Nuclear Structure and astrophysics studies with TITAN's Multiple Reflection Time-Of-Flight Mass Spectrometer

(MR-TOF-MS)

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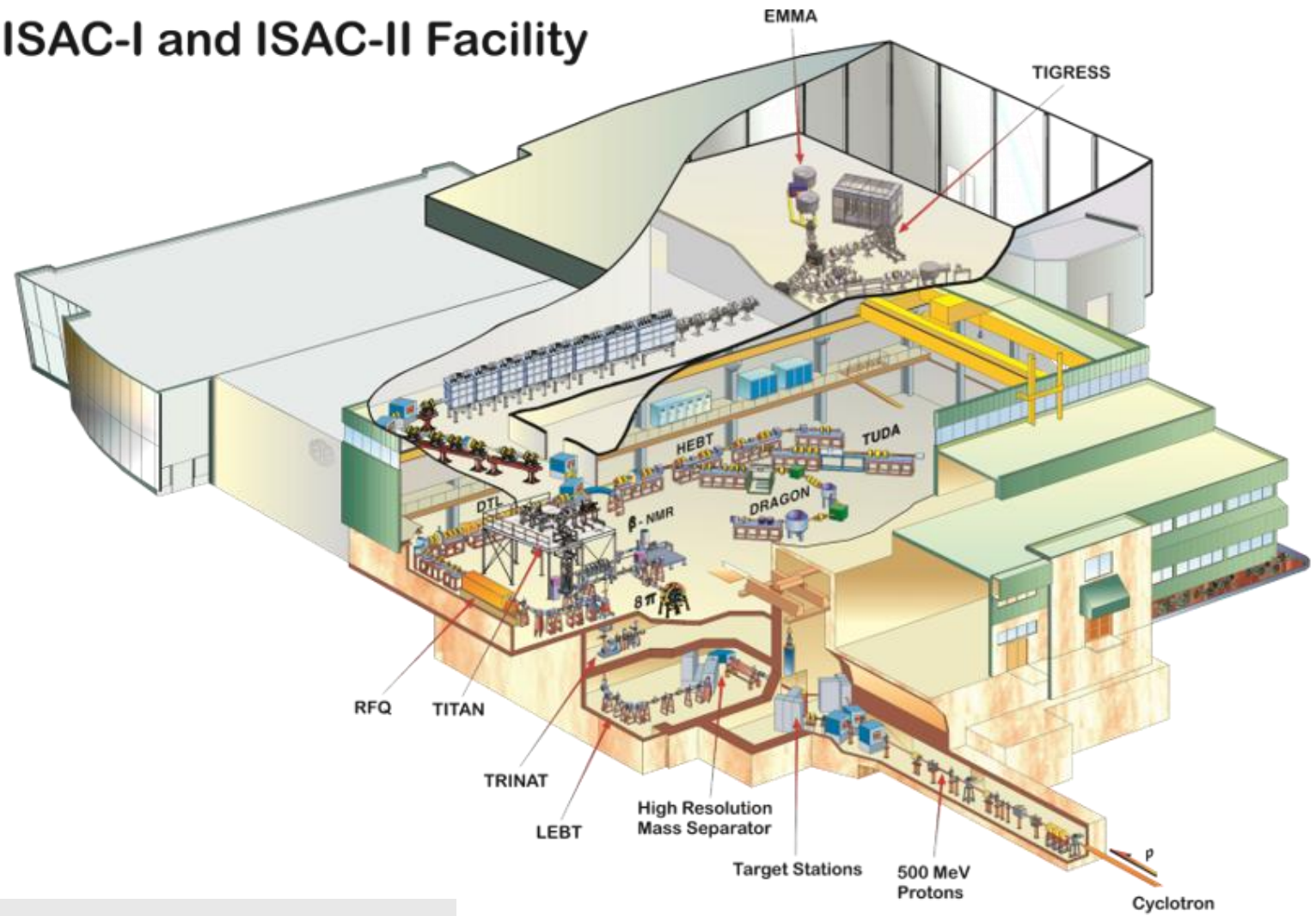
GSI Helmholtz Center for Heavy Ion Research, Darmstadt, Germany
TRIUMF Canada's Particle Accelerator Centre, Vancouver, Canada

September 2025

Outline

- **TRIUMF: an ISOL facility in Vancouver, Canada**
- **Multiple-Reflection Time-of-Flight mass spectrometry (MR-TOF-MS)**
- **Study the 1st and 2nd *r*-process peaks**
- **High-precision mass measurements of Ga and Zn nuclei**
- **Toward the most neutron-rich Sn isotopes**

TRIUMF facility (Vancouver, Canada)



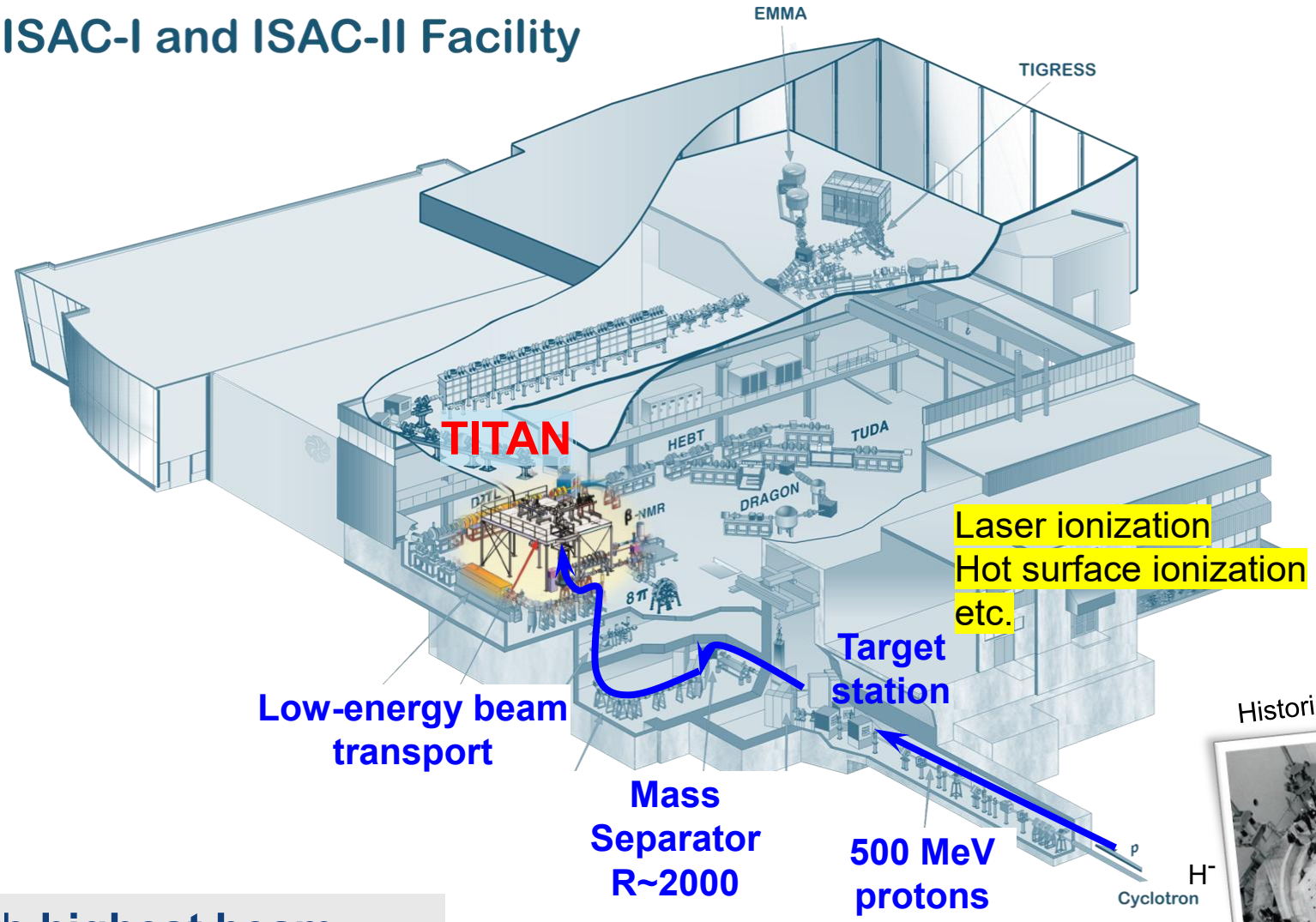
Programs in

- Nuclear structure & reactions
- Nuclear astrophysics
- Electroweak interaction Studies
- Material science
- Life science

ISOL facility with **highest beam power on target** (50 kW)

TRIUMF

TITAN at ISAC/TRIUMF



TRIUMF's Ion Trap for Atomic and Nuclear Science

- High-precision mass measurements
- In-trap decay spectroscopy

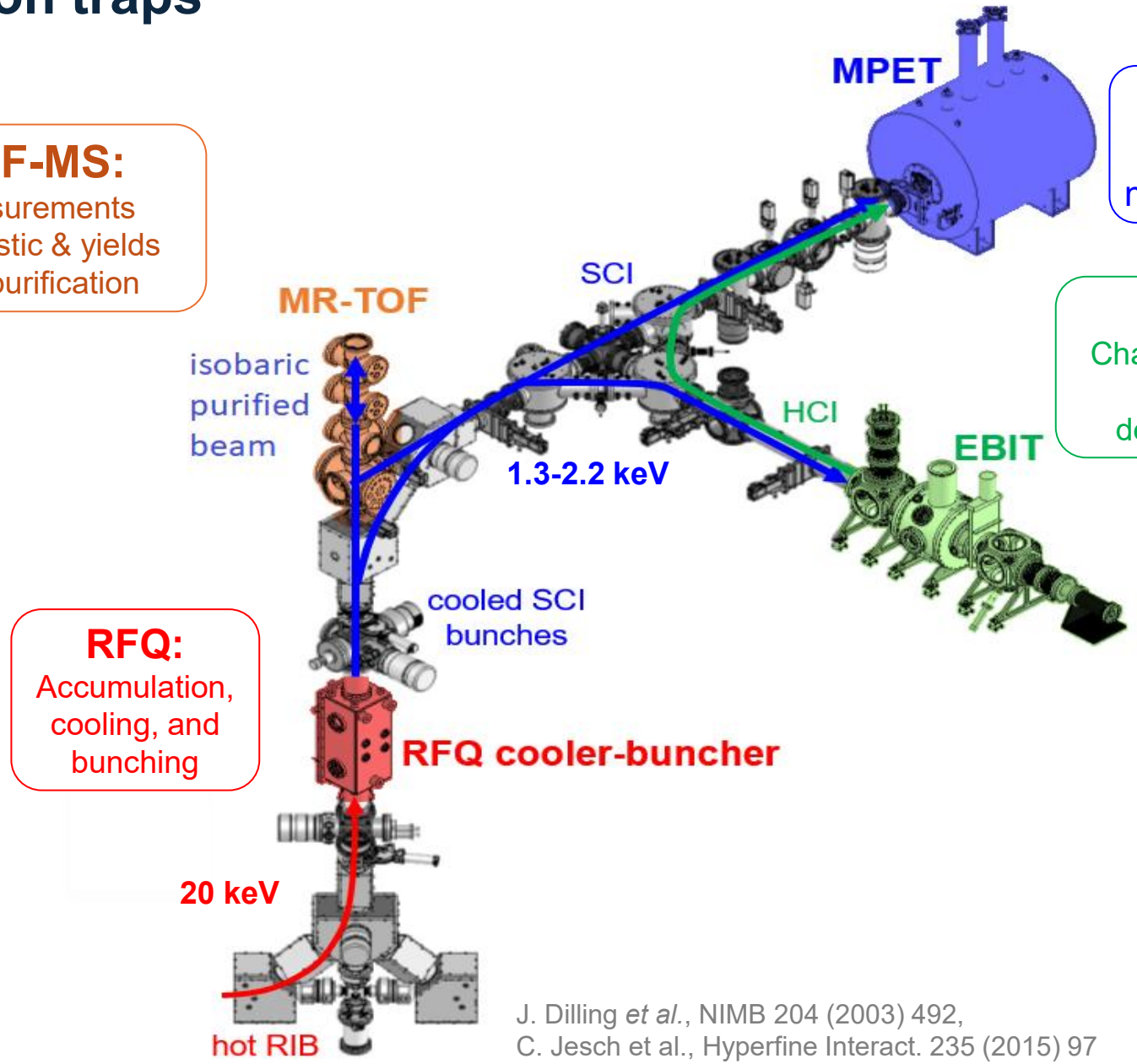
Historical photo of cyclotron

ISOL facility with **highest beam power on target** (50 kW)

