RRTF, Darmstadt 2018

Experimental nuclear physics for the r-process: Masses - Discussion

- Available techniques
- What can be done!
- Precision limits etc.
- Soon to come (T. Dickel)

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June 7th, 2018

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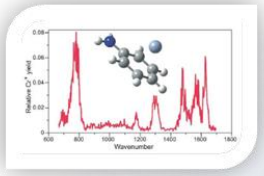
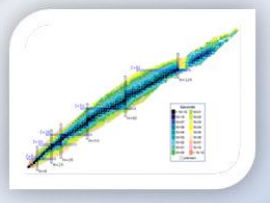
Why measuring atomic masses?





short half-lives

long half-lives

$\delta m/m$

$\leq 10^{-5}$

CHEMISTRY

NUCLEAR STRUCTURE

$\leq 10^{-7}$

ASTROPHYSICS

WI STUDIES

$\leq 10^{-9}$

METROLOGY

NEUTRINO PHYSICS

$\leq 10^{-11}$

CPT/QED TEST

Techniques of choice:

* storage-ring mass spectrometry
* Penning-trap mass spectrometry

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Why are the limits?

Limits	Storage ring	Penning trap (MR-ToF)
accessible $T_{1/2}$	μs	ms
sensitivity/ yield	1/day	1/min
resolving power	~ 100 keV	~ 1 keV (unstable) ~ 1 eV (stable)
precision	~ 10 keV	~ 100 eV (unstable) < 1 eV (stable)

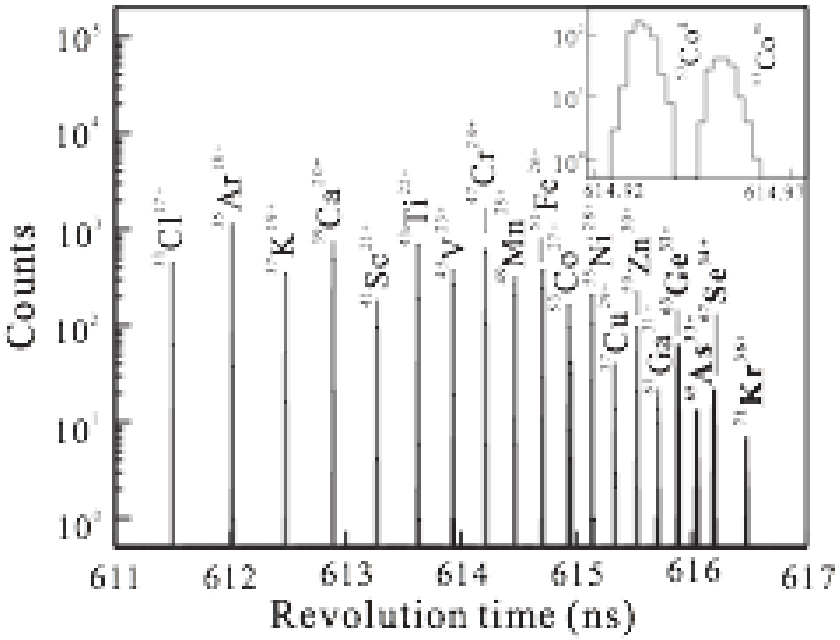
Limit on yields: Storage ring

NUCLEAR ASTROPHYSICS

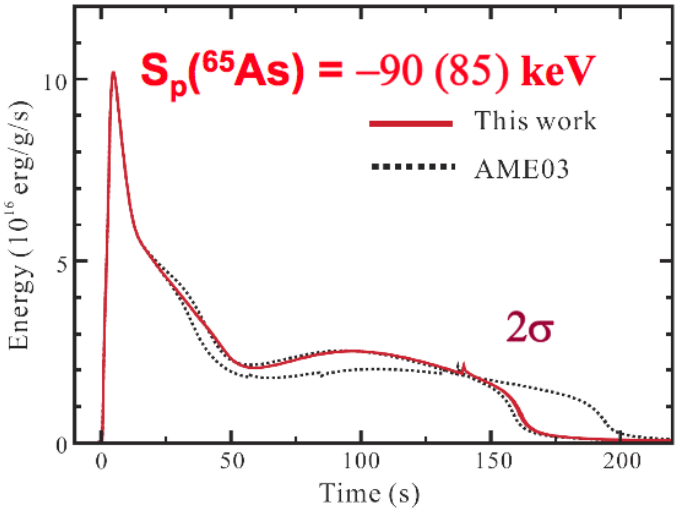
Star bursts pinned down

One of the main uncertainties in the burn-up of X-ray bursts from neutron stars has been removed with the weighing of a key nucleus, ^{65}As, at a new ion storage ring.

