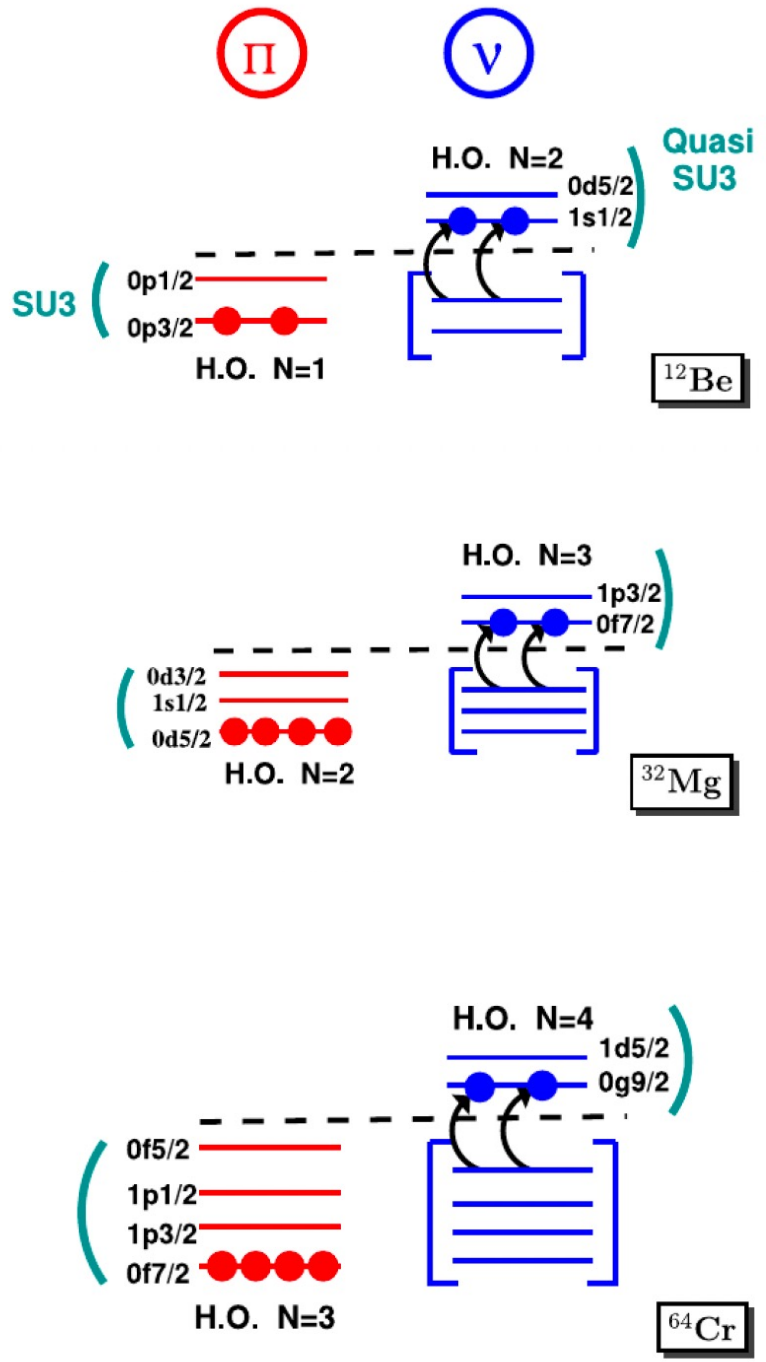
# Shape changes, quadrupole collectivity and configuration inversions along N = Z

Francesco Recchia, Jeongsu Ha
University and INFN Padova
and the e19034 Collaboration

# Development of deformation at N=8,20,40

- **Magic numbers - energy gaps** in the spherical mean field To promote particles above the Fermi levels costs energy
- Some **intruders configurations** can overwhelm their loss of monopole energy with their **huge gain in correlation energy**
- Several examples of this phenomenon exist in stable magic nuclei (as in $^{40}Ca$ nucleus) in the form of **coexisting spherical, deformed and superdeformed** states in a very narrow energy range
- In exotic nuclei the effective nuclear interaction weight very differently proton and neutron interaction than they do at the stability line. Therefore leading in some cases to **the vanishing of established shell closures or to theappearance of new ones**



# Physics Motivation

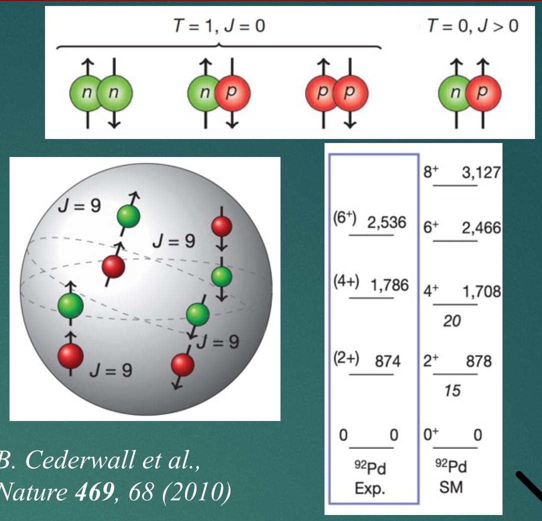


- N = Z nuclei play a special role
  - **(np) collectivity** by the proton-neutron interaction
  - **spatial overlap** of their respective wave functions at the Fermi surface
  - proton and neutrons act coherently.
- Competing **isoscalar np pairing** and normal isovector (T = 1, I = 0) pairing modes
  - a nuclear superfluid **analogous to "Cooper Pairs"** may exists in nuclei
  - Isoscalar predicted prominent in the ground states of heavier (A > 76) N = Z nuclei
  - Difficult to find a smoking gun signature
  - shell-model predict that **isoscalar pairing enhances collectivity → measurements of B(E2)**

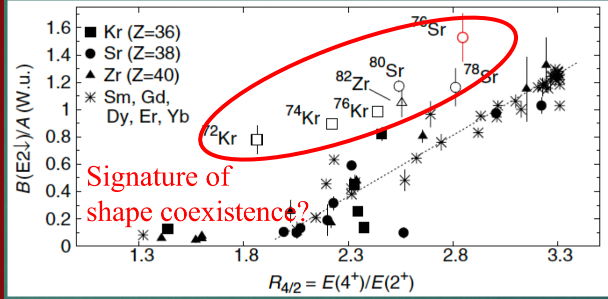
# Physics Motivation

- The self-conjugate $N = Z$ nuclei
  - Proton-neutron correlations: role of np-pairing, …
  - Schematic way to understand the phenomena: Nilsson SU3 scheme, …

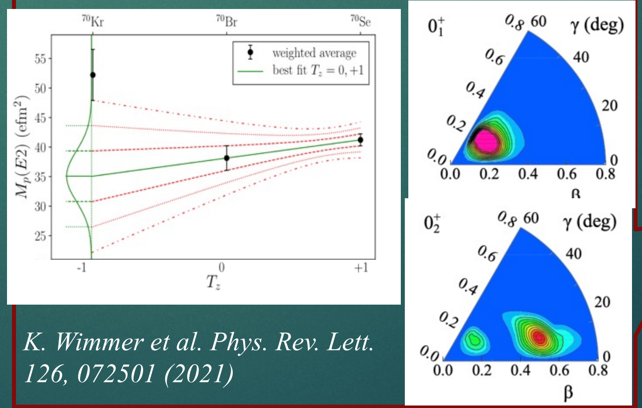
- A significant shape change has been anticipated among the medium-mass nuclides
  → **Competition between shapes is expected**



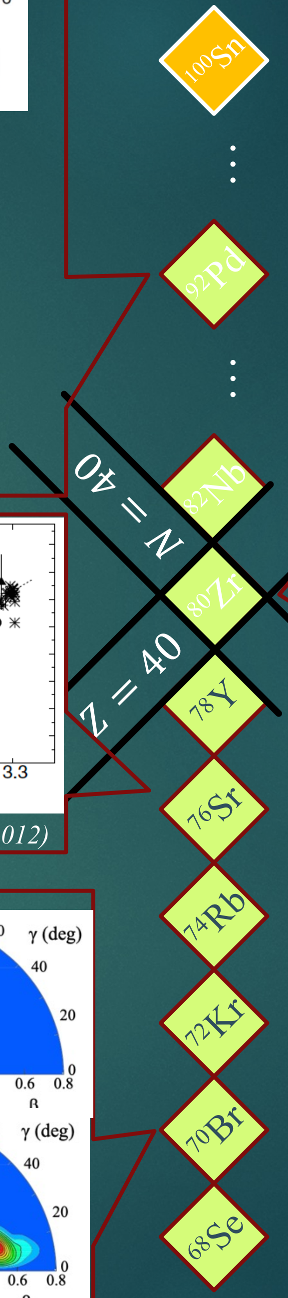
*B. Cederwall et al., Nature **469**, 68 (2010)*



*A. Lemasson et al., Phys. Rev. C 85, 041303(R)(2012)*

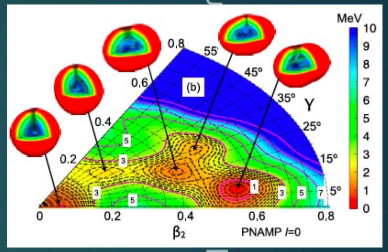


*K. Wimmer et al. Phys. Rev. Lett. 126, 072501 (2021)*




Multiple shape coexistence?

*T. R. Rodríguez and J. L. Egido, Phys. Lett. B **705**, 255 (2011)*

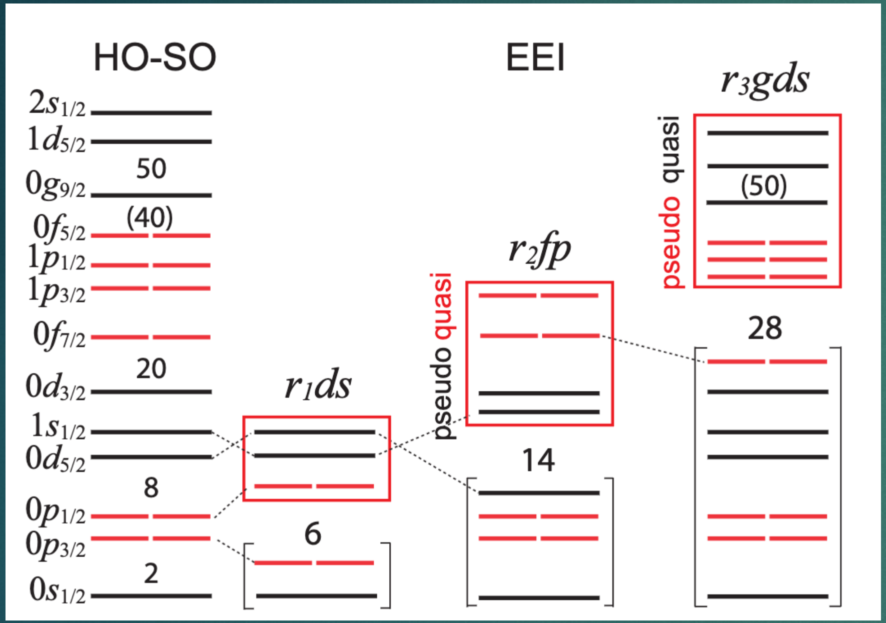



Maximum (prolate) deformation

Prolate-oblate shape coexistence

Oblate collectivity

# Physics Motivation

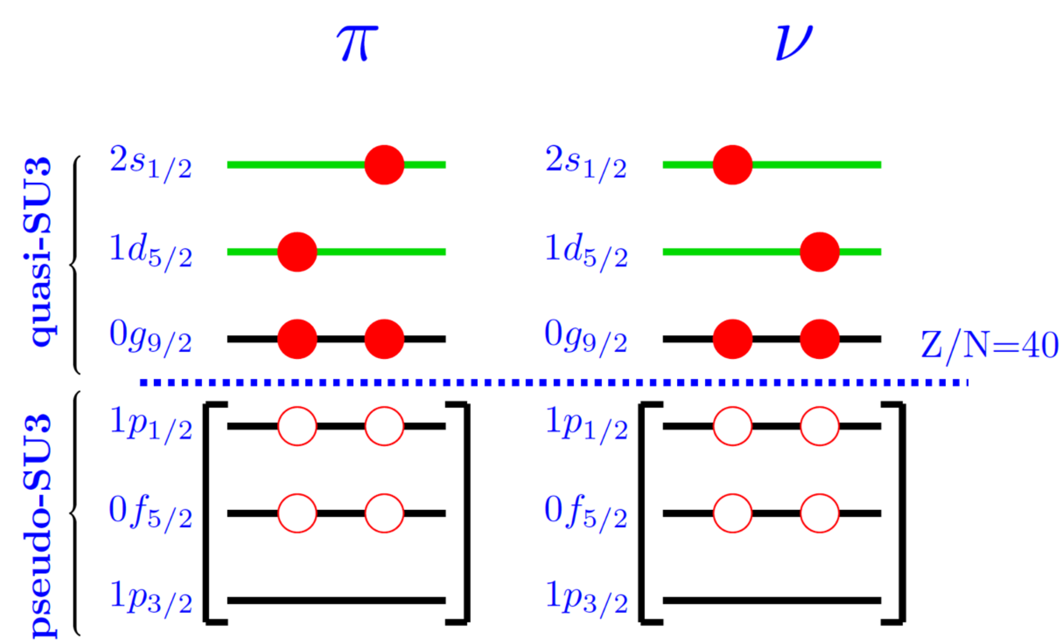



"quadrupole degrees of freedom as the **backbone of nuclear structure**, which in shell-model language translates as dominance of the quadrupole force"

