Precision mass measurements for nuclear astrophysics at ISOLDE/CERN

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CSNSM-Orsay-FRANCE

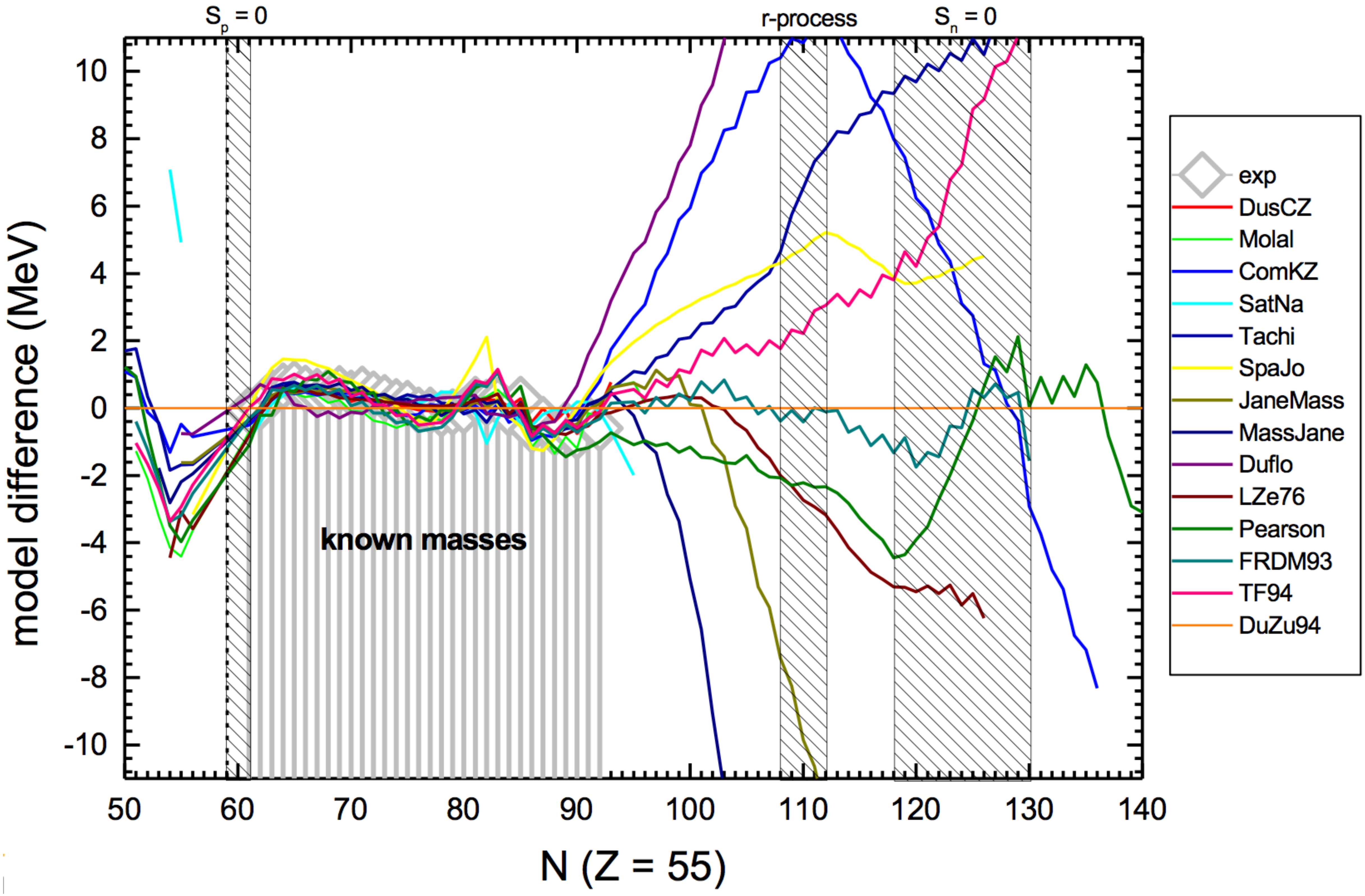
Structure and Reactions for Nuclear Astrophysics Workshop 2017

Outline:

- ISOLTRAP at ISOLDE/CERN
- Recent results
- Conclusions

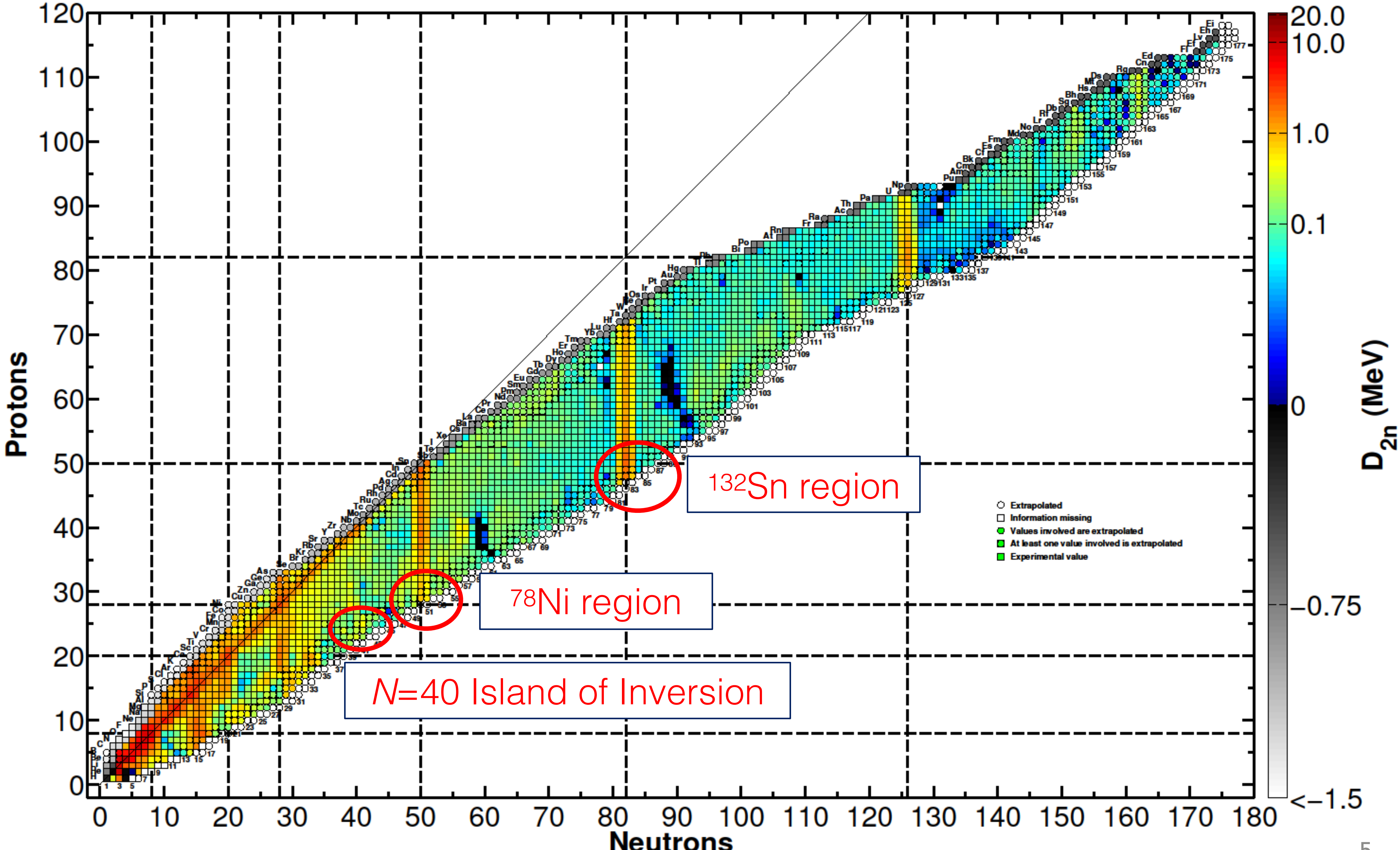
Introduction

Nuclear Mass models



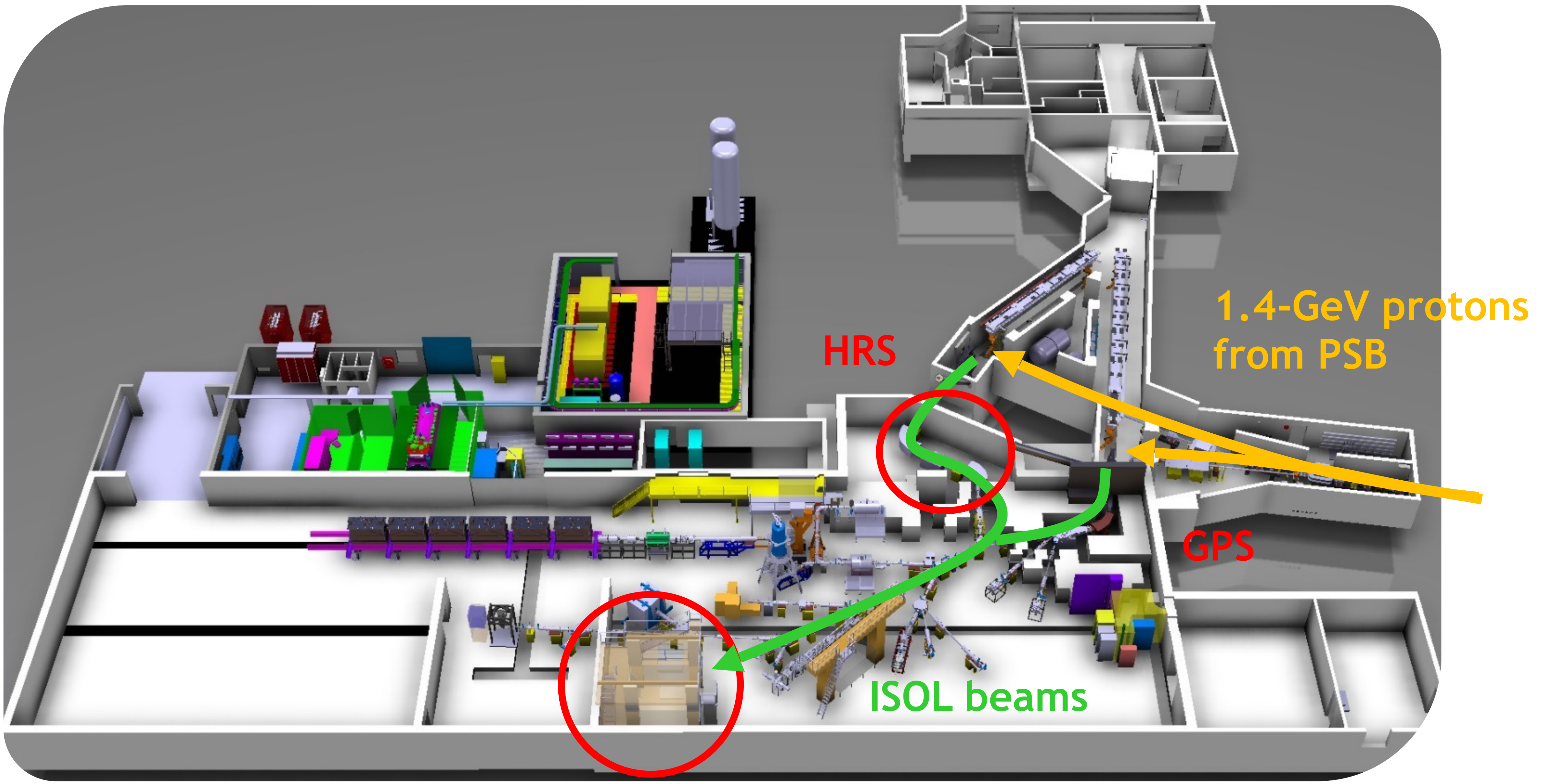
Topology of the mass surface

$$D_{2N} = S_{2N}(N,Z) - S_{2N}(N+2,Z) = 2B(Z,N) - B(Z,N+2) - B(Z,N-2)$$



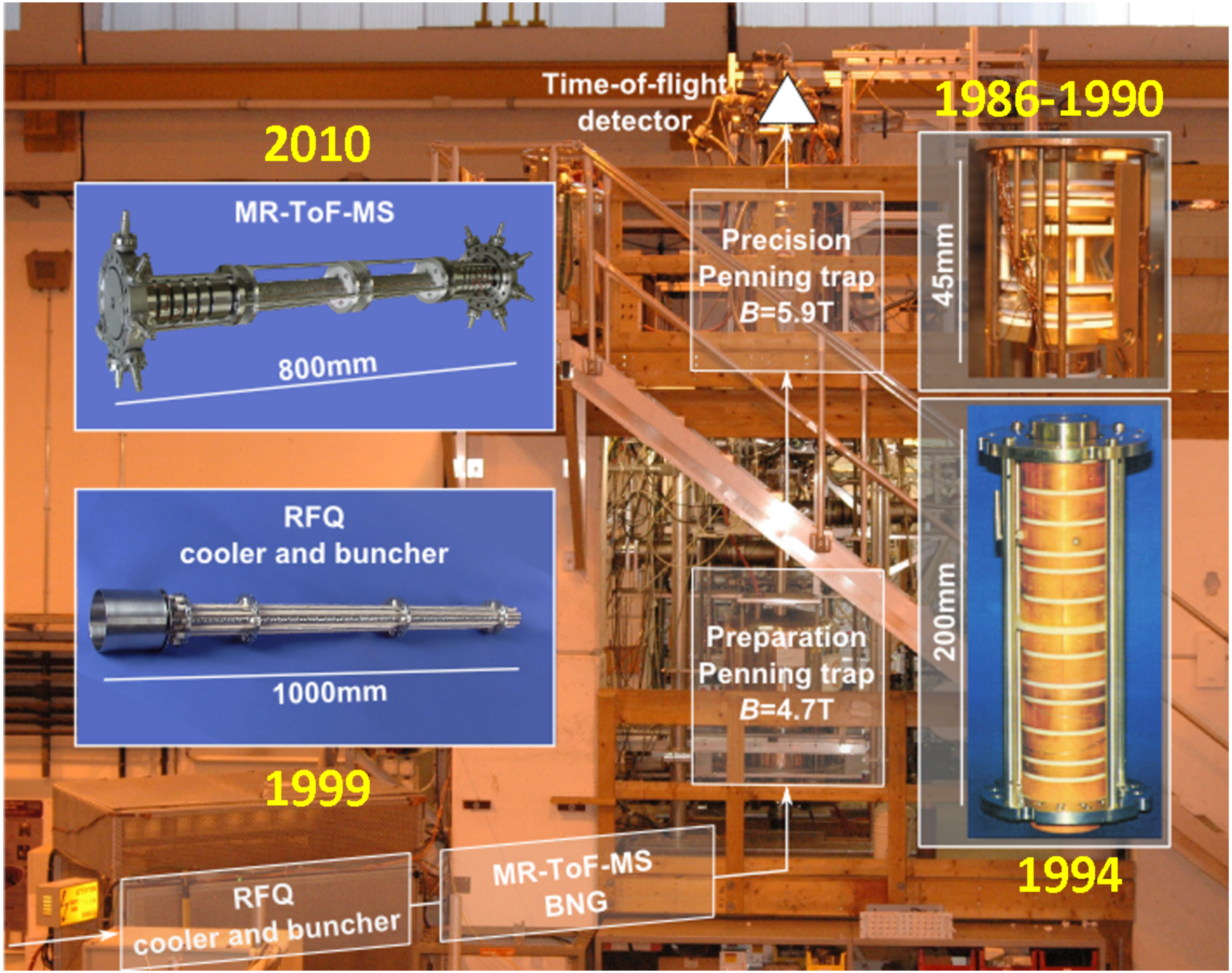
ISOLTRAP at ISOLDE/CERN

ISOLTRAP@ISOLDE@CERN



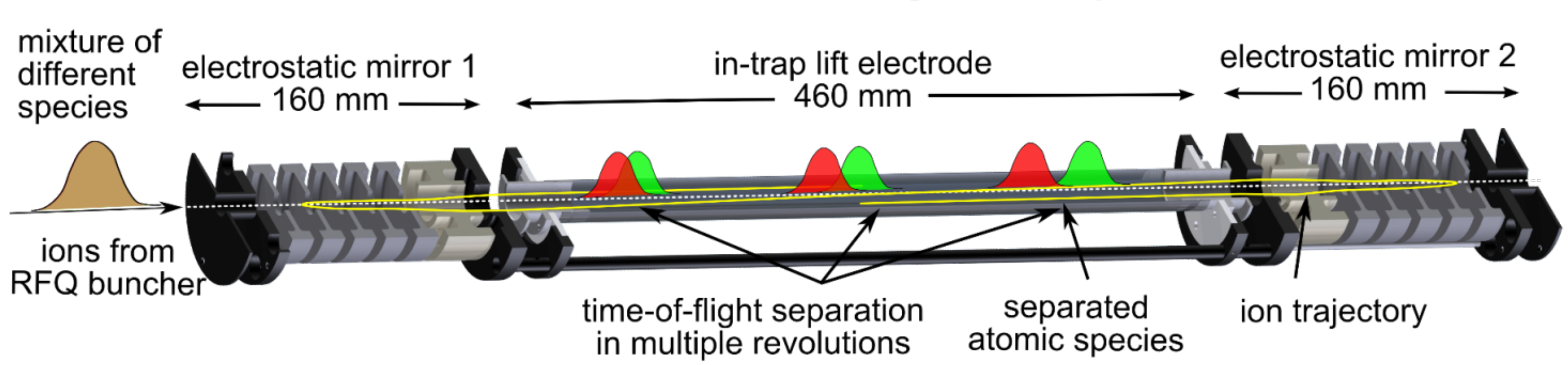
ISOLTRAP

ISOLTRAP mass spectrometer

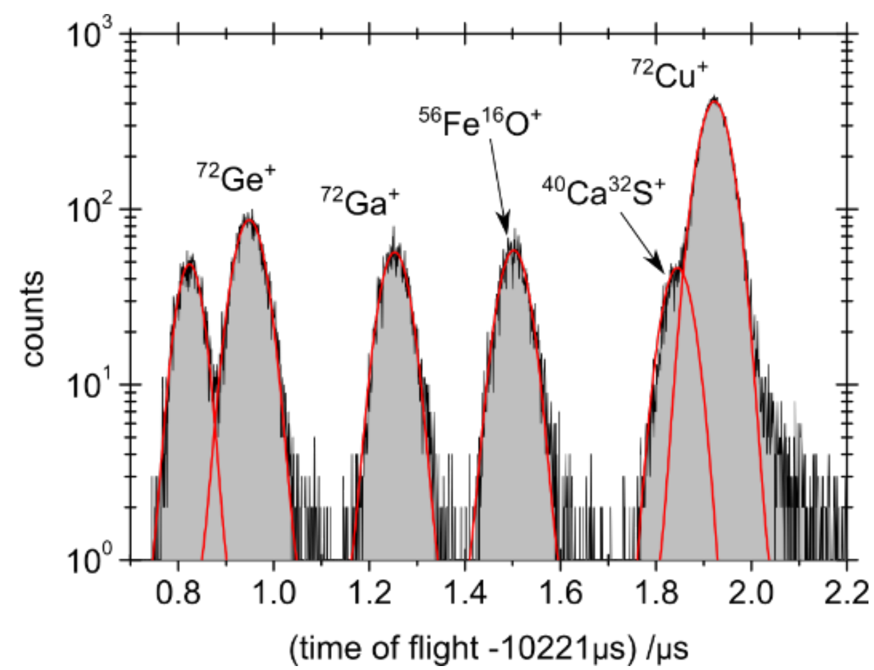


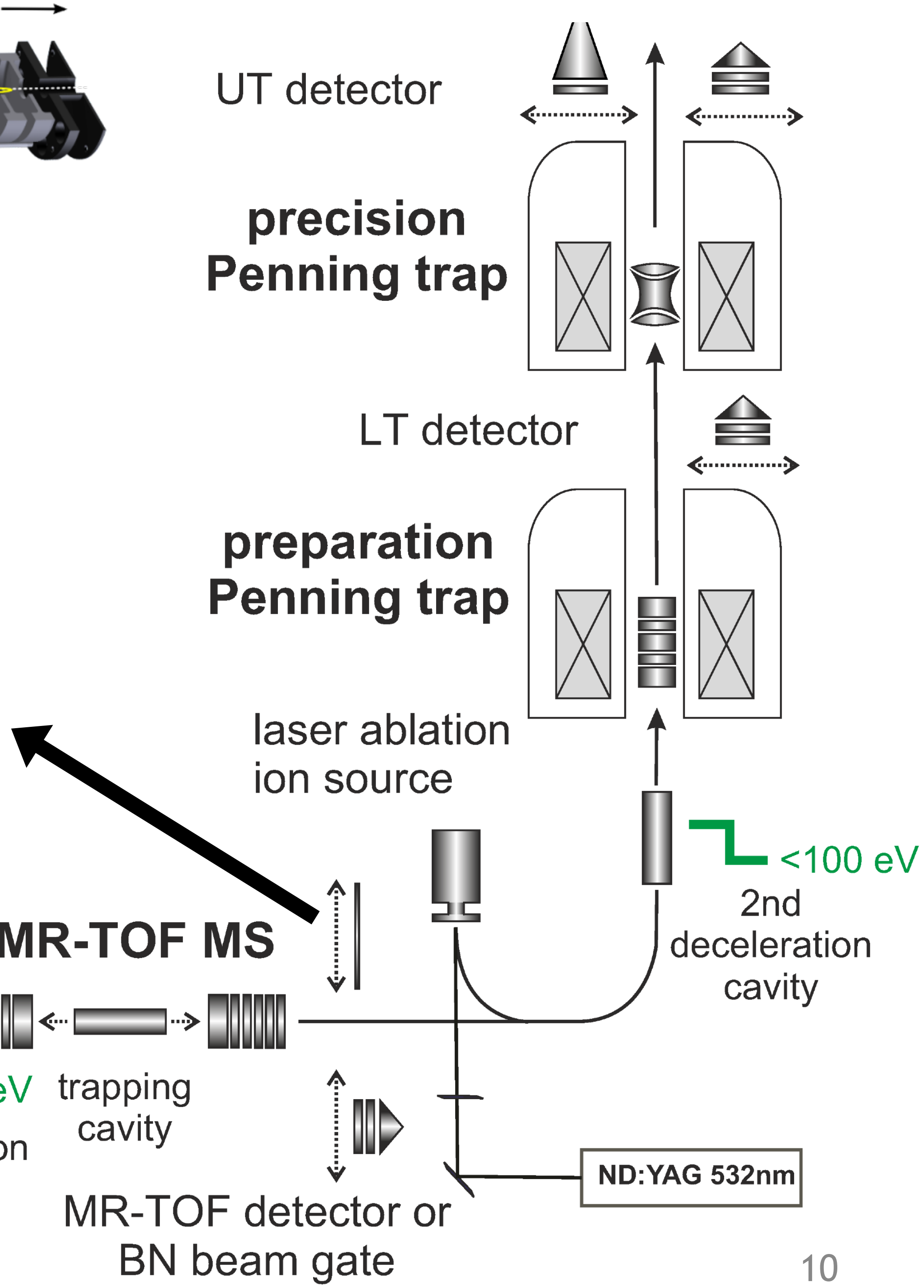
Where is the Ion of Interest?

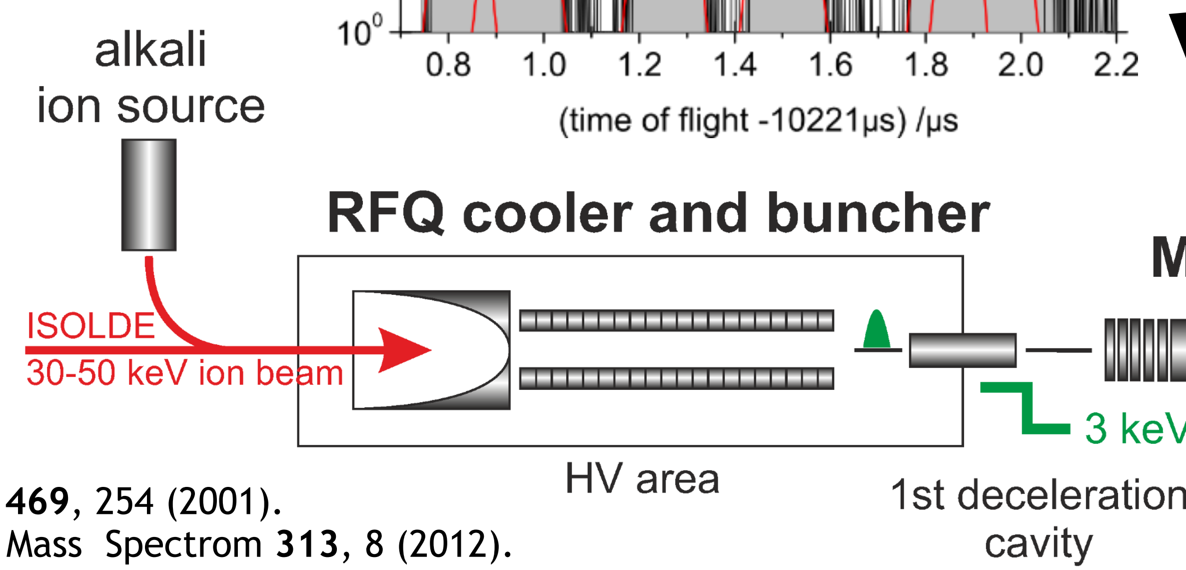
Multi-Reflection Time-Of-Flight Mass Separator



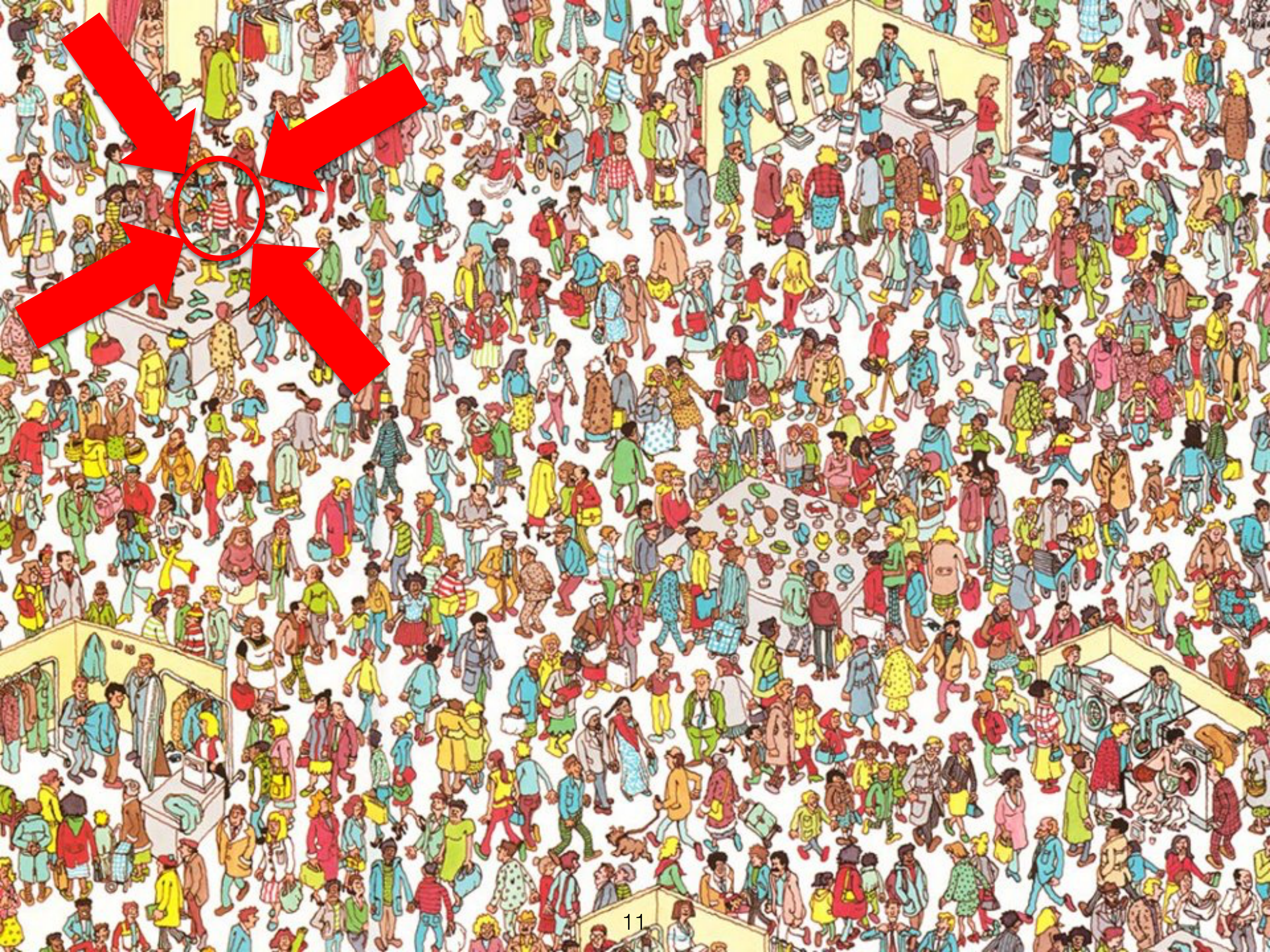
MRToF-MS:
- Yield > 1 / s
- Half-life > 10 ms
- Precision ~ 2 × 10^{-7}



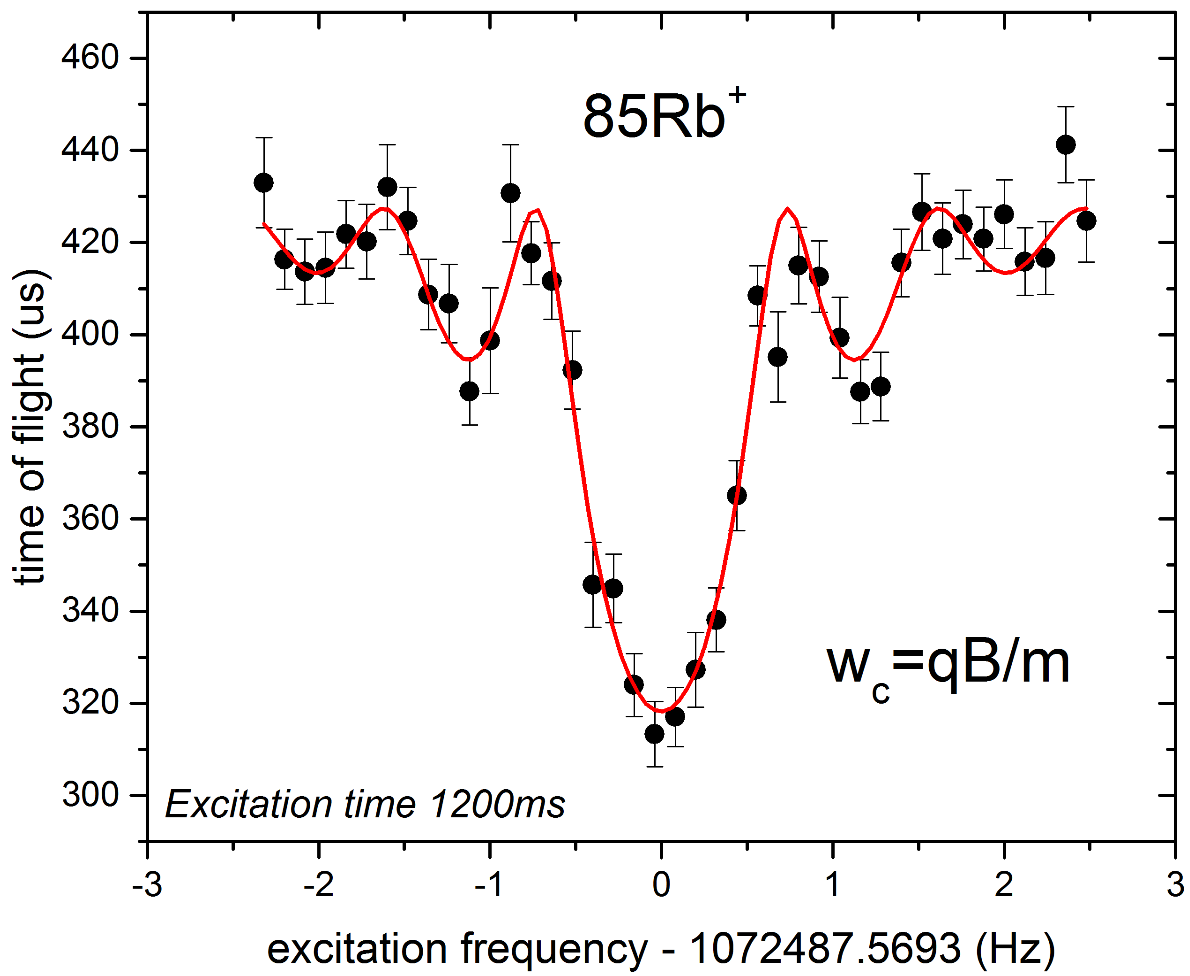




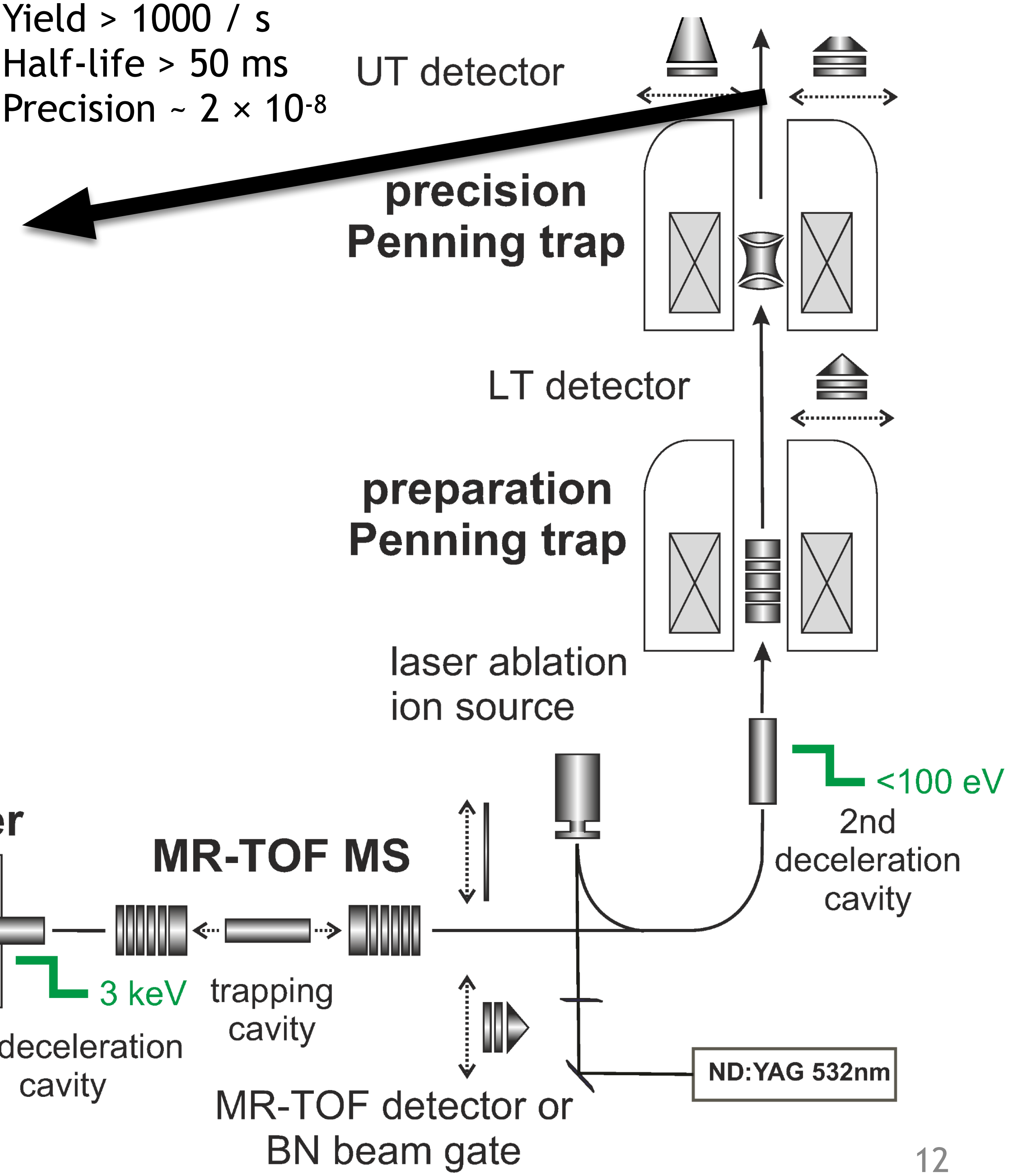
F. Herfurth *et al.*, NIM A **469**, 254 (2001).
R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012).
G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995).

