Hirschegg 2015

High-precision mass measurements on neutron-rich radionuclides with ISOLTRAP for nuclear astrophysics studies

Frank Wienholtz
- University of Greifswald -
for the ISOLTRAP Collaboration

- Motivation and Introduction
- ISOLTRAP setup
  - 82Zn
  - Neutron-rich Ca
  - Neutron-rich Cd
- Summary and Outlook

http://isoltrap.web.cern.ch

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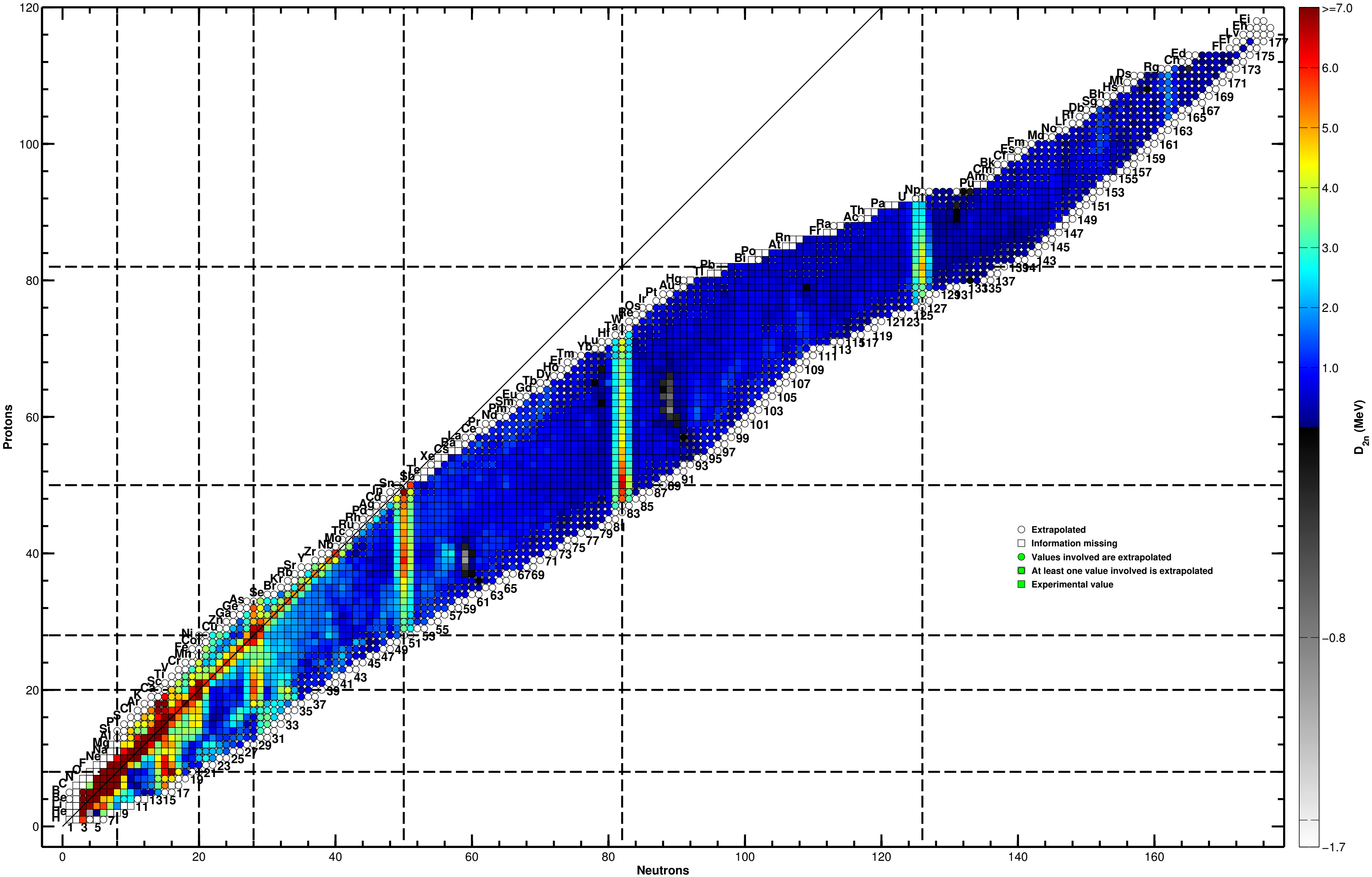
Motivation

$$B(N,Z) = \left(Nm_n + Zm_p - m(N,Z)\right)c^2$$

Different filters:

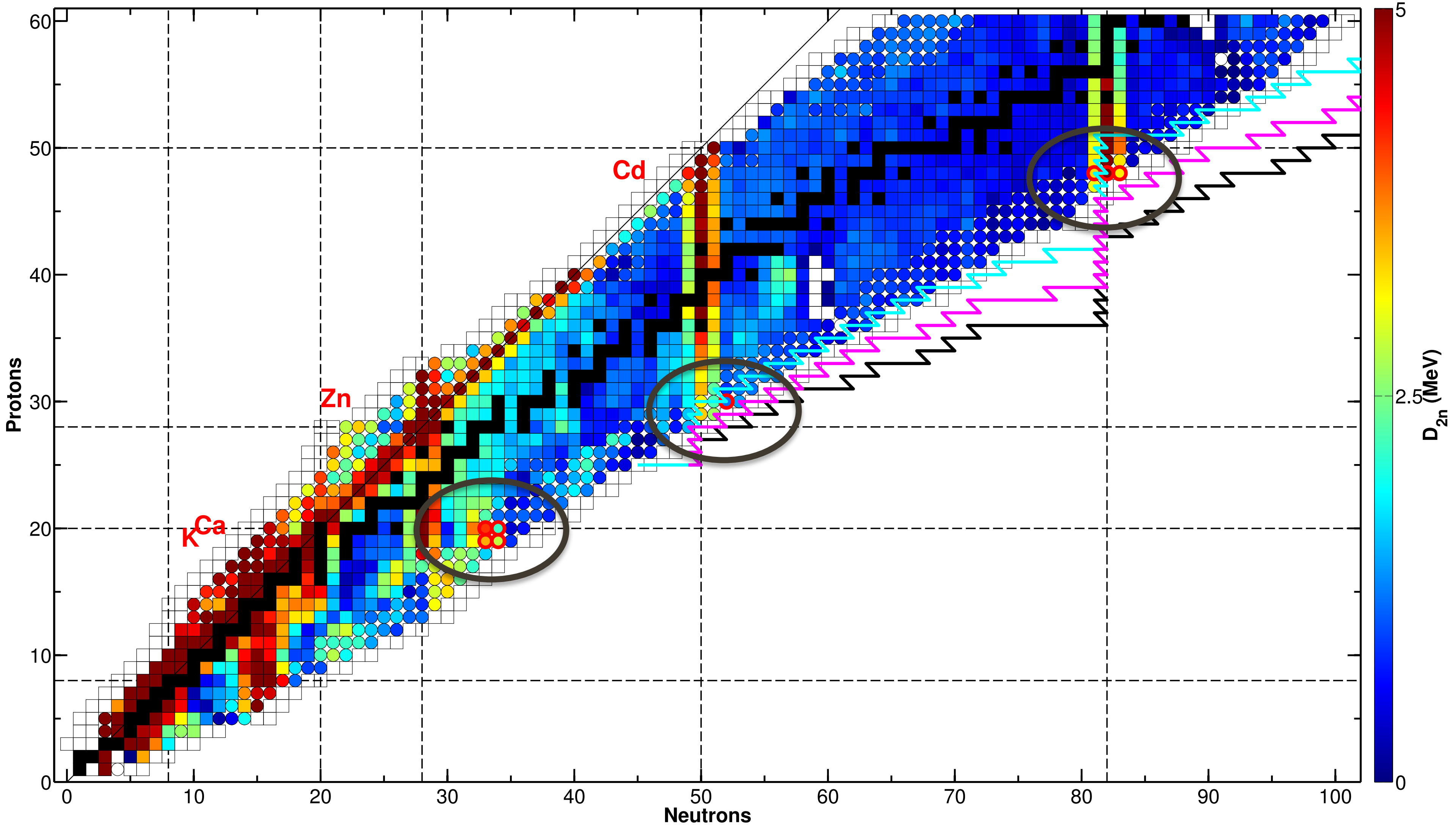
$$S_{2N} = B(N,Z) - B(N-2,Z)$$

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

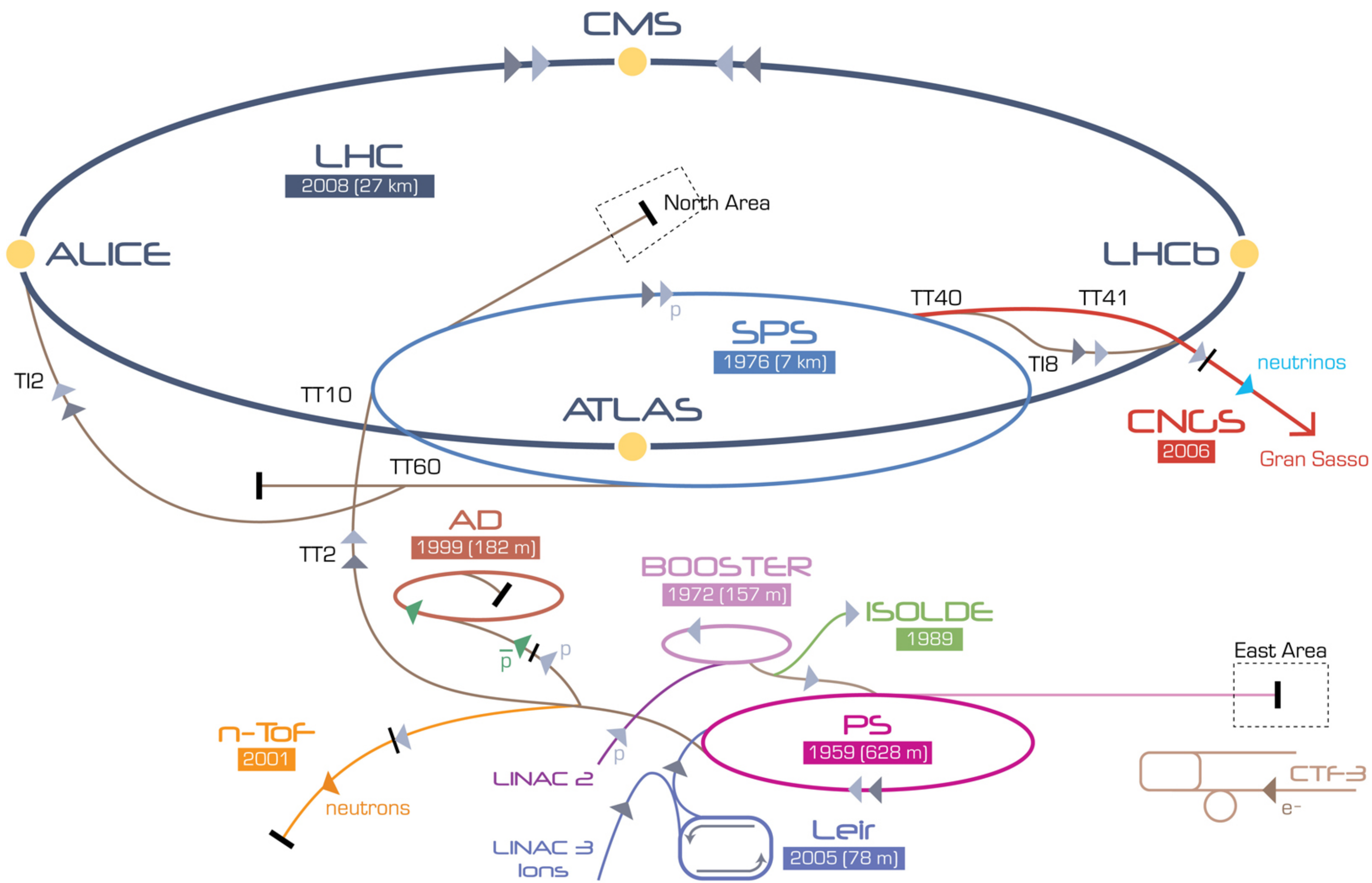


Why measure the mass of neutron rich nuclei?

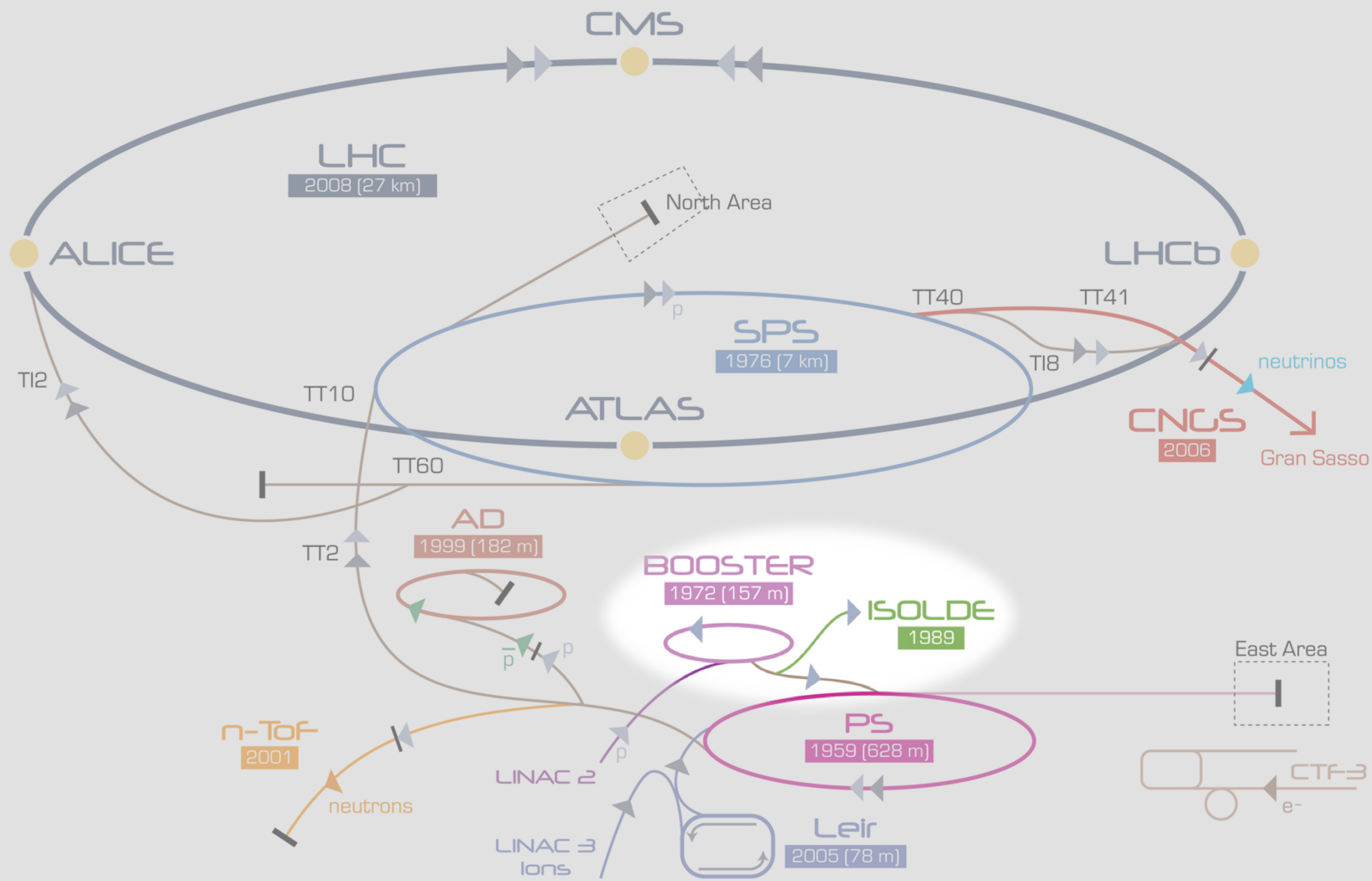
$$D_{2N} = S_{2N}(N,Z) - S_{2N}(N+2,Z) = 2B(Z,N) - B(Z,N+2) - B(Z,N-2)$$