PHYSICAL REVIEW C **92**, 024320 (2015)

**Nilsson-SU3 self-consistency in heavy $N = Z$ nuclei**

A. P. Zuker,[1] A. Poves,[2,3] F. Nowacki,[1] and S. M. Lenzi[4]



# Along N=Z at the NSCL facility

- $^{72}$Kr
  - **First GRETINA campaign 2013-14**
  - **H. Iwasaki et al. Phys. Rev. Lett. 112, 142502 (2014)**
- $^{74}$Rb: A. Lemasson
- $^{76}$Sr
  - **Last SEGA campign ~2010**
  - **A. Lemasson Phys Rev C 85, 0041303(R) (2012)**
- $^{78}$Y: R. D. O. Llewellyn
- $^{80}$Zr
  - **Last GRETINA campaign at NSCL 2019-20**
  - **R. D. O. Llewellyn et al. Phys. Rev. Lett. 124, 152501 (2020)**

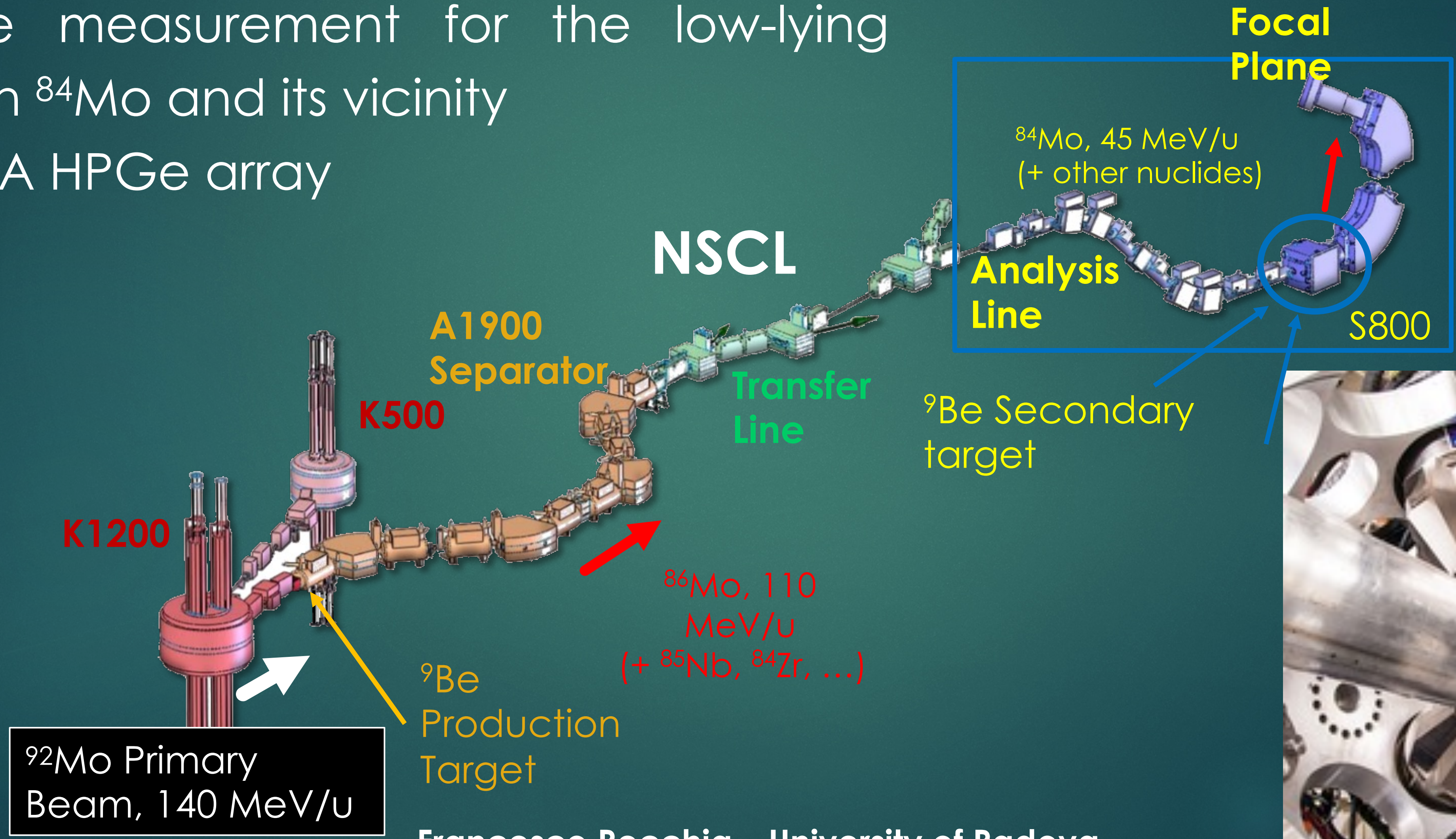
# Experiment at NSCL, Michigan



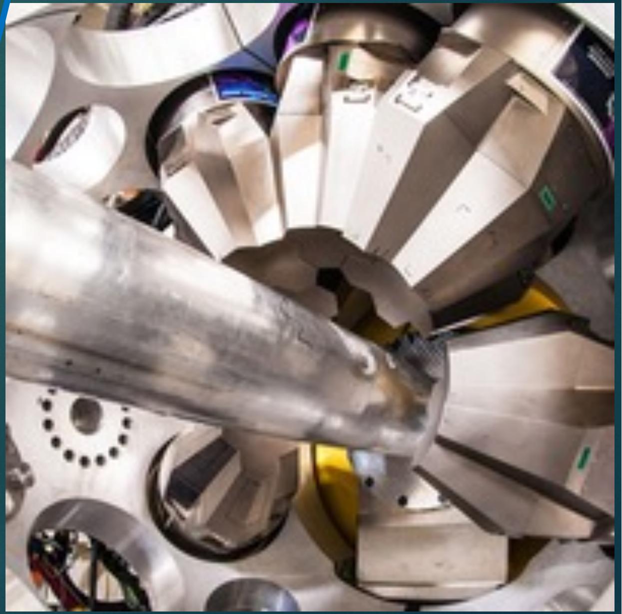
Performed in July 2020

Lifetime measurement for the low-lying states in $^{84}$Mo and its vicinity

GRETINA HPGe array

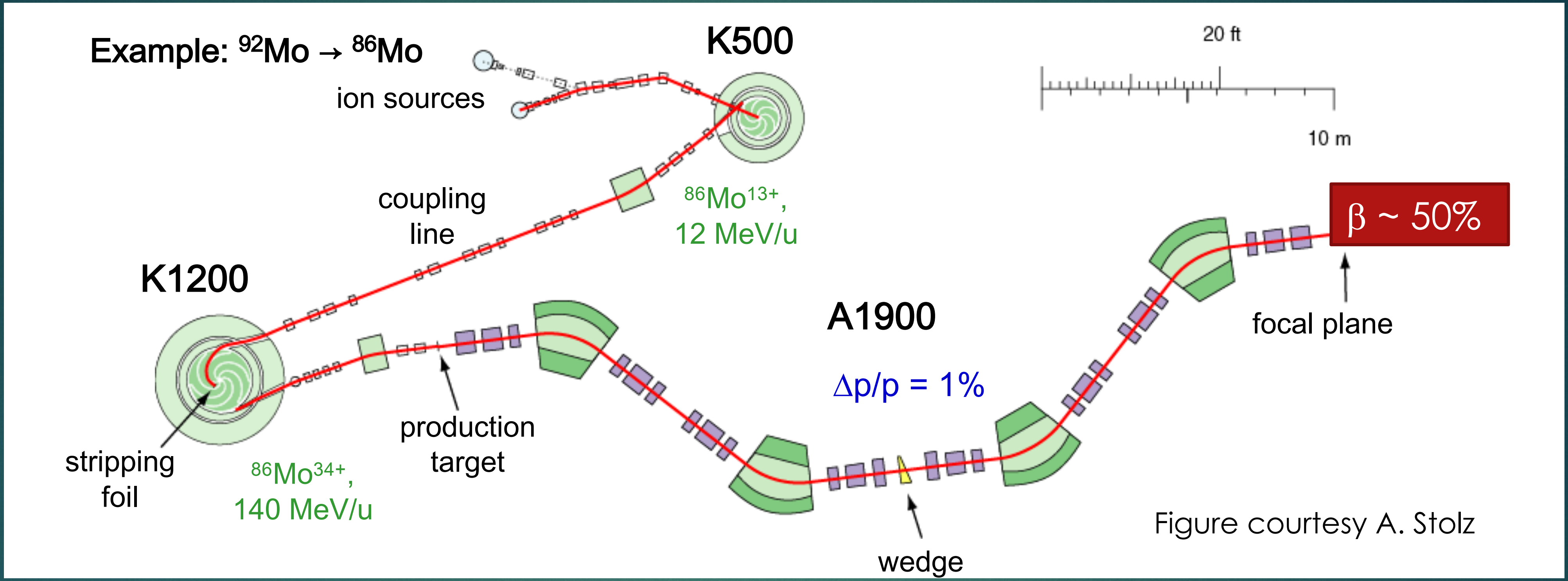



