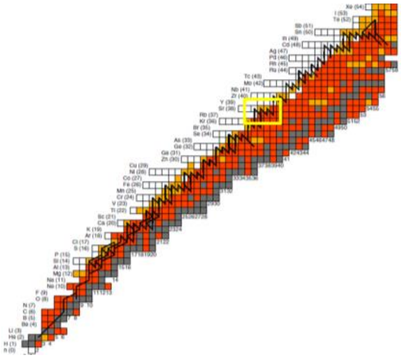
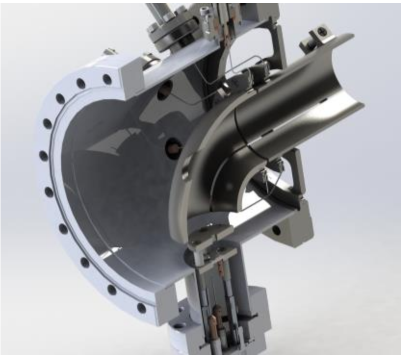
TRIUMF

Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

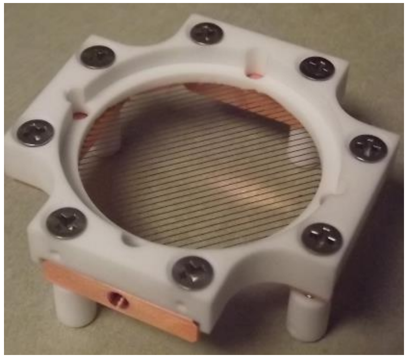


Musings on EMMATrap



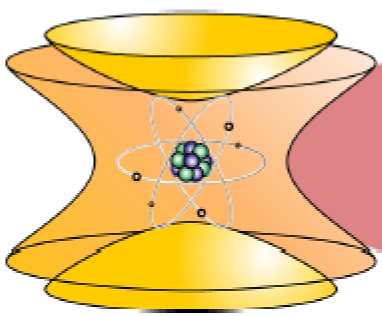
July 19, 2016 - TRIUMF

D. Lascar | Postdoctoral Fellow | TRIUMF
T. Brunner | Professor | McGill & TRIUMF



What do masses tell us?

- Nuclear Masses of Rare Isotopes:
  - Magic numbers of exotic nuclei (new shell closures)



  - R-process waiting points
  - Inform theory
  - CKM matrix

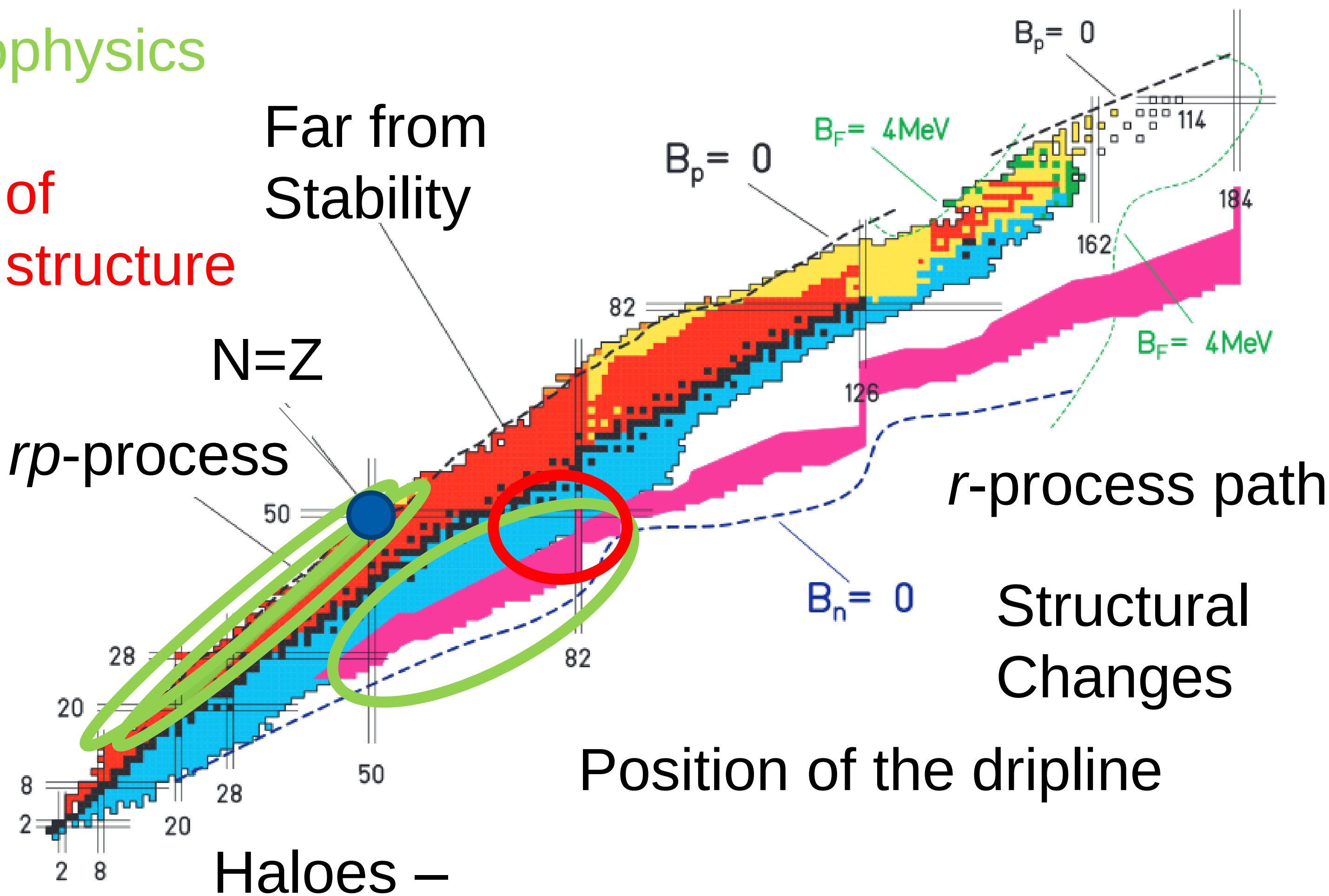
	$\delta m/m$
General physics & chemistry	$\leq 10^{-5}$
Nuclear structure physics - separation of isobars	$\leq 10^{-6}$
Astrophysics - separation of isomers	$\leq 10^{-7}$
Weak interaction studies	$\leq 10^{-8}$
Metrology - fundamental constants Neutrino physics	$\leq 10^{-9}$
CPT tests	$\leq 10^{-10}$
QED in highly-charged ions - separation of atomic states	$\leq 10^{-11}$

