Heavy & Superheavy Nuclei (SHN)

« Description microscopique des noyaux superlourds »,« Decay spectroscopy of SHE », « Laser spectroscopy of the heaviest elements »

Prospectives in2p3

GT02

30-31 Janvier 2019, Caen

Questions

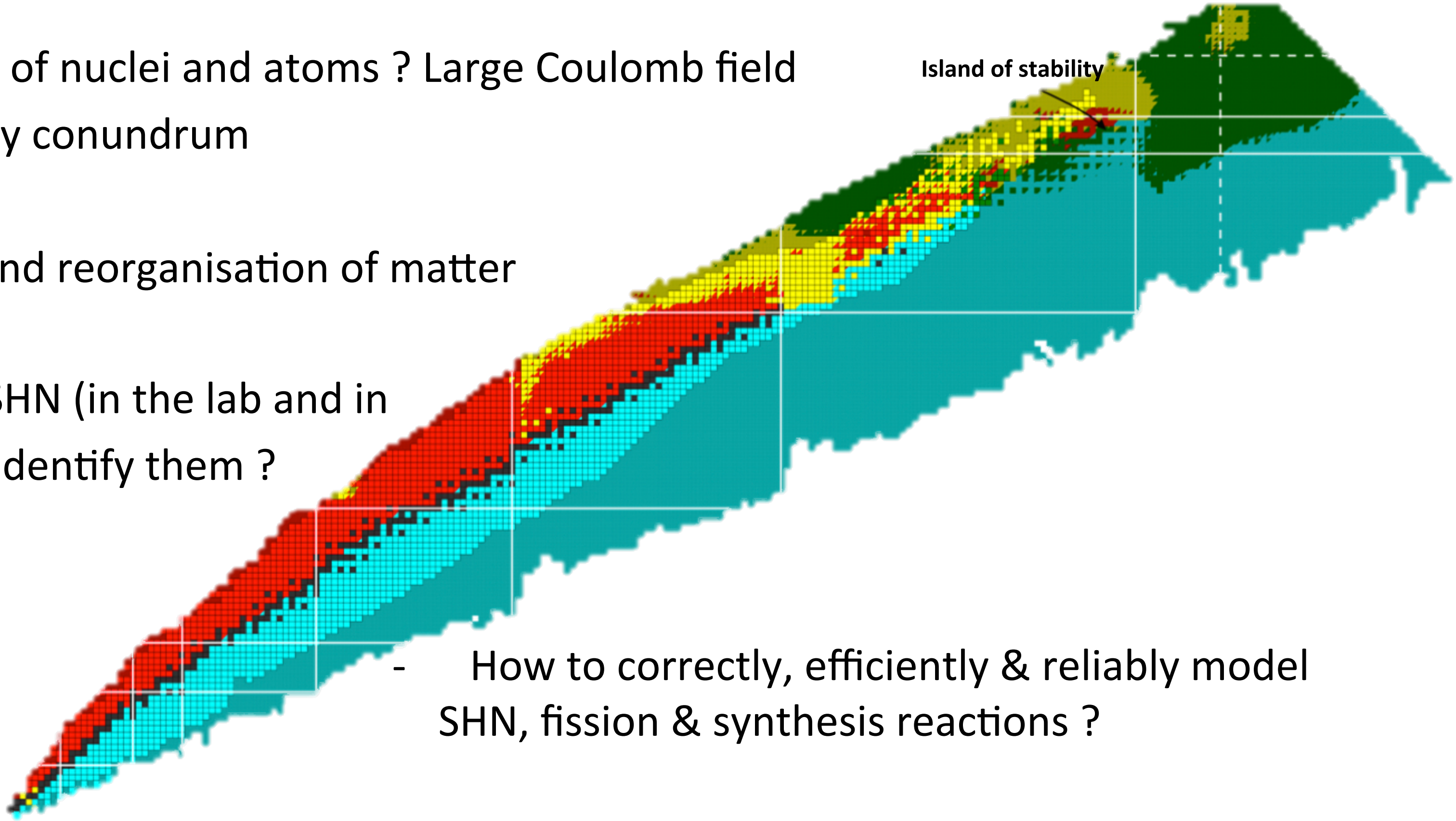
- Limits of the nuclear chart ? Fission is the show stopper

- How many elements in the periodic table ? Can't have an atom without a nucleus

- Shell evolution of nuclei and atoms ? Large Coulomb field & high level density conundrum

- Shapes, sizes and reorganisation of matter

- How to make SHN (in the lab and in the universe) and identify them ?



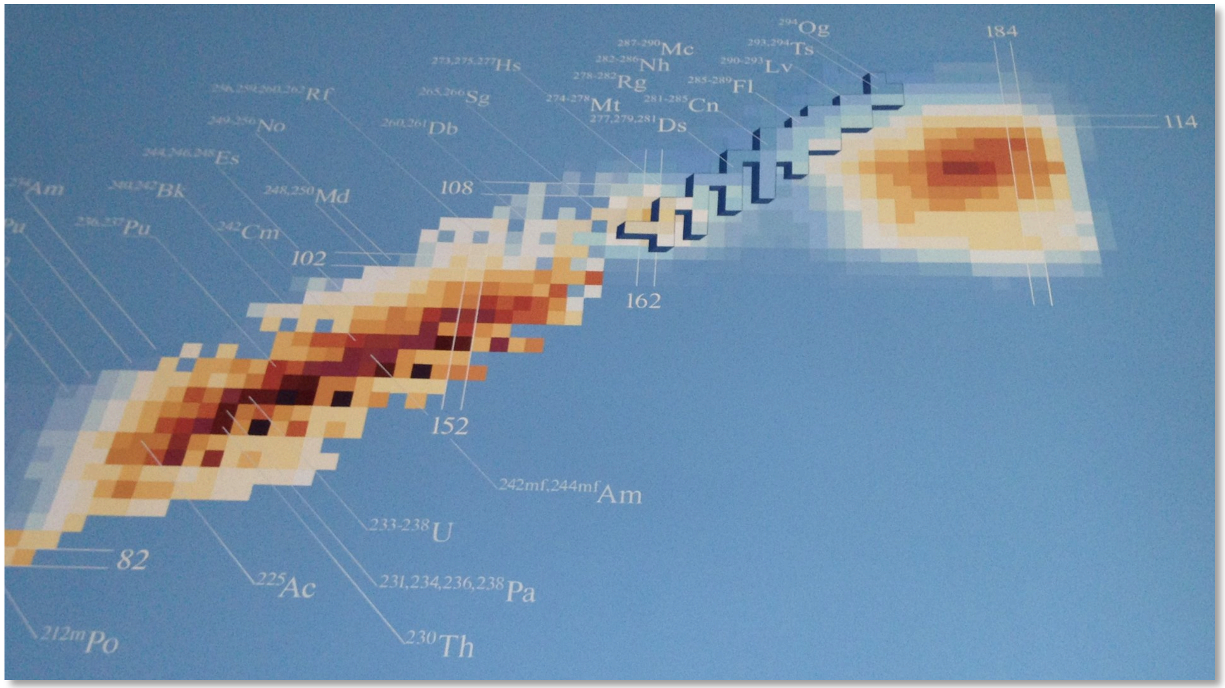
- How to correctly, efficiently & reliably model SHN, fission & synthesis reactions ?

Synergies

GT07:A/Q=7 injector
for SPIRAL2

GT07: Beam Production &
New generation targets

GT02:EDFs
& Symmetry
breaking
and
restauration



GT08: R&D
for AGATA

GT02:Nucleosynthesis
&
origin of the elements

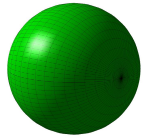
GT02:Complete
description of
fission

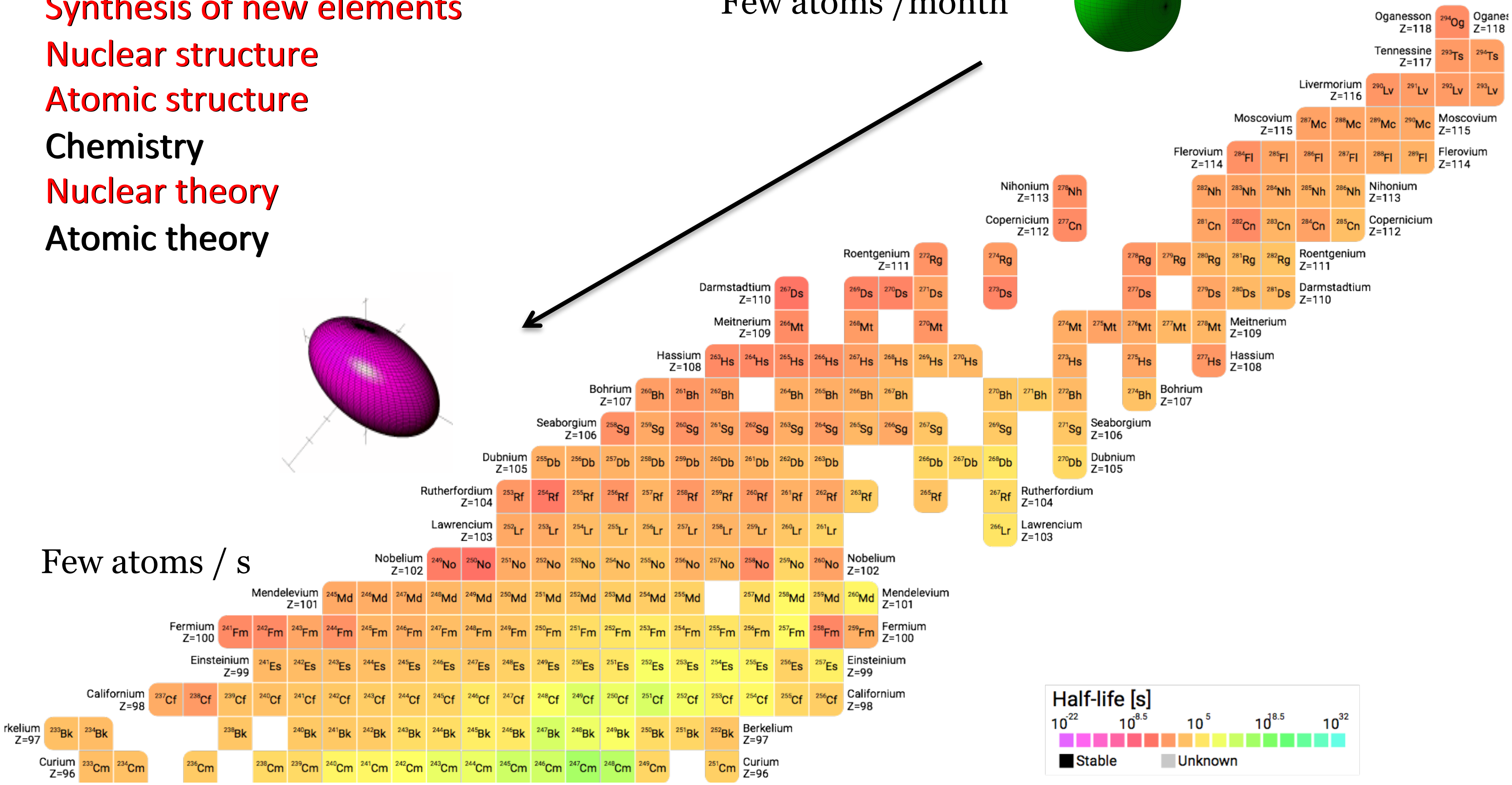
GT02:ISOL &
ground-state
spectroscopy

SHE research program @ in2p3

Reaction studies
Synthesis of new elements
Nuclear structure
Atomic structure
Chemistry
Nuclear theory
Atomic theory