GRETINA

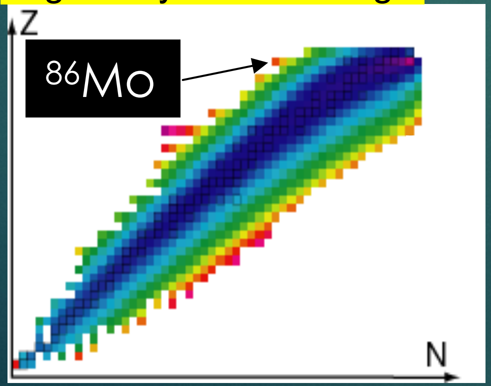


# Secondary beams: fragmentation



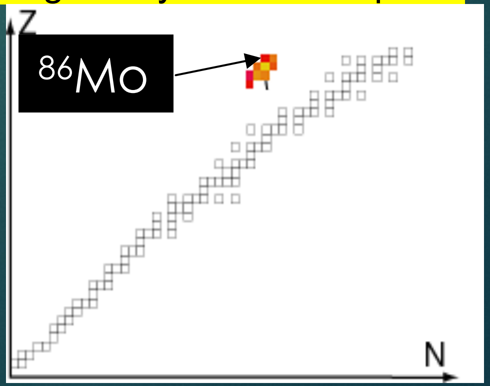



fragment yield after target




- Identification event-by-event
  - B – Rho
  - TOF

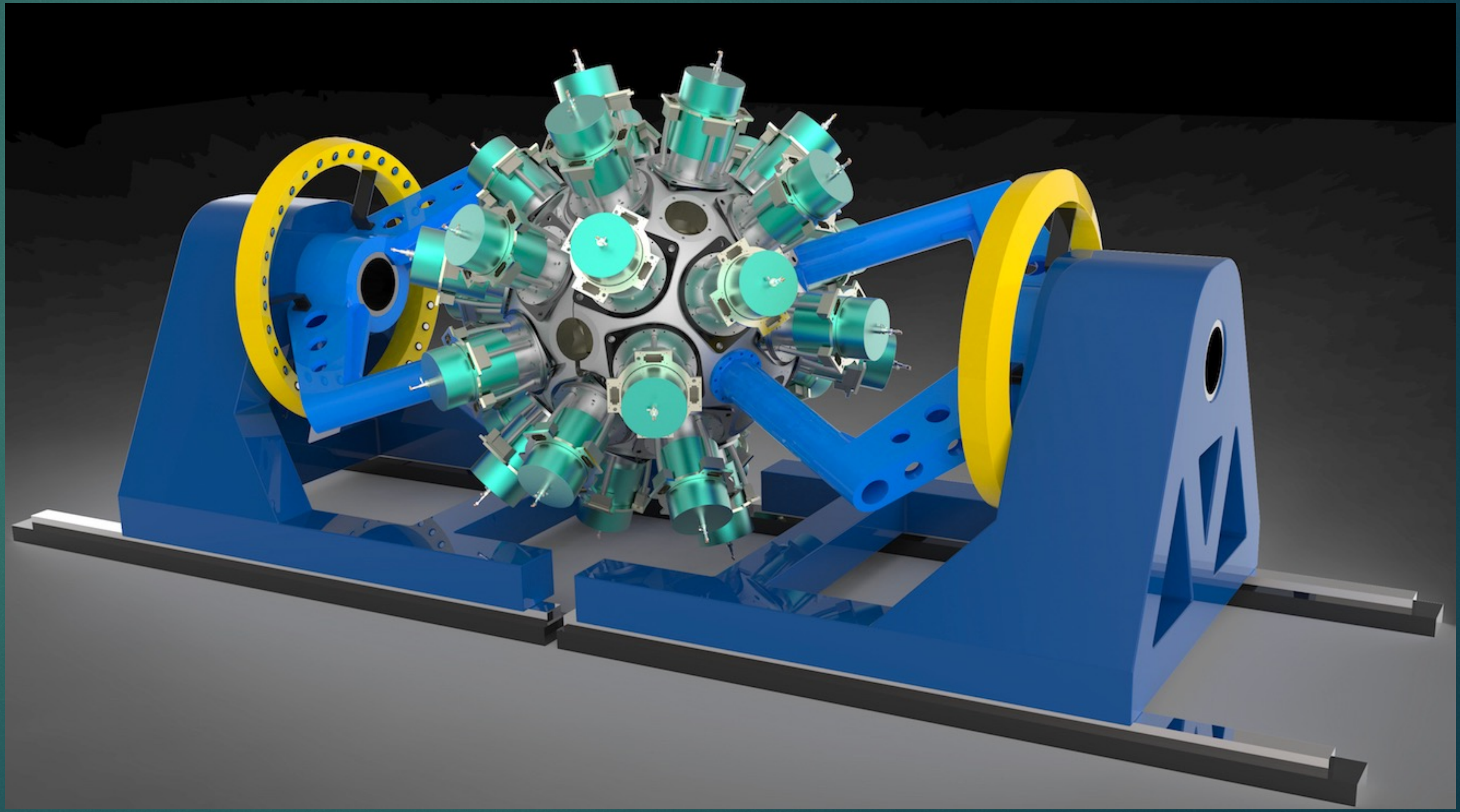
fragment yield at focal plane



# Gamma Ray Energy Tracking Array



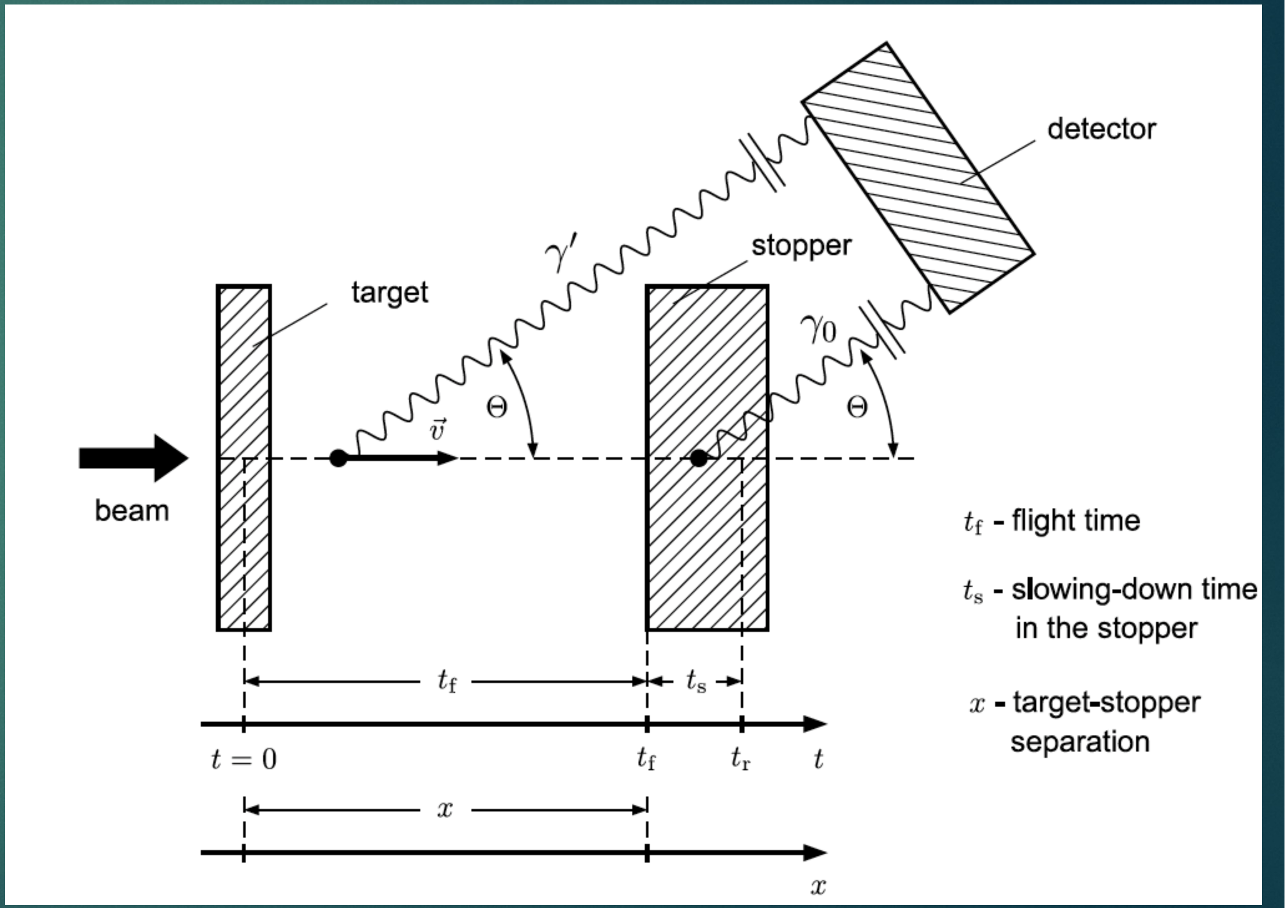
- ***GRETA***: *4 $\pi$ array of 120 HPGe detectors with 36 segments each (USA)*
- ***AGATA***: *Advanced GAmma Tracking Array in Europe*

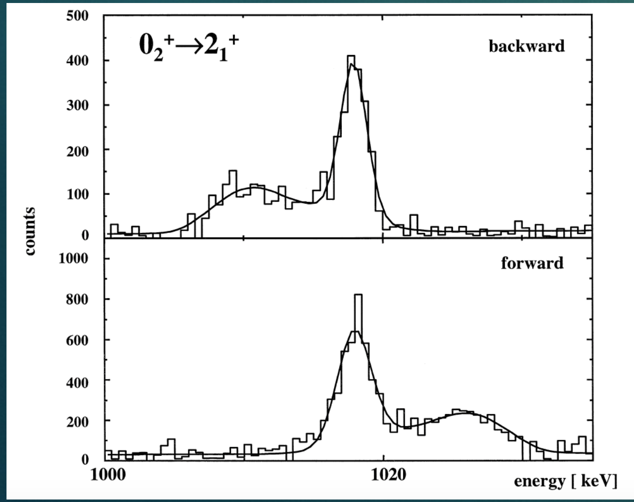


# In-beam lifetime measurements



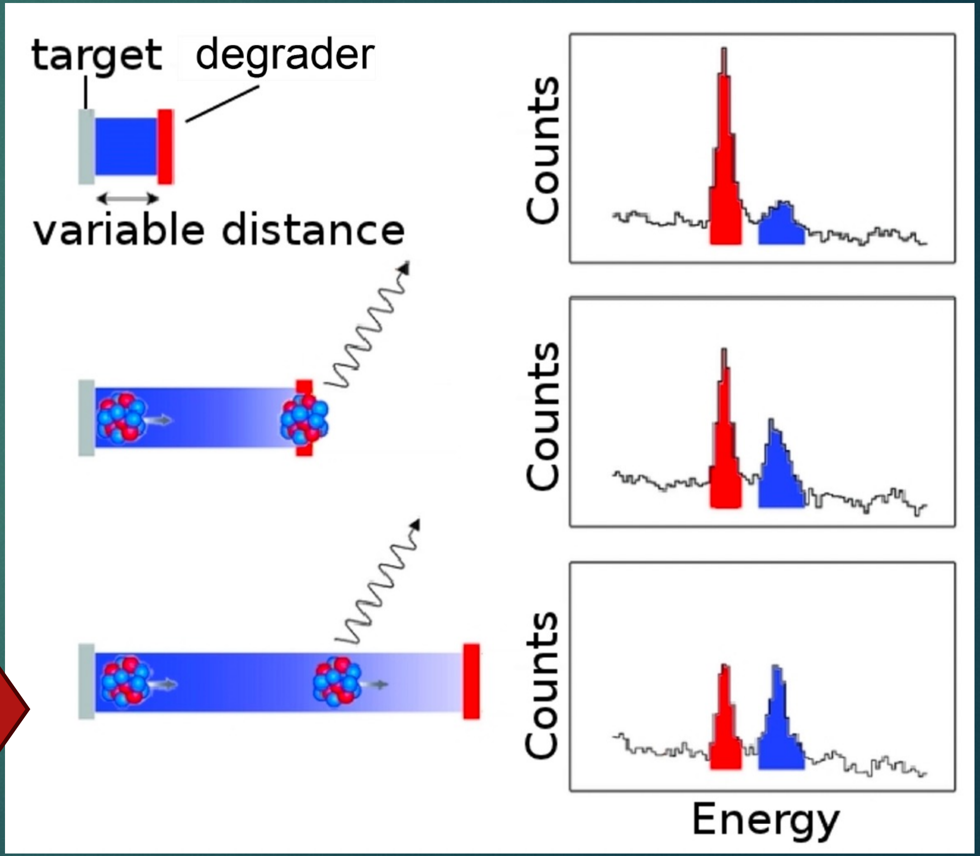
- excited states produced in the target decay in flight
- **measure distance instead of time**
- place a stopper a certain distance after the target
- two components to the spectrum: shifted (in-flight) and stopped



