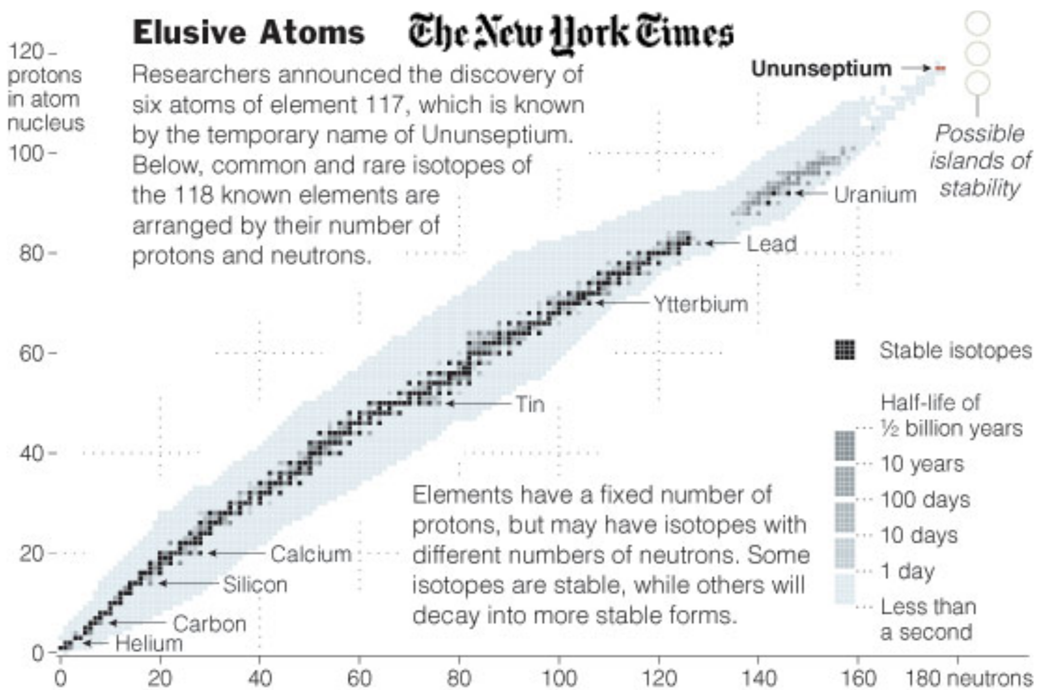
Summary Experiment

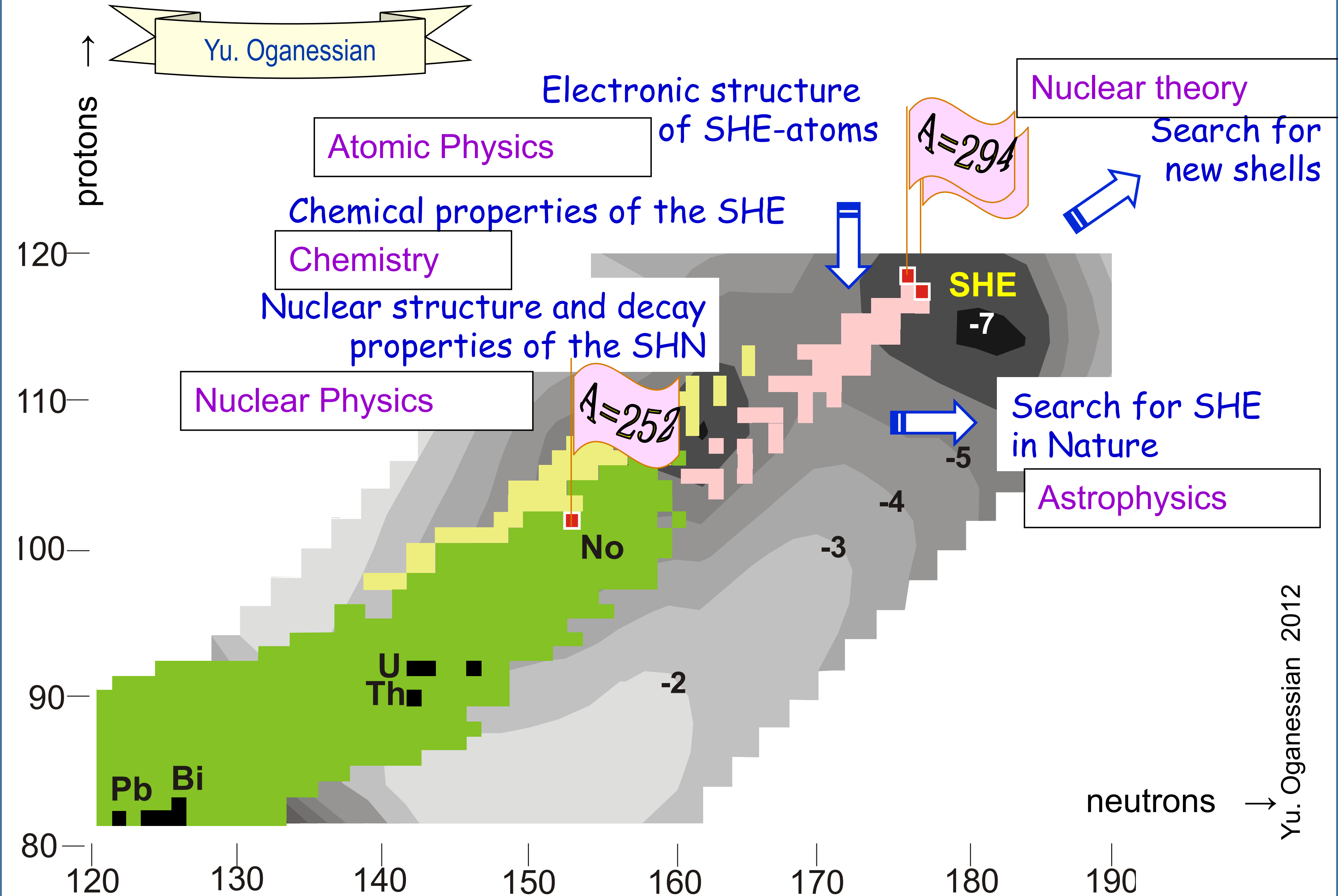
R.-D. Herzberg
Ch.E. Düllmann

Discovery of a new element is as fascinating to the public as landing on the moon (or Mars)

M. Stoyer

"The question we're trying to answer is, 'Does the periodic table come to an end, and if so, where does it end?' "
Kenton Moody -- LLNL





Yuri Oganessian. "Synthesis of SH-nuclei" FUSHE 2012, May14, 2012, Weilrod, Germany

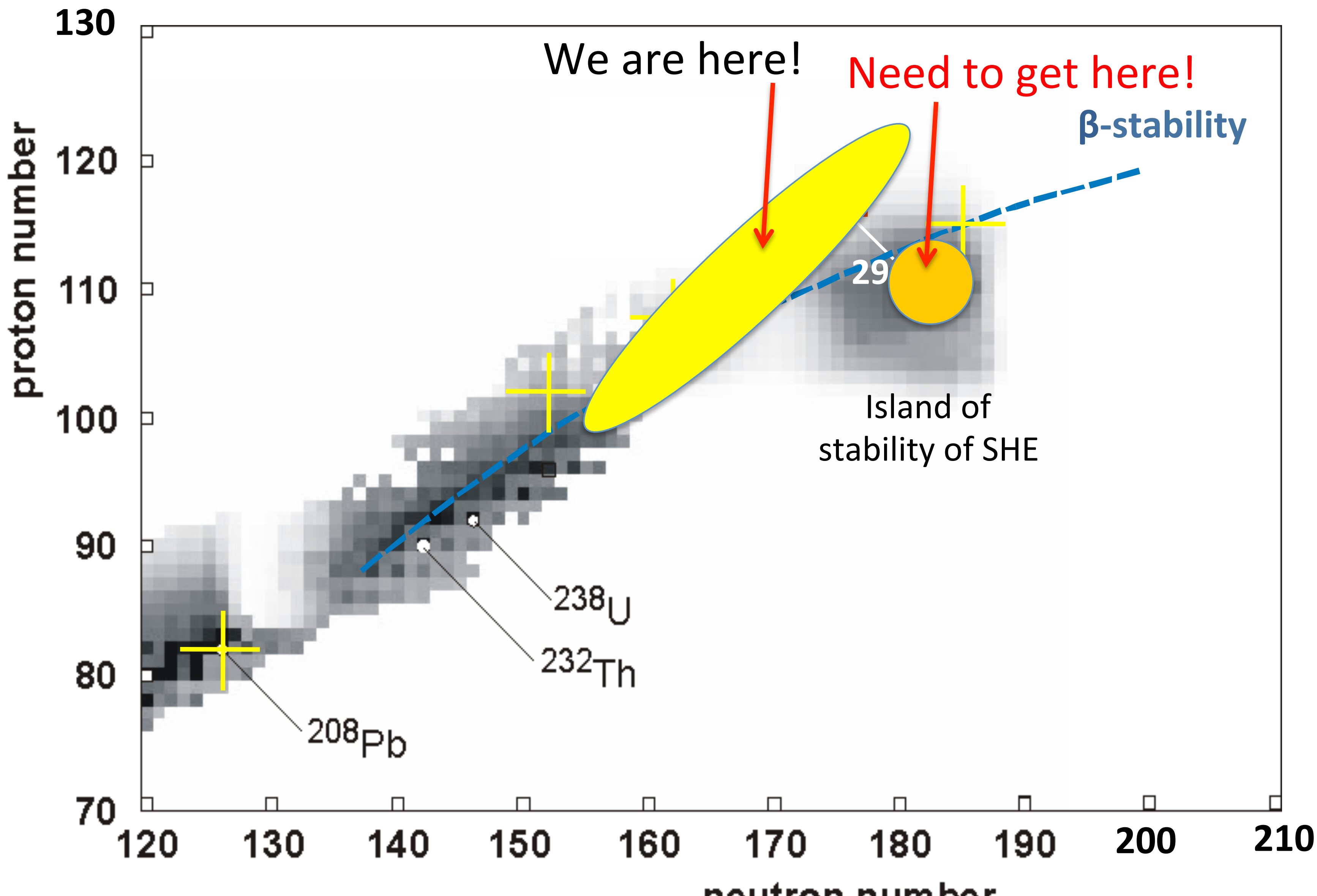
Scientific Questions

- What is the heaviest element we can make?
- What is the heaviest nucleus we can make and what are the best methods to do so?
- What is the nuclear structure in the heaviest nuclei?
- What are the chemical and atomic properties of the heaviest elements and is chemical periodicity altered as relativistic effects become more important?
- Are there astrophysical scenarios in which SHEs are produced or does fission limit the production of SHEs? Do the heaviest elements exist in nature?
- (How) Can we produce weighable quantities on earth?

What is the heaviest element?

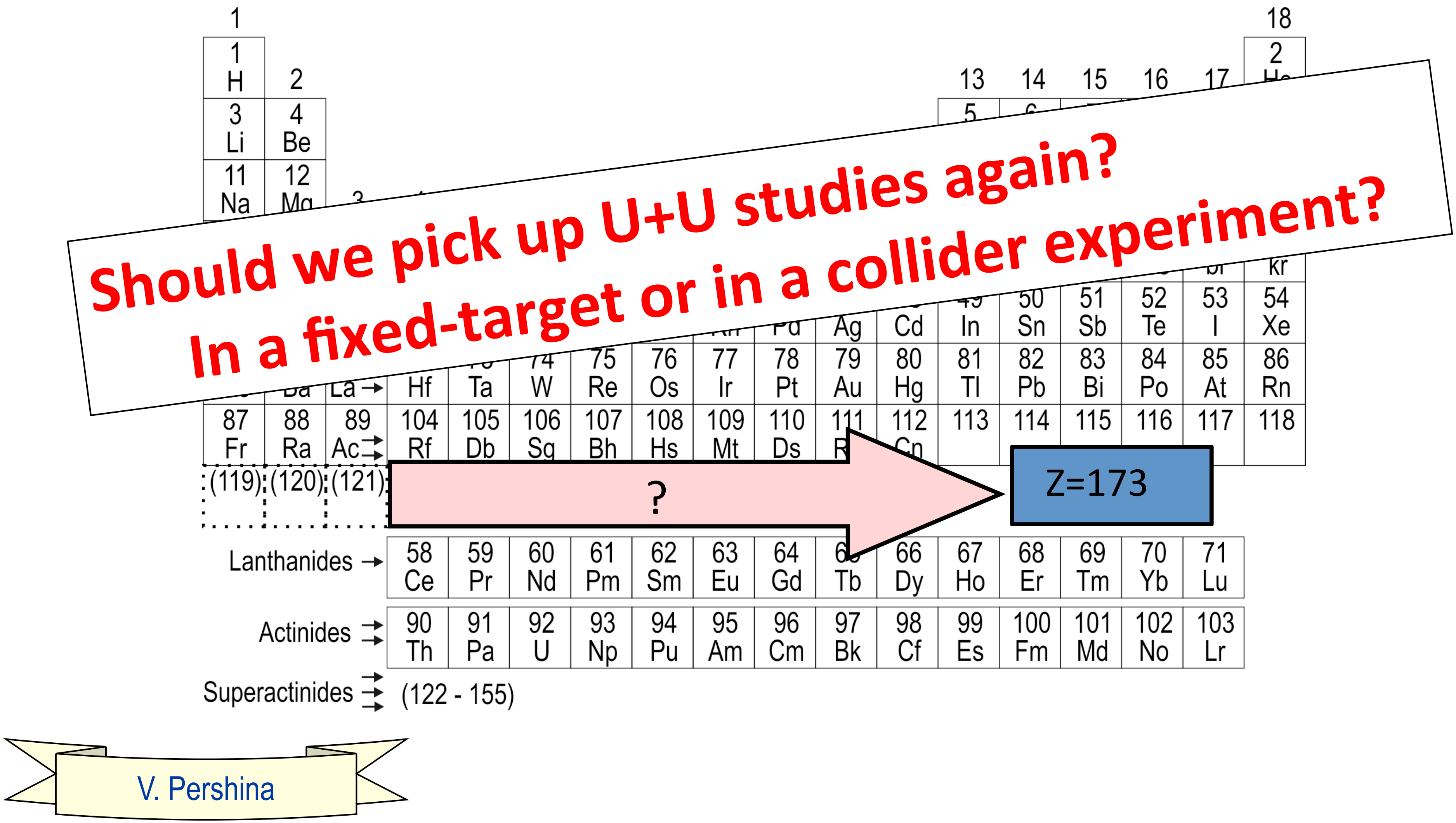
- Where is the island of stability?
- What are the best methods to create them?
- What determines their survival and stability?
- What are their properties?

