TRIUMF

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MR-TOF-MS for yield and mass measurements during the p2n target commissioning

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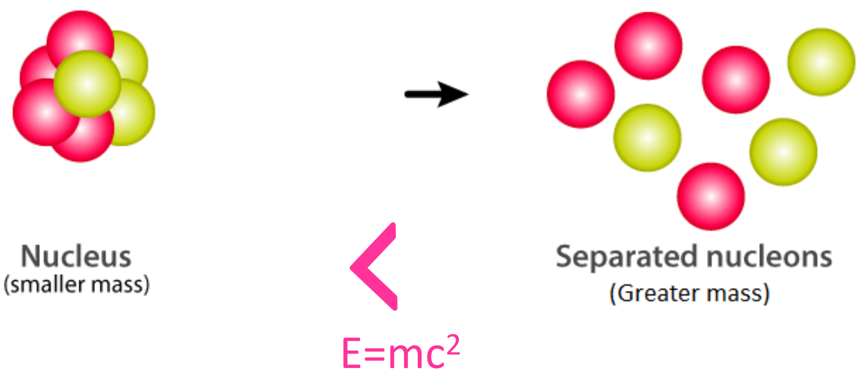
TRIUMF accelerator Centre, Canada

2023, July

Mass and binding energy

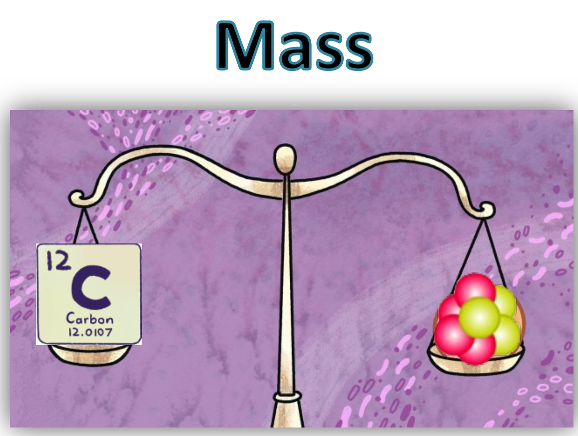
Mass is one of the most fundamental properties of particles which reflects the **binding energy** of a bound system and can reveal information about its properties.



The mass of a neutral atom:

$$M = [(Z \times m_p) + (N \times m_n) - B_{nucleus} + (Z \times m_e) - B_{atom}] / c^2$$

Z: number of protons/electrons
N: number of neutrons
m_p and m_n: mass of free protons and neutrons
m_e: mass of free electron
$B_{nucleus}$: binding energy of nucleons
B_{atom}: binding energy of electrons
c: speed of light



Mass Measurement in Nuclear Physics

Nuclear Structure

- Evolution of shell closure and sub-shell
- Nuclear deformation
- p/n driplines
- Decay properties
- Halo nuclei
- Etc.

$\delta m/m \approx 10^{-6} - 10^{-7}$

MR-TOF-MS
Storage Ring

Nuclear Astrophysics

- Nuclear Synthesis models:
  - r-process
  - s-process
  - rp-process
- Abundance of heavy elements
- Etc.

$\delta m/m \approx 10^{-7}$

MR-TOF-MS
Storage Ring

Fundamental symmetries and interactions

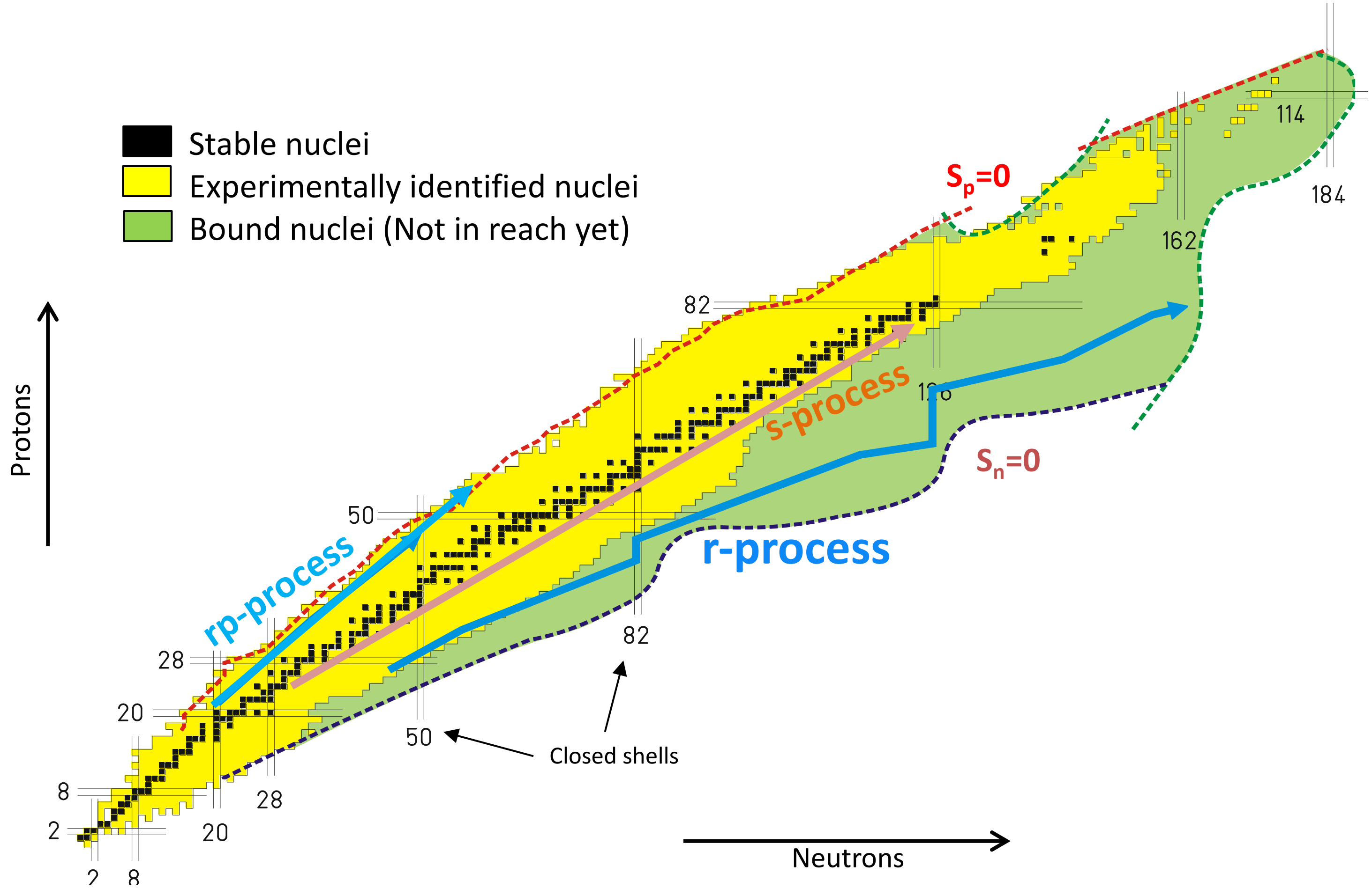
- Physics beyond Standard Model
- CKM matrix elements
- Neutrino Physics
- Double beta decay
- Interactions
- Etc.

$\delta m/m \approx 10^{-9}$

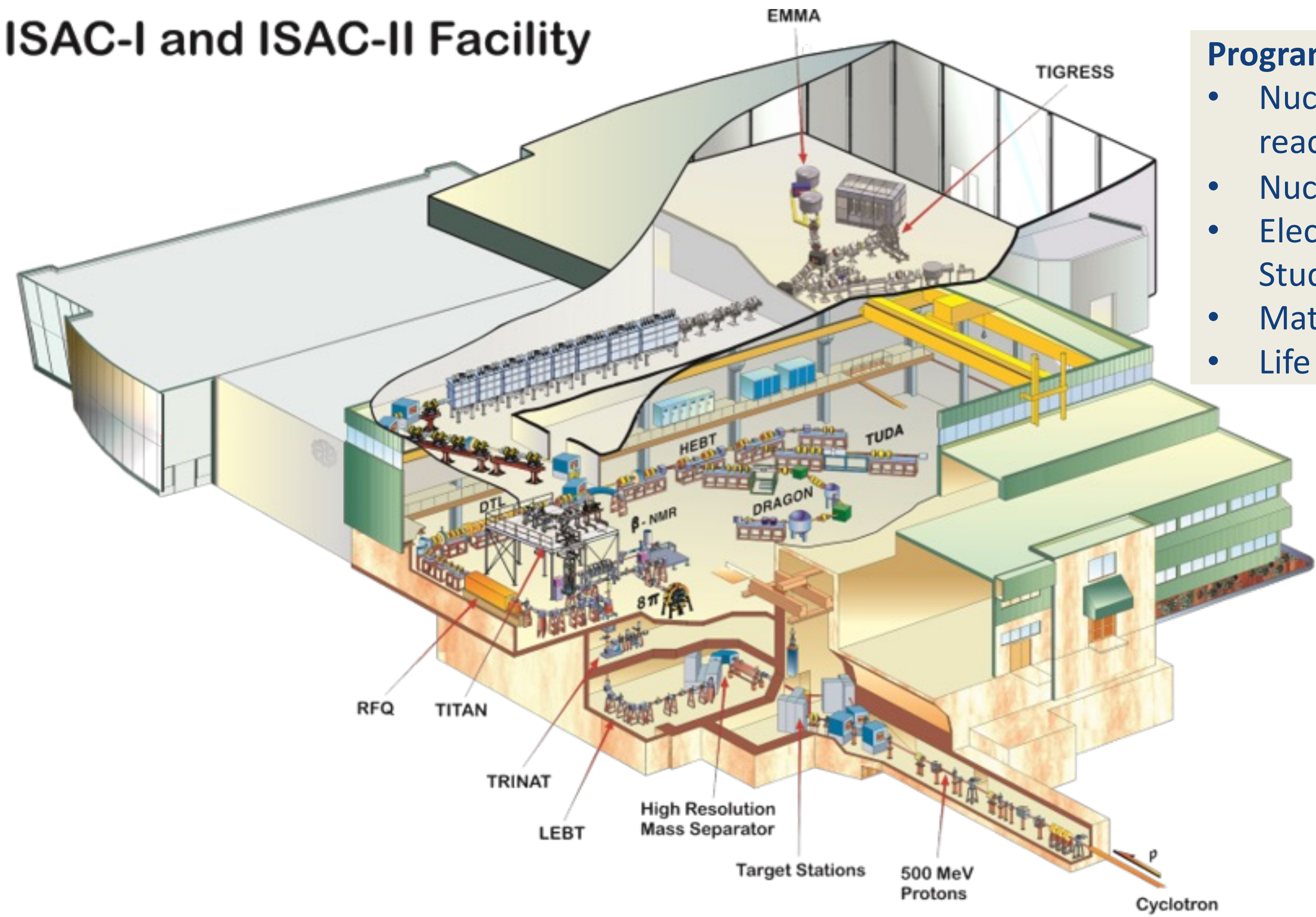
Penning Trap

Nuclear Structure and Astrophysics

- Studying nuclear structure and astrophysics **within the r-process path**
- At the limit of facilities or beyond
- **Need for continues developments and upgrades**



