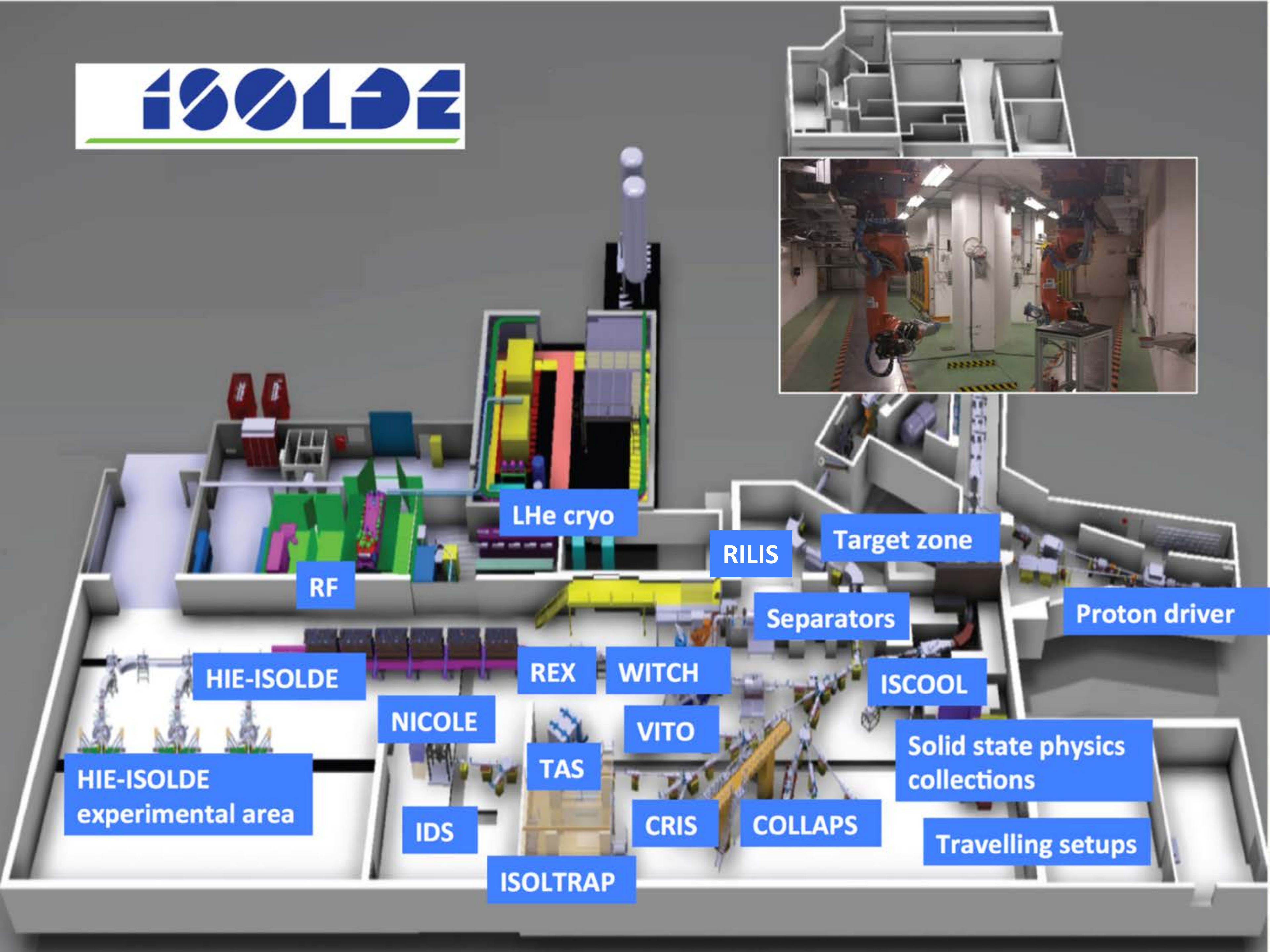
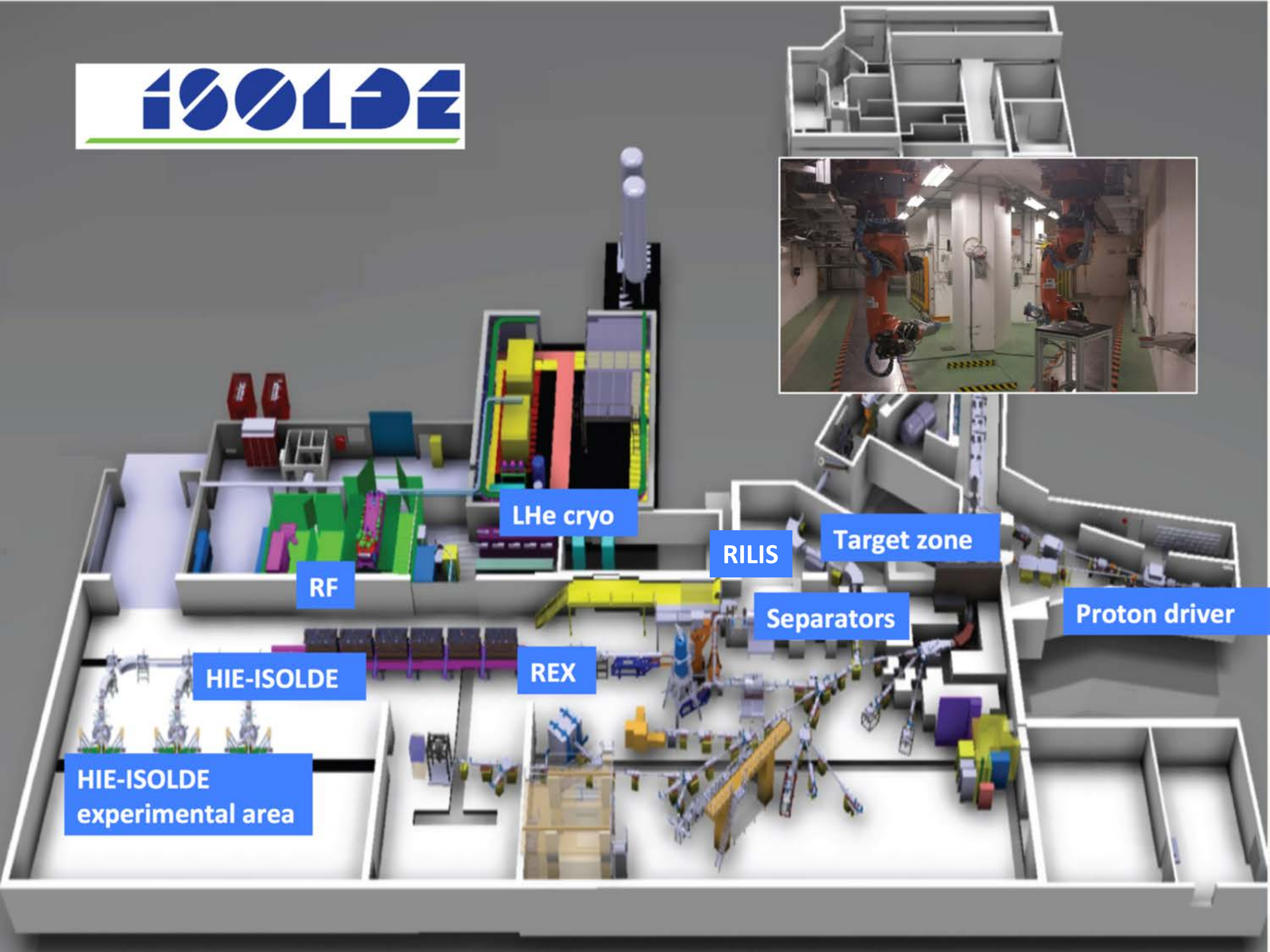
# Miniball at HIE-ISOLDE

**Liam Gaffney (CERN)**

*NUSTAR 2019, GSI Darmstadt, 01/03/2019*

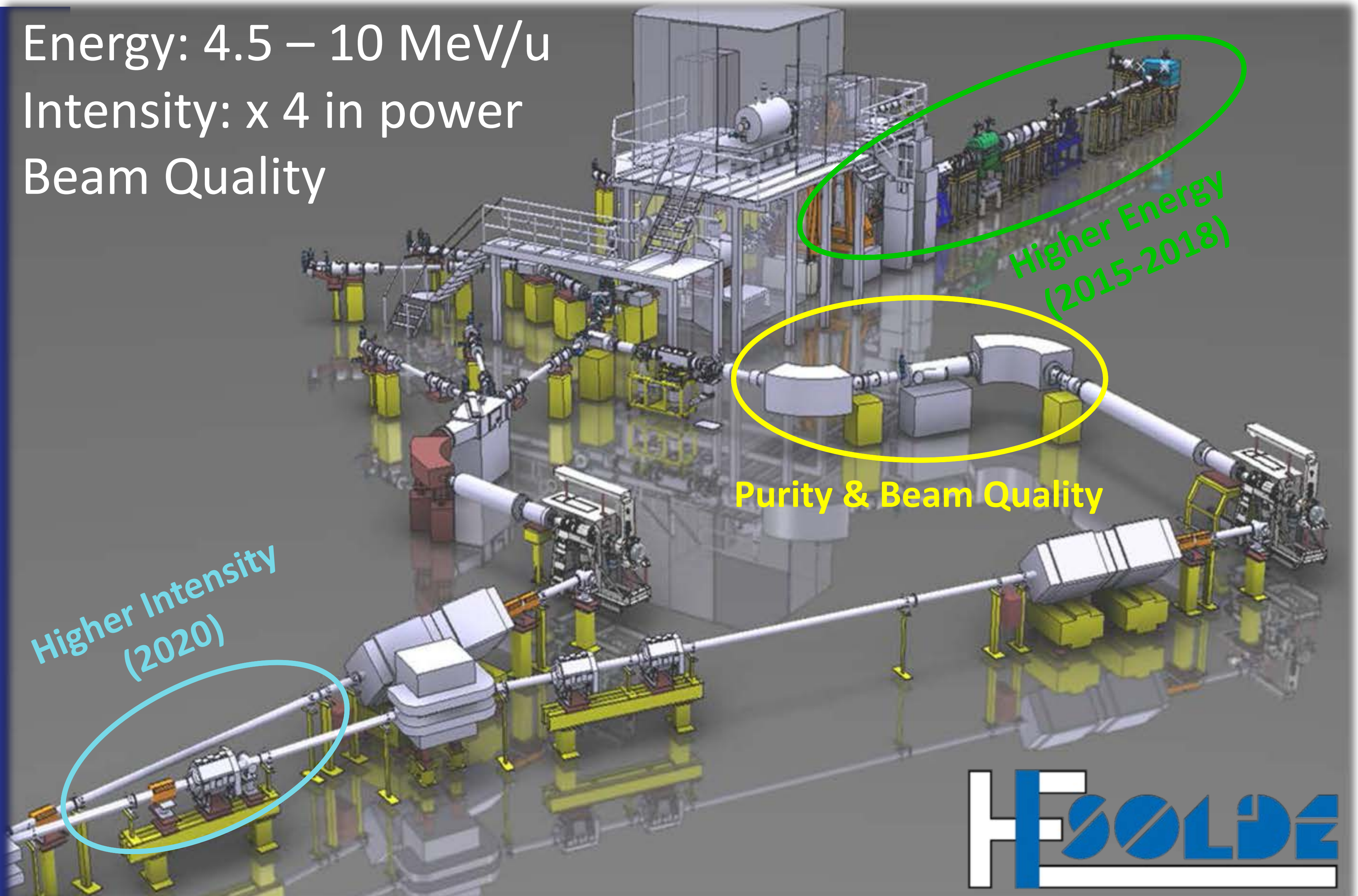

ISOLDE
LHe cryo
RILIS
Target zone
RF
Separators
Proton driver
HIE-ISOLDE
REX
WITCH
ISCOOL
NICOLE
VITO
Solid state physics collections
TAS
HIE-ISOLDE experimental area
IDS
CRIS
COLLAPS
Travelling setups
ISOLTRAP



