Binding energy studies for nuclear astrophysics

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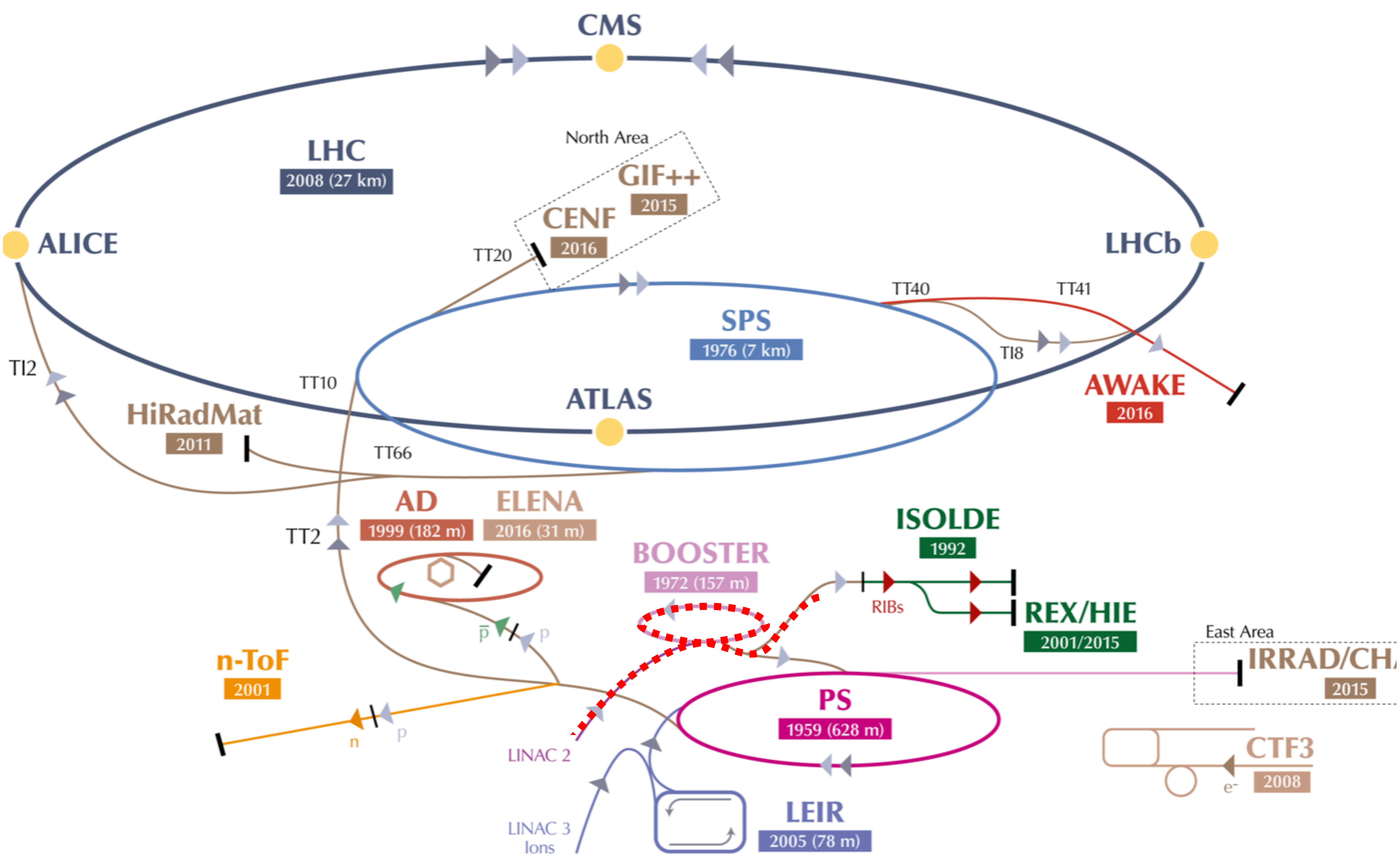
KRINA Workshop 2022 - ECT Trento – 12 December 2022*

Outline

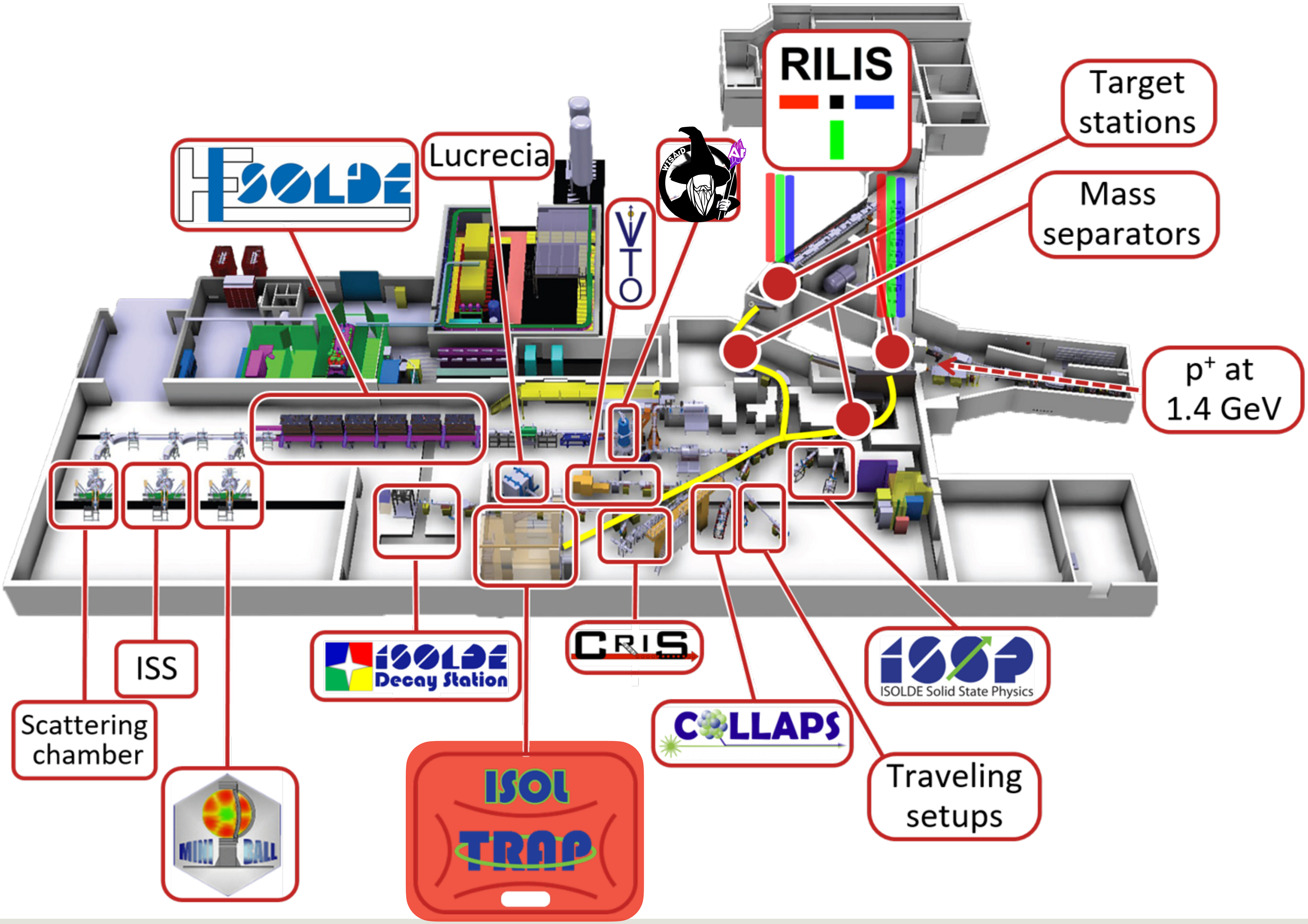
- Introduction :ISOLTRAP@ISOLDE@CERN
- Neutron-rich Cadmium isotopes
- Neutron-deficient Indium isotopes
- Projects at IGISOL/University of Jyväskylä
- Conclusion

INTRODUCTION

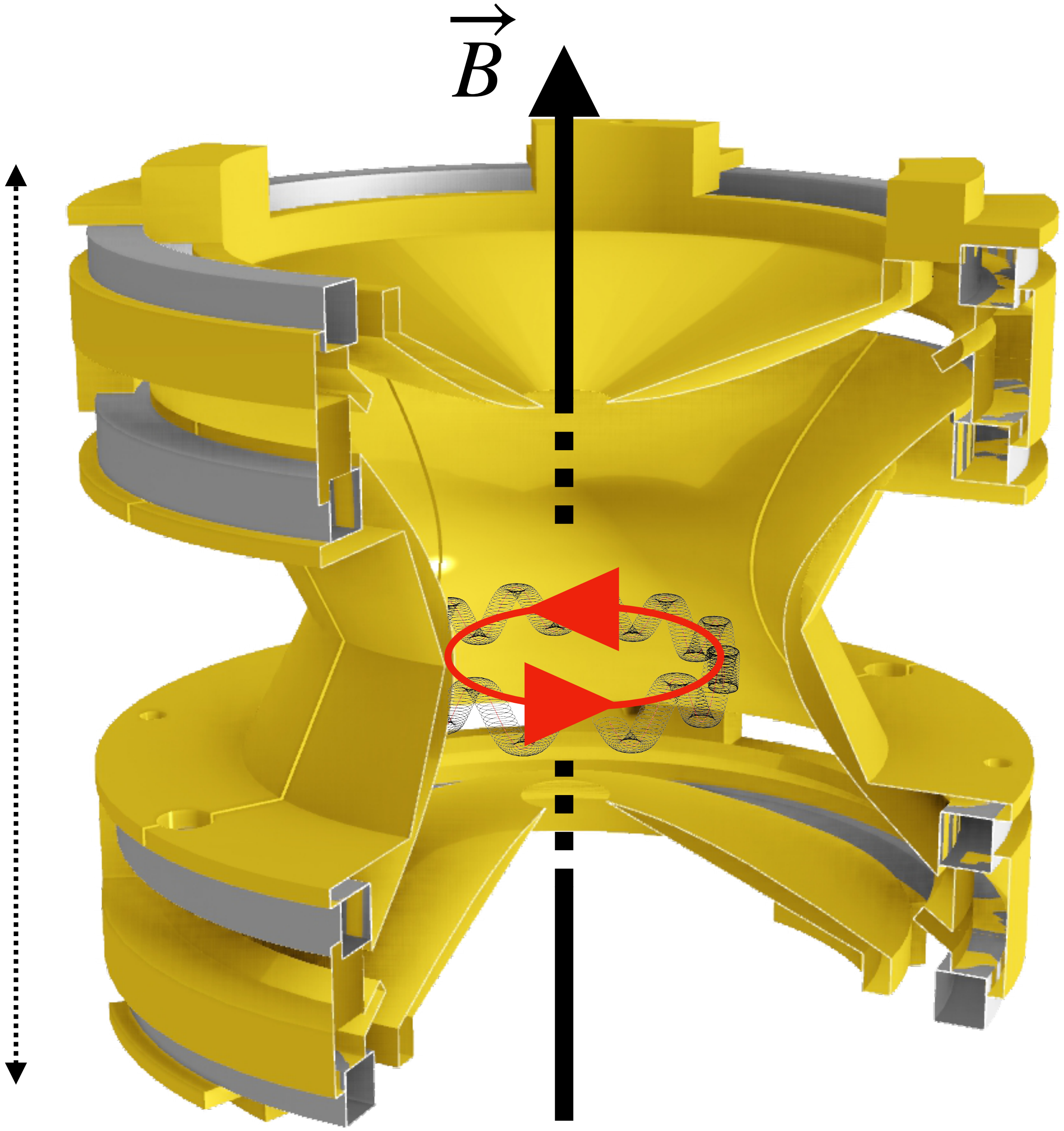
ISOLDE@CERN

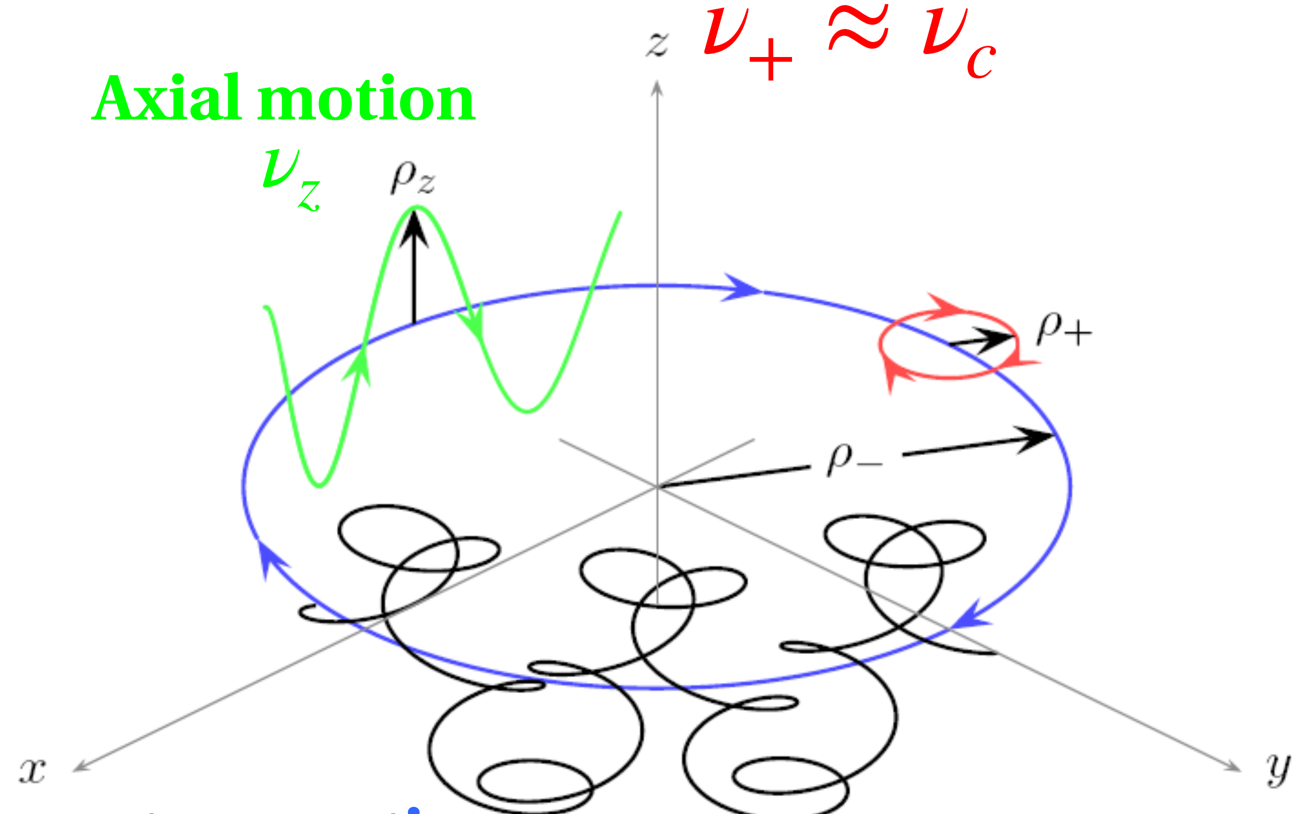

CMS
LHC
2008 (27 km)
North Area
GIF++
2015
CENF
2016
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT66
AD
1999 (182 m)
ELENA
2016 (31 m)
ISOLDE
1992
TT2
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
p̄
p
East Area
n-ToF
2001
IRRAD/CH
2015
PS
1959 (628 m)
n
p
LINAC 2
CTF3
2008
e⁻
LINAC 3
Ions
LEIR
2005 (78 m)