RIB beam at TRIUMF



Programs in

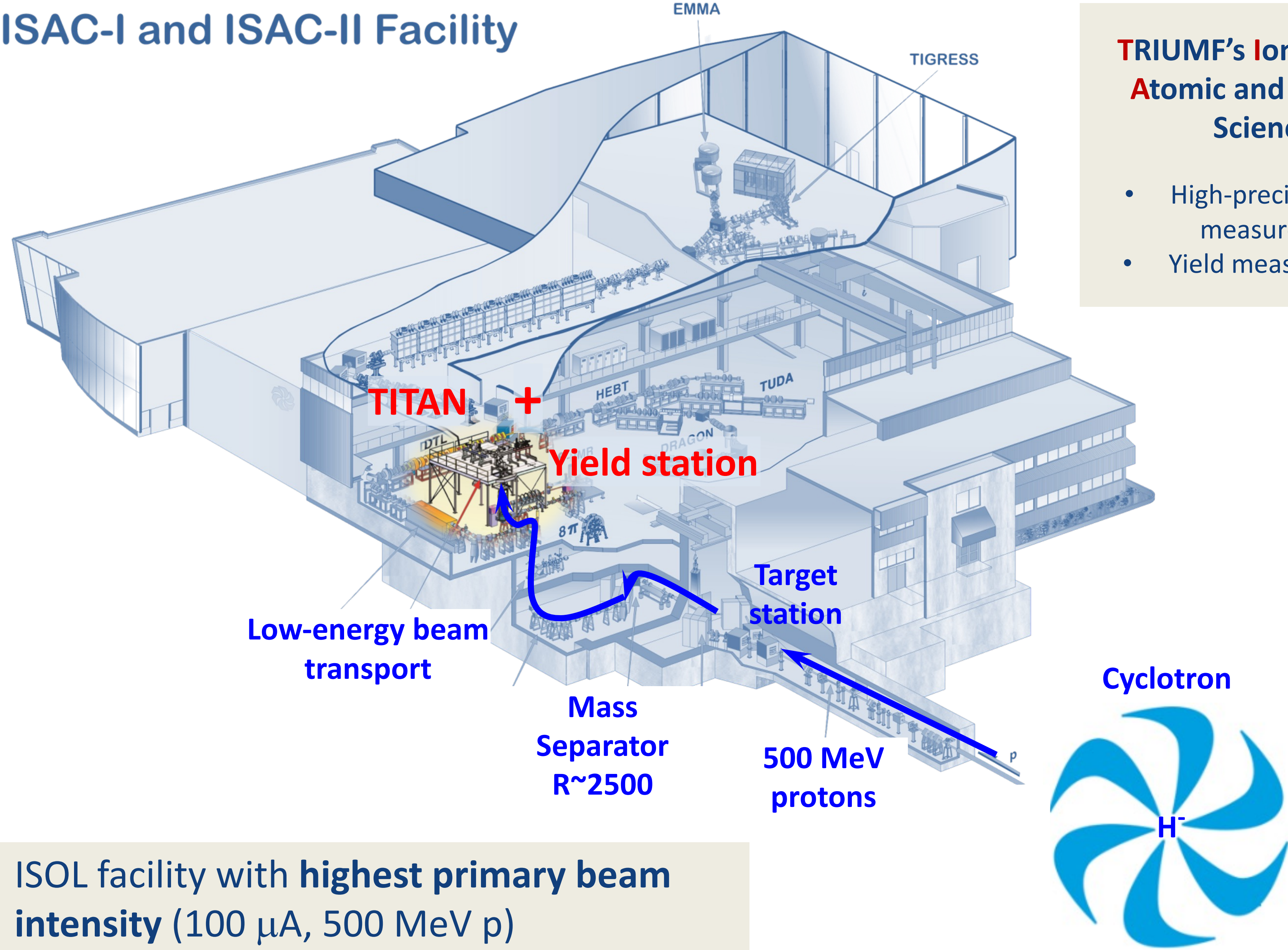
- Nuclear structure & reactions
- Nuclear astrophysics
- Electroweak interaction Studies
- Material science
- Life science

ISOL facility with **highest primary beam intensity** (100 μA, 500 MeV p)

TRIUMF

TITAN and Yield Station at ISAC/TRIUMF

ISAC-I and ISAC-II Facility

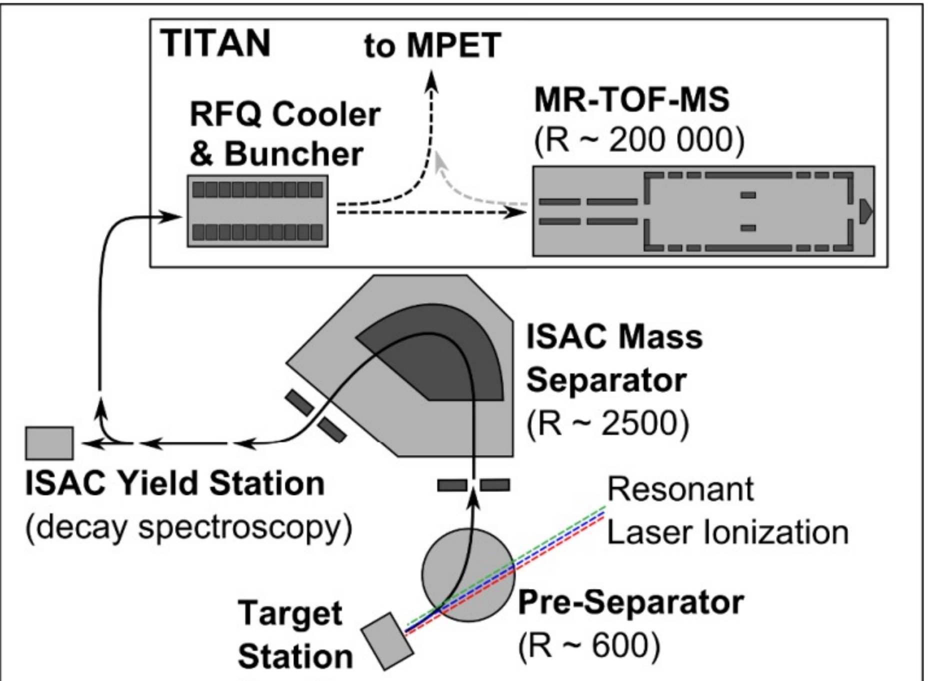


TRIUMF's Ion Trap for Atomic and Nuclear Science

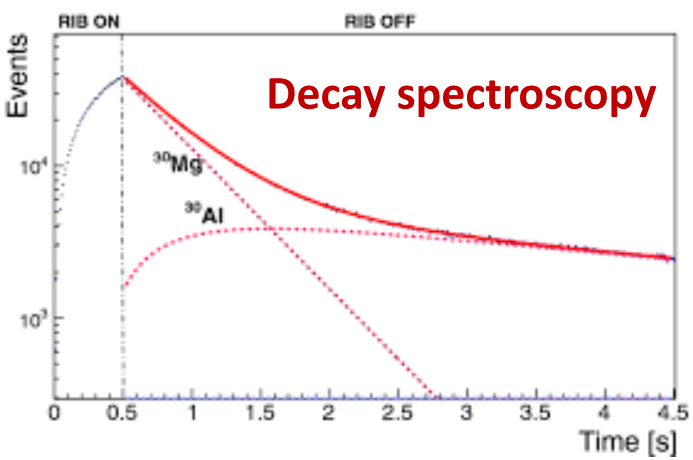
- High-precision mass measurements
- Yield measurements

ISOL facility with **highest primary beam intensity** (100 μA, 500 MeV p)

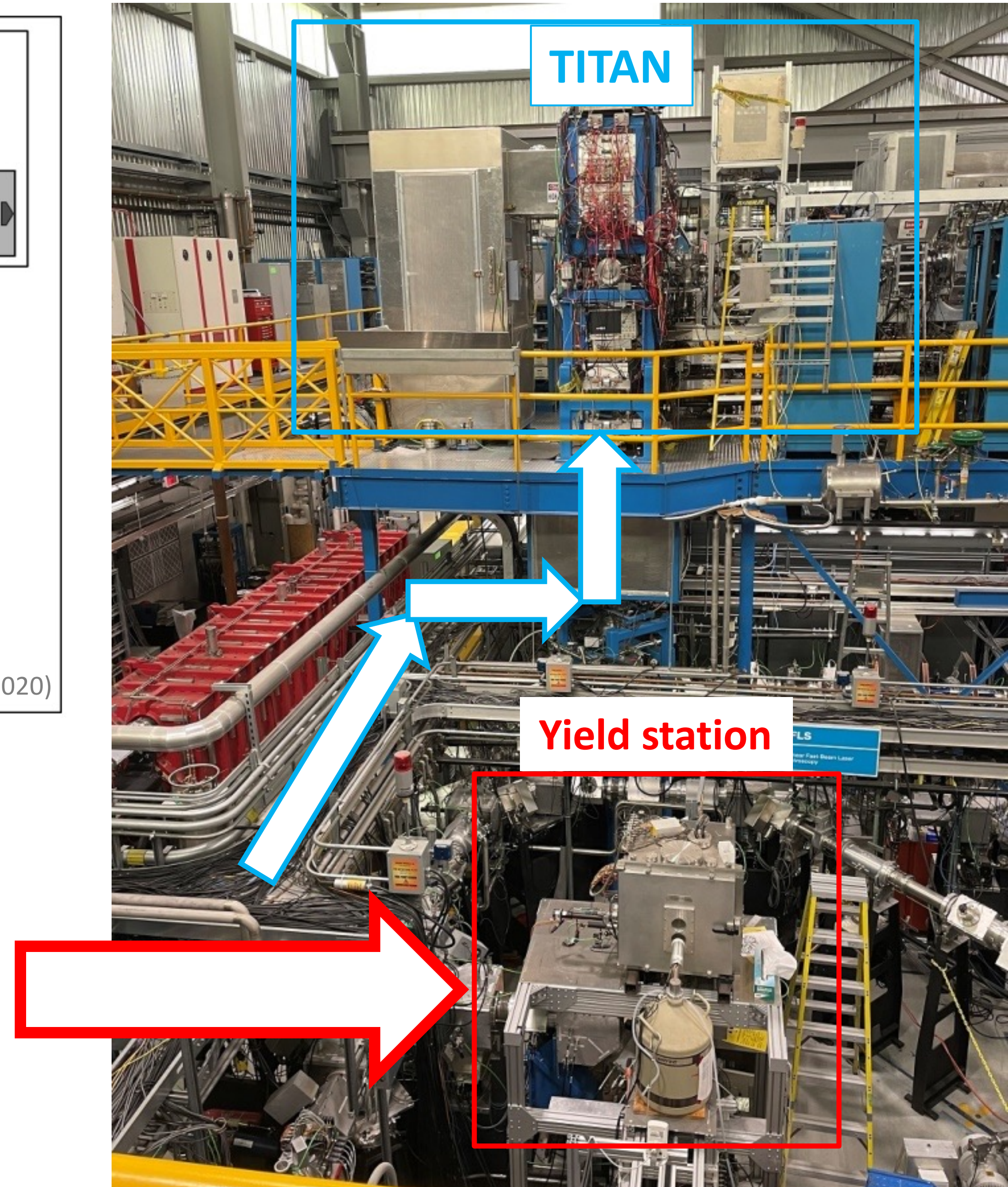
Yield measurements at ISAC I



M.P. Reiter *et al.*, NIMB **463** (2020)