# In-beam lifetime measurements .. with radioactive beams

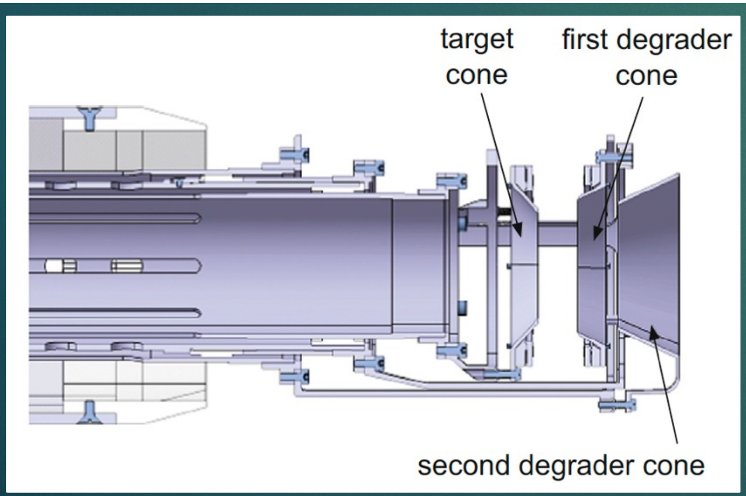
- the beam **intensity is low**, beam time is scarce
- use a **degrader instead of a stopper**→ residual nucleus can be identified event by event
- two different emission velocities, **two peaks** in spectrum
- Variations over distances to adapt to the lifetime(s) of interest

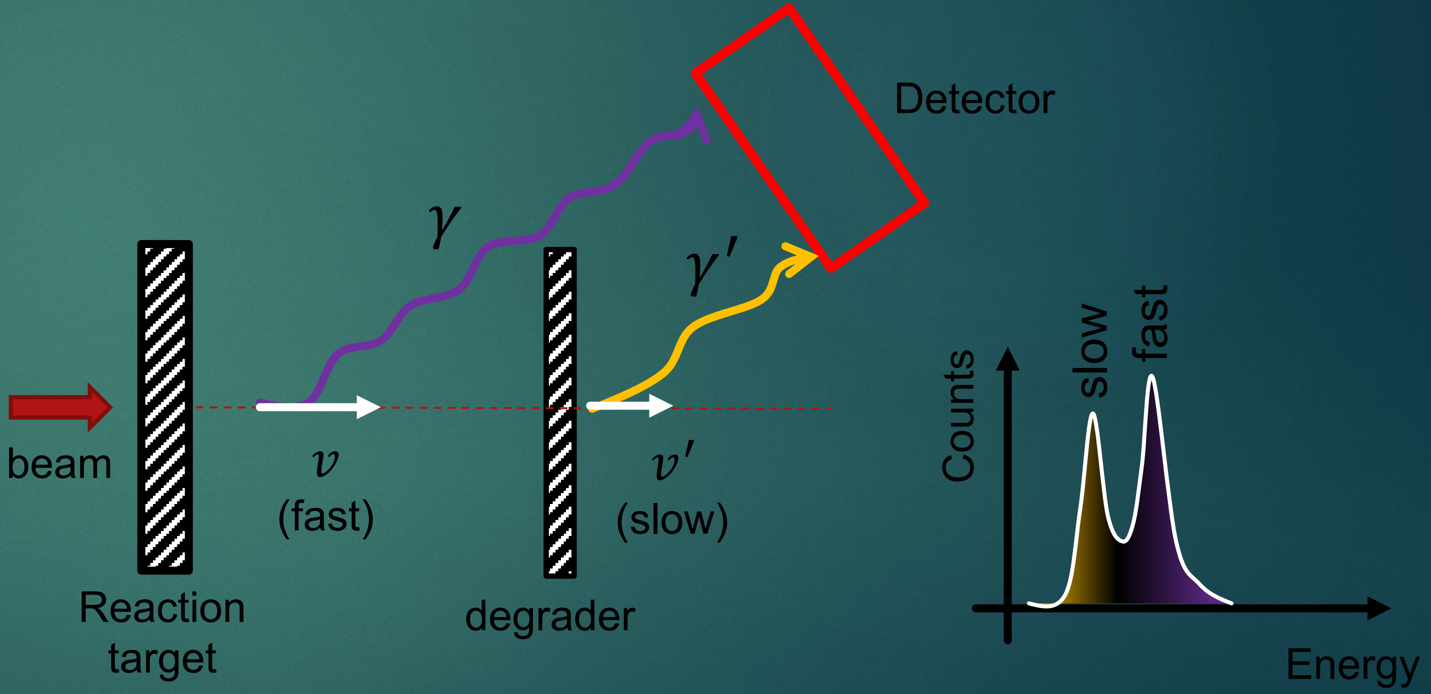


# The experiment at NSCL



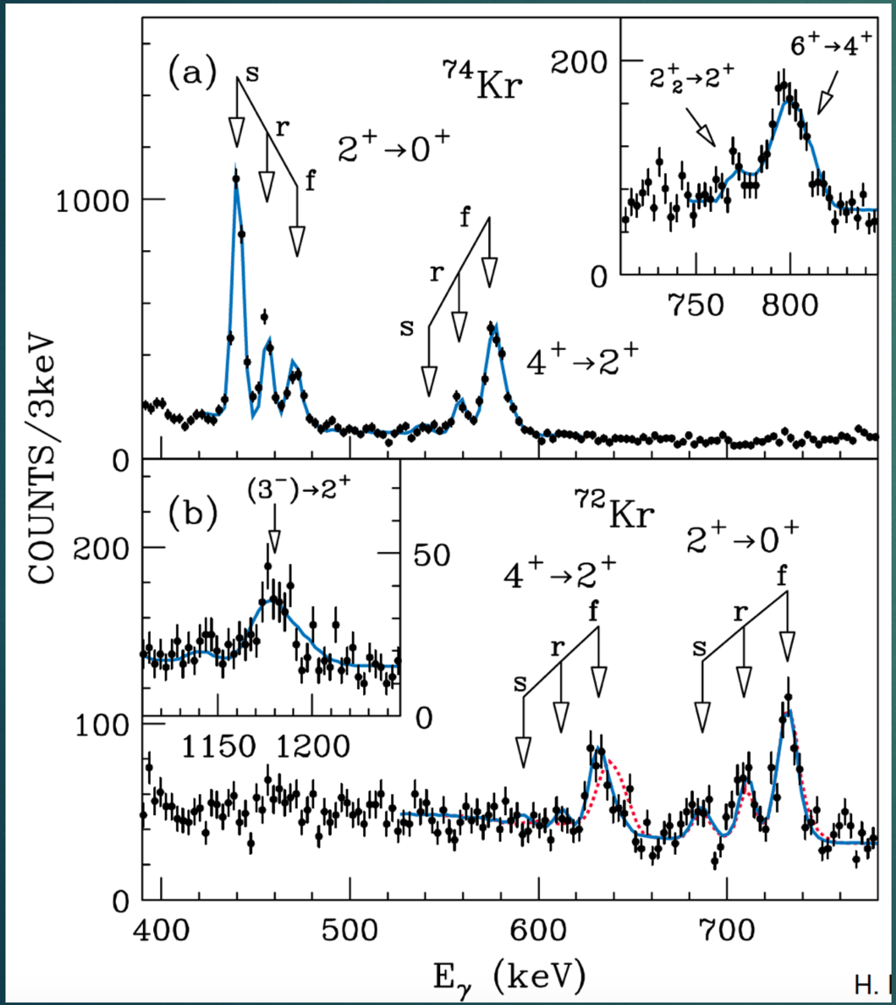
- **GRETINA** was coupled to the plunger TRIple PLunger for EXotic beams (TRIPLEX)
- With a secondary target, the **TRIPLEX plunger** can hold up to two degrader foils which facilitate to extract the lifetime from a single measurement

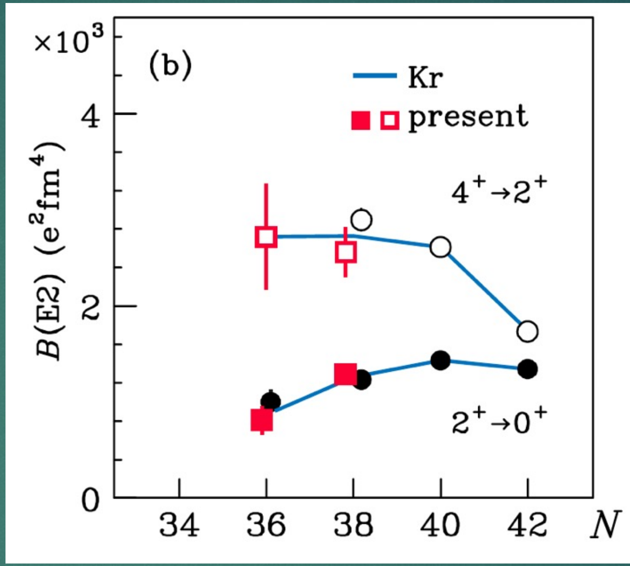


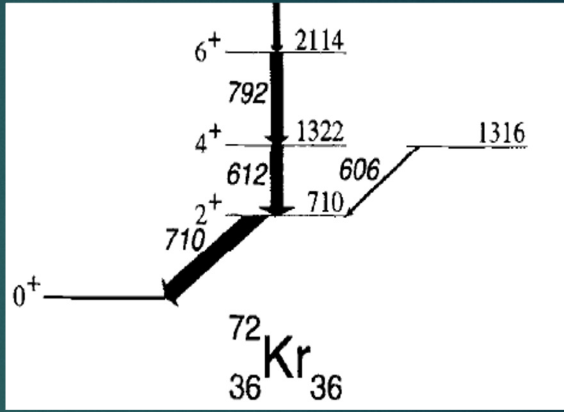




*H. Iwasaki et al., Nuclear Inst. and Methods in Physics Research A* ***806****, 123 (2016)*

