Precision mass measurements of neutron-rich cadmium for r-process studies

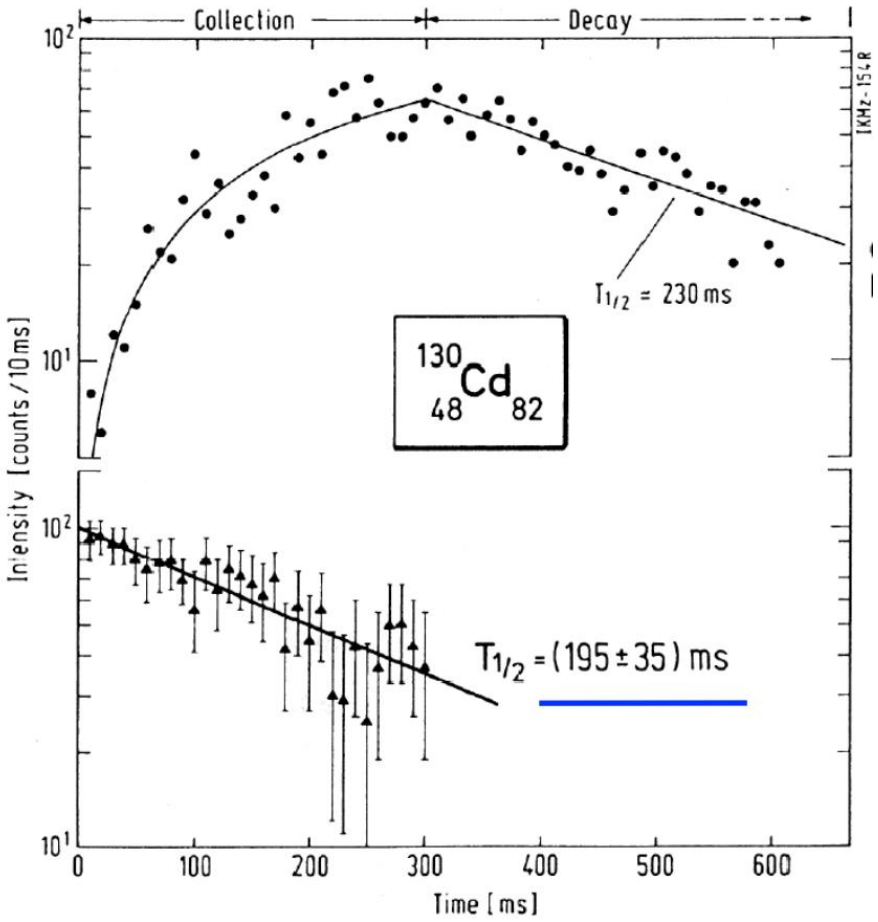
Dinko Atanasov
Max-Planck Institute for Nuclear Physics

NUSTAR Annual Meeting
29 February – 4 March 2016, GSI, Germany

Outline

- Measurements in the region
- Interest for Nuclear astrophysics
- Production of neutron-rich cadmium – ISOL type facility
- The mass spectrometer ISOLTRAP
- Results
- Summary

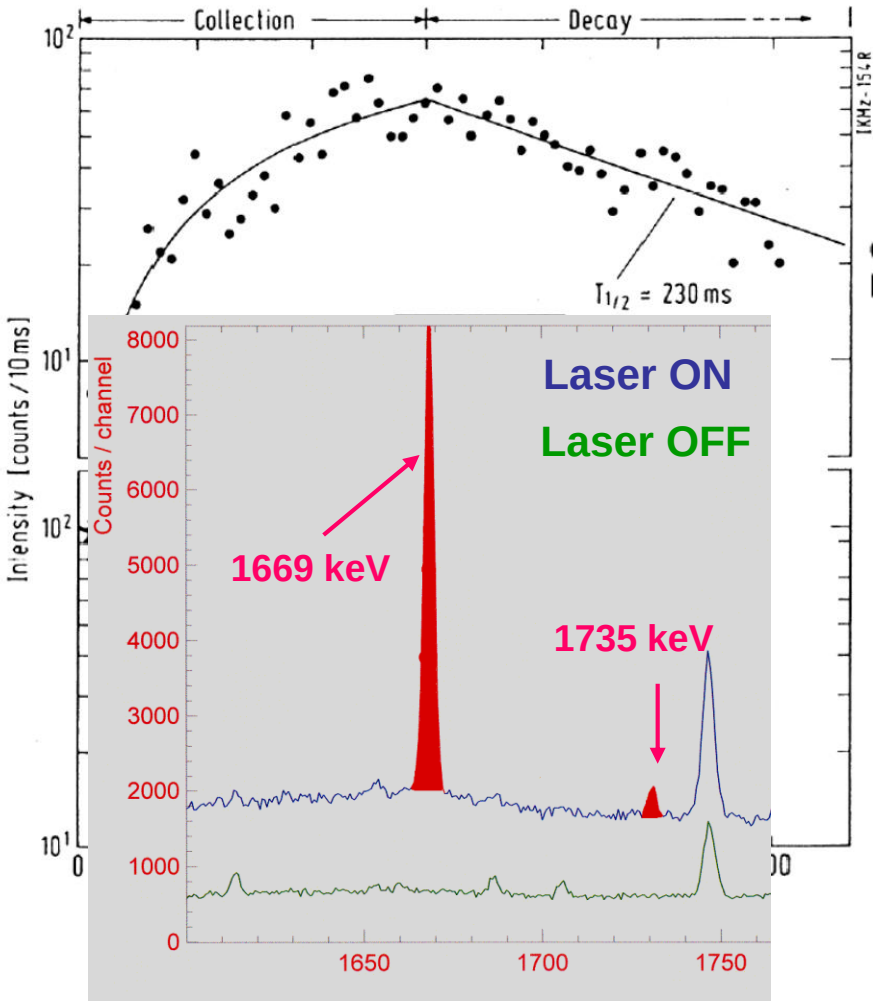
Previous investigations in the region



- 1986 - ISOLDE – Half-Life measurements

K. –L. Kratz et al., ZPhys (1986)

Previous investigations in the region

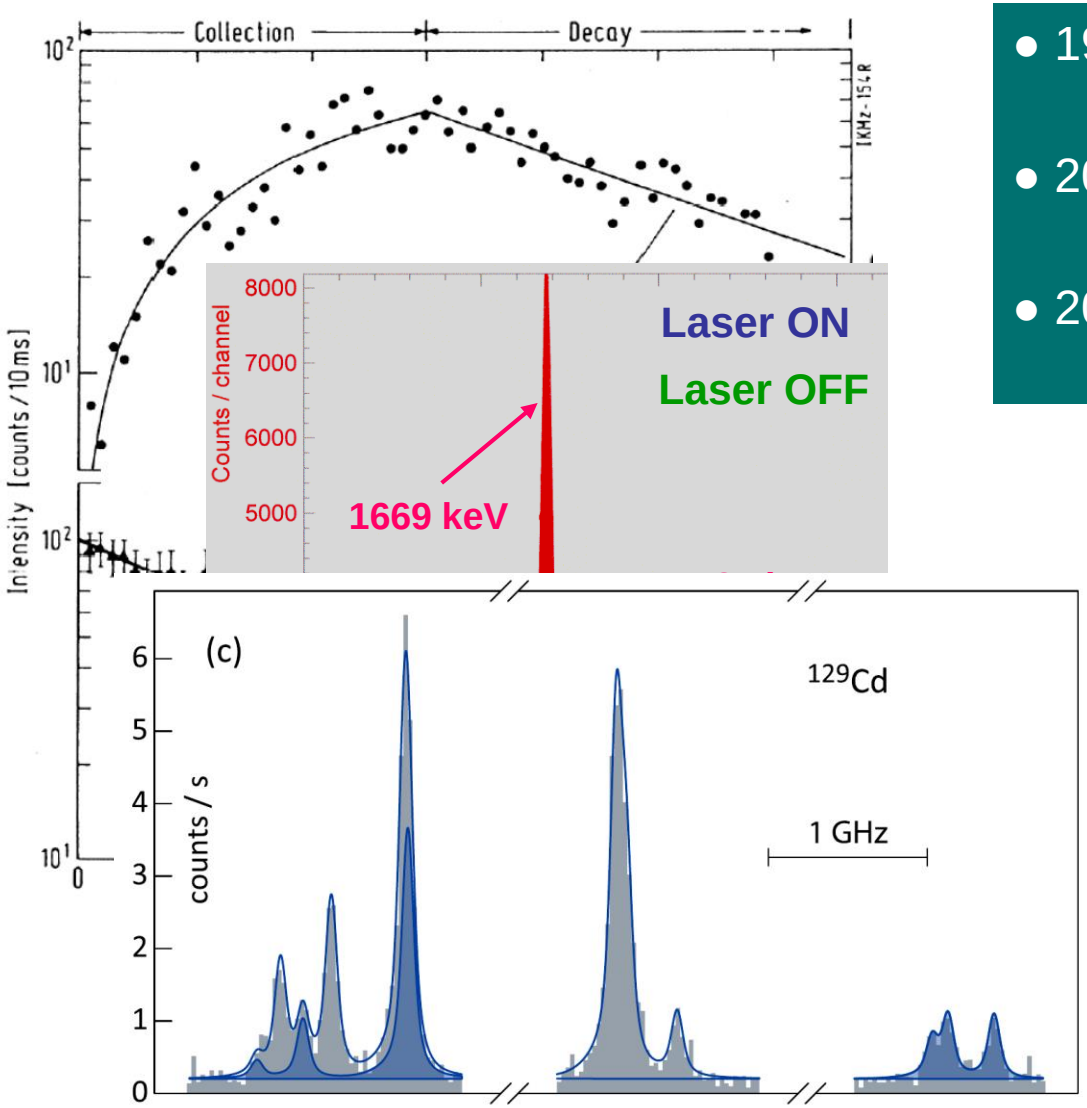


- 1986 - ISOLDE – Half-Life measurements
- 2003 - ISOLDE – Beta and Gamma Spectroscopy

