

THE SEASTAR PROGRAM AT RIBF

A. Corsi
CEA Saclay

NUSTAR Annual Meeting, GSI, March 2nd 2016

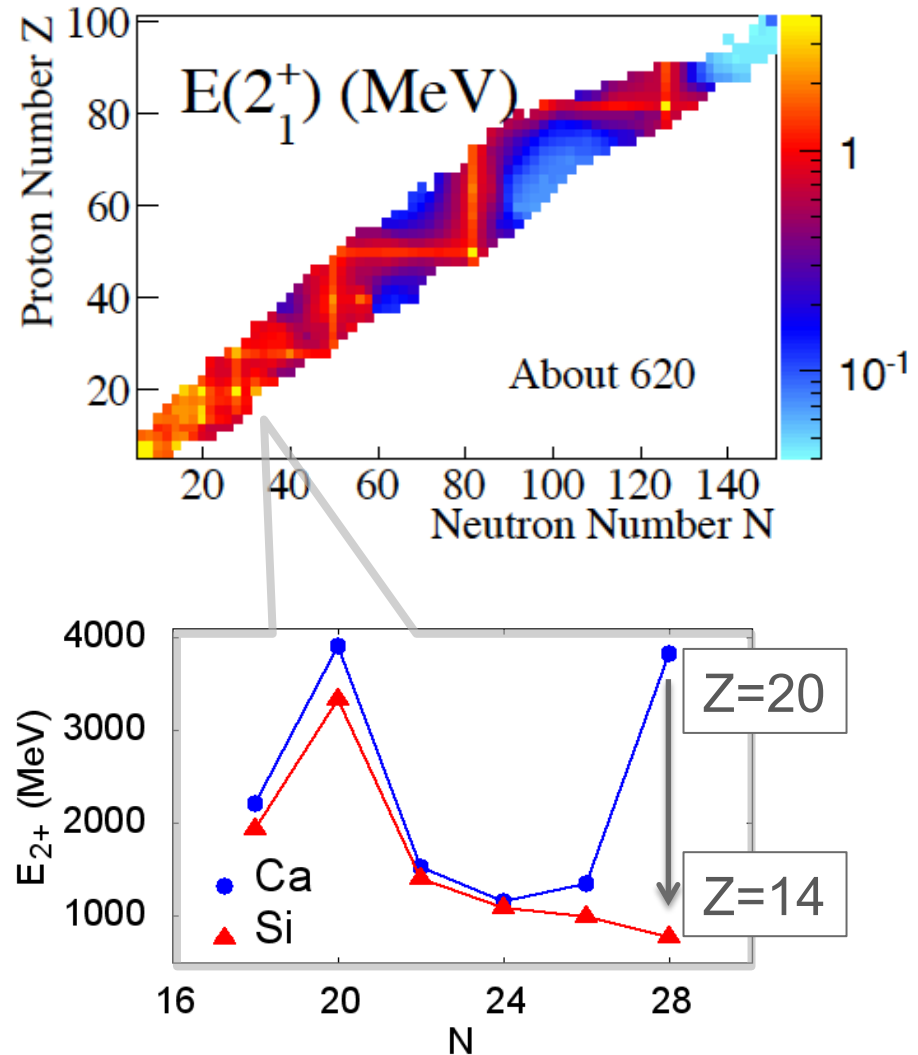
✧ In-beam gamma spectroscopy of exotic nuclei

✧ MINOS+DALI2 @ RIBF

✧ SEASTAR Shell Evolution and Search for Two-plus Energies At the RIBF

- ^{66}Cr , $^{70,72}\text{Fe}$
- ^{78}Ni
- N=56, 58 between Zn and Kr
- ^{110}Zr
- Beyond and below ^{54}Ca

- 2^+ observable sensitive to shell structure
- Shell evolution far from stability
- Driving mechanism
 - Central force
T. Otsuka et al., PRL 87 (2001)
 - Tensor force
T. Otsuka et al., PRL 104 (2010)
 - 3 body force
G. Hagen et al., PRC 80 (2009)
- Need of systematics measurements



How to measure 2^+ states in exotic nuclei

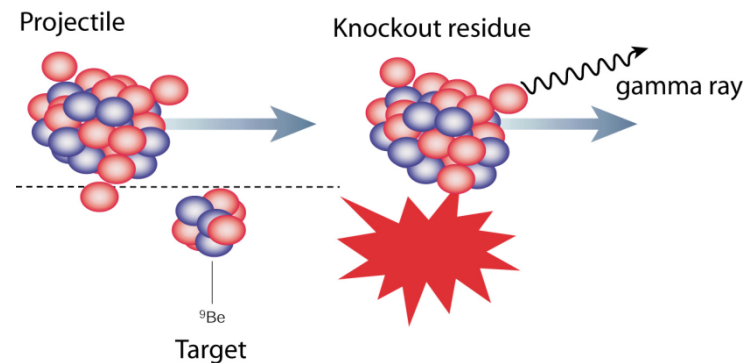
In-beam gamma spectroscopy:

- more exotic with respect to **beta-gamma** and **isomer spectroscopy**
- emission in fragment frame, need to apply Doppler correction (β , θ)

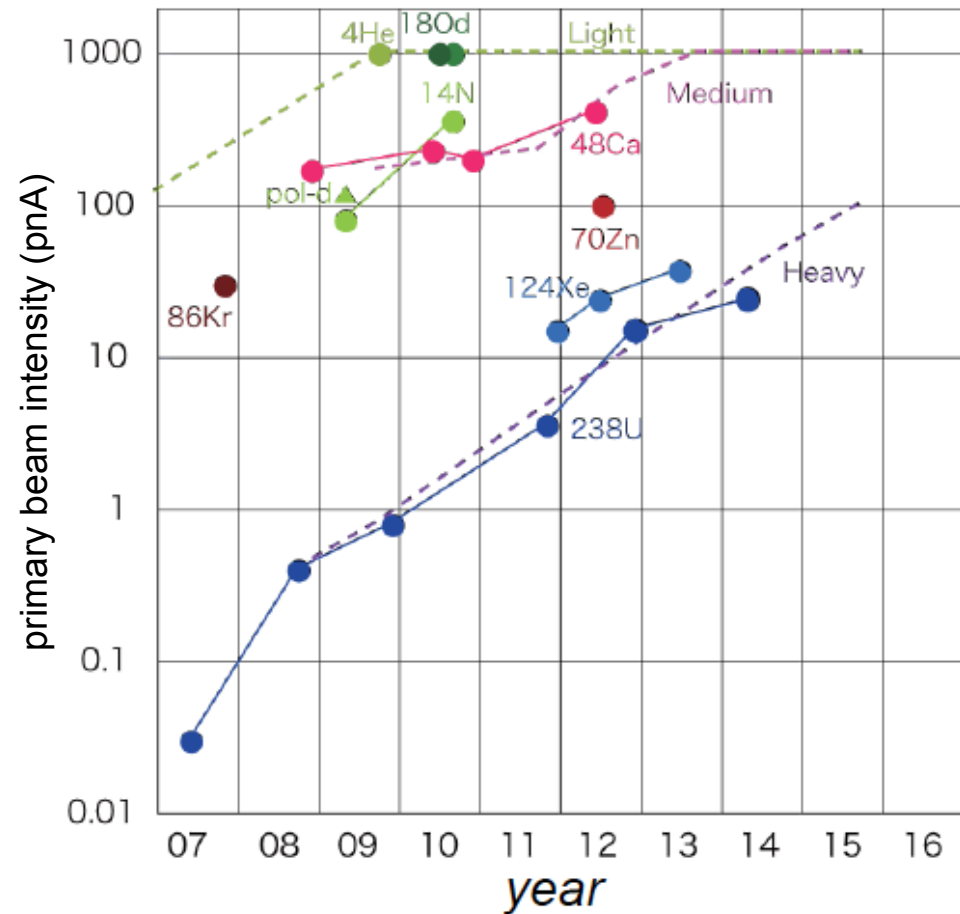
	^{76}Ni		^{78}Ni	
		^{76}Co		

^{76}Ni : P.A.Soderstrom *et al.*, PRC 91 (2015)

^{78}Ni : SEASTAR (2014)