Few atoms /month

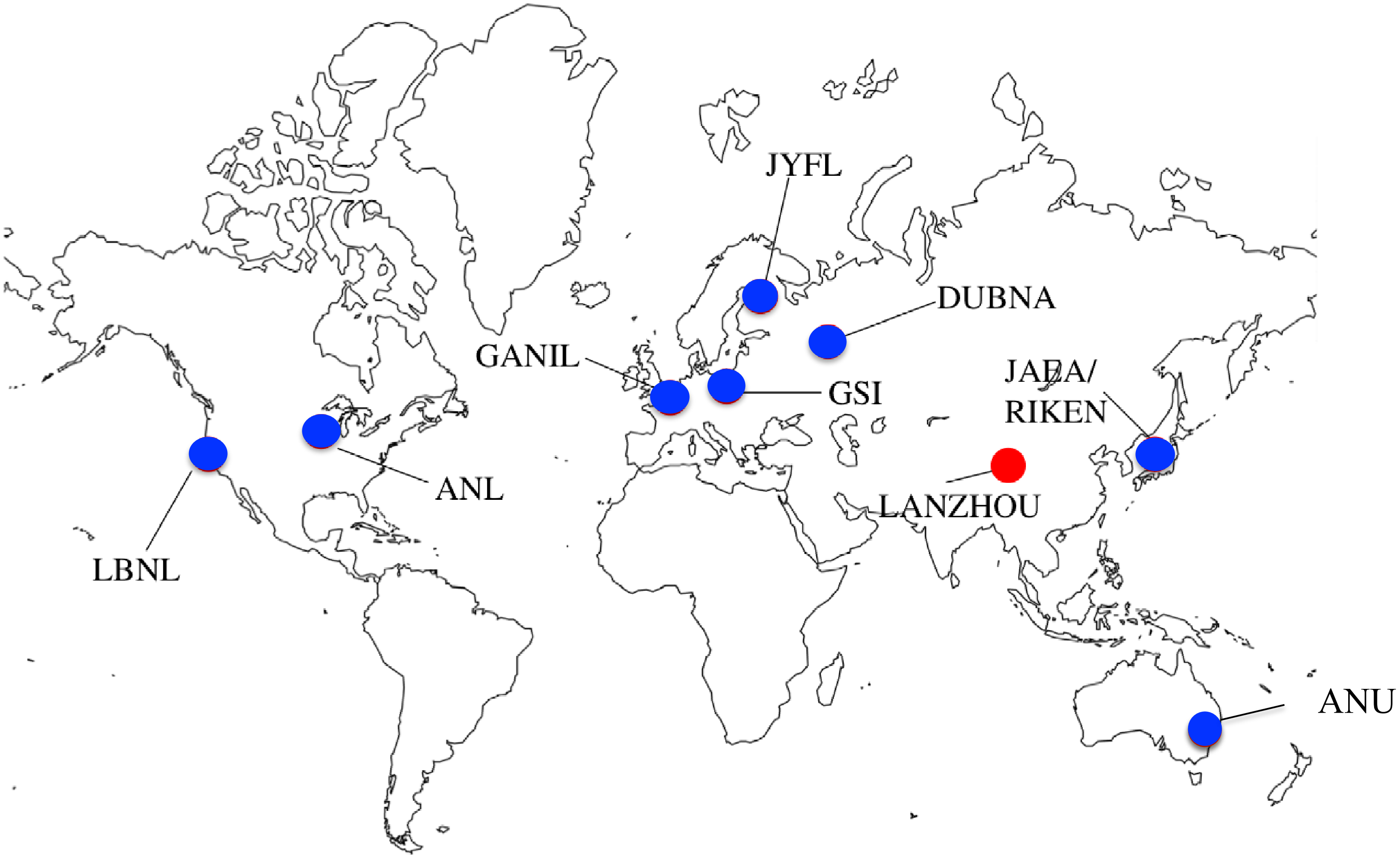




Few atoms / s

Laboratories: CEA, GANIL, IJClab, IP2I, IPHC, LPC

International collaborations & Competition

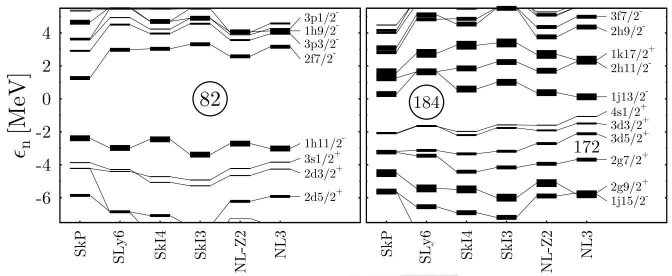


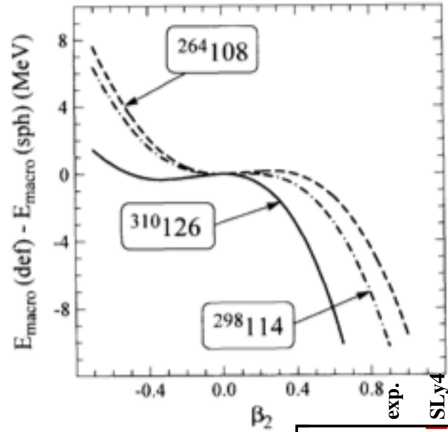
Long irradiation times, dedicated setups (with maximised production, transport & detection efficiencies), beam/target/instrumentation/theory developments

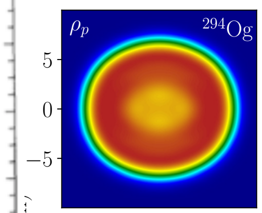
Superheavy Nuclei: a theoretical challenge

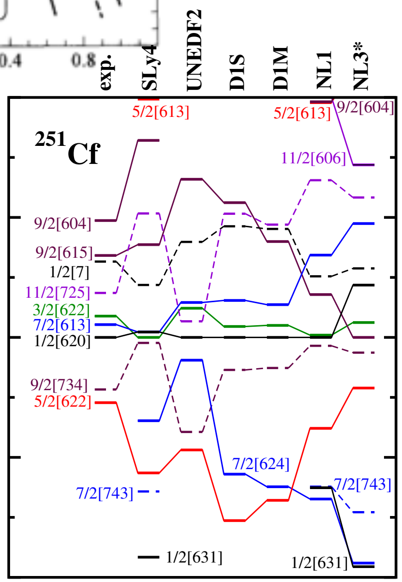
Structure:

- Large level density & Coulomb frustration
- Limitations of existing energy density functionals
- Treatment of pairing correlations & inclusion of beyond mean field effects (coupling to vibrational states…)
- Microscopic treatment of fission & alpha-decay lifetimes
- Open conceptual & technical questions how to model fission of blocked configurations (K isomers, odd & odd-odd systems)







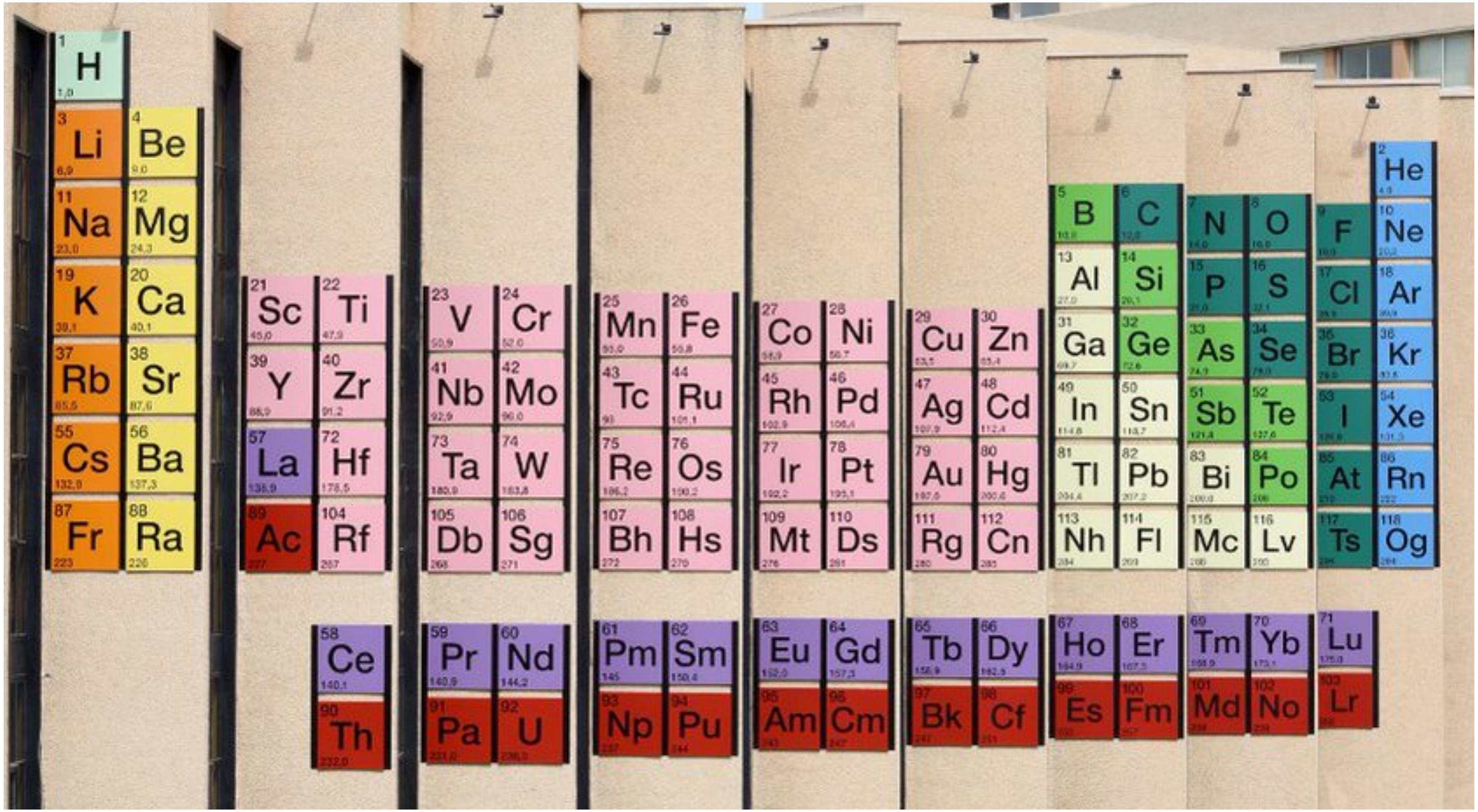


Reactions:

- Predictive microscopic model of reaction cross sections

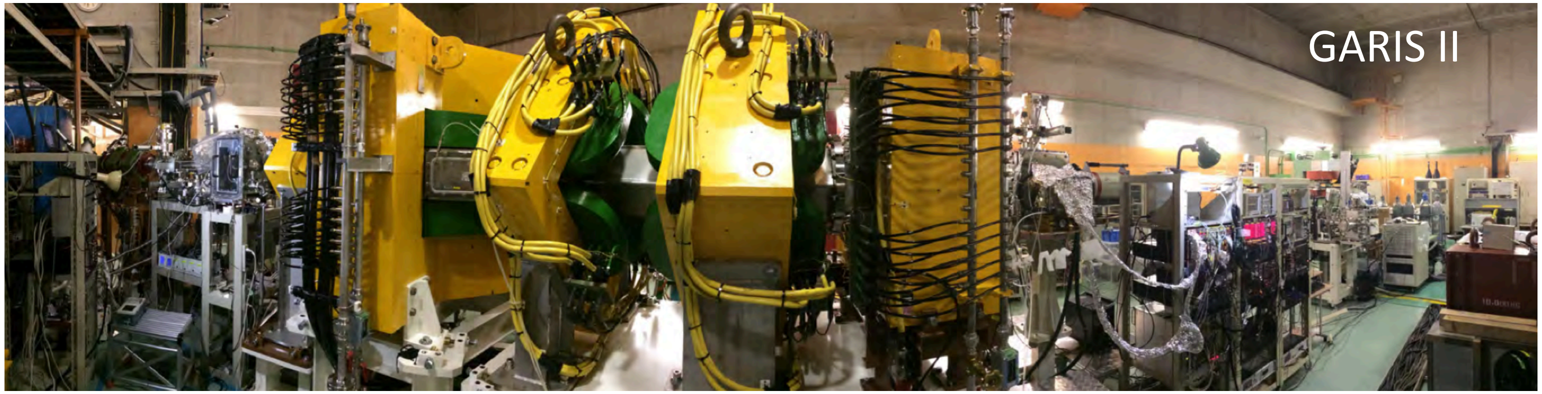
Few theoreticians in France & in Europe working in this field
ANR « New energy functional for heavy nuclei » (NEWFUN)

The 7th period is complete



Chemistry Department, University of Murcia,

Search for New Elements



E118: ^{50}Ti + ^{248}Cm —> ^{295}Og + 3n — MIVOC beam (IPHC) @ RILAC — Experiment paused

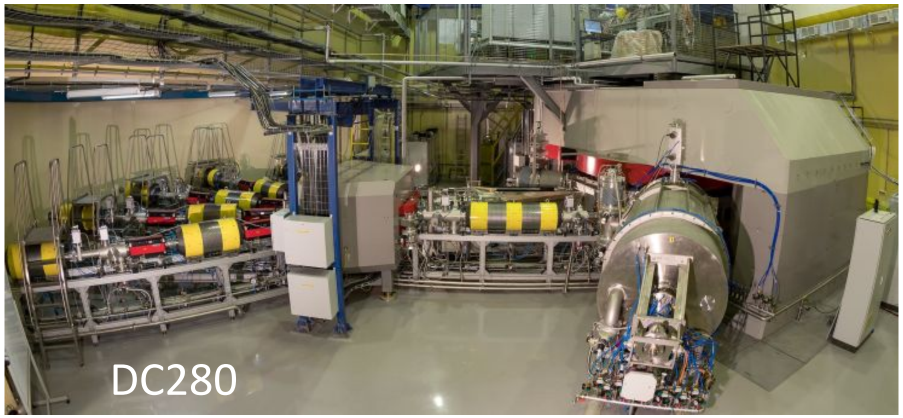
E119: ^{51}V + ^{248}Cm —> $^{299-x}$Uue + xn — HT oven @ RRC cyclotron

-> Several campaigns since 2017, ongoing

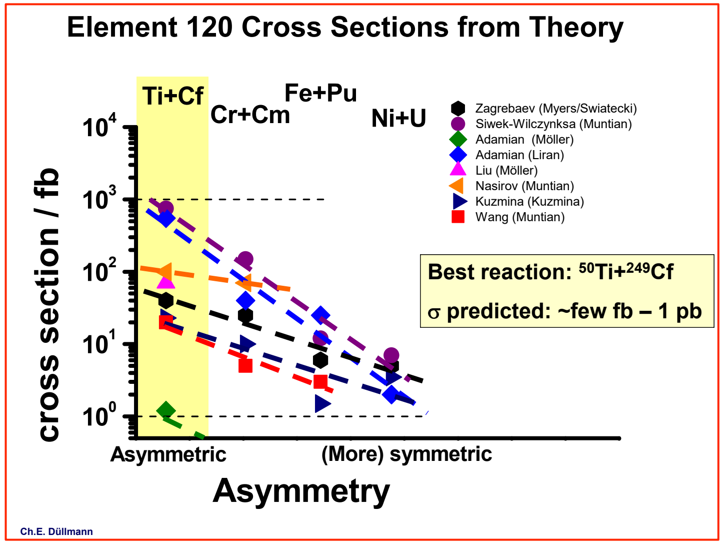
2020: Start nRILAC (SC) + GARIS III -> continue E119 campaign

