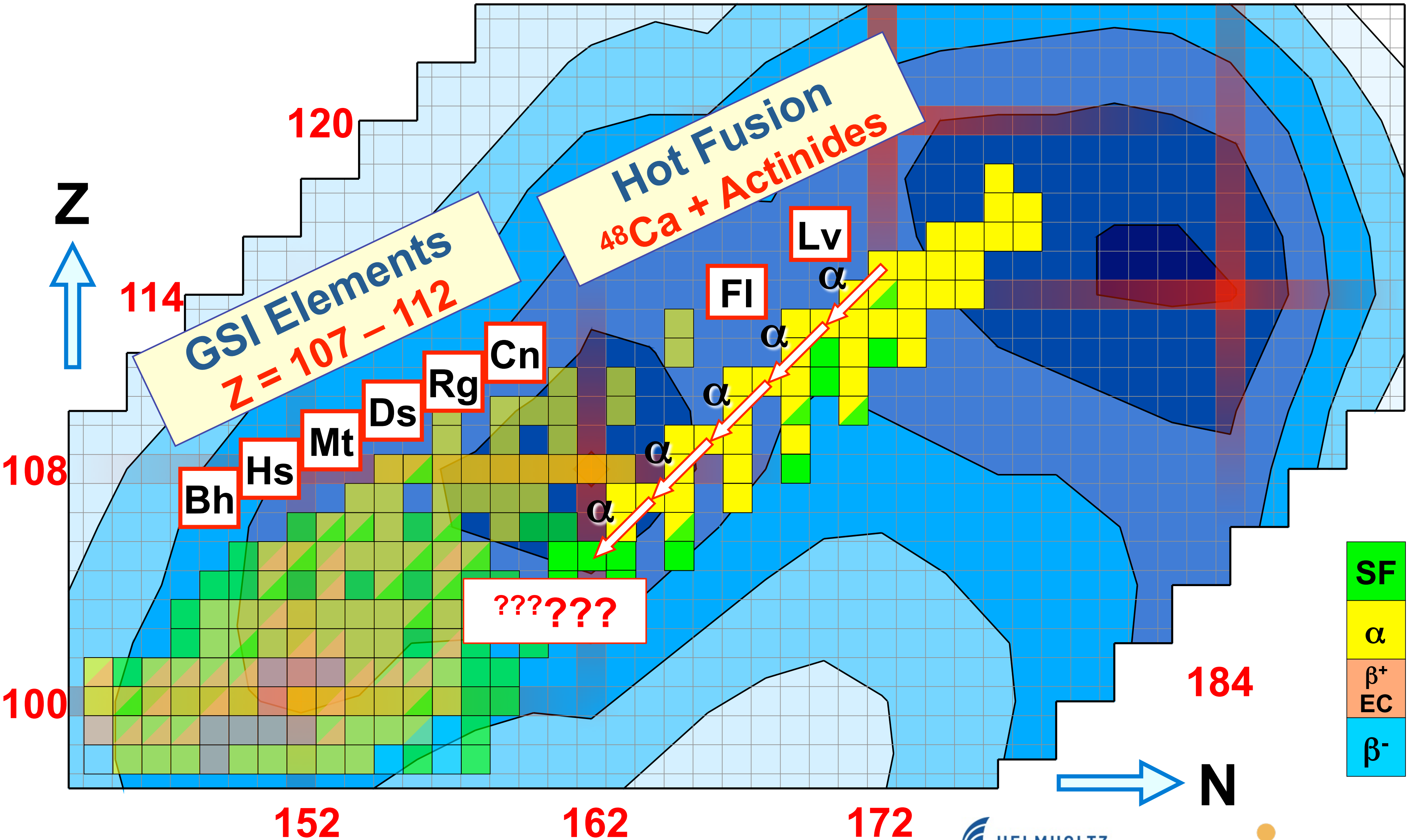
Bormio Winter Meeting 2015

Superheavy Element Research at GSI and HIM

Michael Block

GSI Darmstadt and Helmholtz Institute Mainz

Superheavy Elements – Current Status



HELMHOLTZ | ASSOCIATION

GSI

Helmholtz Institute Mainz

Courtesy Ch.E. Düllmann

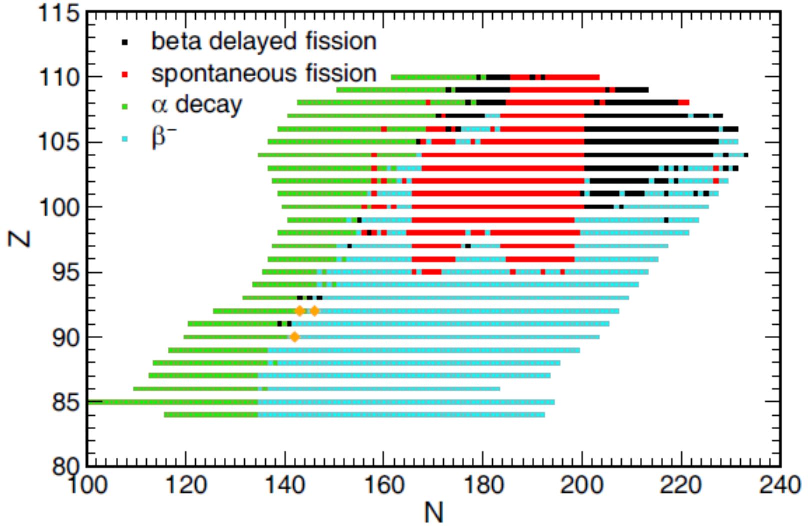
Superheavy Elements – Key Questions

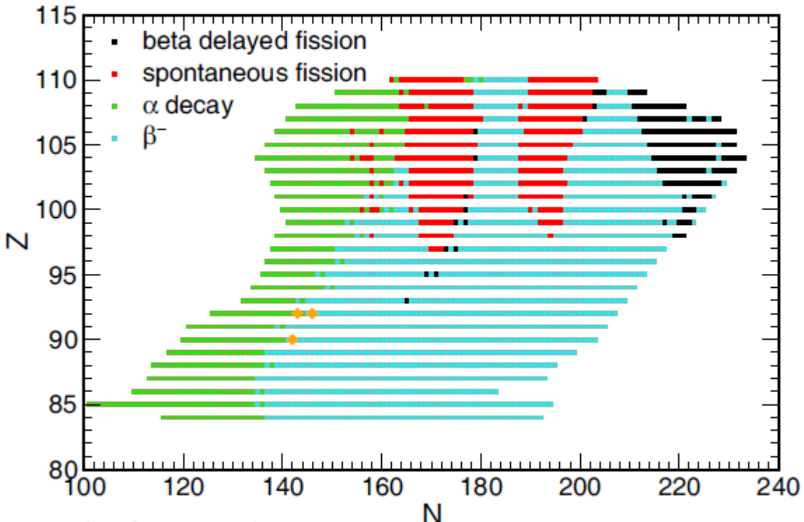
- Where is the end of the periodic table in atomic number and mass?
- What is the heaviest element that we can synthesize today and in the future?
- What are the properties and boundaries of the predicted ”island of stability” for superheavy elements?
- Can we understand the details of the fission process and competing decay modes?
- Do superheavy elements exist in the universe, and how are they produced?
- Are there remnants of long-lived superheavy elements on earth?

GSI/HIM: Comprehensive approach to investigate atomic, chemical, and nuclear properties of SHE

Have superheavy elements been produced in nature?

TF/FRDM



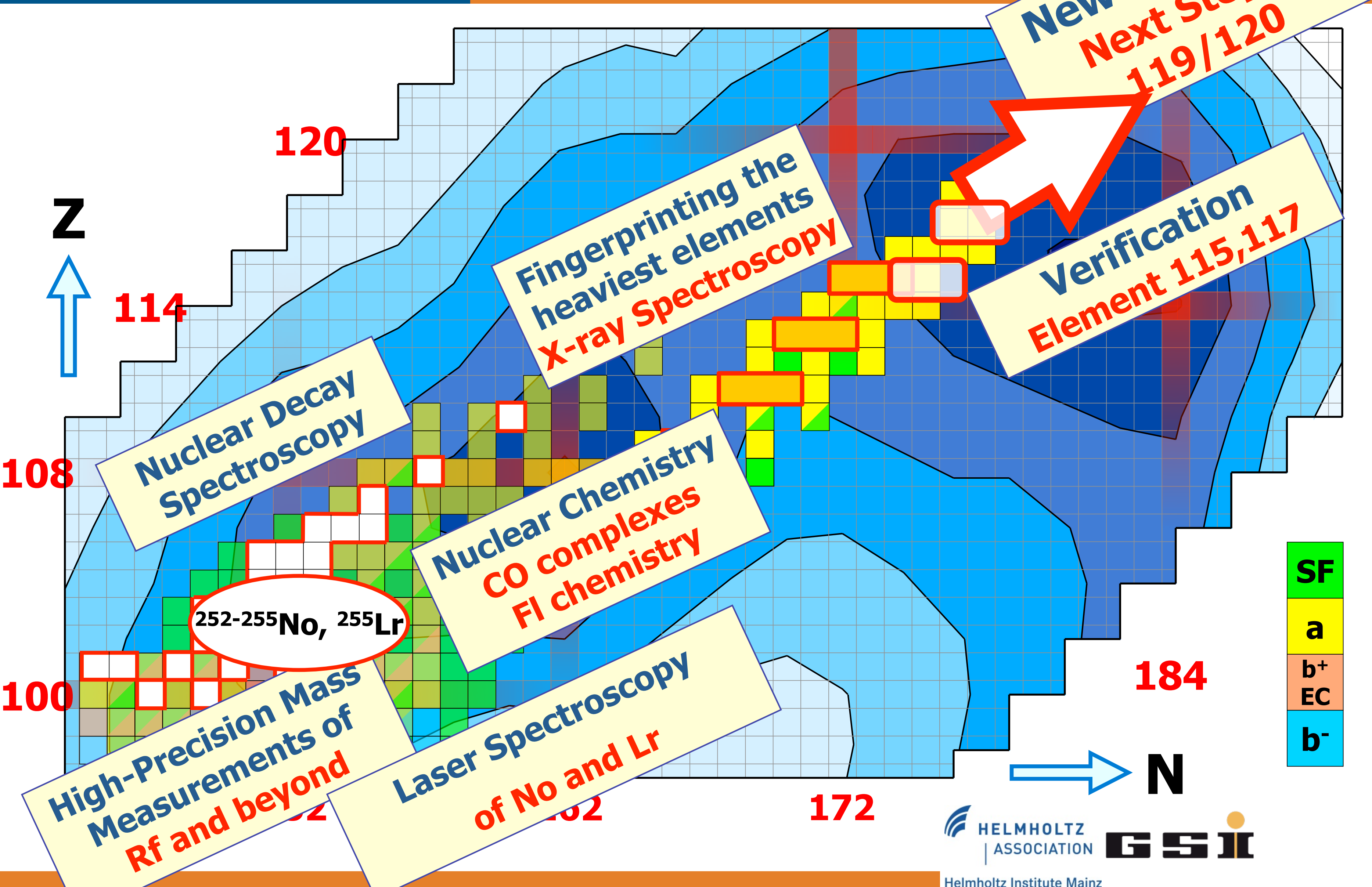


ETFSI/ETFSI

- Have SHE been produced in r process?
- Bypass fission are for high n-density?
- Fission recycling?
- Predictions require accurate description of fission (barriers)
- Need masses, half-lives etc.

I. Petermann et al. EPJA (2012) 48 122

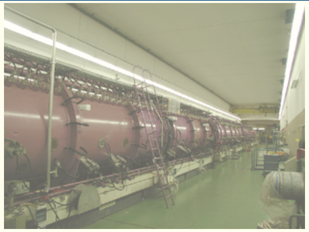
Superheavy Elements – The hottest Topics



Courtesy Ch.E. Düllmann

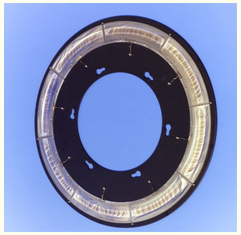
Unique Combination for SHE Studies

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

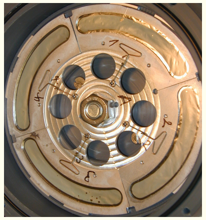


ECR/PIG + UNILAC

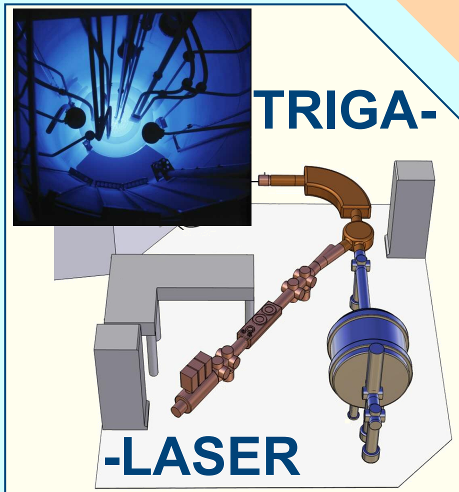
Beam



Stable targets

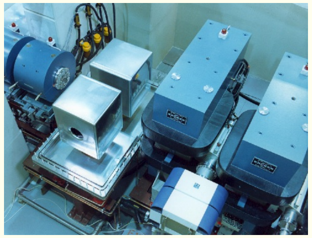


Actinide targets

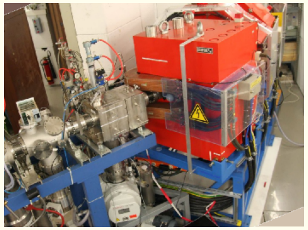


TRIGA- -LASER -TRAP

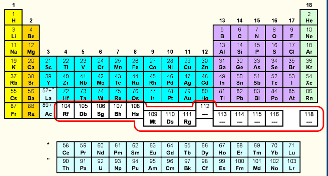
Radiochem. labs



SHIP

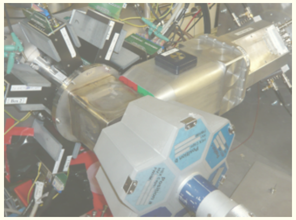


TASCA

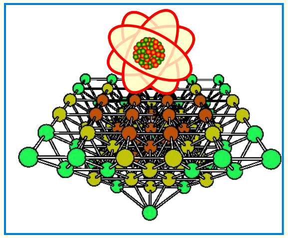


Chemistry

SHIPTRAP

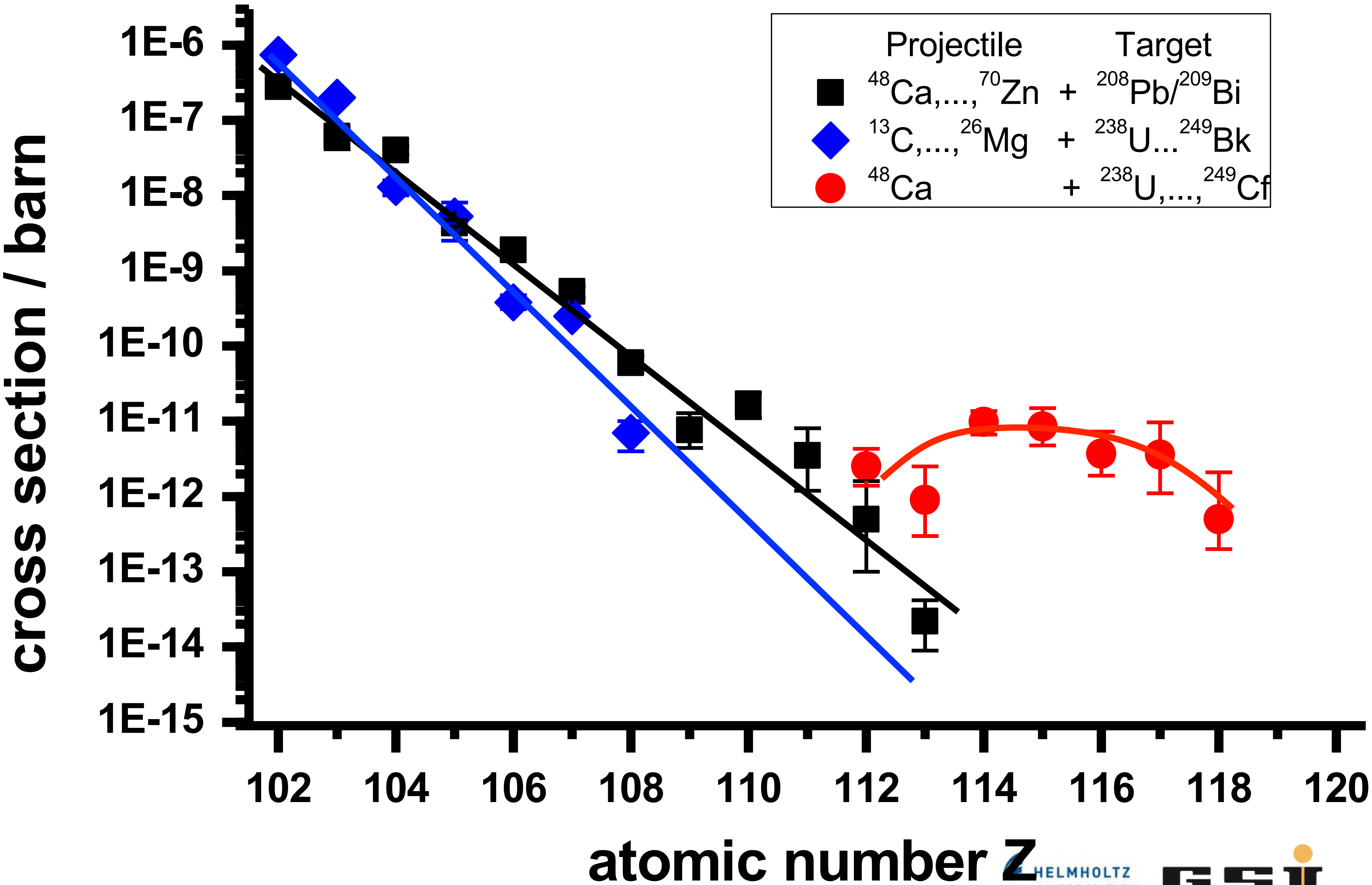


TASISpec



Chemical theory

Cross Sections for SHE Synthesis



Courtesy Ch.E. Düllmann / A. Yakushev

Requirements – Some Facts and Figures

Beam intensity:

- present: 6×10^{12} pps ($1\mu A_p$) for typical beams ^{48}Ca, ^{50}Ti, …
- future: 6×10^{13} pps ($10\mu A_p$) feasible

  ➢ need for high power targets

Targets

- 0.5-
- abo … metries
- Prob

Due to low intensities radioactive beam intensities not competitive yet!

➢ **Intensity of 10^9 pps corresponds to $0.5\ \mu g / cm^2$ targets**

Recoil separator

- High transmission (for synthesis: short separation time)
- low background (beam suppression, shielding of n, γ)

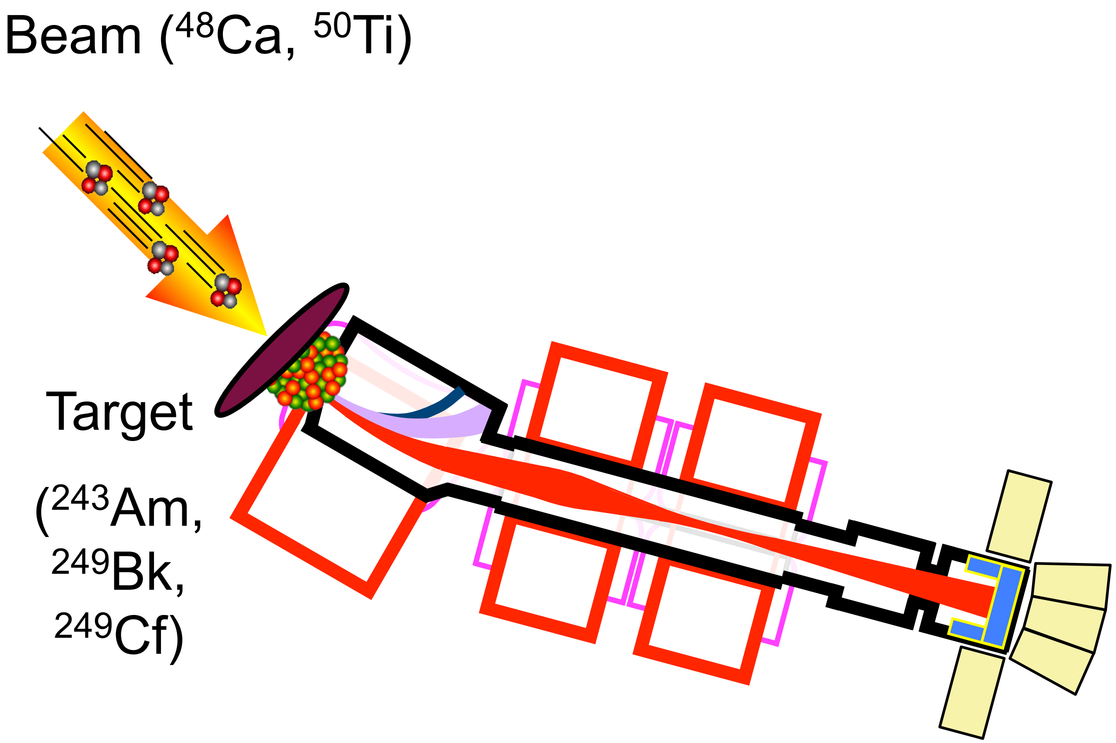
Synthesis, separation and identification of SHE

TASCA

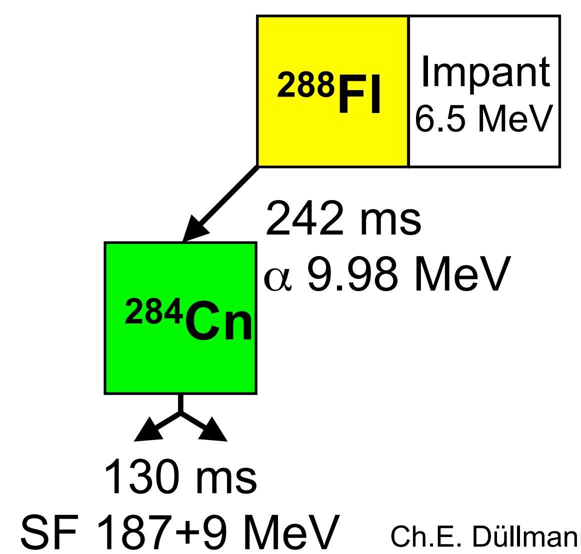
TransActinide Separator and Chemistry Apparatus

Particle Detector (α; e⁻; SF)

Photon Detector (γ; X)