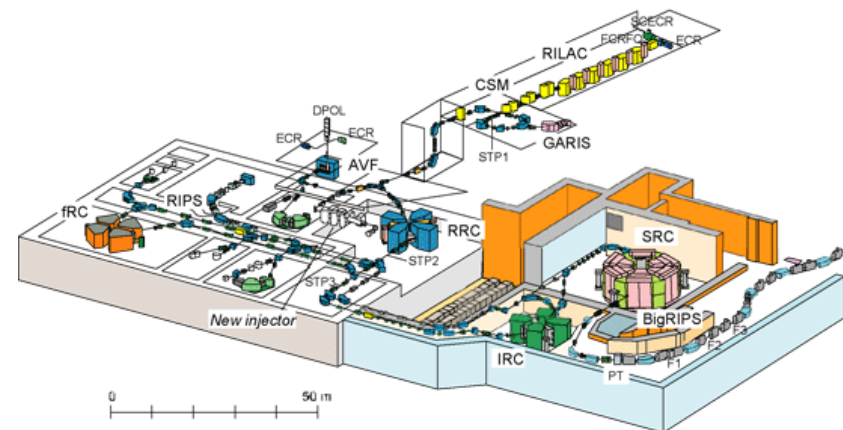


RIBF facility at RIKEN

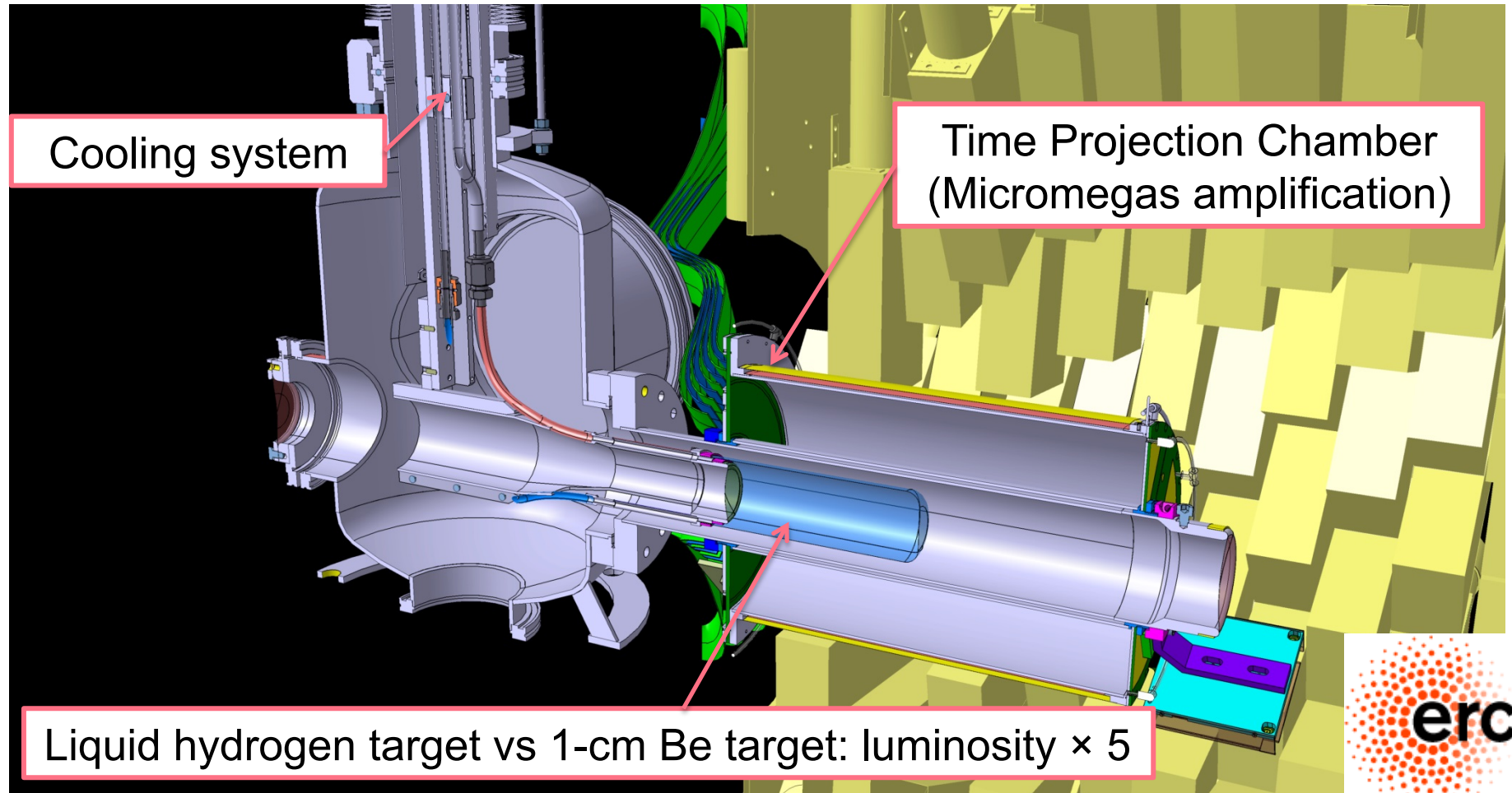


Primary beam	Energy (MeV/u)	Secondary beam (ΔN)	i (pps)
^{48}Ca	350	^{41}Al (14)	1 (2014)
^{70}Zn	350	^{55}Sc (10)	12 (2012)
^{238}U	350	^{79}Cu (15)	5 (2014)

ΔN : number of neutrons from the stability



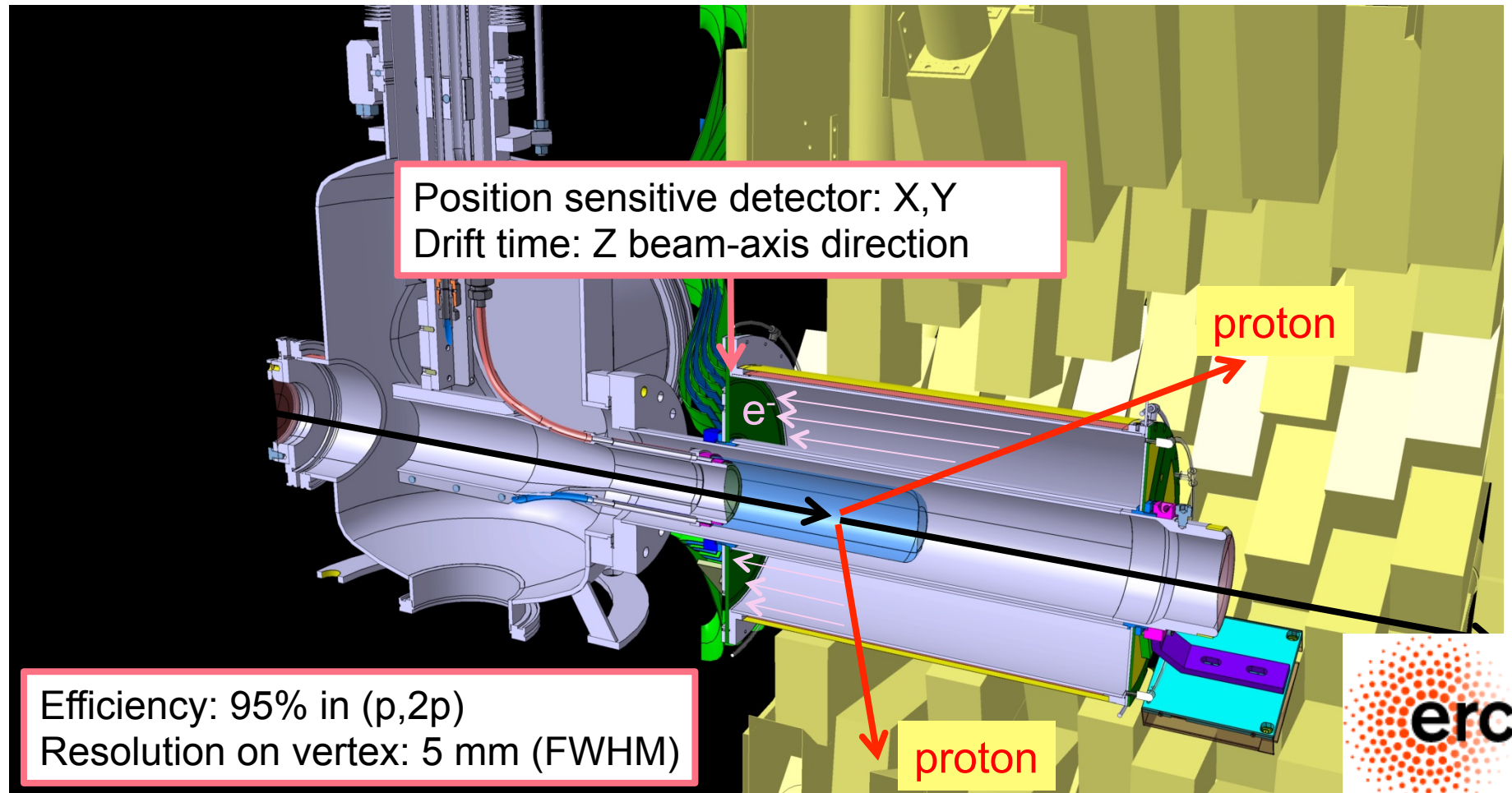
MINOS : Magic Numbers Off Stability



A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)