Slide courtesy of B. Kootte

Exotic nuclei at EMMA

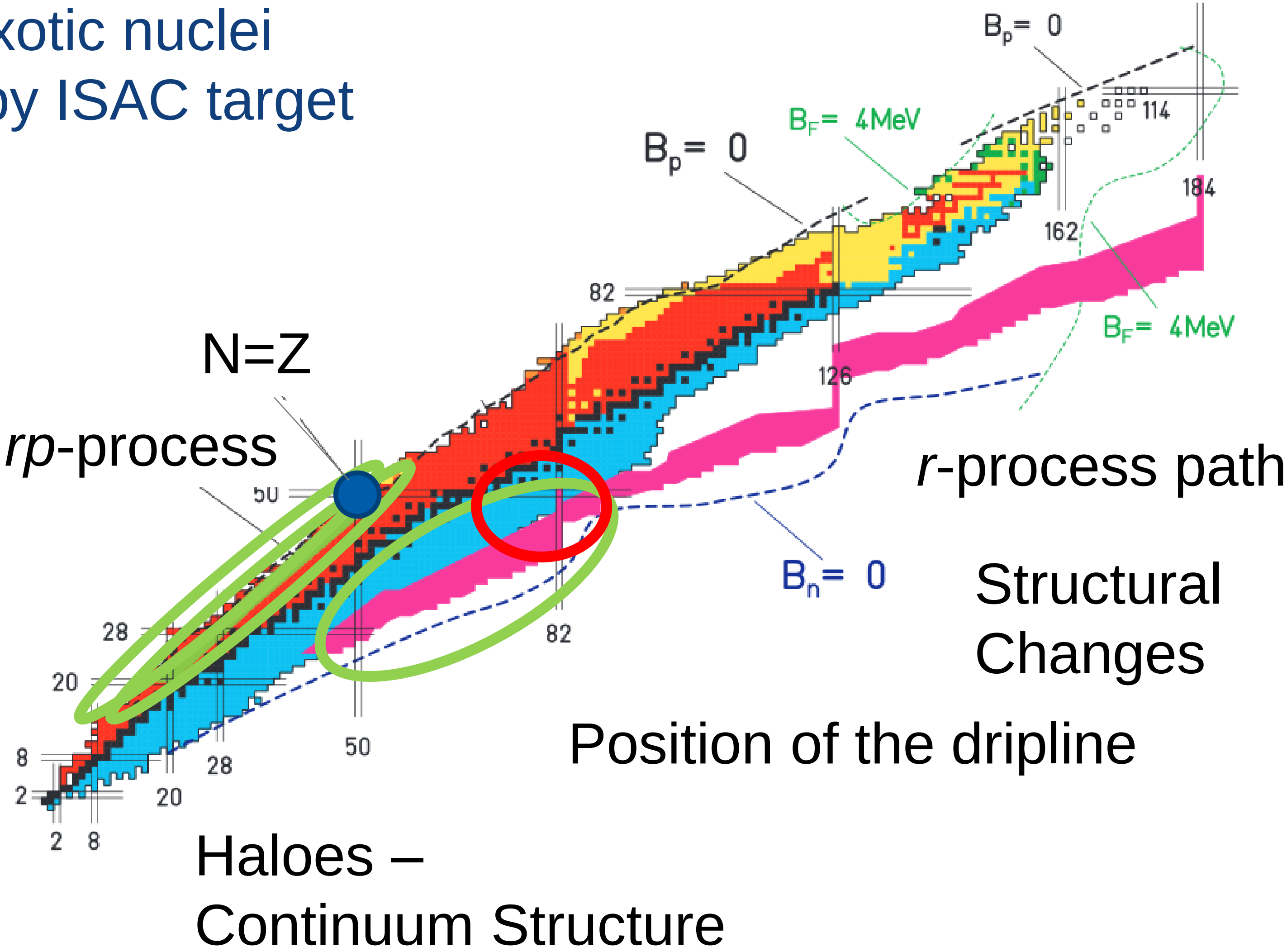
Physics Motivation

- Nuclear astrophysics
- N=Z studies
- Investigation of nuclear shell structure



Advantages of EMMATrap

- Contamination reduction of ~10^5
- Access to exotic nuclei
- Not limited by ISAC target chemistry



The community has moved to neutron-rich

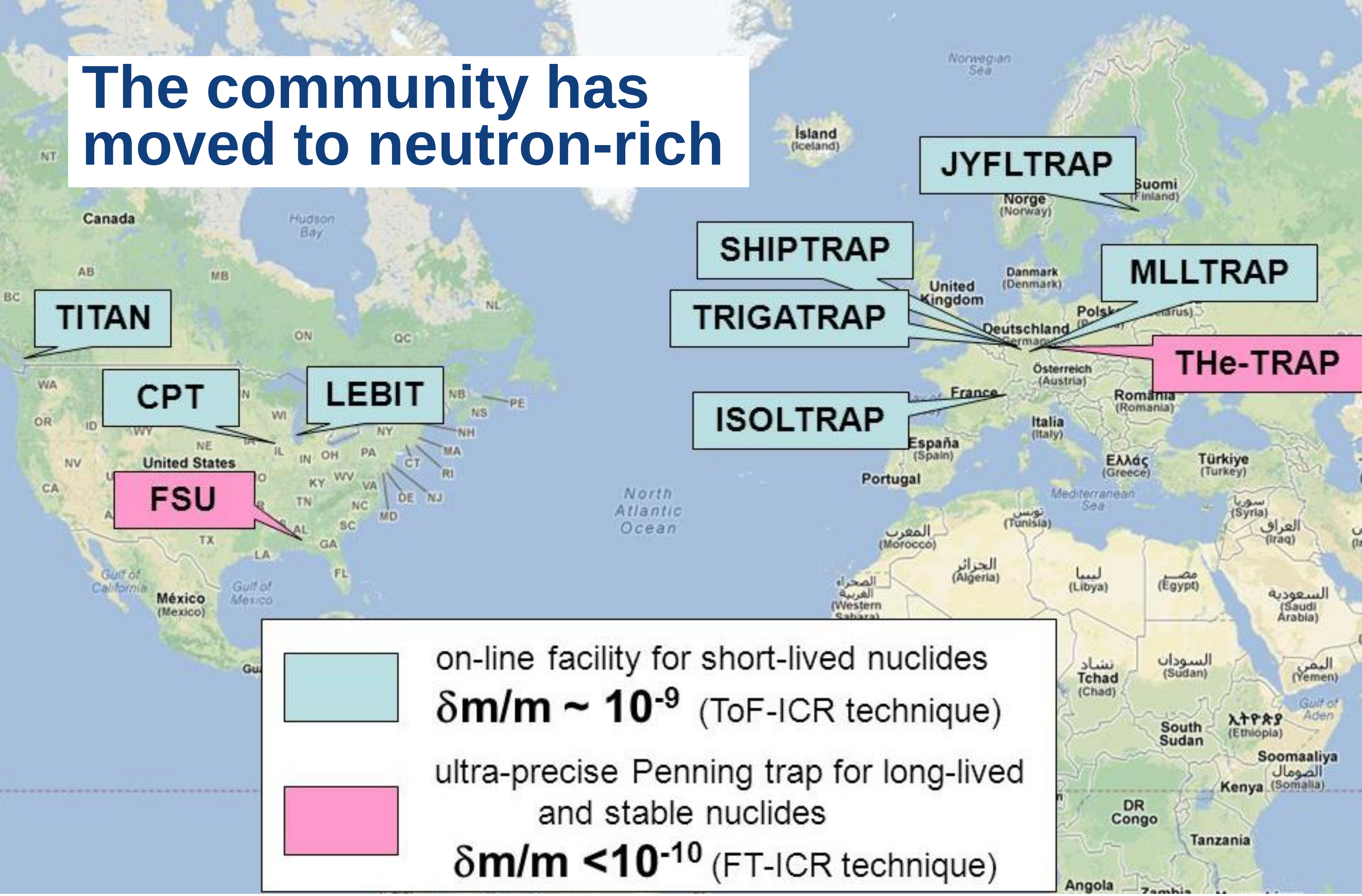
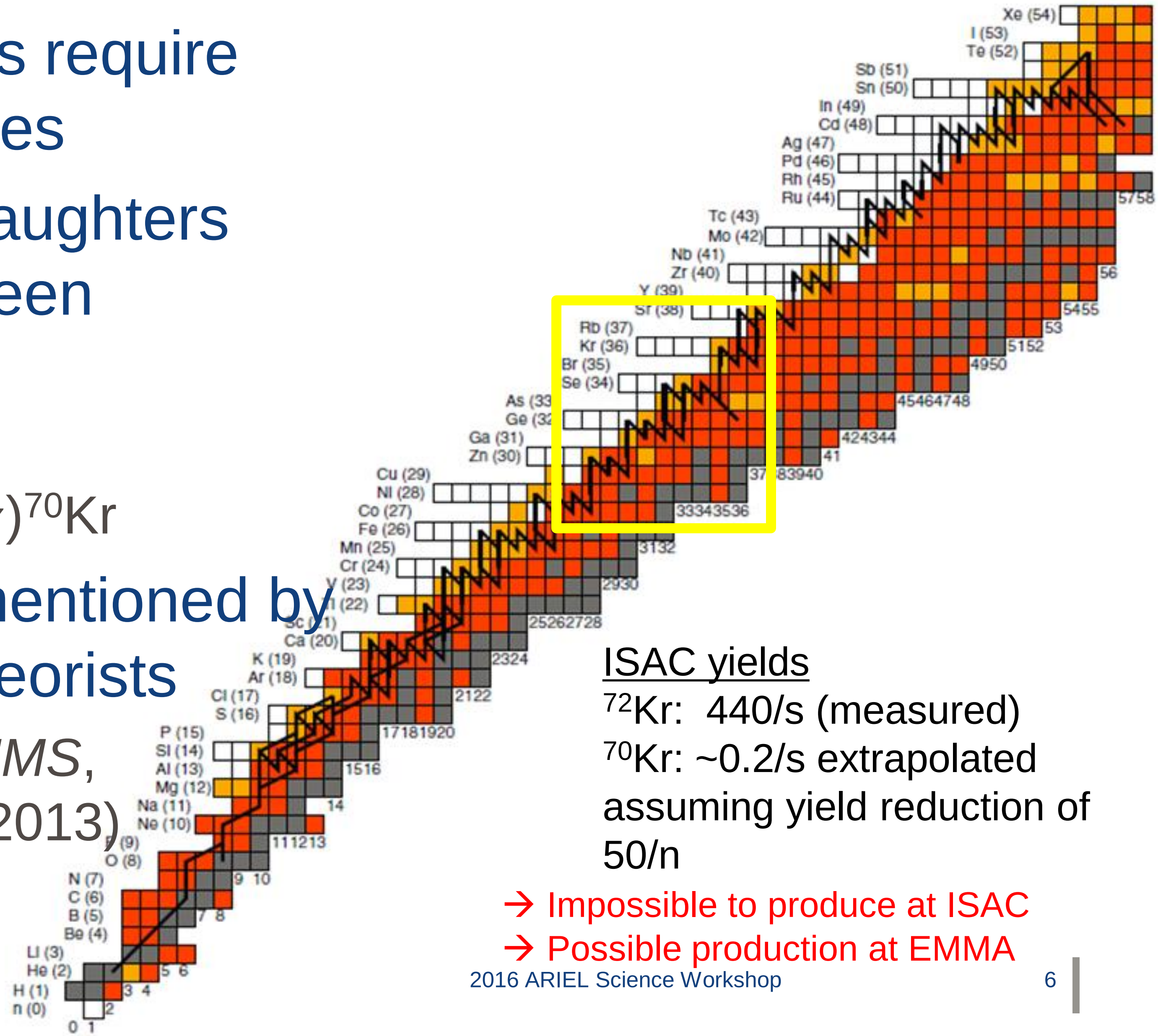