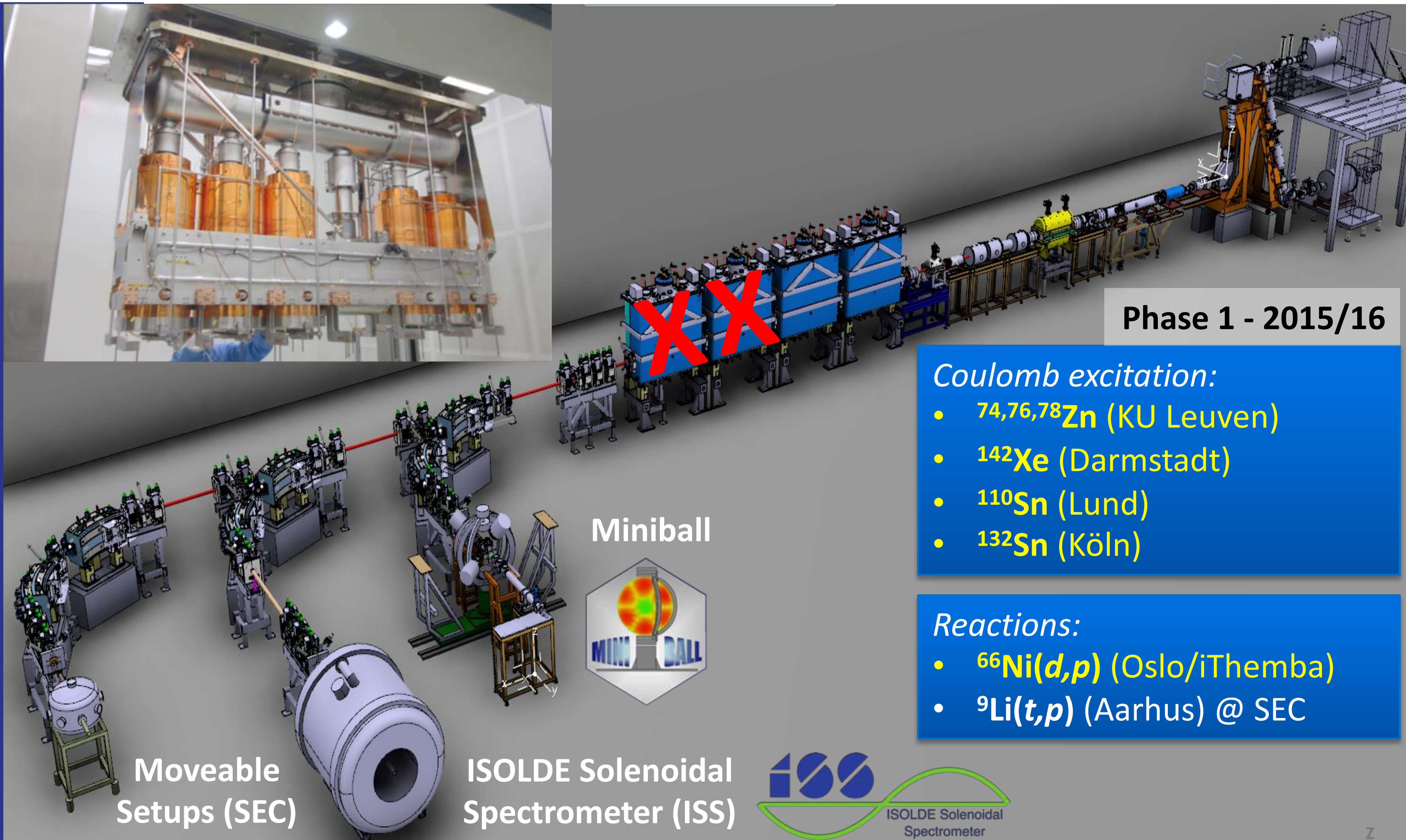
ISOLDE
LHe cryo
RILIS
Target zone
RF
Separators
Proton driver
HIE-ISOLDE
REX
HIE-ISOLDE
experimental area

# The HIE-ISOLDE project (2010 -)

Energy: 4.5 – 10 MeV/u
Intensity: x 4 in power
Beam Quality



# HIE-ISOLDE Phase 1 (2016)




*Coulomb excitation:*

- **$^{74,76,78}$Zn** (KU Leuven)
- **$^{142}$Xe** (Darmstadt)
- **$^{110}$Sn** (Lund)
- **$^{132}$Sn** (Köln)

*Reactions:*

- **$^{66}$Ni(*d*,*p*)** (Oslo/iThemba)
- **$^{9}$Li(*t*,*p*)** (Aarhus) @ SEC

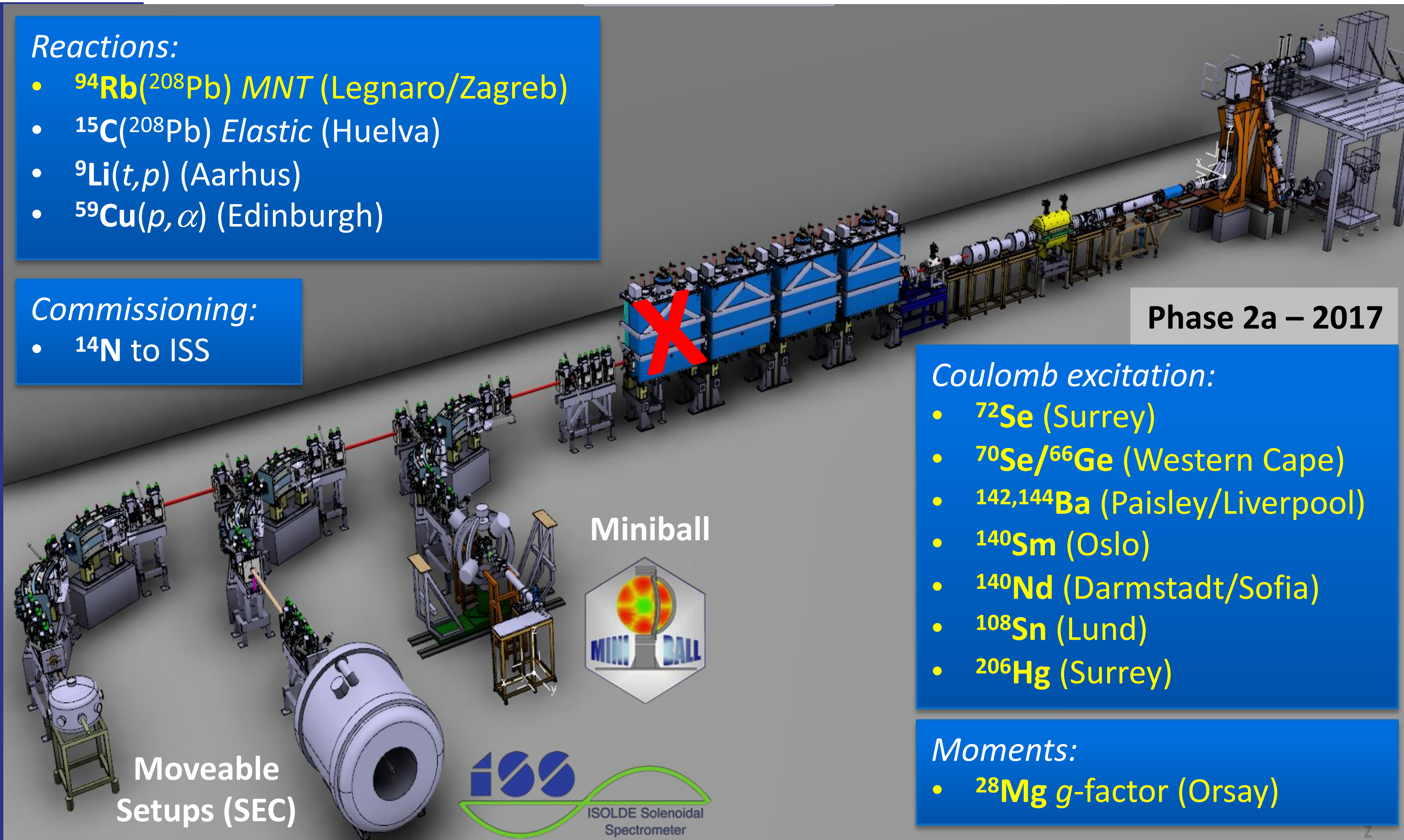
# HIE-ISOLDE Phase 2a (2017)

*Reactions:*

- $^{94}$**Rb**($^{208}$Pb) *MNT* (Legnaro/Zagreb)
- $^{15}$**C**($^{208}$Pb) *Elastic* (Huelva)
- $^{9}$**Li**($t,p$) (Aarhus)
- $^{59}$**Cu**($p,\alpha$) (Edinburgh)

*Commissioning:*

- $^{14}$**N** to ISS




*Coulomb excitation:*

- $^{72}$**Se** (Surrey)
- $^{70}$**Se**/$^{66}$**Ge** (Western Cape)
- $^{142,144}$**Ba** (Paisley/Liverpool)
- $^{140}$**Sm** (Oslo)
- $^{140}$**Nd** (Darmstadt/Sofia)
- $^{108}$**Sn** (Lund)
- $^{206}$**Hg** (Surrey)

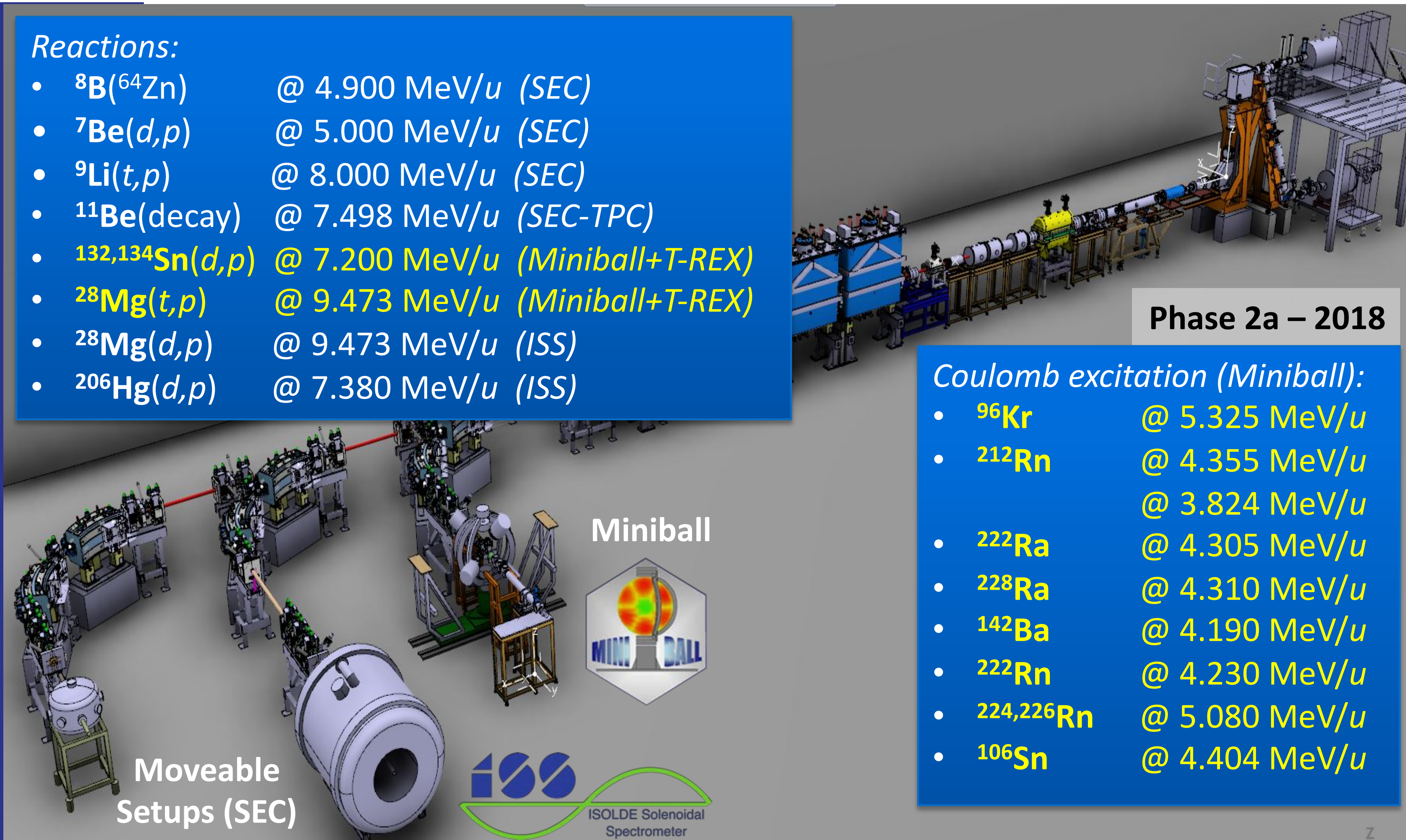
*Moments:*

- $^{28}$**Mg** *g*-factor (Orsay)

# HIE-ISOLDE Phase 2b (2018)

*Reactions:*

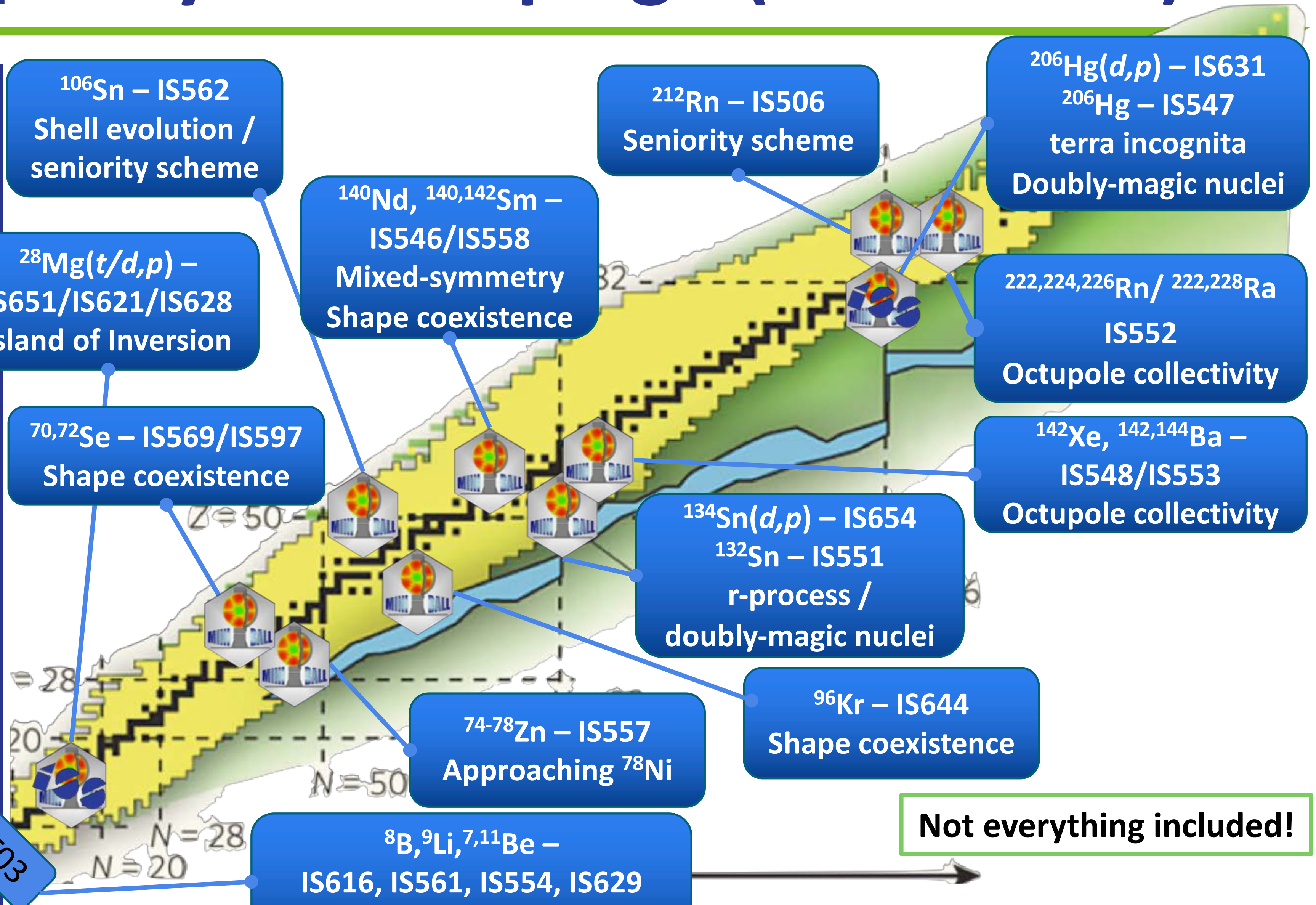
- $^{8}$**B**($^{64}$Zn) @ 4.900 MeV/*u* *(SEC)*
- $^{7}$**Be**(*d,p*) @ 5.000 MeV/*u* *(SEC)*
- $^{9}$**Li**(*t,p*) @ 8.000 MeV/*u* *(SEC)*
- $^{11}$**Be**(decay) @ 7.498 MeV/*u* *(SEC-TPC)*
- $^{132,134}$**Sn**(*d,p*) @ 7.200 MeV/*u* *(Miniball+T-REX)*
- $^{28}$**Mg**(*t,p*) @ 9.473 MeV/*u* *(Miniball+T-REX)*
- $^{28}$**Mg**(*d,p*) @ 9.473 MeV/*u* *(ISS)*
- $^{206}$**Hg**(*d,p*) @ 7.380 MeV/*u* *(ISS)*