<http://minos.cea.fr>

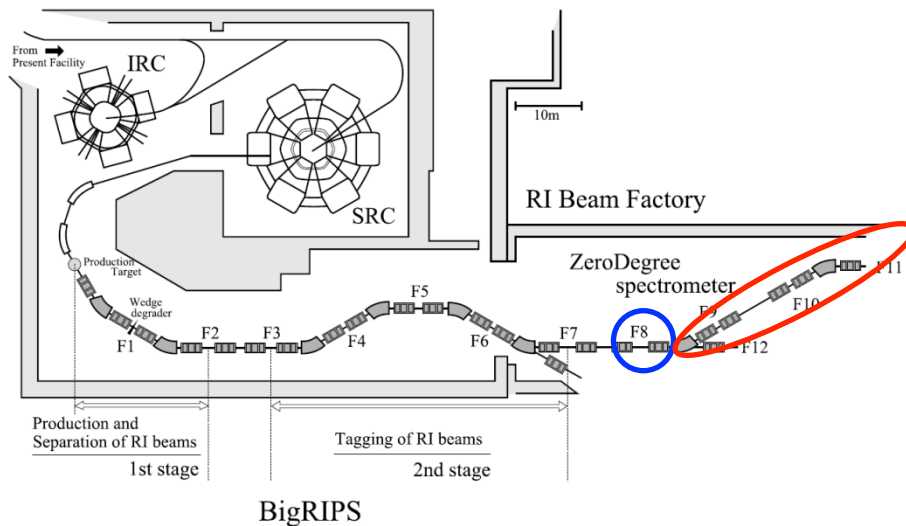
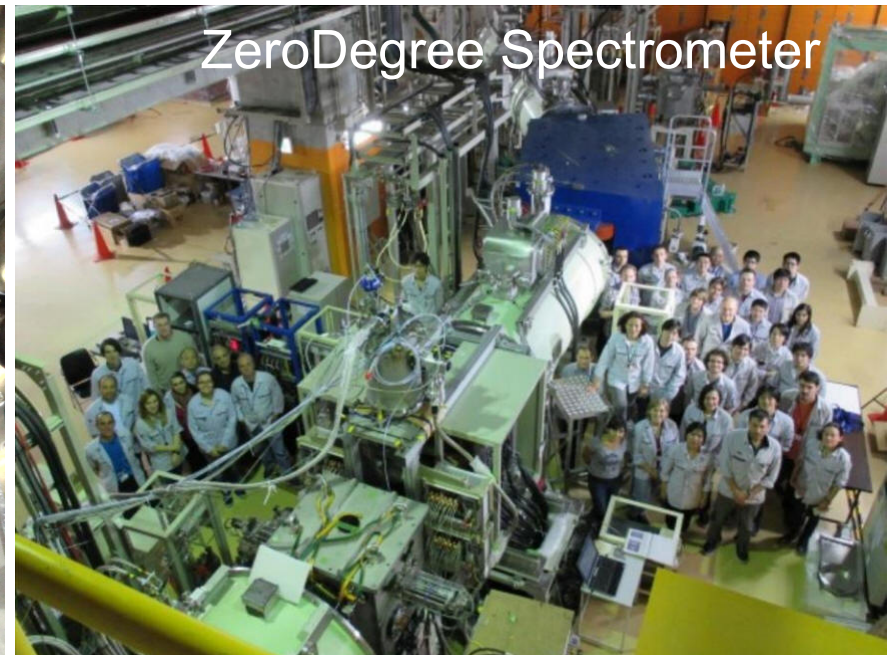
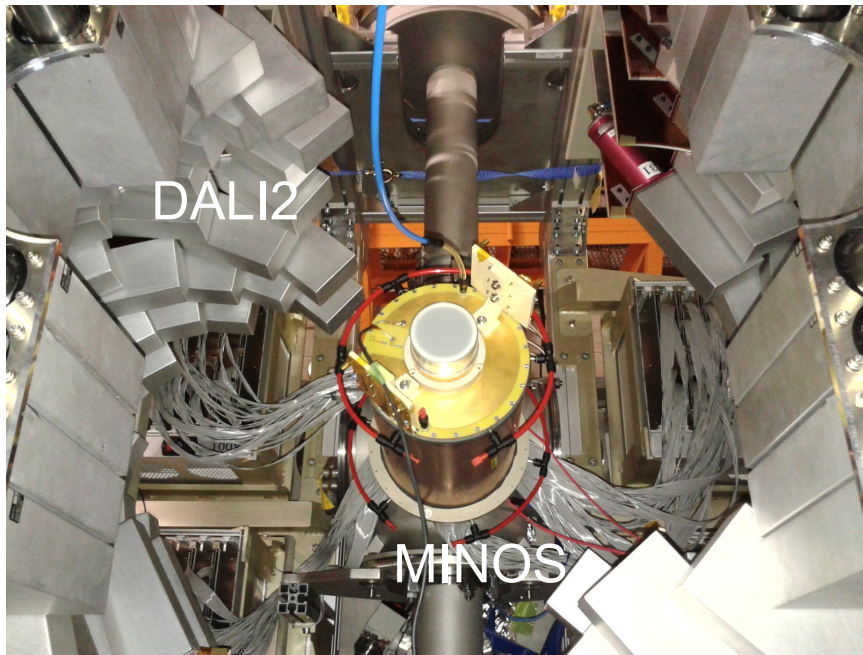
MINOS : Magic Numbers Off Stability



A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)

<http://minos.cea.fr>

DALI2-MINOS-ZeroDegree setup



DALI2

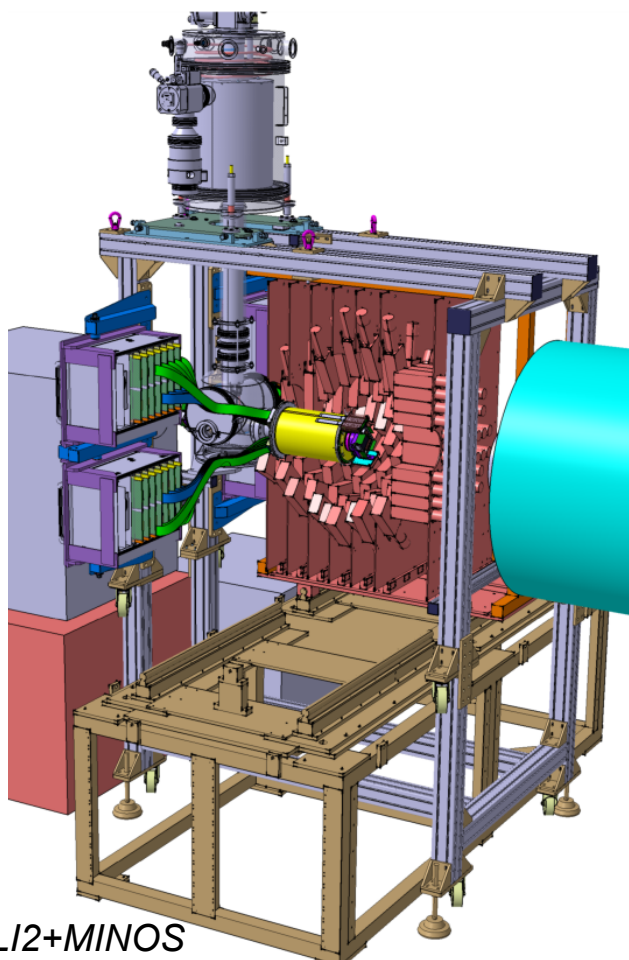
- $^{186}\text{NaI(Tl)}$, $\sim 10^\circ$ opening angle
- $\varepsilon=20\%$ and $\Delta E/E=10\%$ @ 1 MeV and $\beta=0.6$

ZeroDegree Spectrometer

- Momentum acceptance: $\pm 3\%$
- High resolution: $P/DP \approx 6000$

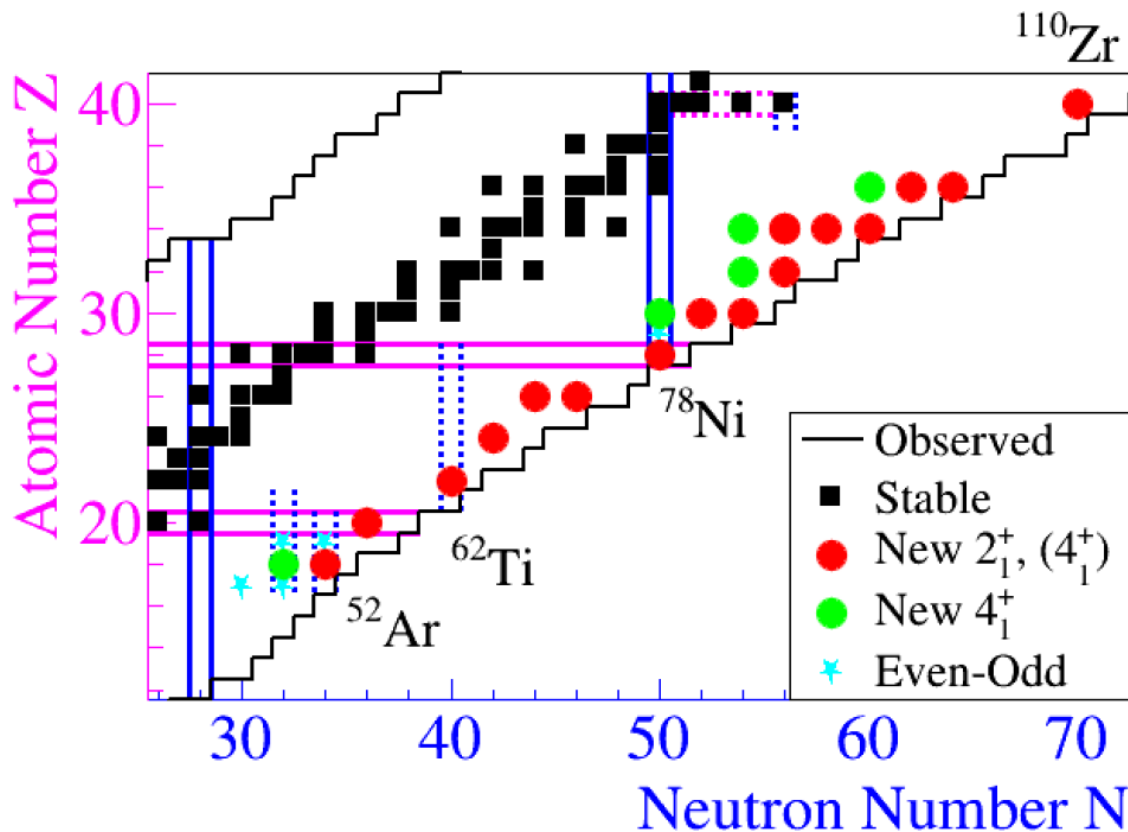
Shell Evolution and Search for Two-plus Energies At the RIBF (SEASTAR)