2020: Start of the SHE Factory @ DUBNA Metallic ions beams of ^{50}Ti, ^{51}V & ^{54}Cr (MIVOC + Inductive oven)

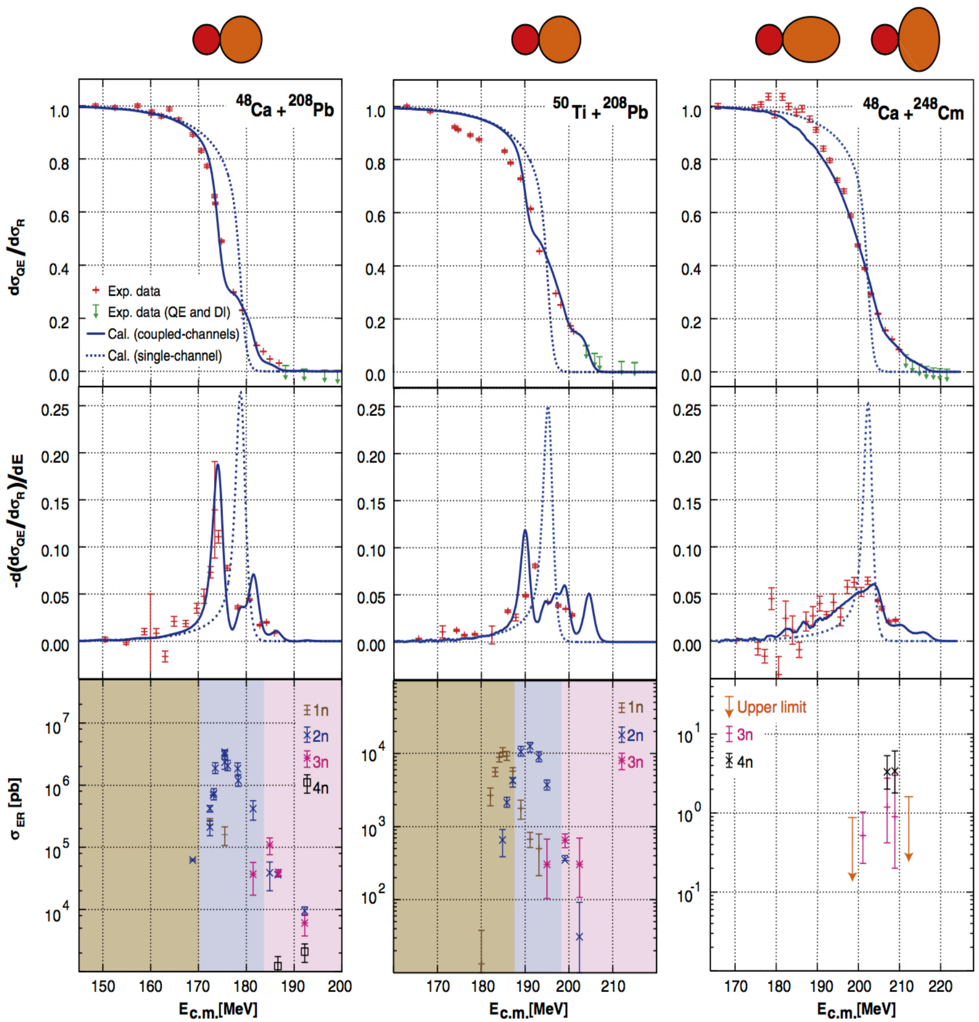
⇒ up to 10 pμA on target
⇒ two parallel programs in Dubna and RIKEN



Reaction studies



T. Tanaka et al., Journal of the Physical Society of Japan 87 (2018) 014201

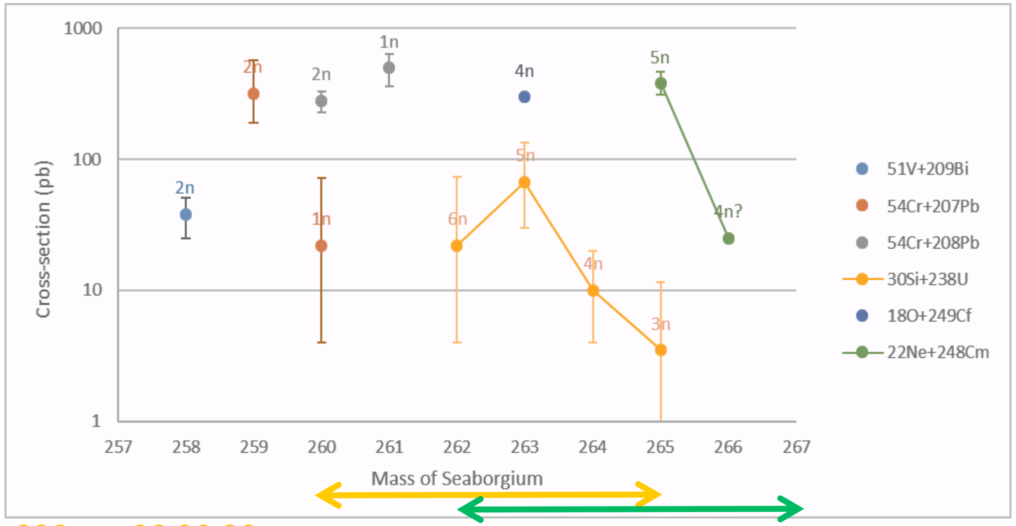


Find optimal bombarding energy for the synthesis of new elements (IPHC)

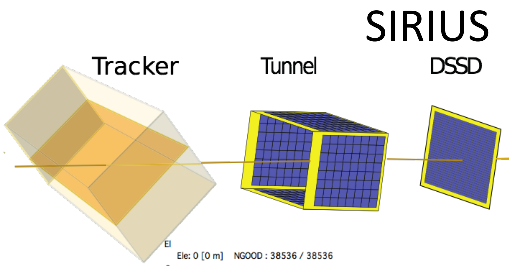
Measurement of excitation functions (xn, pxn…) to test model parameter space and improve predictive power of theories

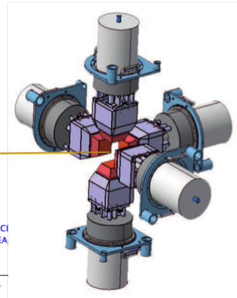
Reaction studies

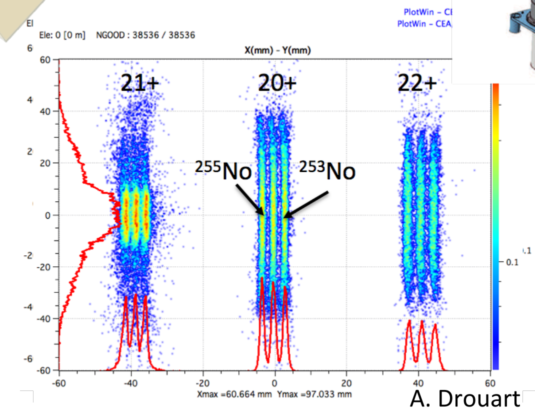
Systematic study of fusion-evaporation reactions with SIRIUS @ S^3 (high production yields with A/Q=7 & inflight A/Q ID): Z=106-112 with projectiles ranging from S to Ca (CEA, GANIL, IJCLab, IPHC)

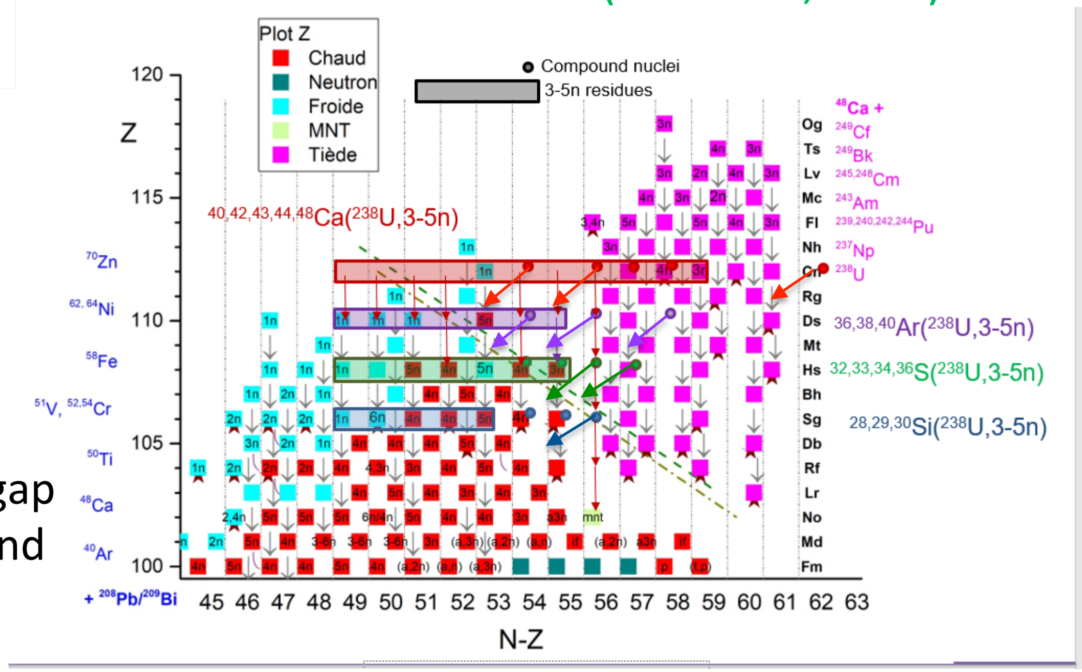


^{238}U ($^{28,29,30}Si$, 3-6n) ^{248}Cm ($^{20,21,22}Ne$, 3-6n)





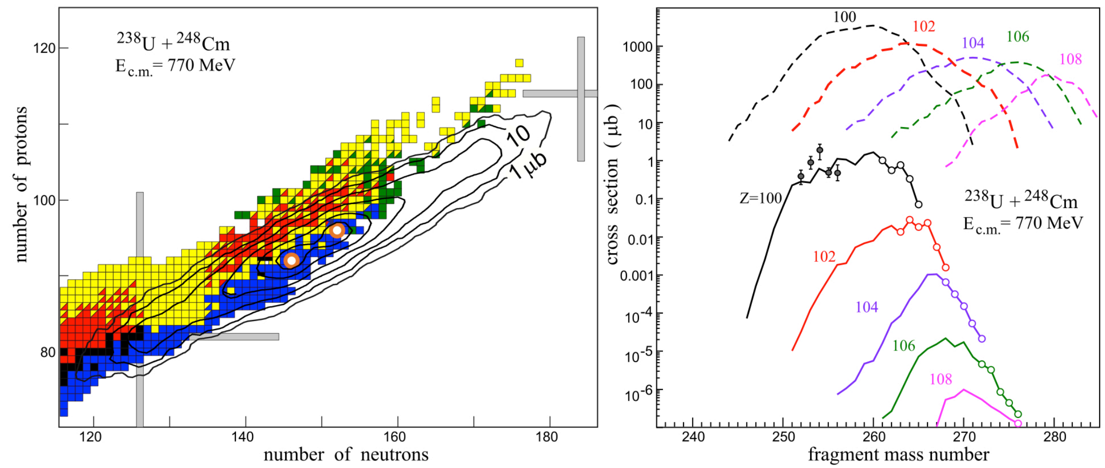


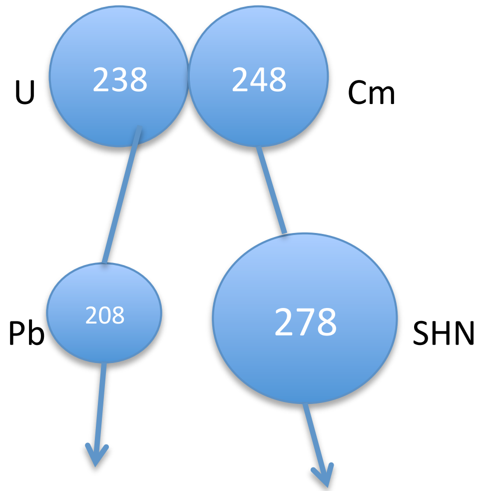


Synthesize new isotopes & bridge the gap between hot & cold fusion chains around N=162

Multinucleon transfer (MNT)