K. –L. Kratz et al., ZPhys (1986)

I. Dillmann et al., PRL (2003)

Previous investigations in the region



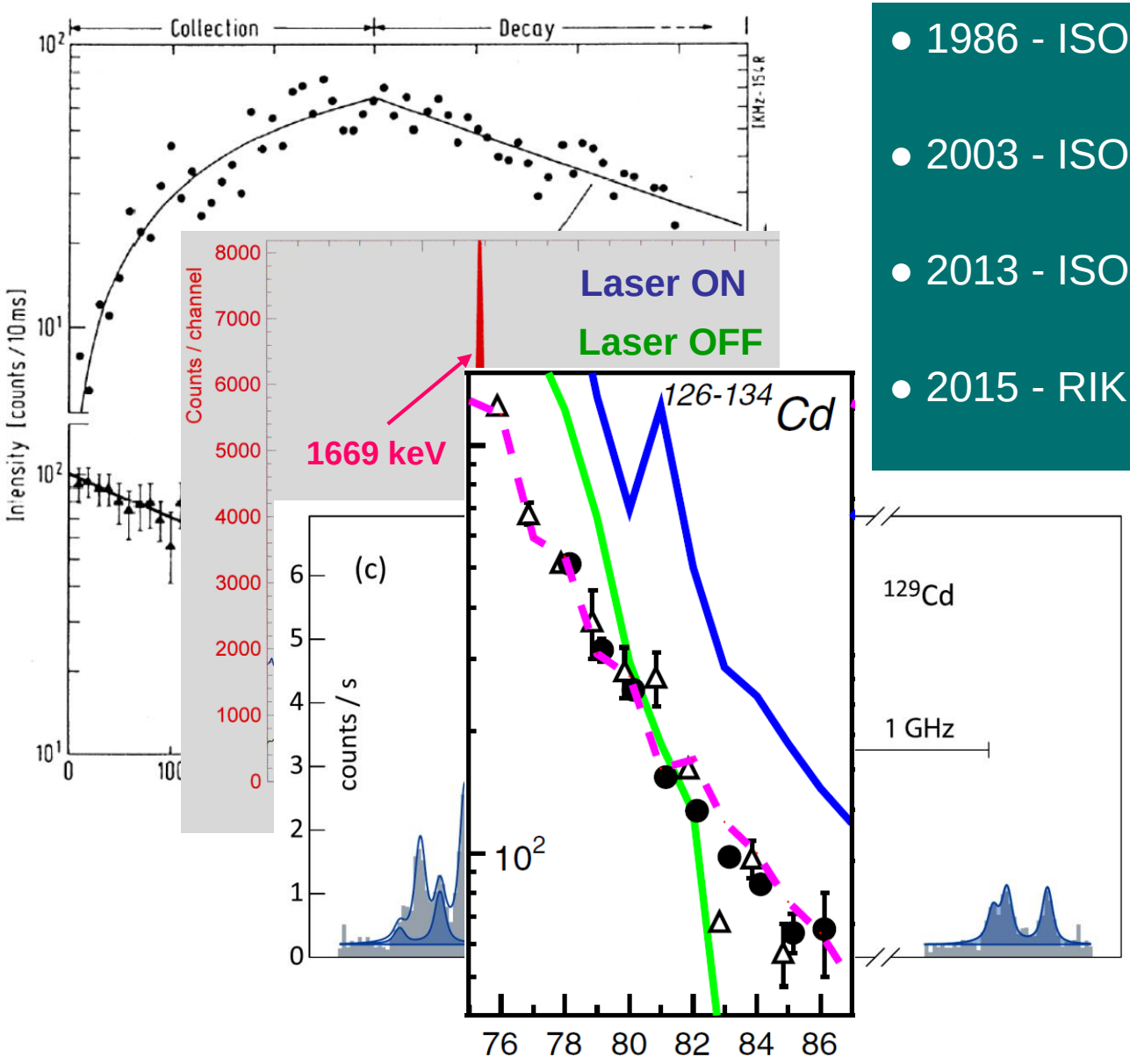
- 1986 - ISOLDE – Half-Life measurements
- 2003 - ISOLDE – Beta and Gamma Spectroscopy
- 2013 - ISOLDE – HFS from Laser spectroscopy

K. –L. Kratz et al., ZPhys (1986)

I. Dillmann et al., PRL (2003)

D. Yordanov et al., PRL (2013)

Previous investigations in the region



- 1986 - ISOLDE – Half-Life measurements
- 2003 - ISOLDE – Beta and Gamma Spectroscopy
- 2013 - ISOLDE – HFS from Laser spectroscopy
- 2015 - RIKEN – Half-Life measurements

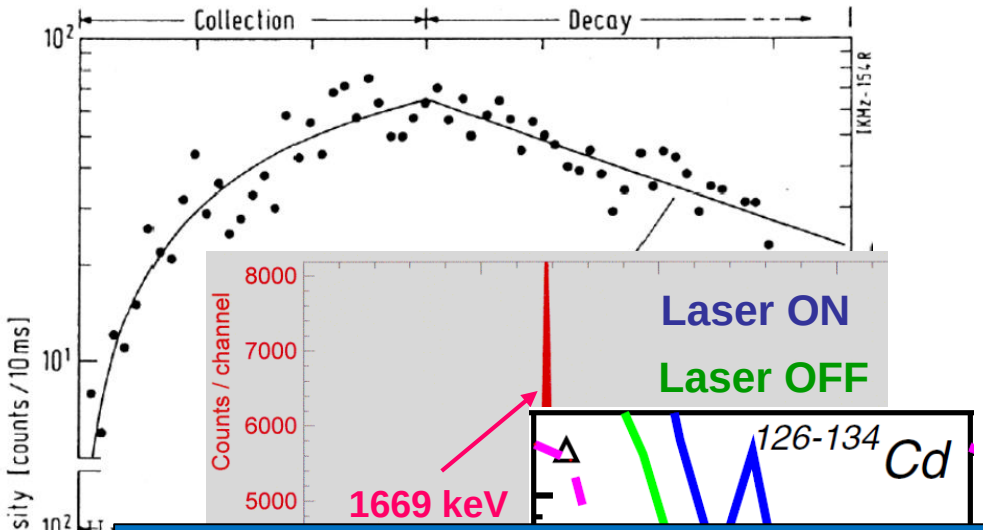
K. –L. Kratz et al., ZPhys (1986)

I. Dillmann et al., PRL (2003)

D. Yordanov et al., PRL (2013)

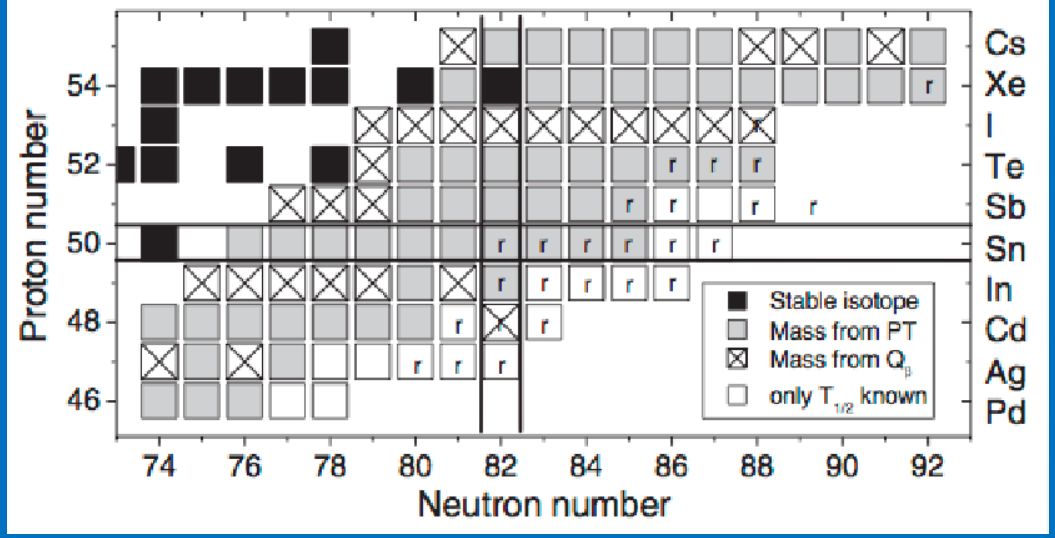
G. Lorusso et al., PRL (2015)

Previous investigations in the region



- 1986 - ISOLDE – Half-Life measurements
- 2003 - ISOLDE – Beta and Gamma Spectroscopy
- 2013 - ISOLDE – HFS from Laser spectroscopy
- 2015 - RIKEN – Half-Life measurements

Missing **direct** mass measurements



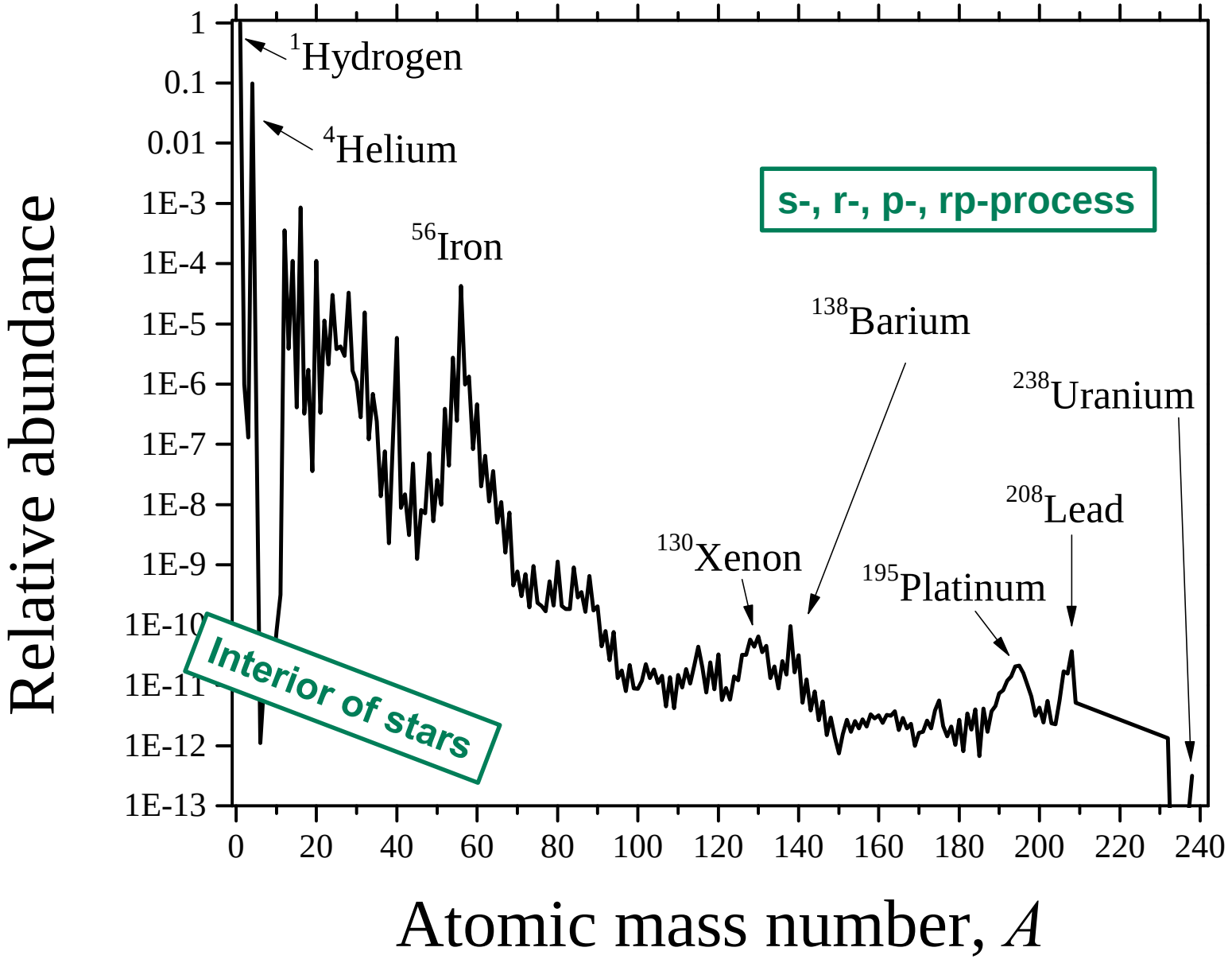
K. –L. Kratz et al., ZPhys (1986)