Spokespersons: P. Doornenbal (RIKEN), A. Obertelli (CEA)



DALI2+MINOS

Full program: 30 days of beam time



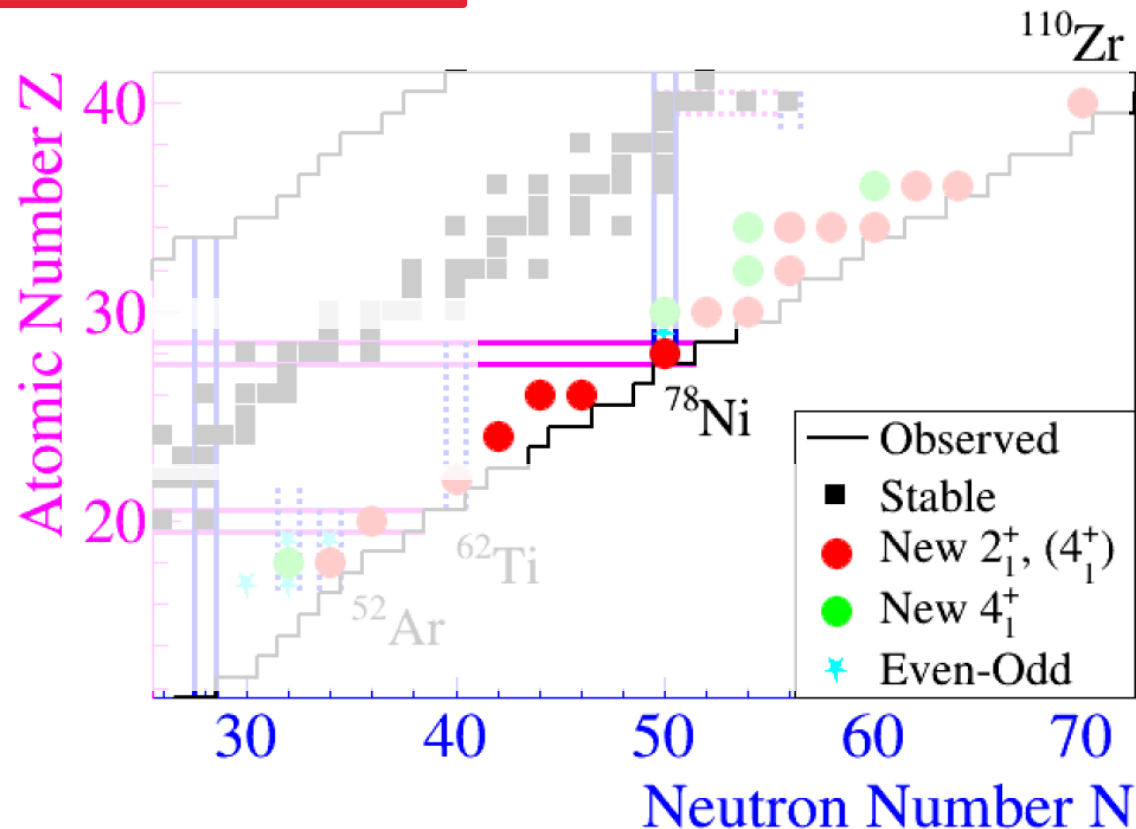
Proposal for a Scientific Program promoted by H. Sakurai (RNC, Univ. of Tokyo) and T. Uesaka (RNC)

May 2014, 1 week, primary beam ^{238}U (13 pnA)

Spectroscopy of:

- ^{66}Cr , $^{70,72}\text{Fe}$
 - ^{78}Ni
 - ^{79}Cu
-
- $^{67,68}\text{Fe}$, ^{67}Mn
 - ^{76}Ni
 - $^{69,71,73,75}\text{Co}$
 - $^{63-66}\text{Mn}$, $^{58-63}\text{V}$
 - $^{65,69,71}\text{Fe}$
 - ^{79}Zn
 - $^{81,82}\text{Zn}$
 - $^{75,77}\text{Cu}$
 - $^{72,74}\text{Ni}(p,p')$, $^{76,78,80}\text{Zn}(p,p')$
 - ^{77}Ni
 - isomers

Survey of (p,xp) and (p,pxn) inclusive cross sections

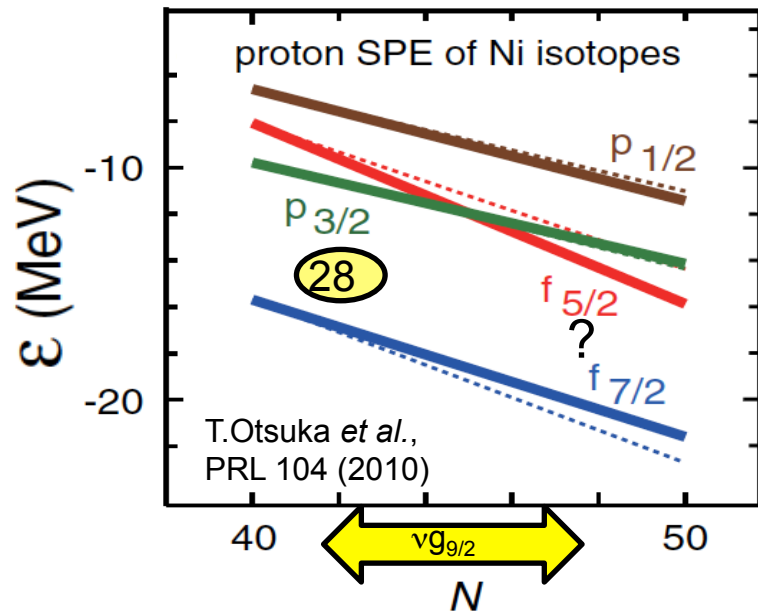


SEASTAR 1/3: collectivity towards N=50

- Erosion of Z=28 gap and/or N=50?

Flaganan *et al.*, PRL 103 (2009)

Hakala *et al.*, PRL 101 (2008)



- Lifetime measurement consistent with gap at Z=28 and N=50

P.Hosmer *et al.*, PRL 94 (2005)

Z.Y.Xu *et al.*, PRL 113 (2014)

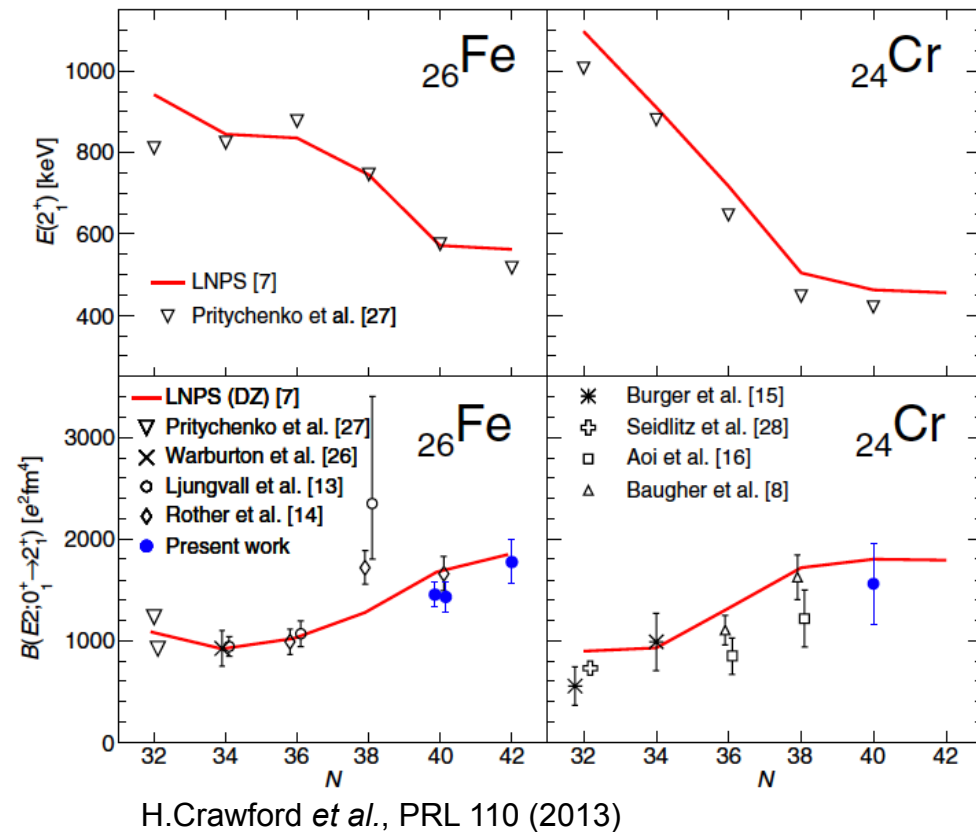
- Predictions for $^{78}\text{Ni}(2^+)$ sparse: 2-3 MeV