NATURE PHYSICS | VOL 7 | APRIL 2011 | www.nature.com/naturephysics



Light curve shape of Type I x-ray burst



Rate of ^{71}Kr was just 2 ions/day

X.Tu, et al., PRL 106 (2011) 112501

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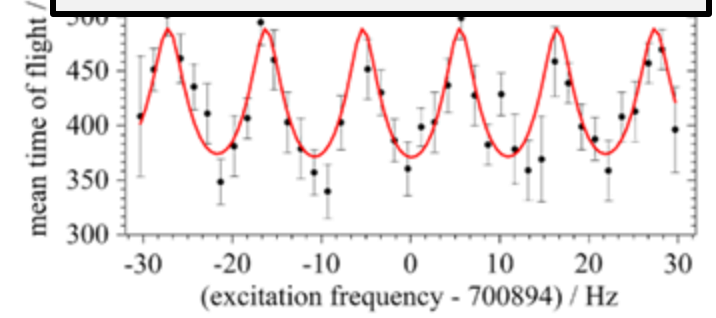
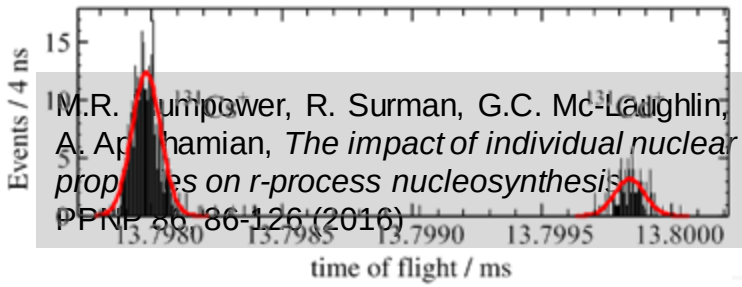
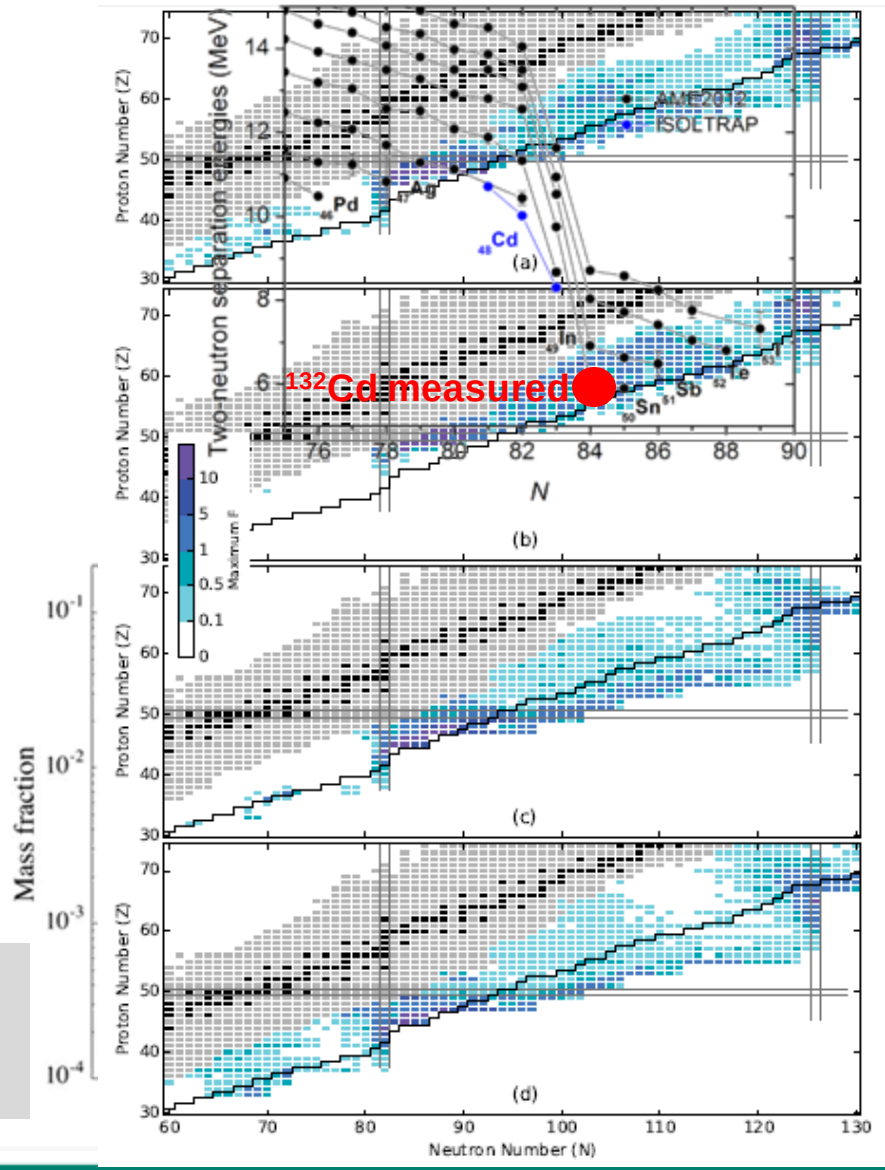
Limits on yields: Penning traps / MR-ToF

Cd	Measured with	Half life /ms	Yield /ions/uC
129	Penning trap MR-ToF-MS	(242?) (104?)	12000
130	Penning trap MR-ToF-MS	162	330
131	MR-ToF-MS	68	39
132	**MR-ToF-MS**	**98**	**~4**