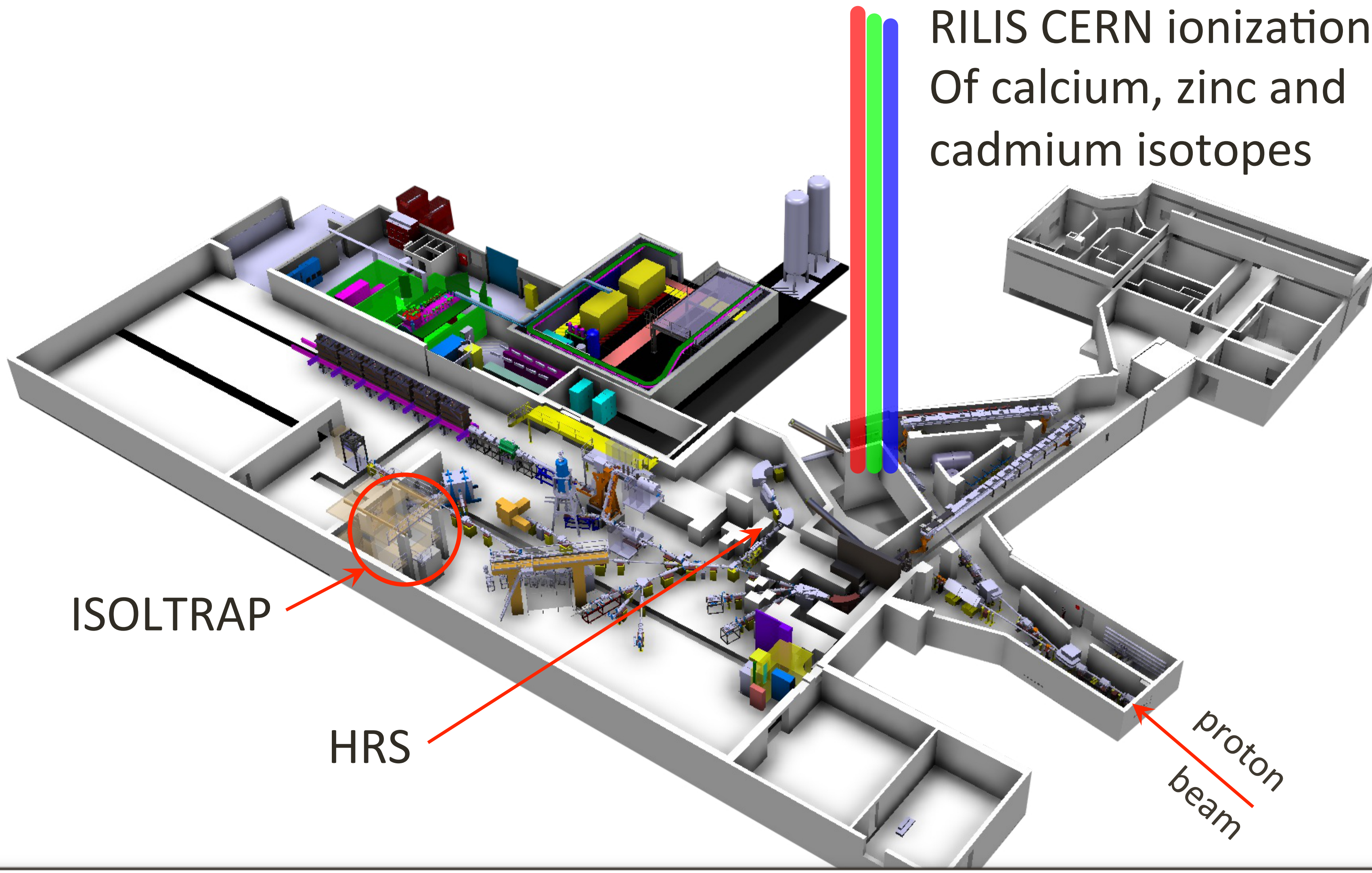
CERN accelerator complex



CERN accelerator complex

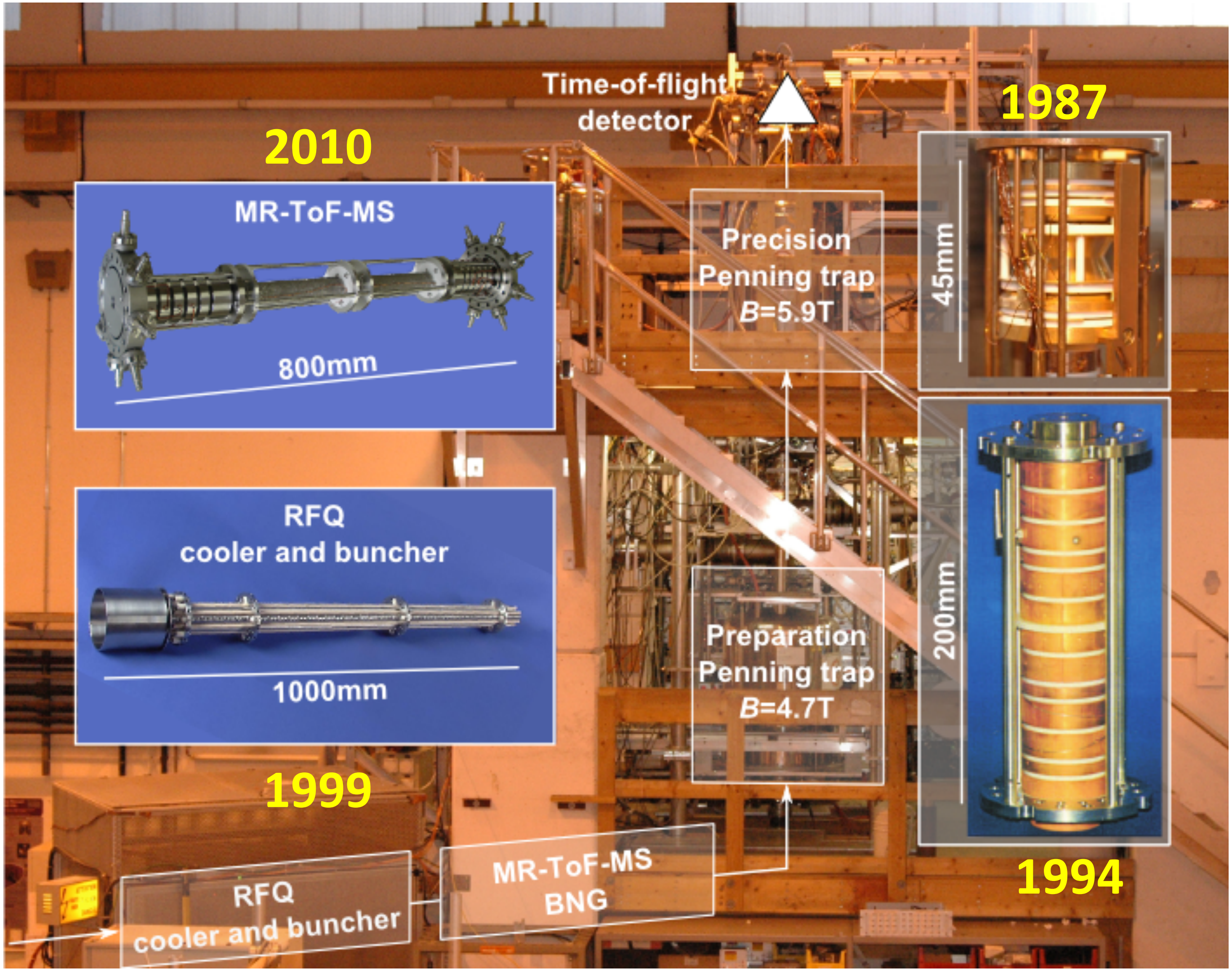


ISOLDE – Isotope Separator On-Line (DEvice) / CERN

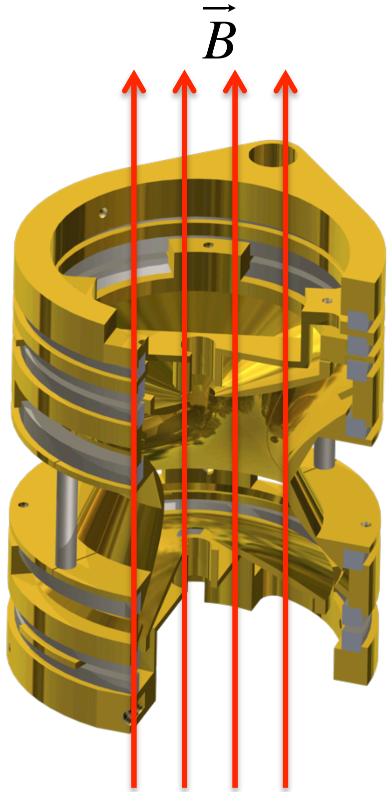


Production of radioactive nuclides via *fission*, or *fragmentation* reactions in a thick target, irradiated with a proton beam of 1.4GeV and an intensity up to 2μA

ISOLTRAP overview



ISOLTRAP overview: the Penning-trap / ToF ICR



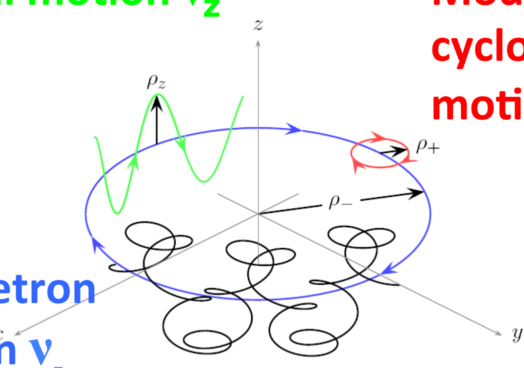
$$\nu_C = \frac{1}{2\pi}\frac{q}{m}\cdot B$$

$$\nu_c = \nu_+ + \nu_-$$

Axial motion ν_z

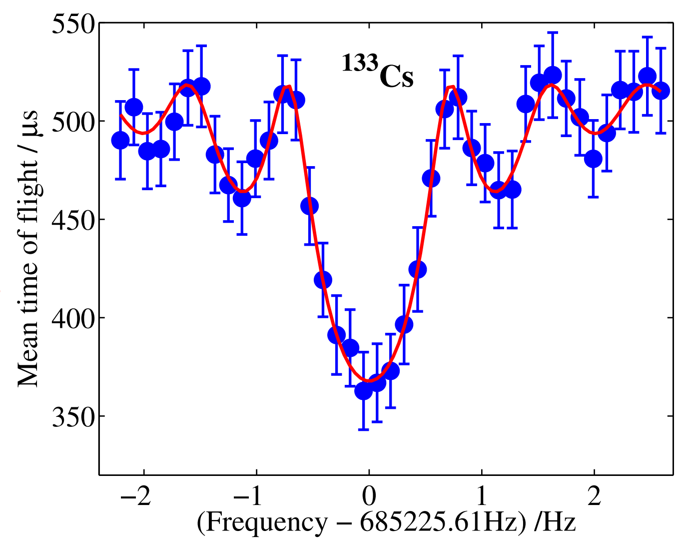
Modified cyclotron motion ν_+

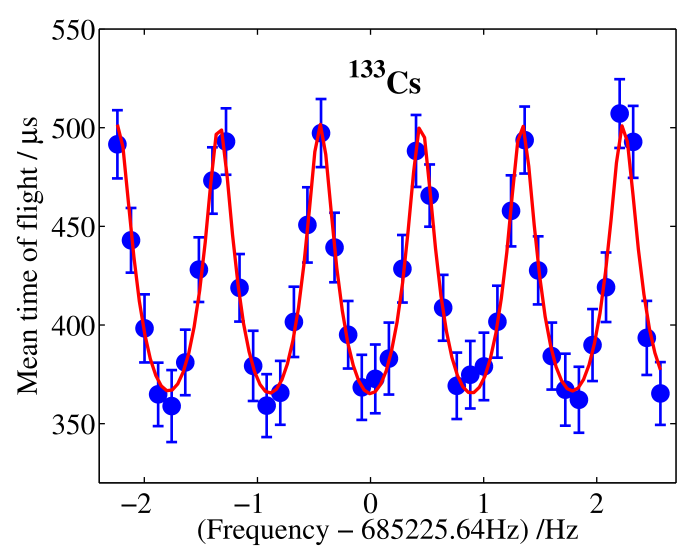
Magnetron motion ν_-



Radial frequencies:

$$\nu_\pm = \frac{\nu_c}{2} \pm \sqrt{\frac{\nu_c^2}{4} - \frac{\nu_z^2}{2}}$$





Brown & Gabrielse, Rev. Mod. Phys. 58, 233 (1986); Gräff *et al.*, Z. Physik A -- Atoms and Nuclei 297, 35 (1980); S. George et al., Phys. Rev. Lett. 98, 162501 (2007)

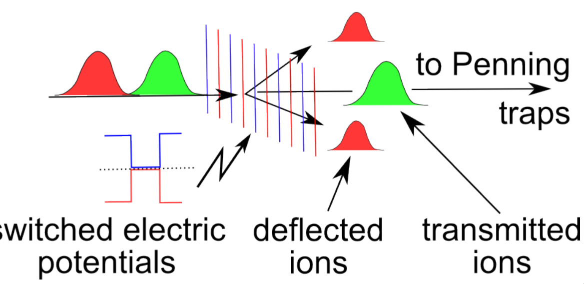
ISOLTRAP overview: MR-ToF-MS[1]

Requirements:

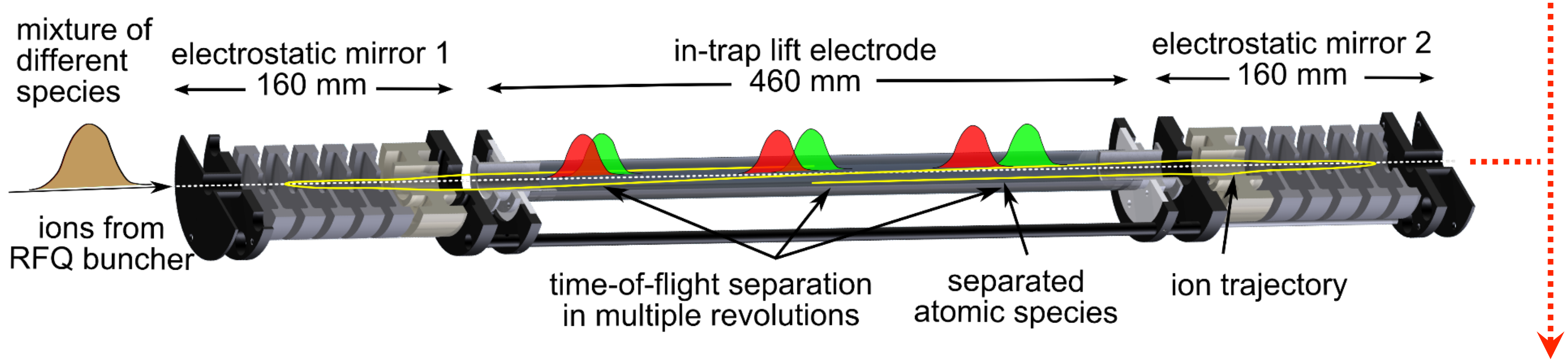
- mass resolving power $m/\Delta m \geq 100000$
- fast separation $\approx 10 ms$
- effective contamination suppression

Bradbury-Nielsen gate

mass separator



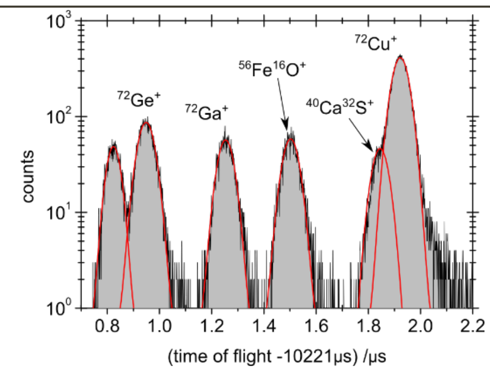
multi-reflection time-of-flight mass separator



MR-ToF-MS:

- 2 electrostatic ion mirrors + drift tube
- ToF separation due to different *m/q*
- non-scanning device for isobars
- single-ion sensitivity

mass spectrometer

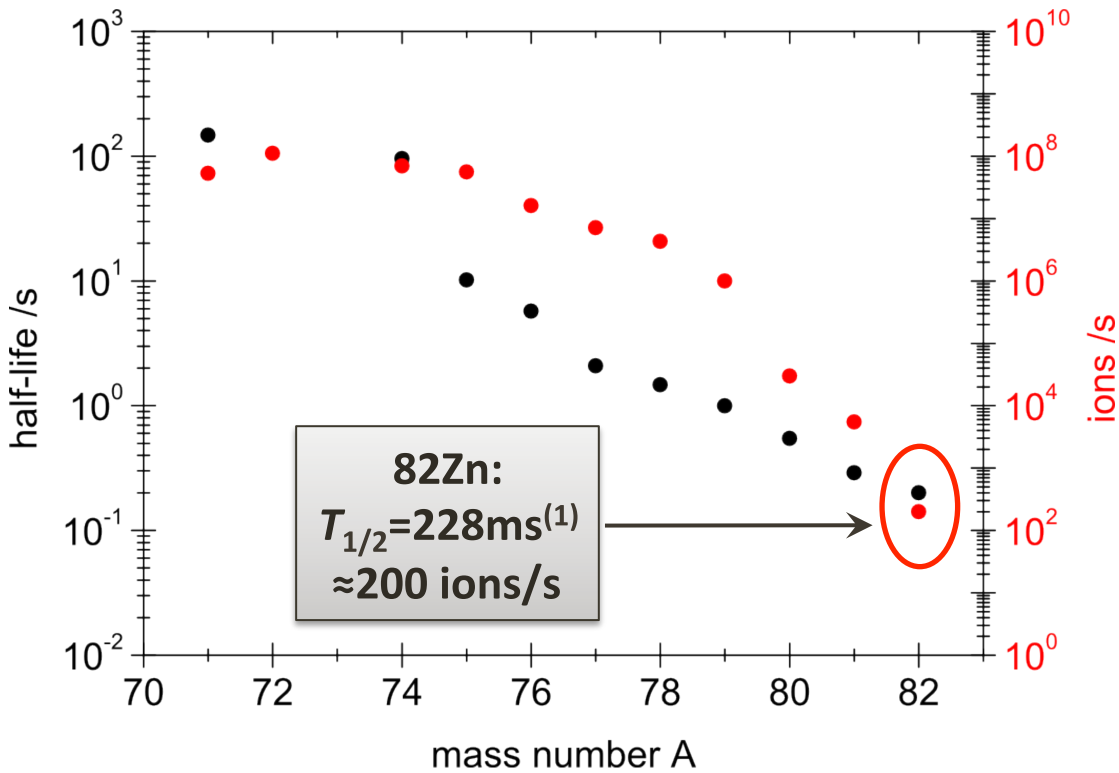


1: Wollnik & Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990); Wolf *et al.*, IJMS **313**, 8 (2012); Wolf *et al.*, IJMS 349-350, 123 (2013);

The first mass measurement of ^{82}Zn

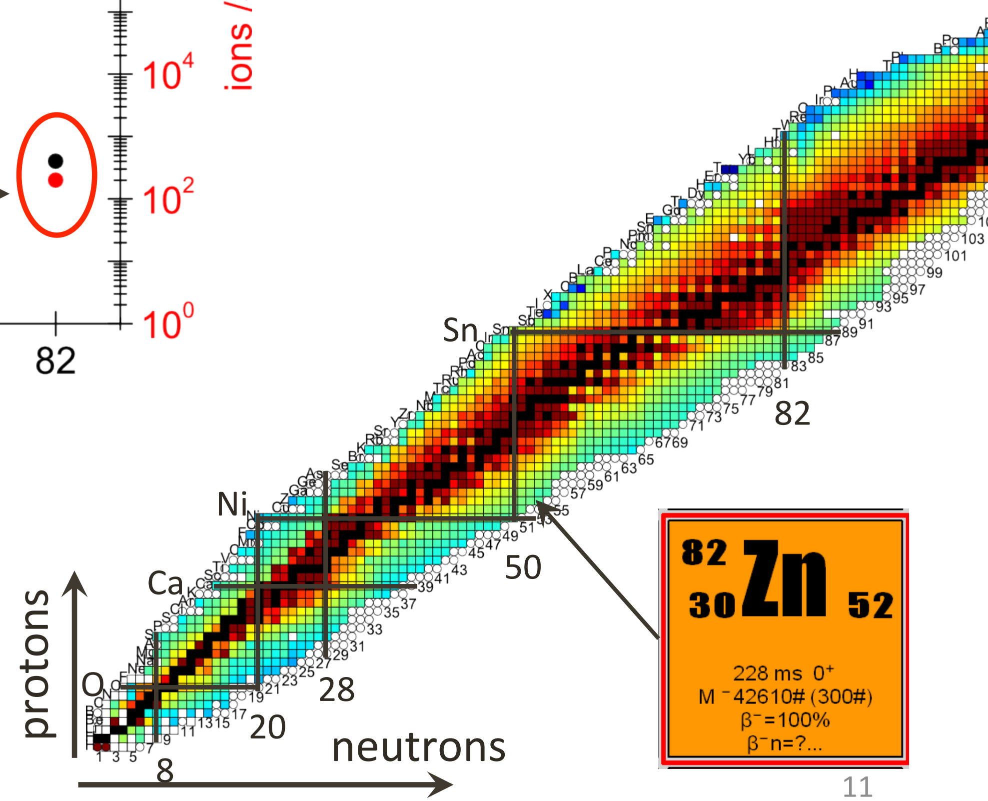
Neutron-rich Zn isotopes

half-life and production at ISOLDE



Production ratio:

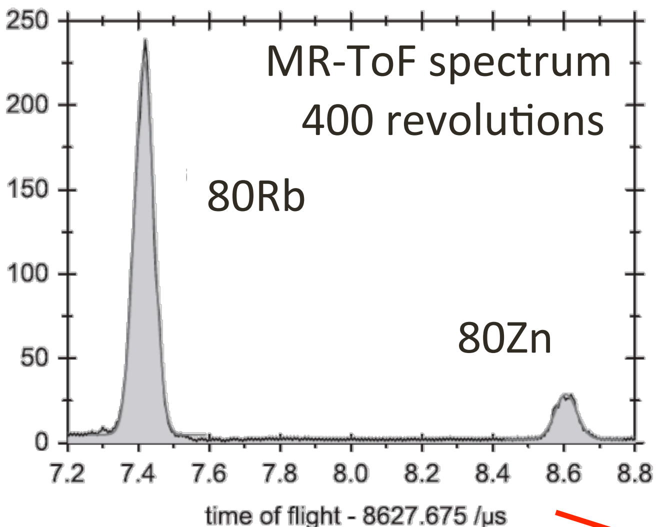
$$\frac{82\text{Rb}}{82\text{Zn}} > 10^4$$



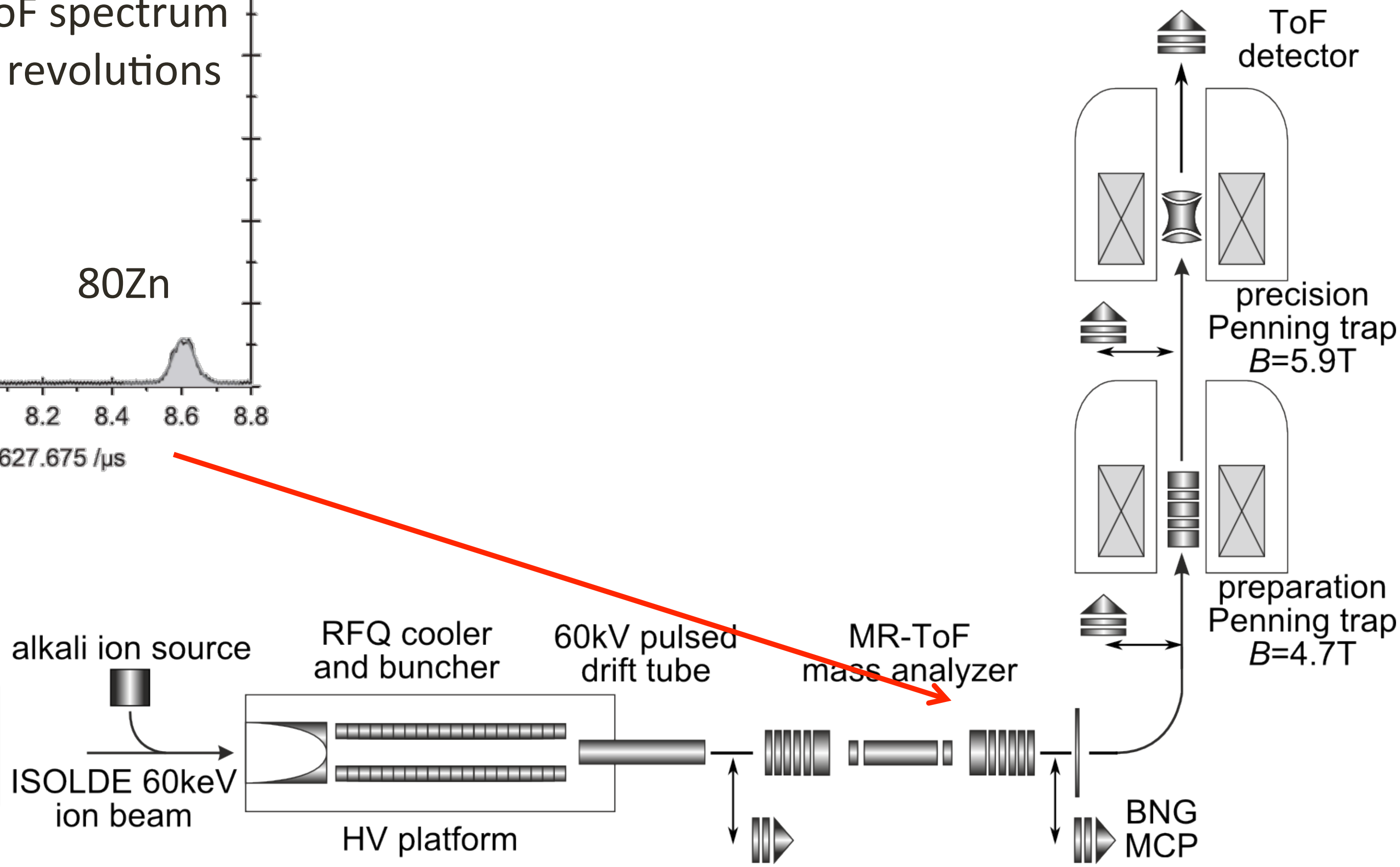
1: Madurga *et al.*, PRL 109, 112501 (2012)