MCSM T. Tsunoda *et al.*, PRC 89 (2014)

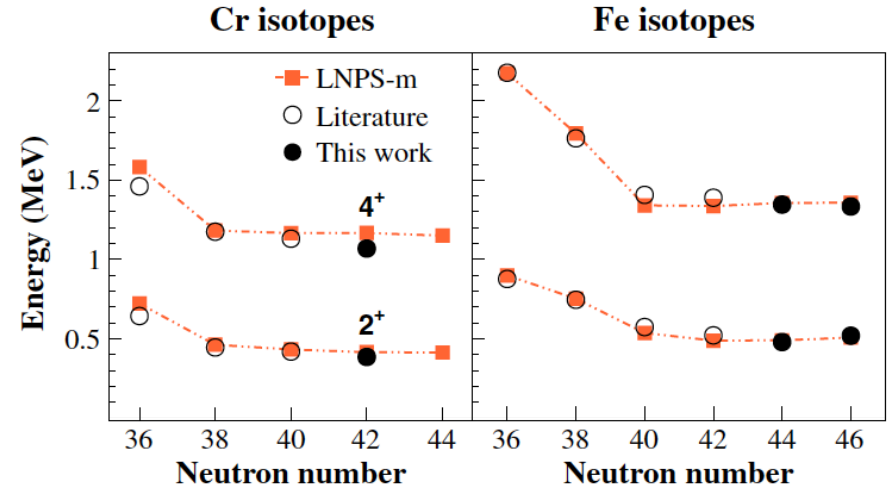
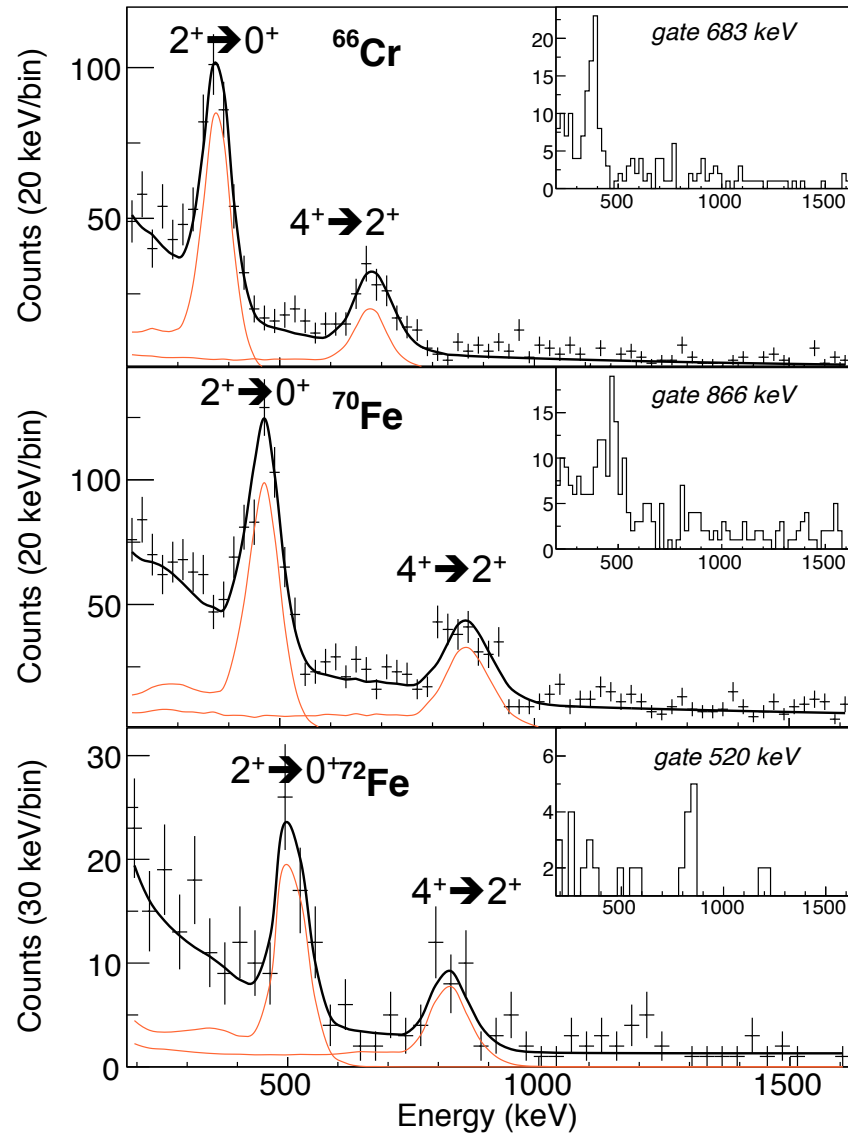
SM pf-fpgd K.Siejia and F.Novacki, PRC 85 (2012)

QRPA S. Péru *et al.*, EPJA 50 (2014)

- Quenching of N=40 gap btw Ni and Ca
- Island of inversion at N=40-50?



SEASTAR 1/3: Collectivity beyond N=40



- Extension of N=40 island of collectivity towards N=50
- Interplay of pairing and quadrupole correlations

C.Santamaria, C. Louchart *et al.*, PRL 115 (2015)
SM calculations from F.Nowacki, IPHC Strasbourg

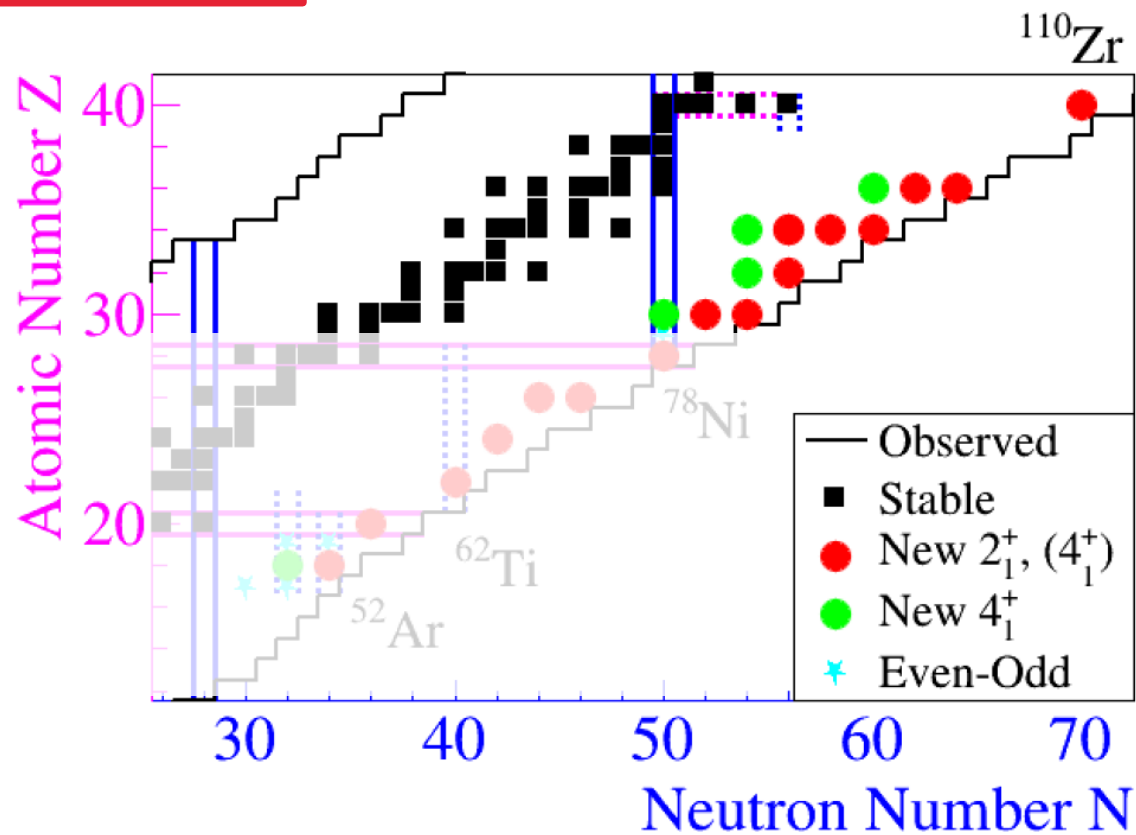
May 2015, 1 week, primary beam ^{238}U (30 pA)

