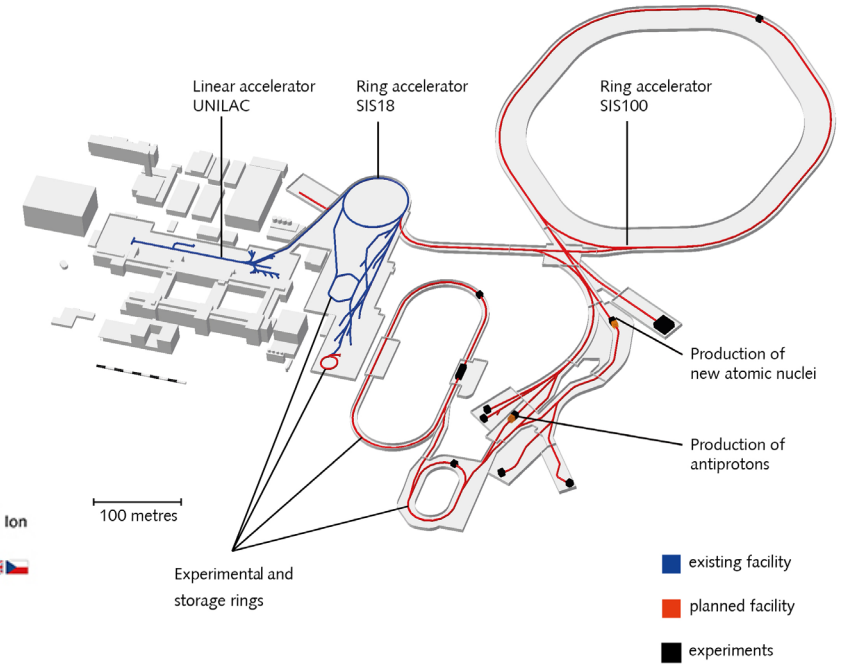
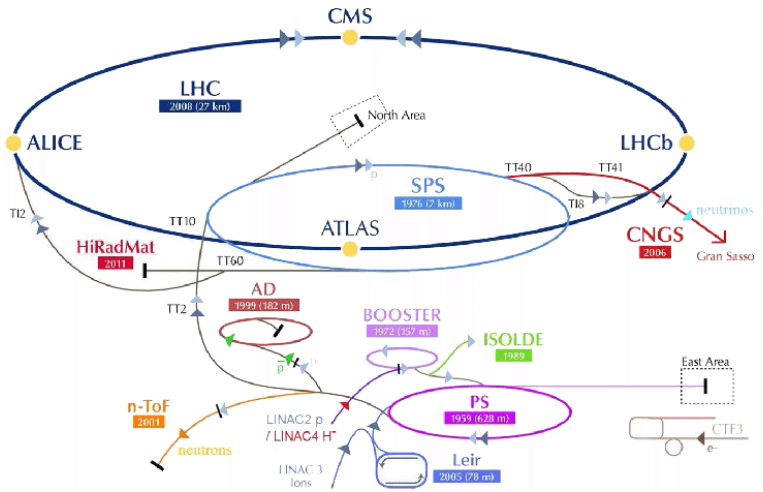
TECHNISCHE UNIVERSITÄT DARMSTADT

ERUM-FSP T07 „NUSTAR“ STATUS & PERSPEKTIVEN



FAIR — Facility for Antiproton and Ion Research in Europe



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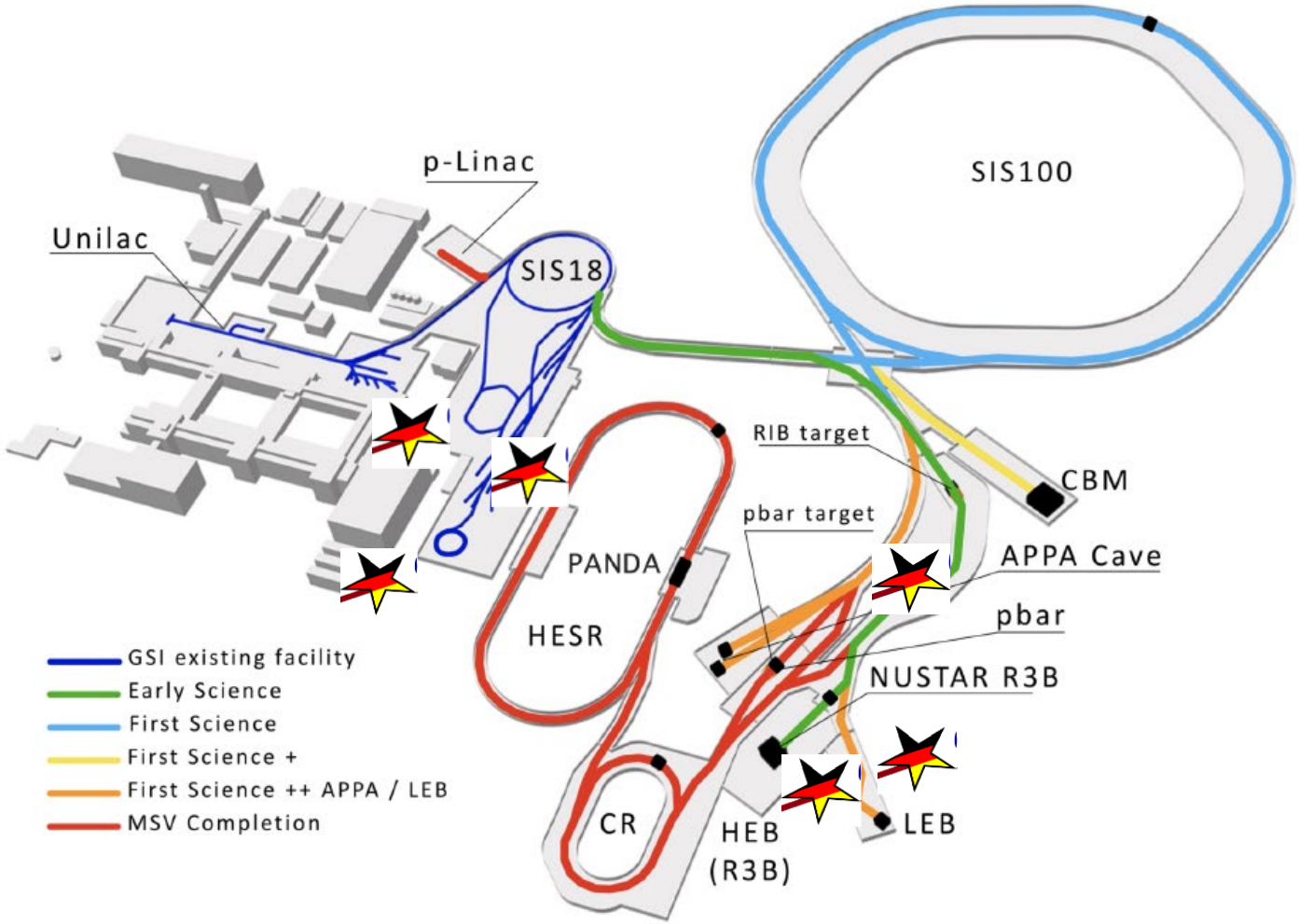

FAIR – NUSTAR Activities

- Super-FRS
- R3B
- HISPEC/DESPEC – AGATA
- ILIMA

- SHE
- MATS / LaSpec

➢ FAIR Phase-0 external

➢ ISOLDE
  - ➢ low-energy
  - ➢ HIE-ISOLDE
  - ➢ PUMA

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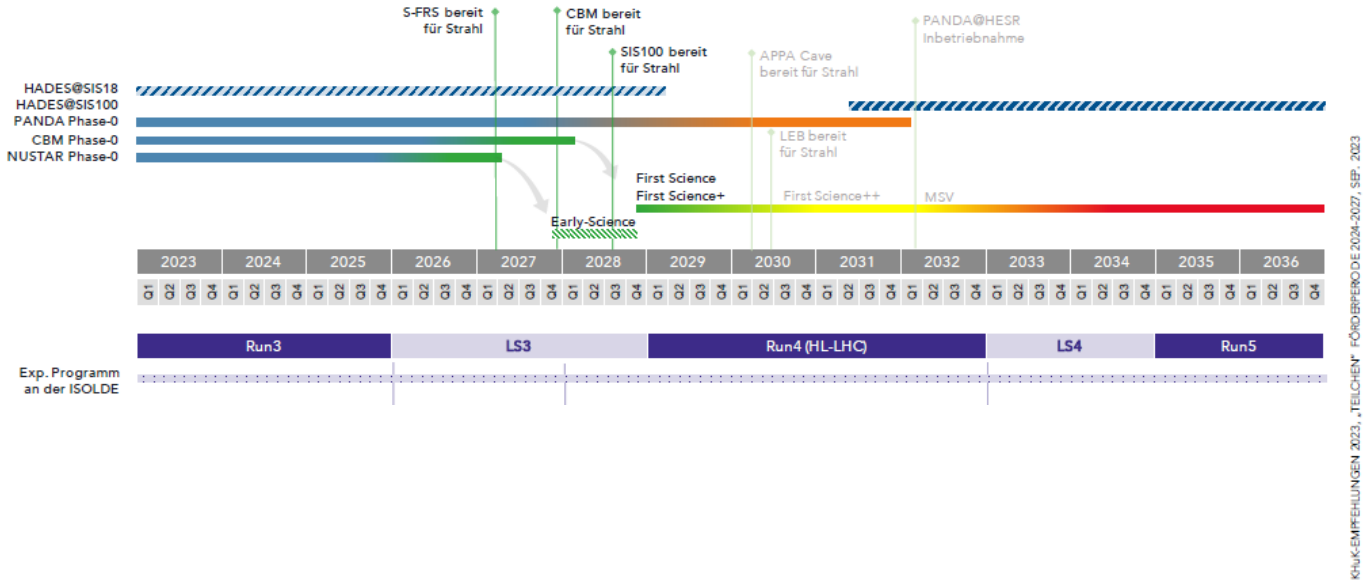

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➢ FAIR Phase-0 external

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FRS ION CATCHER: RECENT RESULTS

S474: Shell gap and Gamov-Teller strength at N=50: Implications for the ^{100}Sn mass

Physics Letters B 839 (2023) 137833

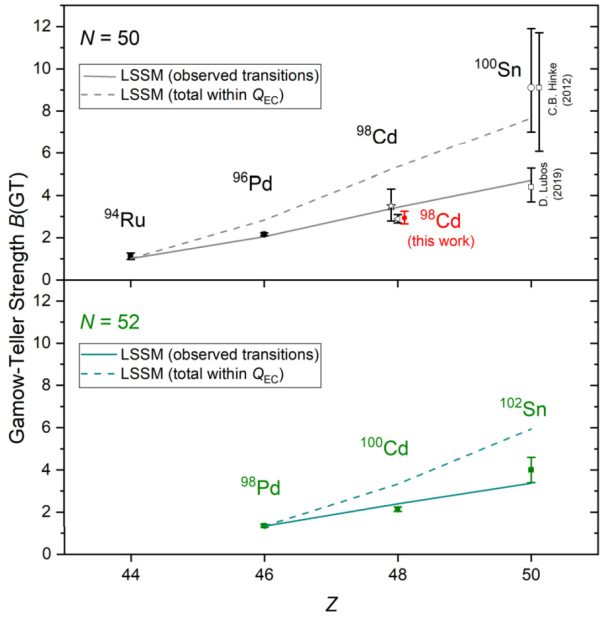
Contents lists available at ScienceDirect

