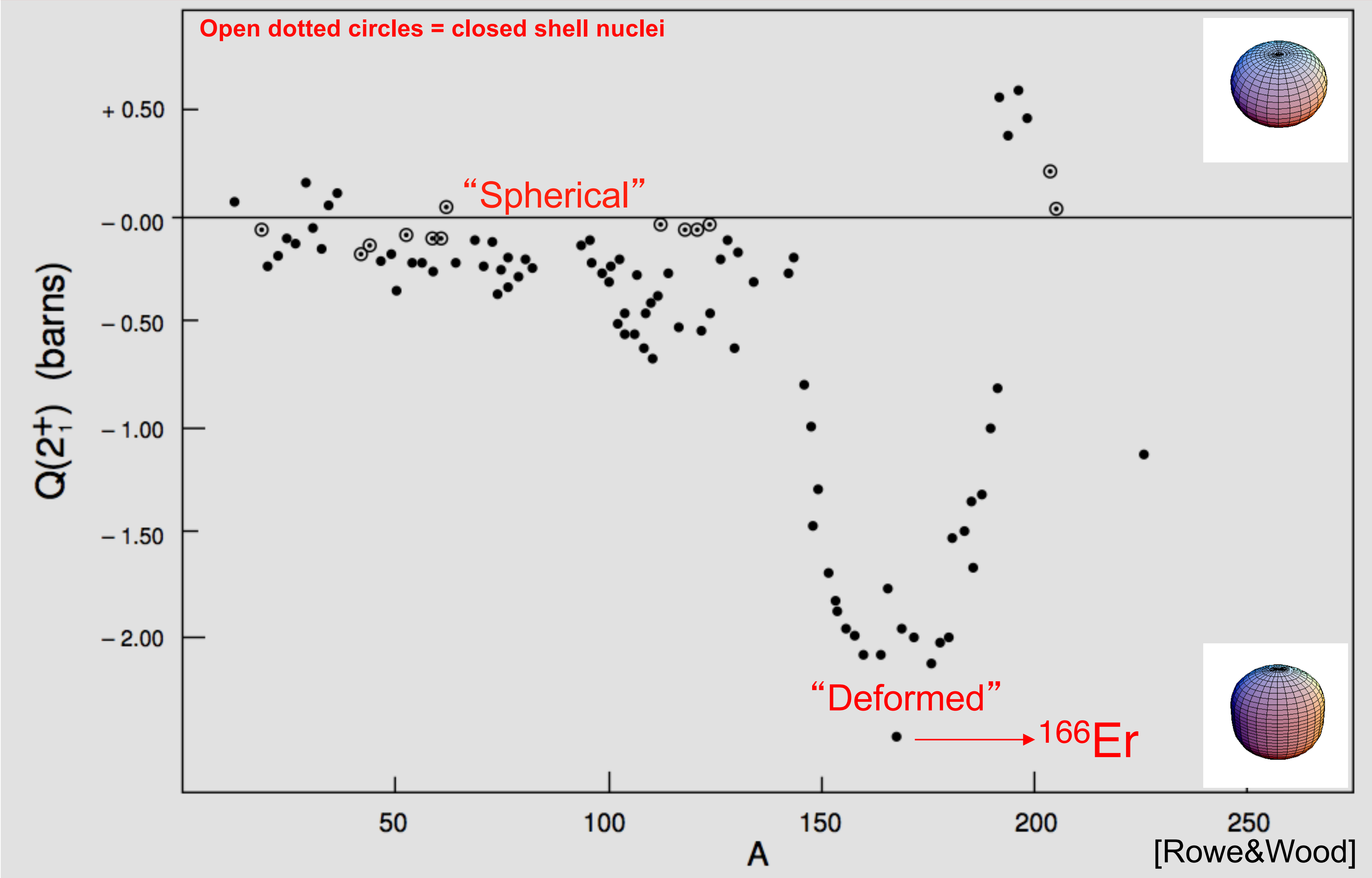
How does collectivity emerge away from shell closures?



Are the n-rich refractory elements oblate or triaxial deformed?

First 2^+ Quadrupole Moment

Nuclei are predominantly between spherical and prolate deformed



Open dotted circles = closed shell nuclei

"Spherical"

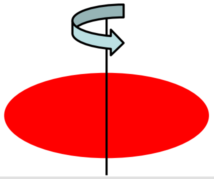
"Deformed"

^{166}Er

[Rowe&Wood]

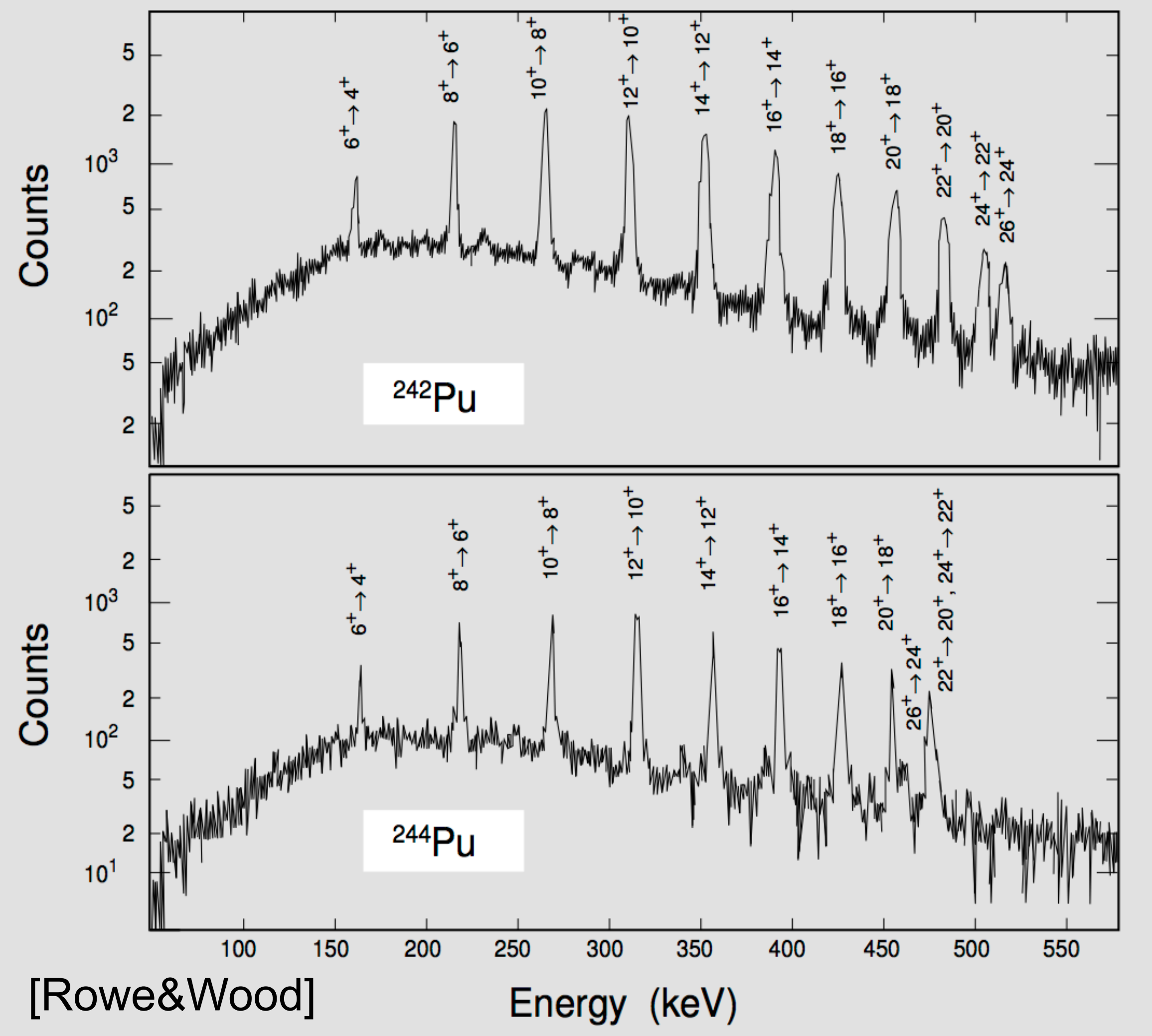
Rotor Example

Sequence of γ-rays following Coulomb excitation of Pu isotopes reveals rotor-like pattern