Image courtesy of S. Eliseev

The *rp*-process

- Waiting Points require nuclear masses
- 2*p* channel daughters have never been measured
  - *Example:* $^{68}Se(p,\gamma)(p,\gamma)^{70}Kr$
- Specifically mentioned by *rp*-process theorists
  - H. Schatz, *IJMS*, **349–350** 1 (2013)



ISAC yields

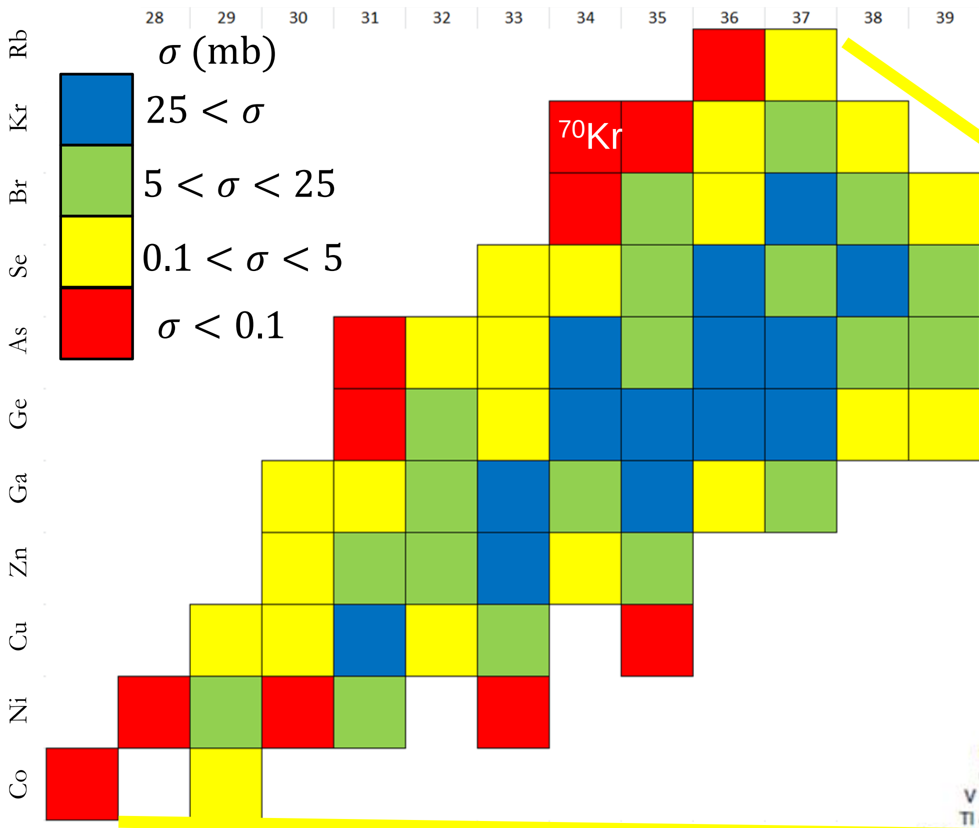
^{72}Kr: 440/s (measured)