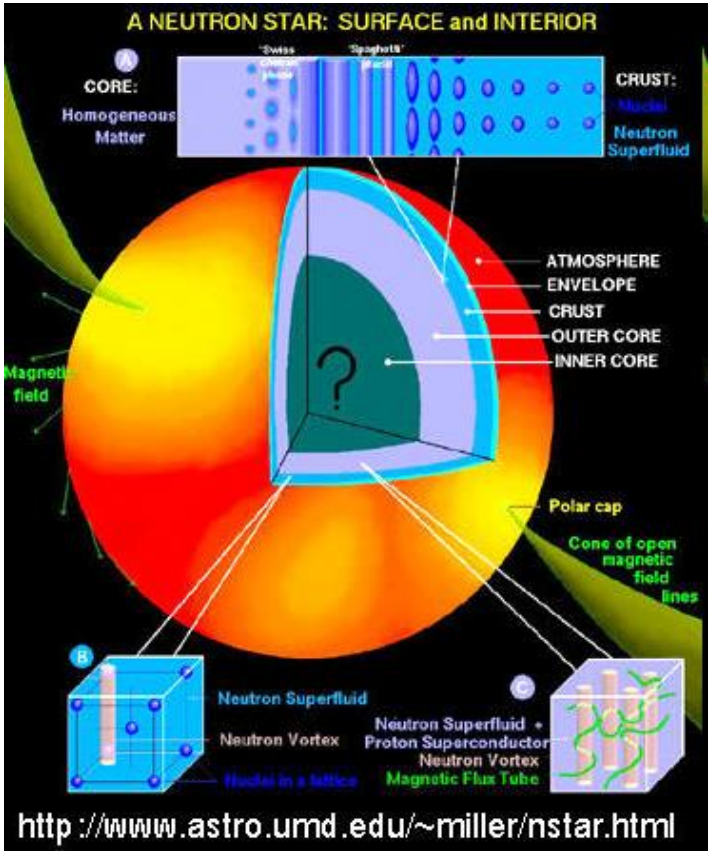
M.R. Mumpower, R. Surman, G.C. Mc-Laughlin, A. Aprahamian, *The impact of individual nuclear properties on r-process nucleosynthesis*, PPNP 86, 86-126 (2016)