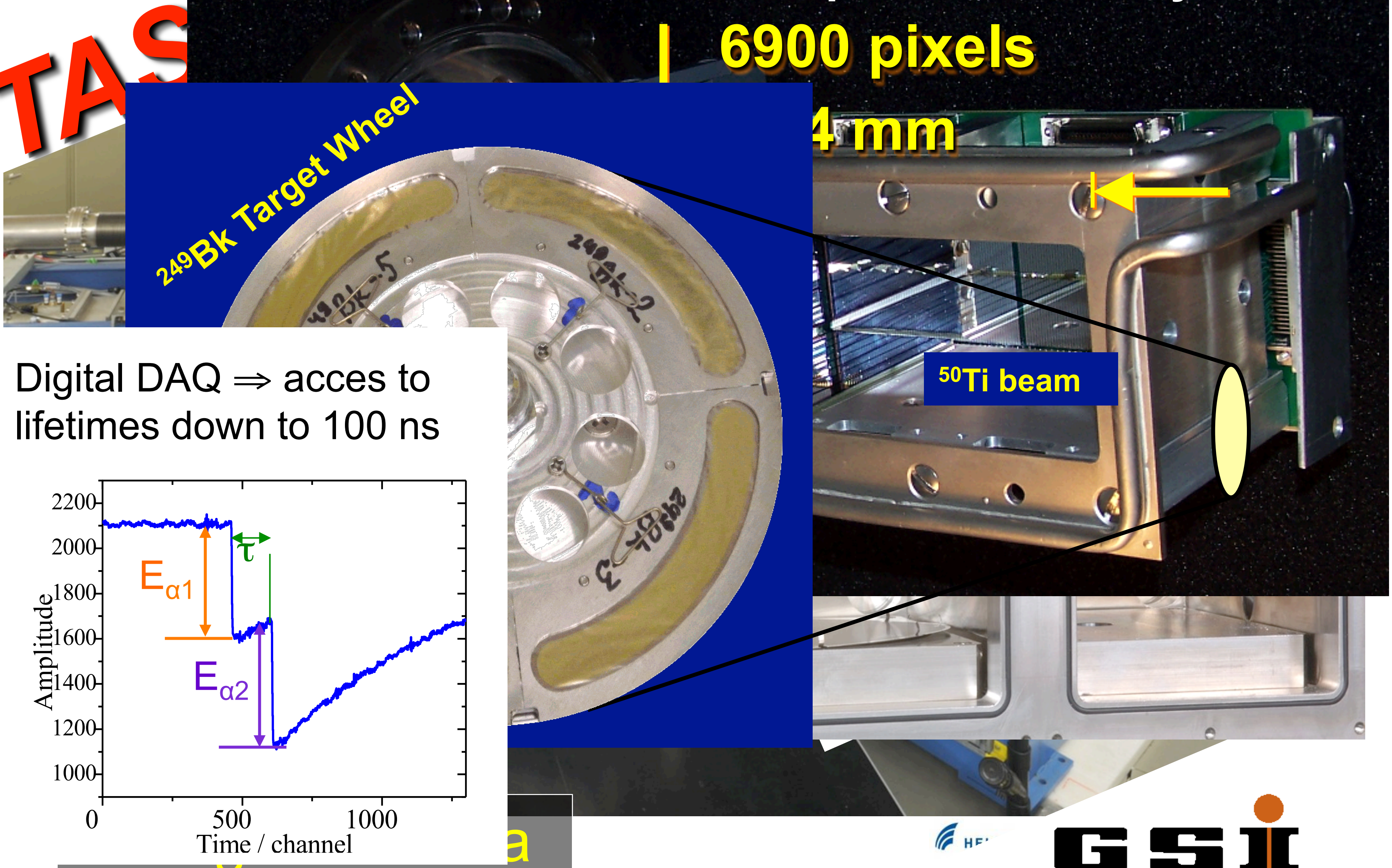
Detection of decay chain



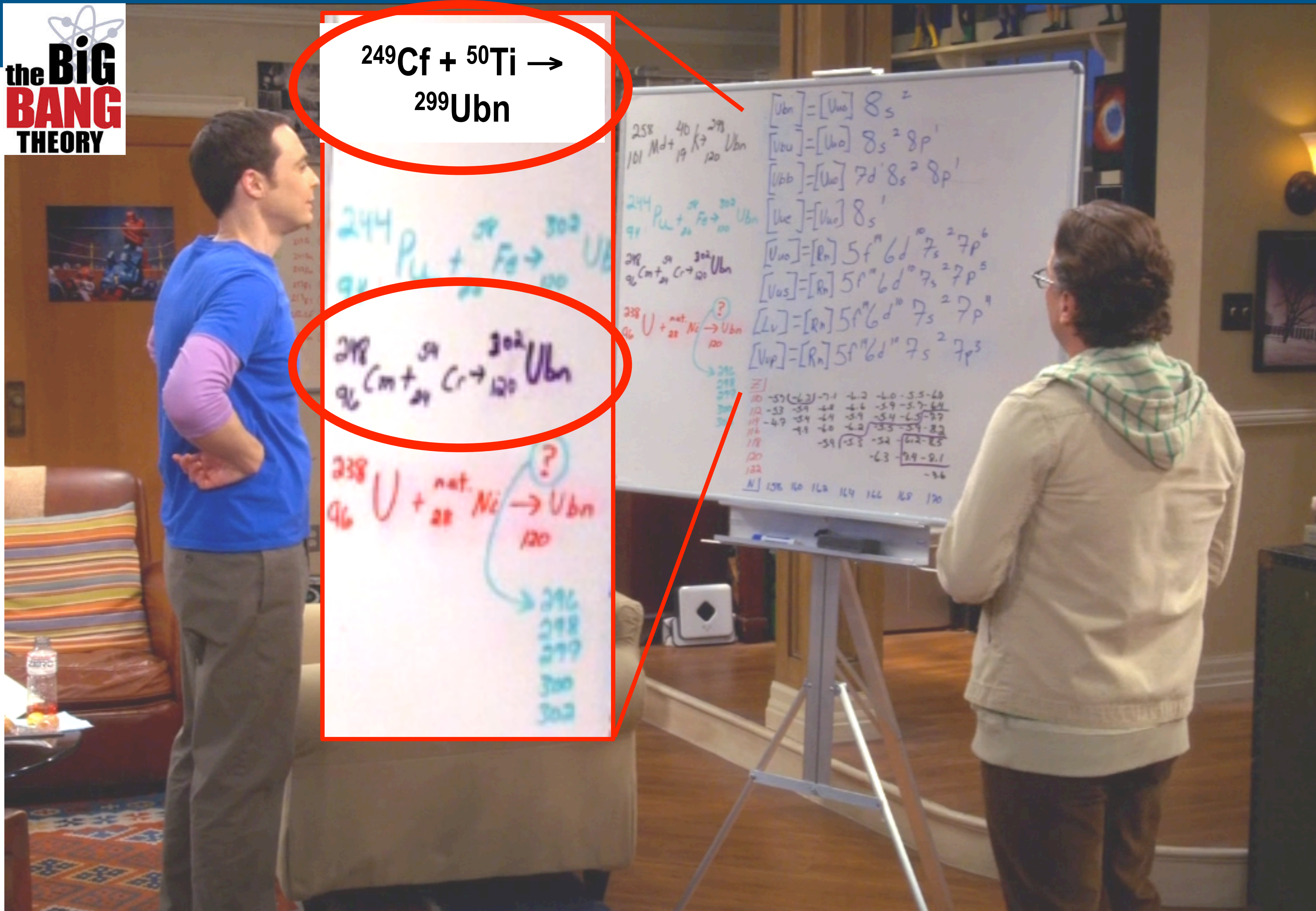
Ch.E. Düllmann et al., PRL 104 (2010) 252701

DSSSD State-of-the-Art Stop Detector Array

Digital DAQ ⇒ acces to lifetimes down to 100 ns



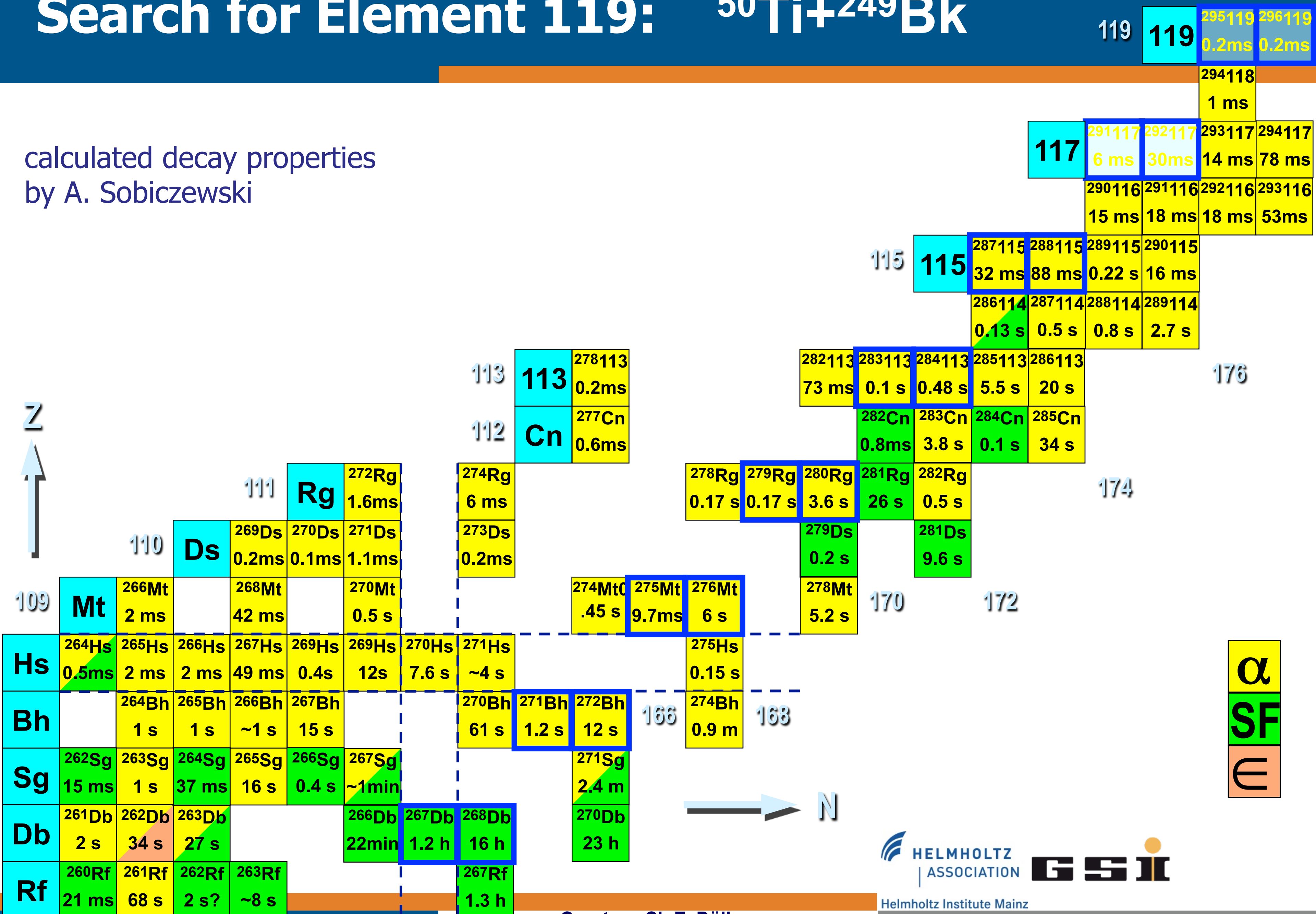
How to synthesize element 120?



Courtesy Ch.E. Düllmann

Search for Element 119: $^{50}Ti+^{249}Bk$

calculated decay properties
by A. Sobiczewski



HELMHOLTZ | ASSOCIATION

Helmholtz Institute Mainz

GSI

Courtesy Ch.E. Düllmann

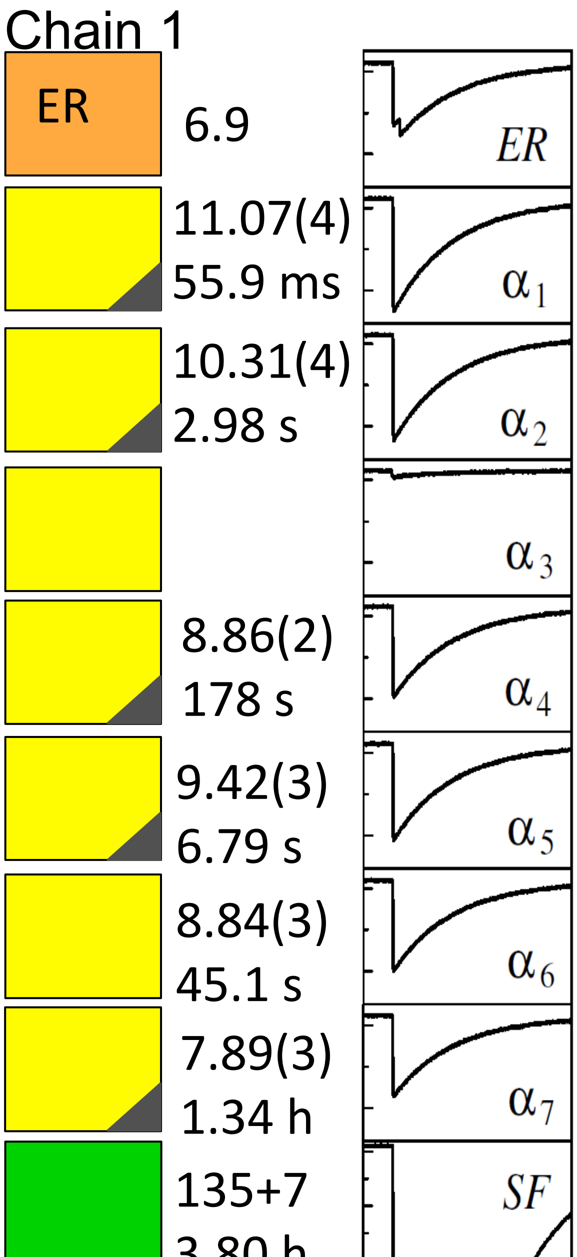
2012: Search for element 119

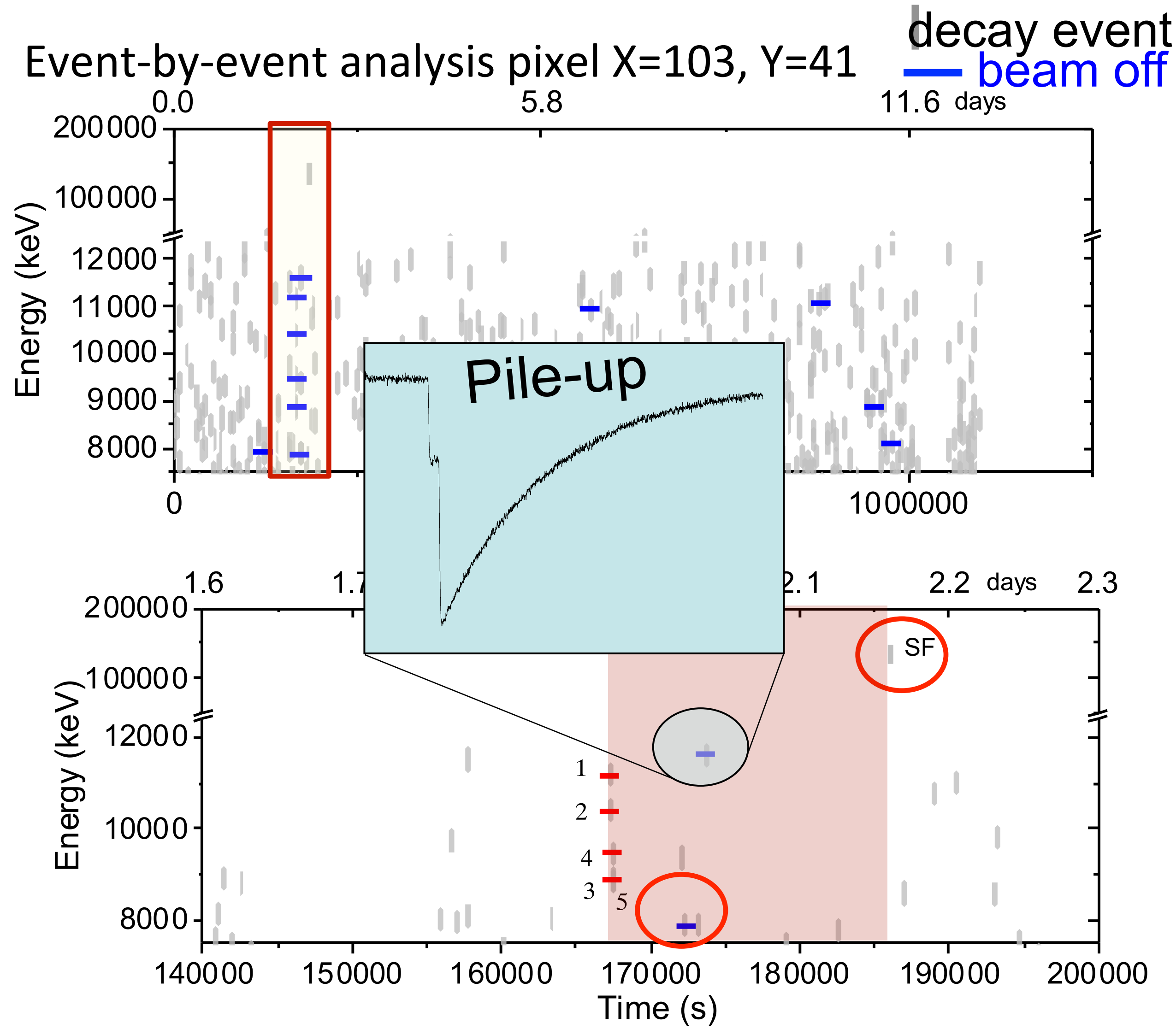
$^{50}Ti + ^{249}Bk \Rightarrow$ Element 119

Status of element 119 search campaign in 2012 at GSI:

- beam dose: $\approx 3.6 \cdot 10^{19}$ particles
- $\approx$40 TB of data (analysis is ongoing)
- Sensitivity $\approx$70 fb for one event (preliminary)
- Current status of data analysis yields
  no evidence for detection of element 119

Element 117 confirmation and discovery of a new long-lived isotope





Random Probability for ER-α-α-α-α-α-α-SF chain with E_{α}=(7.8-12.0) MeV with same Δt's as in chain 1: <5*10^{-15}

J. Khuyagbaatar *et al.*, Phys. Rev. Lett. 112, 172501 (2014)

^{294}117: 4 decay chains from DGFRS — 2 *TASCA* chains — Tot.

Nuclide	DGFRS 1	DGFRS 2	DGFRS 3	DGFRS 4	*TASCA* 1	*TASCA* 2
294 117	10.81 112 ms	10.96 101 ms	10.967 3.99 ms	Missing	11.071 55.9 ms	11.047 92.6 ms
290 115	9.95 0.023 s	10.28 0.3 s	9.77 0.697 s	10.23 0.389 s	10.314 2.98 s	10.17* 0.66 s
286 113	9.63 28.3 s	9.61 5.8 s	9.75 3.7 s	9.65 36.5 s	0.6+7.7 5.5 s	4.64 2.35 s
282 Rg	9.00 0.74 s	9.18 145 s	9.04 29.2 s	9.00 167 s	8.862 172 s	9.053 373 s
278 Mt	9.55 11 s	9.396 4.17 s	9.38 7.2 s	missing	9.421 6.79 s	9.471 3.53 s
274 Bh	8.80 78 s	8.79 103 s	8.69 55.7 s	8.73 39.1 s	8.837 45.1 s	8.83* 41.3 s
270 Db	219 33.4 h	142 37.5 h	196 23.5 h	221.7 1.1 h	7.887 1.3 h	7.904 1.6 h
266 Lr					135+7 3.8 h	189 29.3 h

a few alpha-like events (7.7-8.2 MeV)

J. Khuyagbaatar *et al.*, Phys. Rev. Lett. 112, 172501 (2014)

Element 117 among top ten APS news stories 2014

APS physics

American Physical Society Sites | APS | Journals | PhysicsCentral | Physics

Search

Login | Become a Member | Contact Us

Publications | Meetings & Events | Programs | Membership | Policy & Advocacy | Careers in Physics | About APS

Publications

- Journals
- **APS News**
  - News Updates
  - Issue Archives
  - Features Archives
  - Announcements

Home | Publications | APS News | January 2015 (Volume 24, Number 1) | **Top Ten Physics News Stories in 2014**

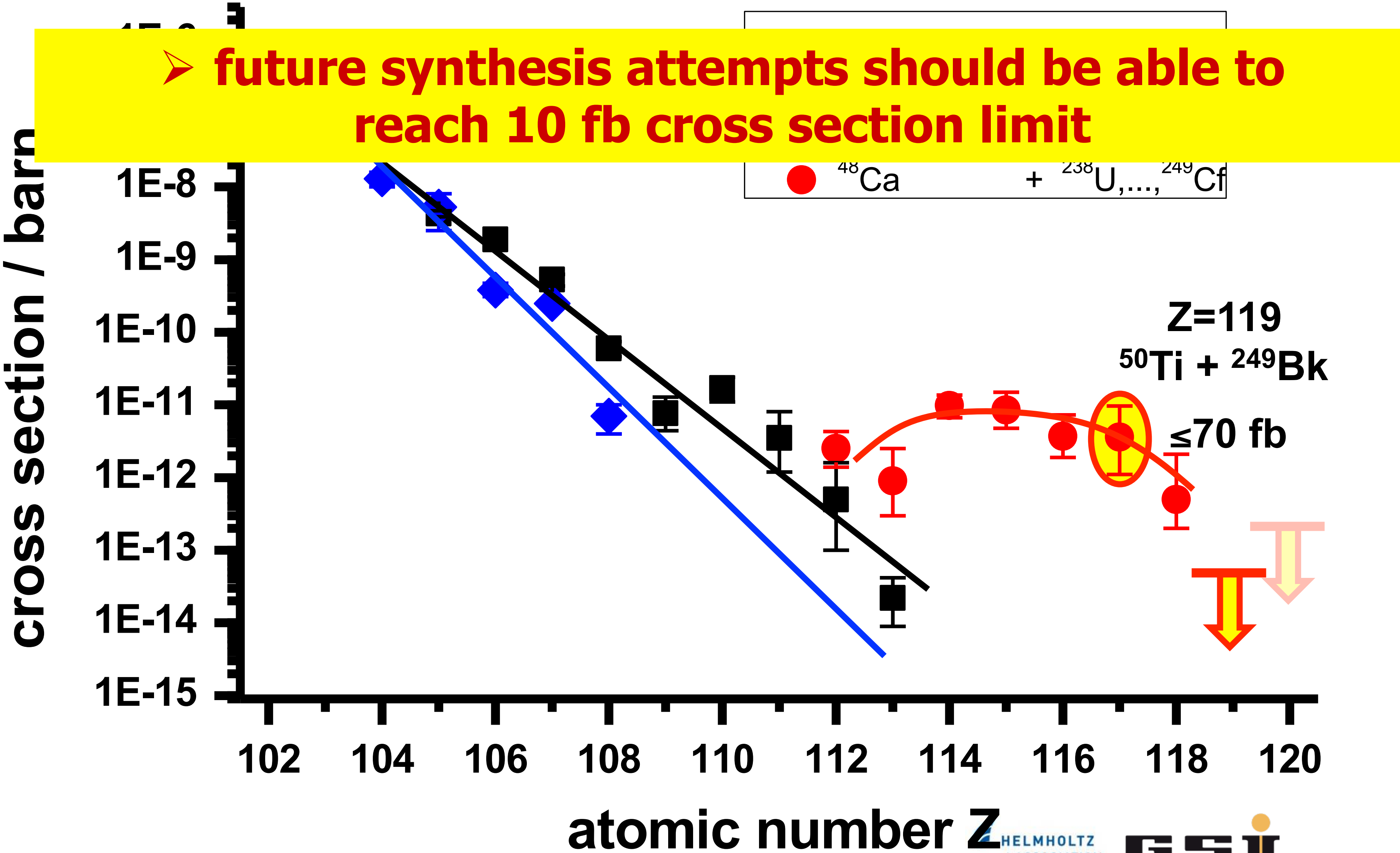
Top Ten Physics News Stories in 2014

Every year, APS News looks back to see which physics news stories grabbed the attention of the public. This list is not necessarily a compilation of the most important advances or discoveries of the year, but rather the ones that seemed to garner the most headlines and column-inches. In (roughly) chronological order, the top ten physics stories of 2014 were:

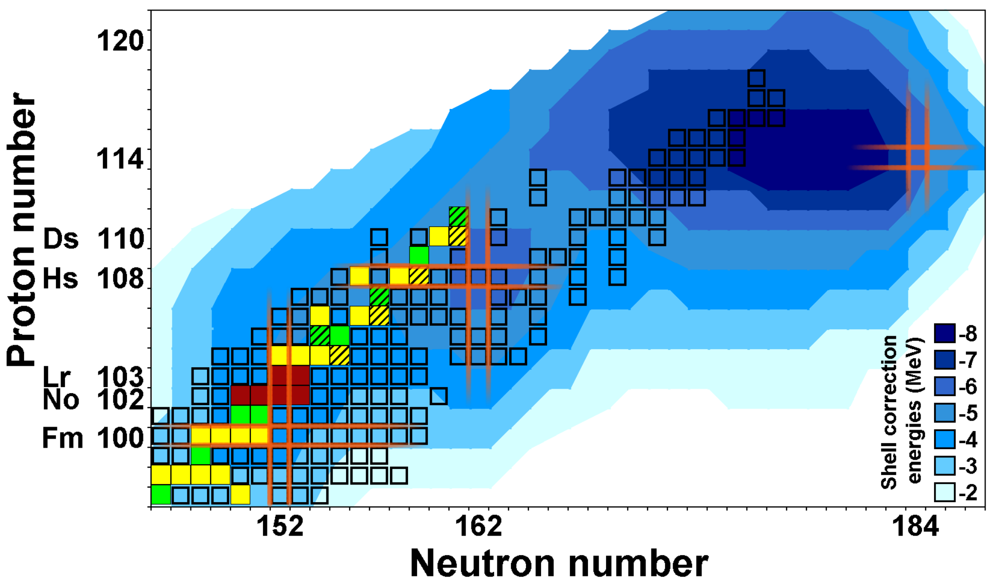
Element 117
Ununseptium, the placeholder name for element 117, was spotted for an instant in Germany in **May**. At the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, scientists bombarded a berkelium target with accelerated calcium atoms to create the short-lived artificial element. This follows up on an experiment in Russia in 2010 that first created the element, confirming its existence and likely paving the way for its official inclusion on the periodic table of the elements. In addition, one of the isotopes of lawrencium discovered in the process had a half-life of nearly eleven hours, giving physicists hope that experiments might be bringing them close to the hypothesized shores of the "Island of Stability" for super-heavy elements.

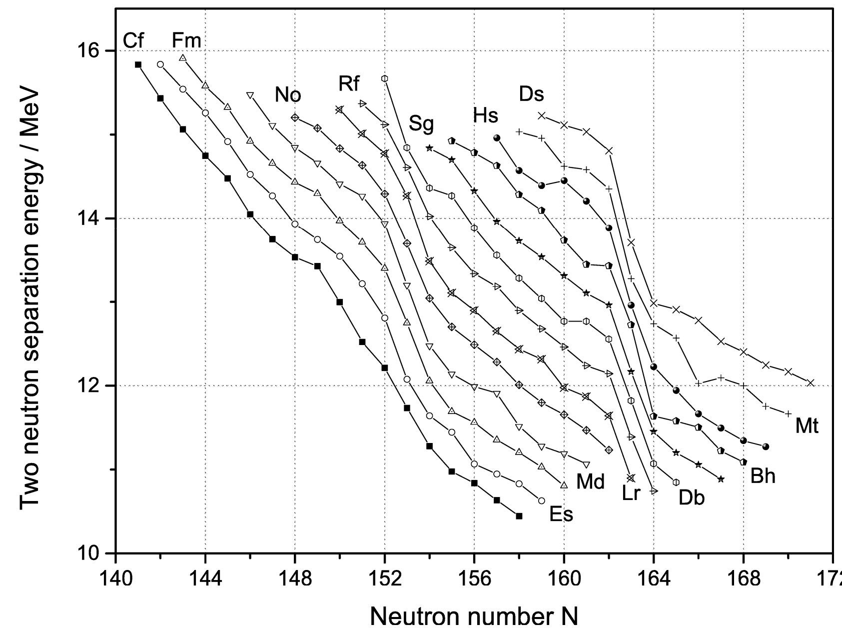
Element 115 fingerprinting was one of the highlights 2013

Cross Sections for SHE Synthesis



Importance of Masses for Z > 100



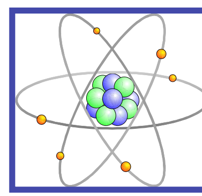


high-precision mass measurements provide

- accurate absolute binding energies to map nuclear shell effects
- anchor points to fix decay chains

➡ Studies the nuclear structure evolution

➡ Benchmark theoretical nuclear models



= N · (neutron) + Z · (proton) + Z · (electron)

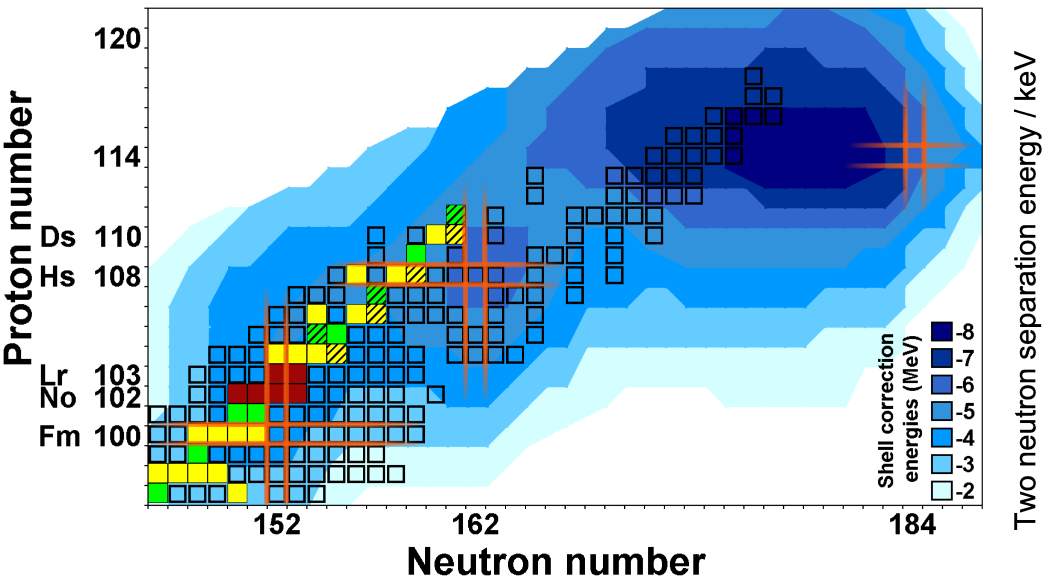
- binding energy

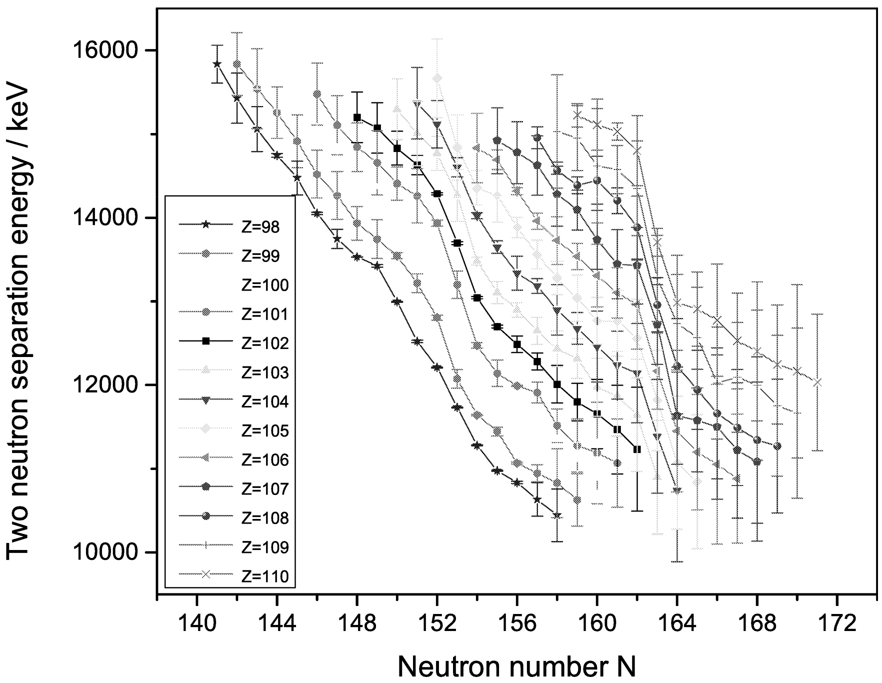
Helmholtz Association

GSI

Helmholtz Institute Mainz

Importance of Masses for Z > 100



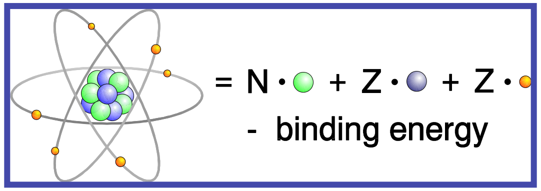


high-precision mass measurements provide

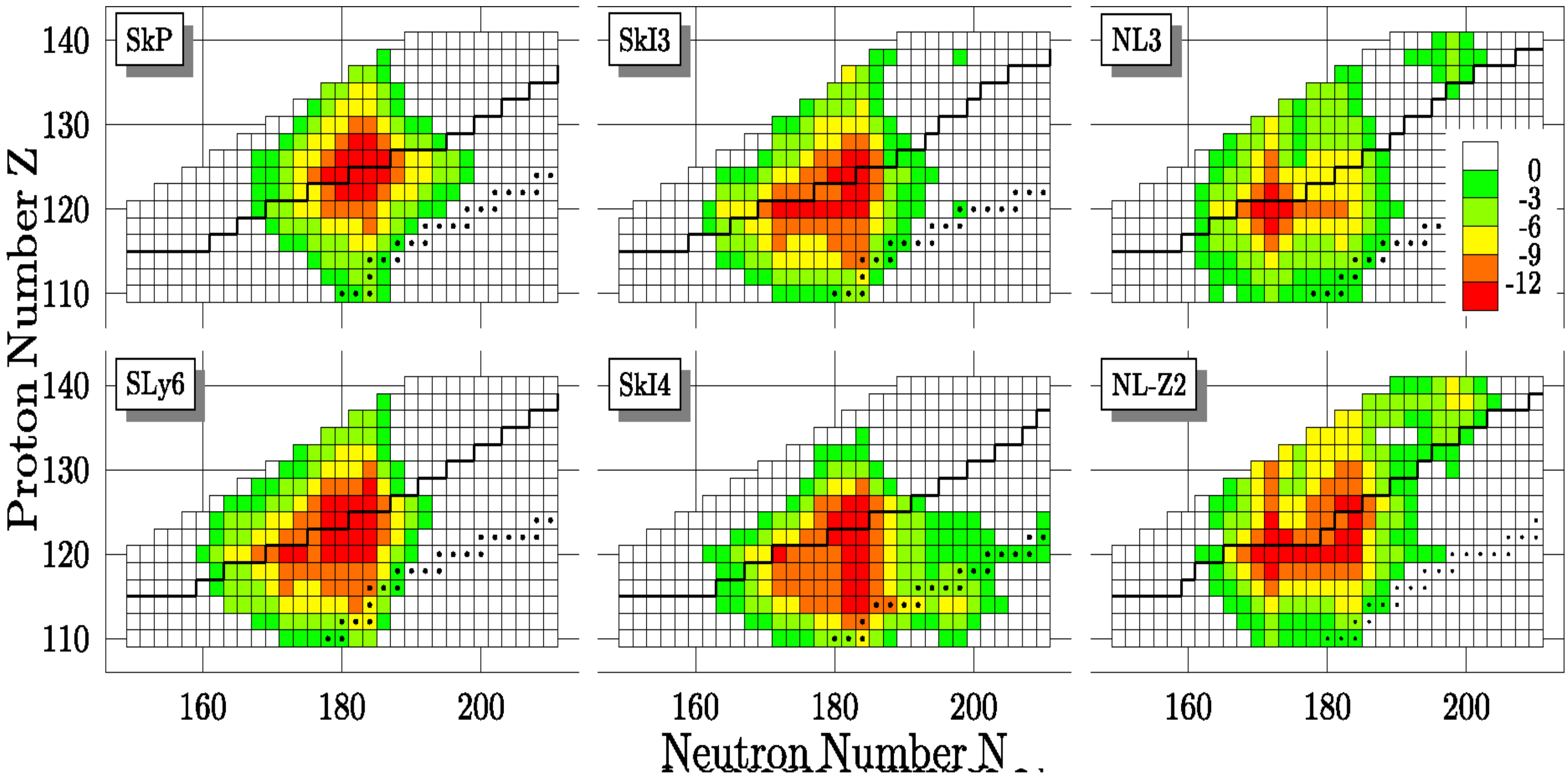
- accurate absolute binding energies to map nuclear shell effects
- anchor points to fix decay chains

➡ Studies the nuclear structure evolution

➡ Benchmark theoretical nuclear models



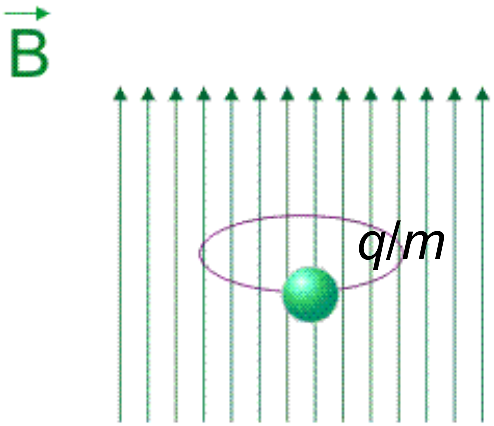
Nuclear Shells: Magic Numbers in SHE?

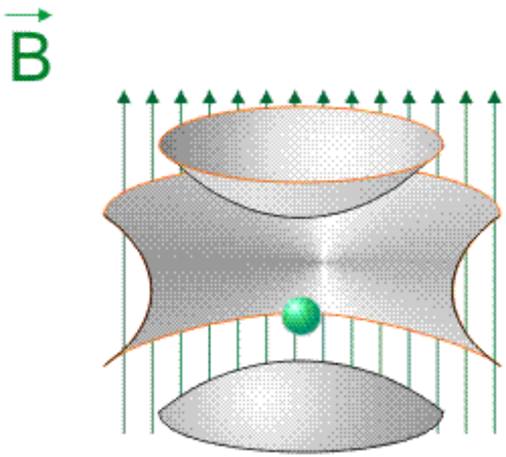


M. Bender et al., Phys. Lett. B 515 (2001) 42

Principle of Penning Traps

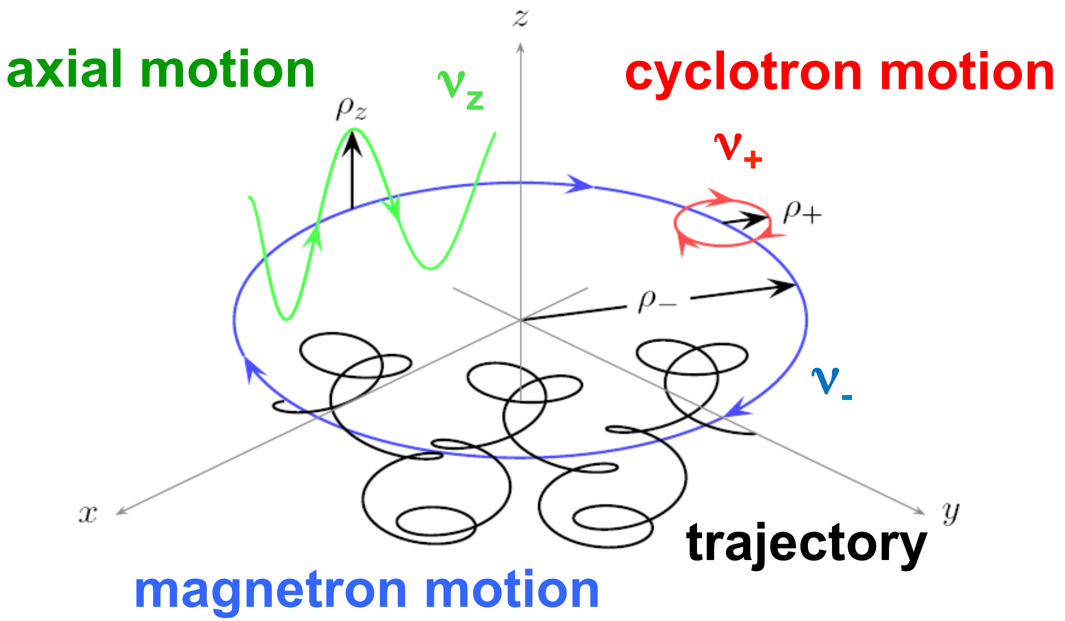
PENNING trap





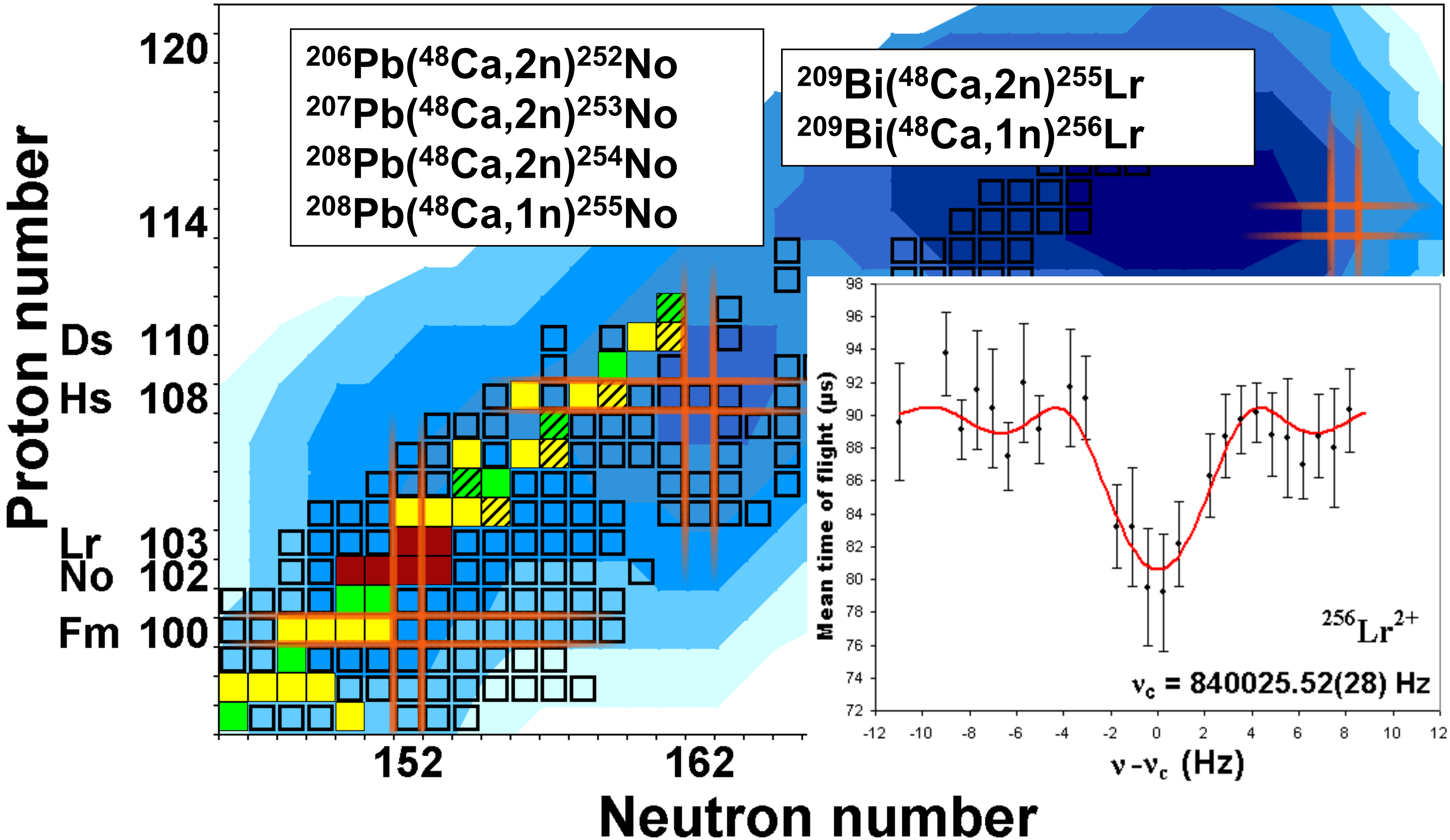
- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field