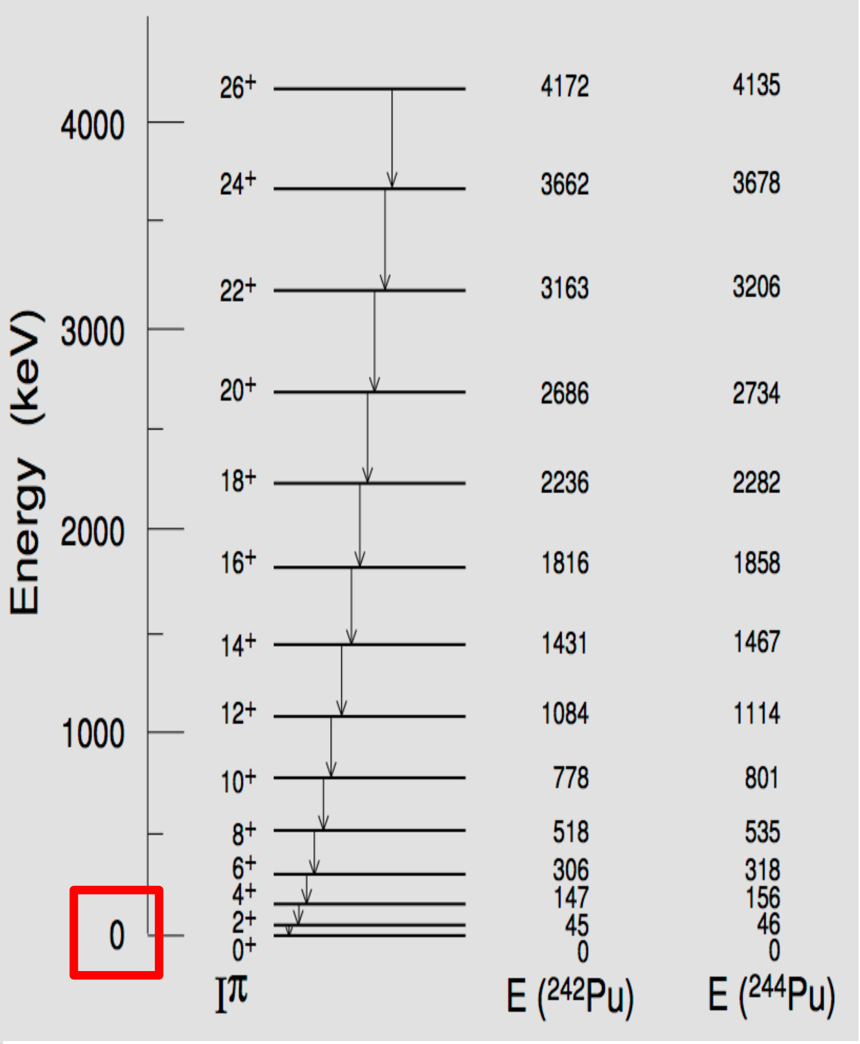


$E = A\,I(I+1)$

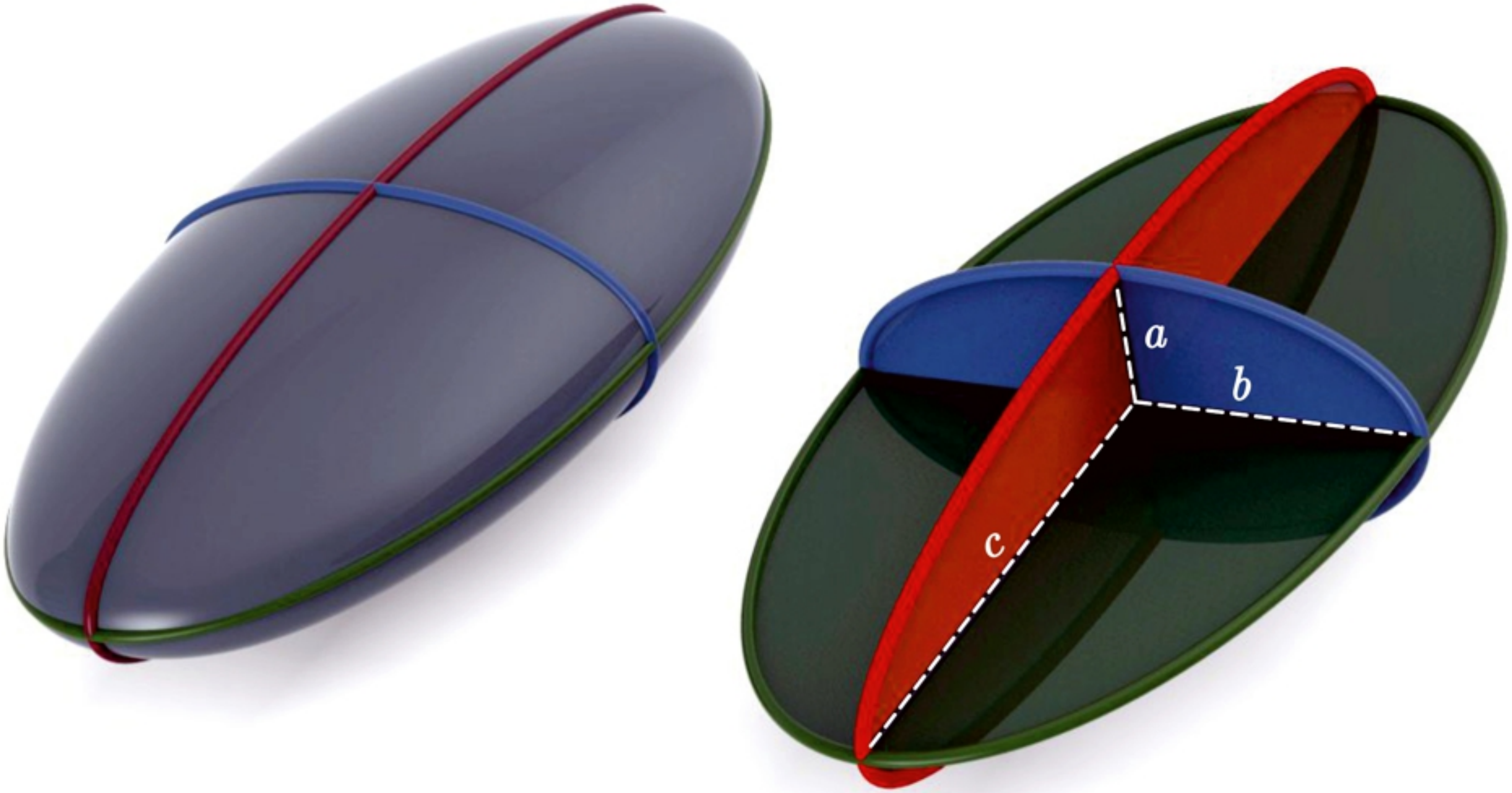
condition=γ-ray singles



[Rowe&Wood]



Triaxial (ellipsoid) Shapes?



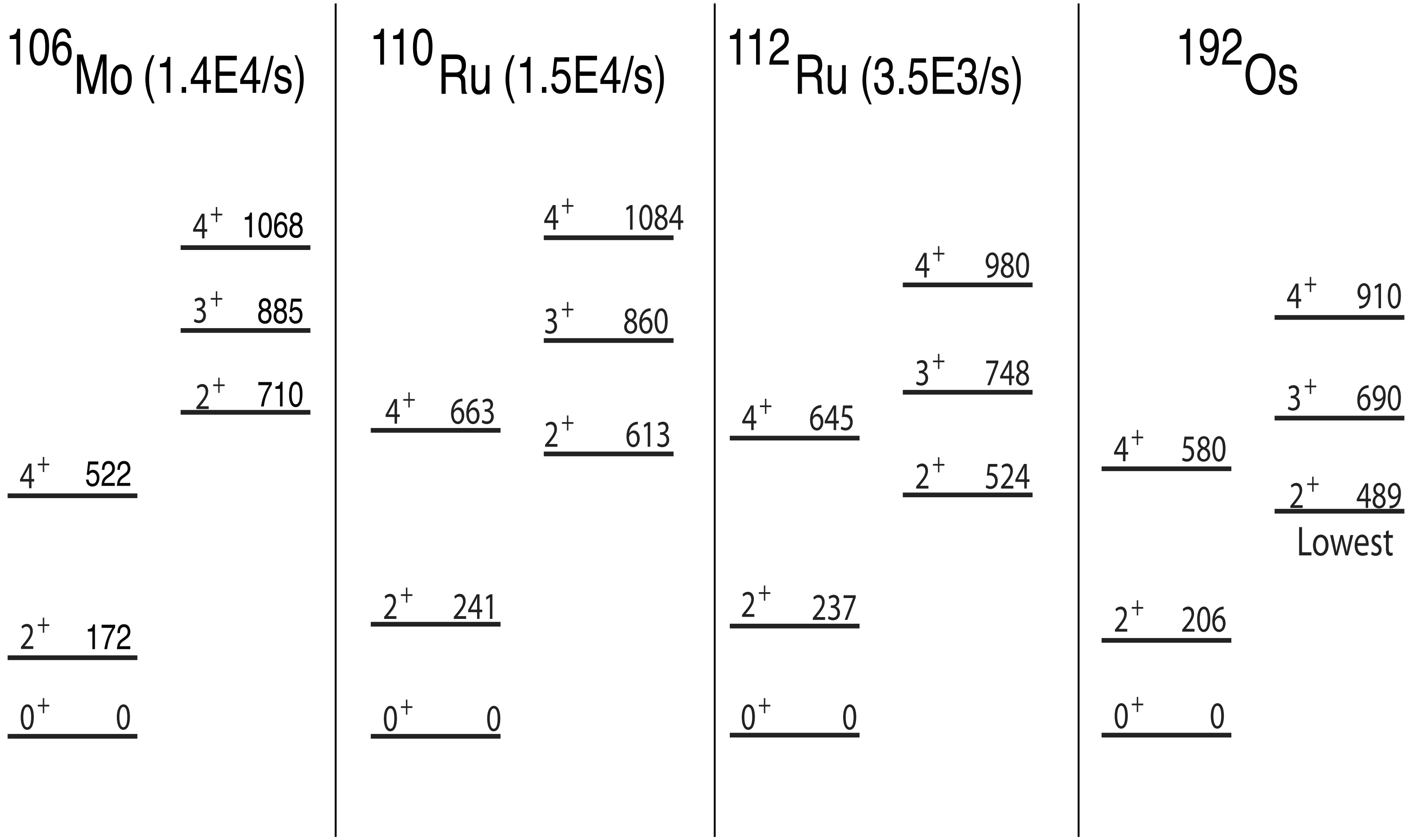
c > b > a

Search for Triaxial Shapes

low second 2^+ state is a signature for triaxial deformation

RIBs from CARIBU

STABLE



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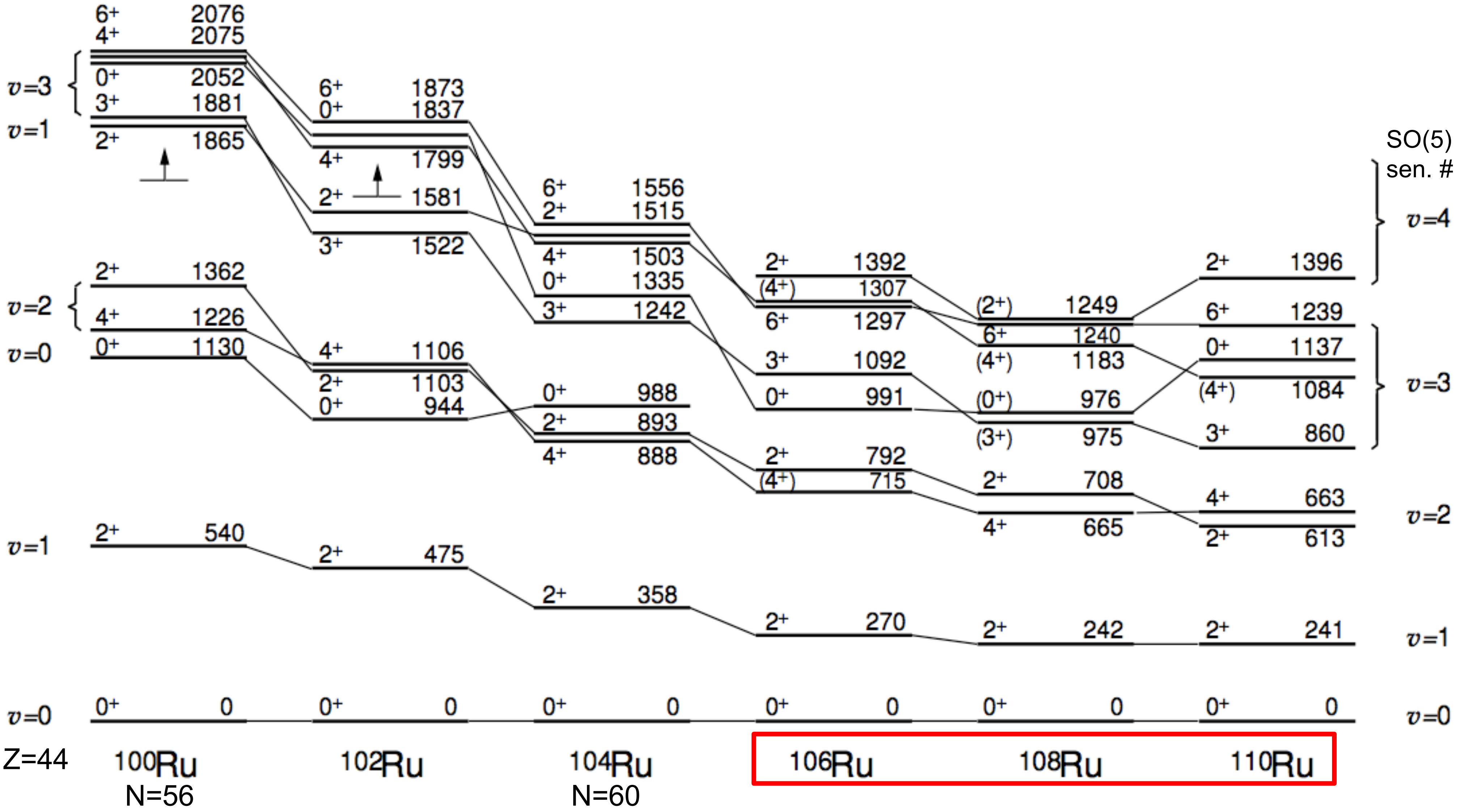
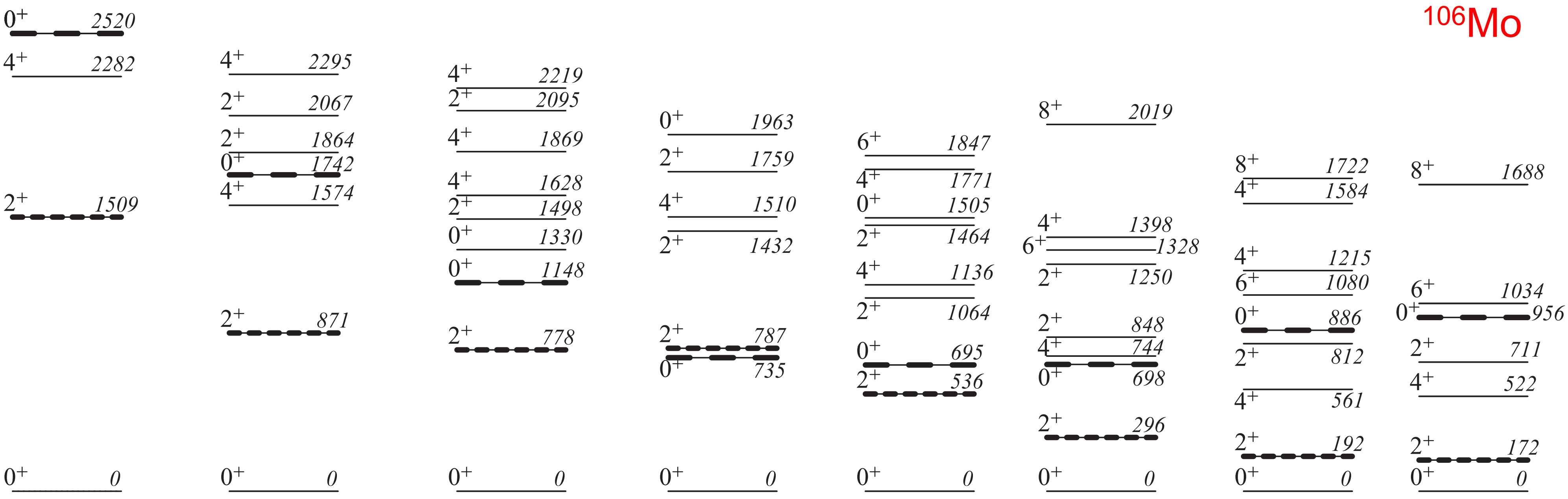
Onset of Deformation for Ru



RADIOACTIVE (available at CARIBU)

*figure from [Rowe&Wood]