*Coulomb excitation (Miniball):*

- $^{96}$**Kr** @ 5.325 MeV/*u*
- $^{212}$**Rn** @ 4.355 MeV/*u*
  @ 3.824 MeV/*u*
- $^{222}$**Ra** @ 4.305 MeV/*u*
- $^{228}$**Ra** @ 4.310 MeV/*u*
- $^{142}$**Ba** @ 4.190 MeV/*u*
- $^{222}$**Rn** @ 4.230 MeV/*u*
- $^{224,226}$**Rn** @ 5.080 MeV/*u*
- $^{106}$**Sn** @ 4.404 MeV/*u*

# Physics campaign (2016-2018)




$^{106}$Sn – IS562
Shell evolution / seniority scheme

$^{28}$Mg(*t*/*d*,*p*) – IS651/IS621/IS628
Island of Inversion

$^{70,72}$Se – IS569/IS597
Shape coexistence

$^{140}$Nd, $^{140,142}$Sm – IS546/IS558
Mixed-symmetry
Shape coexistence

$^{212}$Rn – IS506
Seniority scheme

$^{206}$Hg(*d*,*p*) – IS631
$^{206}$Hg – IS547
terra incognita
Doubly-magic nuclei

$^{222,224,226}$Rn/ $^{222,228}$Ra
IS552
Octupole collectivity

$^{142}$Xe, $^{142,144}$Ba – IS548/IS553
Octupole collectivity

$^{134}$Sn(*d*,*p*) – IS654
$^{132}$Sn – IS551
r-process / doubly-magic nuclei

$^{96}$Kr – IS644
Shape coexistence

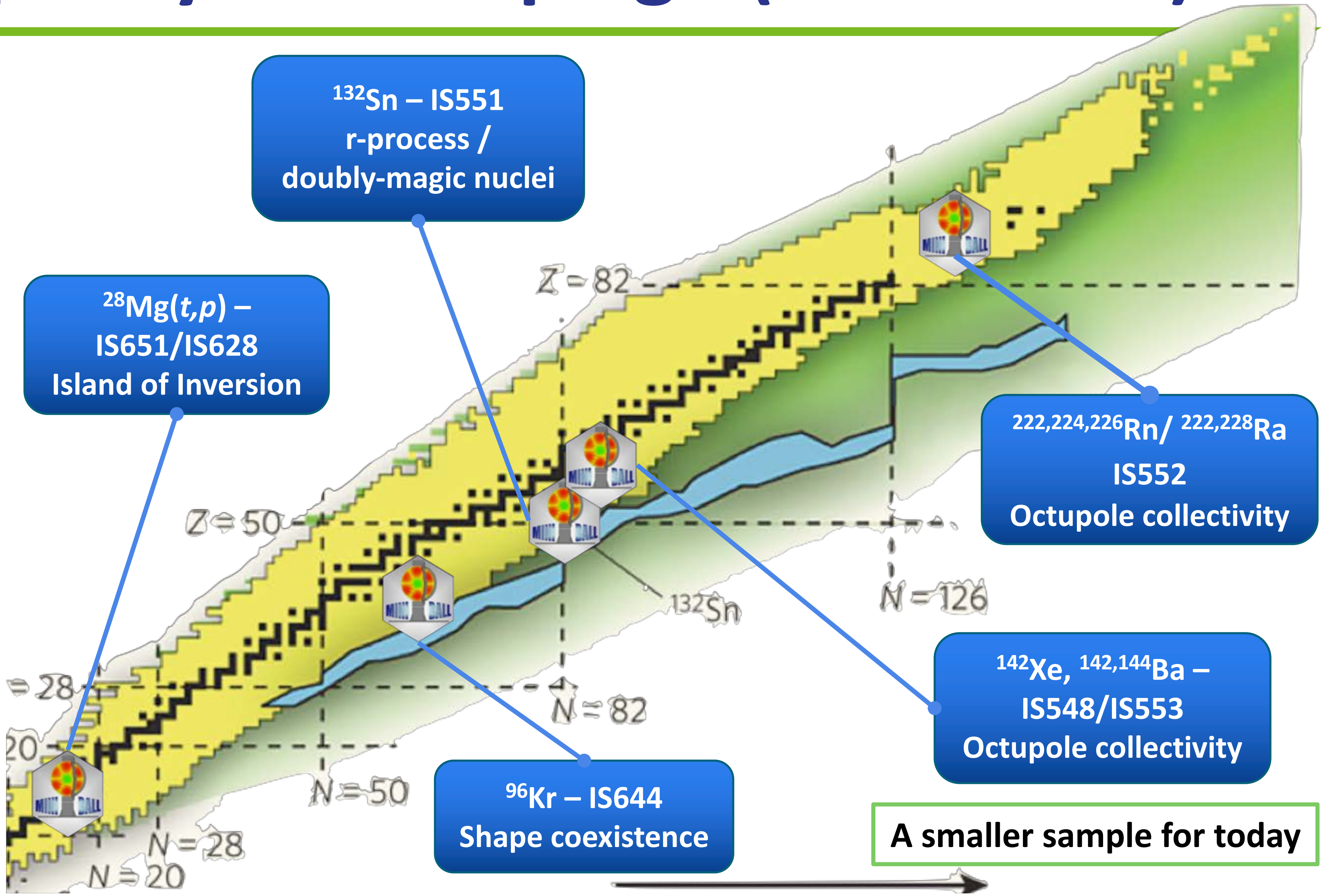
$^{74\text{-}78}$Zn – IS557
Approaching $^{78}$Ni

$^{8}$B, $^{9}$Li, $^{7,11}$Be –
IS616, IS561, IS554, IS629
Halo nuclei, astrophysics

**Not everything included!**

ISOLDE

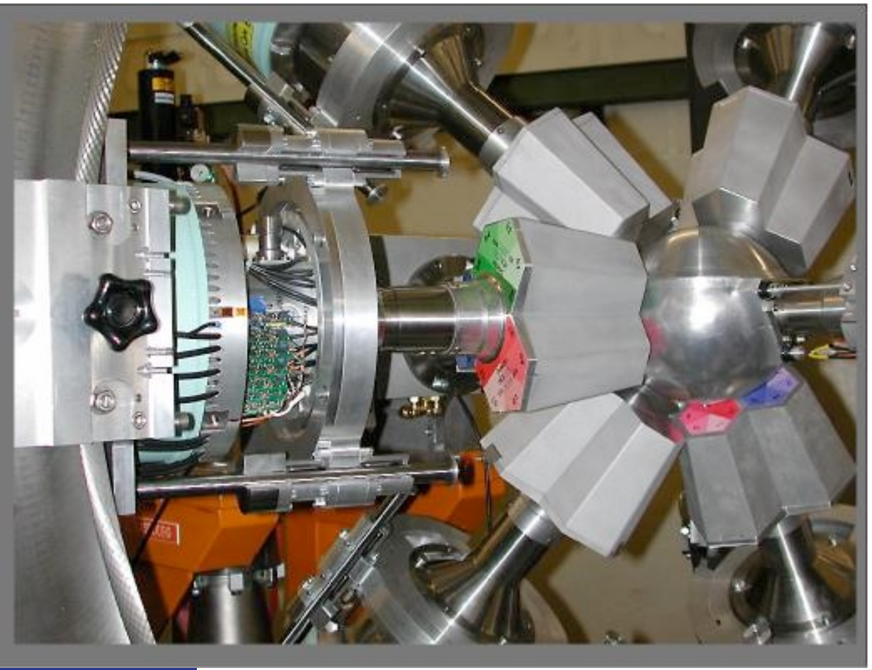
# Physics campaign (2016-2018)




A smaller sample for today

# Miniball @ HIE-ISOLDE

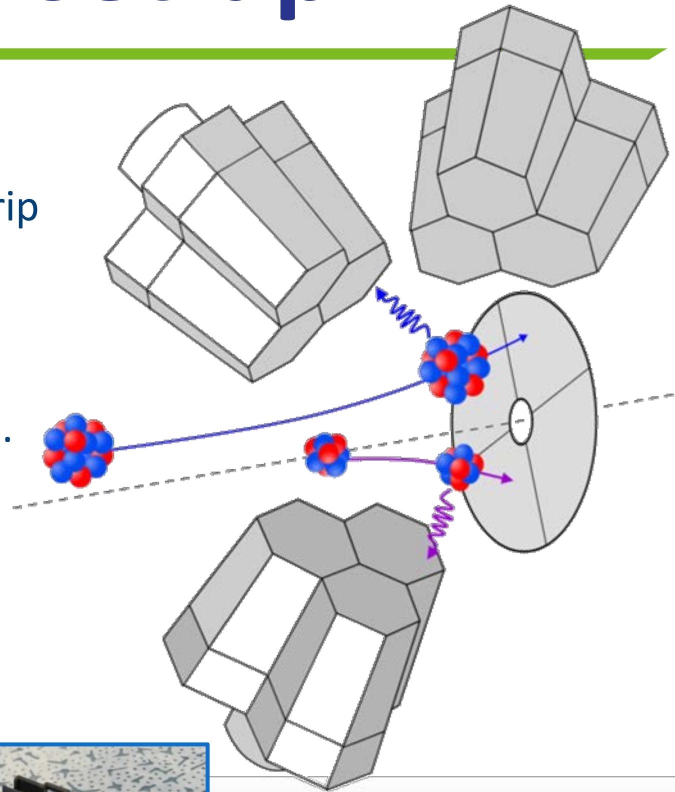
# Miniball: Coulex set-up



Particle ID in a Double-Sided Si Strip Detector (DSSSD).

Event-by-event Doppler correction.

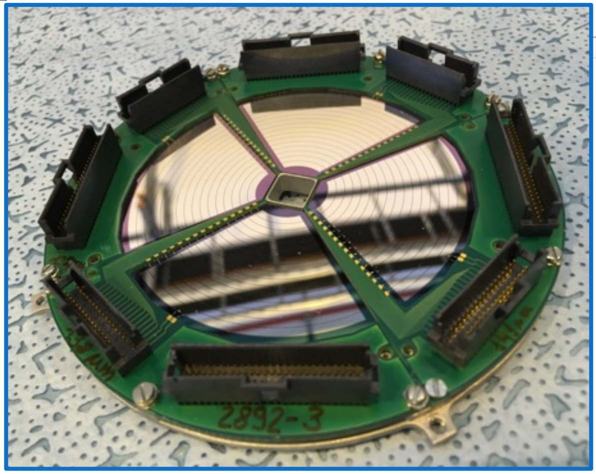
$\sim 20^\circ < \theta_{lab} < \sim 60^\circ$