Cyclotron frequency: $f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$



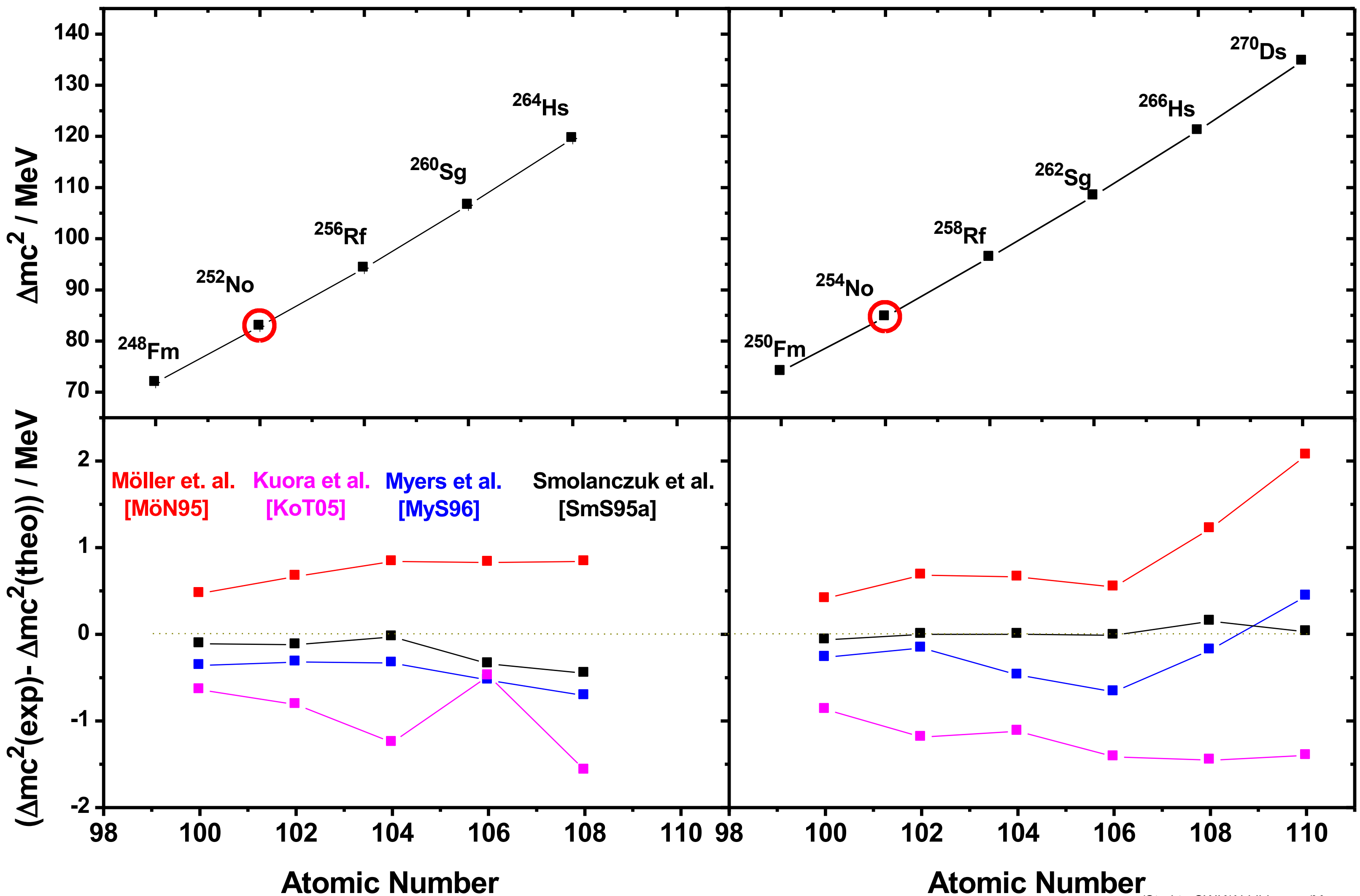
L. S. Brown and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233
G. Gabrielse, Int. J. Mass Spectr. 279, (2009) 107

Direct mass measurements with SHIPTRAP



M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

Masses of even-even $N - Z = 48$ and $N - Z = 50$ Nuclei



/StrukturSWK/Abbildungen/Massen,
F.P. Heßberger, 3.9.2013

HELMHOLTZ ASSOCIATION

GSI

Helmholtz Institute Mainz

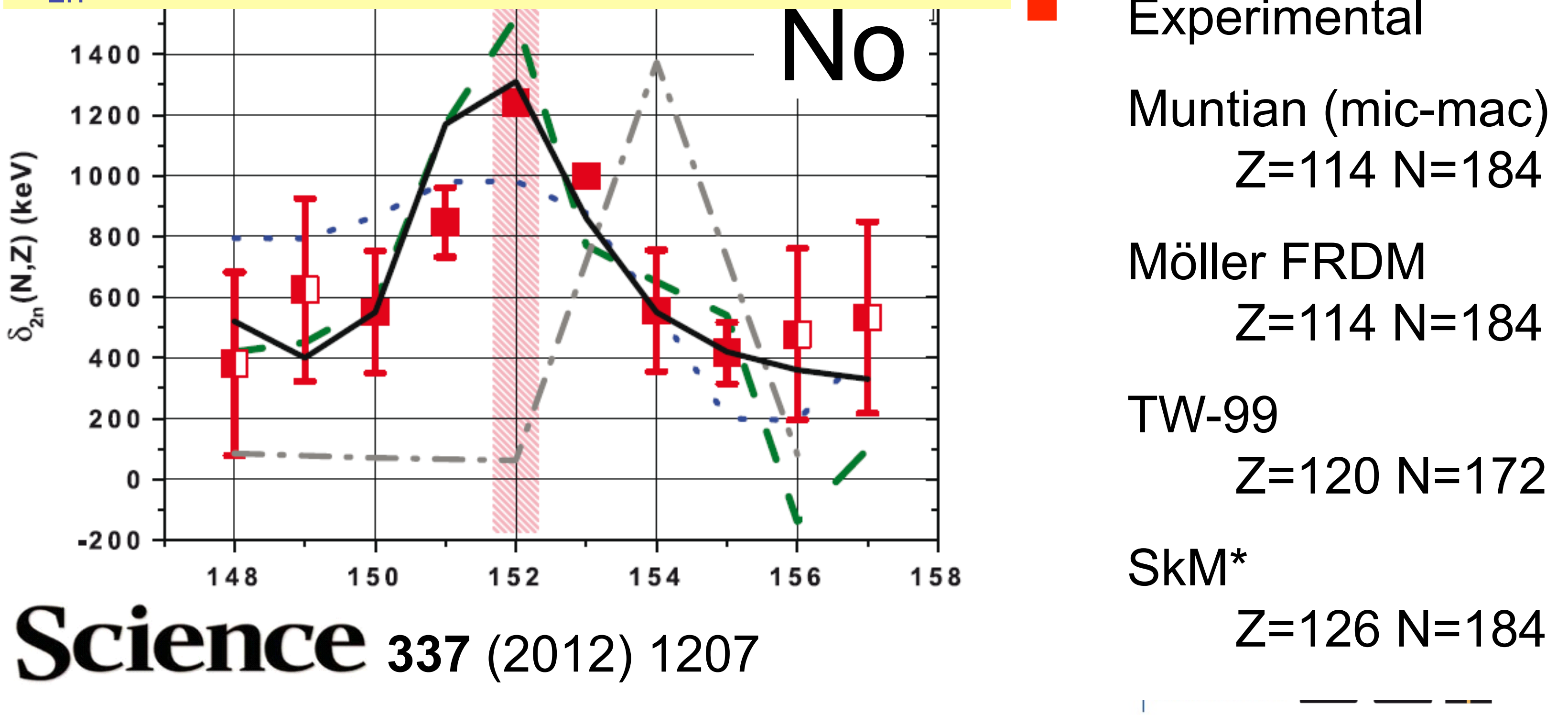
courtesy F. P. Hessberger

SHIPTRAP: Probing the Strength of Shell Effects

Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

E. Minaya Ramirez,[1,2] D. Ackermann,[2] K. Blaum,[3,4] M. Block,[2*] C. Droese,[5] Ch. E. Düllmann,[6,2,1] M. Dworschak,[2] M. Eibach,[4,6] S. Eliseev,[3] E. Haettner,[2,7] F. Herfurth,[2] F. P. Heßberger,[2,1] S. Hofmann,[2] J. Ketelaer,[3] G. Marx,[5] M. Mazzocco,[8] D. Nesterenko,[9] Yu. N. Novikov,[9] W. R. Plaß,[2,7] D. Rodríguez,[10] C. Scheidenberger,[2,7] L. Schweikhard,[5] P. G. Thirolf,[11] C. Weber[11]

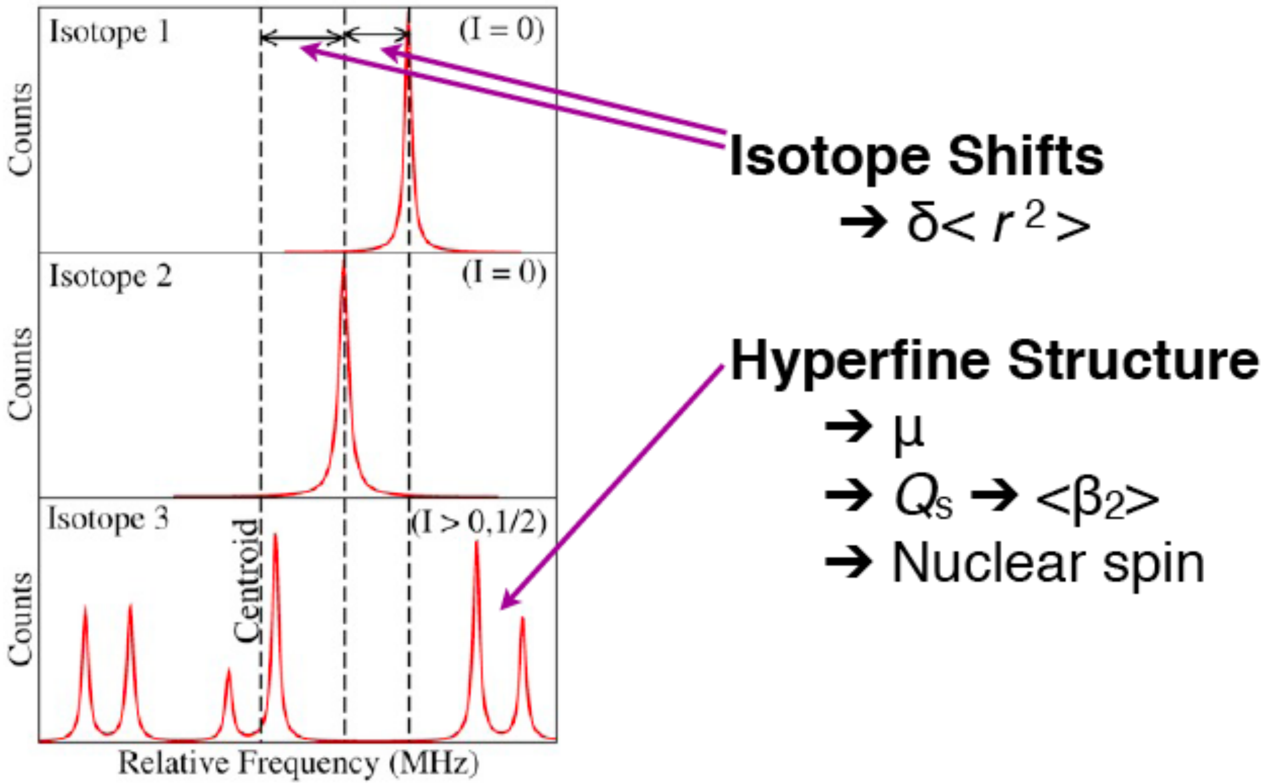
$\delta_{2n}(N,Z) = 2B(N,Z) - B(N-2,Z) - B(N+2,Z)$



Science 337 (2012) 1207

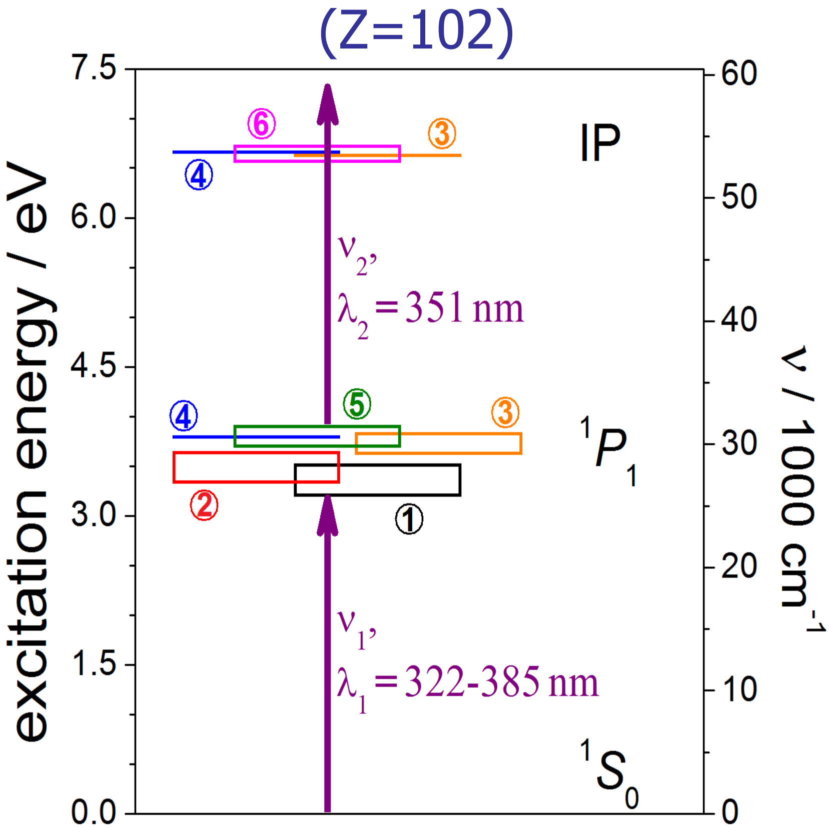
Laser Spectroscopy of the Heaviest Elements

Methods:	Search for atomic levels	hyperfine spectroscopy	Measurement of isotopic shifts
Motivation:	**relativistic and QED effects**	**Nuclear moments & spins**	**changes in mean square charge radii**



Search for Atomic Transitions Nobelium

Theoretical predictions for the $^1S_0$-$^1P_1$- transition in the element nobelium



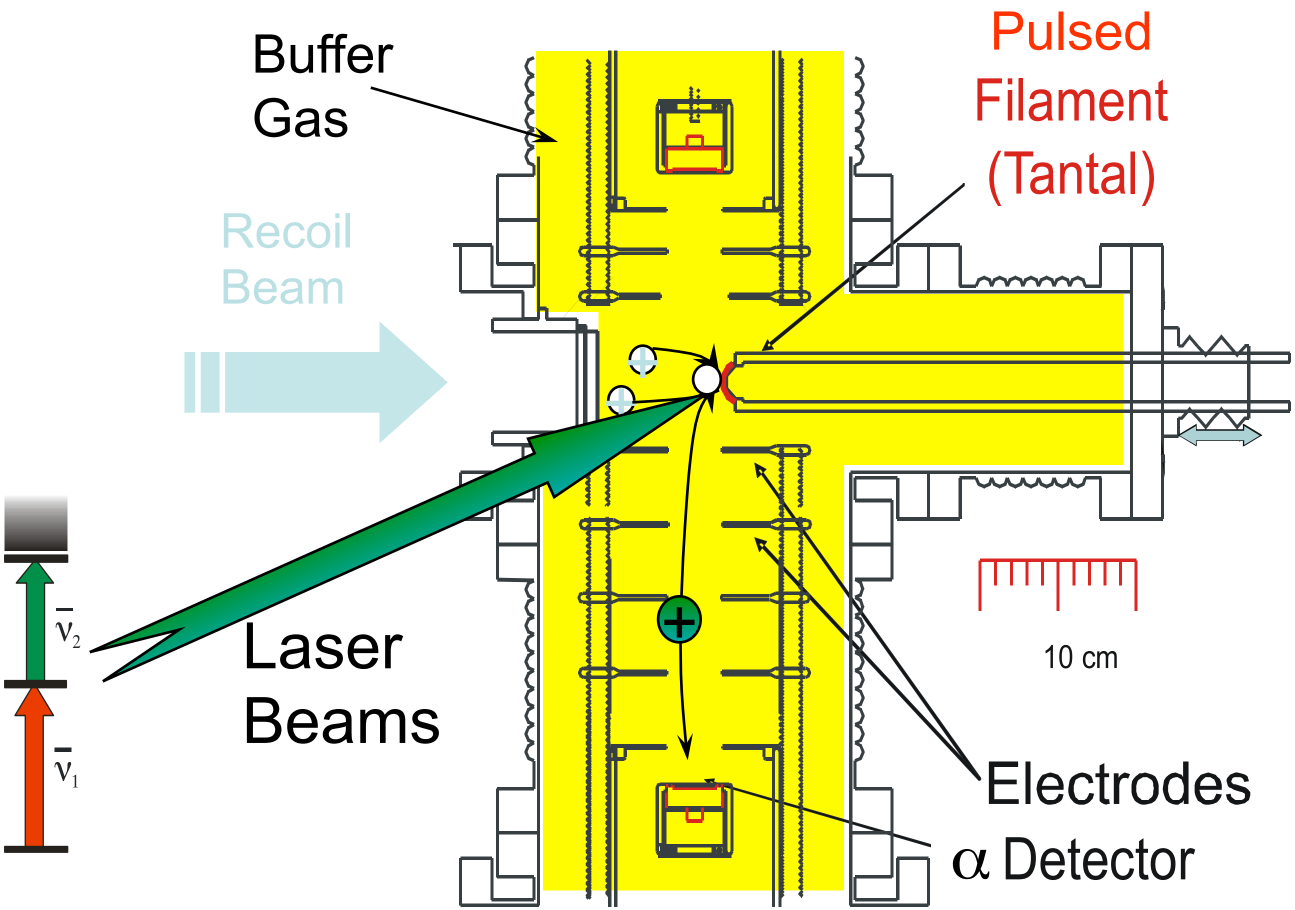
- Calculations benchmarked by comparison to homologs
- Uncertainties large from compared to experimental resolution

Experiment:

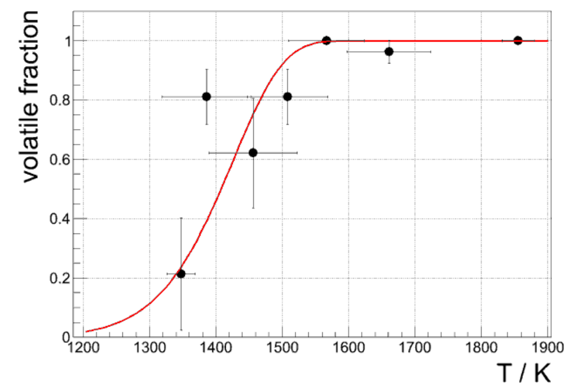
- two step RIS with non-resonant second step excitation
- search for $^1P_1$ level in range predicted by different theories
- determine IP from Rydberg series

[1],[2]: S. Fritzsche, Eur. Phys. J. D 33 (2005) 15
[3]: A. Borschevsky et al., Phys. Rev. A 75 (2007) 042514
[4]: Y. Liu et al., Phys. Rev. A 76 (2007) 062503
[5]: P. Indelicato et al., Eur. Phys. J. D 45 (2007) 155
[6]: J. Sugar, J. Chem. Phys. 60 (1974) 4103

Resonant Ionization Laser Spectroscopy of Nobelium



Desorption of ^{254}No from Ta:



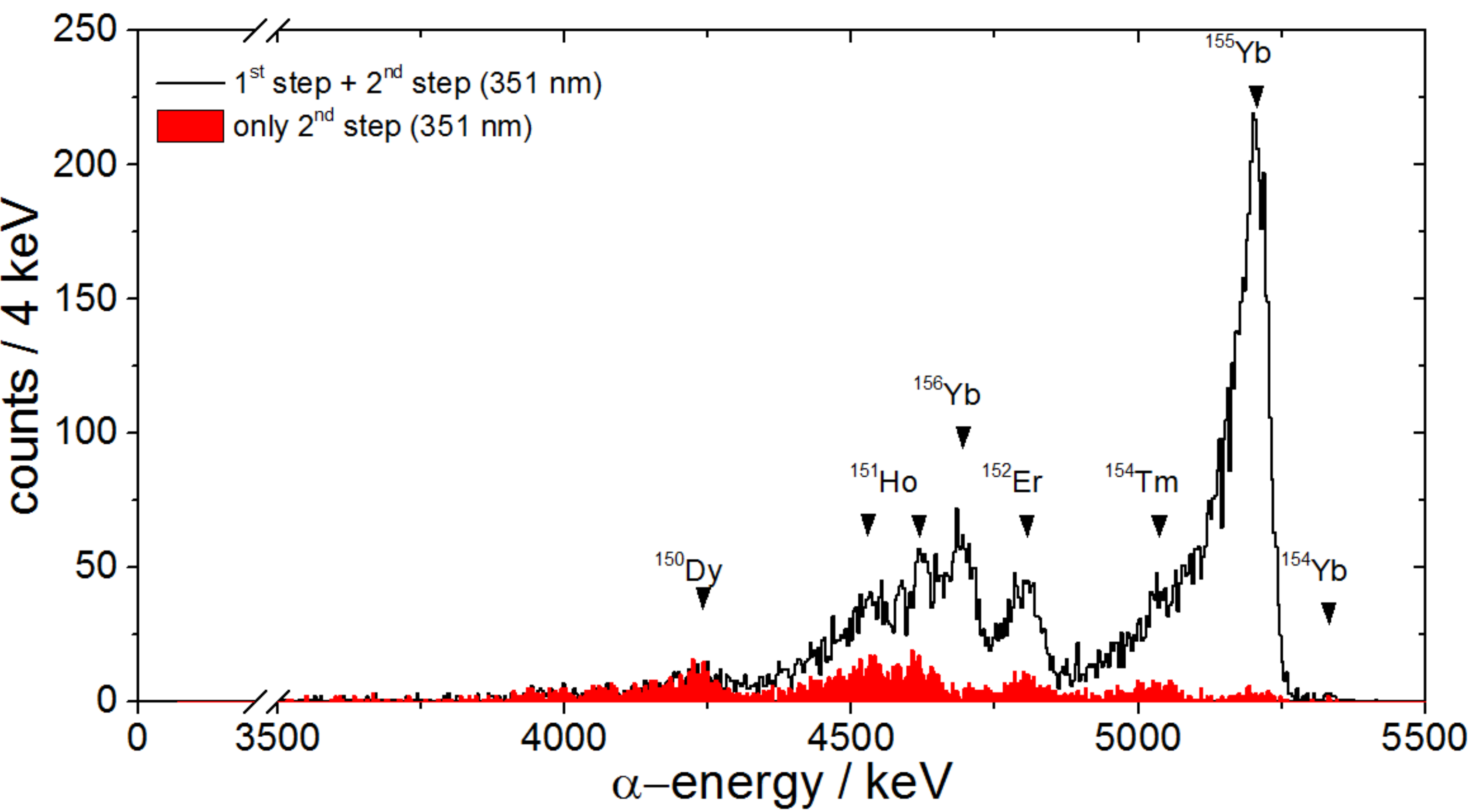
evaporation temperature

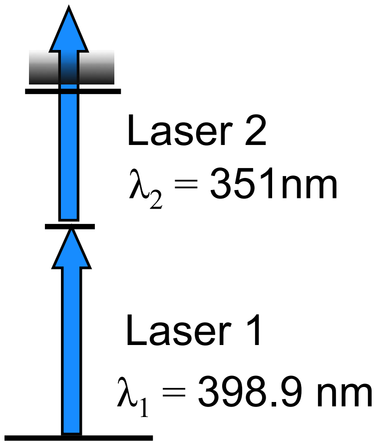
1350(20) K

M.Laatiaoui et al., Eur. Phys. J. D 68 (2014) 71
H. Backe et al., Eur. Phys. J. D 45, 99 (2007)