Onset of Deformation for Mo



N=50
closed
shell

N=52

N=54

N=56

N=58

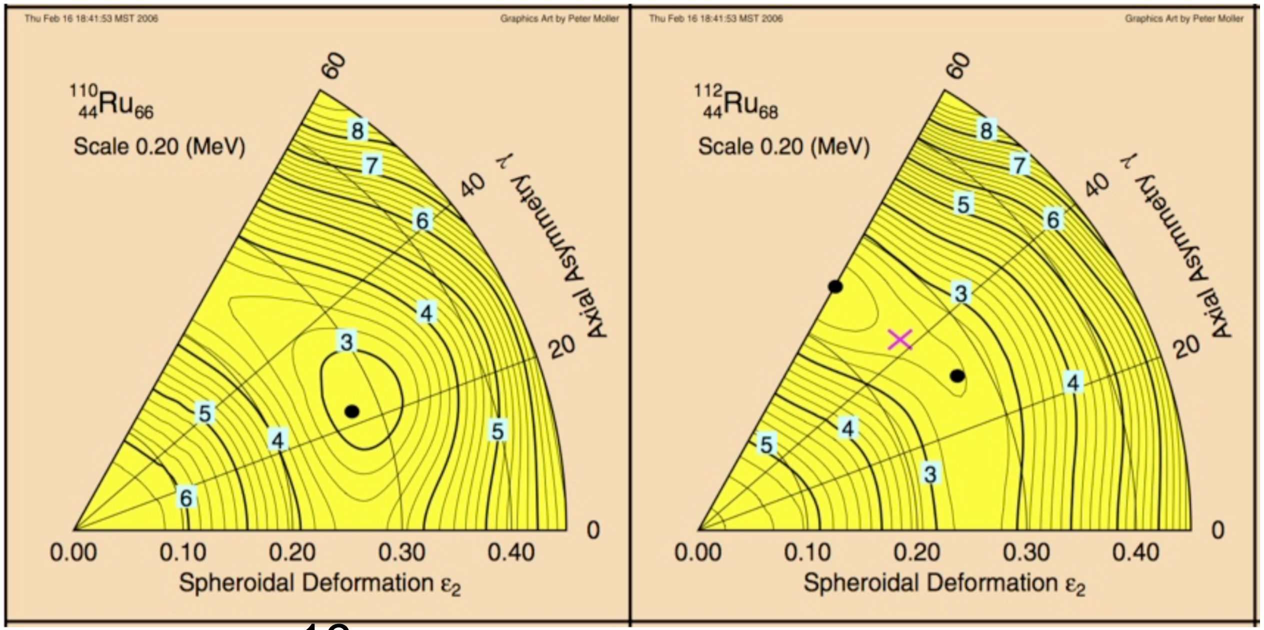
N=60 N=62 N=64

RADIOACTIVE
available at CARIBU

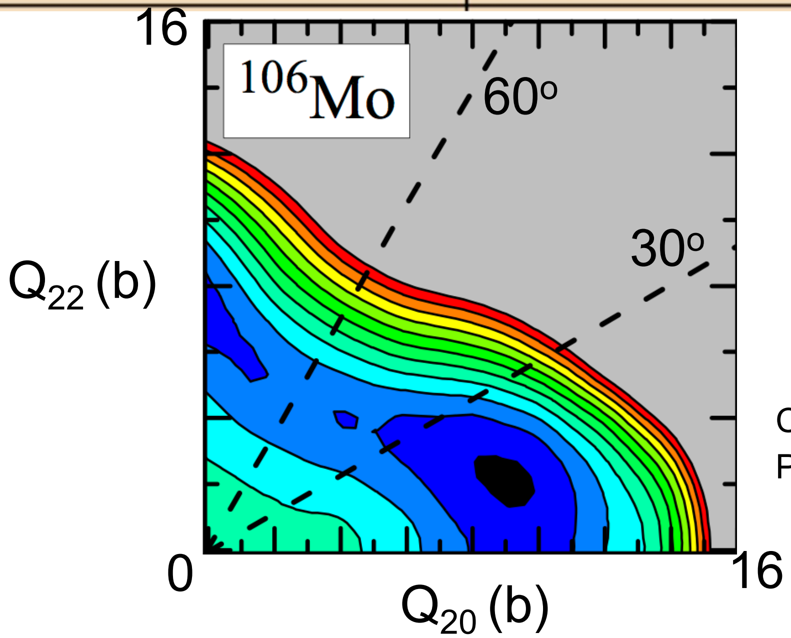
*Figure from [K. Wrzosek-Lipska et al., PRC 86, 064305 (2012)]

Ground-State Shape Predictions

Both prolate-triaxial and oblate shapes predicted



P. Möller et al.,
ADNDT **94**, 758 (2008).



C. L. Zhang et al.,
PRC **92**, 034307 (2015).

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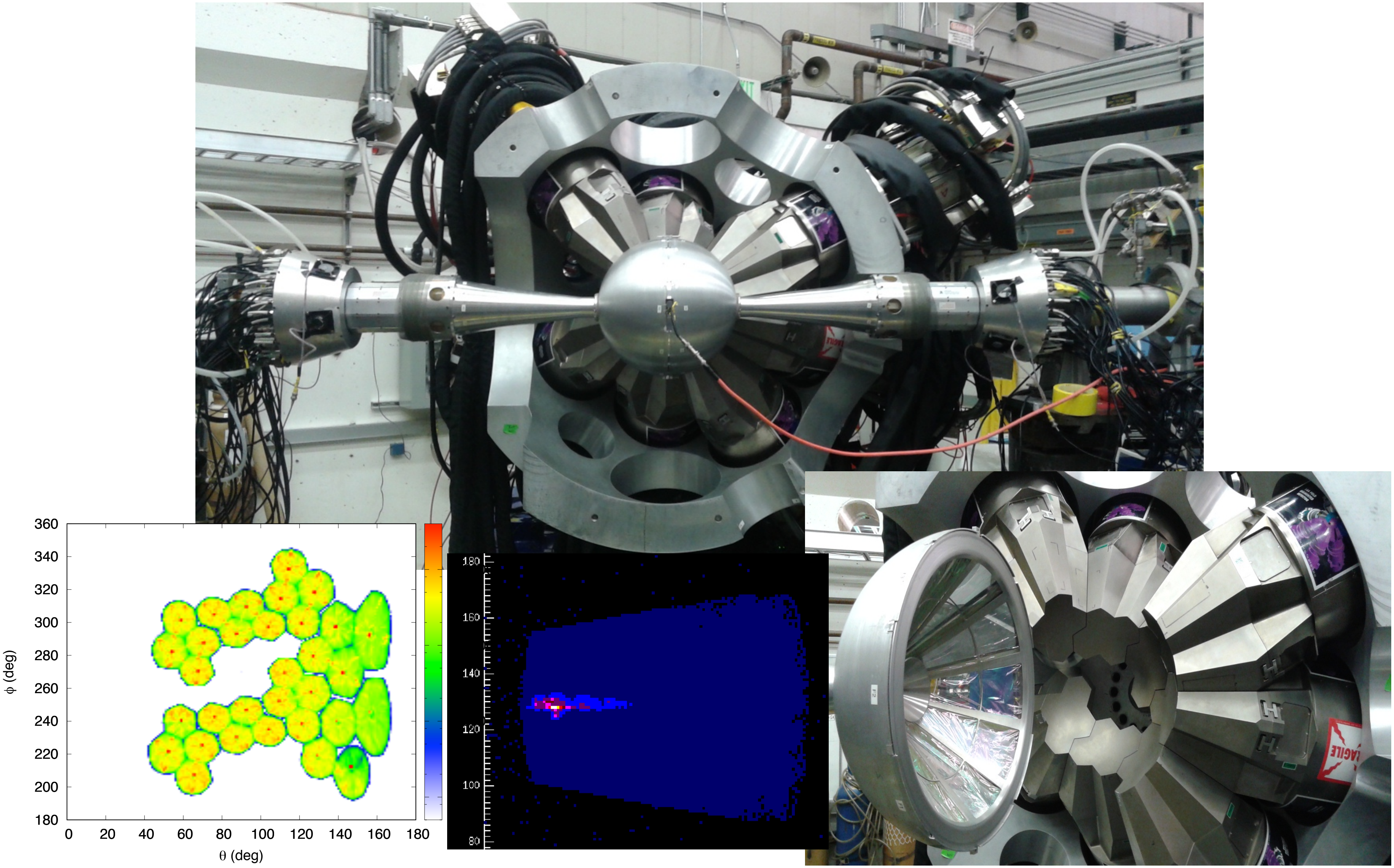
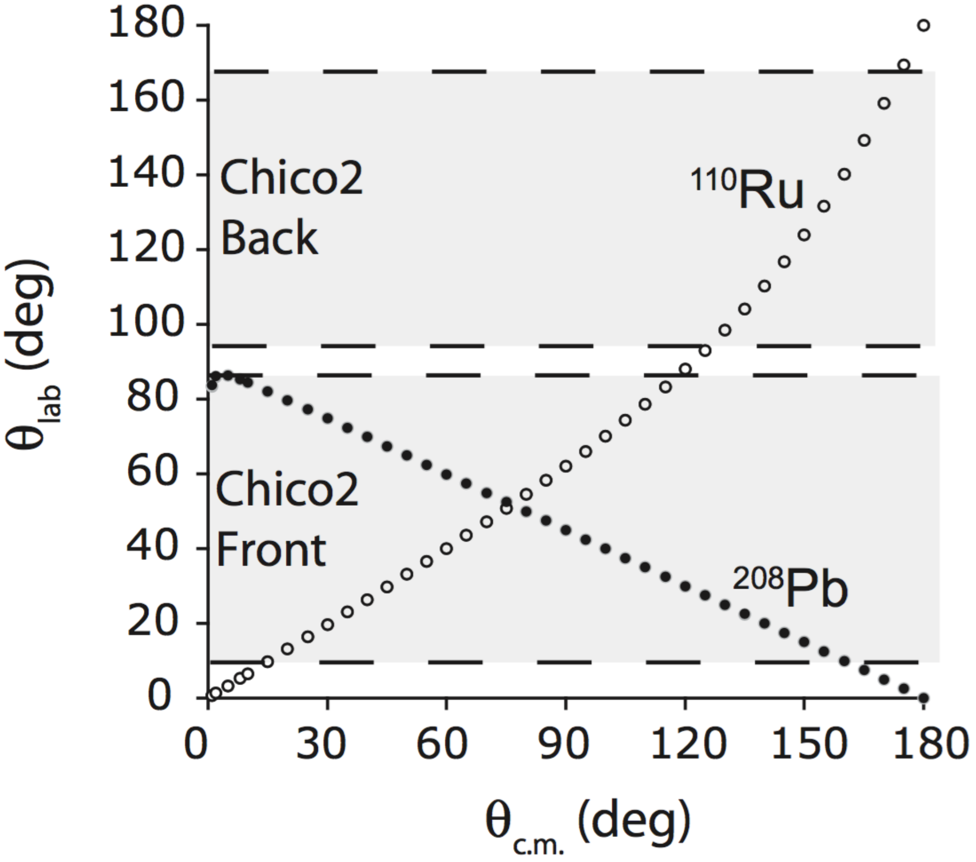
GRETINA-CHICO2

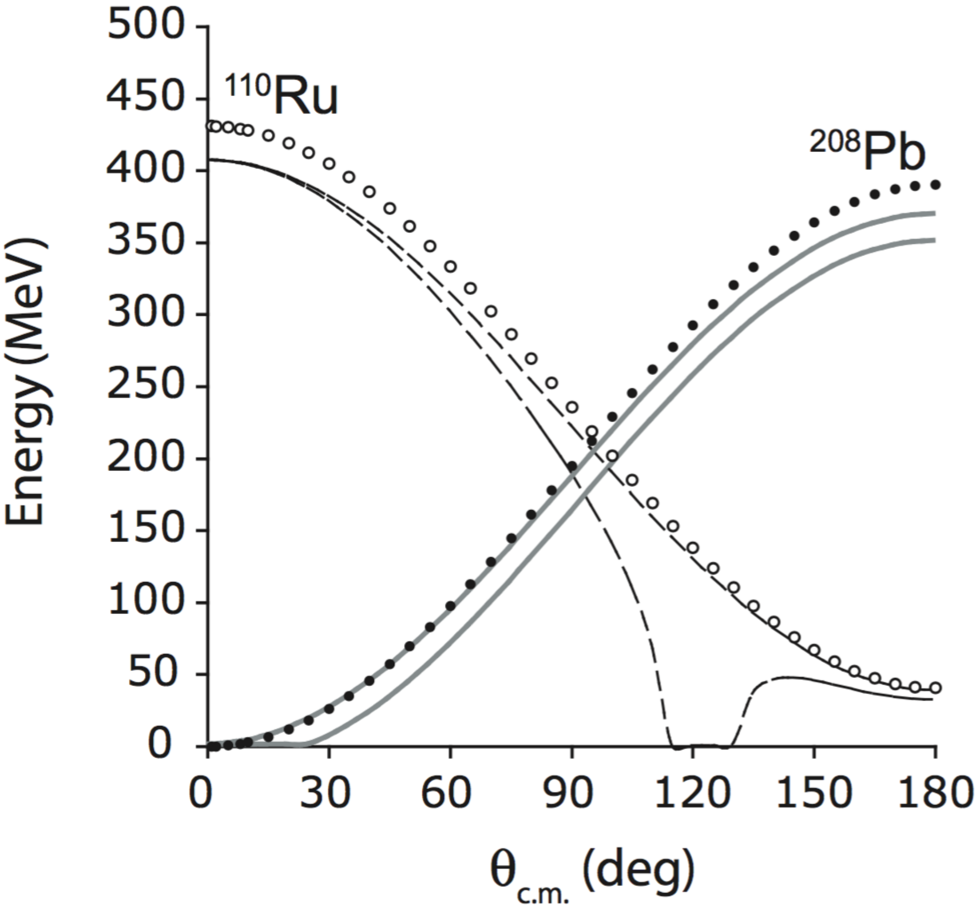
High granularity (and efficiency) in both γ-ray and particle detection