TRIUMF

TITAN ion traps

MR-TOF-MS:
Mass measurements
Beam diagnostic & yields
RIB beam purification



MPET:
Penning trap for
mass measurements

EBIT:
Charge State Breeding
and
decay spectroscopy

RFQ:
Accumulation,
cooling, and
bunching

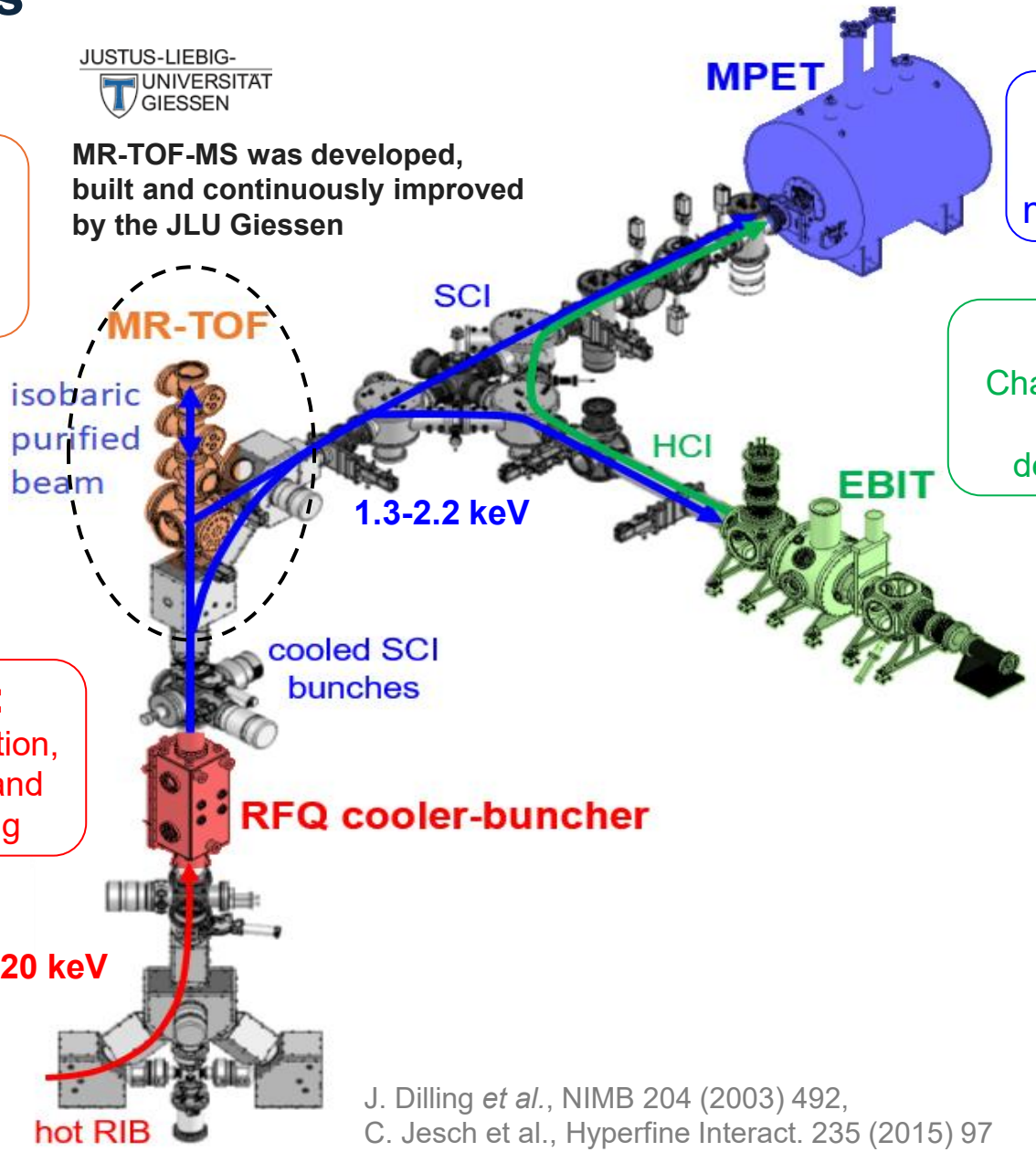
J. Dilling *et al.*, NIMB 204 (2003) 492,
C. Jesch et al., Hyperfine Interact. 235 (2015) 97

TITAN ion traps

MR-TOF-MS:
Mass measurements
Beam diagnostic & yields
RIB beam purification

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MR-TOF-MS was developed, built and continuously improved by the JLU Giessen



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TRIUMF
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SFU
UNIVERSITY OF CALGARY
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University of Victoria
COLORADOSCHOOLOFMINES
UNIVERSITY OF NOTRE DAME
UBC
WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER
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cnrs
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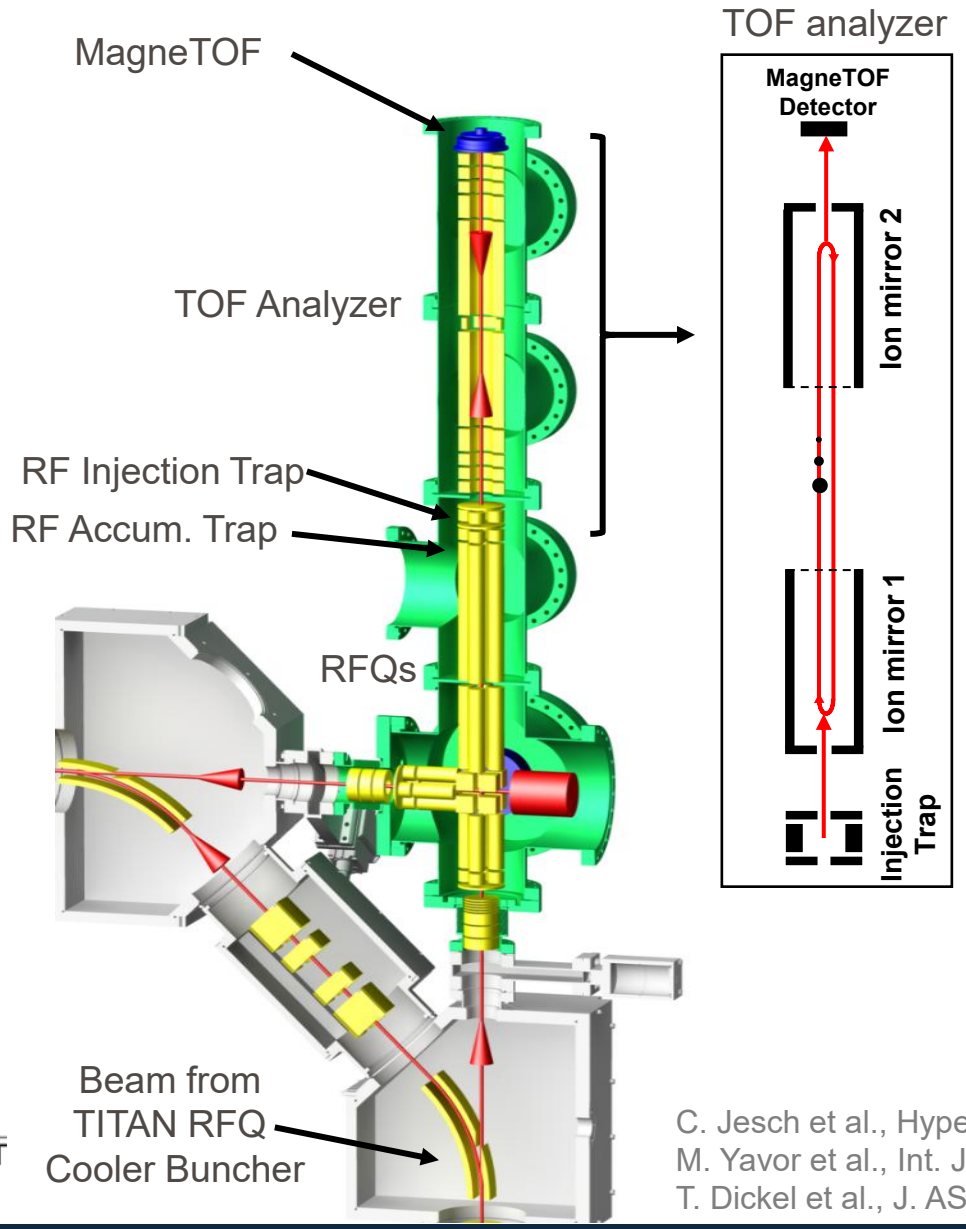
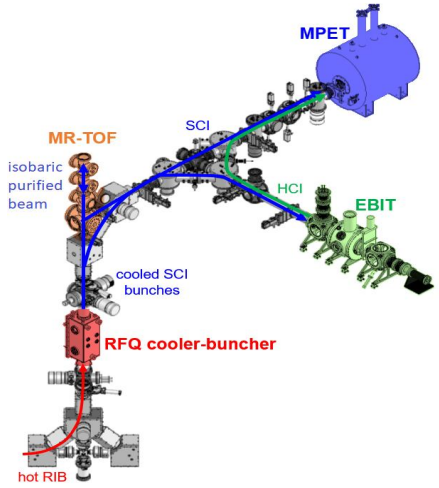
Multiple Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS)



- Measurement of mass-to-charge ratio by measurement of time-of-flight:

$$E = \frac{1}{2}mv^2 = qeU$$

$$\Rightarrow \frac{m}{q} \propto TOF^2$$



C. Jesch et al., Hyperfine Interact. 235 (2015) 97
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T. Dickel et al., J. ASMS 28 (2017) 1079

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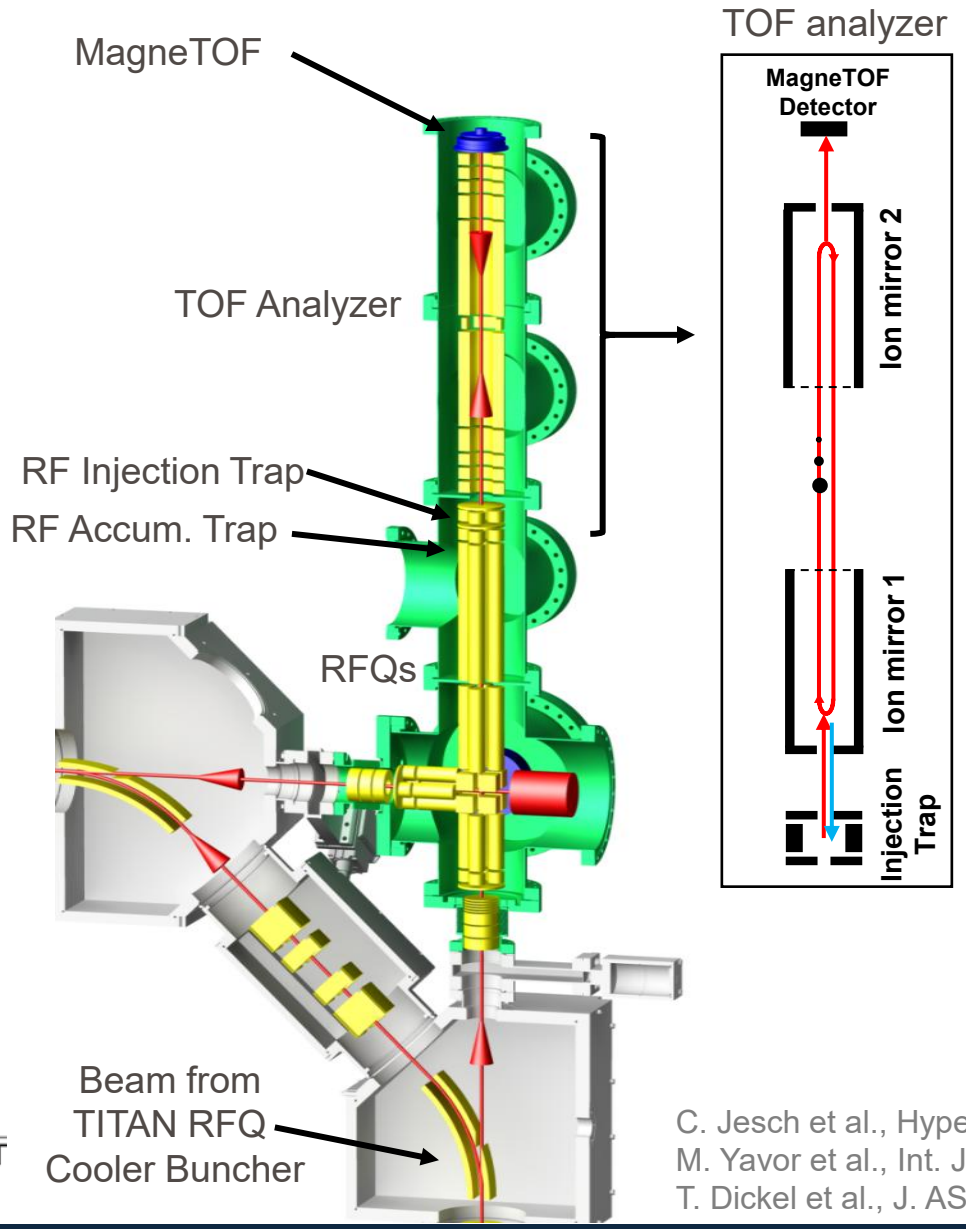