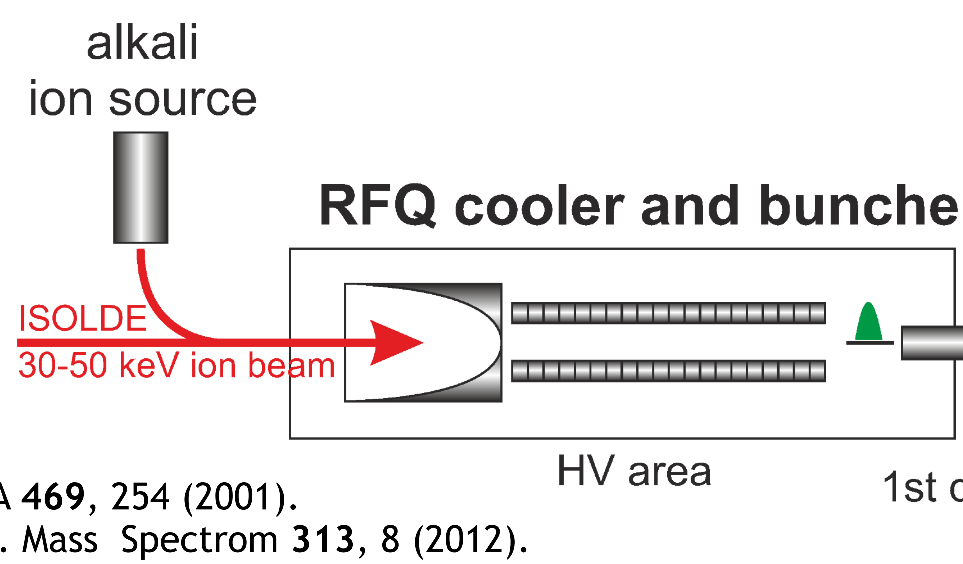


An overview of the ISOLTRAP setup



Penning Trap:
- Yield > 1000 / s
- Half-life > 50 ms
- Precision ~ 2×10^{-8}





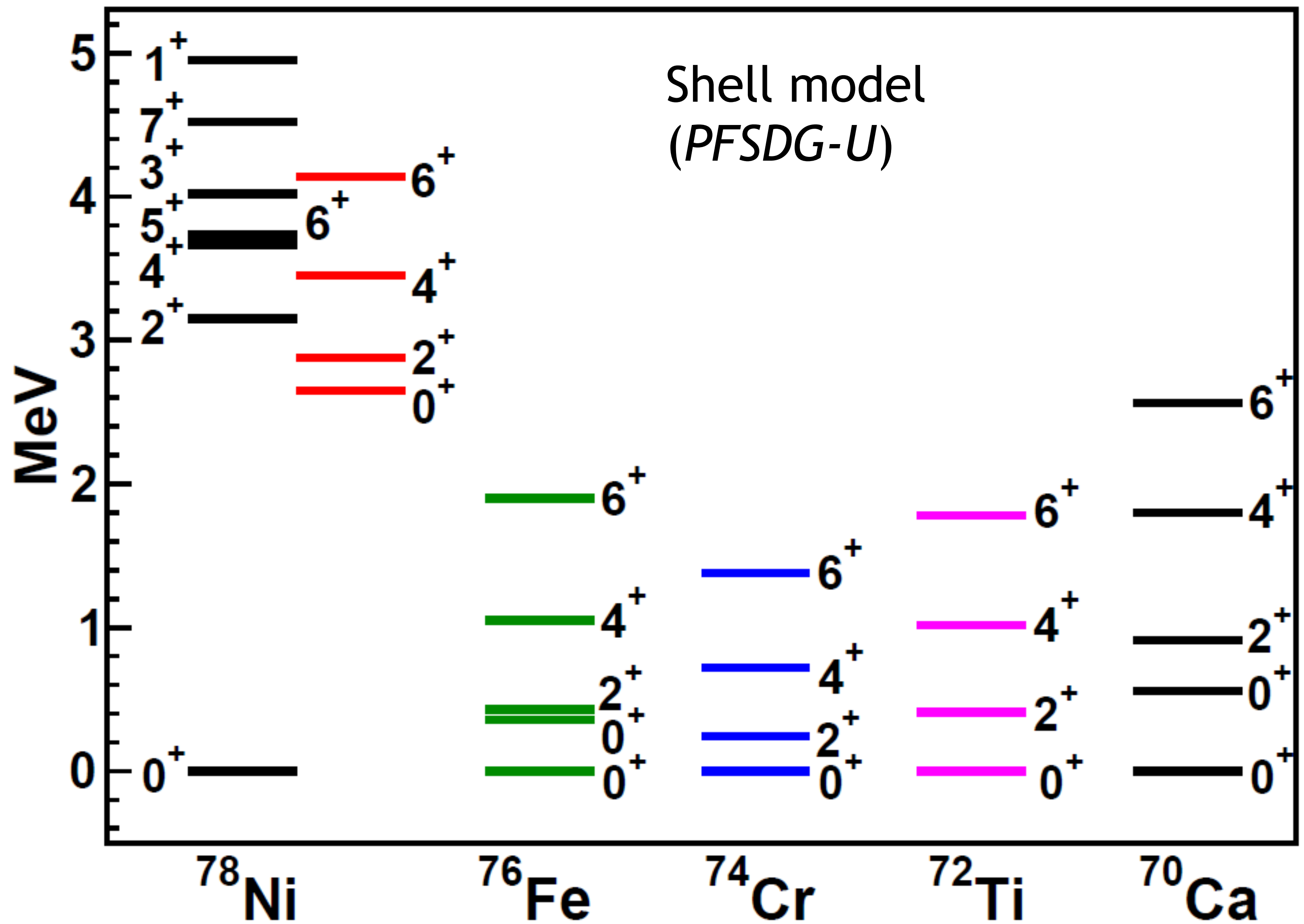
F. Herfurth *et al.*, NIM A **469**, 254 (2001).
R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012).
G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995).

Results

Neutron-rich Cu isotopes

The neighbouring of ^{78}Ni

- ^{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.

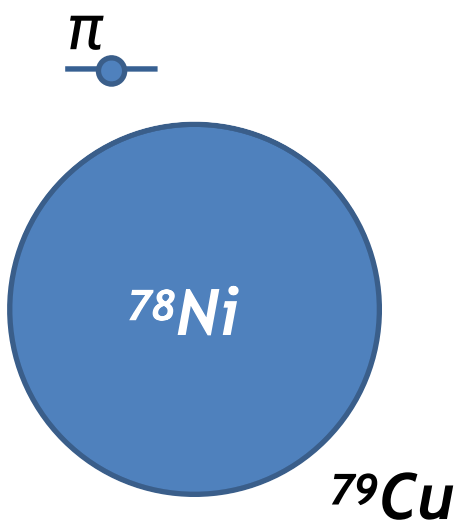


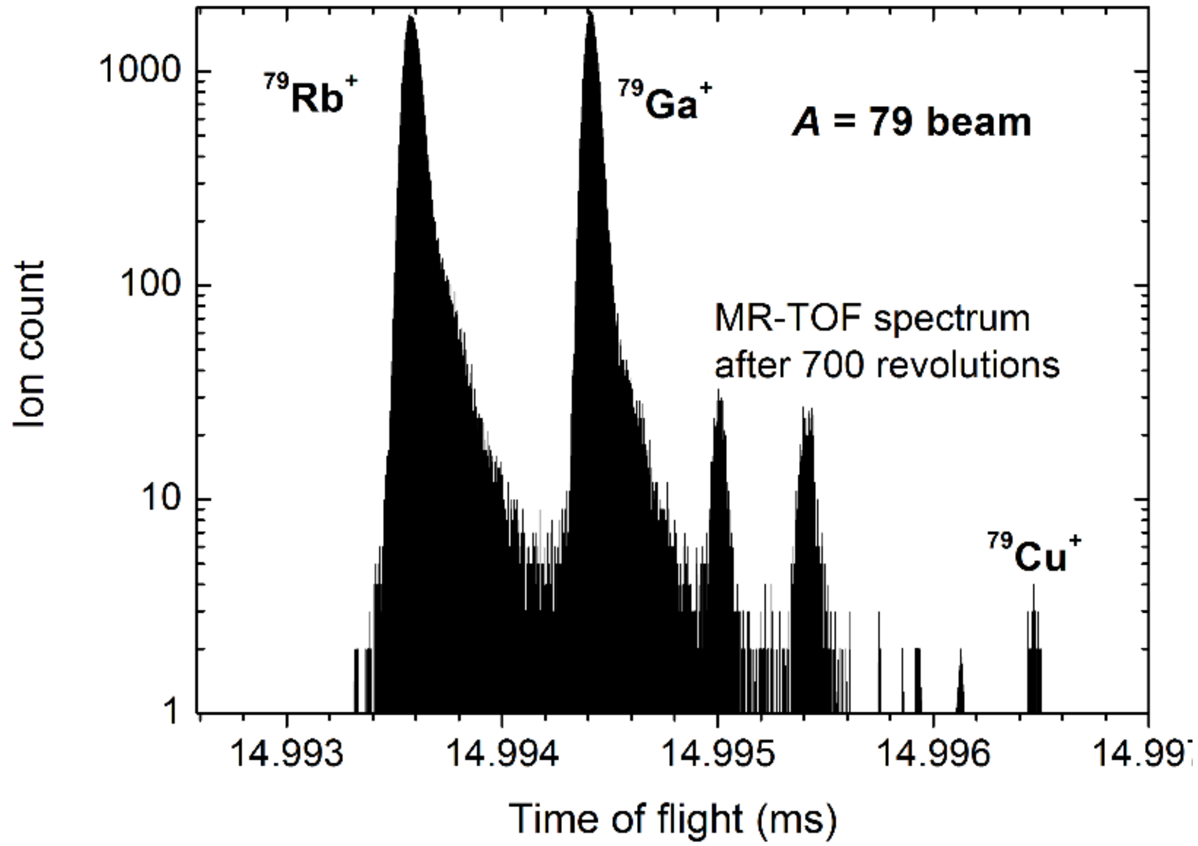
F. Nowacki, A. Poves, E. Caurier, B. Bounthong, Phys. Rev. Lett. 117, 272501 (2016).

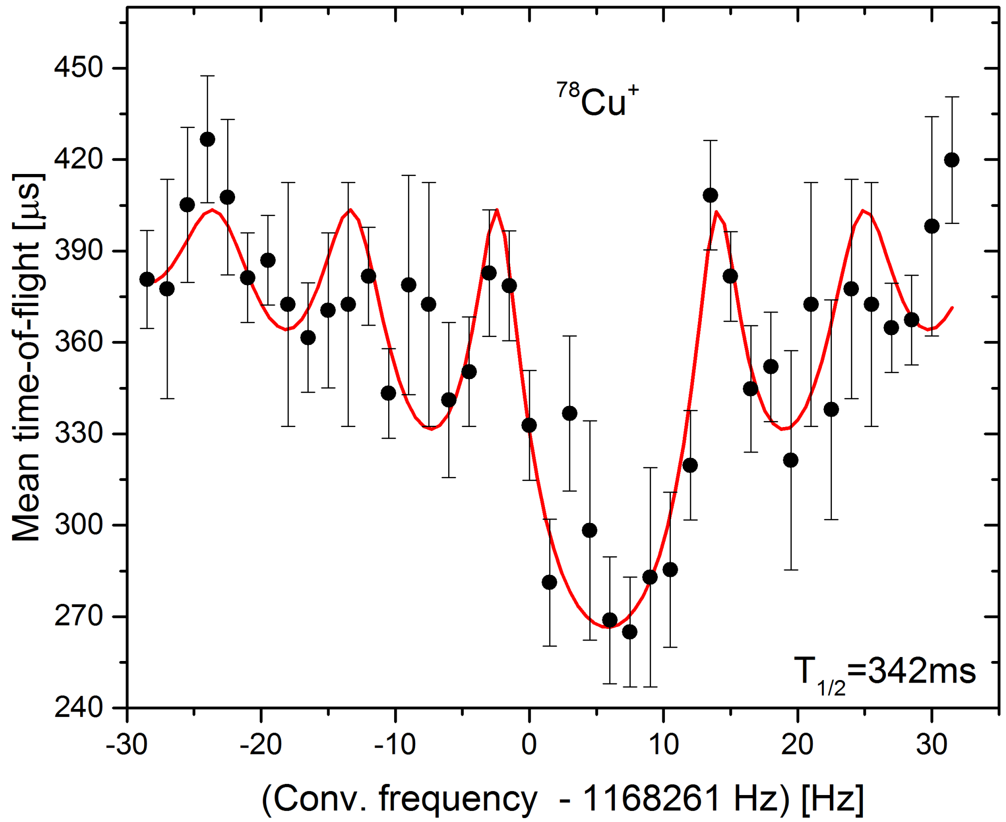
Mass measurements of $^{75-79}Cu$

- 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.