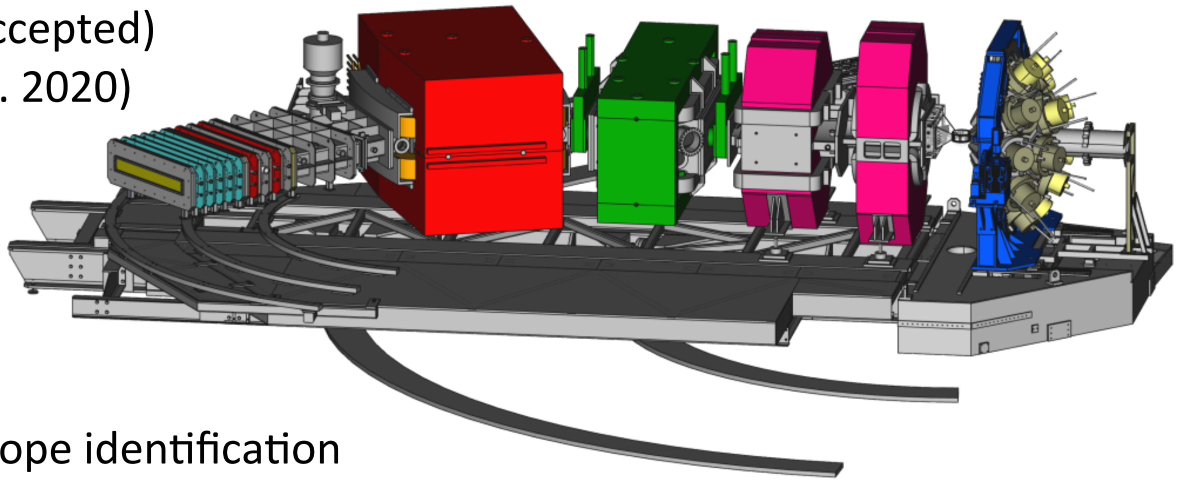
V.I. Zagrebaev, A.V Karpov and W. Greiner, EPJ Web of Conferences **86**, 00066 (2015)





Investigation of production of heavy nuclei via MNT (CEA, IJCLab, GANIL, IPHC):

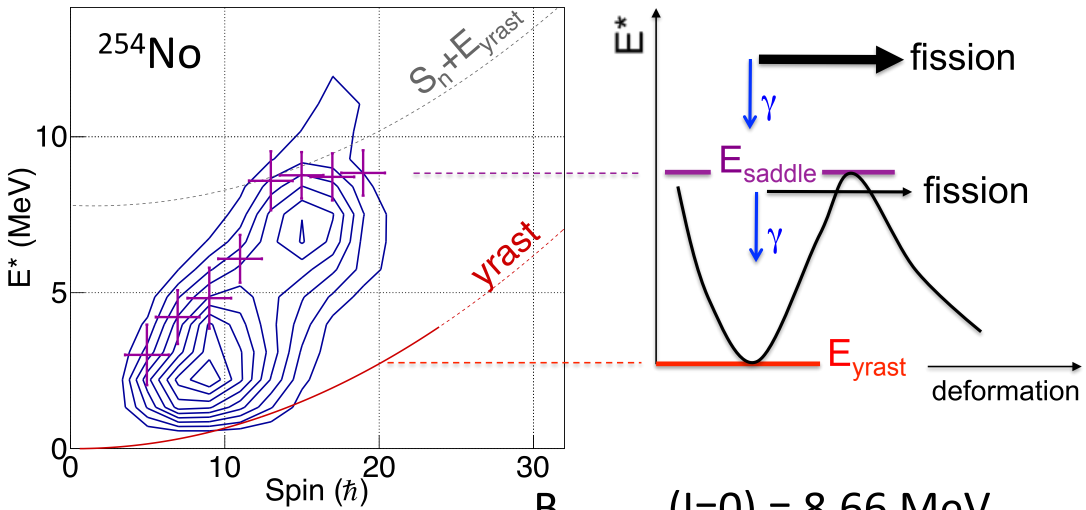
GAMMASPHERE + AGFA: $^{136}Xe+^{238}U$ (Oct. 2019)
AGATA+LEPS+VAMOS: $^{238}U+^{238}U$ (accepted)
GABRIELA+SHELS: $^{48}Ca+^{243}Am$ (april. 2020)

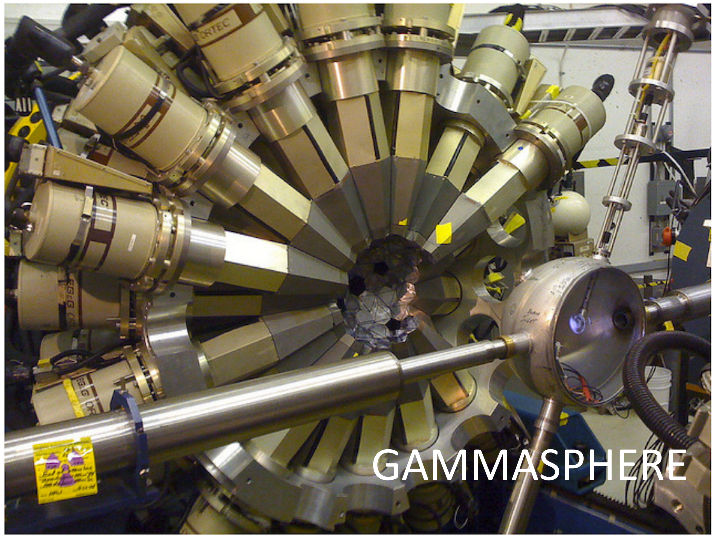


Challenges of MNT: half-lives & isotope identification

Fission barriers

G. Henning et al., Phys. Rev. Lett. 113, 262505 (2014)





$B_f(0)$=6.6(0.9) MeV

$B_{f,\ Gogny}$(I=0) = 8.66 MeV

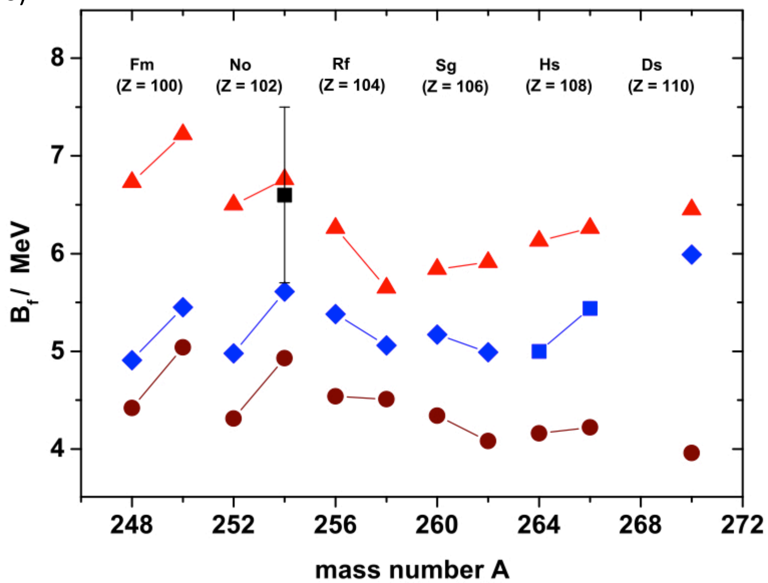
J.L.Egido and L.M. Robledo Phys. Rev. Lett. 85 (2000)

Only method (with ECDF) to extract fission barriers in the region: GAMMASPHERE (BGO+Ge) coupled to a recoil separator is the only tool

Important for reliable fission-barrier predictions

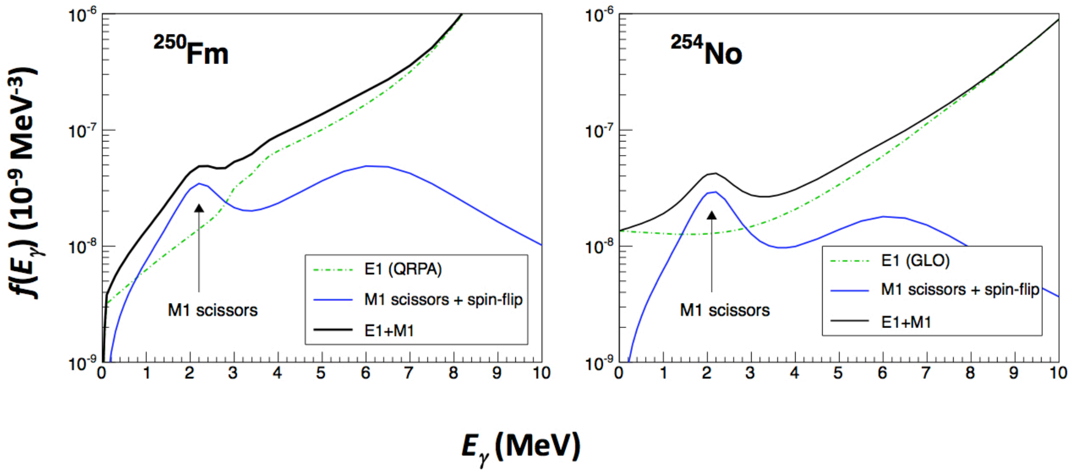
Research program at GAMMASPHERE (CEA, GANIL, IJCLab, IPHC)
2020: ^{255}Lr experiment scheduled

To be continued with tracking arrays AGATA & GRETA



F.P. Hessberger, Eur. Phys. J. A (2017) 53: 75

Resonance studies

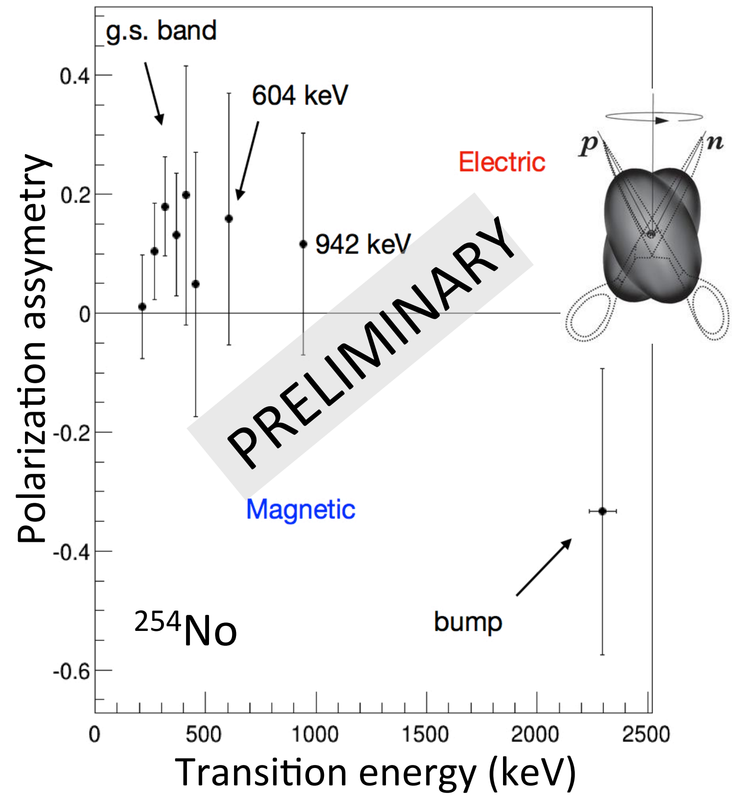


Search for scissors mode in deformed heavy systems (IJCLab, IPHC)

Impact on (nucleo)synthesis rates

Experiment with JUROGAM@RITU: Evidence for an enhancement of magnetic nature in the γ-ray energy spectrum at high energy

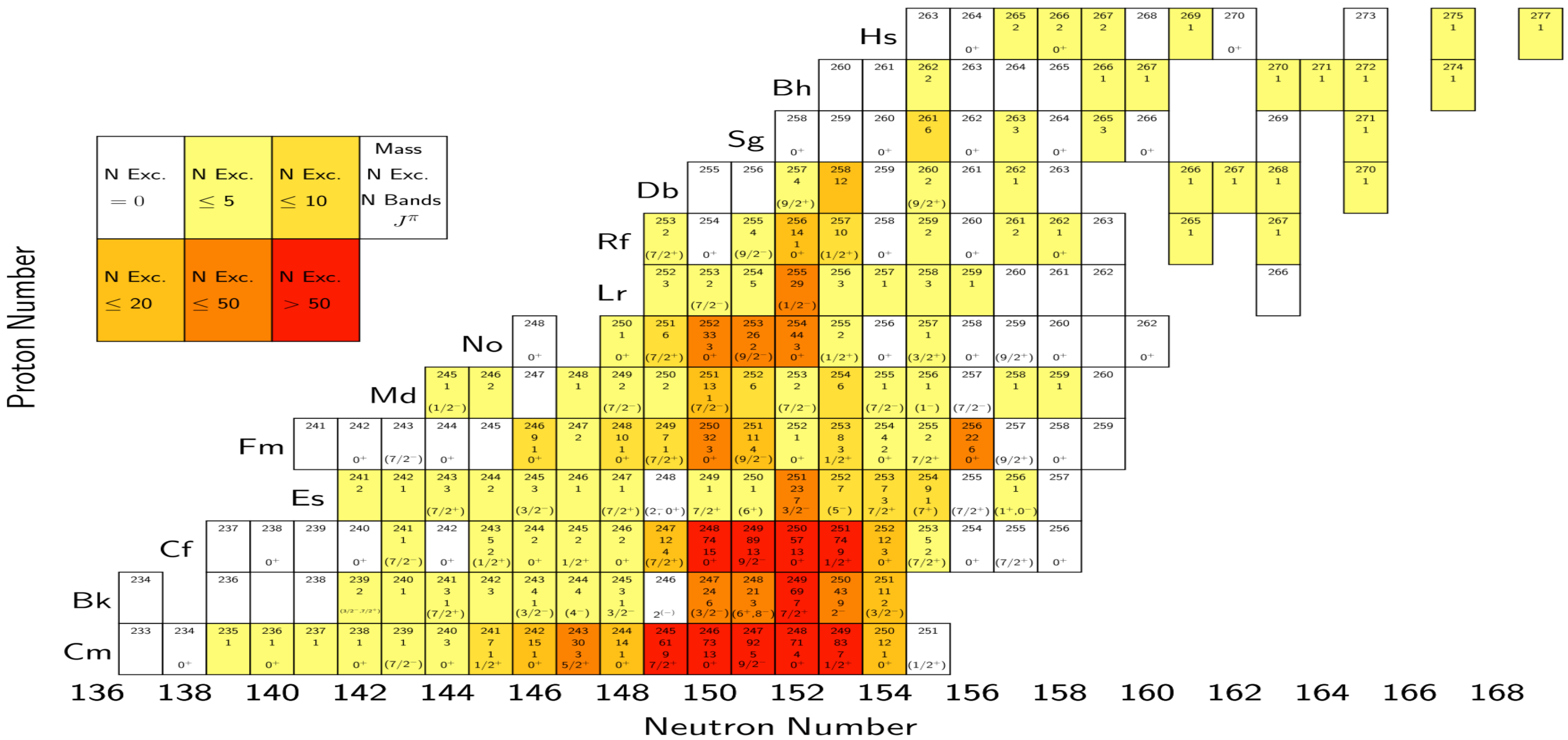
F. Bello Garrote, A.C. Larsen, A. Lopez-Martens et al.,