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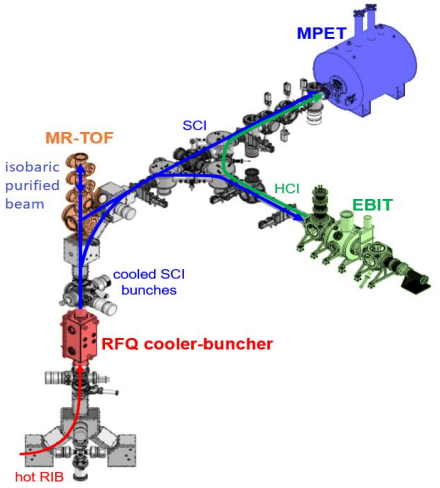
- Isobaric separator and beam purification for **itself** and **other traps**

Mass Selective Re-Trapping



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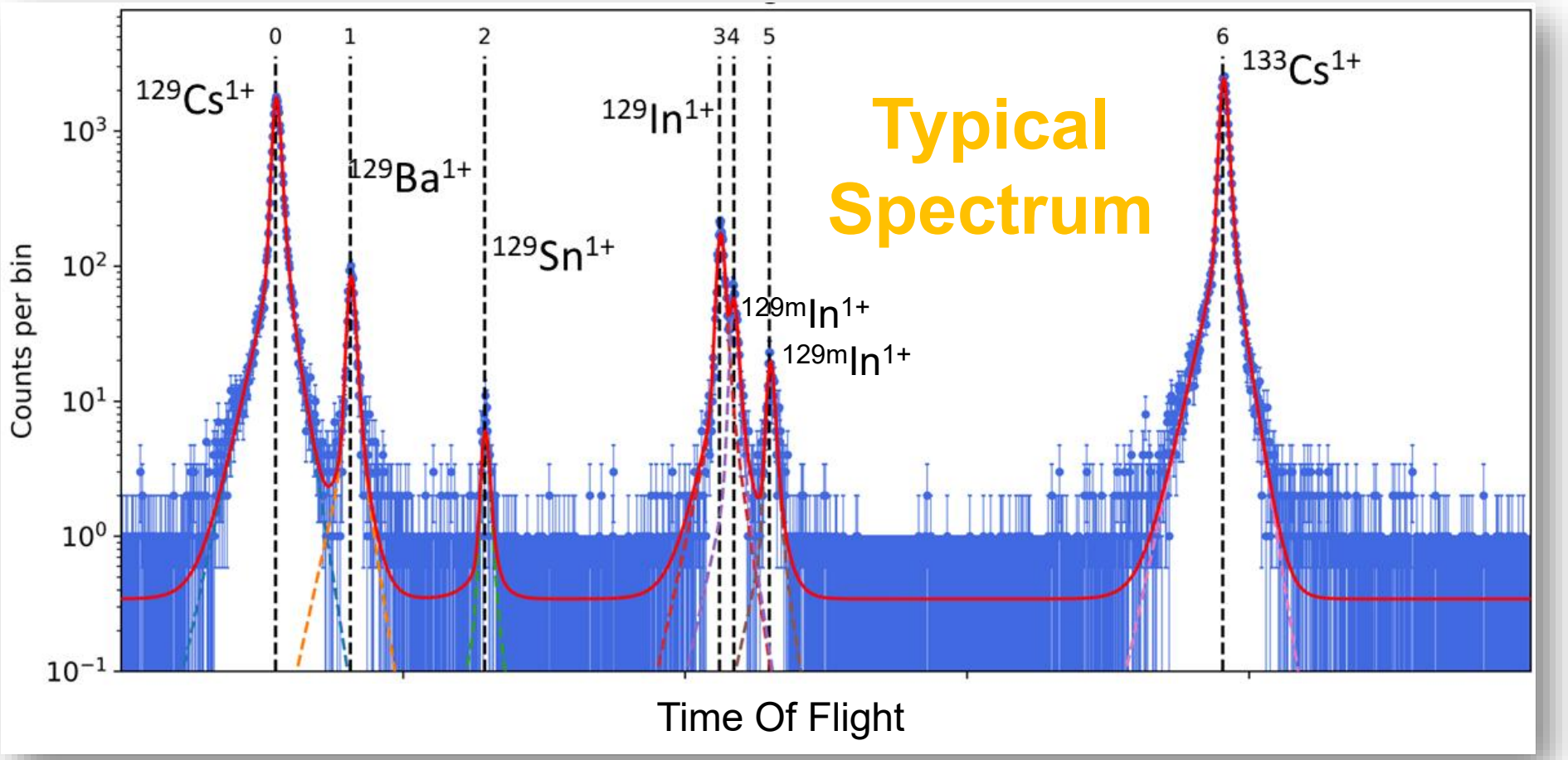

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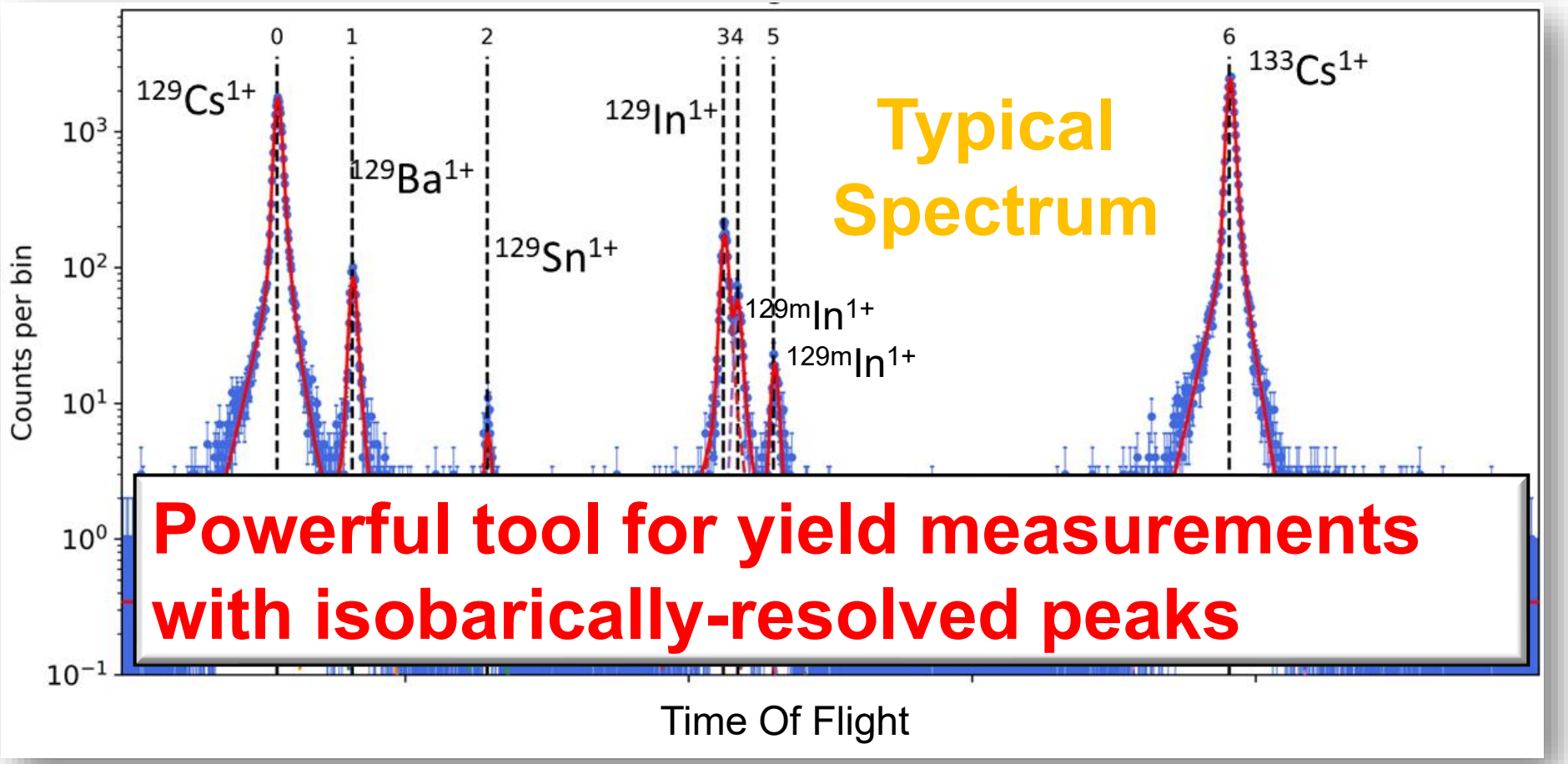
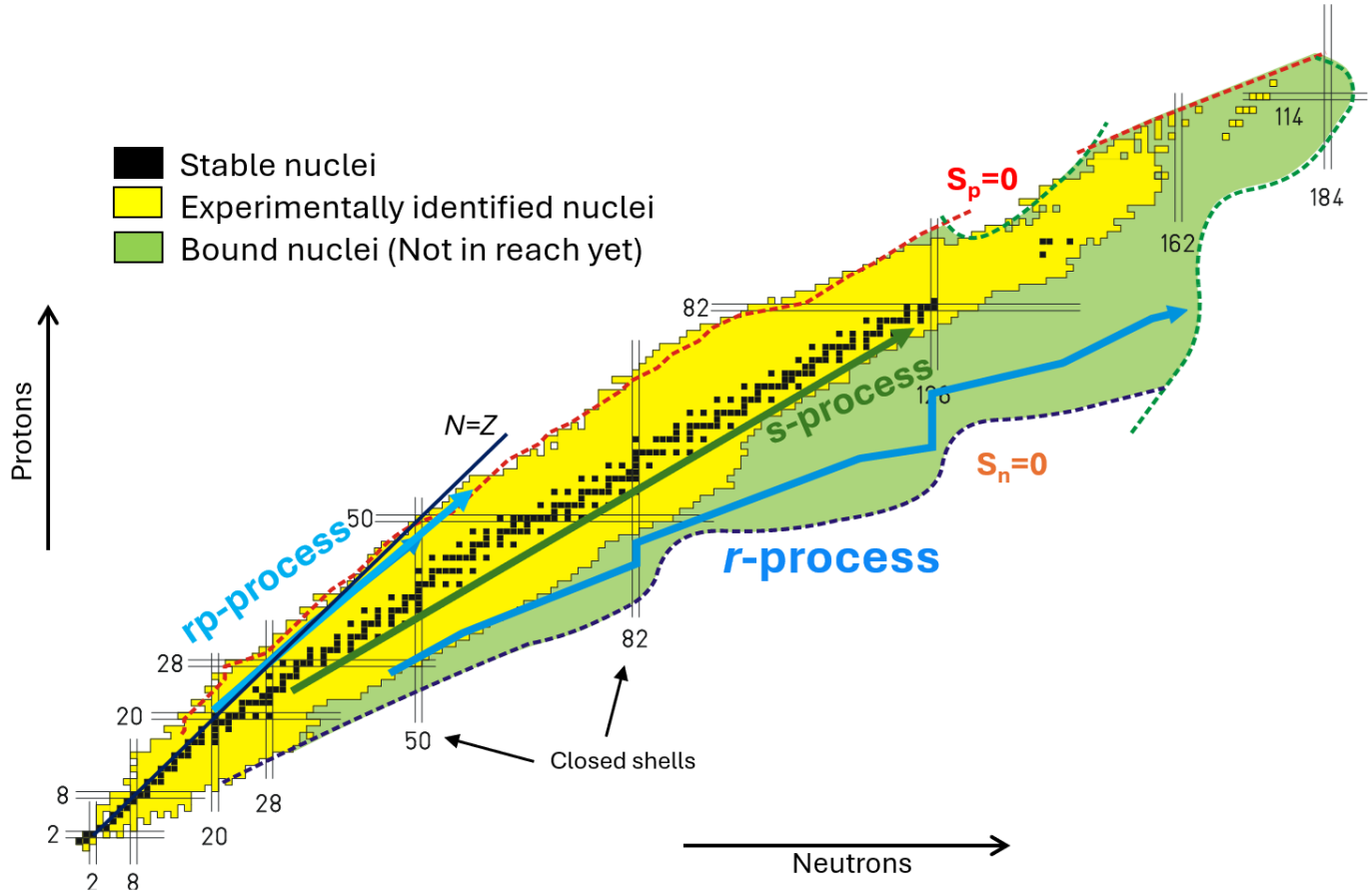


