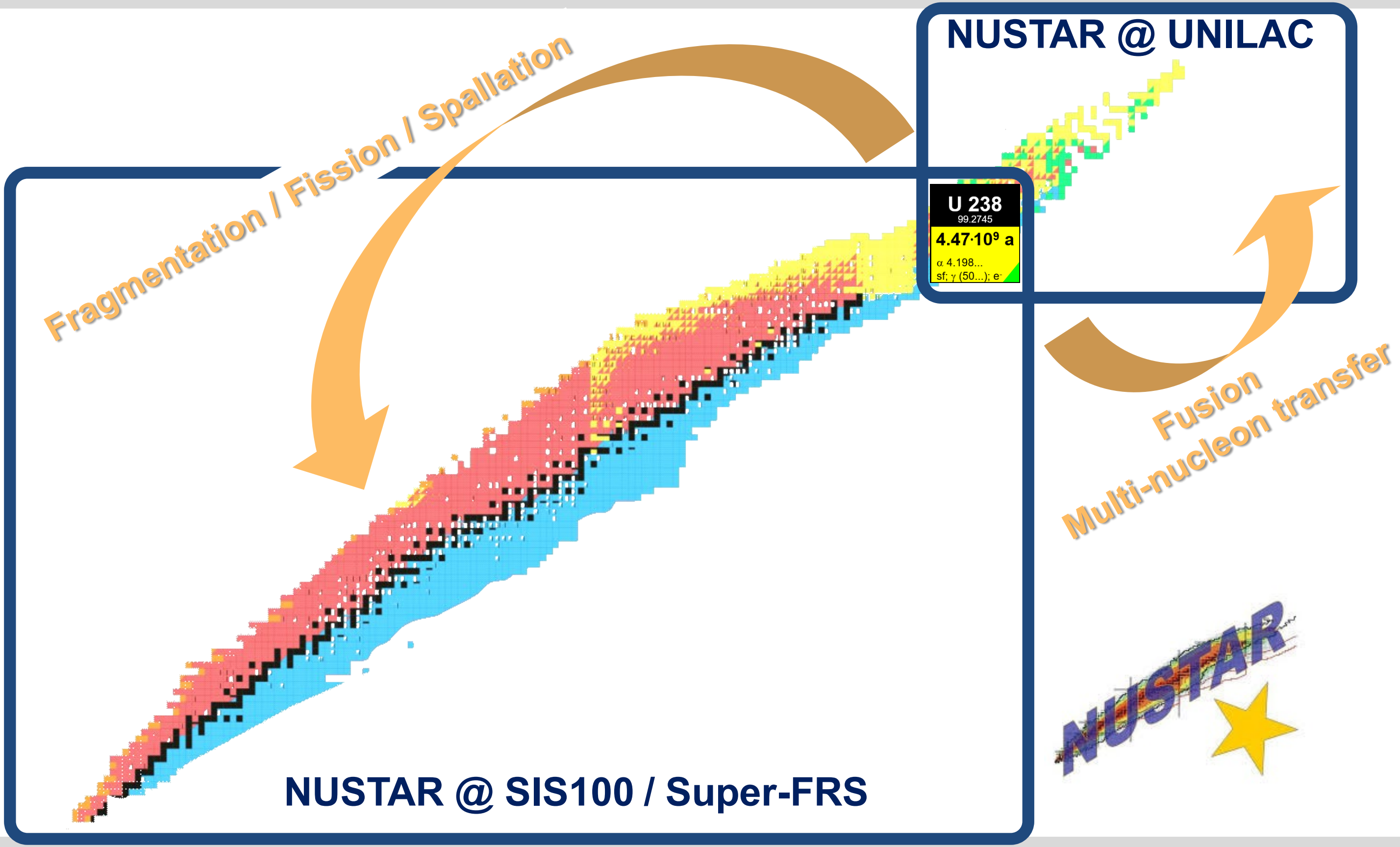
From PoF IV to PoF V

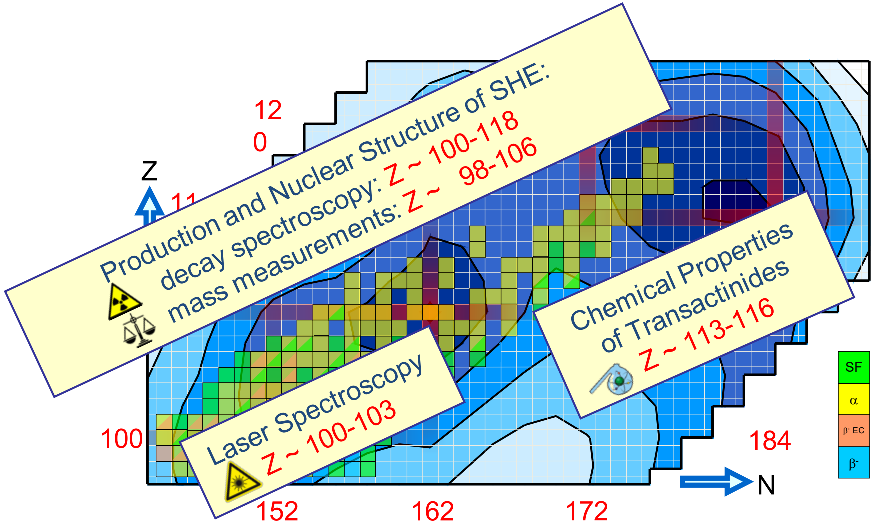
SHE Chemistry department

Ch.E. Düllmann, A. Yakushev, J. Khuyagbaatar, J. Ballof *et al.*

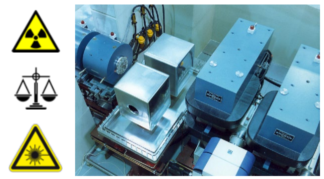
Superheavy Elements
– FAIR / NUSTAR science above $_{92}$U



The GSI superheavy element program in PoF IV



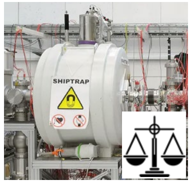
Recoil separators



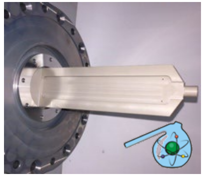
SHIP

TASCA

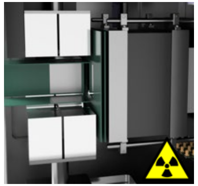
Ancillary setups



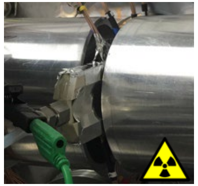
SHIPTRAP



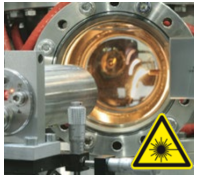
miniCOMPACT



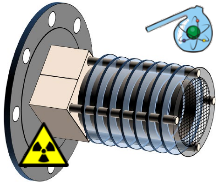
LUNDIUM



ANSWERS



RADRIS



UniCELL

Comprehensive investigation of **production** and of **atomic, chemical and nuclear properties** of elements **Z ~ 100 – 118** using **novel techniques** and **GSI-unique suite** of experimental setups around recoil separators SHIP and TASCA

Not included: search for new elements during FAIR construction phase

SHE Highlights from the last 20 years at GSI
(in red: since 2020)

Reaction studies toward Z=120 (ANU)

H.M. Albers *et al.*, Phys. Lett. B 808 (2020) 135626 (Z=120)

Search beyond Z=118

J. Khuyagbaatar *et al.*, PRC 102 (2020) 064602 (Z=119&120)
S. Hofmann, Russ. Chem. Rev. 78 (2009) 1123 (Z=120)
S. Hofmann *et al.*, EPJA 52 (2016) 180 (Z=120)