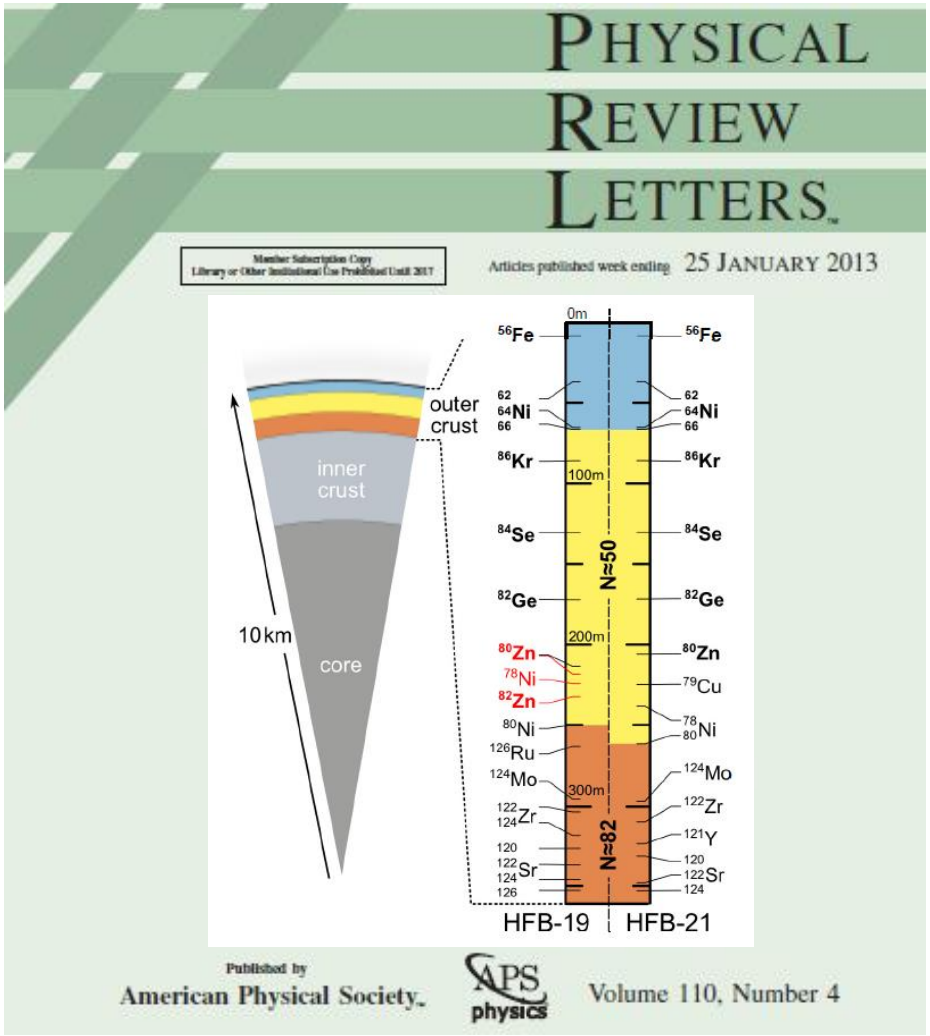


PRL

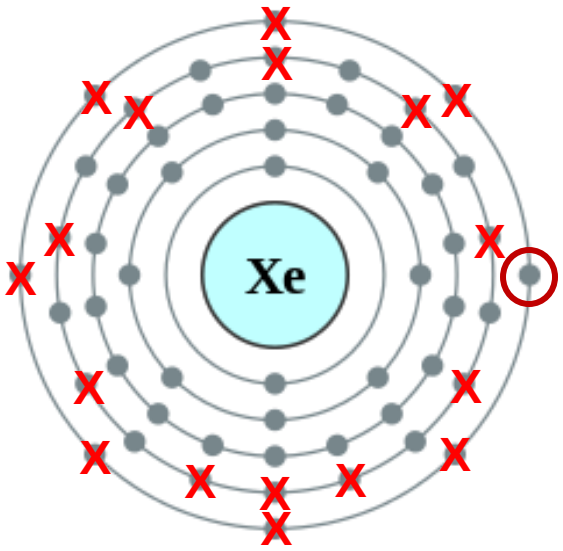
Limits on mass precision: traps (I)

Composition of the outer crust of a neutron star





Limits on mass precision: traps (II)



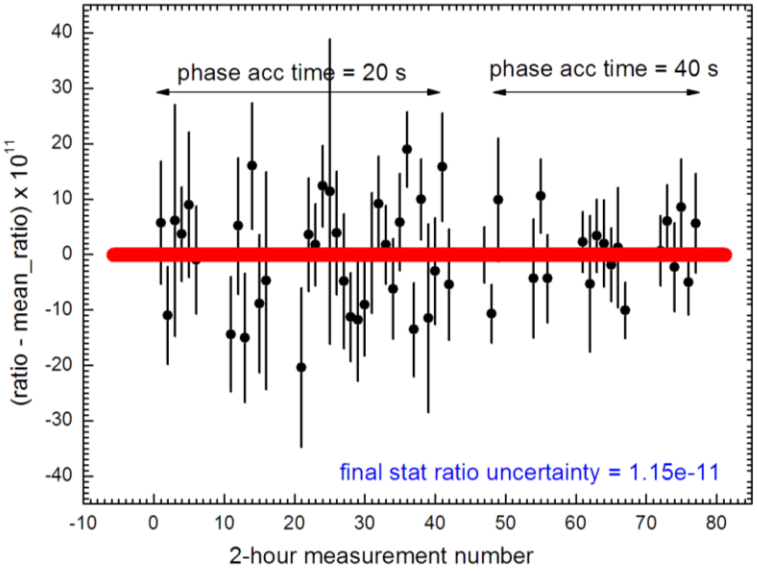
Electron configuration of xenon ($Z = 54$):

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6$

$[Kr]\ 5s^2\ 4d^{10}\ 5p^6$

Measure the mass difference of Xe^{17+} and Xe^{18+} yields the binding energy of the 18th electron.

→ *Stringent tests of BS-QED calculations!*



PENTATRAP@MPIK:

$\delta m/m = 1.1 \cdot 10^{-11}$ ($\delta m \sim 1.4$ eV)