Production/identification of exotic nuclei

- At the limit of facilities or beyond (in-flight and ISOL productions)
- **Low production cross sections, short half-lives and background contamination**
- Needs for **fast** and **efficient** experimental methods



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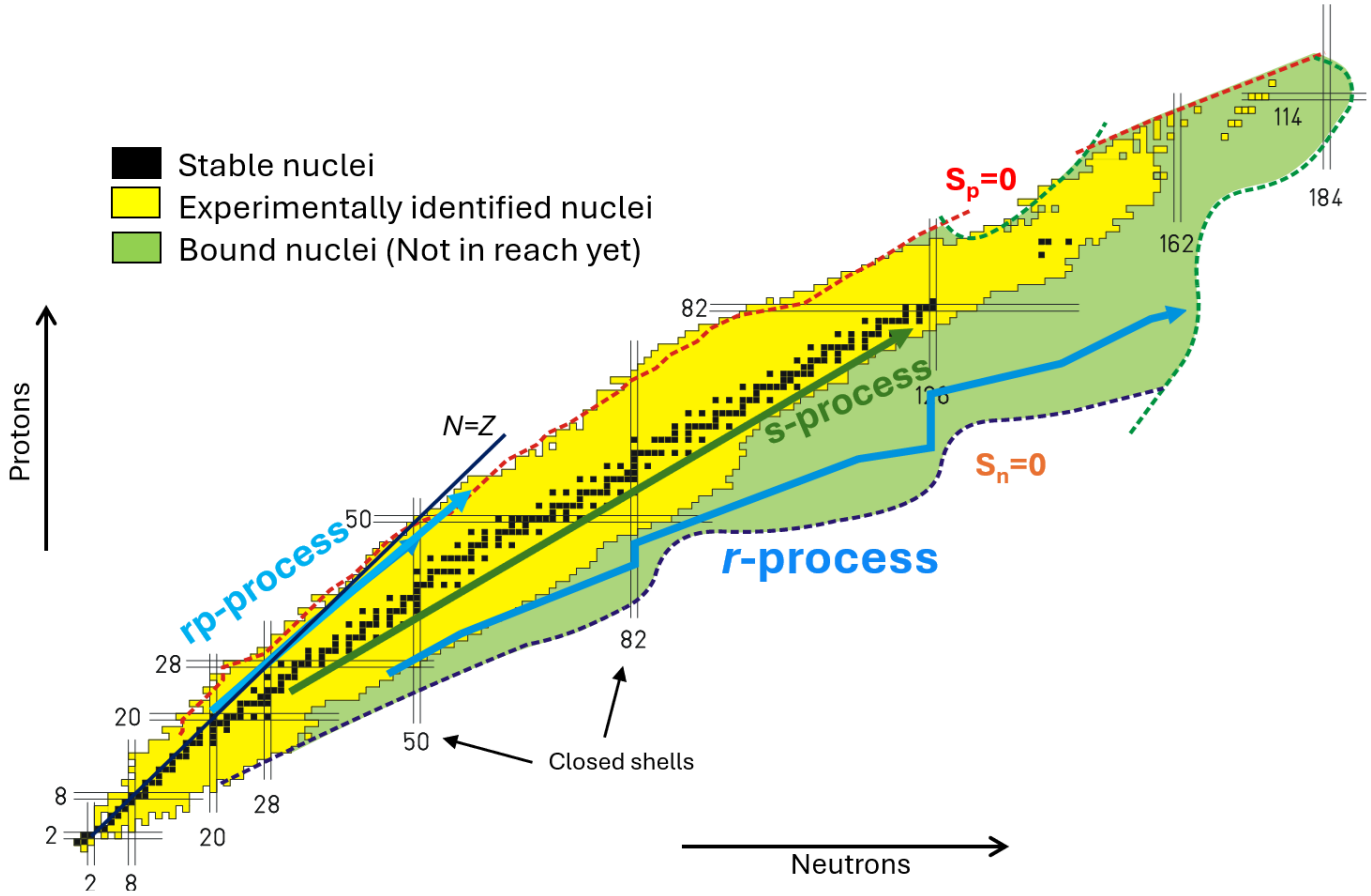
- **Non-scanning** and **Broadband** (RIB beam profile)
- Fast cycles (10s ms)
- 600k mass resolution within 15ms (#IT=1000)
- High mass accuracy 10^{-7}
- Background handling $1:10^{8}$
- High sensitivity 2-3 counts/h



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Z. Hockenbery et al., *Physical Review C* **111** (2025)
E.M. Lykiardopoulou et al., *Physical Review Letters* **134** (2025)
C. Chambers et al., *Physical Review C* **112** (2025)
B. Kootte et al., *Physical Review C* **112** (2025)
A. Czihaly et al., *Atoms* **13** (2025)
A. Jacobs et al., *Physical Review Letters* **134** (2025)
A. Mollaebrahimi et al., *Physical Review Letters* 134 (2025)

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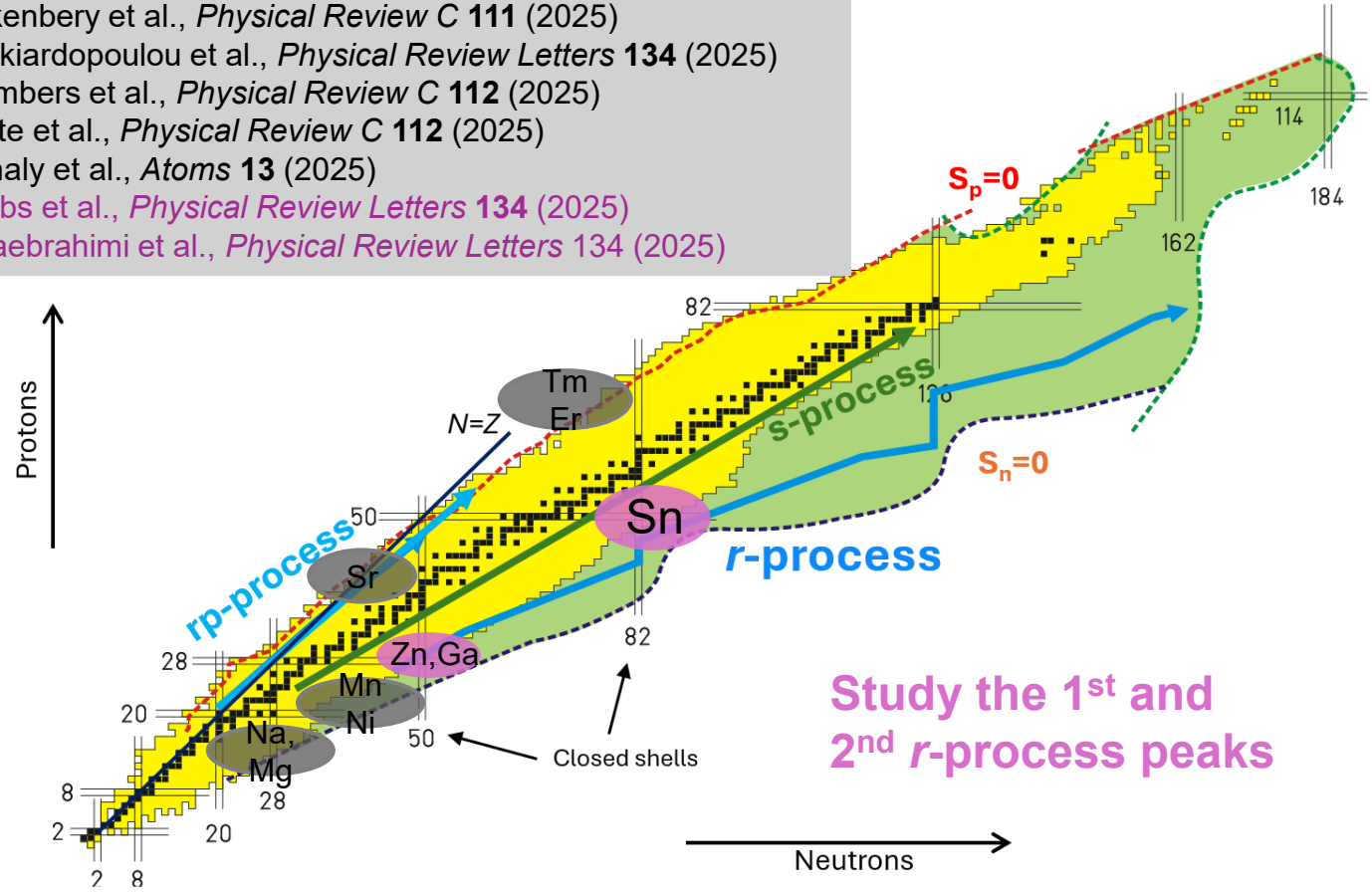
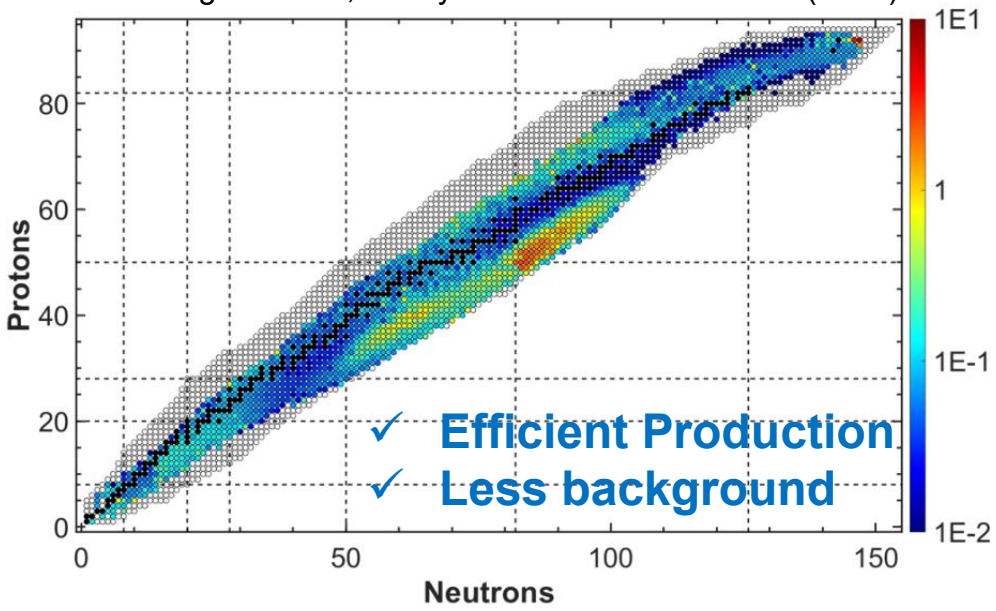