Isobar separation: n-rich Zn isotopes

First application of an MR-ToF-MS to short-lived nuclides



ISOLDE ion beam:
80Zn + 80Rb

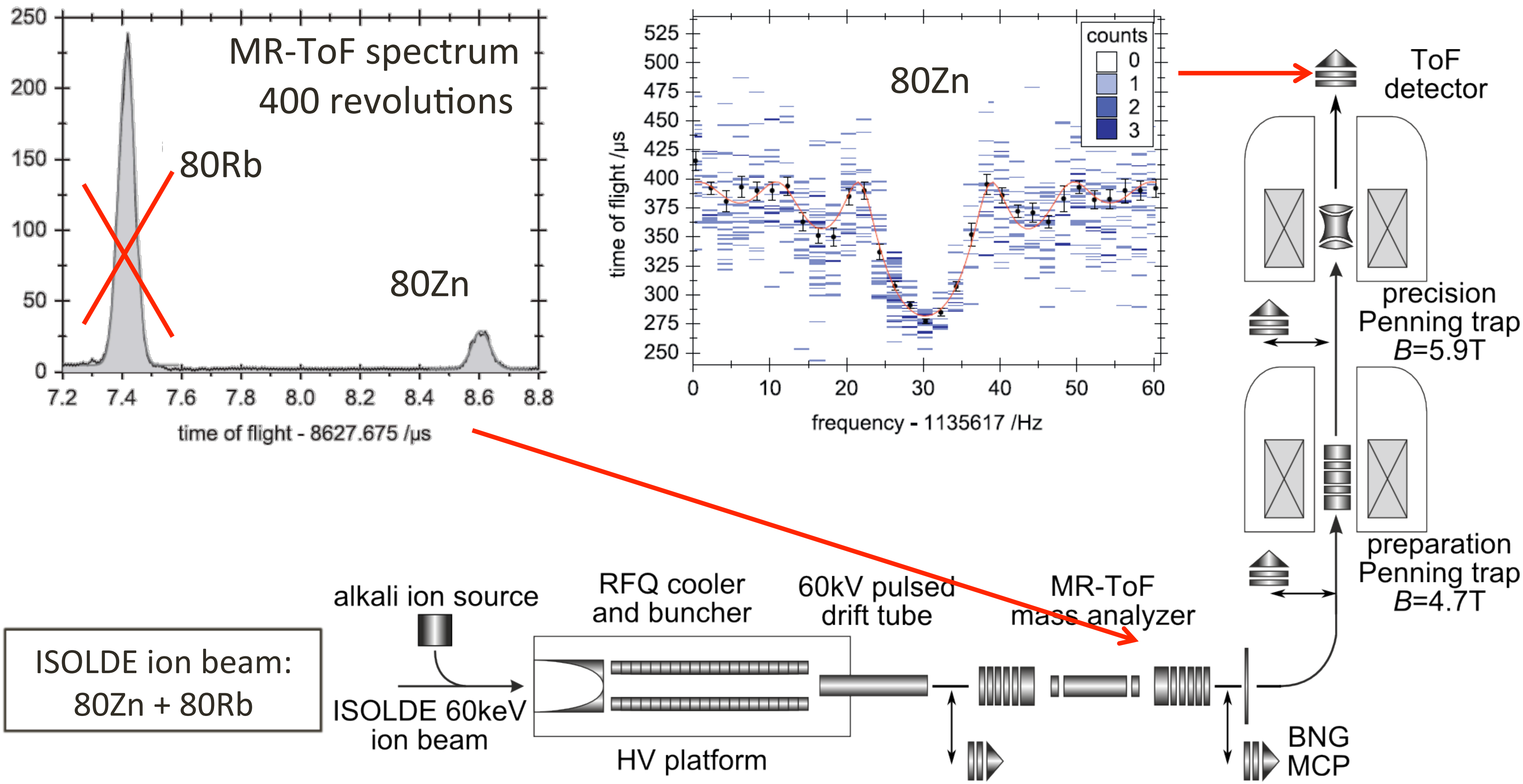


Wolf *et al.*, PRL 110, 041101 (2013); NIM A 686, 82 (2012)

Isobar separation: n-rich Zn isotopes

First application of an MR-ToF-MS to short-lived nuclides

ToF-ICR mass measurement



Wolf *et al.*, PRL 110, 041101 (2013); NIM A 686, 82 (2012)

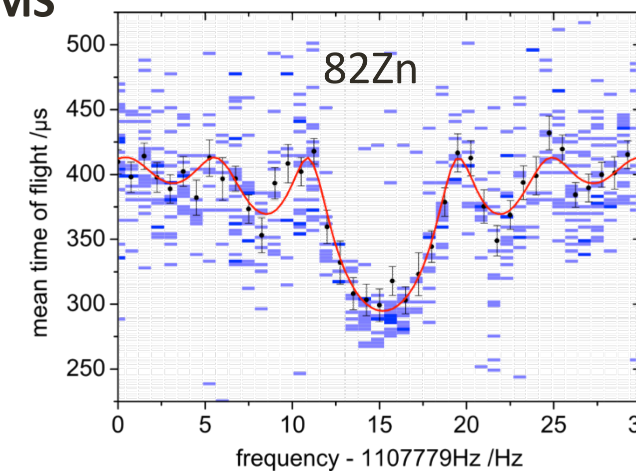
Isobar separation: n-rich Zn isotopes

First application of an MR-ToF-MS to short-lived nuclides

1754 ions/16h ➔ 1.8 ions/min

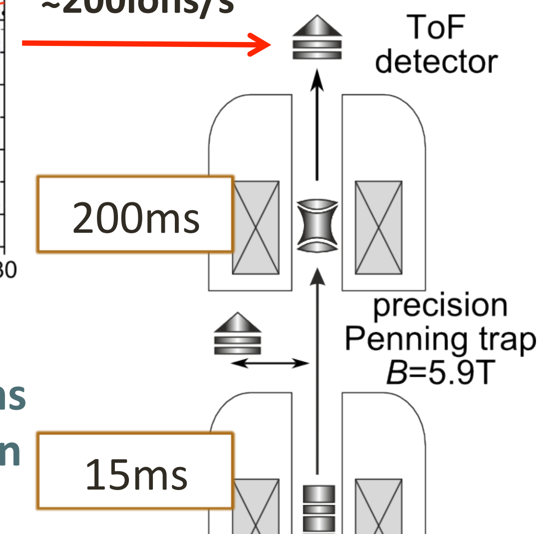
m(82Zn)=81.954574(3)u
$\delta m/m=4\times10^{-8}$

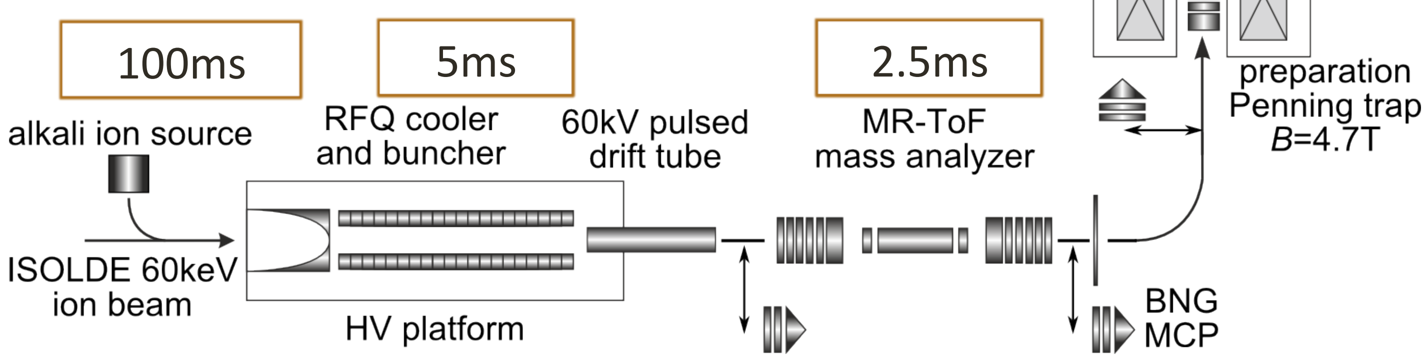
- Mass determined for the first time!
- Most exotic test of the N=50 shell gap!
- Highest relative neutron excess with Z>16!



82Zn:
$T_{1/2}$=228ms
≈200ions/s

MR-ToF separation in only 2.5ms
<25ms for complete preparation





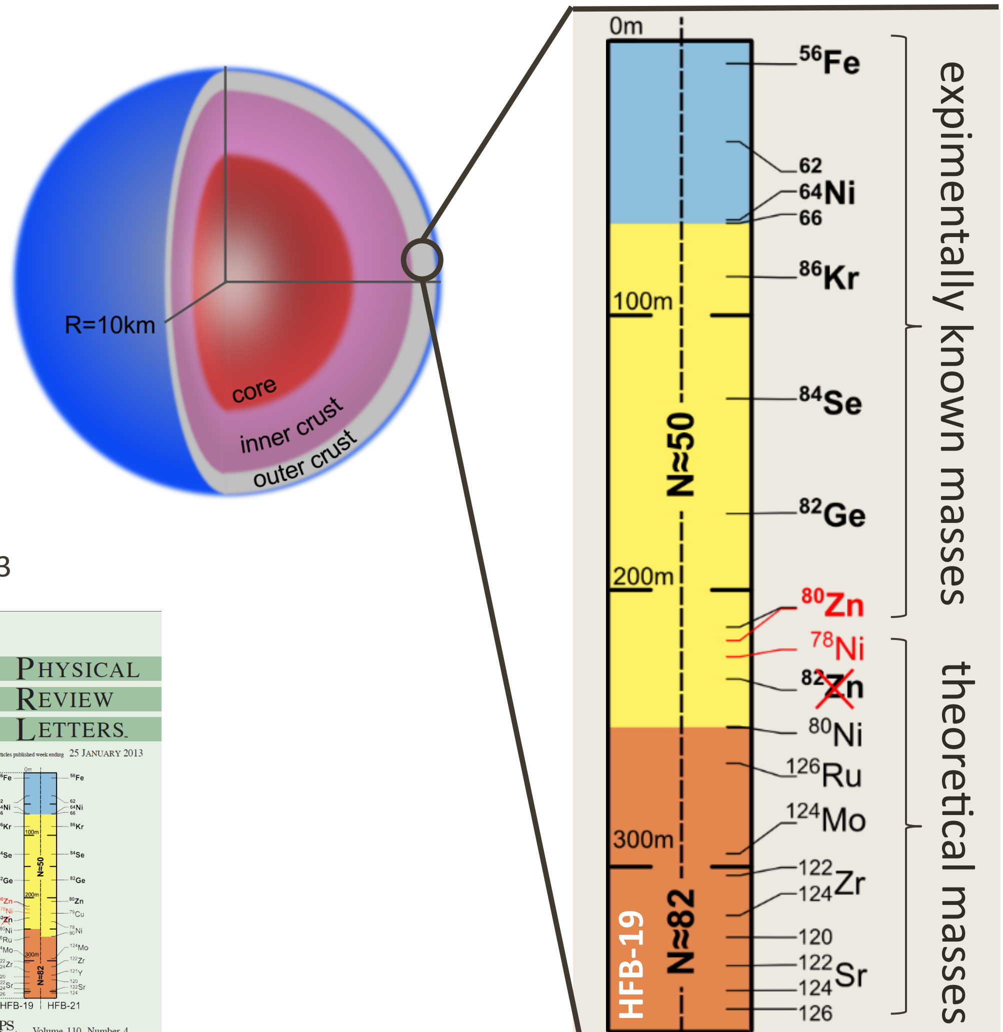
ISOLDE ion beam:
82Zn + 82Rb

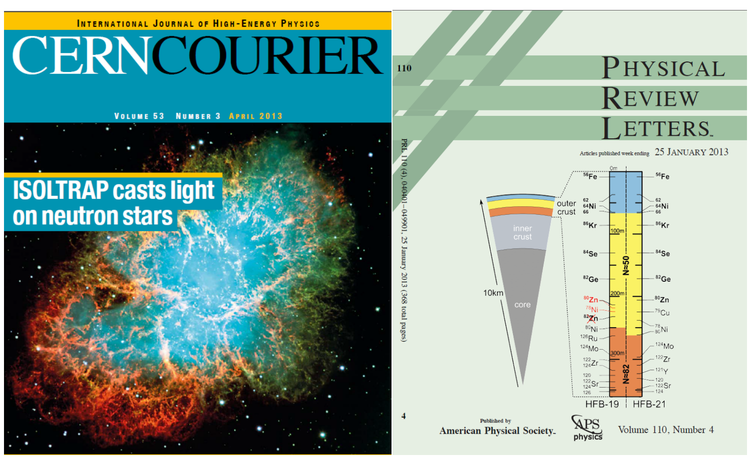
Audi *et al.*, Chinese Phys. C 36, 1157 (2012); Wolf *et al.*, PRL 110, 041101 (2013)

Isobar separation: n-rich Zn isotopes

BPS-model[1] of neutron-star outer crust:

- masses of n-rich nuclei
- 82Zn predicted by some mass models[2]
- first mass measurement: 82Zn is not part of the outer crust
- agreement with astronomical observations of neutron stars[3]



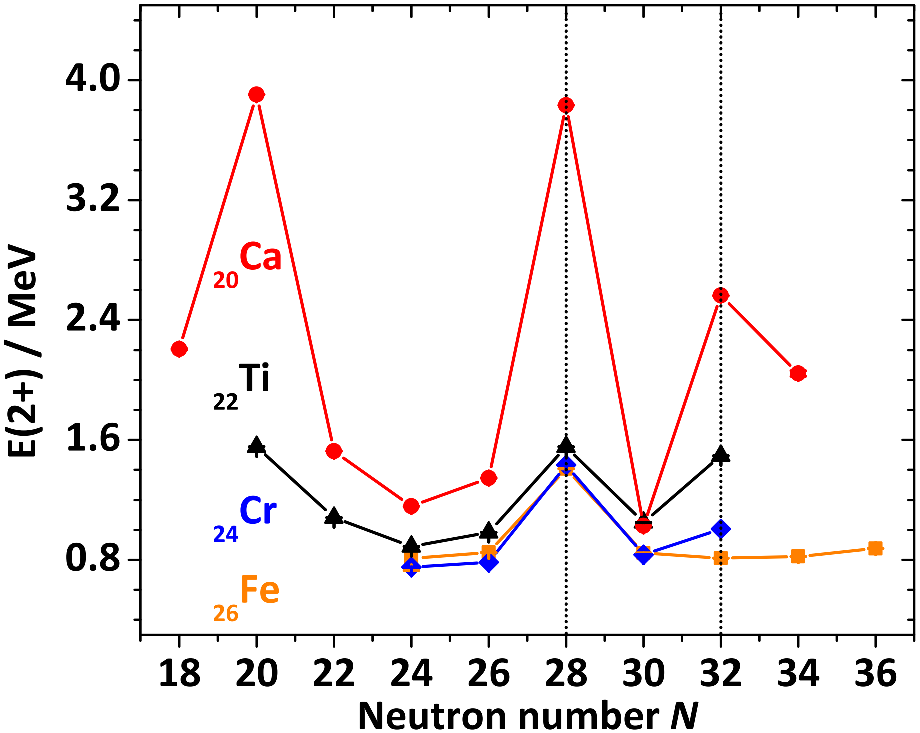


Calculations by
S. Goriely, N. Chamel

1: Baym, Pethick & Sutherland, ApJ 170, 299 (1971); 2: Pearson, PRC 83, 065810 (2011);
3: Demorest *et al.*, Nature 467, 1081 (2010); Antoniadis, Science 340, 1233232 (2013)

The first mass measurements of $^{53,54}Ca$

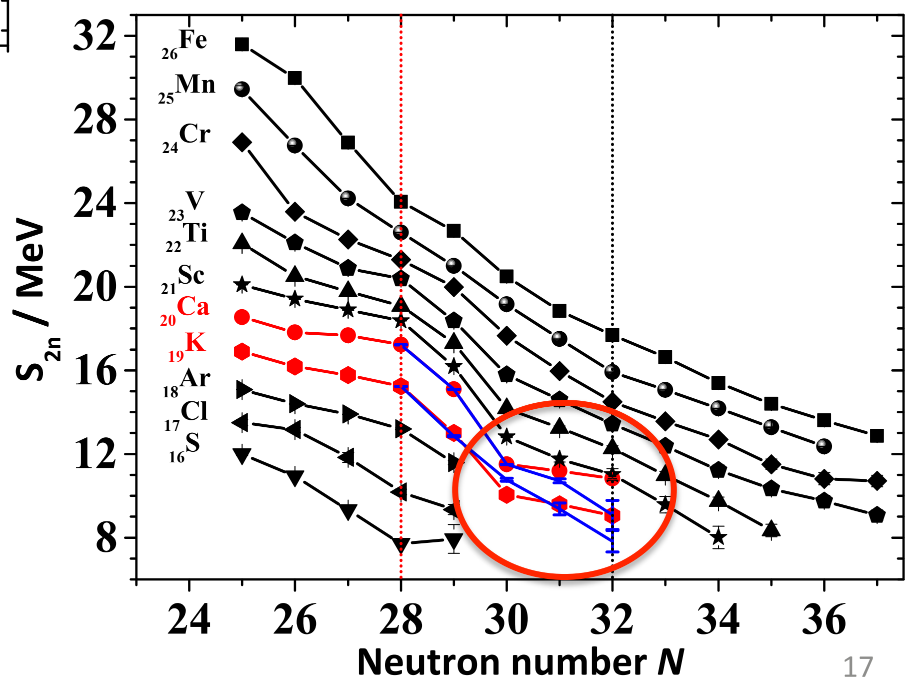
Magic neutron number *N*=32?



Mass measurements performed by TITAN[1] show big deviations from values extrapolated in AME2003.