^{70}Kr: ~0.2/s extrapolated assuming yield reduction of 50/n

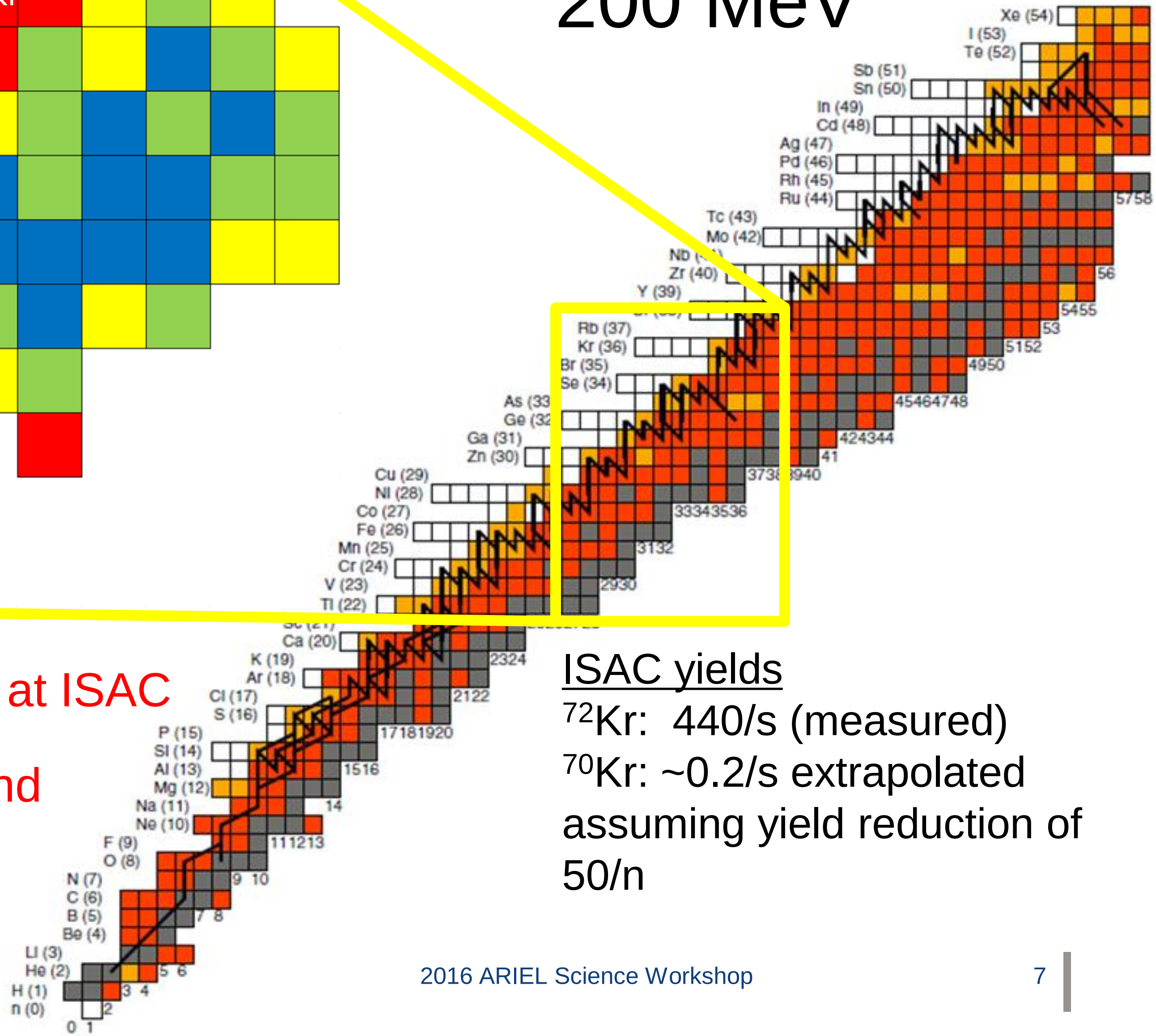
→ Impossible to produce at ISAC

→ Possible production at EMMA

The *rp*-process case ^{70}Kr



^{38}K + ^{40}Ca
200 MeV



→ Impossible to produce at ISAC

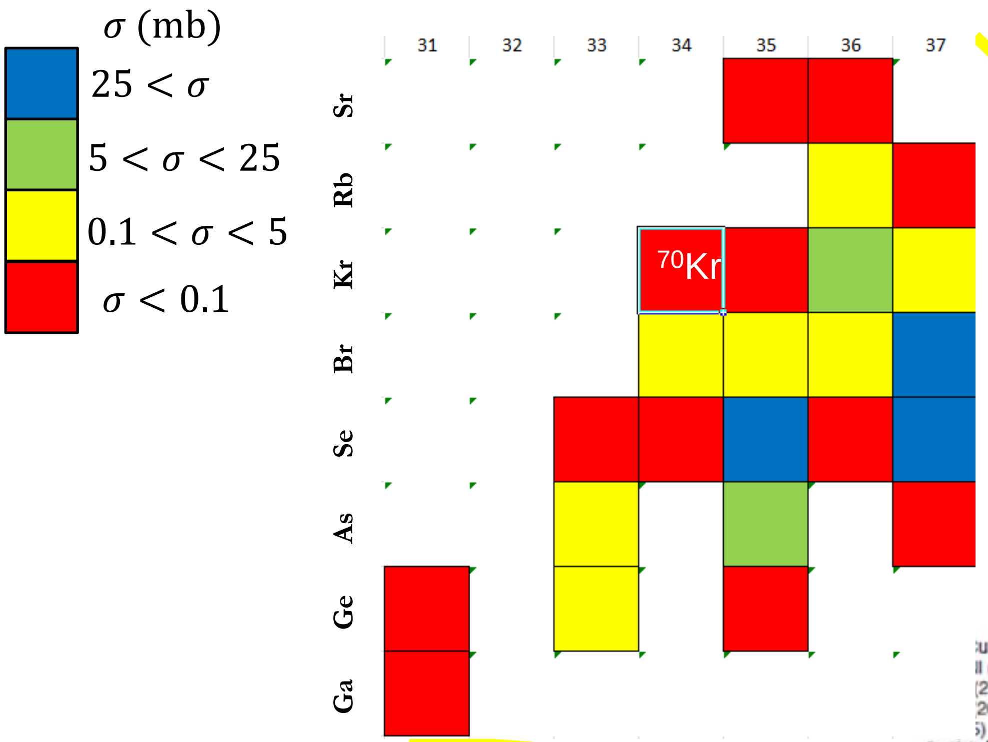
→ Possible production and separation at EMMA

<u>ISAC yields</u>

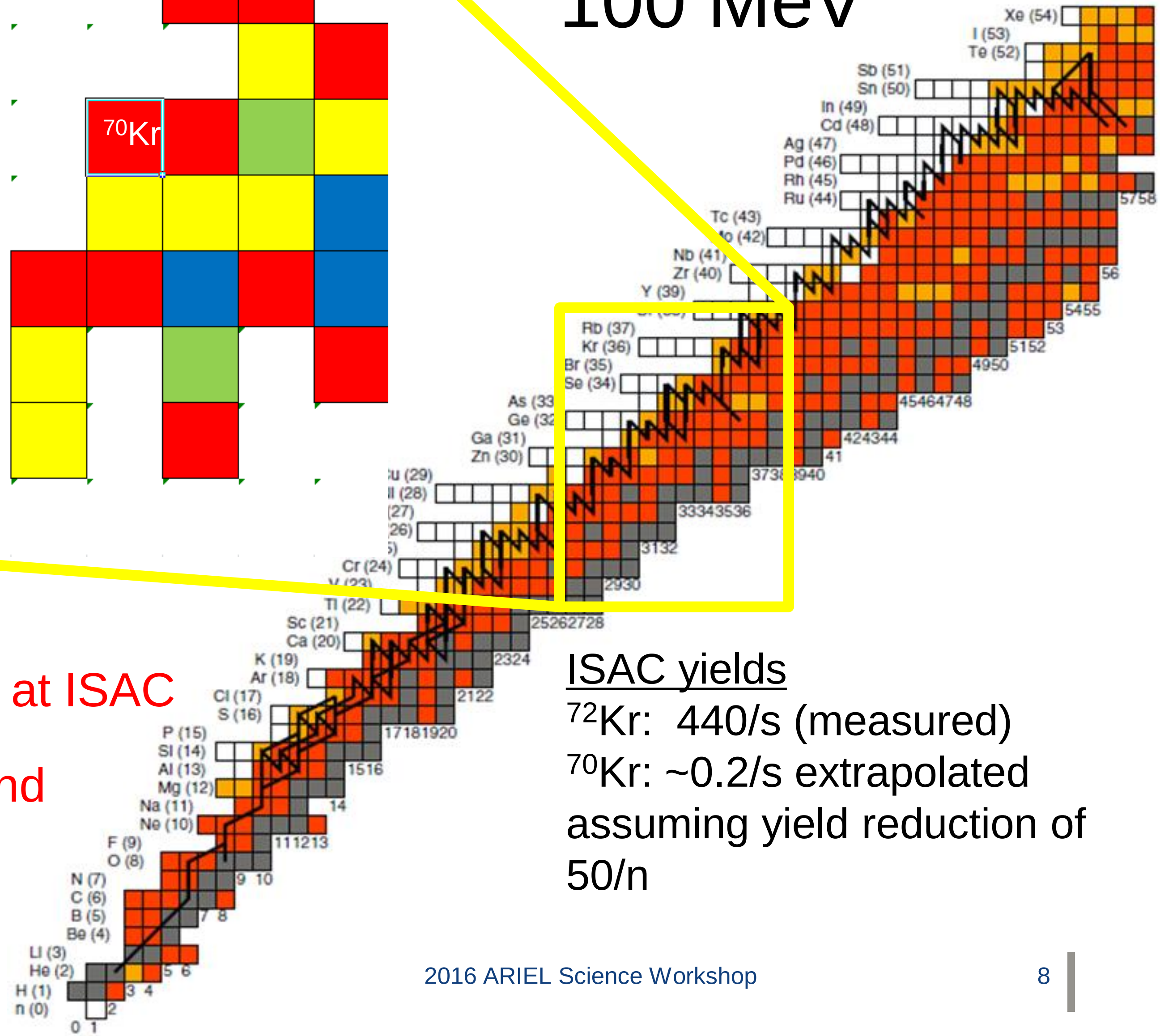
^{72}Kr: 440/s (measured)

^{70}Kr: ~0.2/s extrapolated assuming yield reduction of 50/n

The *rp*-process case ^{70}Kr



^{35}Ar + ^{40}Ca
100 MeV



→ Impossible to produce at ISAC

→ Possible production and separation at EMMA

<u>ISAC yields</u>

^{72}Kr: 440/s (measured)