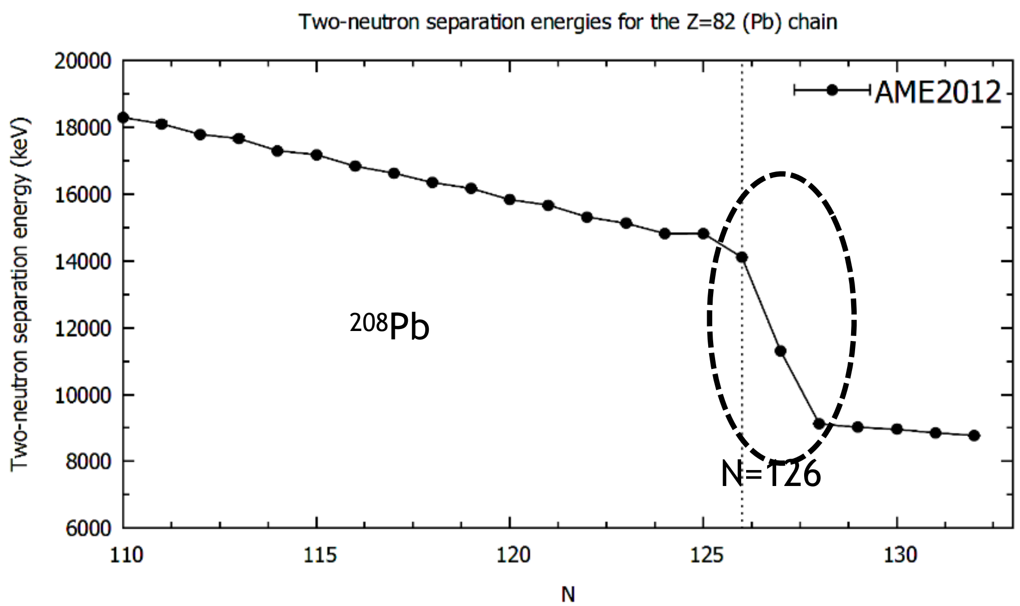


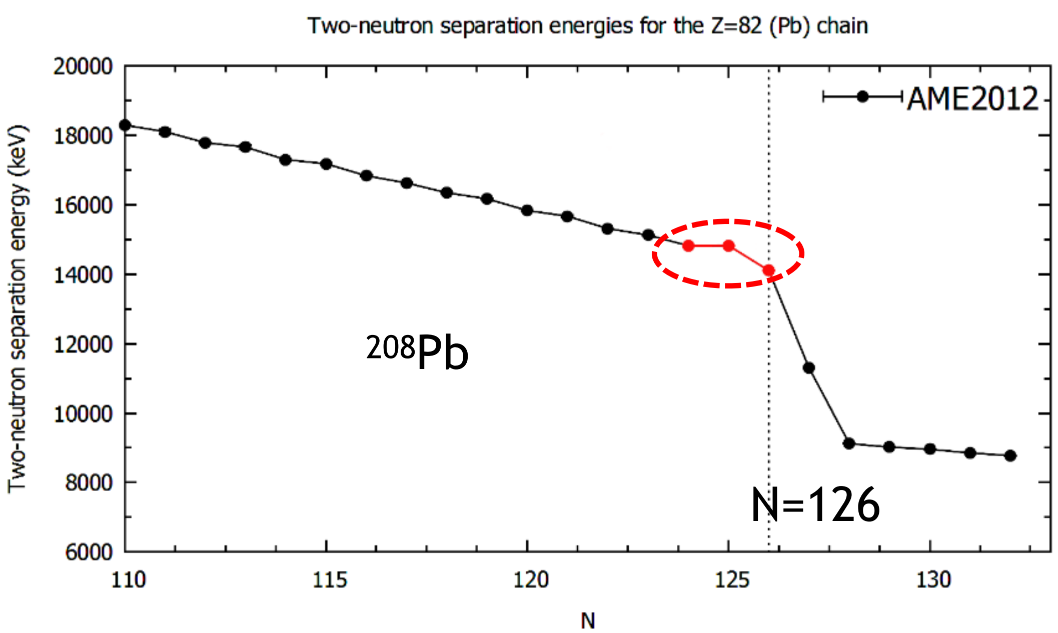




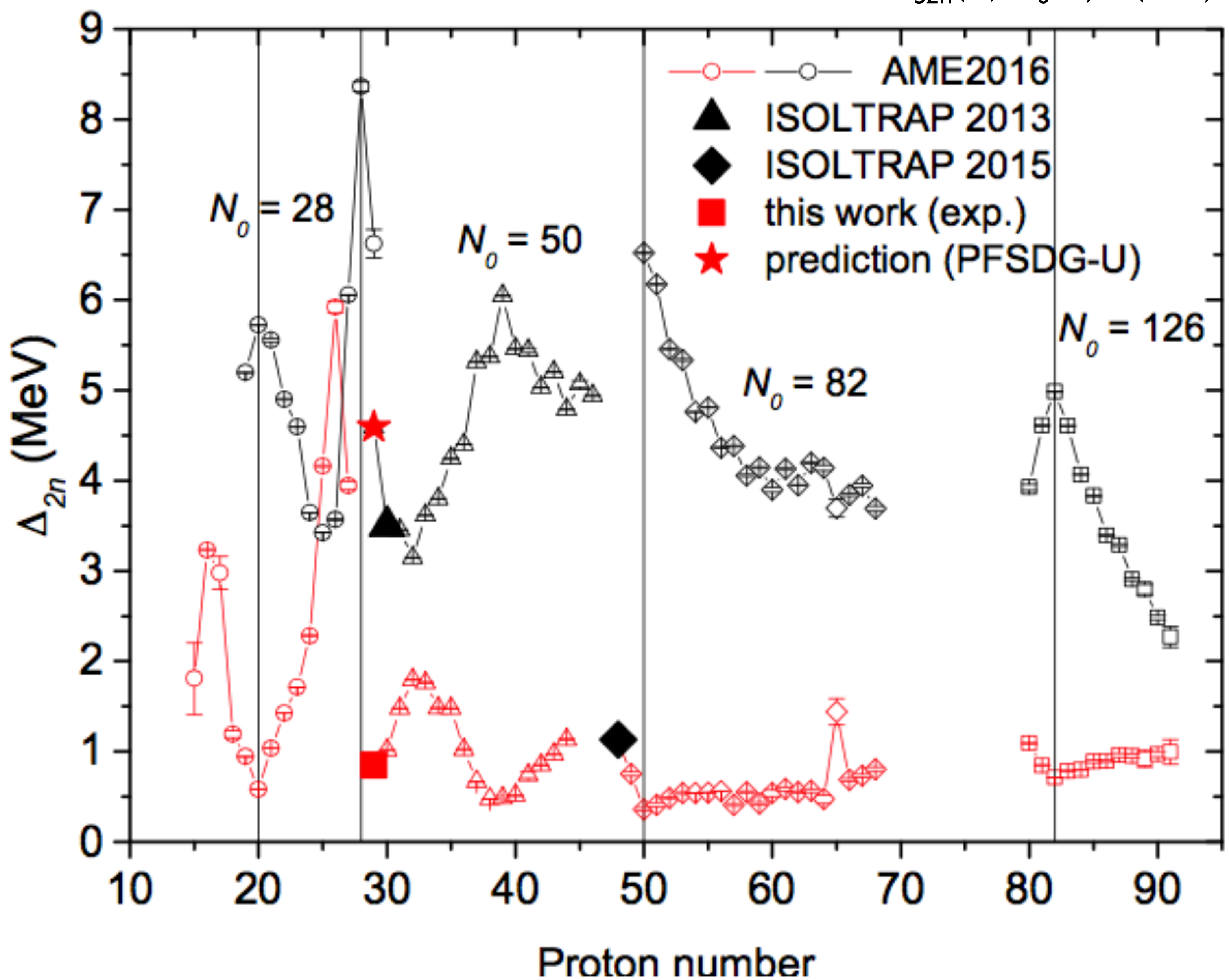
A glimpse at the nature of ^{78}Ni:

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

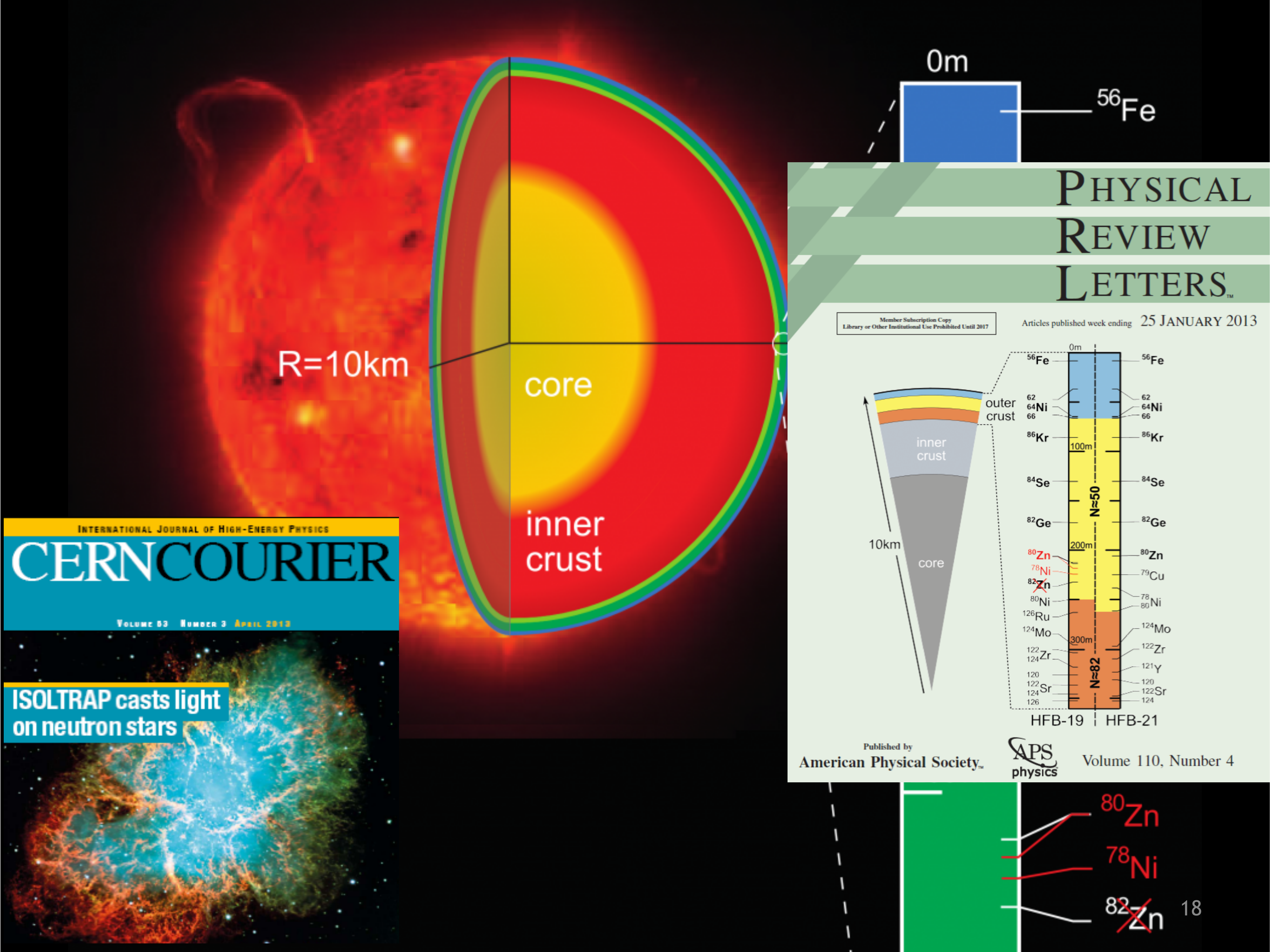




$\Delta_{S2n}(Z, N_0)$ (black)
$\Delta_{S2n}(Z, N_0\text{-}2)$ (red)



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


R=10km
core
inner
crust
0m
^{56}Fe
^{80}Zn
^{78}Ni
^{82}Zn
International Journal of High-Energy Physics
CERN COURIER
Volume 53 Number 3 April 2013
ISOLTRAP casts light
on neutron stars
Physical
Review
Letters
Member Subscription Copy
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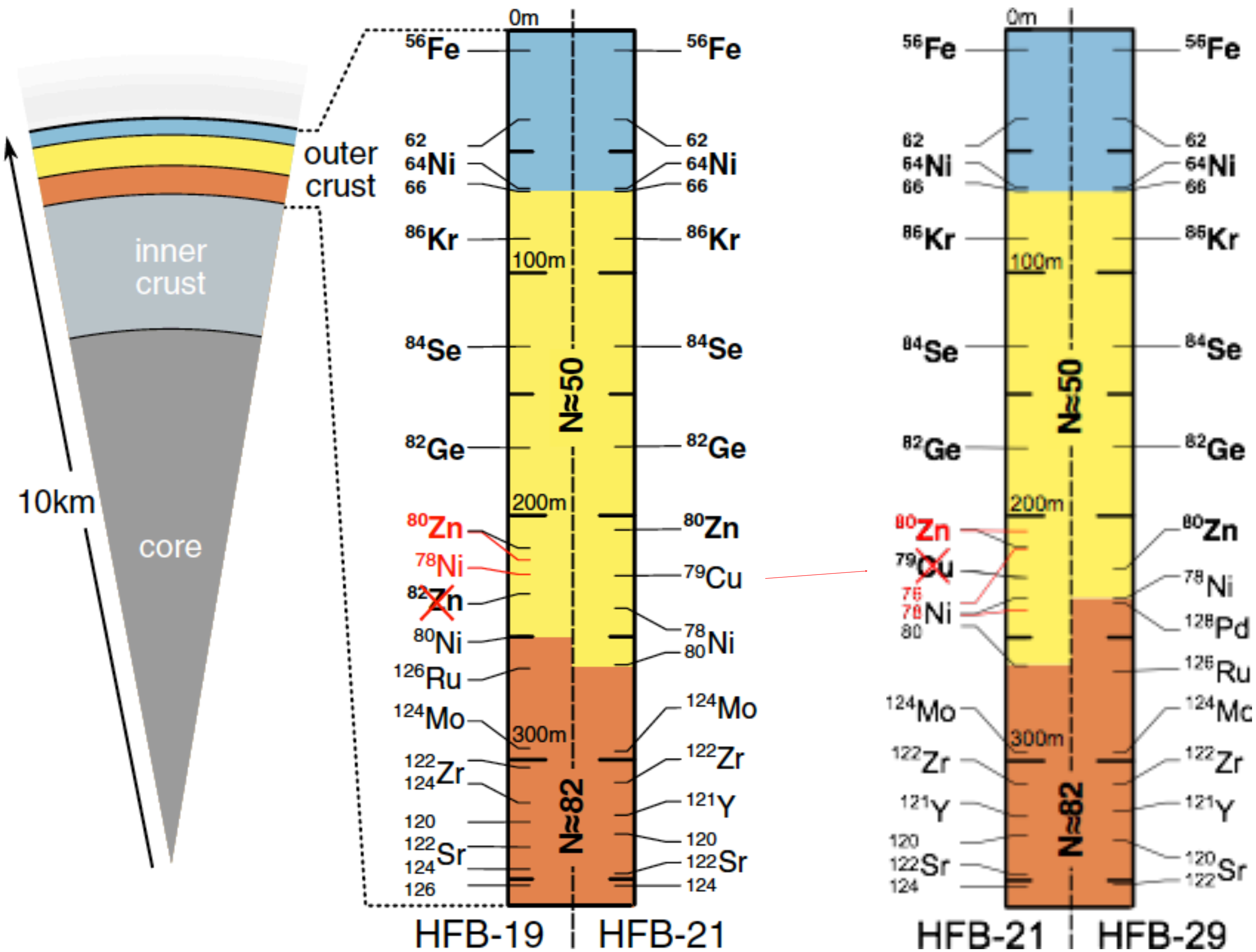
Articles published week ending 25 January 2013
outer
crust
inner
crust
10km
core
100m
200m
300m
N≈50
N≈82
^{56}Fe
62
^{64}Ni
66
^{86}Kr
^{84}Se
^{82}Ge
^{80}Zn
^{78}Ni
^{82}Zn
^{80}Ni
^{126}Ru
^{124}Mo
122
^{124}Zr
120
122
^{124}Sr
126
^{79}Cu
78
^{80}Ni
^{124}Mo
^{122}Zr
^{121}Y
120
^{122}Sr
124
HFB-19
HFB-21
Published by
American Physical Society
APS physics
Volume 110, Number 4

Is ^{79}Cu present in the neutron star crust ?

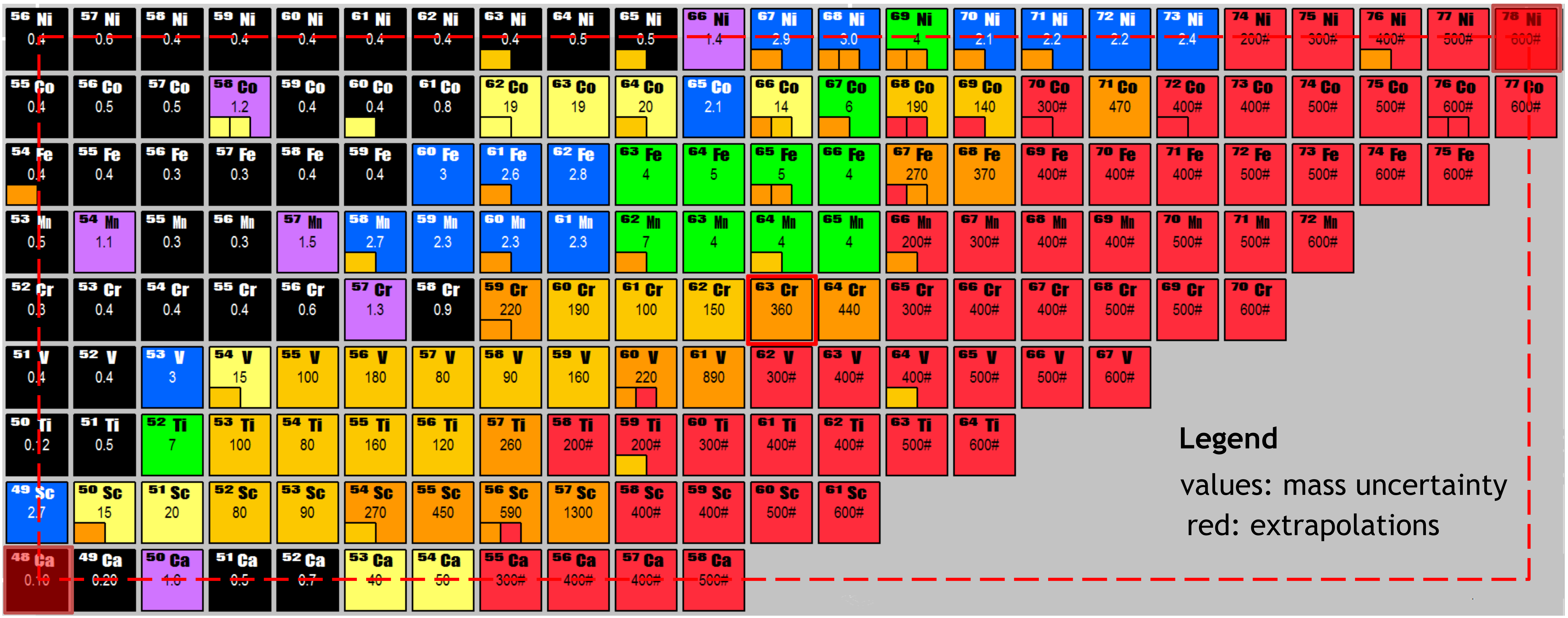


^{82}Zn from Wolf et al. PRL (2013)