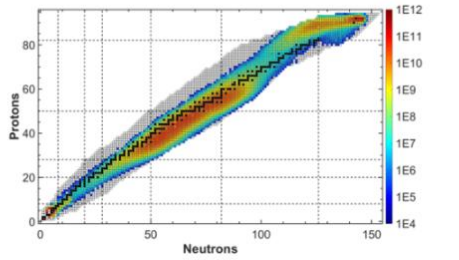
Experiments made possible thanks to the new target developments

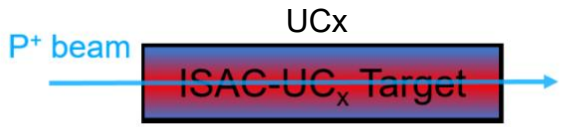
- Commissioning of the new **p-to-n target**
- Fission yields measurements (MR-TOF-MS)

L. Egoriti et al., J. Phys. Conference Ser. 1067 (2018)



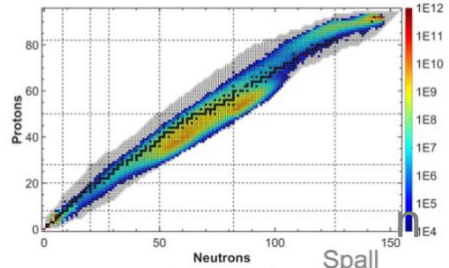
Conventional Target

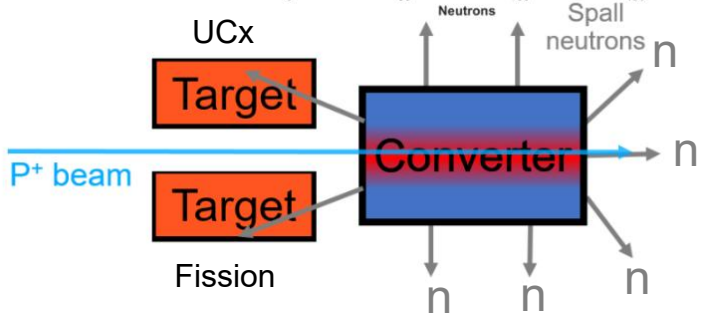


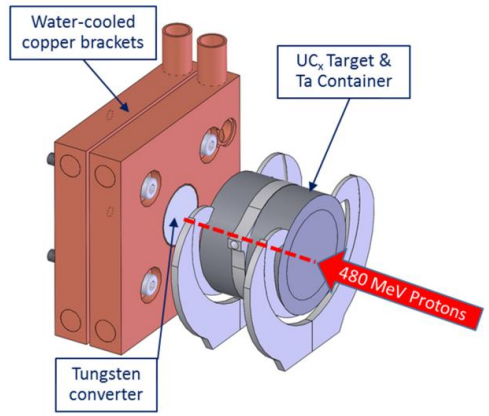


Spallation
Fission
Fragmentation

P-to-n Target







L. Egoriti et al., J. Phys. Conference Ser. 1067 (2018)

Neutron-rich Zn and Ga nuclei

- ✓ First mass measurement of ^{83}Zn and ^{86}Ga
- ✓ Improved precision (x3) for ^{85}Ga
- ✓ The isomer at ^{79m}Zn with Exc.=941 keV:

In agreement with [L. Nies et al., Phys. Rev. Lett. 131 (2023)]

Atomic Mass Excess (ME) of $^{79\text{-}83}$Zn and ^{85,86}Ga

Species	Calibrant	Mass ratio	ME_{TITAN} (keV/c^2)	$ME_{AME2020}$ (keV/c^2)	Difference (keV/c^2)
^{79}Zn	^{79}Ga	1.000 136 781 (51)	−53 430.0 (79)	−53 432.3 (22)	2.3 (8.4)
^{79m}Zn	^{79}Ga	1.000 136 78 (16)	−52 491 (14)	−52 330 (150)*	161 (151)
^{80}Zn	^{80}Rb	1.000 275 561 (48)	−51 661 (10)	−51 648.6 (26)	−12 (11)
^{81}Zn	^{81}Ga	1.000 151 46 (11)	−46 209 (12)	−46 200 (5)	−9 (13)
^{82}Zn	^{82}Ga	1.000 139 116 (91)	−42 312 (10)	−42 314 (3)	2 (10)
^{83}Zn	^{83}Ga	1.000 167 56 (22)	−36 311 (18)	…	…
^{85}Ga	^{85}Rb	1.000 536 66 (15)	−39 720 (14)	−39 740 (40)	20 (42)
^{86}Ga	^{86}Rb	1.000 612 03 (23)	−33 768 (20)	…	…

A. Jacobs et al., *Physical Review Letters* **134** (2025)

Study the 1st *r*-process peaks

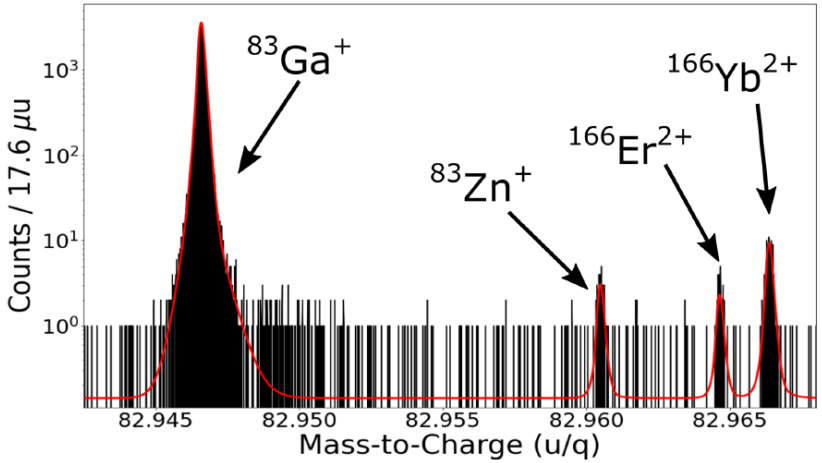
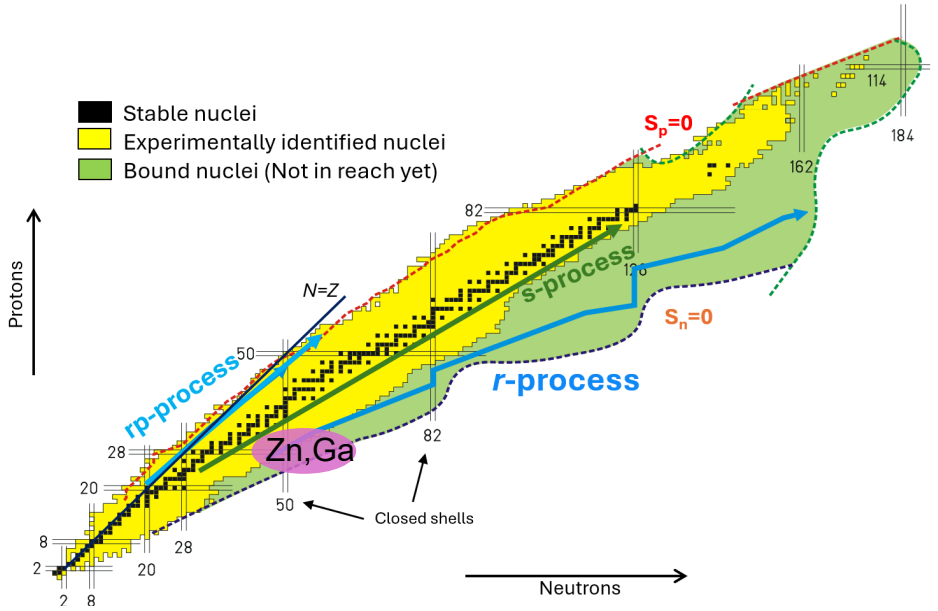
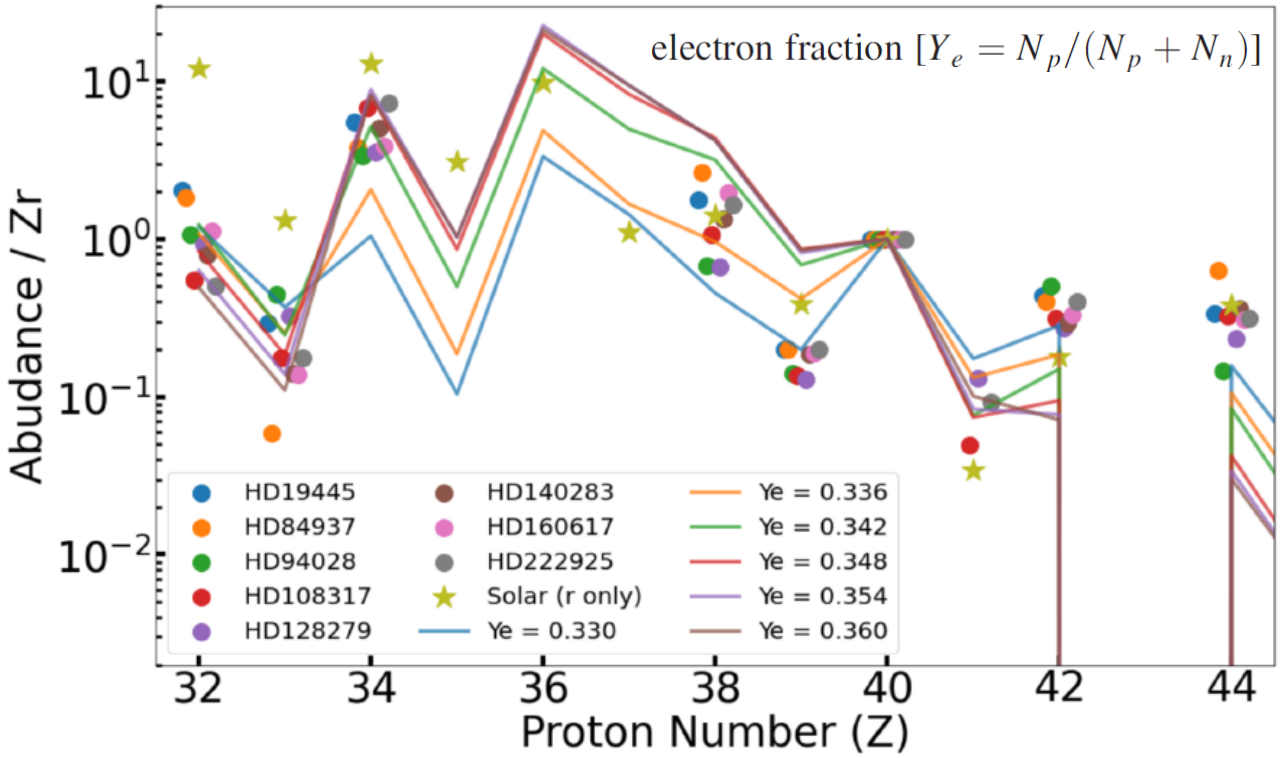


FIG. 1. The spectrum and fit (red) for A/q = 83 at 900 turns after 2.5 h accumulation. ^{83}Ga$^+$ has been used as the calibration species.