Detailed study only possible with AGATA & GRETA
(need for efficiency @ high energy and polarization sensitivity)

Spectroscopy of SHN

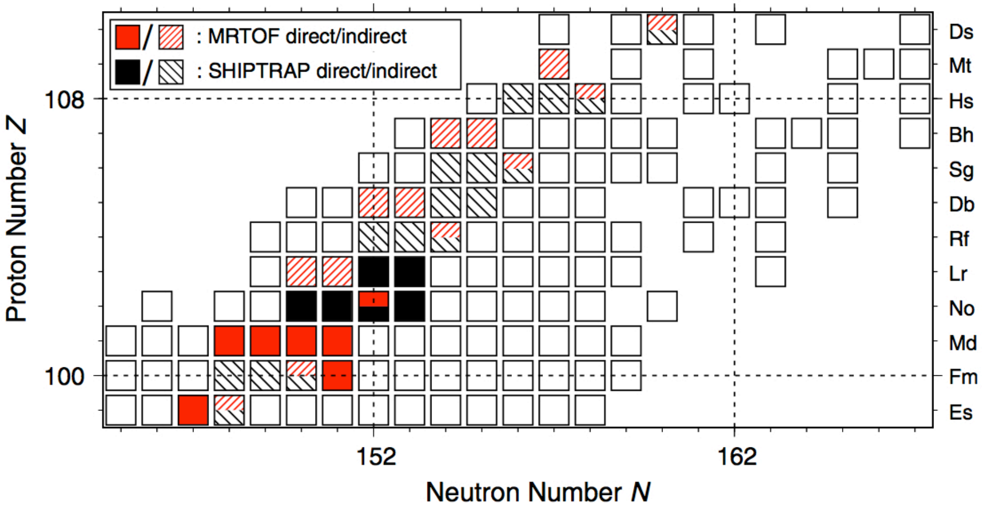
Very little information is available; mostly gs and low-lying states populated by α decay
Assignments mostly based on α-decay hindrance factors & systematics
Very few firm anchor points in I & π and mass
Very few measurements of moments (deformation information from rotational bands, presence of K isomers)
Lifetimes known only for gs and isomers



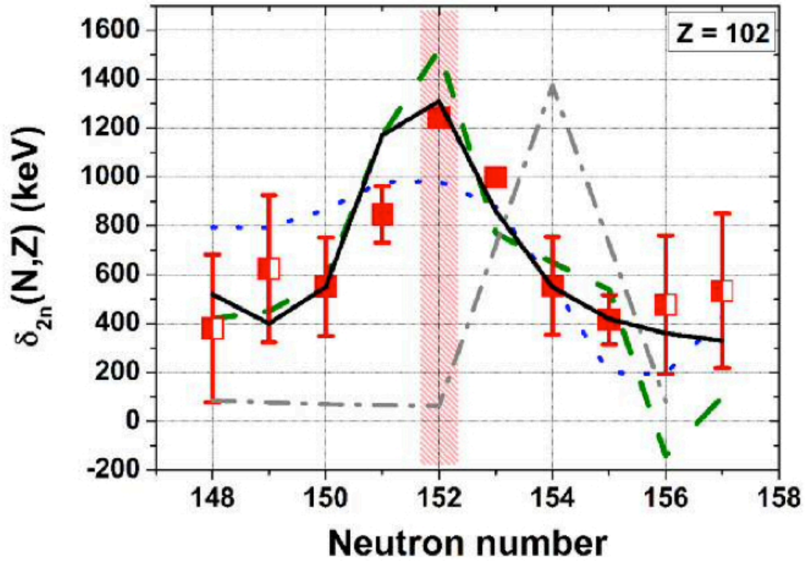
Ch. Theisen et al., Nucl. Phys. A 944 (2015) 333

Low-energy SHE experiments - Mass measurements

Y. Ito et al., Phys. Rev. Lett. 120 (2018) 152501



E. Minaya Ramirez et al., Science 337, 1183 (2012)



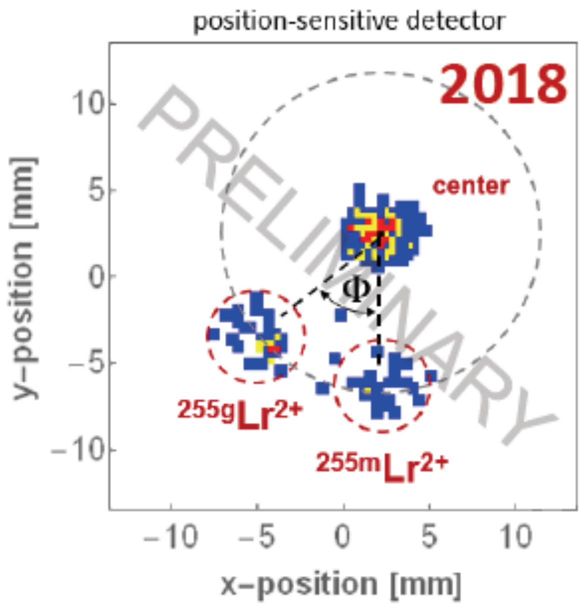
Anchor points of the mass landscape

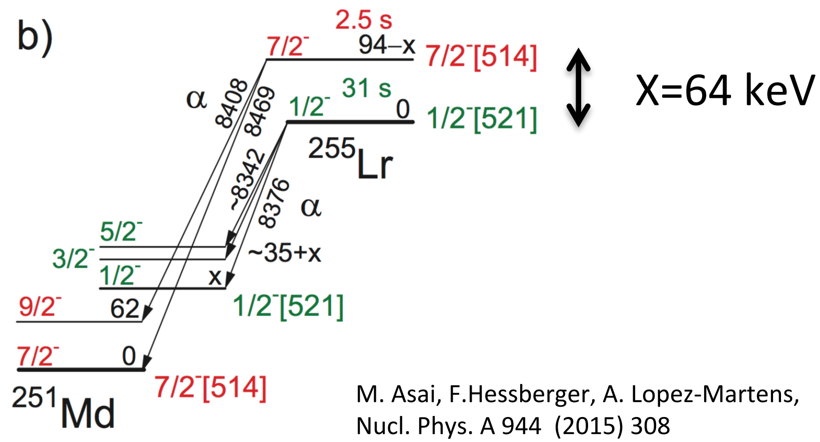
Precise benchmarking of binding energies & their derived quantities

$\delta 2n(N,Z) = 2B(N,Z) – B(N-2,Z) – B(N+2,Z)$

Low-energy SHE experiments - Mass measurements

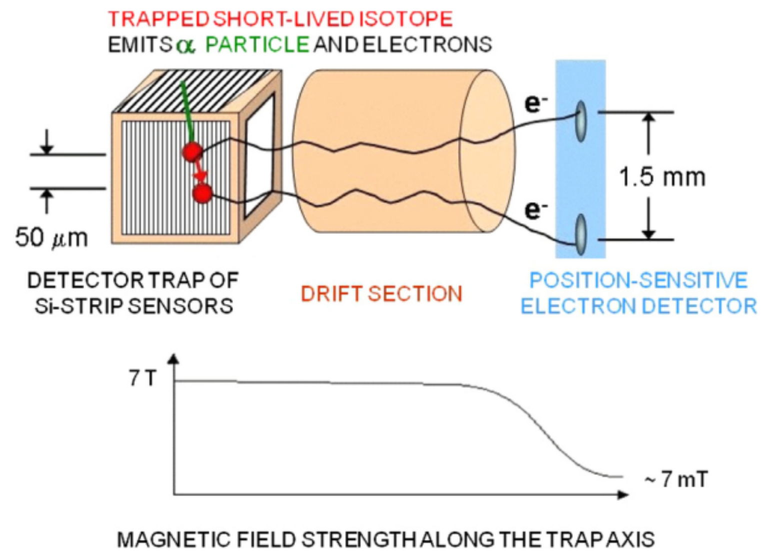
Improved sensitivity at SHIPTRAP (PI-ICR, cryogenic cell, FT-ICR for very exotic nuclides…)





M. Asai, F.Hessberger, A. Lopez-Martens, Nucl. Phys. A 944 (2015) 308

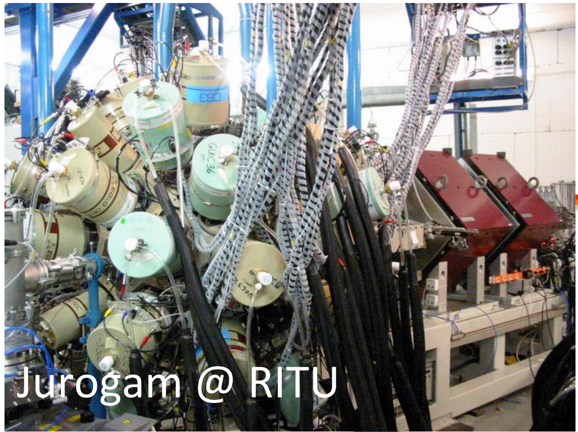
2020: No, Lr, Rf runs at SHIPTRAP (IJCLab)

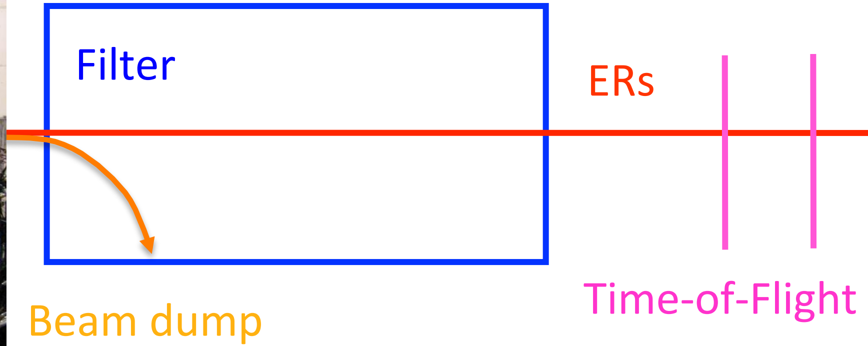


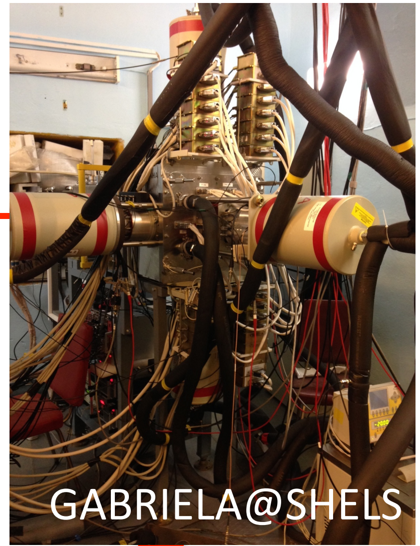
> 2025 : Mass measurements with MLLTrap@DESIR with added functionnalitites (IJCLab):