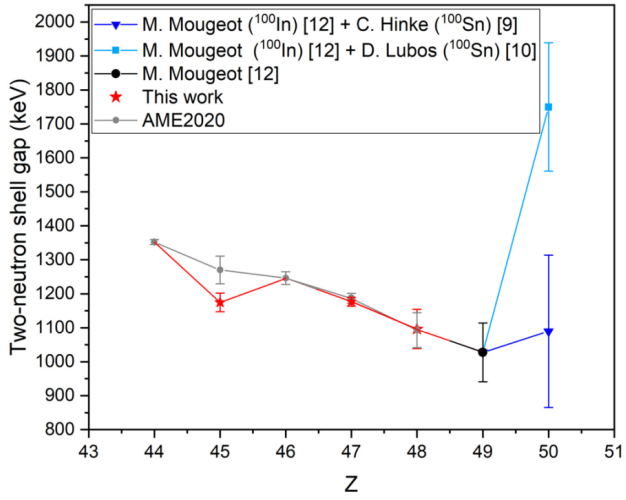
Physics Letters B

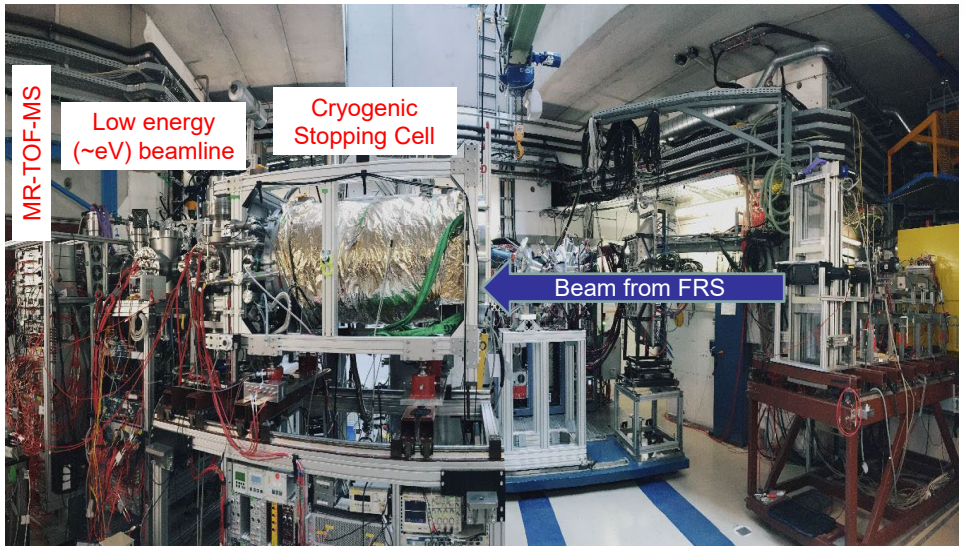
journal homepage: www.elsevier.com/locate/physletb

Studying Gamow-Teller transitions and the assignment of isomeric and ground states at $N = 50$

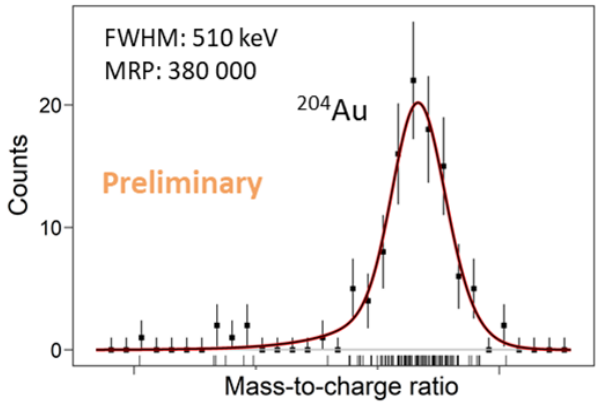
Ali Mollaebrahimi [a,b,c,*], Christine Hornung [b,c], Timo Dickel [b,c], Daler Amanbayev [b], Gabriella Kripko-Koncz [b], Wolfgang R. Plaß [b,c], Samuel Ayet San Andrés [b,c], Sönke Beck [b,c], Andrey Blazhev [d], Julian Bergmann [b], Hans Geissel [b,c], Magdalena Górska [c]

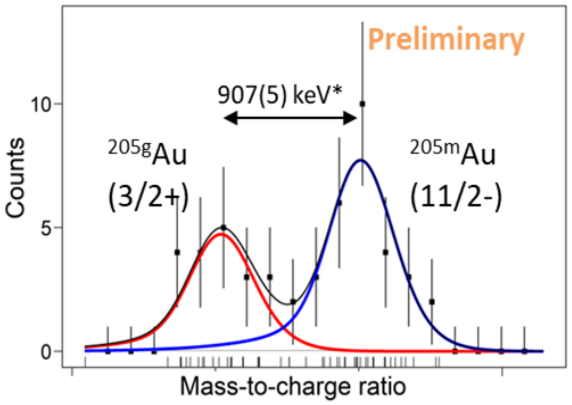






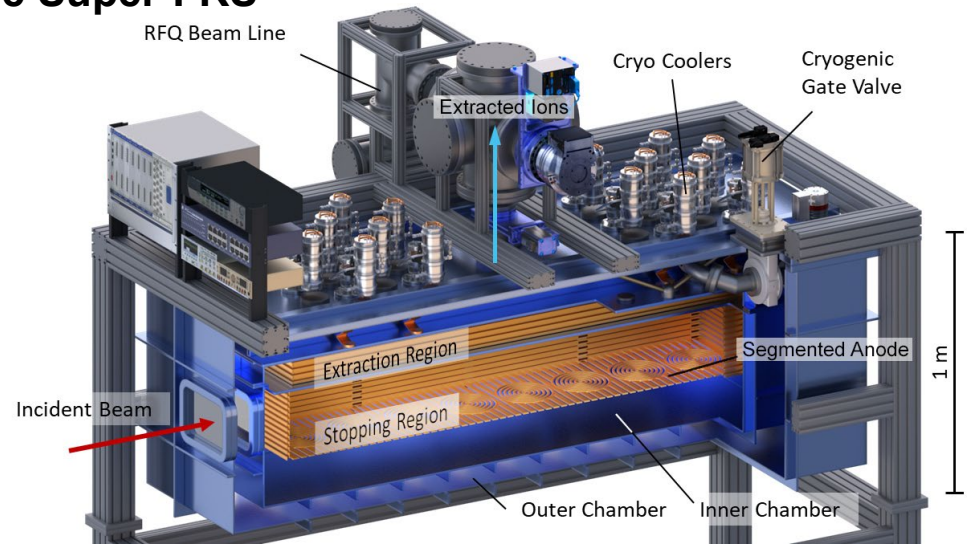
S468: Isotope search experiment: New masses at N=126





SUPER-FRS ION CATCHER: STATUS AND PLANS FOR EARLY/FIRST SCIENCE

Status of the Cryogenic Stopping Cell (CSC) for the Super-FRS



- GSI-FAIR In-Kind Contract signed
- First procurements completed, construction started
- Planning for installation at the Super-FRS at the focal plane FHF1 underway
- Construction / assembly continued in 2024-2026, commissioning in 2027

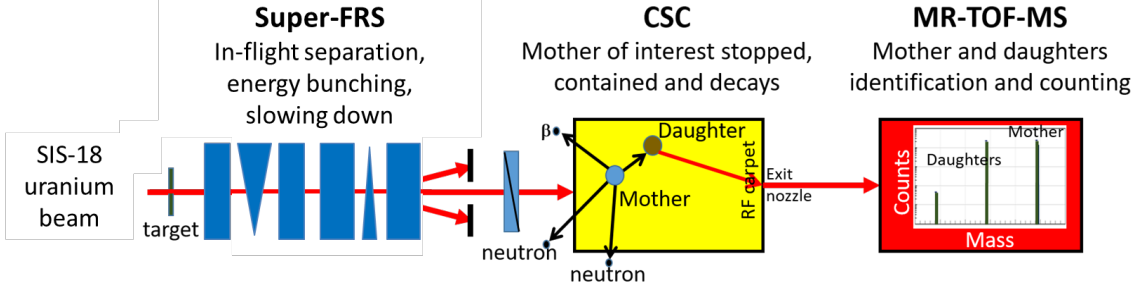
Scheidenberger, Plass et al.

Collaboration

Plans for Experiments with the Super-FRS Ion Catcher

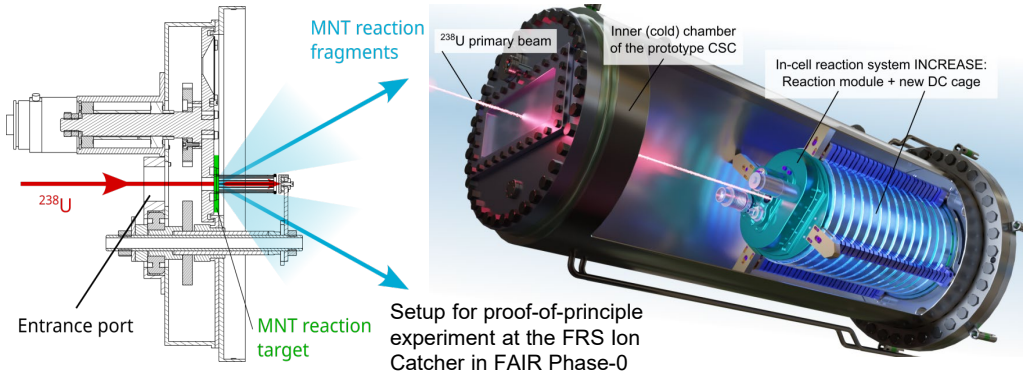
Early Science:

Measurement of β-delayed single- and multi-neutron emission probabilities (Pxn) (and also masses and half-lives)



First Science:

Multi-nucleon transfer reaction studies with secondary beams

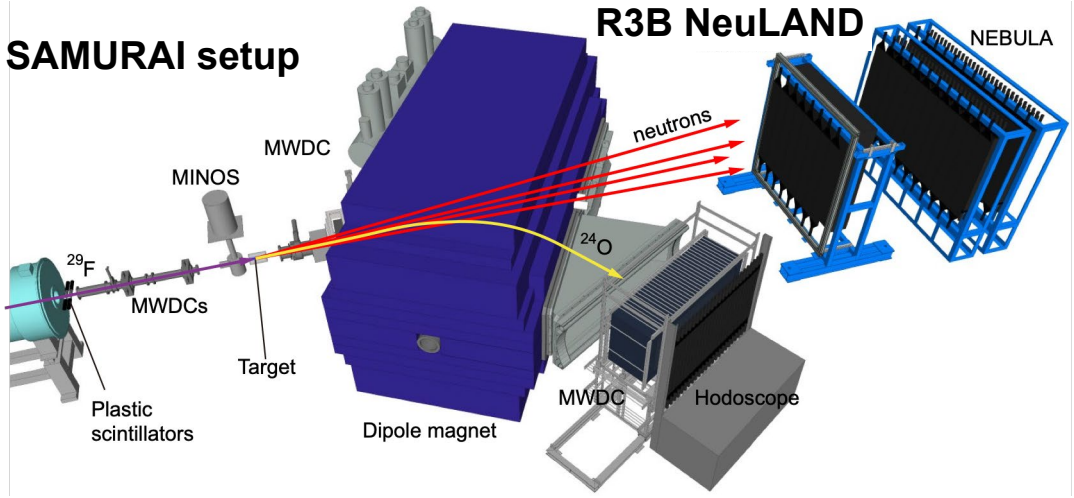


Setup for proof-of-principle experiment at the FRS Ion Catcher in FAIR Phase-0

First observation of ^{28}O with R^{3}B NeuLAND as a key detector

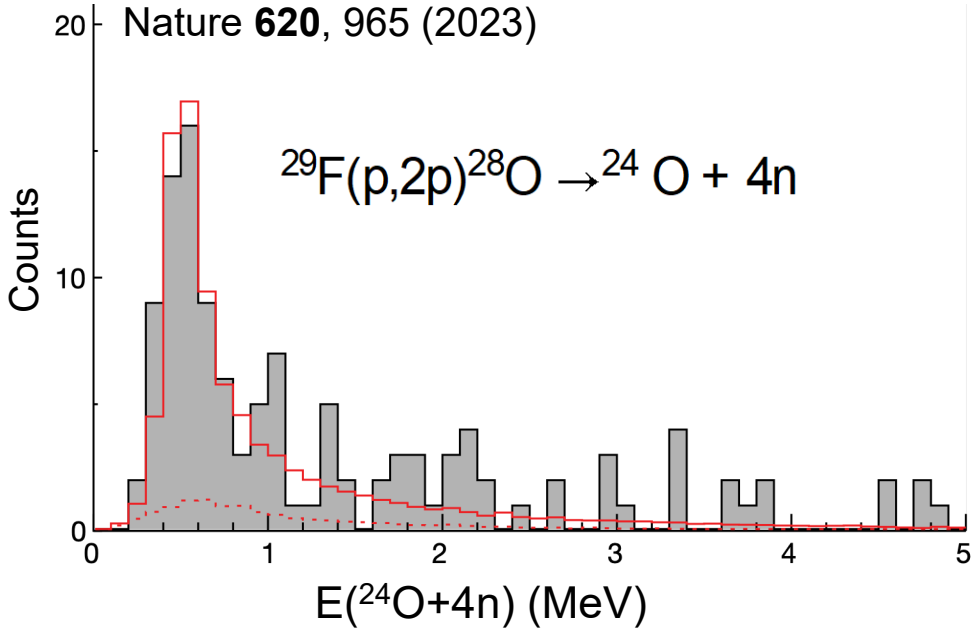
The experimental challenge: 4 neutrons beyond drip-line

- ^{28}O was expected as the most neutron-rich doubly-magic nucleus
- First invariant-mass spectroscopy with four neutrons in coincidence
- **Only possible due to the addition of the R3B NeuLAND demonstrator** to the neutron-detection system of SAMURAI
- Reaction: $^{29}F(p,2p)^{28}O \rightarrow ^{24}O + 4n$
- High-intensity ^{48}Ca beam of RIBF to produce ^{29}F beam



Result

- ^{28}O ground-state resonance observed with $E = 0.46(5)$ MeV and $\Gamma < 0.7$ MeV
- ^{28}O is not a doubly-magic nucleus
- Result provides a benchmark to test chiral interactions used in ab initio theories



NeuLAND arrives in RIKEN in 2015

Aumann, Duer, Obertelli et al.