Yu. Oganessian



Yuri Oganessian. "Synthesis of SH-nuclei" FUSHE 2012, May14, 2012, Weilrod, Germany

Modern Periodic Table of Elements



New Elements / Isotopes

Observed are mainly integral quantities:

- The atom itself!
- Decay mode
- Half-life
- Q-value or TKE

A rich and growing body of data!

Creation

- Reaction mechanisms?
- Best target/beam combinations?
- How reliably is theory predicting cross sections?

Superheavies:

V. Zagrebaev

1. Theoretical models of formation dynamics
(the problems to be solved)

Experimental possiblities

- **Fusion reactions** **(new SH elements and isotopes)**
- **Transfer reactions** **(new neutron-rich SH nuclei)**
- **Neutron capture** **(SHE in nature)**

2. SHE experiments
(what could be really done within the next few years)

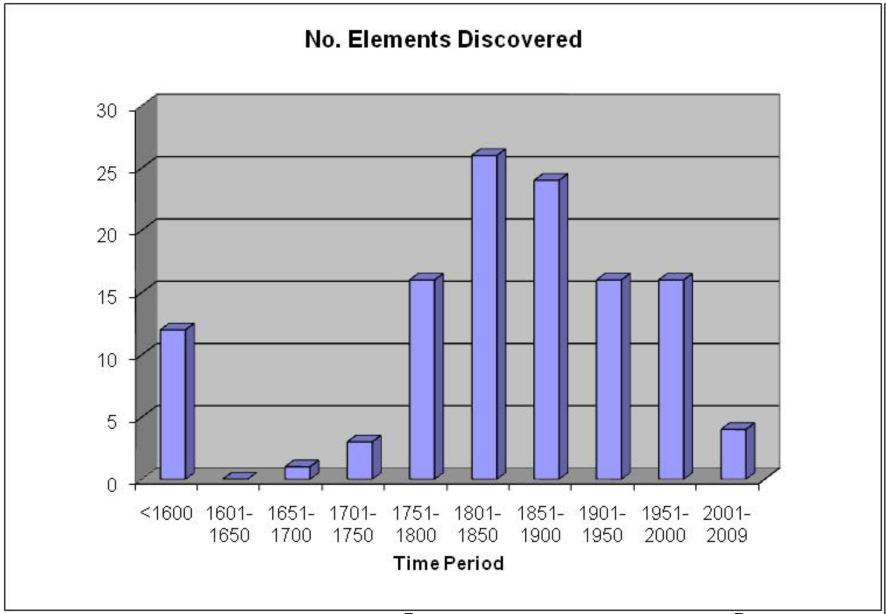
Valeriy Zagrebaev

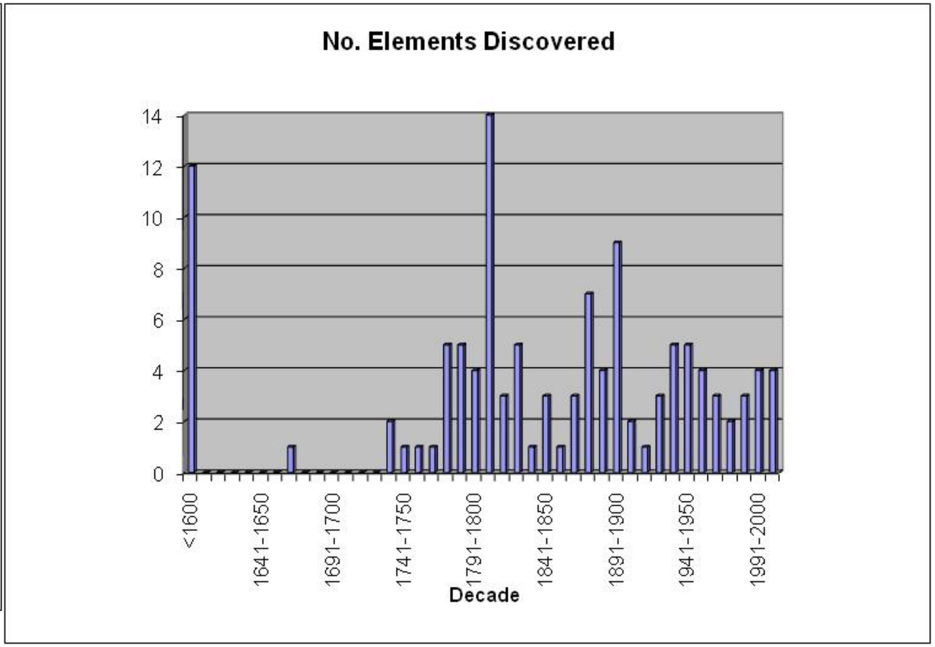
Flerov Laboratory of Nuclear Reactions, JINR, Dubna

for "Future of Super Heavy Elements", *May 14, 2012*, Weiltal, Germany

New element discovery has progressed steadily since the 1700's

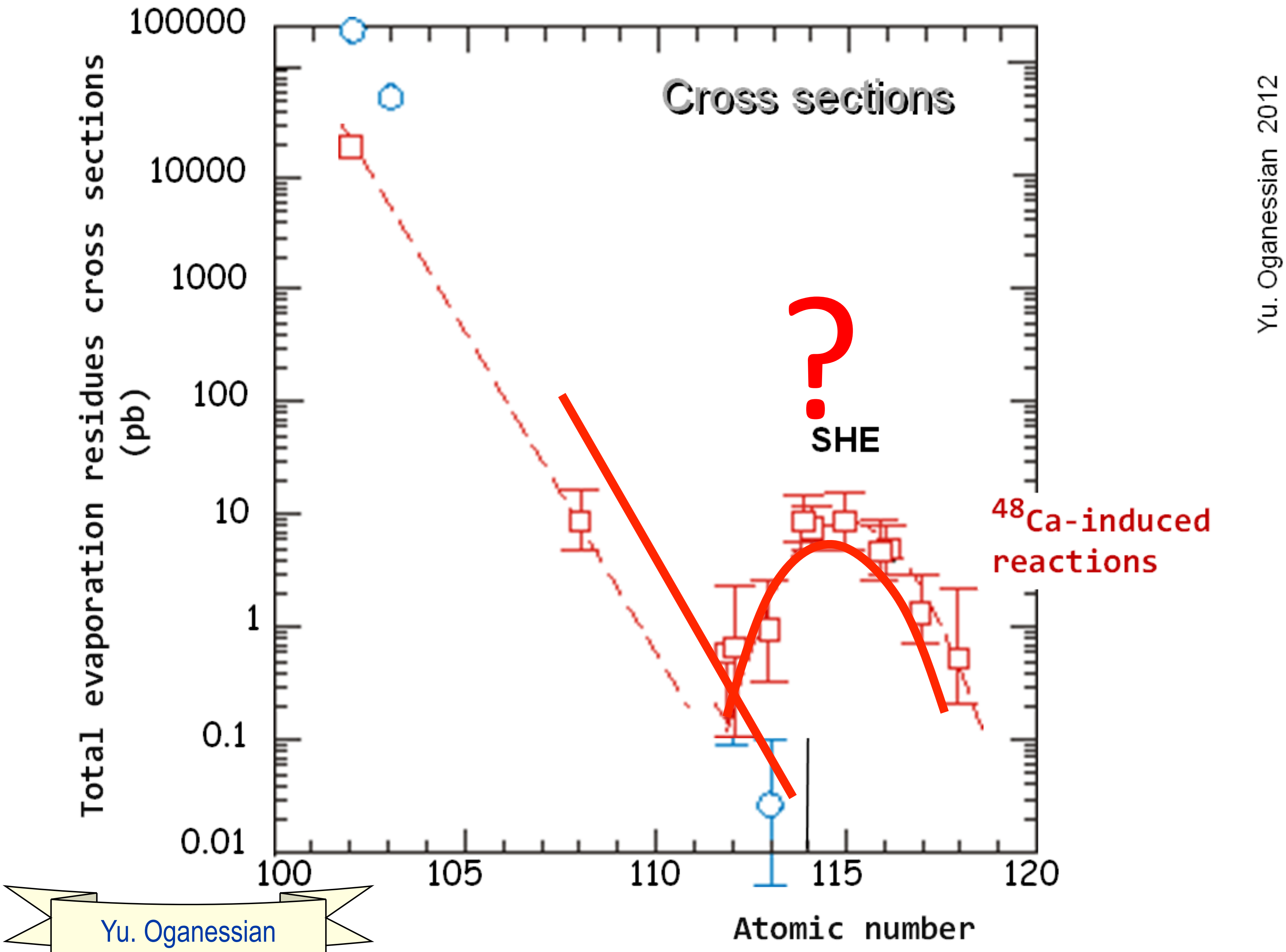
M. Stoyer





On average, just under 20 elements have been discovered every half-century

On average, about 4 elements have been discovered every decade



Cross sections
Total evaporation residues cross sections (pb)
100000
10000
1000
100
10
1
0.1
0.01
100
105
110
115
120
Atomic number
?
SHE
48Ca-induced reactions
Yu. Oganessian 2012
Yu. Oganessian

Making new elements

E120

Z_{Beam}	Beam	Target	Asymmetry	$E^*@B_{Bass}$
22	^{50}Ti	^{249}Cf		31.7
23	^{51}V	^{249}Bk		35.9
24	^{54}Cr	^{248}Cm		33.0
25	^{55}Mn	^{243}Am		34.5
26	^{58}Fe	^{244}Pu		33.9
27	^{59}Co	^{237}Np		32.9
28	^{64}Ni	^{238}U		27.3

Similar ... Ti

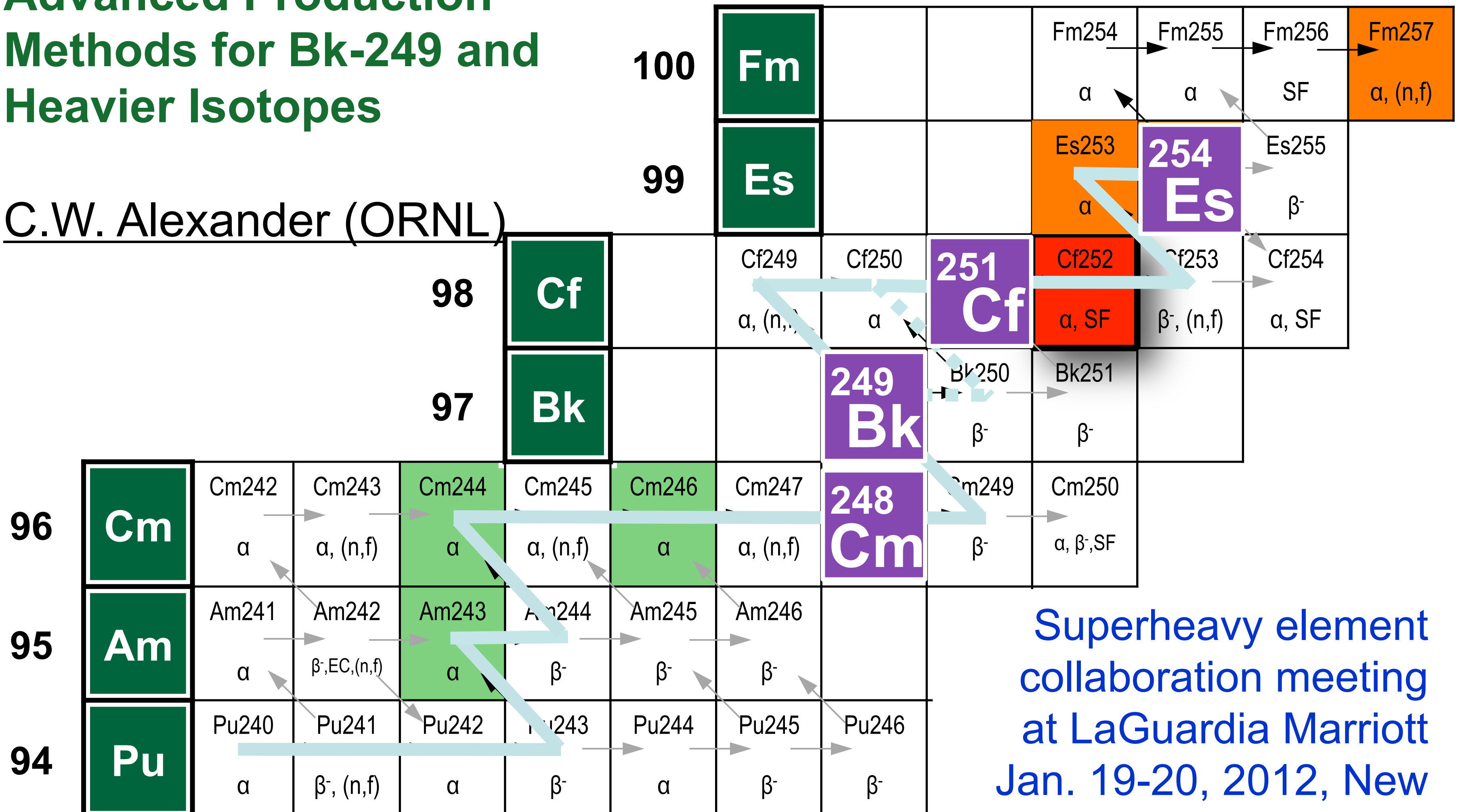
$+^{249}$ ...

Strategic aspect:
The community depends on access to transuranium isotopes in mg quantities!