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

Data: AME2012[2], **AME2003**



- Spectroscopic information available at *N*=32
- E(2+) energy particularly high in 40,48Ca and 52Ca

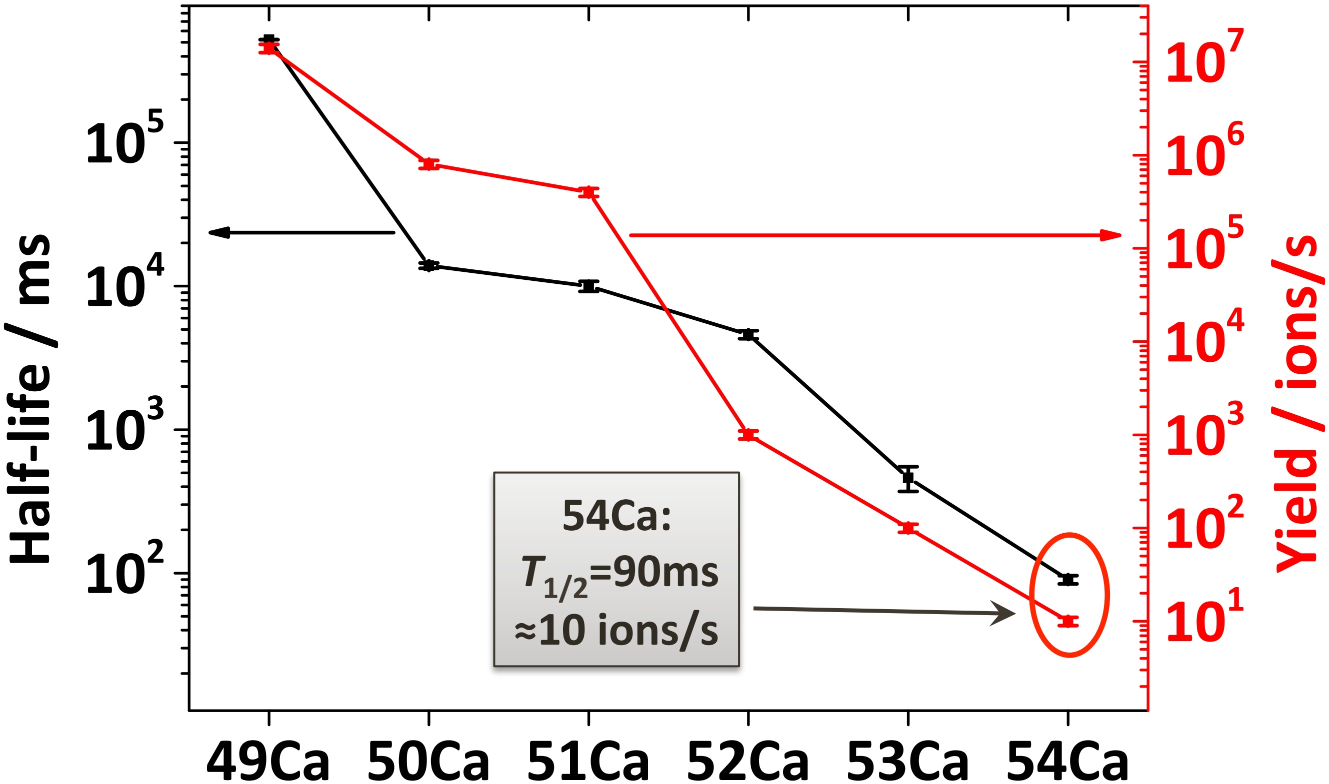
A. Huck *et al.*, Phys. Rev. C **31**, 2226–2237 (1985)

D. Steppenbeck *et al.*, Nature **502,** 207-210 (2013) DOI/10.1038/nature12522

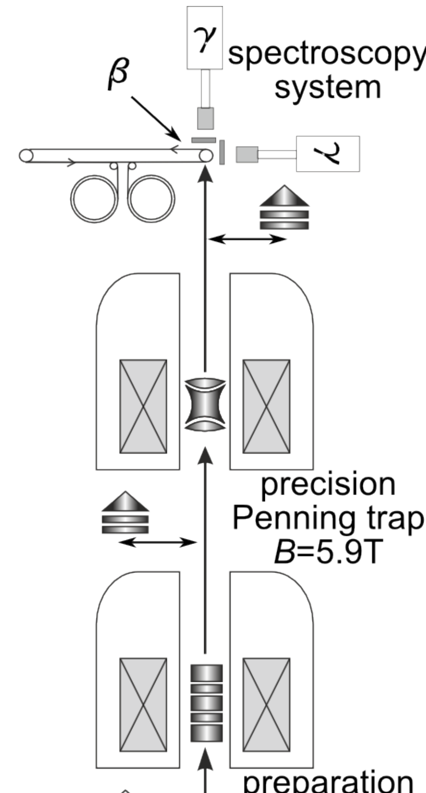
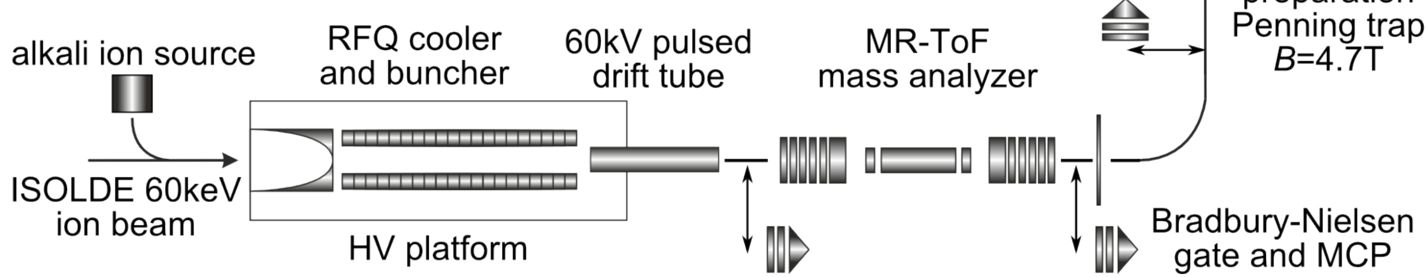
1: A. T. Gallant *et al.,* Phys. Rev. Lett. **109**, 032506 (2012)

2: M. Wang et al., Chinese Phys. C **36**, 1603 (2012)

ISOLTRAP setup and the calcium measurements

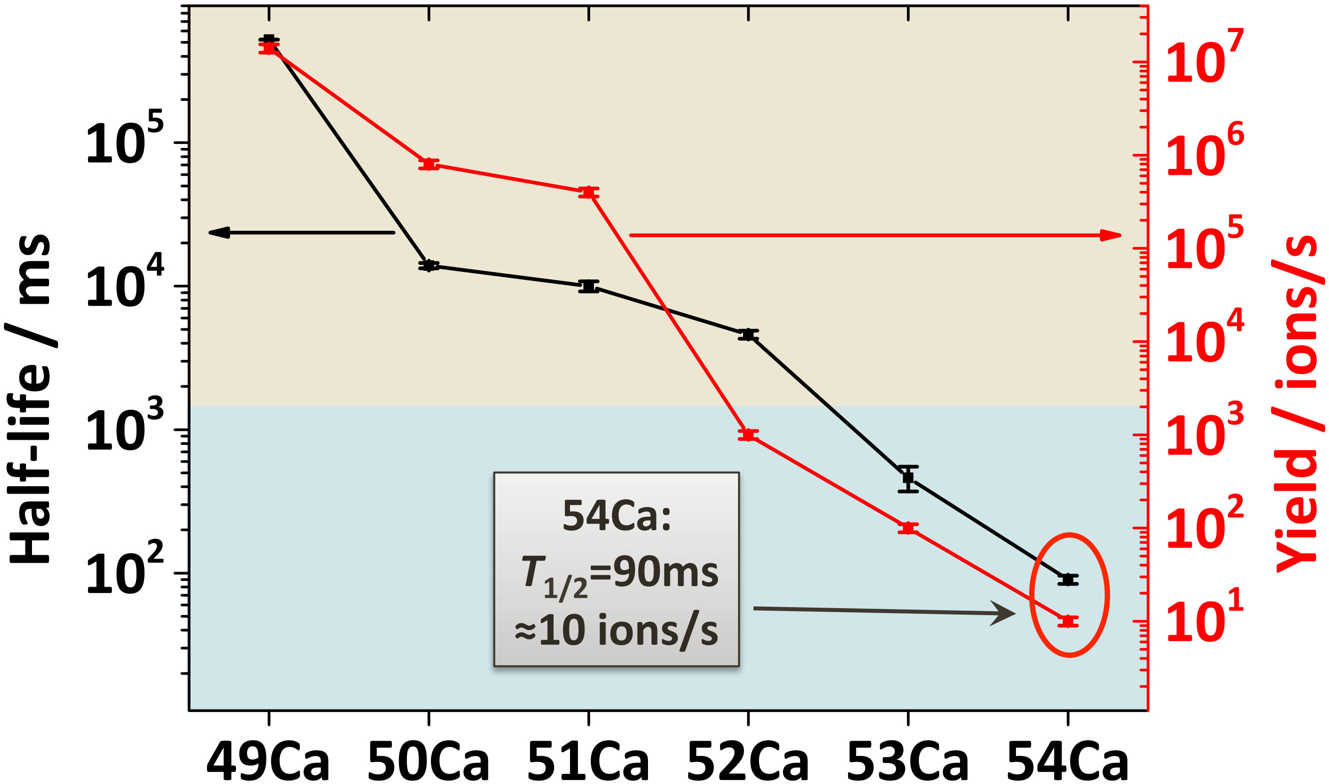


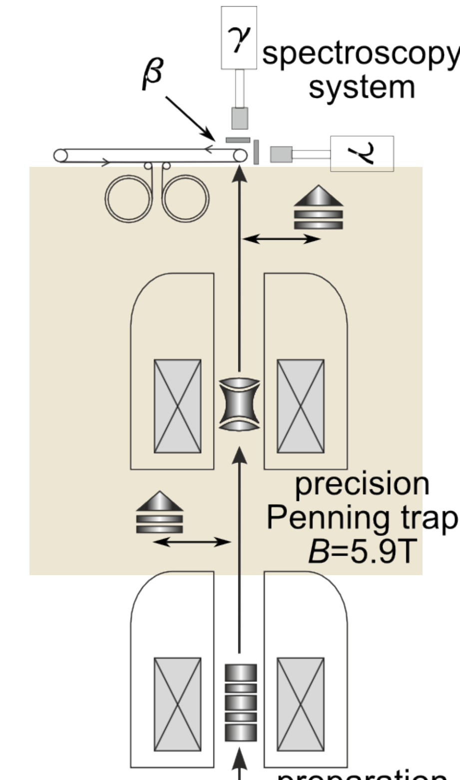
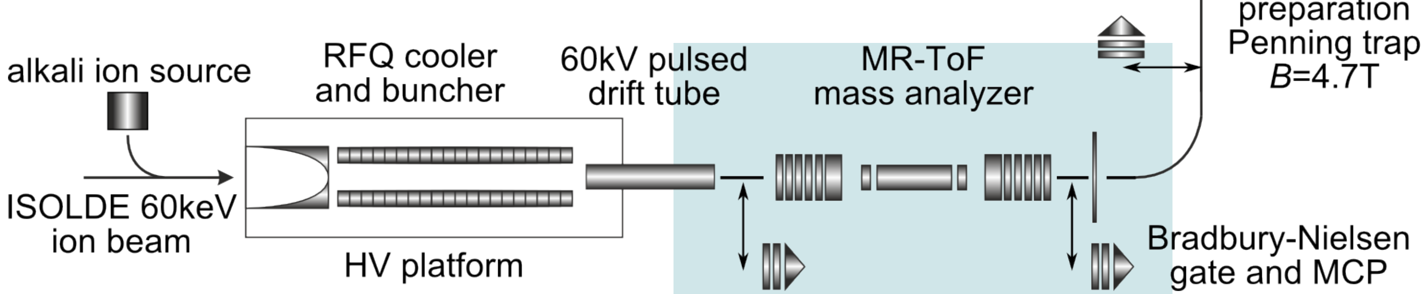
ISOLDE delivers a **mixture of isobaric species**

Wienholtz *et al.*, Nature 498, 346 (2013)

ISOLTRAP setup and the calcium measurements



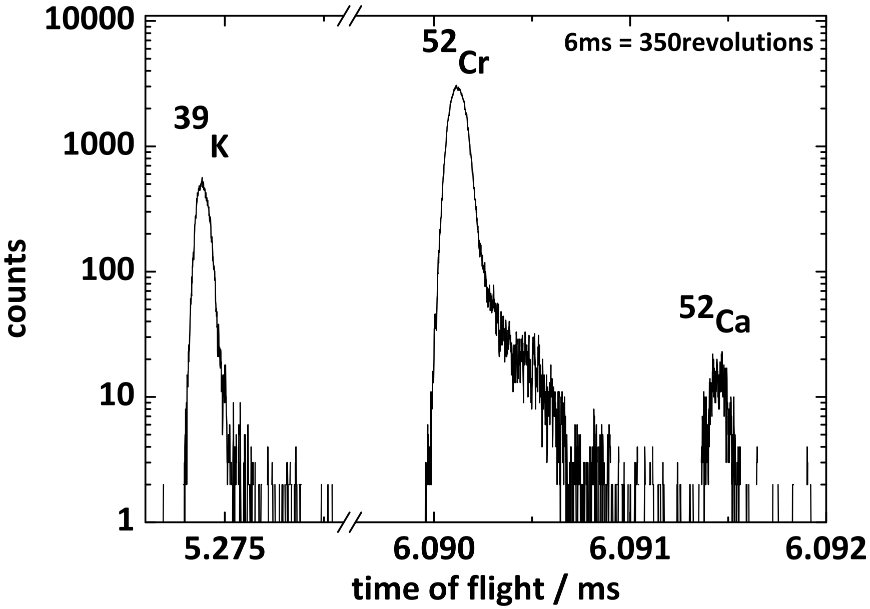



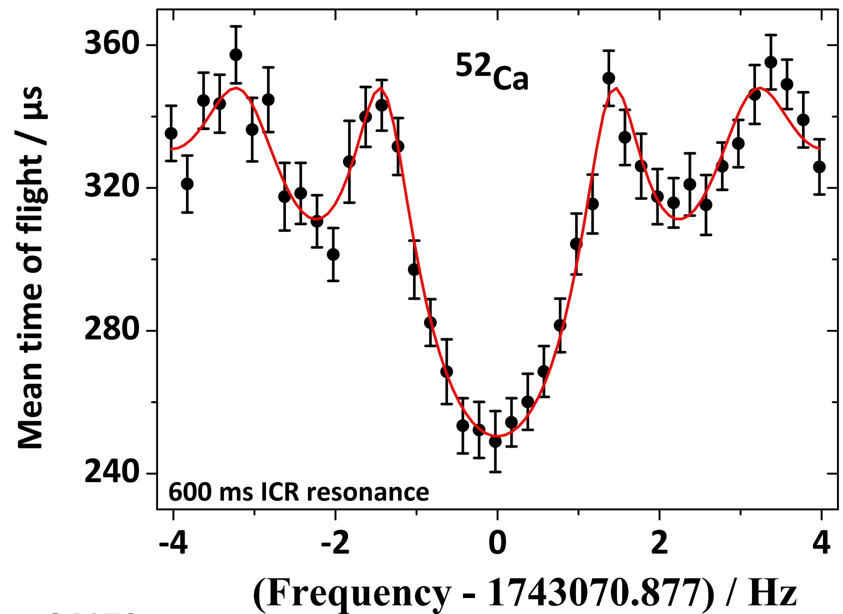
ISOLDE delivers a **mixture of isobaric species**

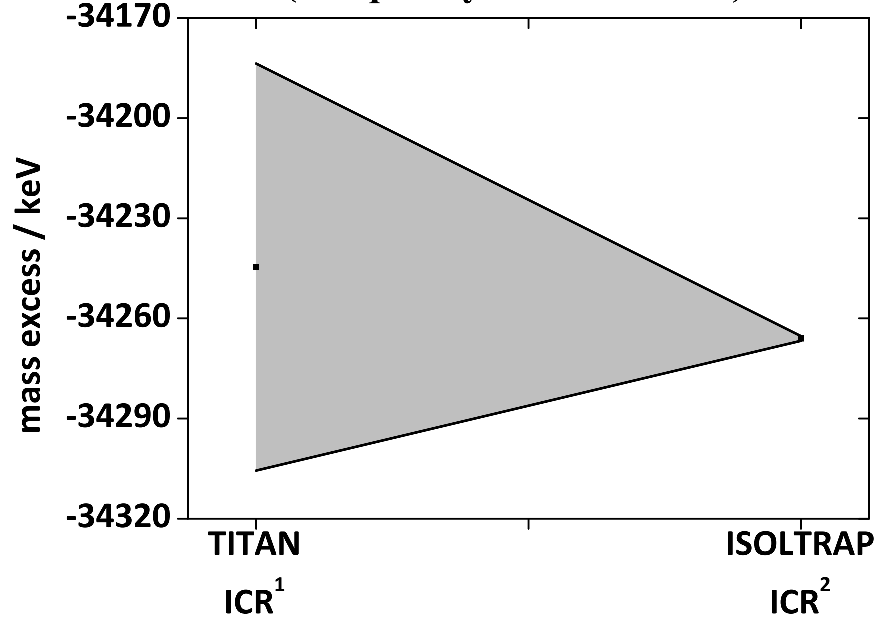
Wienholtz *et al.*, Nature 498, 346 (2013)

ISOLTRAP setup and the calcium measurements 52Ca

\\ n-rich Calcium isotopes – ^{52}Ca

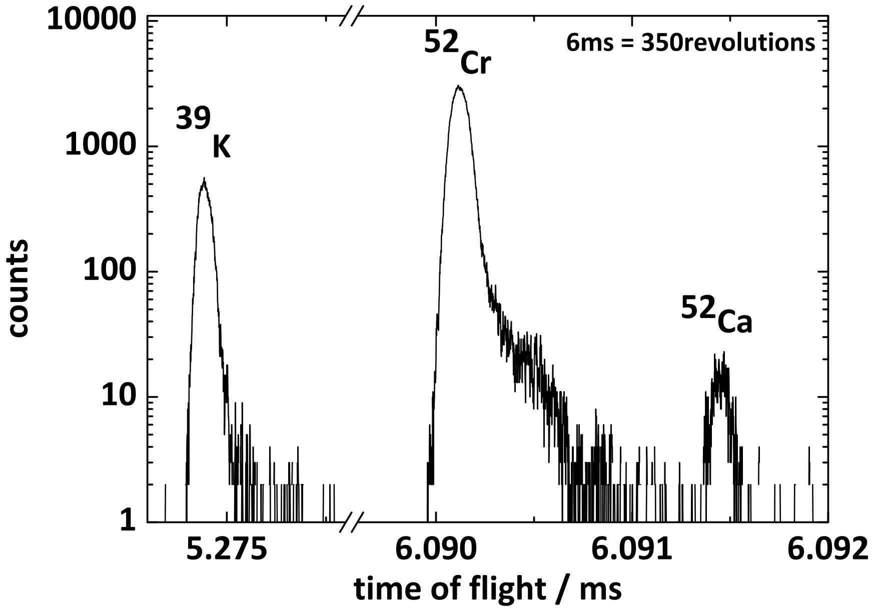


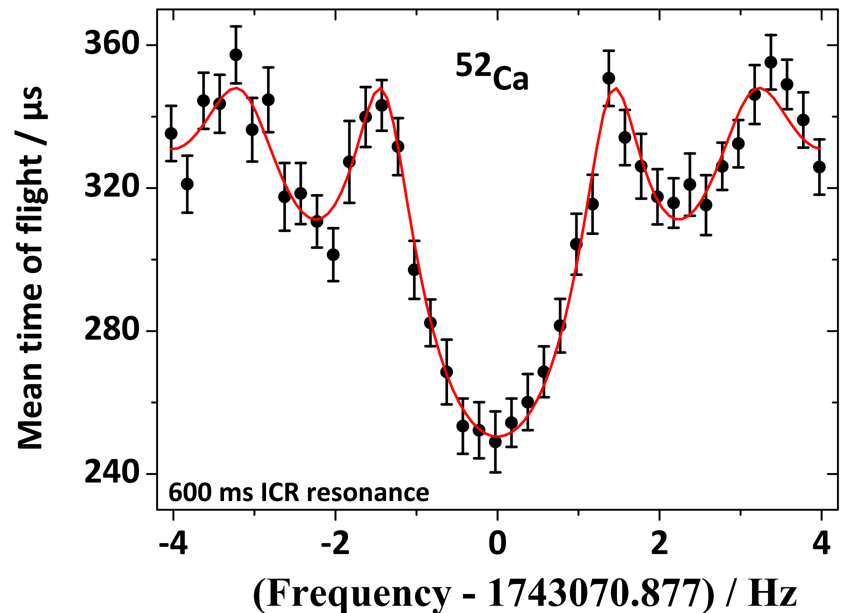


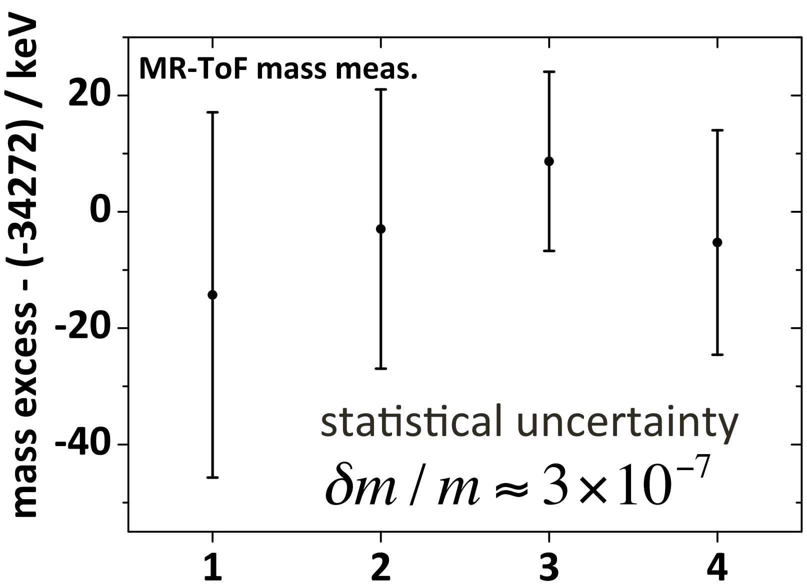


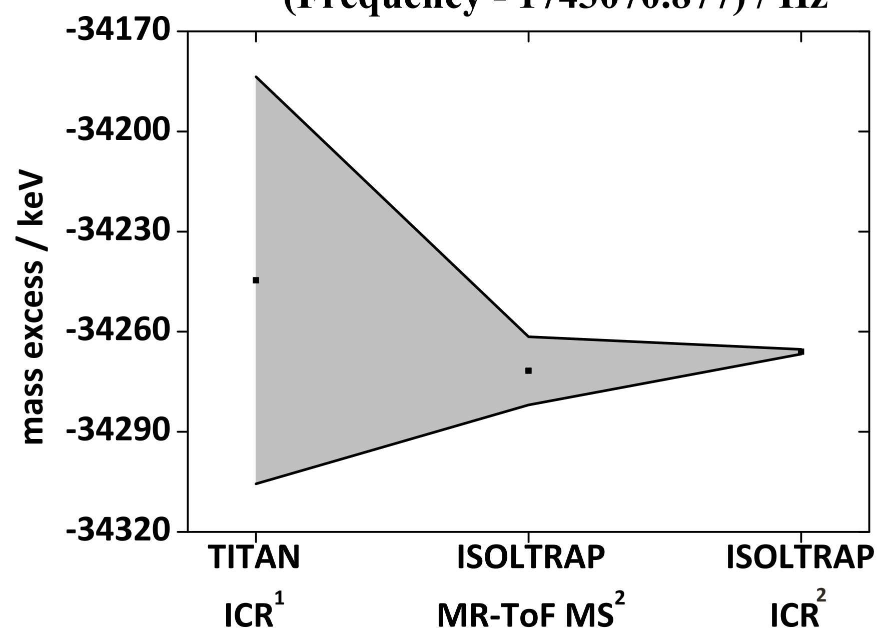
1: A. T. Gallant *et al.,* Phys. Rev. Lett. **109**, 032506 (2012)
2: Wienholtz *et al.*, Nature **498,** 346-349 (2013) DOI/10.1038/nature12226