Chemical studies

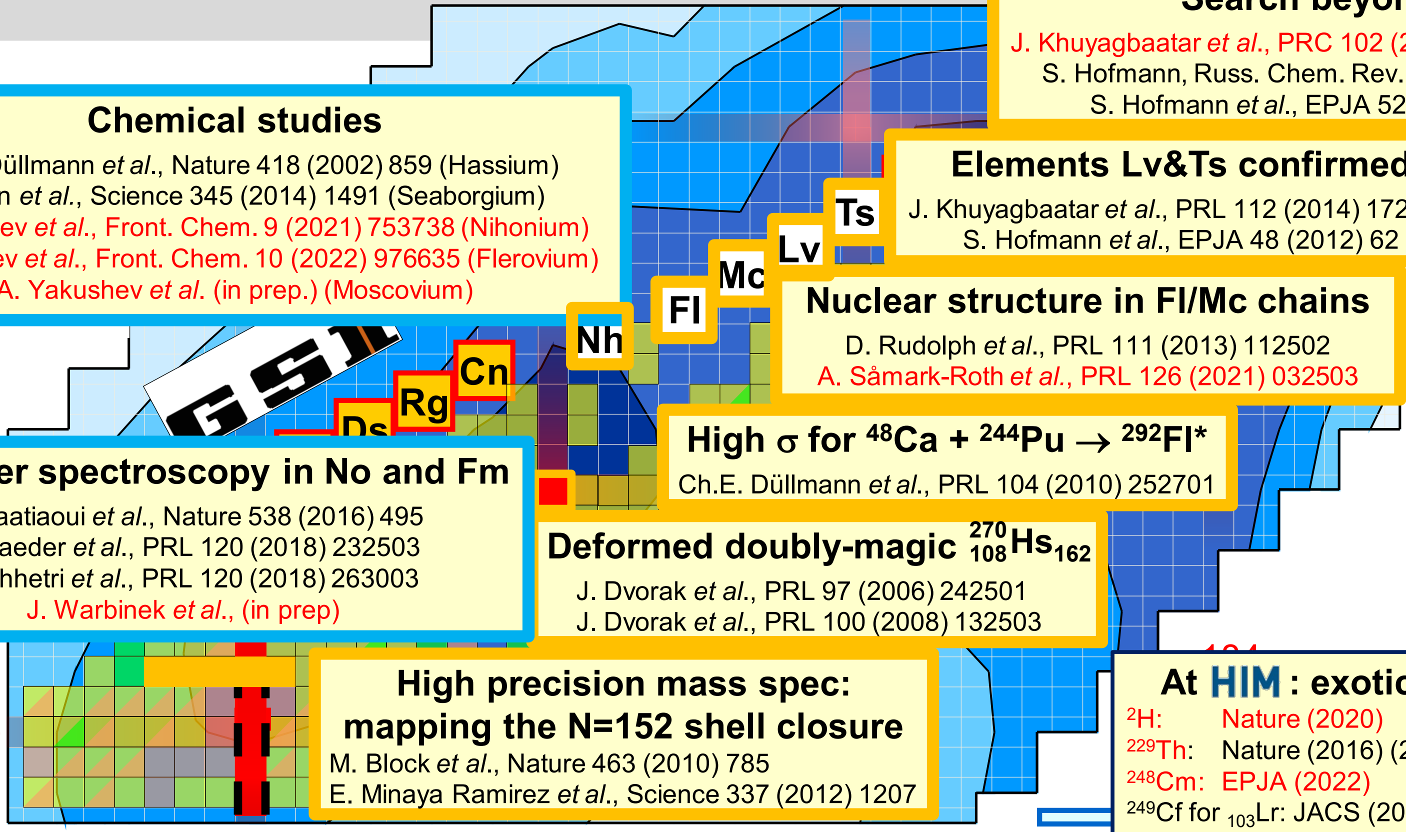
Ch.E. Düllmann *et al.*, Nature 418 (2002) 859 (Hassium)
J. Even *et al.*, Science 345 (2014) 1491 (Seaborgium)
A. Yakushev *et al.*, Front. Chem. 9 (2021) 753738 (Nihonium)
A. Yakushev *et al.*, Front. Chem. 10 (2022) 976635 (Flerovium)
A. Yakushev *et al.* (in prep.) (Moscovium)

Elements Lv&Ts confirmed

J. Khuyagbaatar *et al.*, PRL 112 (2014) 172501
S. Hofmann *et al.*, EPJA 48 (2012) 62

Nuclear structure in Fl/Mc chains

D. Rudolph *et al.*, PRL 111 (2013) 112502
A. Såmark-Roth *et al.*, PRL 126 (2021) 032503



High σ for ^{48}Ca + ^{244}Pu → ^{292}Fl*

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

First laser spectroscopy in No and Fm

M. Laatiaoui *et al.*, Nature 538 (2016) 495
S. Raeder *et al.*, PRL 120 (2018) 232503
P. Chhetri *et al.*, PRL 120 (2018) 263003
J. Warbinek *et al.*, (in prep)