Status and next steps towards FAIR Early and First Science

Remaining FAIR Phase-0 Program

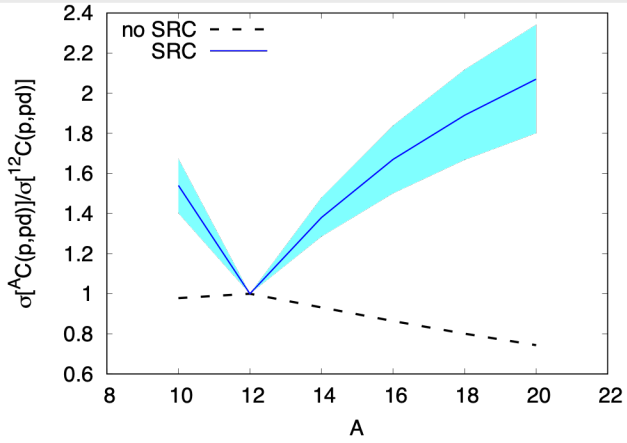
- Finalising analysis of FAIR Phase-0 experiments
- 2024: Experiment on short-range correlations SRC using $^{A}C(p,pd)^{A-2}Be$

  → **Isospin dependence of SRC within isotopic chain**
- 2025: Measurement of the total reaction cross section for hypernuclei (HYDRA)

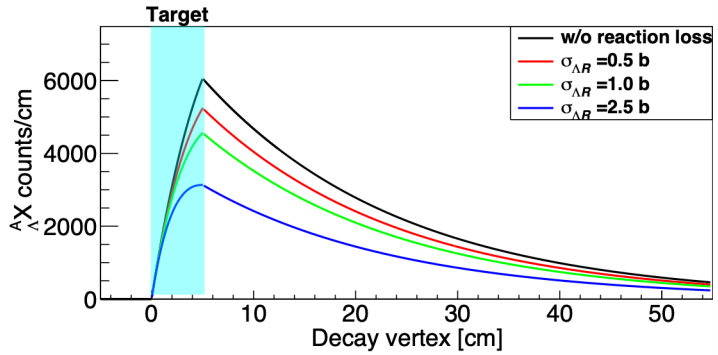
  → **Matter radius of the hyper halo candidate** $^{3}_{\Lambda}H$
- 2025: ASY-EOS II: neutron-proton elliptic flow as a function of beam energy

  → **Symmetry energy at different densities up to** $2\rho_0$

Expected in case of n-p SRC dominance



Expected decay yield



Next steps

- 2025-2027: construction and installation of additional NeuLAND double planes
  construction of proton-arm spectrometer (PAS)
  installation and commissioning of R3B in the FAIR High-Energy Cave

From 2028: full beam commissioning and start of Early and First Science Program

- Comprehensive program to determine **EOS symmetry-energy** parameters from different experiments with **key nucleus ^{132}Sn** neutron-removal cross sections (skin), (p,pn) reactions (orbital size), el. p scattering (matter distribution), α scattering (giant monopole)
- **Fission** of neutron-rich nuclei towards the **r-process**: fragment mass distributions and fission barriers
- **Short-range correlations** in heavier n-rich nuclei including **^{132}Sn**

● ● ● Write-up for complete science program in progress

Aumann, Duer, Obertelli et al.

HISPEC/DESPEC COLLABORATION

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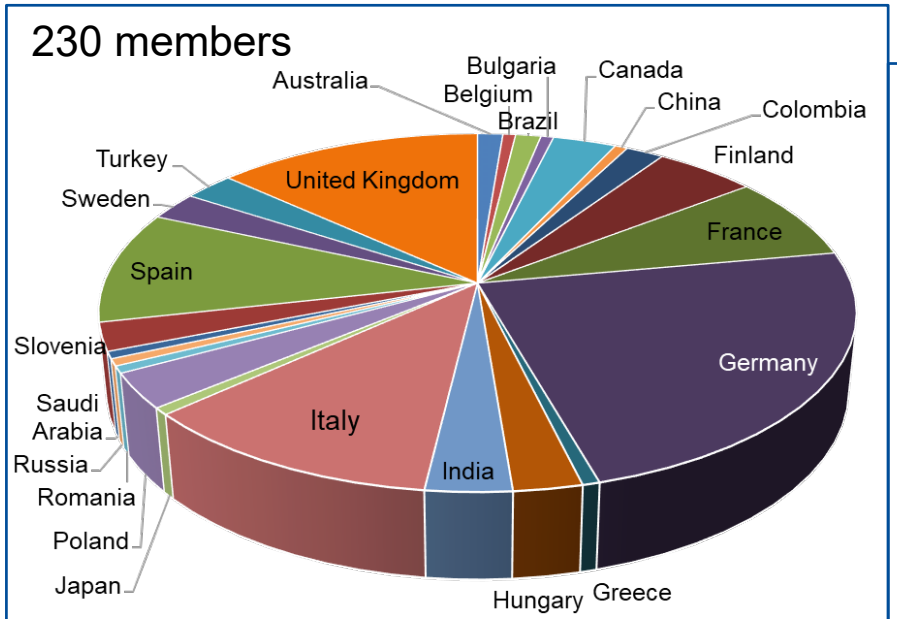
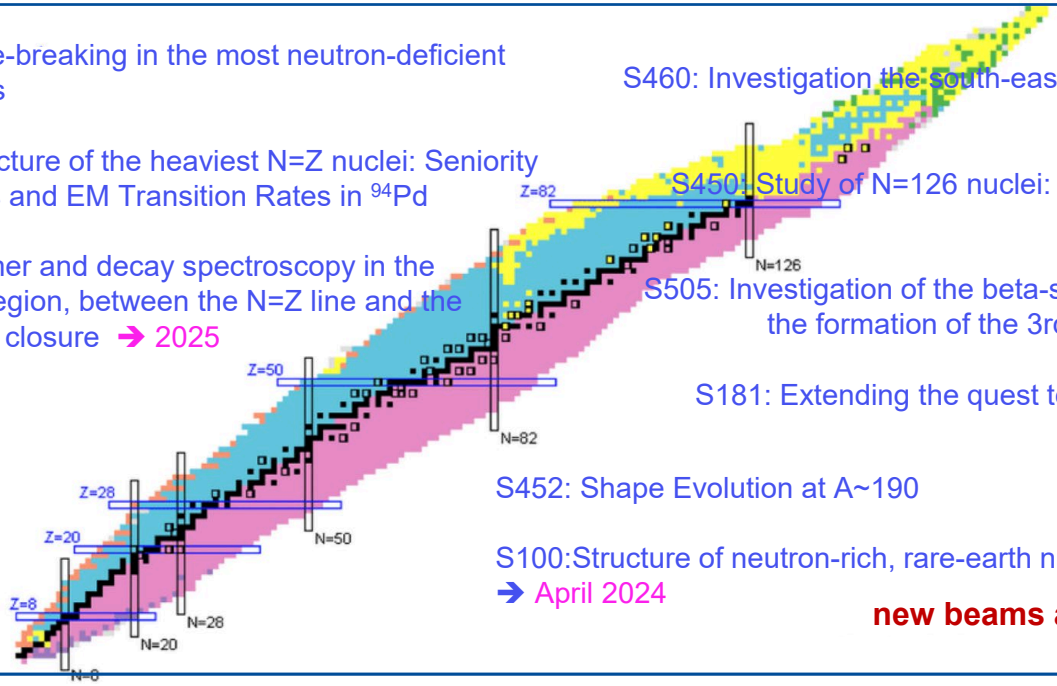


S496: Core-breaking in the most neutron-deficient tin isotopes

S480: Structure of the heaviest N=Z nuclei: Seniority Transitions and EM Transition Rates in ^{94}Pd

S101: Isomer and decay spectroscopy in the A~80-90 region, between the N=Z line and the N=50 shell closure ➔ 2025



S460: Investigation the south-east frontier of the A~225 island of octupole deformation

S450: Study of N=126 nuclei: Isomeric and beta decays in ^{202}Os and ^{203}Ir

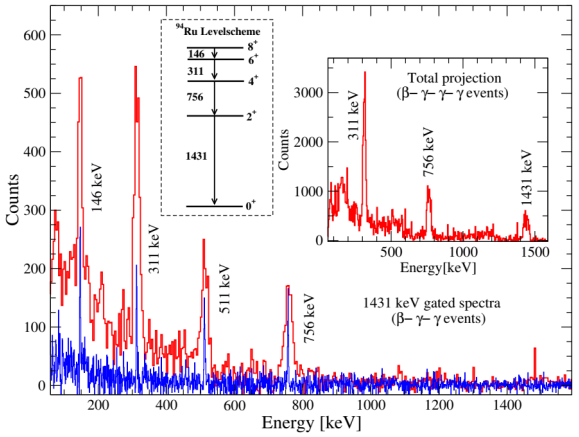
S505: Investigation of the beta-strength crossing N=126 and the formation of the 3rd r-process abundance peak

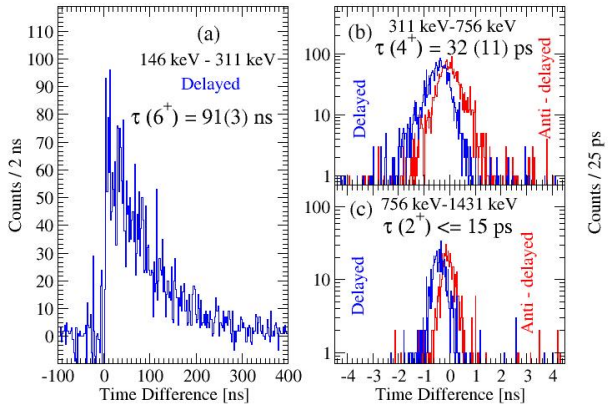
S181: Extending the quest towards the N=126 r-process waiting point ➔ June 2024

S452: Shape Evolution at A~190

S100:Structure of neutron-rich, rare-earth nuclei far from stability ➔ April 2024

new beams at GSI/FAIR !





Excited states of ^{94}Ru (N=50) populated via β-delayed proton emission of ^{95}Pd nuclei

Nature of symmetry breaking in the semimagic nucleus ^{94}Ru

B. Das, B. Cederwall, C. Qi, M. Gorska, P.H.Regan et al., Phys. Rev. C **105**, L031304 (2022).

NUSTAR.de
ErUM - FSP - T07

STATUS AND PERSPECTIVES AGATA

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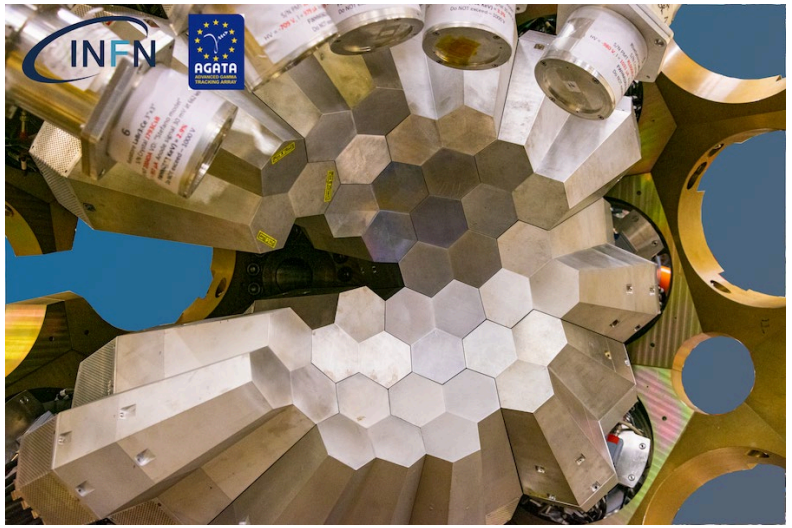
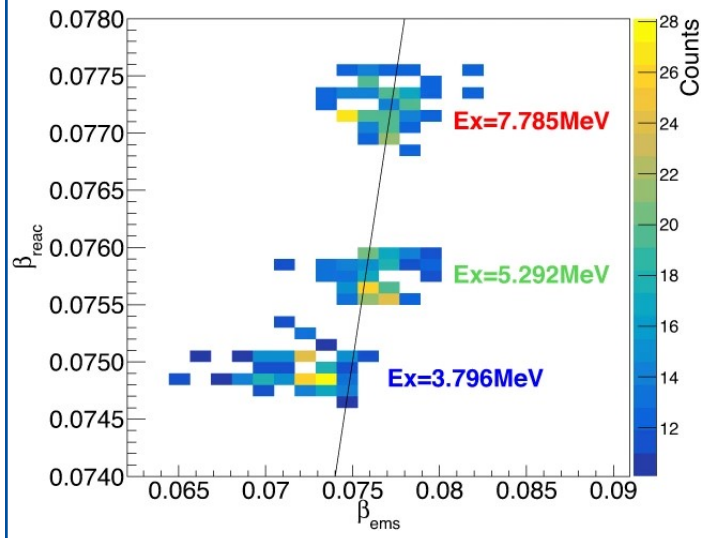