ISOLTRAP@ISOLDE



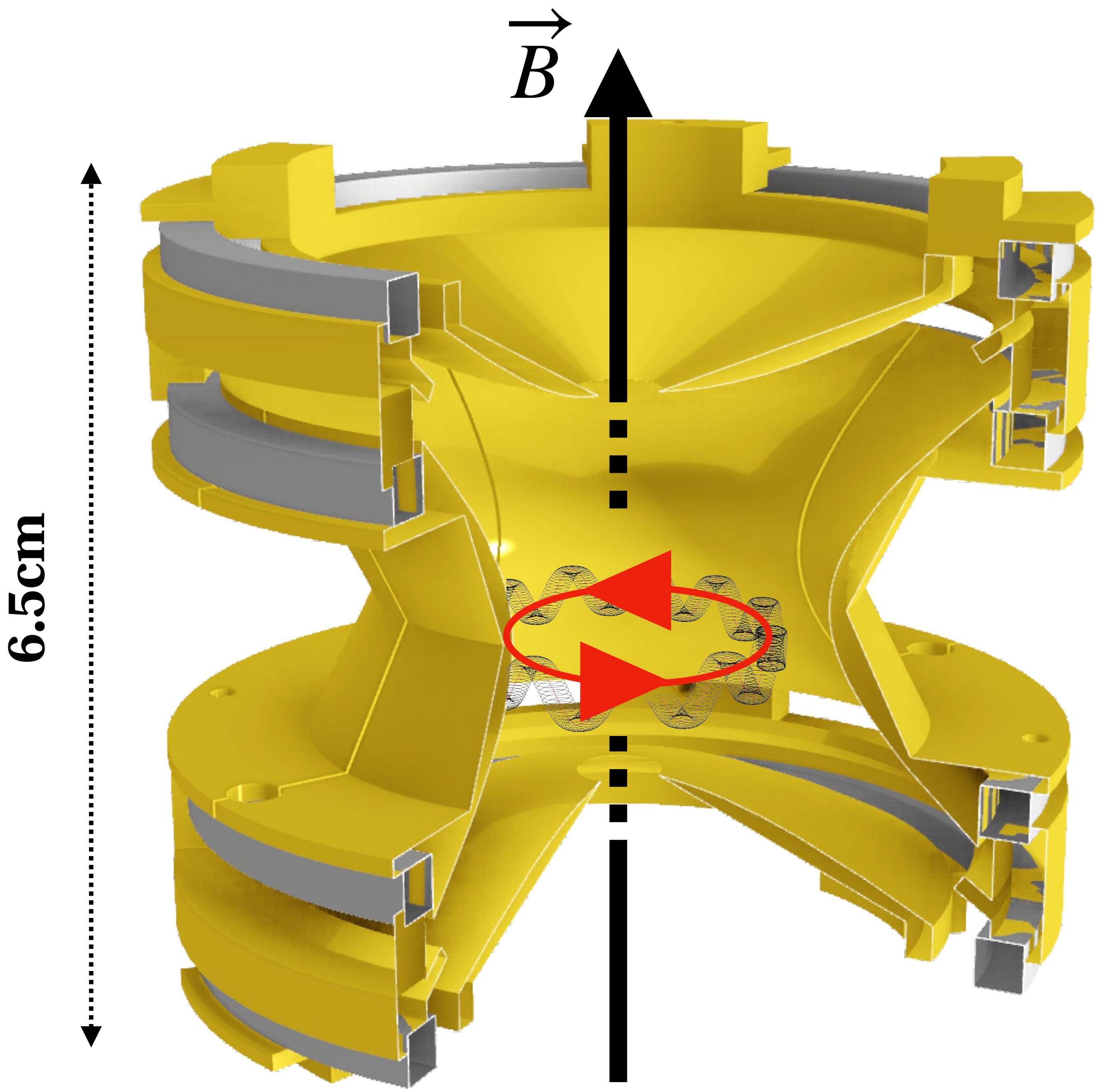
The Penning trap

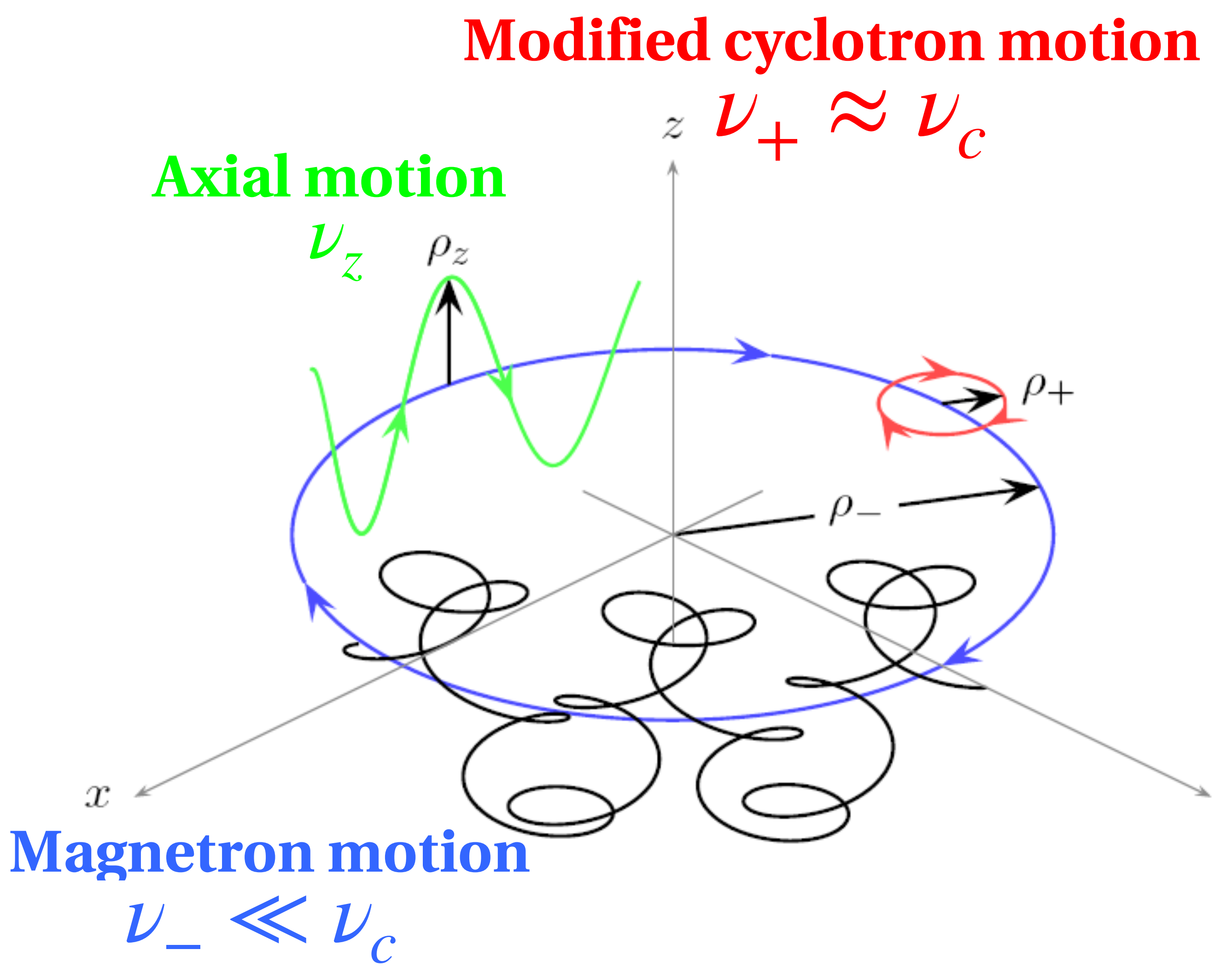




Important relation : $\nu_c = \nu_+ + \nu_- = \dfrac{qB}{2\pi m_{ion}}$

The Penning trap

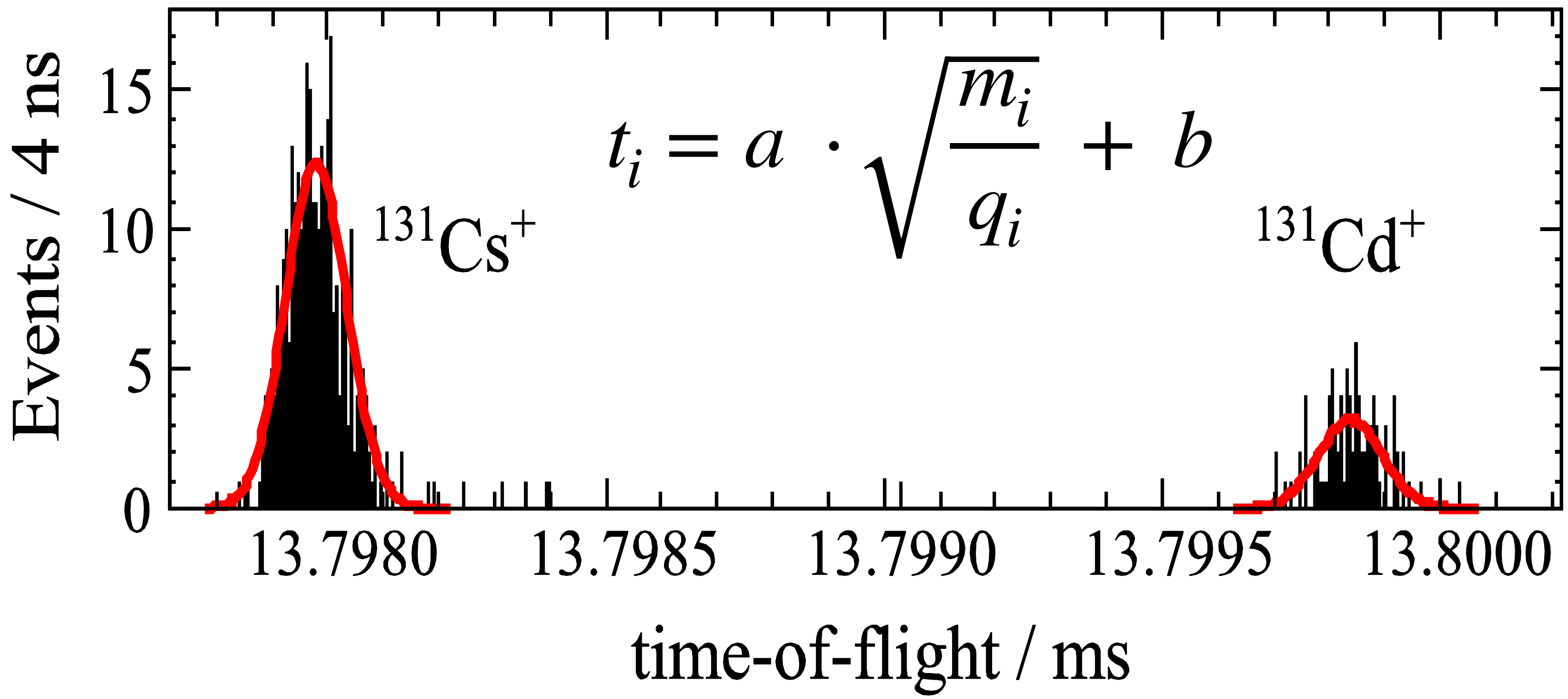




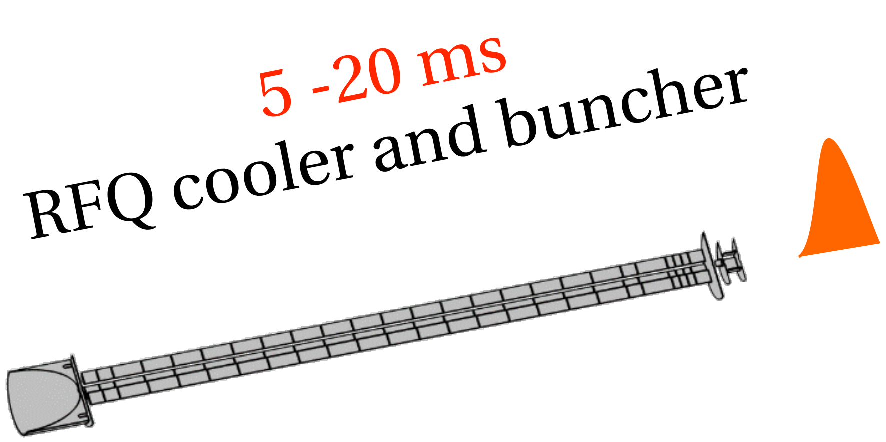
Important relation : $\nu_c = \nu_+ + \nu_- = \dfrac{qB}{2\pi m_{ion}}$

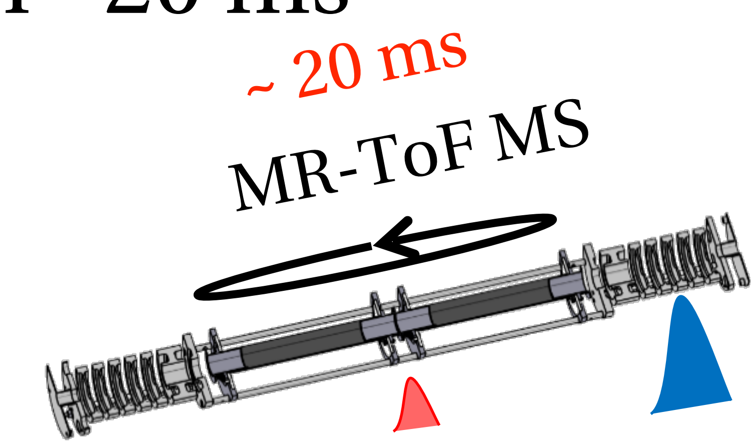
Where is the Ion of Interest?

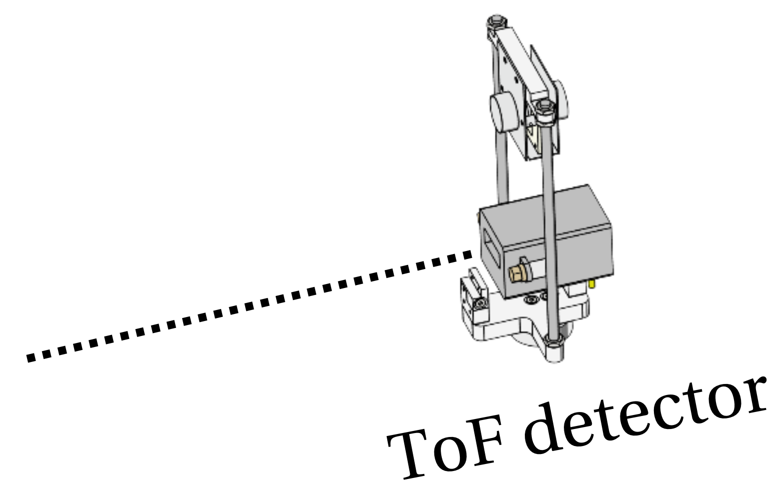
The MRToF-MS



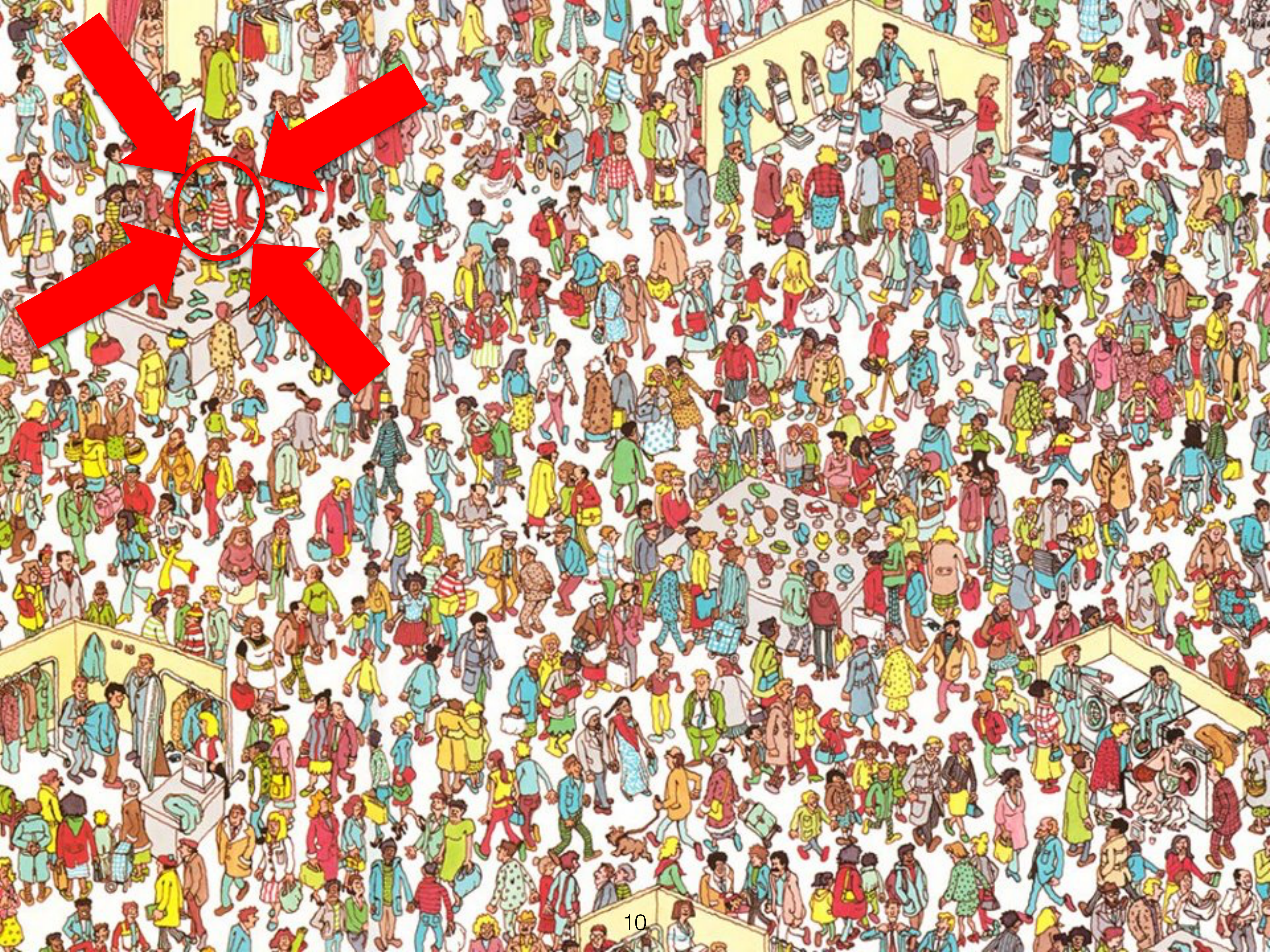
- Limitation < 1 pps / 10 ms half-life
- Resolving power ≈ 10^5 in ~20 ms
- Precision ≈ 10-20 keV



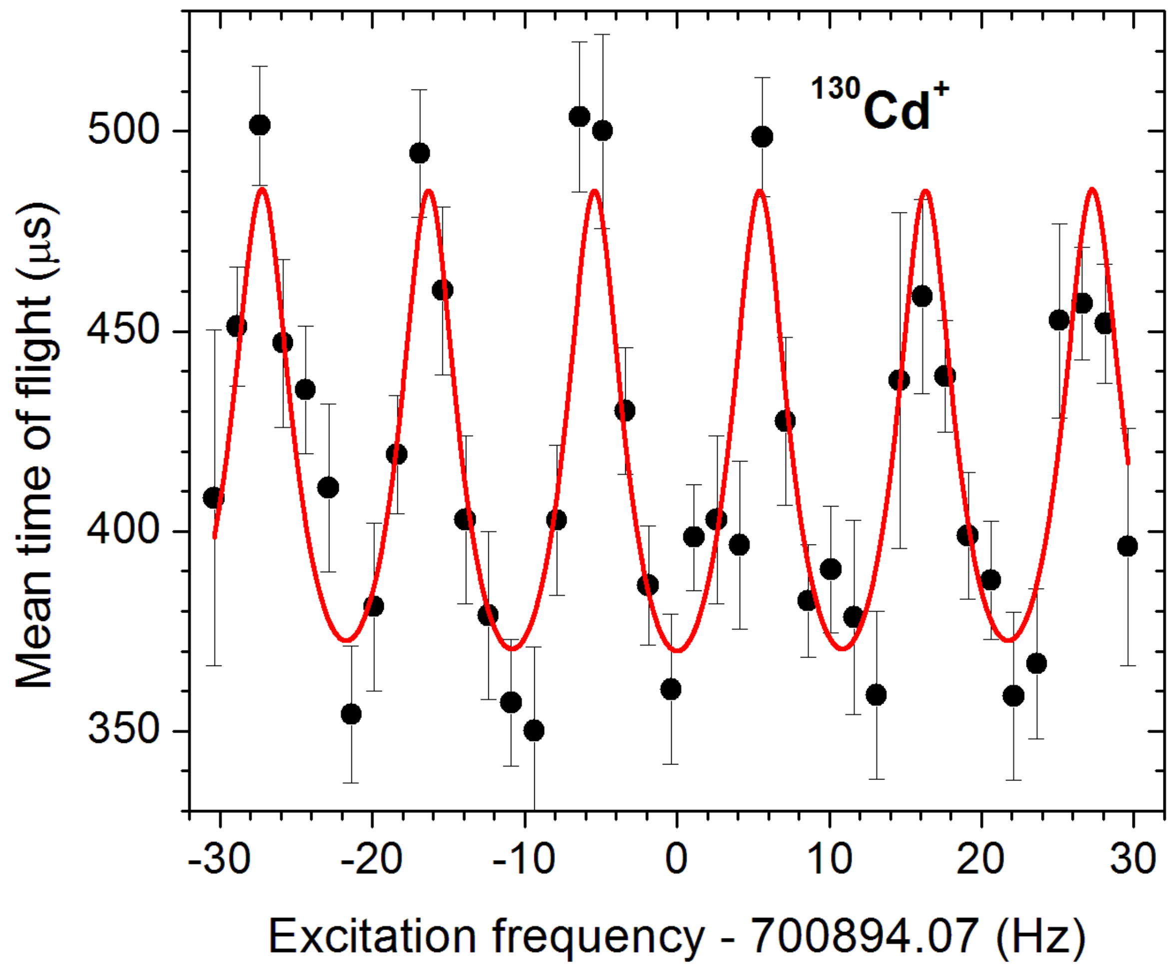


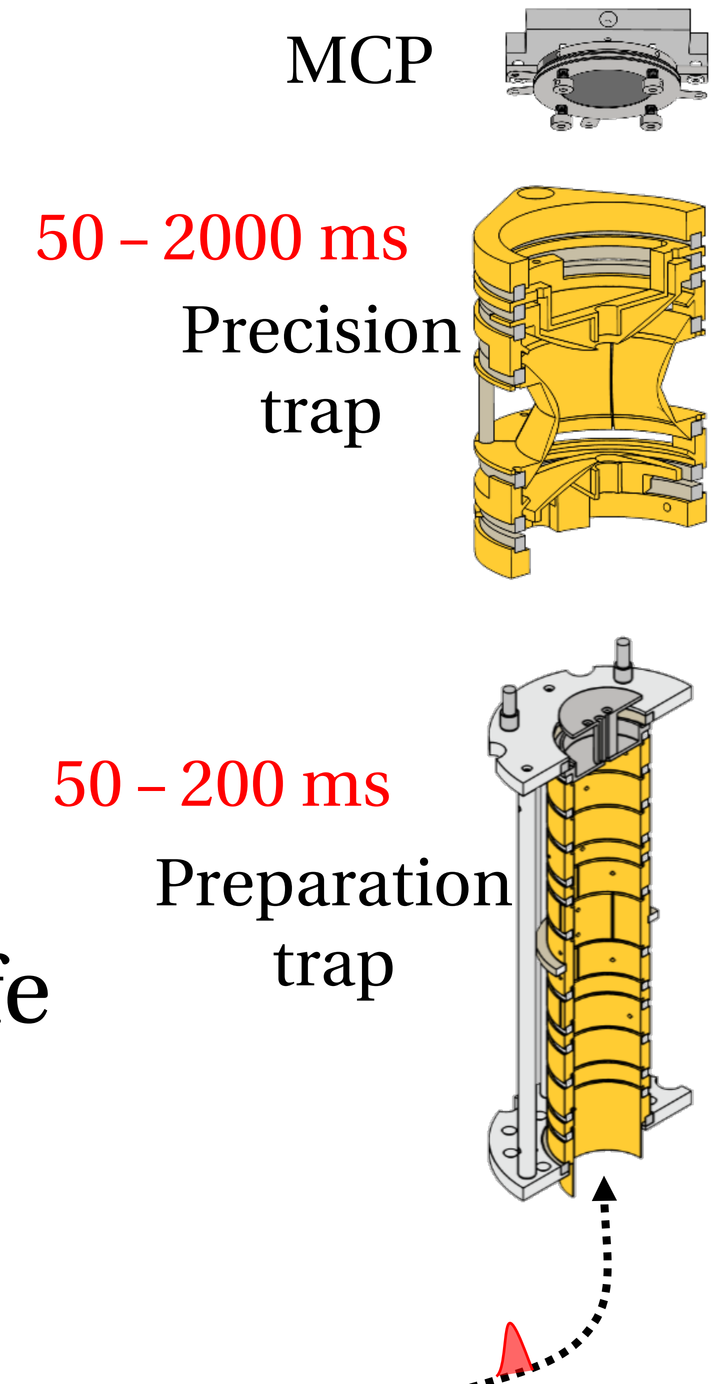


F. Herfurth *et al.*, NIM A **469**, 254 (2001).
R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012).
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).
F. Wienholtz et al., Int. J. Mass Spectrom. **421**, 285-293 (2017)



The ToF-ICR technique



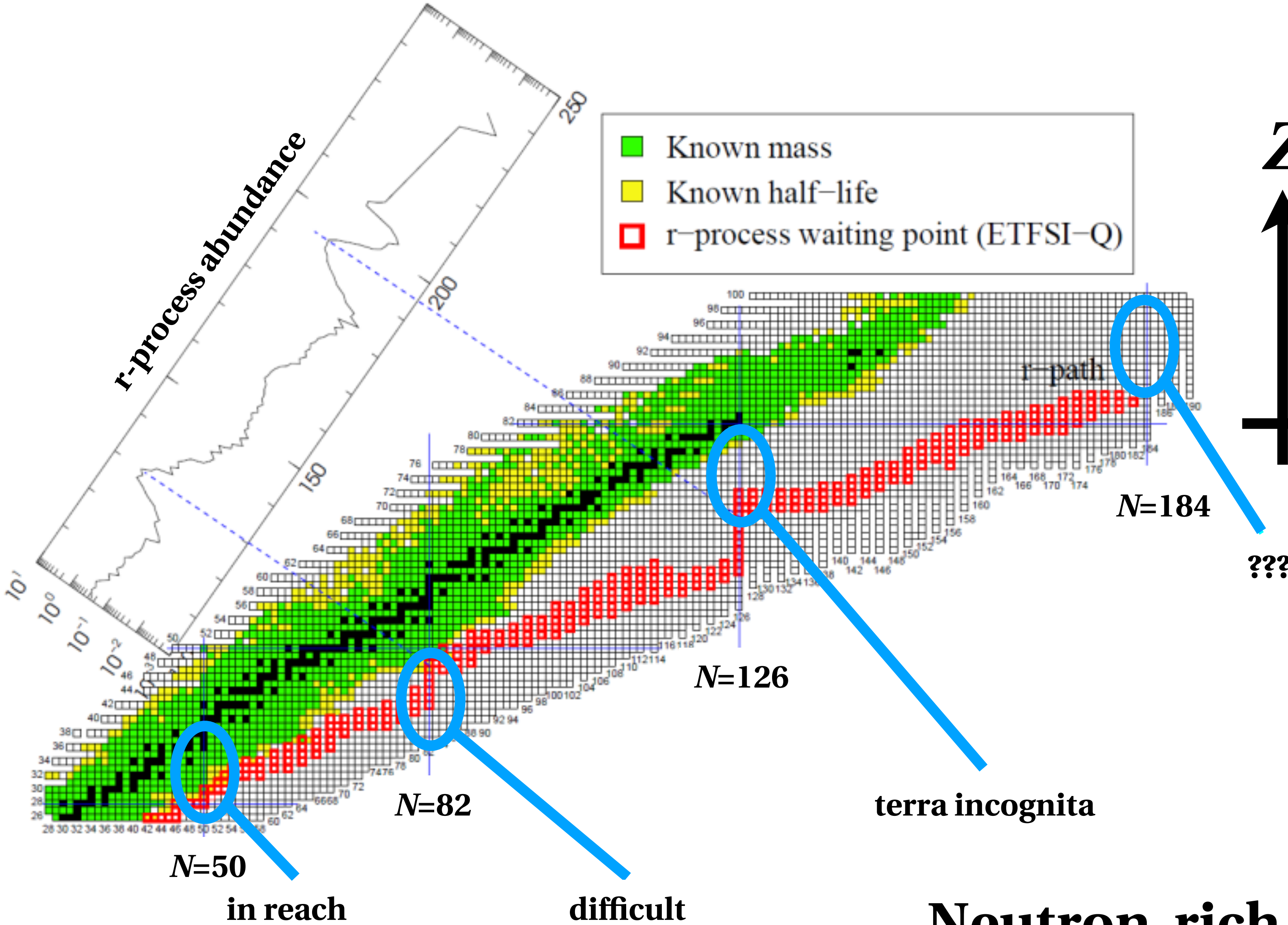


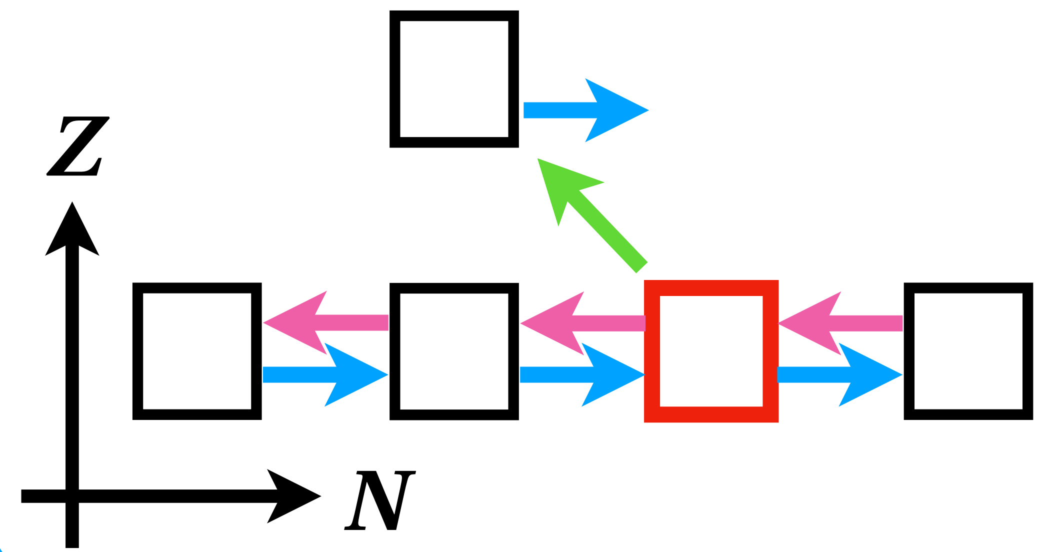
- Limitation < 100 pps / 50 ms half-life
- Resolving power ≈ 10^6 in ~ 1s
- Precision ≈ 0.1-10 keV
- Main disadvantage
  –> Scanning technique

G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995).
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).