Spectroscopy of:

- $^{82,84}\text{Zn}$
- $^{86,88}\text{Ge}$
- $^{90-94}\text{Se}$
- $^{98,100}\text{Kr}$
- ^{110}Zr

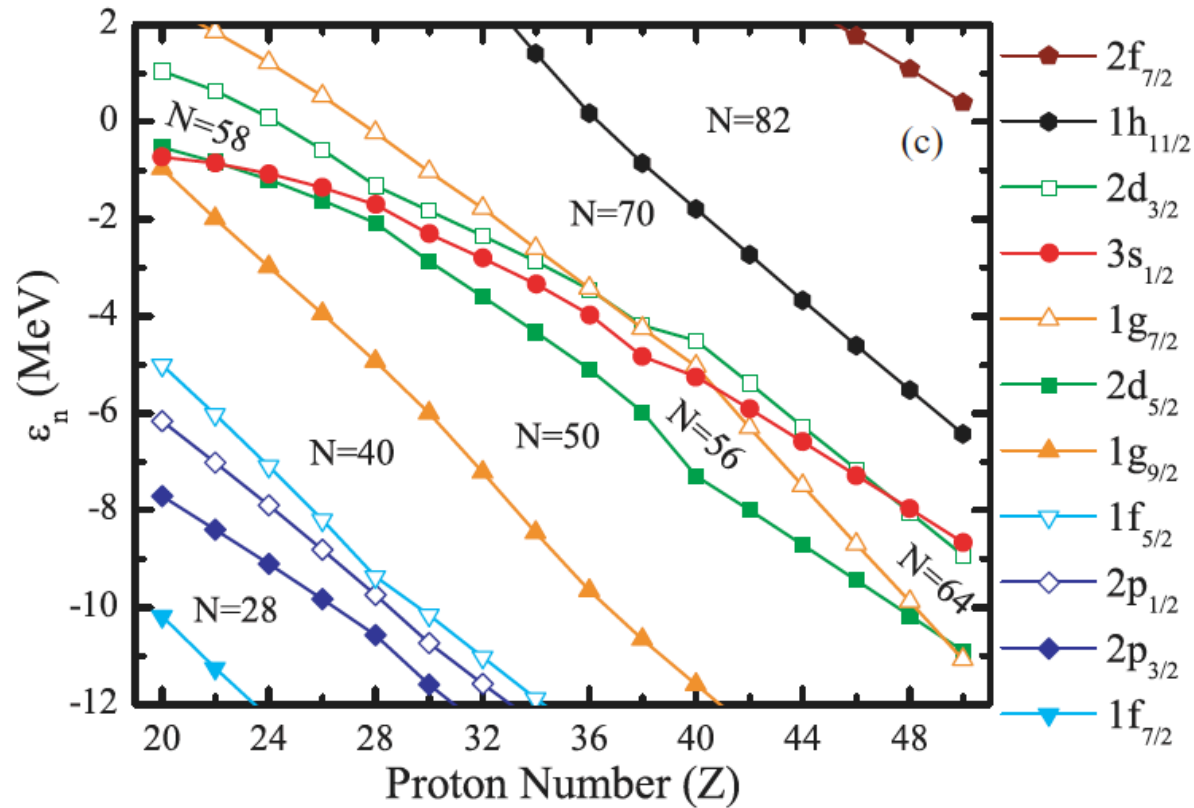
-
- $^{97,99}\text{Kr}$
 - $^{83-85}\text{Ga}$
 - ^{102}Y , $^{112,113}\text{Tc}$, ^{105}Zn
 - ^{83}Zn
 - ^{87}Ge
 - ^{111}Mo , ^{111}Nb
 - ^{108}Zr , $^{110,112}\text{Mo}$
 - $^{93,95,97}\text{Kr}$
 - $^{89-95}\text{Br}$, $^{95-101}\text{Rb}$
 - $^{99-104}\text{Sr}$
 - $^{70}\text{Ni}(p,p')$, $^{86,88}\text{Ge}(p,p')$, $^{94,96}\text{Kr}(p,p')$
 - Isomers

Survey of (p,xp) and (p,pxn) inclusive cross sections



SEASTAR 2/3: Collectivity above Ni

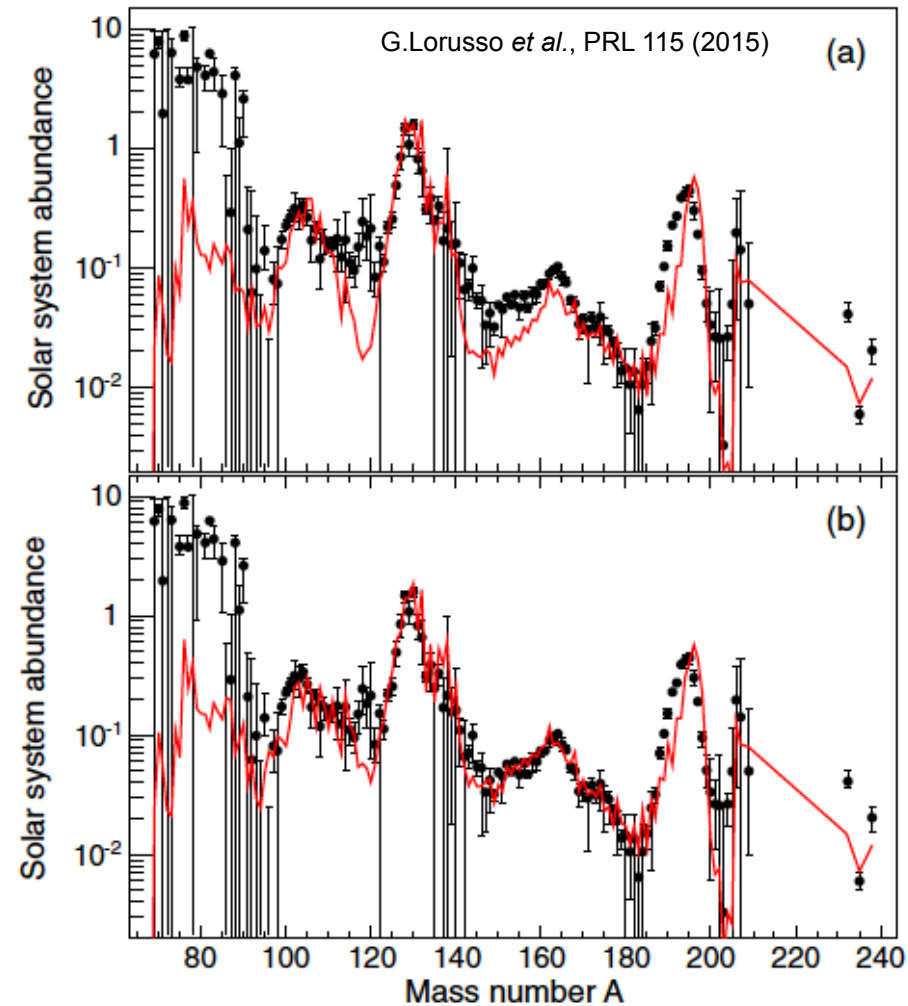
Subshell closure at N=56, 58, 70?