Neutron-rich Zn and Ga nuclei

- Elemental abundances for Solar and other stars
- Different astrophysical conditions [*Ye*], expected range for a binary neutron star (BNS) mergers
- High sensitivity on the *Ye* of BNS merger near 1st r-process peak
- By varying the *Ye*, we can reproduce the abundance of several metal-poor (old) stars → question the need for i-process
- By varying the Ye, we reproduce the correlations between key elemental ratios



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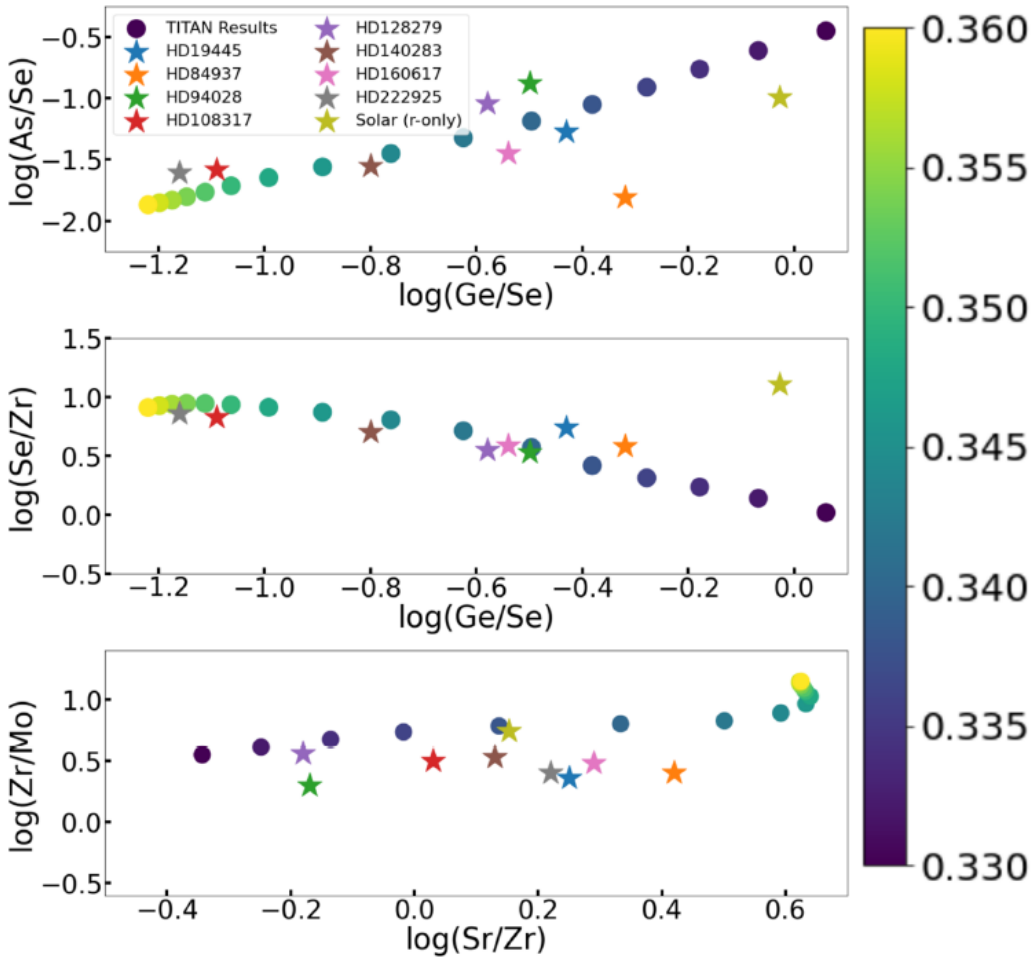
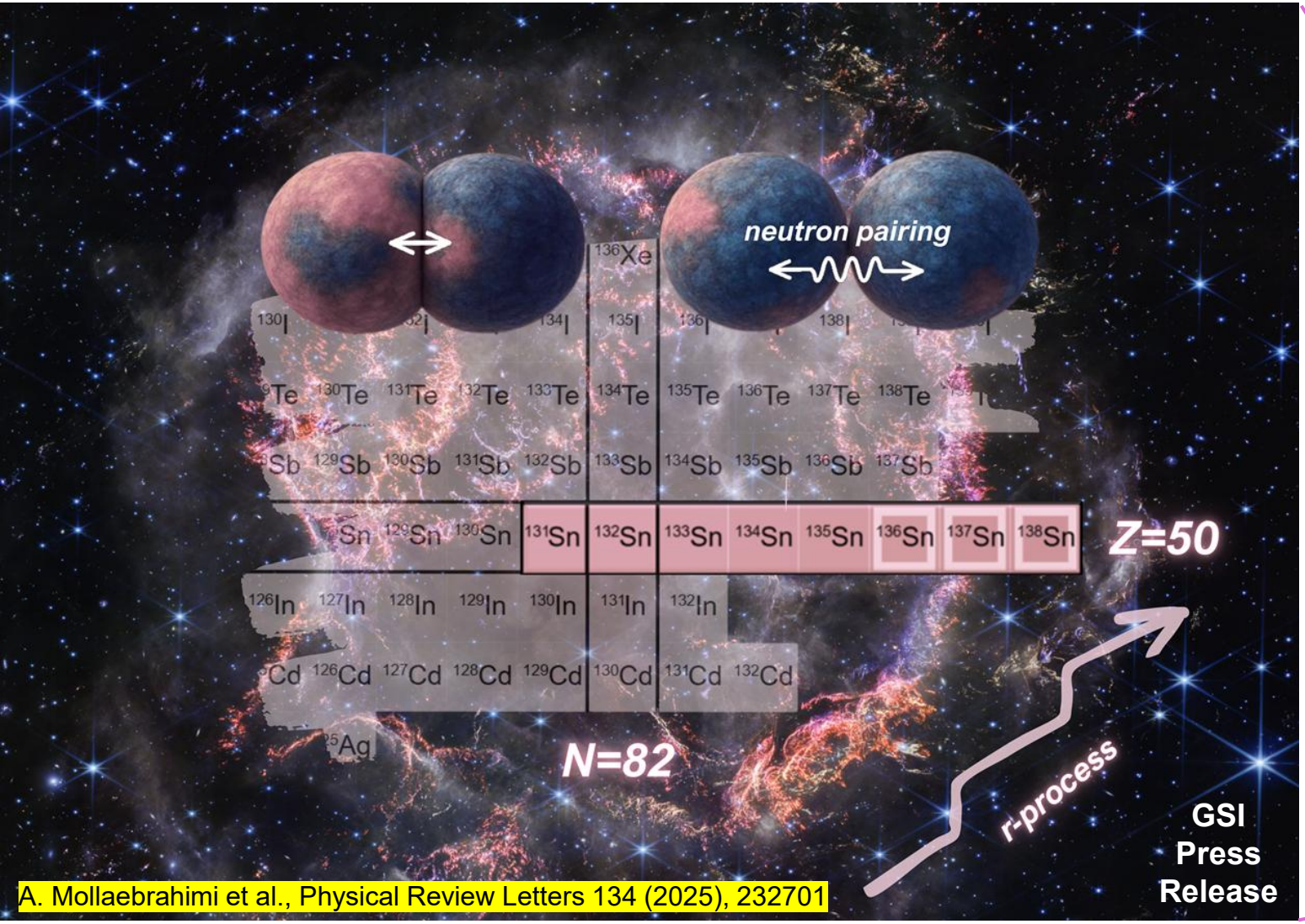


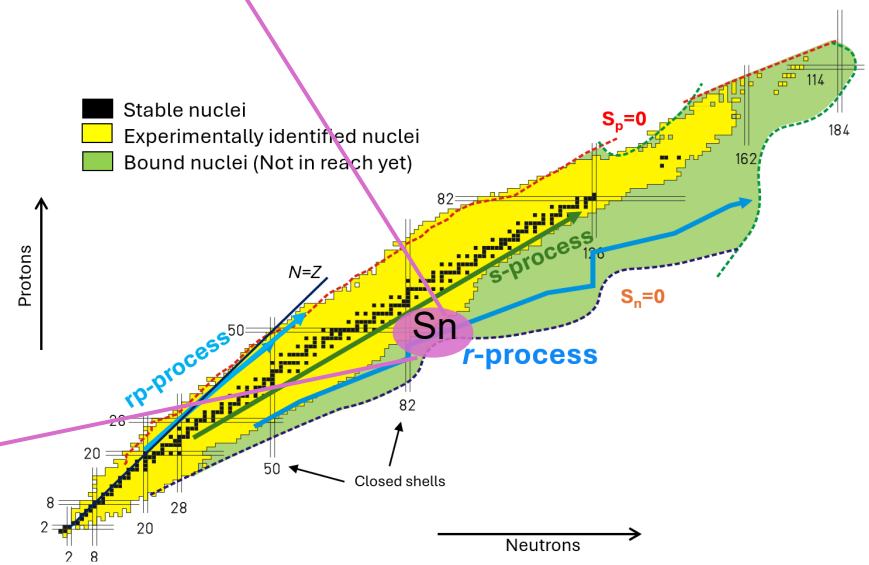
Mass measurements of the neutron-rich Sn isotopes



A. Mollaebrahimi et al., Physical Review Letters 134 (2025), 232701

NASA, ESA, CSA, STScI, Danny Milisavljevic (Purdue University), Ilse De Looze (UGhent), Tea Temim (Princeton University). AI tools were used to generate the image.