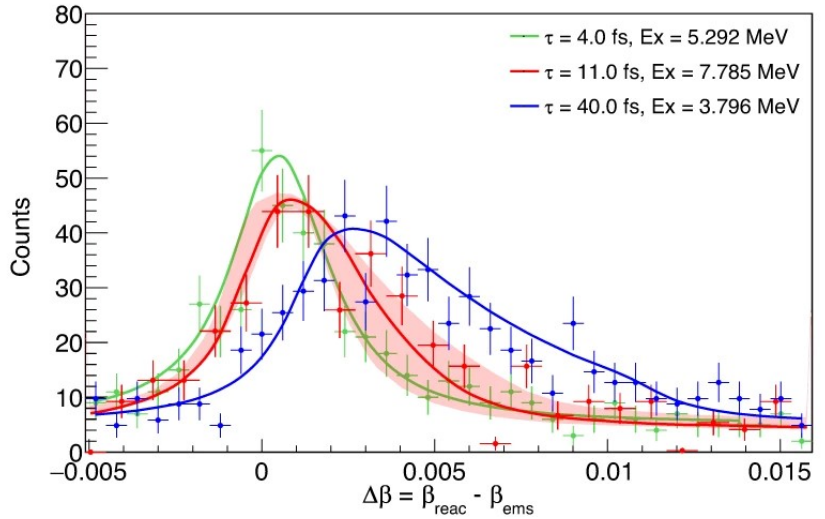
AGATA campaign @ INFN Legnaro

- 18 in-beam experiments performed since commissioning in May 2022
- 80% of Legnaro beam time
- AGATA coupled to particle spectrometer PRISMA
- Lifetime measurements

AGATA consists in Nov. 2023 out of
23 triple cluster detectors (full configuration 60)

Search for ^{22}Na in novae supported by a novel method for measuring femtosecond nuclear lifetimes





C. Fougères, et al.; Nature communications 14 (1), 4536 (2023)

High-precision spectroscopy of ^{20}O benchmarking ab-initio calculations in light nuclei
I. Zanon et al. Phys. Rev. Lett. accepted (2023)

Eur. Phys. J. A, Topical Issue AGATA: Advancements in Science and Technology

16 contributions in Eur. Phys. J. A 59 (2023)

- Agata detector technology: recent progress and future developments*
- Agata characterisation and pulse shape analysis*
- Agata: in-beam spectroscopy with relativistic beams*

* German contributions by
P. Reiter (U Köln), K. Wimmer (GSI)

Reiter, Jolie, Wimmer, NP et al.

SCHOTTKY AND ISOCHRONOUS STORAGE-RING MASS SPECTROMETRY

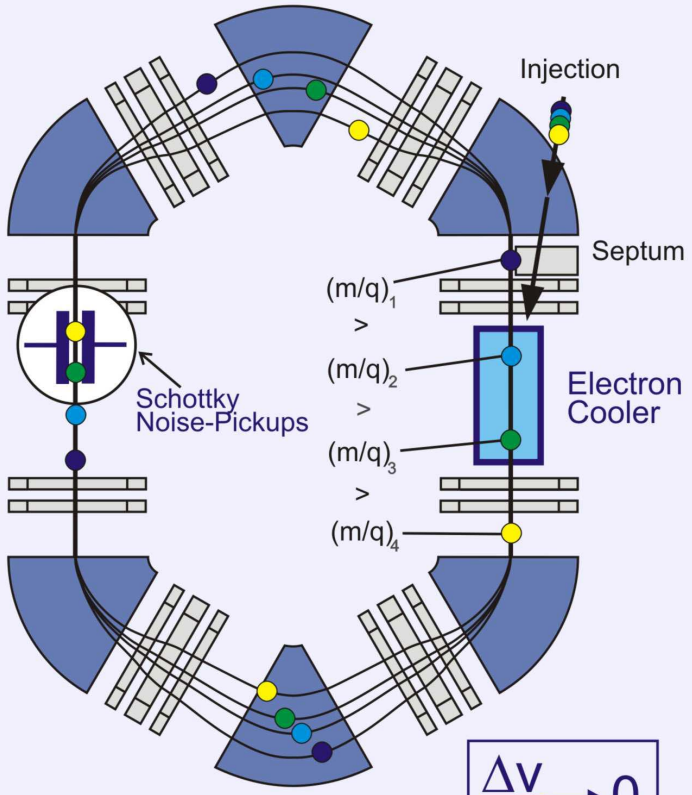
TECHNISCHE UNIVERSITÄT DARMSTADT

SCHOTTKY MASS SPECTROMETRY

Cooling: Takes time

Non-Destructive Detection (Schottky detectors)

- Bandwidth
- Resolving power
- Speed
- Sensitivity



Cooled Fragments

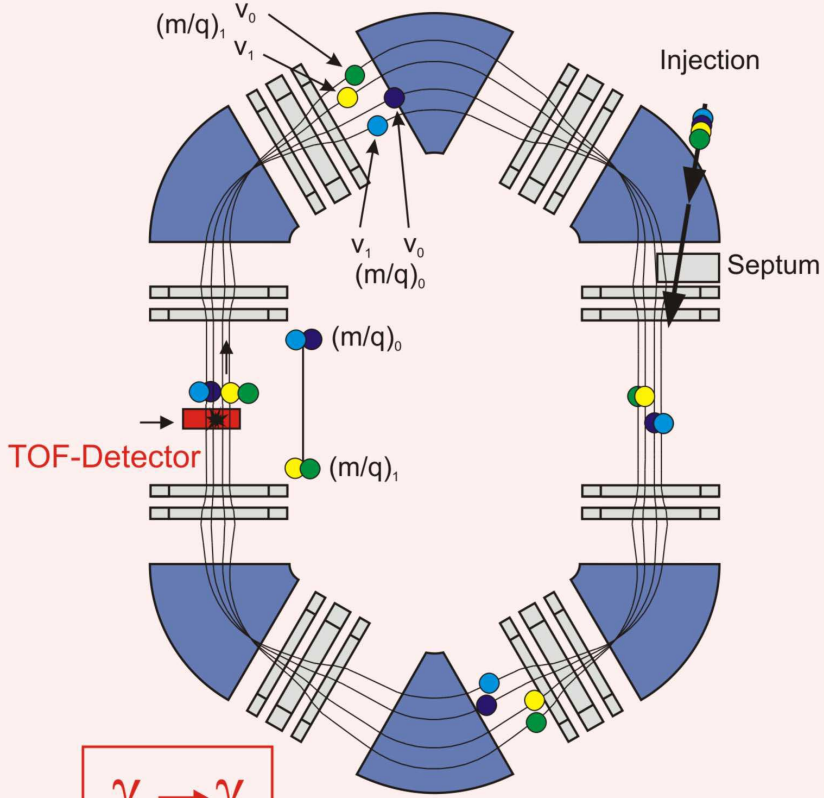
$$\frac{\Delta v}{v} \rightarrow 0$$

ISOCHRONOUS MASS SPECTROMETRY

Destructive Detectors (foil-based Secondary electron detectors)

No cooling

- Bandwidth
- Resolving power
- Speed
- Sensitivity



Hot Fragments

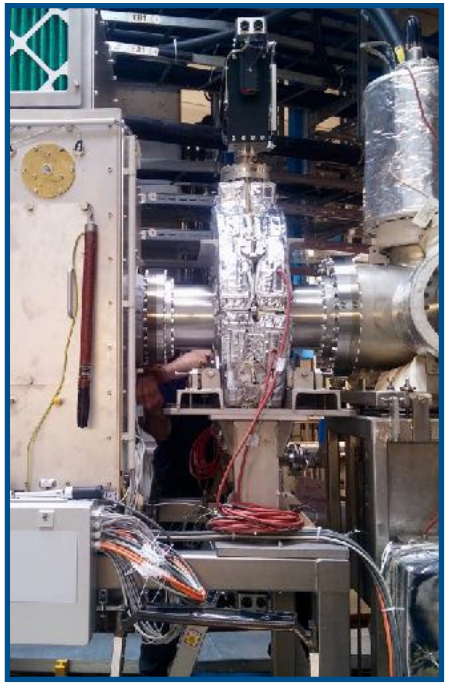
$$\gamma_t \rightarrow \gamma$$

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

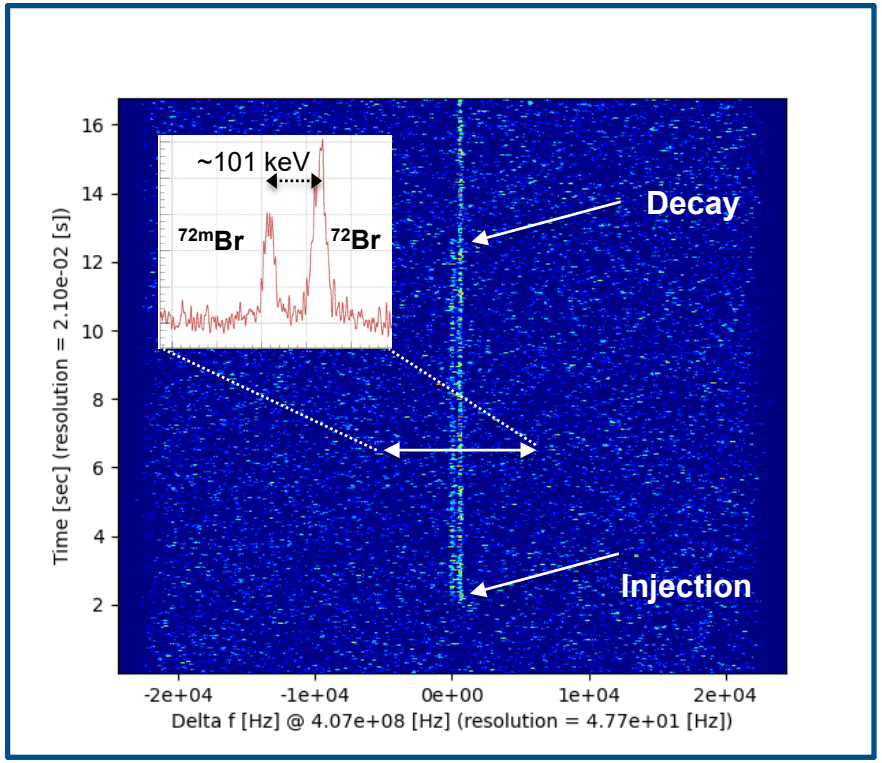
Litvinov et al.