Neutron-rich Cadmium isotopes

r-process





waiting point:
→ n-capture and photo-disintegration rate equilibrium

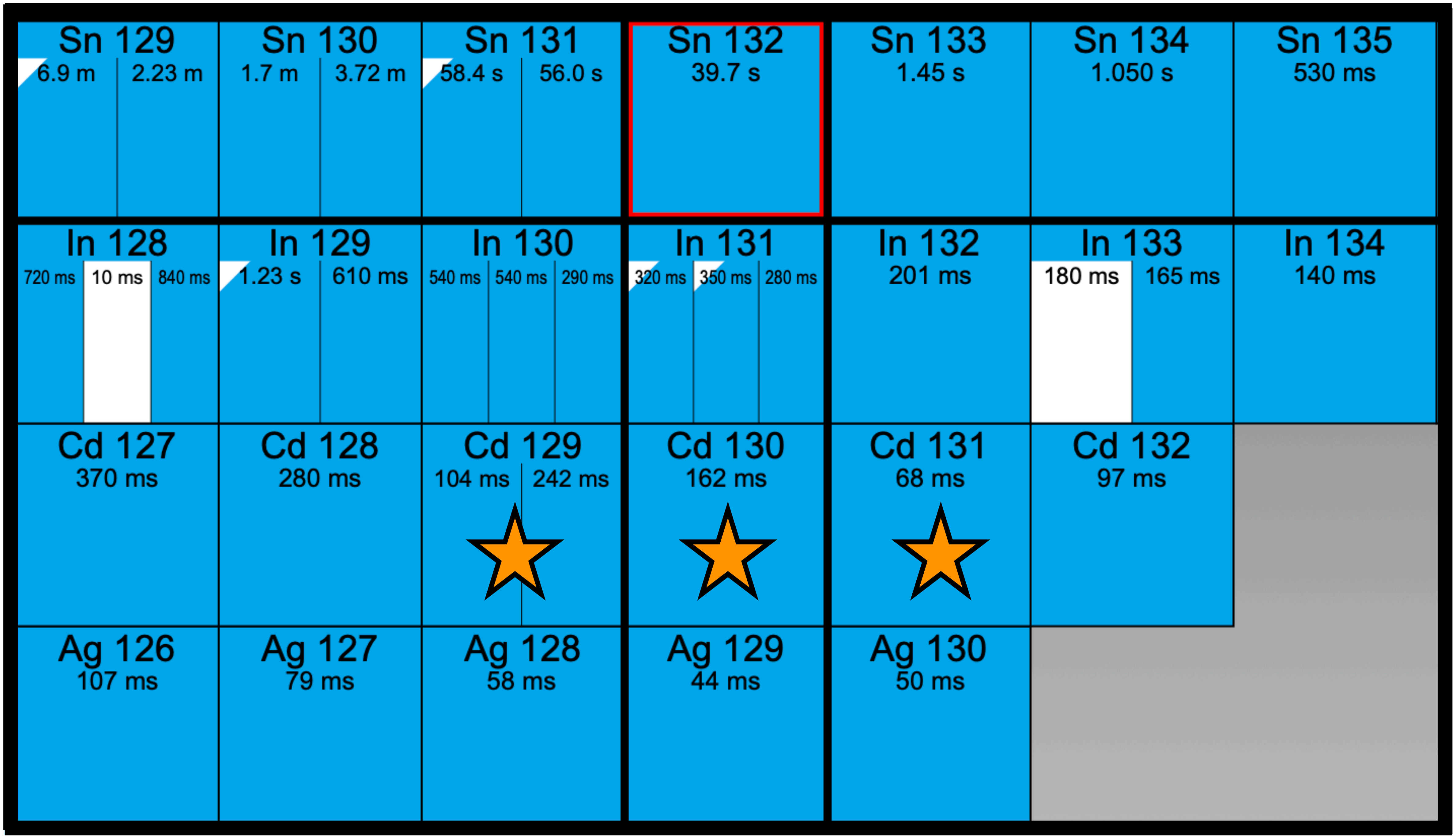
- **neutron capture**
- **photodisintegration (γ,n)**
- **β-decay**

- **Neutron-rich environments required (core-collapse supernova, n-star merger, …)**
- **High temperatures: GK**
- **Densities ~ 300 g/cm³**
- **Timescales ~ ms-μs**

Slide courtesy J. Karthein

Strength of $N = 82$ gap ?

Z=50

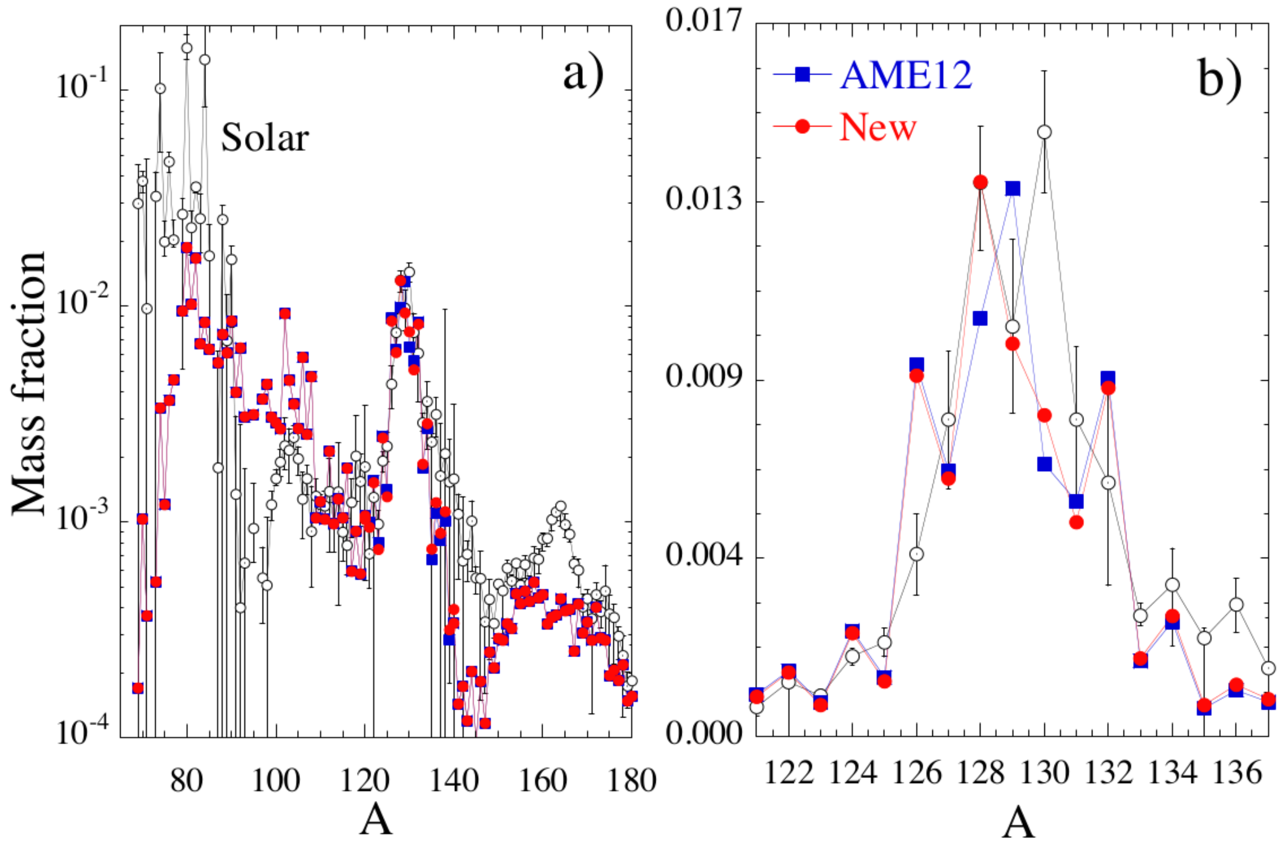


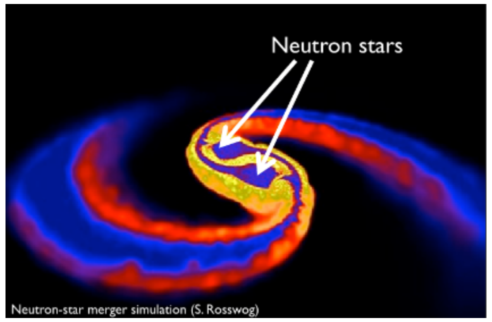
★ D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015)

N=82

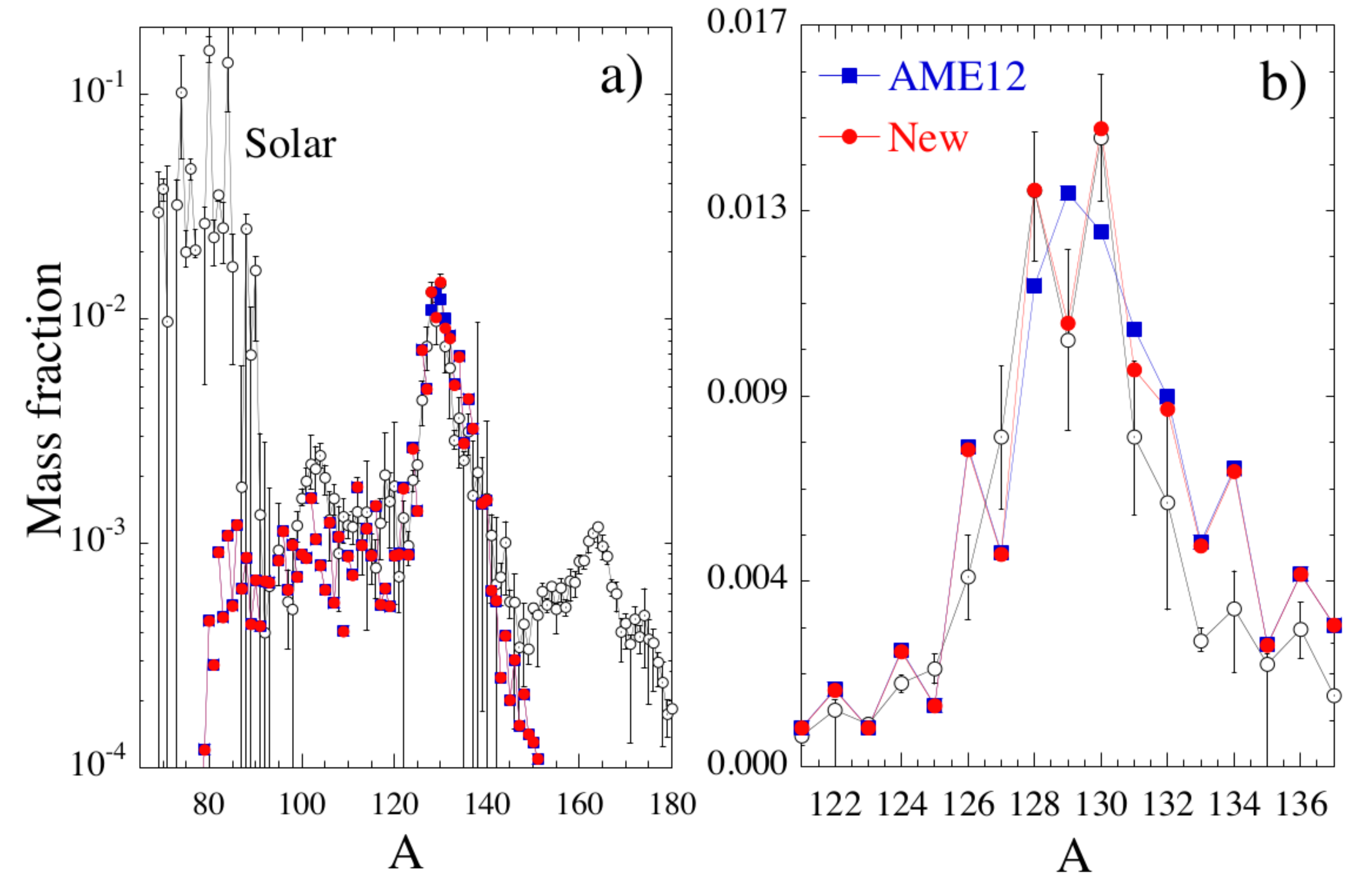
Impact on the abundance pattern

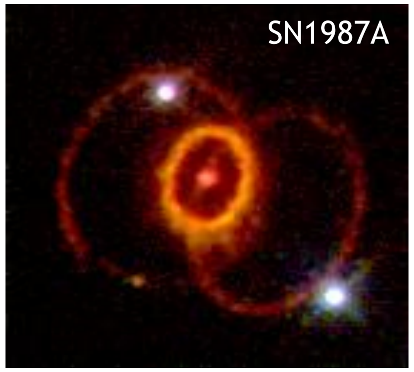
- Neutron star mergers scenario :





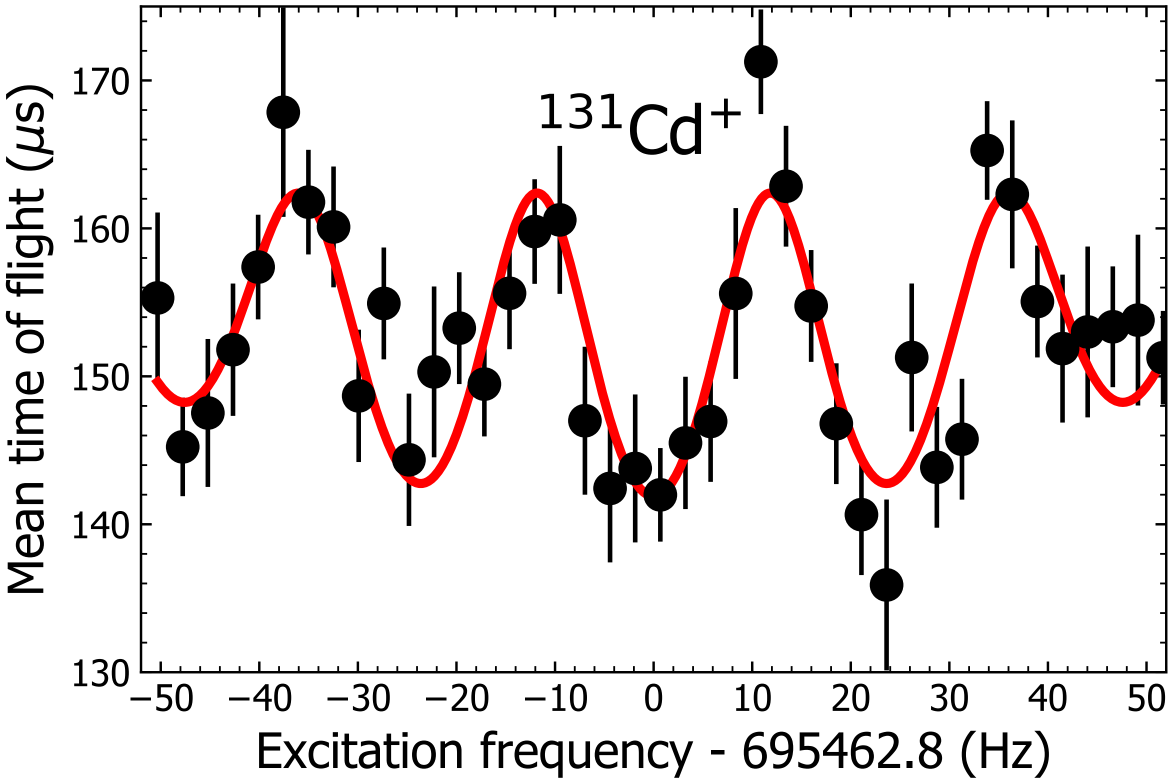
- Core-collapse supernova scenario :



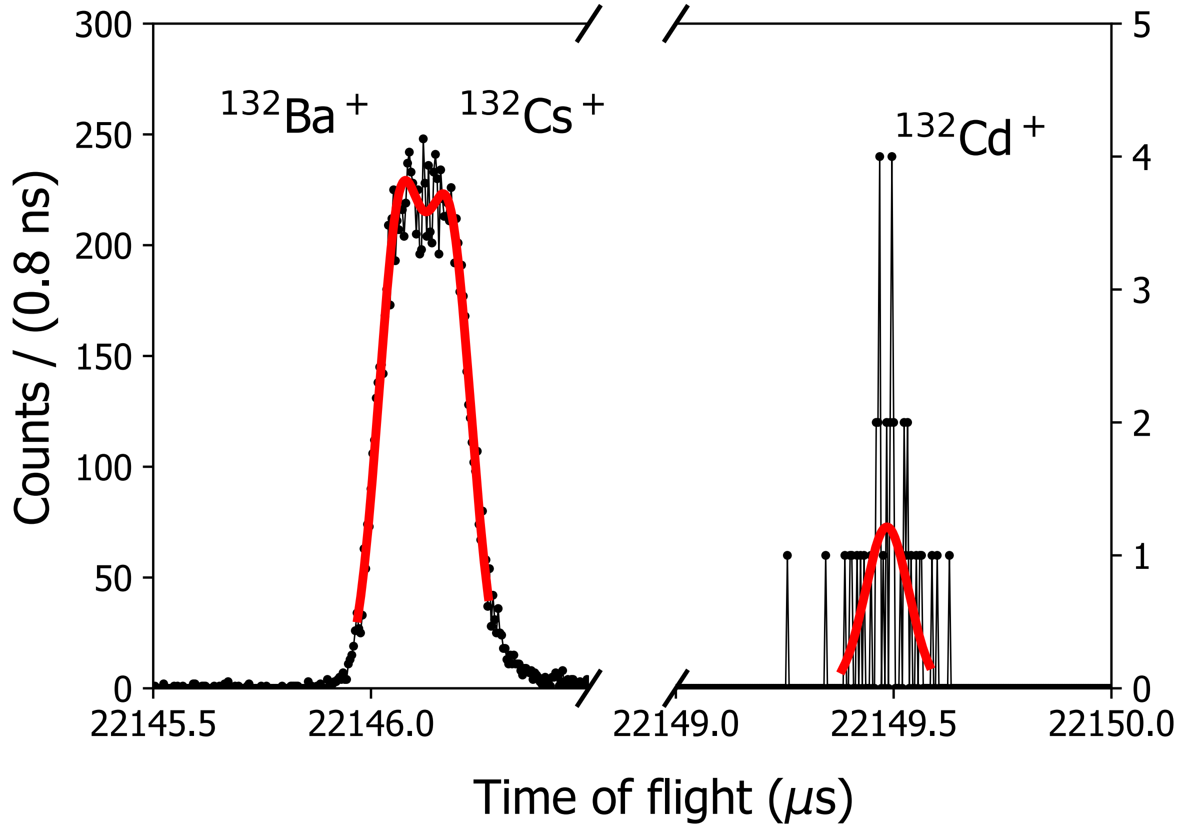


D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).

A > 130 isotopes



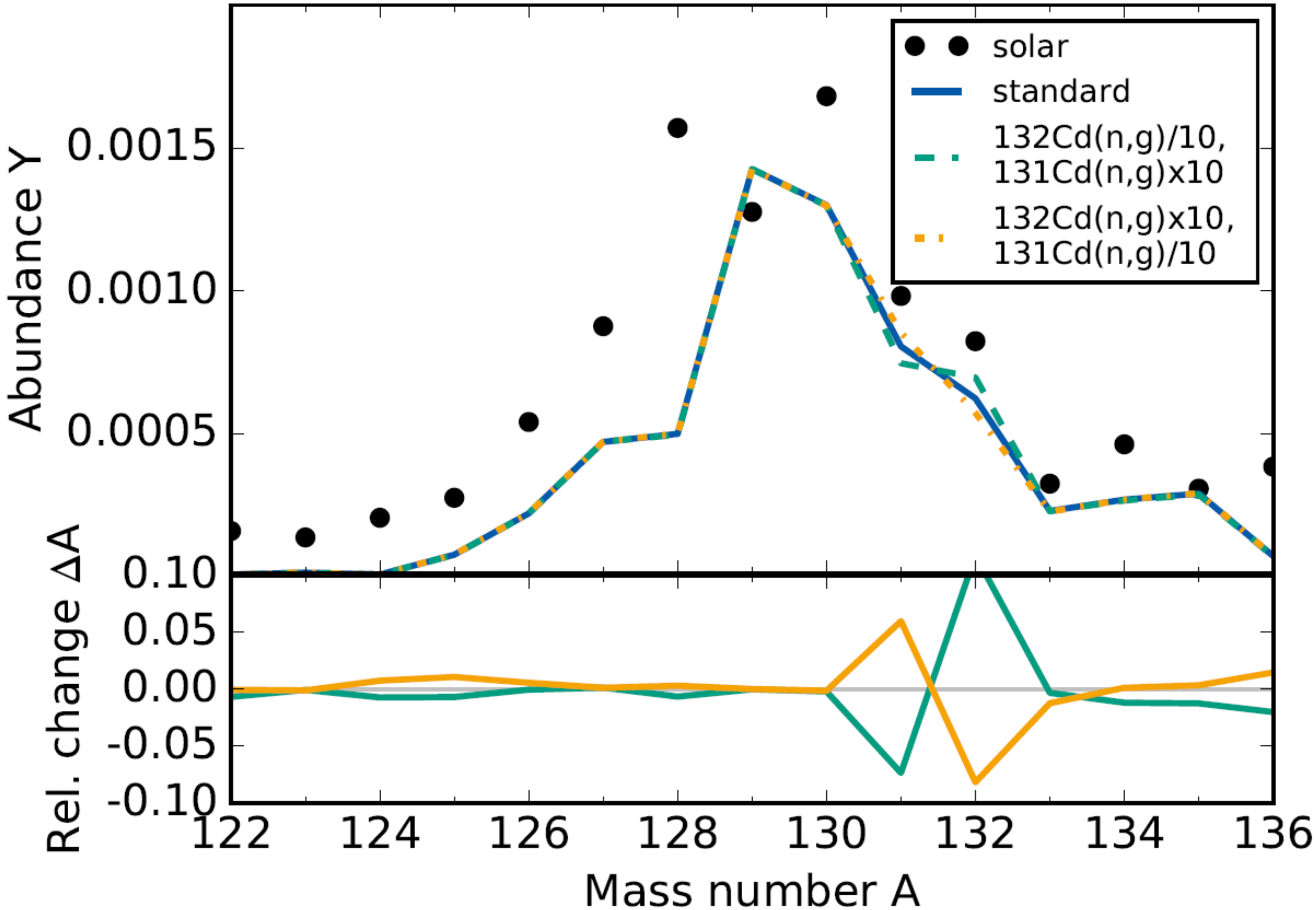
- Confirms previous MRToF result.
- Three-fold improvement of the uncertainty.



- Clean spectrum
- Unambiguously identified
- First mass measurement !

V. Manea, J. Karthein *et al.*, Phys. Rev. Lett. **124**, 092502 (2020)

r-process impact ?