I. Dillmann et al., PRL (2003)

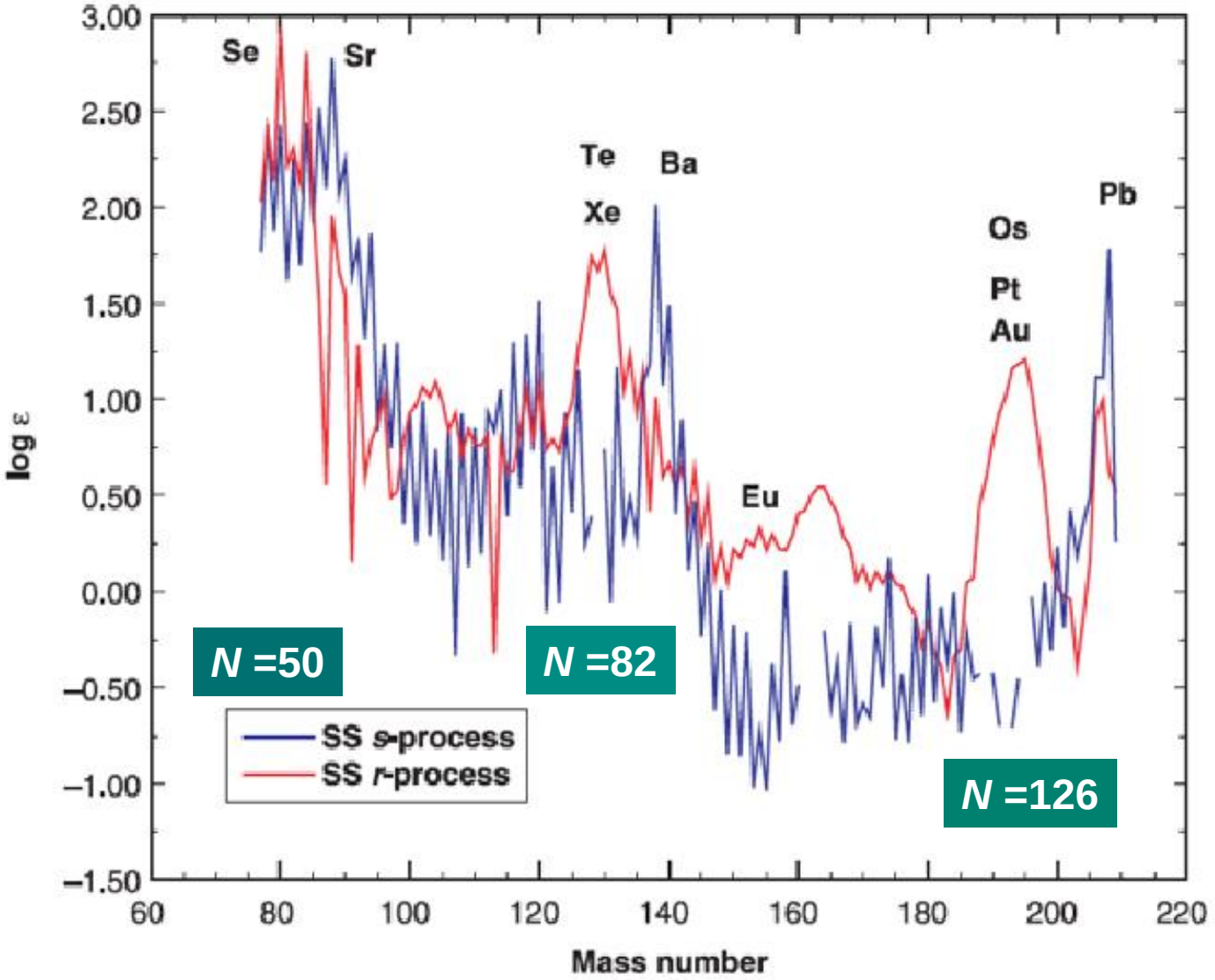
D. Yordanov et al., PRL (2013)

G. Lorusso et al., PRL (2015)

Elemental abundance in the Solar system



Solar system r-process residuals

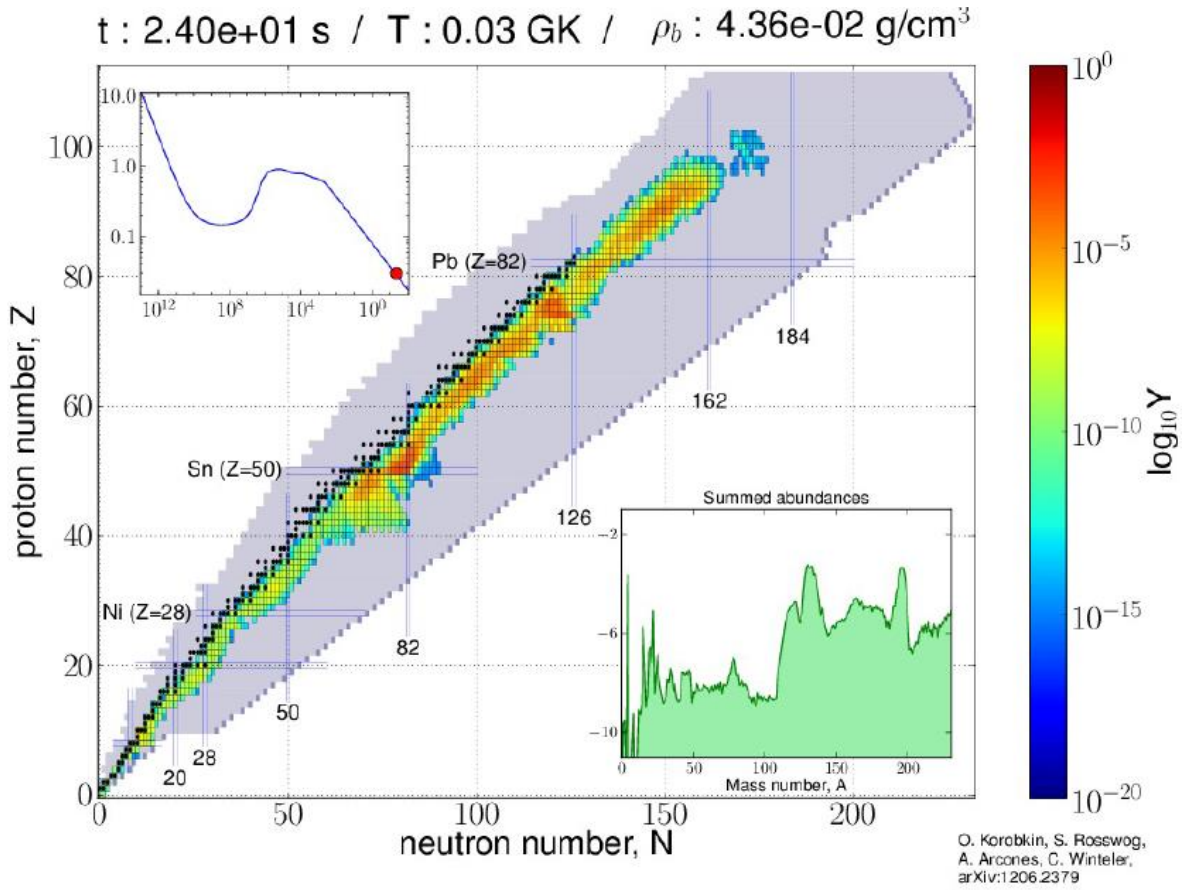


Atomic mass number, *A*

Sneden and Cowan 2003

The r-process

About half of the elements heavier than iron are formed by neutron capture reactions that occur rapidly in comparison with beta decays