Exp. (prel.): $B(4d^1)_{Xe} = 434.6\ (1.4)$ eV

Theorie : $B(4d^1)_{Xe} = 434.0\ (0.5)$ eV

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Approved experiments at GSI

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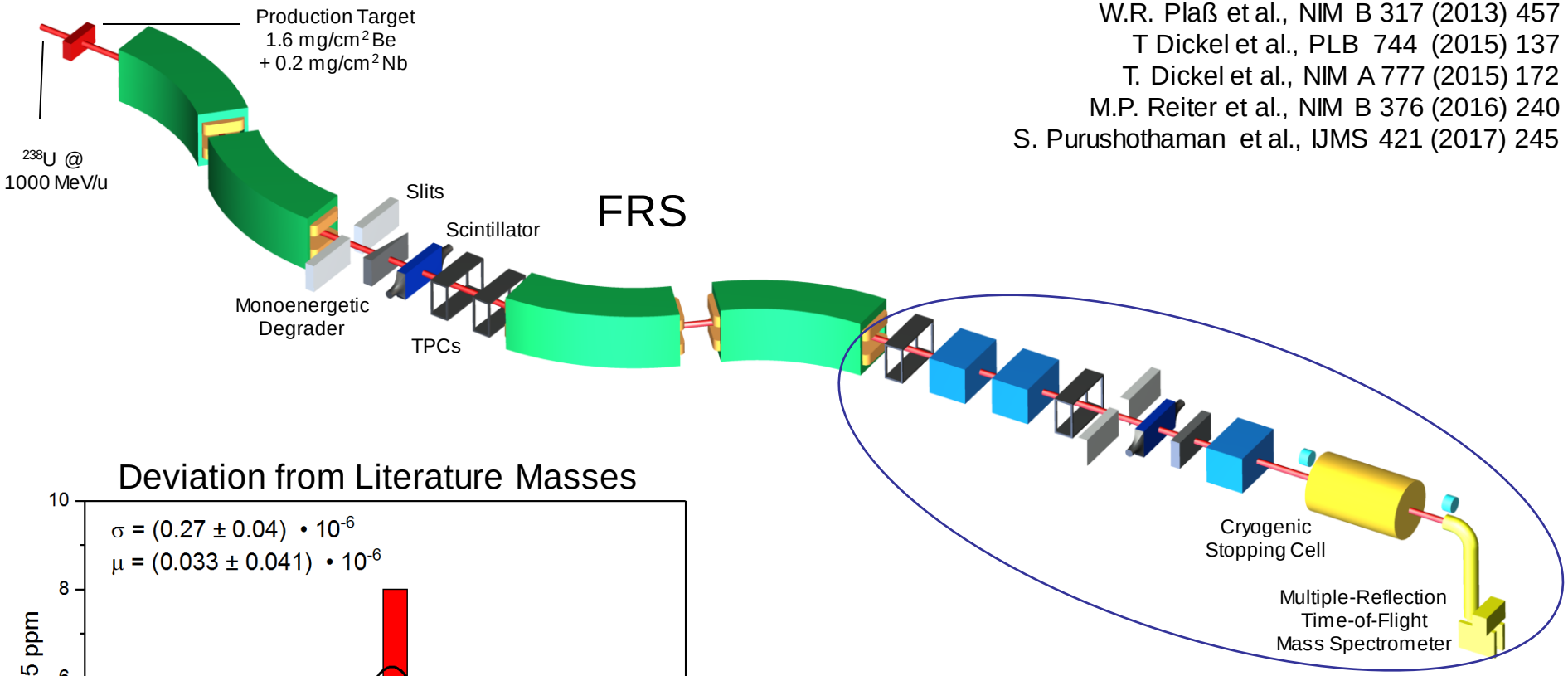
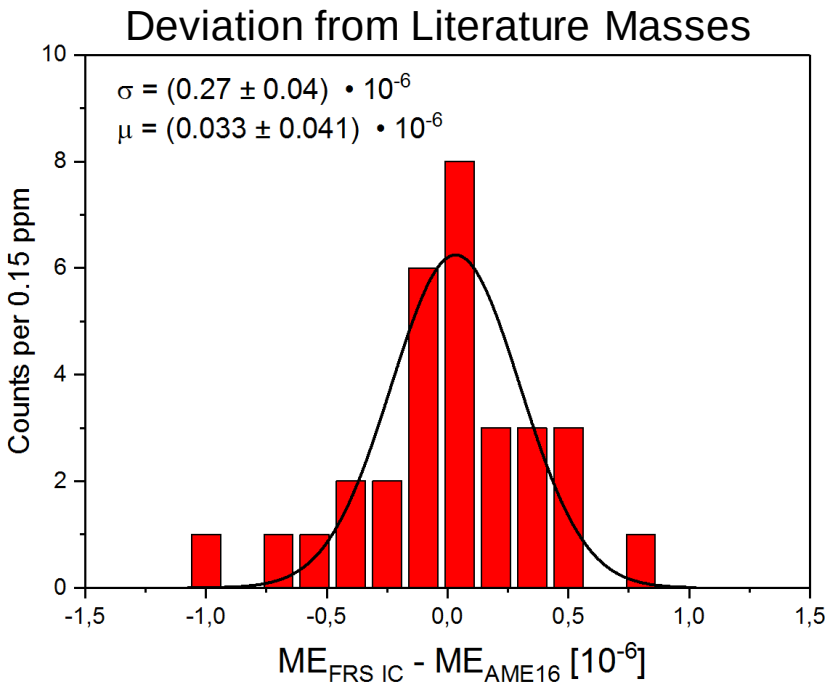
Timo Dickel

Mass Measurements with the FRS Ion Catcher

W.R. Plaß et al., NIM B 317 (2013) 457
T Dickel et al., PLB 744 (2015) 137
T. Dickel et al., NIM A 777 (2015) 172
M.P. Reiter et al., NIM B 376 (2016) 240
S. Purushothaman et al., IJMS 421 (2017) 245