Coulomb Excitation of Exotic ^{110}Ru

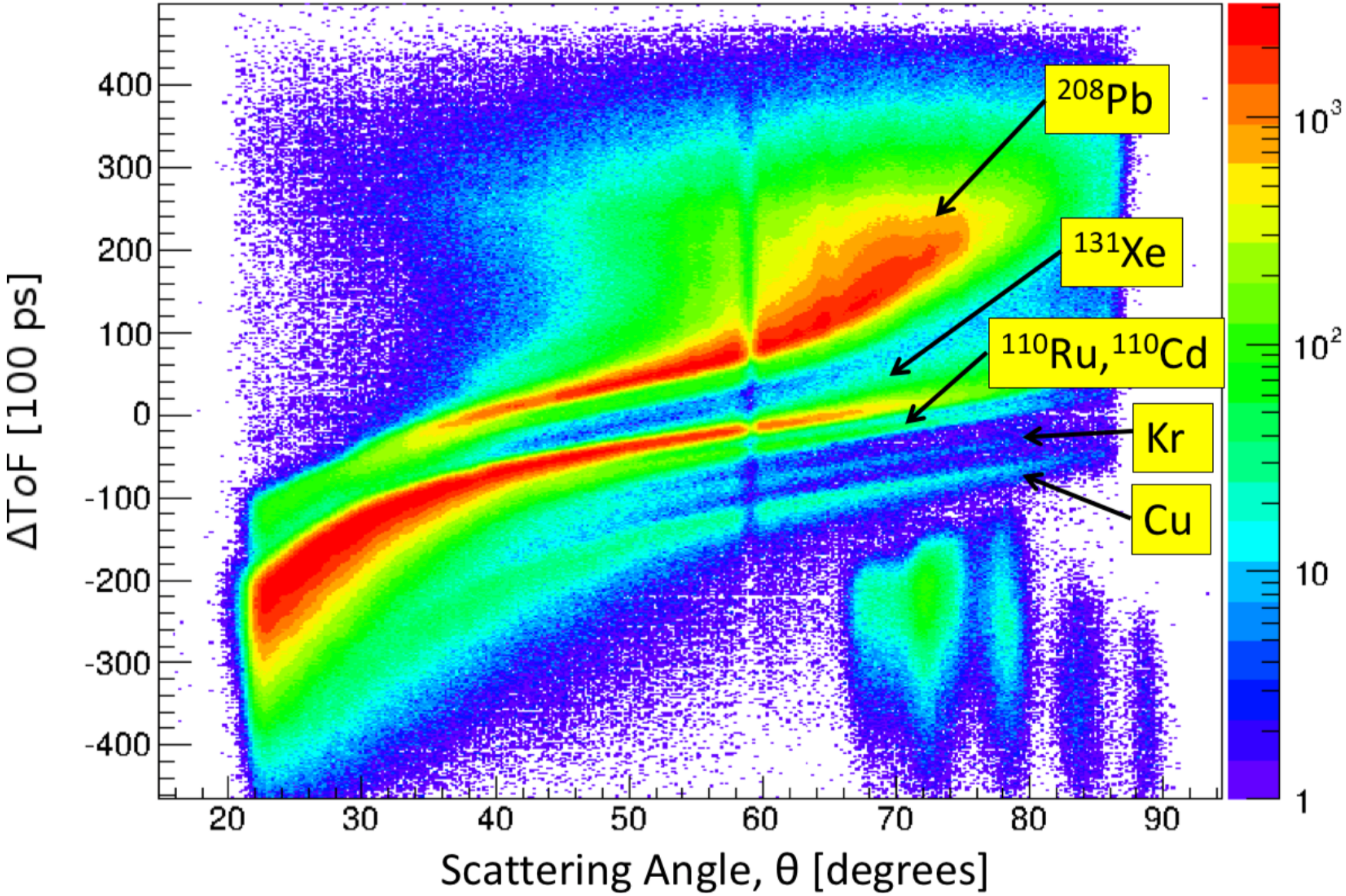
normal kinematics on Pb target at "safe" energy: CHICO has good coverage!





Particle Identification with CHICO2

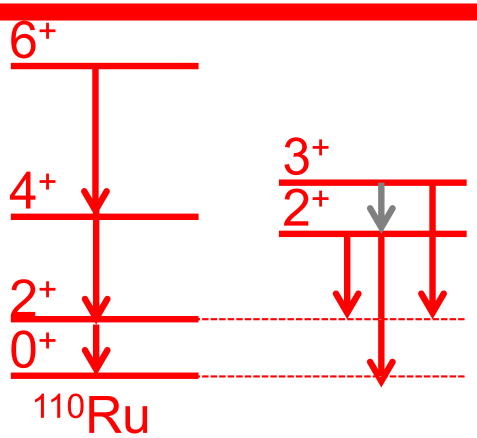
Δt of CHICO2 needed for selecting ^{110}Ru from ECR contaminants



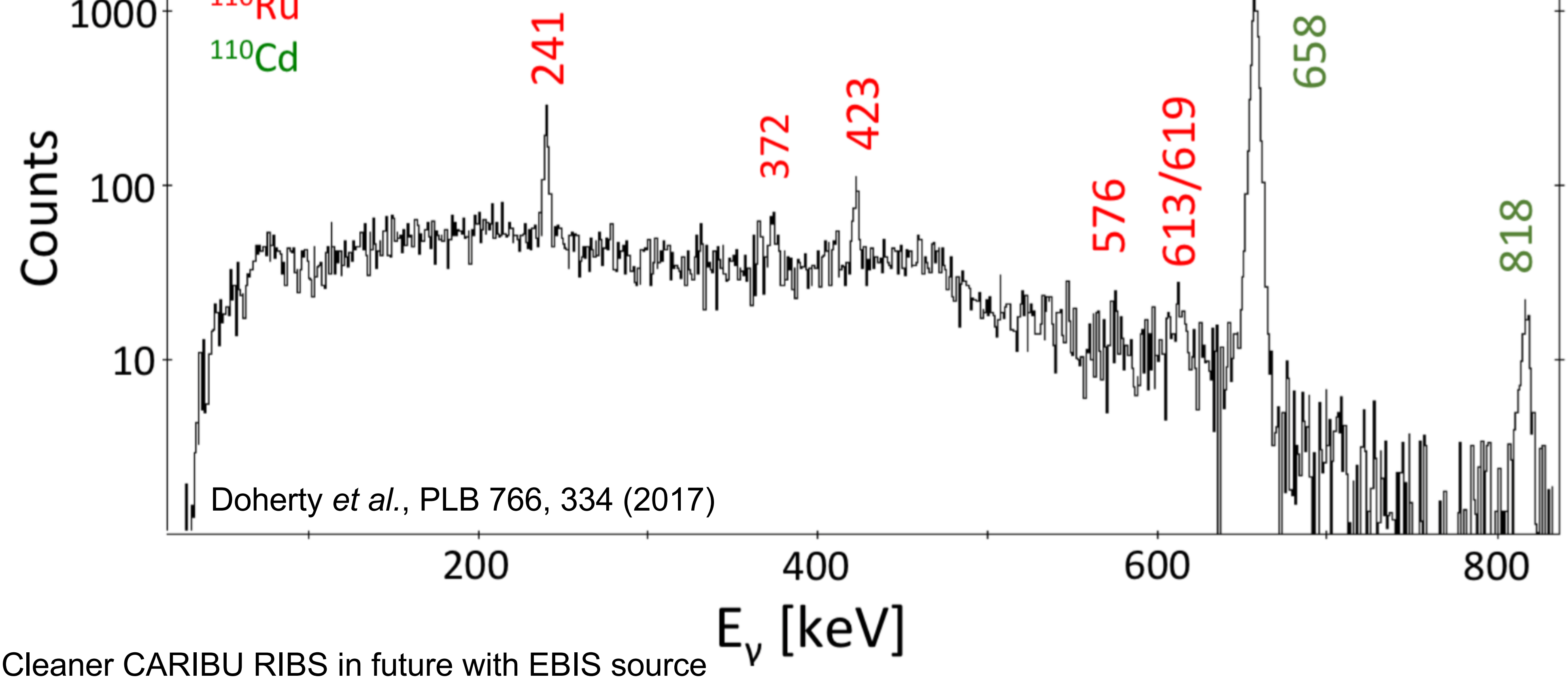
*Cleaner CARIBU RIBS in future with EBIS source

Coulomb Excitation of Exotic ^{110}Ru

Resolution of GRETINA-CHICO2 needed for selecting ^{110}Ru from ECR contaminants



*2_2 and 3_1 branches previously measured [ENSDF]

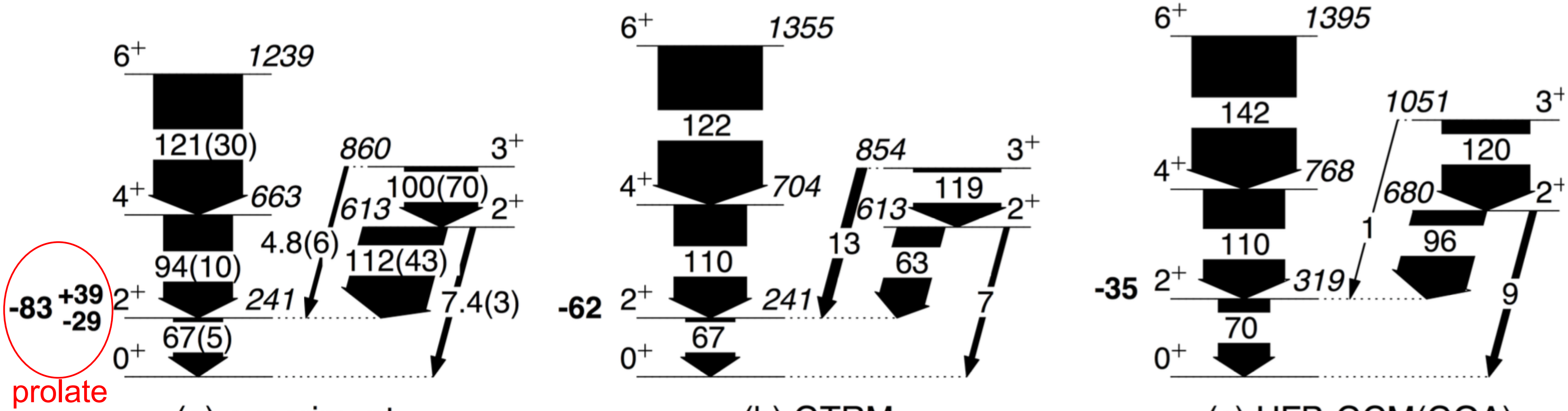


Doherty *et al.*, PLB 766, 334 (2017)

*Cleaner CARIBU RIBS in future with EBIS source

Coulomb Excitation of Exotic ^{110}Ru

Experimental results are consistent with an axially asymmetric (triaxial) shape



(a) experiment

(b) GTRM

(c) HFB-GCM(GOA)