Online-Experiment @ SHIP – October 2014

Homolog Yb (Z =70) $^{112}Sn(^{48}Ca,5n)^{155}Yb$ ($t_{1/2}$=1.75 s, α)





HELMHOLTZ ASSOCIATION
GSI
Helmholtz Institute Mainz

Superheavy Elements (SHE): a new collaboration in NUSTAR @ FAIR

Proposal to integrate new "Superheavy Element" subcollaboration in NUSTAR @ FAIR submitted to Board of Representatives (Summer '14)

Focus: synthesis, nuclear structure, atomic physics, nuclear chemistry experiments in region Z ≥ 100

Existing facilties: SHIP, TASCA, SHIPTRAP, Chemistry beamline
Developments for high-intensity cw-Linac ongoing (HIM, GSI, U Frankfurt)

Complementary to existing NUSTAR activities at Super-FRS

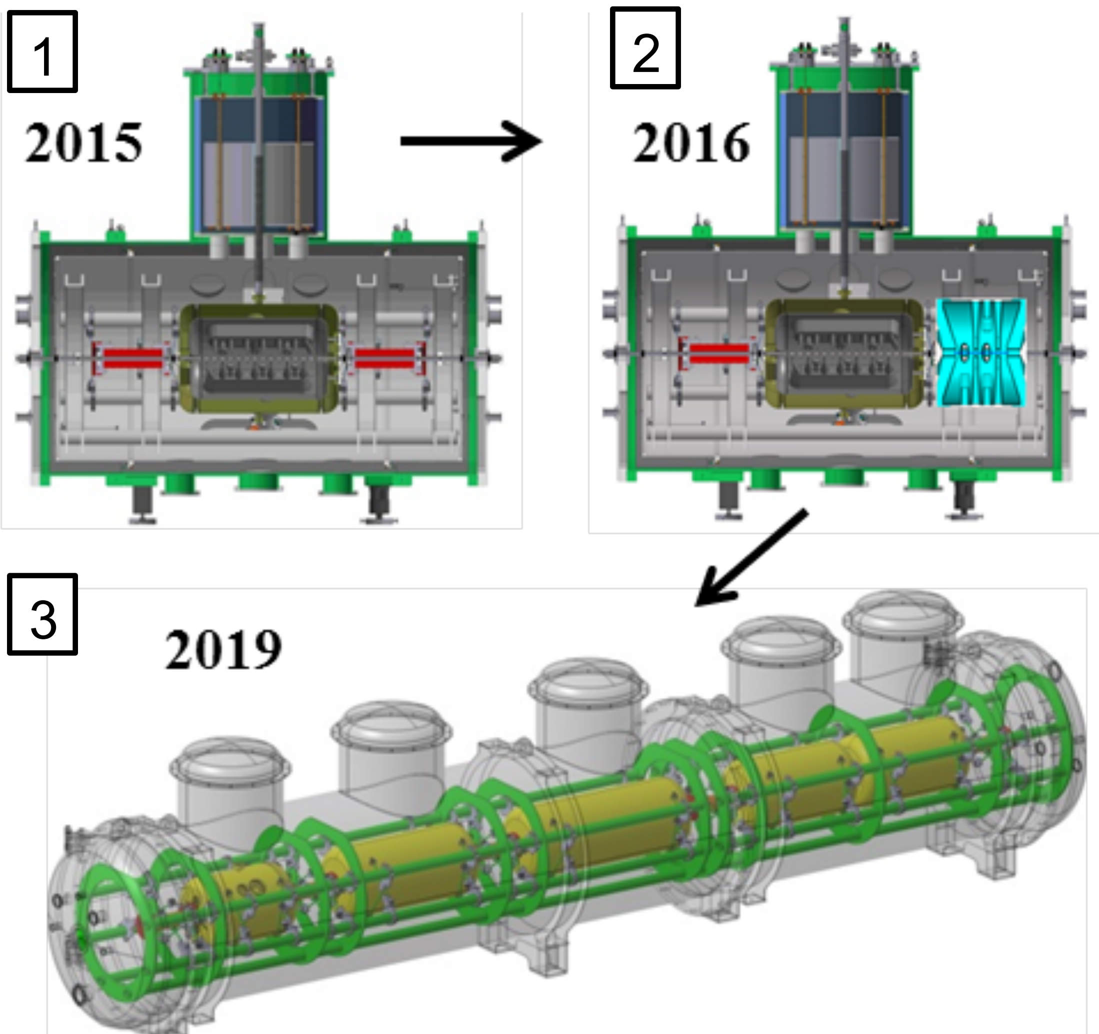
Organizational Structure:

Spokesperson:	R.-D. Herzberg (Univ. Liverpool)
Deputy:	M. Block (GSI/HIM)
Technical Director:	A. Yakushev (GSI)

Currently includes 9 German and 17 international institutes

Endorsed by NUSTAR Collaboration Committee: Sept. 25, 2014
submitted to FAIR management: Oct. 27, 2014

Staged Approach towards cw linac for SHE



1. Full performance test of sc cw LINAC Demonstrator

- @GSI HLI
- proof of principle

2. Full performance test of a shorter sc cavity

- energy variation (by Ampl & Phase)
- 8 gaps
- simpler design
- easier to fabricate

3. Advanced Demonstrator

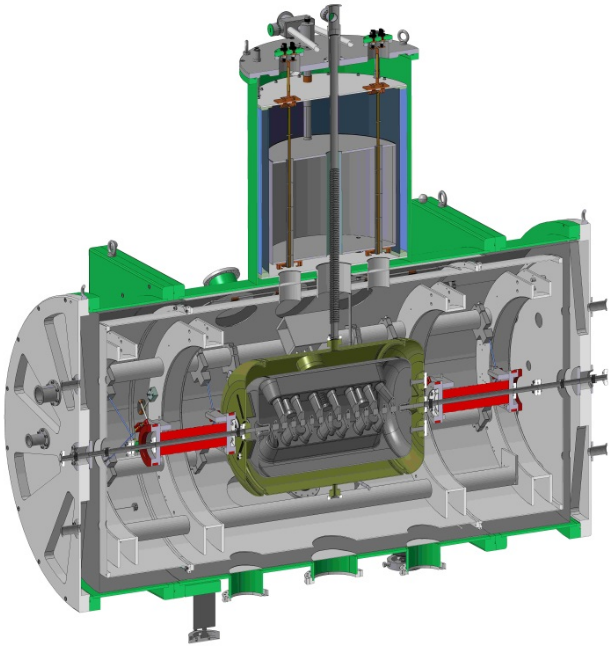
- up to 4.61 MeV/u @ $A/Q = 6$
- 5× sc CH-Cavity, 5× sc Solenoid
- possible to place in HLI@GSI

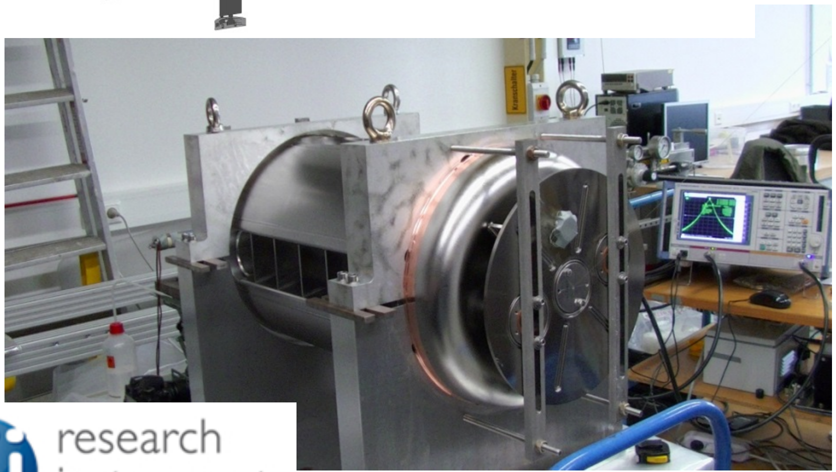
cooperation: GSI, HIM, Uni Frankfurt

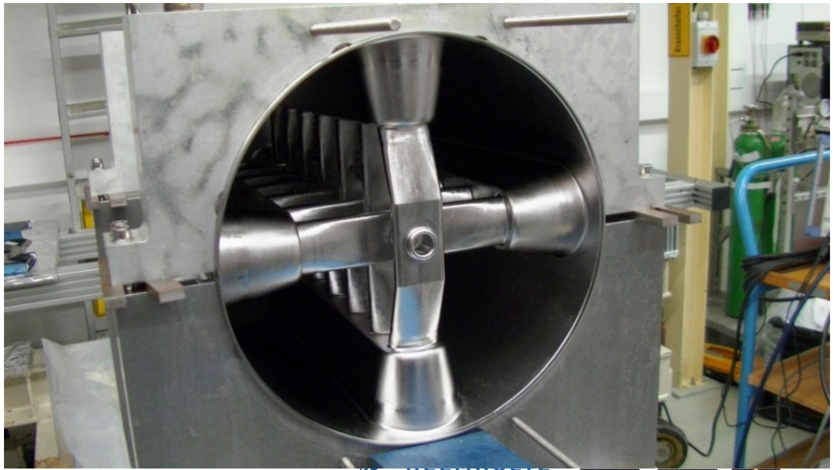
HELMHOLTZ ASSOCIATION

Material courtesy of V. Gettmann / W. Barth

First components – October 2014







research instruments

ASSOCIATION GSI

Helmholtz Institute Mainz

Conclusions and Perspectives

- Recent attempts to synthesize new elements 119 and 120 yield cross section limits of about 70 fb
- New attempts demand high-intensity stable beam accelerator
- x-ray finger printing provides practical method to pin down odd-*Z* elements 113, 115, 117 unambiguously
- High-precision mass measurements adds powerful tool to map strength and location of shell closures
- laser spectroscopy probes relativistic effects on the atomic structure and gives access to nuclear properties (spins, moments)

Thank you for your attention !

HELMHOLTZ ASSOCIATION GSI

Helmholtz Institute Mainz

This page is left intentionally blank

TASCA High Power Target Wheel used for E119 at GSI

Ø Target Wheel: 100 mm
Ø Beam Spot: 8 mm

Target wheel with Gd tested up to 2500 particle·nA

Cf 249
350.6 a
α 5.812; 5.758..
sf; γ 388...; g

↖ β^-

Bk 249
320 d
β^-; α 5.419;
5.391...; sf; γ

March 6, 2012:
^{249}Bk arrives in Mainz

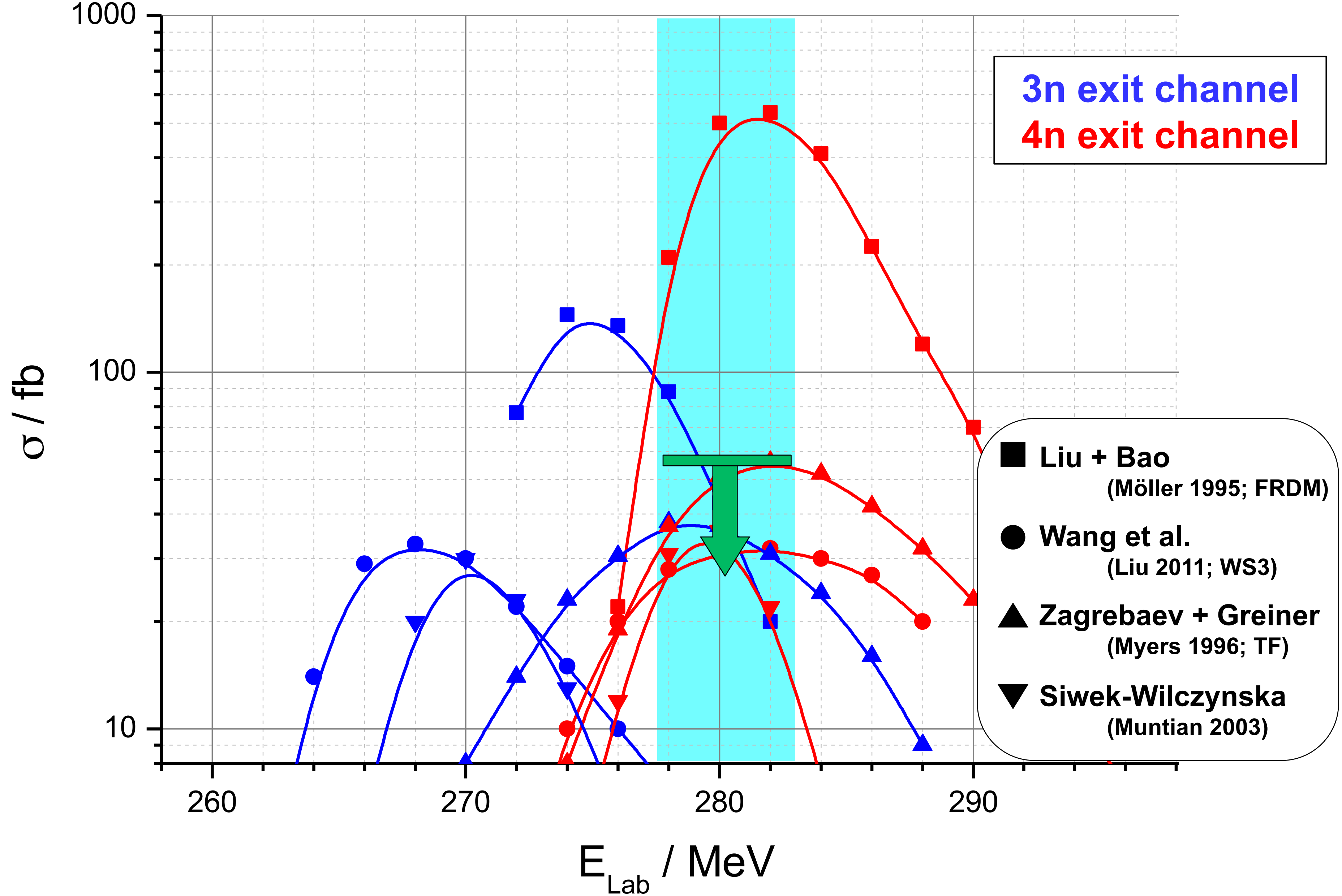
March 23, 2012:
Targets arrive at GSI

April 12, 2012:
Targets mounted in TASCA

April 14, 2012:
Begin Element 119 search

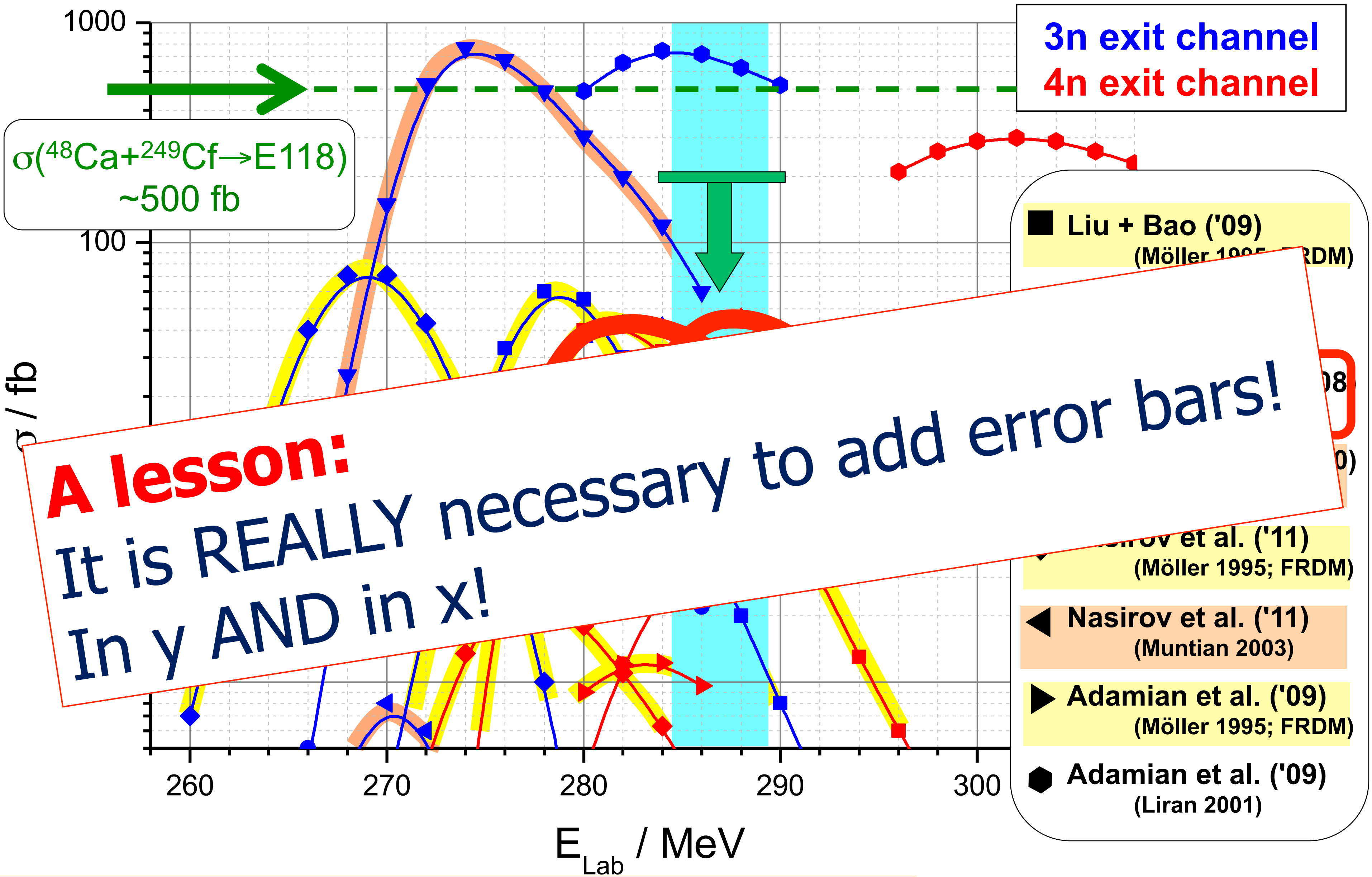
Wheel system: E. Jäger *et al*., J. Radioanal. Nucl. Chem.; in print
Bk Target: J. Runke *et al*. J. Radioanal. Nucl. Chem.; in print

$^{50}Ti + ^{249}Bk$ Excitation Function



Courtesy Ch.E. Düllmann

$^{50}Ti+^{249}Cf$ Excitation Function

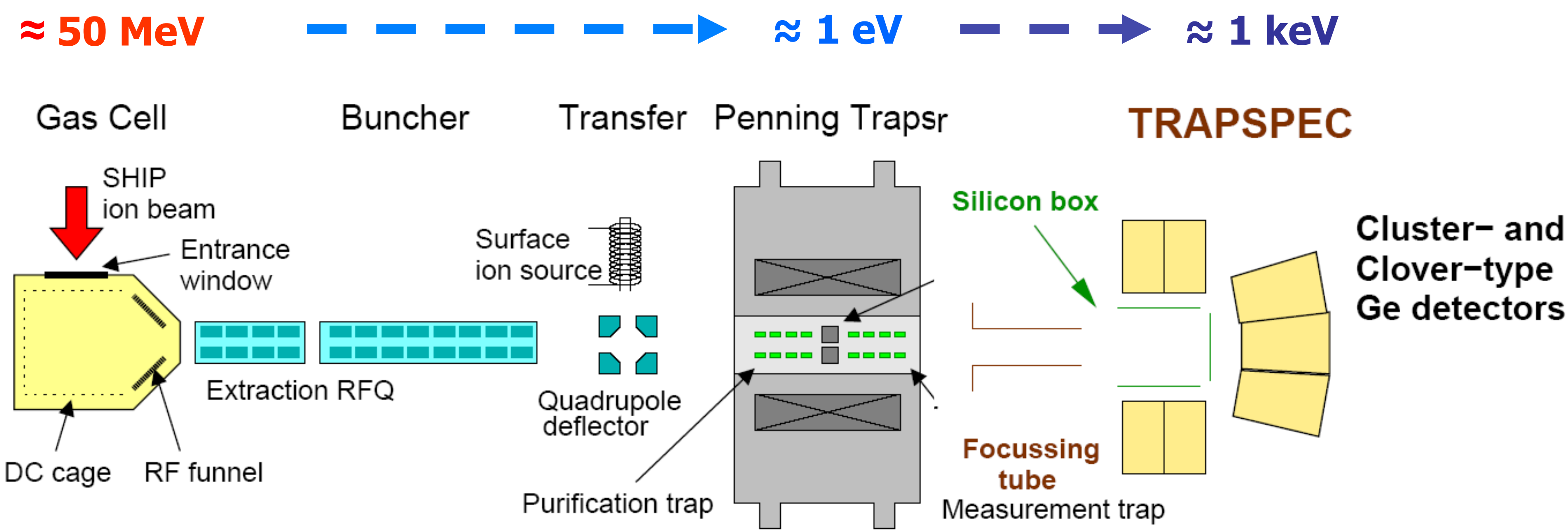


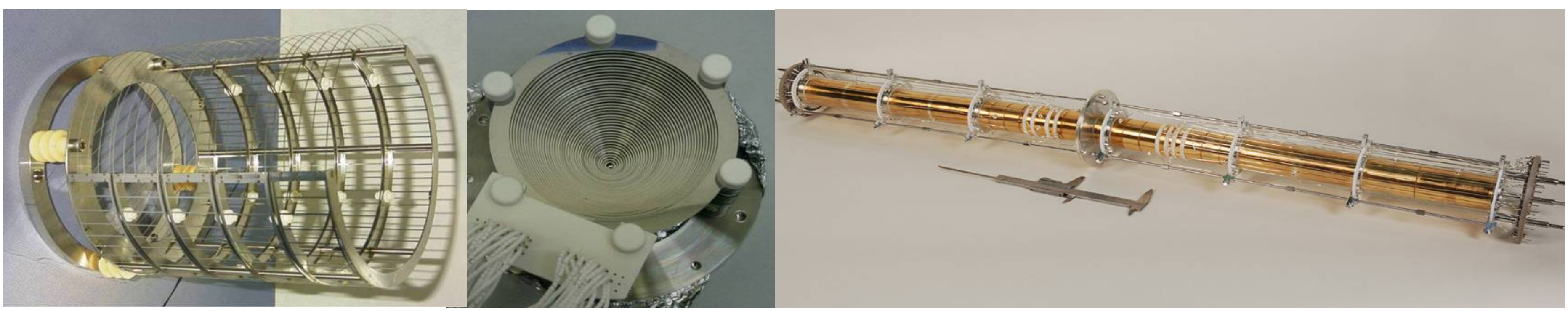
A lesson:

It is REALLY necessary to add error bars!

In y AND in x!