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

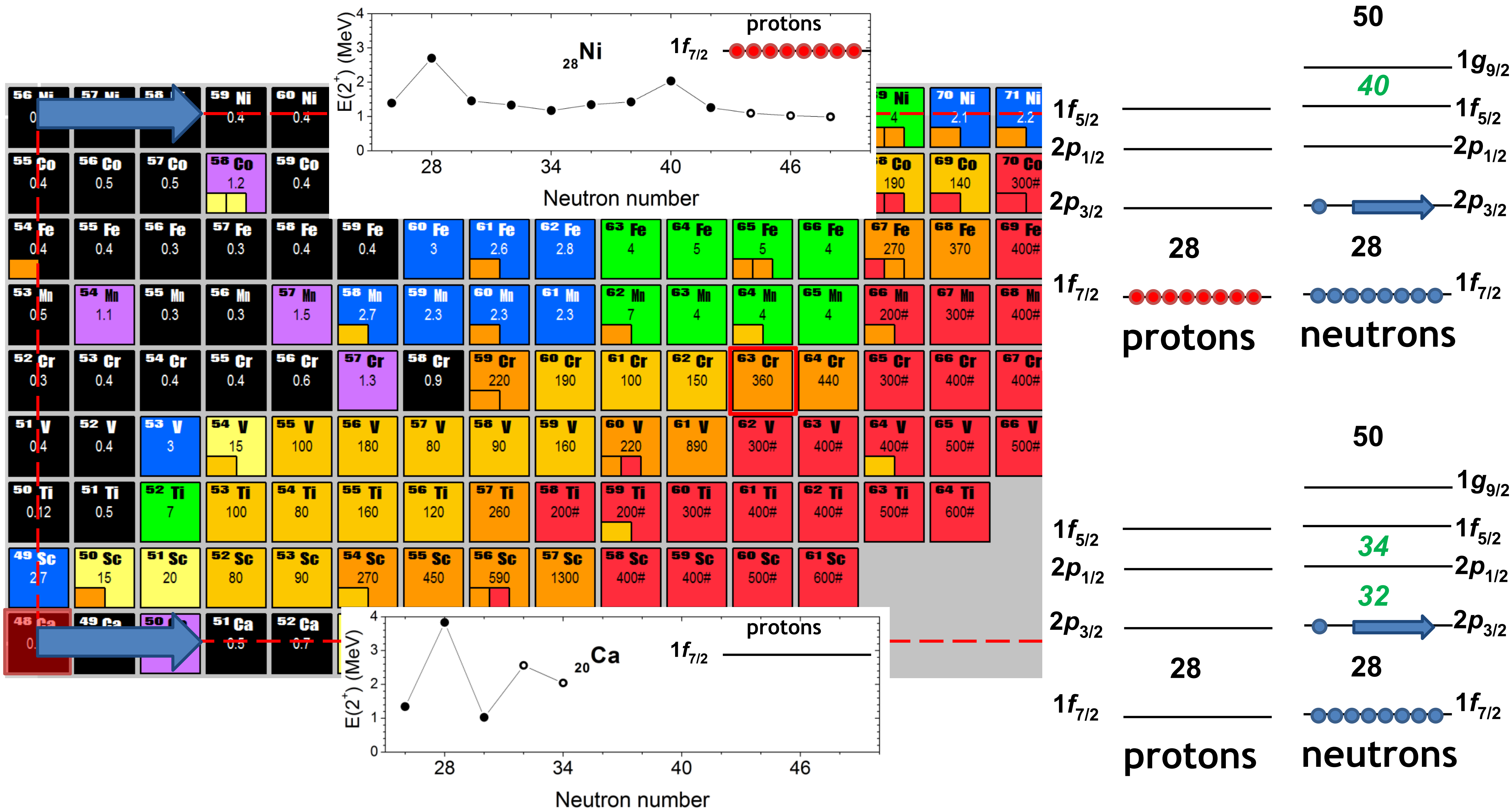
Neutron-rich Cr isotopes

Pf-shell nuclei



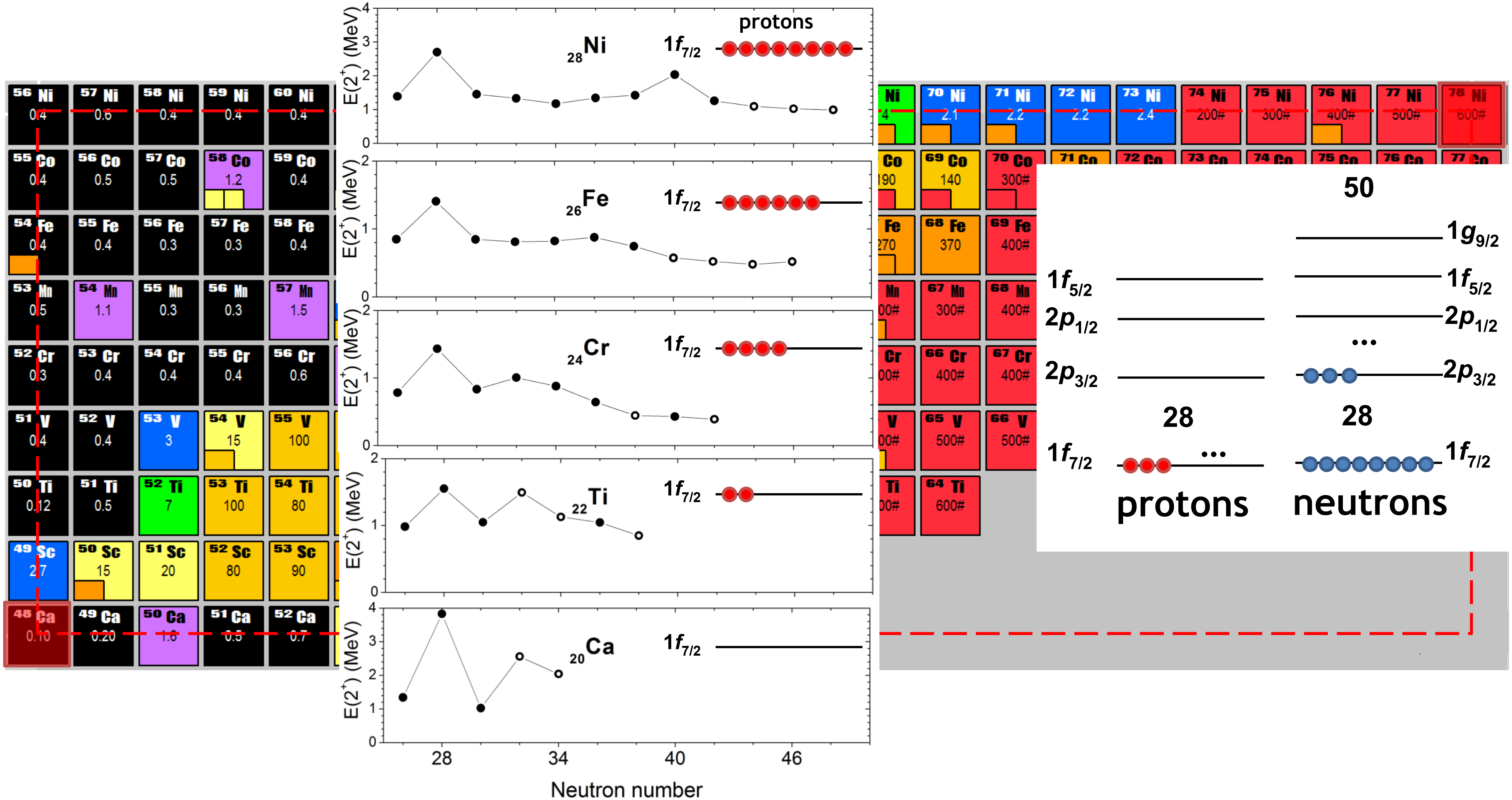
. Audi *et al.*, Chinese Phys. C **41**, No. 3 (2017).

Closed-proton-shell nuclei



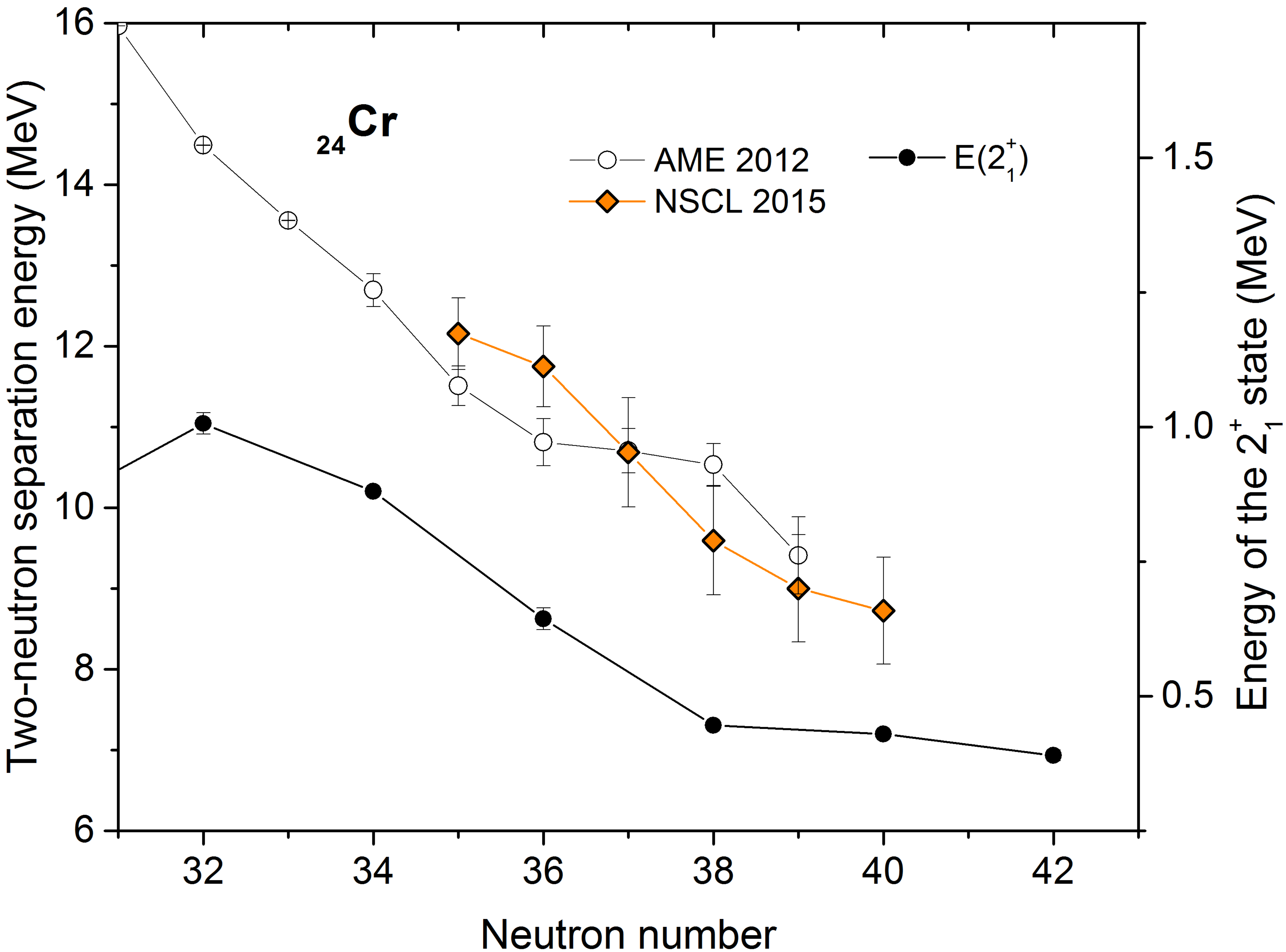
G. Audi *et al.*, Chinese Phys. C **41**, No. 3 (2017).
ENSDF database (2015).
D. Steppenbeck, Nature **502**, 207 (2013).

Open-proton-shell nuclei



G. Audi *et al.*, Chinese Phys. C **41**, No. 3 (2017).
ENSDF database (2015).
D. Steppenbeck, Nature **502**, 207 (2013).
C. Santamaria *et al.*, Phys. Rev. Lett. **115**, 192501 (2015).

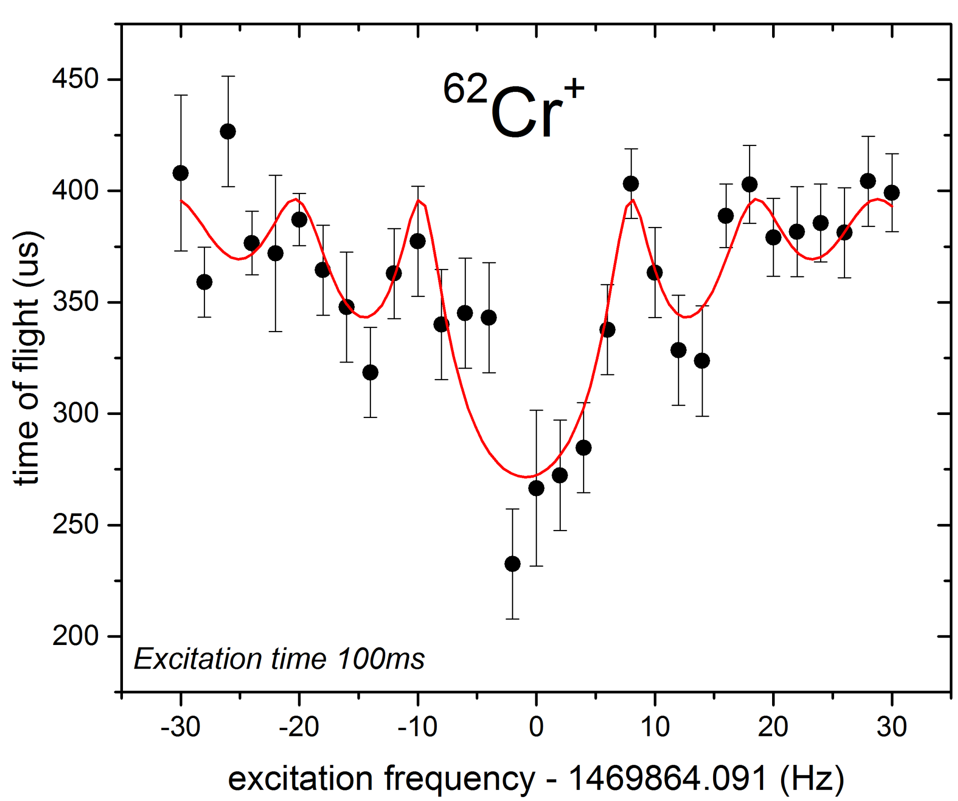
A close up on the Chromium chain

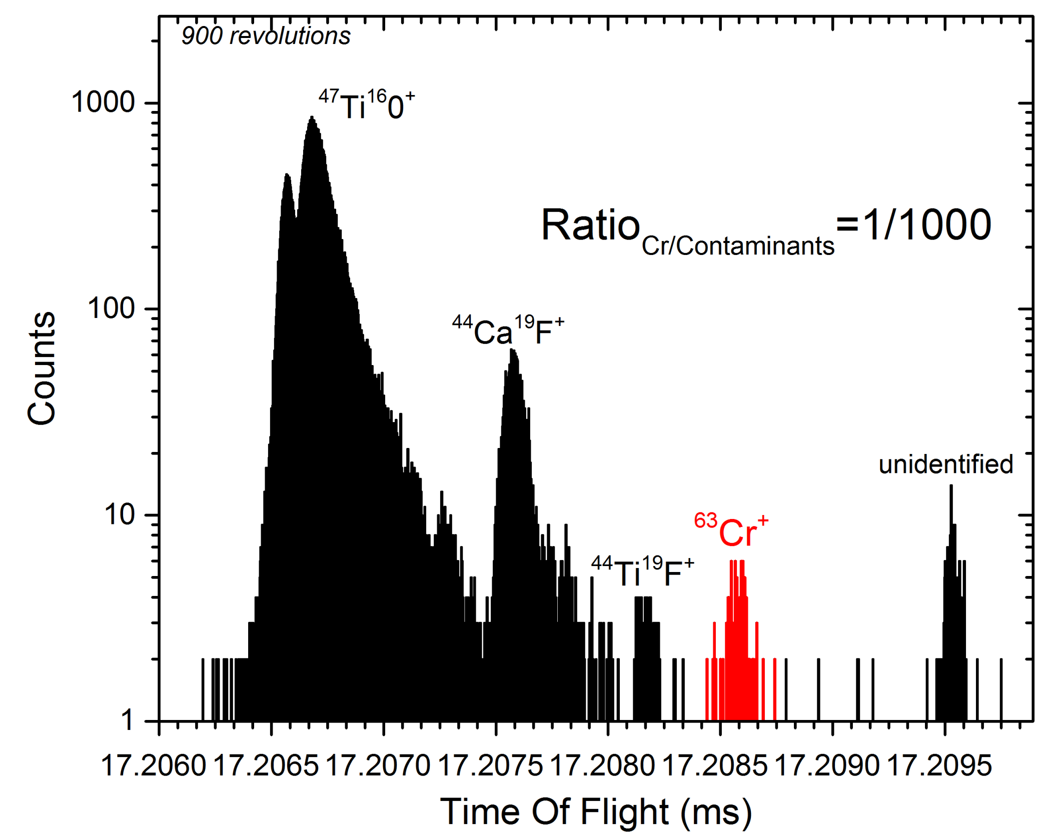


Z. Meisel *et al.*, Phys. Rev. C **93**, 035805 (2016).
ENSDF database (2015).
C. Santamaria *et al.*, Phys. Rev. Lett. **115**, 192501 (2015).

Mass measurement of $^{59-63}Cr$

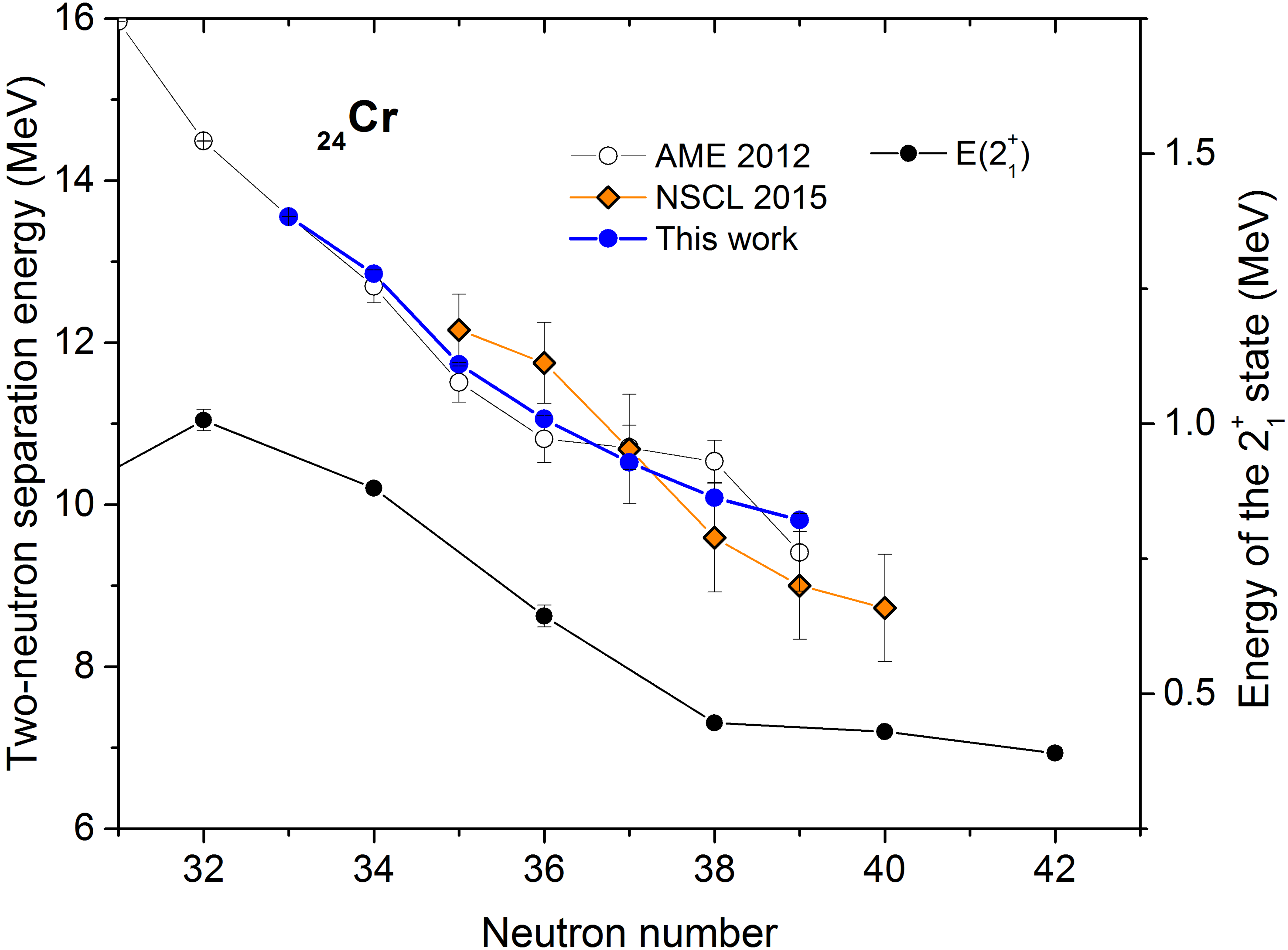
isotope	Measured with	Half life (ms)	Yield (ions/s)
^{59}Cr	Penning Trap/MR-TOF	1050	3×10^5
^{60}Cr	Penning Trap/MR-TOF	490	2×10^4
^{61}Cr	Penning Trap/MR-TOF	243	2×10^3
^{62}Cr	Penning Trap/MR-TOF	206	3×10^2
^{63}Cr	MR-TOF	129	3×10^1