B. Franzke, H. Geissel, G. Münzenberg, Mass Spectr. Rev. 27 (2008)

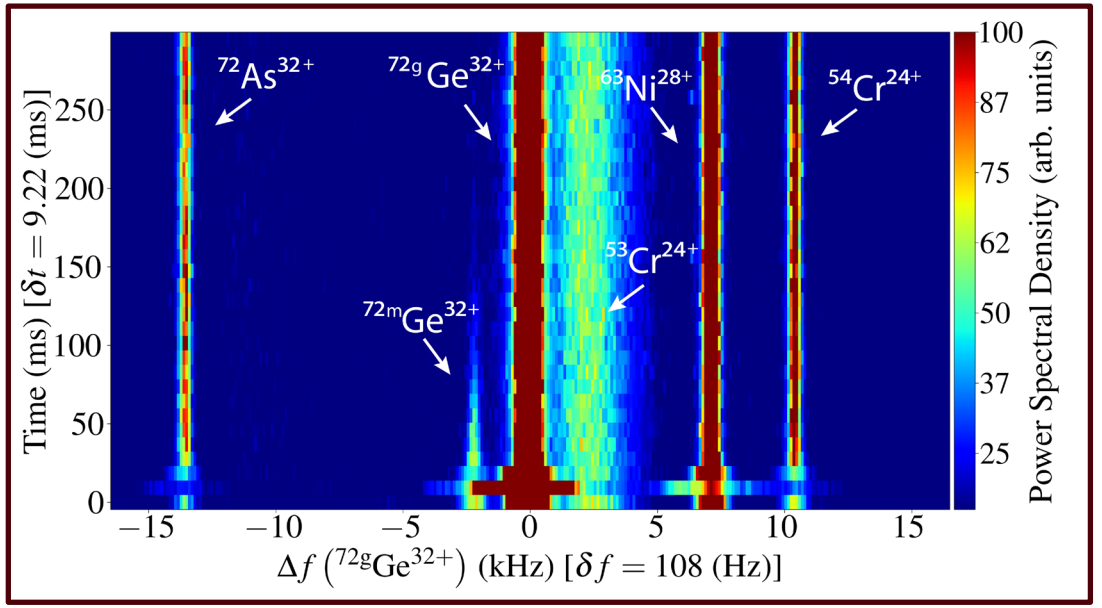
COMBINED ISOCHRONOUS+SCHOTTKY MASS SPECTROMETRY



New sensitive Schottky cavity
Resonance frequency 410 MHz



D. Fernandez et al., to be published



D. Fernandez et al., to be published

ASTRUm erc **Litvinov et al.**

S.Sanjari et al., Rev. Sci. Instr. **91, 083303** (2020)

First application of Schottky diagnosis in isochronous mode, i.e. without lengthy beam cooling
- **access to short-lived species in milisecond range**
- **high mass resolving power (~1'000'000), see resolved isomer of ^{72}Br**

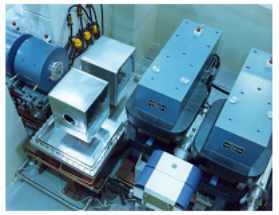
First measurement of isolated two-photon decay in fully-ionized ^{72}Ge
- **the first excited 0^+ state at 671 keV**
- **IPC, IC and 1γ decays are disabled – only 2γ decay is open**

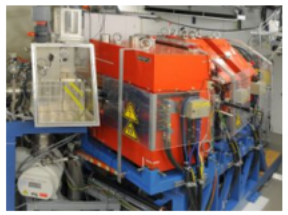
Korten, Litvinov, NP et al.

Next generation setups to study production, nuclear, atomic, and chemical properties at SHIP and TASCA

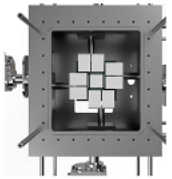
	2022 Beamtime	2023 Eng. run	2024 - 2025 Beamtime	Beamtime	Day-1 Beamtime	Day-1 Setups
Production and nuclear structure (decay spec.)						
TASISpec ⟶ LUNDIUM	👎 Commiss. ($_{94}$Pu)		Finalize LUNDIUM			LUNDIUM
ANSWERS Setup	✓ Commiss. (Z=82-94): Recoil-α-/γ-/CE-spec.		👍 $_{115}$Mc decay chains			ANSWERS
Atomic properties:						
Masses (SHIPTRAP)	✓ (ran in 2021)	SHIP PS test	👍 $_{105}$Db			SHIPTRAP
Laser spec in gas-cell	✓ $_{100}$Fm/$_{102}$No/$_{103}$Lr	RADRIS test	👍 $_{98}$Cf, $_{100}$Fm – $_{103}$Lr			RADRIS
in gas-jet	✓ Online Commiss.	SHIP PS test	👍 $_{102}$No			In-Gas-Jet
Chemical properties:						
RTC-based ($T_{1/2}$ >500 ms)	✓ Homologs (parasitic)	^{54}Cr beam test	👍 $_{106}$Sg carbonyls			miniCOMPACT
UniCell ($T_{1/2}$ >2 ms)	Design	Construct	Construct / commiss.			UniCell

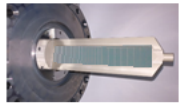
👎 Beamtime goals not reached (problems with ^{48}Ca beam)
✓ Successful beamtime
👍 Beamtime in schedule

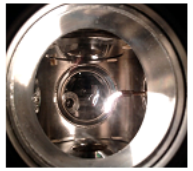

SHIP

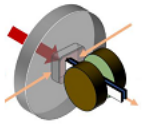

TASCA

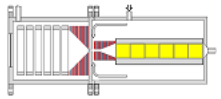

SHIPTRAP

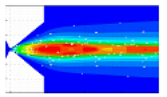

LUNDIUM


miniCOMPACT


RADRIS


ANSWERS


UniCell


Laser Gas-Jet

Block, Düllmann et al.

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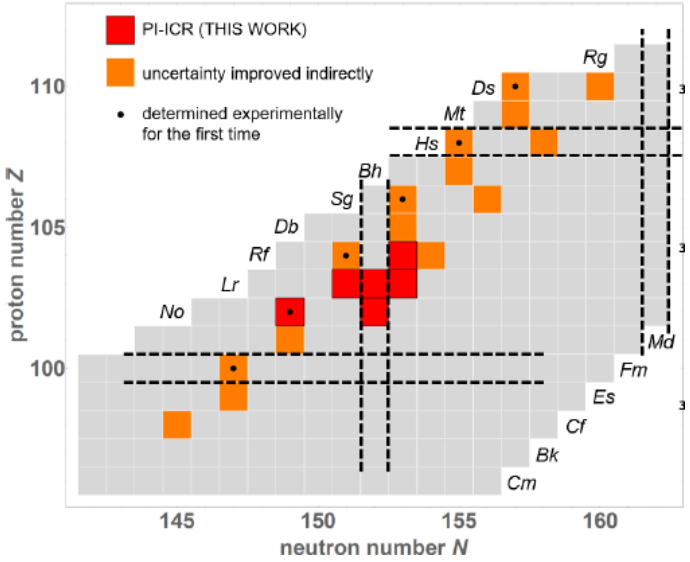
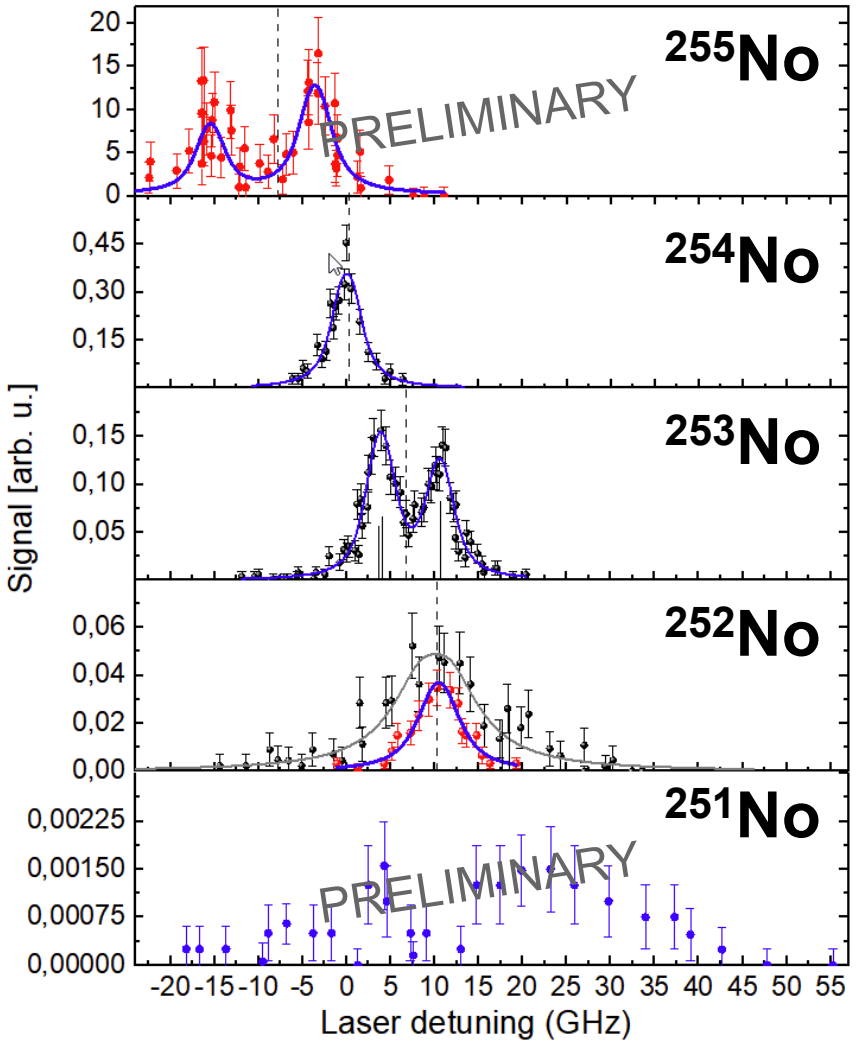
Isotope	Ions	Ratios	R_{mean}	rel. unc.	$R_{ToF-ICR}$	rel. unc.	$ME(keV/c^2)$	$ME_{lit}(keV/c^2)$	$ME_{new}(keV/c^2)$
^{251}No	39	9	0.944614687(9)	9.5E-9	-	-	82851.3(23)	82849(181)	82851.1(21)
^{254}No	2448	24	0.955908554(6)	6.3E-9	0.955908520(60) [22] 0.955908550(40) [23]	6.3E-8 4.2E-8	84733.5(15)	84723.3(97)	84733.3(15)
^{254}Lr	156	14	0.955928750(27)	2.8E-8	-	-	89734.0(67)	89645.9(913)	89733.9(64)
^{255}Lr	278	6	0.959691642(7)	7.3E-9	0.959691740(60) [23]	6.3E-8	89933.0(17)	89947.3(177)	89932.6(17)
^{256}Lr	124	11	0.963461017(23)	2.4E-8	0.9634610(3) [23]	3.1E-7	91737.2(57)	91746.6(829)	91737.2(57)
^{257}Rf	5	2	0.967240149(670)	6.9E-7	-	-	95960(170)	95866.4(108)	95866.4(108)



- several masses measured separately
- additional masses improved using AME links
- future: extension to heavier elements
- beamtime approved for **$_{105}$Db masses and isomer energies** (25 shifts A / 45 shifts A-)

FAIR Phase 0 Research Program

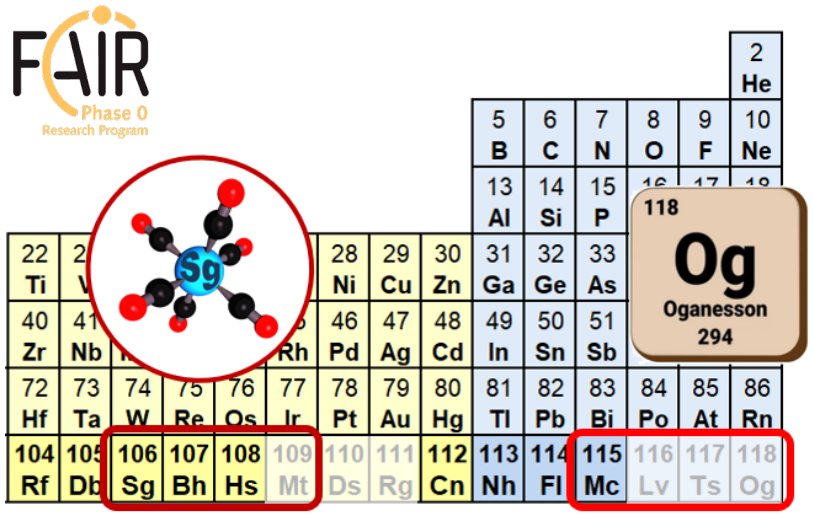
O. Kaleja et al., Phys. Rev. C 106 (2022) 054325



- first laser spectroscopy spectroscopy beyond Z=100 with yields as low as 0.05 atoms / sec
- isotope shift measurements for fermium and nobelium isotopes provided changes in mean-square charge radii around $N = 152$
- magnetic dipole and electric quadrupole moment of ^{253,255}No obtained
- future plan: extension to additional elements
- beamtime approved for **$_{98}$Cf, $_{100}$Fm, $_{102}$No, $_{103}$Lr laser spectroscopy** (65 shifts A / 36 shifts A-)

Block, Walther et al.

Probing the extremes of the periodic table in the superheavy elements



Transition metal molecular studies towards $_{109}$Mt

Chemistry towards $_{118}$Og

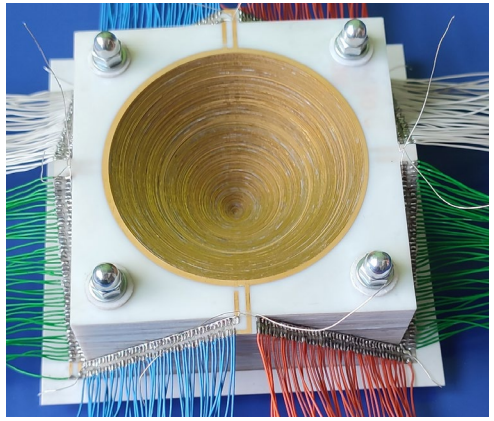
Molecular studies
- J. Even et al., Science 2014
- M. Götz *et al.*, RCA 2021
- M. Götz *et al.*, RCA 2022

TASCA **Beamtime spring 2024**

Chemical study of $_{114}$Fl
A. Yakushev et al., Front. Chem. (2022)

2020/21: **Chemical study of $_{115}$Mc/$_{113}$Nh**
A. Yakushev et al., Front. Chem. (2021)
A. Yakushev et al., in prep.