Array of HPGe of 8 triple clusters

6-fold electronic segmentation

ε > 7% for 1.3MeV γ-rays

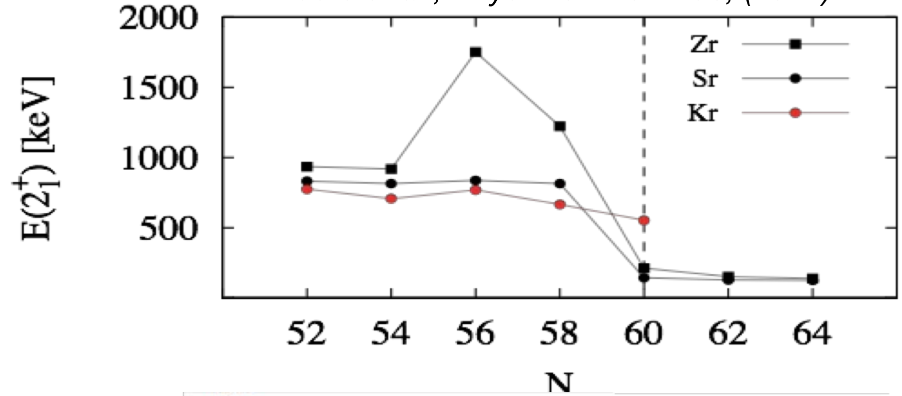


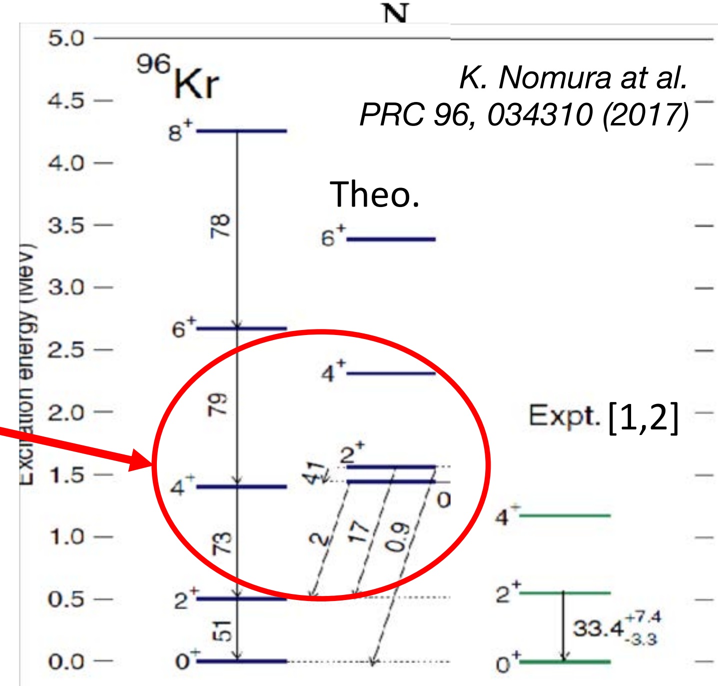
*N. Warr et al.*, EPJ **49** (2013)

# Shape coexistence in $^{96}$Kr

- Sudden shape change in Zr, Sr, Kr
- Drop in $E(2_1^+)$, but not observed for Kr in earlier REX-ISOLDE experiment [1].
- Shape coexistence and mixing?
- New results:
  - $4^+$ from AGATA at GANIL [2]
  - States in $^{98,100}$Kr from RIKEN [3]
  - Preliminary $^{96}$Kr states from RIKEN [4]
- Employ Coulomb-Nuclear Excitation (CNE), to access non-yrast states.

*M. Albers et al., Phys. Rev. Lett 108, (2012)*





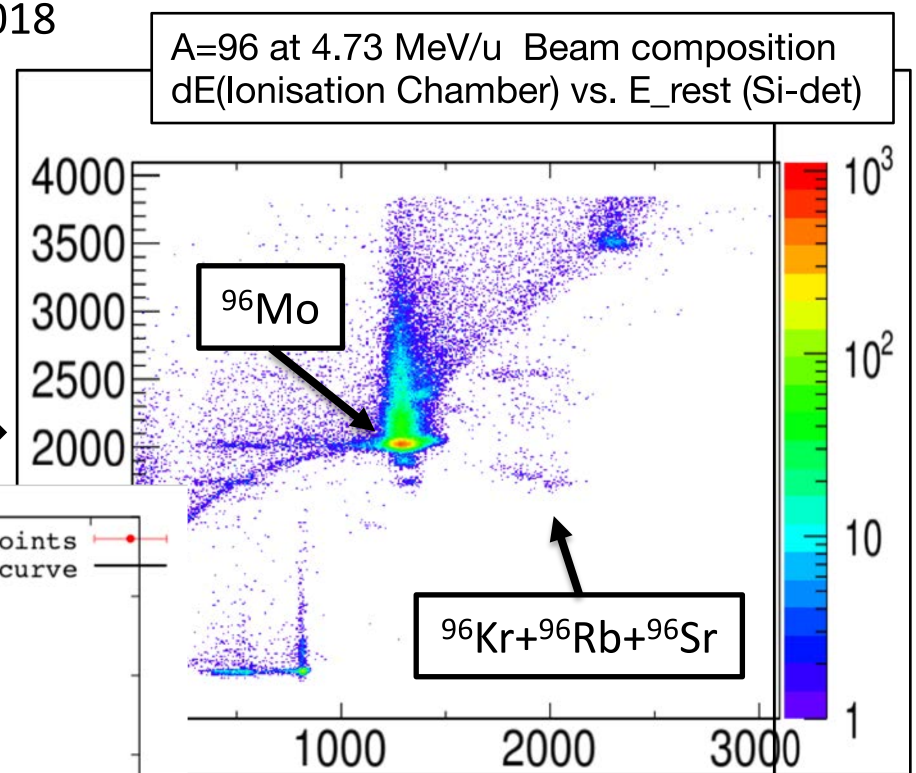
*[1] M. Albers et al., Phys. Rev. Lett 108, (2012)*
*[2] Dudouet et. al PRL 118, 162501 (2017)*
*[3] Flavigny et. al PRL 118, 242501 (2017)*
*[4] K. Moschner et al., in preparation*

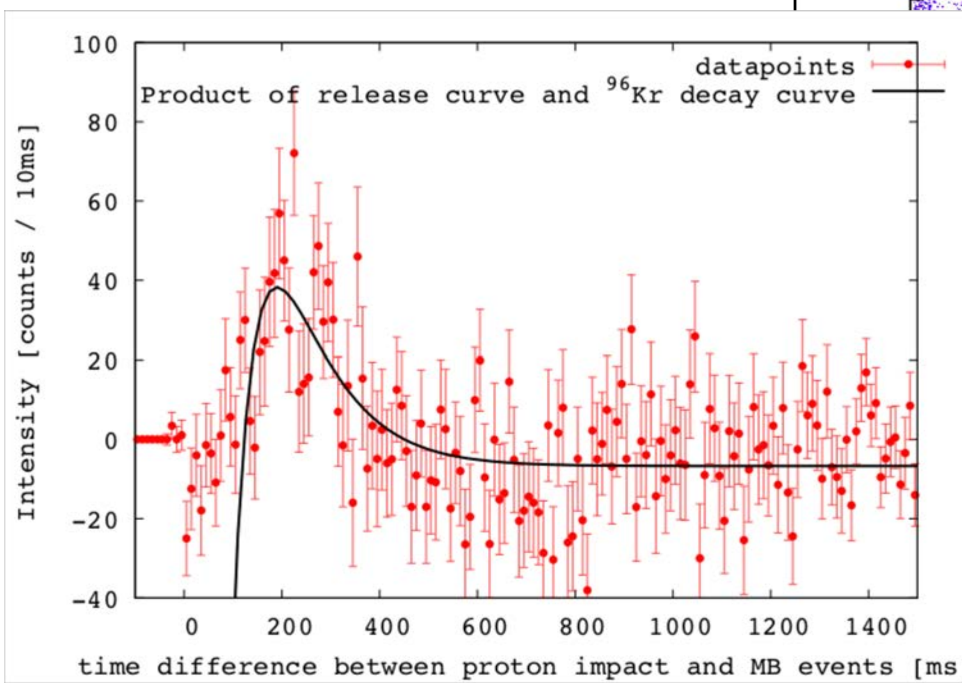



Courtesy of A. Blazhev, Köln

# A challenging beam: $^{96}Kr$

- First Miniball/HIE-ISOLDE run of 2018
- In-beam decay to $^{96}Rb$ + $^{96}Sr$
  - $T_{½}(^{96}Kr)$ = **80 ms**
  - $T_{release}$ ~ 50 ms
  - $T_{EBIS}$ ~ 100 ms
- Zero-degree ionisation chamber →



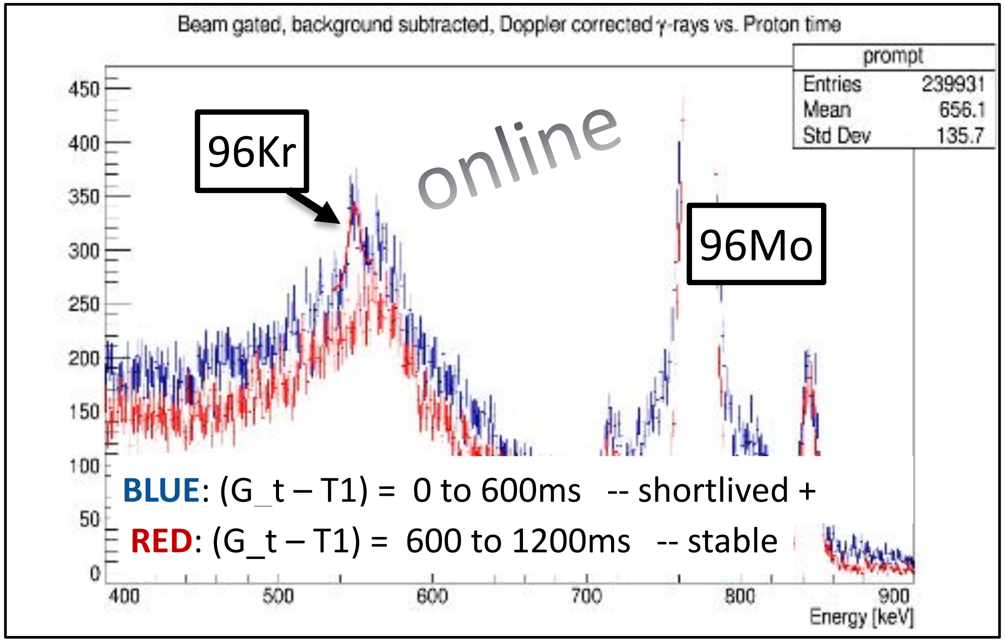

← Identifying gamma-rays with lifetime of $^{96}Kr$

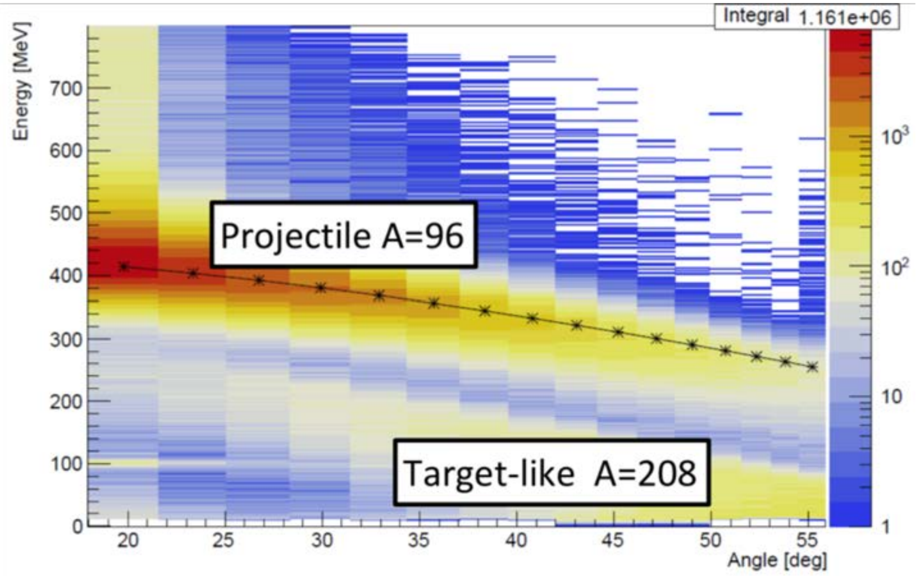
ISOLDE

# Identifying states in $^{96}$Kr

- CERN "heartbeat" of 1.2s
- $^{96}$Kr only present in first half
- Use proton – Miniball timing to get "clean" $^{96}$Kr spectrum

- Analysis on-going…
  - Search for high-lying states
  - Low statistics due to saturation of ion-source