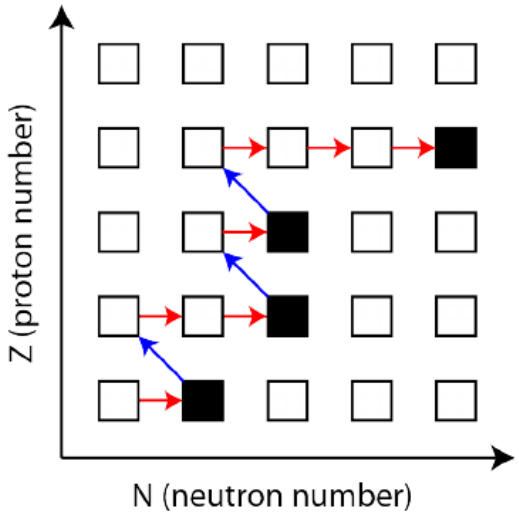


Neutron Capture / Photo-dissociation

$$(Z,N) + n \leftrightarrow (Z,N+1) + \gamma$$

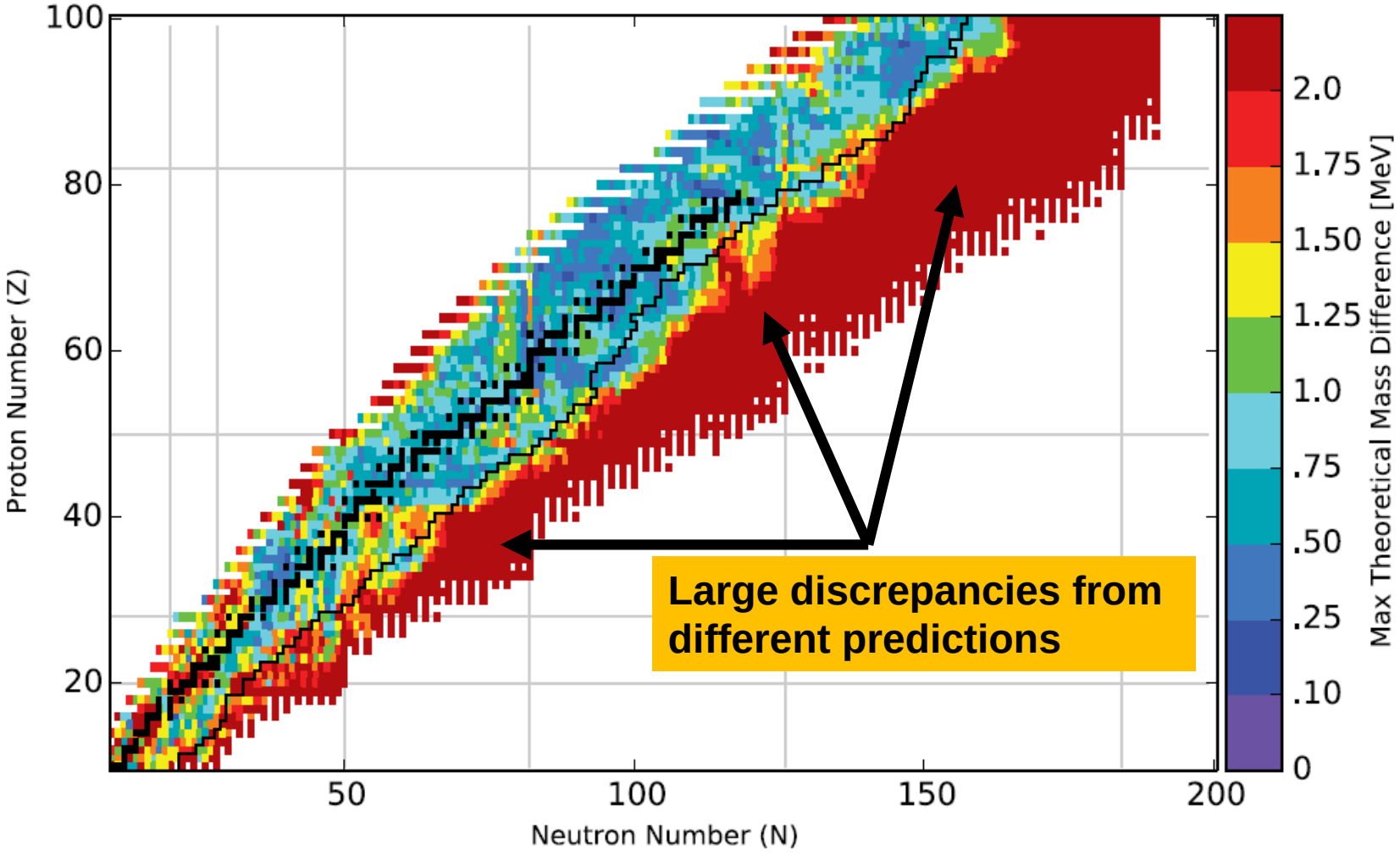
Beta Decay

$$(Z,N) \rightarrow (Z+1,N-1) + e^- + \bar{\nu}_e$$

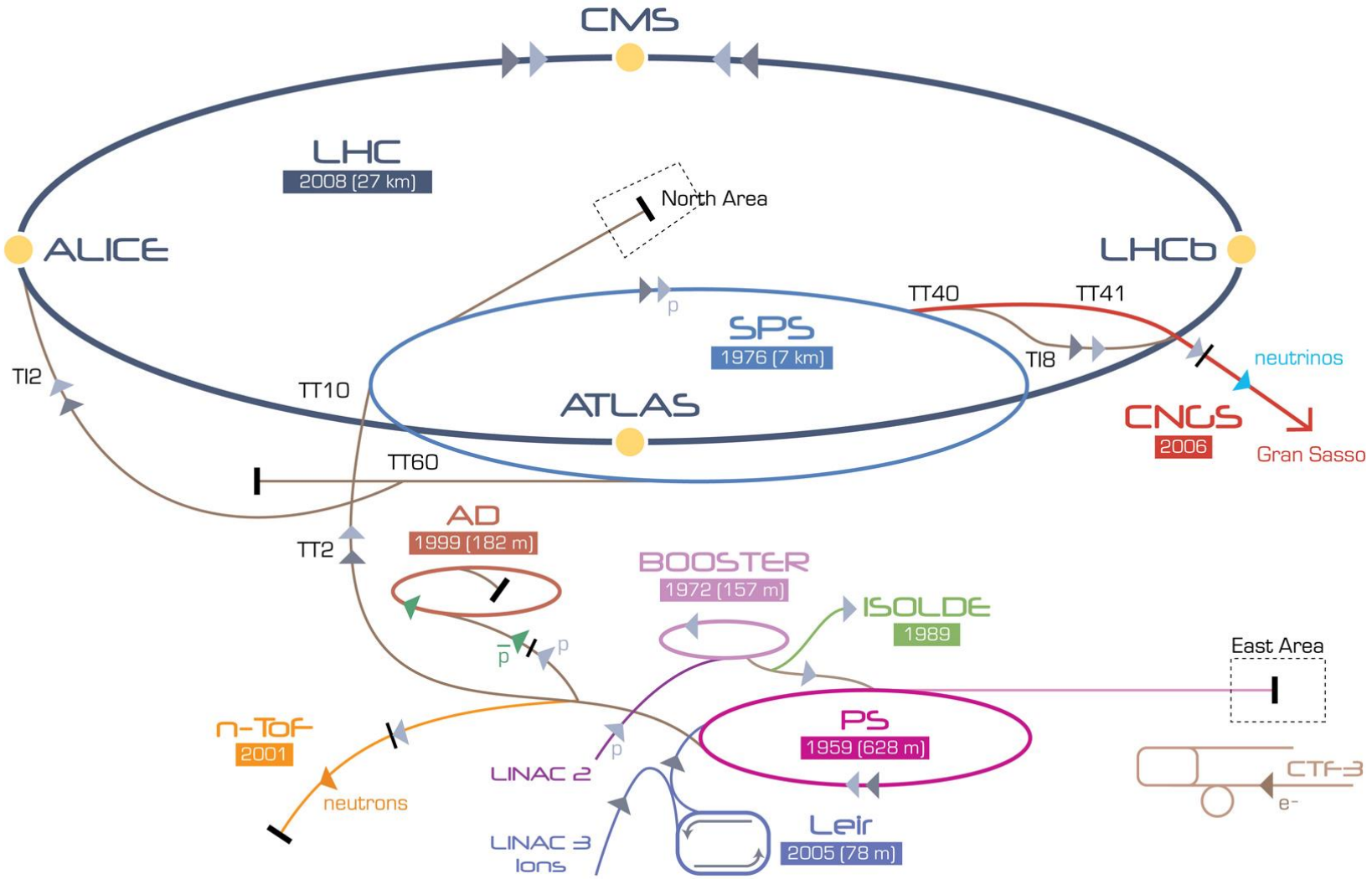


Nuclear mass models

- **Experimental data still missing for important r-nuclei**
- **Rely on theoretical extrapolations**

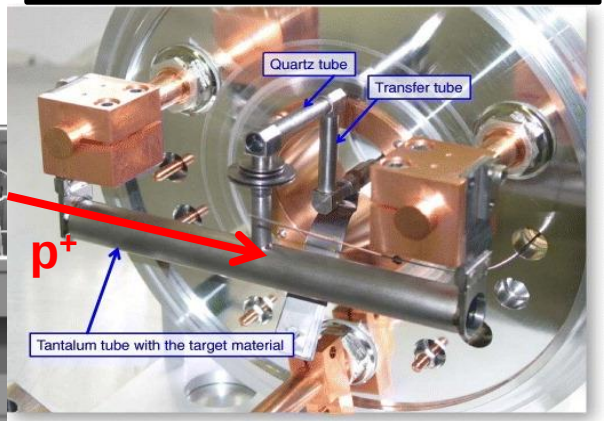


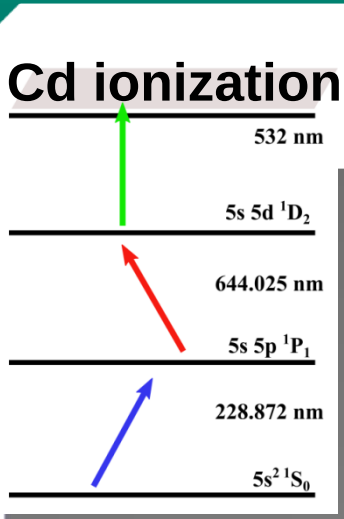
Experimental facility



Production mechanism

Target – UCx, neutron converter and quartz line





RILIS

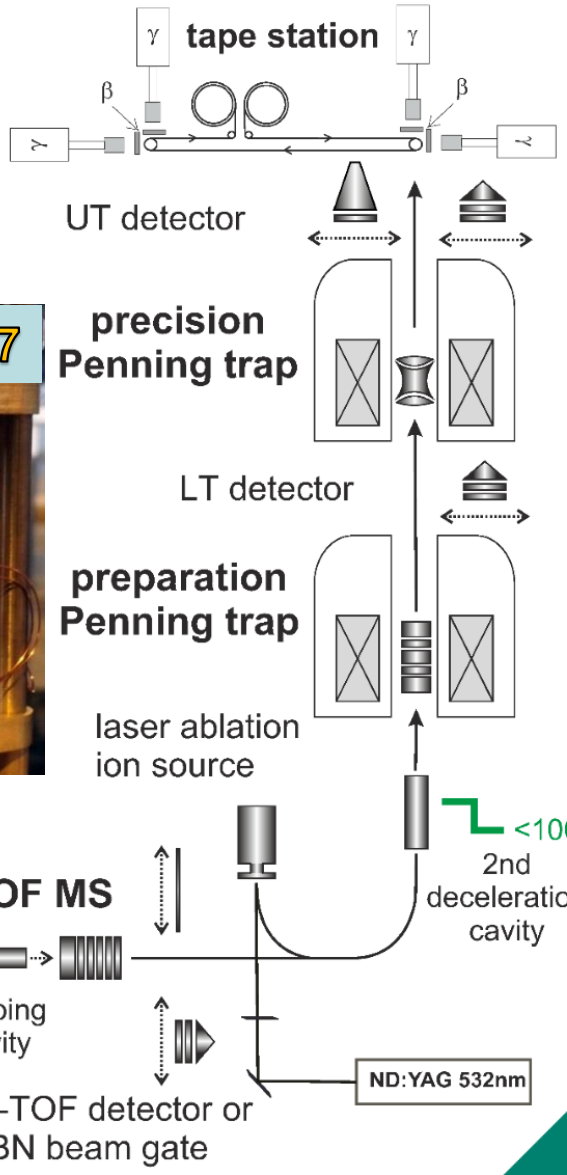
HRS mass separation

proton beam
E = 1.4 GeV

ISOLTRAP

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

ISOLTRAP setup



M. Mukherjee *et al.*, Eur. Phys. J. A **35**, 1 (2008); S. Kreim *et al.*, Nucl. Instrum. Methods B **317**, 492 (2013).