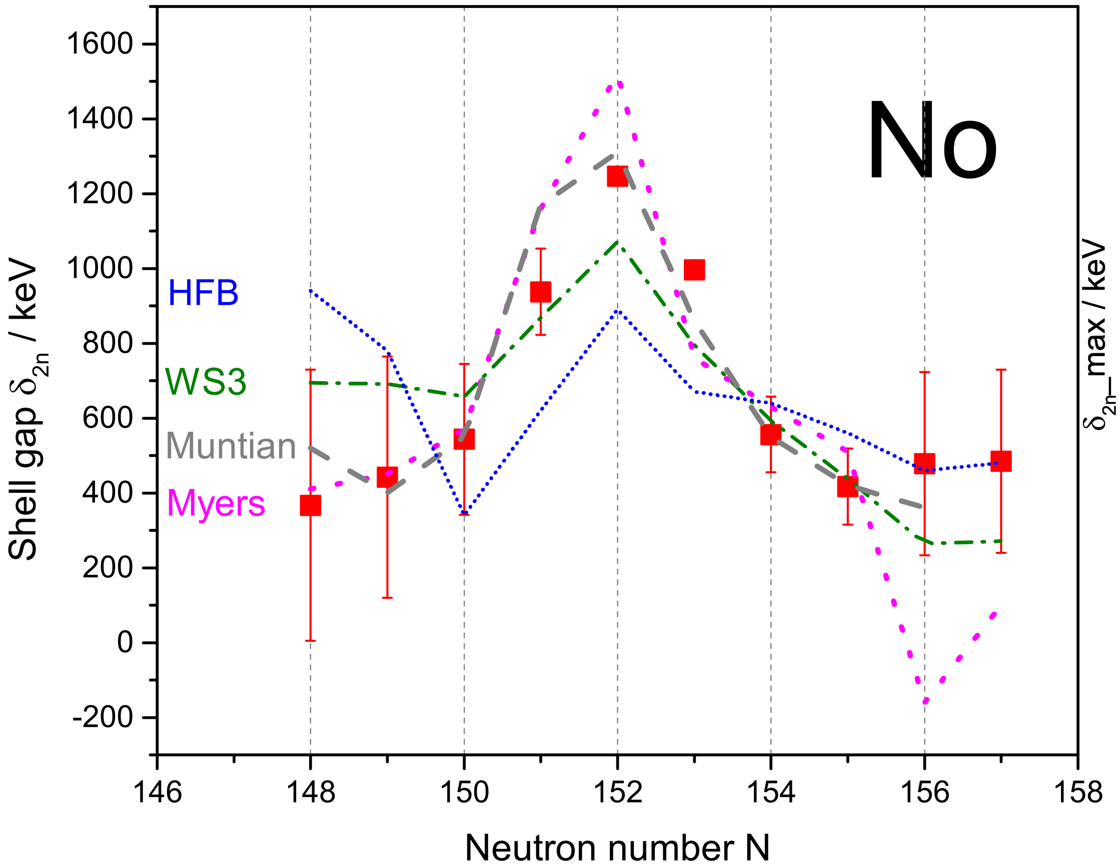
SHIPTRAP Setup

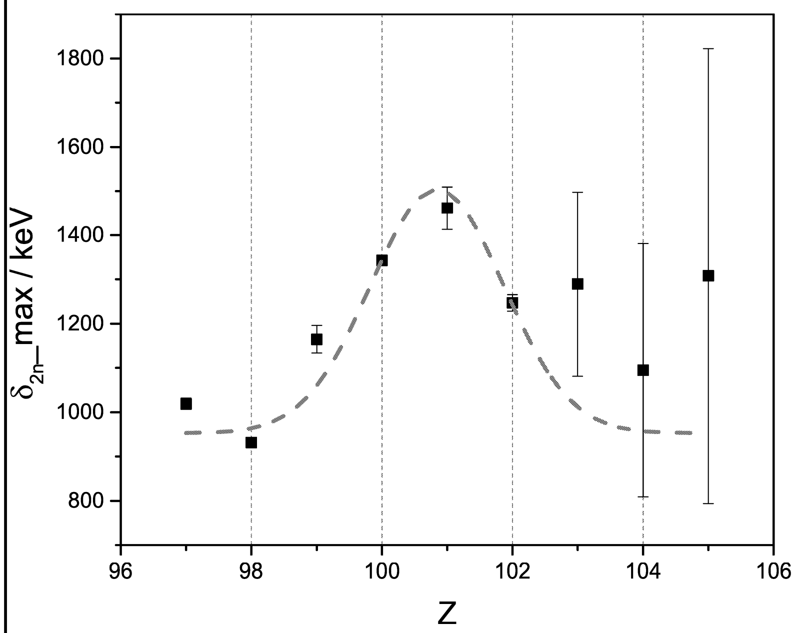




SHIPTRAP: Probing the Strength of Shell Effects

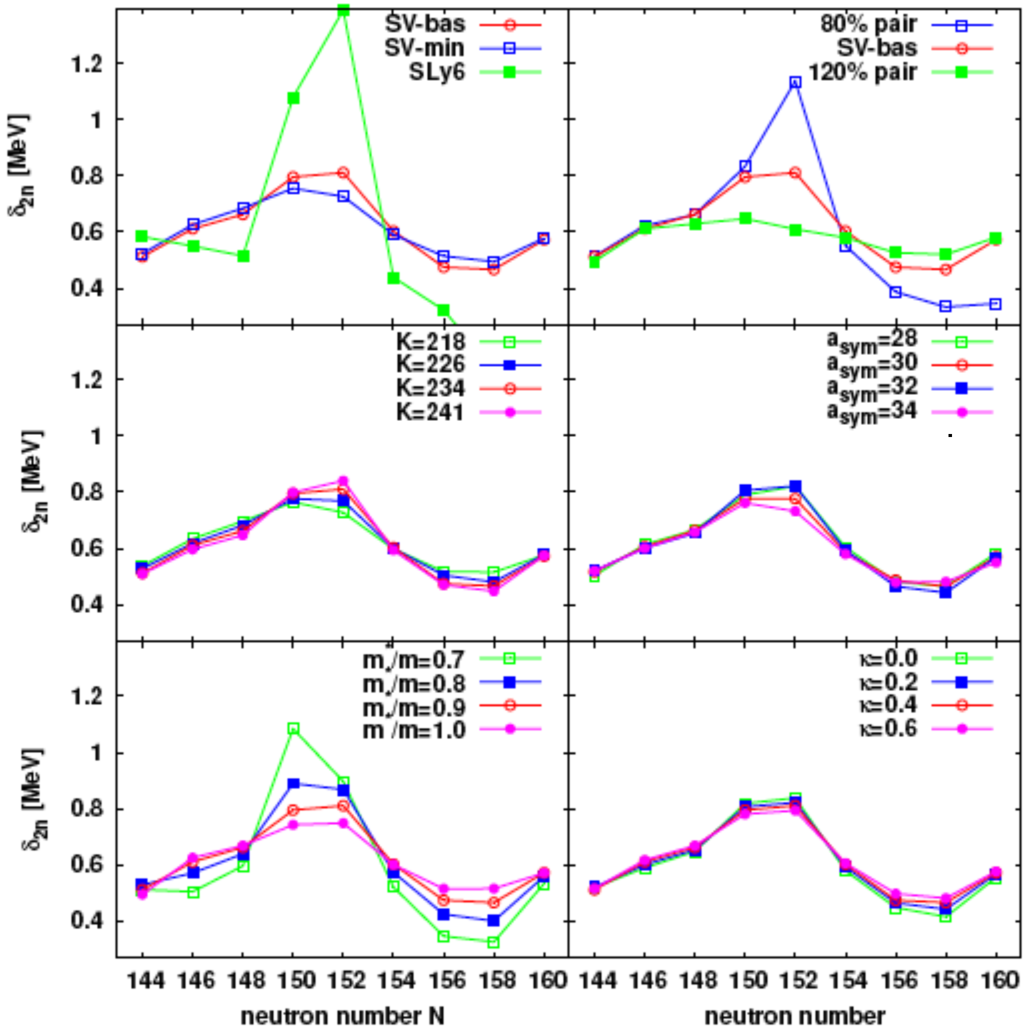
$$\delta_{2n}(N,Z) = 2B(N,Z) - B(N-2,Z) - B(N+2,Z)$$



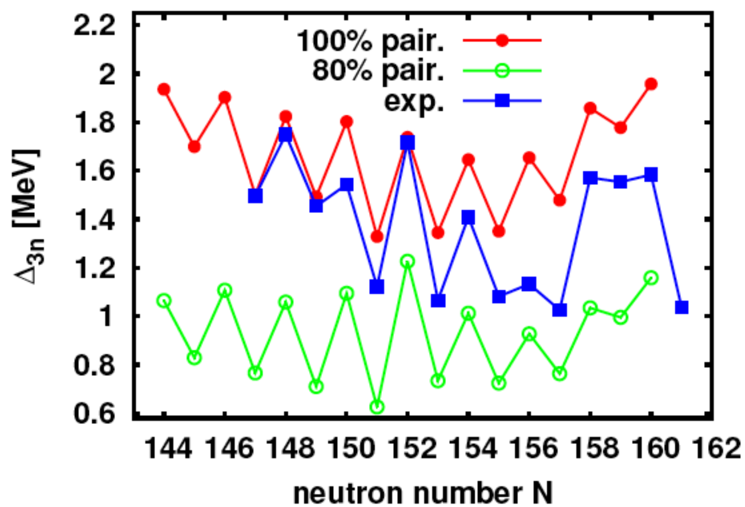


Calculations with Skyrme Forces

No isotopes



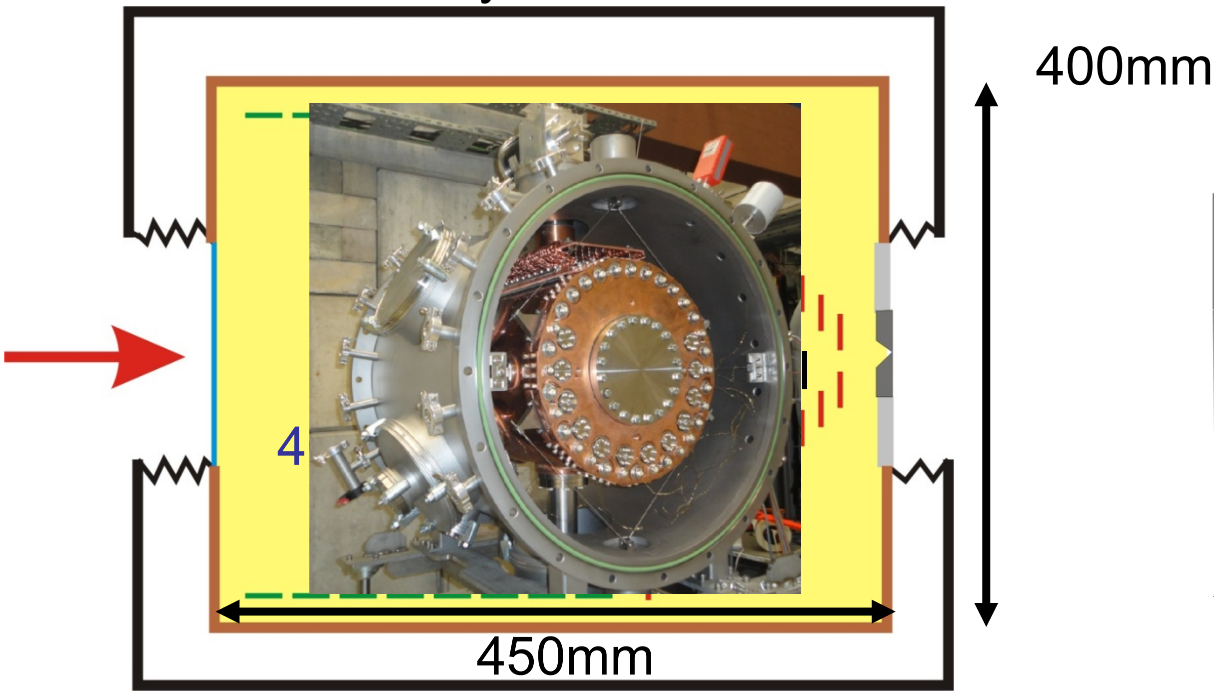
3-point difference (pairing gap), No isotopes



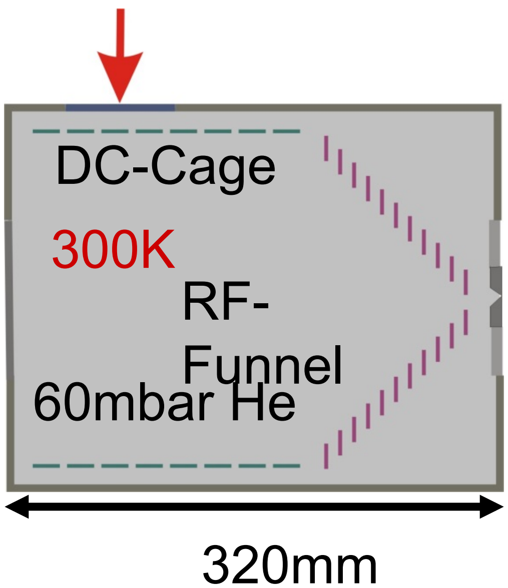
P. G. Reinhard

CryoCell Setup

Cryo Cell



Gas Cell

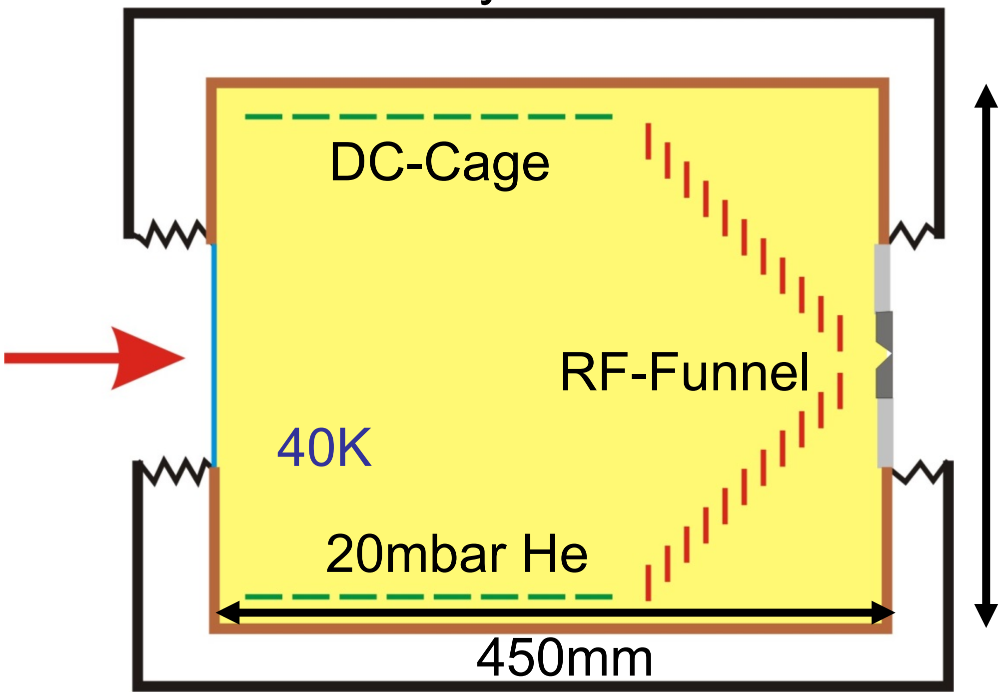


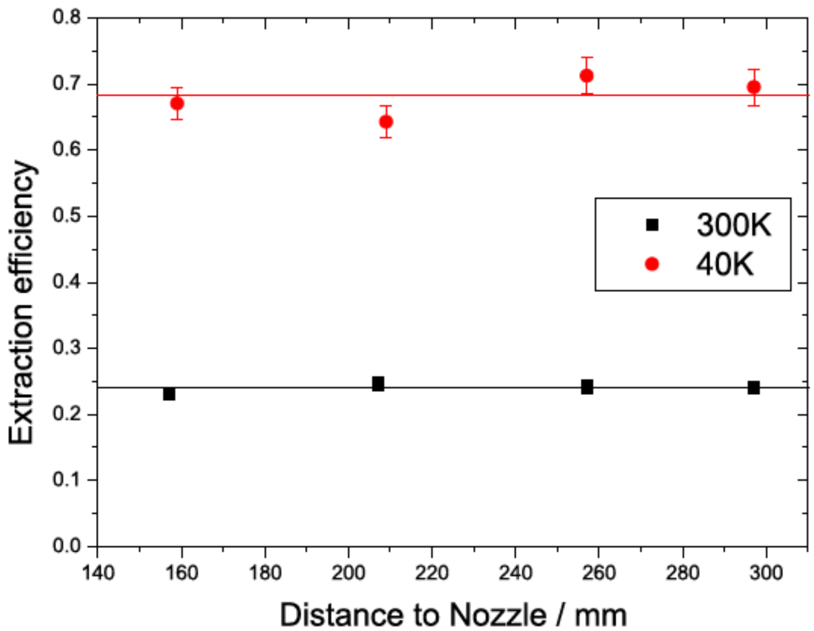
Advantages compared to 1st generation gas cell:

- Larger stopping volume and Coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Larger gas density at a lower absolute pressure

C. Droese et al. NIM B 338, 126 (2014)

CryoCell Setup



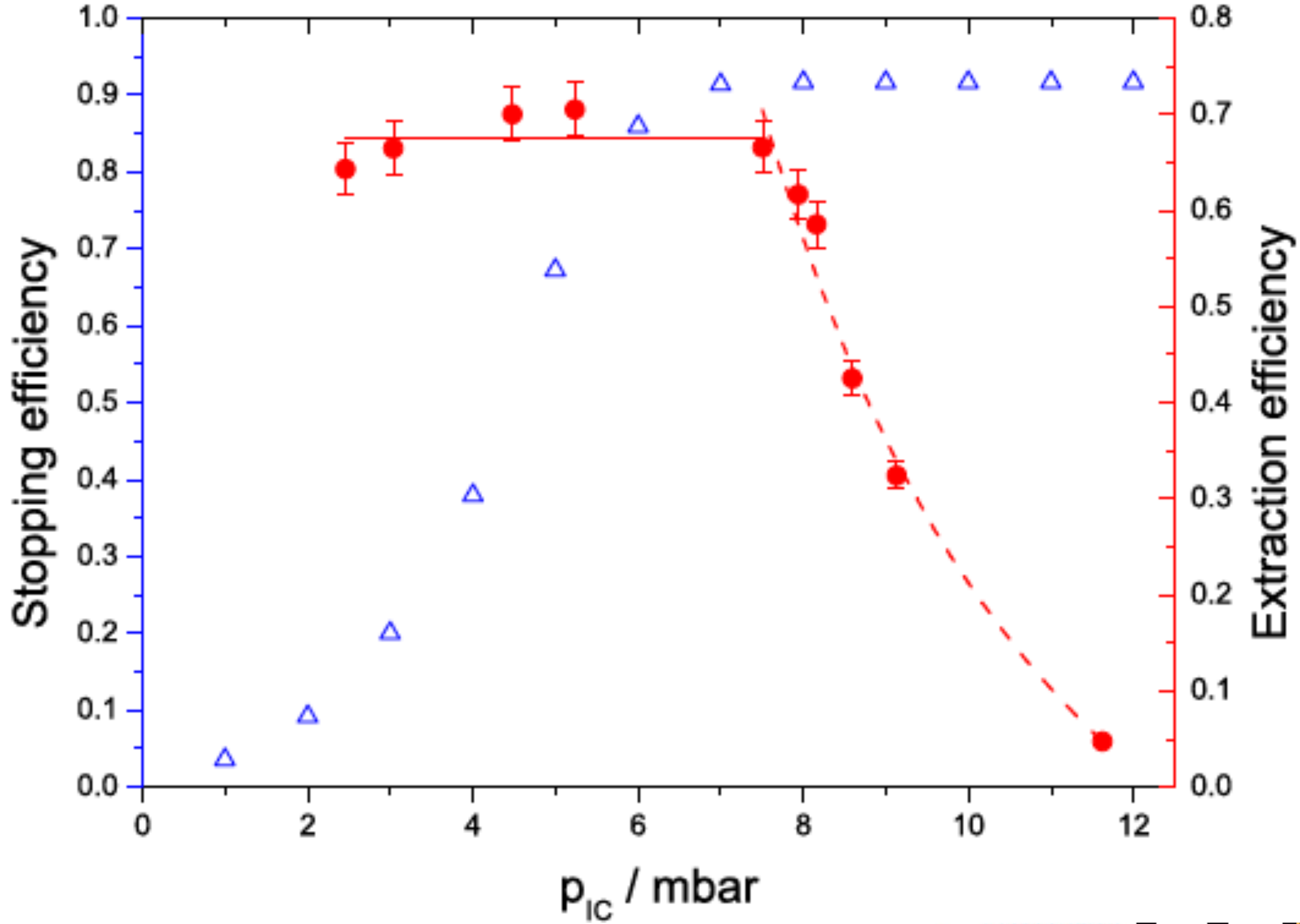


Advantages compared to 1st generation gas cell:

- Larger stopping volume and Coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Larger gas density at a lower absolute pressure

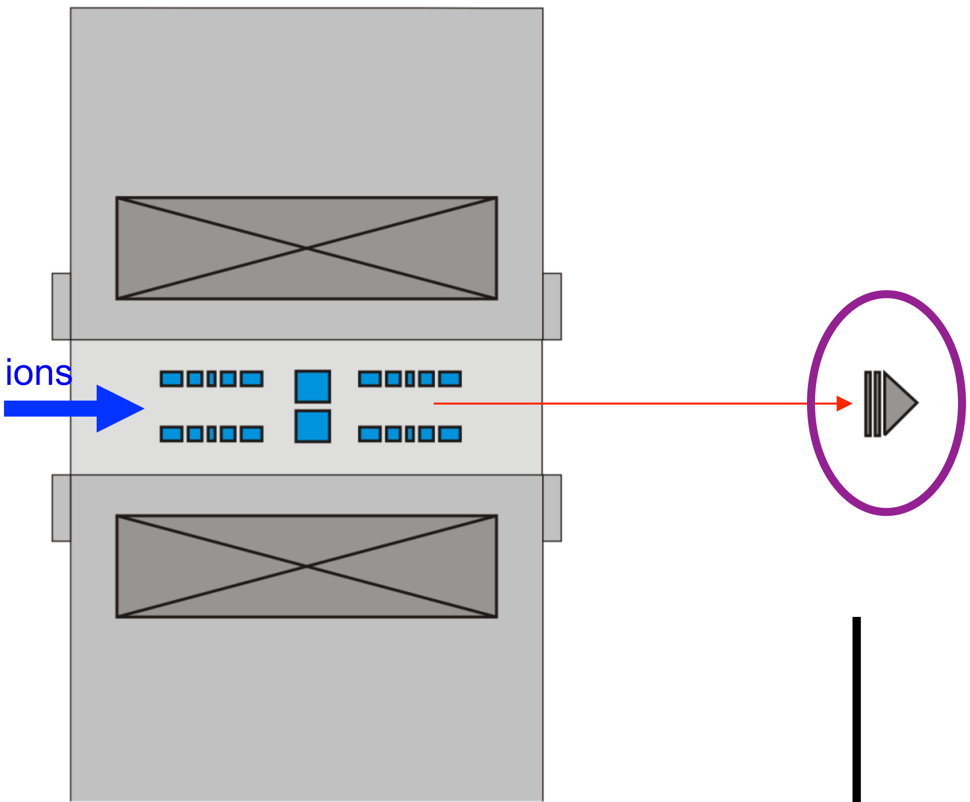
C. Droese et al. NIM B 338, 126 (2014)