$\langle\gamma\rangle = 29^{o}$
$\sigma\langle\gamma\rangle = 0^{o}$

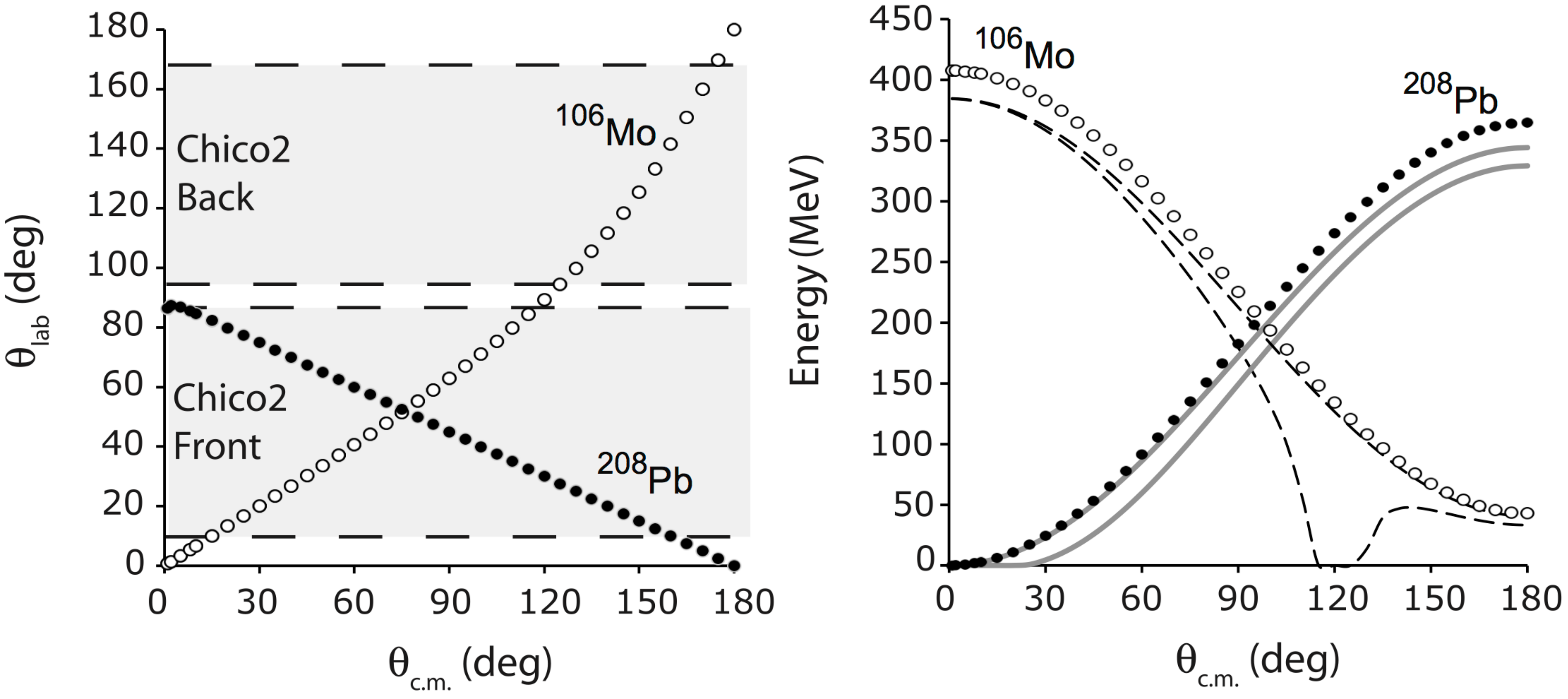
$\langle\gamma\rangle = 26^{o}$
$\sigma\langle\gamma\rangle = 12^{o}$

cf. 2^+ mixing strengths
^{110}Ru(Γ = -10.7^{o}, G = -9.8 keV)
^{192}Os(Γ = -8.7^{o}, G = -6.4 keV)

Doherty *et al.*, PLB 766, 334 (2017)

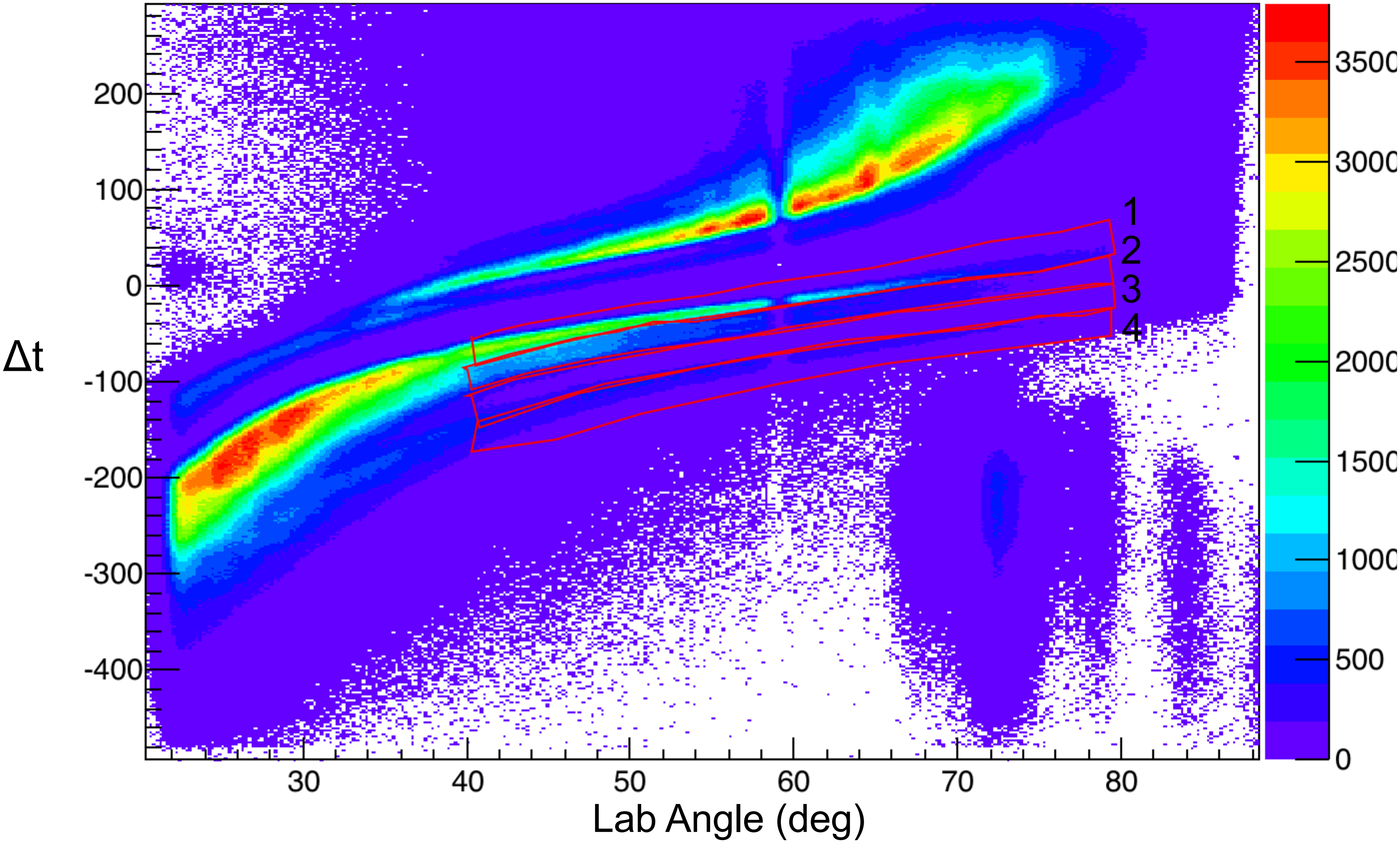
Coulomb Excitation of Exotic ^{106}Mo

normal kinematics on 1.1 mg/cm² Pb target at “safe” energy, 408 MeV



Particle Identification with CHICO2

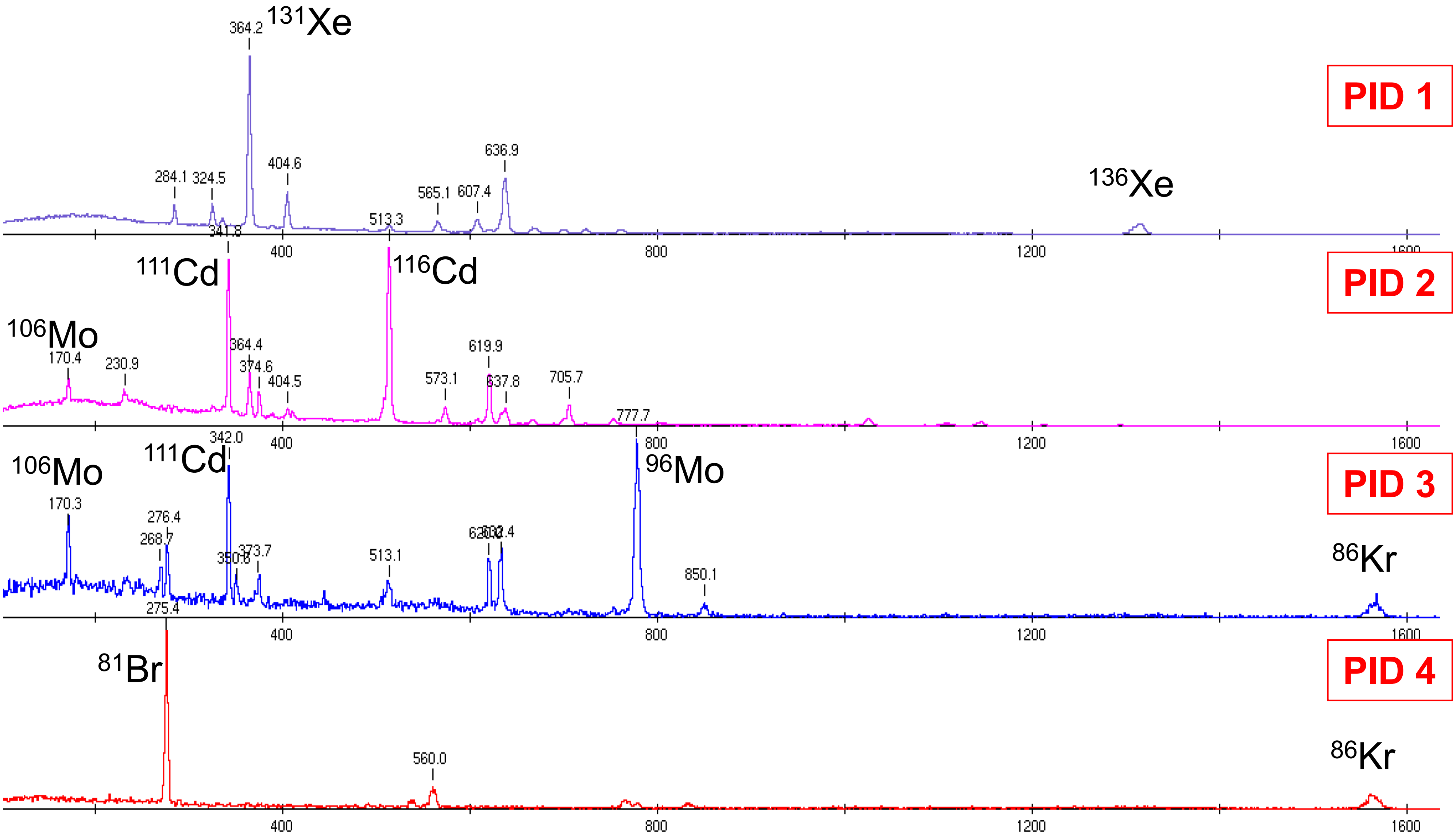
Δt of CHICO2 needed for selecting ^{106}Mo from ECR contaminants