Mass measurements at ISOLTRAP

Penning trap using ToF-ICR technique

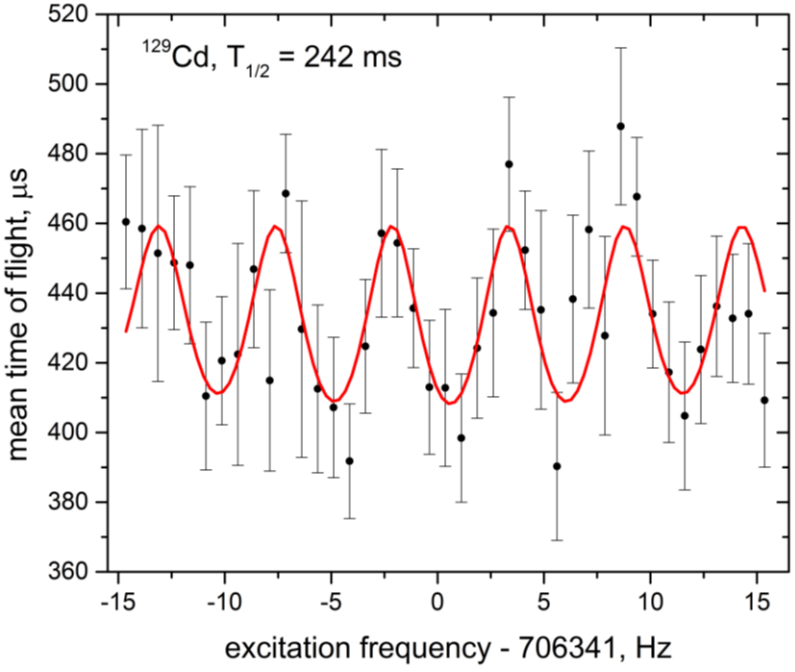
$$\nu_c = \frac{qB}{2\pi\, m}$$

rf excitation

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

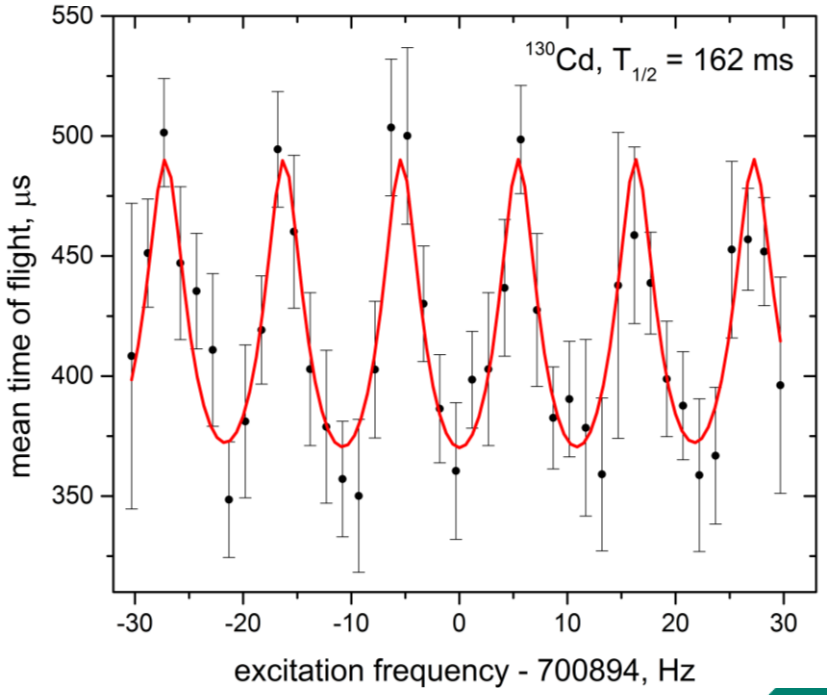
$T_{ex}(^{129}Cd)$ = 20-160-20 ms

4 resonances with >1500 events



$T_{ex}(^{130}Cd)$ = 10-80-10 ms

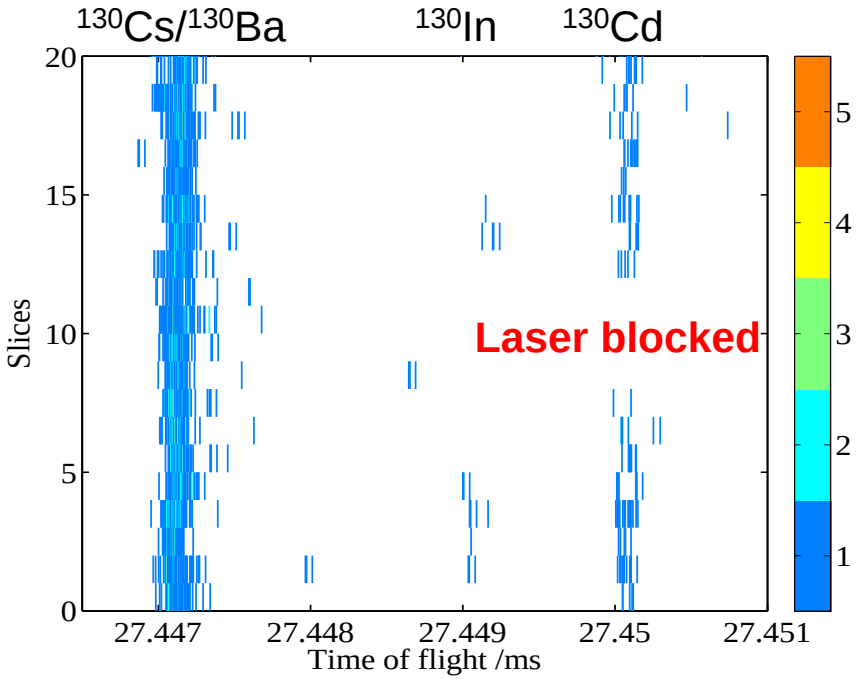
3 resonances with >550 events

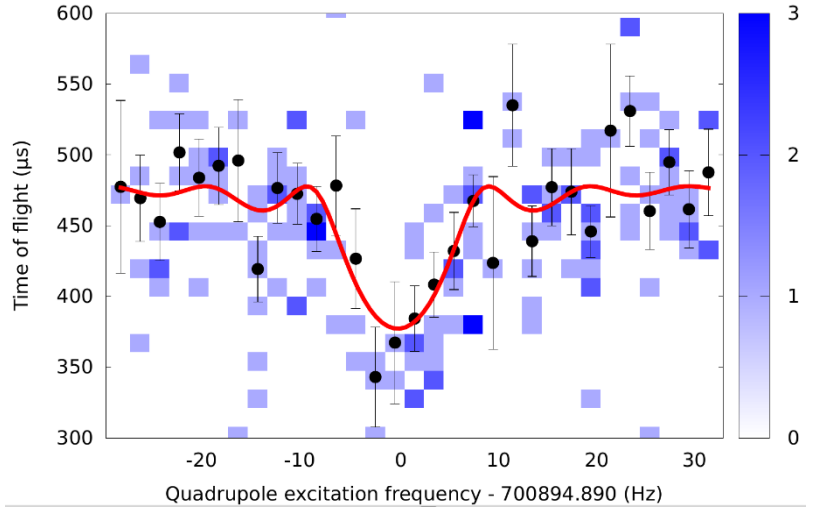


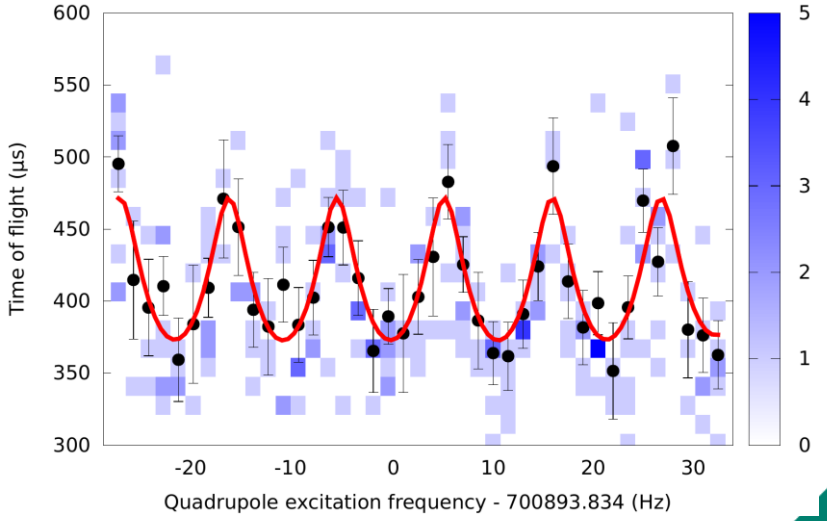
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995); S. George *et al.*, Phys. Rev. Lett. **98**, 162501 (2007);

Identification and PT spectra of $^{130}Cd^{+}$

- Quartz insert reduced contamination by 4 orders of magnitude for Cs and In
- Laser Identification of ^{130}Cd in MR-ToF