Deformed doubly-magic $^{270}_{108}Hs_{162}$

J. Dvorak *et al.*, PRL 97 (2006) 242501
J. Dvorak *et al.*, PRL 100 (2008) 132503

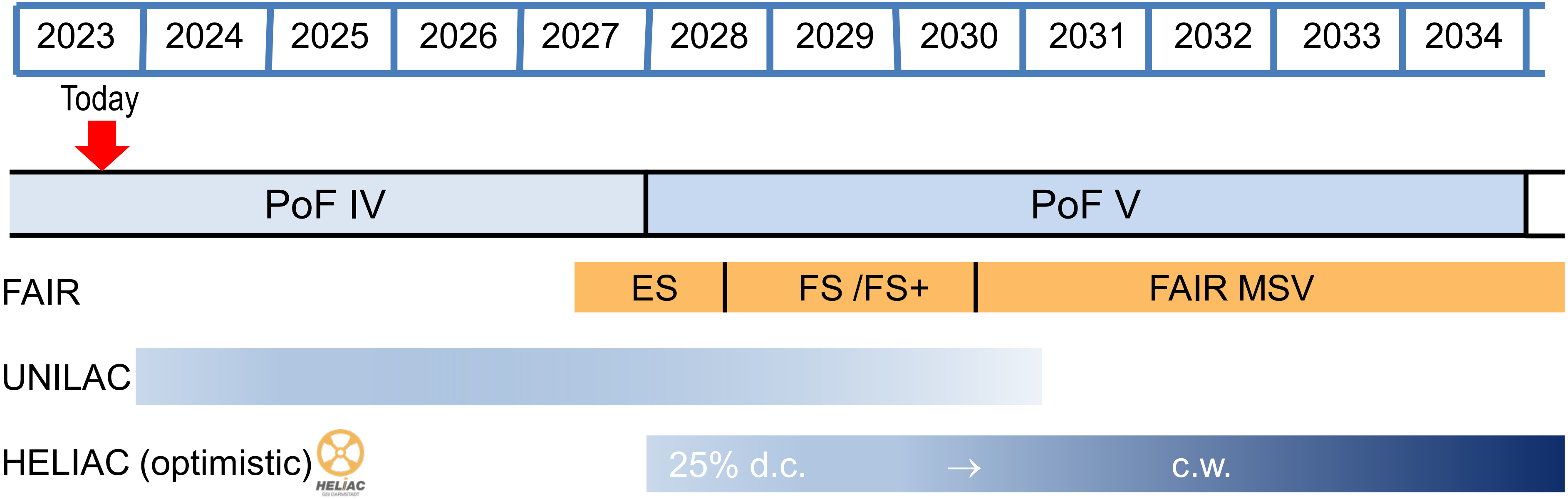
High precision mass spec: mapping the N=152 shell closure

M. Block *et al.*, Nature 463 (2010) 785
E. Minaya Ramirez *et al.*, Science 337 (2012) 1207

At HIM : exotic nuclear targets

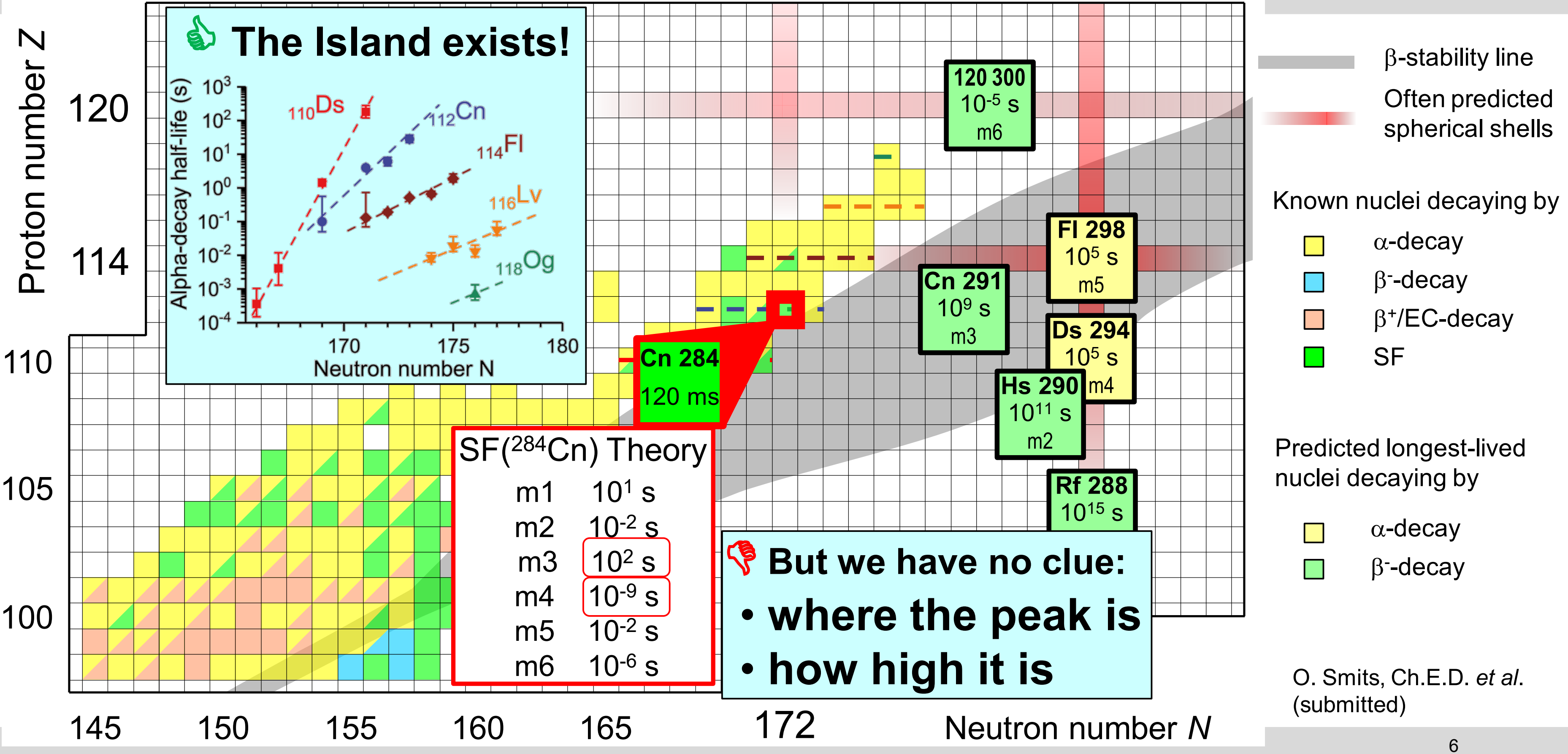
^{2}H: Nature (2020)
^{229}Th: Nature (2016) (2018) (2019); PRL (2020)
^{248}Cm: EPJA (2022)
^{249}Cf for $_{103}$Lr: JACS (2018)
^{255}Es: Atoms (2022); PRR (2022); PRC (2023)