^{70}Kr: ~0.2/s extrapolated assuming yield reduction of 50/n

Stellar reaction rates

- Paper details a list of more than 1,000 nuclei that contribute to asymmetric reaction rates in:
  - (α, γ)
  - (p, γ)
  - (γ, n)
  - (p, n)
  - (α, n)
  - (α, p)
- Most are neutron-deficient
- This is a goldmine of astrophysical motivation

PHYSICAL REVIEW C **88**, 035803 (2013)

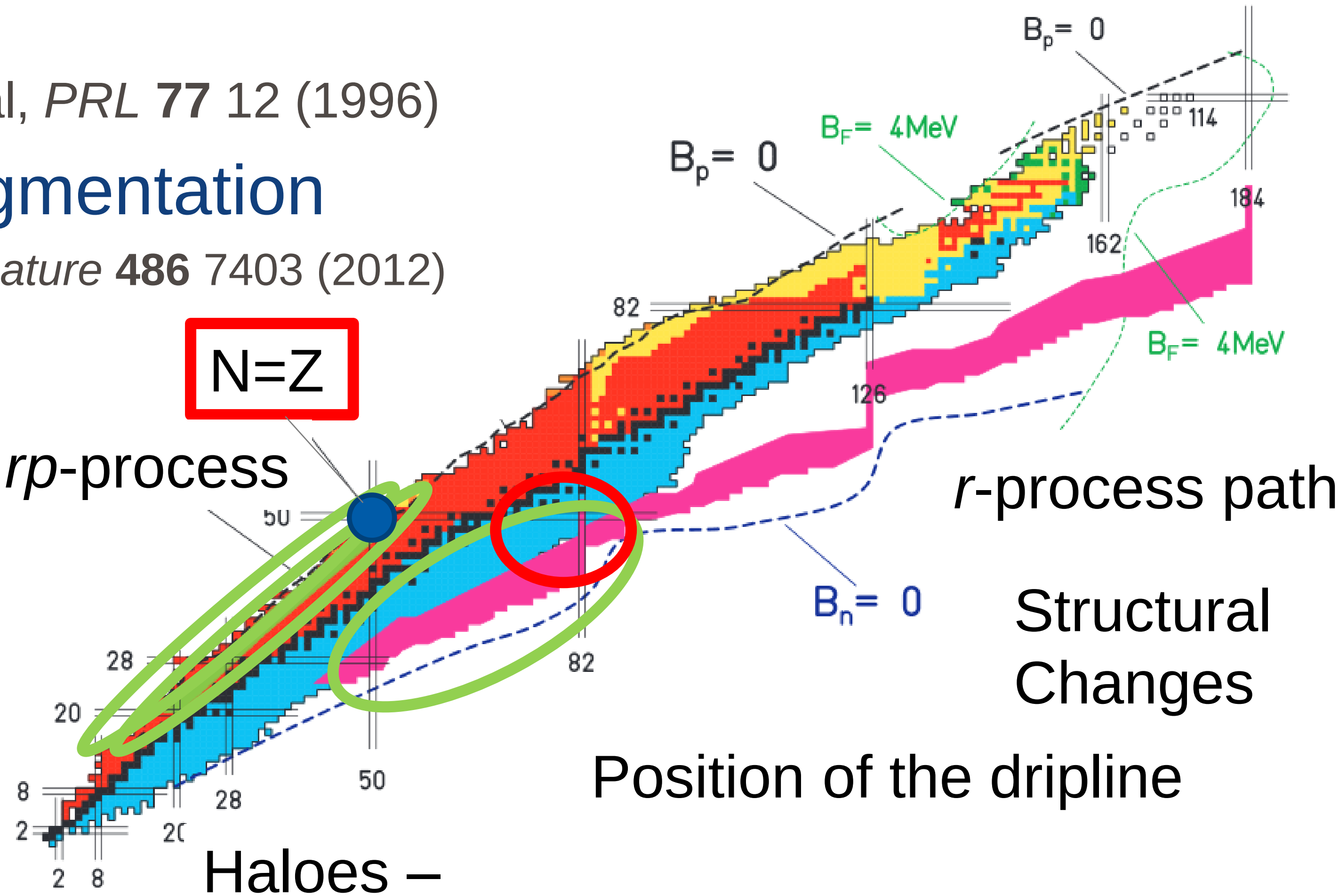
Suppression of excited-state contributions to stellar reaction rates

T. Rauscher*

Nuclear structure – ^{100}Sn

Two production mechanisms:

- $^{50}Cr + ^{58}Ni$
  - Chartier et al, *PRL* **77** 12 (1996)
- $^{124/3}Xe$ Fragmentation
  - Hinke et al, *Nature* **486** 7403 (2012)



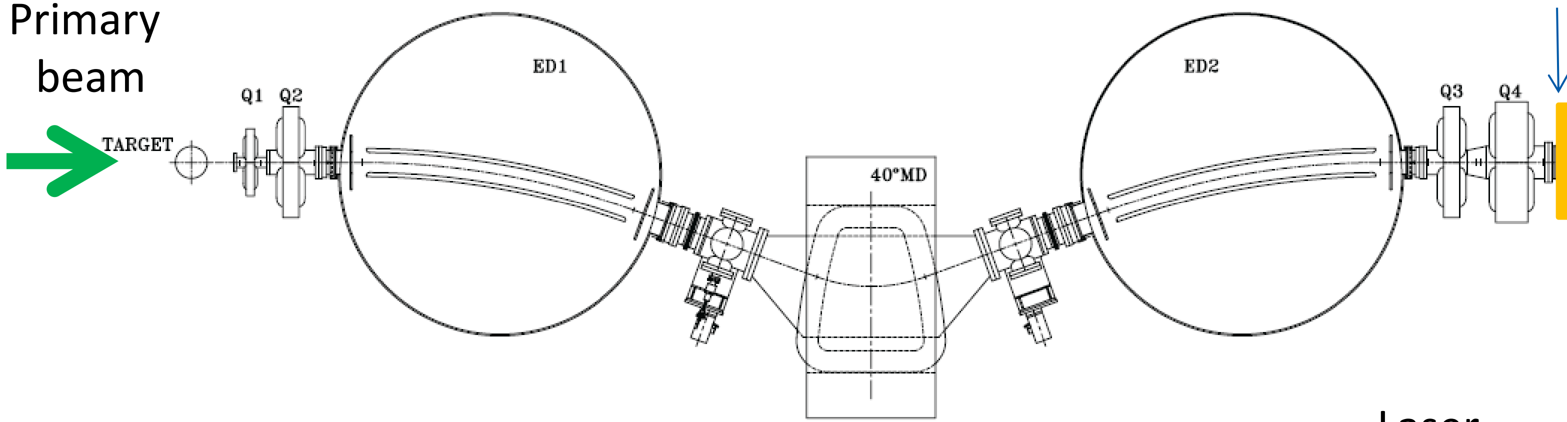
Haloes –
Continuum Structure

Slide courtesy of T. Brunner

EMMATrap

Primary beam

Particle tagging

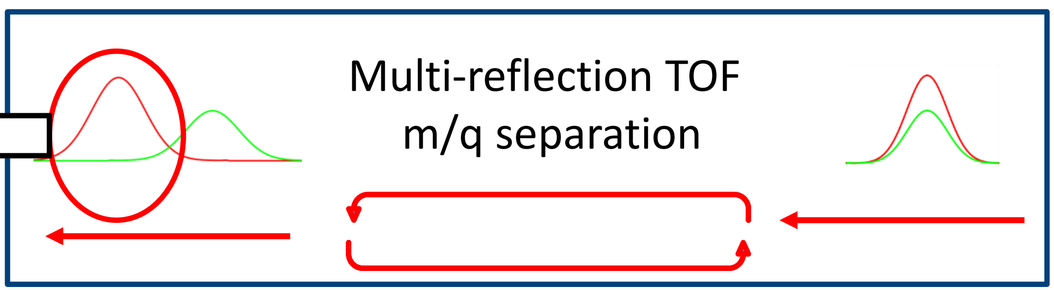


Stopper gas cell

Laser ionization

Quadrupole stopper and buncher (LPT)

1. Tagging of reaction products
2. Stopping of ions in He gas cell
3. Possibility of laser-ionization (optional)
4. Cooling and bunching of ions
5. Separation from contamination in TOF spectrometer
6. High-precision m/q measurement in Penning trap