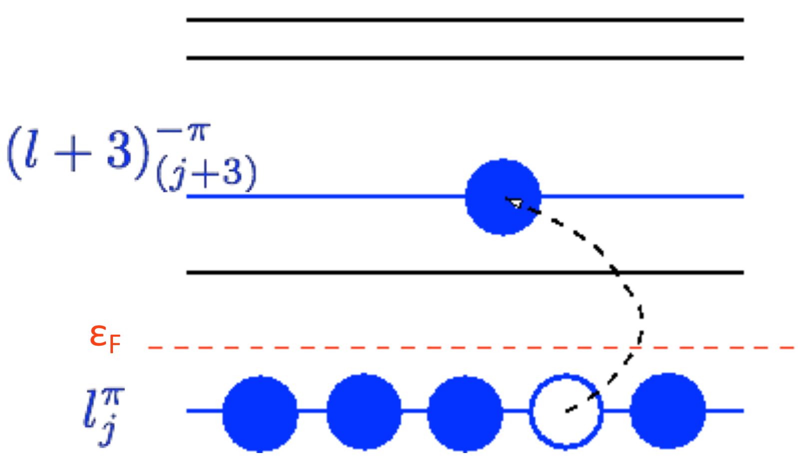



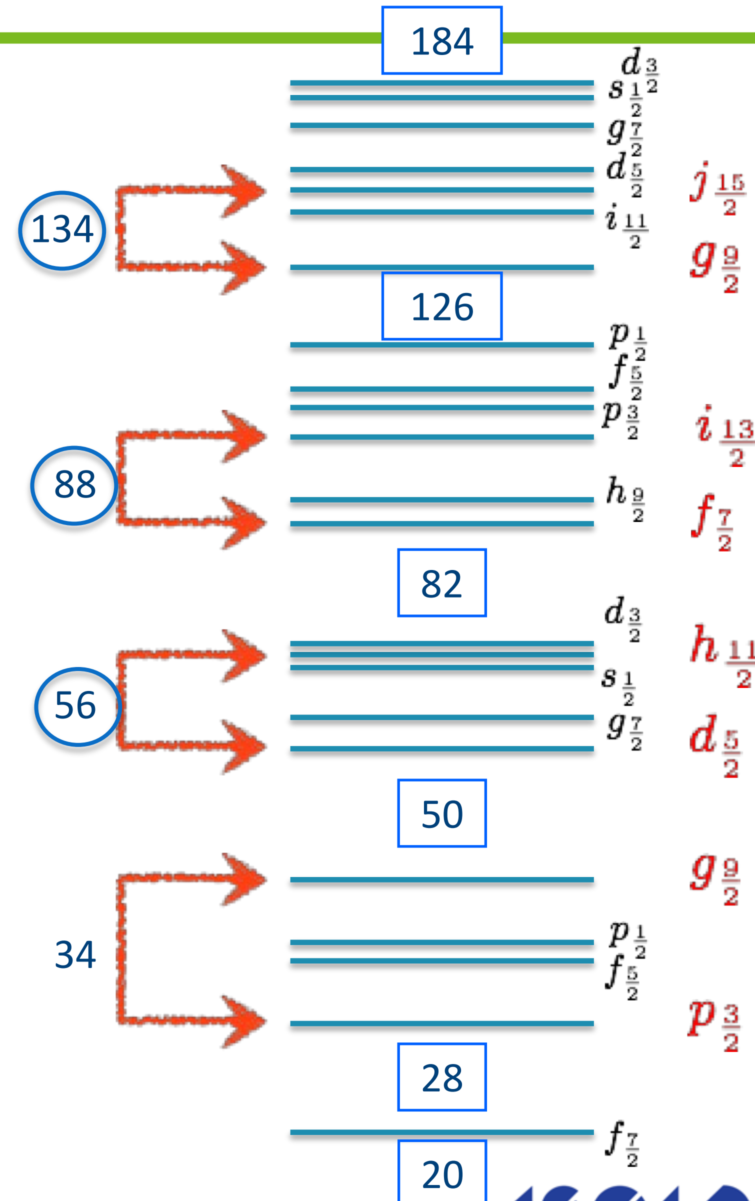

Courtesy of A. Blazhev, Nigel Warr and Julia Litzinger, Köln

# Octupole Collectivity

**Microscopically driven...**

Intruder orbitals of opposite parity and ΔJ, ΔL = 3 close to the Fermi level



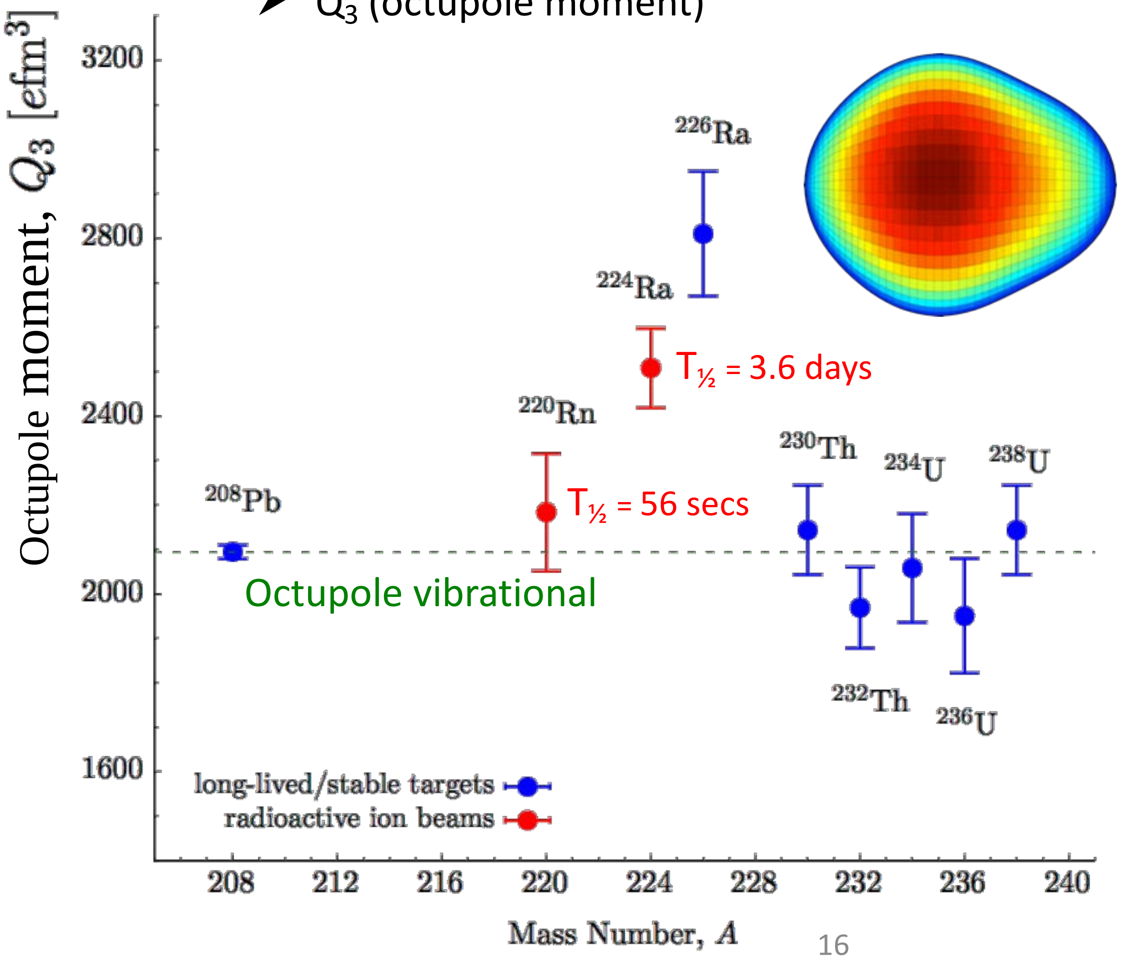



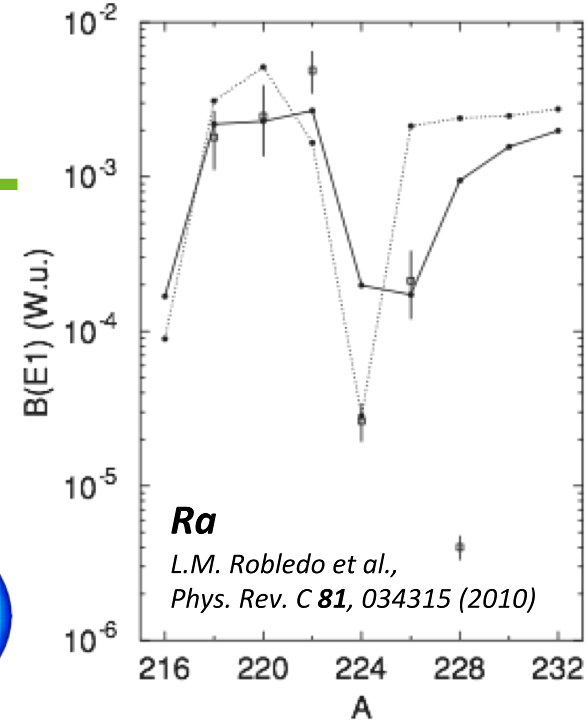

$^{224}$**Ra** (actinides)
*Z* = 88, *N* = 134 region

$^{144}$**Ba** (lanthanides)
*Z* = 56, *N* = 88 region

# The Actinides

- B(E1) sensitive to microscopic effects →
- B(E3) accessible with Coulex
  - $Q_3$ (octupole moment)



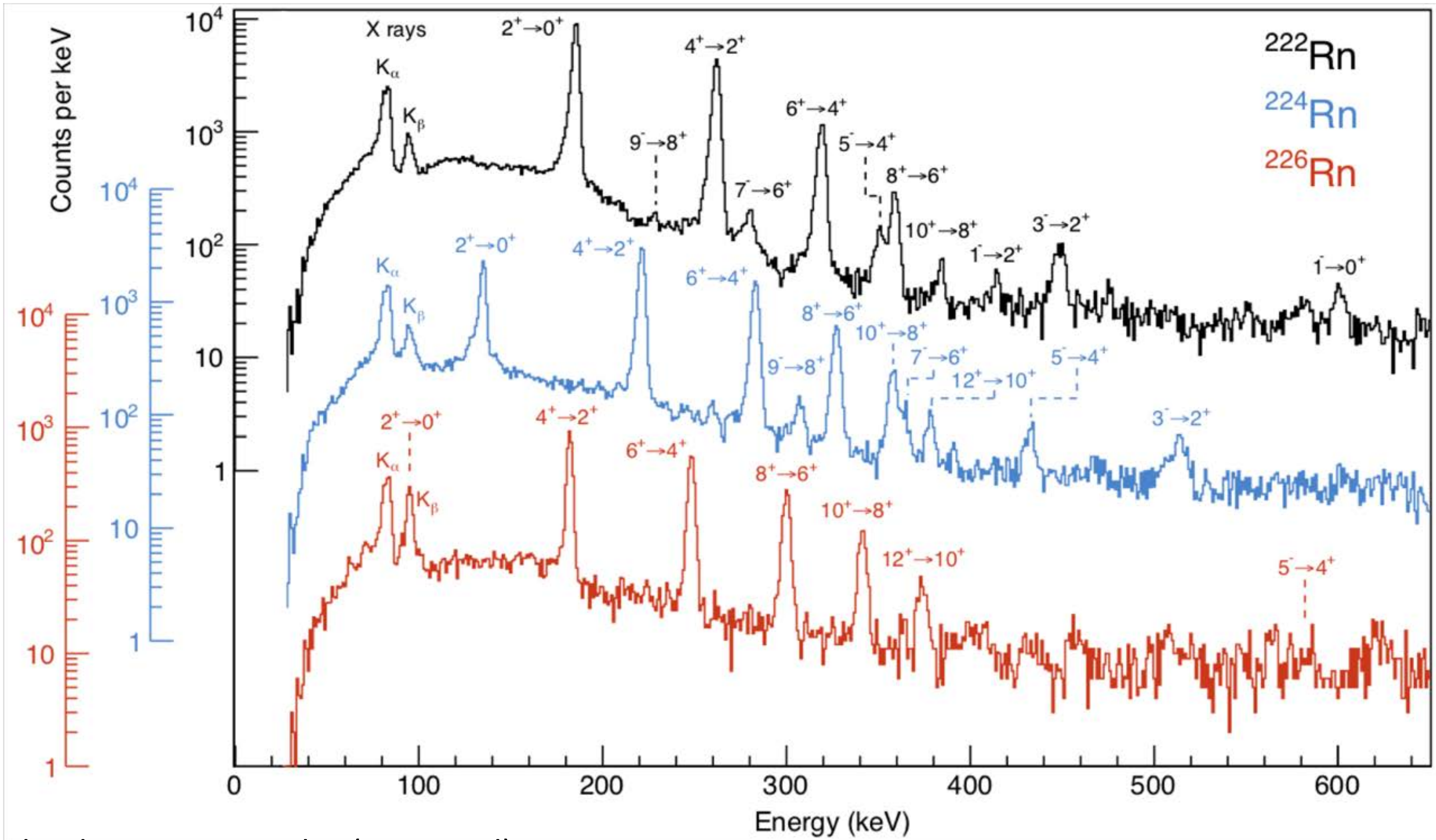




*L.M. Robledo et al., Phys. Rev. C **81**, 034315 (2010)*


*L. P. Gaffney et al., Nature **497**, 199 (2013)*

# $^{224,226}$Rn – Virgin nuclei

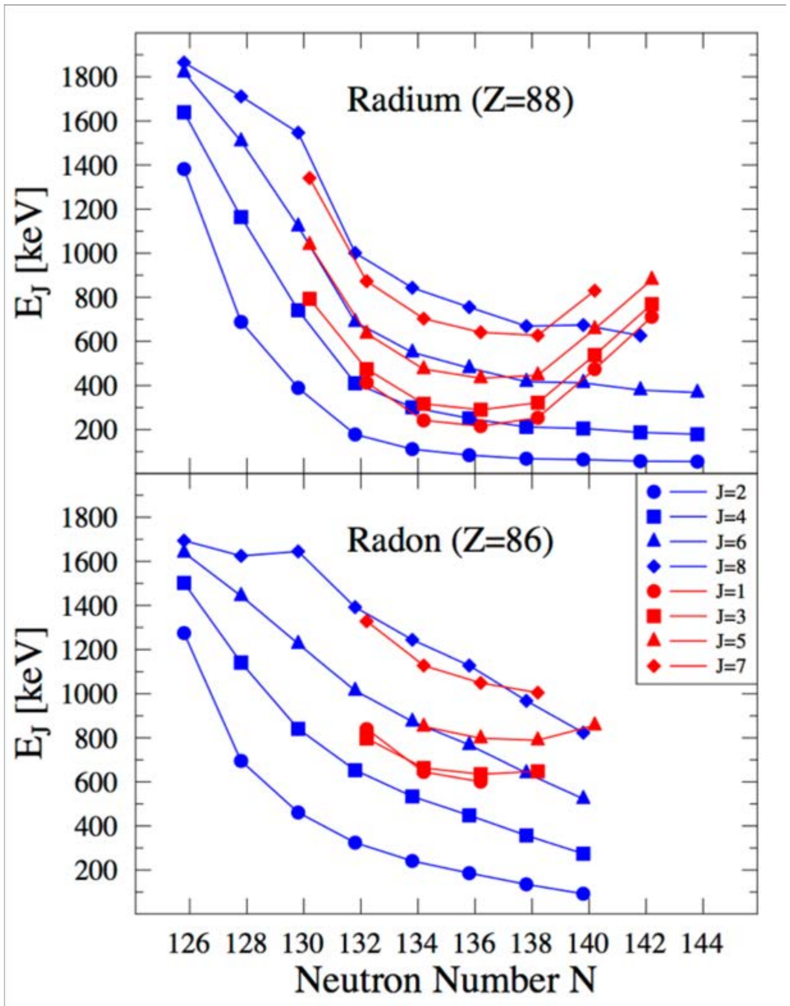
- Higher beam energy (5.1 MeV/*u*), with aim of maximising multi-step excitation