Transuranium Nuclide Production Paths

Advanced Production Methods for Bk-249 and Heavier Isotopes

C.W. Alexander (ORNL)



Superheavy element collaboration meeting at LaGuardia Marriott Jan. 19-20, 2012, New York

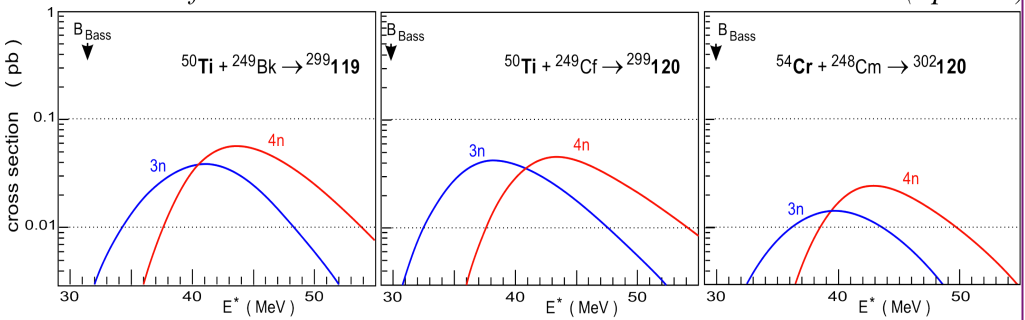
Yu. Oganessian

Fusion evaporation reactions

❑ High intense stable beams beyond ^{48}Ca

Ti beam:
scheduled for 2012 at TASCA

Cr beam:
started at SHIP (April 23)



factor $\frac{1}{20}$ as compared to ^{48}Ca

V. Zagrebaev et al.

Fusion reactions to Z=120

$^{50}Ti + ^{249}Cf \rightarrow ^{295,296}120 + 3,4n$

$^{54}Cr + ^{248}Cm \rightarrow ^{298,299}120 + 3,4n$

$^{58}Fe + ^{242}Pu \rightarrow ^{296,297}120 + 3,4n$

Dubna : $\sigma < 0.4$pb

$^{64}Ni + ^{238}U \rightarrow ^{298,299}120 + 3,4n$

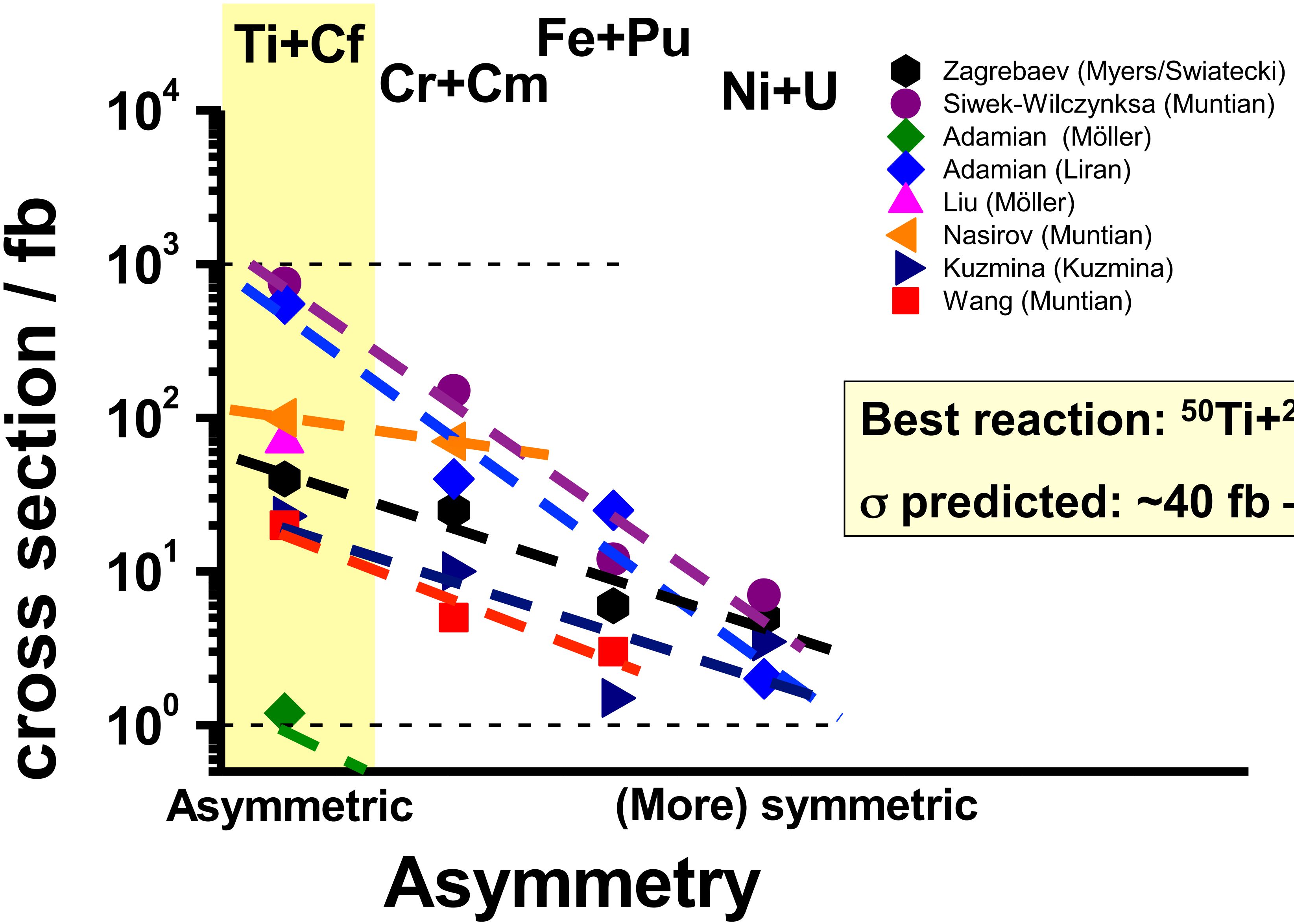
GSI: $\sigma < 0.1$ pb

$^{88}Sr + ^{208}Pb \rightarrow ^{294,295}120 + 1,2n$

Today: $I \approx 5 \times 10^{12}/s$ ➔ $\sigma_{limit} \approx 0.1pb$

Future: $I \approx 10^{14}/s$ ➔ $\sigma_{limit} \approx 1$ fb

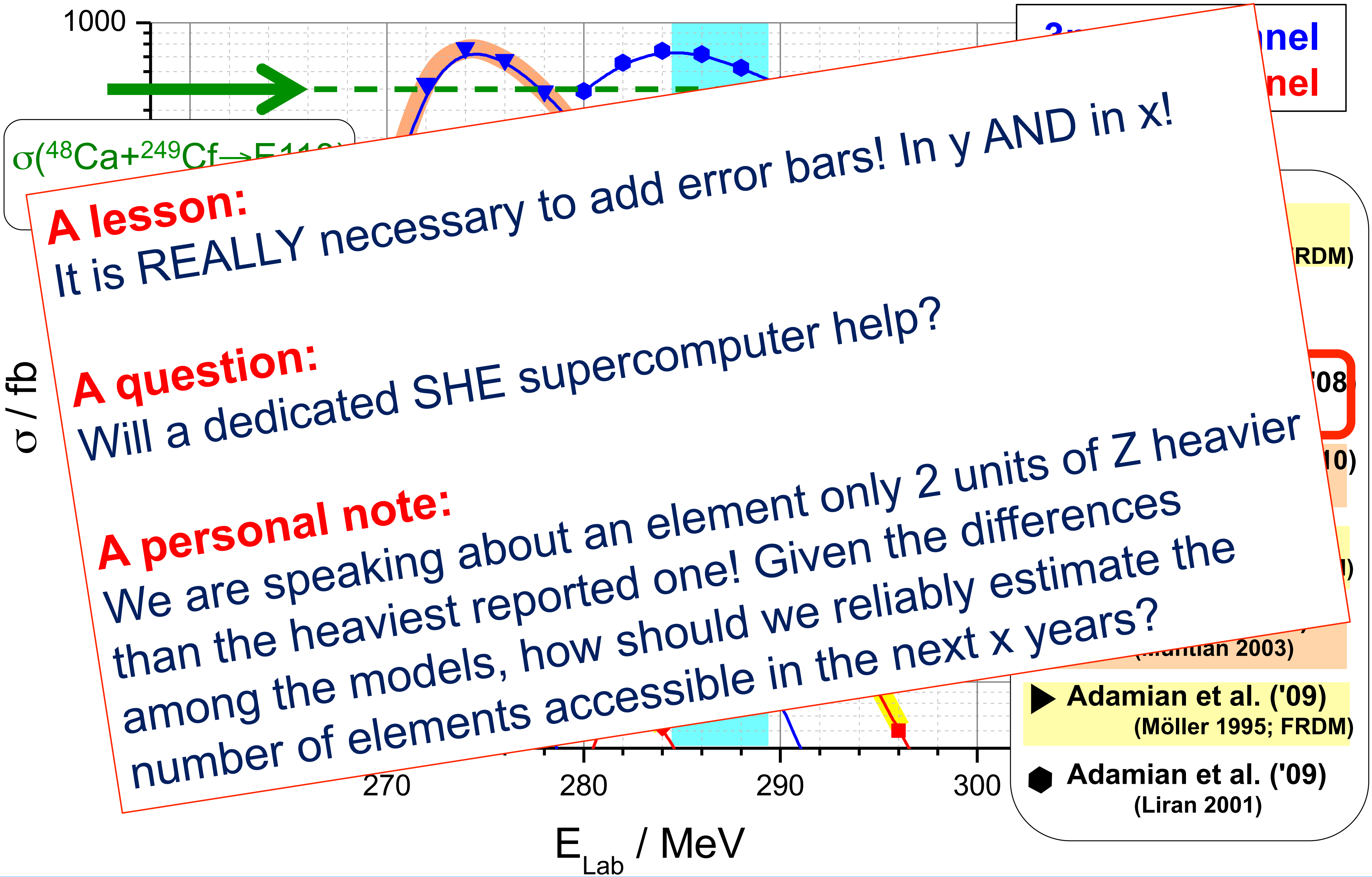
Cross sections: current predictions from theory



Best reaction: $^{50}Ti+^{249}Cf$

σ predicted: ~40 fb – 1 pb

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

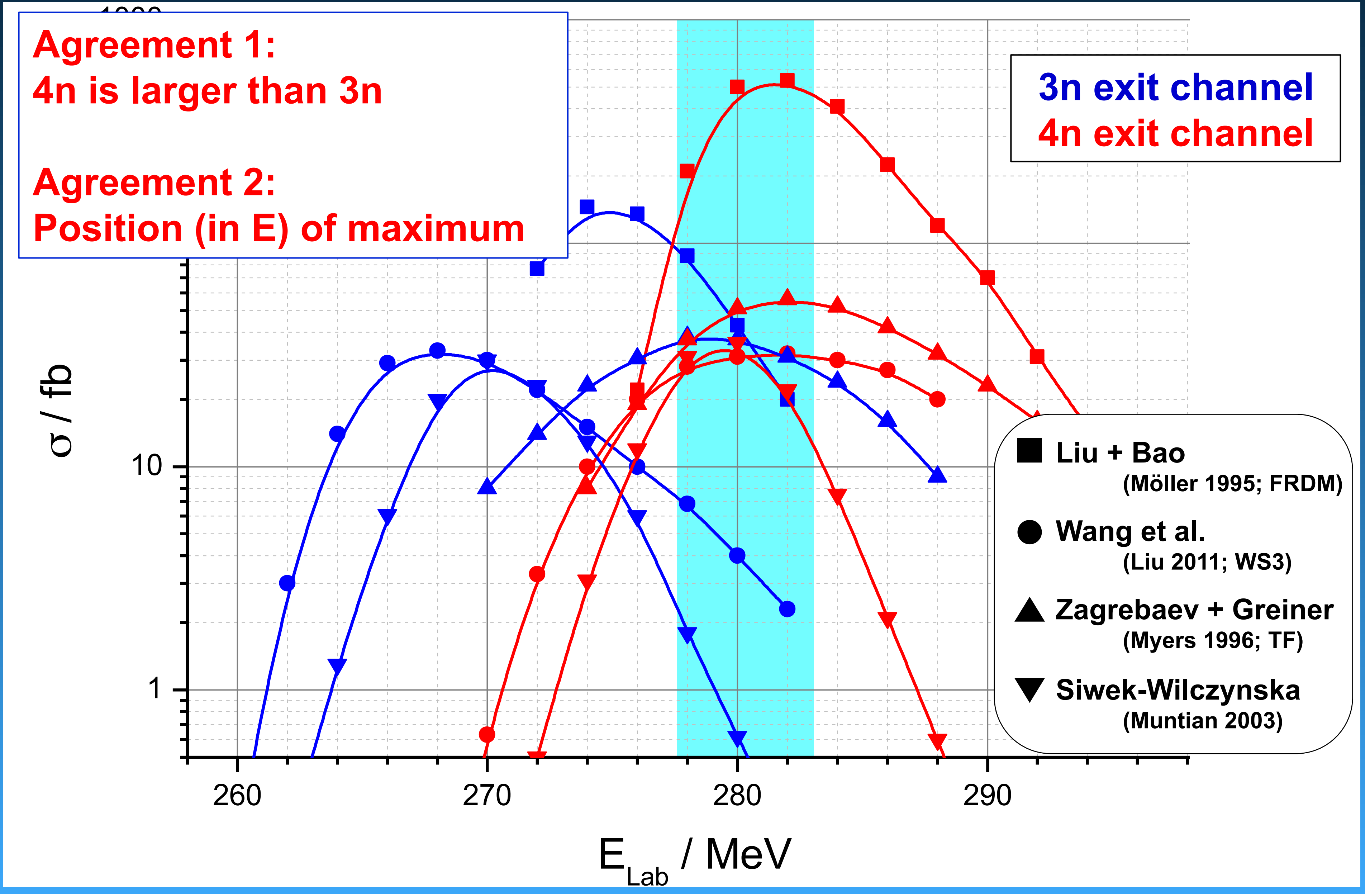


A lesson:
It is REALLY necessary to add error bars! In y AND in x!

A question:
Will a dedicated SHE supercomputer help?

A personal note:
We are speaking about an element only 2 units of Z heavier than the heaviest reported one! Given the differences among the models, how should we reliably estimate the number of elements accessible in the next x years?