HELMHOLTZ ASSOCIATION GSI

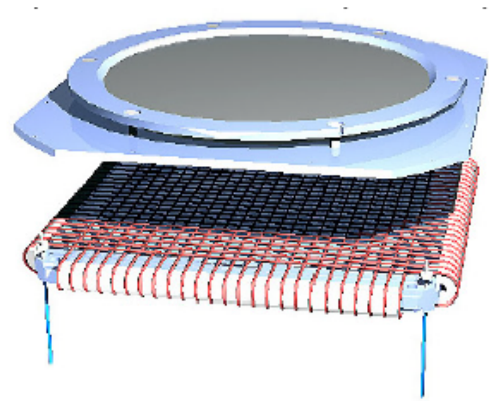


Stopping efficiency
Extraction efficiency
p_{IC} / mbar
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 2 4 6 8 10 12

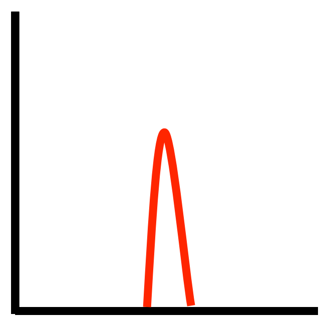
Phase Imaging Ion Cyclotron Resonance (PI-ICR)

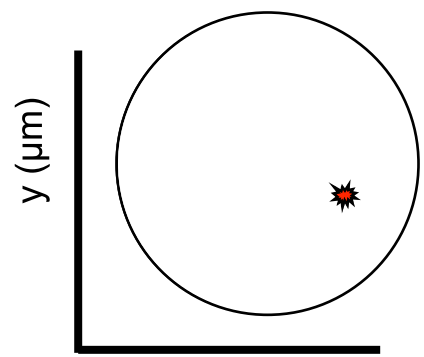


Delay-Line Detector by Roentdek GmbH



Position sensitive detector

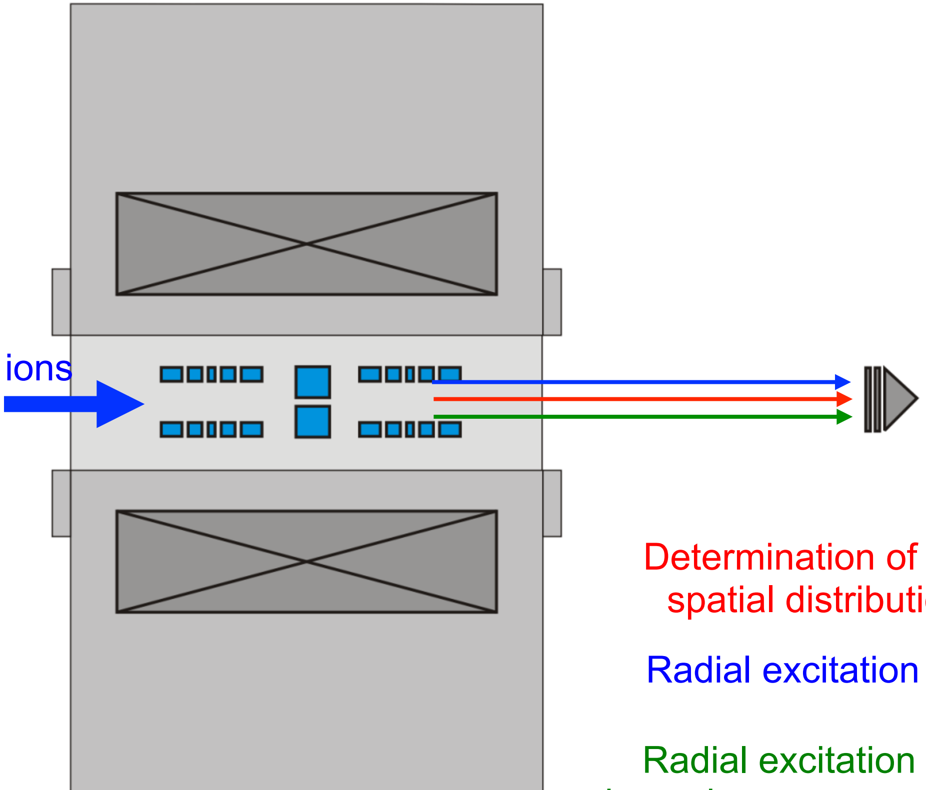




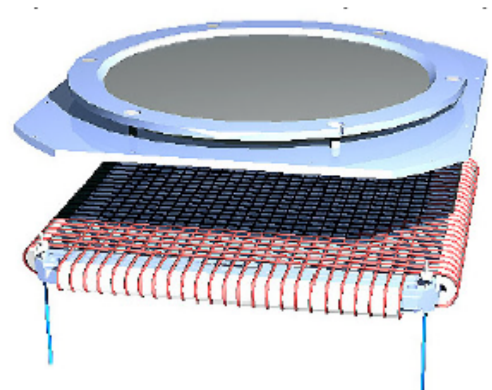
- **position resolution : 70 µm**
- **active diameter : 42 mm**

HELMHOLTZ ASSOCIATION GSI

Phase Imaging Ion Cyclotron Resonance (PI-ICR)



Delay-Line Detector by Roentdek

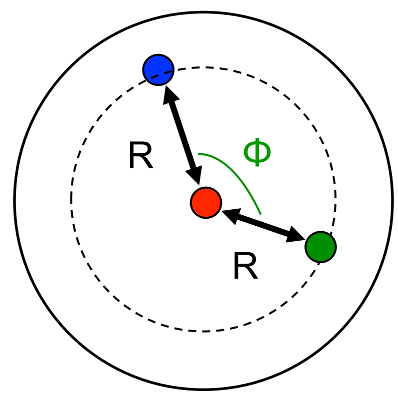


Independent Measurements of Eigenfrequencies ν_+ and ν_-

Determination of the spatial distribution

Radial excitation

Radial excitation followed by a phase accumulation time



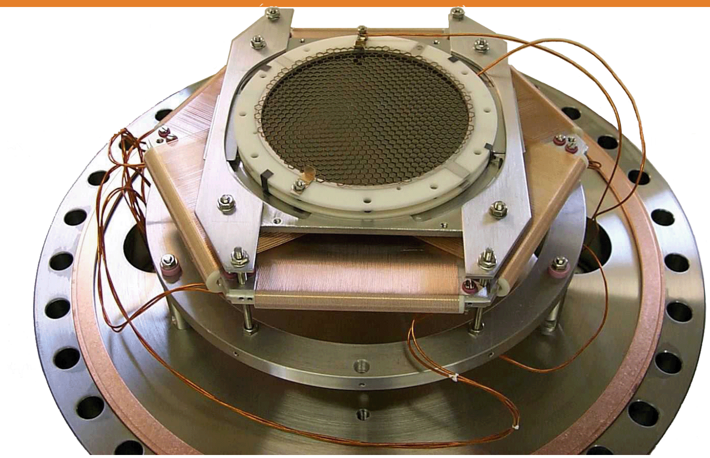
$$\phi + 2\pi n = 2\pi \nu t$$

$$\Delta\nu = \frac{\Delta\phi}{2\pi t} = \frac{\Delta R}{\pi t R}$$

HELMHOLTZ ASSOCIATION GSI

position-sensitive delayline detector (RoentDek GmbH DLD40)

Active diameter	42 mm
Channel diameter	25 µm
Open area ratio	>50 %
Position resolution	**70 µm**
Max. B-field	**a few mT**
Time resolution	~ 10 ns



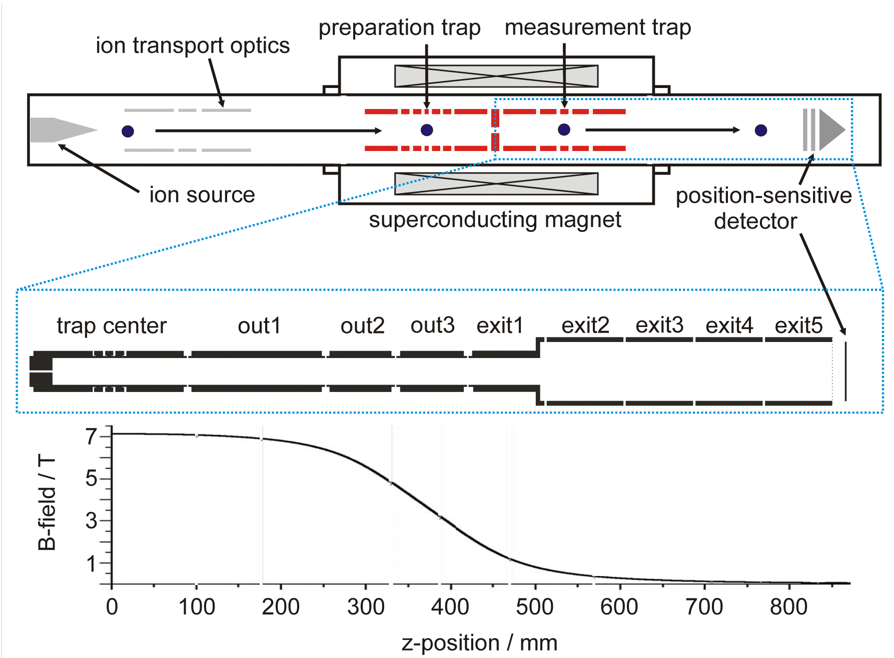
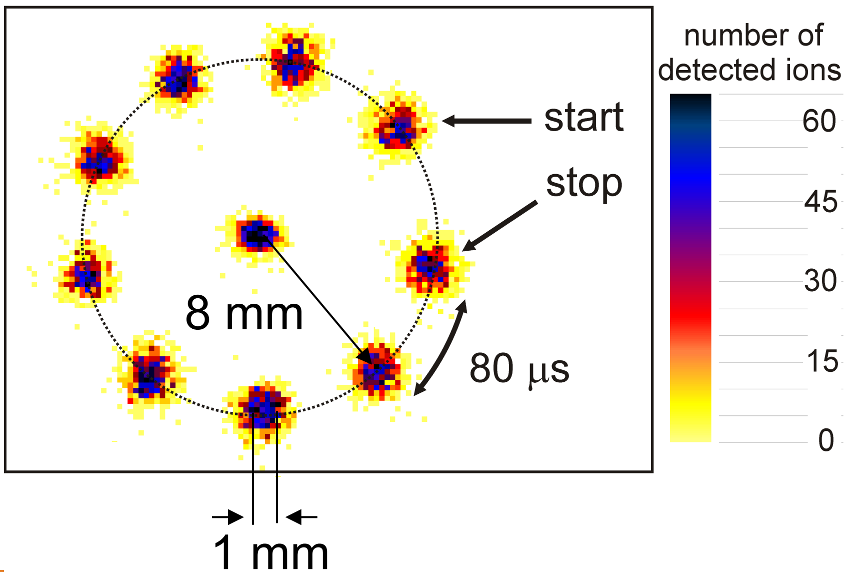
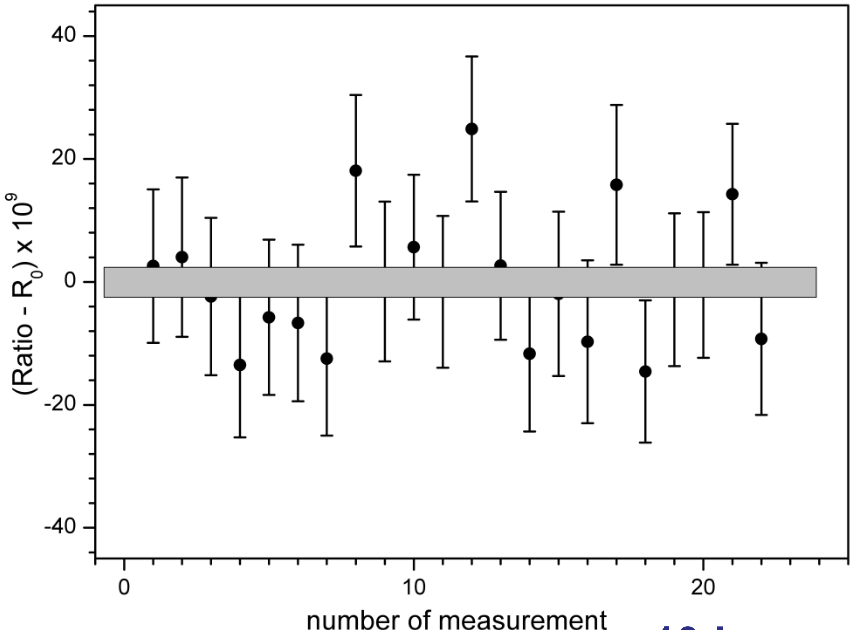


image of magnetron motion (*G* ” 20)

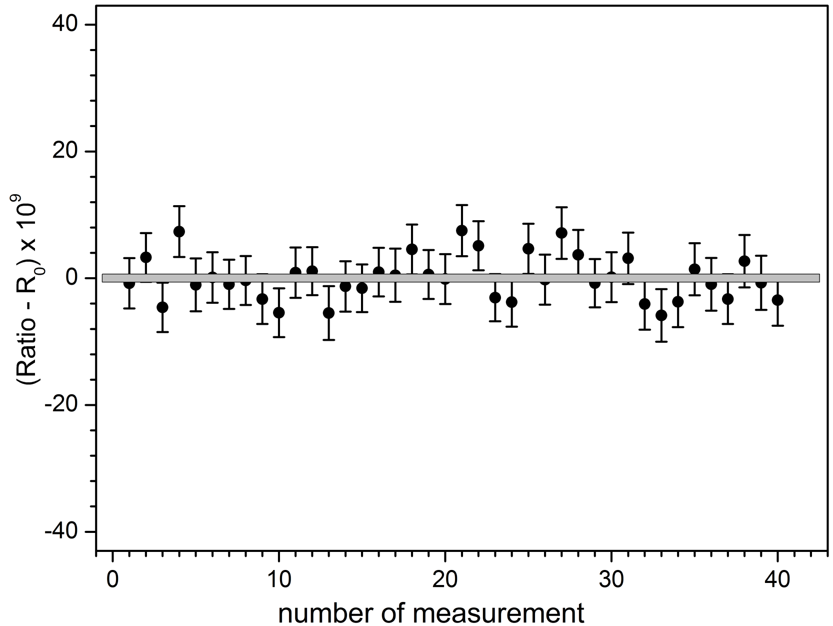


PI-ICR vs. ToF-ICR in experiment

ToF-ICR



PI-ICR



10-hour measurements

$\delta[M(^{124}Xe) - M(^{124}Te)] \sim 300$ eV

$\delta[M(^{132}Xe) - M(^{131}Xe)] \sim 70$ eV !!!

Gain in Precision ~ 4.5 !!!

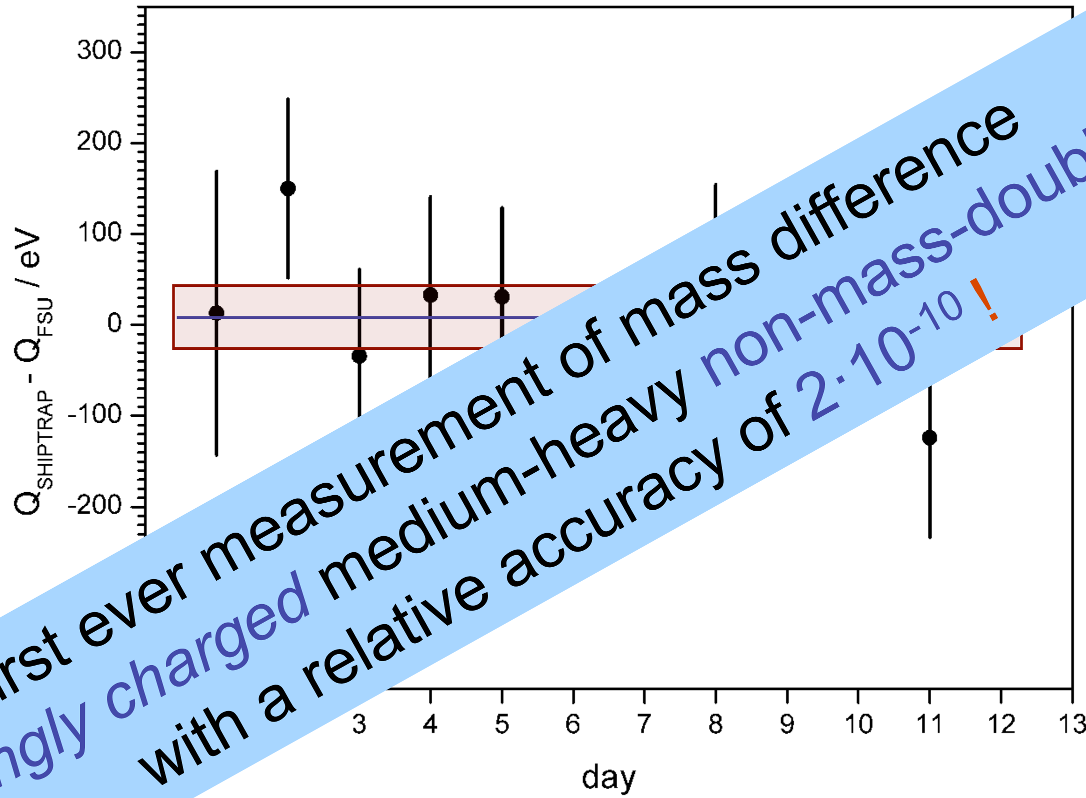
HELMHOLTZ ASSOCIATION

GSI

Helmholtz Institute Mainz

Veryfying the Accuracy of PI-ICR

$$\Delta M = M(^{132}Xe) - M(^{131}Xe)$$



first ever measurement of mass difference
of *singly charged* medium-heavy *non-mass-doublets*
with a relative accuracy of $2 \cdot 10^{-10}$!

$$(\Delta M)_{SHIPTRAP} = (30_{stat})(12_{sys})\ eV$$

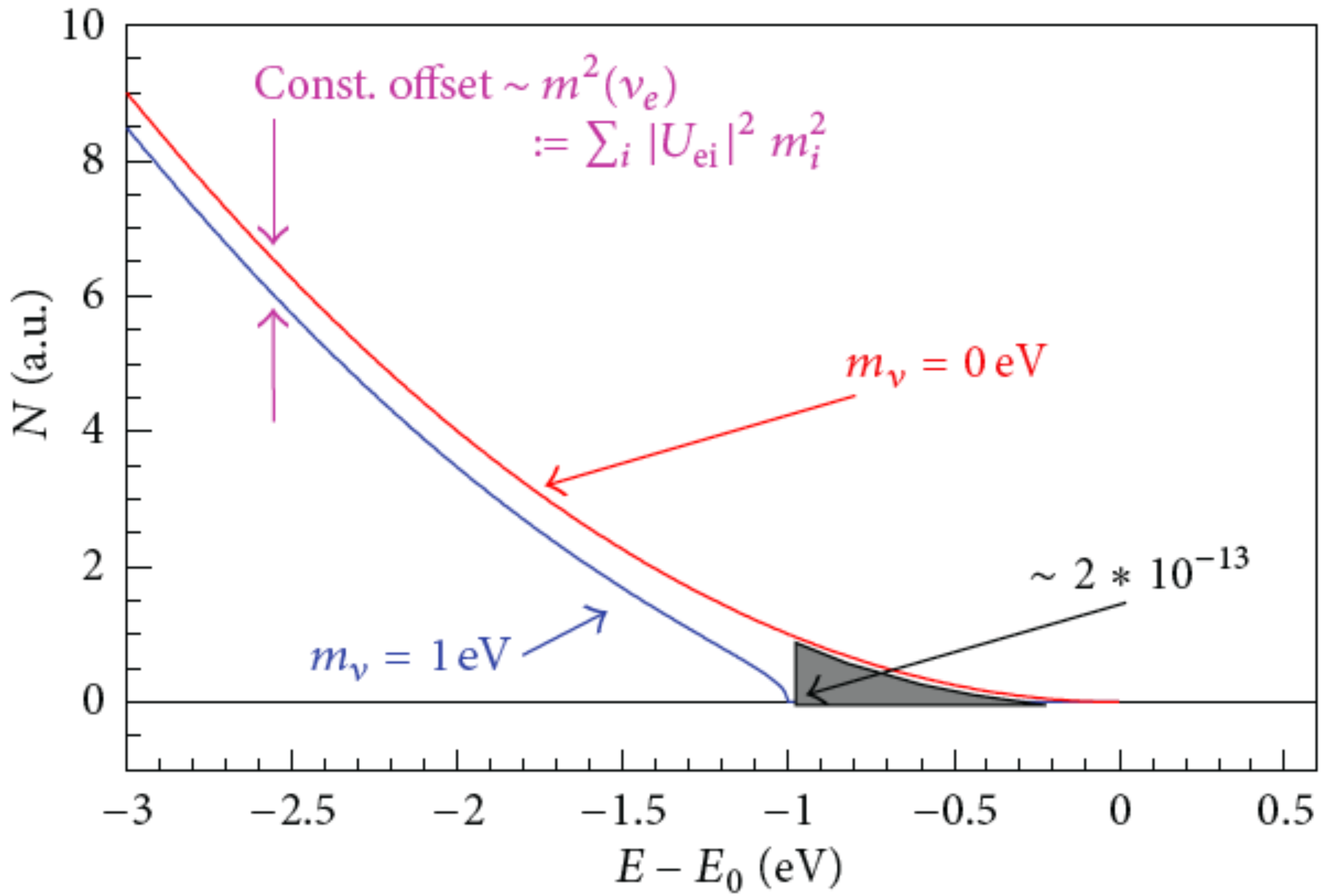
$$\Delta M_{SHIPTRAP} - \Delta M_{FSU} = (8 \pm 35)\ eV$$

Neutrino mass determination via β/EC decay

beta transitions between **nuclear ground states** with very **low Q-values**

β^--decay of ^{3}H;	Q-value ≈ 18.6 keV	**KATRIN**
β^--decay of ^{187}Re;	Q-value ≈ 2.47 keV	**MARE**
EC in ^{163}Ho;	Q-value ≈ 2.55 keV	**ECHo** **HOLMES**