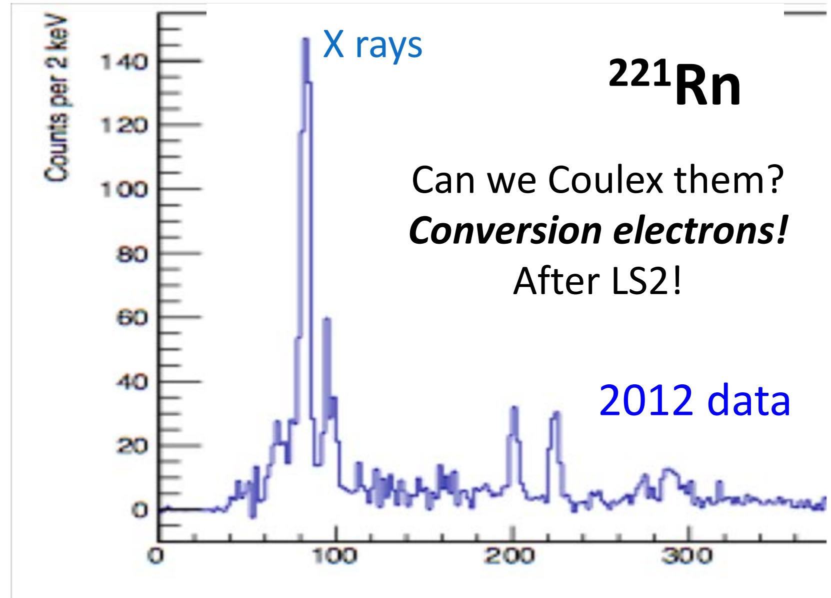



Thanks to Peter Butler (Liverpool)
and Pietro Spagnoletti (UWS Paisley)

# What about odd-mass Rn?

- Are $^{221,223}$Rn good candidates for the EDM measurements?



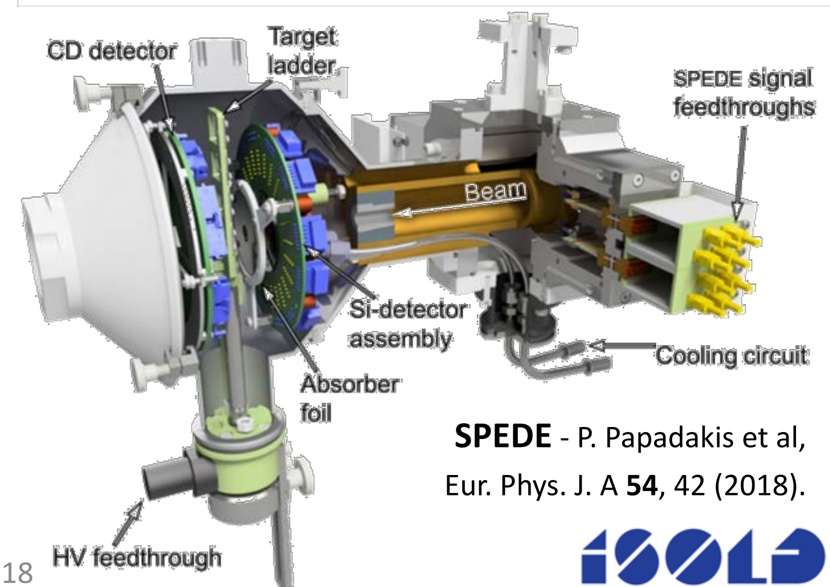

**$^{221}$Rn**

Can we Coulex them?

***Conversion electrons!***

After LS2!

2012 data

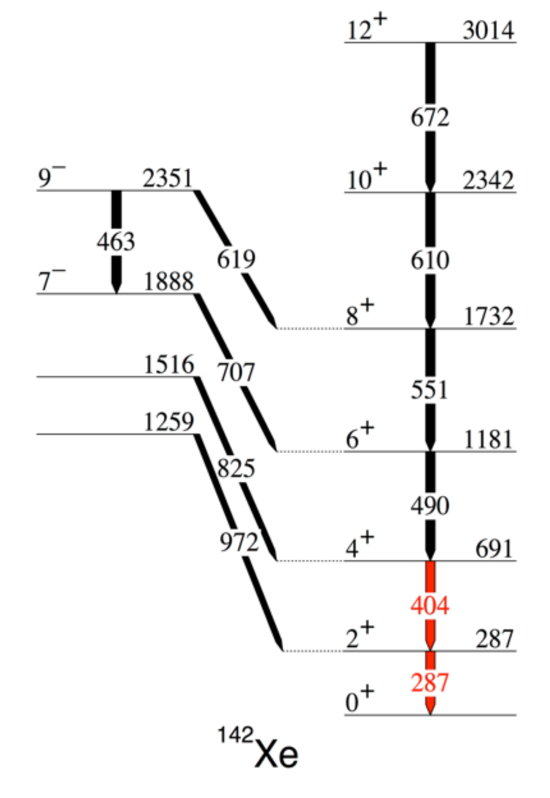


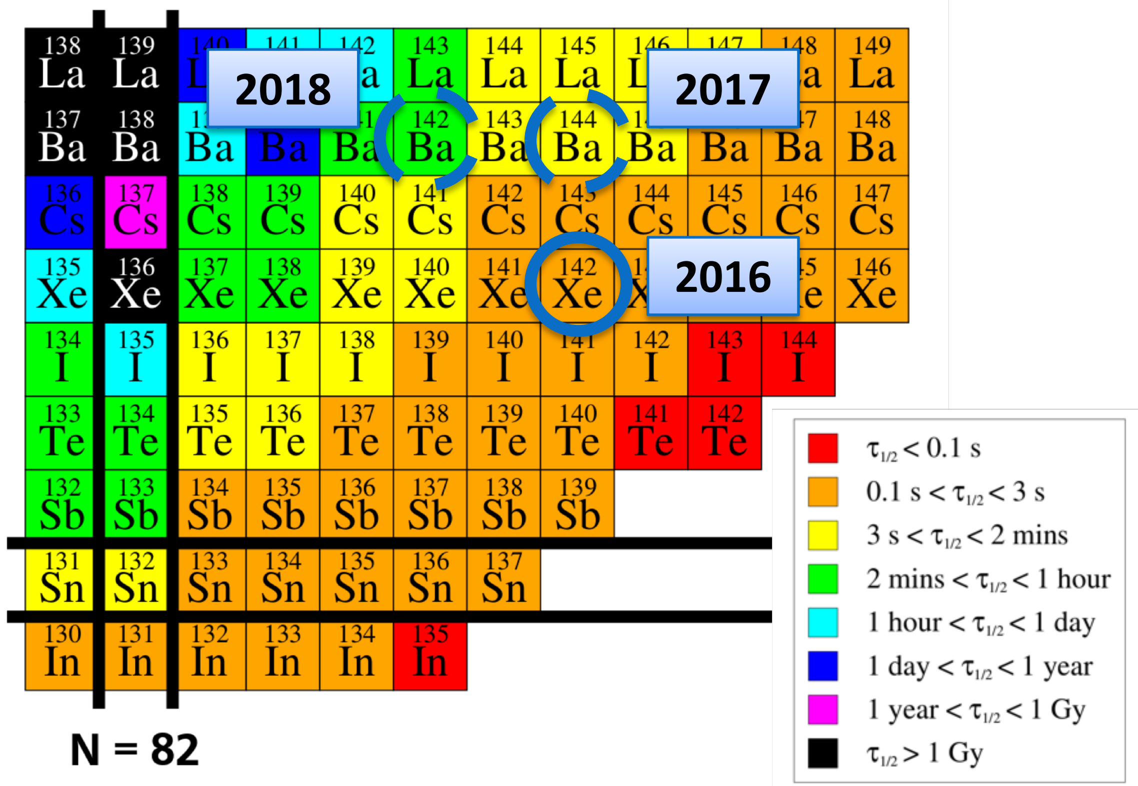

**SPEDE** - P. Papadakis et al, Eur. Phys. J. A **54**, 42 (2018).

# The Lanthanides

- Regions to the north-east of doubly-magic shell closures, good candidates for octupole deformation.
- B(E3) known to be good measure; CARIBU@ANL[1,2] – $^{144}$Ba = $48^{+25}_{-34}$ W.u.

  $^{146}$Ba = $48^{+21}_{-29}$ W.u.



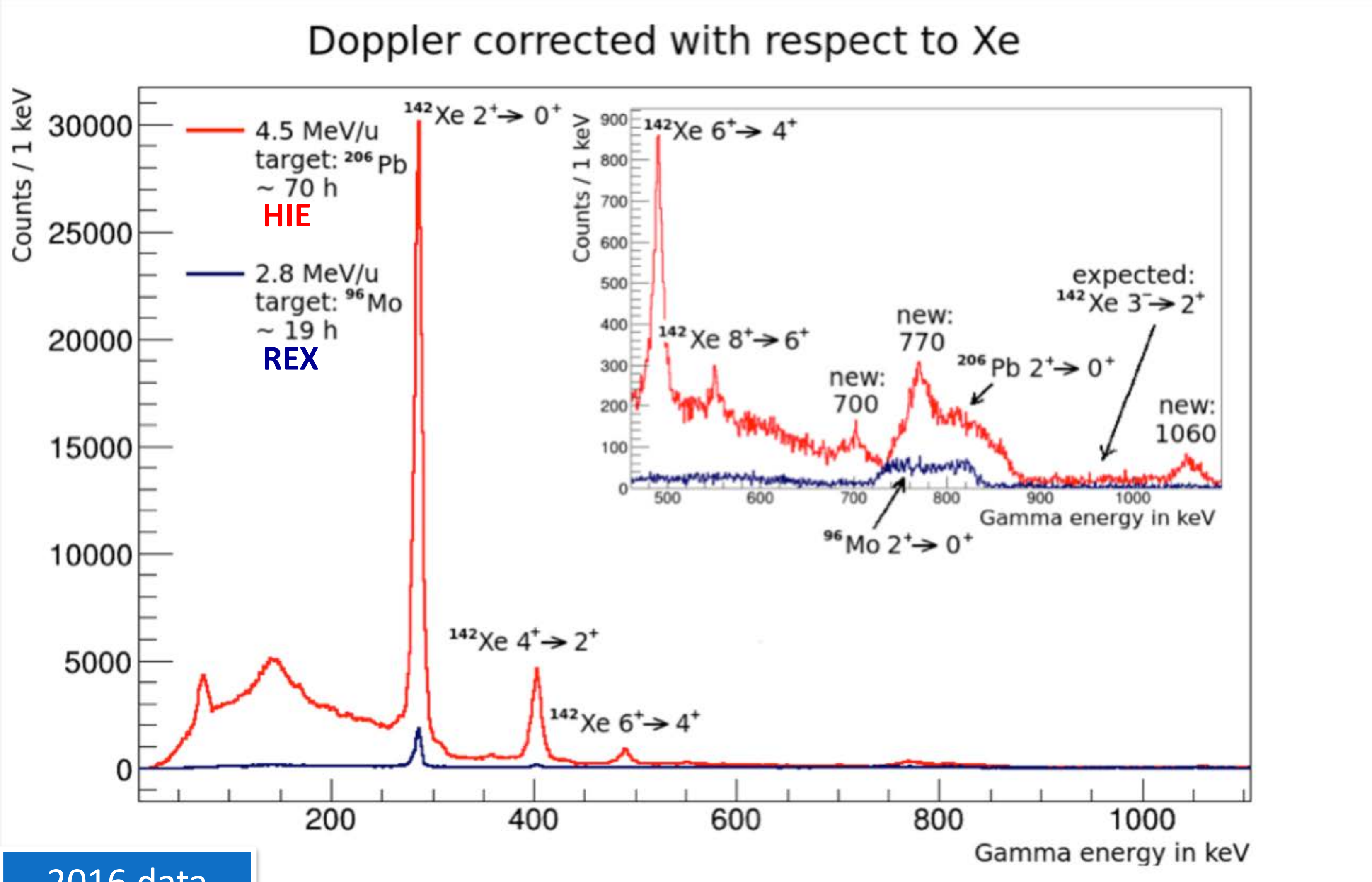





[1] B. Bucher et al. *Phys. Rev. Lett.* **116**, 112503 (2016)

[2] B. Bucher et al. *Phys. Rev. Lett.* **118**, 152504 (2017)