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



The *TASCA* Element 119 Collaboration

GSI Darmstadt (D) D. Ackermann, M. Block, F.P. Heßberger, A. Hübner, E. Jäger,

March 6:
Arrival of ^{249}Bk in Mainz

March 23:
Arrival of Targets at GSI

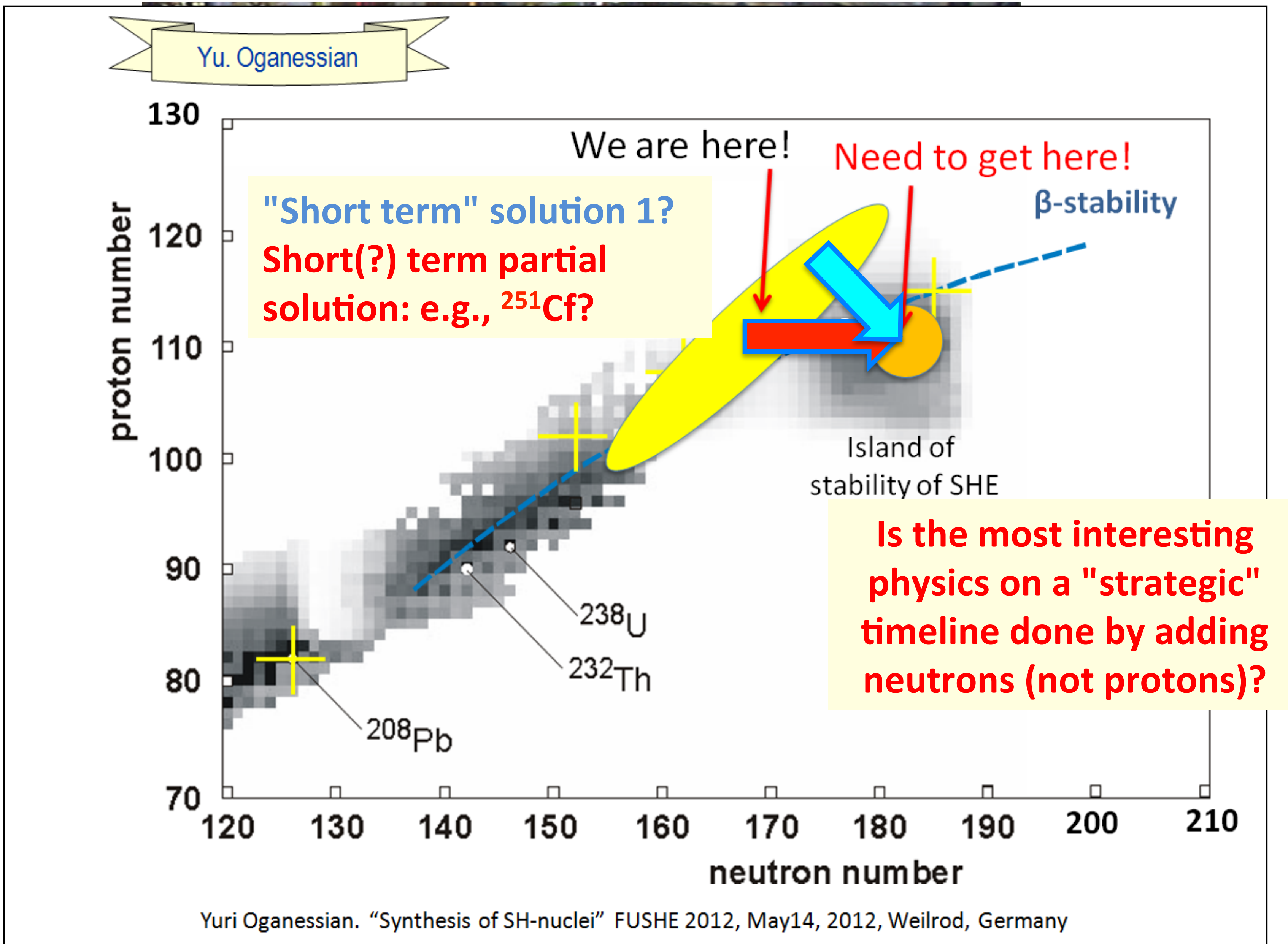
April 12:
Mounting Targets in TASCA

April 14:
Begin Search for Element 119

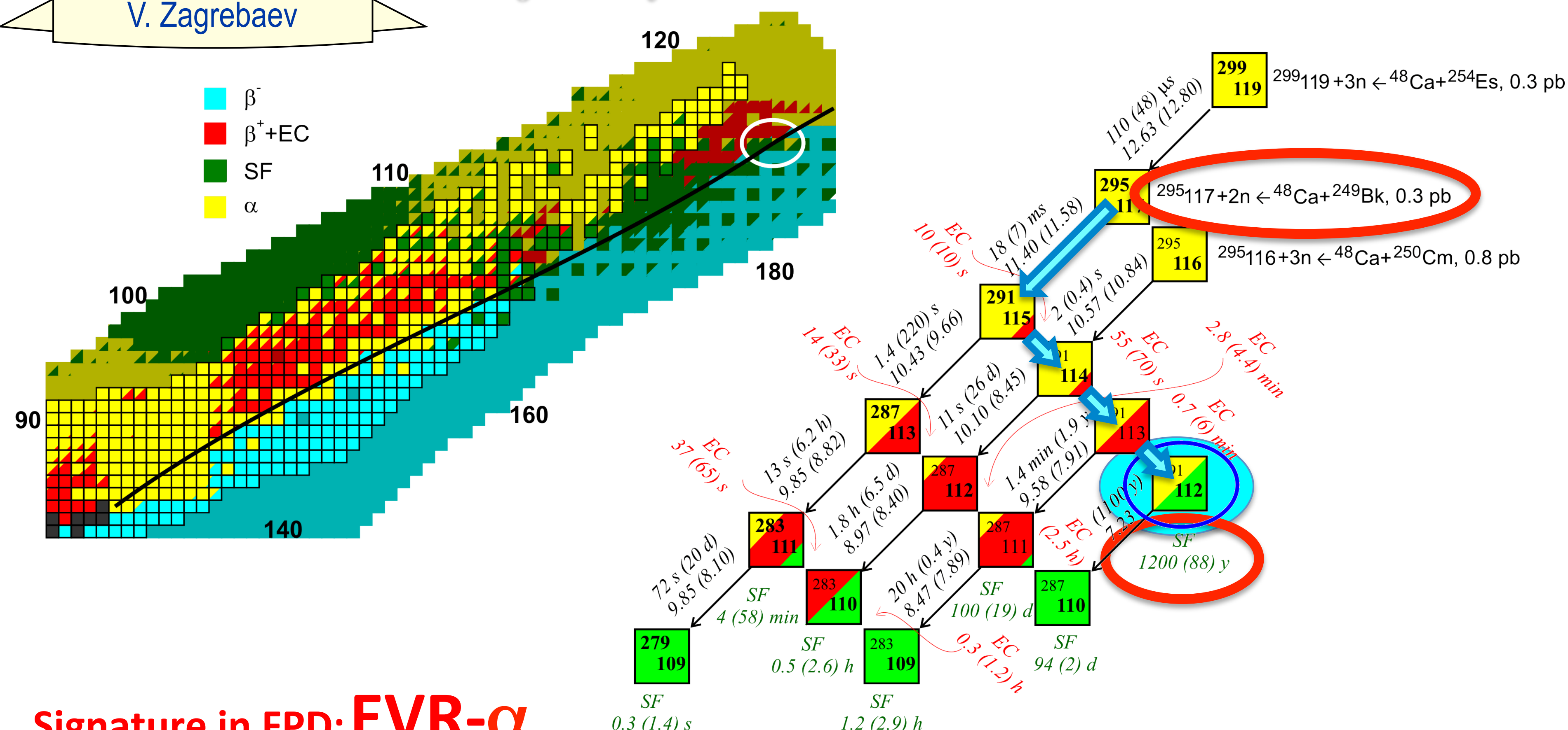
U Bogota L.G. Sarmiento

ITE Warsaw (PL) M. Wegrzecki

(How) can we produce weighable quantities



Narrow pathway to the island of stability just by fusion reactions !



Signature in FPD: EVR-α...

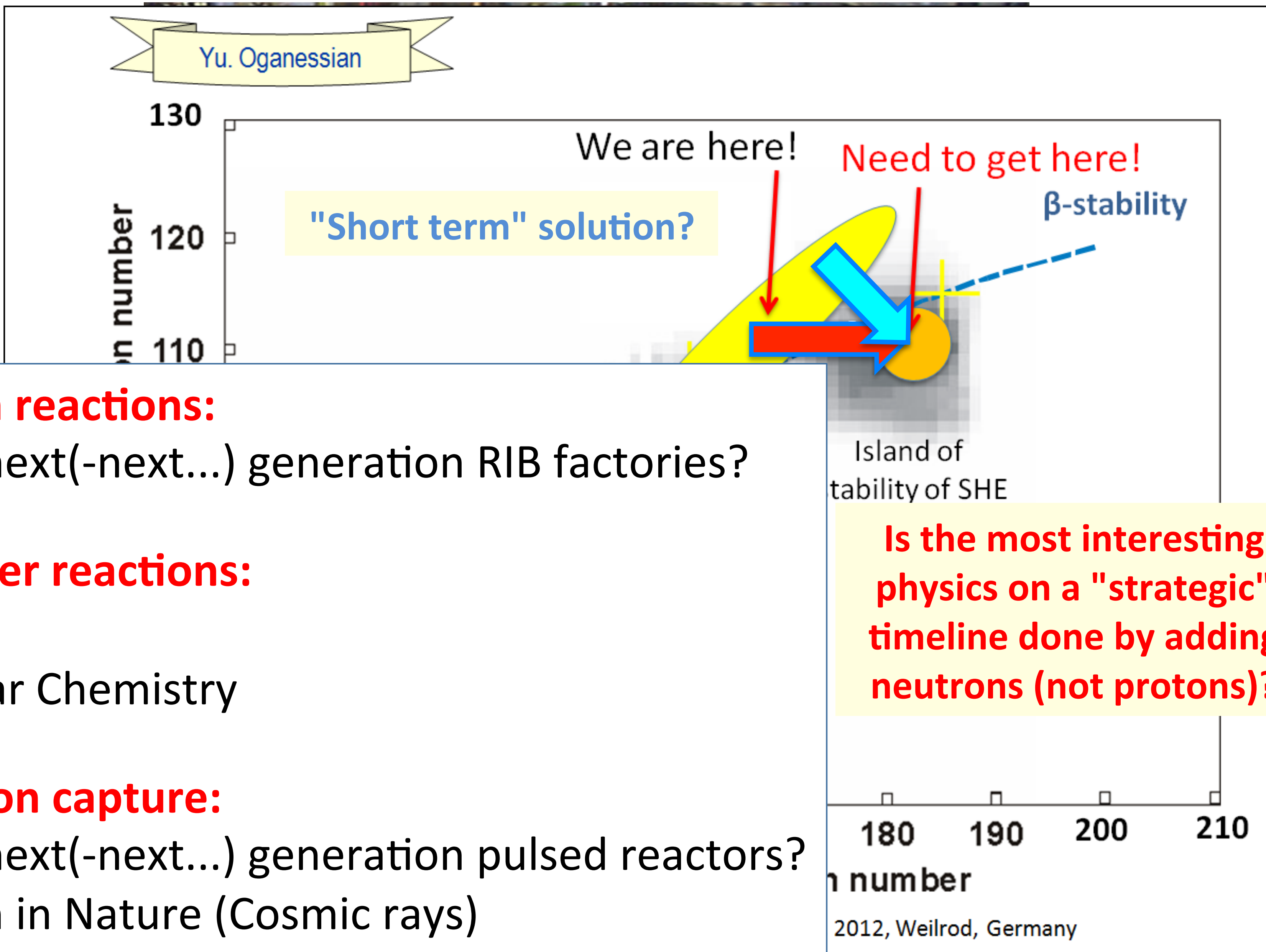
(unobserved ....EC-EC-EC...)

...SHE exists for 1200 a, but nobody knows!!

Need 1: detection system for EC

Need 2: non-destructive 1 atom detection / manipulation method!

(How) can we produce weighable quantities



Fusion reactions:

Next-next(-next...) generation RIB factories?

Transfer reactions:

IRiS?

Nuclear Chemistry

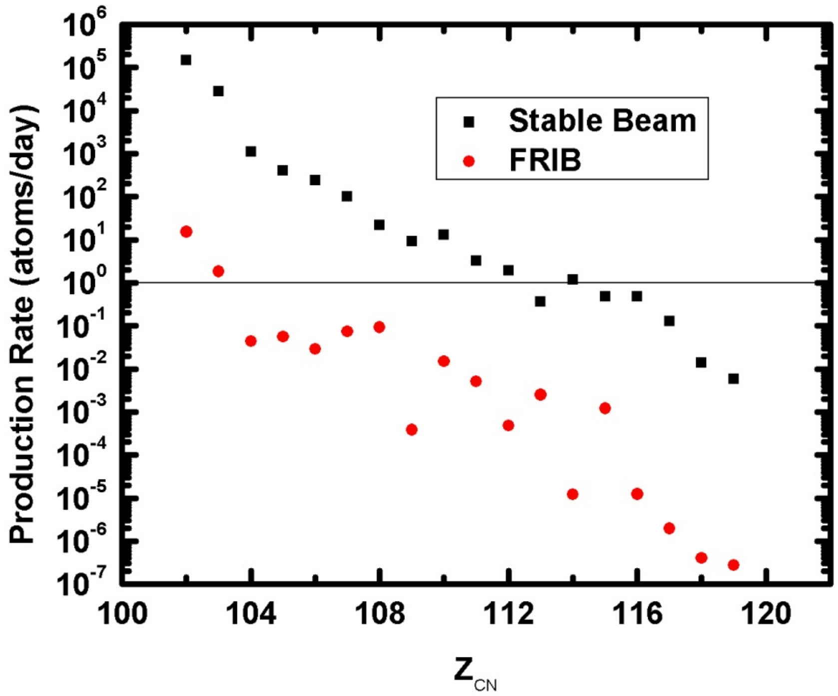
Neutron capture:

Next-next(-next...) generation pulsed reactors?