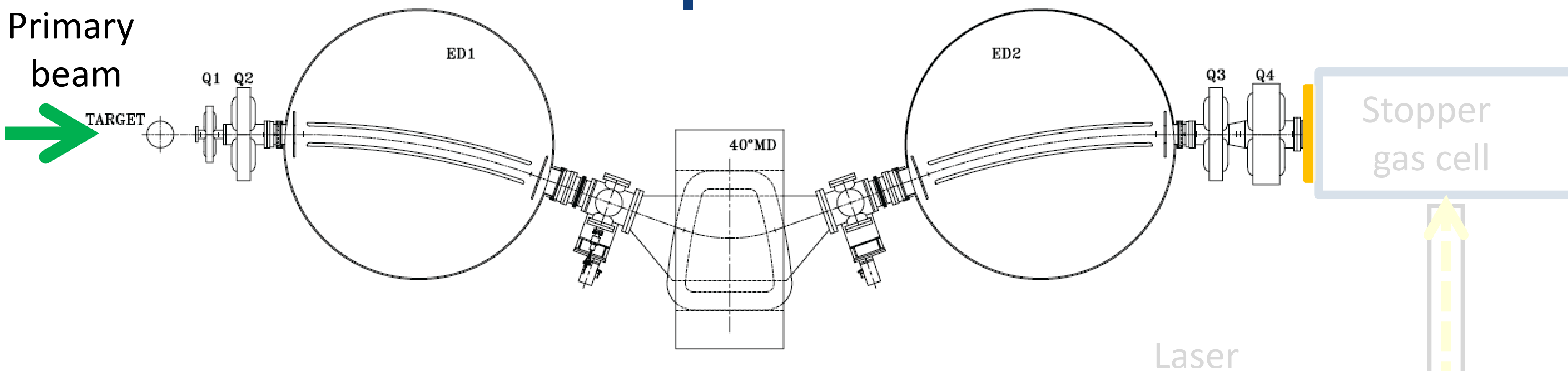


Mass measurement Penning trap

$$\nu_c = \frac{q}{m}\frac{B}{2\pi}$$

Slide courtesy of T. Brunner

EMMA without trap



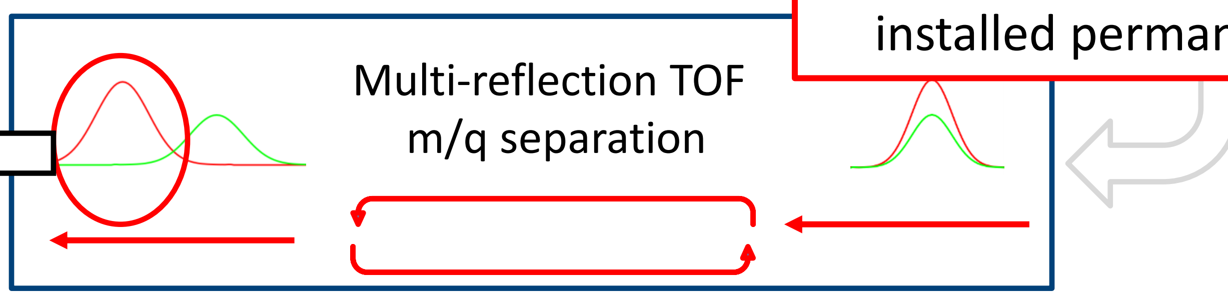
1. Tagging of reaction products
2. Stopping of ions in He gas cell
3. Possibility of laser-ionization (optional)
4. Cooling and bunching of ions
5. Separation from contamination in TOF spectrometer
6. High-precision m/q measurement in Penning trap

Mounted on a platform

- Off-line test of setup
- Interchangeable with focal plane detector of EMMA
- Penning trap will be installed permanently

Mass measurement
Penning trap

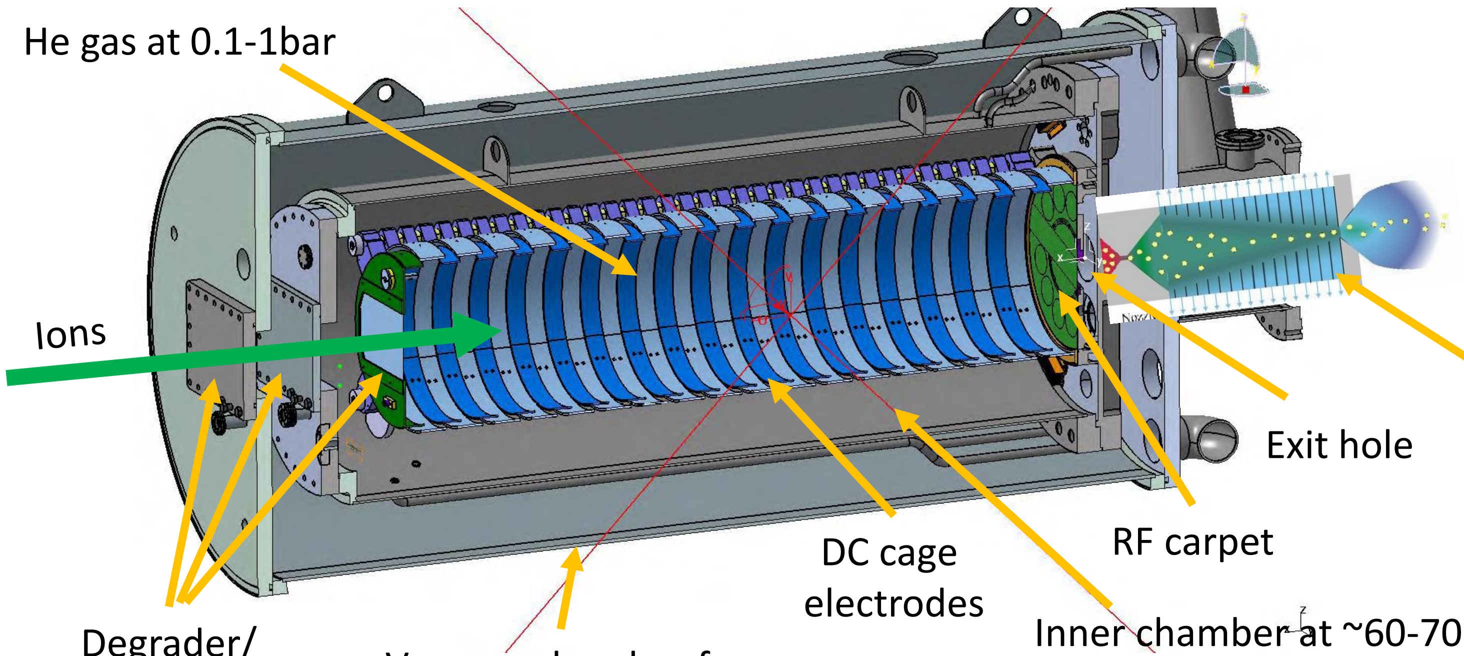
$$\nu_c = \frac{q}{m}\frac{B}{2\pi}$$

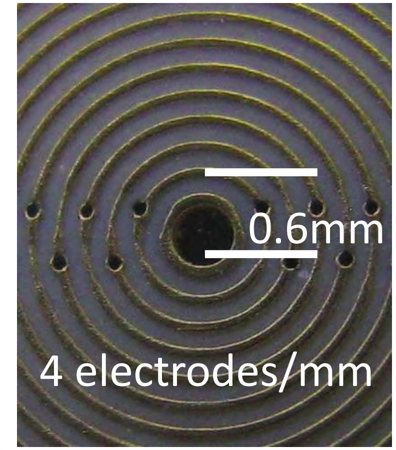


Gas stopper cell

Slide courtesy of T. Brunner

Design of cryogenic gas catcher for the Super-FRS @ FAIR
From http://www.euroschoolonexoticbeams.be/site/files/2013_05_ExoBeams13_PThirolf_GasCell.pdf