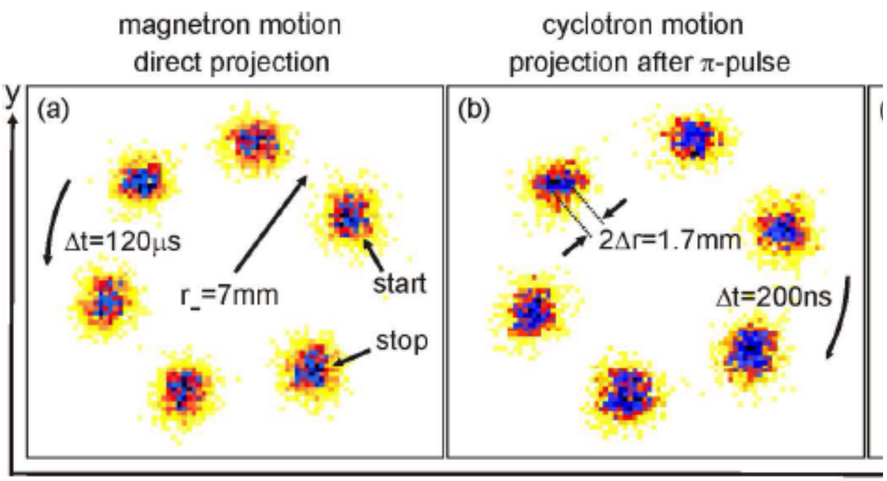
β⁻ decay endpoint measurement



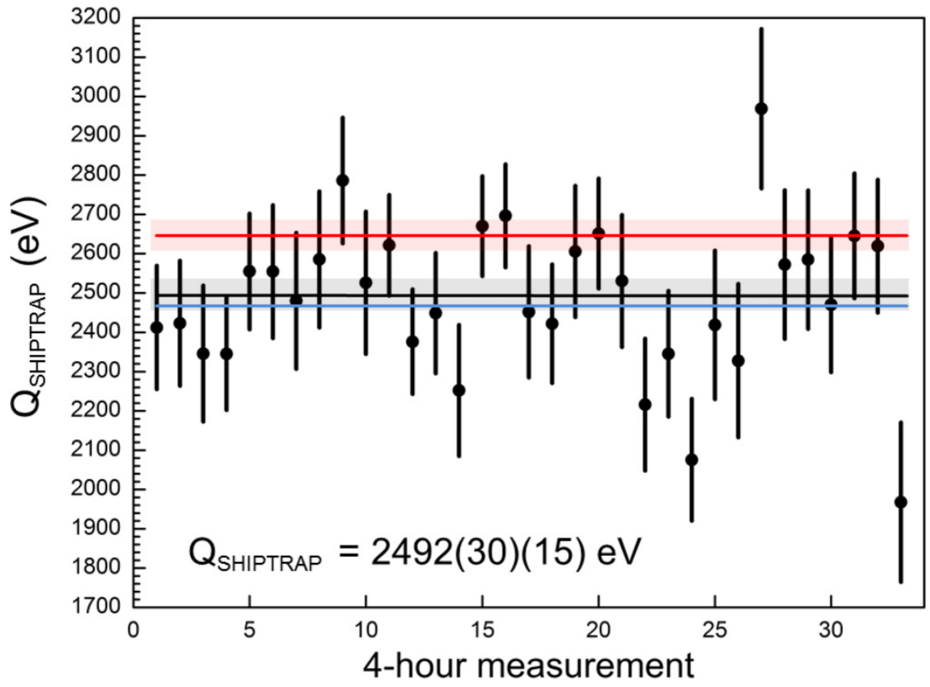
G. Drexlin, V. Hannen, S. Mertens, and C. Weinheimer
Advances in High Energy Physics Volume 2013 (2013)

HELMHOLTZ ASSOCIATION
Helmholtz Institute Mainz

PI-ICR measurements

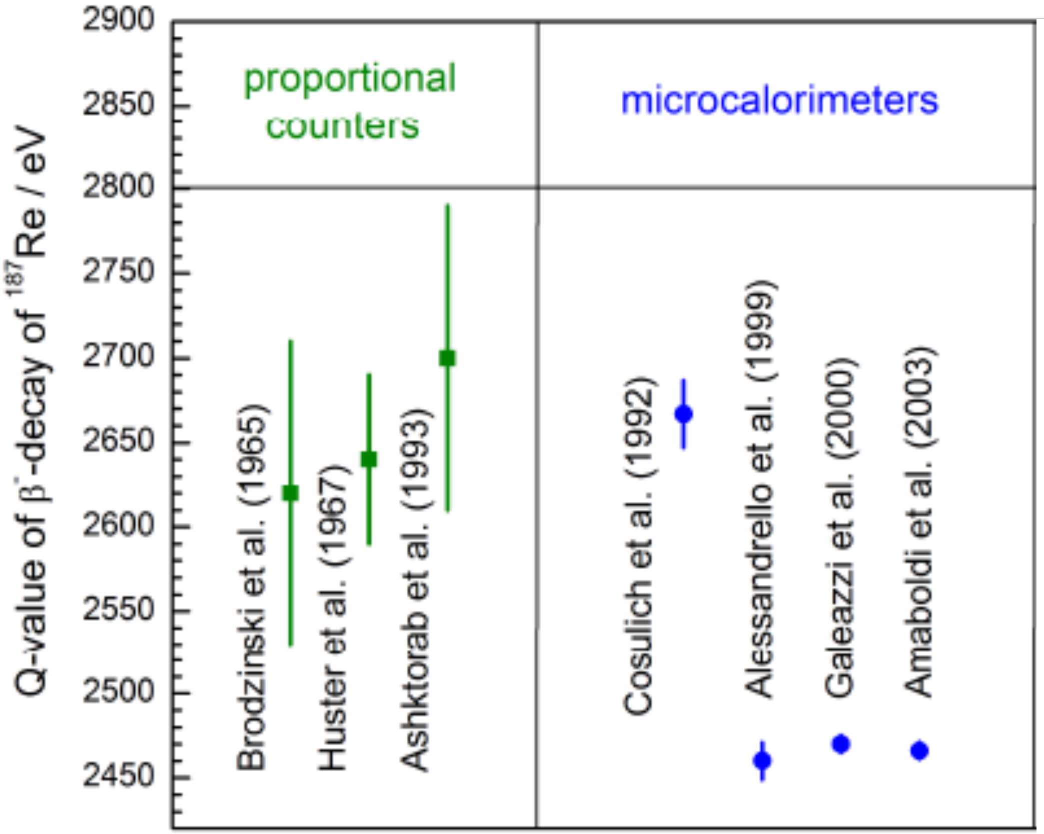


SHIPTRAP experiment on ^{187}Re-^{187}Os mass difference



S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013)
S. Eliseev et al., Appl. Phys. B (2014)
D. Nesterenko et al., Phys. Rev. C 90, 042501(R) (2014)

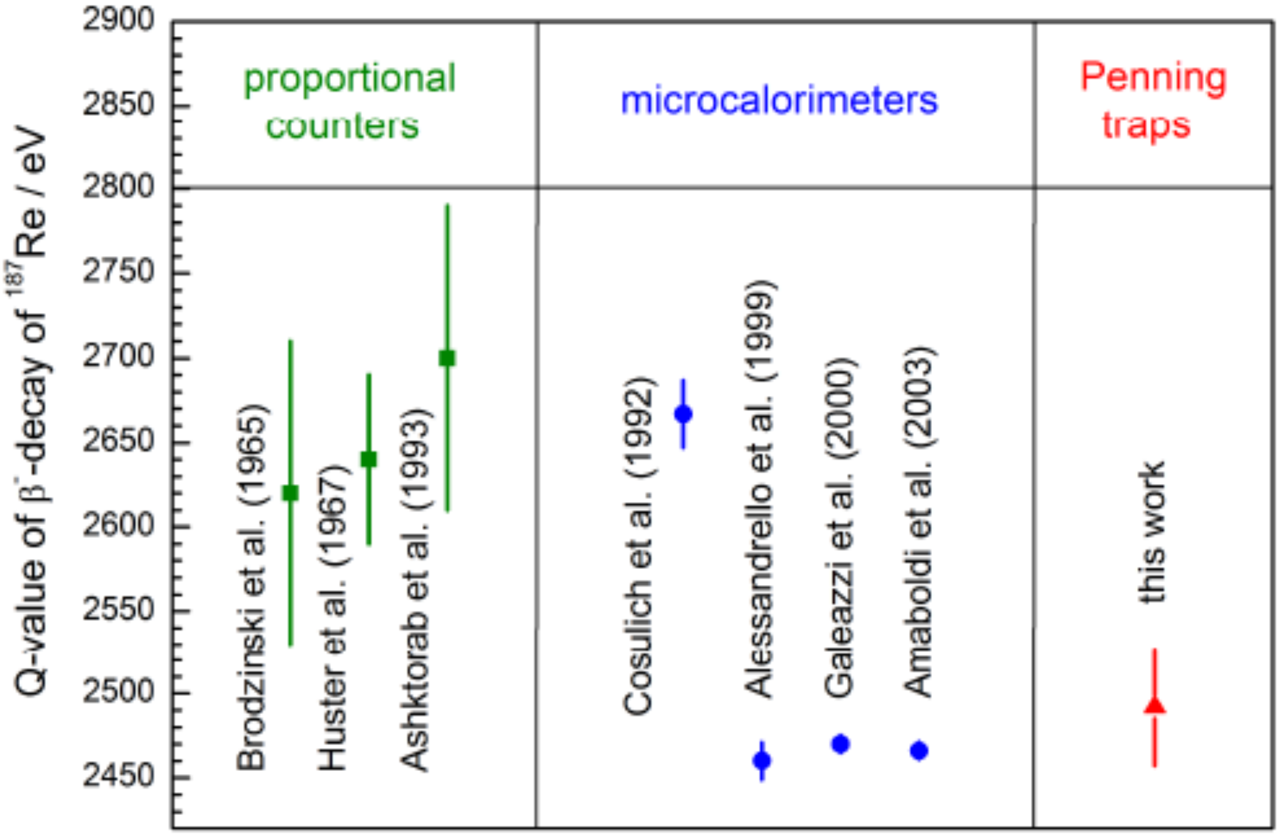
^{187}Re-^{187}Os mass difference measurement



- Large discrepancy between measurements by proportional counters and micro-calorimeters

D. Nesterenko et al., Phys. Rev. C 90, 042501(R) (2014)

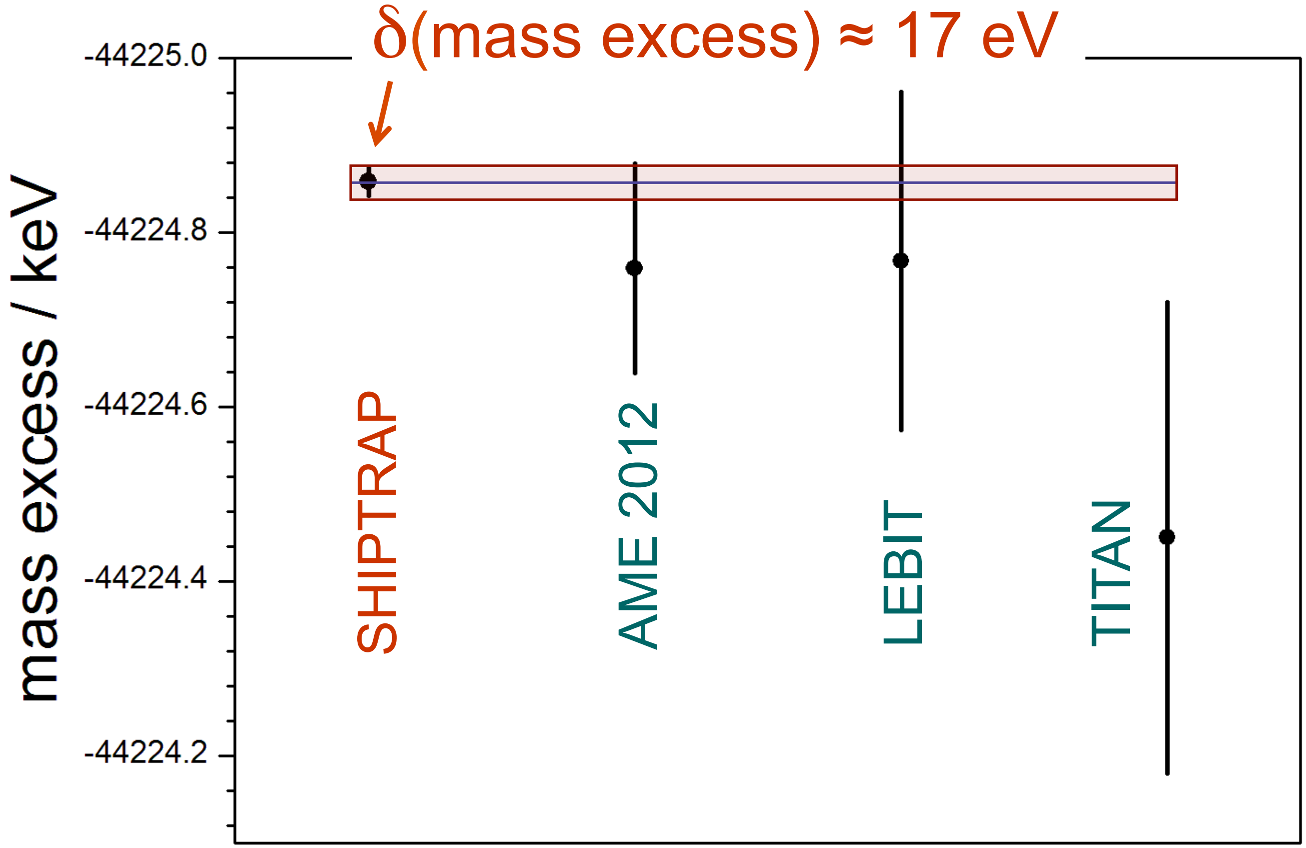
187Re/187Os mass difference measurement



- Large discrepancy between measurements by proportional counters and micro-calorimeters
- SHIPTRAP result confirms latest micro-calorimeter results

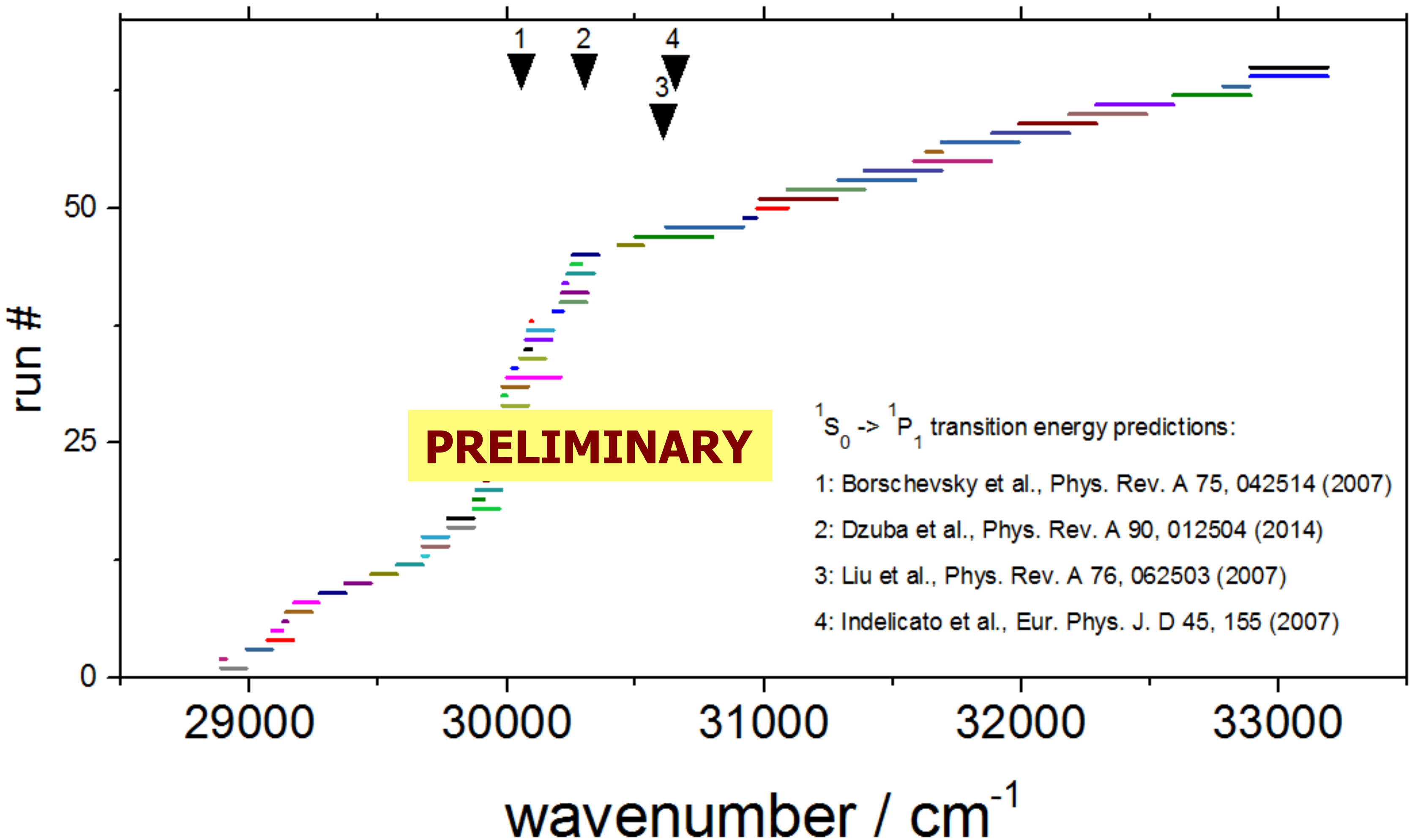
D. Nesterenko et al., Phys. Rev. C 90, 042501(R) (2014)

Mass of ^{48}Ca



$$\frac{\nu_c(^{48}Ca^+)}{\nu_c(C_4^{\ +})} = 1.000\ 990\ 101\ 75(36_{stat})\ (15_{sys})$$

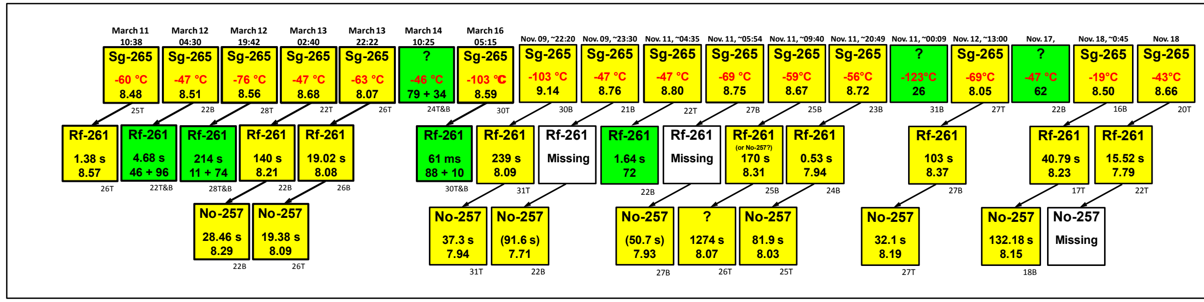
Online-Experiment @ SHIP – October 2014



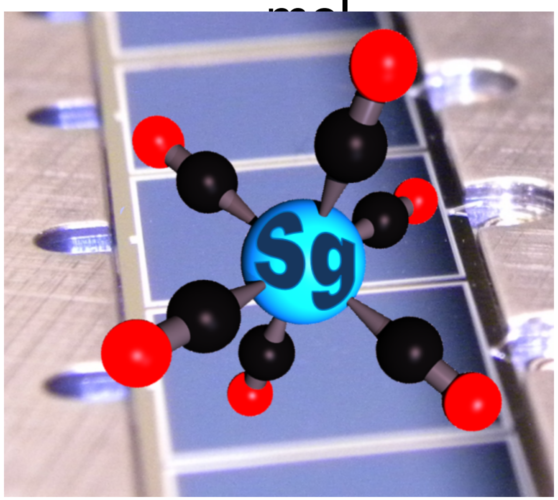
2013 at RIKEN – after 40+ years SHE chemistry:

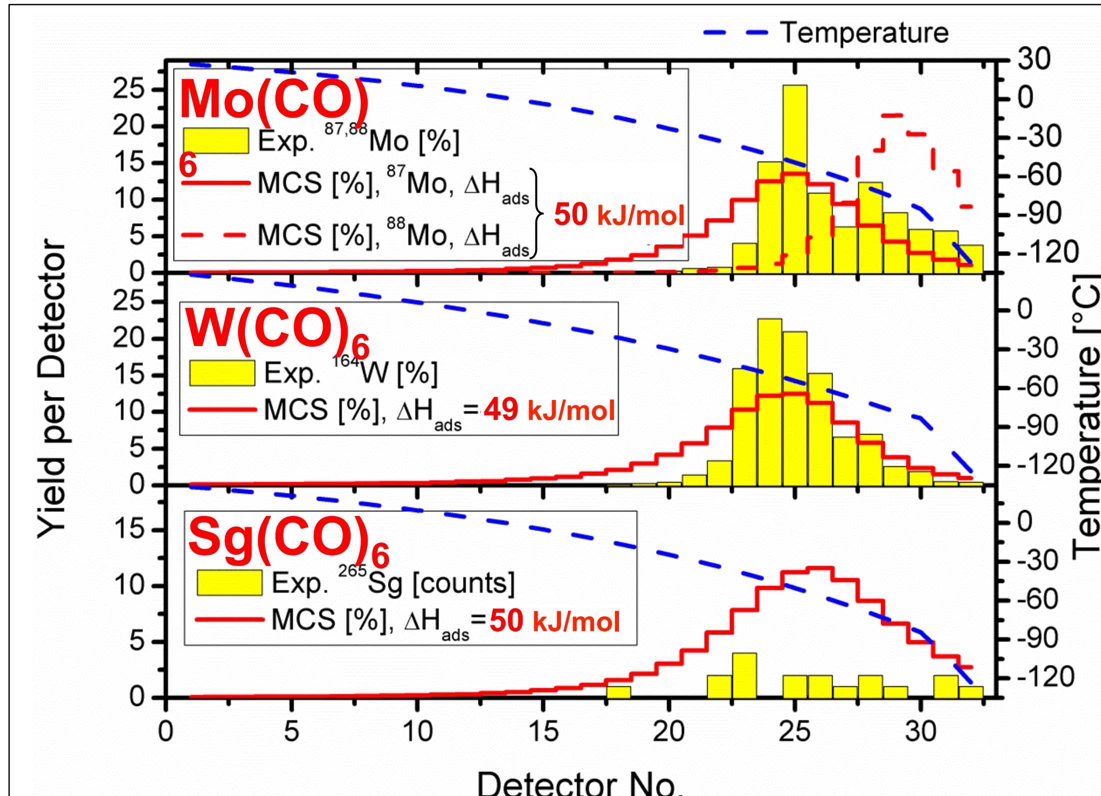
First step in the direction of organometallic SHE chemistry: $Sg(CO)_6$

Group 6	$-\Delta H_{ads}$(theo) Pershina et al., JCP 2013
24 Cr	
42 Mo	48.1 kJ/mol
74 W	46.5 kJ/mol
106 Sg	46.2 kJ/mol



Hexacarbonyls:
$Mo(CO)_6$ / $W(CO)_6$ / $Sg(CO)_6$





J. Even *et al.* Science 345 (2014)

see www.superheavies.de