Strategic PoF V timeline



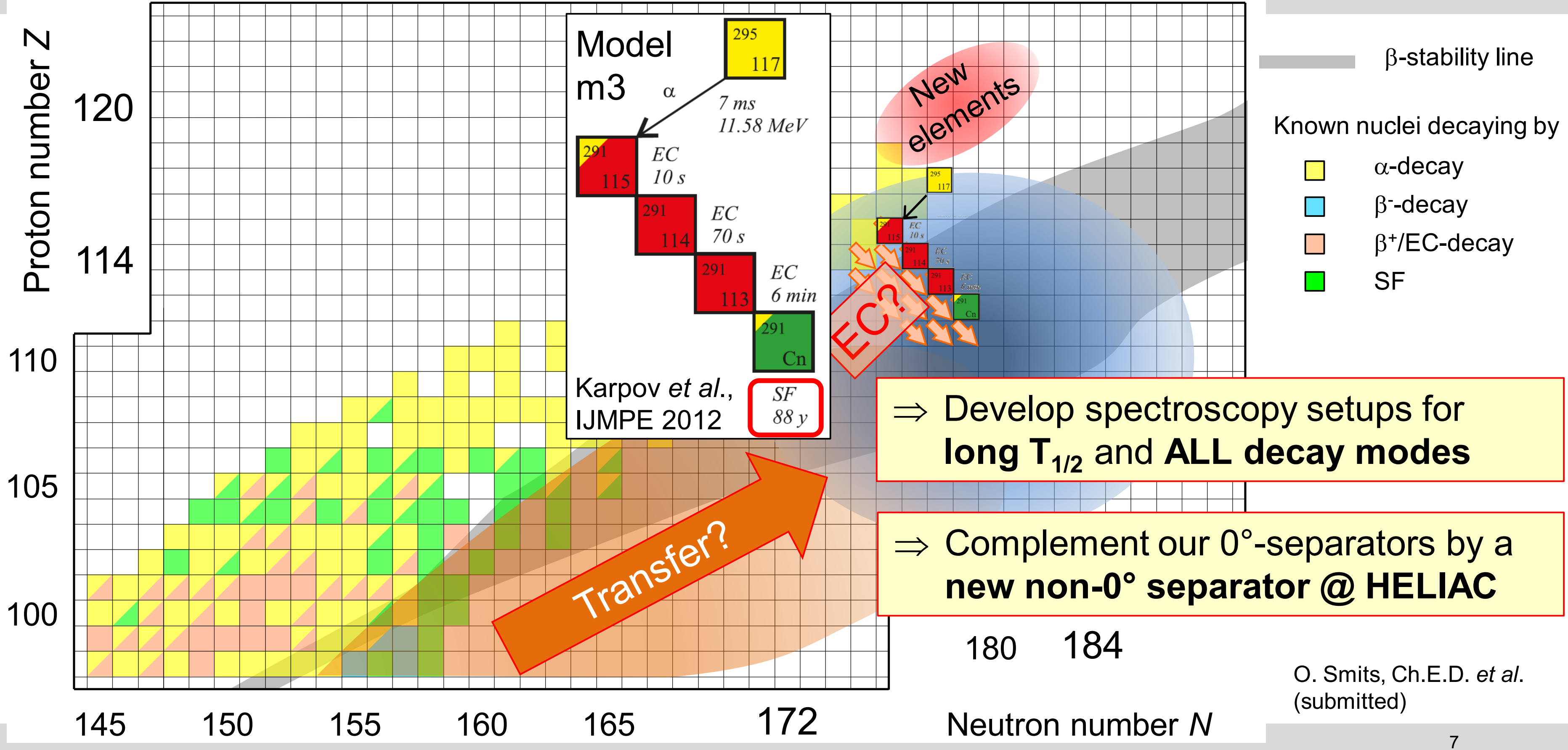
Irrespective of the exact starting year, HELIAC will deliver beams for SHE during PoF V