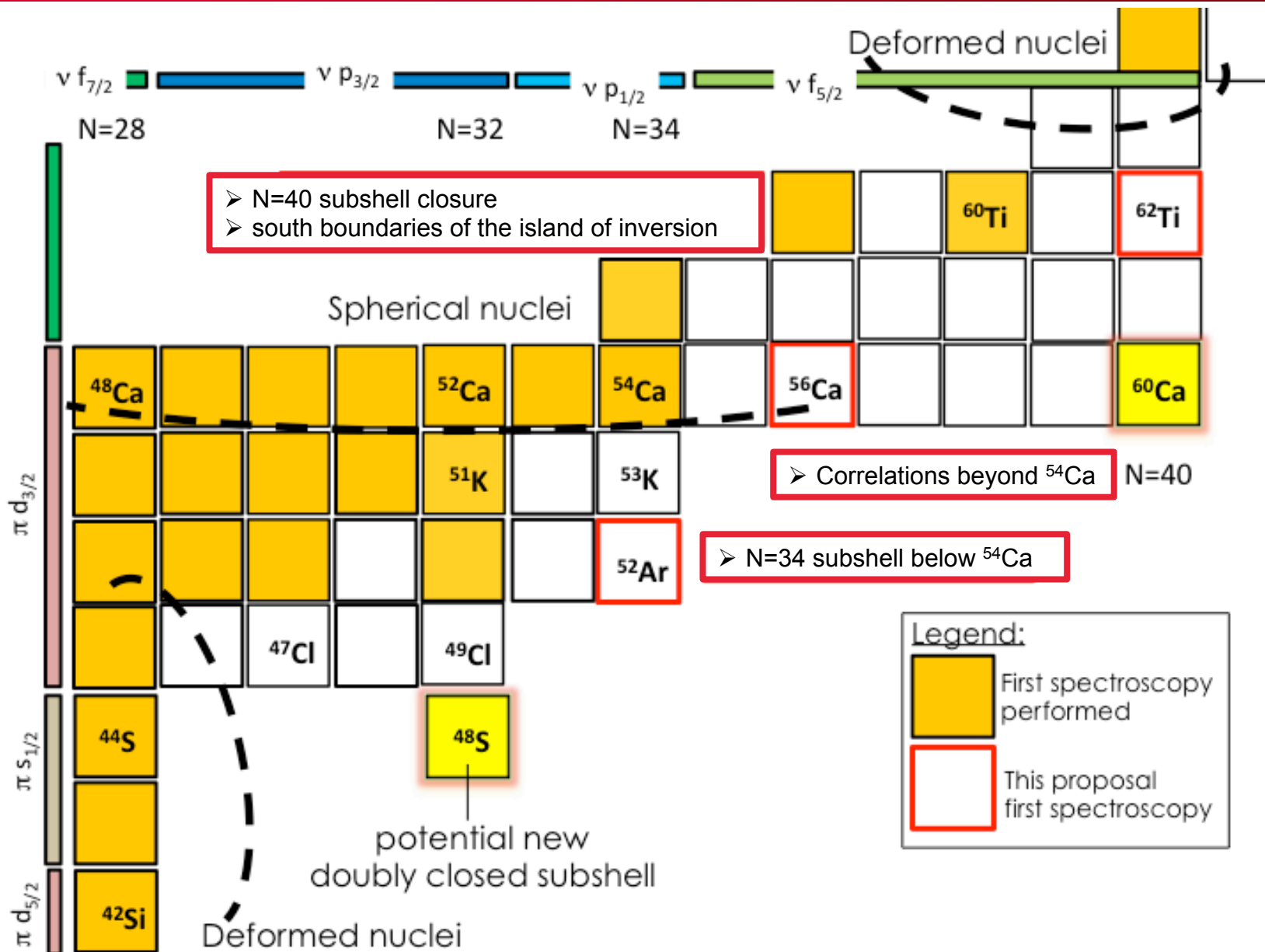


HFB calculations from Winger *et al*, PRC 81 (2010)

SEASTAR 2/3: Shell closure at N=70

- N=70 shell gap used to explain the dip before A=130
[Pfeiffer *et al.*, NPA 2001](#)
- No need of N=70 gap with new lifetime measurements
[G.Lorusso *et al.*, PRL 115 \(2015\)](#)
- Various theoretical predictions:
 - Tetraedral gap at N=70 and Z=40
[Dudek *et al.*, PRL 88 \(2002\)](#)
[Shunck *et al.*, PRC 69 \(2004\)](#)
 - Spherical gap
[Bender *et al.*, PRC 80 \(2009\)](#)
 - Deformed, shape coexistence
[Delaroche *et al.*, PRC 81 \(2010\)](#)
[Petrovici *et al.*, J.Phys. 312 \(2011\)](#)
- Experimental evidence for persistence of deformation up to ^{108}Zr
[Sumikama *et al.*, PRL 106 \(2011\)](#)
[Kameda *et al.*, PRC 86 \(2012\)](#)
[Navin *et al.*, PLB 728 \(2014\)](#)





SEASTAR 3/3: Spectroscopy of ^{52}Ar

New sub-shell closure at N=34

Steppenbeck *et al.*, Nature 502 (2013)

Driving mechanism:

- tensor force

T. Otsuka *et al.*

- 3 body force

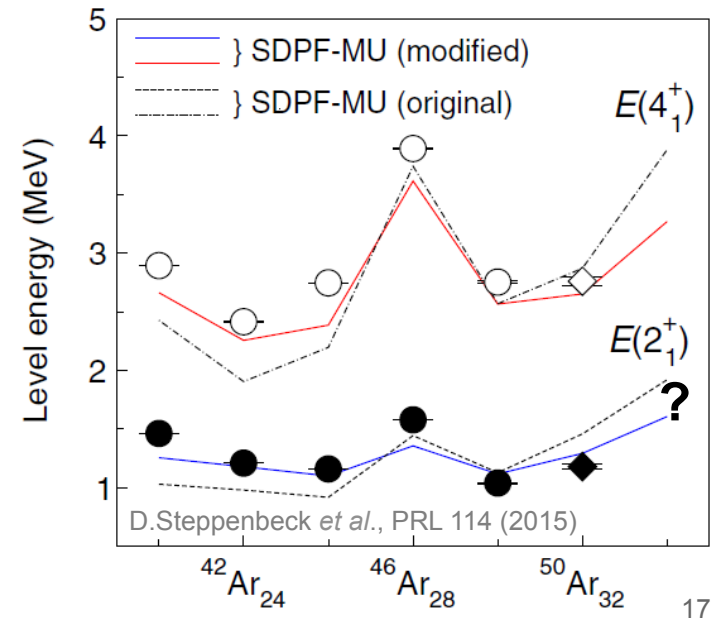
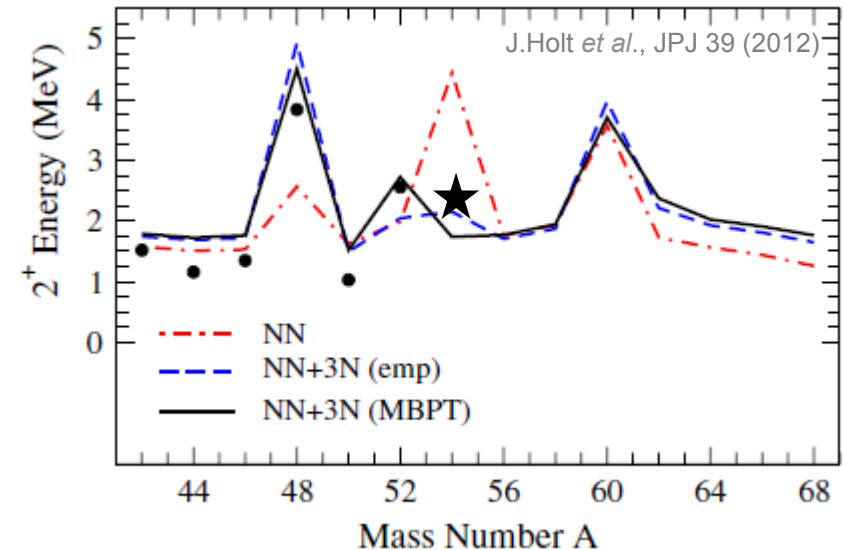
J.D.Holt *et al.*, G. Hagen *et al.*

Does N=34 persist below ^{54}Ca ?

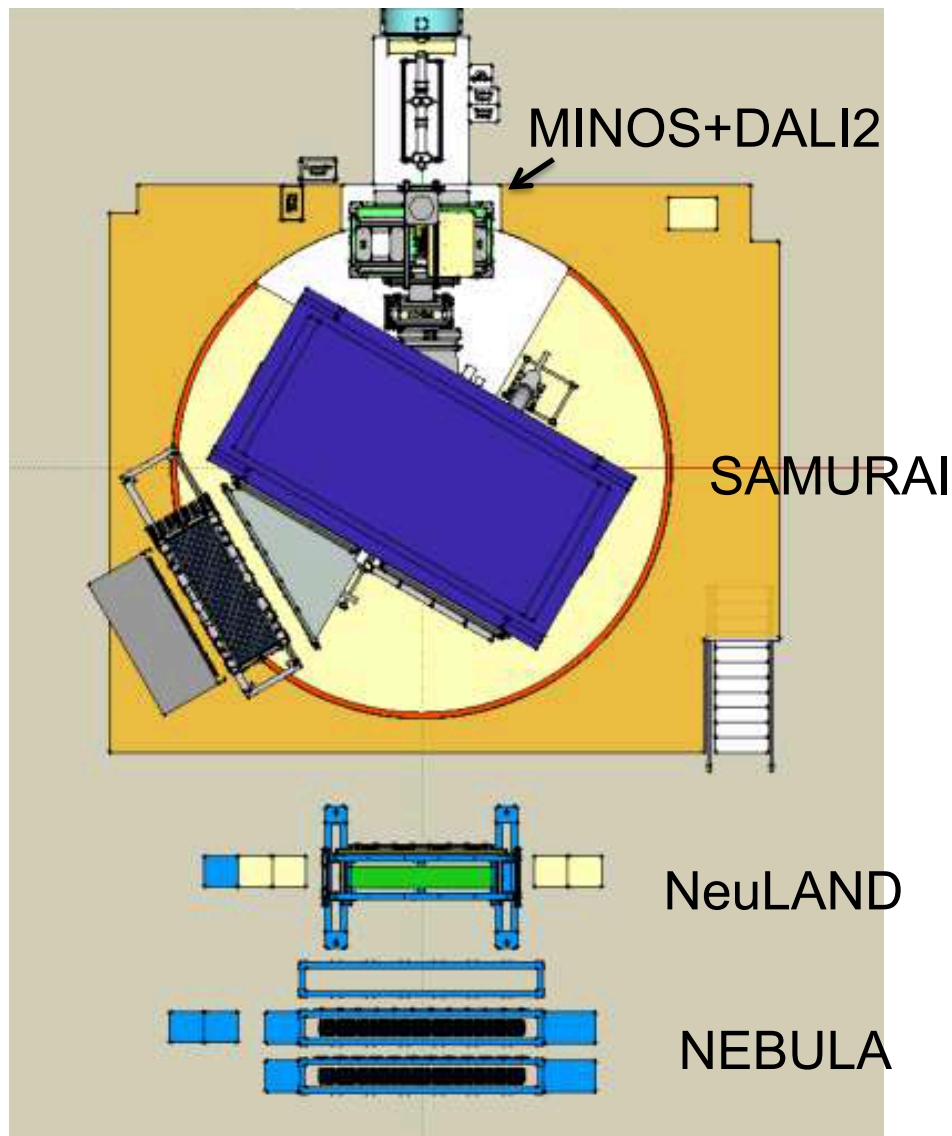
- N=32 gap at Z=18, 20 and 22
- N=34 gap quenched at Z=22