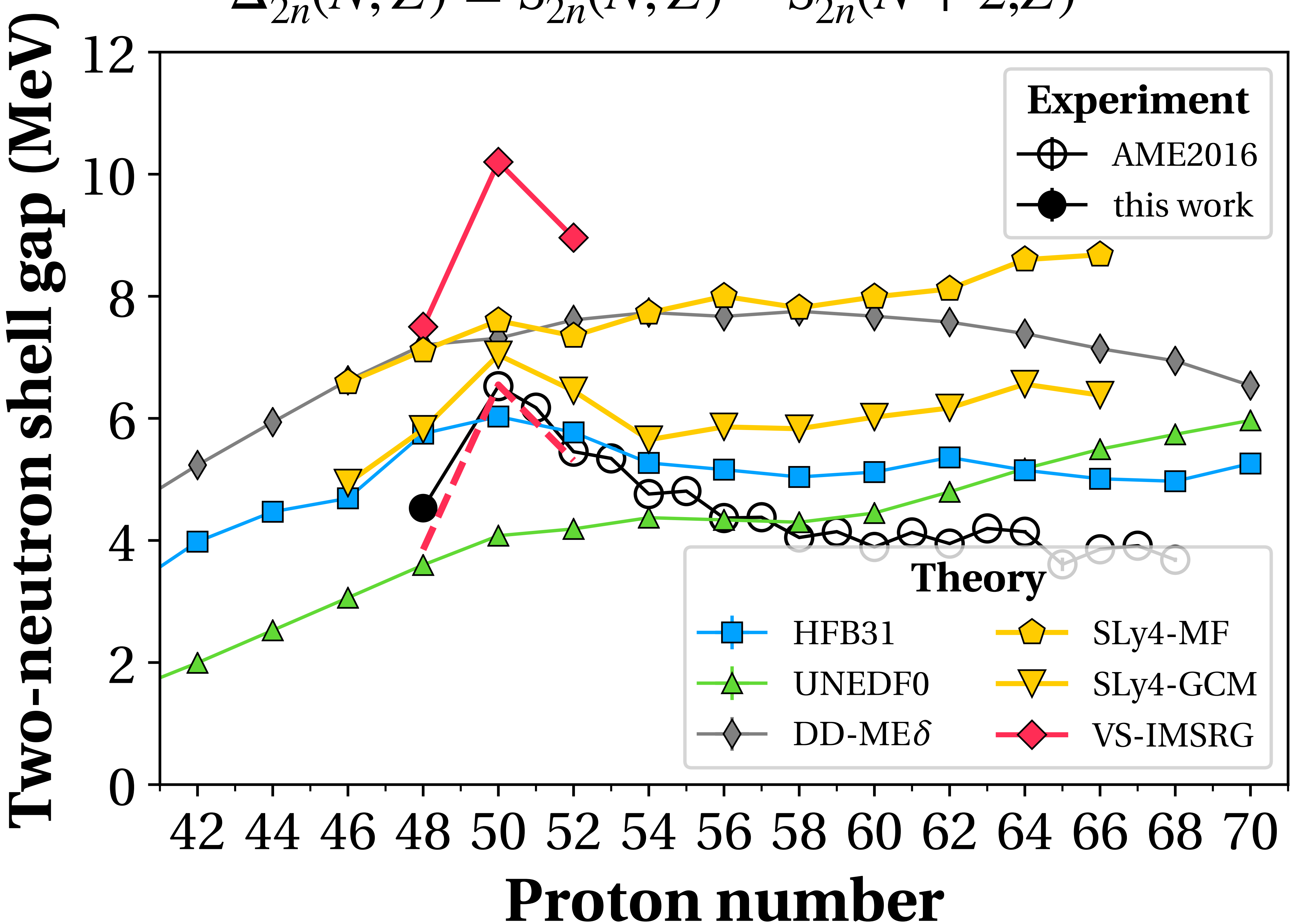


Courtesy V. Manea, A. Arcones

- R-process simulations are not specifically sensitive to the new masses –> fission recycling

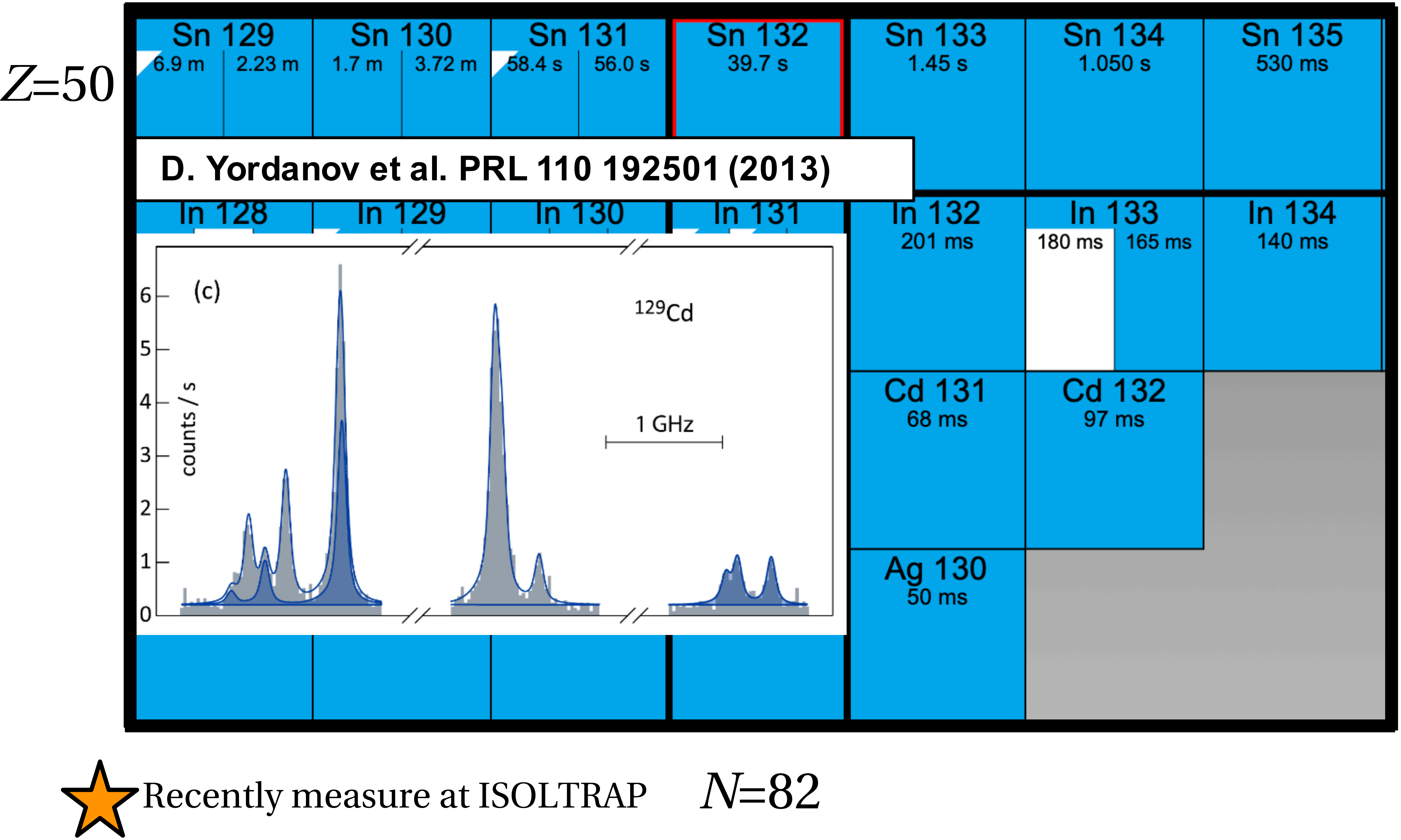
Strength of $N = 82$ gap ?

$$\Delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$



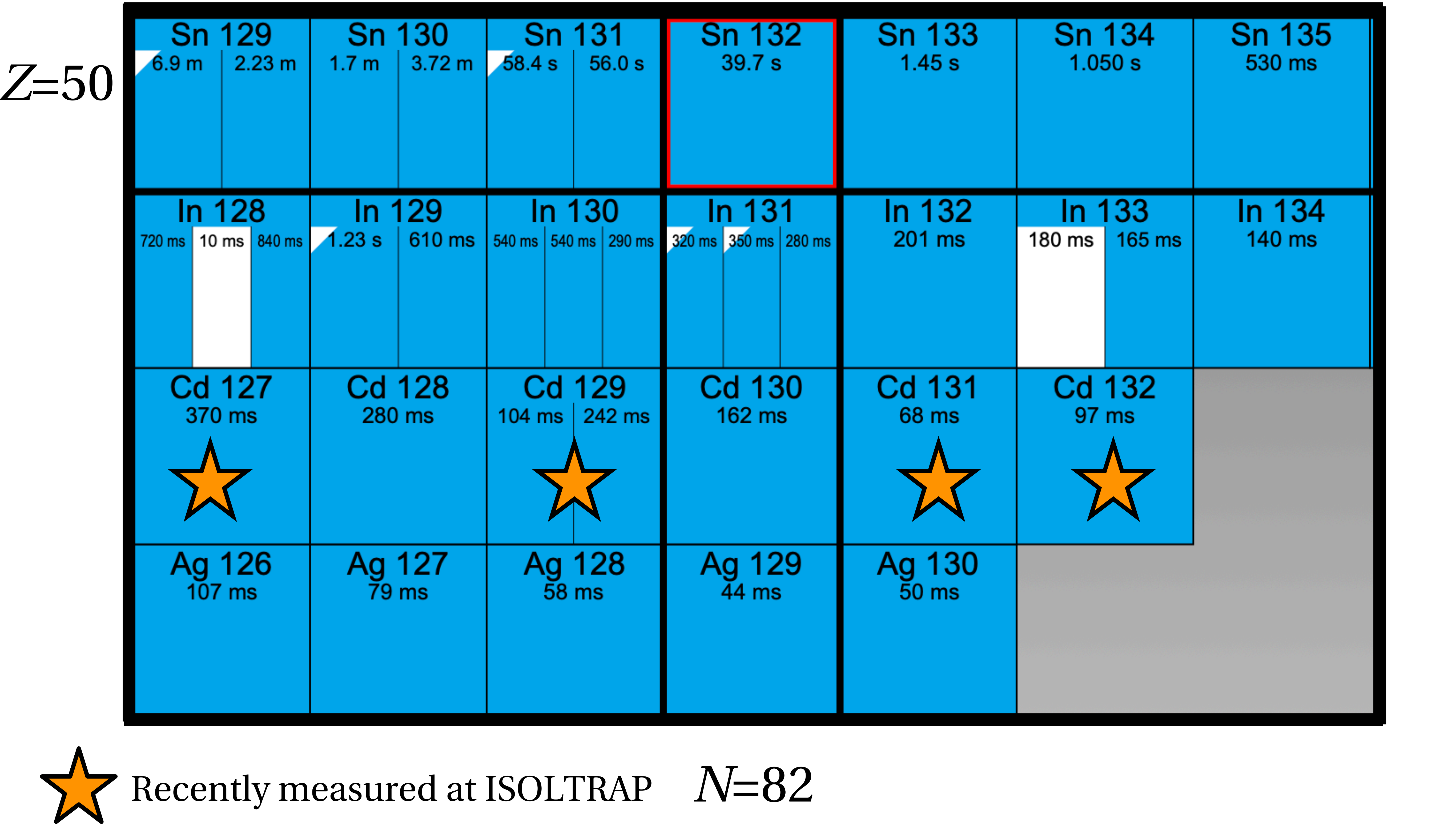
S

What about A < 130 ?

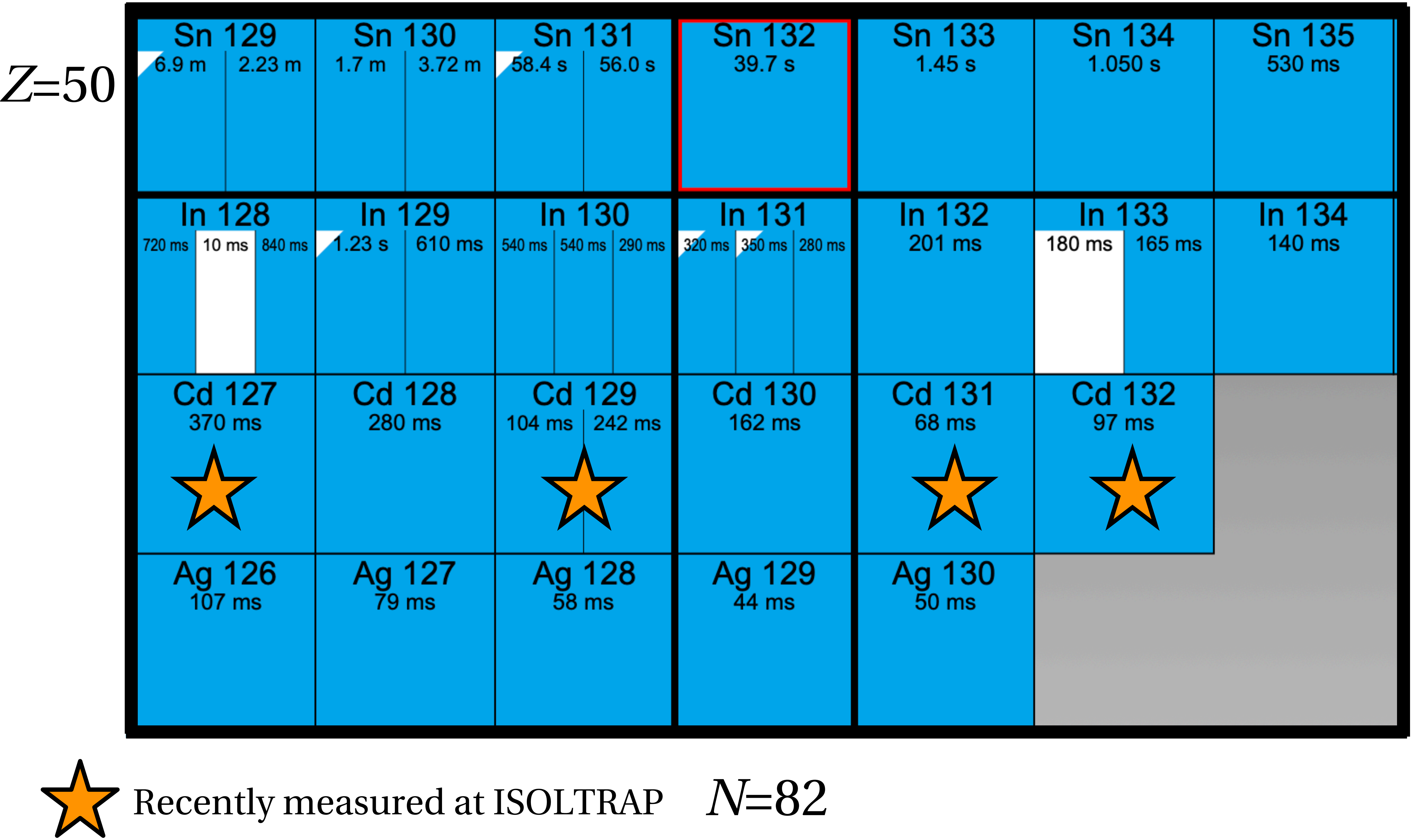


Recently measure at ISOLTRAP

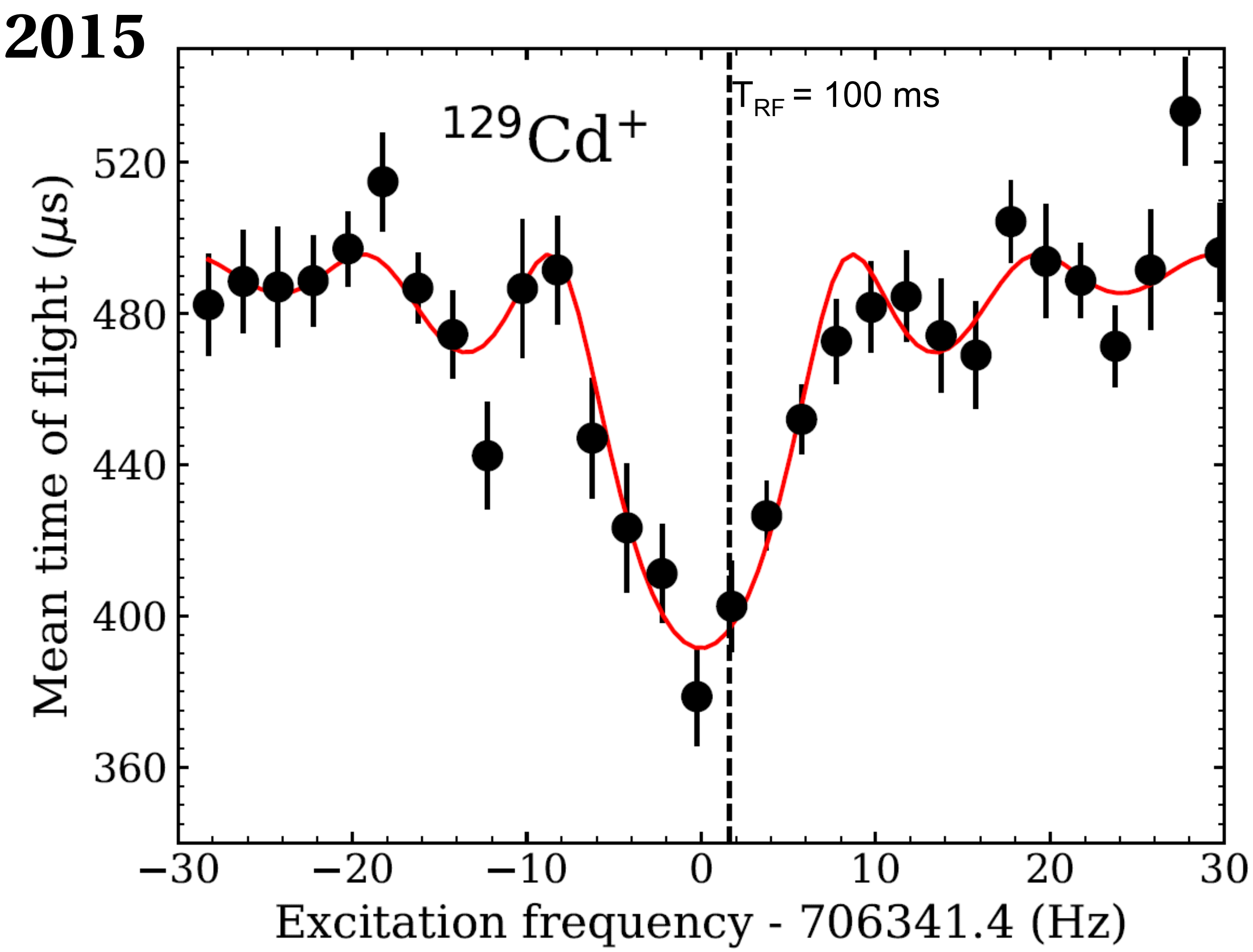
^{127,129}Cd : Isomeric separation

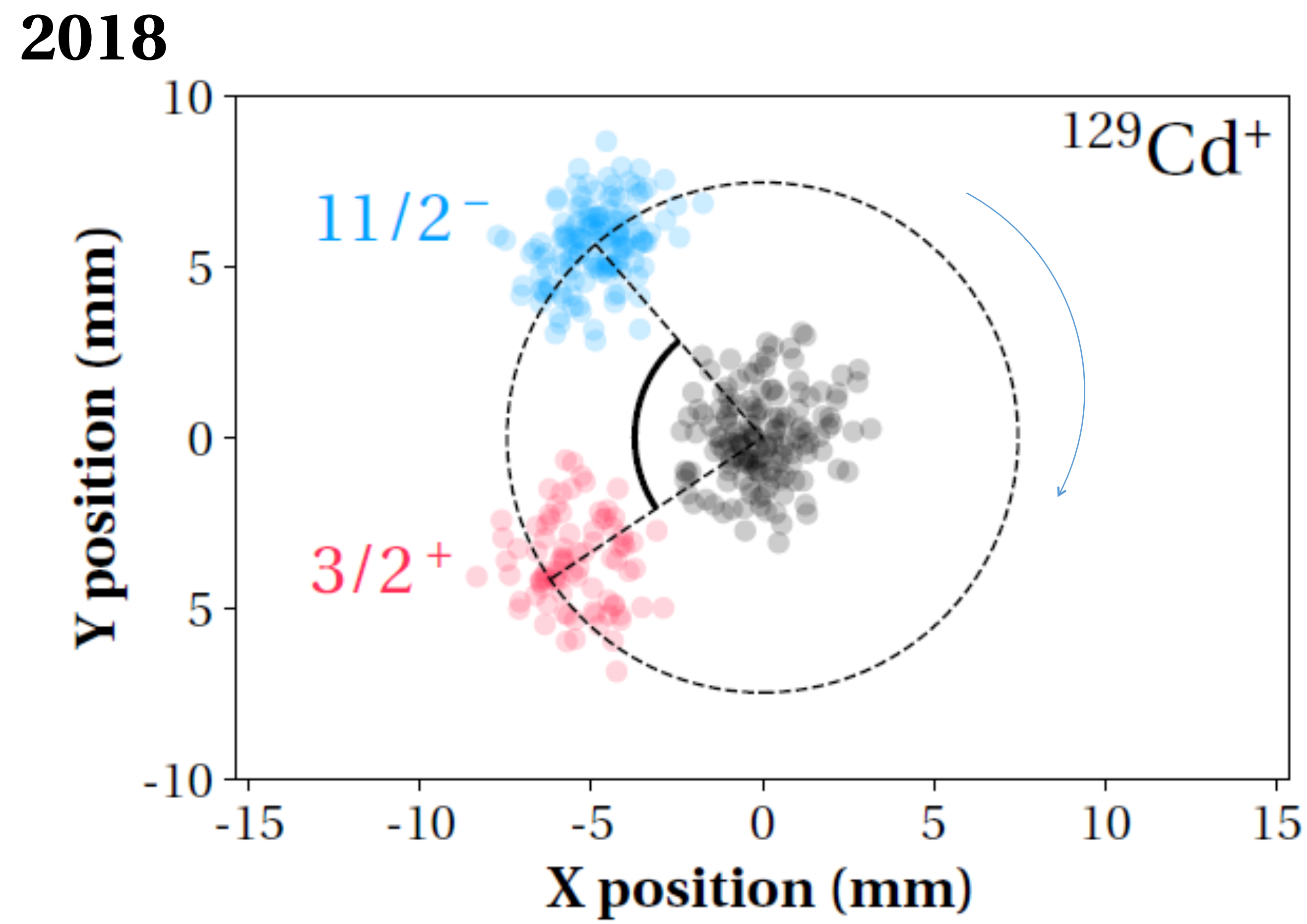


^{127,129}Cd : Isomeric separation



^{129g,m}Cd isomeric separation



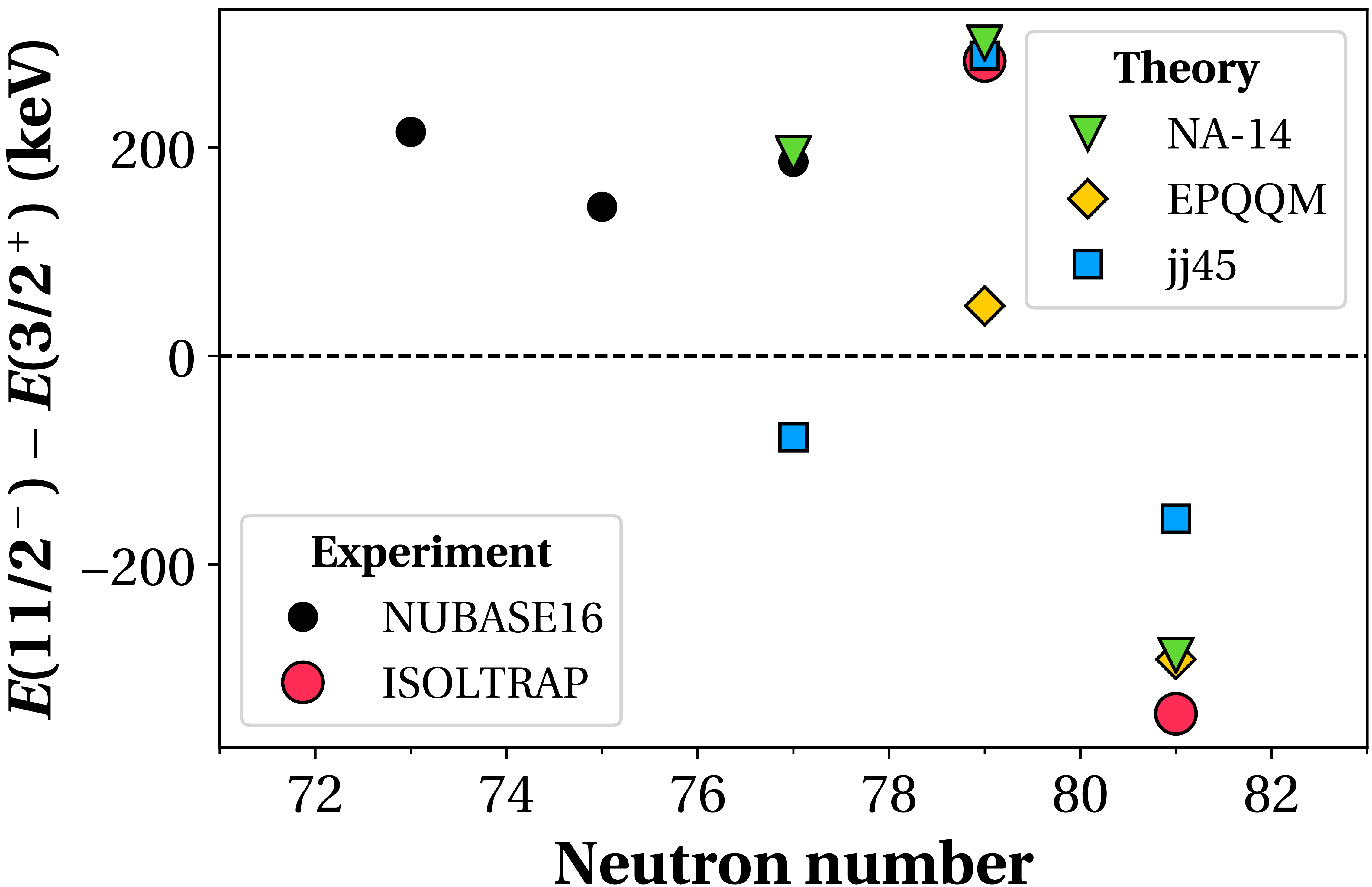


- Resolving power > 10^6 in ~ 100 ms
- ^{129m}Cd excitation energy measured for the first time
- COLLAPS: ratio $(11/2^{-})/(3/2^{+})$ = **2.4(2)**
- ISOLTRAP: ratio $(11/2^{-})/(3/2^{+})$ = **2.2(2)**