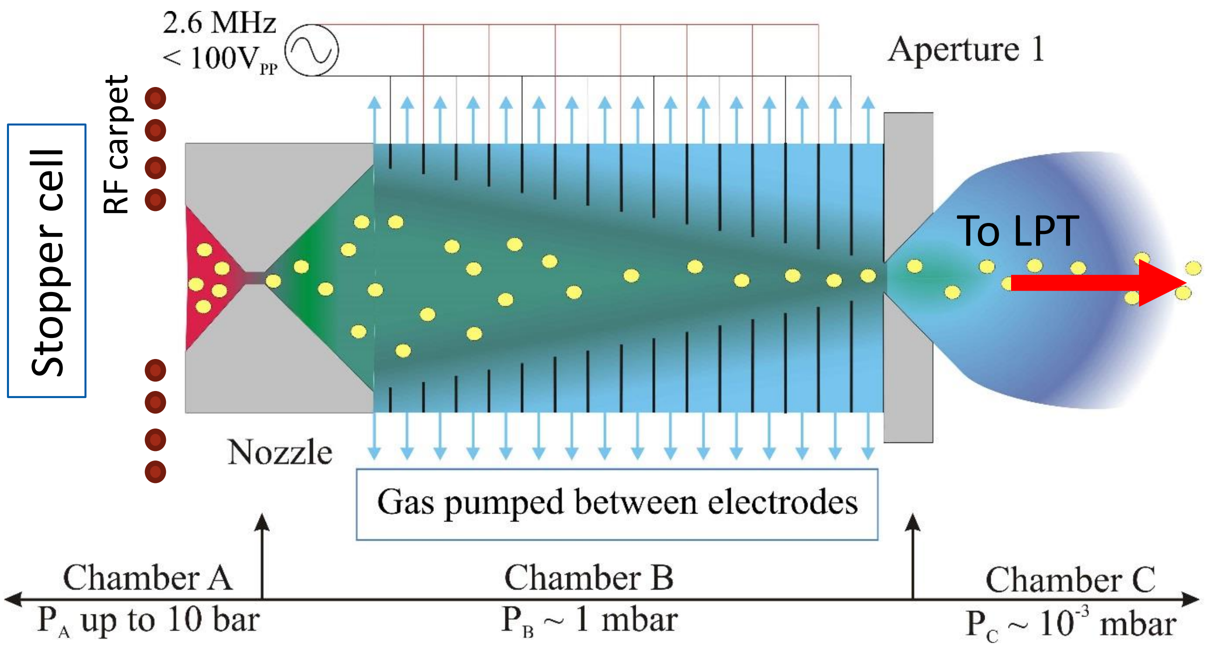


RF-carpet of cryogenic stopper
EPL, 96 (2011) 52001

- Gas stopper cells used at fragmentation facilities to stop RI-beams (GSI/FAIR, FRIB, RIKEN, KUL Leuven, CARIBU @ ANL, …)
- Extraction efficiencies of >10% have been observed
- Extraction times on the order of 10ms
- Up to 10^3 ions/s space charge effects negligible; at higher ion intensities reduced transmission efficiency due to space-charge effects
- Extreme pure gas required to reduce charge exchange and neutralization in the gas

RF funnel concept

Slide courtesy of T. Brunner



RF-funnel concept for Ba-tagging:

- Converging-diverging nozzle
- 2 Stacks total 301 electrodes
- RF-field applied to electrodes
- P_A = 10 bar, P_B = 1 mbar

V_{RF} = 120 V, f = 10 MHz
Simulated Ba^+ transmission ~95%

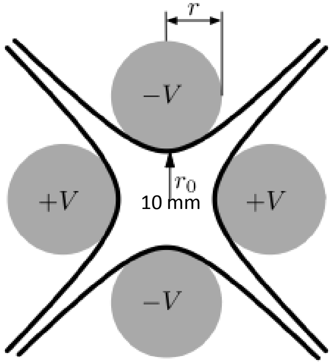
V_{RF} = 25V, f = 2.6 MHz
Simulated Ba^+ transmission ~72%

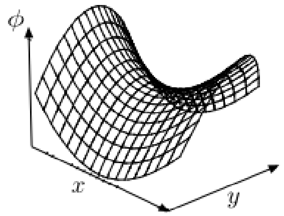
Int. J. Mass Spec. 379, 110 (2015)

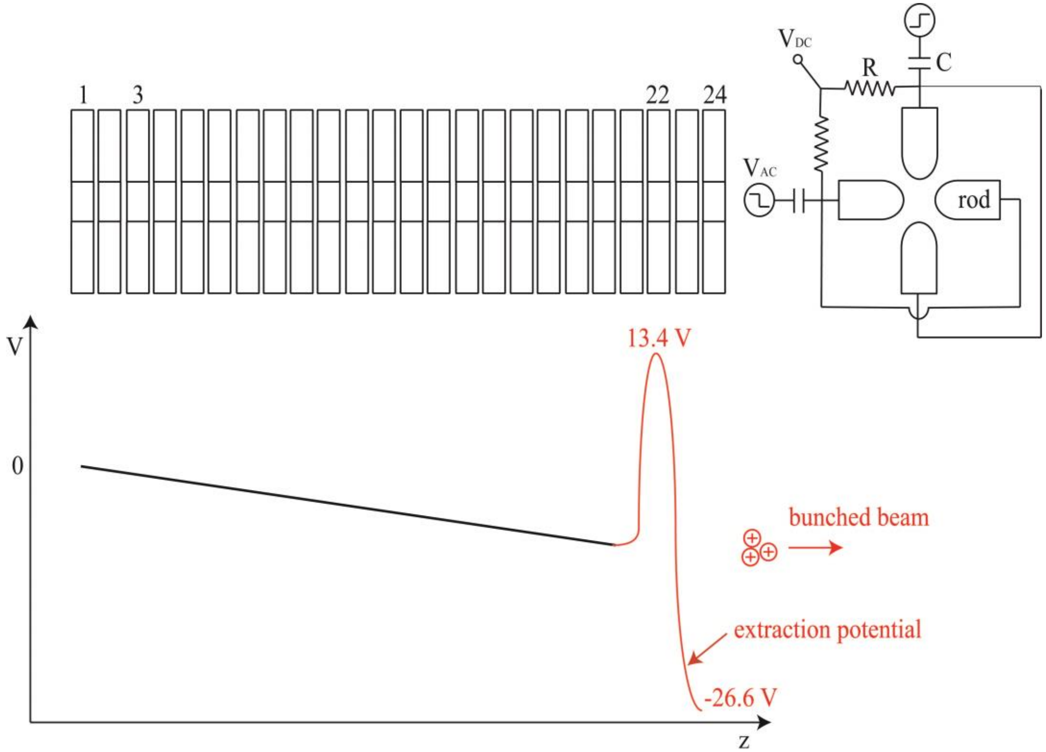
Possible to extract ions from 10 bar Xe → initial design (and Ba-tagging design) by V. Varentsov for ion extraction from 0.1-1bar He
→ Optimization of design by V. Varetsov at GSI-FAIR
→ Extraction times O(10ms)

Linear Paul Trap

Slide courtesy of T. Brunner

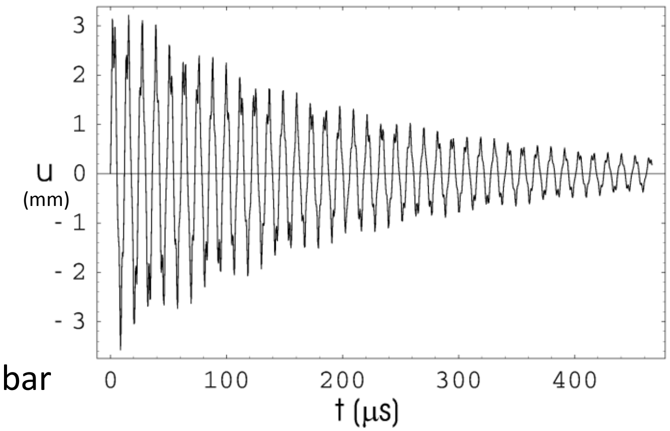






Necessary ingredients

- 250 kHz to 1 MHz RF along the electrodes
- Axial DC gradient
- Buffer gas cooling on the order of a few ms