\\ n-rich Calcium isotopes – ^{52}Ca







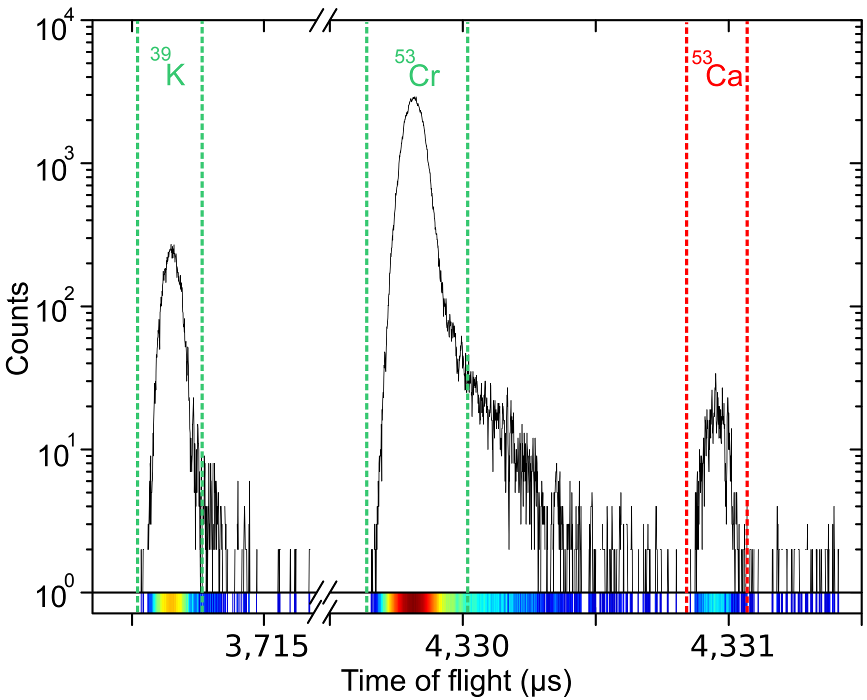


1: A. T. Gallant *et al.,* Phys. Rev. Lett. **109**, 032506 (2012)
2: Wienholtz *et al.*, Nature **498,** 346-349 (2013) DOI/10.1038/nature12226

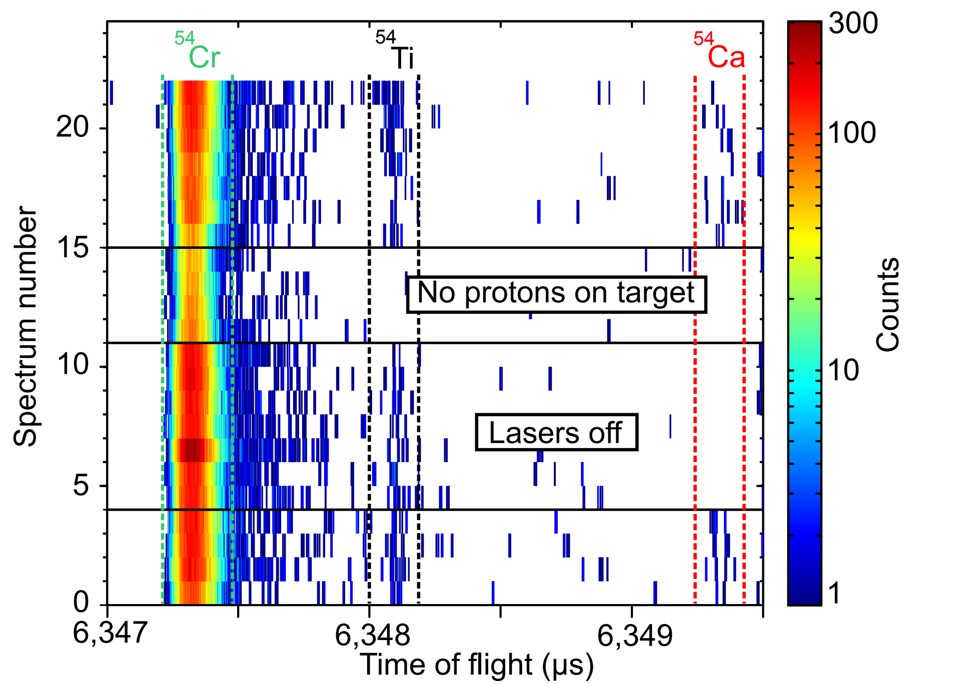
ISOLTRAP setup and the calcium measurements 53Ca and 54Ca

\\ n-rich Calcium isotopes: ^{53}Ca and ^{54}Ca

***A*=53:** measurement cycle ≈ 4ms



***A*=54:** measurement cycle ≈ 6ms



6413 counts/12.6h ➔ 9 counts/minute

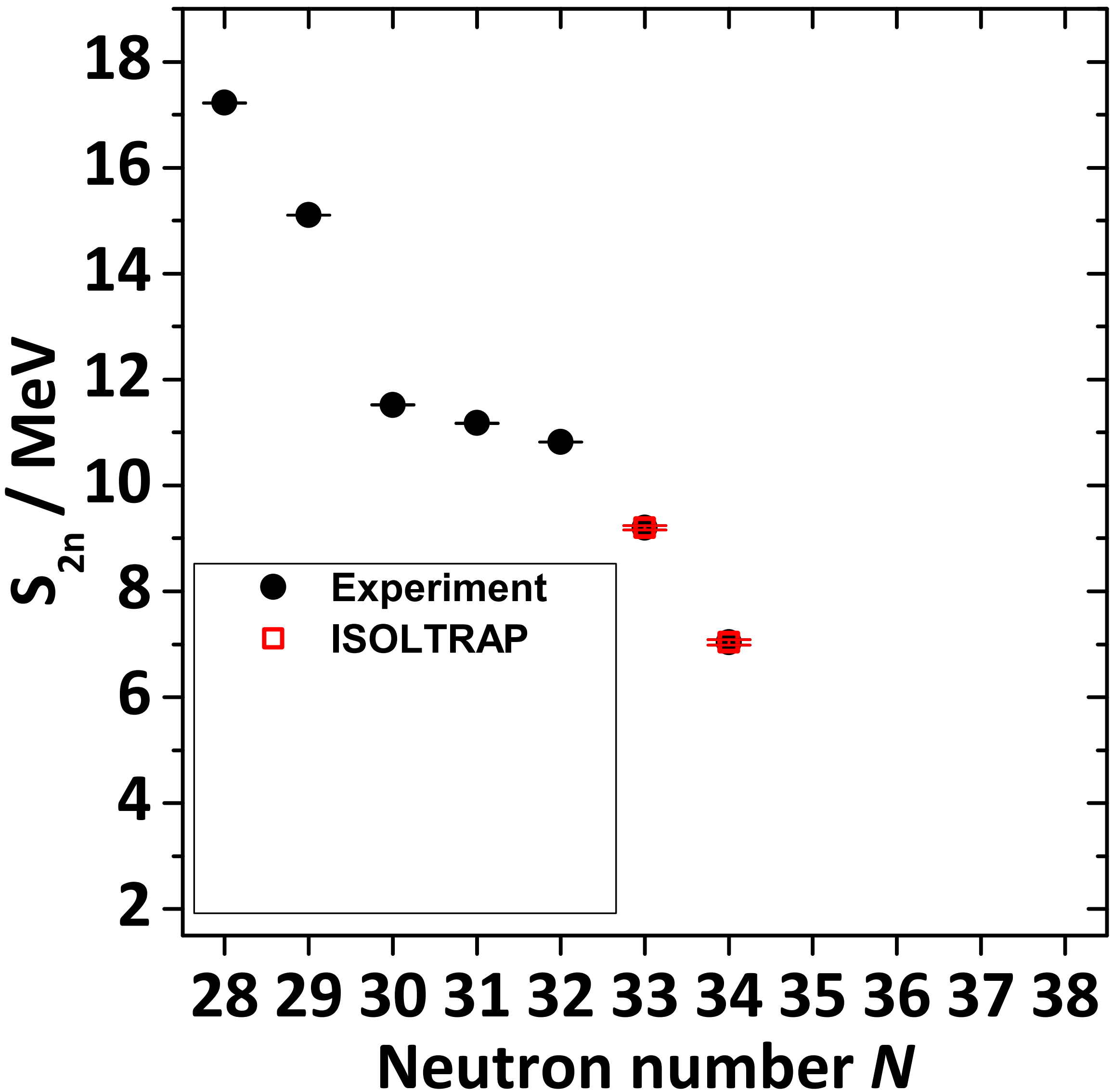
2314 counts/18.2h ➔ 2 counts/minute

statistical uncertainty ≈ 45keV ➔ $\delta m/m \approx 9\text{x}10^{-7}$

Masses of 53Ca and 54Ca determined for the first time!

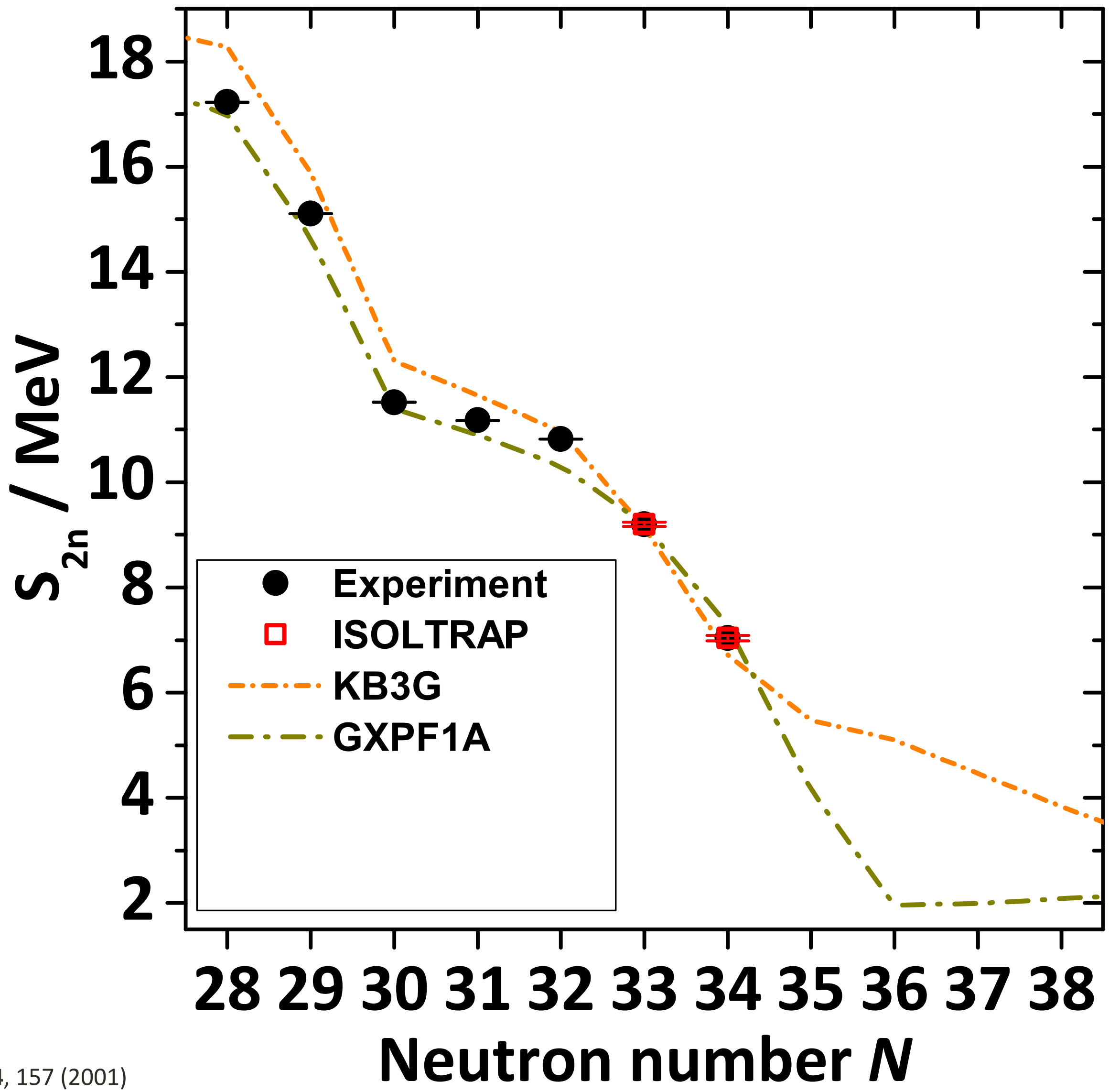
Wienholtz *et al.*, Nature **498,** 346-349 (2013) DOI/10.1038/nature12226

\\ Comparison with theory



Wienholtz *et al.*, Nature **498,** 346-349 (2013)

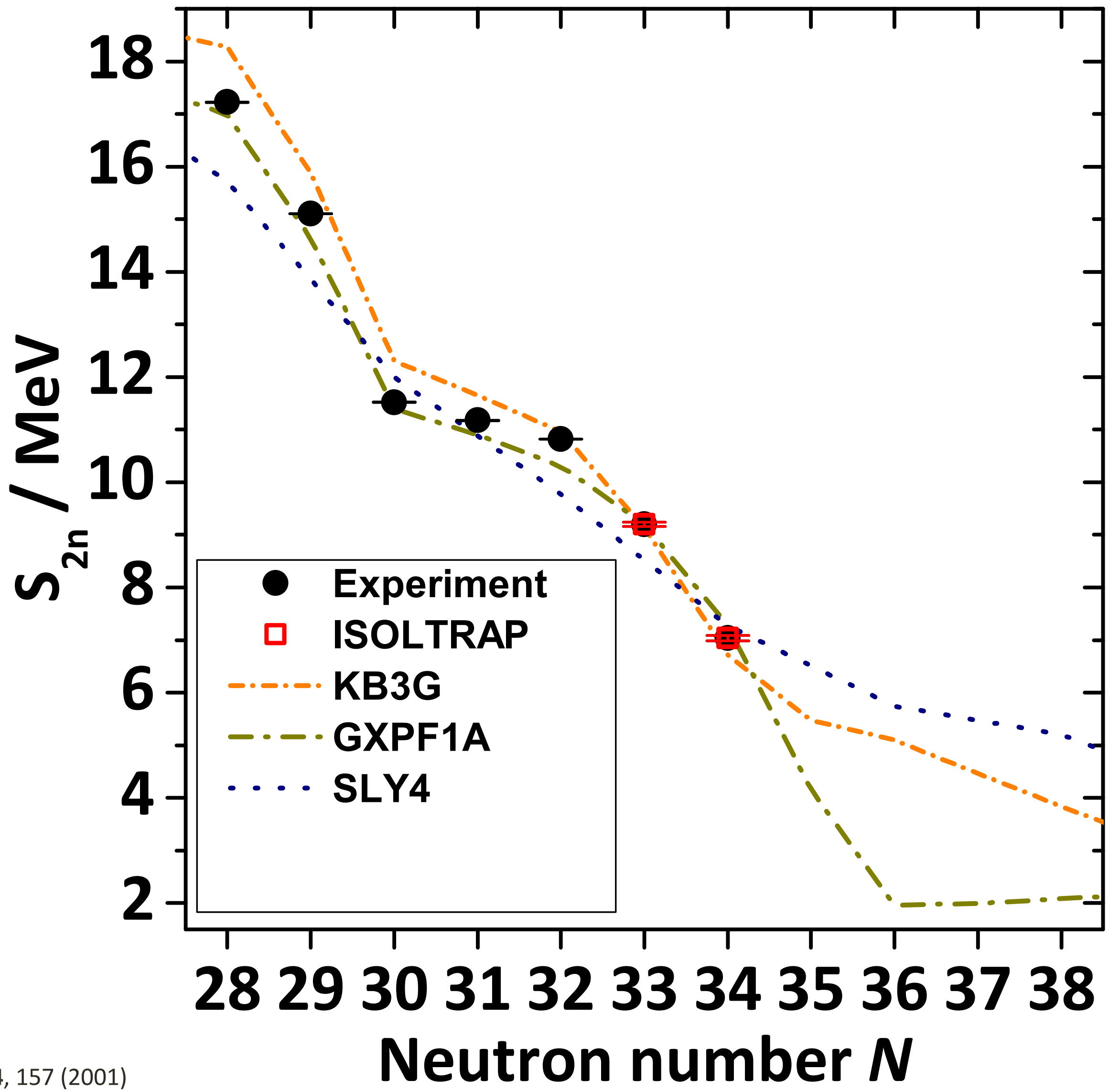
\\ Comparison with theory



Poves *et al.*, Nucl. Phys. A **694**, 157 (2001)
Honma *et al.*, Eur. Phys. J. A 25, Suppl. 1, 499 (2005)

Wienholtz *et al.*, Nature **498,** 346-349 (2013)