D. Yordanov *et al.*, Phys. Rev. Lett. **110**, 192501 (2013)
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).
V. Manea, J. Karthein *et al.*, Phys. Rev. Lett. **124**, 092502 (2020)

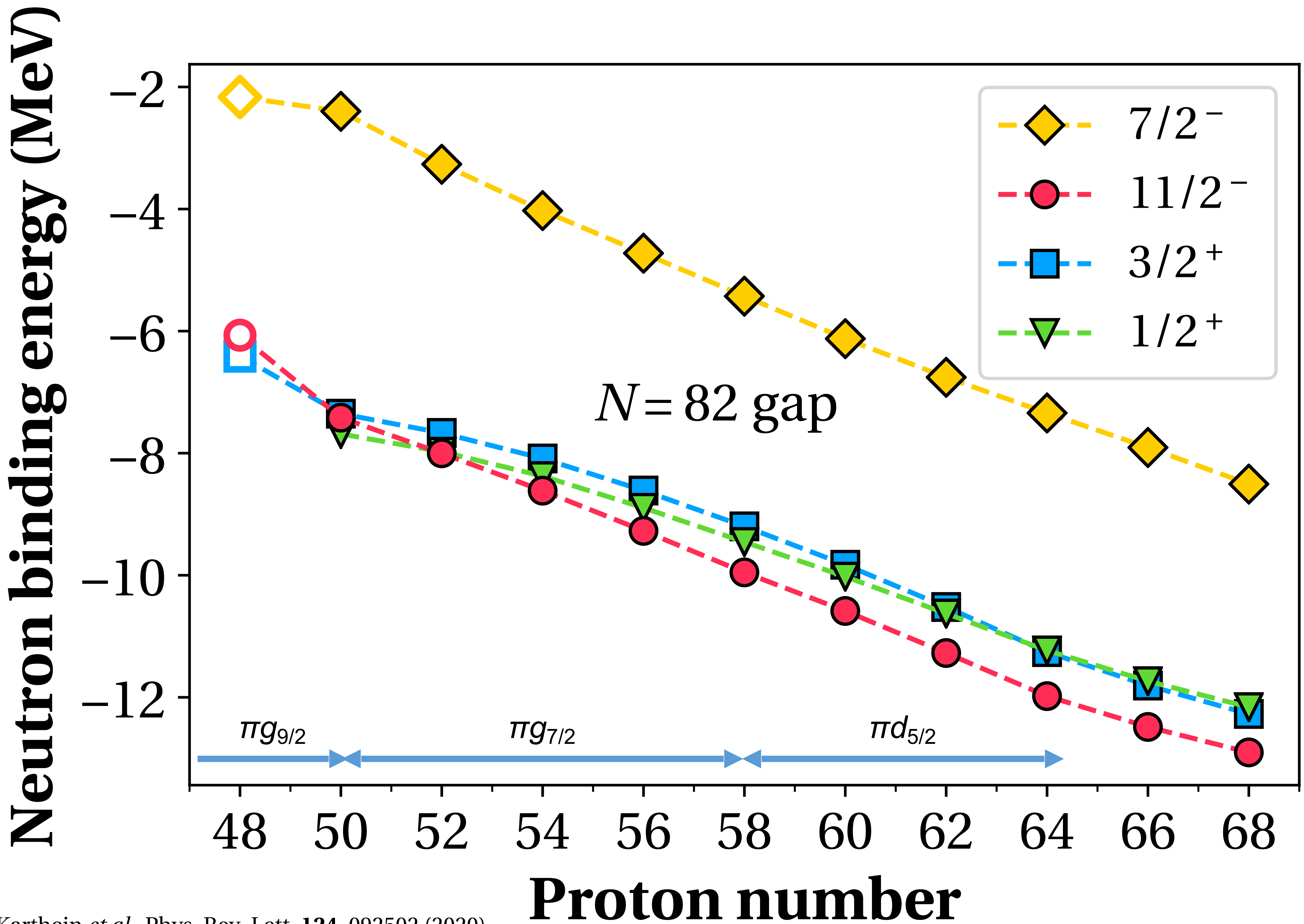
Technique of particular interest for astromer studies –>
G. W. Misch *et al.*, Astron. Journ. Lett. **913 1** (2021)

$^{127\text{-}129g,m}$Cd : State inversion



V. Manea, J. Karthein *et al.*, Phys. Rev. Lett. **124**, 092502 (2020)

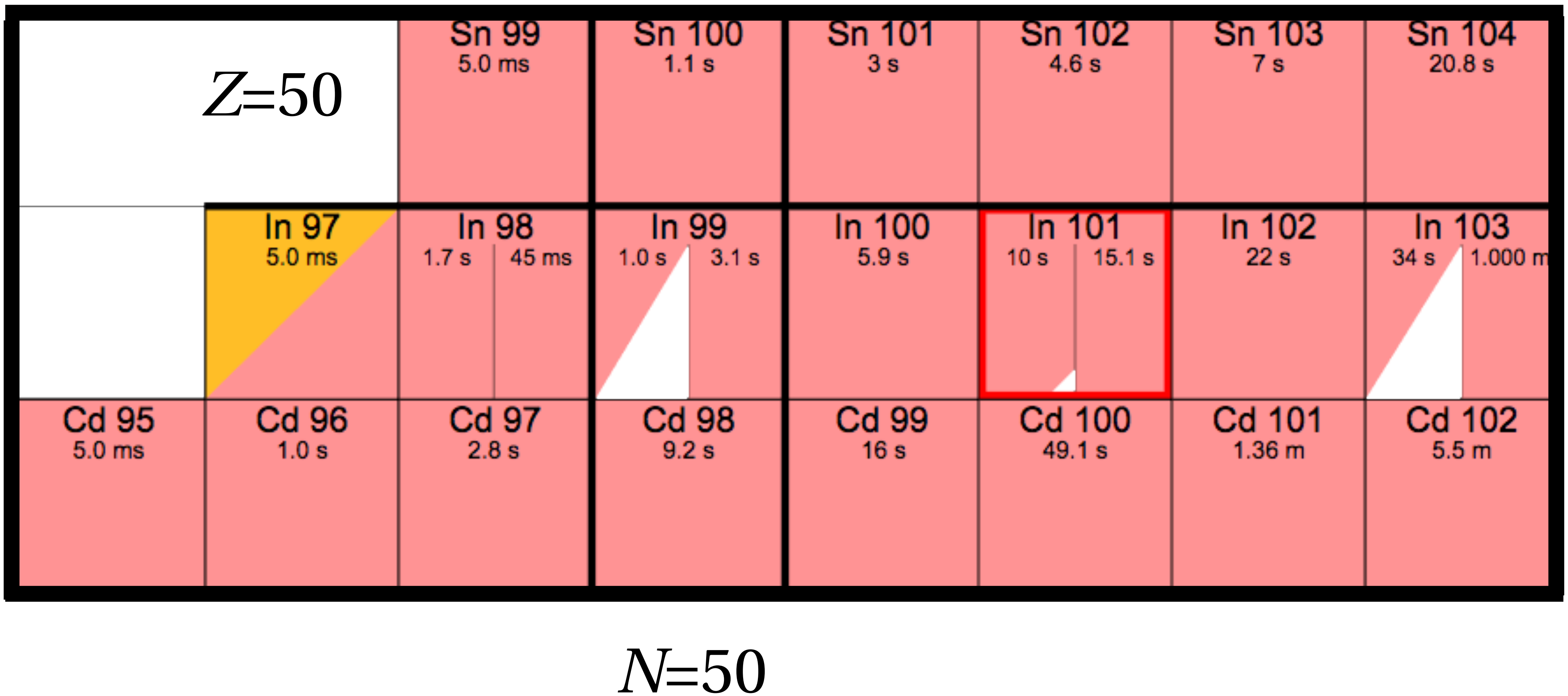
Evolution of the N=82 gap for Z<50



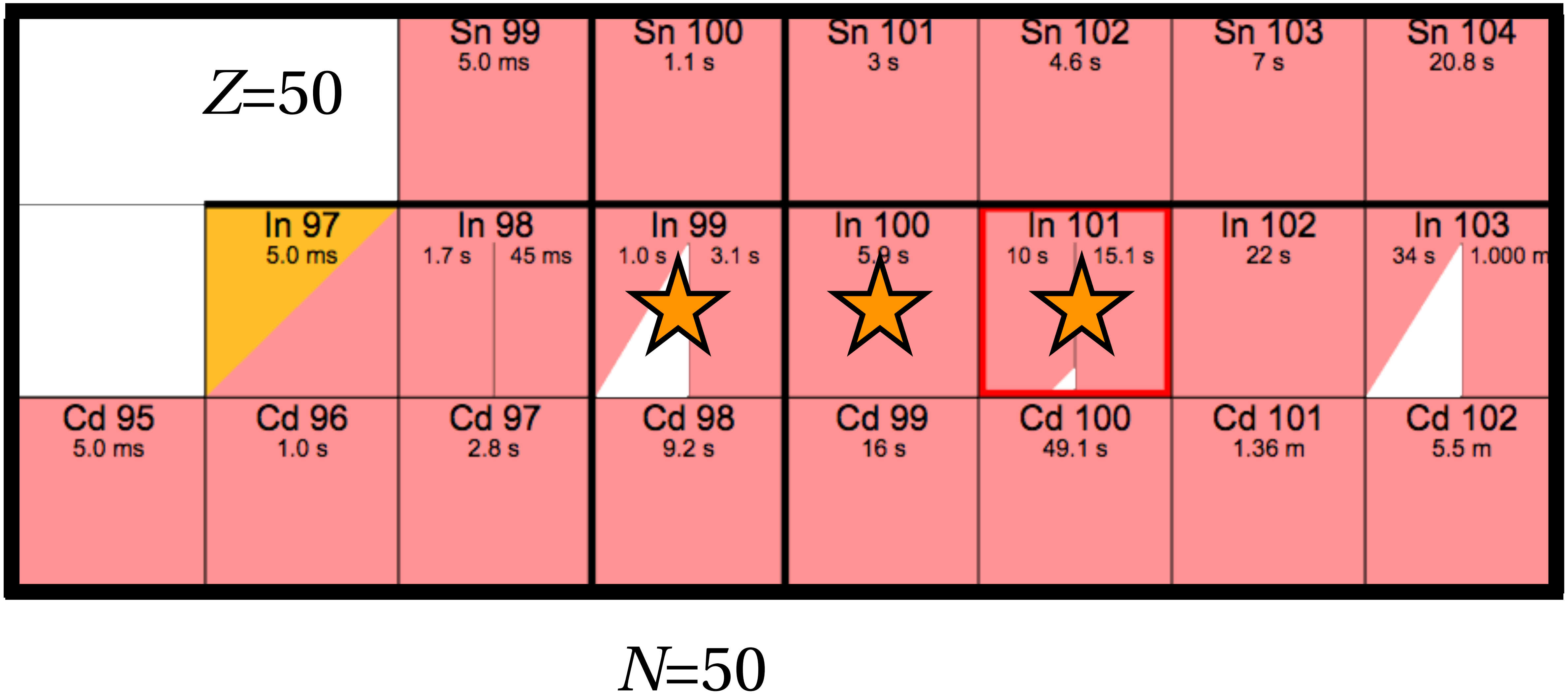
V. Manea, J. Karthein *et al.*, Phys. Rev. Lett. **124**, 092502 (2020)

Neutron-deficient Indium isotopes

The ^{100}Sn region



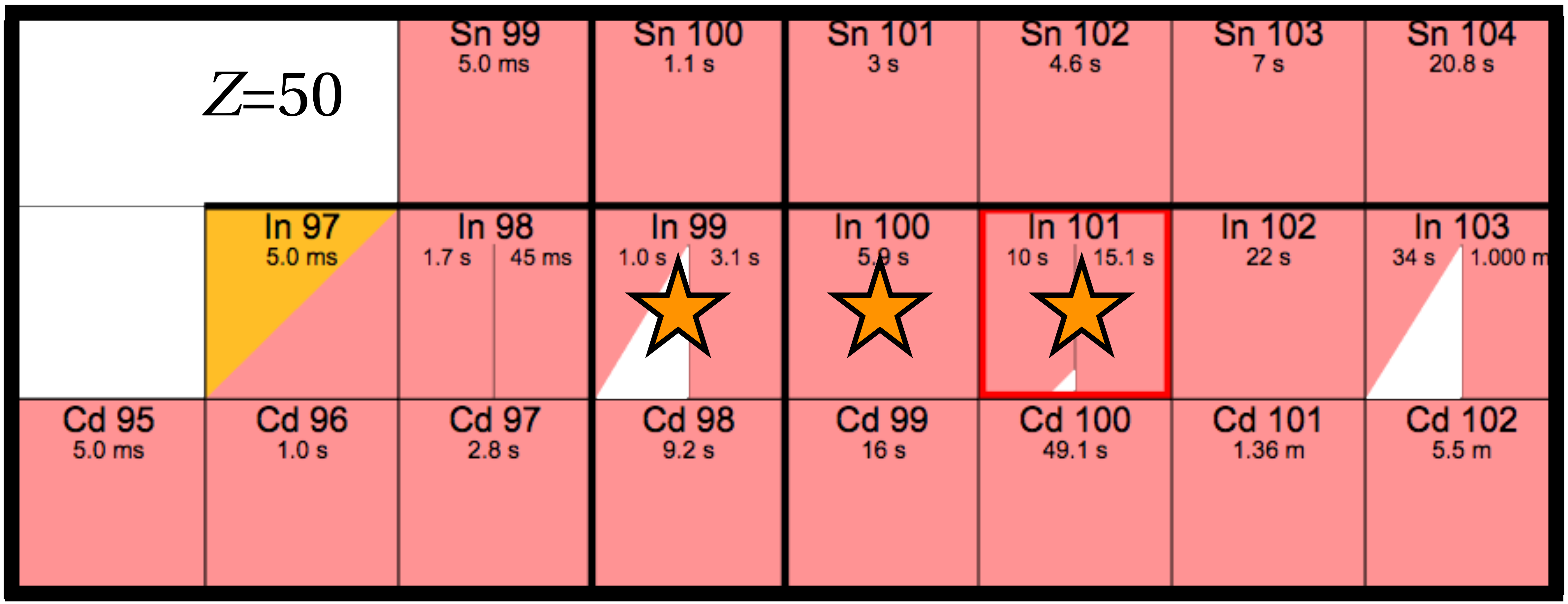
Opportunistic mass measurement



- 3 isotopes in 3 days with 3 different techniques !

★ Recently measured at ISOLTRAP

Evolution of the N=82 gap for Z<50

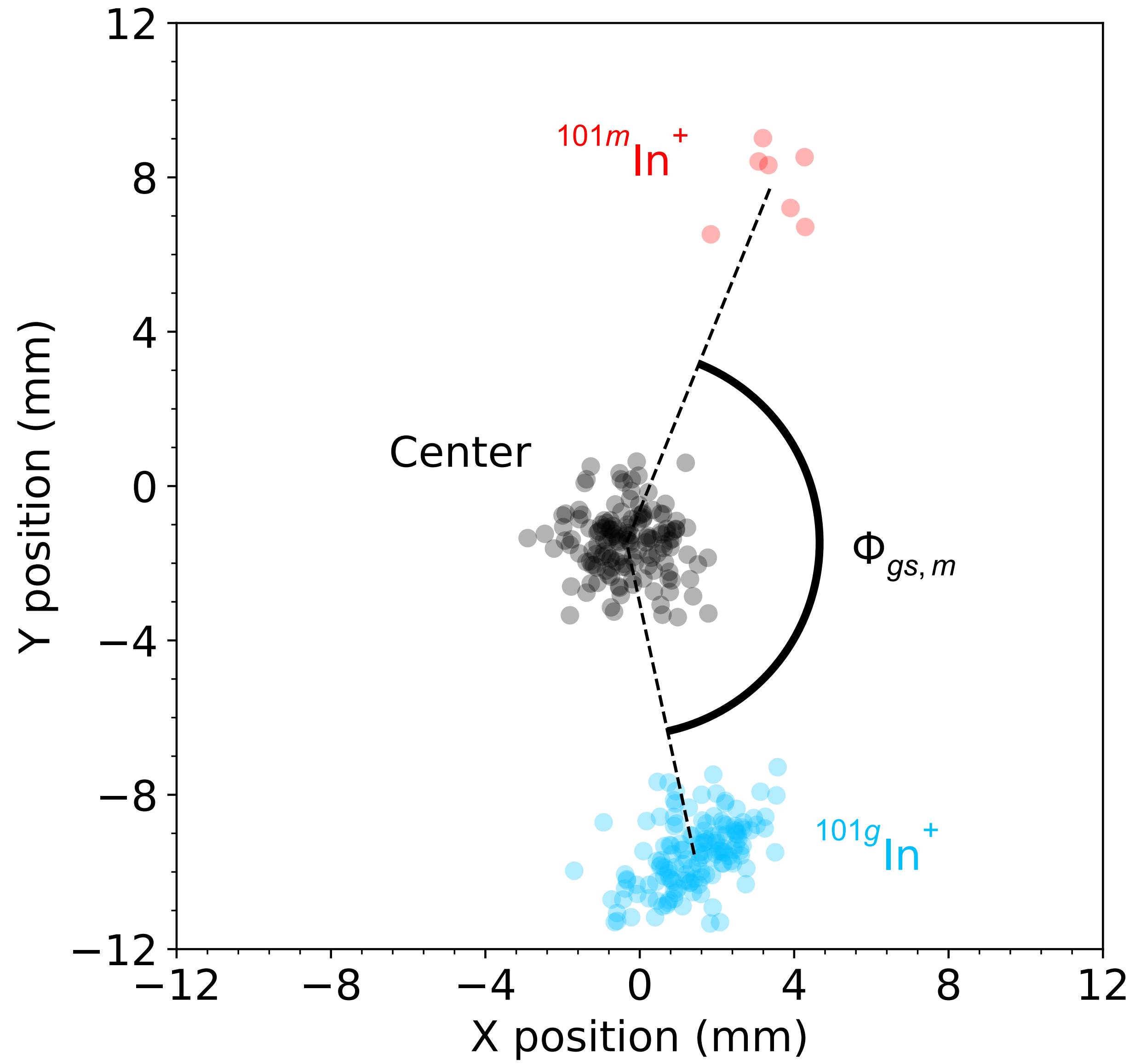


N=50

- 3 isotopes in 3 days with 3 different techniques !