P. Kunz *et al.*, Rev. Sci. Instrum. **85** (2014)

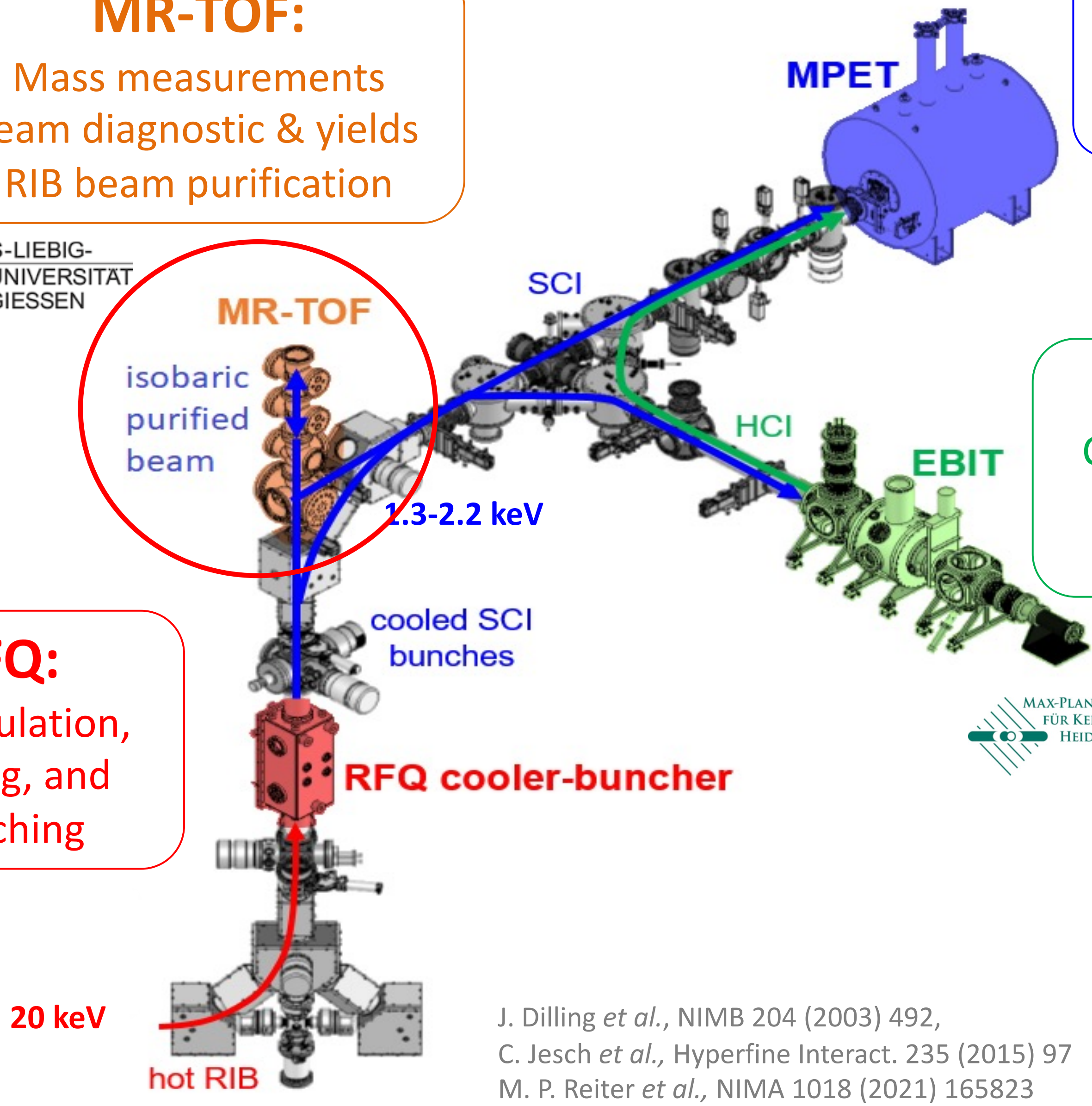


TITAN ion traps

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

MPET:
Penning trap for
mass measurements

$$\frac{\delta m}{m} \propto \frac{1}{qBT_{RF}\sqrt{N_{ions}}}$$



EBIT:
Charge State Breeding
and
decay spectroscopy

RFQ:
Accumulation,
cooling, and
bunching

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

TRIUMF, TECHNISCHE UNIVERSITÄT DRESDEN, SFU, UNIVERSITY OF CALGARY, McGill, University of Victoria, COLORADO SCHOOL OF MINES, UNIVERSITY OF NOTRE DAME, UBC, Westfälische Wilhelms-Universität Münster, university of groningen, GANIL, cnrs

J. Dilling *et al.*, NIMB 204 (2003) 492,
C. Jesch *et al.*, Hyperfine Interact. 235 (2015) 97
M. P. Reiter *et al.*, NIMA 1018 (2021) 165823

Low-energy beam transport to MR-TOF-MS

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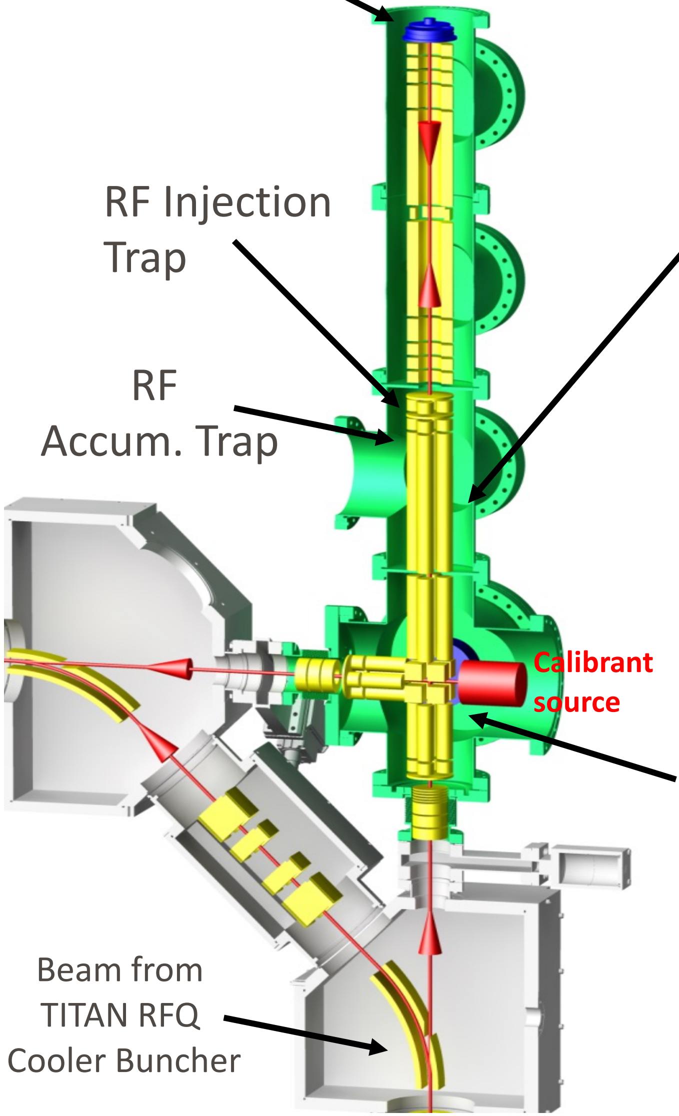
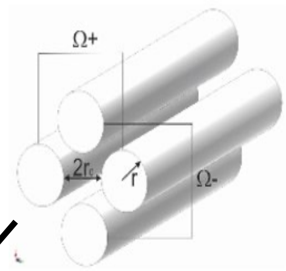


RFQ

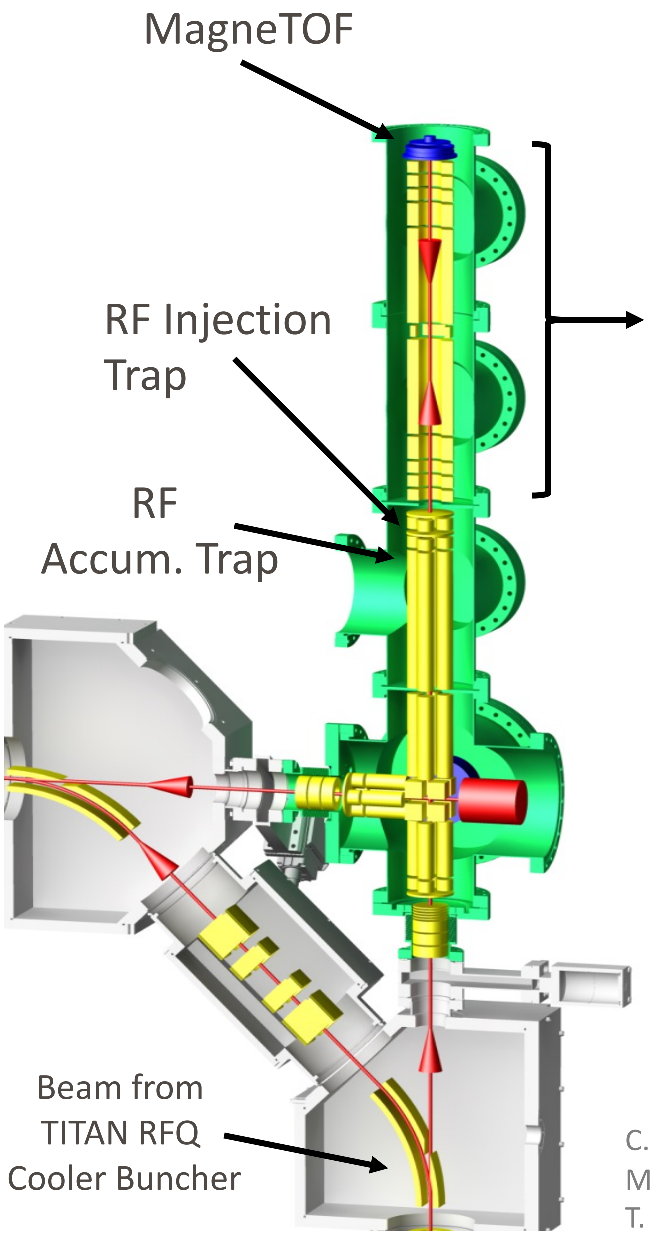


RFQ Switchyard

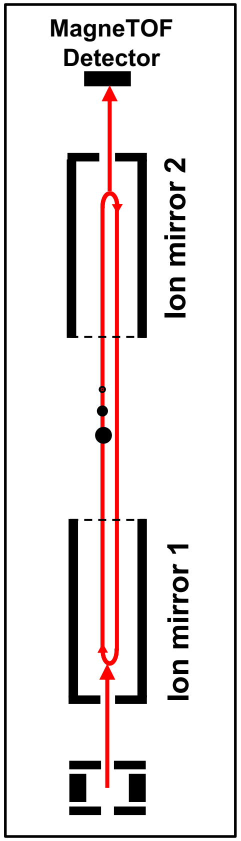
- **Gas filled RFQs:**
  - Beam re-capture and cooling (10^{-2} mbar)
- **RFQ Switchyard:**
  - Merging of calibrations ions
  - Redirection of cleaned ions
- **RFQ Trap:**
  - Prepare ion bunch

C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079

Multiple-Reflection Time of Flight Mass Spectrometer



TOF analyzer



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

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

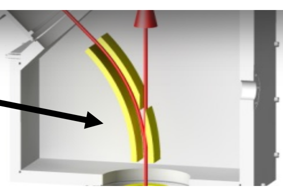
$$\Rightarrow \frac{m}{q} \propto TOF^2$$

- **Yield Measurements**

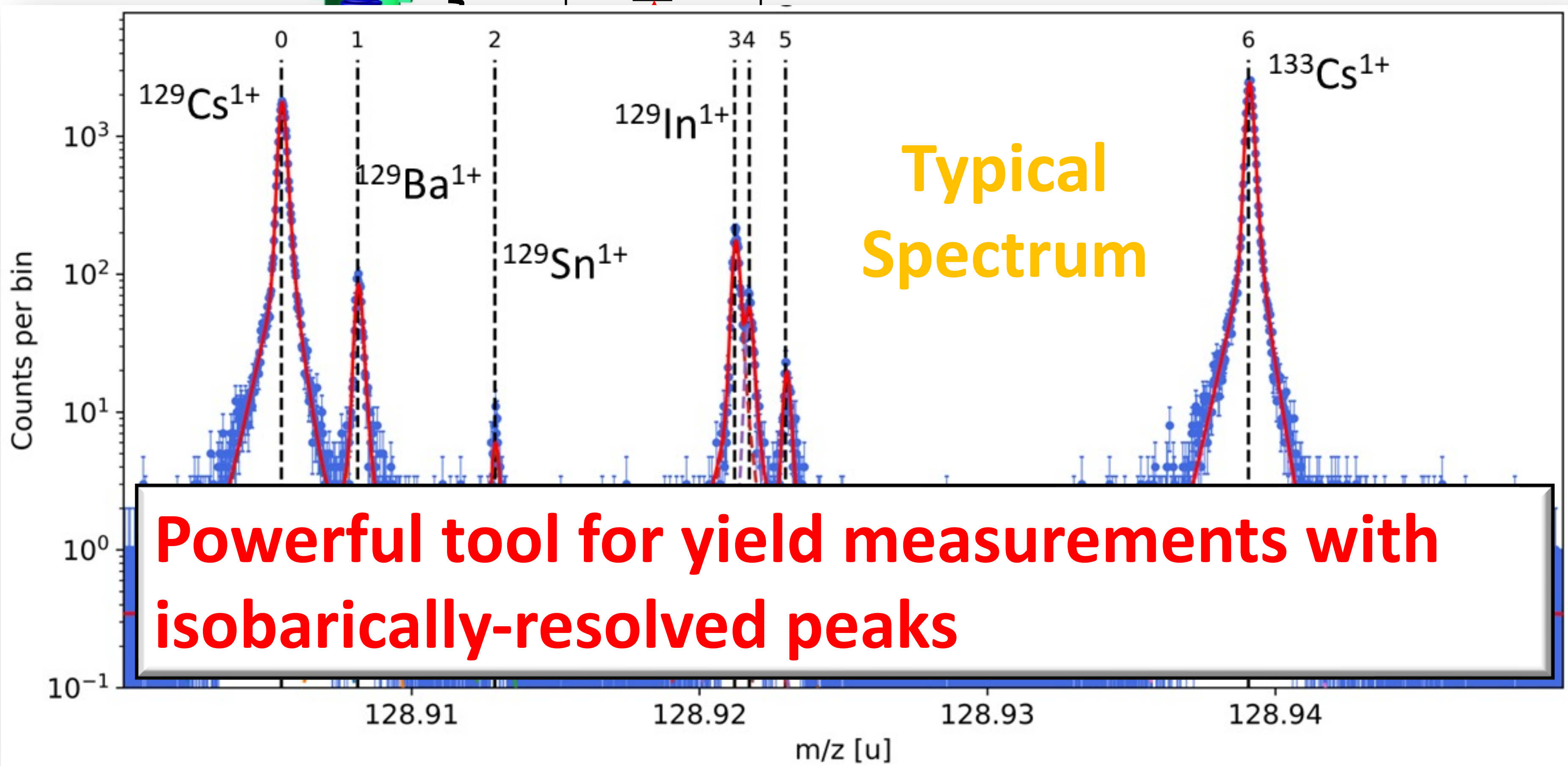
- Isobaric separator and beam purification for **itself** and **other traps**