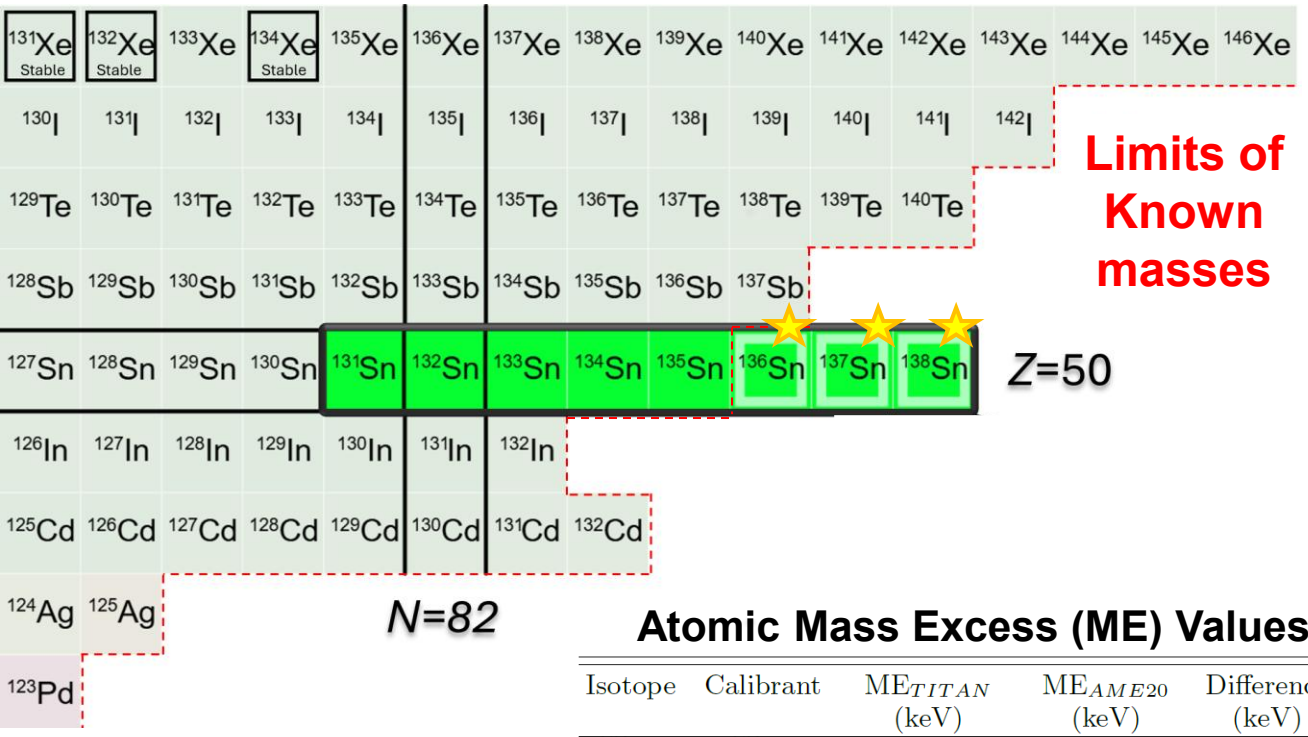
Impact on the 2nd *r*-process peak



Neutron-rich Sn isotopes

- First time mass measurements of $^{136\text{-}138}$**Sn isotopes**

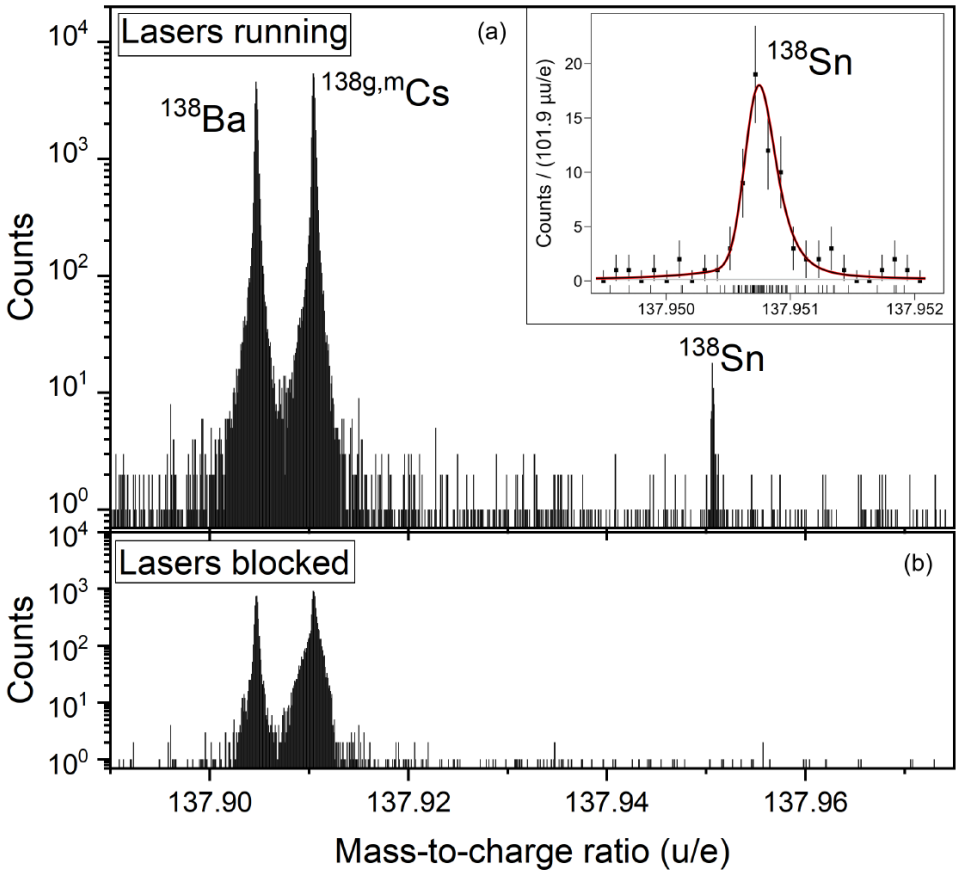
A. Mollaebrahimi et al., Physical Review Letters 134 (2025), 232701



Atomic Mass Excess (ME) Values

Isotope	Calibrant	ME_{TITAN} (keV)	ME_{AME20} (keV)	Difference (keV)
^{131}Sn	^{131}Cs	-77268 ± 22	-77265 ± 4	-3 ± 23
^{132}Sn	^{132}Cs	-76539 ± 11	-76547 ± 2	7 ± 11
^{133}Sn	^{133}Cs	-70870 ± 24	-70874 ± 2	4 ± 24
^{134}Sn	^{134}Ba	-66445 ± 26	-66434 ± 3	-11 ± 27
^{135}Sn	^{135m}Cs	-60647 ± 15	-60632 ± 3	-15 ± 15
^{136}Sn	^{136}Ba	-56074 ± 29	...	...
^{137}Sn	^{137}Cs	-50110 ± 10	...	...
^{138}Sn	^{138}Ba	-45442 ± 21	...	...

Identification by mass and Lasers

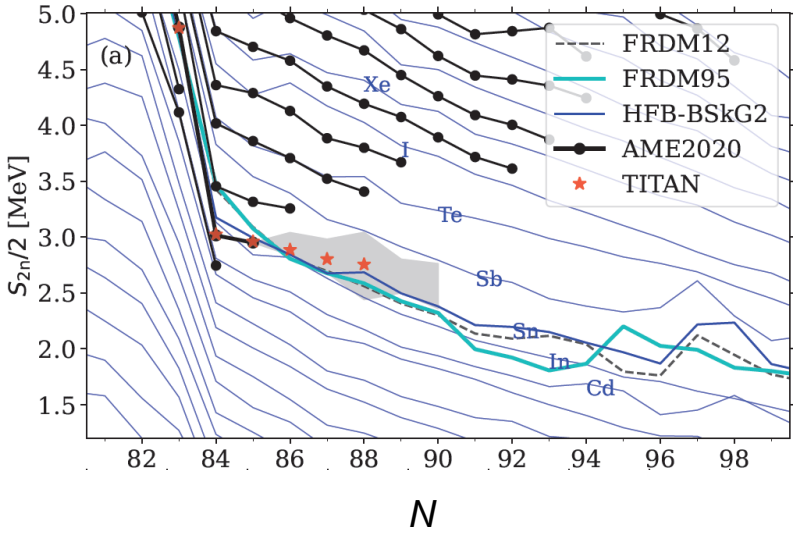


- Three-step resonant laser ionization scheme:
  301.001 nm, 811.62 nm and 823.67 nm
- Cs/Ba as mass calibrants (surface ionization)

Nuclear structure beyond *N=82*

- **Extend the S_{2n} beyond *N=82* neutron shell**
- **Lower S_{2n} slope compared to heavier elements [shell gap Δ_{2n}]**
- **In agreement with the new sets of ab-initio calculations**
- **Possible shell closure at *N=90* (seen in ab-initio)**

A. Mollaebrahimi et al., Physical Review Letters 134 (2025), 232701



Two neutron separation energy

$$S_{2n} = [M(Z, A-2) - M(Z, A) + 2M_n] \times c^2$$

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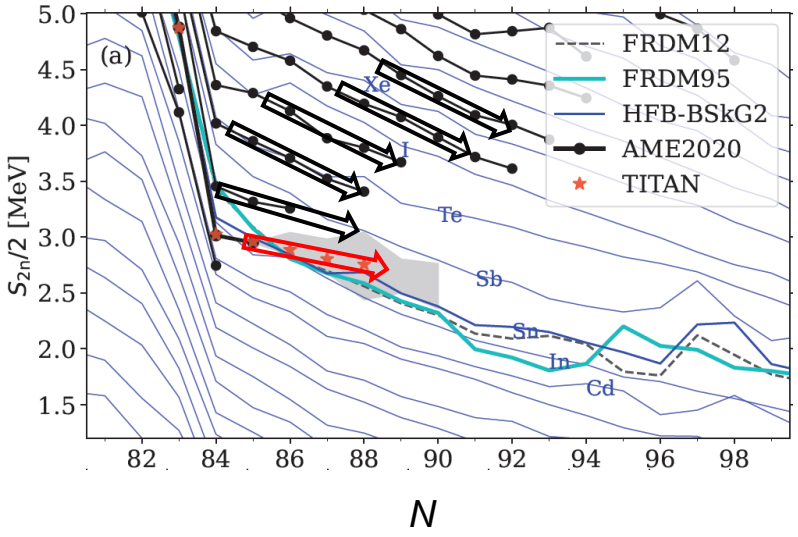

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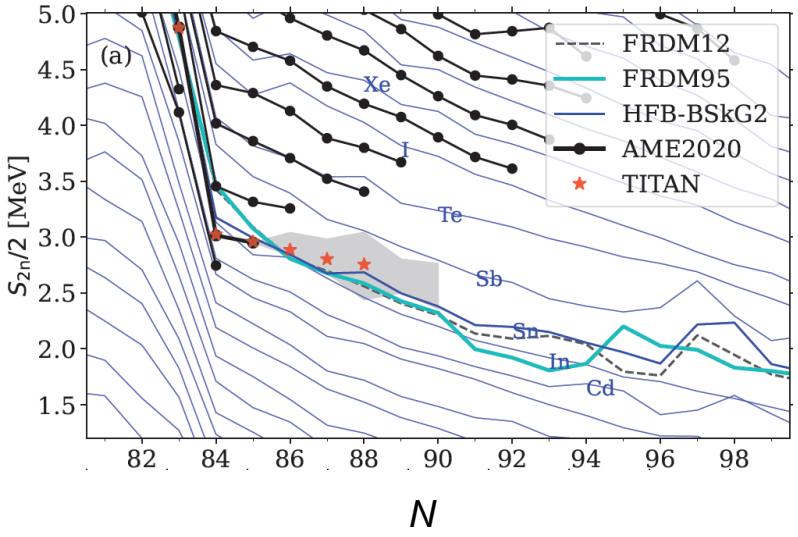

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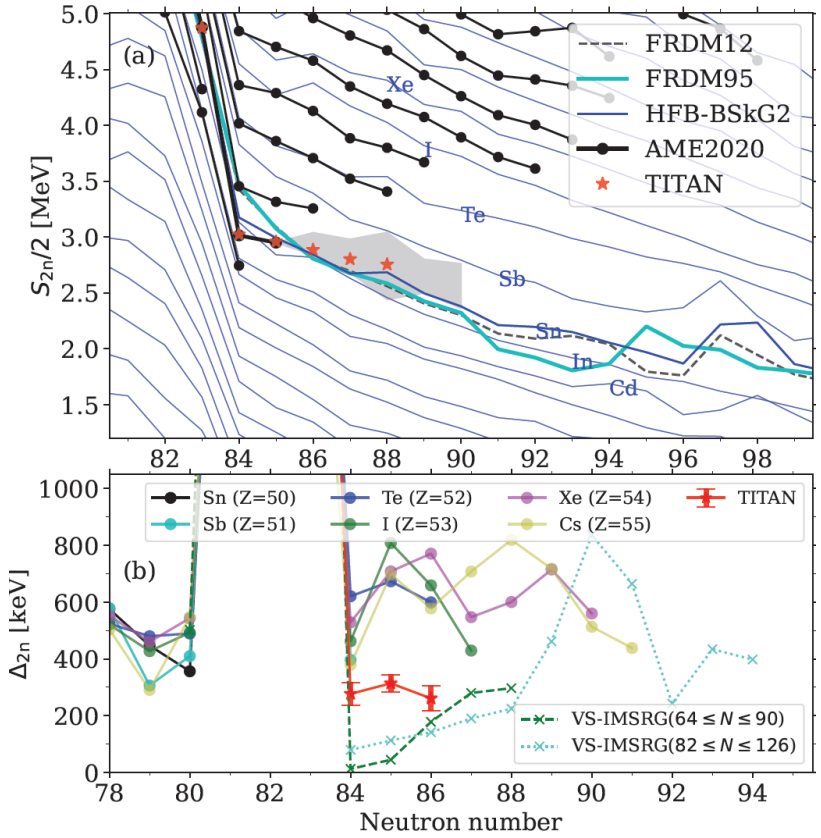

Two neutron separation energy

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Two neutron shell gap

$$\Delta_{2n} = S_{2n}(Z, N) - S_{2n}(Z, N+2)$$

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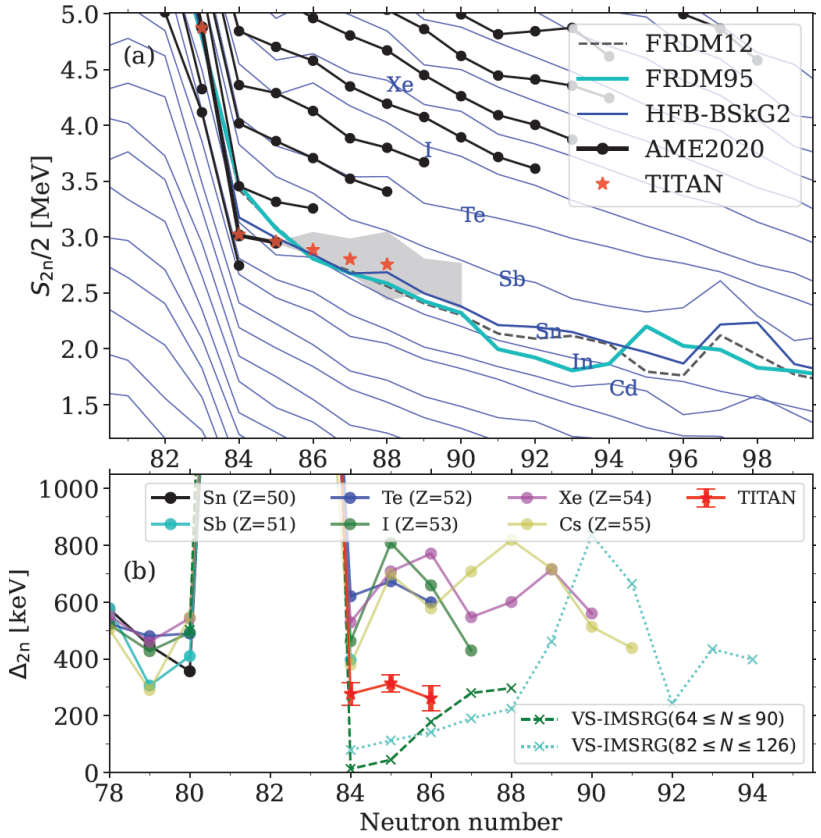