Ab-initio calculations for Ar

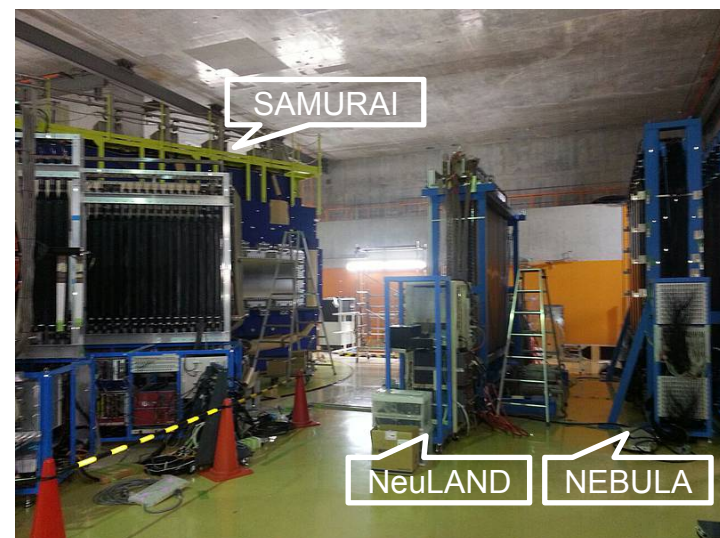
V.Somà *et al.*, PRC 89 (2014)



SEASTAR 3/3: setup at SAMURAI



- Spectroscopy of **unbound states** (^{62}Ti , ^{56}Ca , ^{52}Ar) thanks to NEBULA+NeuLAND
 $\varepsilon_{1n}=56\%$
- Large momentum acceptance with SAMURAI
- Upgraded DALI2 (220 crystals)
- ^{70}Zn primary beam, 200 pA



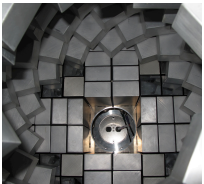
Summary and perspectives

Current SEASTAR program @ RIBF:

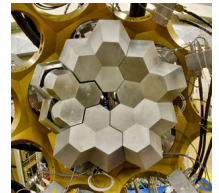
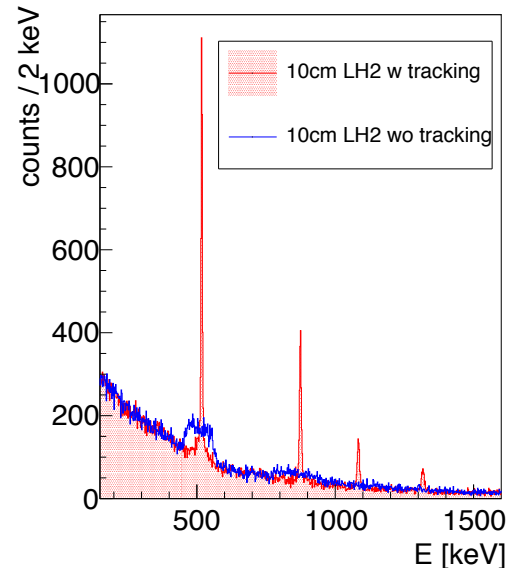
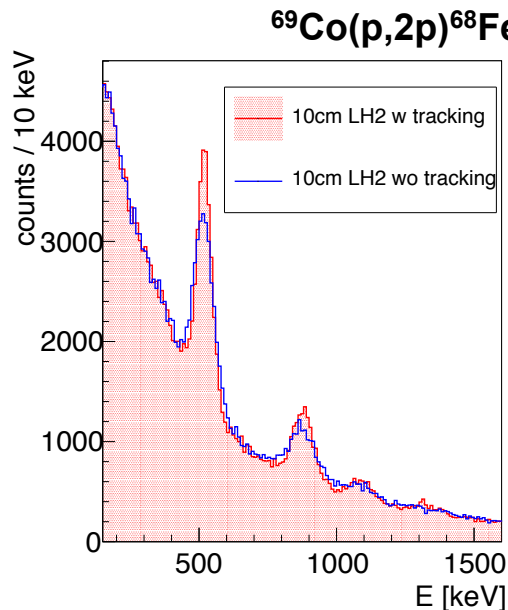
- New regions explored in 2014-2015
- Approved physics program up to 2016, possible extension: ^{100}Sn

Beyond this program: HISPEC

- High-resolution gamma array
- Full use of AGATA capabilities



DALI2



AGATA
5T+5D clusters

MINOS development and local teams

S. Anvar, L. Audirac, G. Authelet, H. Baba, B. Bruyneel, D. Calvet, F. Chateau, A. Corsi, A. Delbart, P. Doornenbal, J.-M. Gheller, A. Giganon, T. Isobe, Y. Kubota, C. Lahonde-Hamdoun, D. Leboeuf, D. Loiseau, M. Matsushita, A. Mohamed, J.-Ph. Mols, T. Motobayashi, M. Nishimura, A. Obertelli, S. Ota, H. Otsu, C. Péron, A. Peyaud, E.C. Pollacco, G. Prono, J.-Y. Rousse, H. Sakurai, C. Santamaria, M. Sasano, R. Taniuchi, S. Takeuchi, T. Uesaka, Y. Yanagisawa, K. Yoneda



TECHNISCHE
UNIVERSITÄT
DARMSTADT



Physics collaborations

SEASTAR N. Alamanos, T. Ando, G. de Angelis, N. Aoi, H. Baba, C. Barbieri, C. Bertulani, A. Blazhev, D. Bing, F. Browne, A. Bruce, A. Corsi, M.L. Cortes, F. Delaunay, M. Dewald, Z. Dombradi, **P. Doornenbal**, T. Duguet, F. Flavigny, S. Franchoo, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, S. Grévy, J.D. Holt, E. Ideguchi, T. Isobe, A. Jungclaus, N. Kobayashi, T. Kobayashi, Y. Kondo, W. Korten, Y. Kubota, I. Kuti, V. Lapoux, S. Leblond, J. Lee, S. Lenzi, M. Lettmann, H. Liu, C. Lizarazo, G. Lorusso, C. Louchart, R. Lozeva, F.M. Marques, I. Matea, K. Matsui, Y. Matsuda, M. Matsushita, J. Menendez, D. Mengoni, S. Michimasa, T. Miyazaki, S. Momiyama, K. Moschner, P. Morfouace, T. Motobayashi, T. Nakamura, Nagamine, Nakatsuka, D. Napoli, F. Naqvi, M. Niikura, C. Nita, **A. Obertelli**, N. Orr, S. Ota, H. Otsu, T. Otsuka, Z. Patel, N. Paul, N. Pietralla, Z. Podolyak, E.C. Pollacco, G. Potel, G. Randisi, F. Recchia, Saito, E. Sahin, H. Sakurai, C. Santamaria, M. Sasano, A. Schwenk, Y. Shiga, Y. Shimizu, S. Shimoura, C. Sidong, J. Simonis, P.A. Soderstrom, S. Sohler, V. Soma, I. Stefan, D. Steppenbeck, T. Sumikama, H. Suzuki, M. Tanaka, R. Taniuchi, K.N. Tuan, T. Uesaka, J. Valiente Dobon, Zs. Vajta, D. Verney, H. Wang, V. Werner, K. Wimmer, Zh. Xu, R. Yokoyama, K. Yoneda, L. Zhong