- lifetime measurements
- matter&summing-free α-decay spectroscopy

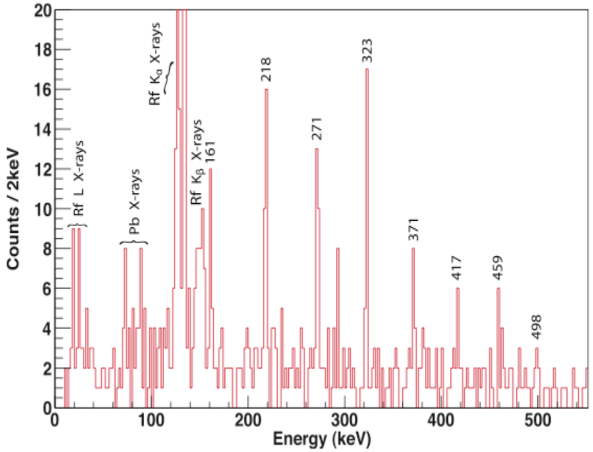
Complementary spectroscopy



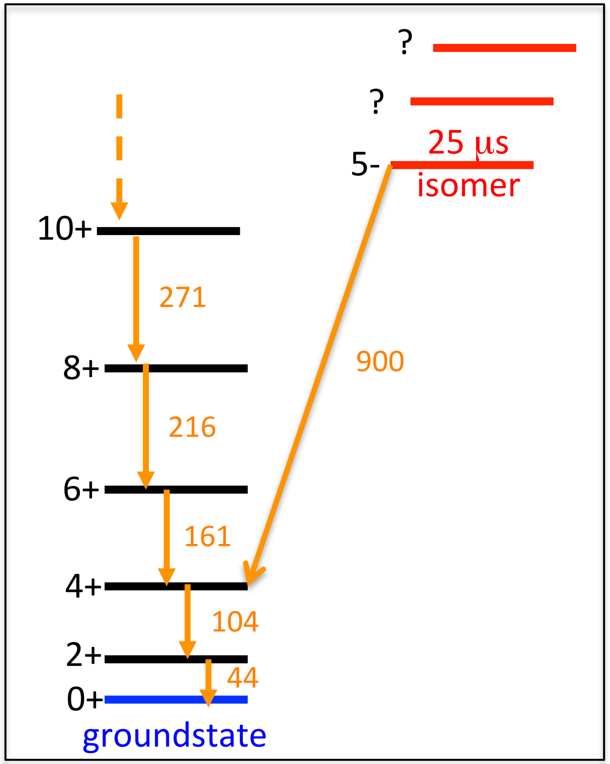




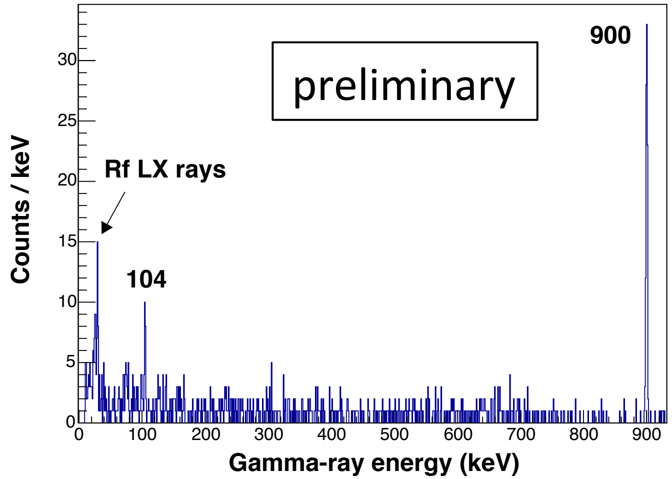
^{256}Rf @ JYFL



P.T. Greenlees, Phys. Rev. Lett. 109 (2012) 012501
J. Rubert, PhD thesis, Université de Strasbourg (2013)



^{256}Rf @ FLNR



K. Hauschild et al., in preparation

Prompt spectroscopy

Electron spectroscopy is only possible with SAGE@RITU

10 nb cross section & <30 mn $t_{1/2}$ are the current limits for SAGE@RITU

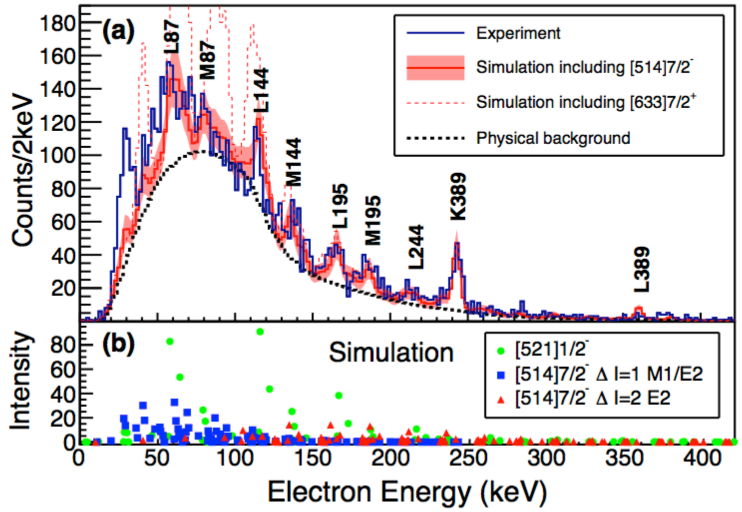
Experiments @ ANL (CEA, GANIL, IJCLab, IPHC):
can gain a factor of ~2-3 in cross section with GAMMASPHERE @ AGFA :
^{254}No, ^{255}Lr, ^{254}Rf

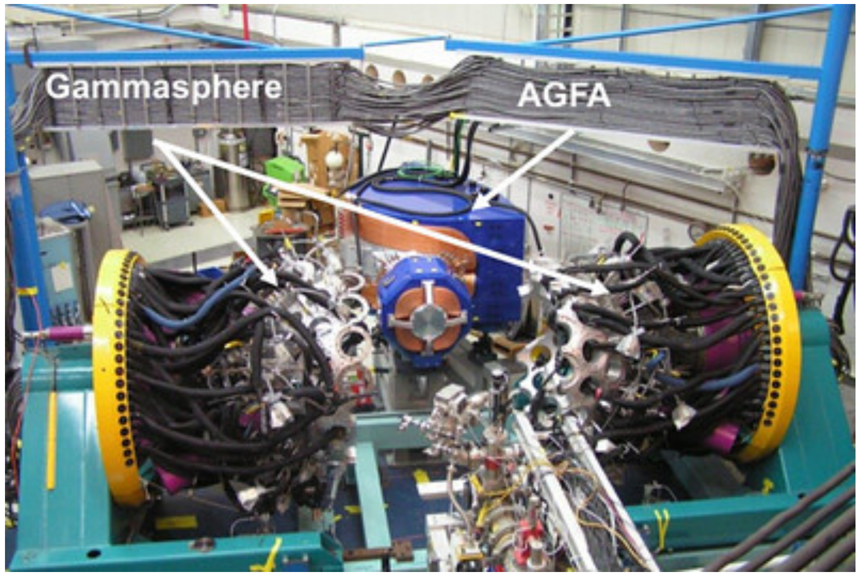
Can study long-lived species (^{252}Fm for eg) using the mass sensitivity of FMA

- 2025-2030: Experiments with tracking arrays with Ω approaching 4π:

AGATA@RITU/VAMOS-GF, GRETA@AGFA/FMA,

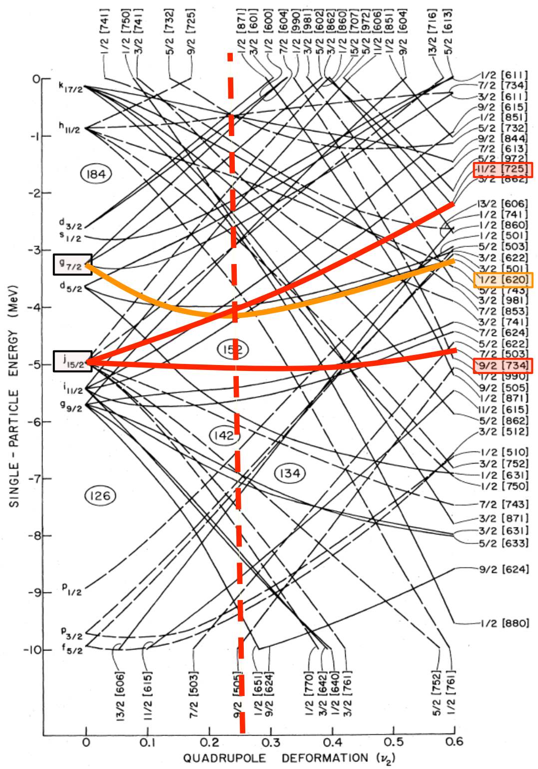
R. Briselet et al., in preparation ^{251}Md

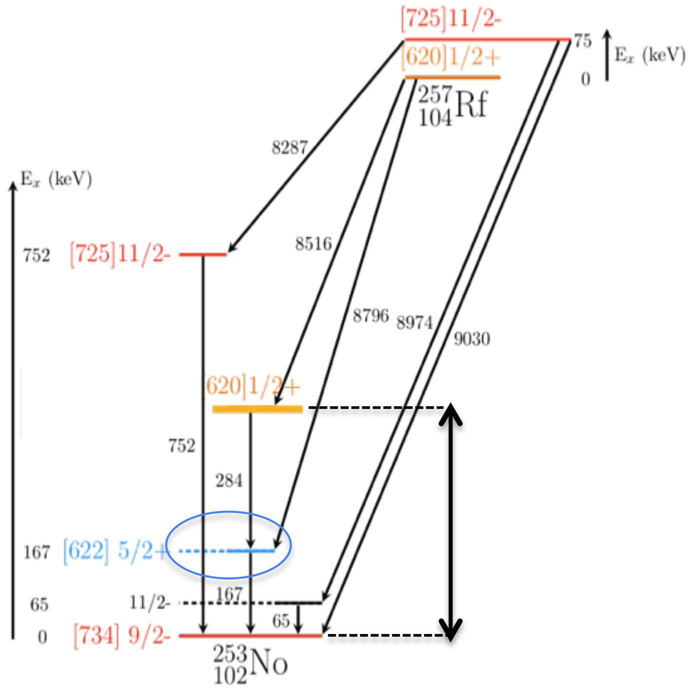




Decay spectroscopy

R.R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)





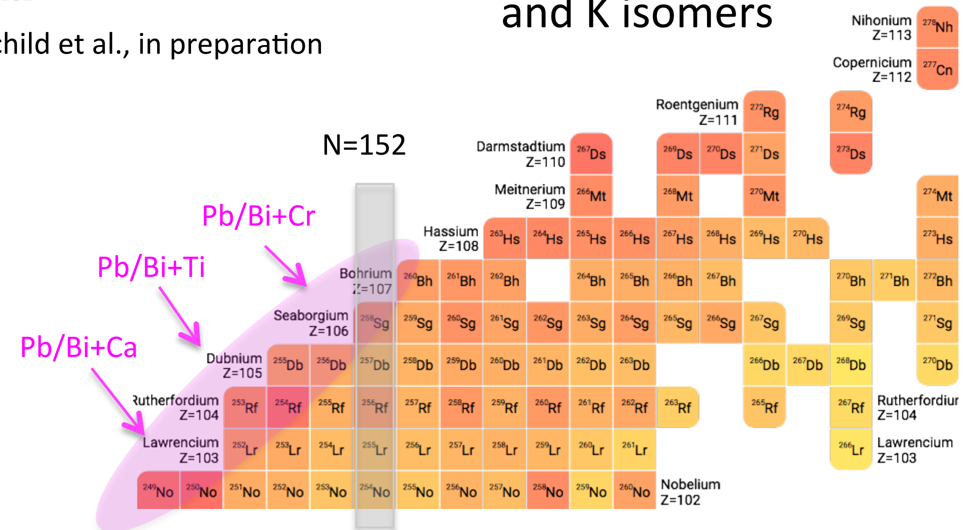
K. Hauschild et al., in preparation

GABRIELA+@SHELS (GANIL, IJClab, IPHC): Sequence, and evolution of states as Z & N increase towards more neutron-rich nuclei

Degree of collectivity (B(Eλ) through combined ICE & γ-ray spectroscopy)

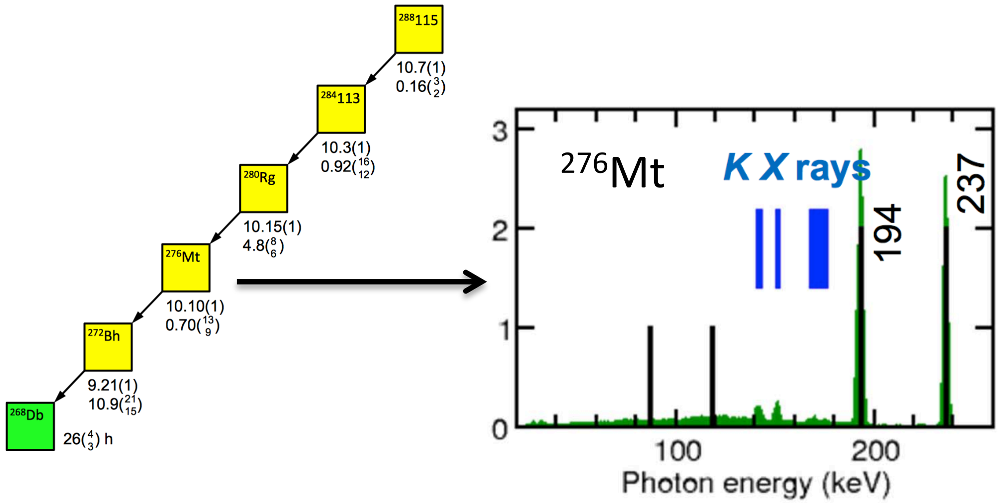
Decay properties of gs and K isomers

SIRIUS@S^3 with A/Q ID (CEA, GANIL, IJCLab, IPHC): Study isotopes (& synthesize new ones) at the fission « drip-line »: shell structure & fission hindrance of multi-particle states