2022-24: **Construct UniCell for faster chemistry ($T_{1/2}$<200 ms)**



High-Pressure UniCell

TASCA Beamtime 2024: **$_{106}$Sg(CO)$_6$ production and chemistry**

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Outlook 2026+: ***TASCA*** beamtime on novel compound **$_{107}$Bh(CO)$_x$**

2020-22 | 2023 | 2024 | 2025

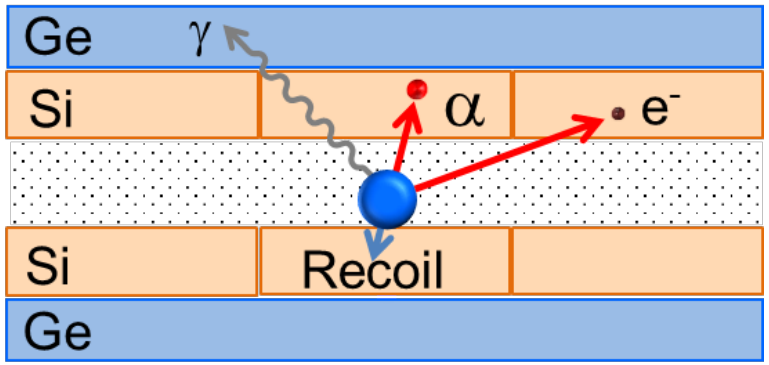
Düllmann et al.

Düllmann et al.

Exploring the nuclear properties on the Island of Enhanced Stability

Gas flow from **TASCA**

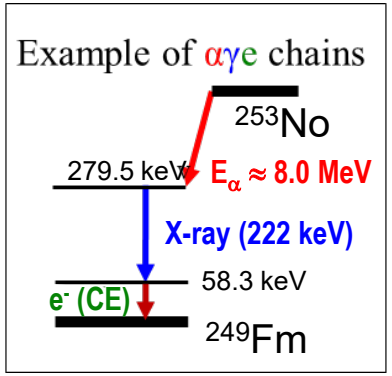
ANSWERS@TASCA

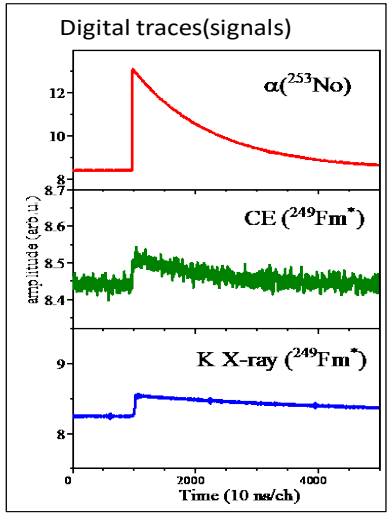


ANSWERS* has a high efficiency for measuring α-, e⁻/CE-, γ/X-, daughter recoil coincidence data

J. Khuyagbaatar and P. Mosat

ANSWERS
commissioning





EC-delayed fission search in new ^{244}Md
J. Khuyagbaatar et al., PRL (2020)

Focal plane α-γ-e⁻-spec. of $^{286-289}$Fl
A. Såmark-Roth et al., PRL (2021)

A new setup: ANSWERS*
2020-22: ANSWERS commissioning
J. Khuyagbaatar et al., in prep.

TASCA Beamtime 2025:
ANSWERS spectroscopy, fission mass distribution along ^{288}Mc chains

2019-22 — 2023 — 2025

*Adsorption-based Nuclear Spectroscopy Without Evaporation Residue Signal

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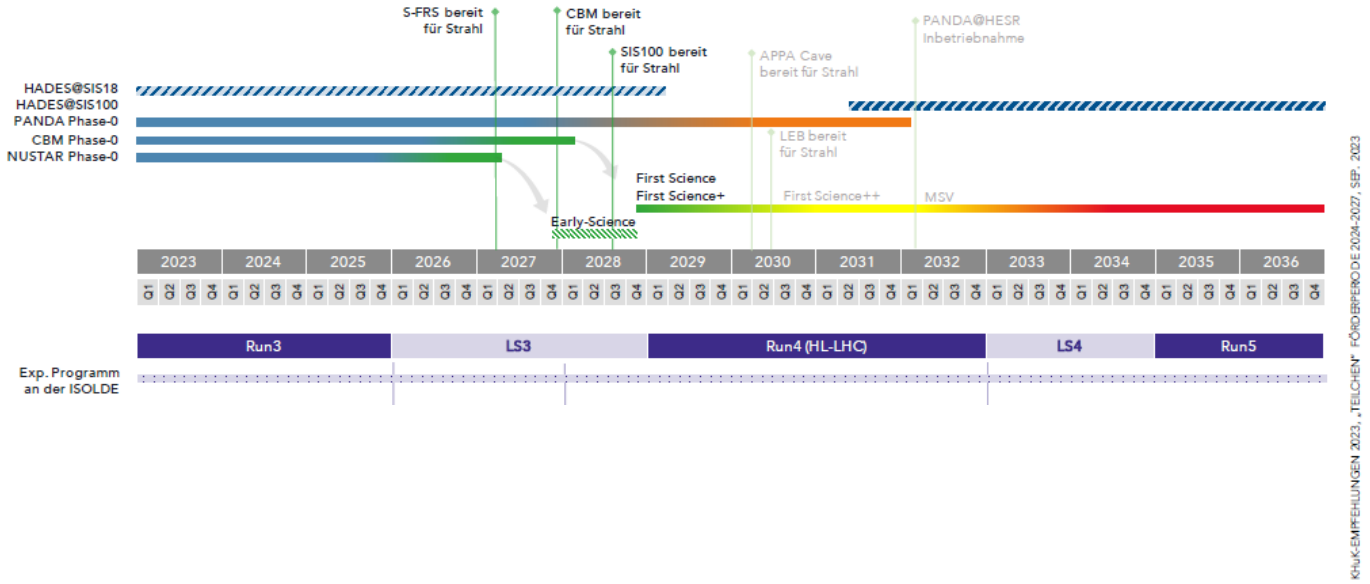


FAIR – NUSTAR Activities

- Super-FRS
- R3B
- HISPEC/DESPEC – AGATA
- ILIMA

- SHE
- MATS / LaSpec

➢ FAIR Phase-0 external

➢ ISOLDE
  - ➢ low-energy
  - ➢ HIE-ISOLDE
  - ➢ PUMA

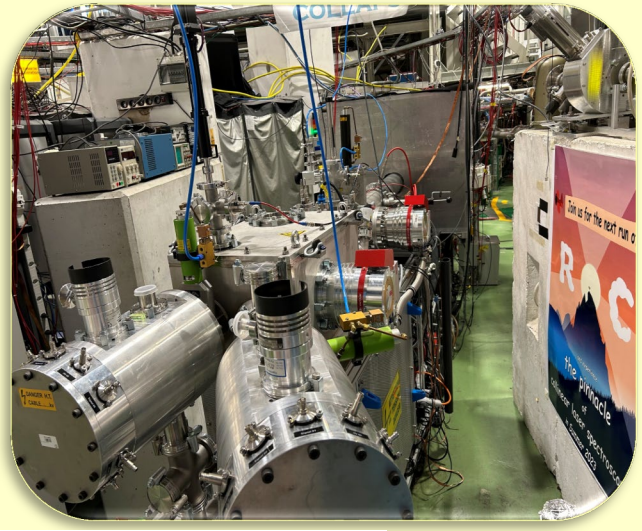
ISOLDE - Low Energy: Laser Spectroscopy at COLLAPS

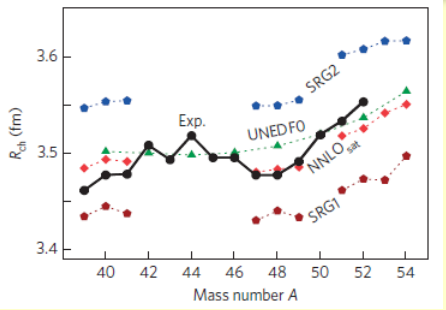
Highlights of 2023

TECHNISCHE UNIVERSITÄT DARMSTADT

W. Nörtershäuser (TU Darmstadt) and
L. Rodriguez (CERN) for the COLLAPS collaboration

First measurement of the ^{53}Ca charge radius!



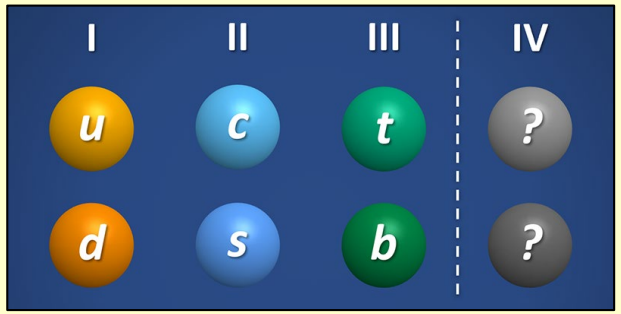


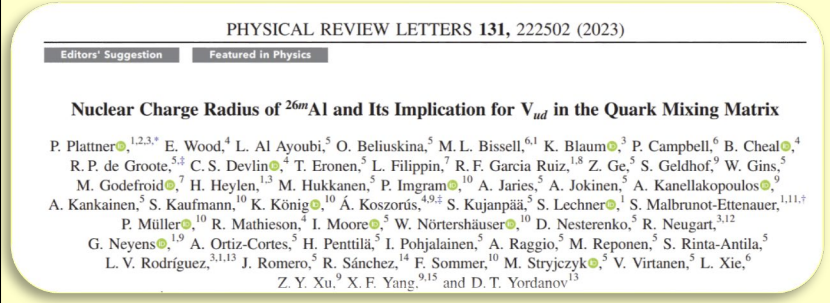
Charge radii across N=32

^{54}Ca in 2024

R. Garcia-Ruiz et al., Nature Phys. 12, 594 (2016)

Quark picture put to the test





PHYSICAL REVIEW LETTERS 131, 222502 (2023)

Editors' Suggestion | Featured in Physics

Nuclear Charge Radius of ^{26m}Al and Its Implication for V_{ud} in the Quark Mixing Matrix

P. Plattner, E. Wood, L. Al Ayoubi, O. Beliuskina, M. L. Bissell, K. Blaum, P. Campbell, B. Cheal, R. P. de Groote, C. S. Devlin, T. Eronen, L. Filippin, R. F. Garcia Ruiz, Z. Ge, S. Geldhof, W. Gins, M. Godefroid, H. Heylen, M. Hukkanen, P. Imgram, A. Jaries, A. Jokinen, A. Kanellakopoulos, A. Kankainen, S. Kaufmann, K. König, Á. Koszorús, S. Kujanpää, S. Lechner, S. Malbrunot-Ettenauer, P. Müller, R. Mathieson, I. Moore, W. Nörtershäuser, D. Nesterenko, R. Neugart, G. Neyens, A. Ortiz-Cortes, H. Penttilä, I. Pohjalainen, A. Raggio, M. Reponen, S. Rinta-Antila, L. V. Rodríguez, J. Romero, R. Sánchez, F. Sommer, M. Stryjczyk, V. Virtanen, L. Xie, Z. Y. Xu, X. F. Yang, and D. T. Yordanov

Single charge radius shifts unitarity value of the top row of the CKM matrix to 0.99856 ± 0.00070.