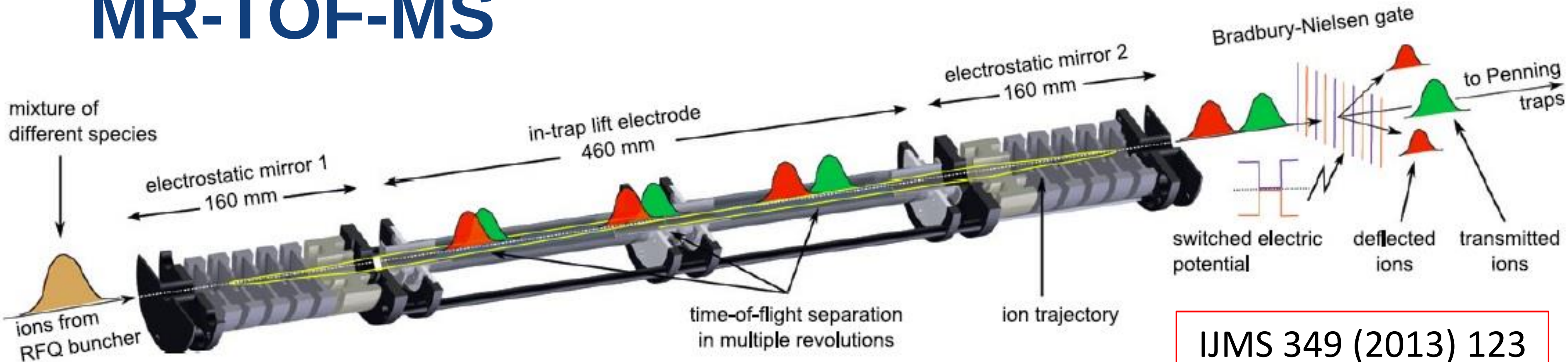


Similar to TITAN RFQ
NIMA 676 (2012) 32

Radial trajectory of ^{133}Cs in 2.5 x 10^{-2} mbar
Viscous drag model calculation

Slide courtesy of T. Brunner

MR-TOF-MS



IJMS 349 (2013) 123

- Multi-reflection time-of-flight mass spectrometer based on Greifswald/ISOLDE design
- Can be operated in beam cleaning mode ($\delta m/m \sim 10^{-4}$) or mass-measurement mode ($\delta m/m > 10^{-5}$)

$$R = \frac{t}{2\Delta t} = \frac{t_0 + nT}{2\sqrt{\Delta t_0^2 + (n\Delta T)^2}} = \frac{t_0/n + T}{2\sqrt{\Delta t_0^2/n^2 + \Delta T^2}}$$

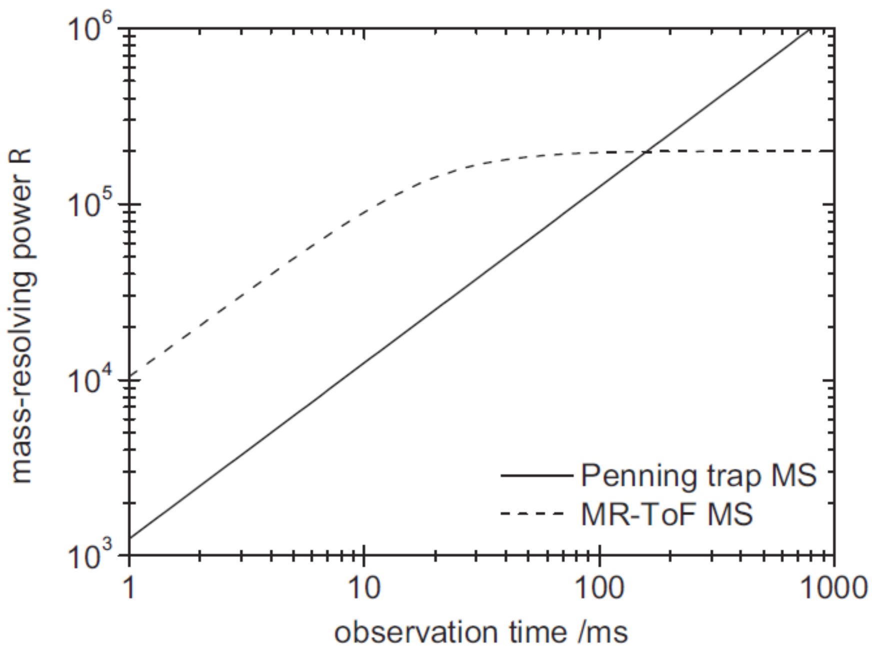
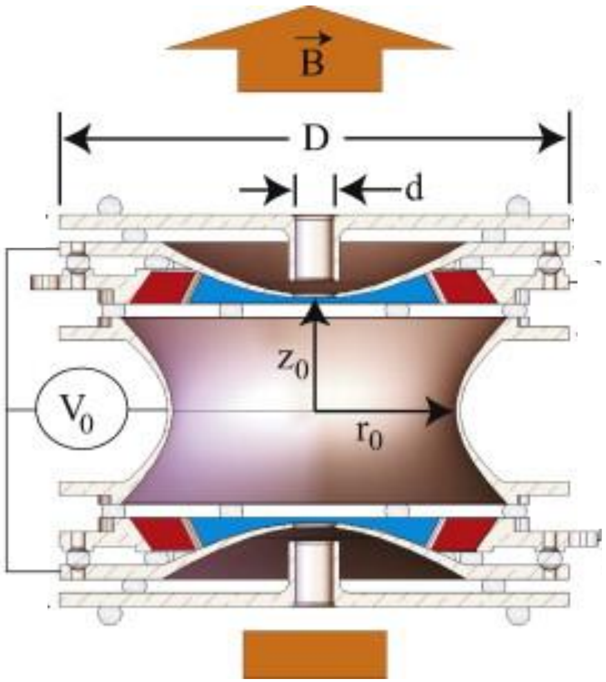


Fig. 11. Mass resolving power as a function of the observation time for ISOLTRAP's precision Penning trap ($B = 5.9$T) and MR-ToF MS for a typical ion of $A/z \approx 90$.

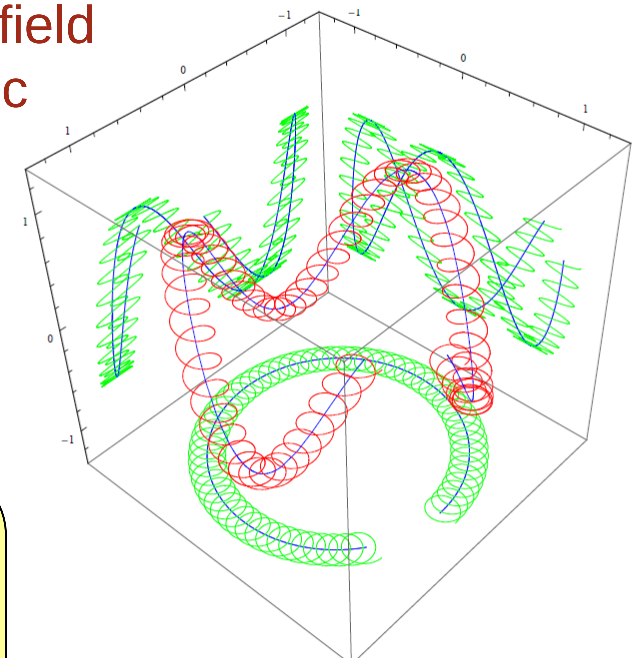
Resolution limited by dispersion of MR TOF

Penning trap



Cyclotron frequency: $\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$

Superposition of
- strong magnetic field
- weak electrostatic quadrupole field



Motion of ions well understood:

Three Eigenmotions can be coupled using RF

$$\nu_- + \nu_+ = \nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Allows us to manipulate motion:
transfer from one motion into the other

$\delta m/m > 10^{-7}$
Half lives below 10ms
measured at TITAN

Summary

- EMMATrap allows measurement of very exotic isotopes that are inaccessible through ISAC
- All techniques proposed for EMMATrap well established at radioactive ion facilities
- Local ion trapping expertize at TITAN
- Ion extraction development using RF funnel at McGill in collaboration with V. Varentsov

Thank you!
Merci

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