# Comparison of REX/HIE – $^{142}Xe$



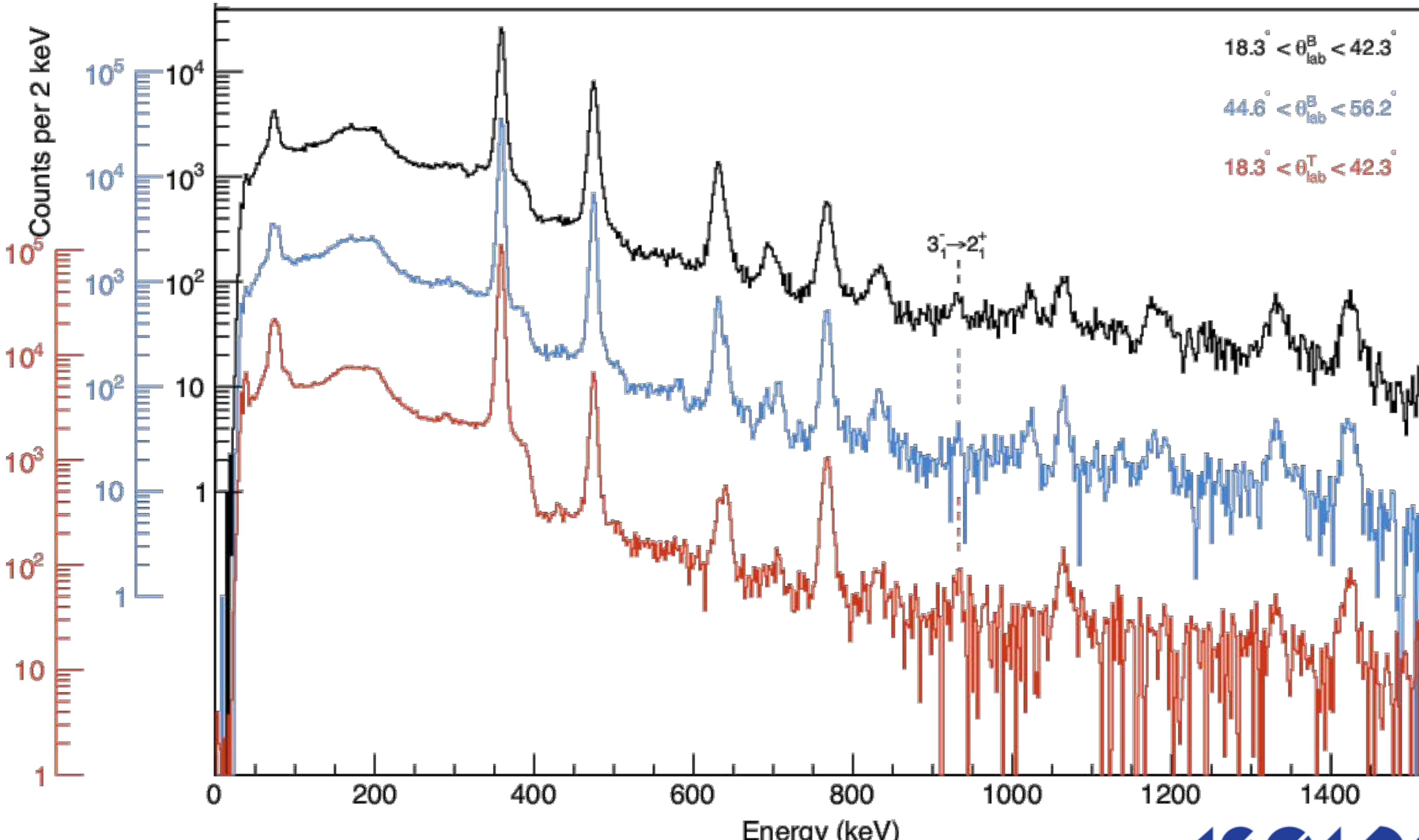

2016 data

Thanks to Corinna Henrich and Thorsten Kröll (Darmstadt)

# $^{142}Ba$ on $^{208}Pb$

2018 data

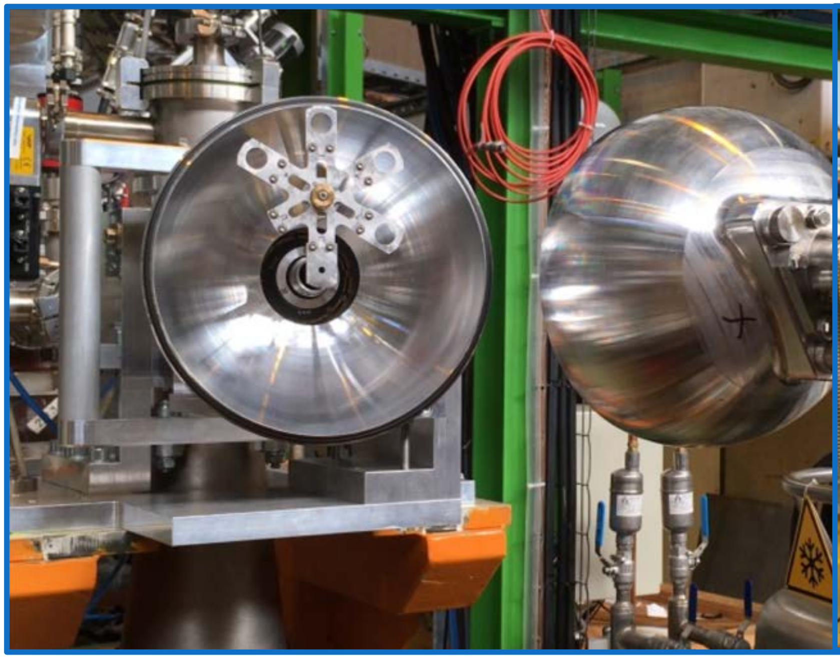
- Laser ionised (RILIS) with Cs suppressed using beam gate.
- Small contamination from isobars, but 50% duty cycle from beam gate.



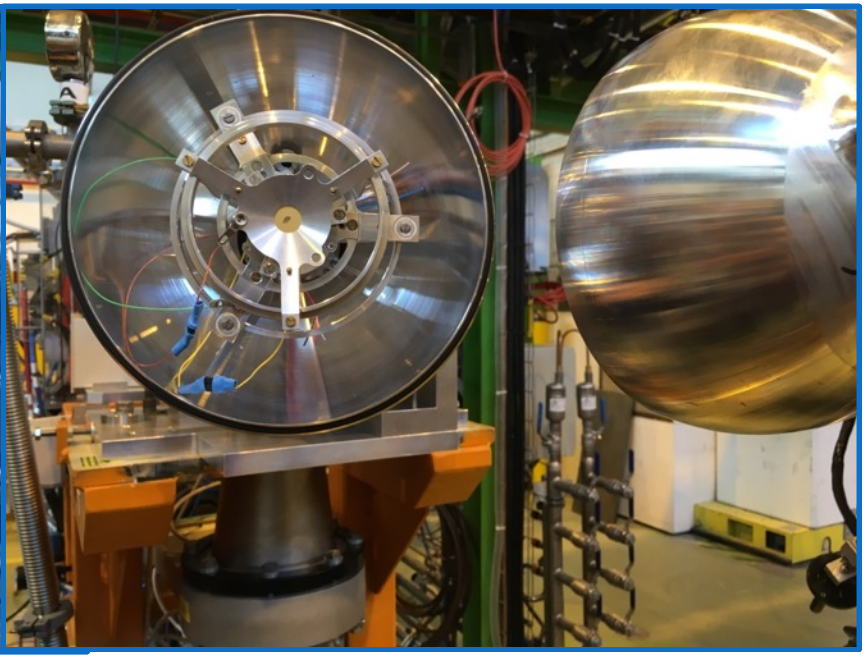
# New developments: Plunger

- New plunger chamber installed for 2017.
- Developed at IKP Köln.
- Excited-state lifetime measurements, g-factors, etc.

**Coulex target wheel**



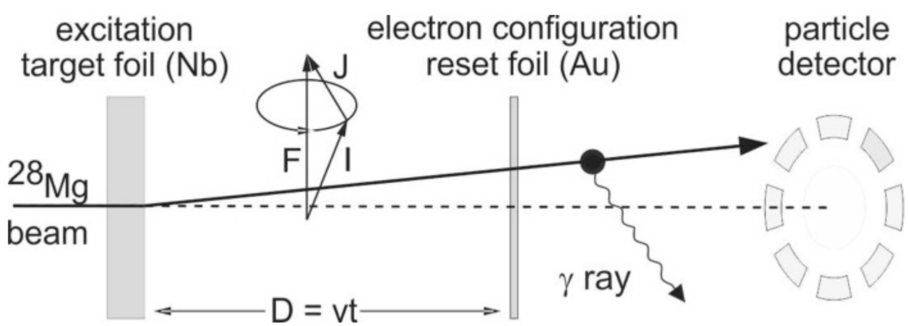
**Plunger**



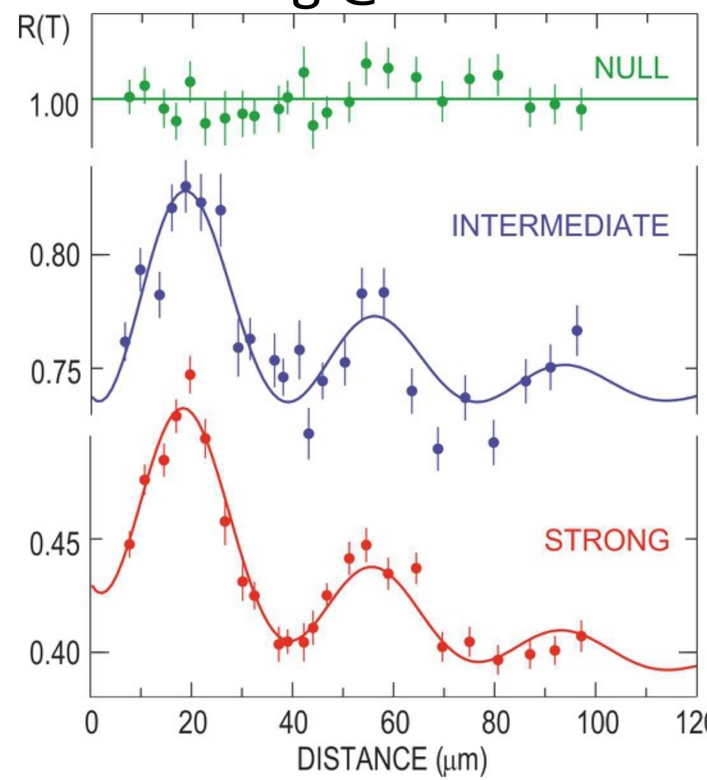
# TDRIV on H-like ions – IS628

- TDRIV - Interaction between the nuclear spins (oriented by the reaction) with the electron spins (random) for well defined time (plunger)

- H-like ions → well defined magnetic field (*1s*)



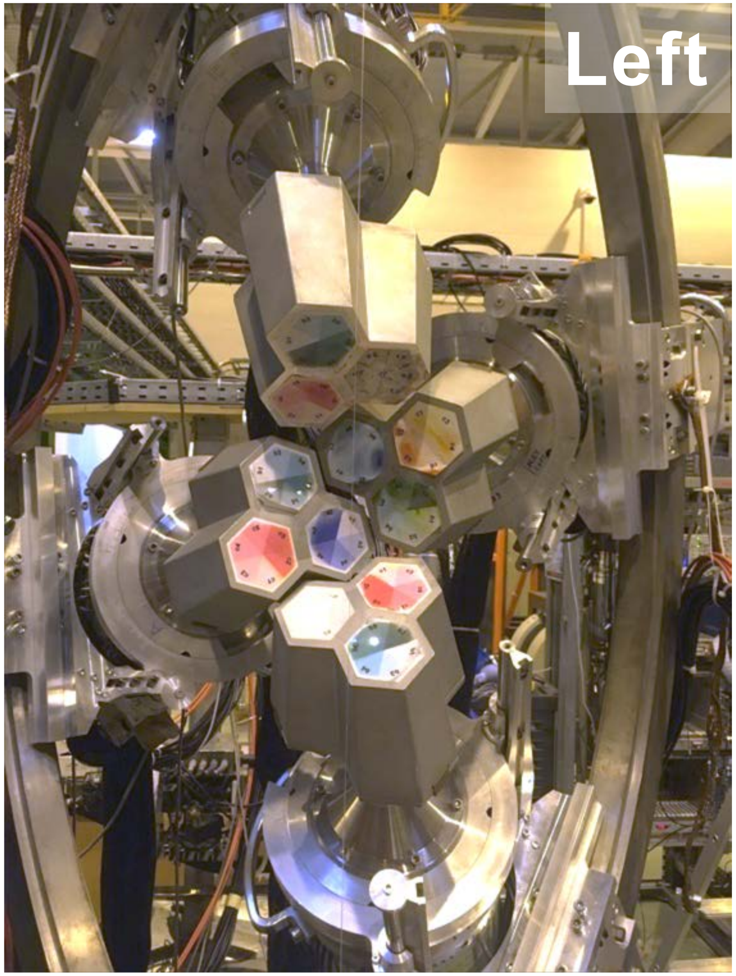

$^{24}Mg$ @ ALTO




$$W(\theta_p,\theta_\gamma) = \sum_{k,q} \sqrt{2k+1}\rho_{kq}(\theta_p) G_k F_k Q_k D_{q0}^{k*}(\phi_\gamma - \phi_p, \theta_\gamma, 0)$$

Amar Boukhari and Georgi Georgiev (IPN Orsay)
Andrew Stuchbery (ANU)

# Experimental setup – IS628



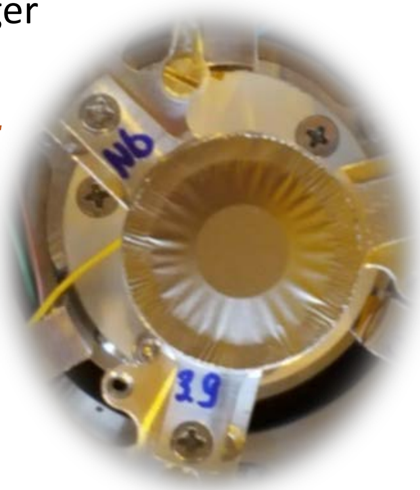

DSSD for particle detection

angular coverage:
θ = 21° – 50°
14 strips
φ = 0° – 360°
4 quadrants, 12 sectors

First use of Miniball plunger

*3.9 mg/cm² Nb target*

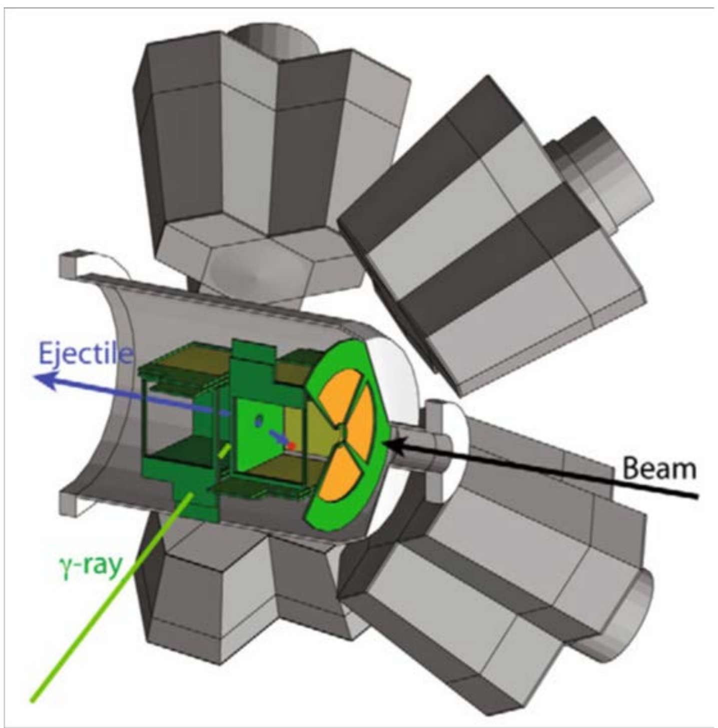
*1.1 mg/cm² Ta degrader*




Amar Boukhari and Georgi Georgiev (IPN Orsay)
Andrew Stuchbery (ANU)