Towards the p-emitter nucleus ^{147}Tm

- Successful measurements on ^{155}Tm to ^{175}Tm
- Discovery of new isomeric states

- Target and laser beam developed to reach the sensitivity needed to measure p-emitter ^{147}Tm

Outlook:

- pushing the sensitivity limit at COLLAPS: development of collisional ionization to explore the so far unreached fluorine chain
- unexplored region of light nuclei: He-like light systems, like B^{3+}, C^{4+}

COLLAPS

NUSTAR de ErUM - FSP - T07

NUCLEAR PHYSICS STUDIES THROUGH MASS SPECTROMETRY

Highlights of 2023

L. Schweikhard (U Greifswald) and
L. Nies (CERN) for the ISOLTRAP collaboration

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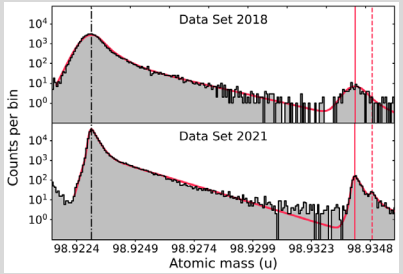
Closing in on ^{100}Sn: Investigation of shell evolution near doubly-magic

- First-ever measurement of ^{99m}In challenges nuclear theory



Nies et al., Phys. Rev. Lett. **131**, 022502 (2023)

- First direct measurement of ^{97gs,m}Cd yields new data point for single-neutron binding energy at N=50

D. Lange et al., in preparation

- Improvement of ^{103}Sn mass refines mass surface en rout towards ^{100}Sn

Nies et al., in preparation

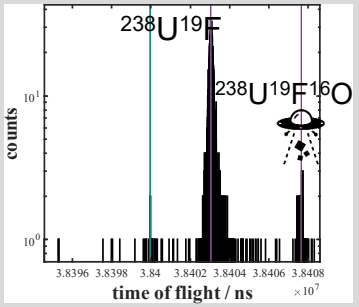
Actinide Studies with LISA

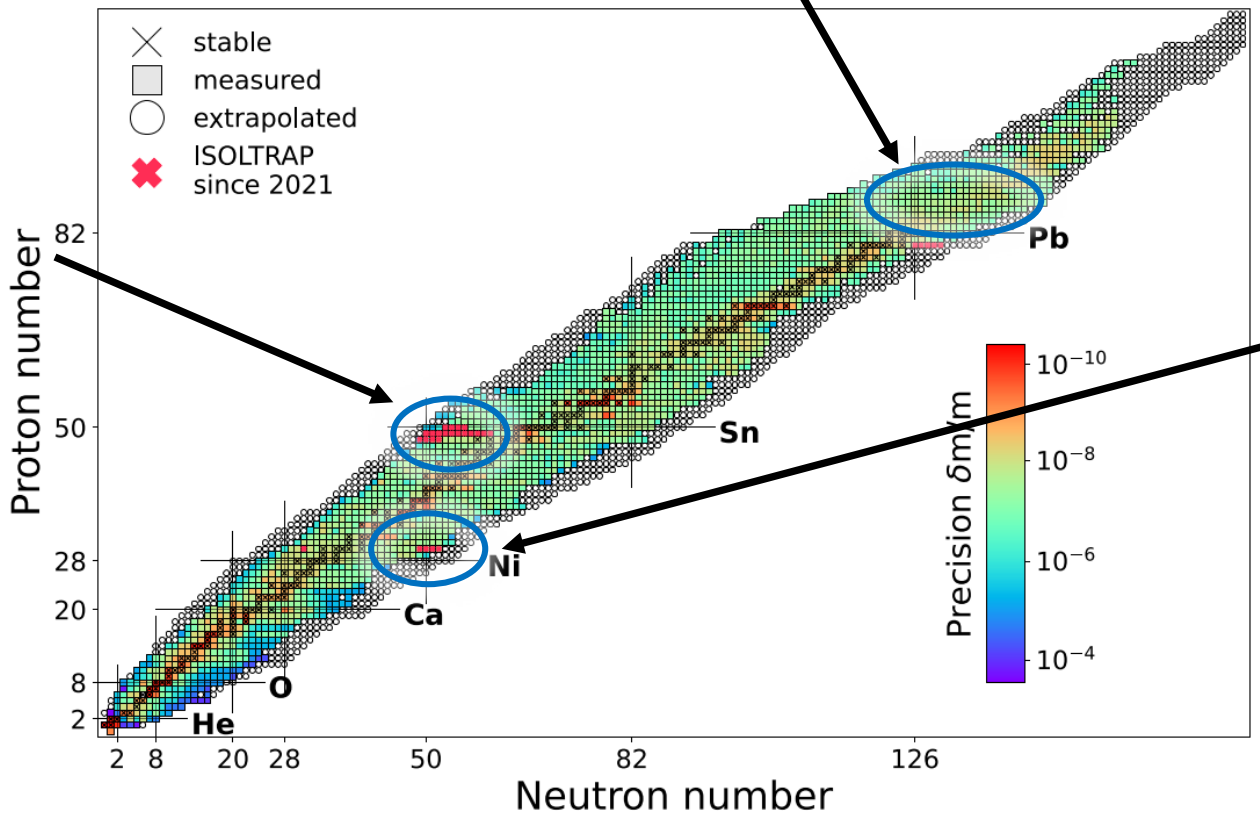
- Target and ion source development together with the „Laser Ionization and Spectroscopy of Actinides" ITN consortium

M. Au et al., Phys. Rev. C **107**, 064604 (2023)
M. Au et al., NIM B **541** (2023), p. 375-379

- Production and extraction of ^{225}AcFF for medical applications

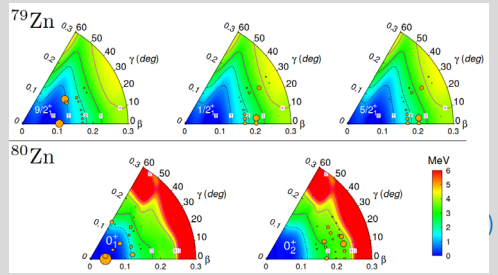
M. Au et al., in preparation





Further evidence for shape coexistence near doubly-magic ^{78}Ni

- First direct measurement of ^{79}Zn isomeric state together with new shell model tool provides further evidence for shape coexistence near ^{78}Ni



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ErUM - FSP - T07

NUCLEAR STRUCTURE STUDIES WITH MINIBALL AT HIE-ISOLDE

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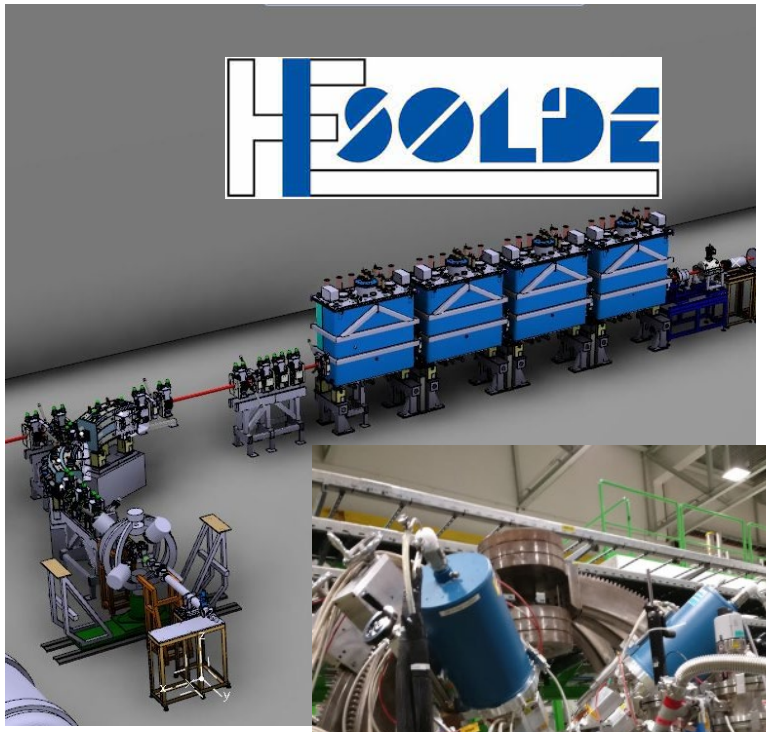
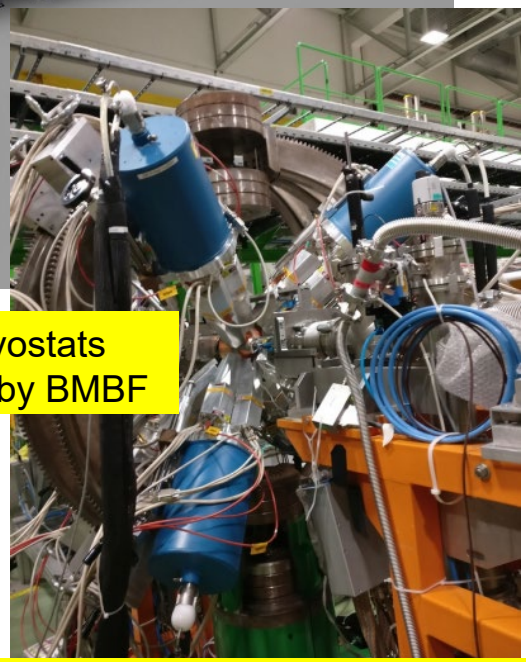




New cryostats funded by BMBF

Goal: Study of nuclear structure by reactions with exotic ions from the world-leading ISOL facility … post-acceleration to beam energies far below the FAIR regime

High-resolution γ-ray spectroscopy with coincident particle detection

Set up and operated by the international MINIBALL collaboration with significant contributions from Germany

Operational since 2000 … and still the by far most requested instrumentation at HIE-ISOLDE … highly sustainable investments!!!

Synergies with NUSTAR @FAIR
- instrumentation / electronics
- analysis methods
- training of ECRs

FEBEX cards developed for FAIR and used by MINIBALL too

German groups involved: TU Darmstadt, GSI, Univ. of Cologne, TU/LMU Munich

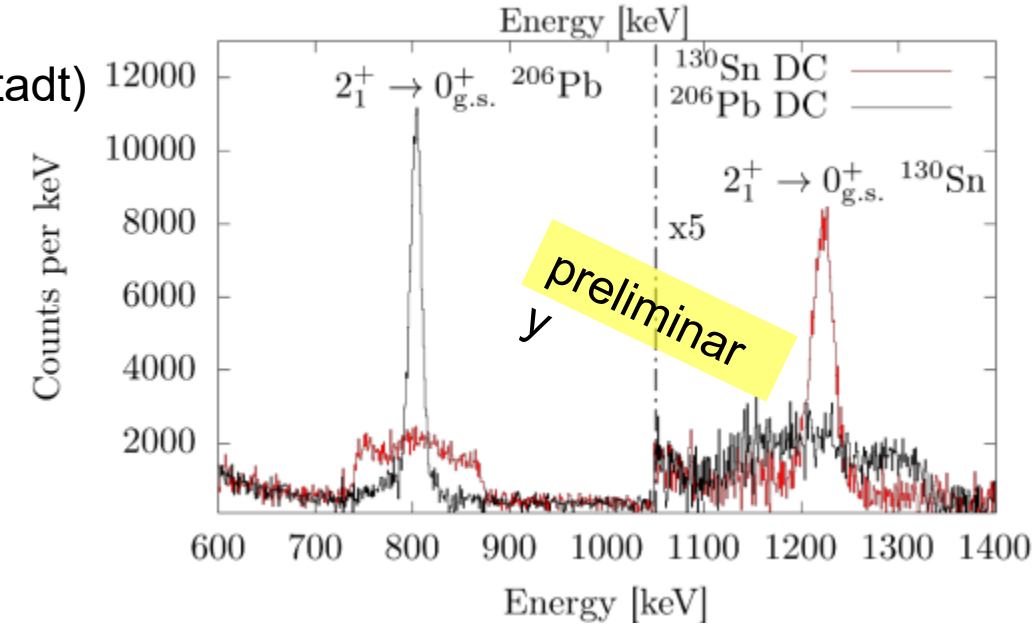
Kröll, Reiter, Jolie, NP et al.