Island of Stability – Status 2023



O. Smits, Ch.E.D. *et al.* (submitted)

PoF V: Exploring the Island of Enhanced Stability



⇒ Develop spectroscopy setups for **long $T_{1/2}$** and **ALL decay modes**

⇒ Complement our 0°-separators by a **new non-0° separator @ HELIAC**

O. Smits, Ch.E.D. *et al.* (submitted)

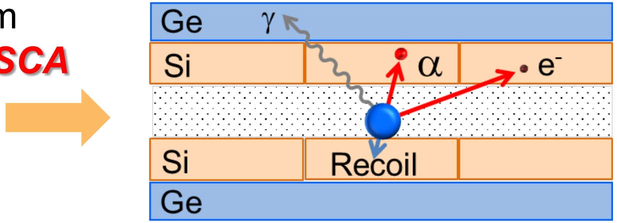
Nuclear decay spectroscopy with ANSWERS

Adsorption-based **N**uclear **S**pectroscopy **W**ithout **E**vaporation **R**esidue **S**ignal (**ANSWERS**) at ***TASCA***

Methods breakthrough to overcome limitations of mature state-of-the art decay spectroscopy of SHE

ANSWERS@*TASCA*

Gas flow from ***TASCA***

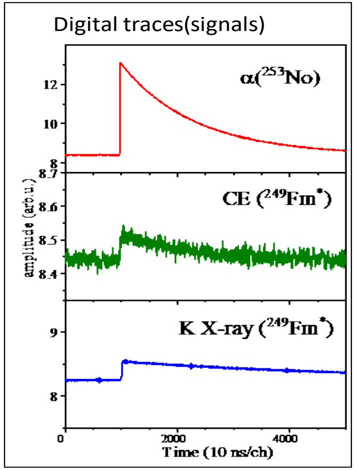


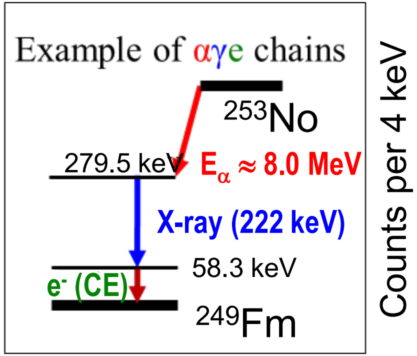
ANSWERS has a high efficiency for measuring α-, e⁻/CE-, γ/X-, daughter recoil coincidence data

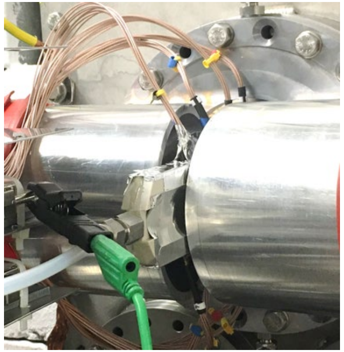
J. Khuyagbaatar and P. Mosat

- High efficiency multi-coincidence nuclear spectroscopy setup
- Successful decay spectroscopy studies on α-/γ-/CE decays up to Z=104
- Fission-fragment mass distributions in Z=102 region measured