# T-REX: (*t*/*d*,*p*) with Miniball

- Successful utilised at REX-ISOLDE.
- Transfer (*t*/*d*,*p*) in inverse kinematics.
- 66% solid angle (ΔE-E) for proton detection.
- γ-rays used to select states → high resolution




V. Bildstein et al, Eur. Phys. J. A (2012) **48**: 85

- Experiments in 2018:
  - **$^{134}$Sn(*d*,*p*)$^{135}$Sn**
  - **$^{28}$Mg(*t*,*p*)$^{30}$Mg**

# First publication: $^{132}$Sn

- Doubly-magic nucleus on the r-process path

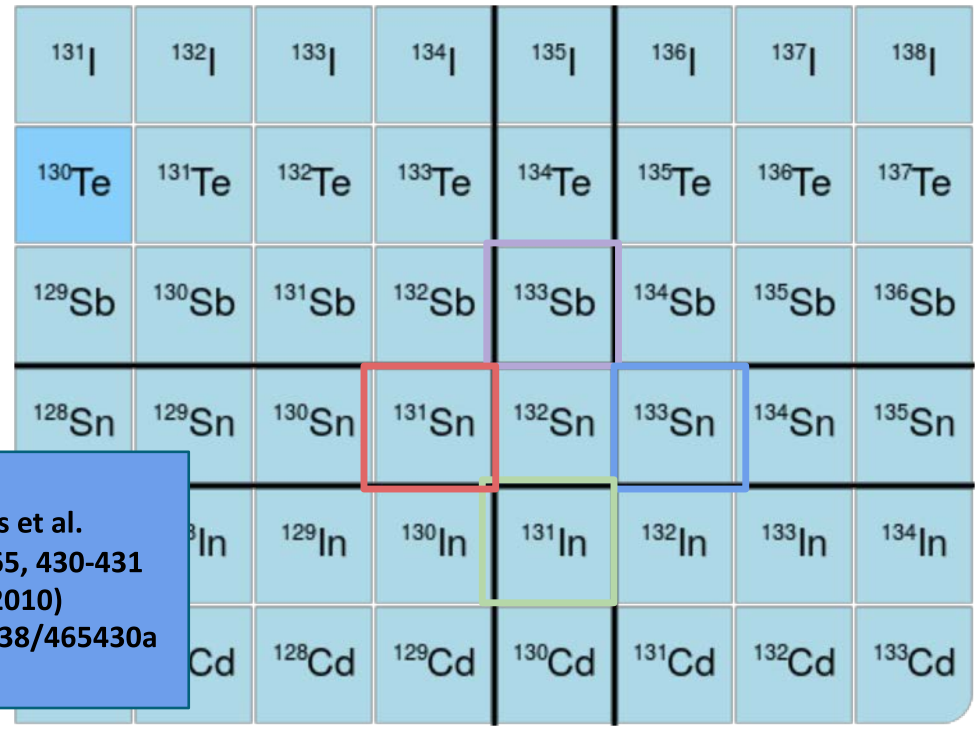
Single-particle properties:

**G. Bocchi et al.**
**PLB 760, 273-278 (2016)**
**Doi:10.1016/ j.physletb. 2016.06.065**

**R. L. Kozub et al.**
**PRL, 109, 172-177 (October 2012)**
**doi:10.1103/ PhysRevLett. 109.172501**

**K. L. Jones et al.**
**Nature 465, 430-431 (27 May 2010)**
**doi:10.1038/465430a**

**M. Gorska et al.**
**PLB 672, 4, 313-316, (2009)**
**doi:0.1016/j.phys letb. 2009.01.027**



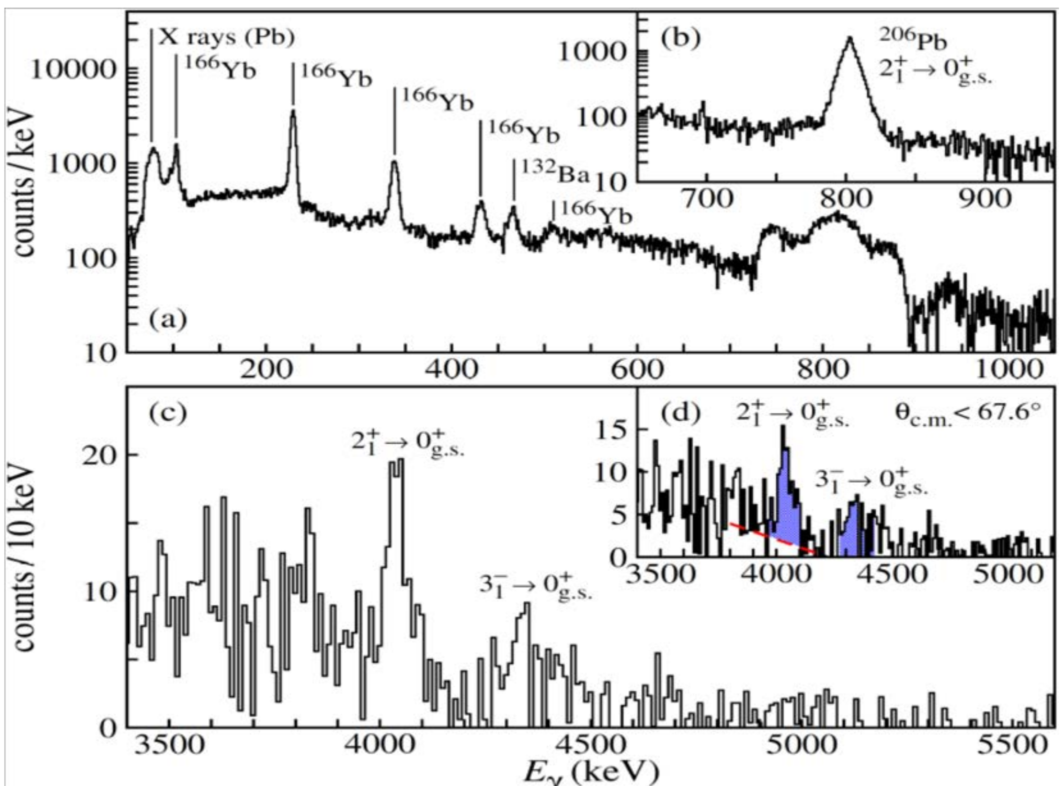

Coulomb excitation of $^{132}$Sn:
Collective properties?

D. Rosiak et al., *Phys. Rev. Lett.* **121**, 252501 (2018).

# First publication: $^{132}$Sn

- Molecular ISOLDE beam: $^{132}Sn^{34}S$
- HIE-ISOLDE beam: $^{132}Sn^{31+}$ @ 5.49 MeV/u
- Total RIB intensity: ~**3.0 x 10⁵** ions/s
- 'safe' scattering angles: lab = 17.8 - 41.5°
- Beam composition: $^{132}$Sn, $^{132}$Sb, $^{132}$Ba, $^{166}$Yb

C-REX Si array

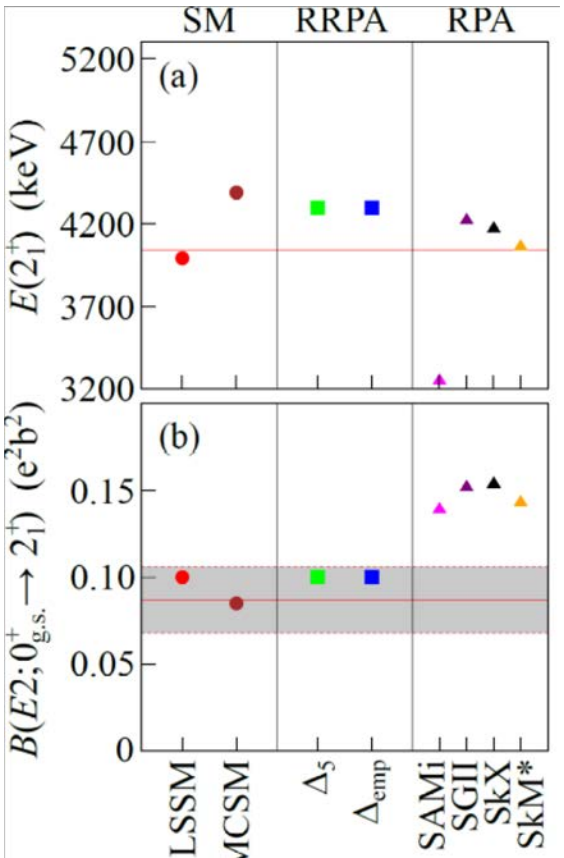


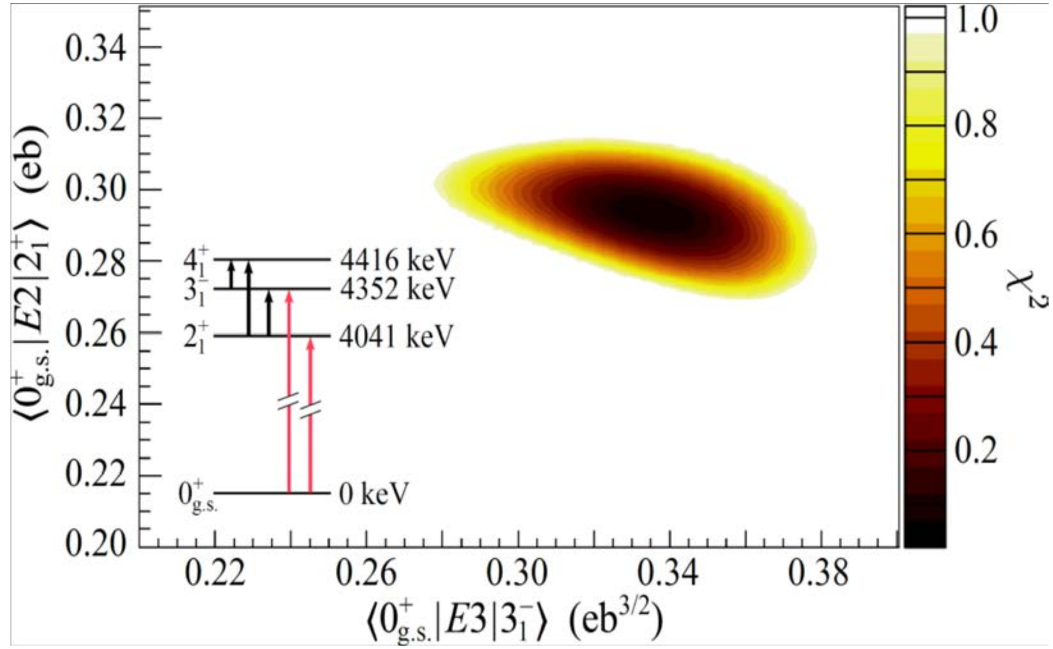

High energy efficiency using "fresh" $^{66}$Ga source, produced at ISOLDE

D. Rosiak et al., *Phys. Rev. Lett.* **121**, 252501 (2018).

# First publication: $^{132}$Sn

- Gosia used to extract B(E2) and B(E3) values
- Direct measurement of collectivity in $^{132}$Sn!




| | this work | previous |
|---|---|---|
| $B(E2; 0^+ \rightarrow 2^+)$ | 0.087(19) $e^2b^2$ | 0.14(6) $e^2b^2$ / 0.11(3) $e^2b^2$ |
| $B(E3; 0^+ \rightarrow 3^-)$ | 0.11(4) $e^2b^3$ | > 0.0512 $e^2b^3$ |
| $B(E1; 2^+ \rightarrow 3^-)$ | 9.1(31) x $10^{-6}$ $e^2b$ | > 3.97 x $10^{-6}$ $e^2b$ |

D.C. Radford *et al.*, Nucl. Phys. A 746, 83 (2004)
J.R. Beene *et al.*, Nucl. Phys. A 746, 471 (2004)
D.C. Radford *et al.*, Nucl. Phys. A 752, 264 (2005)
R.L. Varner *et al.*, Eur. Phys. J. A 25, s01, 391 (2005)
B. Fogelberg *et al.*, Phys. Rev. Lett. 73, 2413 (1994)

# Conclusions

**<u>HIE-ISOLDE physics</u>**

- HIE-ISOLDE is operating as a reliable and exciting new facility.
  - Three beam lines are now in use, **Miniball**, **ISS** and **SEC**.
- 2016: **6** RIB experiments, 5 of them at Miniball
- 2017: **12** RIB experiments, full campaign from July-November.
- 2018: **12** RIB experiments, 2 at new ISOLDE Solenoidal Spectrometer (ISS)