TECHNISCHE UNIVERSITÄT DARMSTADT

2023: despite the early stop of protons at CERN a highly busy campaign with 8 experiments successfully performed with the refurbished and upgraded set-up

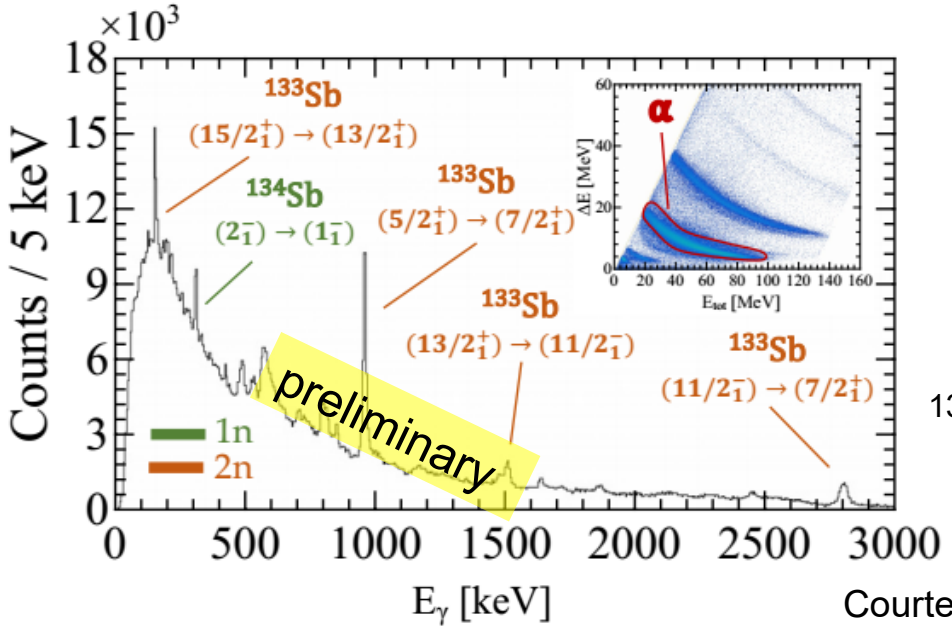
Two examples of complementary experimental approaches to the structure in the ^{132}Sn region

IS702: Coulomb excitation of ^{130}Sn
(lead by Univ. of Cologne / TU Darmstadt)



Courtesy of Max Droste
(doctoral candidate at Univ. of Cologne)

IS595: Incomplete fusion reactions on ^{132}Sn



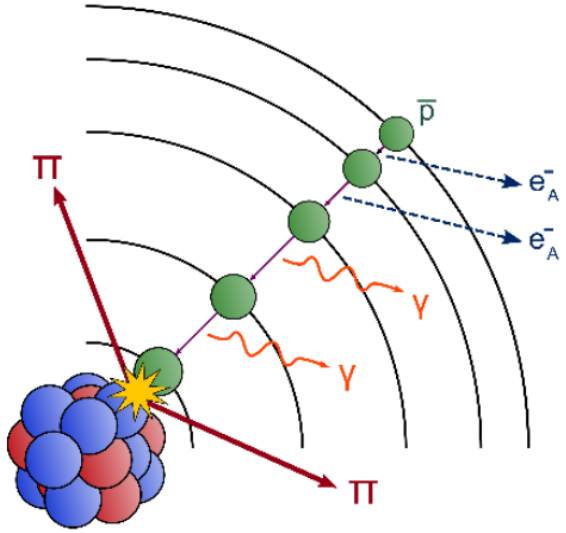
^{132}Sn(^{7}Li,α xn)^{133,134}Sb

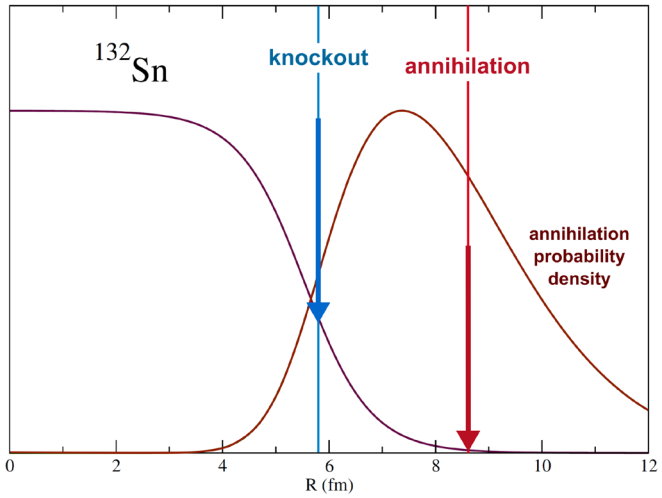
Courtesy of Simone Bottoni (Univ. di Milano)

PUMA

Obertelli et al.

PROBING SKINS WITH ANTIPROTONS



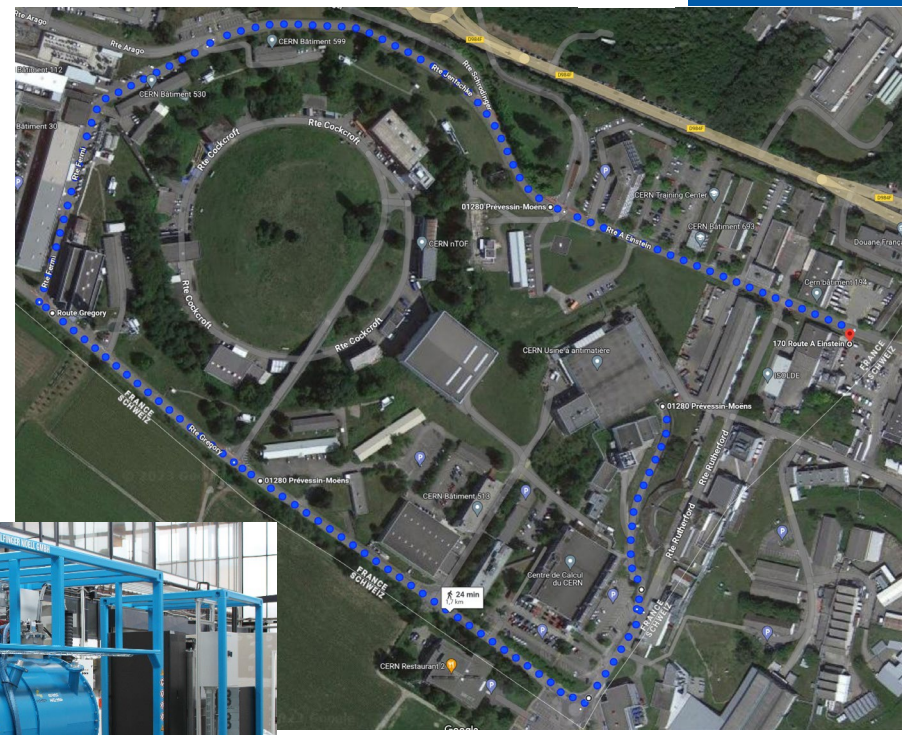


- $\bar{p}$ captured in excited antiprotonic orbital (~QED)
- then annihilate in tail $\rho_{n/p}(r)$ (QCD)
- Conservation of total charge

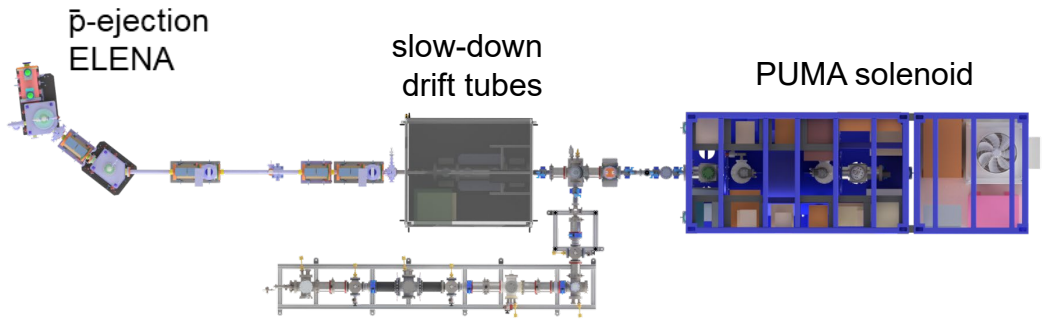
$$\sum_{\pi} q_{\pi} = \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases}$$

$\sum_{\pi} q_{\pi}$ of all reactions $\leftrightarrow \frac{N_n}{N_p} \leftrightarrow \frac{\rho_n}{\rho_p}$ (density tail)

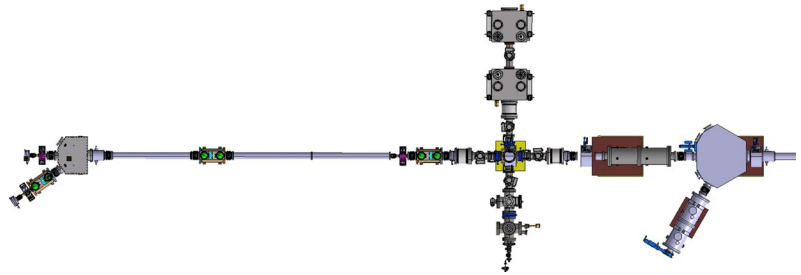
PUMA solenoid
@TU Darmstadt



STATUS AND PLANS



- Low energy antiproton beam line: **validated** (2023)
- Off line ion source: **built**, tuning ongoing
- Trap / solenoid: **built**
- Time projection chamber: **to be finalized in 2023**
- Full experiment installed at ELENA in April 2024
- First measurements with stable nuclei from 2024



- New RC6 beamline including, isotopic selection (HV MR-ToF) and bunching (RfQ) UHV (10^{-9} mbar)
- Beam line finalized in 2024
- First physics experiments at ISOLDE in 2025 (Xe, Ne)

Obertelli et al.

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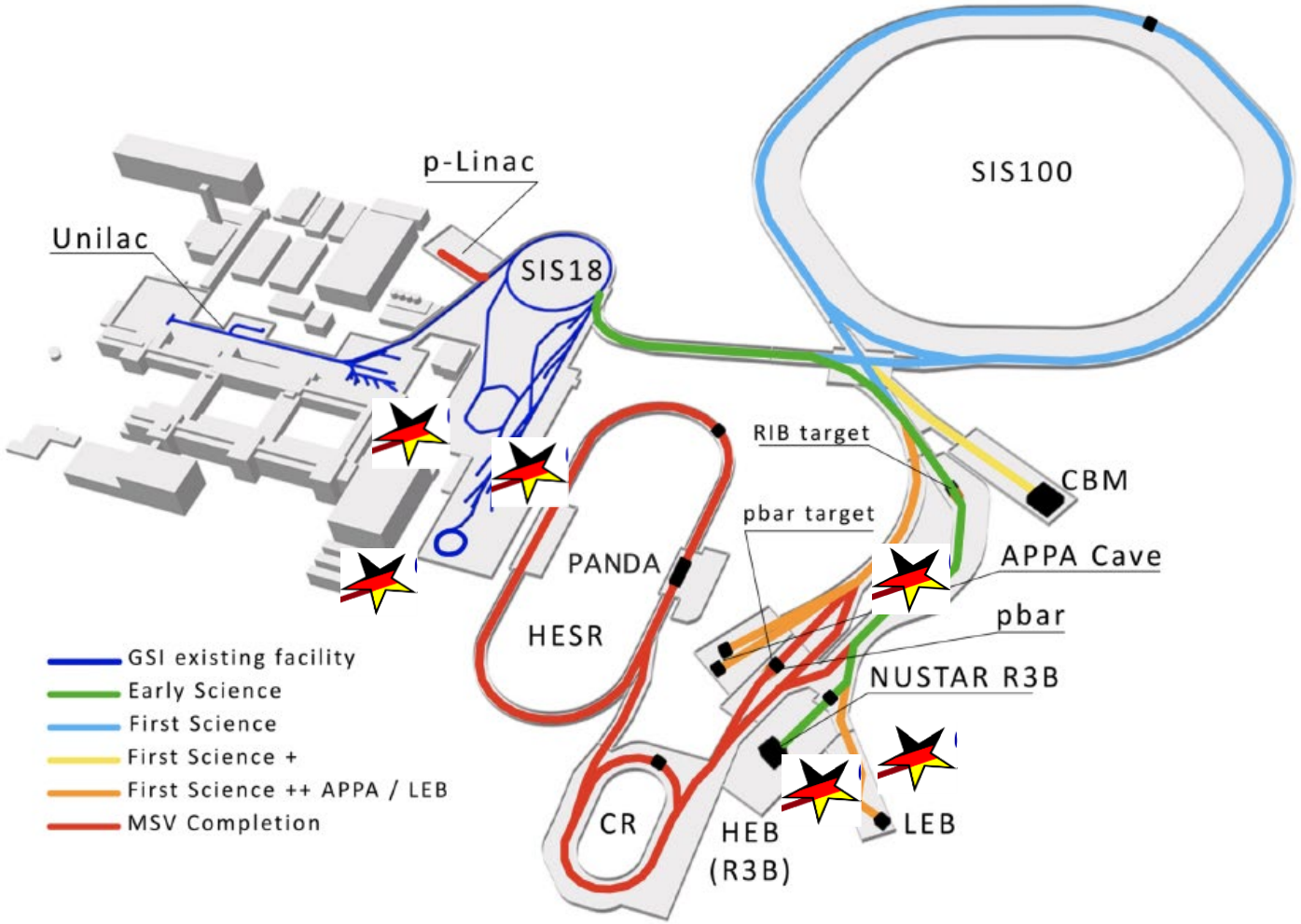
Thank you



FAIR – NUSTAR Activities

- Super-FRS
- R3B
- HISPEC/DESPEC – AGATA
- ILIMA

- SHE
- MATS / LaSpec

➢ FAIR Phase-0 external

➢ ISOLDE
  - ➢ low-energy
  - ➢ HIE-ISOLDE
  - ➢ PUMA