Search in Nature (Cosmic rays)

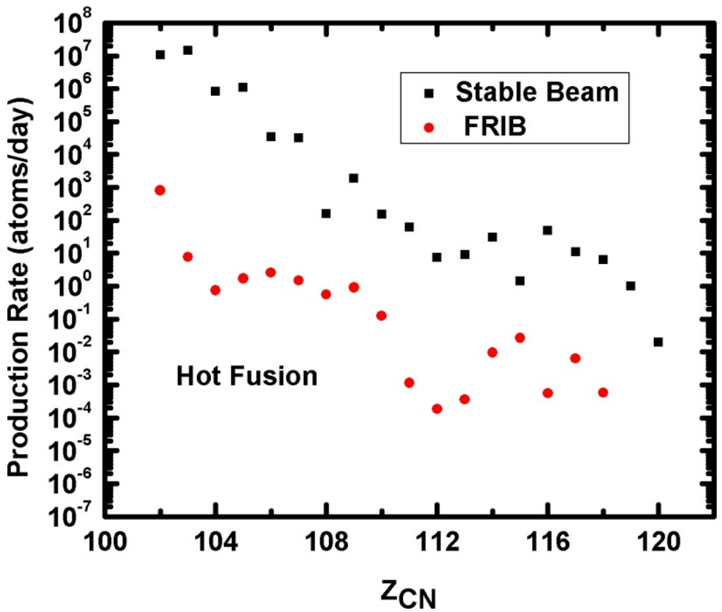
Is the most interesting physics on a "strategic" timeline done by adding neutrons (not protons)?

Cold fusion



W. Loveland

New elements from RIB facilities (LOL)



Detection

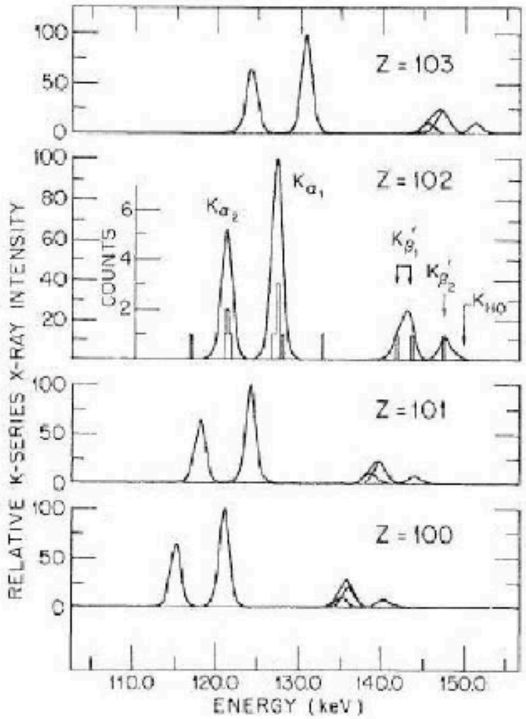
- Shortest halflives:
  - Survival through separator?
  - Disentangling of fast decays?
- Longest halflives:
  - Detection by decay chain not optimal
- Identification through:
  - Chemical ID
  - Mass measurement
  - X-ray fingerprinting
  - cross bombardment
  - alpha chains

X–ray Fingerprinting of Superheavy Nuclei

Courtesy: Spokesperson D. Rudolph, Lund Uni, Sweden

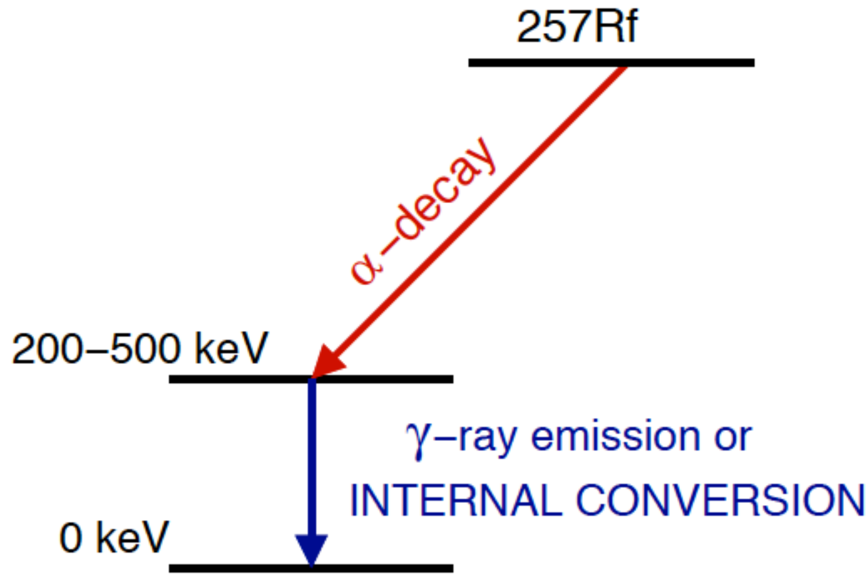
in the spirit of

R. Bemis *et al.*, PRL31, 647 (1973)



15 alpha-photon coincidences consistent with No ($Z = 102$) K X rays

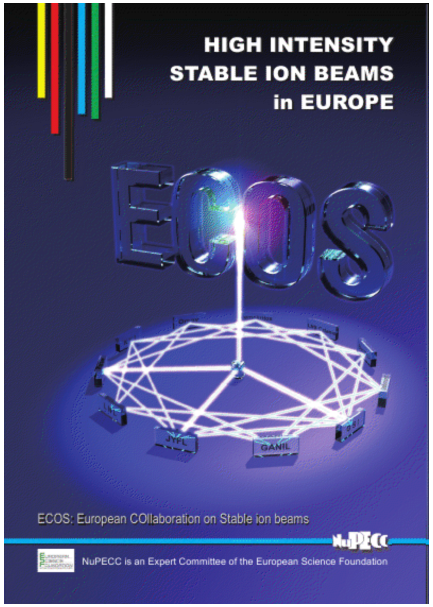
Identification of Rf ($Z = 104$)



=> K X–rays

L.-L. Andersson

Rates?



- Factories planned:
  - Dubna
  - GSI
  - Others?

ECOS report recommended dedicated facilities

What do we use the extra beamdose for?

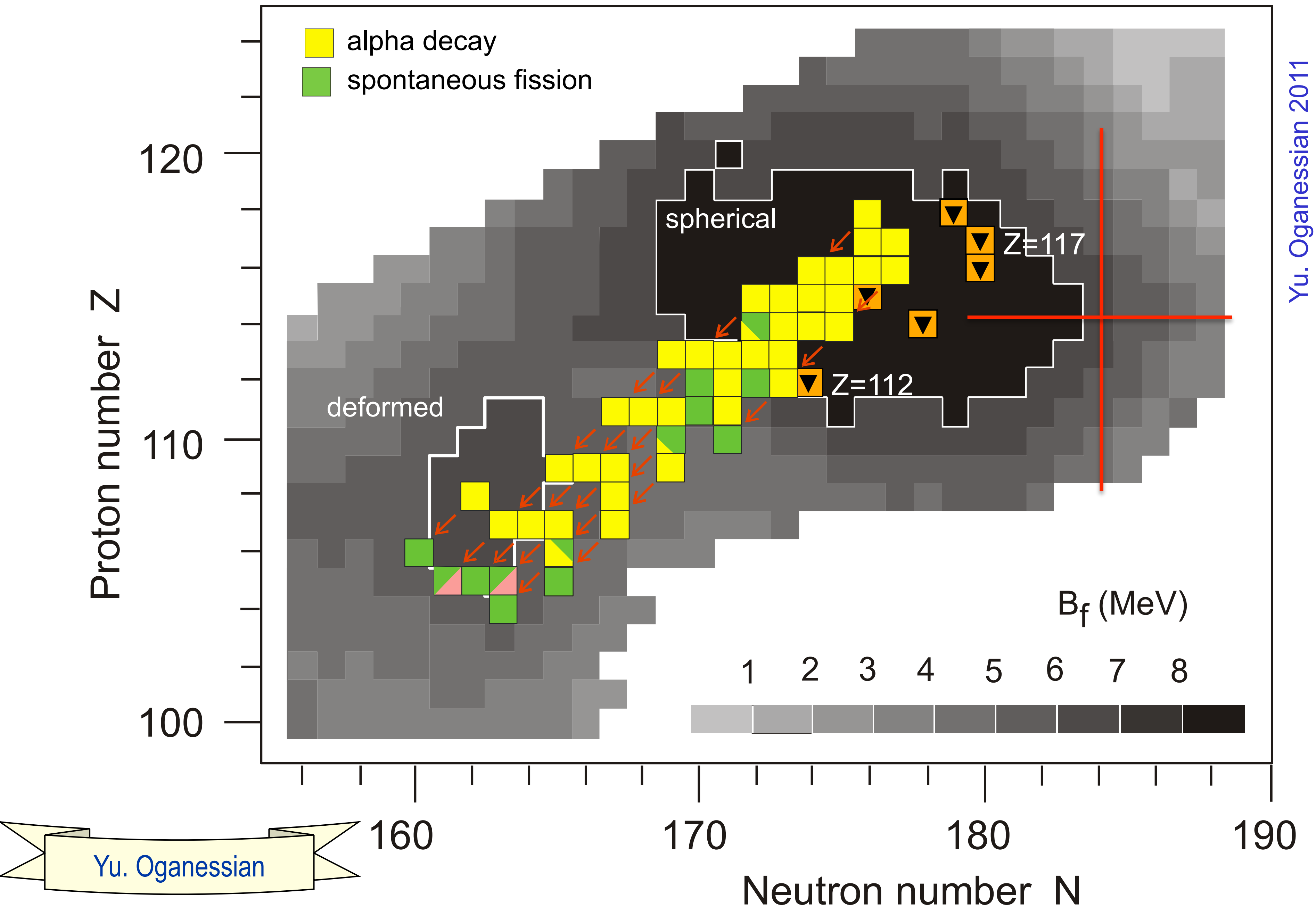
-> Push boundaries

-> Precision studies

Spherical Shells

- Where is the island of stability?
  - Where is the shoreline?
  - Where is the peak?

- Experimental body of data still very neutron deficient



Yuri Oganessian. “Synthesis of SH-nuclei” FUSHE 2012, May14, 2012, Weilrod, Germany

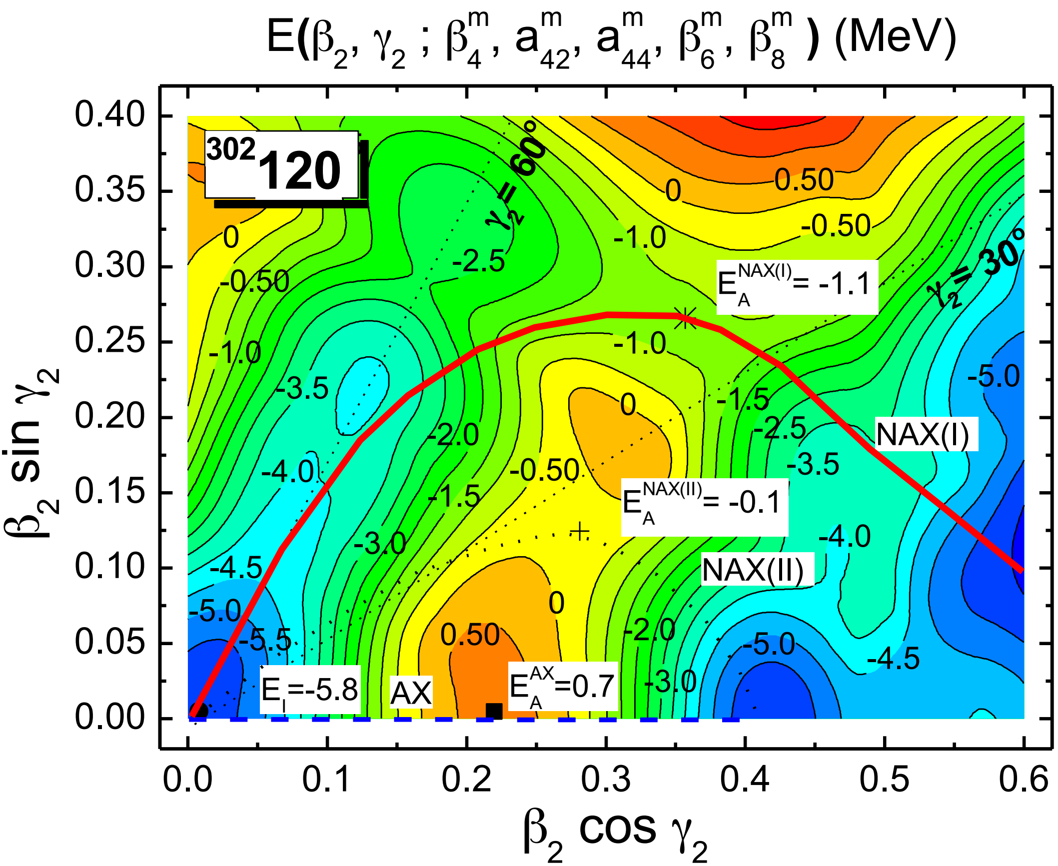
Fission

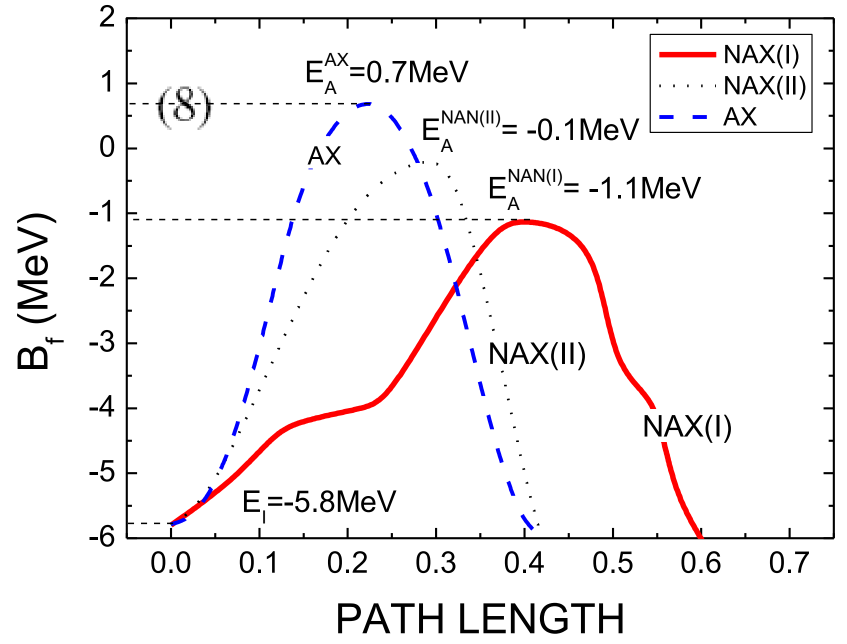
- Fission barriers are key to the problem.
- Experiment: Half-life and height
- BUT: underlying structure is highly complex!