*Cleaner CARIBU RIBS in future with EBIS source

CHICO2 Gated γ-ray Spectra

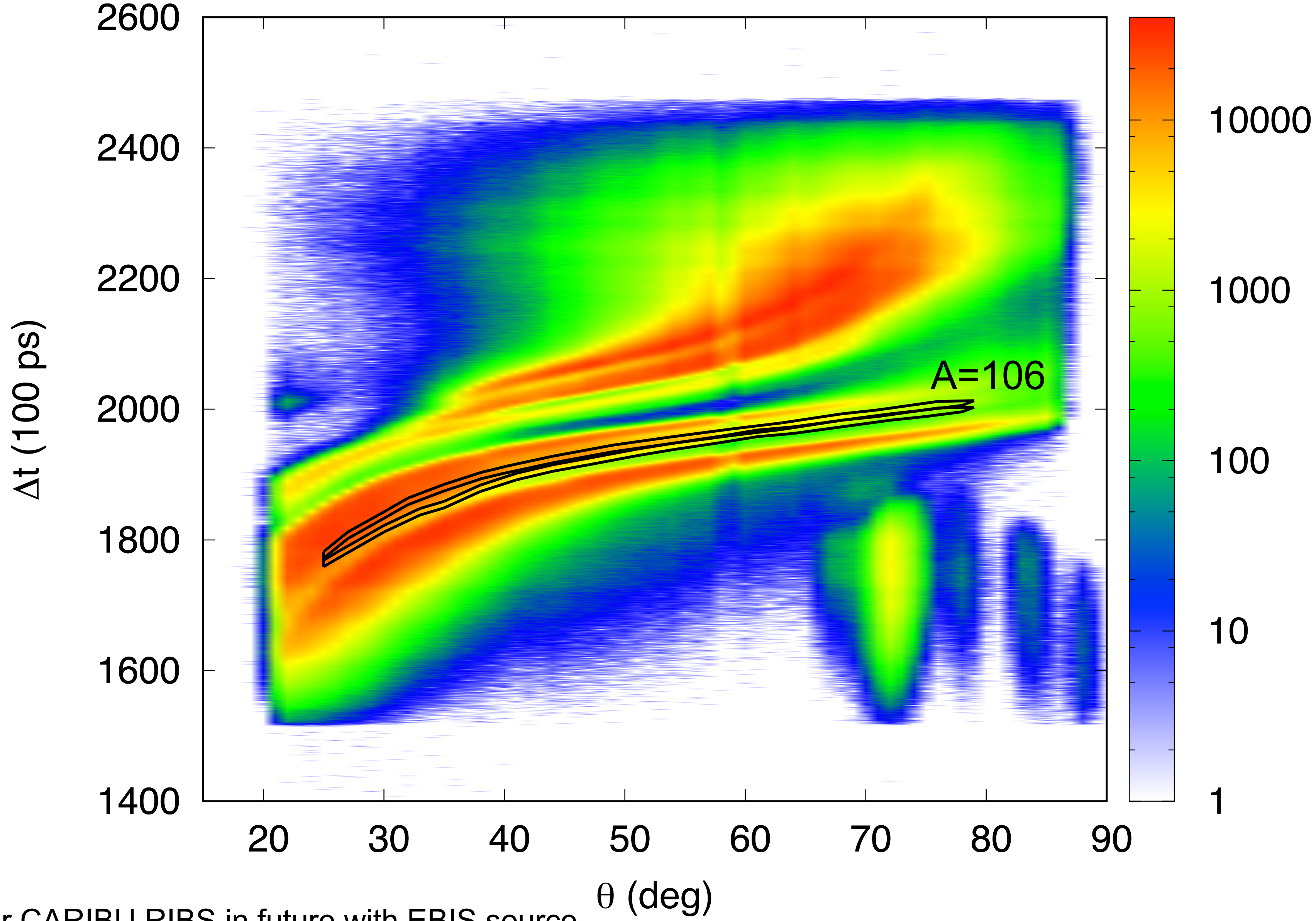
Δt of CHICO2 has mass selectivity. Ideal A~106 between PID 2 and 3.



*Cleaner CARIBU RIBS in future with EBIS source

Particle Identification with CHICO2

Δt of CHICO2 needed for selecting ^{106}Mo from ECR contaminants

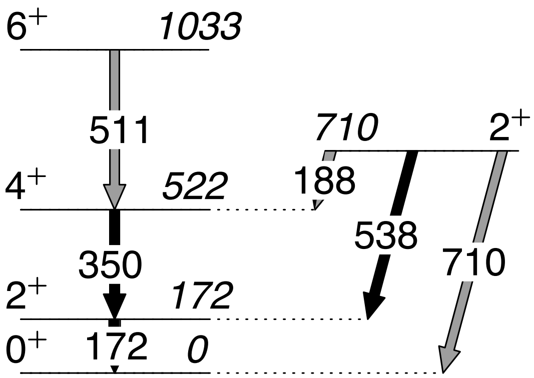


*Cleaner CARIBU RIBS in future with EBIS source

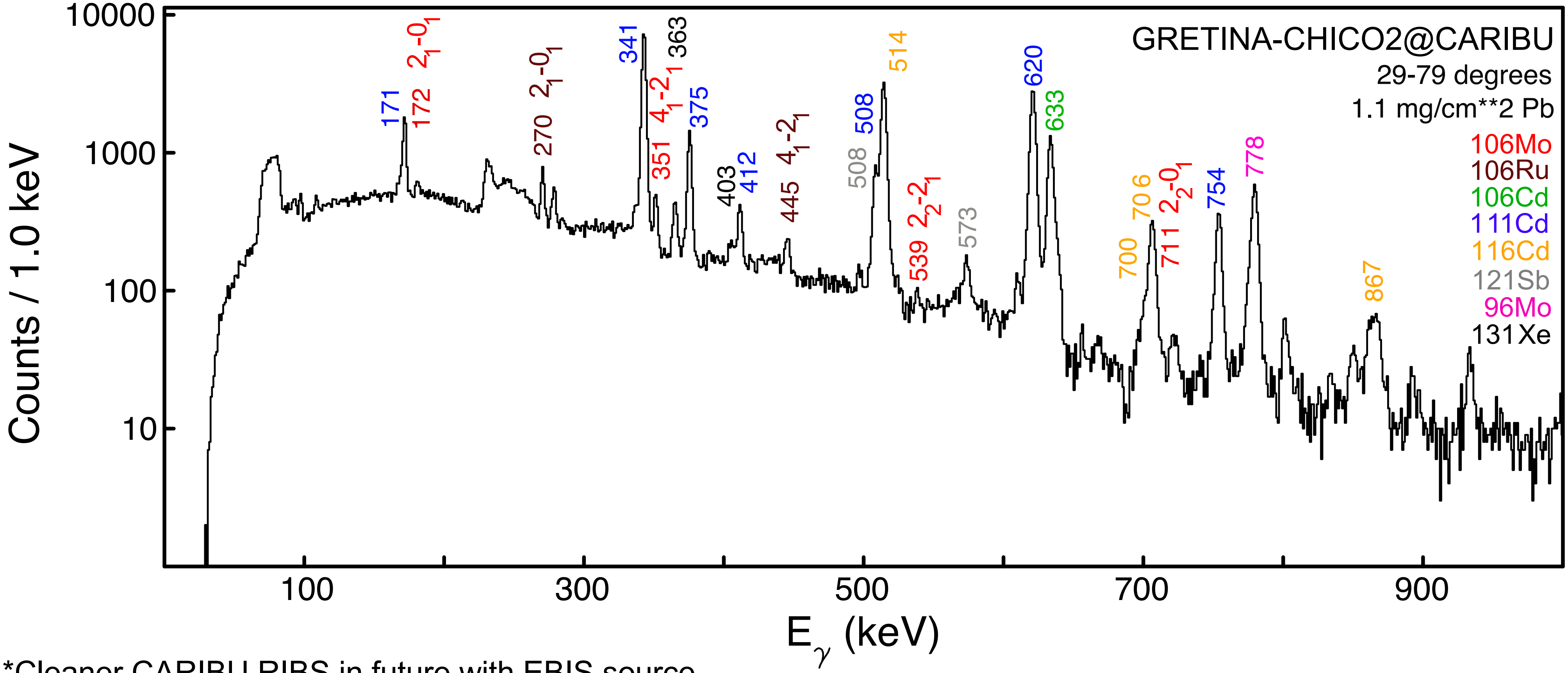
Coulomb Excitation of Exotic ^{106}Mo

Resolution of GRETINA-CHICO2 needed for selecting ^{106}Mo from ECR contaminants

*6_1 decay measured by γ-γ



*2_2 branches measured in β decay of ^{106}Nb.