T.D Goodacre *et al.*, Spectrochimica Acta B **129**, 58-63 (2017)

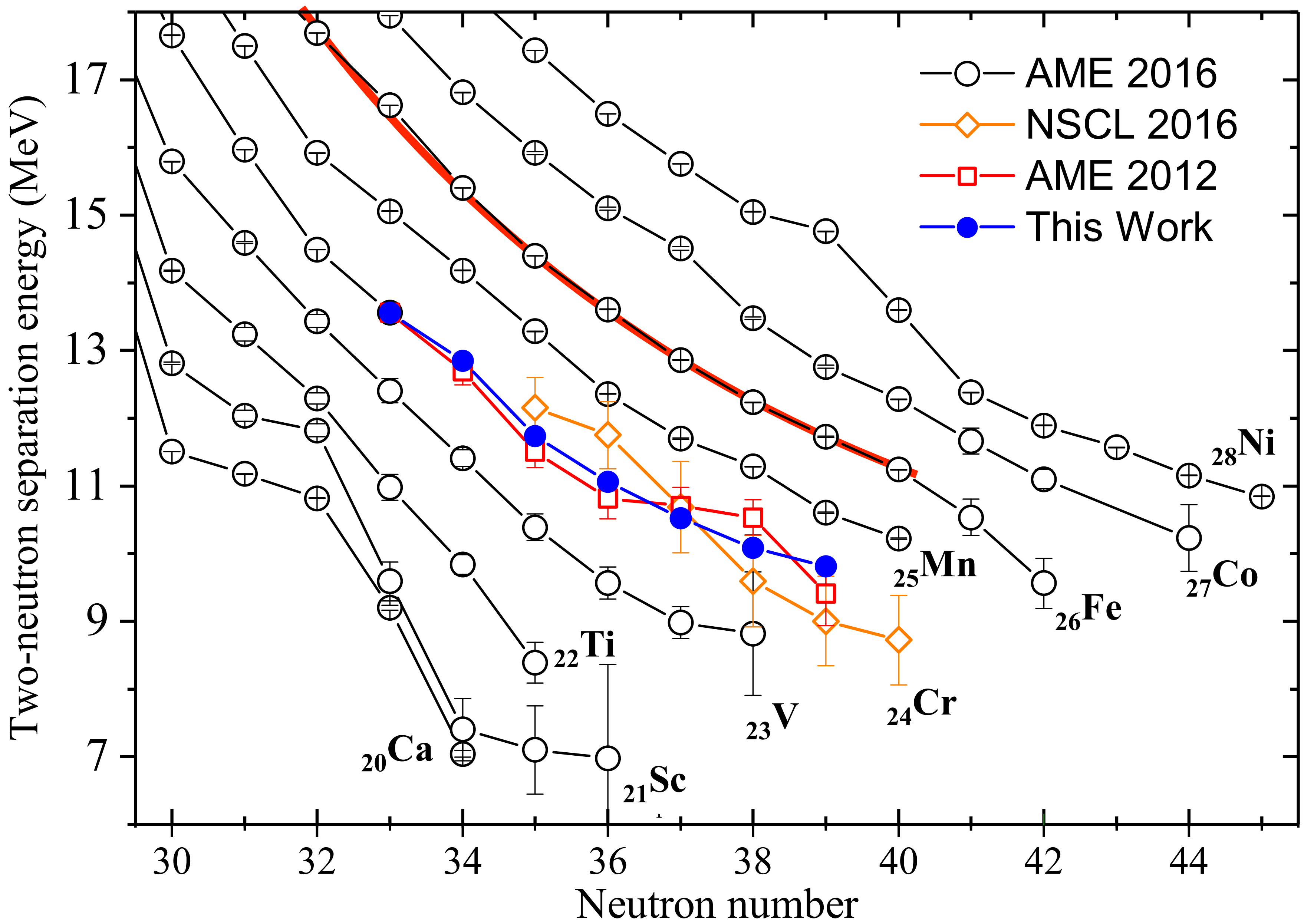
The new S_{2n} trend



Z. Meisel *et al.*, Phys. Rev. C **93**, 035805 (2015).
ENSDF database (2015).
C. Santamaria *et al.*, Phys. Rev. Lett. **115**, 192501 (2015).

Ground-state collectivity towards N=40 : qualitative discussion

1. Fit a quadratic trend on the Fe S2n curve

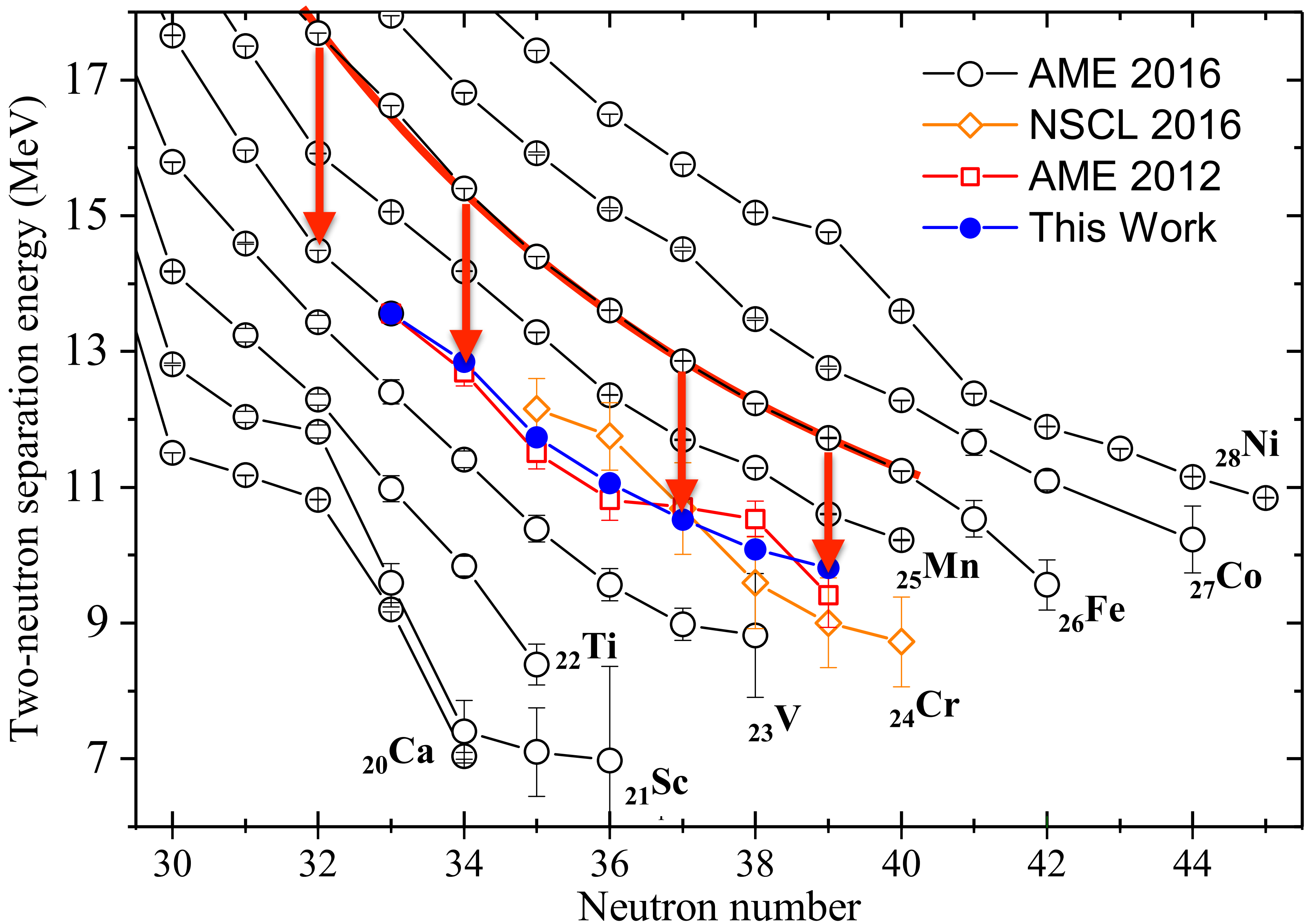


Z. Meisel *et al.*, Phys. Rev. C **93**, 035805 (2016).
G. Audi *et al.*, Chinese Phys. C **41**, No. 3 (2017).
M.Mougeot *et al.*, article in preparation.

Ground-state collectivity towards N=40 : qualitative discussion

1. Fit a quadratic trend on the Fe S2n curve

2. Shift and subtract to Cr and Mn experimental trends



Z. Meisel *et al.*, Phys. Rev. C **93**, 035805 (2016).
G. Audi *et al.*, Chinese Phys. C **41**, No. 3 (2017).
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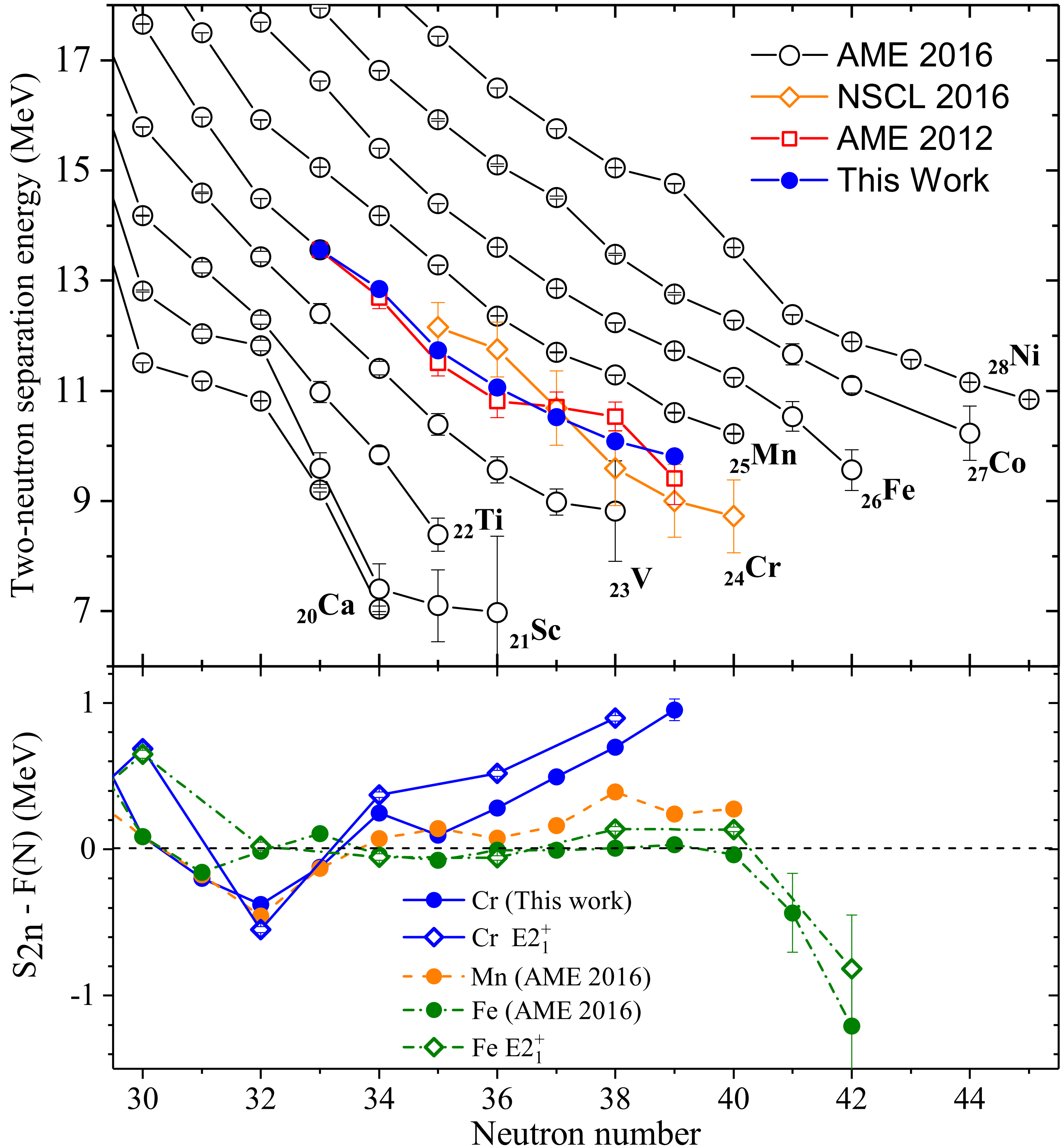
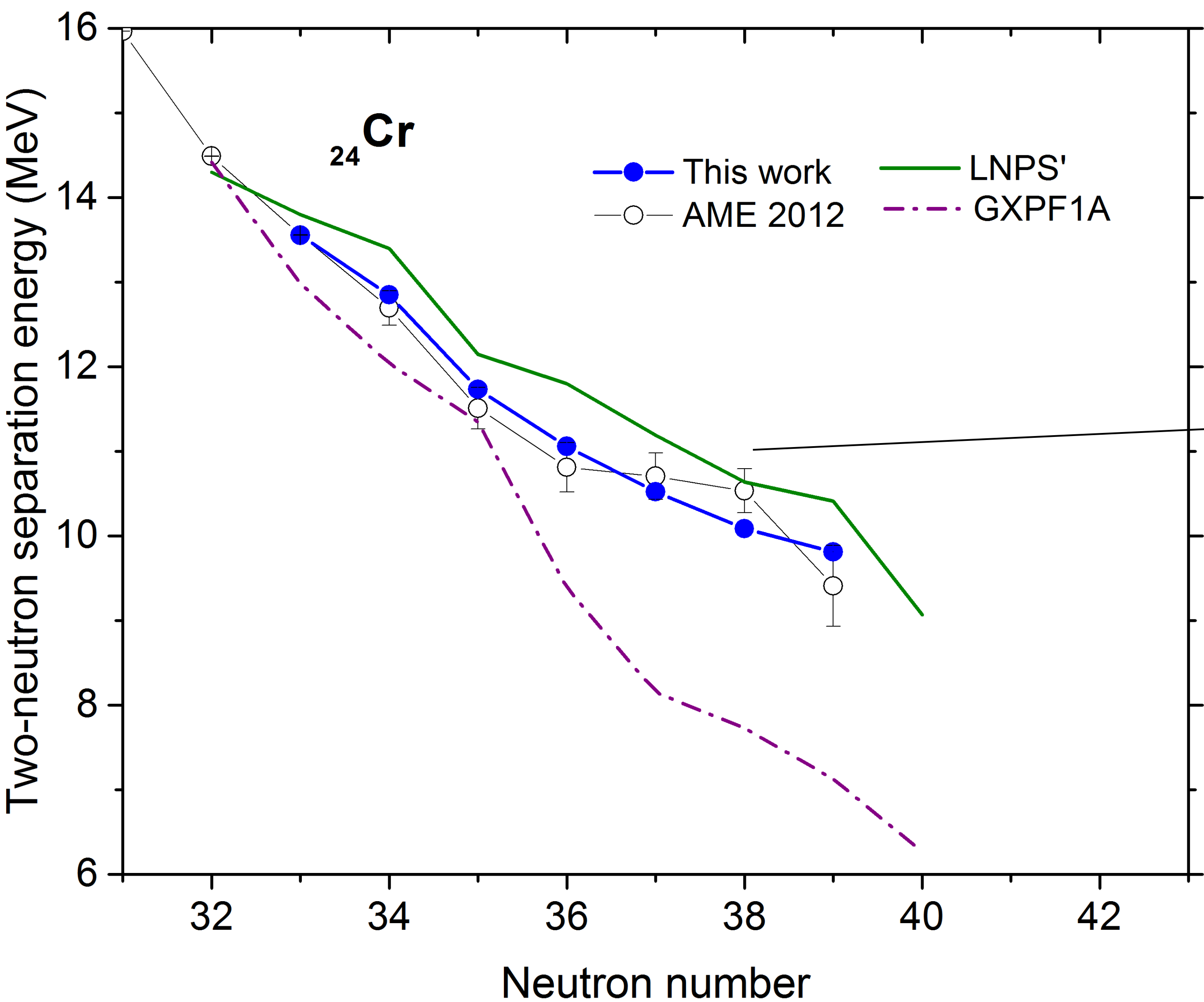
Ground-state collectivity towards N=40 : qualitative discussion

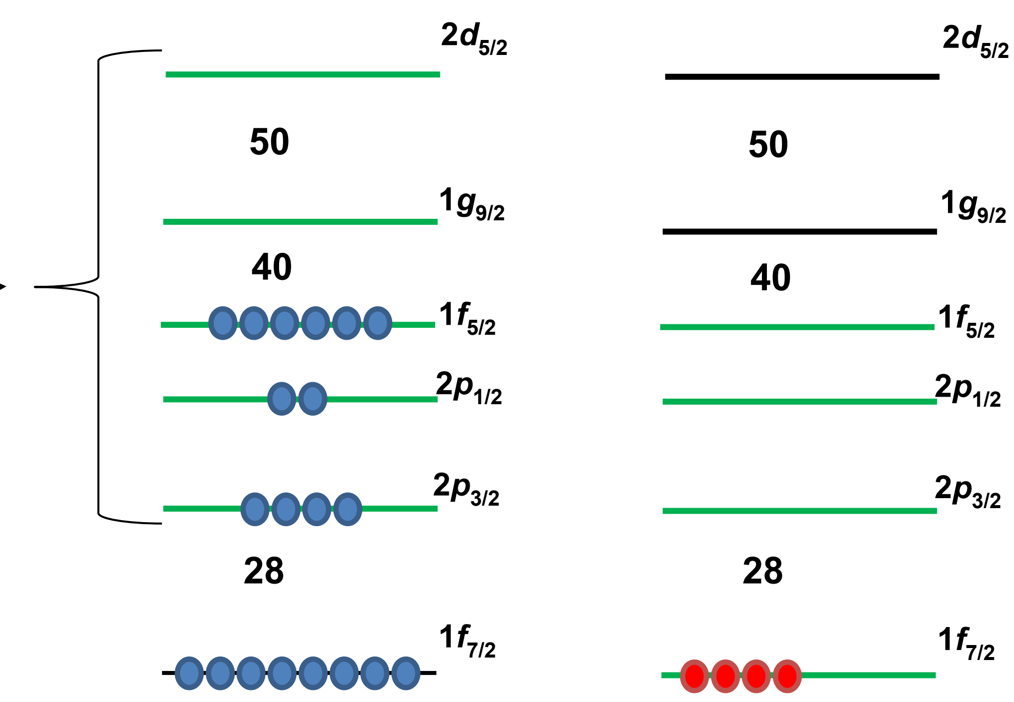


Z. Meisel *et al.*, Phys. Rev. C **93**, 035805 (2016).
G. Audi *et al.*, Chinese Phys. C **41**, No. 3 (2017).
M.Mougeot *et al.*, article in preparation.