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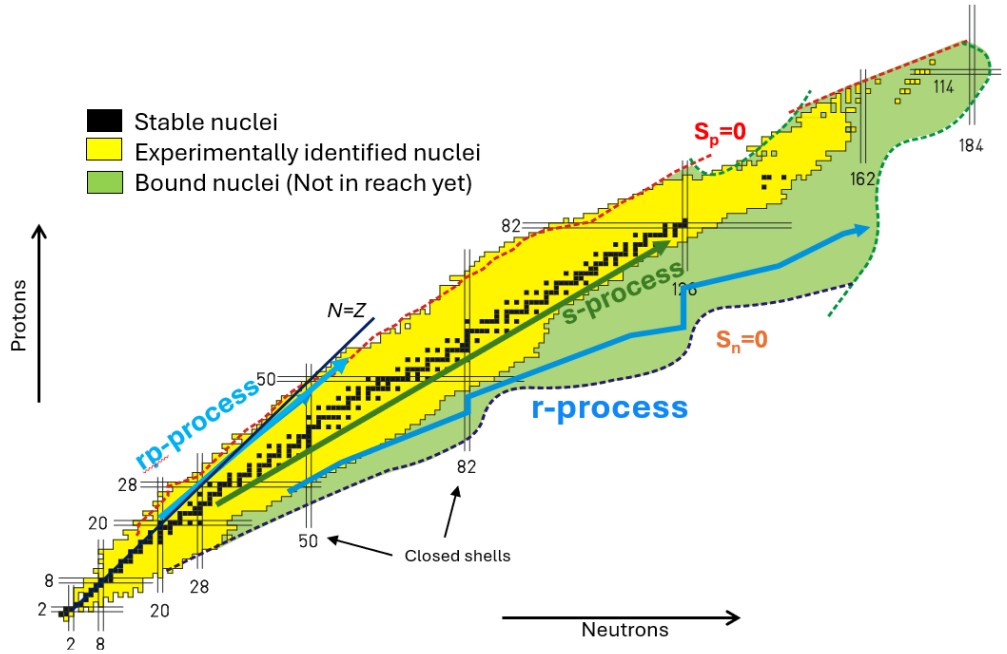
$$S_{2n} = [M(Z, A-2) - M(Z, A) + 2M_n] \times c^2$$

Two neutron shell gap

$$\Delta_{2n} = S_{2n}(Z, N) - S_{2n}(Z, N+2)$$

r-process

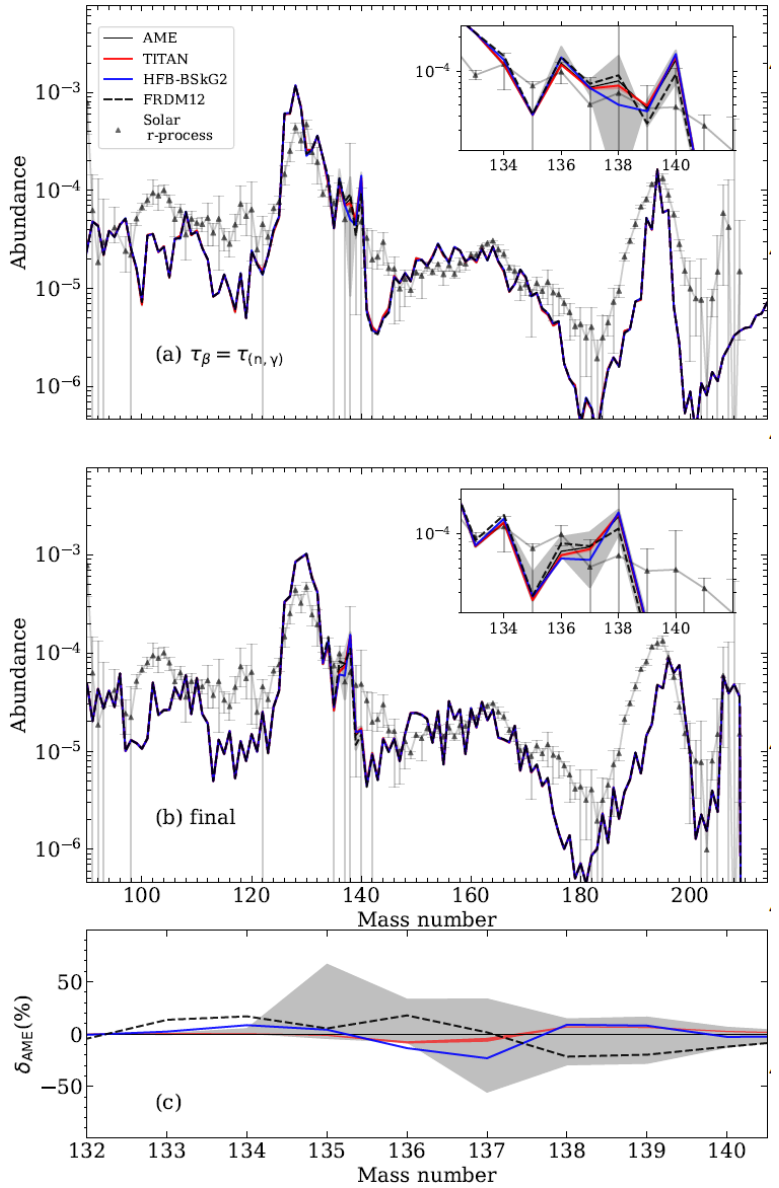
- **Flat trend of S_{2n} after the shell closure *N*=82**
  - → significant shift in the neutron drip line
  - → Affecting the *r*-process path and overall abundances



Impact on the 2nd *r*-process peak

A. Mollaebrahimi et al., Physical Review Letters 134 (2025), 232701

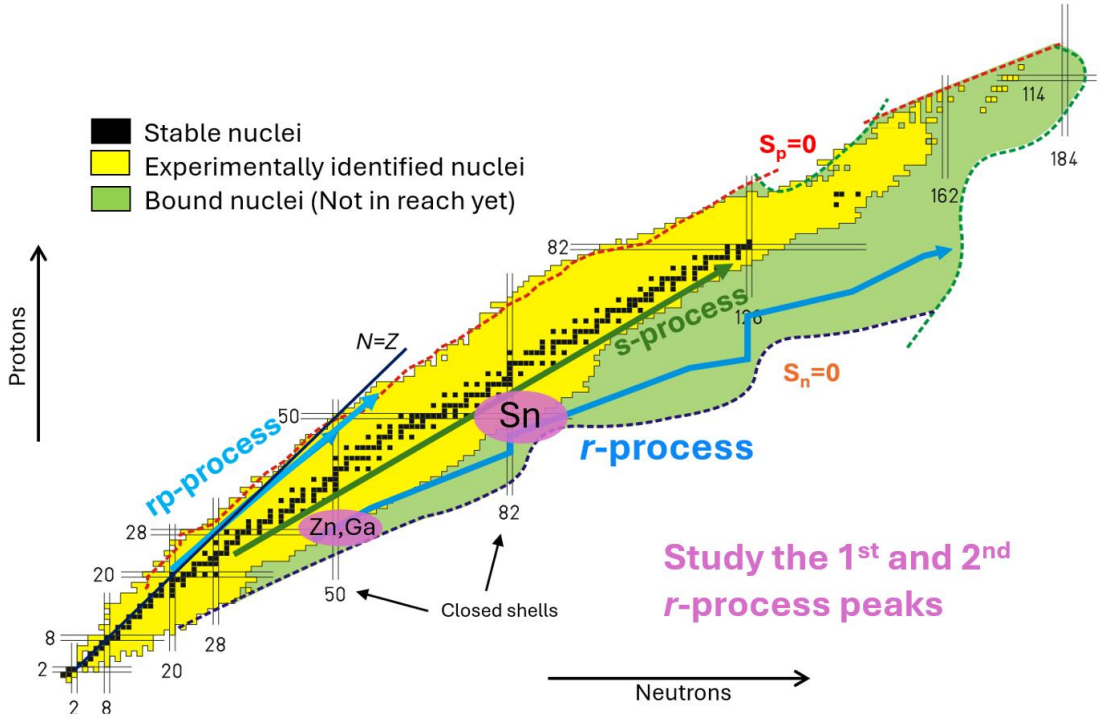
- **Local effects near the 2nd peak:**
  - → (a) beta decays dominate over neutron capture reactions ($\tau_\beta = \tau_{n,\gamma}$)
    - AME20 uncertainty for *A=138* spans over more than 1 order of mag.
  - → (b) Final abundances
    - ***β* delayed neutron emissions** at *A=138* and *A=136* (when decaying toward stability)
    - Uncertainty translates into *A=137* and *A=135*
  - → (c) Relative difference respect to AME20
    - Large AME20 variation ($\pm 60\%$) gray band
    - Remove uncertainty by the new experimental mass values



Neutron capture rates: TALYS code
Entropy $s = 20\ k_b/baryon$
Electron fraction $Y_e = 0.2$
(Add 15% of material with $Y_e = 0.15$ and $s = 25\ k_b/baryon$ to enhance 3rd peak)

Summary

- **MR-TOF-MS setup at TRIUMF with a great capabilities for mass measurements of exotic nuclei**
- **Production of neutron-rich nuclei to study the 1st and 2nd *r*-process peaks**
- **Mass measurements of $^{79-83}$Zn, ^{79m}Zn and $^{85-86}$Ga**
- **Mass measurements of neutron-rich $^{131-138}$Sn isotopes**



FAIR — Facility for Antiproton and Ion Research in Europe

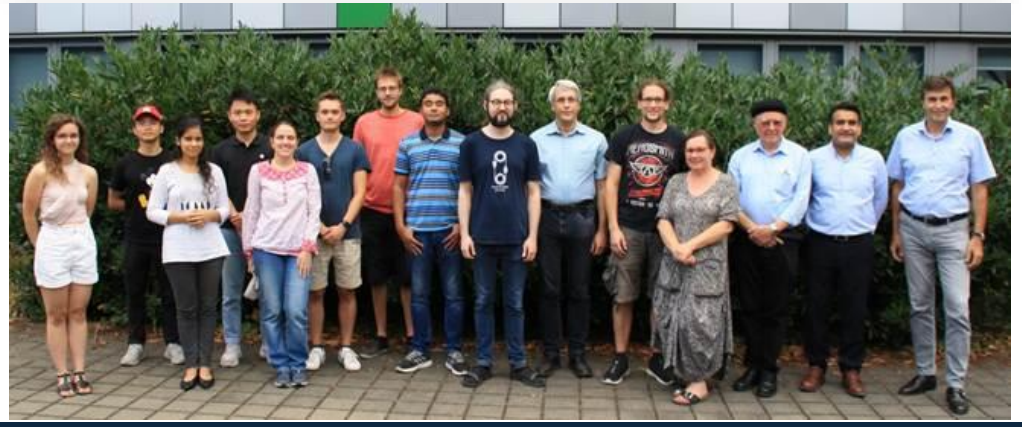
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

TRIUMF

GSI

Thanks!

On behalf of TITAN's Collaboration



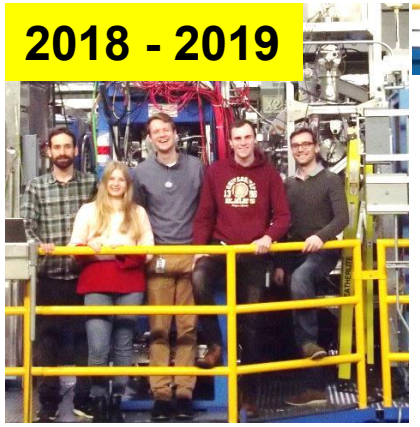
IONAS group
JLU-Giessen

MR-TOF-MS Students and Post-docs:

2016

2017

2018 - 2019



2024

2021