C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079

Multiple-Reflection Time-of-Flight Mass Spectrometer



- Measurement of mass-to-



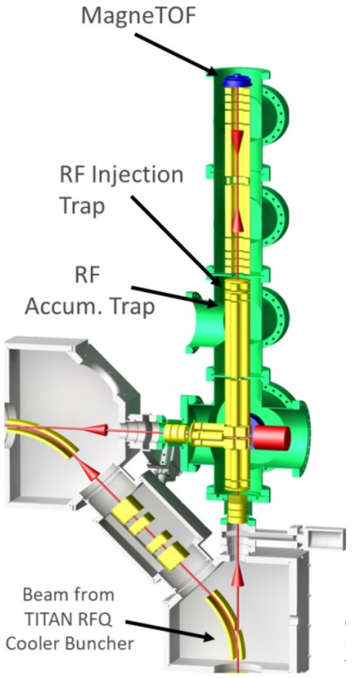
Powerful tool for yield measurements with isobarically-resolved peaks

C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9
T. Dickel et al., J. ASMS 28 (2017) 1079

MR-TOF-MS complementary to the yield station

- Non-scanning and Broadband (RIB beam profile)
- Fast measurement cycles (~10s ms)
- Background handling ~$1:10^8$
- 3-4 orders of magnitude **more sensitive** than yields station
- Monitoring **stable species** as well as RIB isotopes (resolved peaks) and radioactive **molecules**
- Yields determination without relying on decay scheme for radioactivity
- **Optimize RIB delivery through magnet separator** for species-of-interest or its ratio to contamination (isobar sensitivity, low-intensity species)
- Live laser tuning and monitoring only the isotope of interest (not channeltron/FC)

MR-TOF-MS

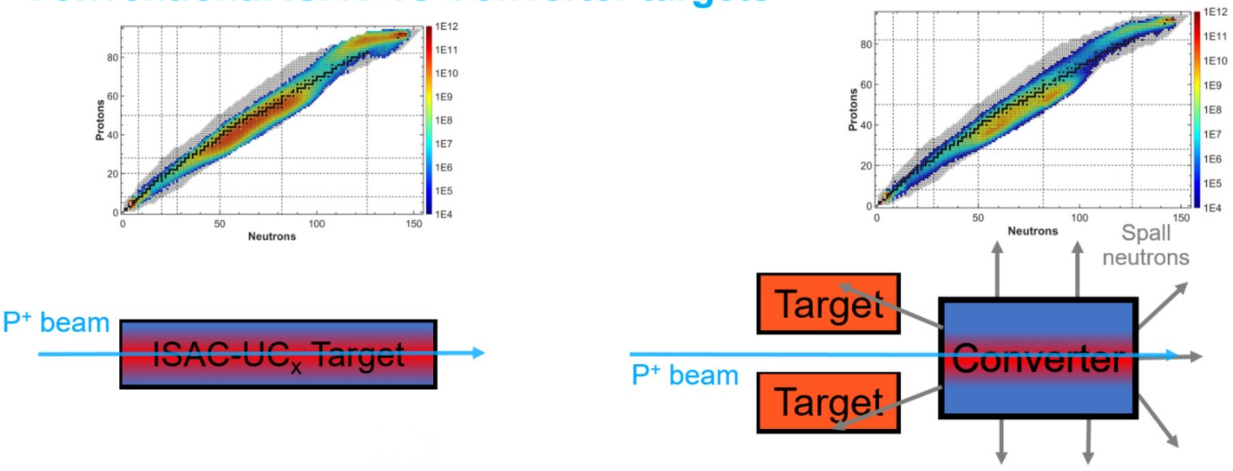


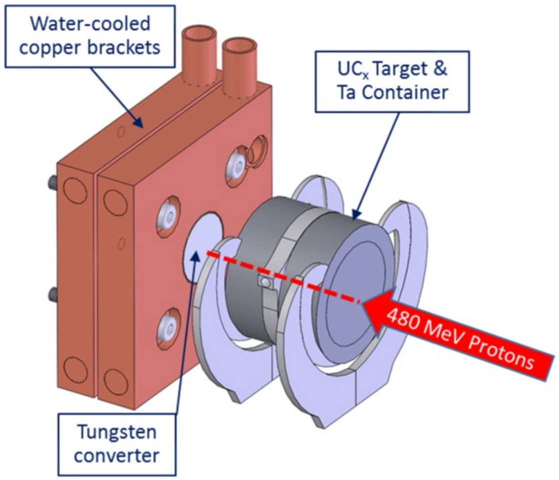
Complements the present capabilities at ISAC for yields determination and beam delivery

Yield station is well suited for high-intensity species through their radioactivity

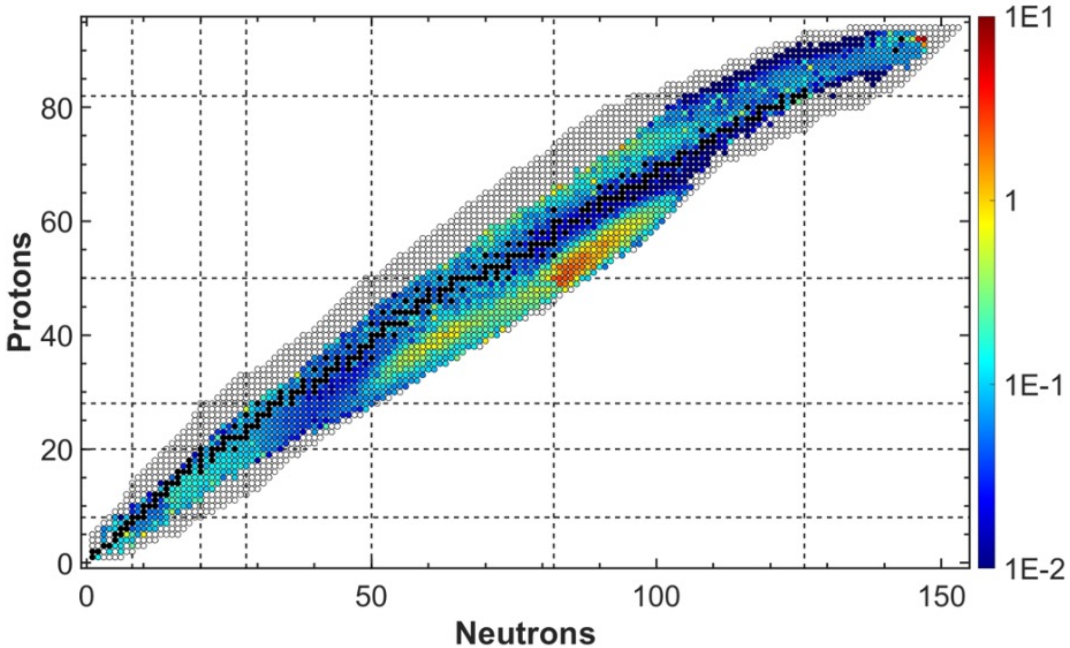
P2n target commissioning

Conventional ISAC vs Converter targets





L. Egoriti et al., J. Phys.: Conf. Ser. **1067** (2018)

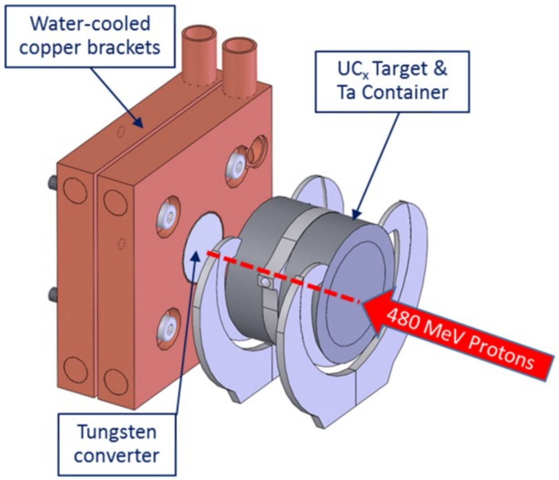


Plots from Luca Egoriti (recently presented in "All Hands Meeting")

Win-win game (Yield and mass measurements)

2021 (take 1):
Cs, Rb (yields)
Zn, Cs (masses)

2022 (take 2):
Sn, Rb, Cs (yields)
Sn, Cs, Ba, Ga (masses)
g,mIn isomers-to-ground- state ratios