Recently measured at ISOLTRAP

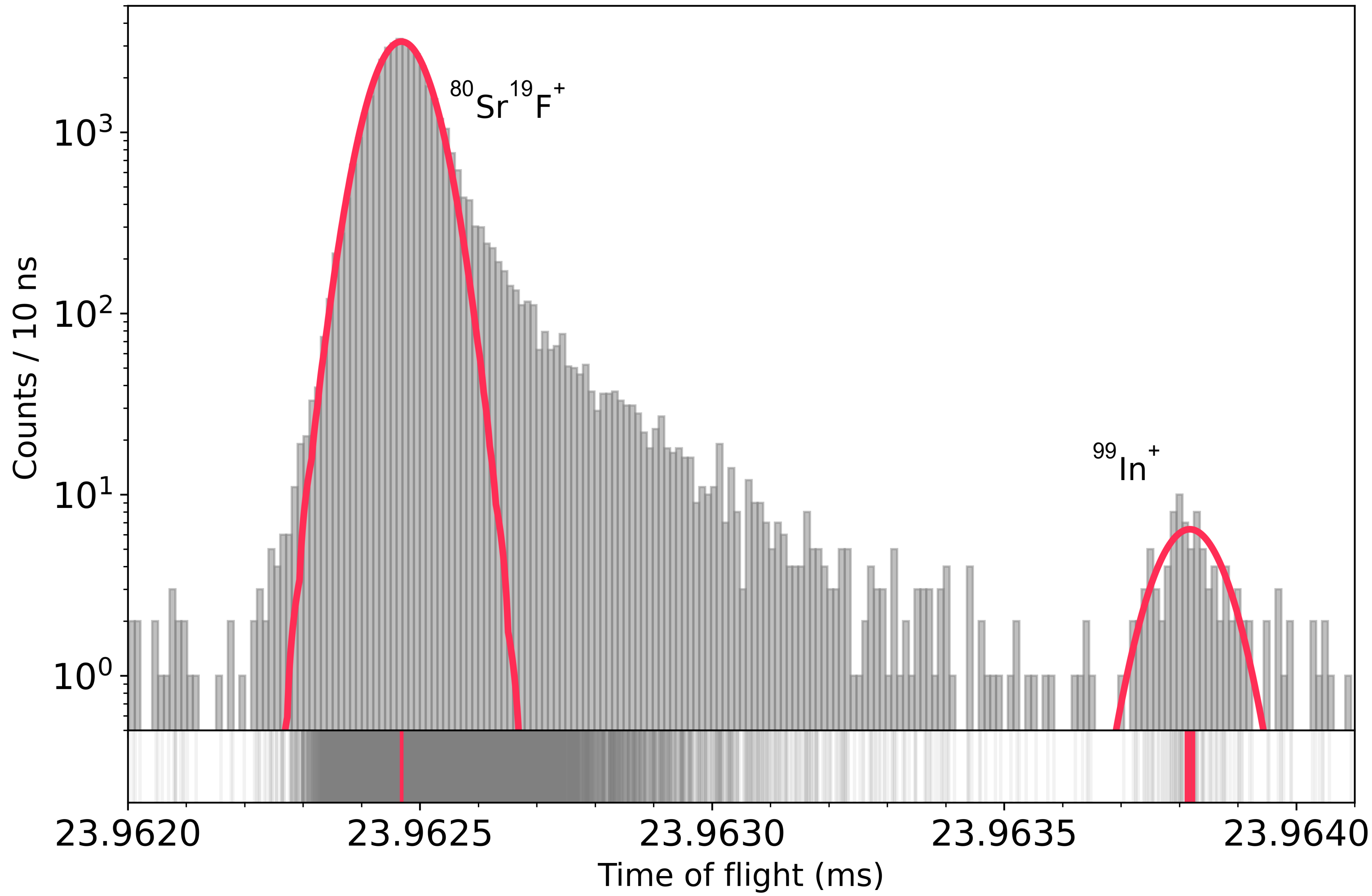
^{101}In PI-ICR separation



- Resolving power >10^6 in t_{acc} = 65ms
- Uncertainty < 10 keV
- Agrees with and improve on previous measurements

X. Xu *et al.*, Phys. Rev. C 100(5), 051303(R) (2019)
C. Hornung *et al.*, Phys. lett. B 802, 135200 (2020)
M. Mougeot et al., Nature Physics 17, 1099–1103 (2021)

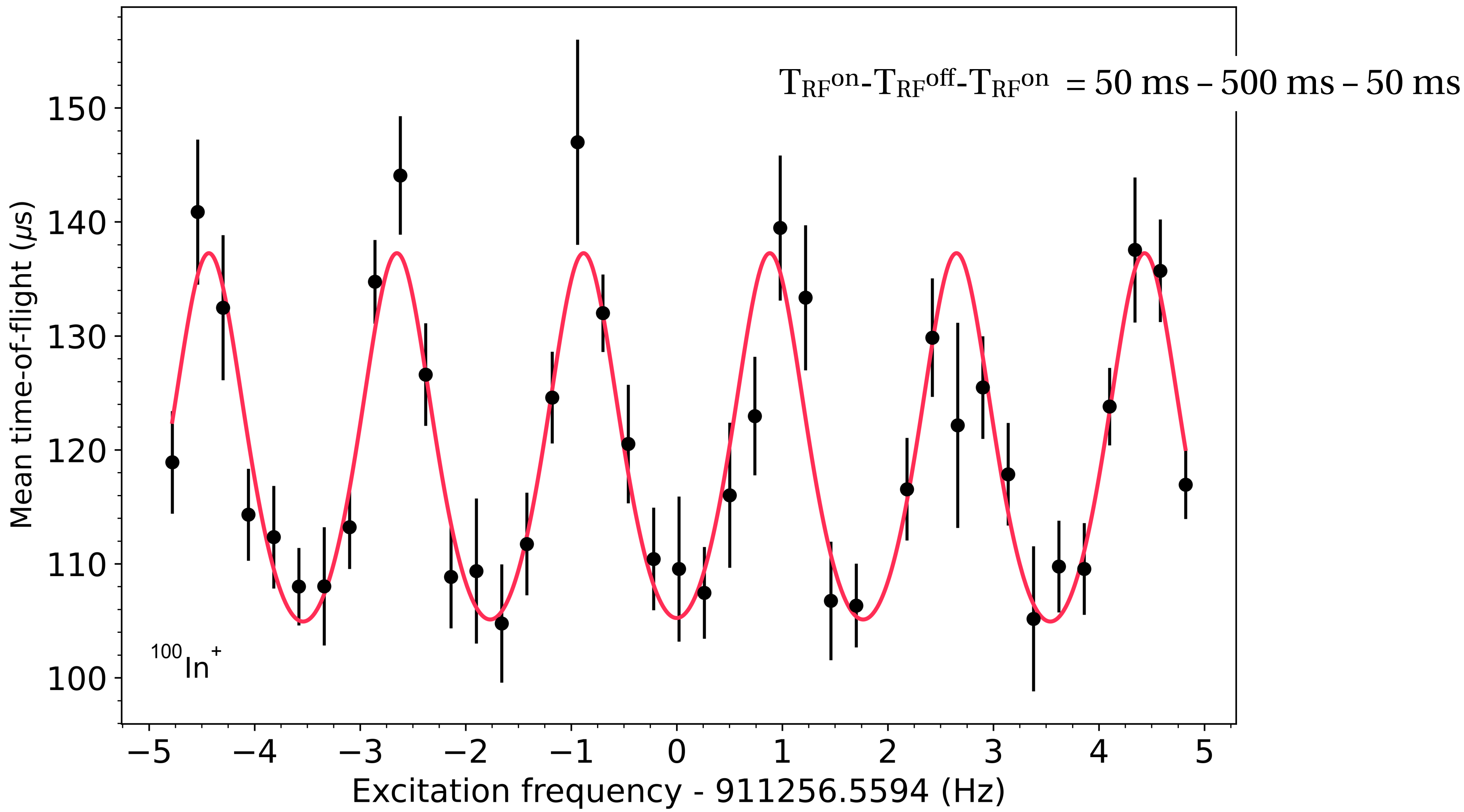
^{99}In MRToF-MS measurement



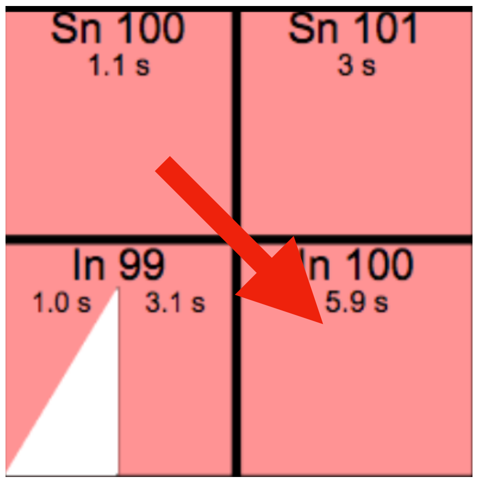
- Well separated
- Clear laser on/off effect
- A few hundred ions collected
- First measurement !

M. Mougeot et al., Nature Physics 17, 1099–1103 (2021)

^{100}In ToF-ICR measurement

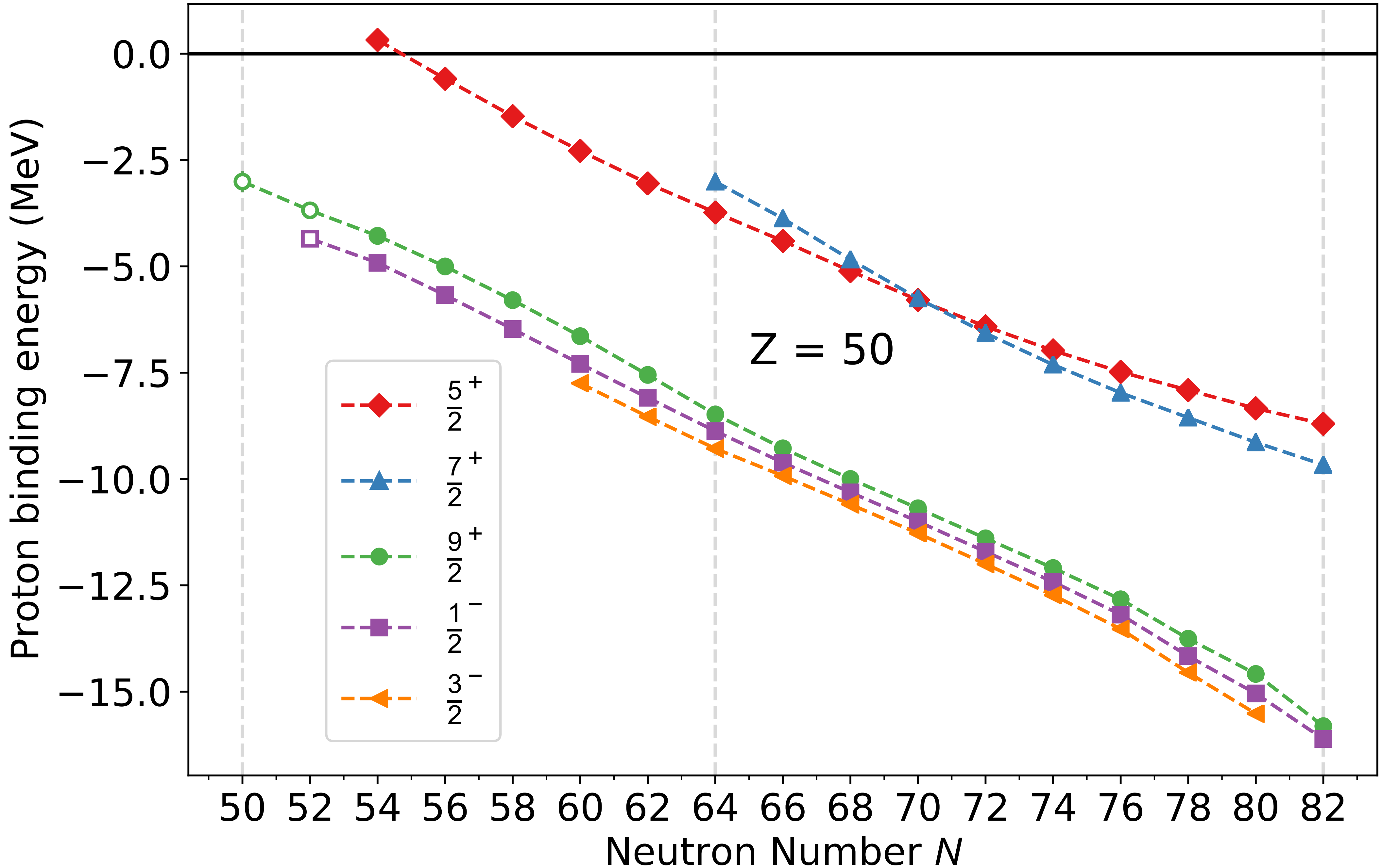


- ~ keV precision (90 times more precise)
- 2 resonances
- PI-ICR study –> No long lived isomers
- Direct link to ^{100}Sn !



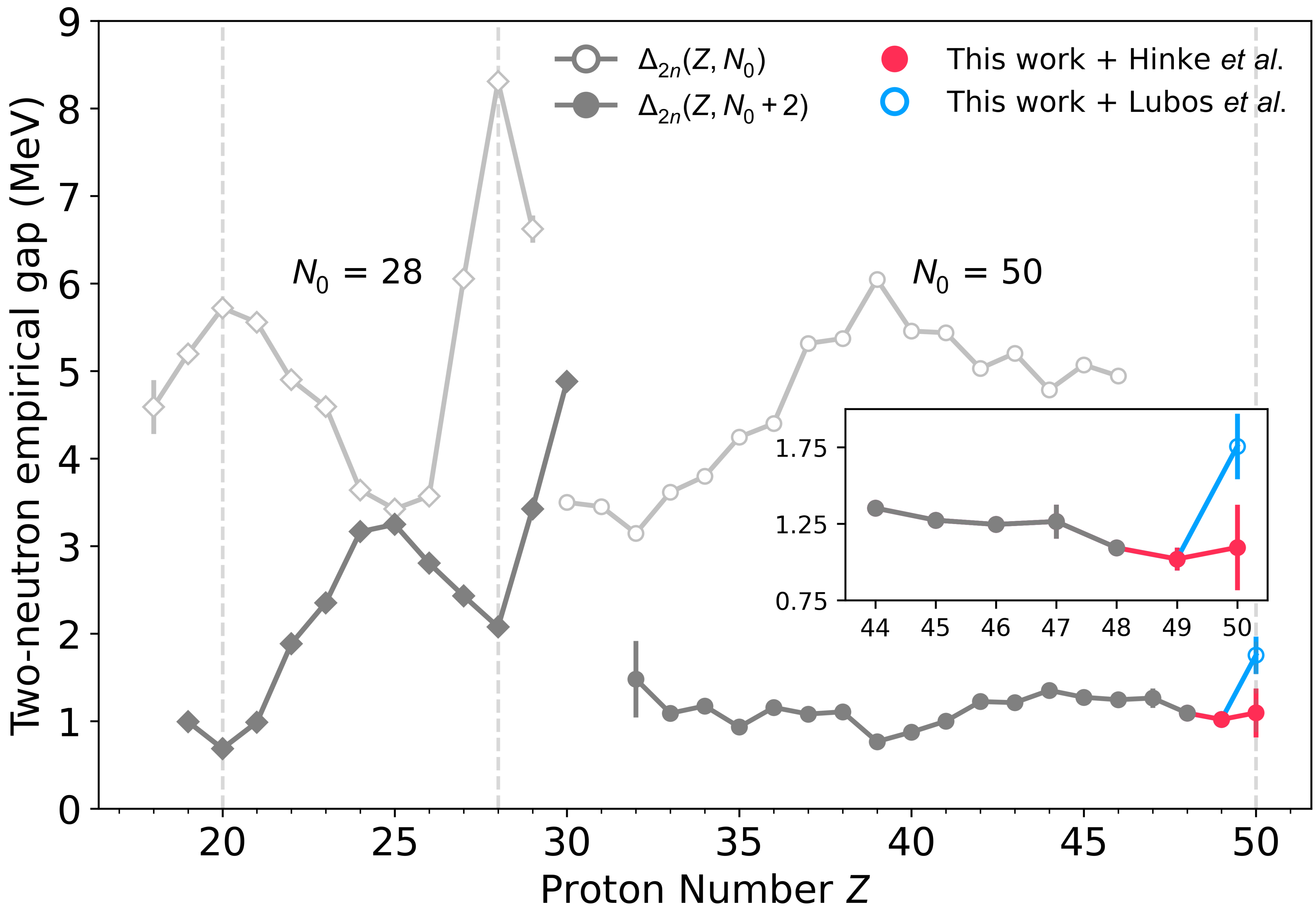
M. Mougeot et al., Nature Physics 17, 1099–1103 (2021)

Journey towards $N = Z = 50$



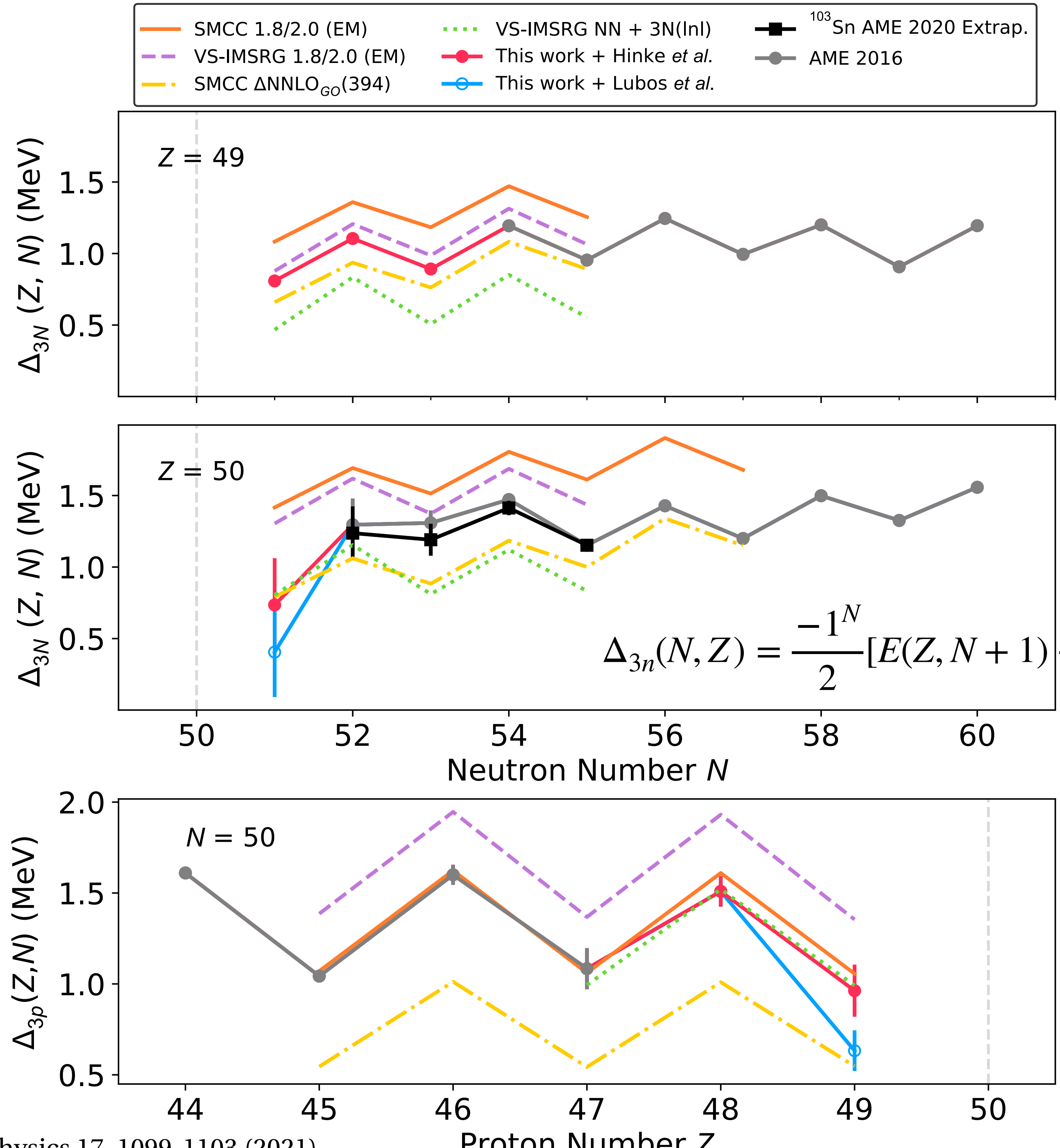
- Important input for phenomenological shell-model

A closer look at ^{100}Sn



M. Mougeot et al., Nature Physics 17, 1099–1103 (2021)
C. B. Hinke *et al.*, Nature 486, 343 (2012)
D. Lubos *et al.*, Phys. Rev. Lett. 122, 222502 (2019)

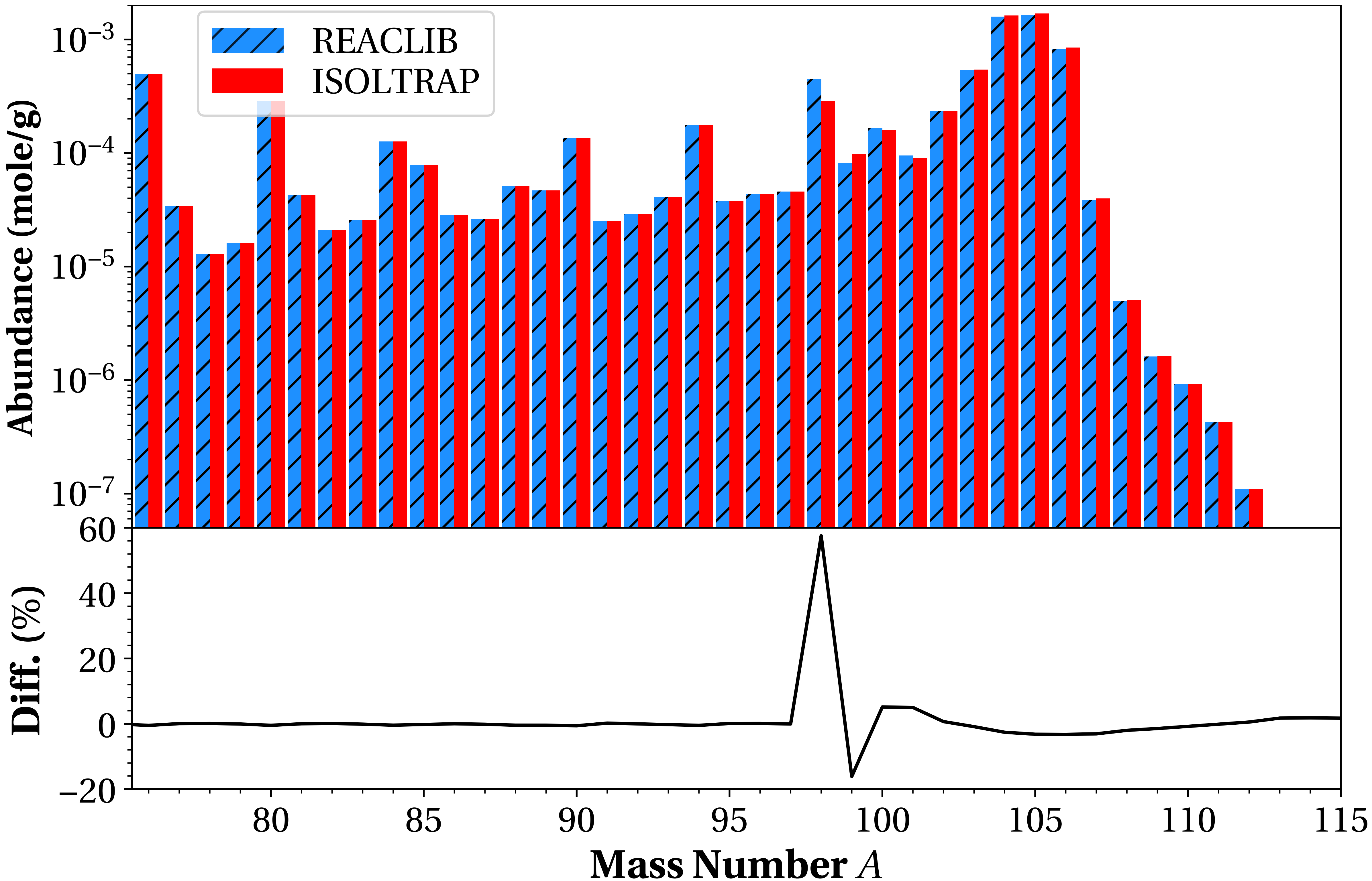
Testing *ab initio* theories



$$\Delta_{3n}(N,Z) = \frac{-1^N}{2}[E(Z,N+1) - 2E(Z,N) + E(Z,N-1)]$$

M. Mougeot et al., Nature Physics 17, 1099–1103 (2021)

Impact on the rp-process:

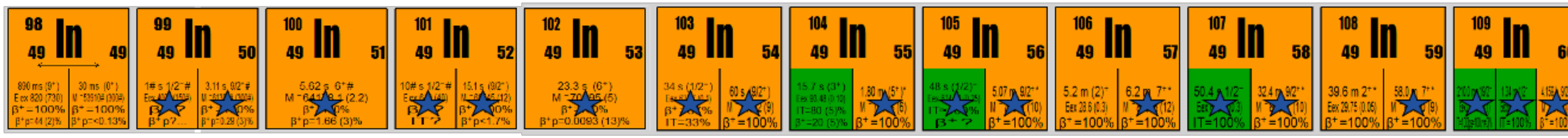


Courtesy of Wei Jia Ong

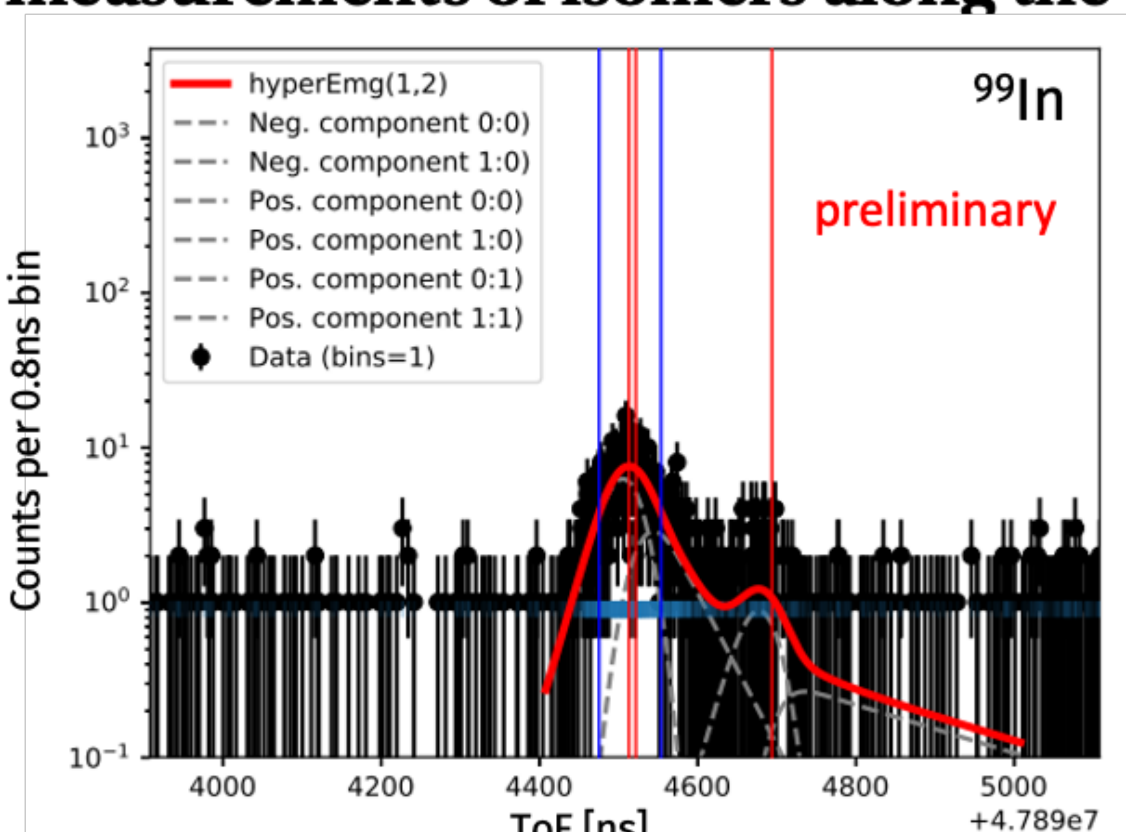
The 2021 campaign

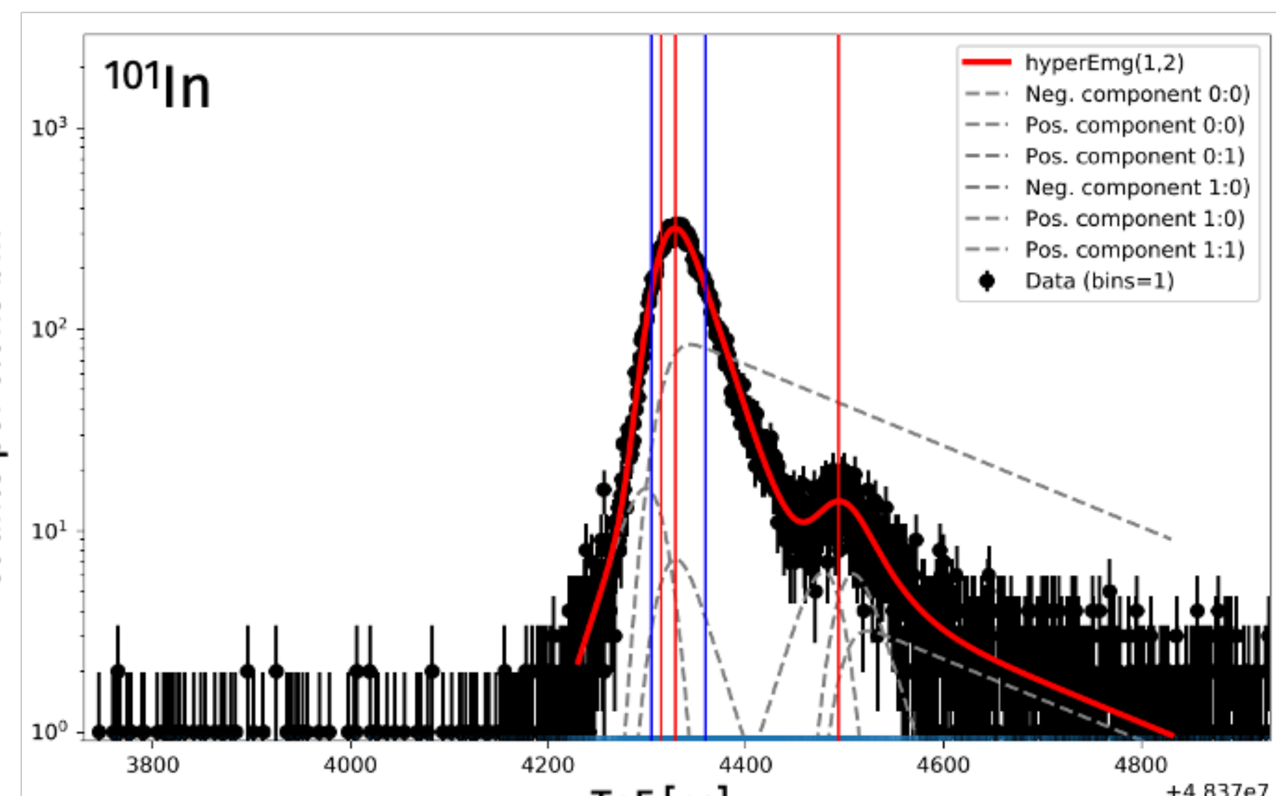
MR-ToF MS measurements of full neutron deficient indium chain

- 11 Ground states and 7 isomers for physics and systematic studies
- First isomeric separation of $^{99g.s,m}$In



Unprecedented MR-ToF mass resolving power at ISOLTRAP enables measurements of isomers along the chain





L. Nies *et al,* in preparation

Perspectives

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 771036 (ERC CoG MAIDEN).

Perspectives: IGISOL-4

The IGISOL production technique

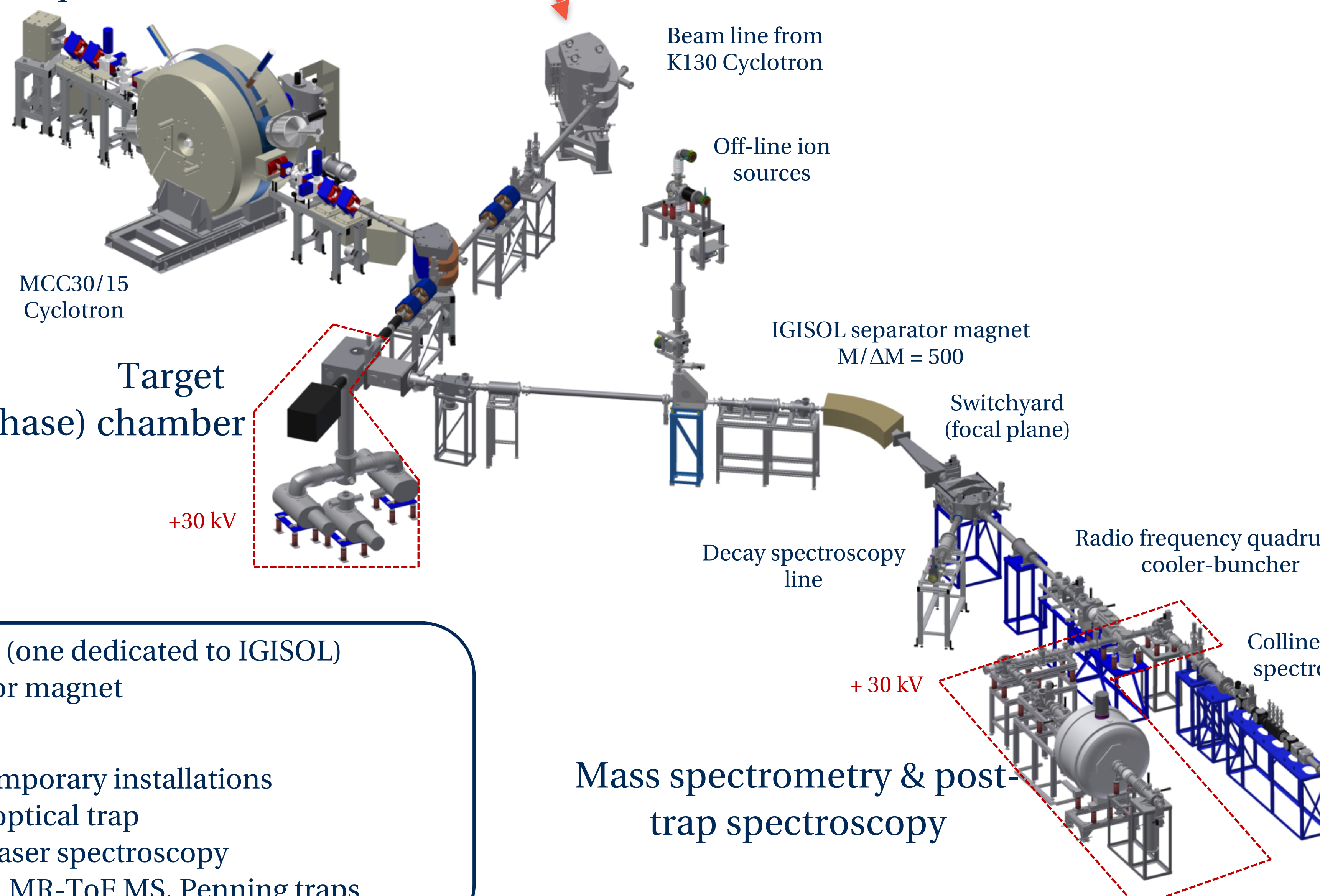
1. Primary beam from cyclotron hits a thin target
2. The recoils are stopped in He buffer gas
3. Supersonic jet guides products into a sextupole: SPIG

Fast and chemically insensitive technique, thus universal

IGISOL

Different geometries for

- →Light-ion fusion
- →Fusion evaporation
- →Fission
- →n-induced fission (testing phase)
- →Cryogenic (building)



- Two cyclotrons (one dedicated to IGISOL)
- Dipole separator magnet
- Beamlines:
  - Line for temporary installations
  - Magneto-optical trap
  - Collinear laser spectroscopy
  - JYFLTRAP: MR-ToF MS, Penning traps

Courtesy A. De Roubin

Future campaigns at IGISOL 1/2

I284: Mass measurements in the vicinity of 78Ni for nuclear astrophysics and nuclear structure studies

In the vicinity of $Z = 28$ and $N = 50$ closed shells for

1. Study of abundances origin
   - Understanding the residual solar abundances associated to the *r*-process
   - Better constrain theoretical models with precise mass measurements
2. Nuclear structure studies
   - Is the Z $= 28$ shell gap modified for neutron rich nuclei?
   - Contradictory experimental observations → possible shape coexistence
   - Subshell gap $N = 40$ exhibits doubly magic features in ^{68}Ni, but not in ^{69}Co → shape coexistence ?
   - Nuclear mass can provide an experimental estimation of the gaps

Utilization of two experimental techniques:

- The double Penning traps with the **PI-ICR** technique for high precision measurements
- The new **MR-TOF MS** for beam purification and fast mass measurements

11 allocated days:

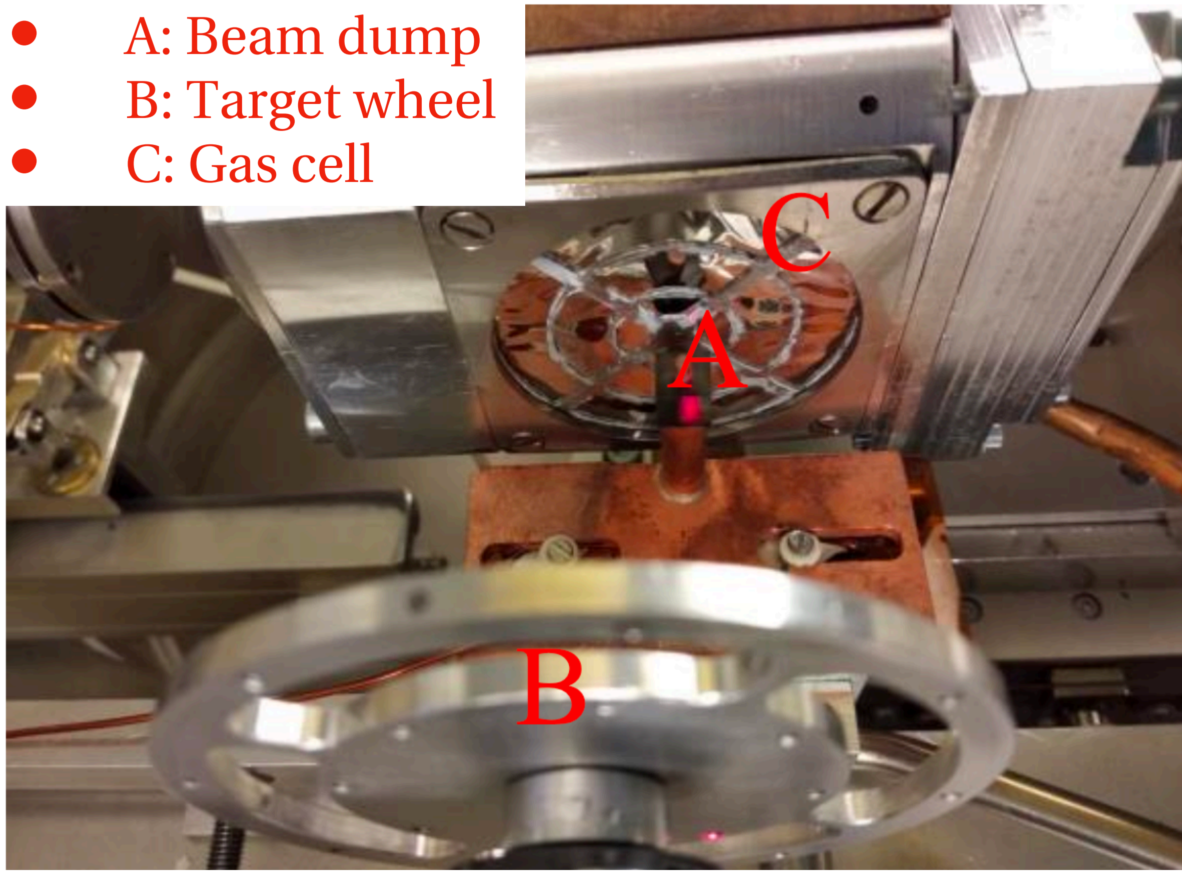
- First part from 17th to 23rd of October this year
- Second part during Spring next year, to be schedule

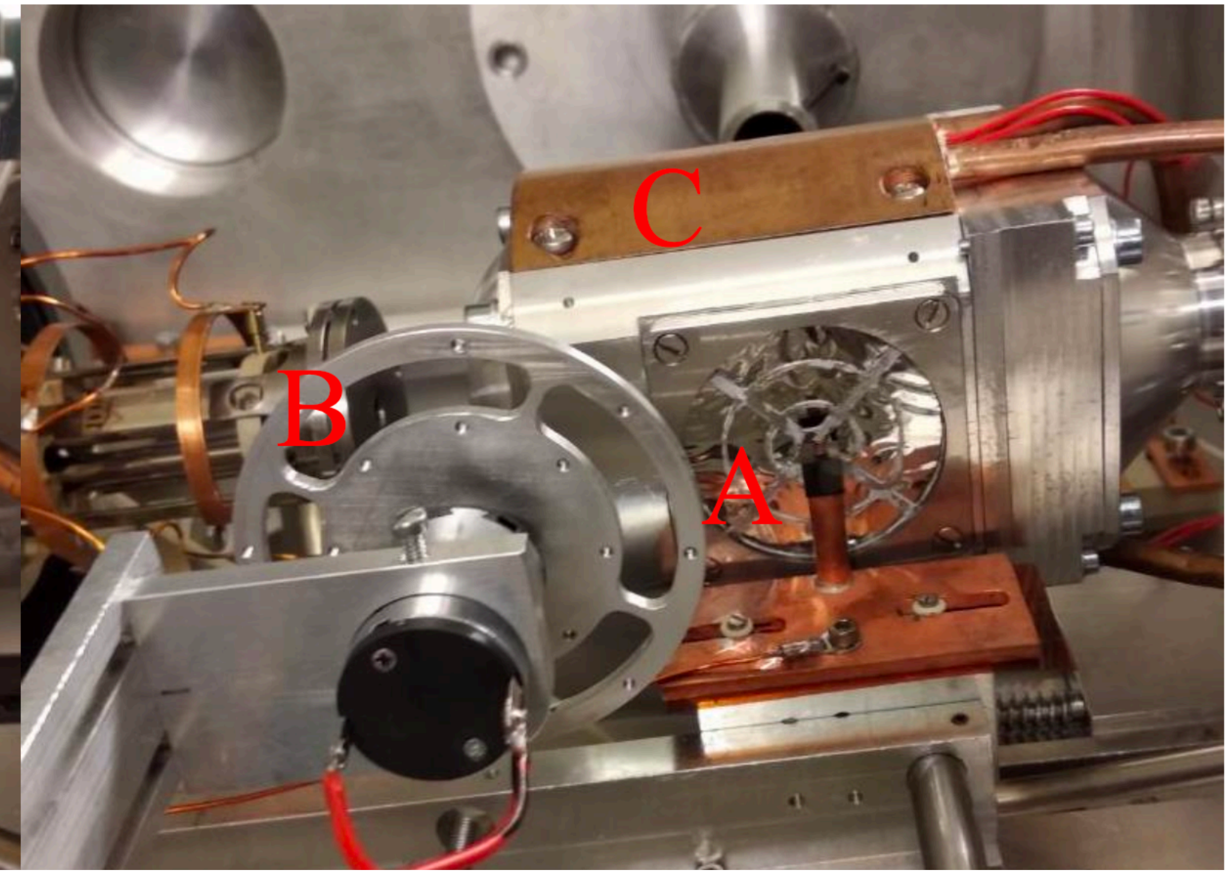
L. Canete et al., Phys. Rev. C ***101****, 041304 (2020)*
S. Giraud, et al., PLB, ***833****, 137309 (2022)*

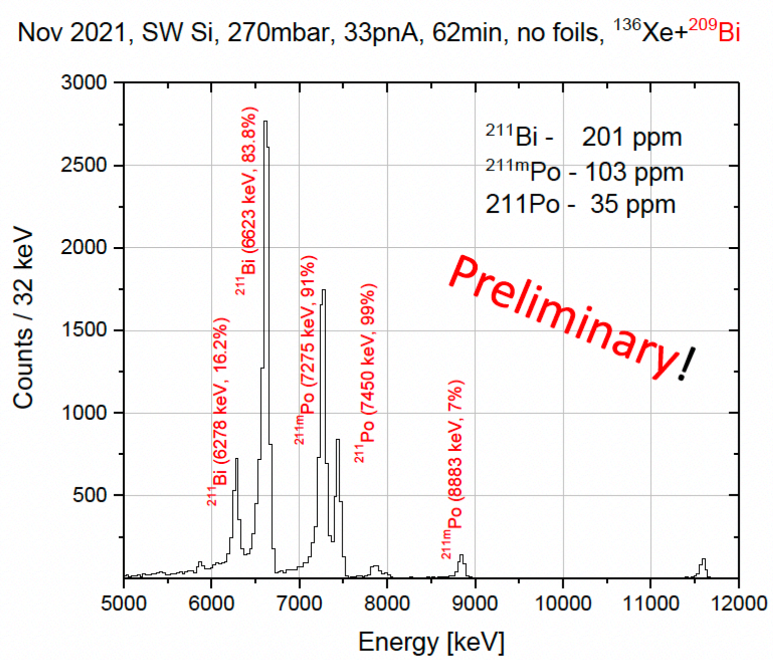
Project lead by A. De Roubin
Slide courtesy of A. De Roubin

Future campaigns at IGISOL 2/2

- A: Beam dump
- B: Target wheel
- C: Gas cell

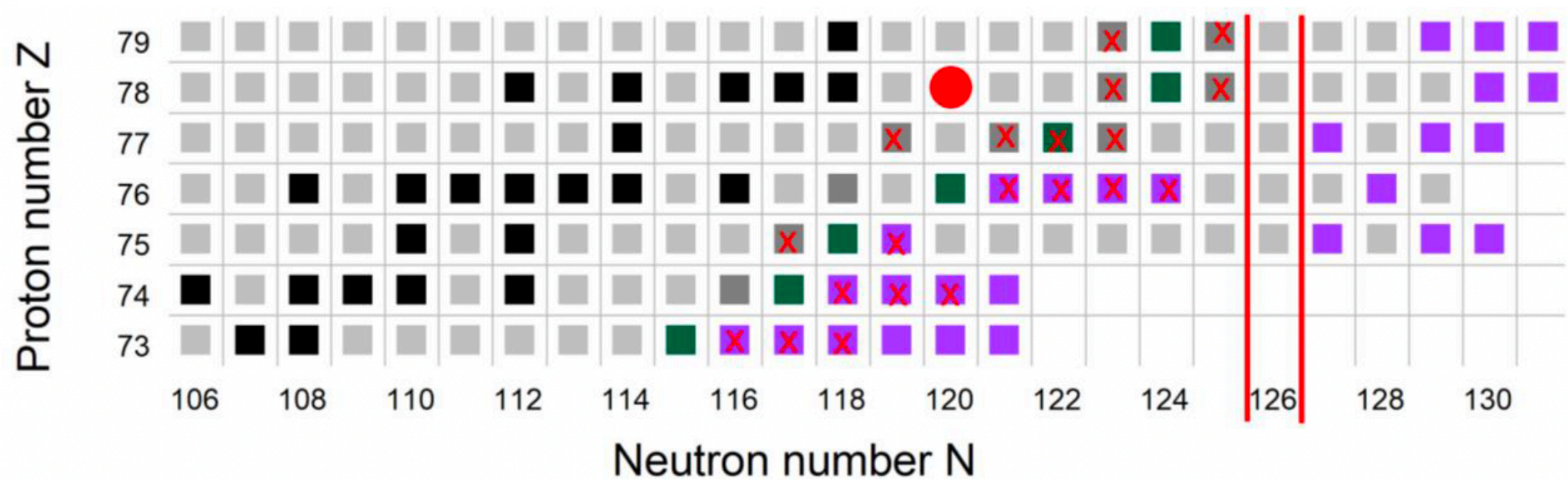






Project lead by O. Beliuskina

^{136}Xe + ^{138}Pt



Conclusion

Summary

High-precision mass measurements for nuclear astrophysics:

- Key to guide nuclear astrophysical modelling
- Particularly challenging measurements but ion manipulation techniques always more performant
- New projects/upgrades at existing facilites (MNT at IGISOL, EPIC at ISOLDE)

Acknowledgement:

D. Atanasov, K. Blaum, T. Cocolios,
S. Eliseev, F. Herfurth, A. Herlert,
J. Karthein, I. Kulikov,
Y. A. Litvinov,
D. Lunney, V. Manea, M. Mougeot,
L.Nies, D. Neidherr,
L. Schweikhard,
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Federal Ministry of Education and Research