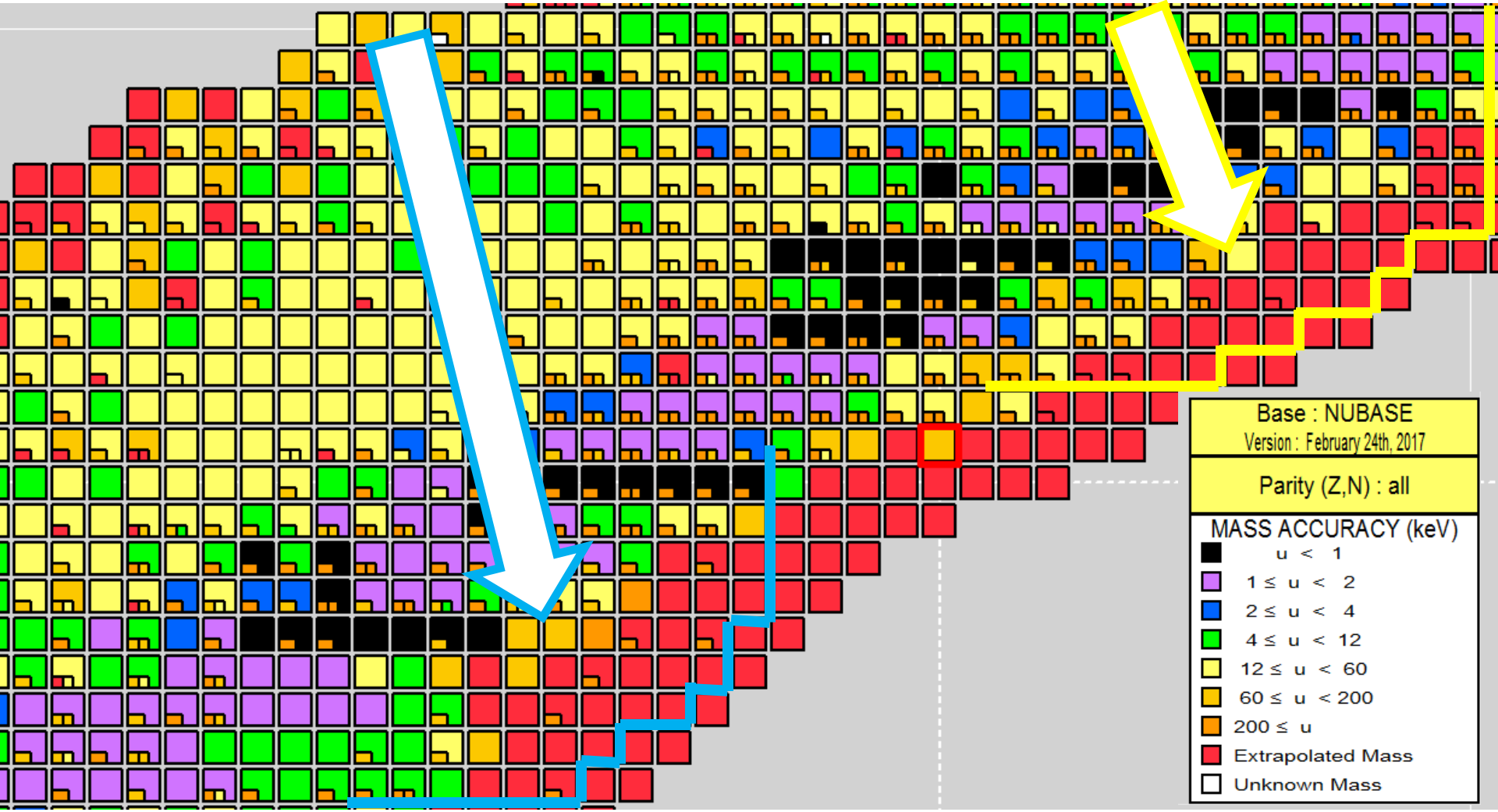
Mass measurements with an accuracy >= $6 \cdot 10^{-8}$

- > 40 short-lived ground states
  (as short lived as 18 ms)
- 15 isomers
- down to 10 events only

Reach of Mass Measurements in FAIR Phase-0

Multi-Nulceon Transfer
(S475, 2019, T. Dickel et al)
Rare-earth peak r-process

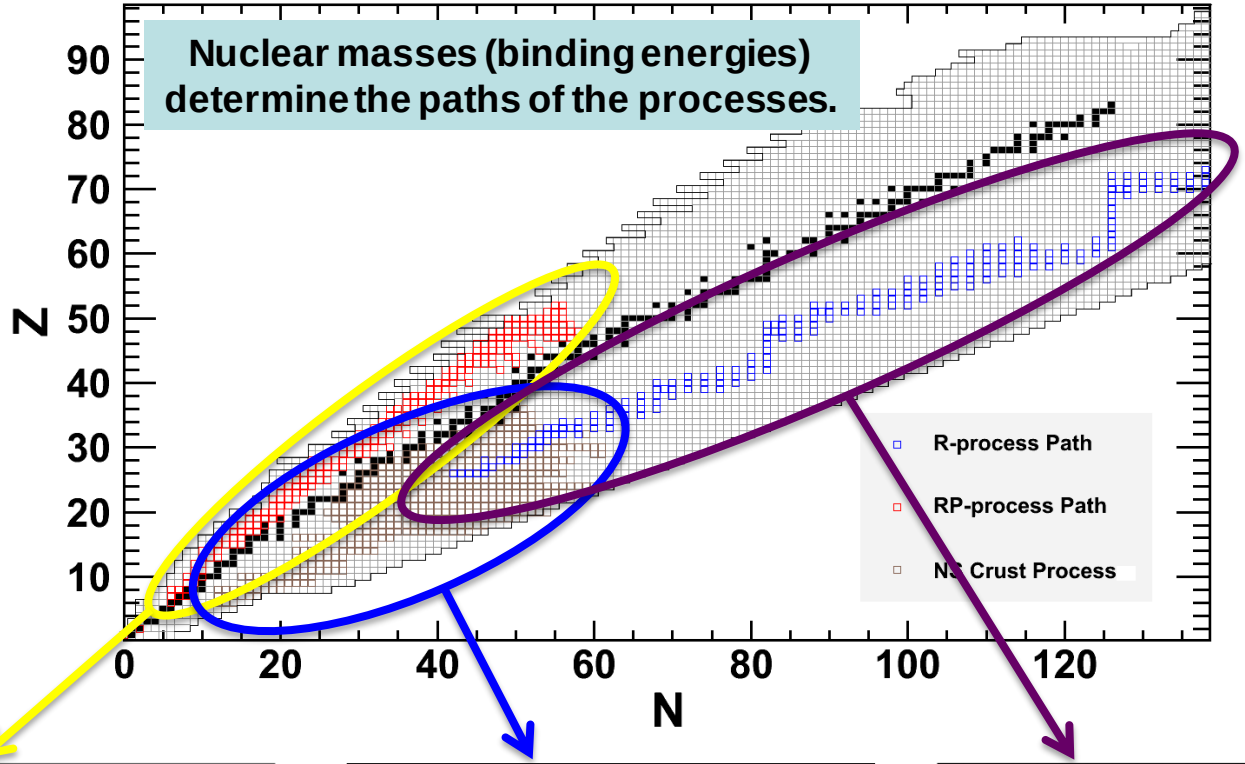
New Isotope Search
(S468, 2018, S. Pietri et al)
3rd peak r-process