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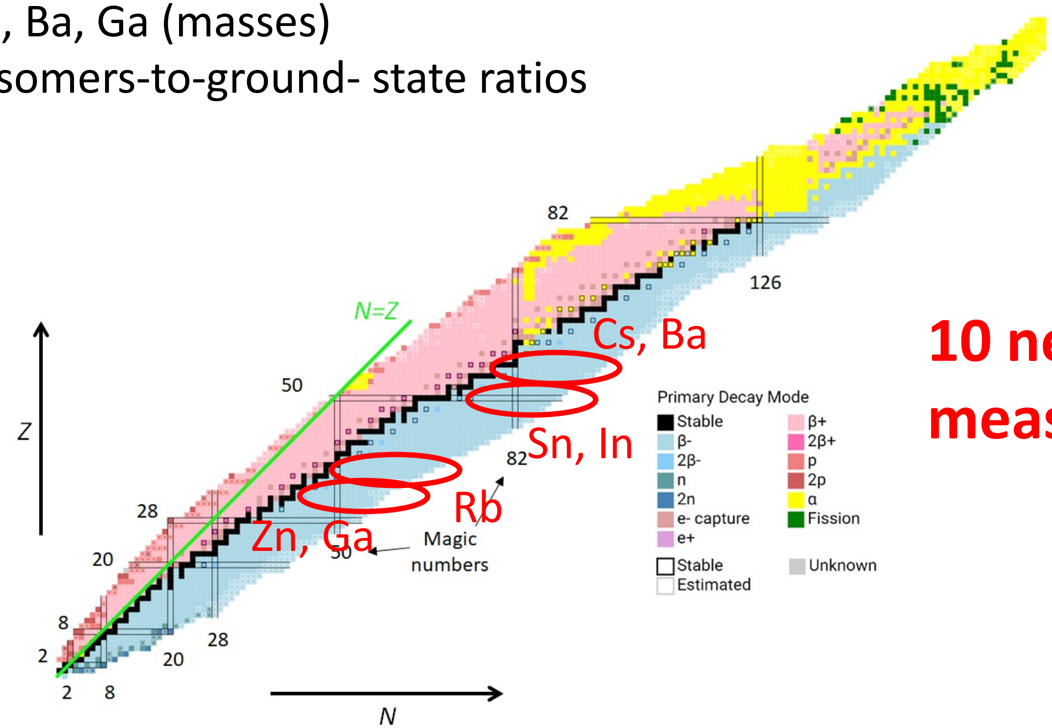
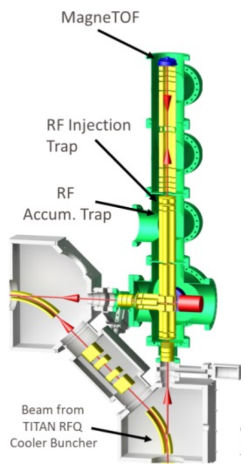
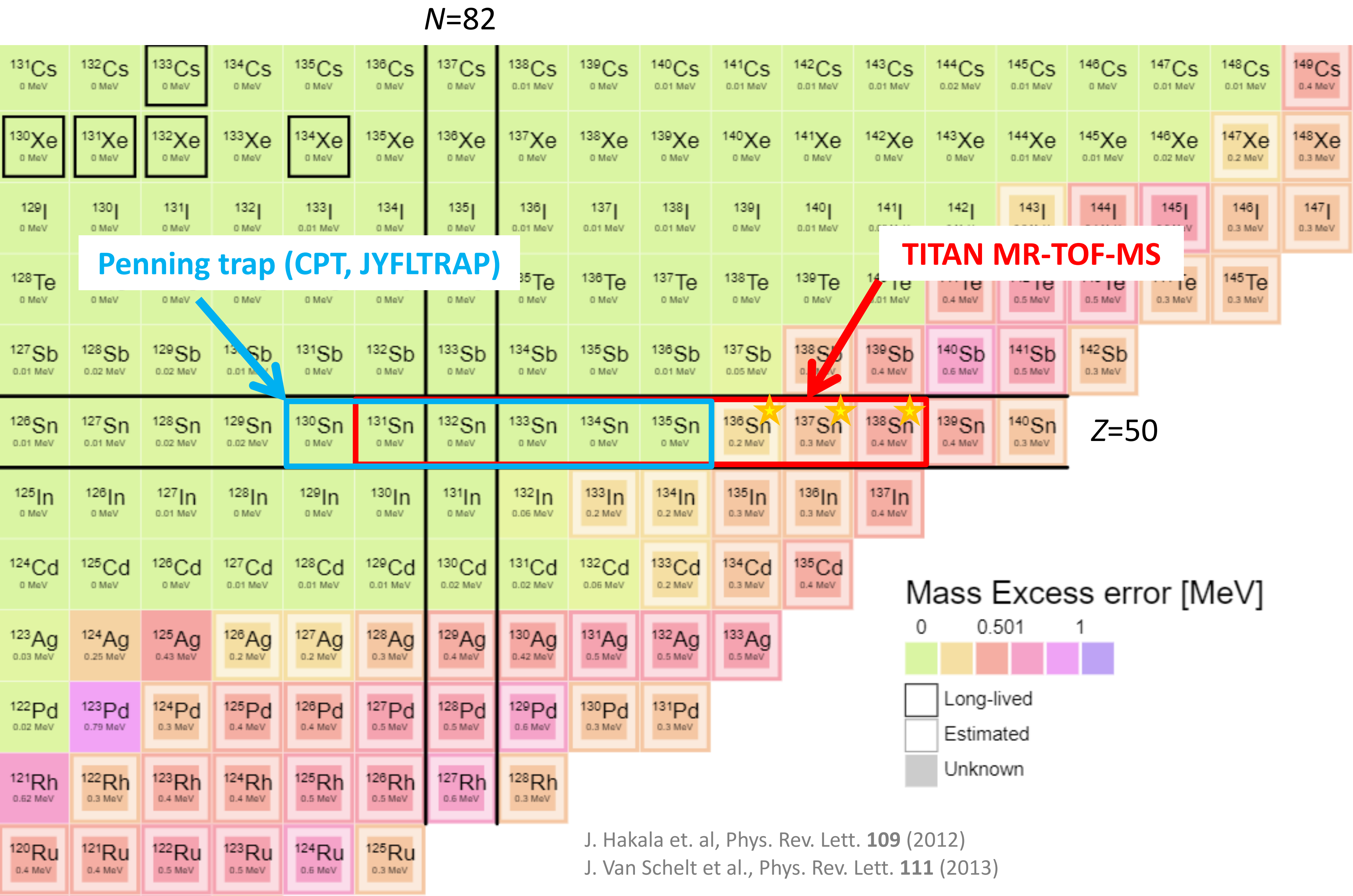


10 new mass measurements

MR-TOF-MS



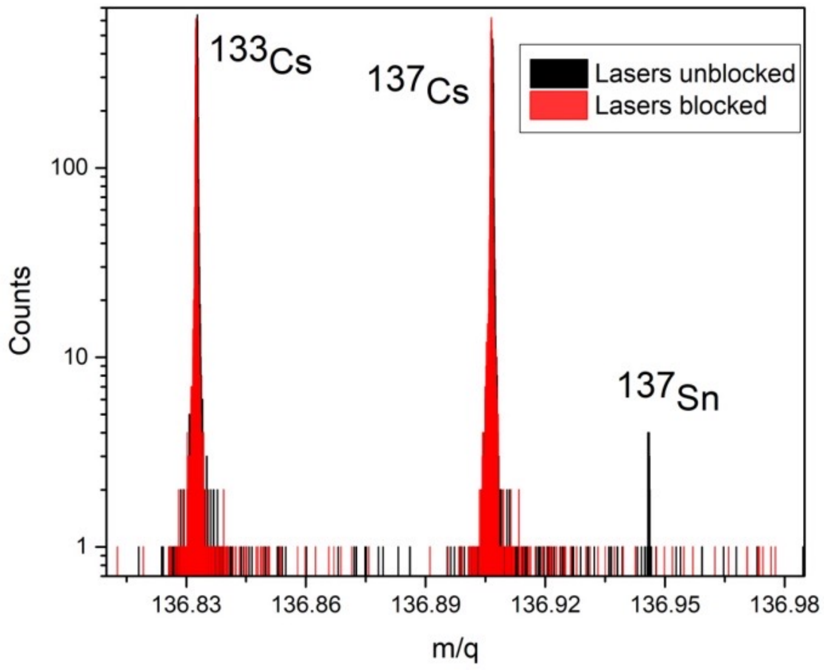
First mass measurement of neutron-rich Sn isotopes

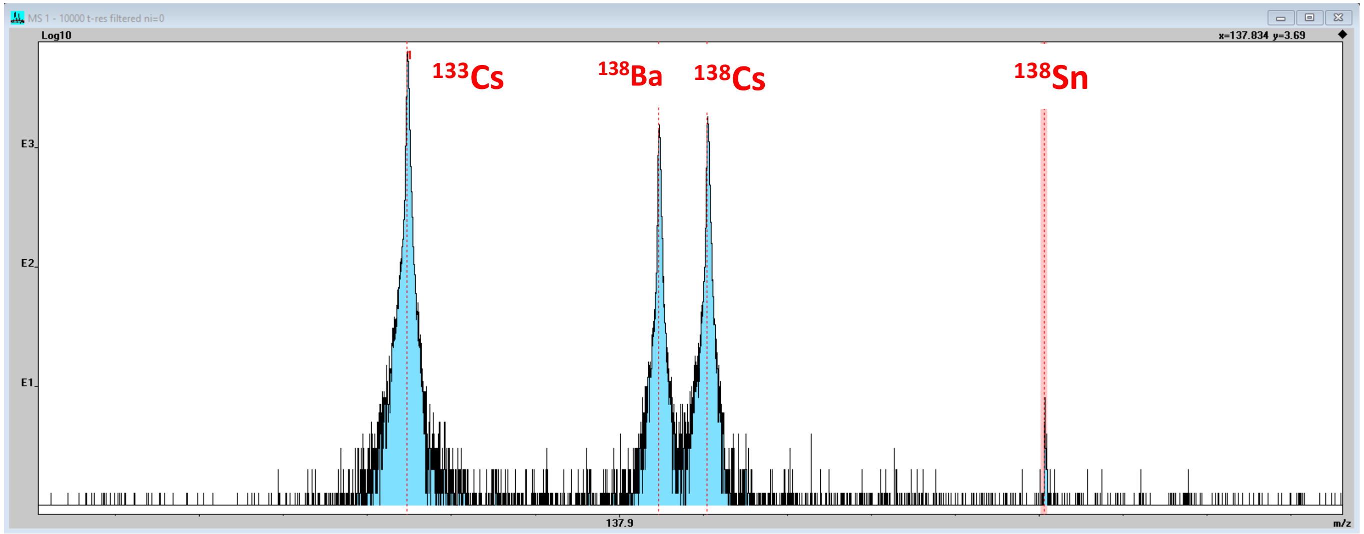


J. Hakala et. al, Phys. Rev. Lett. **109** (2012)
J. Van Schelt et al., Phys. Rev. Lett. **111** (2013)

Neutron-rich Sn isotopes

- ➢ TRILIS Laser ions source (ionization of Sn isotopes)
- ➢ Laser Block/unblock for identification
- ➢ Cs and Ba as mass calibrants (surface ionization)