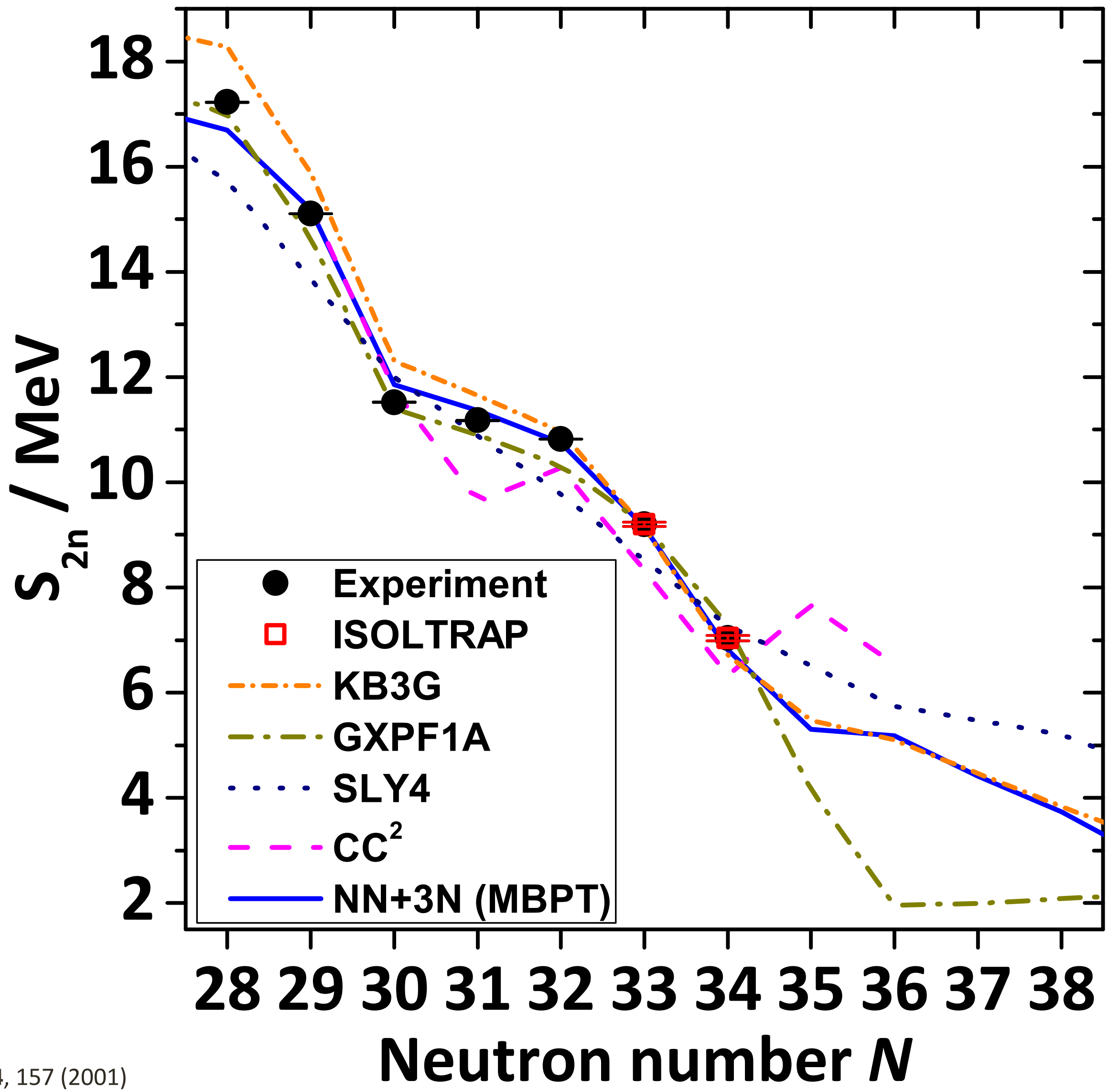
\\ Comparison with theory



Poves *et al.*, Nucl. Phys. A **694**, 157 (2001)
Honma *et al.*, Eur. Phys. J. A 25, Suppl. 1, 499 (2005)
Chabanat *et al.* , Nucl.Phys. A **635**, 231 (1998)

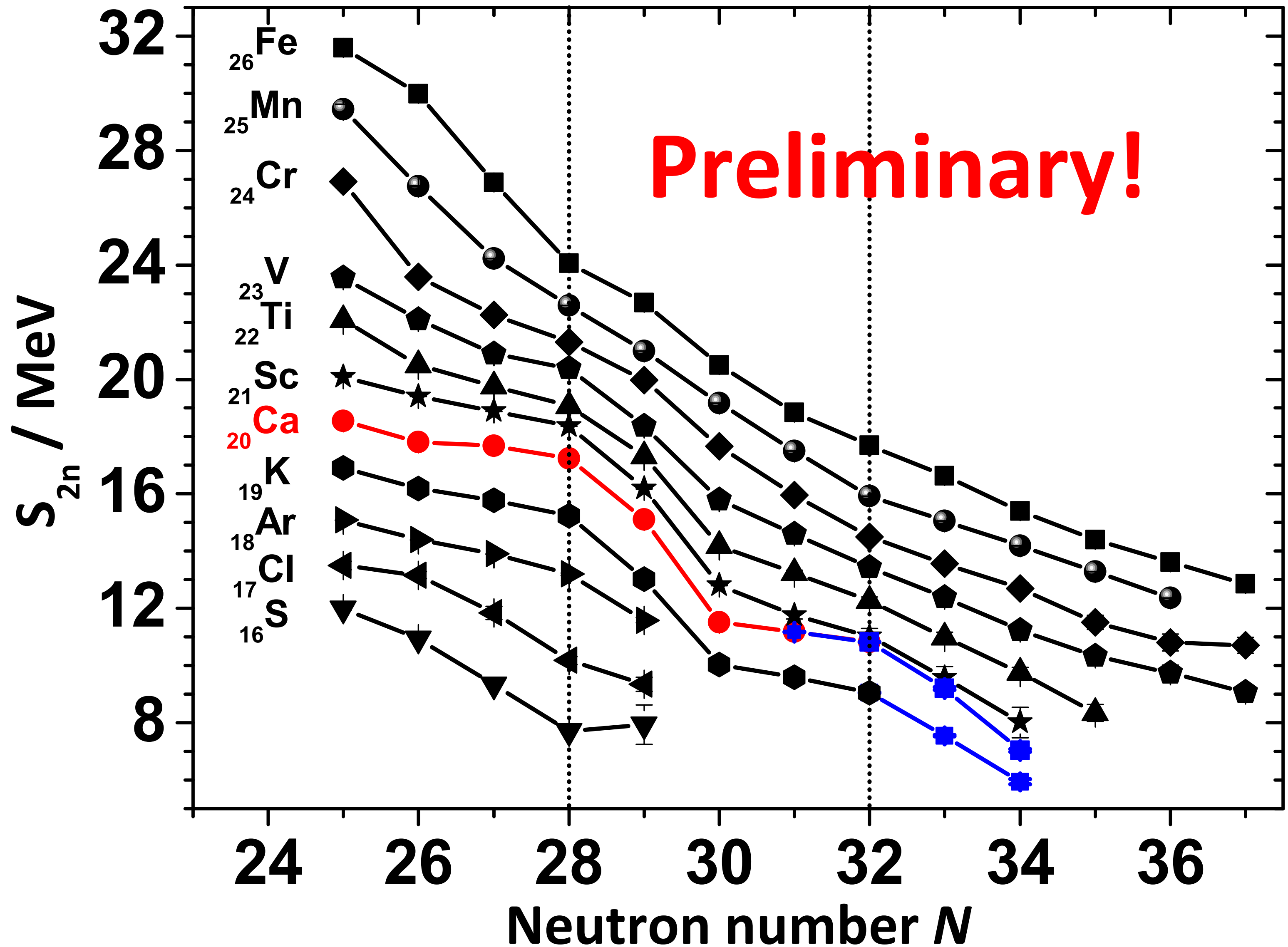
Wienholtz *et al.*, Nature **498,** 346-349 (2013)

\\ Comparison with theory



Poves *et al.*, Nucl. Phys. A **694**, 157 (2001)
Honma *et al.*, Eur. Phys. J. A 25, Suppl. 1, 499 (2005)
Chabanat *et al.* , Nucl.Phys. A **635**, 231 (1998)
Hagen *et al.*, Phys. Rev. Lett. **109**, 032502 (2012)
J.D. Holt *et al.,* J. Phys. G: Nucl. Part. Phys. **40** 075105 (2013)
Wienholtz *et al.*, Nature **498,** 346-349 (2013)

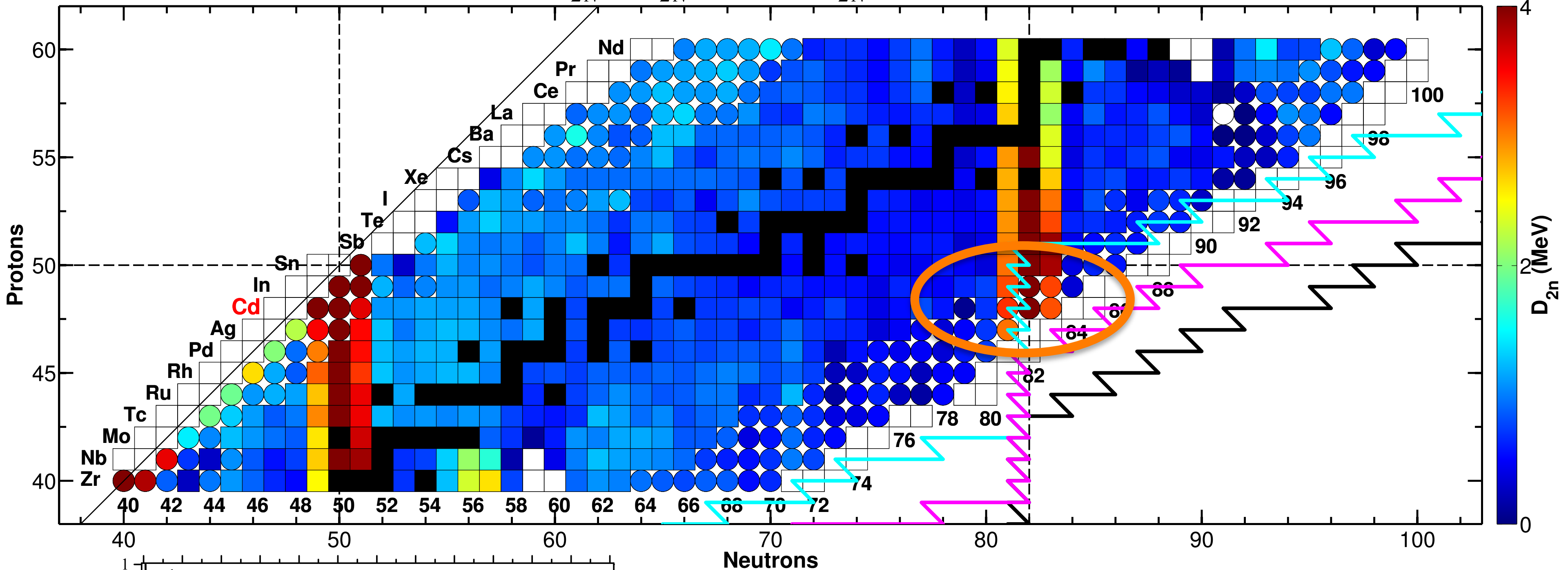
\\ S_{2n} surface including 52 and 53 potassium

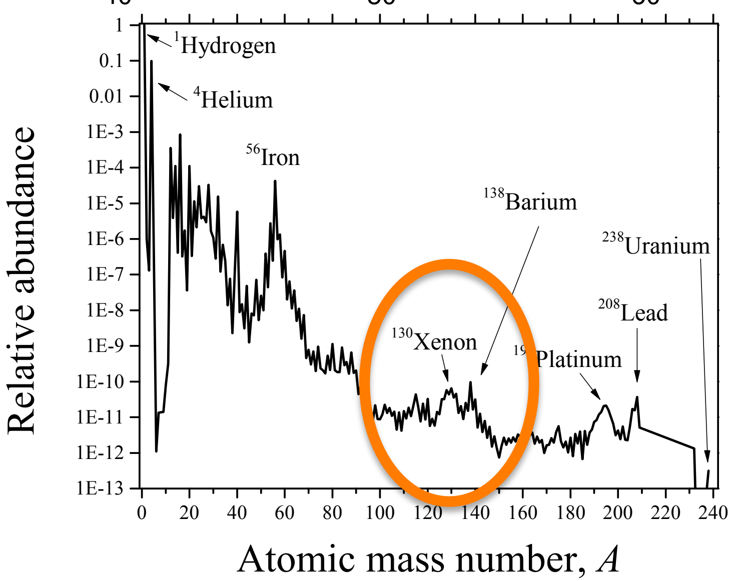


Neutron-rich cadmium isotopes

Motivation - rapid neutron capture process

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

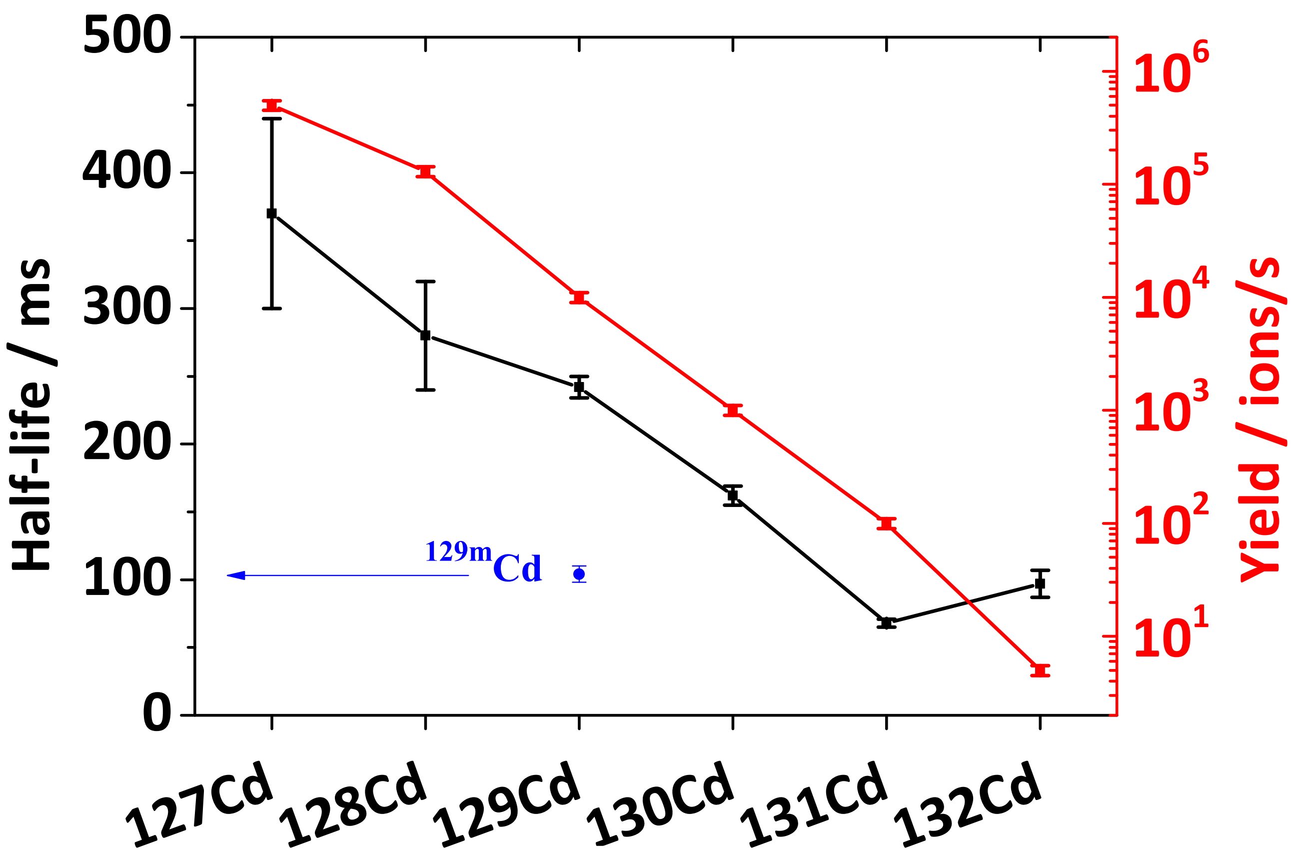


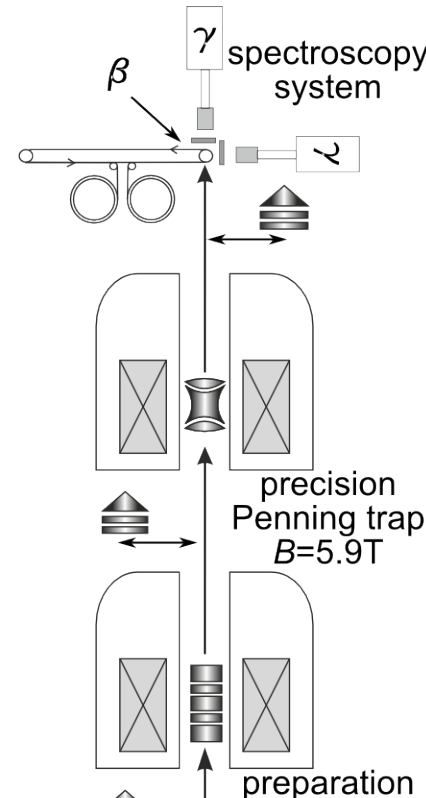
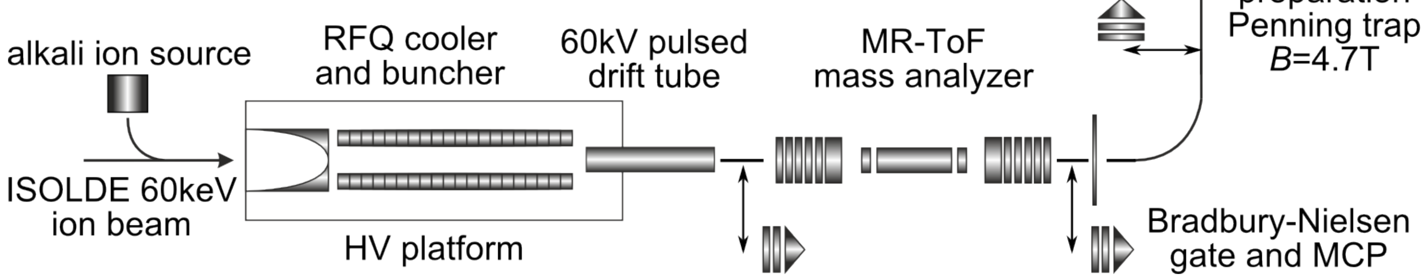


- Half lives, spins and electromagnetic moments of cadmium studied at ISOLDE[1,2,3]
- Mass of the “waiting point” nuclide ^{130}Cd only indirectly determined through β- decay[2]

1: M. Hannawald et al., PRC 62, 054301 (2000); 2: I. Dillmann et al., PRL 16, 162503-1 (2003); 3. D.T. Yordanov et al., PRL 110, 192501 (2013); M. Wang et al., CPC **36** 1603 (2012);