POF V: Extend to full setup with pixelized Ge-detectors: SHE-ANSWERS







The superheavies in the periodic table

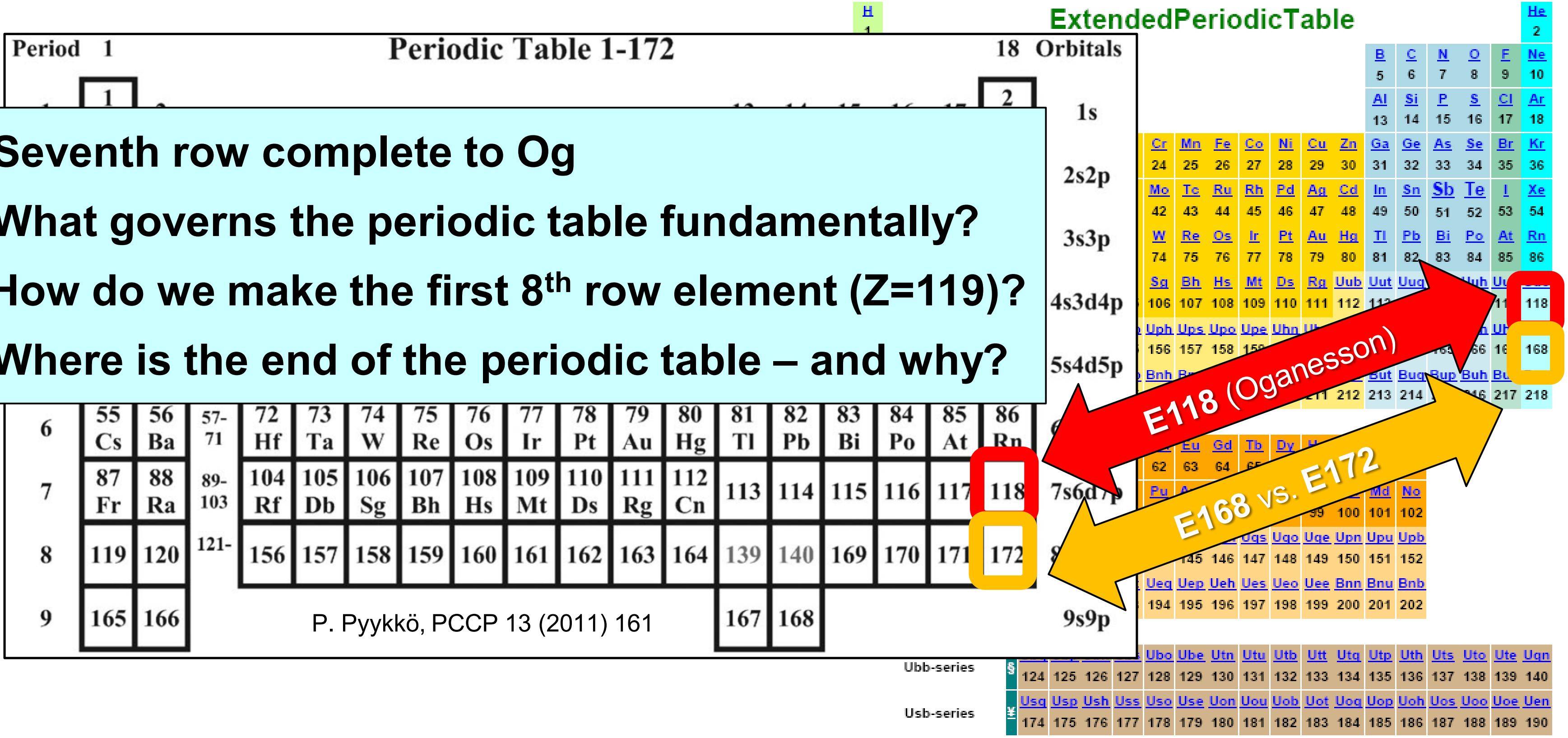
United Nations Educational, Scientific and Cultural Organization

2019 IYPT International Year of the Periodic Table of Chemical Elements

1 H																															2 He
3 Li	4 Be																									5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg																									13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc															22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y															40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Future periodic table(s)?

- Seventh row complete to Og
- What governs the periodic table fundamentally?
- How do we make the first 8th row element (Z=119)?
- Where is the end of the periodic table – and why?



P. Pyykkö, PCCP 13 (2011) 161

Oganesson: current focus of chemical theory

GDCh Communications Angewandte Chemie International Edition

How to cite: Angew. Chem. Int. Ed. **2020**, 59, 23636–23640
International Edition: doi.org/10.1002/anie.202011976

Oganesson

Oganesson: A Noble Gas Element That Is Neither Noble Nor a Gas

Odile R. Smits, Jan-Michael Mewes,* Paul Jerabek,* and Peter Schwerdtfeger**

PHYSICAL REVIEW A **98**, 042512 (2018)

Atomic structure calculations of superheavy noble element oganesson (Z=118)

B. G. C. Lackenby,[1] V. A. Dzuba,[1] and V. V. Flambaum[1,2]
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Cite this: Phys. Chem. Chem. Phys., 2023, 25, 633

The van der Waals interactions in systems involving superheavy elements: the case of oganesson (Z = 118)†

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PHYSICAL REVIEW A **104**, 012819 (2021)

Electron affinity of oganesson

M. Y. Kaygorodov,[1] L. V. Skripnikov,[2,1] I. I. Tupitsyn,[1] E. Eliav,[3] Y. S. Kozhedub,[1] A. V. Malyshev,[1] A. V. Oleynichenko,[2,4] V. M. Shabaev,[1] A. V. Titov,[2] and A. V. Zaitsevskii[2,4]
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GDCh Communications Angewandte Chemie International Edition