M. Kowal

The potential energy is calculated in the following grid points:

$$\beta_2 \cos\gamma_2 = 0(0.05)0.65,$$
$$\beta_2 \sin\gamma_2 = 0(0.05)0.40,$$
$$\beta_4 = -0.20(0.05)0.20.$$





M. Kowal, P. Jachimowicz, and A. Sobiczewski Phys. Rev. C **82**, 014303 (2010)

What is the nuclear structure in SHE?

- What is the single particle structure of SHE?
- What are the collective properties?
- What role do isomeric states play in SHE?

Nuclear Structure

- Provide non-integral data
- Looks at lower mass systems:

”Push the Fermi level towards the major shell gaps”

- Rod Clark

In-beam spectroscopy

- Rotational bands
- Configurations of excited states
- Potential to provide the most detailled and complete picture of nuclear structure

How to make progress with in-beam experiments

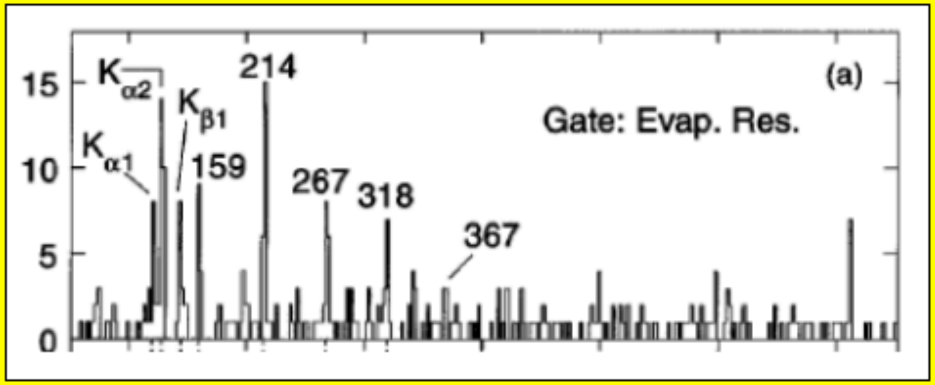
Need:

Better separators (but can only gain a factor of 2 or so in transmission)

Better arrays (ultimate gain factor of 5 in singles)
AGATA, GAMMASPHERE, GRETINA, EXOGAM

Higher beam intensities (digital electronics a must)

One can maybe reach cross sections of ~ 1 nb

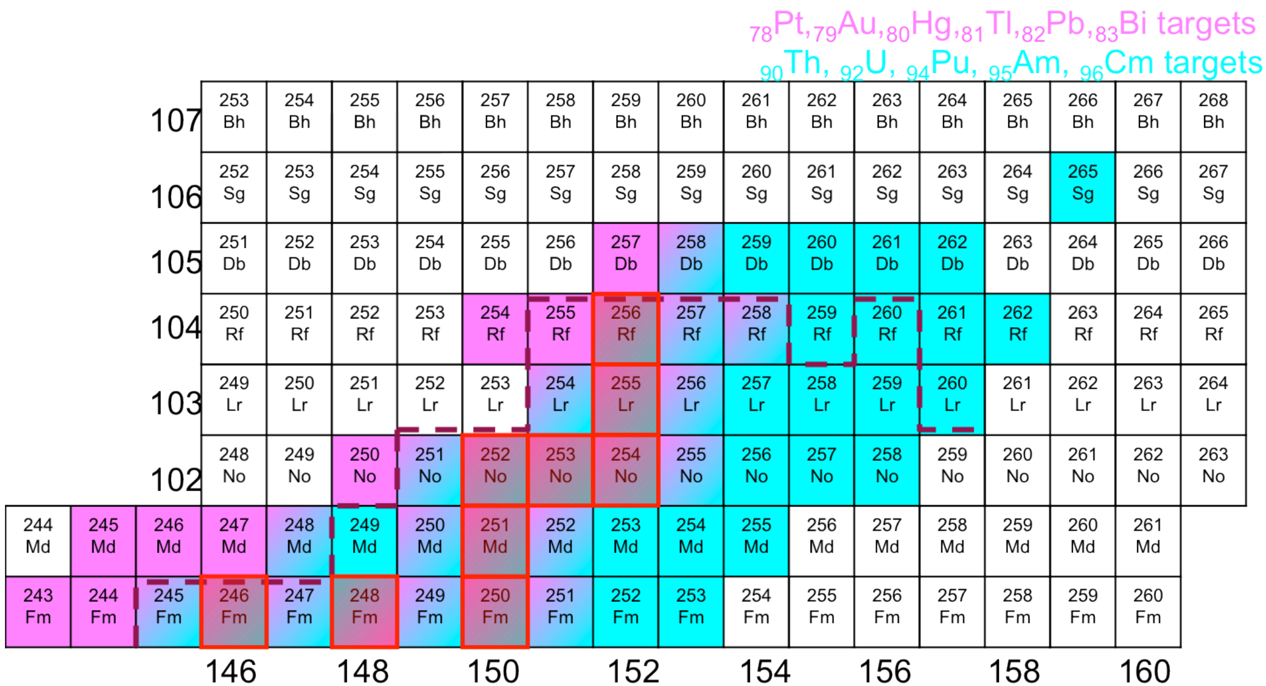


P. Reiter *et al.*, PRL **82**, 509 (1999)

A. Lopez-Martens

Issues

- availability of long-lived (trans)actinide targets
- maximum allowed activity at various facilities and other security issues
- count rates in the arrays due to the activity of the target
- What statistics is required to perform “meaningful” & unambiguous spectroscopy ?



Decay Spectroscopy

- Provides the link between Q-values and masses

- Traces single particle structure

- Can be used with highest beams and smallest cross sections

- Can be used with other methods (chemical, traps)

Physics Motivation for Decay and Nuclear Structure Investigations in the Region of SHE

F.P. Hessberger

Why Decay and Nuclear Structure investigations ?

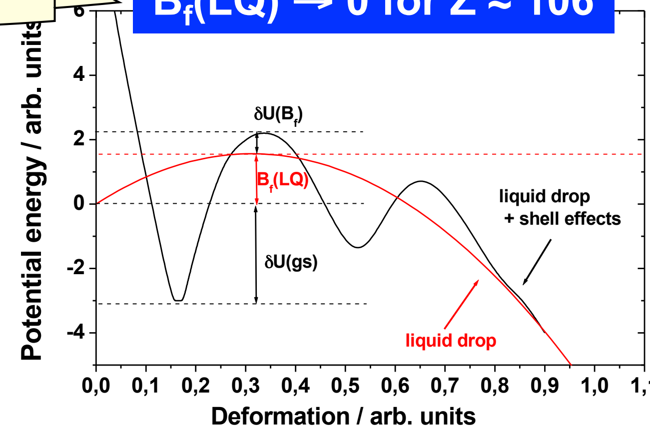
→Atomic nucleus is quantum mechanical ensemble of nucleons (protons, neutrons)

→Properties determined by ‚fundamental' interactions
- nucleon – nucleon interaction
- Coulomb interaction
- spin – orbit interaction
- ….

→Understanding decay properties and nuclear structure – Understanding ‚fundamental' interactions

→Superheavy nuclei (SHE) = ensembles of ‚extremely' large numbers of protons and neutrons

$B_f(LQ) \rightarrow 0$ for $Z \approx 106$



→Nuclear stability limited by fission
- Fission barriers in SHE determined by shell structure; B_{sf} depends on single particle levels

→ mass excess (-> determines Q-values for α- and β- decay)

→Understanding ‚basic' decay properties essential for understanding limits of stability

→Understanding nuclear structure is essential for understanding properties and stability of SHE

Decay spectroscopy

F.P. Hessberger

→ **α- and α - γ – spectroscopy**

Q-values, shell crossings;
Information on low lying Nilsson levels from energy and HF for α-decay as well as from energy, intensity and multipolarity of γ-rays.
→ systematic trends in odd mass – even Z nuclei along isotone line
→ systematic trends in odd mass – odd Z nuclei along the isotope line
Comparison with theory

→ **Spontaneous fission**

Fission barriers, hindrance factors, TKE

→ **EC – decay**

Often population of higher lying levels than by α-decay with notable intensities; similar information,
implantation method requires CE – K X-ray – γ- coincidences for identification

→ **K – Isomers**

Multi – quasiparticle (2q-proton, 2q-neutron, ...) configurations, typically at $E^* > 1$ MeV; information on lower lying qp-states, Nilsson levels, level ordering, vibrational states and bands built up on them
CE – γ coincidences required

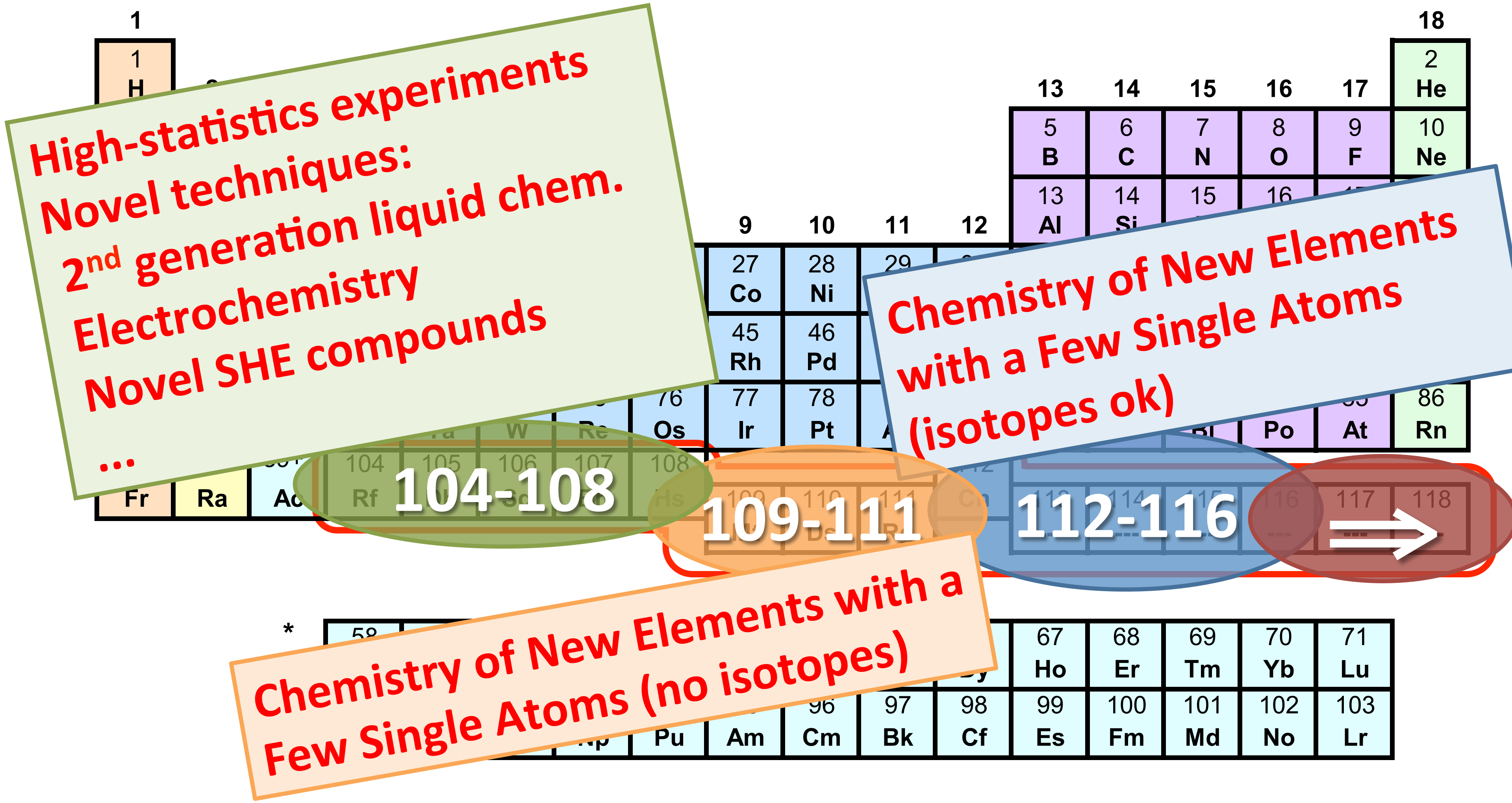
What are the chemical and atomic properties of the heaviest element?

- With their position in the Periodic Table being fixed by Z, do the SHE's chemical properties conform to those of the lighter homologs?

- What is the influence of relativistic effects?