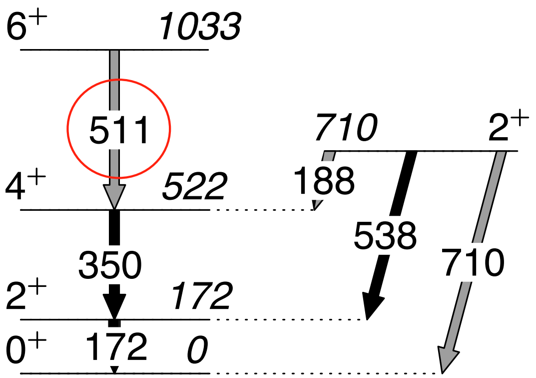


*Cleaner CARIBU RIBS in future with EBIS source

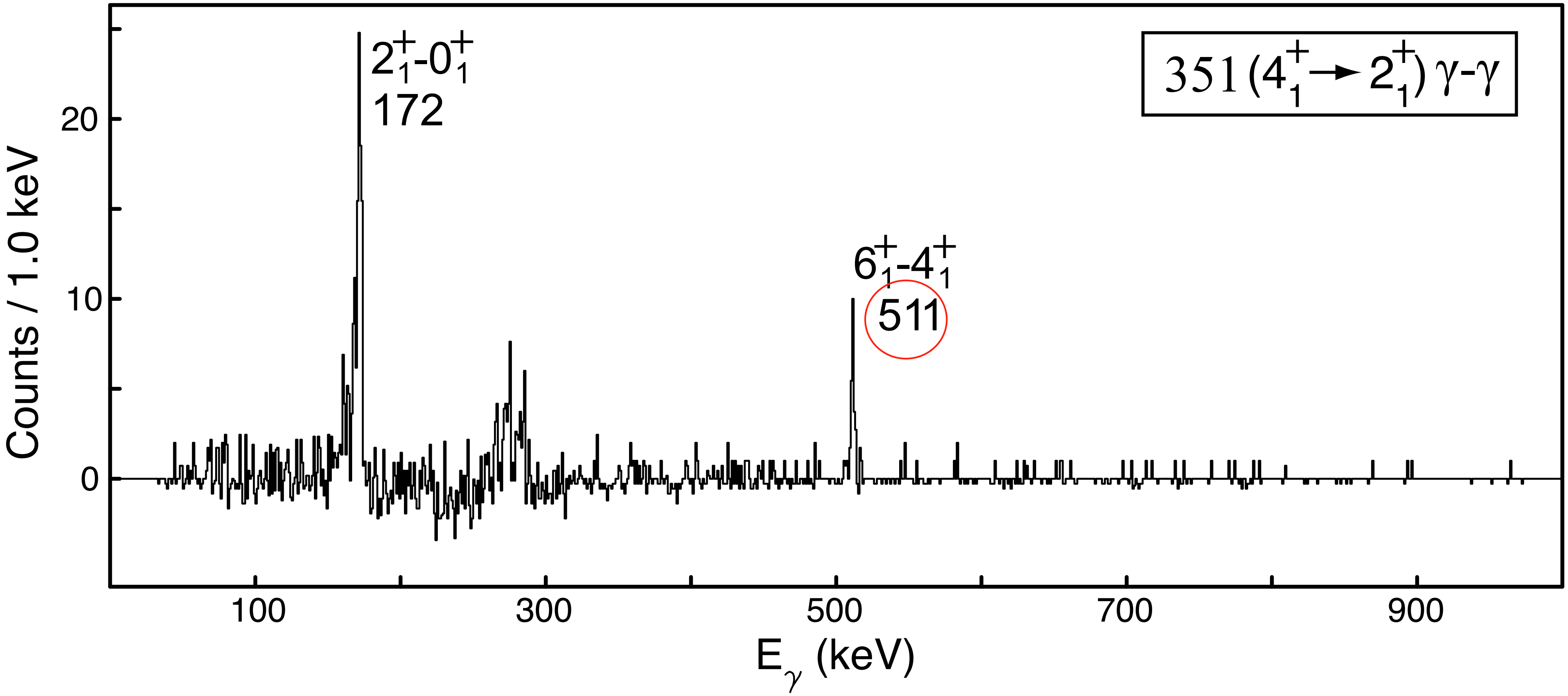
Coulomb Excitation of Exotic ^{106}Mo

Measure 6→4 (511 keV) transition by γ-γ coincidence

*6_1 decay measured by γ-γ

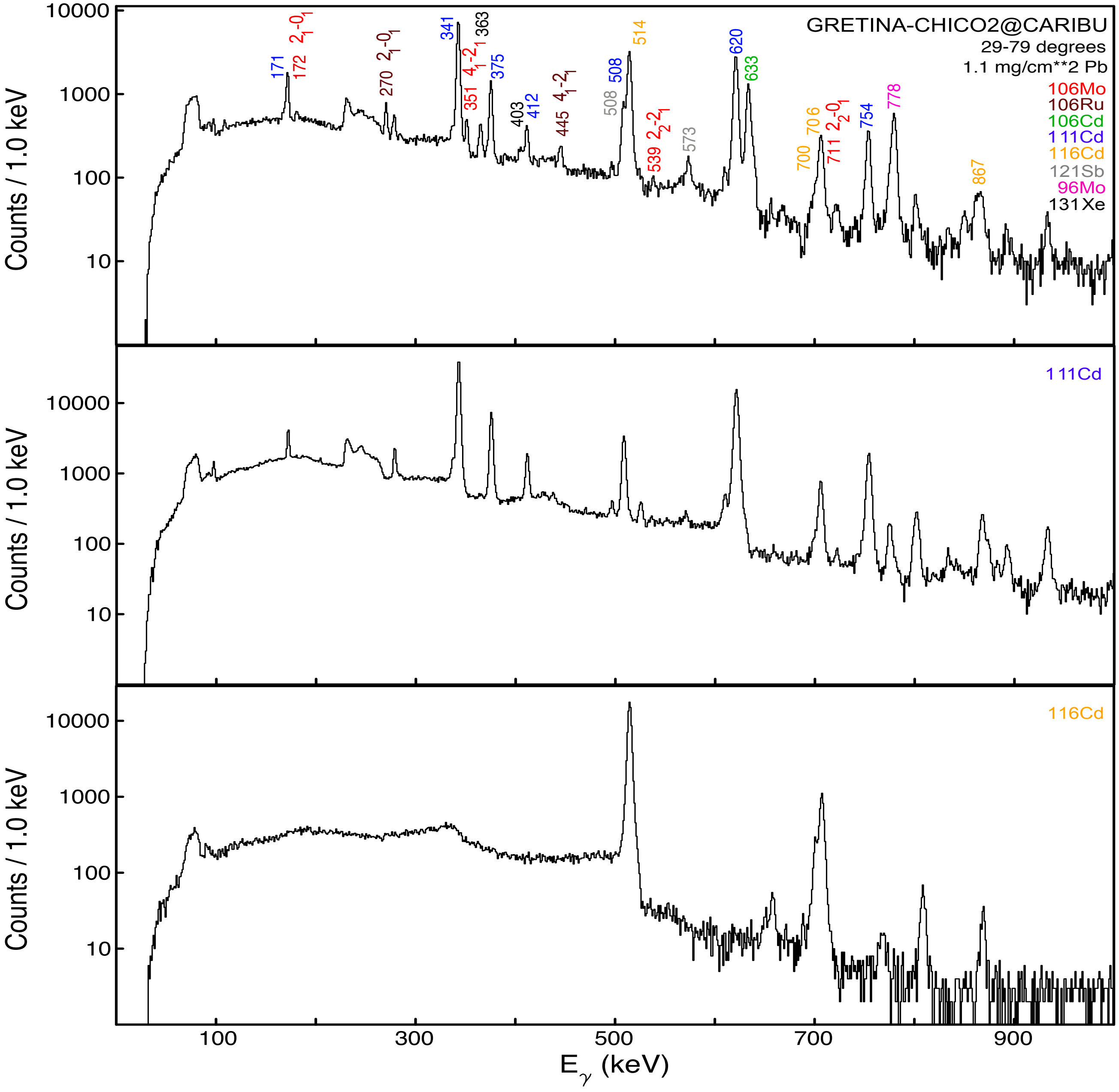


*2_2 branches measured in β decay of ^{106}Nb.



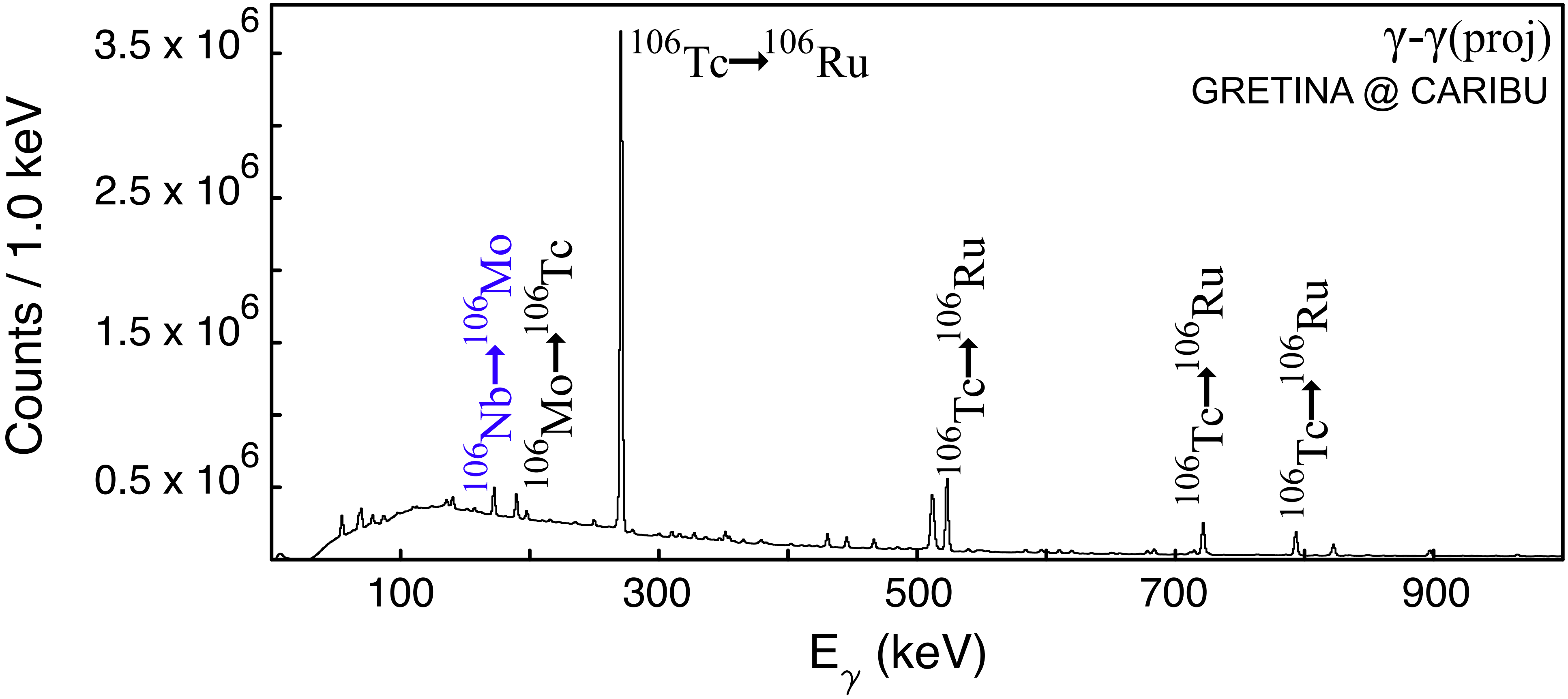
Coulomb Excitation of Exotic ^{106}Mo

Because of ECR contamination, run stable “background” Coulex



Beta Decay of A=106 : γ-γ Projection

^{106}Nb(0.9 s) → ^{106}Mo(8.7 s) → ^{106}Tc(35.6 s) → ^{106}Ru(372 d)

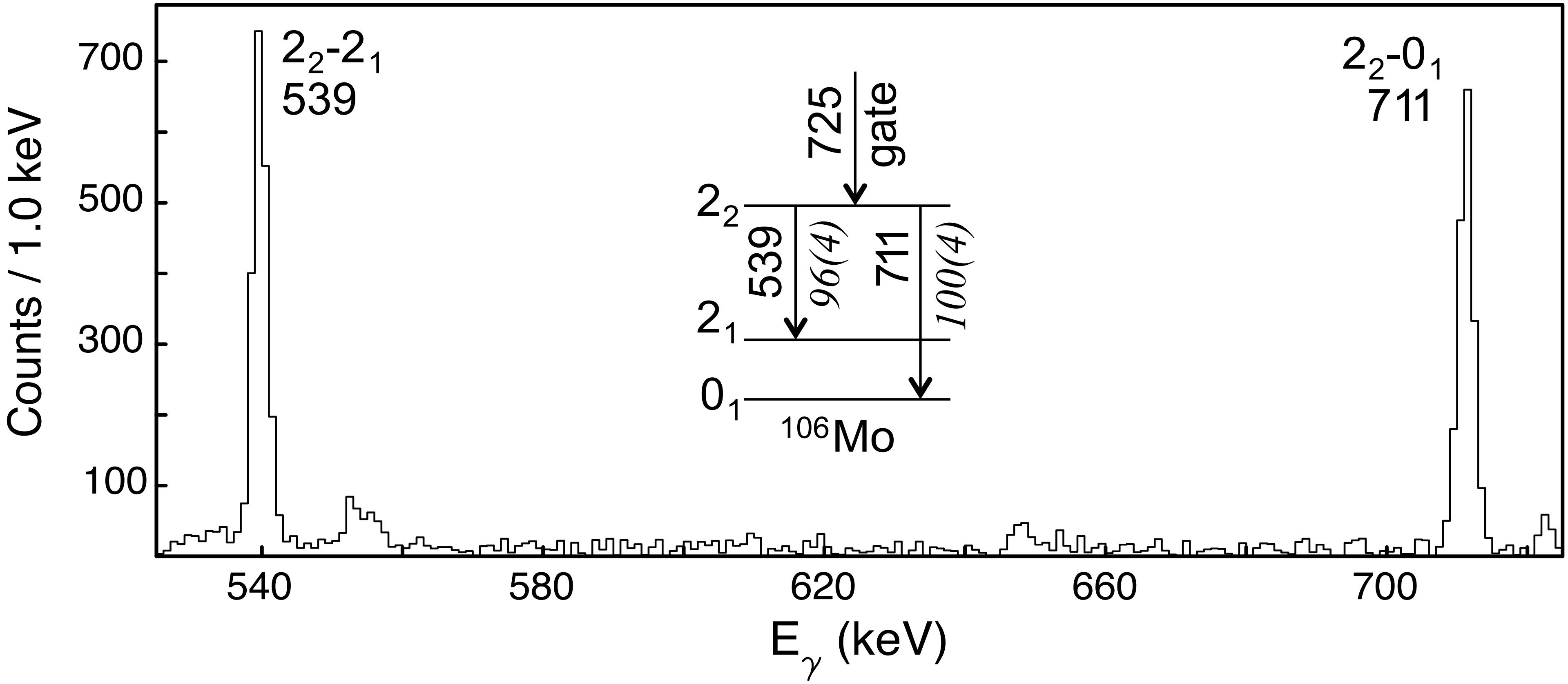


408-MeV beam stopped in thick Au target.

Benefit: ECR-ATLAS removes radioactive molecular contaminants from CARIBU

Beta Decay of ^{106}Nb to ^{106}Mo

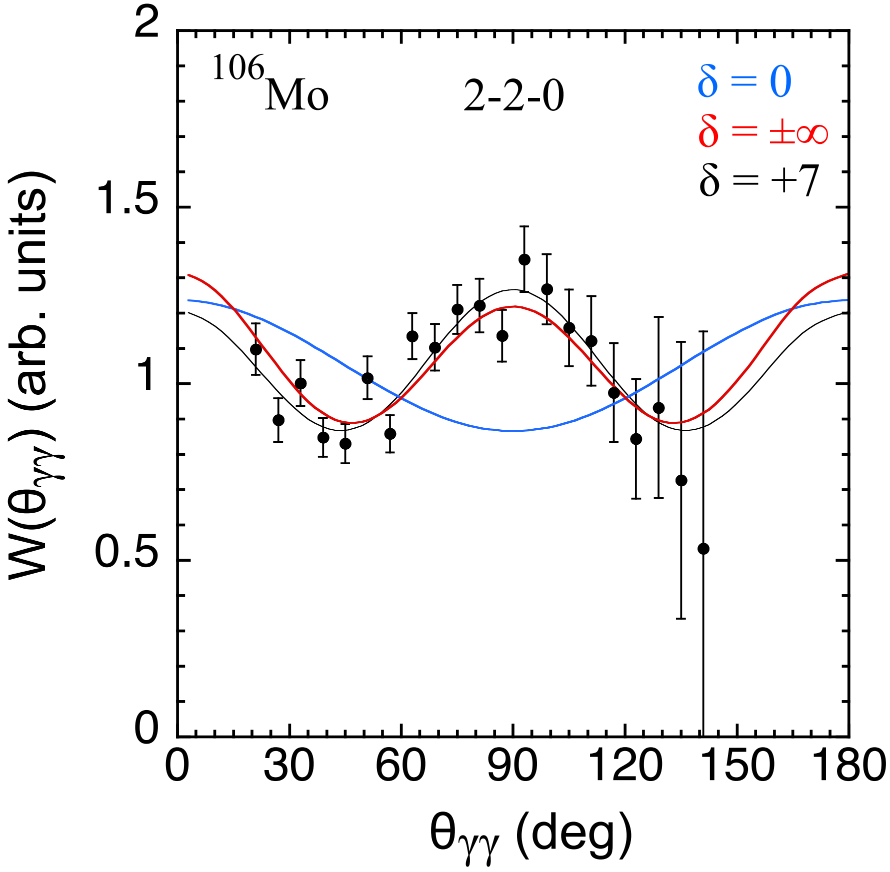
Precise 2_2 branching ratio is critical to defining the electric and inertia asymmetries