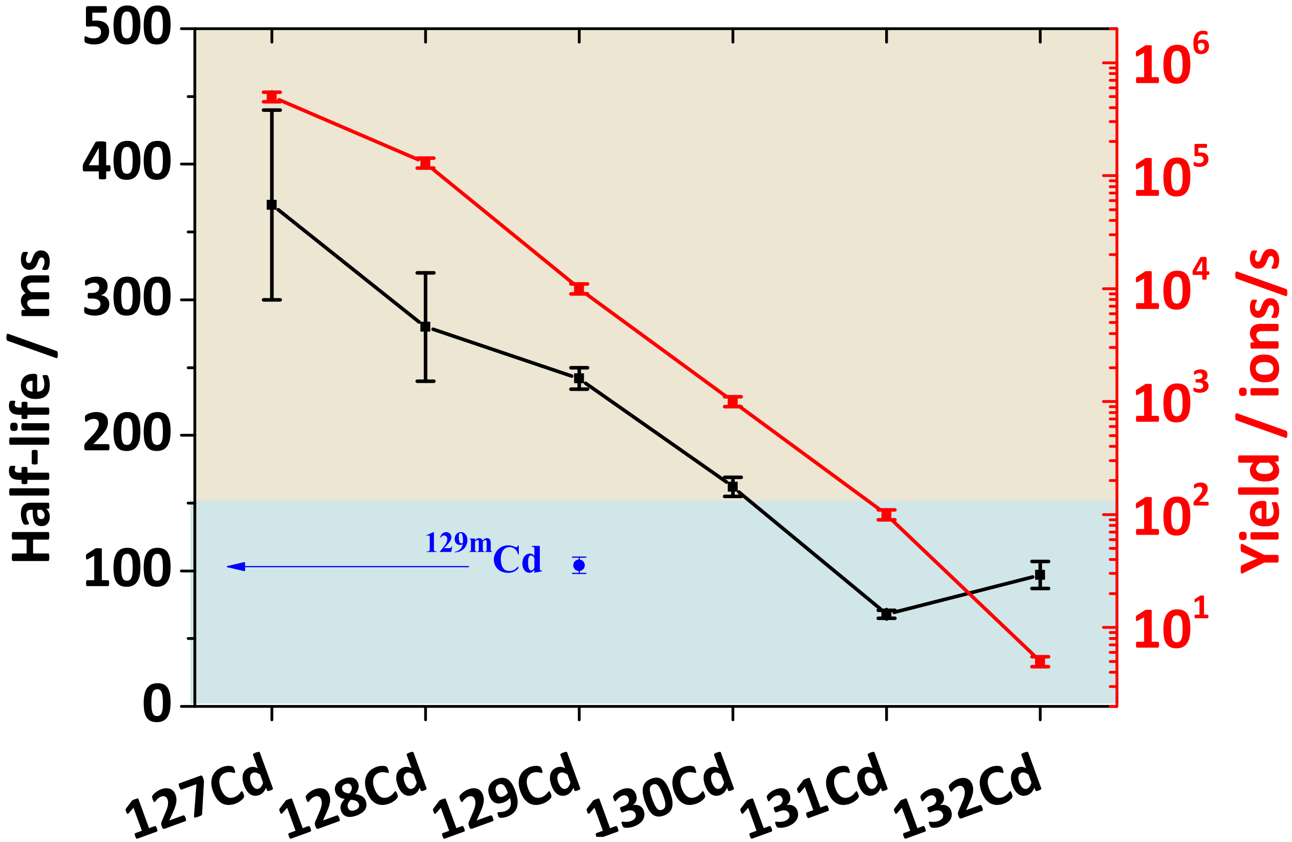
ISOLTRAP setup and cadmium measurements

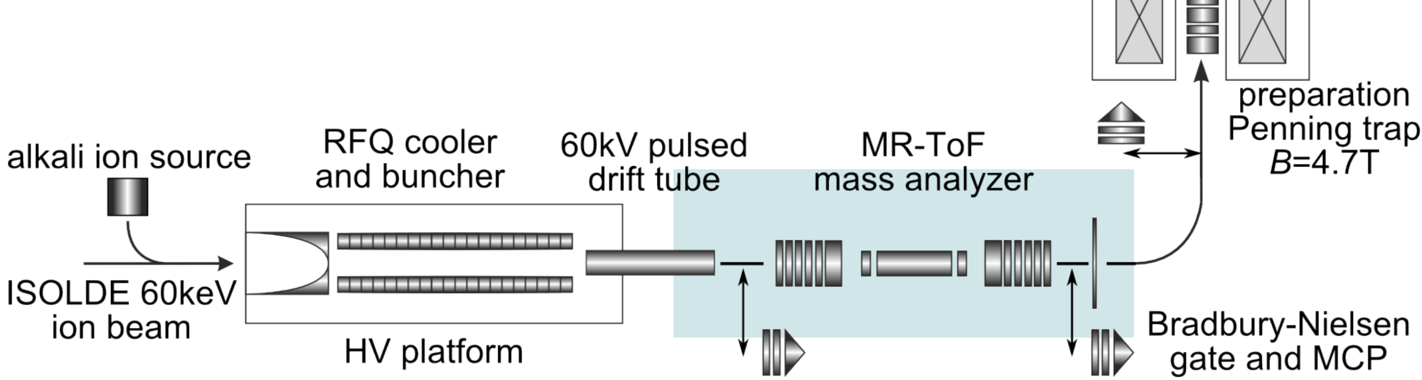


ISOLDE delivers a **mixture of isobaric species**

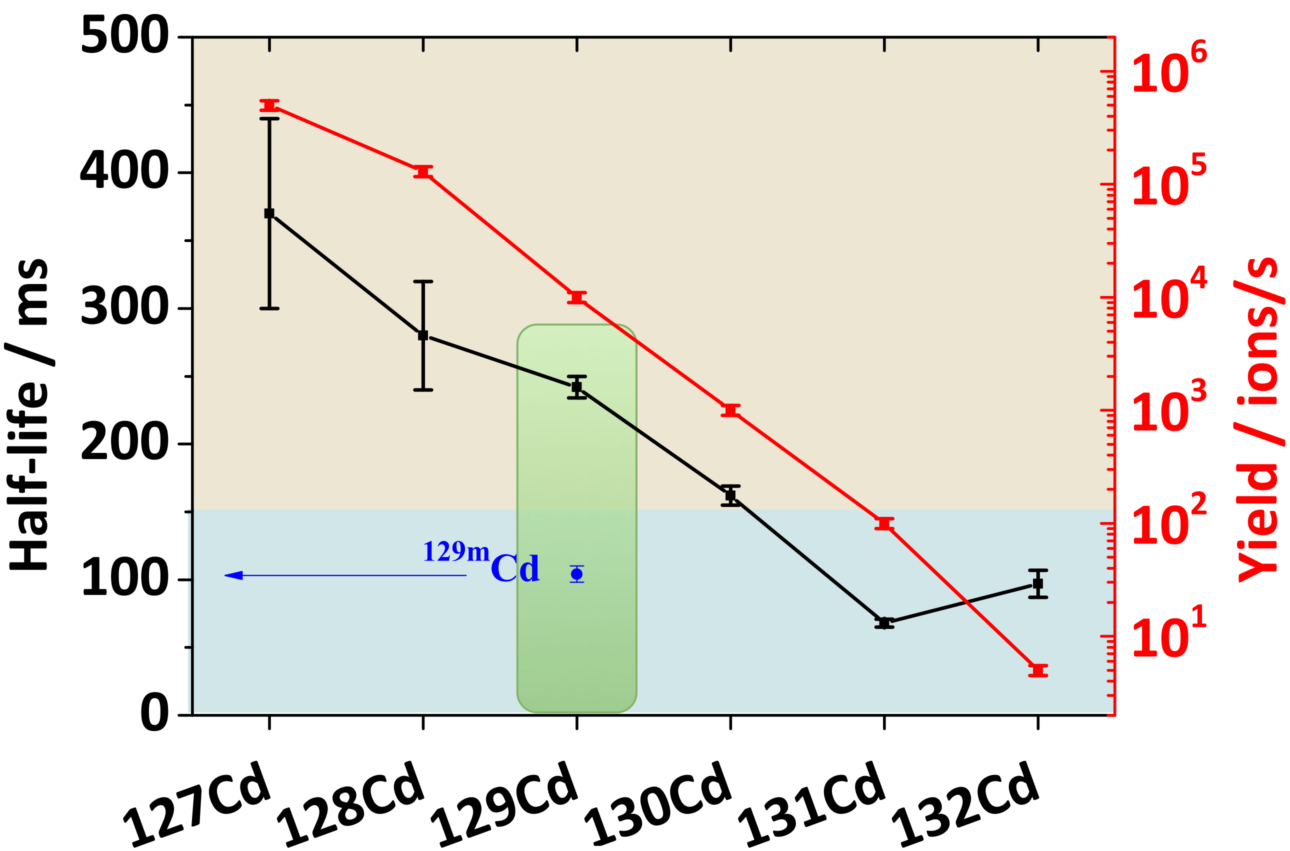
ISOLTRAP setup and cadmium measurements

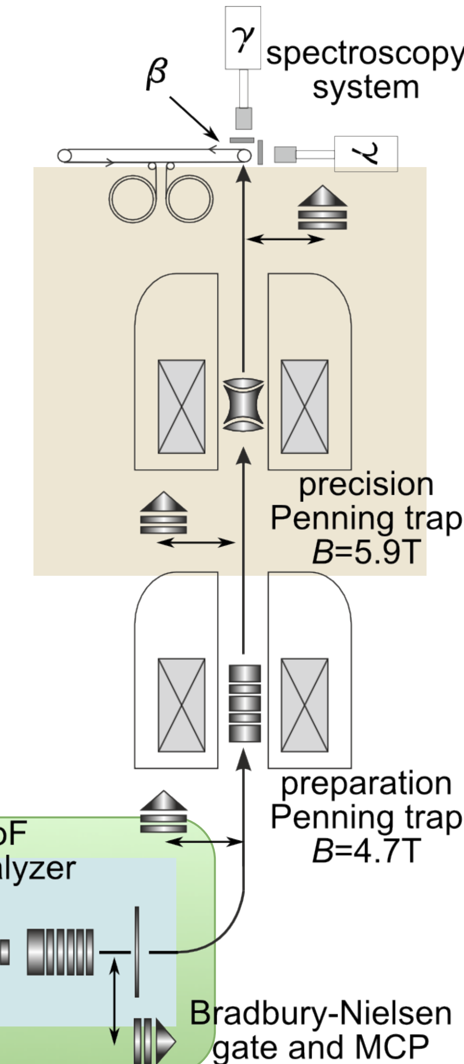




ISOLDE delivers a **mixture of isobaric species**

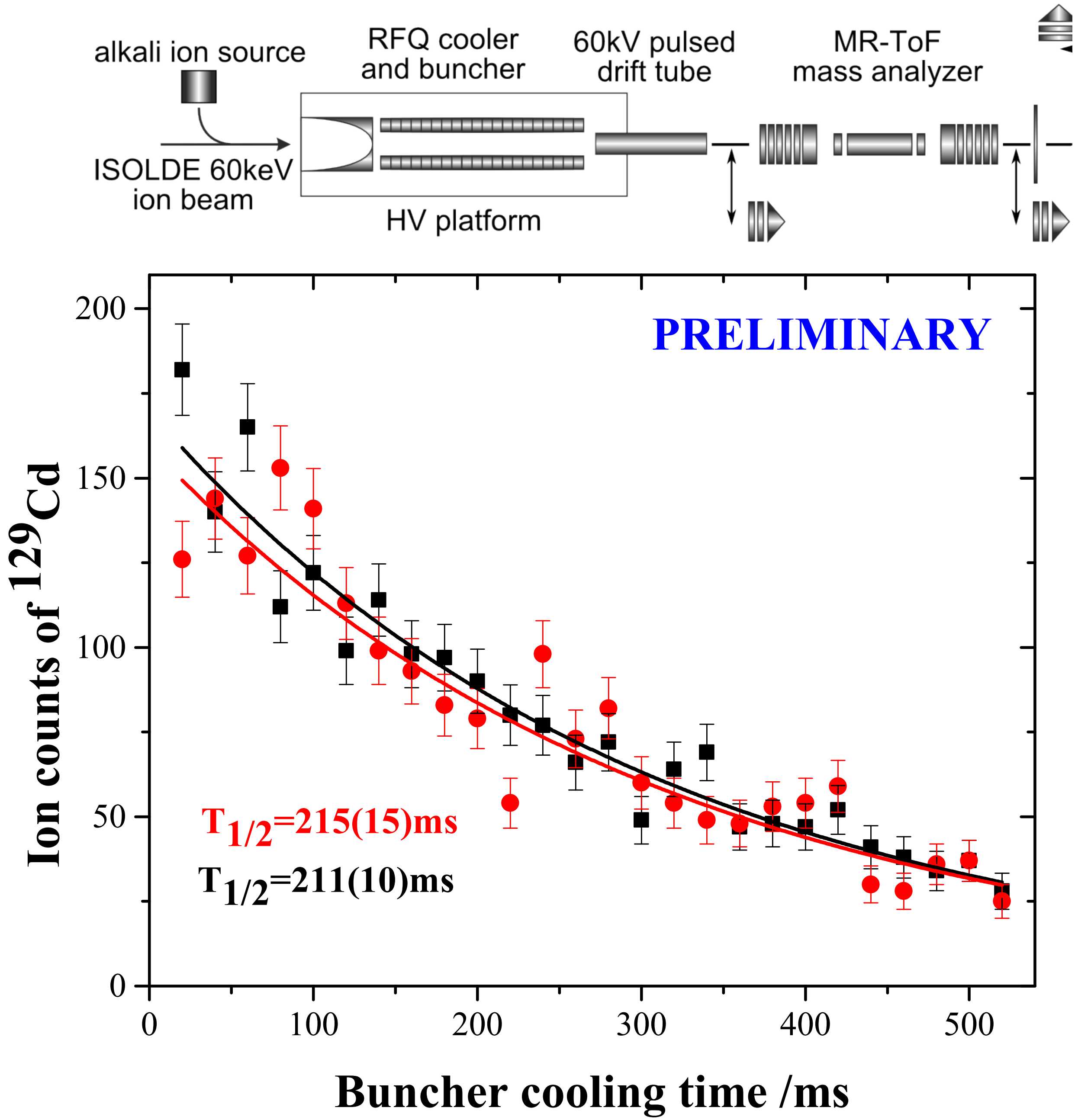
ISOLTRAP setup and cadmium measurements





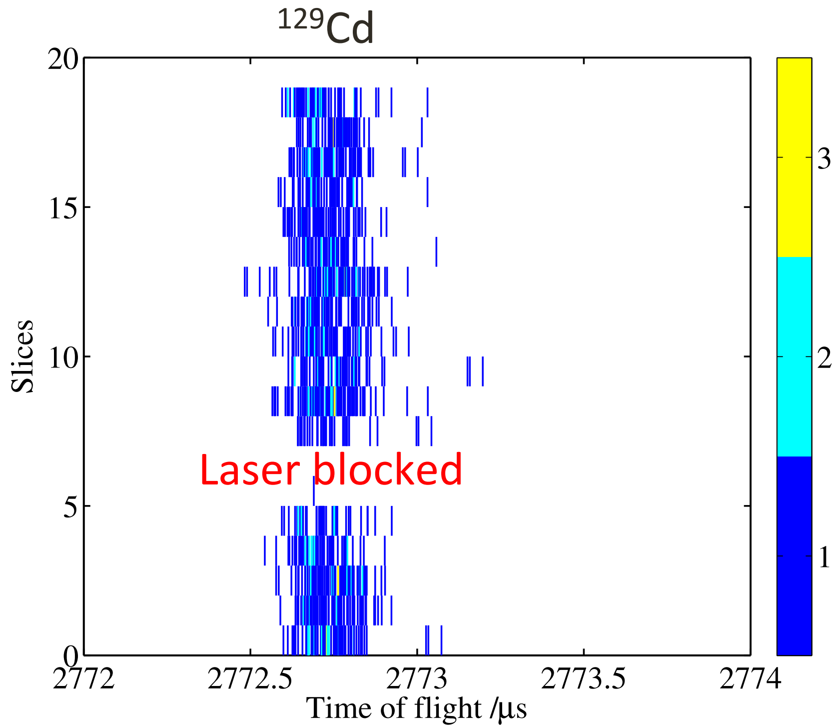
ISOLDE delivers a **mixture of isobaric species**

129Cd – Half life

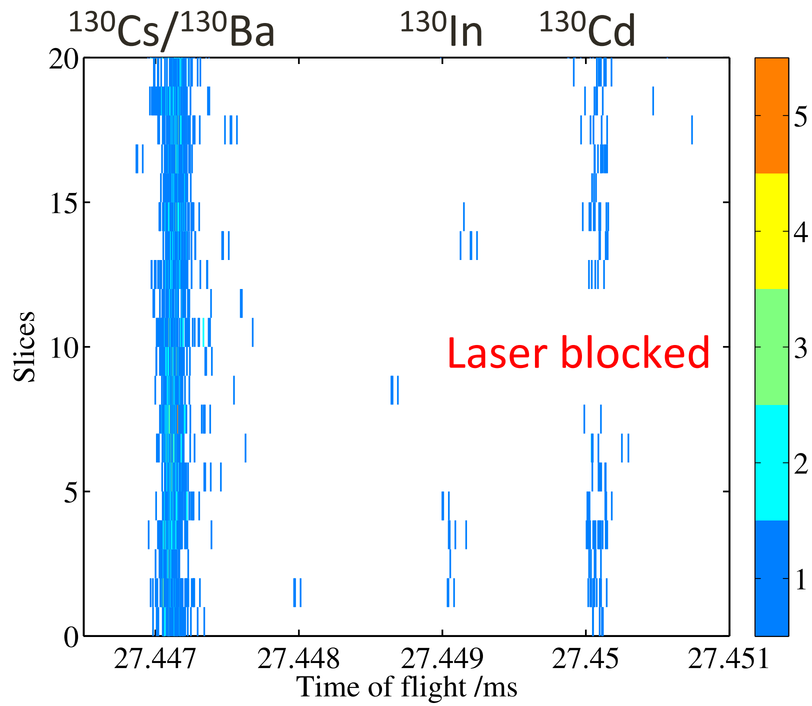


129Cd, 130Cd – Mass measurement

^{129}Cd after 100 revolutions in MR-ToF MS



^{130}Cd after 1000 revolutions in MR-ToF MS



- ≈6300 ions/s from ISOLDE; 1539 ions
- 4 ToF-ICR resonances
  - 1 normal, 3 Ramsey

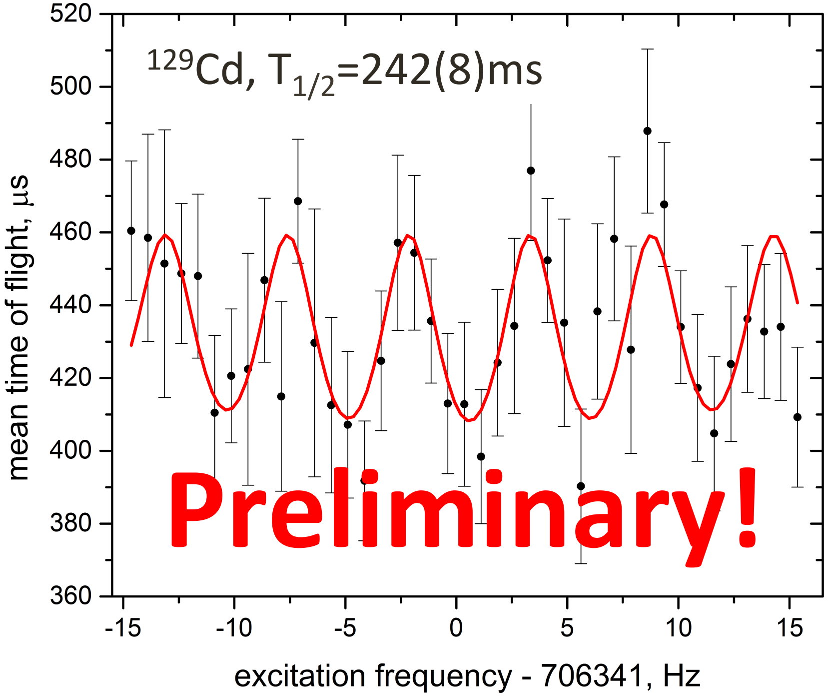
→ **Δm/m≈1.2E-7**

- ≈625 ions/s from ISOLDE; 588ions
- ^{130}Cd/cont. ≈ 0.2; only *R* ≈ 15k needed
- 3 ToF-ICR resonances
  - 1 normal, 2 Ramsey

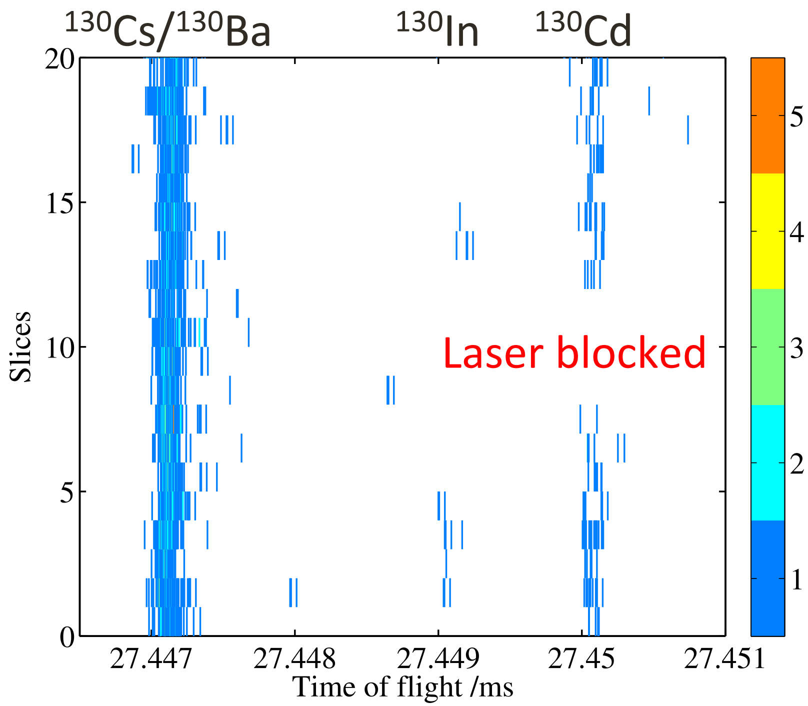
→**Δm/m≈1.6E-7**

129Cd, 130Cd – Mass measurement

^{129}Cd Ramsey-type resonance
20ms – 160ms – 20ms



^{130}Cd after 1000 revolutions in MR-ToF MS



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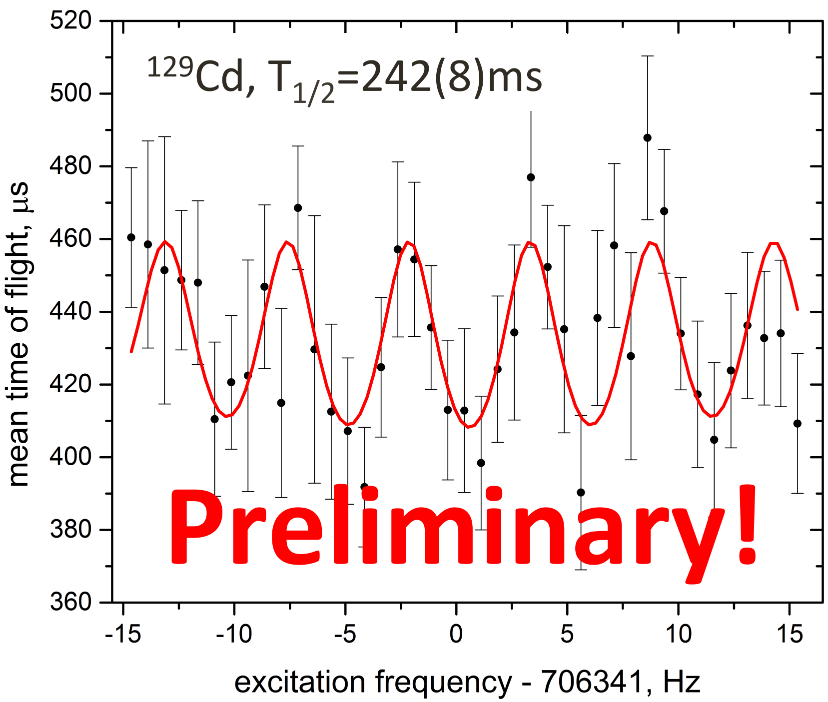
129Cd, 130Cd – Mass measurement