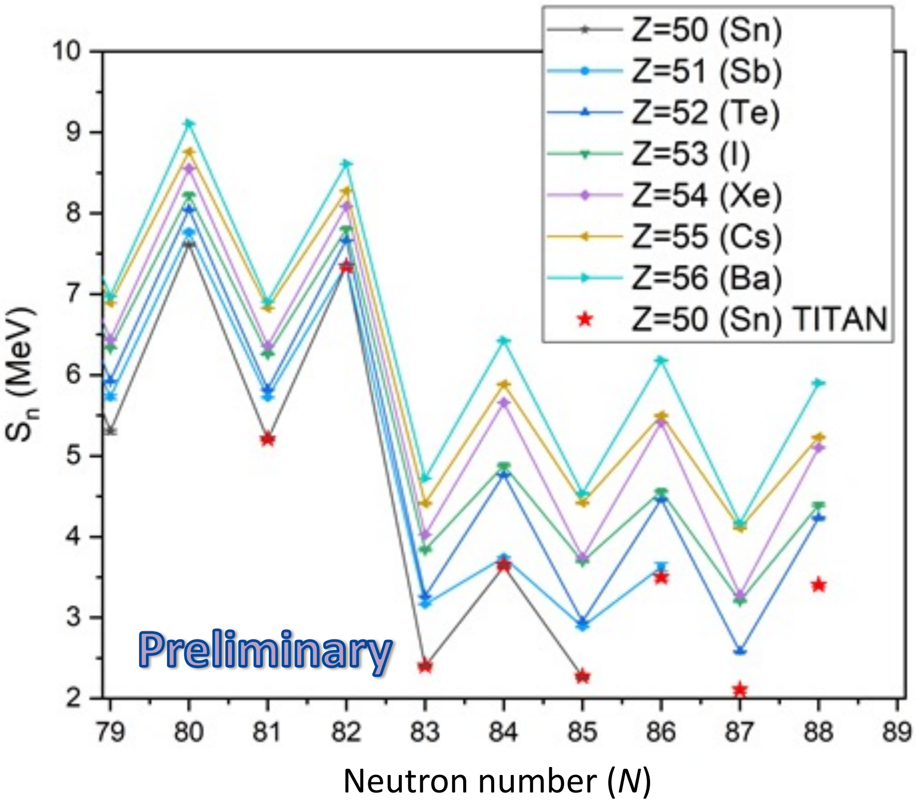
Nuclear structure beyond *N*=82

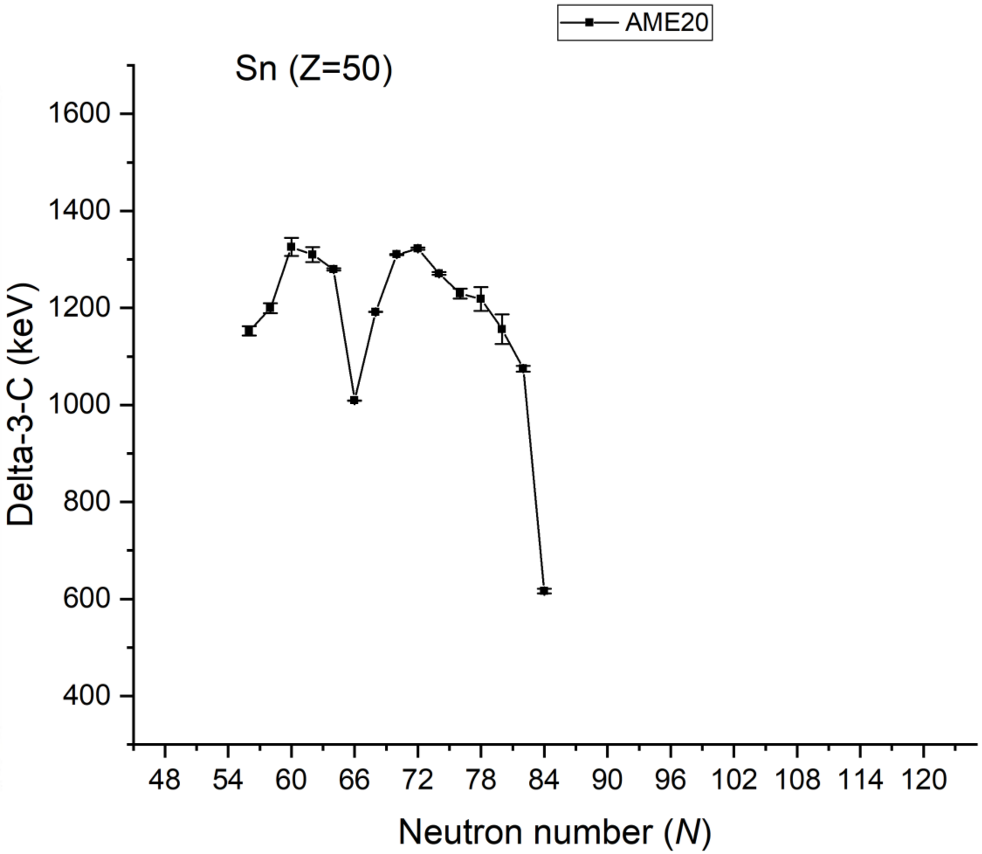
$$S_n = M(N-1,Z) - M(N,Z) + M_n$$

$$\Delta_C^{(3)}(N) = \frac{1}{2}[S_n(N,Z) - S_n(N-1,Z)] = \frac{1}{2}[B(N,Z) + B(N-2,Z) - 2B(N-1,Z)] = \frac{1}{2}[S_{2n}(N,Z) - 2S_n(N-1,Z)],$$

One neutron separation energy

Neutron paring gap





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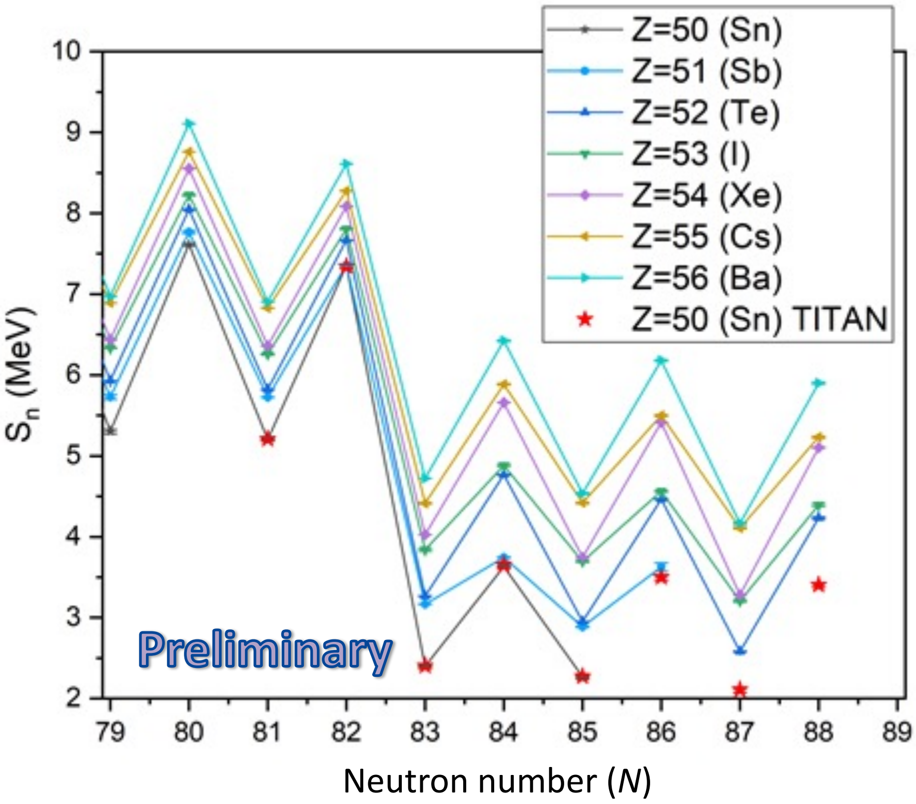
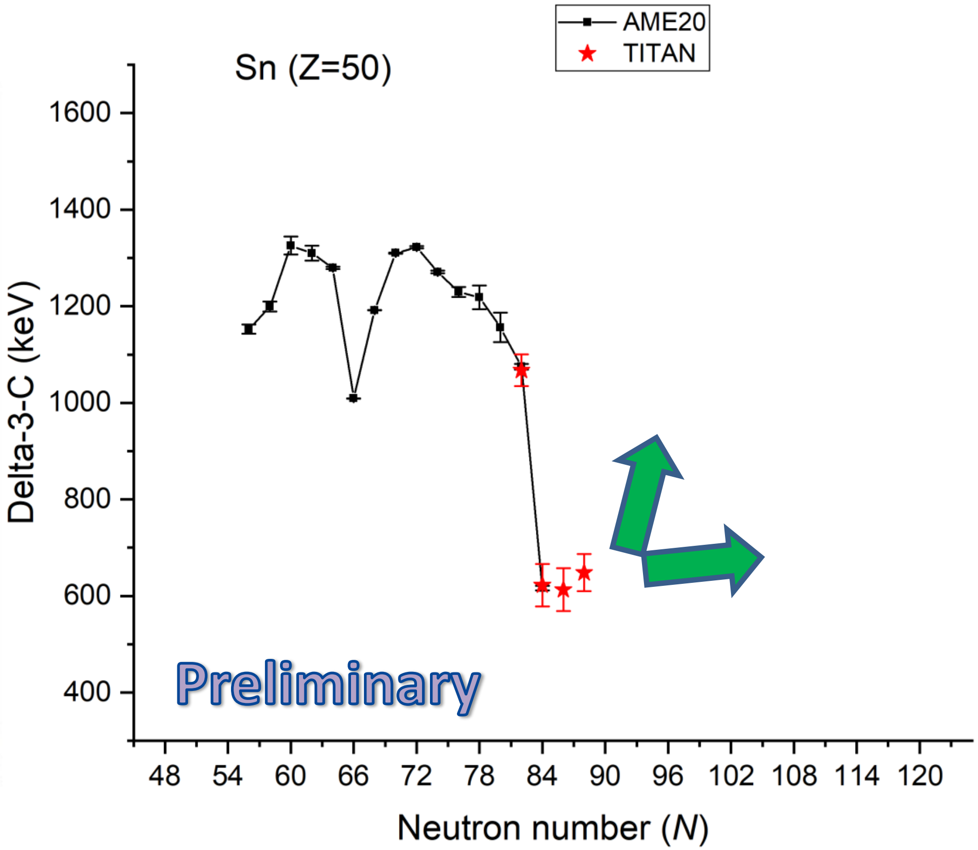


$$\Delta_C^{(3)}(N) = \frac{1}{2}[S_n(N,Z) - S_n(N-1,Z)]$$
$$= \frac{1}{2}[B(N,Z) + B(N-2,Z) - 2B(N-1,Z)]$$
$$= \frac{1}{2}[S_{2n}(N,Z) - 2S_n(N-1,Z)],$$

Neutron paring gap



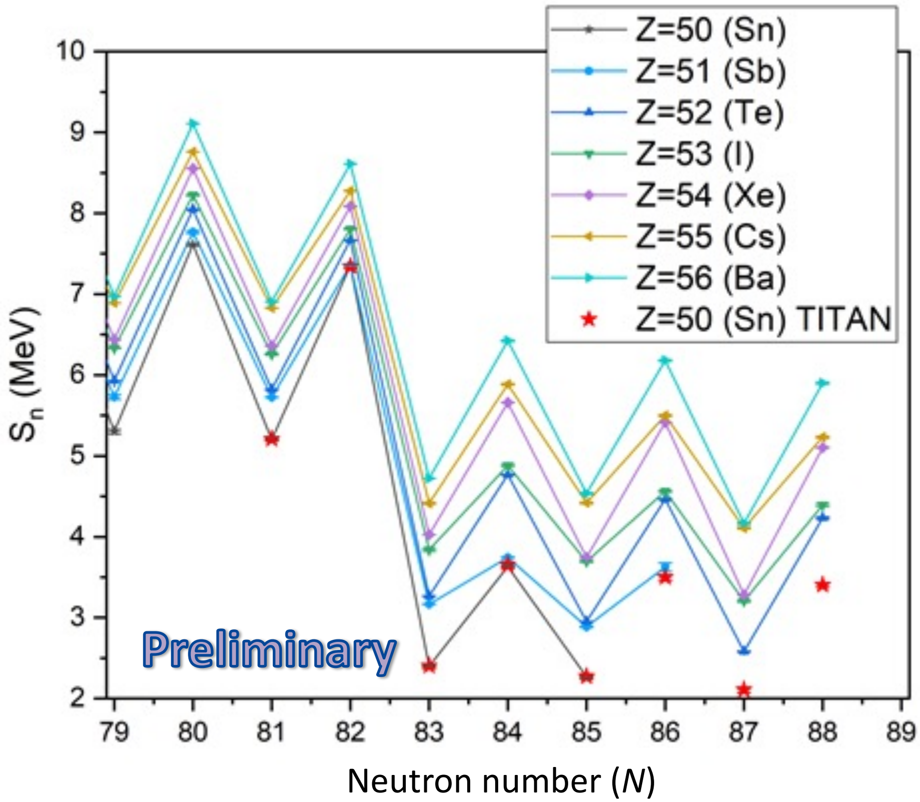
Nuclear structure beyond N=82

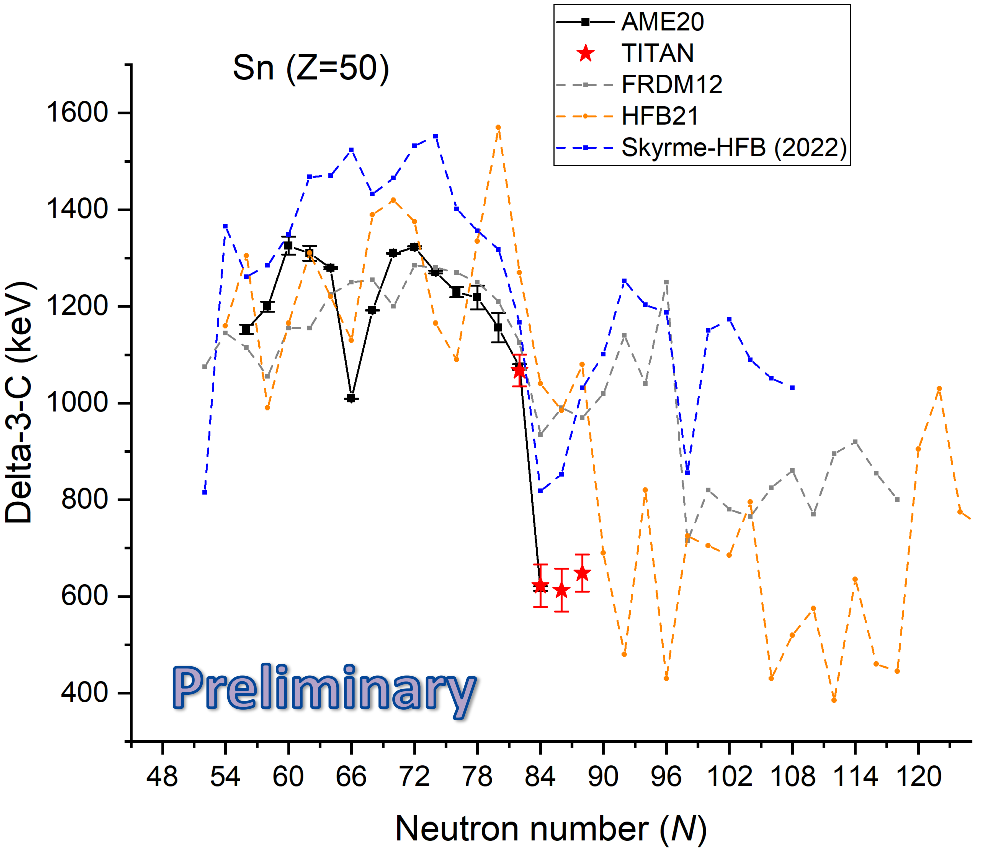
$$S_n = M(N-1,Z) - M(N,Z) + M_n$$

$$\begin{aligned}\Delta_C^{(3)}(N) &= \frac{1}{2}[S_n(N,Z) - S_n(N-1,Z)] \\ &= \frac{1}{2}[B(N,Z) + B(N-2,Z) - 2B(N-1,Z)] \\ &= \frac{1}{2}[S_{2n}(N,Z) - 2S_n(N-1,Z)],\end{aligned}$$