# Lifetimes in $^{72}$Kr : competition of deformations



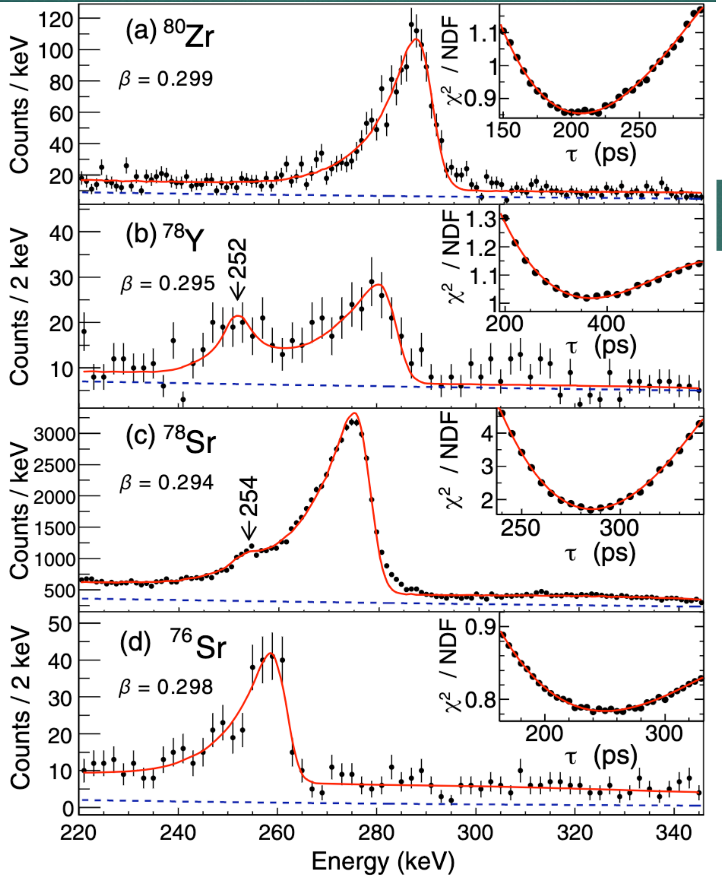



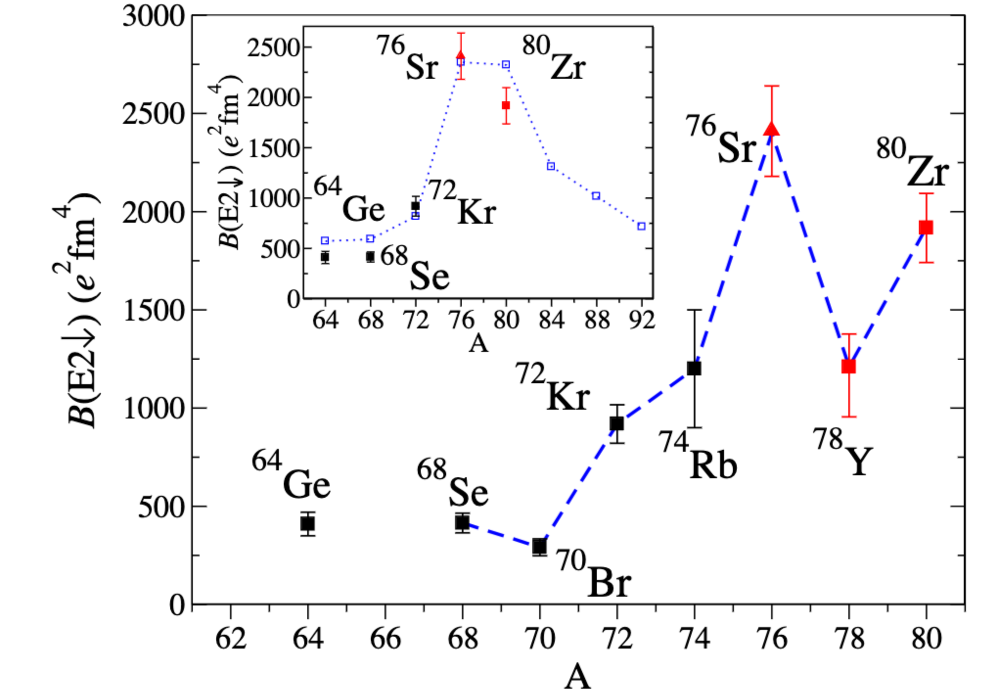

- short lifetime of $4^+$ state in $^{72}$Kr
  - large B(E2; $4^+ \rightarrow 2^+$)
- **shape transition next to the g.s.**
  - oblate ground state,
  - prolate for higher spins as suggested by LNL experiment that measured level spacing in 1997

# Lifetimes extracted from lineshapes for $^{80}$Zr and $^{78}$Y

| | $E(2^+)$ | $\tau$ | $\tau_{prev,1}$ | $\tau_{prev,2}$ | $\tau_{avg}$ | $B(E2\downarrow)$ |
|---|---|---|---|---|---|---|
| $^{80}$Zr | 290.4(4) | 207(19) | | | | 1910(180) |
| $^{78}$Y | 283.6(8) | $369^{+77}_{-54}$ | | | | $1200^{+180}_{-250}$ |
| $^{78}$Sr | 278.1(3) | 286(20) | 276(39)[a] | 224(27)[b] | 266(15) | 1840(100) |
| $^{76}$Sr | 261.6(5) | 250(44) | 296(36)[a] | | 278(28) | 2390(240) |

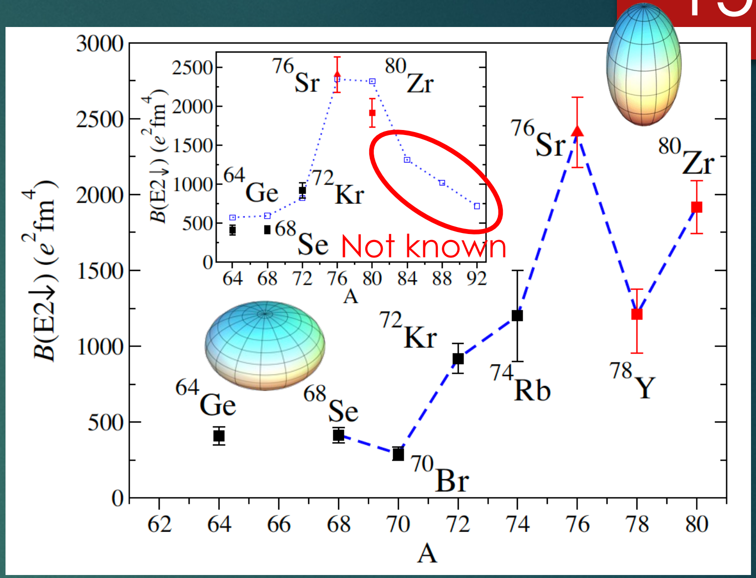
- **Very large quadrupole deformation**
  - **Maximum along N=Z**



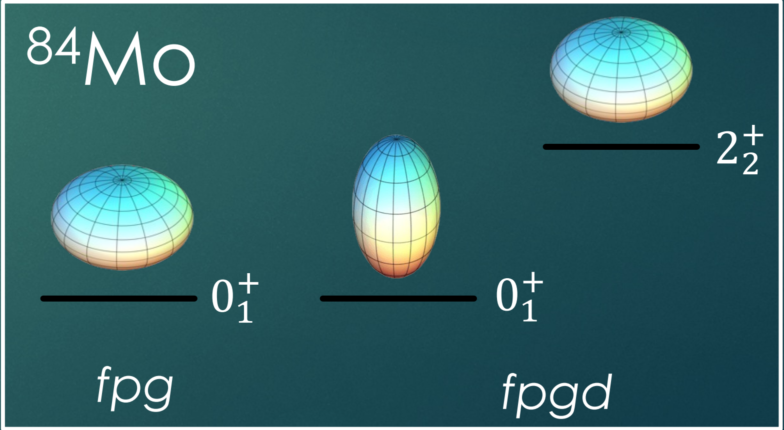



# Physics Motivation

- Along $N = Z$: shape change **from oblate** ($^{64}$Ge, $^{68}$Se) **to prolate** around $^{72}$Kr
- Large deformation continues up to $^{80}$Zr
- Then prolate or oblate??
- Shell model predictions for $^{84}$Mo:
  - with ***fpg* model space (JUN45)**: oblate, $\tau(2_1^+) = 75$ ps
  - with ***fpgd* model space (LNPS)**: prolate , $\tau(2_1^+) = 43$ ps




*R. D. O. Llewellyn et al., Phys. Rev. Lett.* ***124****, 152501 (2020)*



# Objectives



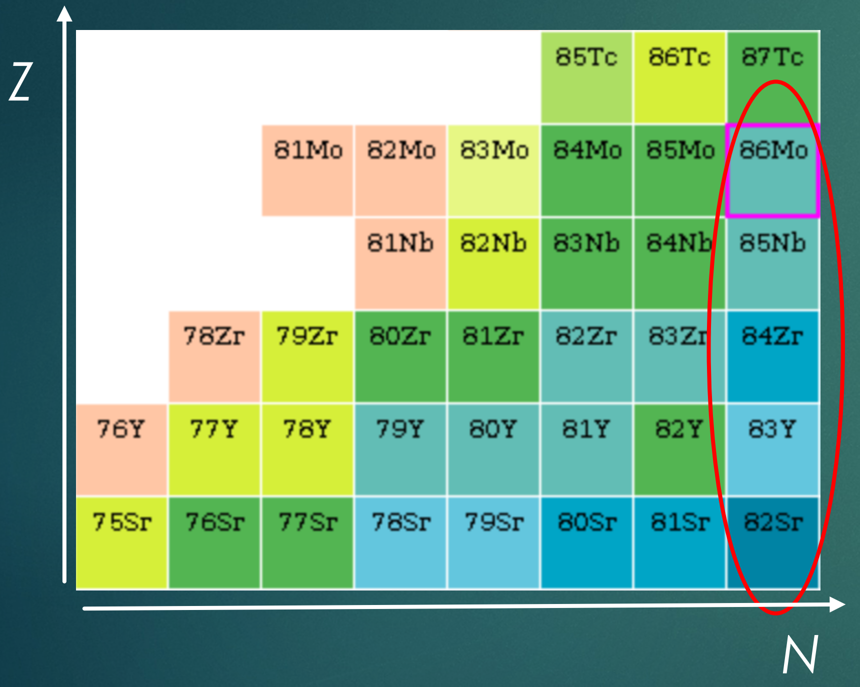
- Measurement of the lifetime of the first **2$^+$ state in $^{84}$Mo** populated by two-neutron knockout from $^{86}$Mo.
- Measurement of the lifetime of the first **2$^+$ state in $^{86}$Mo** using inelastic scattering: $^{86}$Mo($^{9}$Be, $^{9}$Be)$^{86}$Mo$^*$

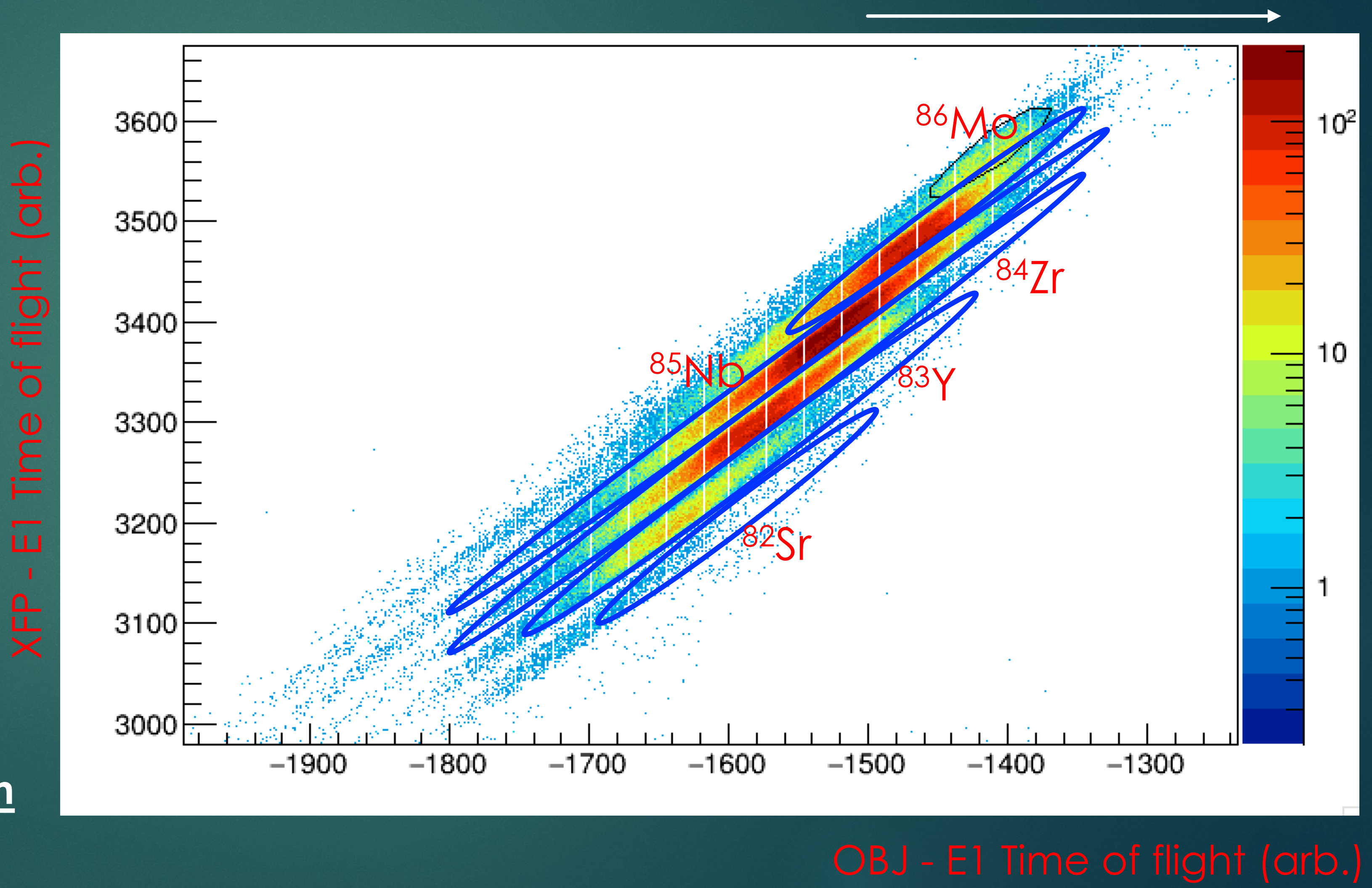
- Understanding the collectivity, shape, of $^{86}$Mo and $^{84}$Mo by comparing to the shell model calculation