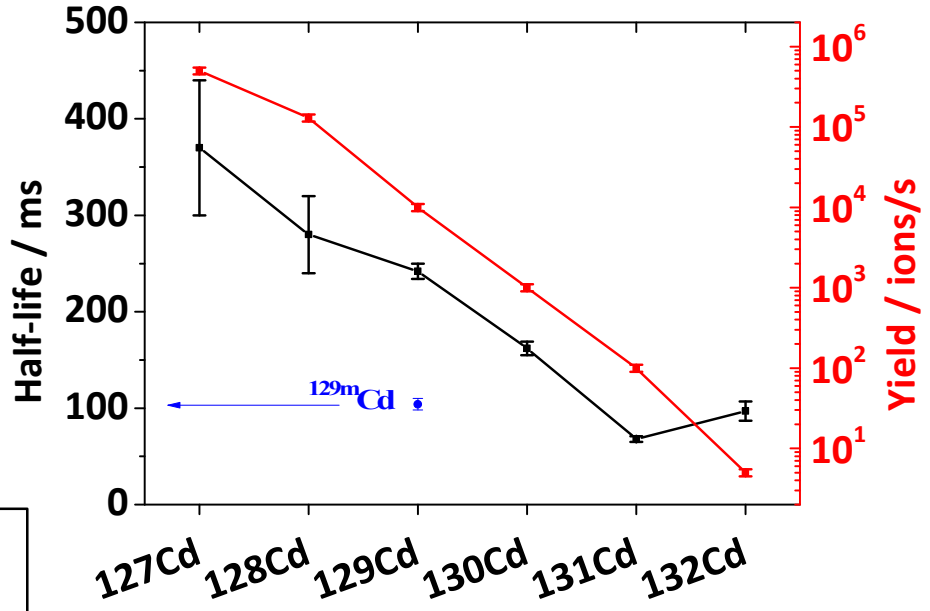




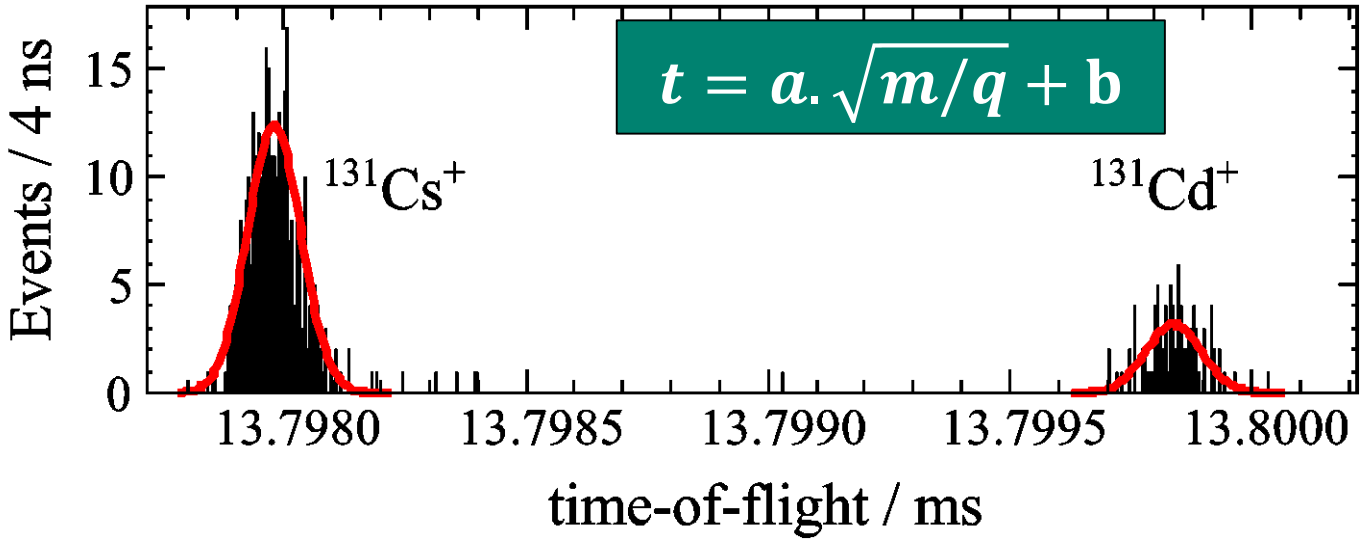
Mass measurements at ISOLTRAP

MR-TOF MS

- ≈ 88 ions/s from ISOLDE
- Total of 11 spectra at 500, 800 and 1000 revolutions
- Totalling ions in 1366 ions



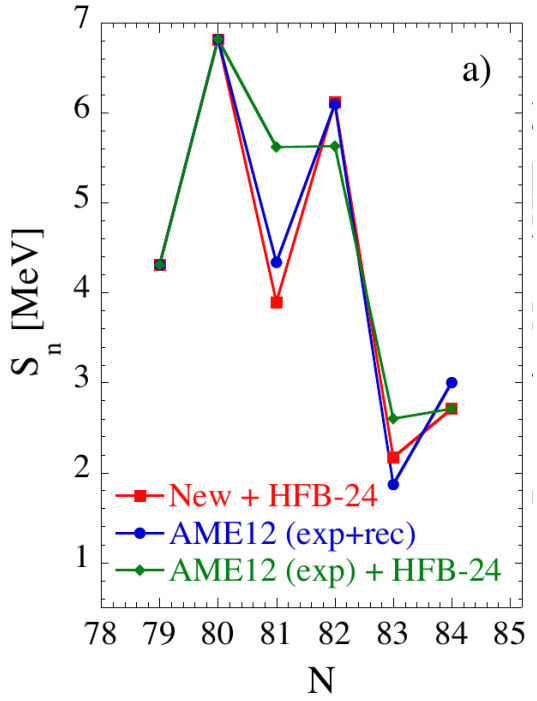
Abundance of contamination in spectra
Ratio of $^{131}Cs^+$ / $^{131}Cd^+$ = 3:1 (per bg = 160 ms)

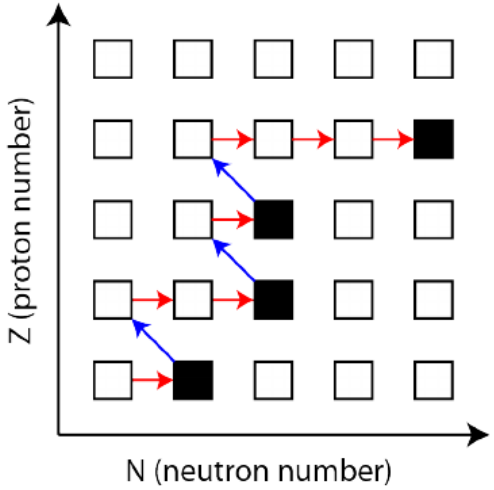


Results

A	Ratio r or C_{ToF}	ME_{new} (keV)	ME_{AME} (keV)	Δ (AME - new) (keV)
129	0.970 105 338(136)	−63 148(74)	-63 510(200)#	-452
130	0.977 645 186(180)	−61 118(22)	-61 530(160)	-412
131	0.482 304 4(539)	−55 215(100)	-55 331(196)#	-116

$S_n(N, Z) = B(N, Z) – B(N\text{-}1, Z)$





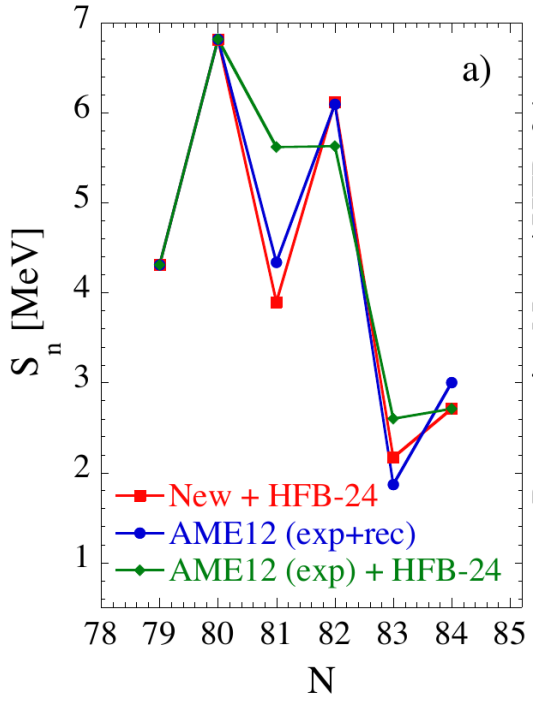
D. Atanasov *et al.*, PRL **115**, 232501 (2015);

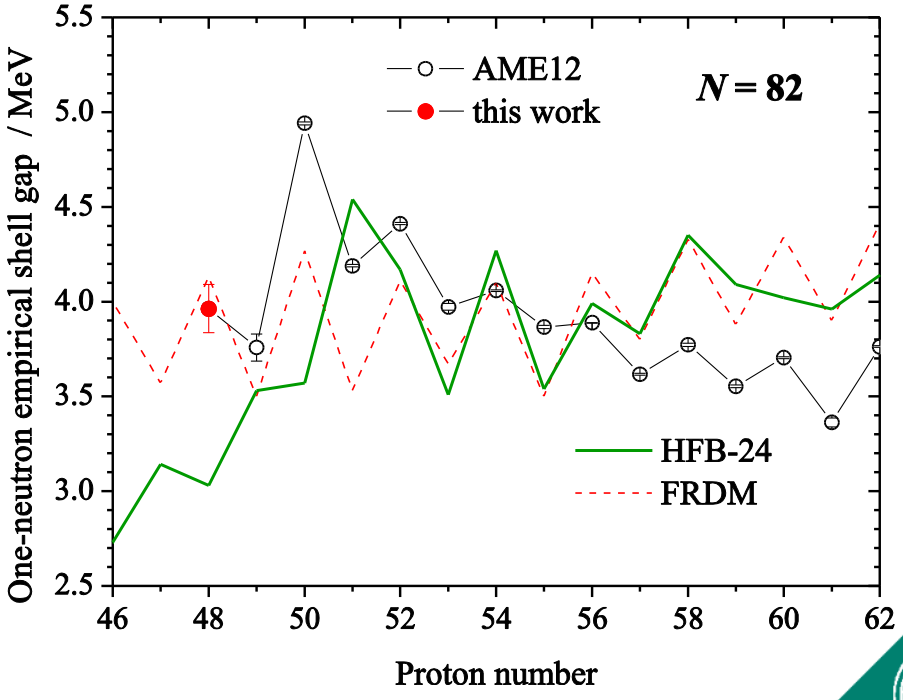
Results

A	Ratio r or C_{ToF}	ME_{new} (keV)	ME_{AME} (keV)	Δ (AME - new) (keV)
129	0.970 105 338(136)	−63 148(74)	-63 510(200)#	-452
130	0.977 645 186(180)	−61 118(22)	-61 530(160)	-412
131	0.482 304 4(539)	−55 215(100)	-55 331(196)#	-116