One neutron separation energy

Neutron paring gap

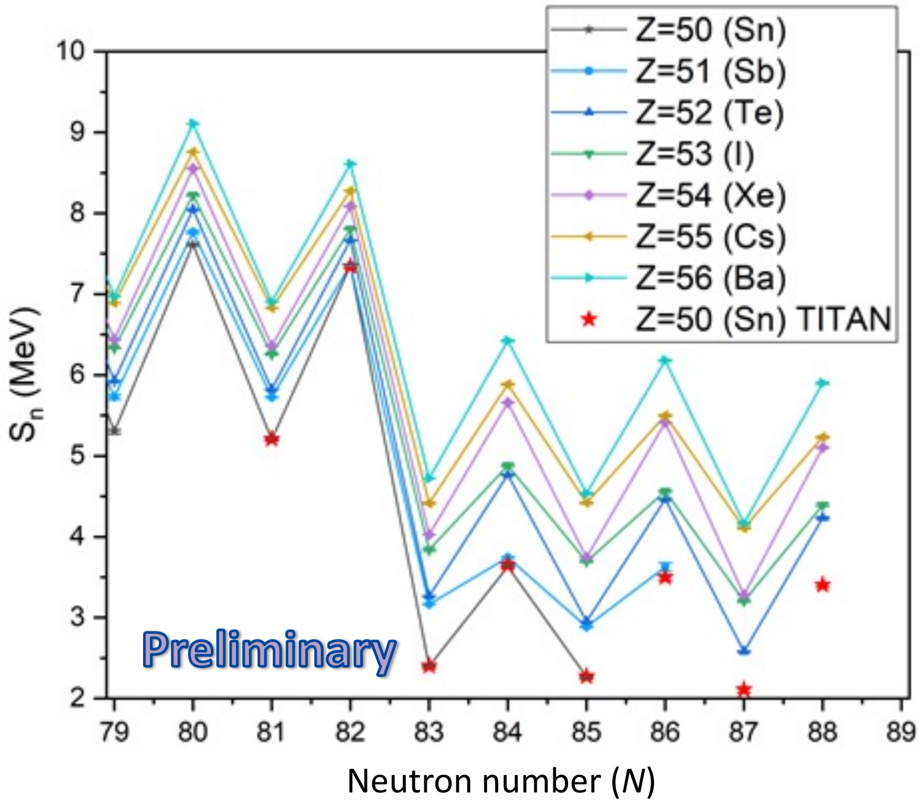




Nuclear structure beyond *N*=82

$$S_n = M(N-1,Z) - M(N,Z) + M_n$$

One neutron separation energy



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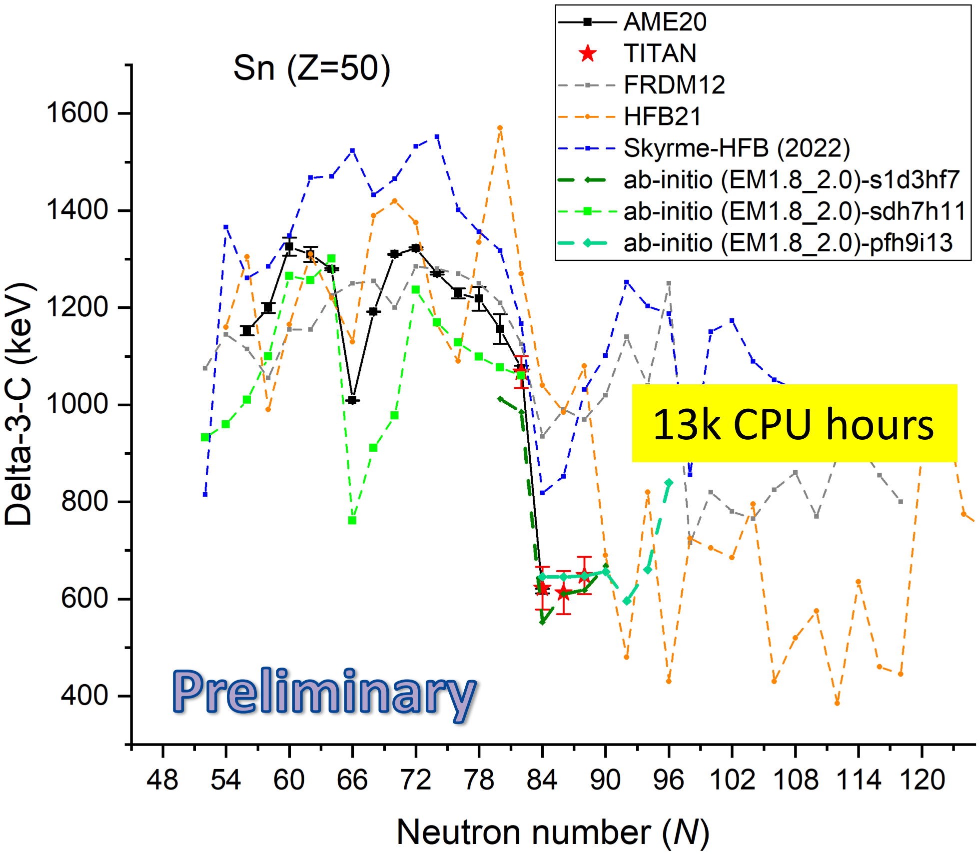
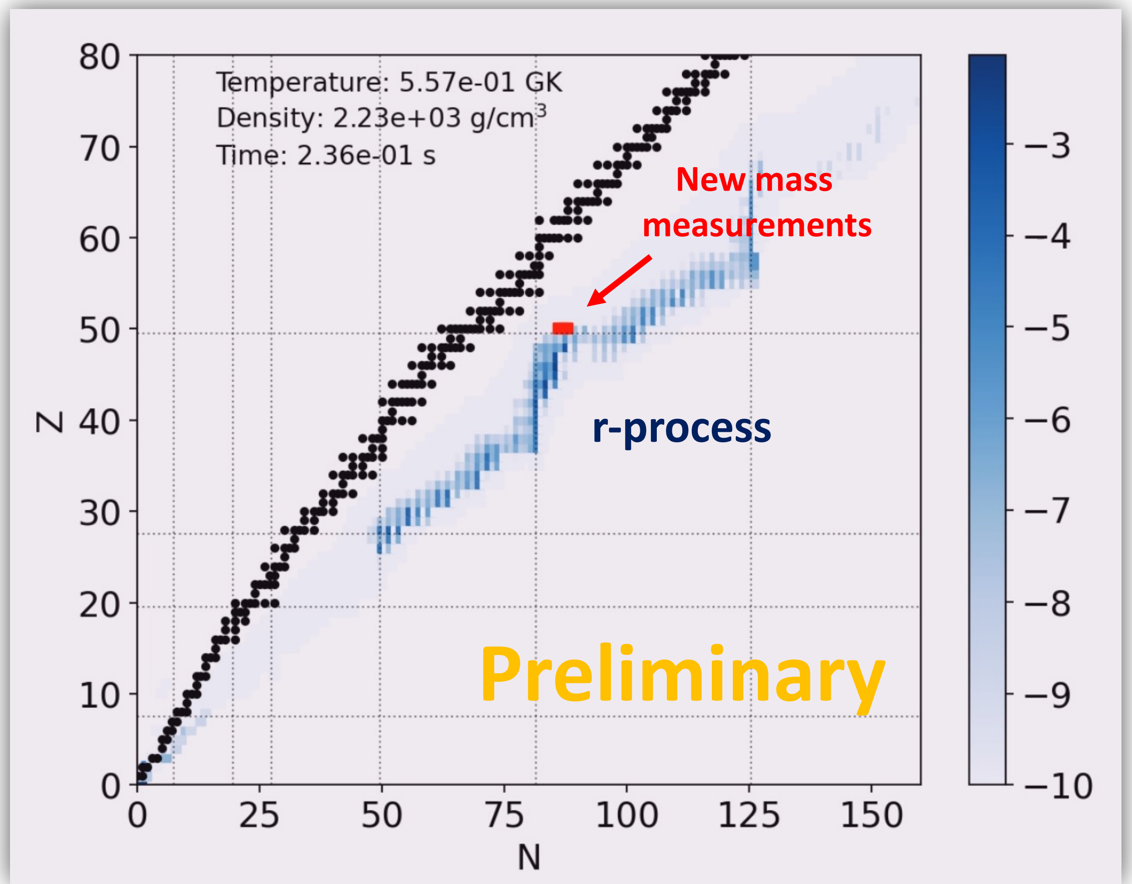
Neutron paring gap



ab-initio calculations in house: Jason Holt, Takayuki Miyagi

Path-line and abundance Calculations:

- N capture cross sections
- Decay modes
- Half-lives
- Branching ratios
- **Binding energies**



Gabriel Mrtinez and Andre Sieverding

Saha equation:

$$\frac{Y(Z,N+1)}{Y(Z,N)} \propto \frac{G(Z,N+1)}{2G(Z,N)} \frac{N_n}{(kT)^{3/2}} \exp\left[\frac{S_n(Z,N+1)}{kT}\right]$$

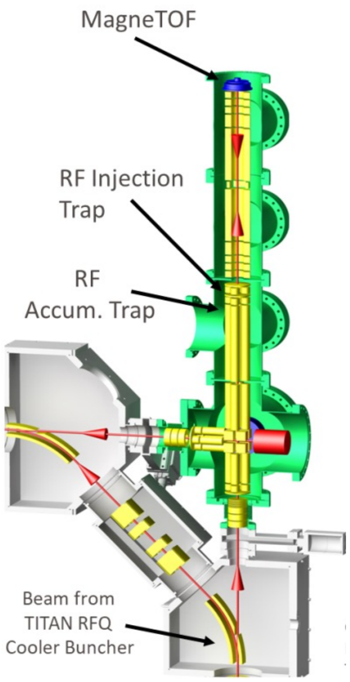
M.R. Mumpower et. al, Phys. Rev. C **92** (2015)

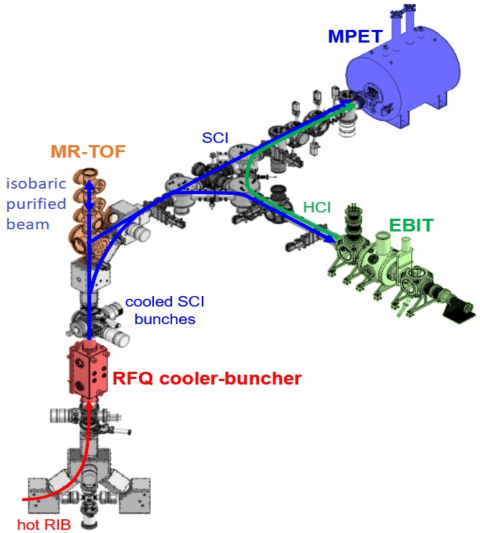
$Y(Z,N)$: Abundance
$G(Z,N)$: Partition function
N_n: Neutron density
kT: Temperature (MeV)
S_n: Neutron separation energy