# Incoming PID



[Selection of the incoming beam]

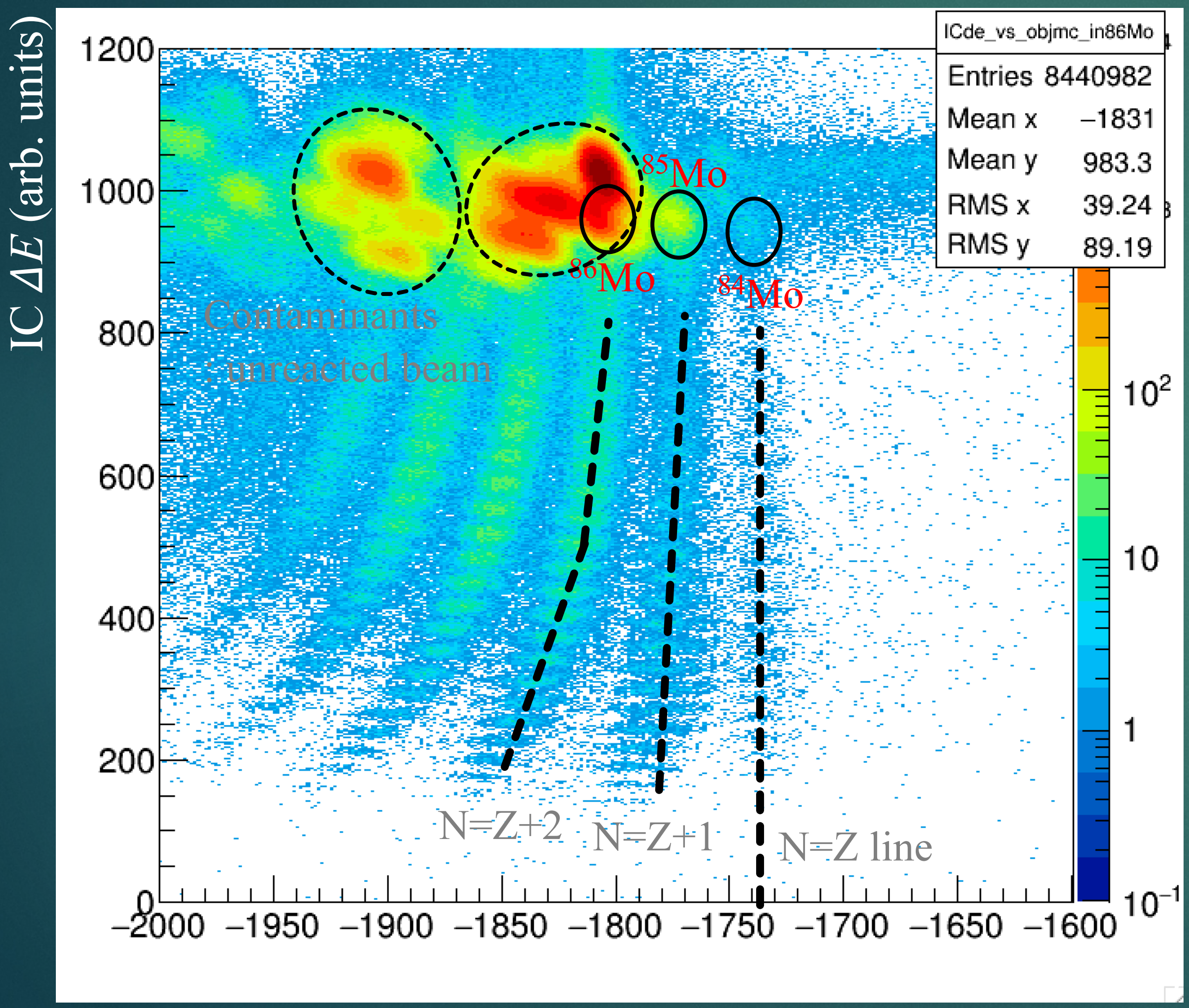


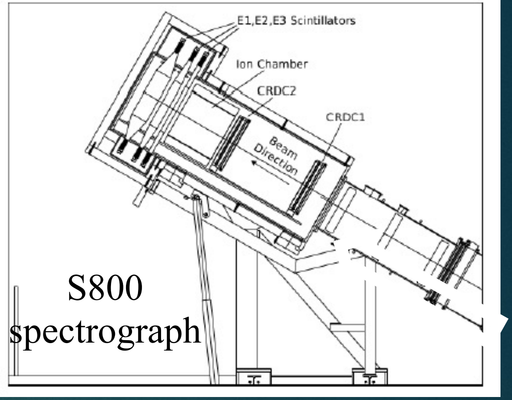



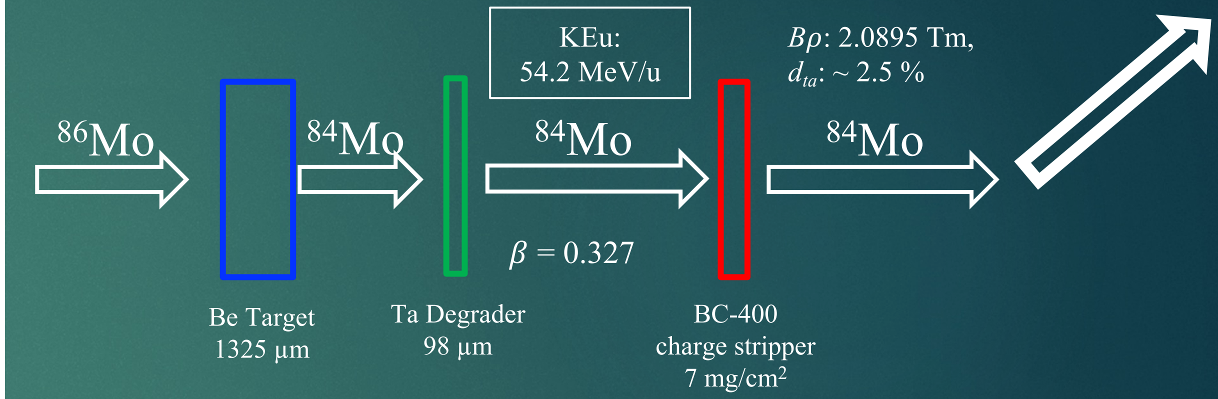

**$^{86}$Mo was 0.8% of incoming beam**

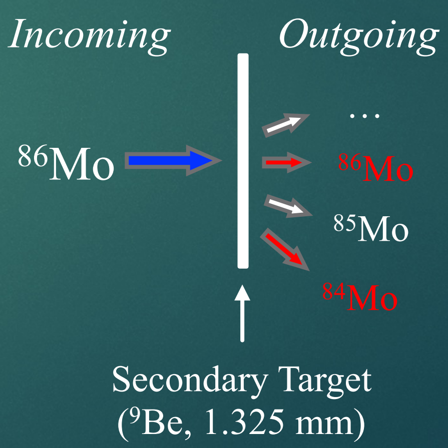
# Analysis

[Outgoing beam PID plot for incoming $^{86}$Mo beam]



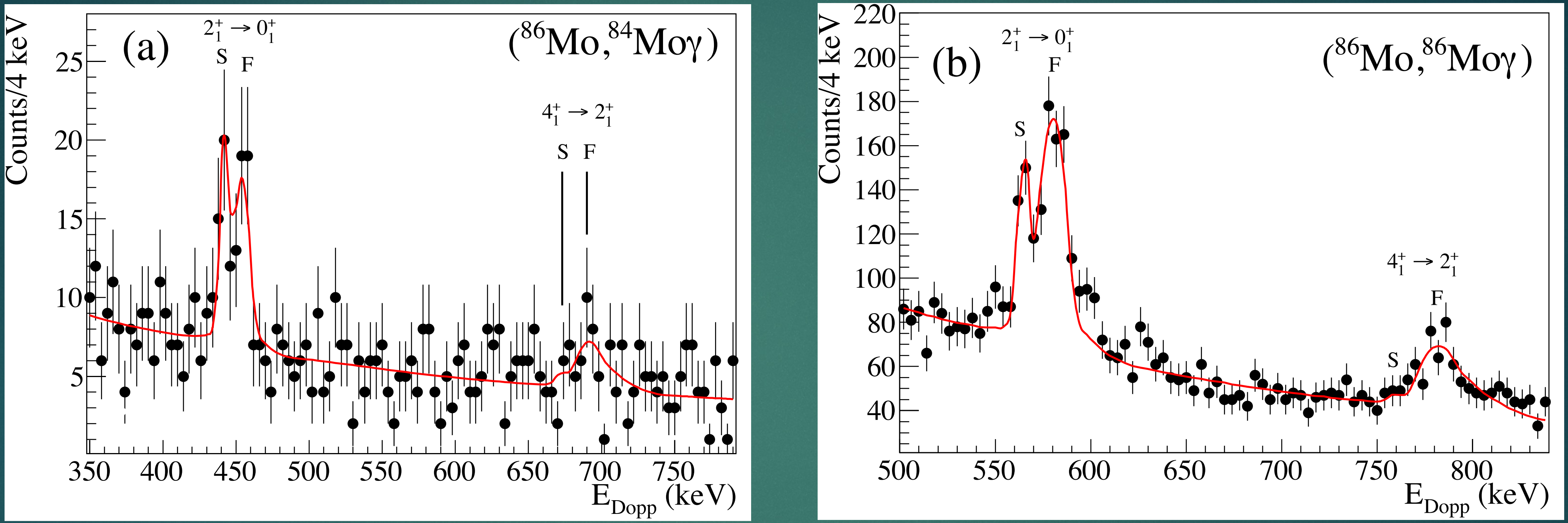



# Comparison to full Monte Carlo






- The spatial and energy distribution of the secondary beam are reproduced in the **simulation**
- Strong **direct** population to $2^+$
  - Residual population to $4^+$ states that decays by a fast transition