$S_n(N, Z) = B(N, Z) - B(N\text{-}1, Z)$

$\Delta_n = S_n(N, Z) - S_n(N+1, Z)$



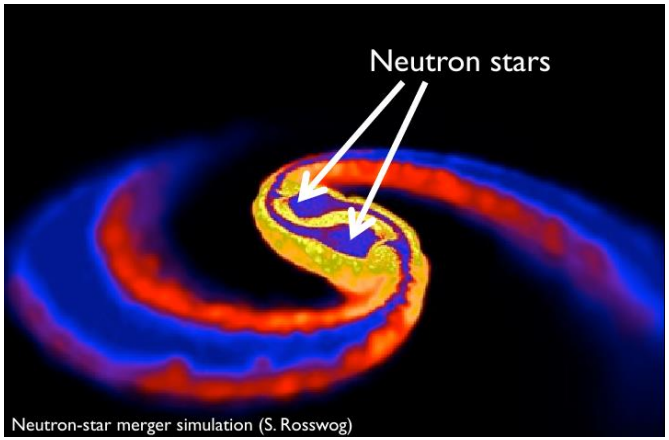


D. Atanasov *et al.*, PRL **115**, 232501 (2015);

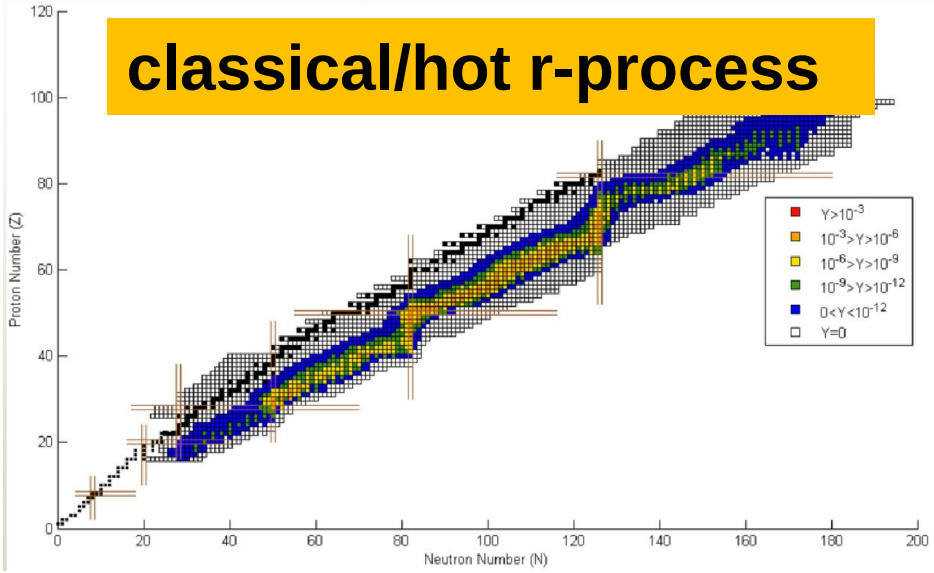
The advanced r-process sites

Core-collapse supernova

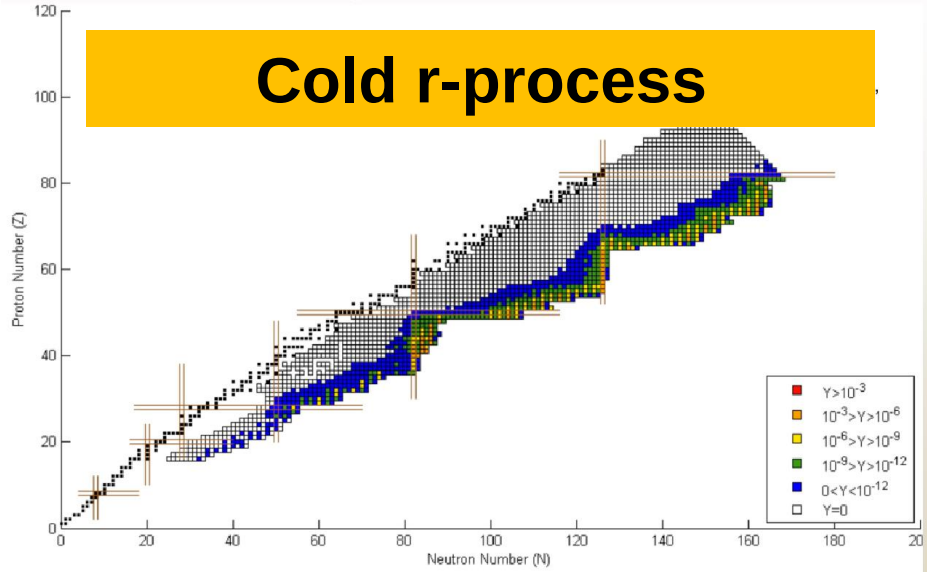
Neutron stars mergers



classical/hot r-process



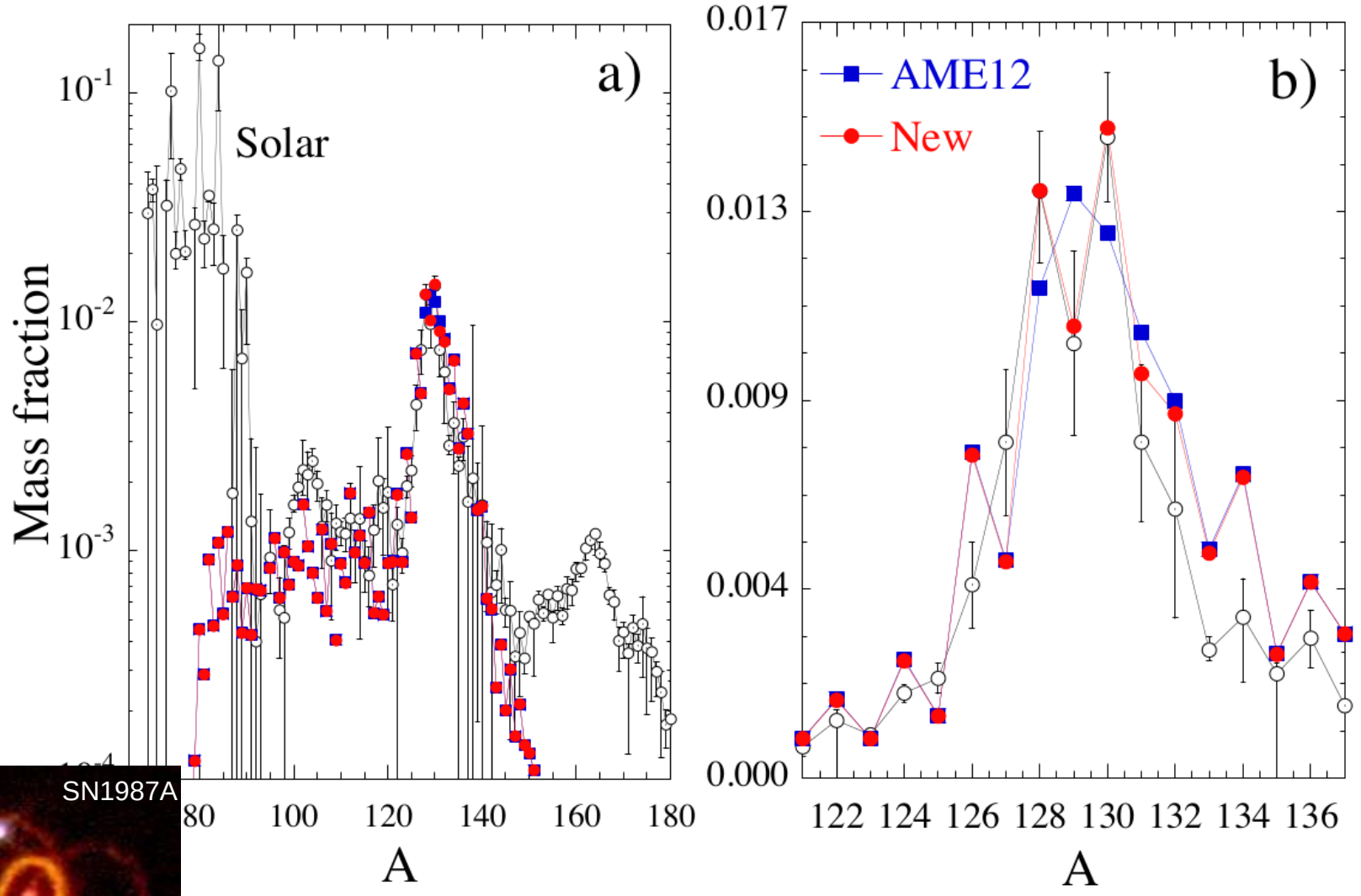
Cold r-process



MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

*T. Tsujimoto A&A **565** L5 2014 , R. Surman Workshop Hirschegg (2013), Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)*