Grants No.:
05P15ODCIA
05P15HGCIA

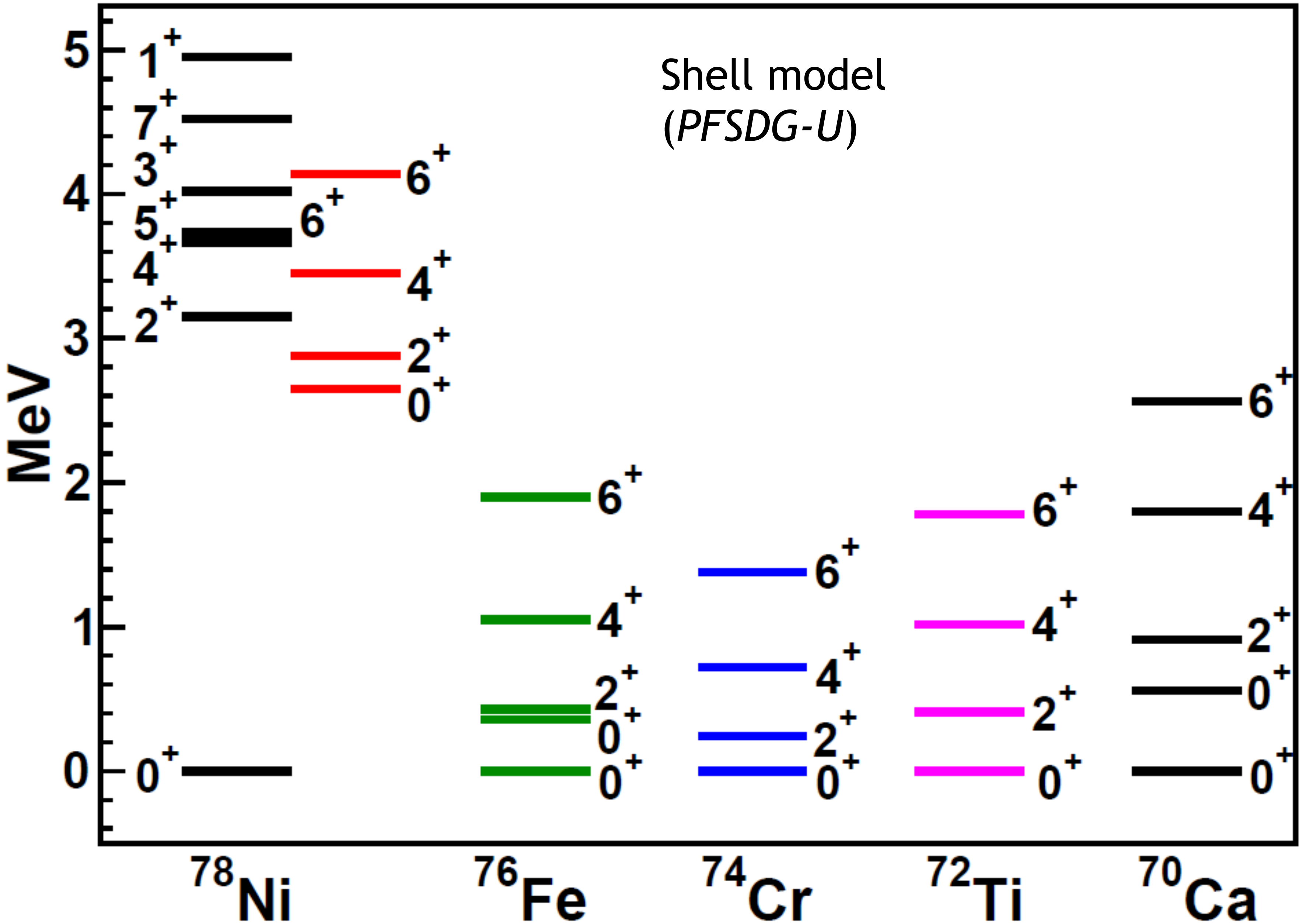
ENSAR/
ENSAR2

https://isoltrap.web.cern.ch

Neutron-rich
Copper isotopes

The neighbouring of 78Ni?

- **^{78}Ni seems to have a doubly-magic character** but shell-model requires **cross-shell excitations** (proton and neutron) to describe the properties of neighbouring nuclides.

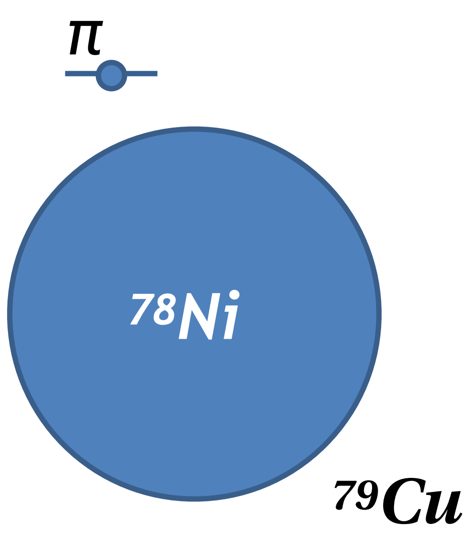


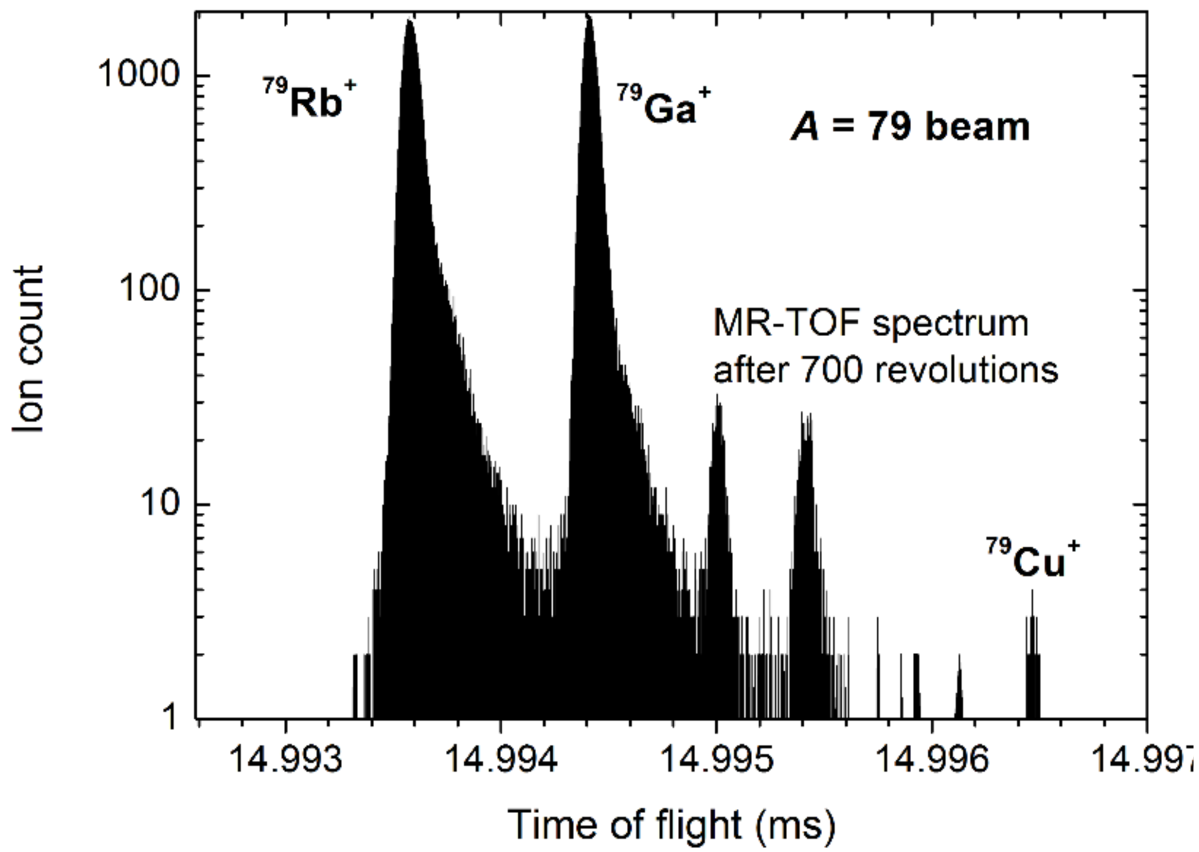
F. Nowacki, A. Poves, E. Caurier, B. Bounthong, Phys. Rev. Lett. 117, 272501 (2016).

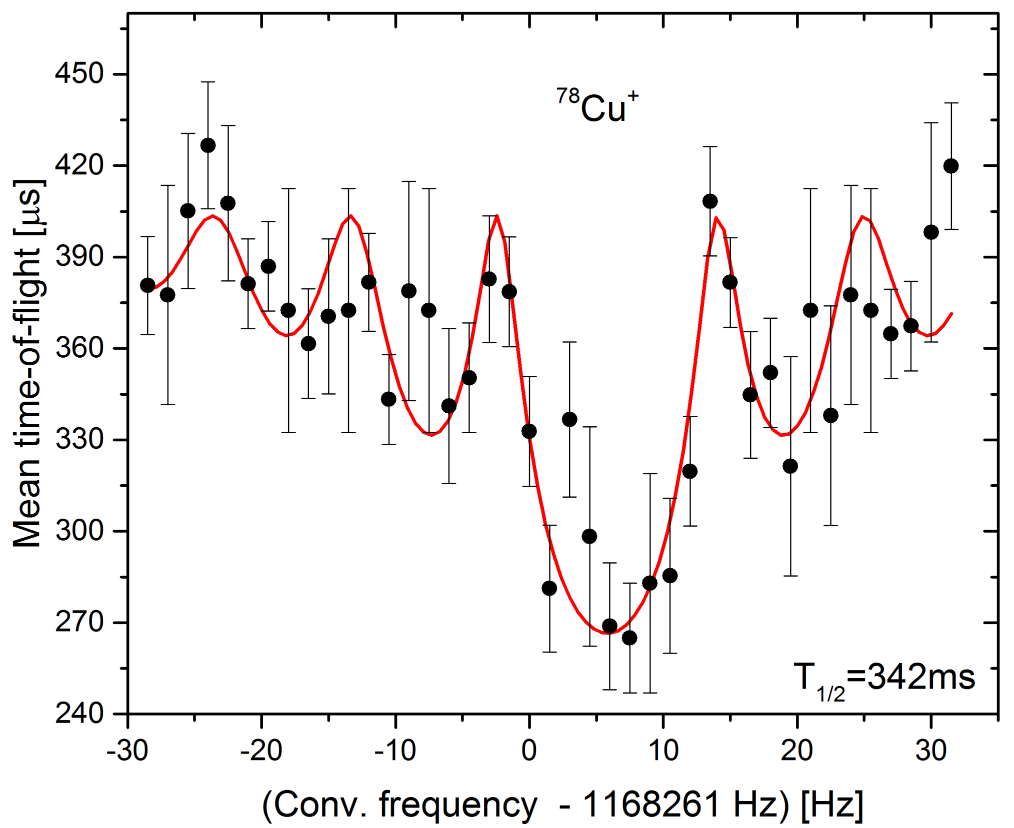
Mass Measurement of $^{75-79}$Cu

- Masses of $^{75-78}$Cu were determined with the precision Penning trap, of ^{78,79}Cu with the MR-TOF MS.

Highly contaminated by Rb and Ga
Rate of less than 10 ions/s.





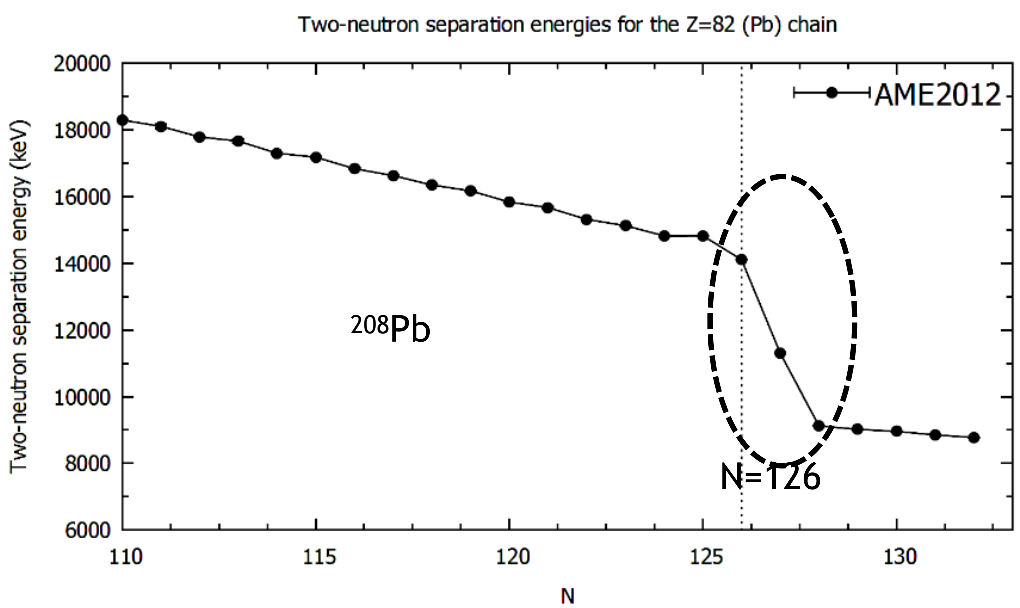


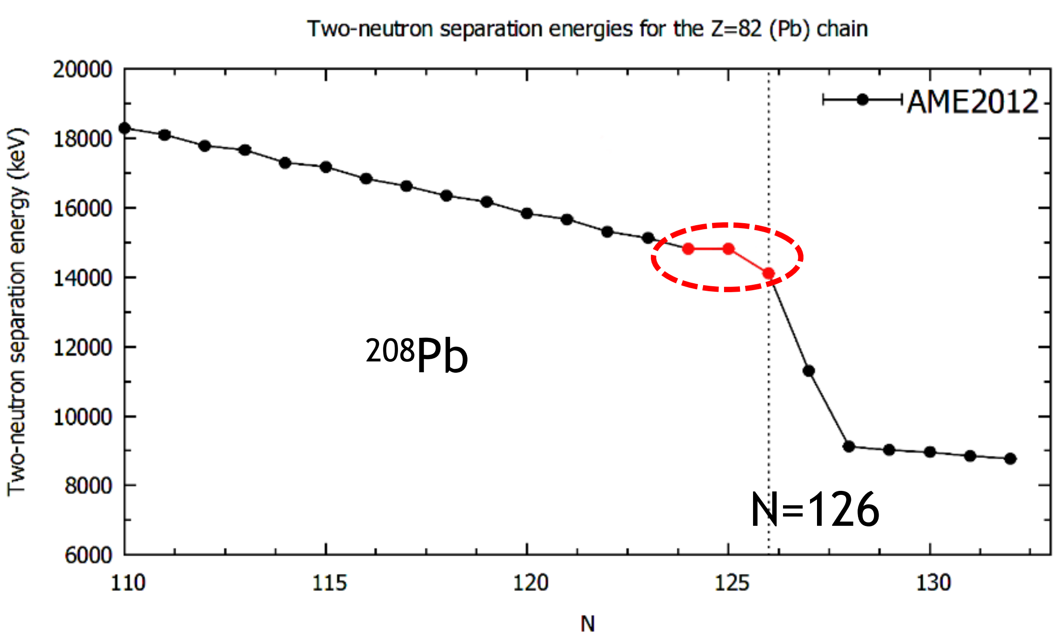
A glimpse at the nature of 78Ni

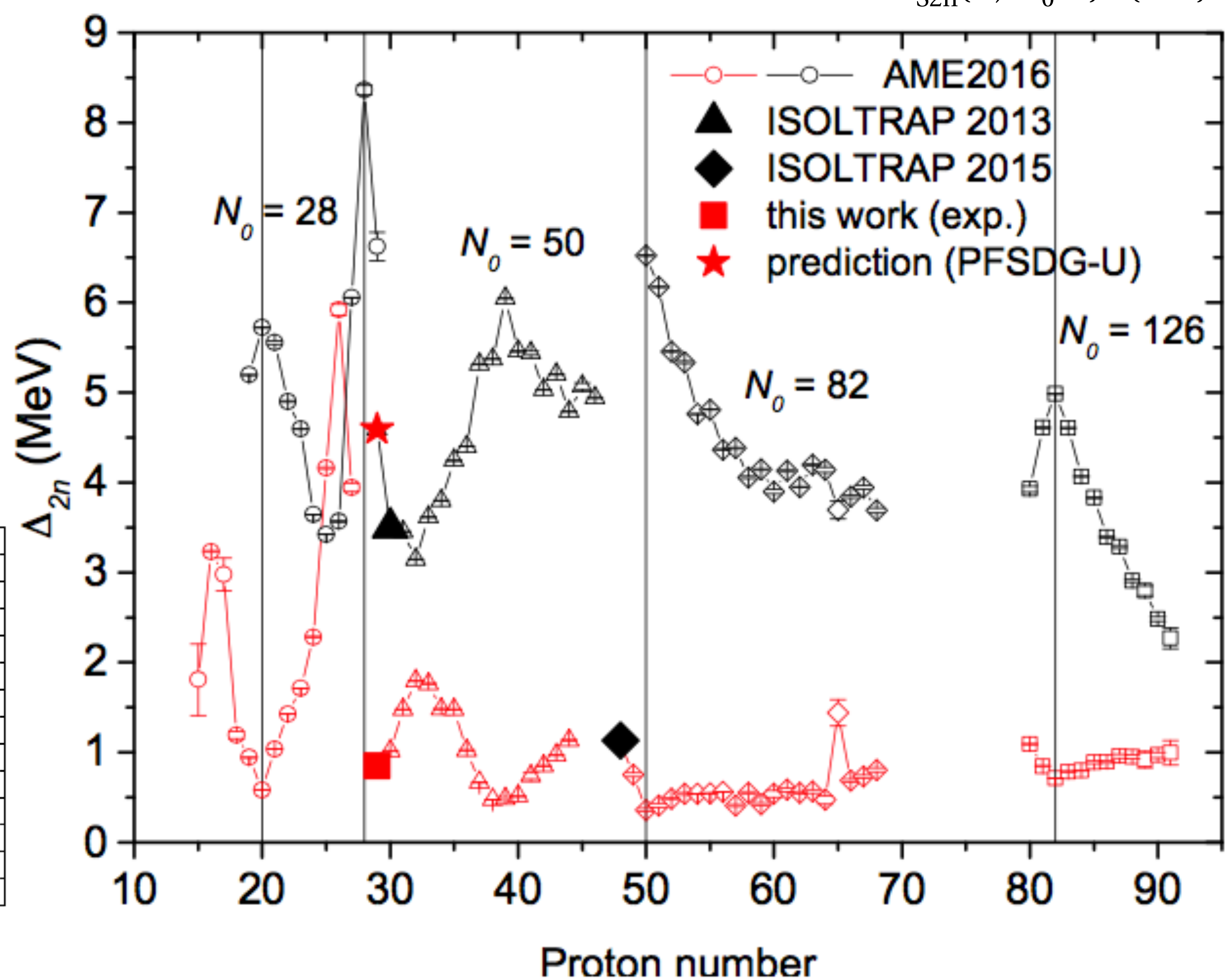
- The trend of S_{2N} in the copper chain before N = 50 behaves as if we are approaching a doubly-magic ^{78}Ni.

$\Delta_{S2n}(Z, N_0)$ (black)

$\Delta_{S2n}(Z, N_0\text{-}2)$ (red)

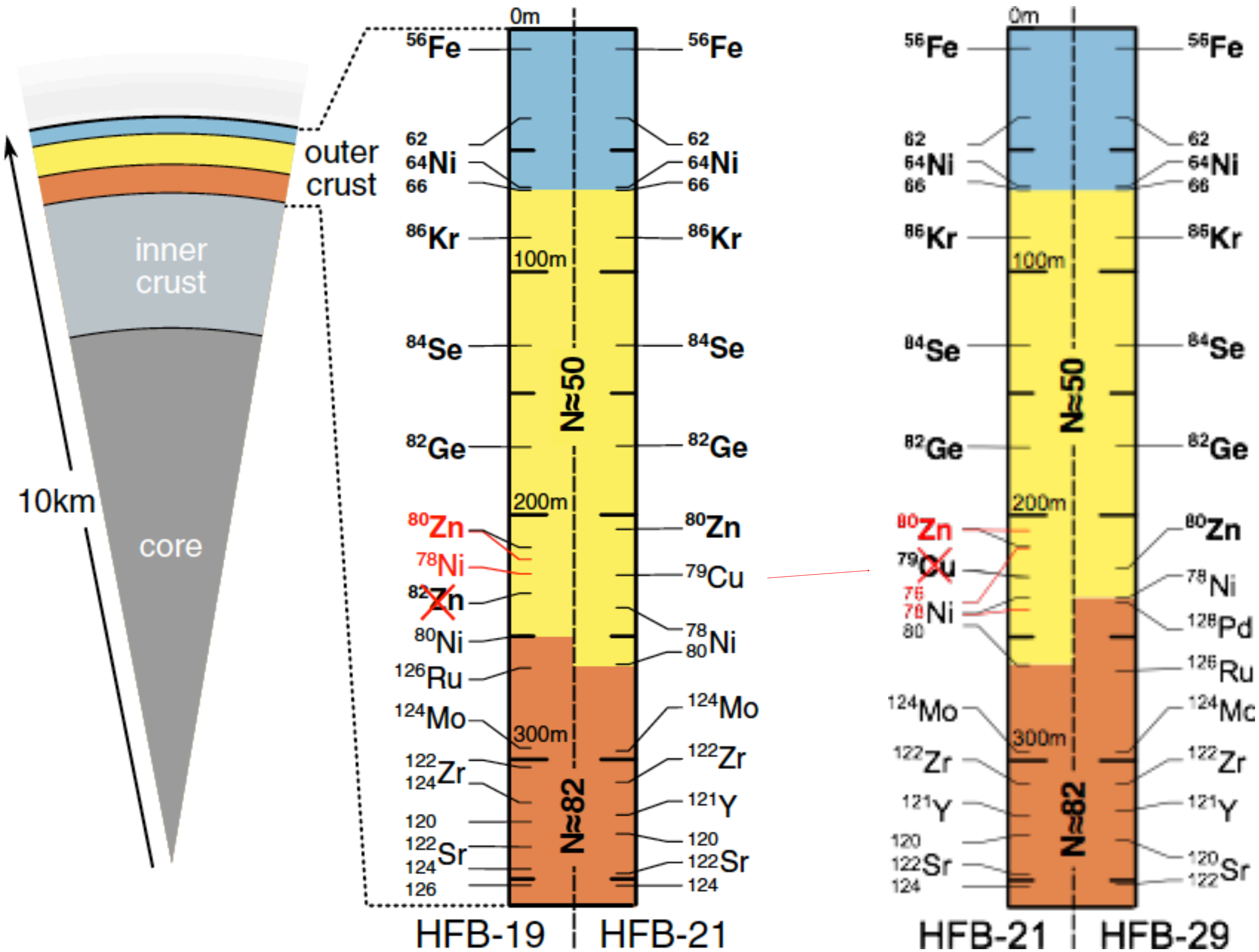






A.Welker et al., Phys. Rev. Lett. 117, 192502 (2017).

Is 79Cu present in Neutron Star Crust ?



^{82}Zn from Wolf et al. PRL (2013)

New calculations by S. Goriely and N. Chamel
^{79}Cu mass from A. Welker et al. PRL (2017)