# $B(E2;\ 2_1^+ \rightarrow 0_1^+)$ along N=Z



$^{84}$Mo

$^{80}$Zr

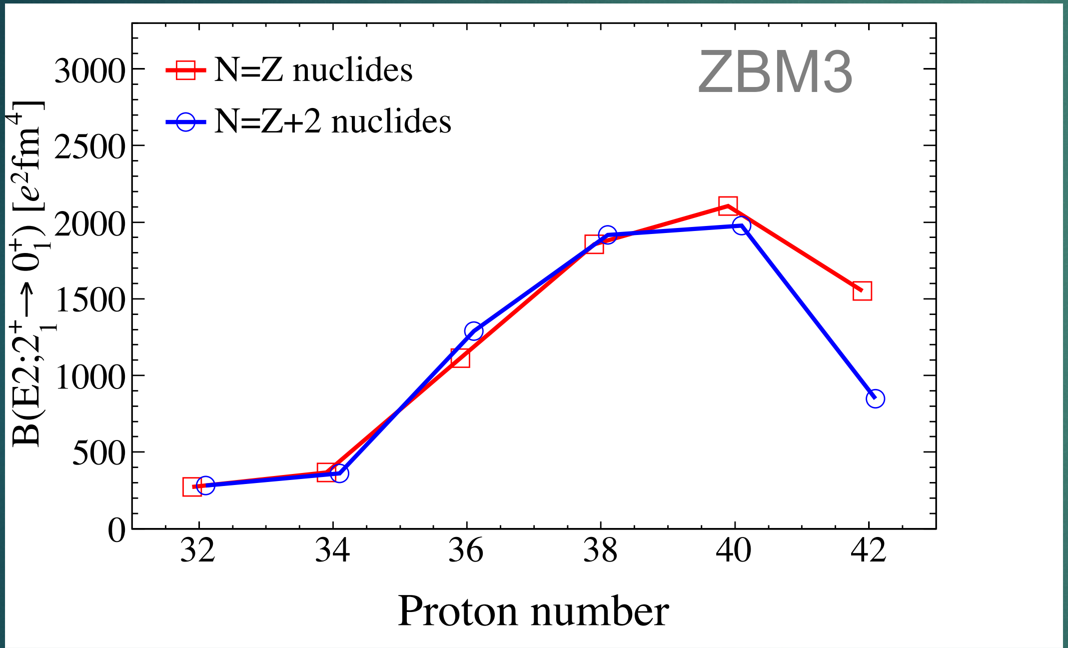
$^{86}$Mo

- First $2^+$ state in $^{84}$Mo understandable in terms of **prolate deformation**
- **Inclusion of $d_{5/2}$ is needed** – lifetime shorter than expected - quadrupole correlations

# Discussion with ZBM3



- The shell model calculation with ZBM3 (*r3gds* model space)
- The $B(E2;\ 2_1^+ \rightarrow 0_1^+)$ calculation shows consistency for $N = Z$ and $N = Z + 2$ nuclides



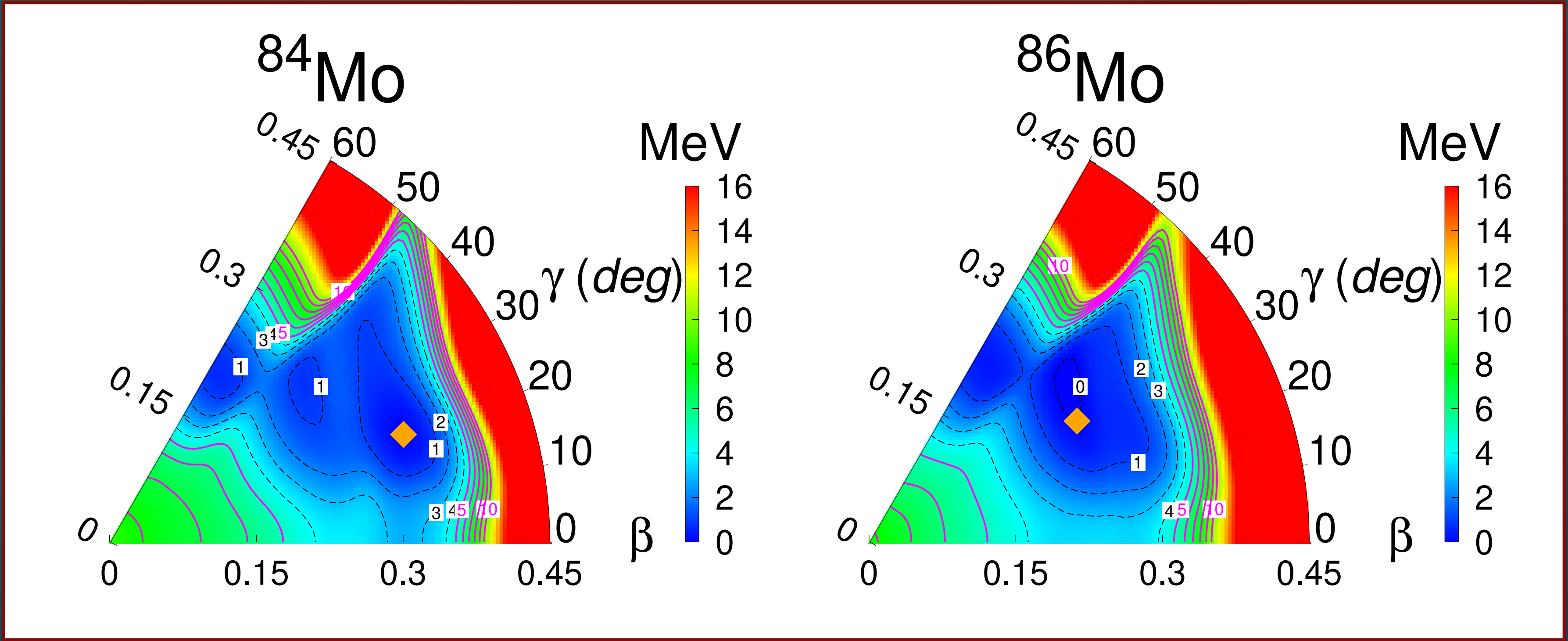


*A. P. Zuker, A. Poves, F. Nowacki, and S. M. Lenzi, Phys. Rev. C **92**, 024320 (2015)*
*A. P. Zuker, B. Buck, and J. B. McGrory, Phys. Rev. Lett. **21**, 39 (1968)*

# Discussion with ZBM3

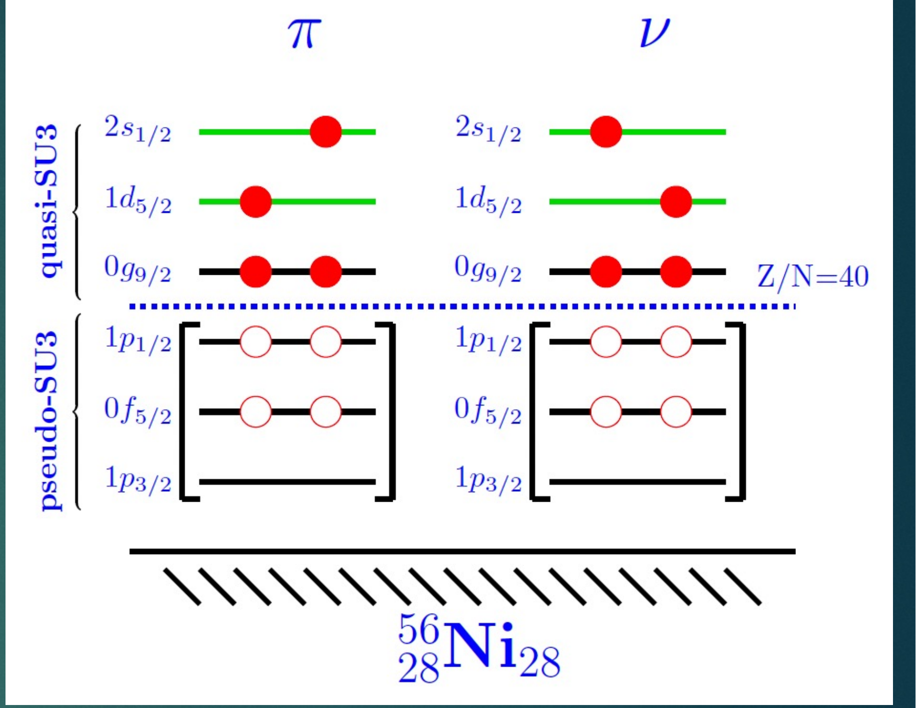


- Generator cohordinate method - check where w.f. falls in the potential energy surface
- The $\beta - \gamma$ plane for $^{84}$Mo and $^{86}$Mo show **triaxial** ground-state shapes
- **Soft potential surface** towards oblate shapes for both $^{84}$Mo and $^{86}$Mo
- Transition between $^{76}$Sr, $^{80}$Zr and less deformed N=Z toward $^{100}$Sn



# Island of deformation at the N=Z line

- **Zuker-Retamosa-Poves** scheme based on $SU_3$ symmetry
  - **π** and **ν** takes the configuration that maximize quadrupole deformation
  - Most deformed cases for $^{76}$Sr, $^{80}$Zr
  - Detailed analysis: we can force a limited number of p-h excitations
- **Shape transition between $^{84}$Mo and $^{86}$Mo**




| nucleus | Np-Nh* | ZRP |
|---|---|---|
| $^{84}$Mo | 4p-4h | 1104 |
| | 8p-8h | 1891 |
| $^{86}$Mo | 0p-0h | 542 |
| | 2p-2h | 1030 |
| | 4p-4h | 1416 |
| | 6p-6h | 1858 |

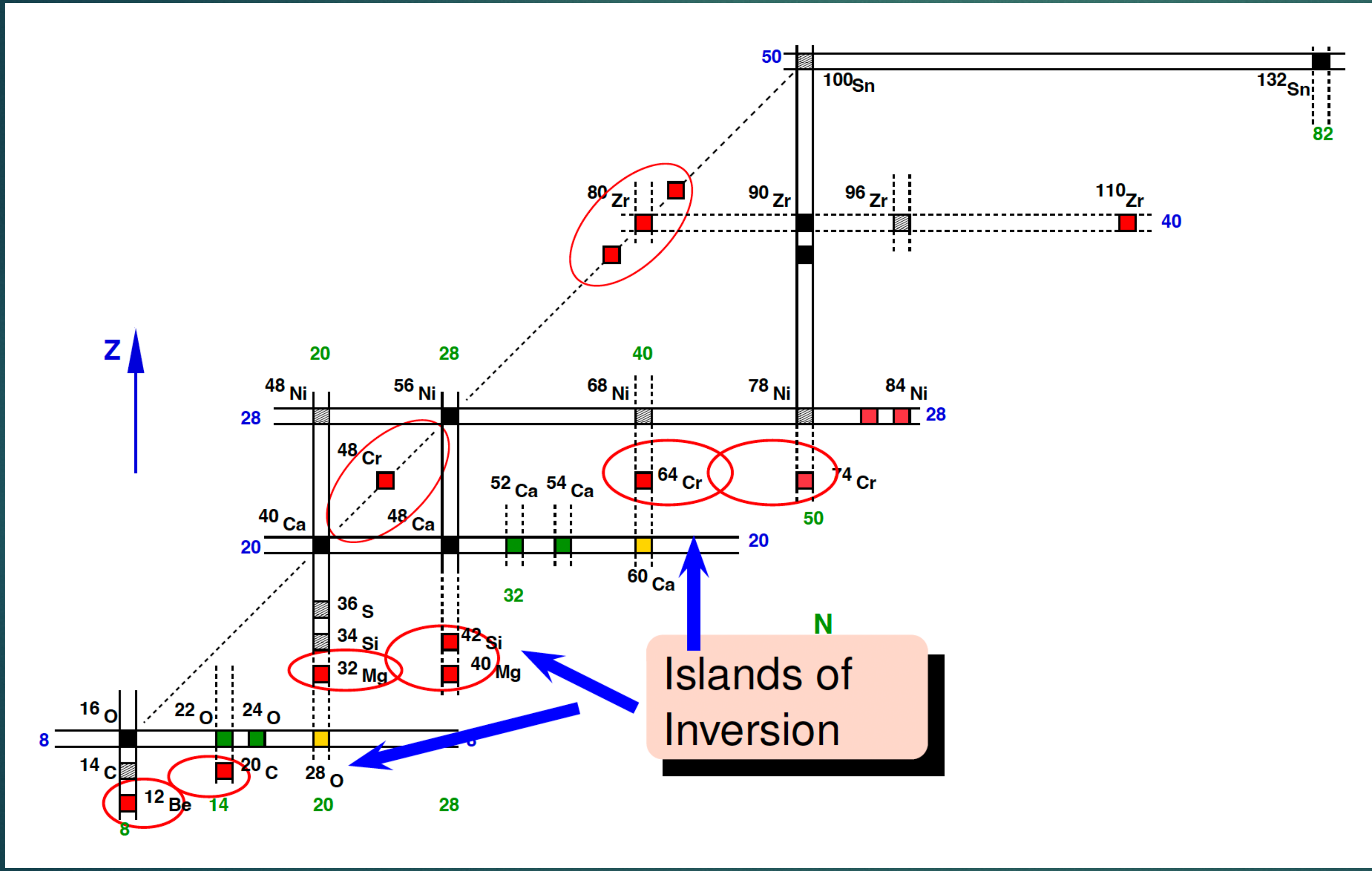
# Conclusion 1/2



- Advanced RIB Facilities and instrumentation allow progress
  - Measure collectivity by B(E2) along N=Z
  - New challenges for theoretical description of the B(E2) measured in the center of the $g_{9/2}$ shell
  - **Quadrupole correlations beyond expectations;** possible **triaxiality**... calculation still in progress
  - Shell model description: new region of deformation and **sharp transition between $^{84}$Mo and $^{86}$Mo**