Shell-model derived S_{2n} trends



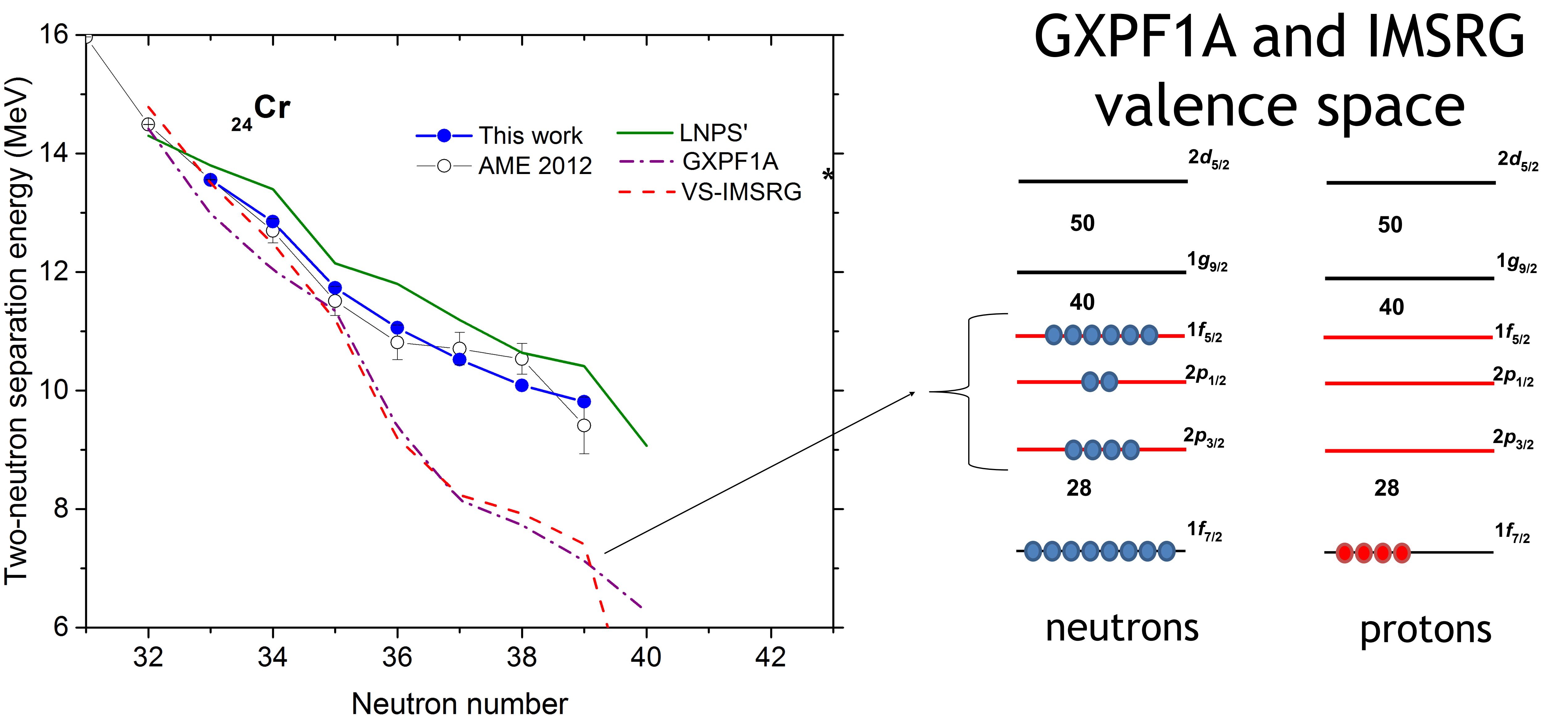
LNPS' valence space



neutrons protons

K. Sieja, private communication(2016).
M. Honma *et al*, Eur. Phys. J. A **25**, 499 (2005)
Stroberg *et al.*, Phys. Rev. Lett. **118**, 032502 (2017).
Stroberg, Holt, Simonis, Schwenk, private communication(2016).

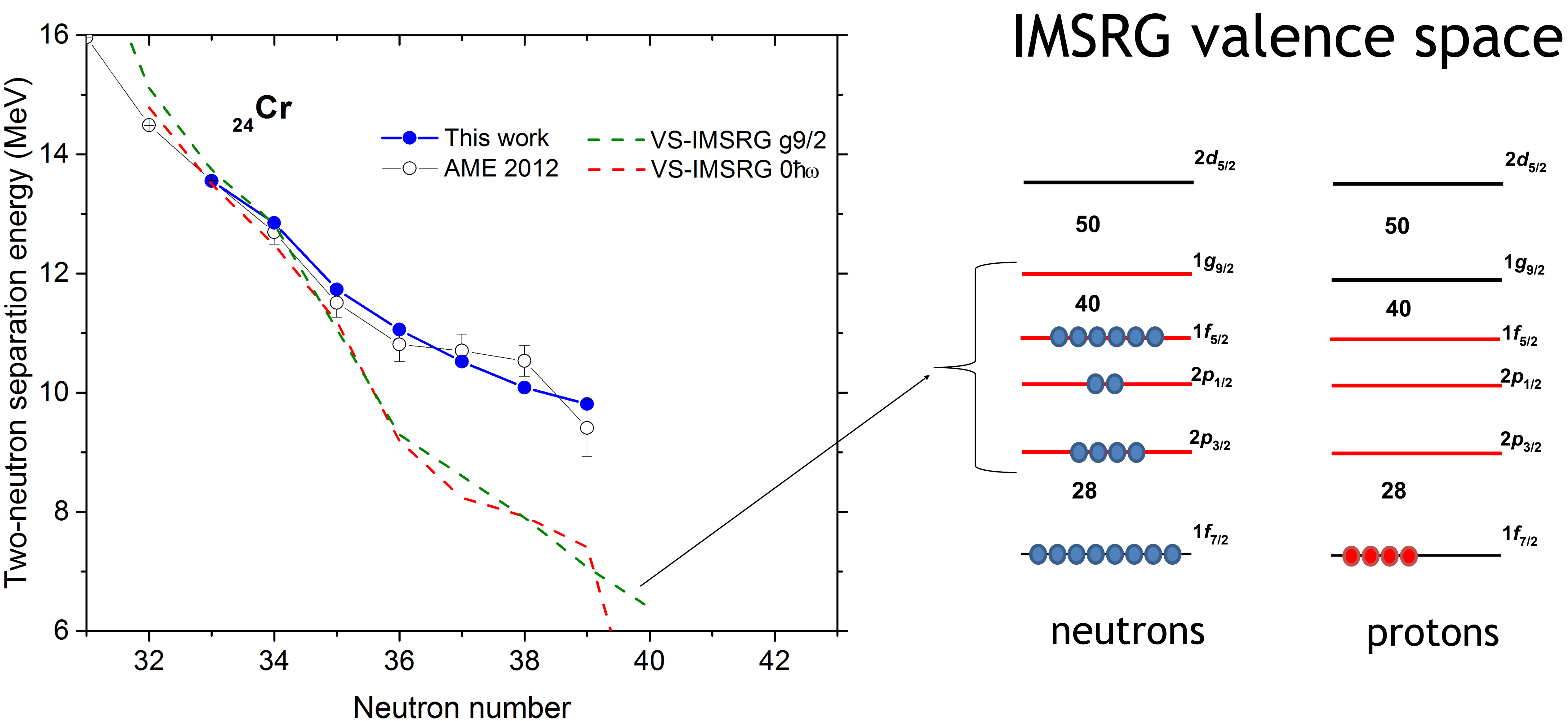
Effect of the valence space ?



*In Medium Similarity Renormalization Group (ab initio method)

K. Sieja, private communication(2016).
M. Honma *et al*, Eur. Phys. J. A **25**, 499 (2005)
Stroberg *et al*., Phys. Rev. Lett. **118**, 032502 (2017).
Stroberg, Holt, Simonis, Schwenk, private communication(2016).

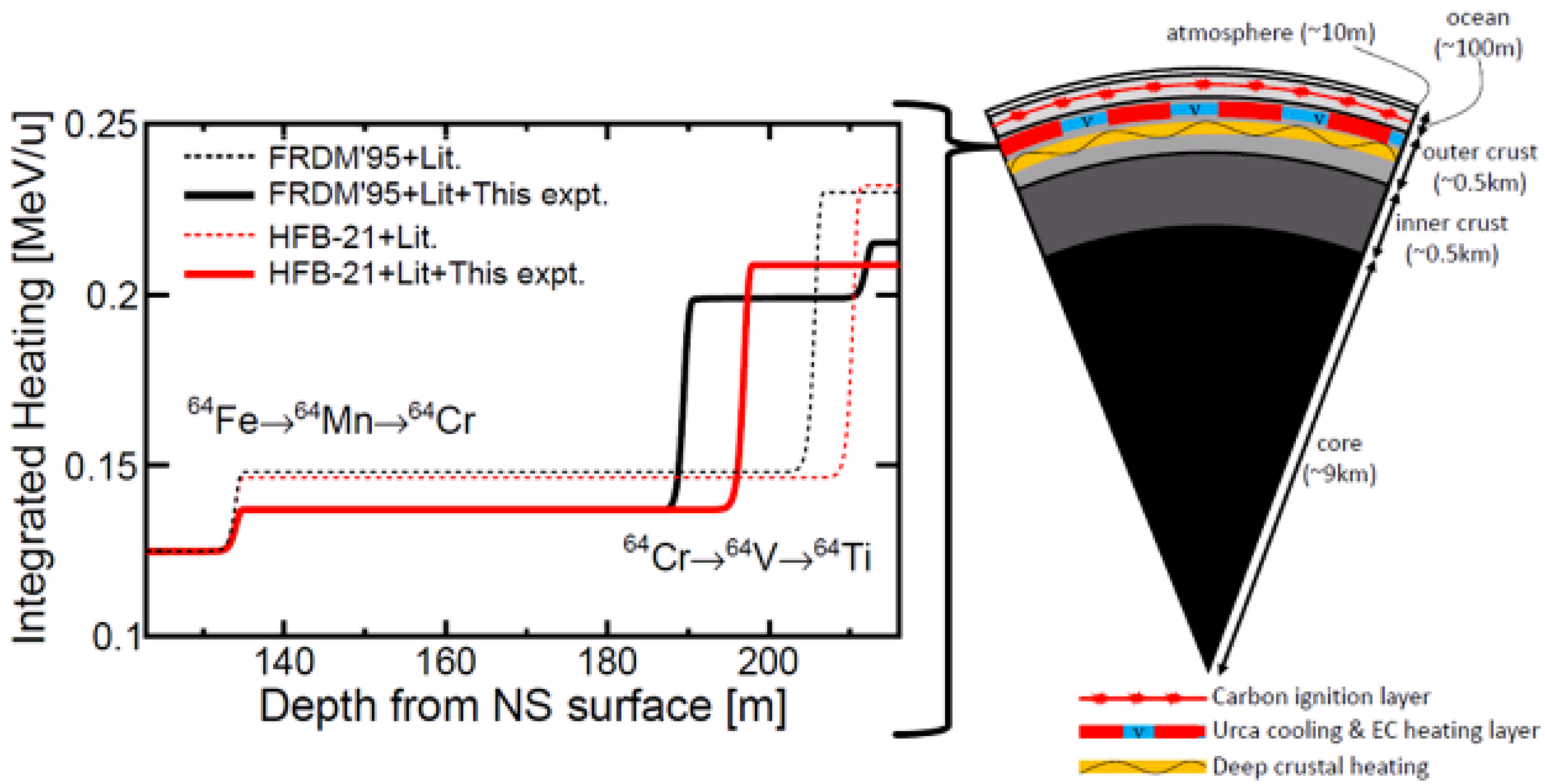
Increasing the VS-IMSRG valence space



Stroberg *et al.*, Phys. Rev. Lett. **118**, 032502 (2017).
Stroberg, Holt, Simonis, Schwenk, private communication(2017).

^{64}Cr and the accreted neutron-star crust :

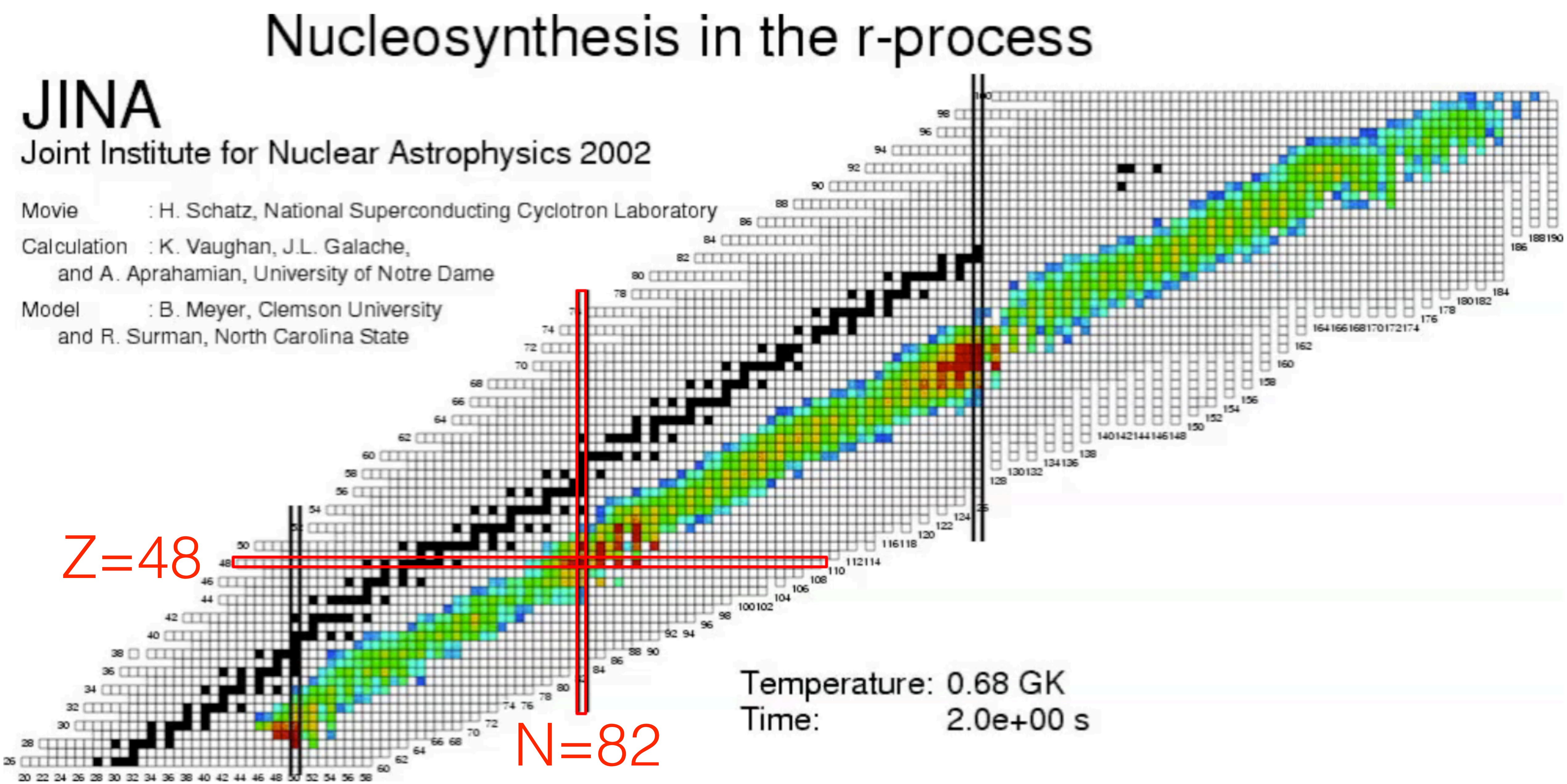
- A=64 nuclides are thought to be largely present in the crust of accreted neutron stars
- lower extent of the outer crust : ^{64}Cr-^{64}V-^{64}Ti EC sequence one of the main heat source
- “Extrapolated” mass for ^{64}Cr from this work -> about 700keV more bound than the NSCL result.