- How well are these – and their consequences – understood

Superheavy Element Chemistry



For a real understanding of SHE chemistry: relevant theoretical work

	104-108	109-111	112-114	115+
$T_{1/2}$				
direct	10 s – 1 min	<< 1s	few s	0.1 s
indirect	1 day	1 s	up to 30 s	0.2 s
Cross section				
	10s nb-pb	"small"	few pb	1 pb
Interest of SHE chemistry community				
	High	Negligible	Very high	to come
	Many techniques			

Anion-exchange behavior of Rf in HF/HNO_3

Y. Nagame

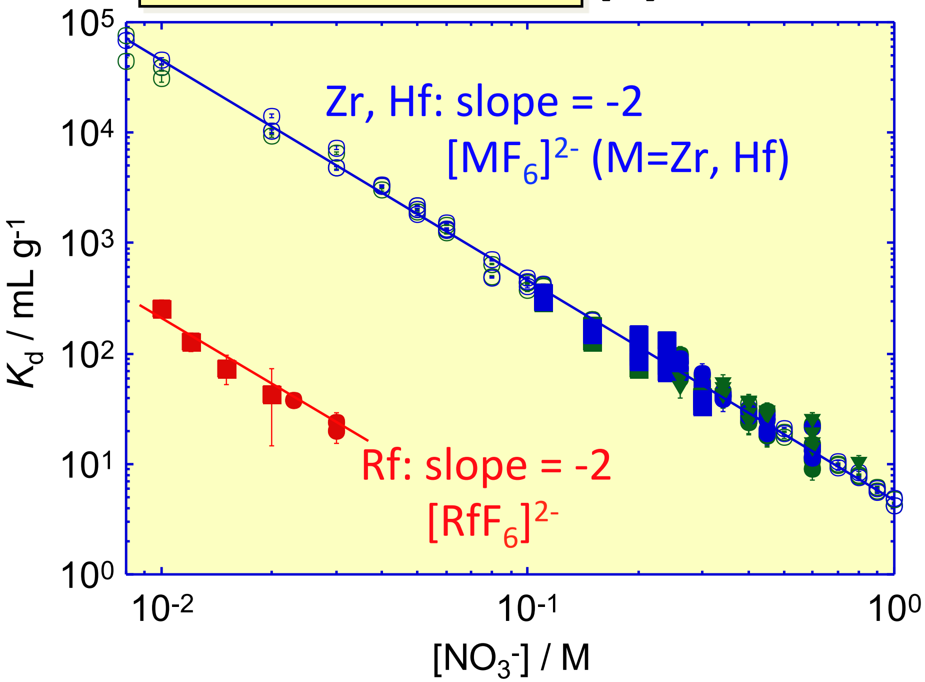
$HF \rightleftarrows H^+ + F^-$

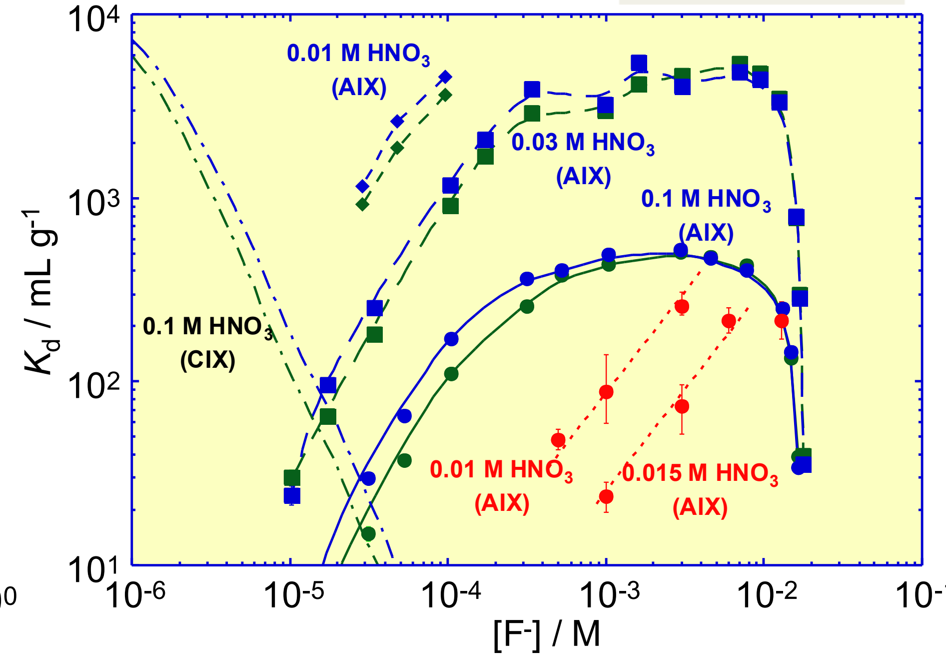
$(HF + F^- \rightleftarrows HF_2^-)$

$HNO_3 \rightleftarrows H^+ +$ **NO_3^-**

Rf (on-line)
Zr (off-line)
Hf (off-line)

$[F^-] = 3 \times 10^{-3}$ M





$R_n\text{-}MF_{4+n} + n\cdot NO_3^- \rightleftarrows n\cdot R\text{-}NO_3 + MF_{4+n}^{\,n-}$

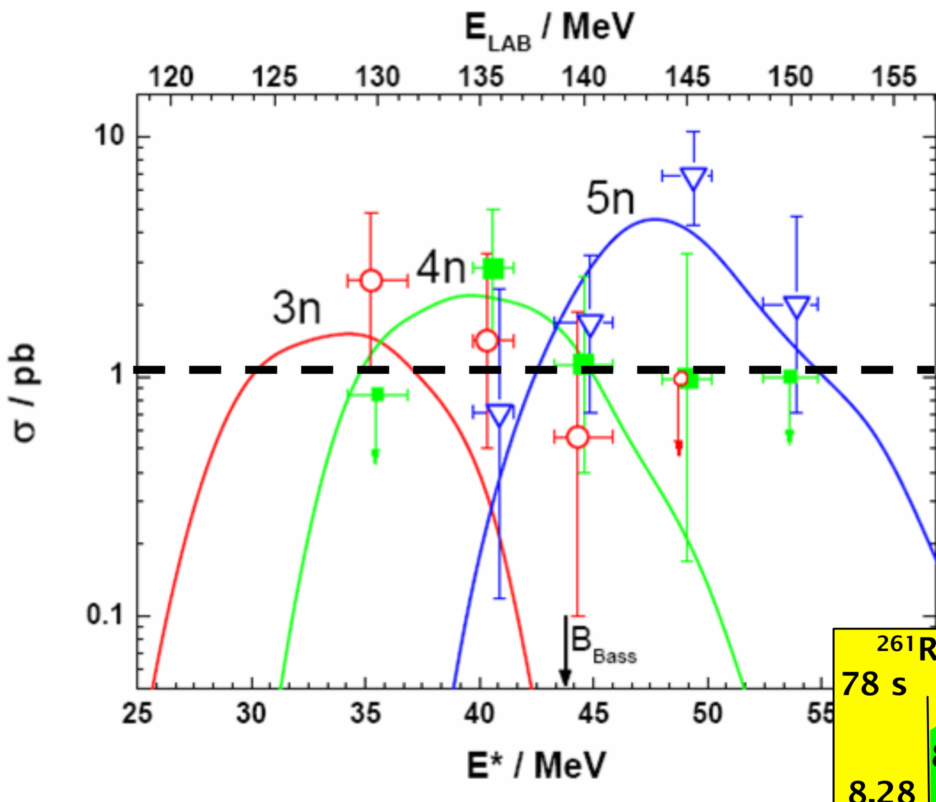
***n* = -2** $\Rightarrow [MF_6]^{2-}$

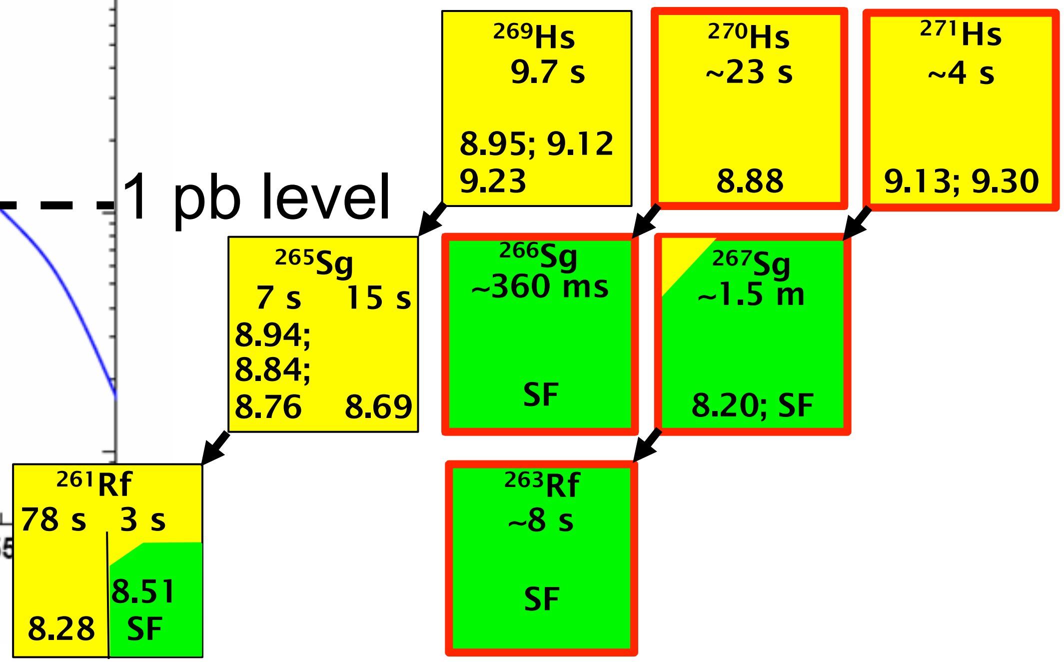
Formation of $[MF_6]^{2-}$: Zr ≈ Hf > Rf

A. Toyoshima *et al.*, Radiochim. Acta **96**, 125 (2008).

Chemistry experiment @ high sensitivity

A. Yakushev





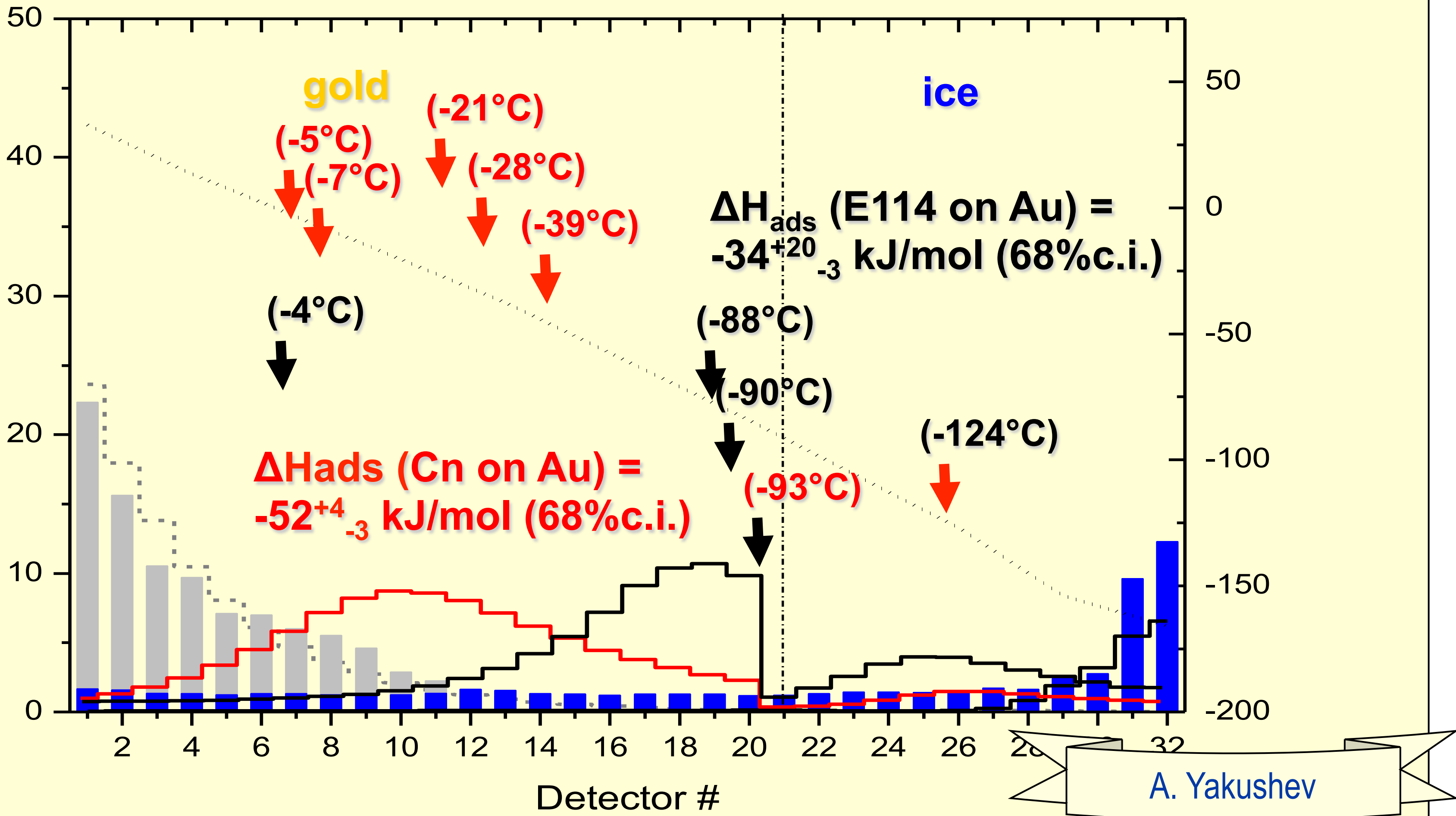
25 decay chains from ^{269,270,271}Hs were detected within 5 weeks
Excitation function was measured @ 5 beam energies

Chemistry of new Elements (Z=109-111)