International Edition: DOI: 10.1002/anie.201908327
German Edition: DOI: 10.1002/ange.201908327

Superheavy Elements | Hot Paper

Oganesson Is a Semiconductor: On the Relativistic Band-Gap Narrowing in the Heaviest Noble-Gas Solids

Jan-Michael Mewes, Paul Jerabek, Odile R. Smits, and Peter Schwerdtfeger*

THE JOURNAL OF PHYSICAL CHEMISTRY A
Article
Cite This: J. Phys. Chem. A 2019, 123, 4201–4211
pubs.acs.org/JPCA

Solid Oganesson via a Many-Body Interaction Expansion Based on Relativistic Coupled-Cluster Theory and from Plane-Wave Relativistic Density Functional Theory

Published as part of The Journal of Physical Chemistry virtual special issue "Leo Radom Festschrift".

Paul Jerabek,*[†] Odile R. Smits,[‡] Jan-Michael Mewes,[‡] Kirk A. Peterson,[¶] and Peter Schwerdtfeger*[‡]

PHYSICAL REVIEW LETTERS **120**, 053001 (2018)
Editors' Suggestion | Featured in Physics

Electron and Nucleon Localization Functions of Oganesson: Approaching the Thomas-Fermi Limit

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VOLUME 77, NUMBER 27 PHYSICAL REVIEW LETTERS 30 DECEMBER 1996

Element 118: The First Rare Gas with an Electron Affinity

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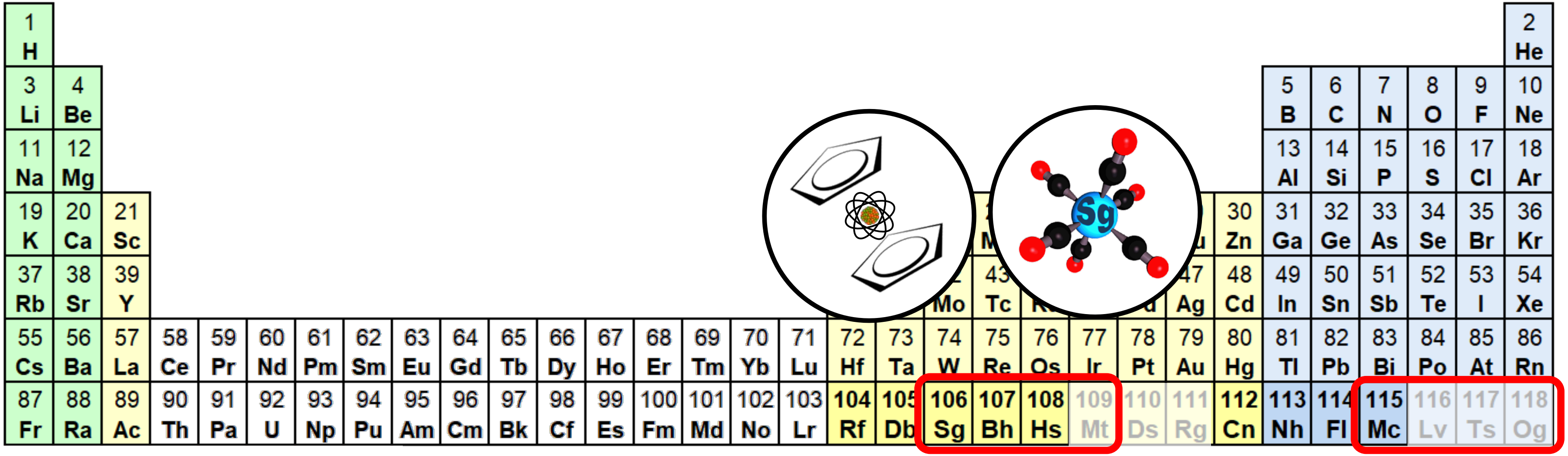
(Received 27 August 1996)

PoF V: Chemical studies of SHE



Opening the 8th period

(E119 may be more impactful for chemistry than for physics!)

Transition metal molecular studies

Chemistry towards $_{118}$Og

PoF V Outlook

SHE in POF V

- Spearhead the exploration of the Island of Stability
- Detailed studies of known SHE
- Expand and explore the end of the Periodic Table

Main infrastructure activities in POF V:

- transition from UNILAC to HELIAC
- edicated non-fusion product separator @ HELIAC
- upgrading “ANSWERS” multi-coincidence setup

Connections within HGF

- r-process
  theory (GSI)
  HZDR (Ion beam center)
- transuranium chemistry
  KIT

(all rather ~NWG and not strategic partnerships with joint professorships)