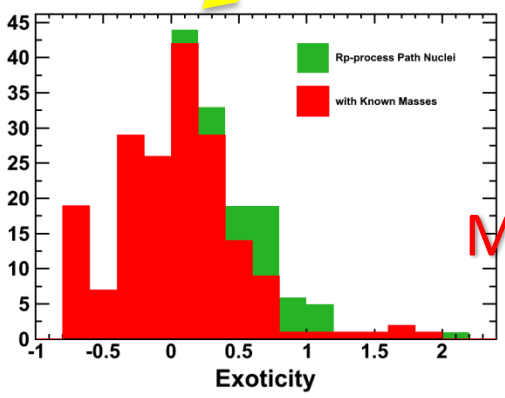


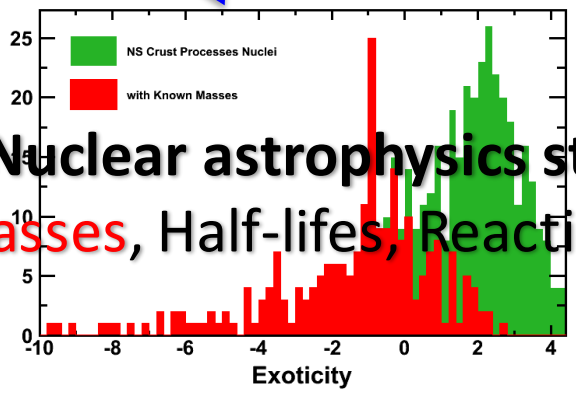
Open questions - Discussion

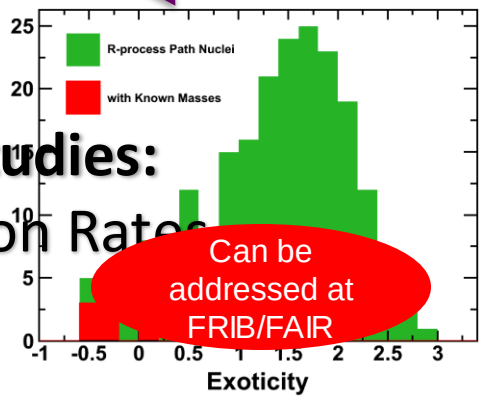
- Is there a key nuclide (holly grail) in r-process physics?
- Is there a key isotopic chain?
- What is the required mass uncertainty? 1keV, 10keV, …
- Which part of that nuclear/atomic physics data is already known, which part remains yet unmeasured, and which part will be accessible in the new RIB-facilities?
- Many nuclides are not accessible and their masses have to be predicted. What are the models of choice? Any specific tests needed?

Future perspectives e.g. at FAIR









Nuclear astrophysics studies:

Masses, Half-lifes, Reaction Rates

Can be addressed at FRIB/FAIR

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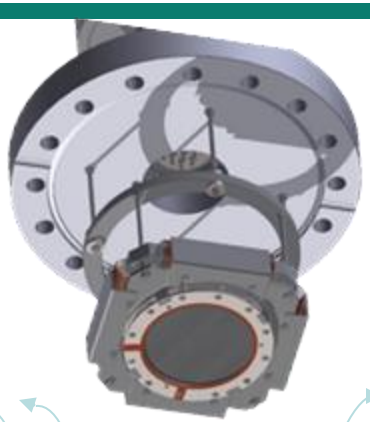
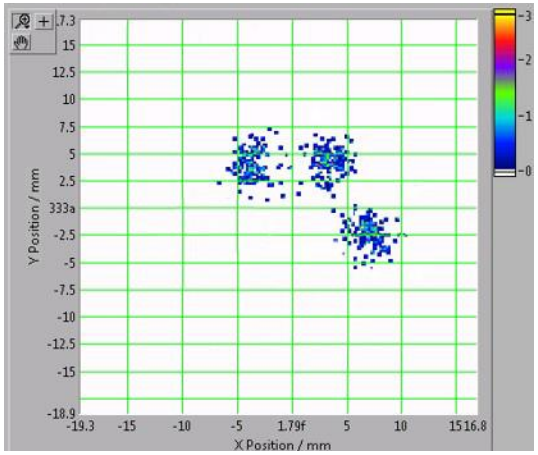
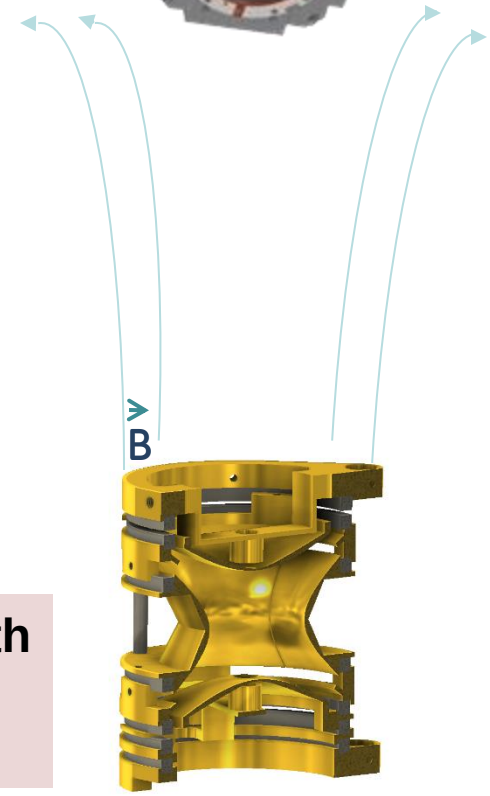
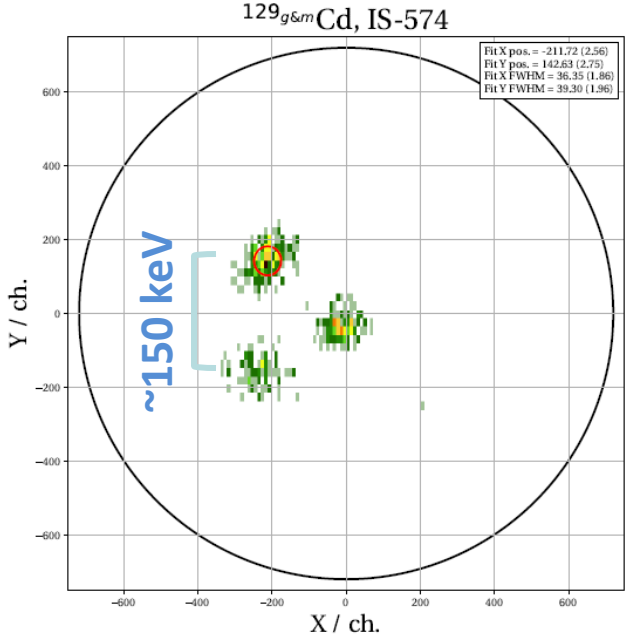
Limits on resolving power: traps

S. Eliseev *et al*., Phys. Rev. Lett. 110 (2013) 082501









Excited states with E_{ex} < 10 keV can be resolved.

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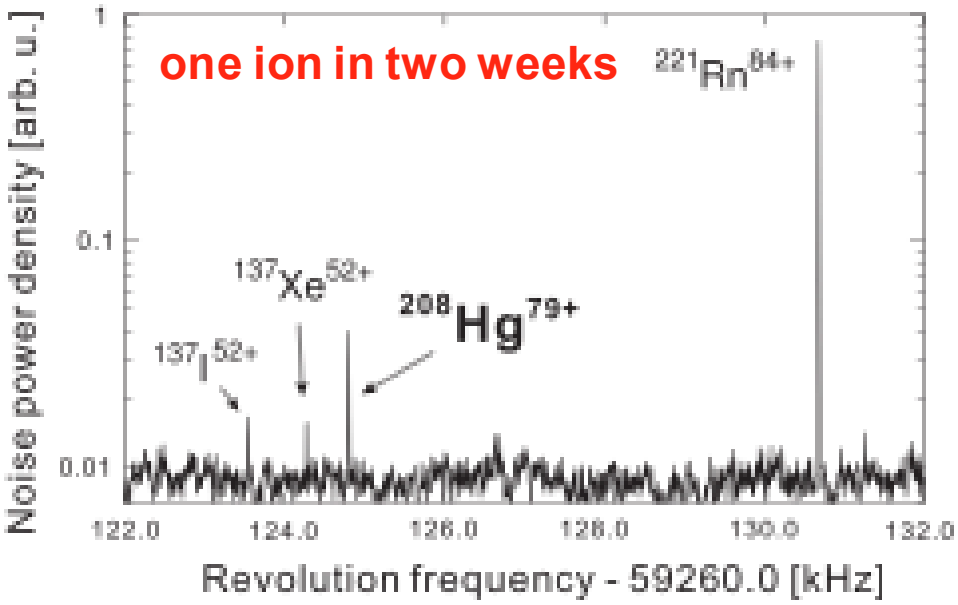
Yield Direct Mass Measurement of ^{208}Hg Nuclide



$$\delta V_{pn}(Z,N) = \frac{1}{4}\Big[B(Z,N) - B(Z,N-2) - B(Z-2,N) + B(Z-2,N-2)\Big]$$

p-n interactions are sensitive to the spatial overlaps of the proton and neutron wave functions

L. Chen, Yu.A. Litvinov, W.R. Plass, et al., PRL 102 (2009) 122503