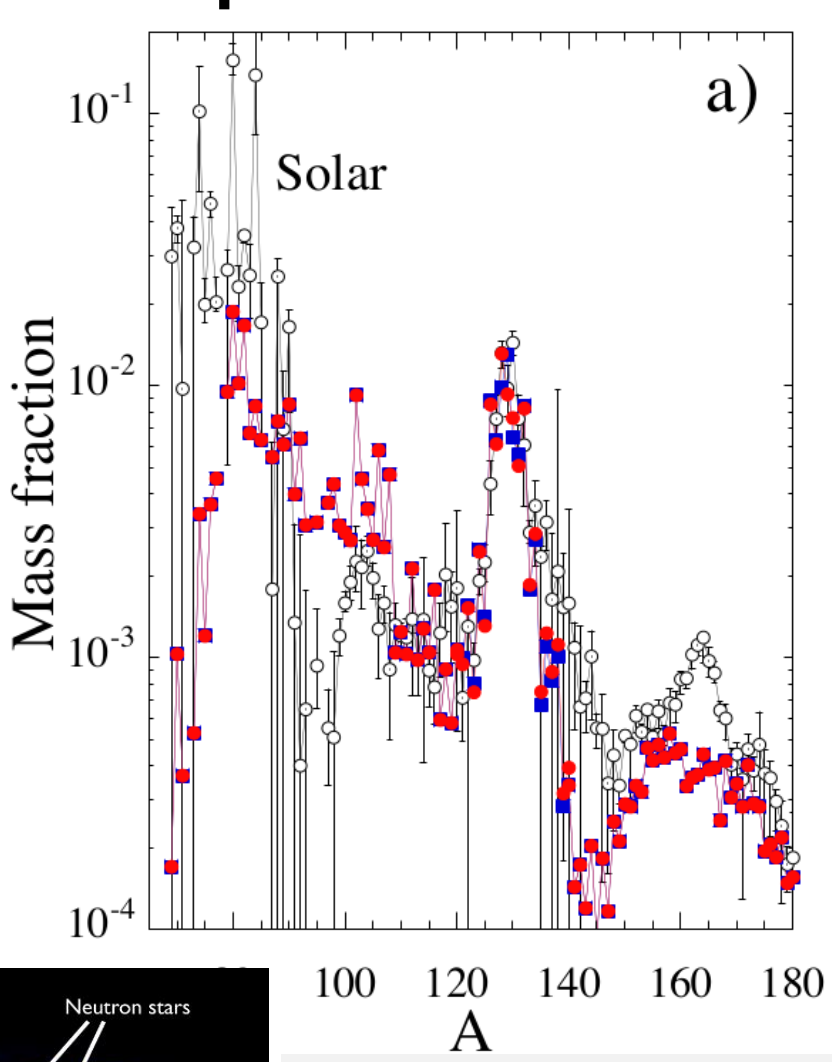
Collapse scenarios - Supernovae

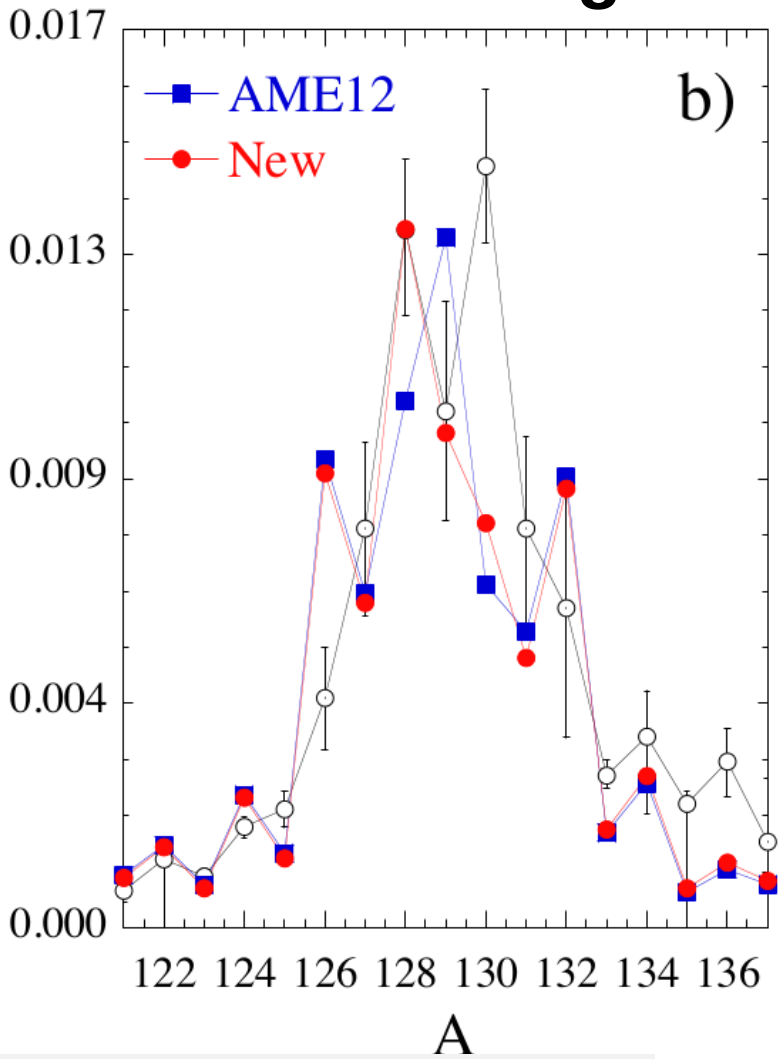


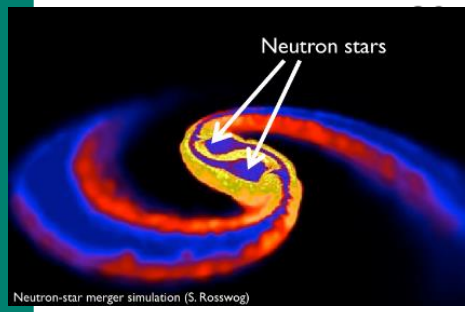
Entropy s_{k_B} **= 193**, electron fraction Y_e **= 0.48**,
Mass loss **dM/dt = 6.10^{-7}M$_{sol}$ s^{-1}** and breeze solution f_w **= 3**

Calculations performed by S.Goriely

Collapse scenarios – Neutron Star Mergers





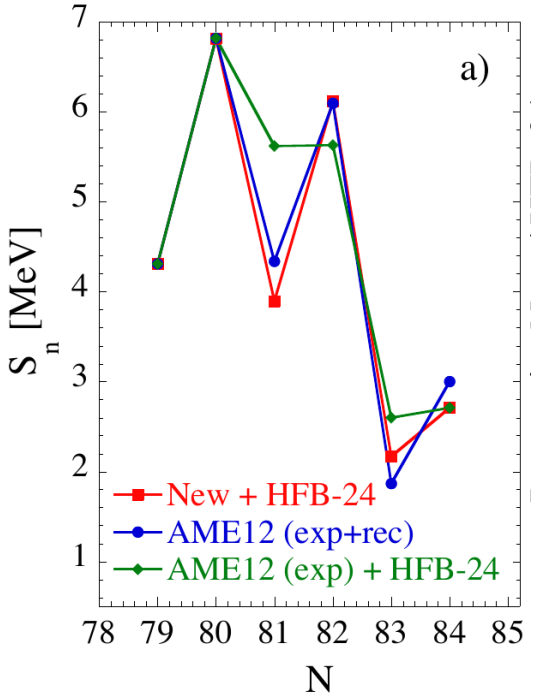


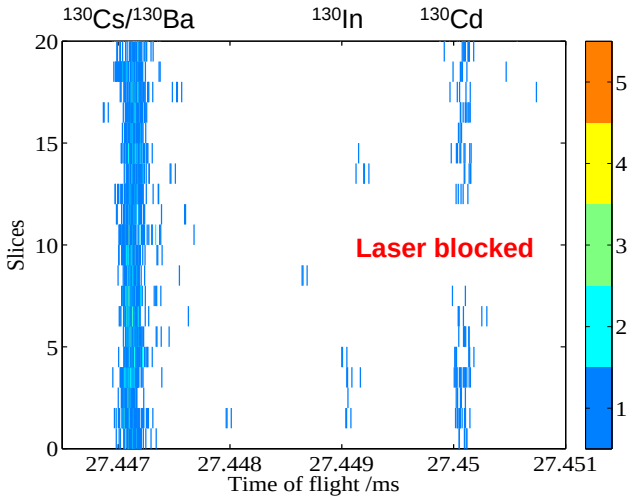
MODEL **M3A8m1a5**
mean entropy $\bar{s}/k_B$**= 28**, electron fraction Y_e **= 0.24**,
total mass ejected M_{ej} **= 2.5x10^{-2}** M_{sol}

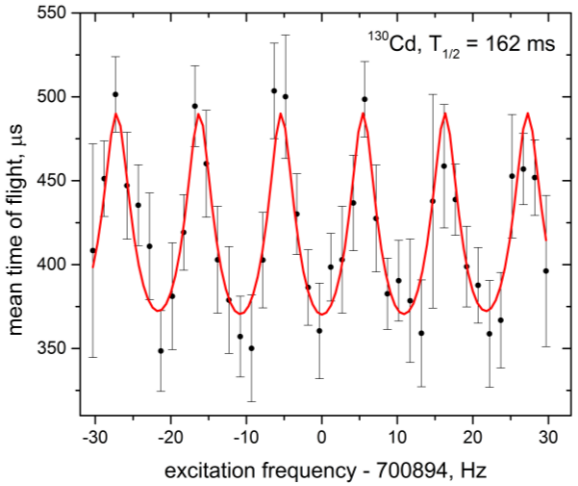
Calculations performed by S.Goriely

Summary

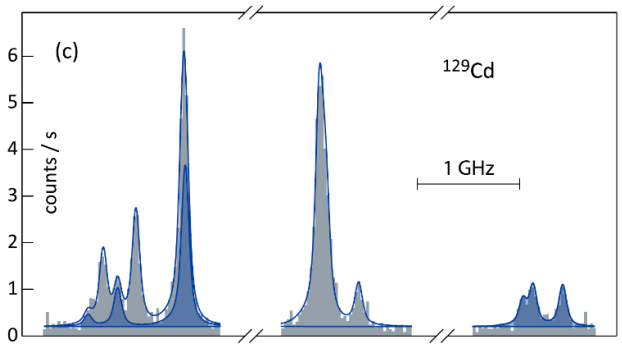
- Mass measurement of exotic $^{129\text{-}131}$Cd
- Aim to bring further reliability in r-process calculations by reducing the nuclear input uncertainties
- Future measurements to more exotic systems like ^{132}Cd







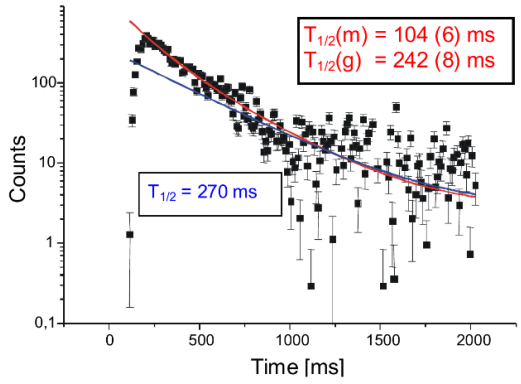
Outlook



Isomeric state of ^{129}Cd

- An isomeric states with spins 3/2 and 11/2 known from HFS

D. Yordanov et al., PRL (2013)

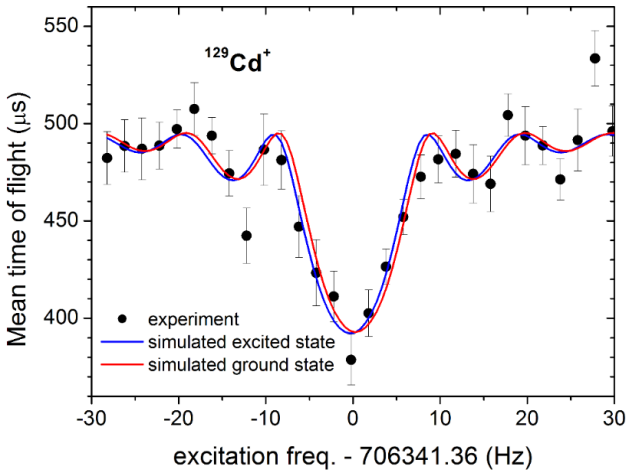


- Two distinct half-lives known to 242(8) ms and 104(6) ms

K. Kratz et al., Eur. Phys. J. A 25, 633 (2005)

- New data available from RIKEN experiment yield 151(15) ms,146(8) ms

J. Taprogge et al., Phys. Rev. C 91, 054324 (2015)



Simulated ToF-ICR for the isomeric state

Estimated energy of the isomer E = 180(100) keV

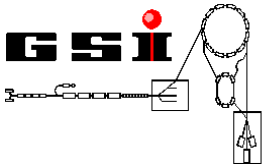
M. König *et al.*, Int. J. Mass Spectrom. **142**, 95 (1995);

http://isoltrap.web.cern.ch

Thank you for your attention

Experiment - P. Ascher, K. Blaum, R. B. Cakirli, T. Cocolios, S. George, F. Herfurth, M. Kowalska, S. Kreim, Yu. A. Litvinov, D. Lunney, **V. Manea**, D. Neidherr, M. Rosenbusch, L. Schweikhard, **A. Welker**, **F. Wienholtz**, R. Wolf, K. Zuber

Theoretical calculations - S. Goriely, H. –T. Janka, O. Just



Grants No.: 5P12HGCI1, 05P12HGFNE, 05P15HGCIA, and 05P09ODCIA) ; HCJRG-108 ; ST/L005743/1, ST/L005816/1
Contract No. 262010; HA216/EMMI;