X-ray identification of SHN

X-ray spectroscopy for Z identification of & β/EC-decay flagging

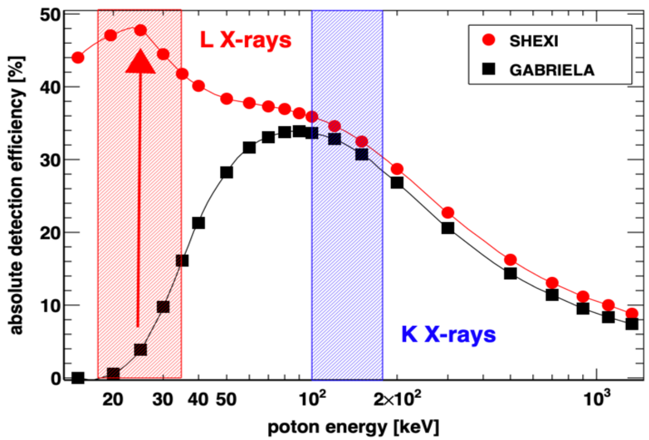


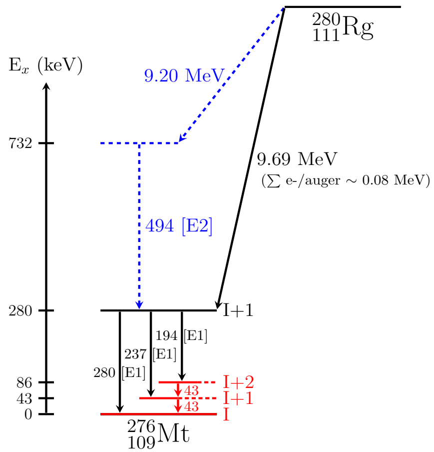
Lundium upgrade of TASISPEC @ TASCA based on Ge: Xray gain x2-3

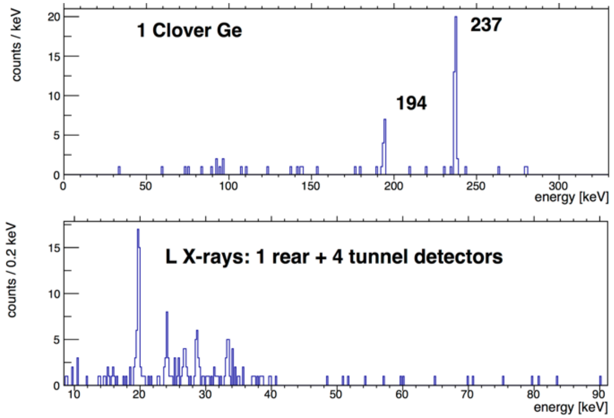
D. Rudolph et al., Phys. Rev. Lett. 111, 112502 (2013)

Spectrum confirmed by: J.M. Gates et al, Phys. Rev. C 92, 021301 (2015)

SHEXI project based on Si @ FLNR (IJCLab, IPHC) - not financed

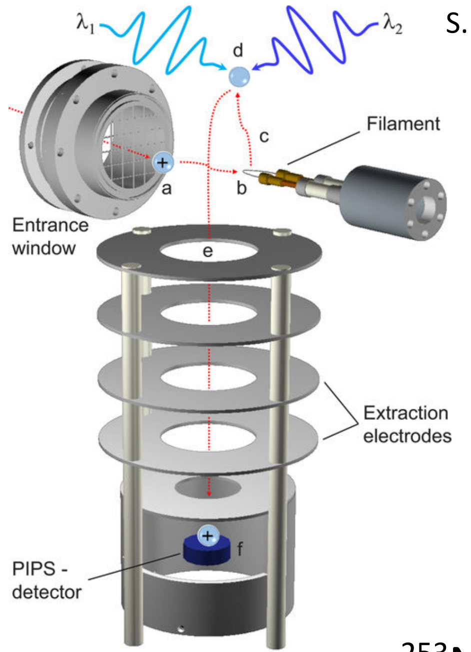






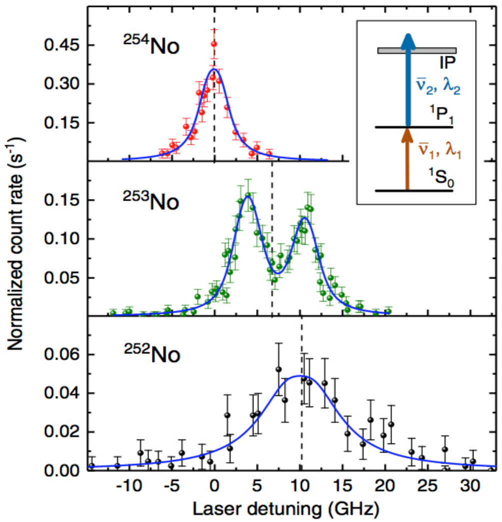
Enhanced X-ray detection efficiency is also desirable for SIRIUS@S3

Low-energy SHE experiment – Laser spectroscopy



RADRIS@SHIP

S. Raeder et la., Phys. Rev. Lett. 120 (2018) 232503

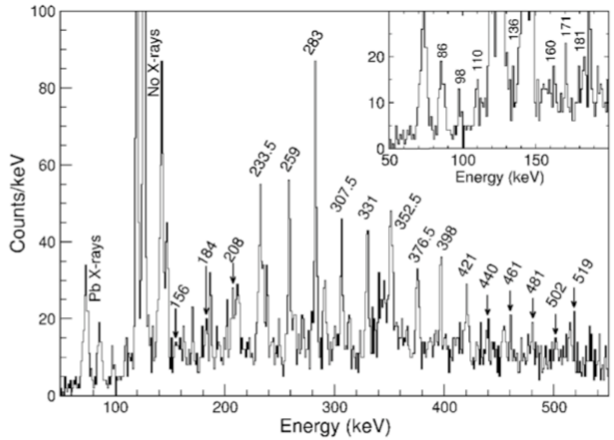


^{253}No: Q_s(gs:9/2)= 5.9(1.4)(0.9) b

g_K(9/2) = -0.22(5)

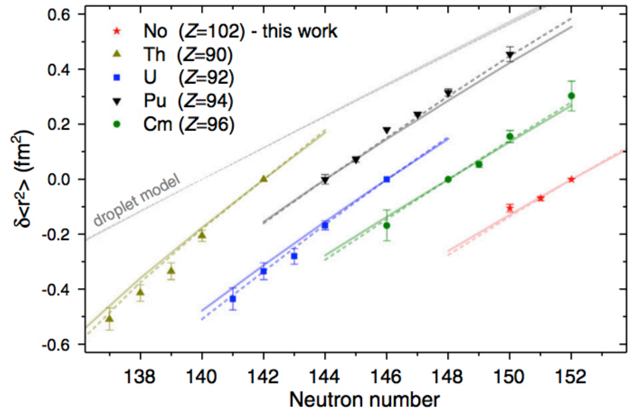
Sarah Eeckhaudt, PhD thesis,University of Jyväskylä, 2006

R.D.Herzberg, et al.,Eur.Phys. J. A42 (2009) 333.

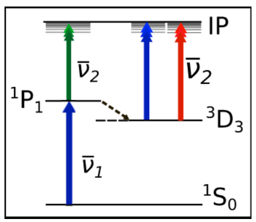


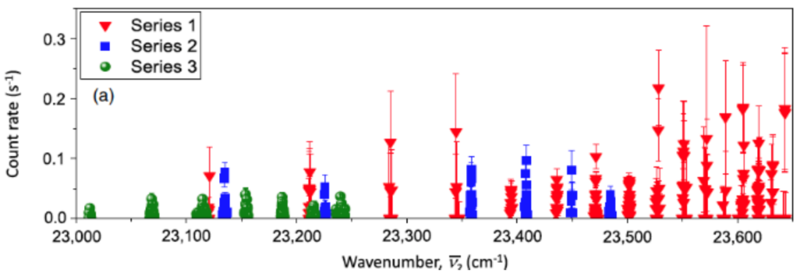
B(M1)/B(E2) depends on $|(g_K-g_R)|/Q_0$

$g_{K,theo}(9/2^-[734])=-0.25$



Change in mean square radii reproduced by models, which predict a strong central depression

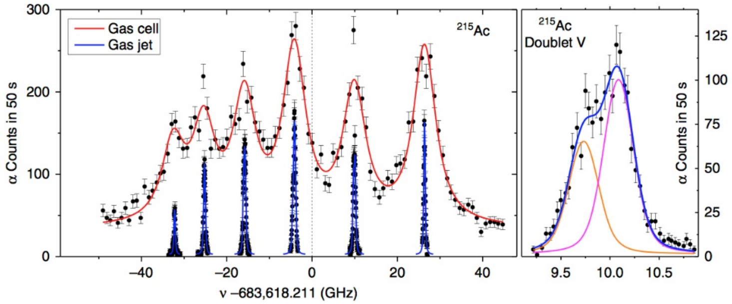




P. Chhetri *et al.*, Phys. Rev. Lett. 120 (2018) 263003

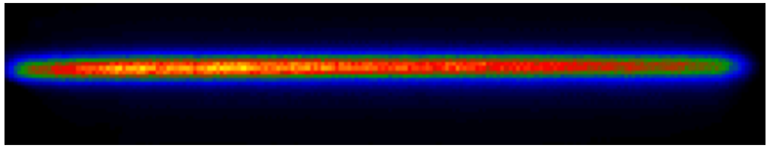
Low-energy SHE experiments – combined techniques

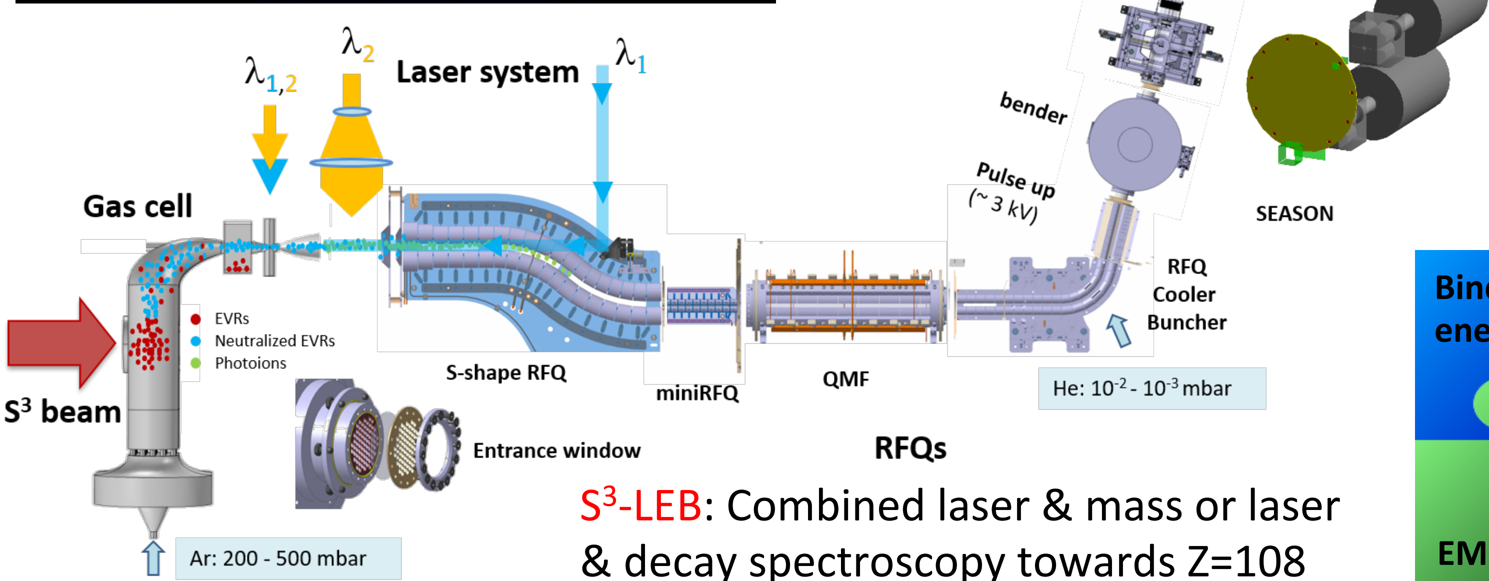
R. Ferrer, Nature Comm. 8 (2017) 14520



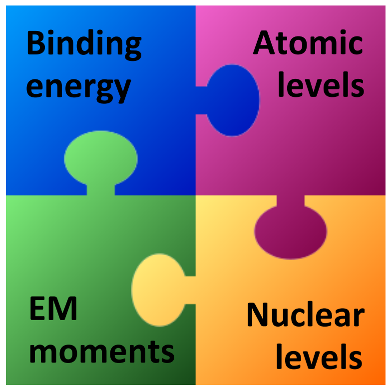
2020: isomers in No & Lr with improved in-gas-jet spectroscopy @ GSI (GANIL, IJCLab)

A. Zadvornaya et al., PRX 8 (2018) 041008





S³-LEB: Combined laser & mass or laser & decay spectroscopy towards Z=108 (CEA, GANIL, IJCLab, LPC)