# Conclusion 2/2

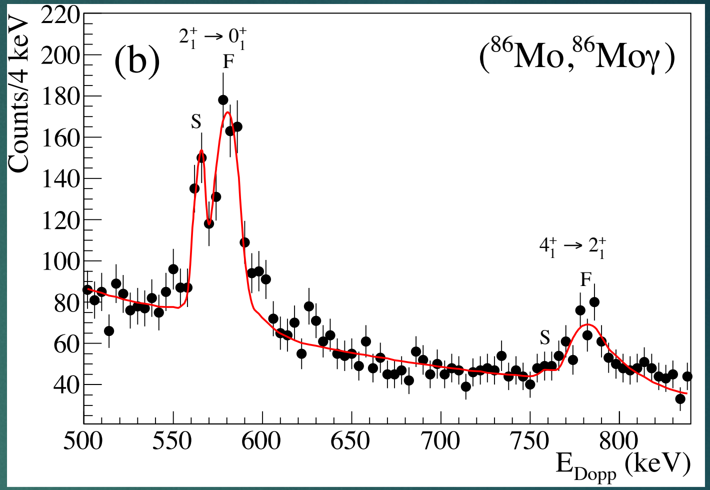





- **Limit of present facilities is reached.** Looking forward for the new ones
  - Heavier nuclei along N=Z: $^{88}$Ru, $^{92}$Pd, $^{96}$Cd
  - odd-odd nuclides ($^{82}$Nb, $^{86}$Tc, …) shape competition and coexistence

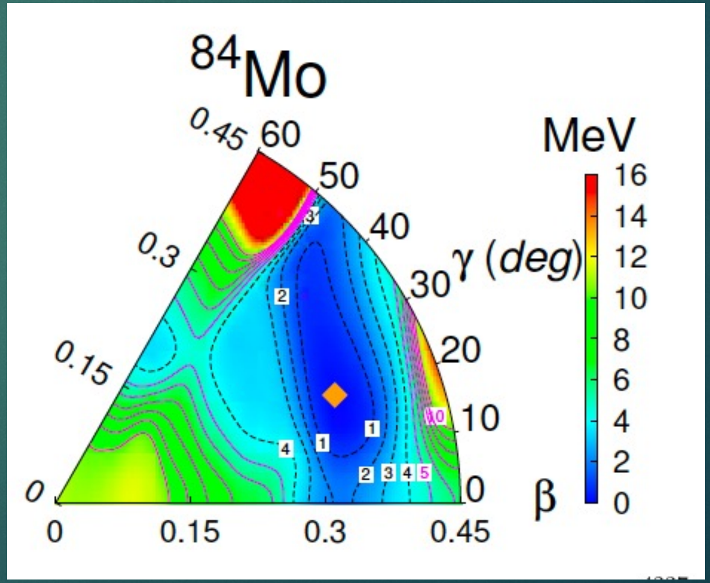
## ONLY POSSIBLE THANKS TO:

Jeongsu Ha
Pablo Aguilera
Sara Carollo




## WITH CALCULATIONS BY:

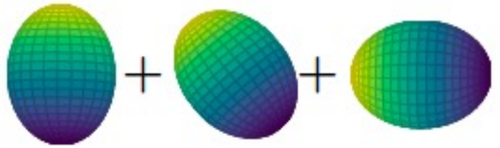
F. Nowacki
D. D. Dao
A. Poves
S. Lenzi




THE FULL NSCL COLLABORATION IS ACKNOWLEDGED

## Generator Coordinate Method: $|\Psi_{\text{eff}}\rangle = \sum_i f_i|\Phi_i\rangle$

1) Deformed Hartree-Fock (HF) Slater determinants
2) Restoration of rotational symmetry
3) Mixing of shapes:

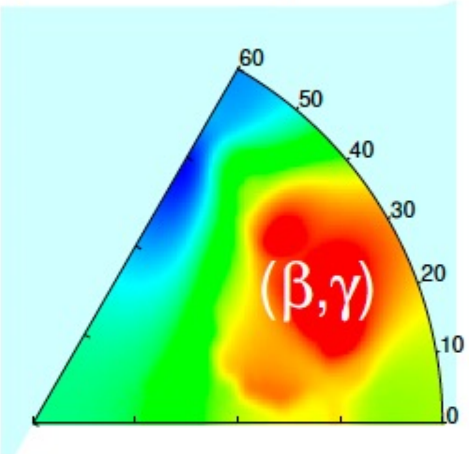
$|\Psi_{\text{eff}}\rangle =$  $\cdots$

## Basis Truncation Method

? *choice of relevant deformed Hartree-Fock states*

- **E. Caurier's Minimization Technique**:

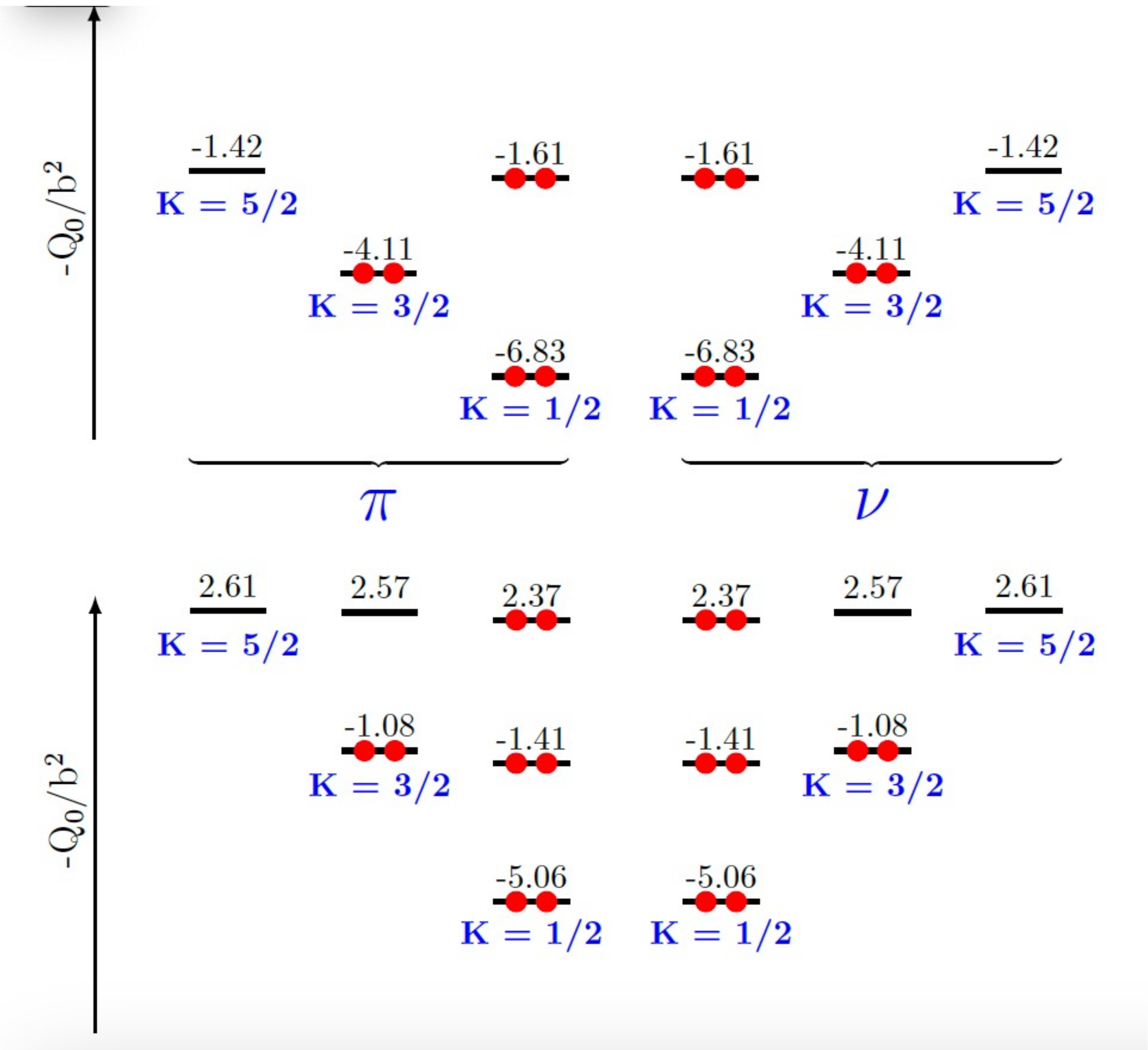
(E. Caurier, Proc. on GCM, BLG report **484** (1975))

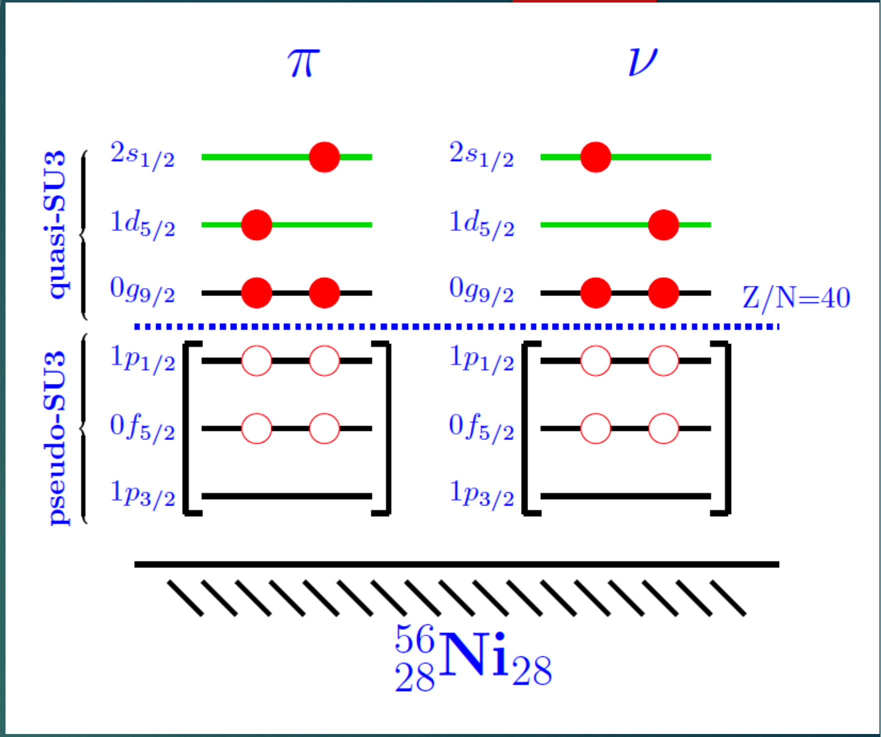



◇ Based on the variational principle

◇ Minimization of the energy of given states $\{J^\pi\}$

Courtesy of F. Nowacki




# ZRP w/ ZBM interaction

A. P. ZUKER, B. BUCK, AND J. B. MCGRORY, PHYS. REV. LETT. 21, 39 (1968);