This page intentionally left blank

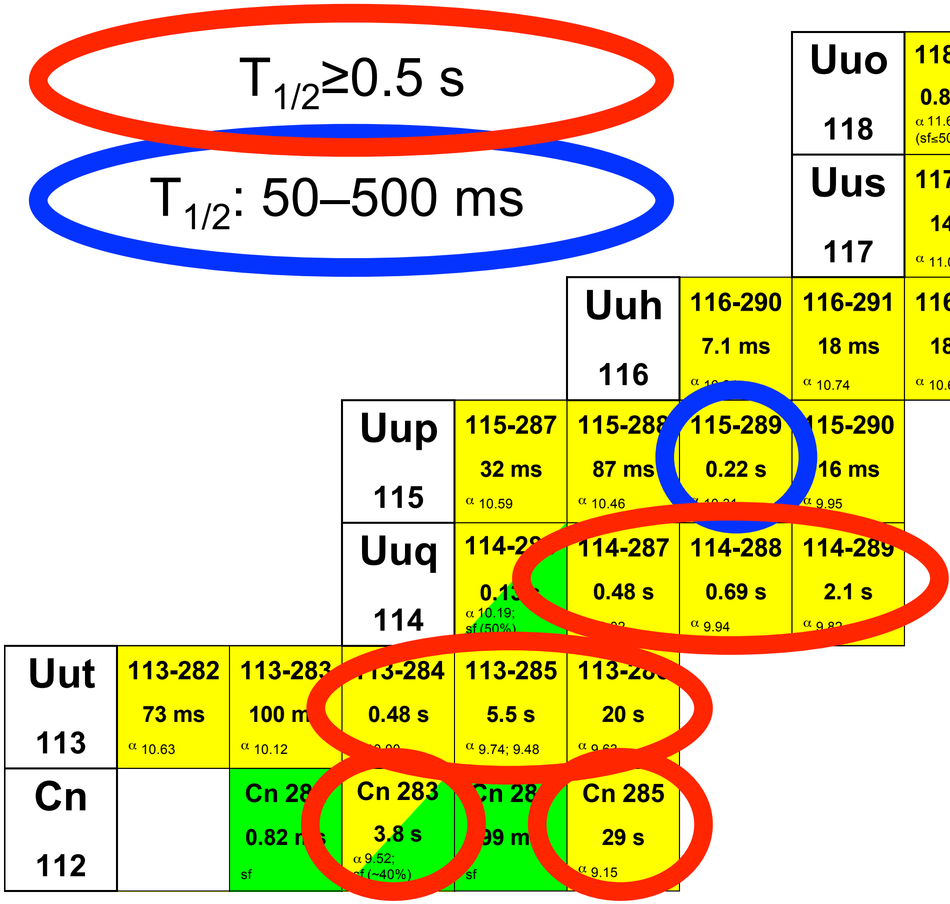
PSI-FLNR results Cn+114 (2006-2008)

Pb ~1000°C	(<<<)	Hg ~ 200°C	<<	Cn -25°C	<	114 -90°C	<	Rn -170°C



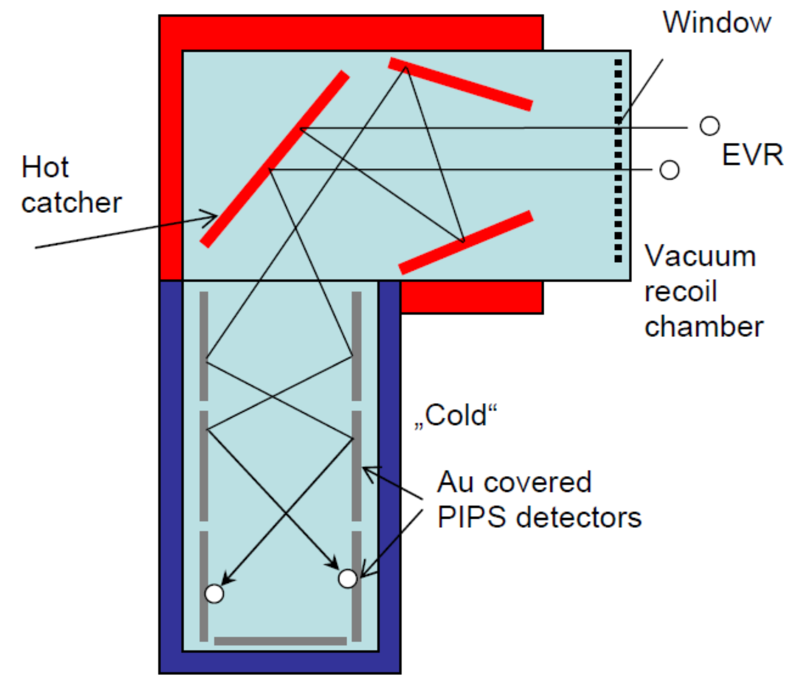
R. Eichler

Chemistry of new Elements (Z=112+)



Z=112 – Z=114: COMPACT / COLD approach ✓

Z≥115: Vacuum chemistry?



SHE Chemistry

What are the most important experiments possible with present facilities?

(-> depends on your facility...)

Which exciting experiments will be enabled with planned accelerator and equipment upgrades?

-> experiments with "unknown" elements

-> new techniques (el.chem; preseparation; ...)

-> high-statistics exps. beyond Db

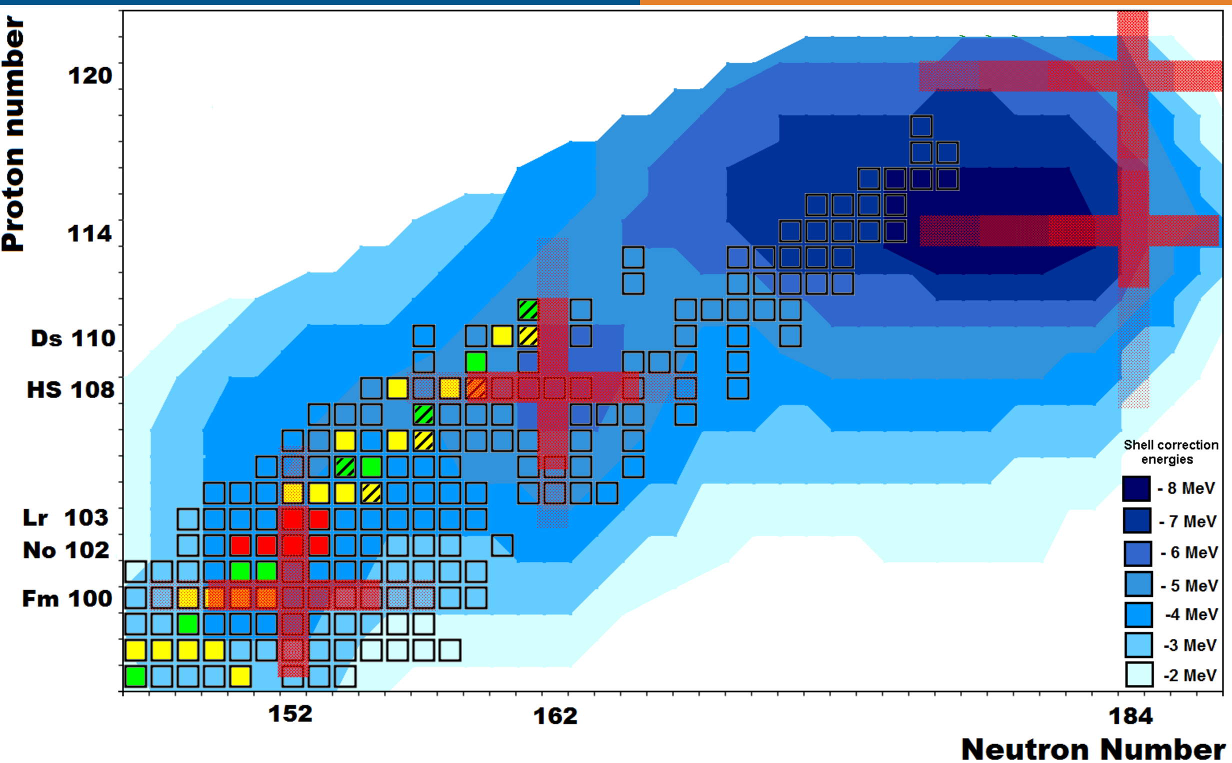
-> new SHE compound classes

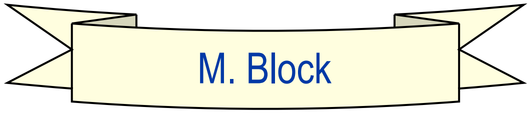
-> access to so far inaccessible observables (mass,...)

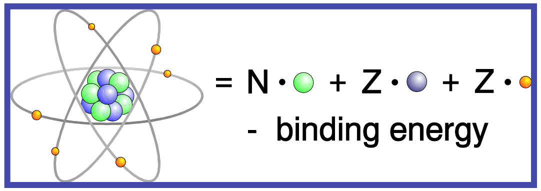
-> chemical separators for nuclear physics

In which directions should future developments proceed to maximize scientific opportunities?

Importance of Masses for Z > 100







- masses provide absolute nuclear binding energies
- masses allow studies of the shell structure evolution
- high-precision mass measurements provide anchor points to fix decay chains
- benchmark nuclear models

HELMHOLTZ ASSOCIATION GSI

Nuclear properties from laser spectroscopy

M. Block

Hyperfine structure interaction

1. Magnetic Dipole HFS

$$A = \frac{\mu_I \langle H_e(0) \rangle}{IJ} \Rightarrow \text{Nuclear magnetic moment } \mu_I$$

2. Electric Quadrupole HFS

$$B = eQ_S \langle \varphi_{jj}(0) \rangle \Rightarrow \text{Spectroscopic quadrupole moment } Q_S$$

3. Coupling

$$\vec{J} + \vec{I} = \vec{F} \Rightarrow \text{Nuclear spin } I$$

Isotope shift

$\langle r^2 \rangle^{A,A'}$ change of mean square charge radius

Challenges (I)

- Create elements beyond E118.
- Fill the gap between the isotopes produced in cold and hot fusion.
- Synthesize more neutron rich isotopes.
- What role can RIBs play?
- Can we shift the reaction paradigm again?

Challenges (II)

Structure:

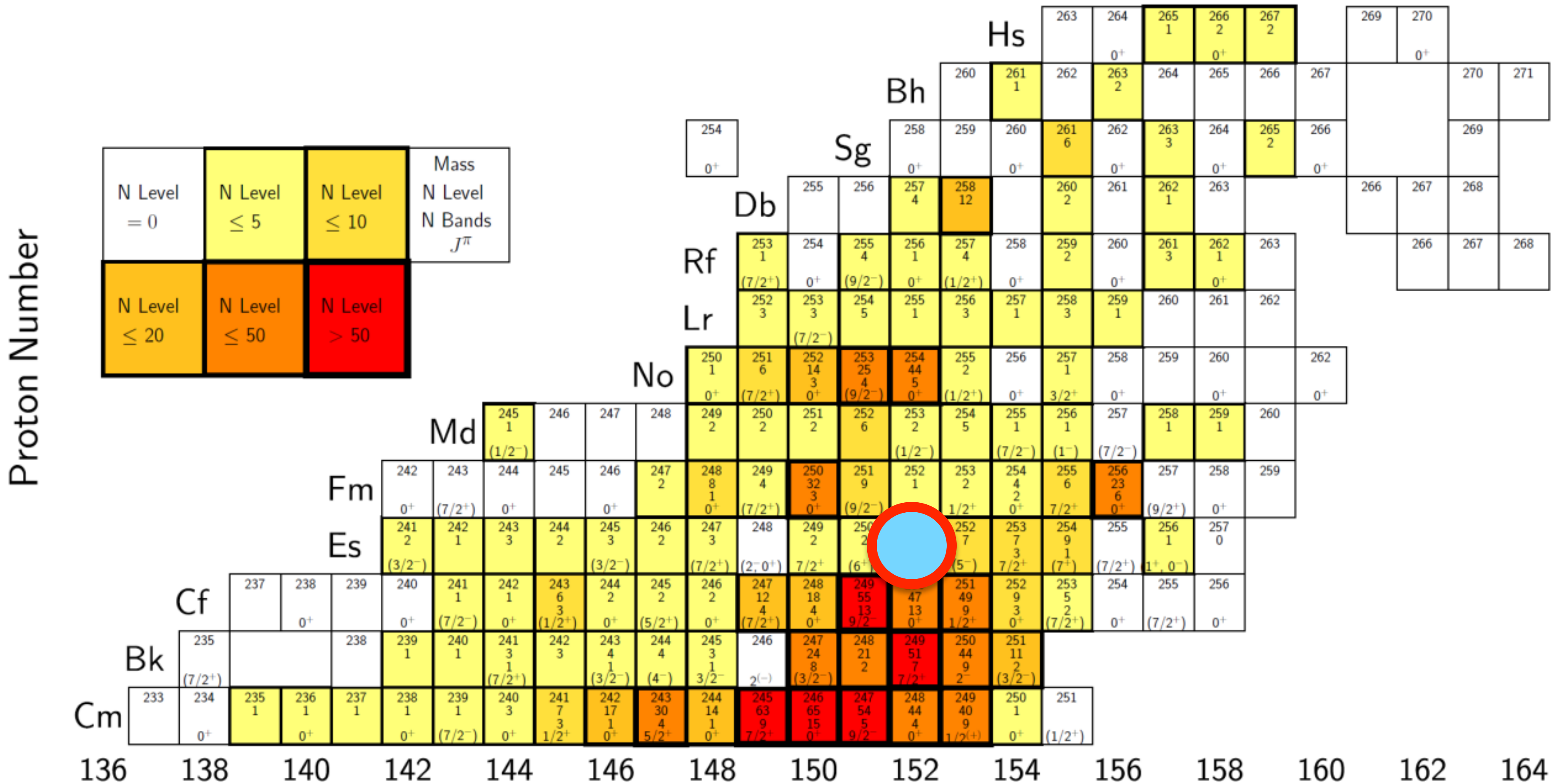
- What are the experimental uncertainties? What data can reliably be used by theorists?
- What new experimental data is needed? Is there guidance from theory in that respect?
- Can we use alternative (optical) methods to extract reliable information on structure?

Urgently needed:(Firm) determination of key observables

M. Leino

Spin-parity: ^{253}Es $I^{\pi} = 7/2^{+}$ from optical spectroscopy, magnetic moment

How to proceed towards higher Z?



P. v. Duppen

Challenges (III)

- Chemistry
  - Increase production rate for long-lived isotopes!
  - Make new elements!

  - New observables?
  - Direct display of relativistic effects: best done where?
  - Direct chemical speciation

  - What new experimental data is needed? Is there guidance from theory in that respect?

Training and Education

- Remember Walter Loveland's question:

  Where does the next generation of SHE scientists come from?