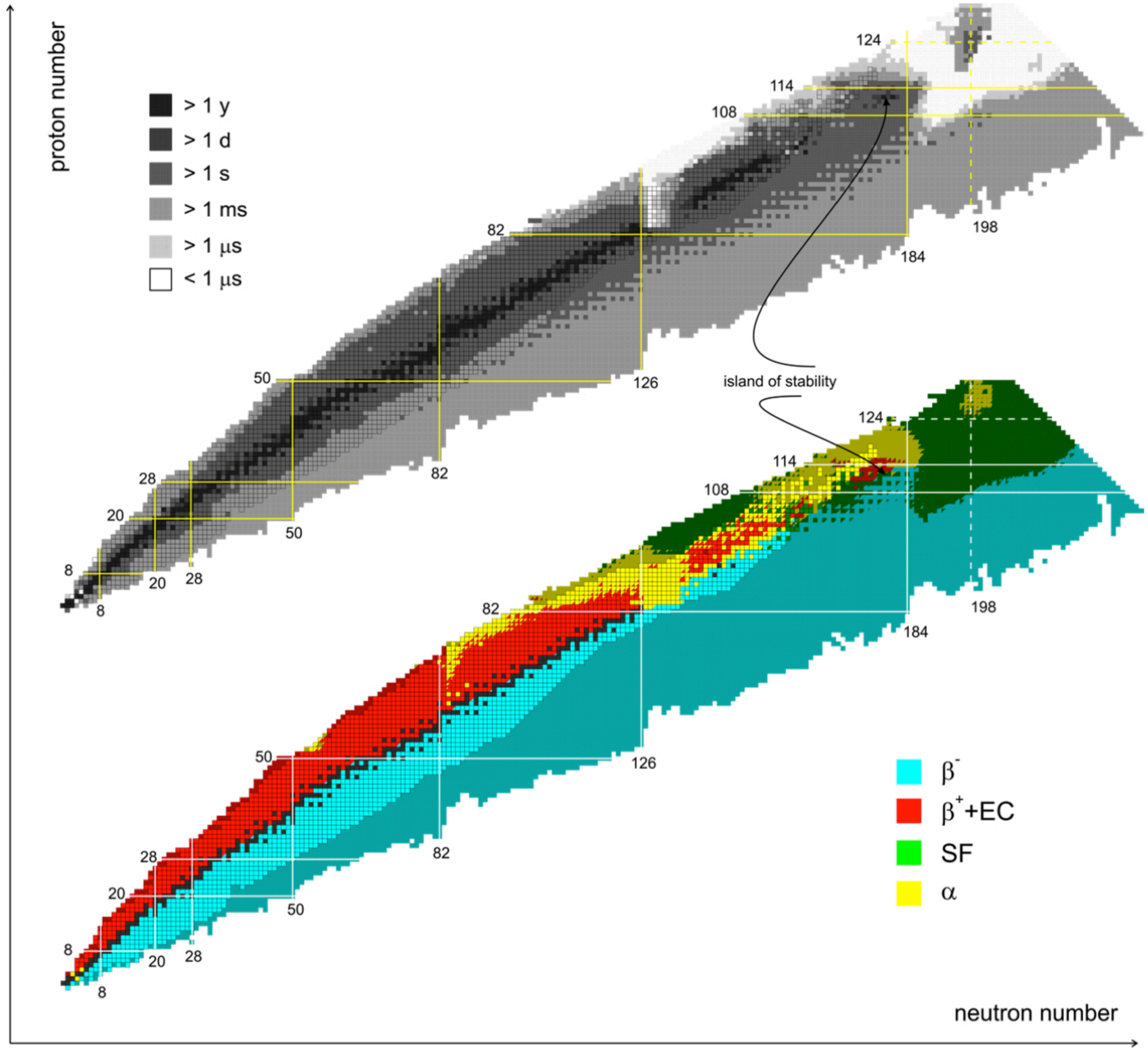
Conclusion & strategy

- Coherent research program exploiting the availability of beam time & setups at different facilities
- Strong visibility and/or leadership for spectroscopy & synthesis experiments at FLNR, RIKEN, SPIRAL2, strong collaborations with ANL, GSI, KU Leuven, JYFL & Mainz
- Collaborations allow for exchange of technologies & know-how
- High beam intensities are of prime importance (A/Q=7 injector for SPIRAL2, target/backing & beam developments)
- Actinide targets are required to study neutron-rich nuclei and go beyong Z=110-113
- Long – very long beam times are necessary (rare events & unknown ionisation schemes) -> this requires HR & mission budget
- Complementary techniques are necessary & measuring more than one observable in one shot is the way to go for such rare events

THANK YOU

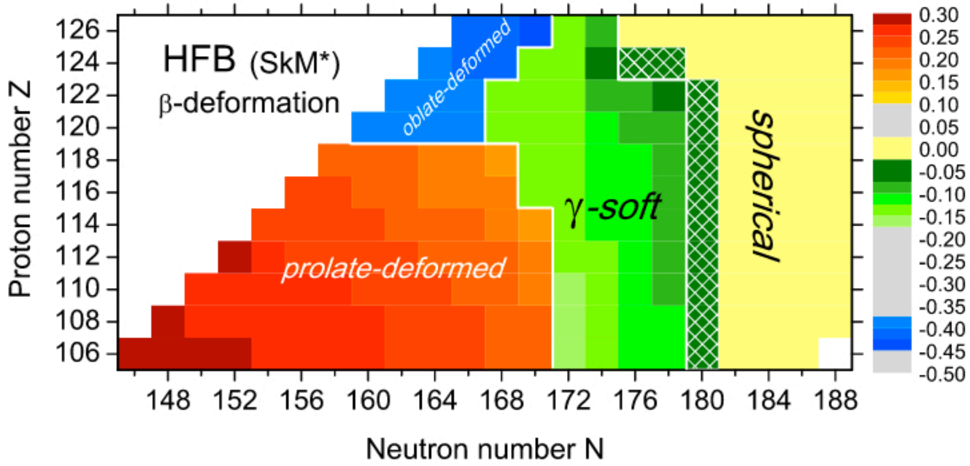
FOR YOUR ATTENTION

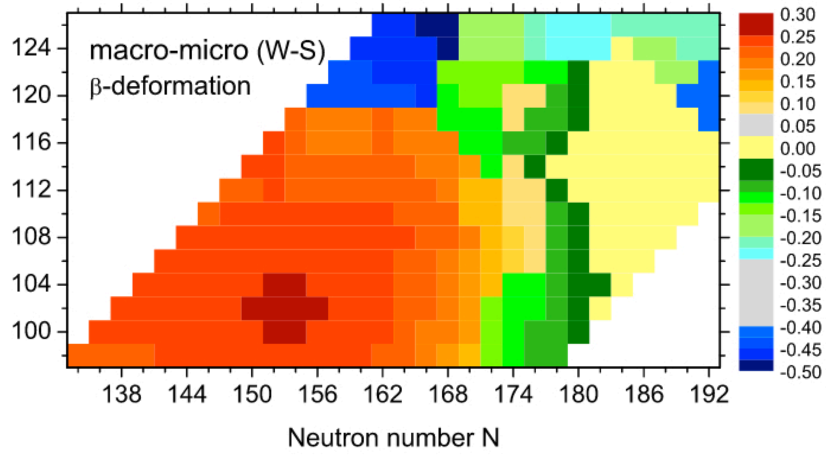
Vaste uncharted region



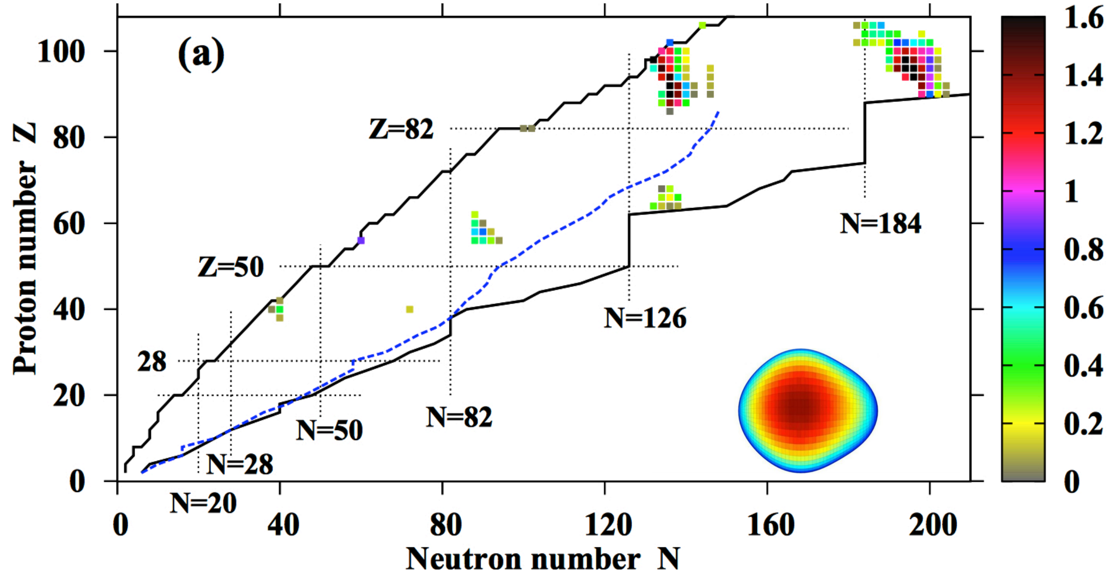
A variety of predicted shapes

P.-H. Heenen et al., Nuclear Physics A 944 (2015) 415–44

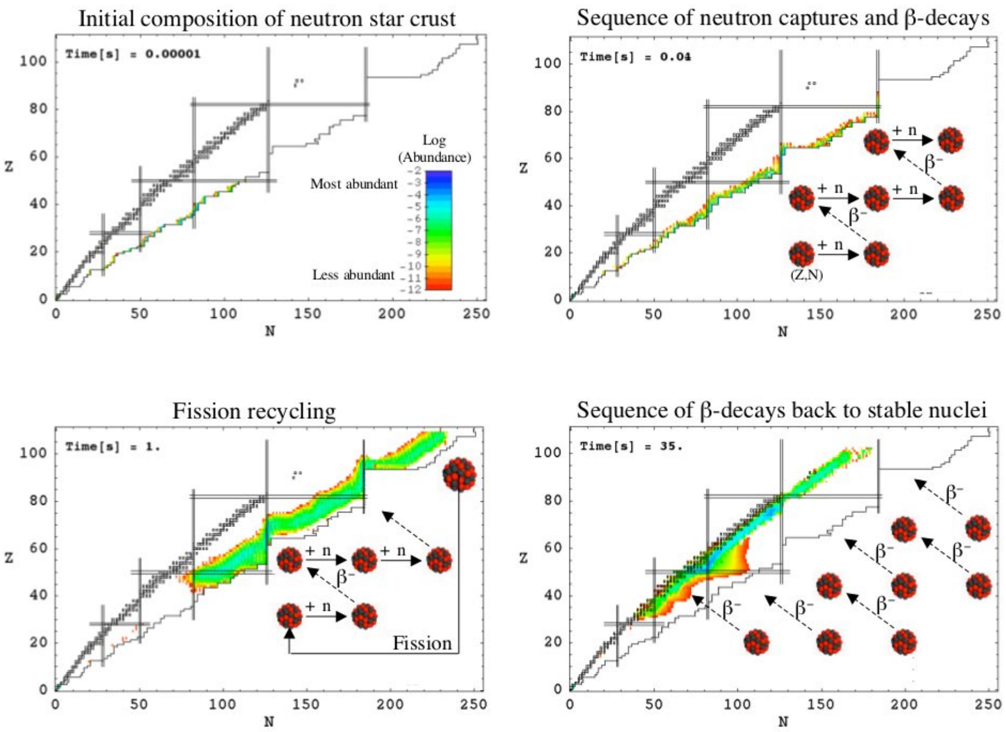




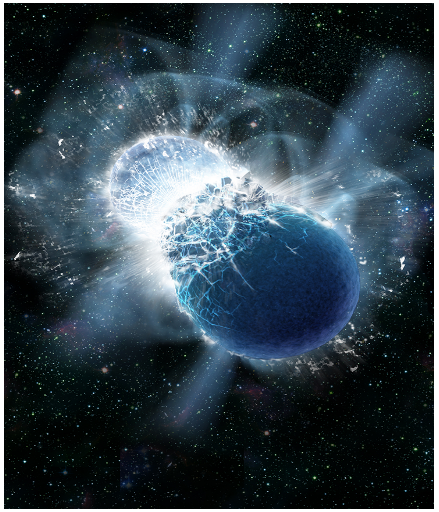
S. E. Agbemava, A. V. Afanasjev, and P. Ring, Phys. Rev. C 93, 044304 (2016)

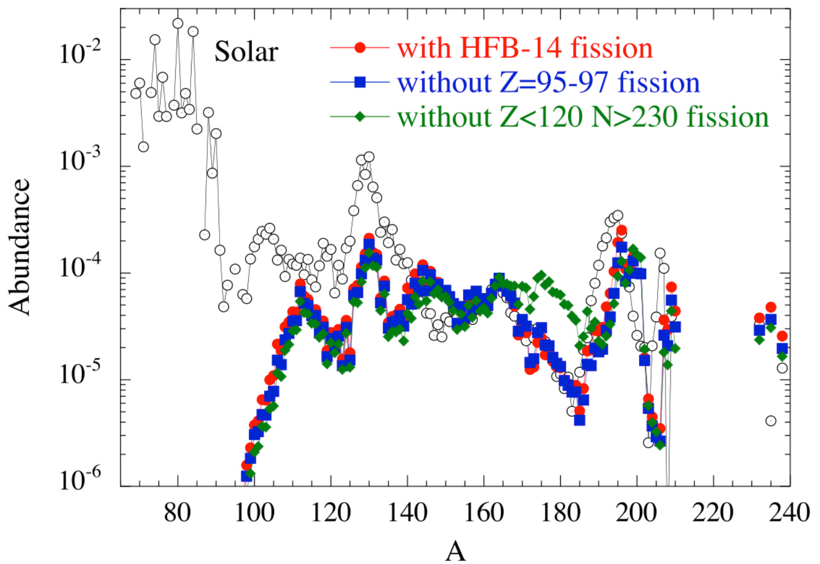


Impact in other fields



S. Goriely et al., Astrophysical Journal 738 (2011) L32





S. Goriely et al., Nuclear Physics A 944 (2015) 158–176

Properties of SHE, in particular fission properties , are crucial for modelling the r process

Need reliable predictions