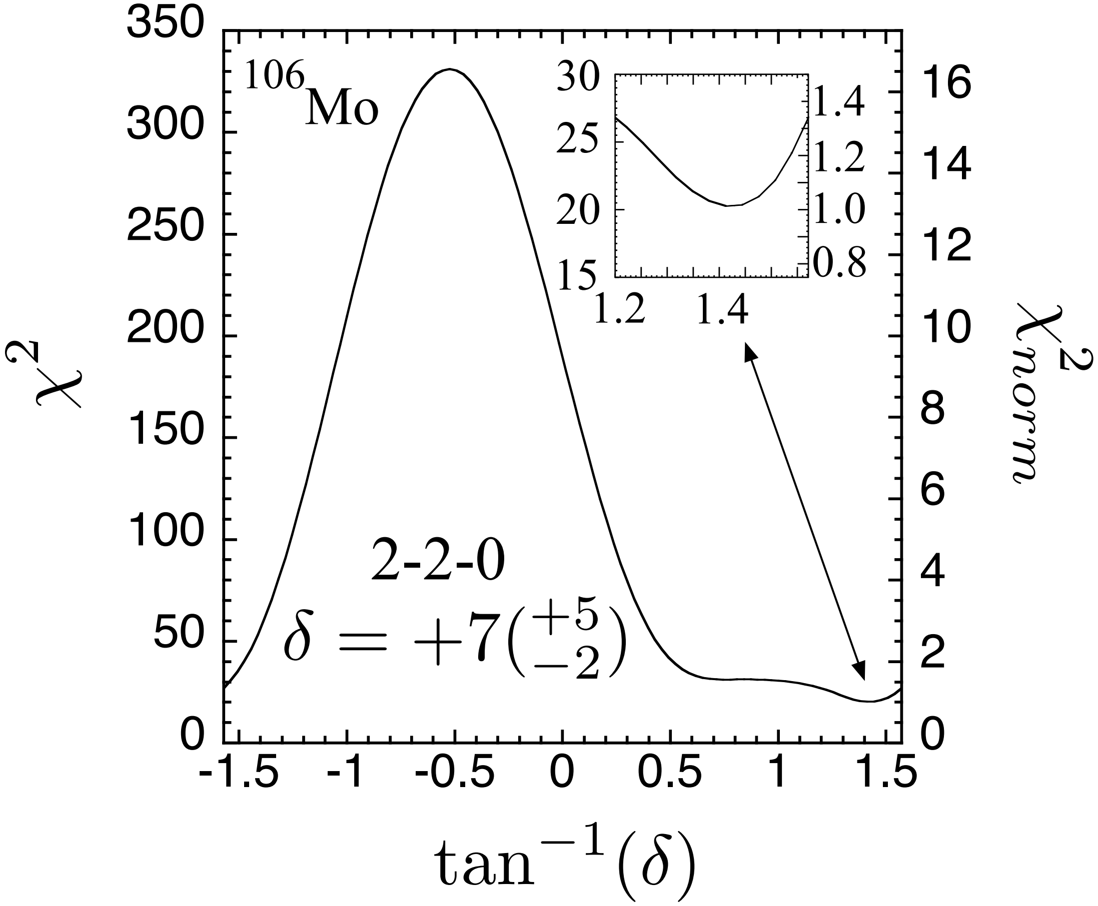


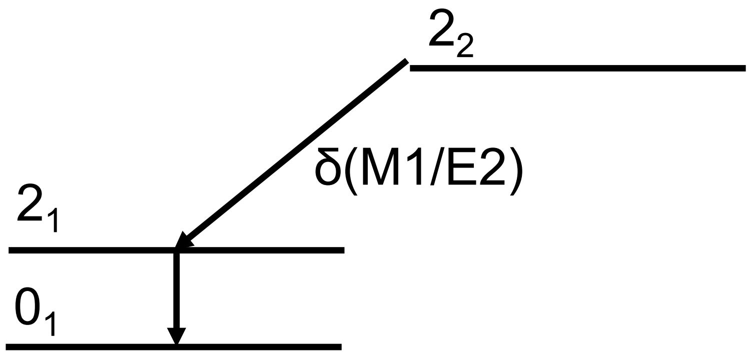
GRETINA@CARIBU	**ENSDF**
$I_\gamma(711) = 100(4)$	$I_\gamma(711) = 73(27)$
$I_\gamma(539) = 96(4)$	$I_\gamma(539) = 100(20)$

^{106}Mo 2-2-0 Angular Correlation

Angular correlation of 2_2-2_1-0_1 cascade can provide M1/E2 of 2_2-2_1







2_2-2_1 transition is 98% E2

^{152}Eu → ^{152}Sm Calibration:

GRETINA: $\delta(2_2\text{-}2_1) = -6(^{+1}_{-2})$

ENSDF: $\delta(2_2\text{-}2_1) = -9.3(6)$

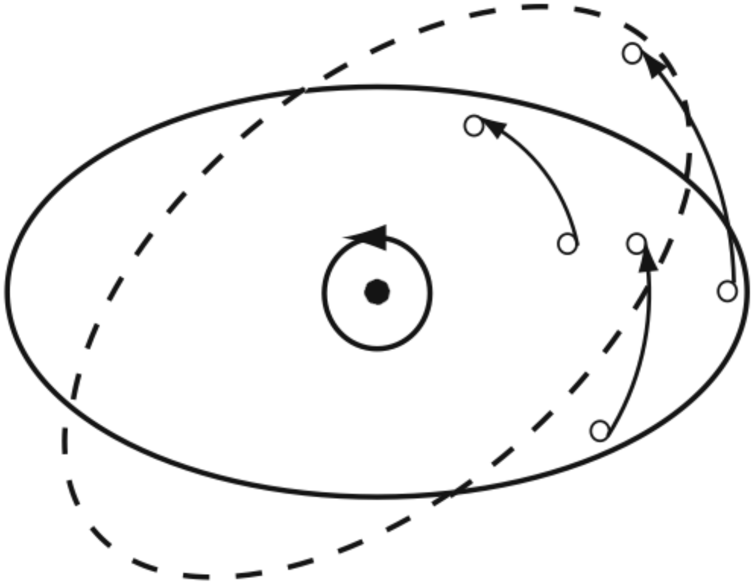
Coulomb Excitation of Exotic ^{106}Mo

Experimental results are consistent with an axially asymmetric (triaxial) shape

Rigid and Irrotational Flow

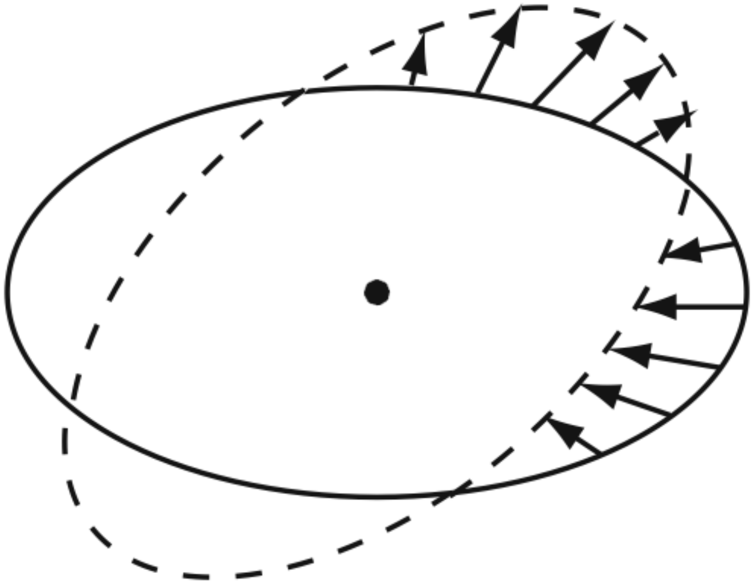
Generates mixing that is too strong; need a better understanding of inertial flow.

Rigid Flow



e.g., like a spinning football

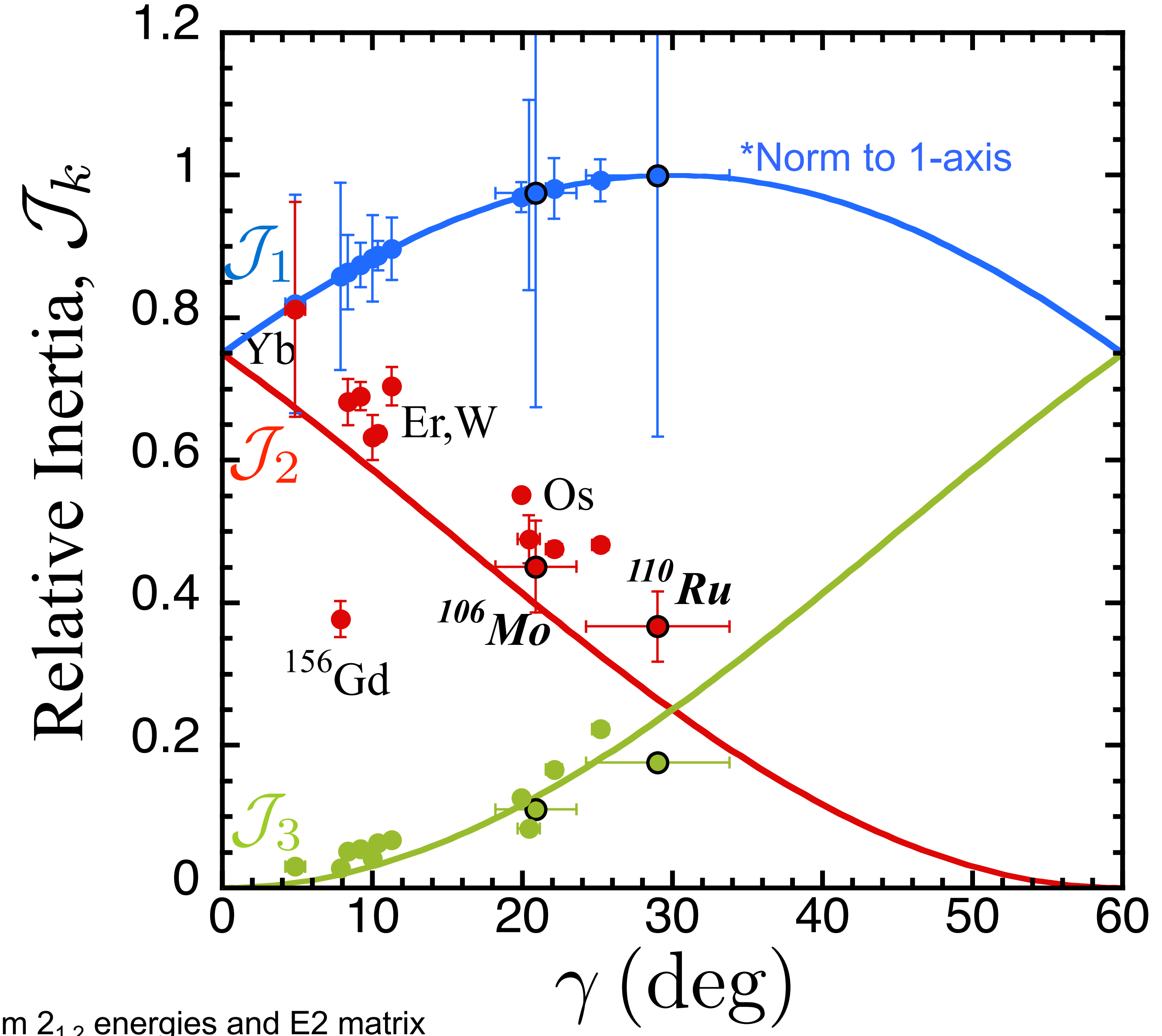
Irrotational Flow



e.g., like a surface wave

Relative Moments of Inertia

^{110}Ru is one of the best candidates for triaxial deformation and ^{106}Mo is similar to Os



*Determined from $2_{1,2}$ energies and E2 matrix elements for cases with E(4)/E(2) > 2.7

Cf., Allmond and Wood, PLB 767, 226 (2017)

Thanks to all of the Collaborators

D. Doherty[2], R.V.F. Janssens[3], W. Korten[2], D.C. Radford[1], S. Zhu[3], A.D. Ayangeakaa[3], S. Bottoni[3], B. Bucher[4], M. Buckner[4], C.M. Campbell[5], M.P. Carpenter[3], H.L. Crawford[5], M. Cromaz[5], H.M. David[3], P. Fallon[5], M. Febbraro[1], A. Galindo-Uribarri[1], C.J. Gross[1], M. Komorowska[6], T. Lauritsen[3], A.O. Macchiavelli[5], P. Napiorkowsi[6], E. Padilla-Rodal[7], S.D. Pain[1], W. Reviol[8], D.G. Sarantites[8], G. Savard[3], D. Seweryniak[3], A.E. Stuchbery[9], R.L. Varner[1], J.L. Wood[10], C.Y. Wu[4], C.-H. Yu[1], M. Zielinska[2]

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