Summary and Outlook

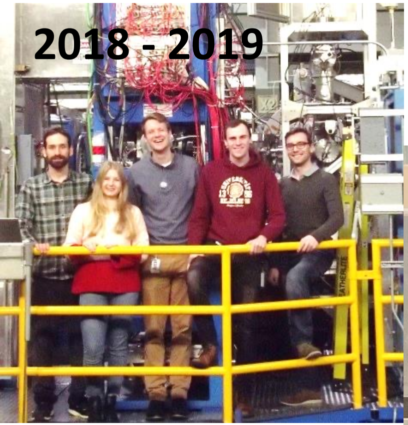
MR-TOF-MS

- TITAN's MRTOF-MS with a complementary role at ISAC I
- MR-TOF-MS contribution to p2n target commissioning
- Win-win game (yields and masses)
- Sn isotopic chain got extended including three new mass measurements
- Nuclear structure (neutron pairing gap)
- Impact on "Nuclear Astrophysics" in calculations (r-process)



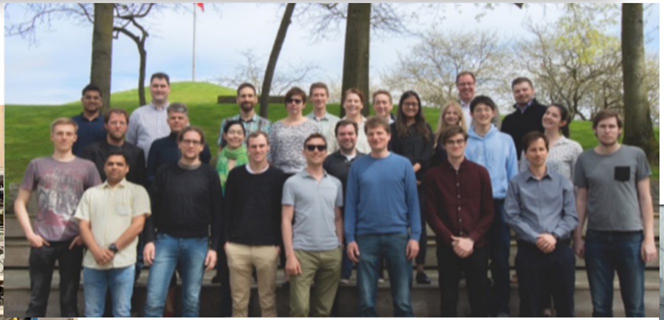


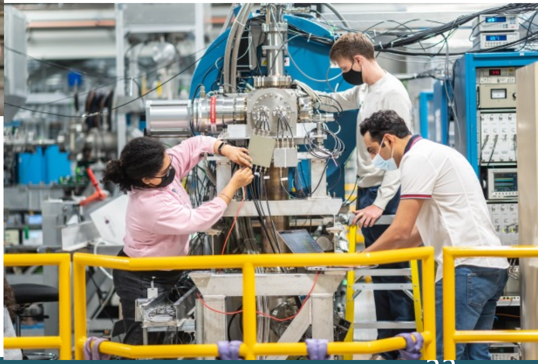
MR-TOF Students



Thanks!

On behalf of TITAN's Collaboration

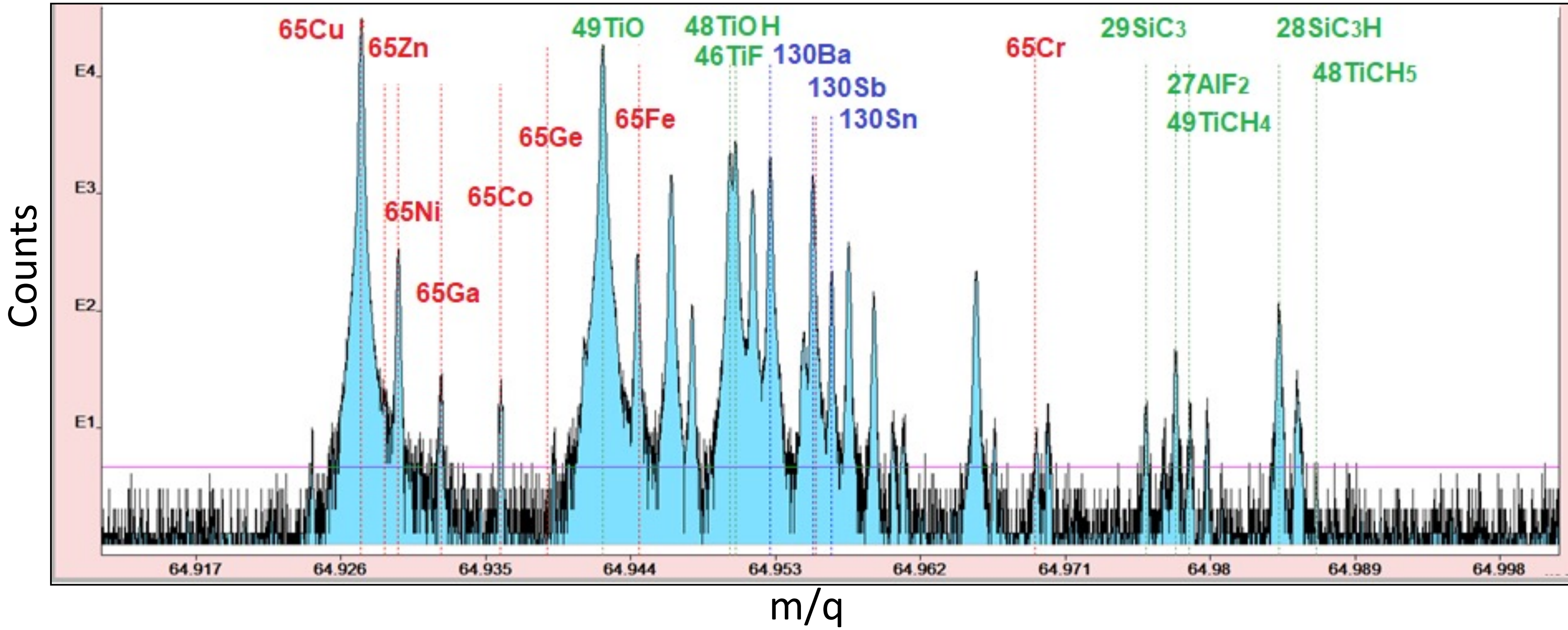




ISOL beams at TRIUMF

- Beam composition after the dipole separator (R=2500)
- A/q=65
- UCx target
- TRILIS ion source

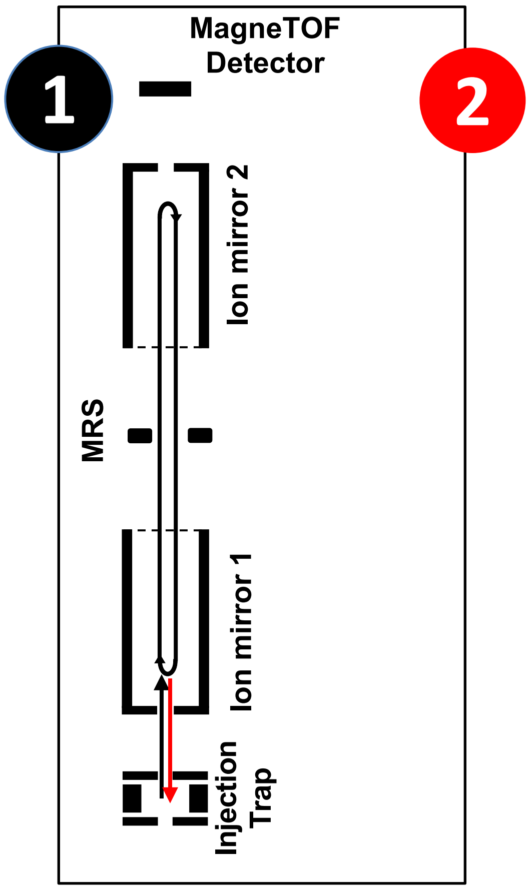
Singly charged ions
Doubly charged ions
Molecular ions

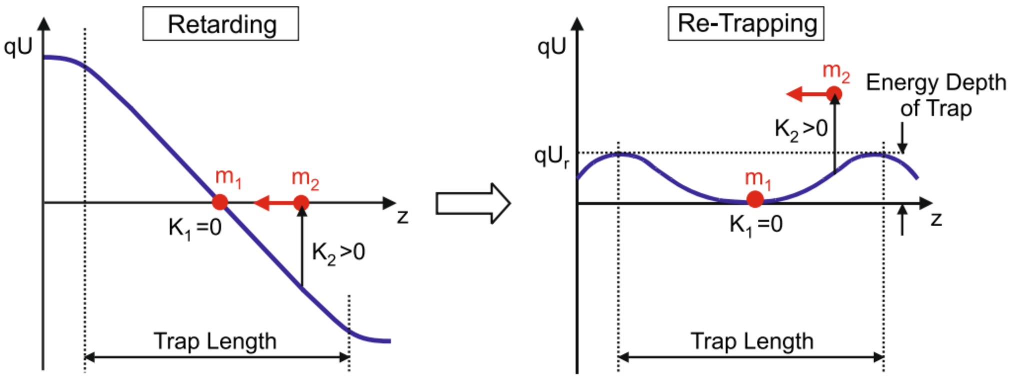


Need for a more powerful separation method

Mass selective re-trapping

TOF analyzer



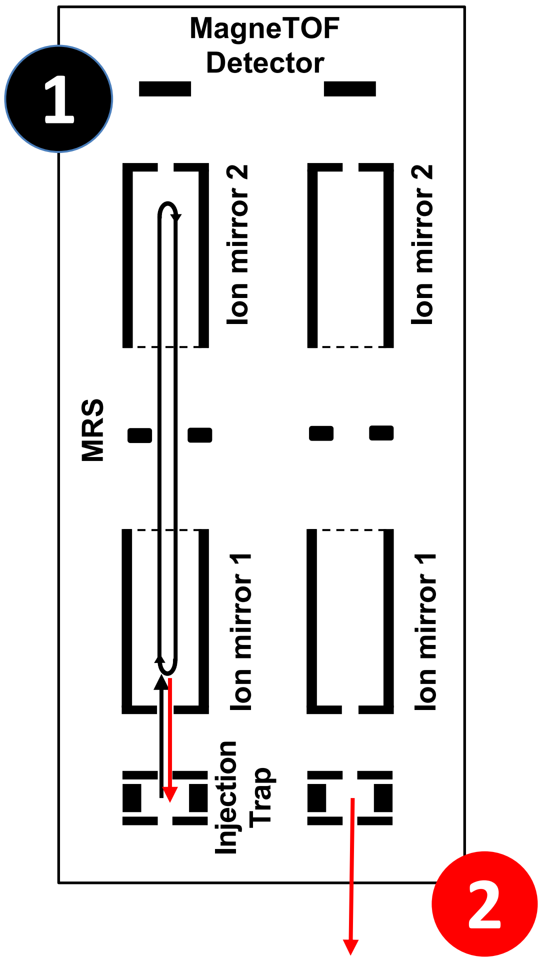


- Use the MR-TOF-MS as its own beam purifier
- Combined **isobar separation** and **mass measurements**

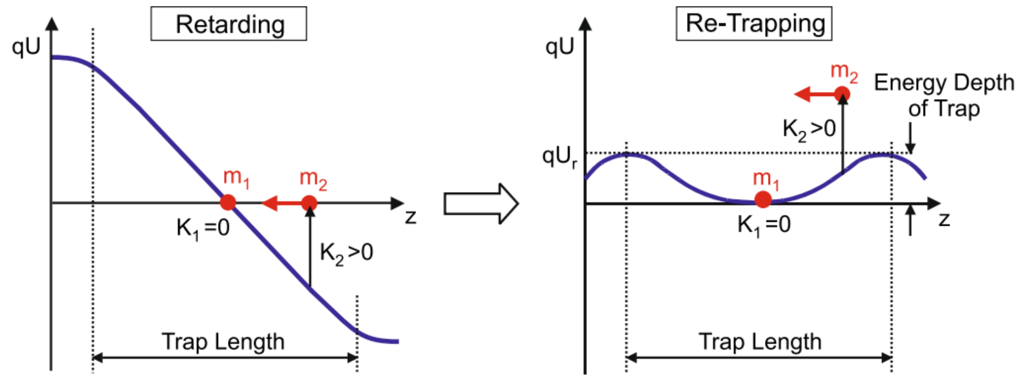
T. Dickel et. al, JASMS, (2017) 28:1079-1090

Mass selective re-trapping

TOF analyzer



Send purified beam
to
MPET, EBIT



- Use the MR-TOF-MS as its own beam purifier
- Combined **isobar separation** and **mass measurements**
- Provide isobarically-purified beam for downstream experiments (e.g., for Penning trap)

Boost in dynamic range
Selection of High-lying isomer/ isobars
Improve precision in mass measurement mode

T. Dickel et. al, JASMS, (2017) 28:1079-1090