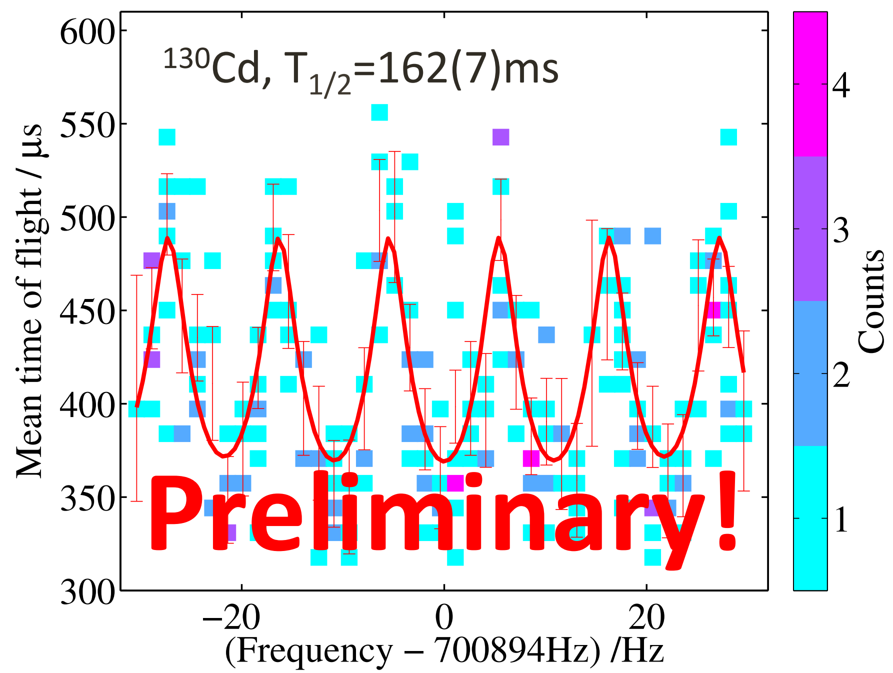
^{129}Cd Ramsey-type resonance
20ms – 160ms – 20ms



- ≈6300 ions/s from ISOLDE; 1539 ions
- 4 ToF-ICR resonances
  - 1 normal, 3 Ramsey

→ **Δm/m≈1.2E-7**

^{130}Cd Ramsey-type resonance
10ms – 80ms – 10ms

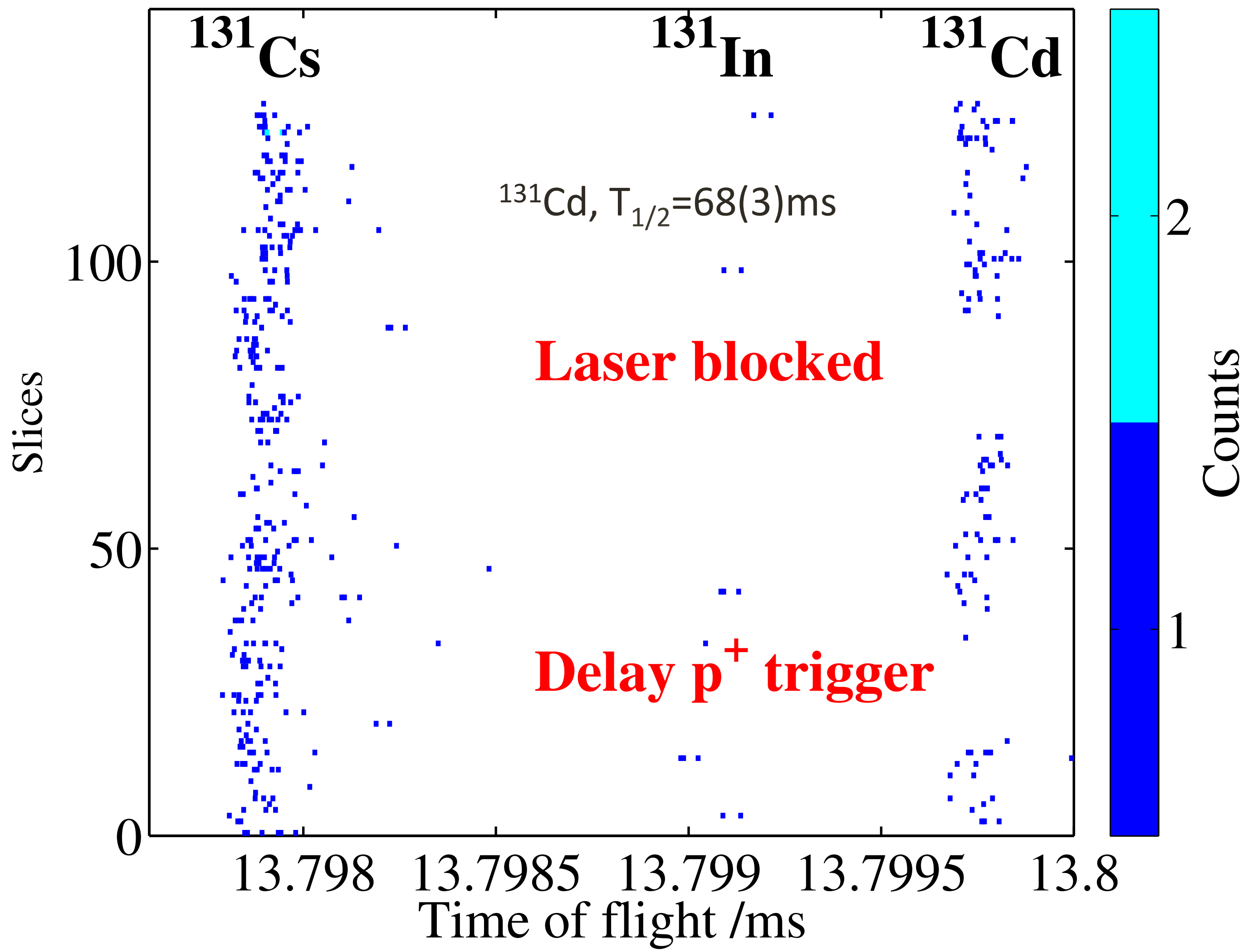


- ≈625 ions/s from ISOLDE; 588ions
- ^{130}Cd/cont. ≈ 0.2; only R ≈ 15k needed
- 3 ToF-ICR resonances
  - 1 normal, 2 Ramsey

→**Δm/m≈1.6E-7**

131Cd – Mass measurement

^{131}Cd after 500 revolutions in MR-ToF MS

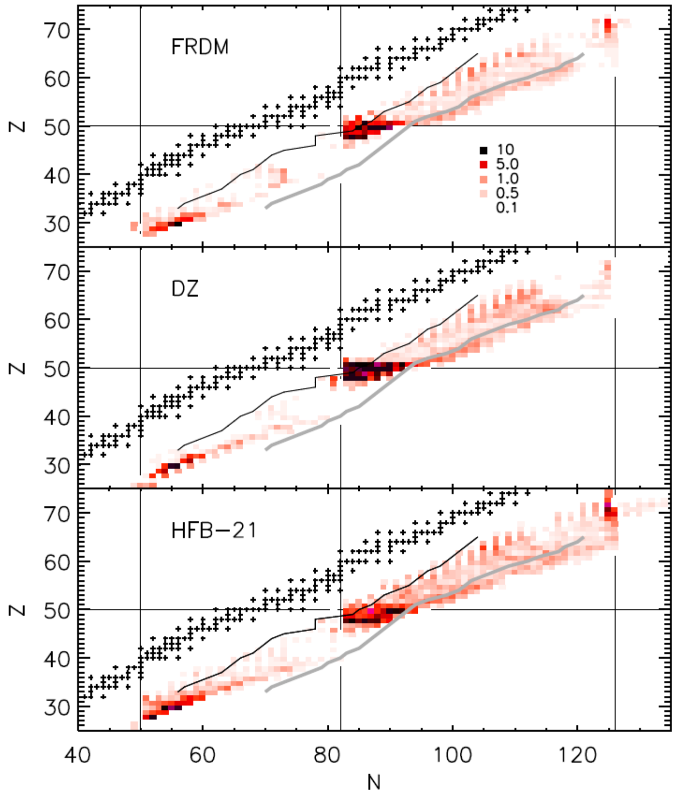


- ≈ 88 ions/s from ISOLDE
- Total of 1366 ions collected after MR-ToF MS in ≈6.6h

Results of the cadmium measurements

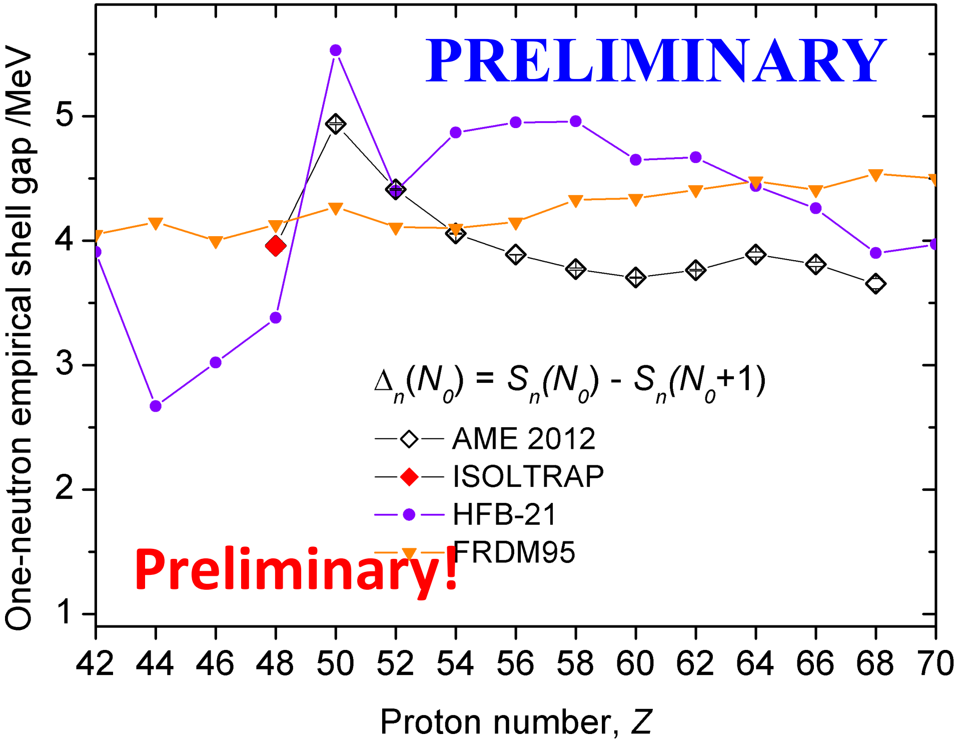
Direct impact:

- Important impact of the neutron separation energy S_n on the predicted r-process abundances.
- Irrespective of model, $^{A>130}$Cd isotopes have among the largest impact.
- ≈0.5 MeV deviations found from AME values and extrapolations (analysis ongoing).



Indirect impact:

The one-neutron shell gap agrees with the picture of a fast reduction (quenching) for $Z < 50$.



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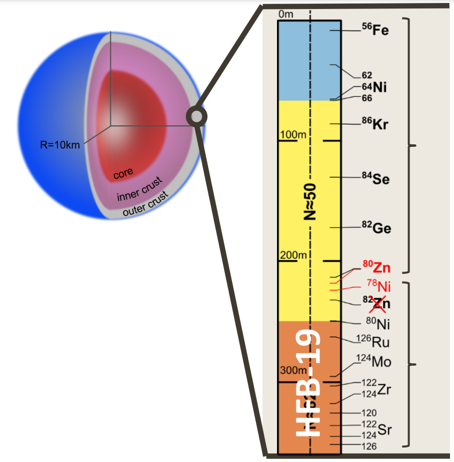
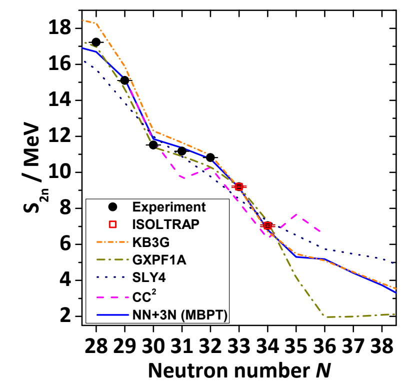
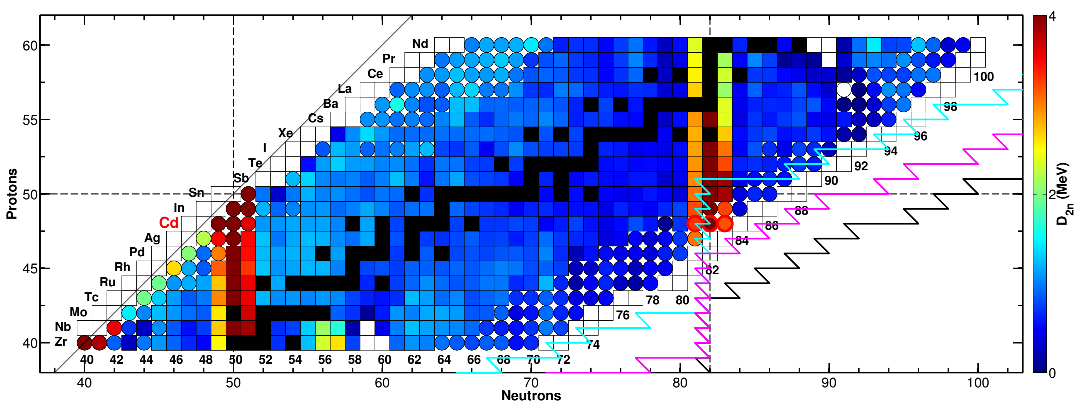
S. Goriely, N. Chamel, J.M. Pearson, Phys. Rev. C **82**, 035804, 2010.
P. Möller, J. R. Nix, W. D. Myers, W. J. Swiatecki, ADNDT **59**, 185, 1995.

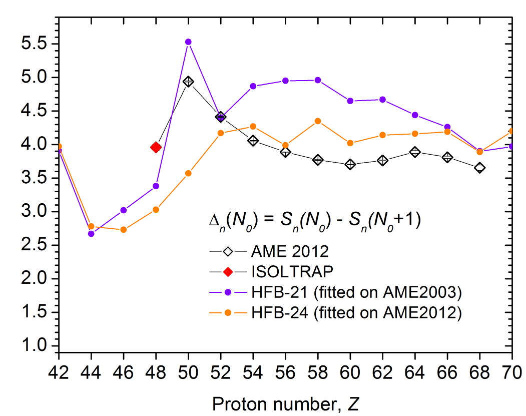
Summary

- Application of the MR-ToF MS as tool for fast ion separation and subsequent Penning trap measurement of 82Zn
- First direct determination of the mass of 53,54Ca
  - Magicity of *N*=32 established
- Successful mass measurement of the "waiting-point" nucleus 130Cd as well as 129Cd and 131Cd
  - Found deviation from literature and AME values which will have an impact on the r-process
- Additional successful measurement campaigns on astatine, chromium, strontium and rubidium





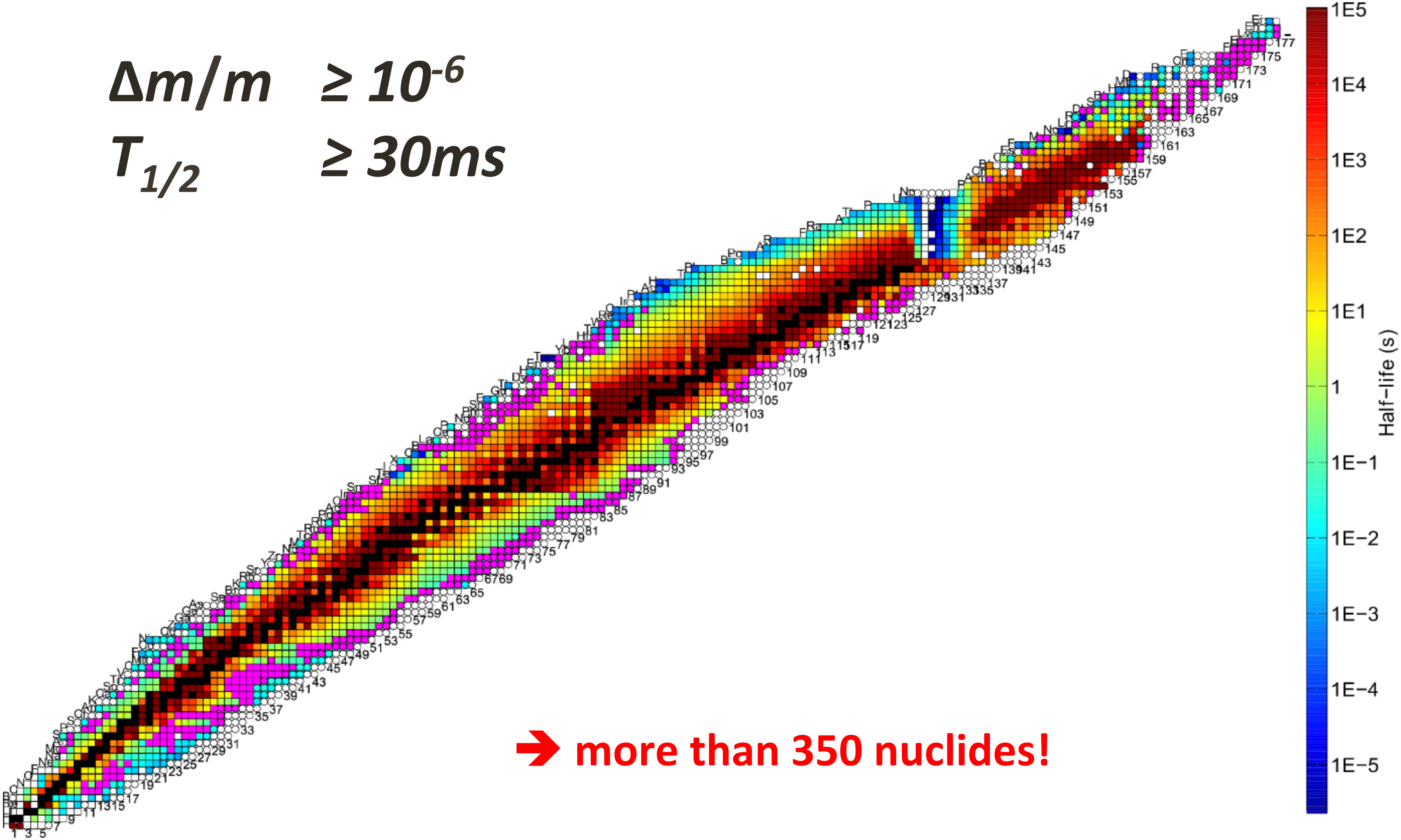




Outlook

$\Delta m/m \quad \geq 10^{-6}$

$T_{1/2} \quad \geq 30ms$



➔ **more than 350 nuclides!**

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Group of A. Schwenk

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