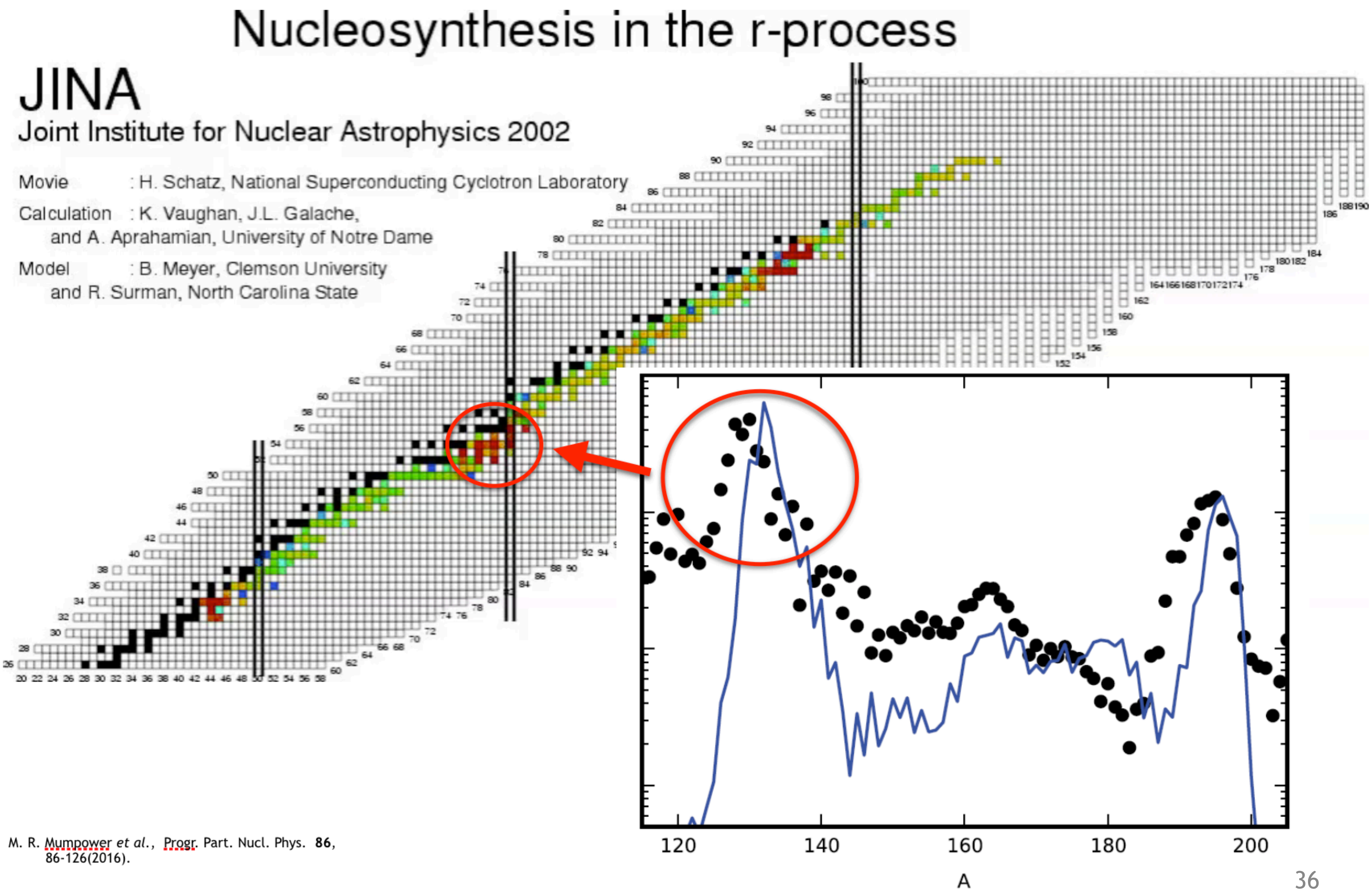
S. Gupta *et al.*, Astro. Journ., 662:1188-1197 (2007).
R. H. Cyburt *et al.*, Astro. Journ., 830:55 (2016).
Z. Meisel *et al.*, Phys. Rev. C **93**, 035805 (2015).

Cd isotopes around ^{132}Sn

The A>129 Cd isotopes



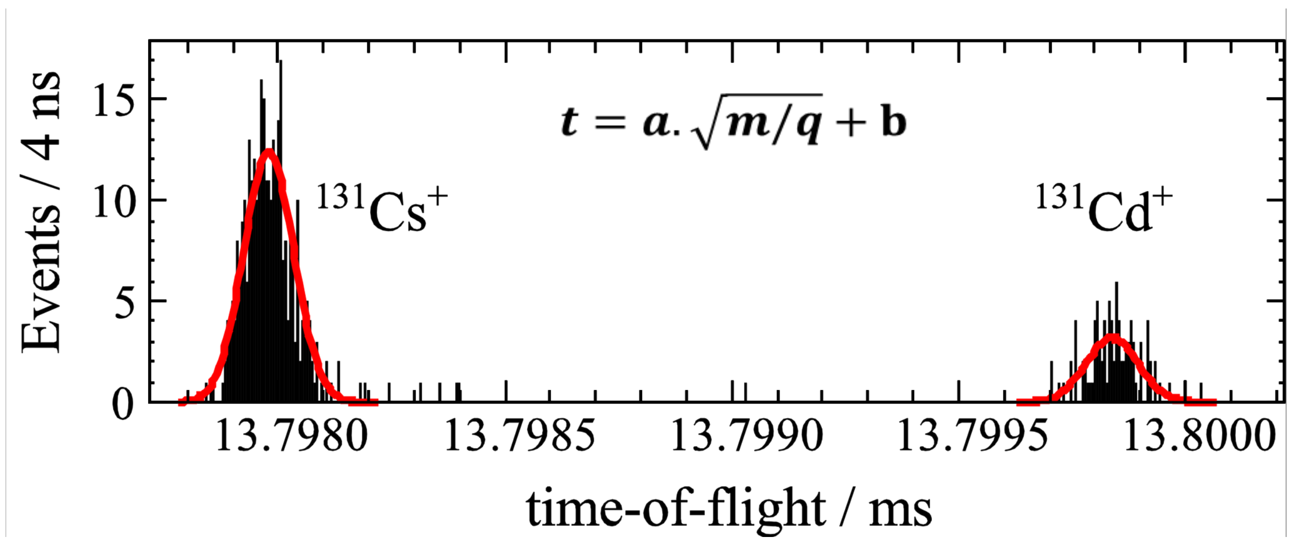
The A=130 abundance peak

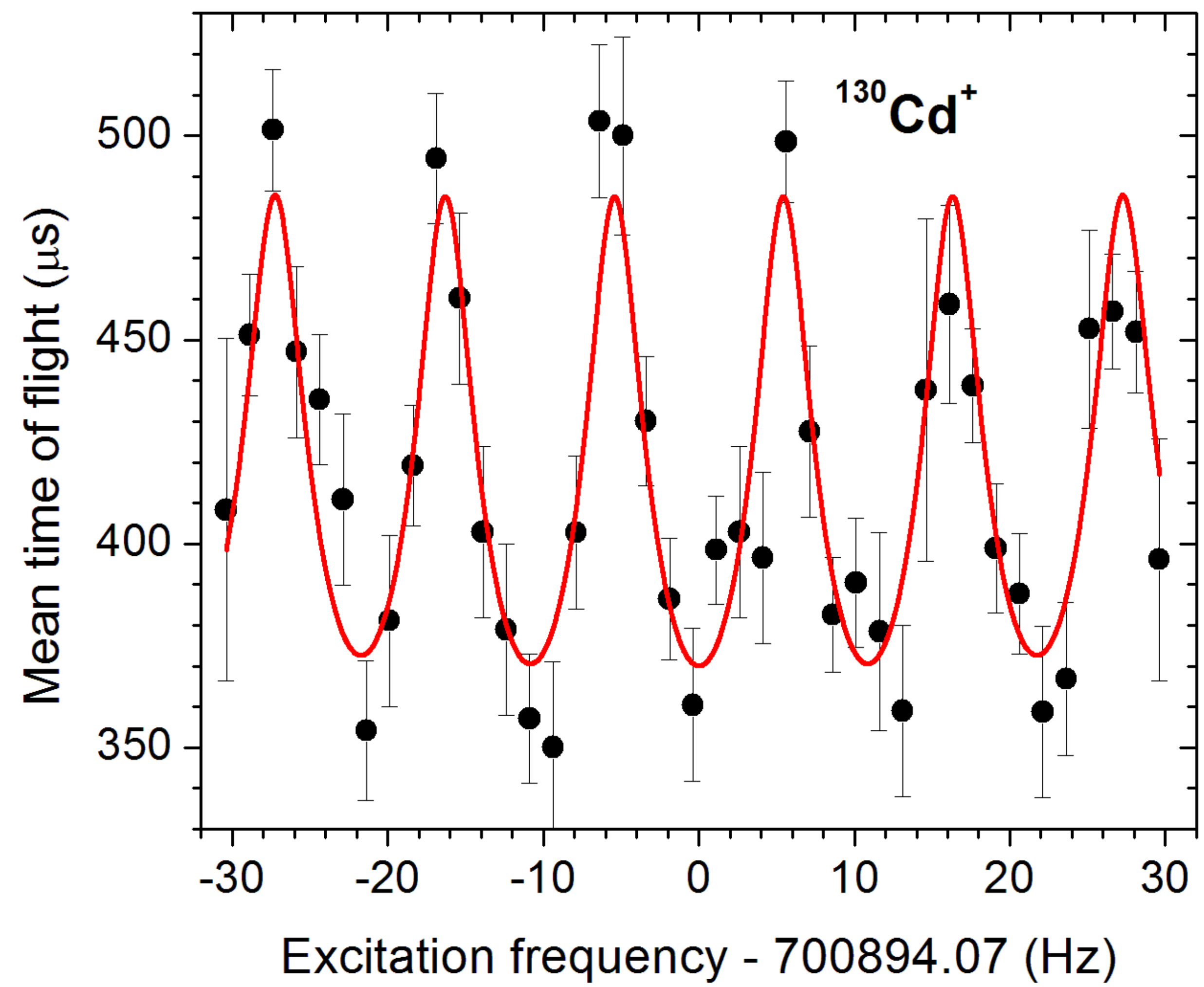


M. R. Mumpower *et al.*, Progr. Part. Nucl. Phys. **86**, 86-126(2016).

Mass measurements of $^{129\text{-}131}$Cd

- N-rich cadmium beams from UC_x with neutron converter and cold quartz line.
- Masses of $^{129\text{-}130}$Cd were determined with the Penning trap, of ^{131}Cd with the MR-TOF MS.

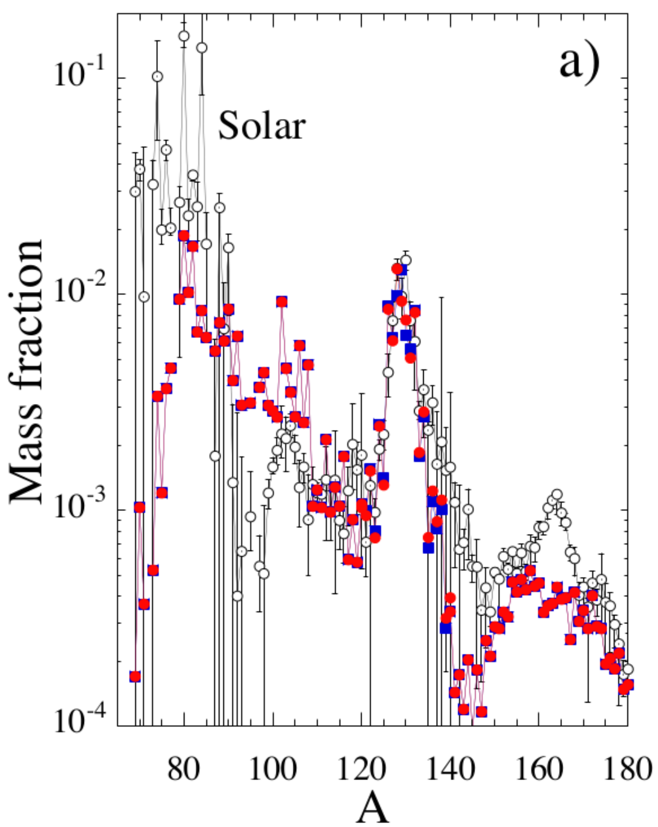


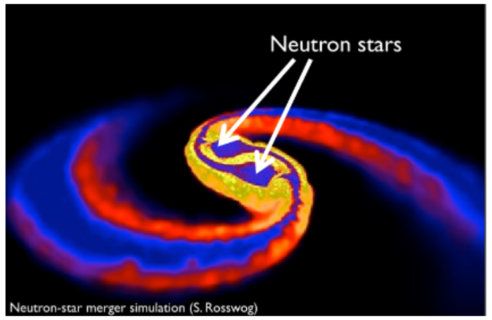


M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).
D. Atanasov *et al.*, Phys. Rev. Lett. **115**, 232501 (2015).

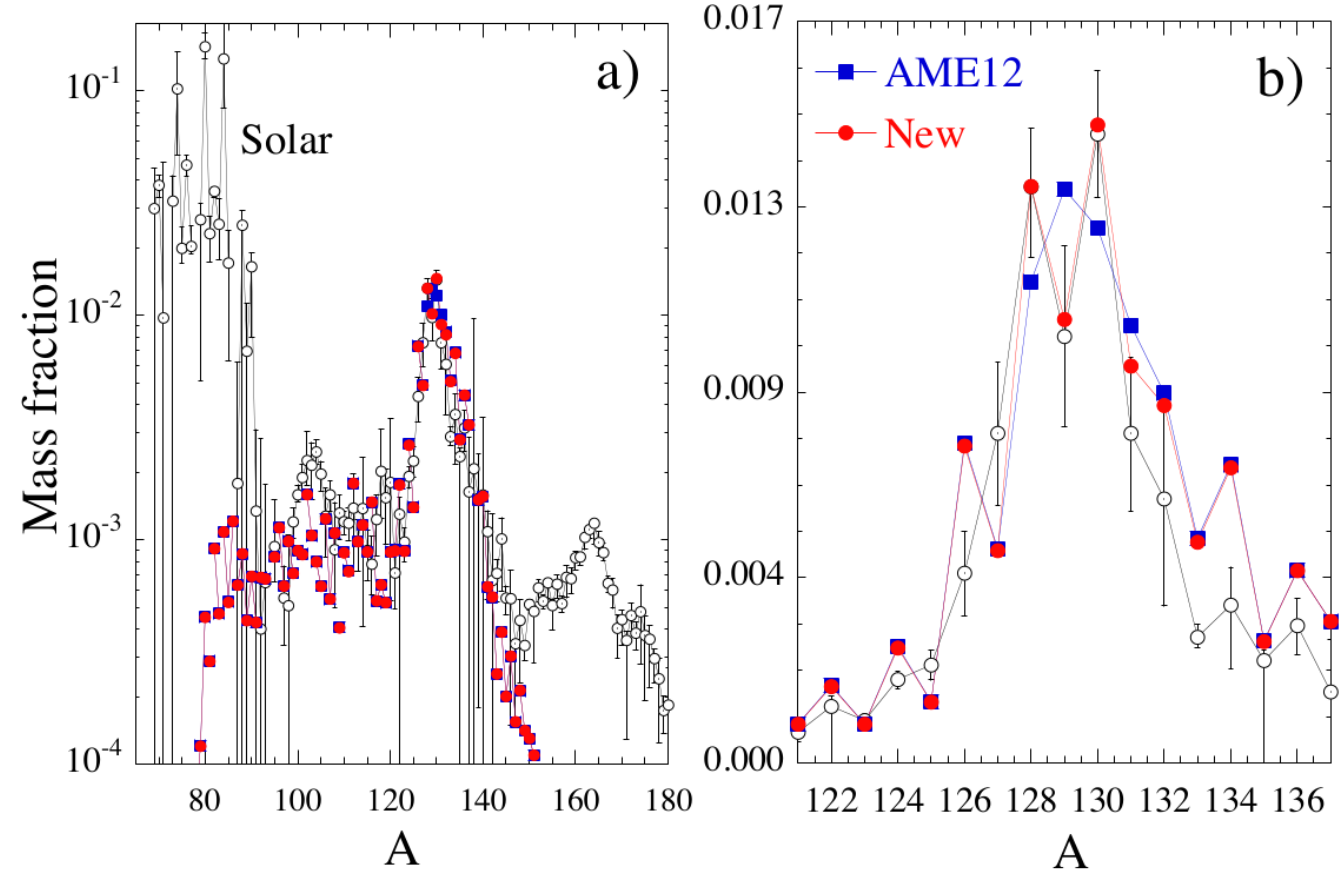
Impact on the abundance pattern :

➢ Neutron star mergers scenario :





➢ Core-collapse supernova scenario :



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

Conclusions

Conclusions

- ISOLTRAP can provide accurate and precise mass values which are valuable for nuclear astrophysics

- Masses of $^{75\text{-}79}Cu$:
  - hint at the doubly-magic nature of ^{78}Ni
  - ^{79}Cu disappears from the neutron star crust

- Ground-state mass of $^{58\text{-}63}Cr$:
  - smooth development of g.s collectivity towards N=40
  - ^{64}Cr of interest for the modelling of EC heating in accreted neutron stars

- $^{129\text{-}131}Cd$:
  - hint at a reduction of the one-neutron shell gap from ^{132}Sn to ^{130}Cd
  - relevant in r-process simulation

Acknowledgements

N. Althubiti, P. Ascher, G. Audi, **D. Atanasov**, D. Beck, K. Blaum, G. Bollen, M. Breitenfeldt, R. B. Cakirli, T. Cocolios, S. Eliseev, S. George, F. Herfurth, A. Herlert, **J. Karthein**, J. Kluge, M. Kowalska, S. Kreim, Yu. A. Litvinov, D. Lunney, **V. Manea**, E. Minaya-Ramirez, D. Neidherr, M. Rosenbusch, A. de Roubin, L. Schweikhard, M. Wang, **A. Welker**, **F. Wienholtz**, R. Wolf, K. Zuber

ISOLDE Target and Technical Group

Federal Ministry of Education and Research

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Mikhail Goncharov, Achim Czasch

http://isoltrap.web.cern.ch

Thank you for your attention!