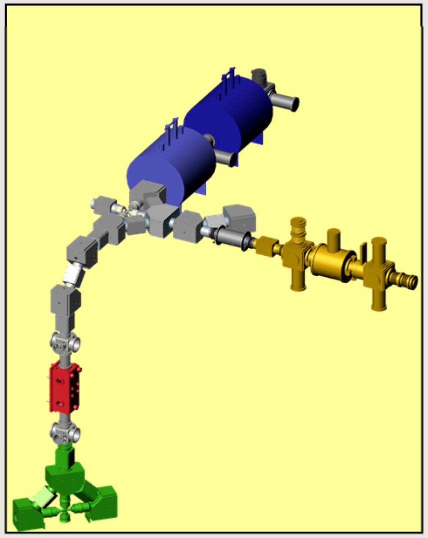


nuclear physics with TITAN

Precision mass measurements
using ion traps
for Nuclear Physics

J. Dilling

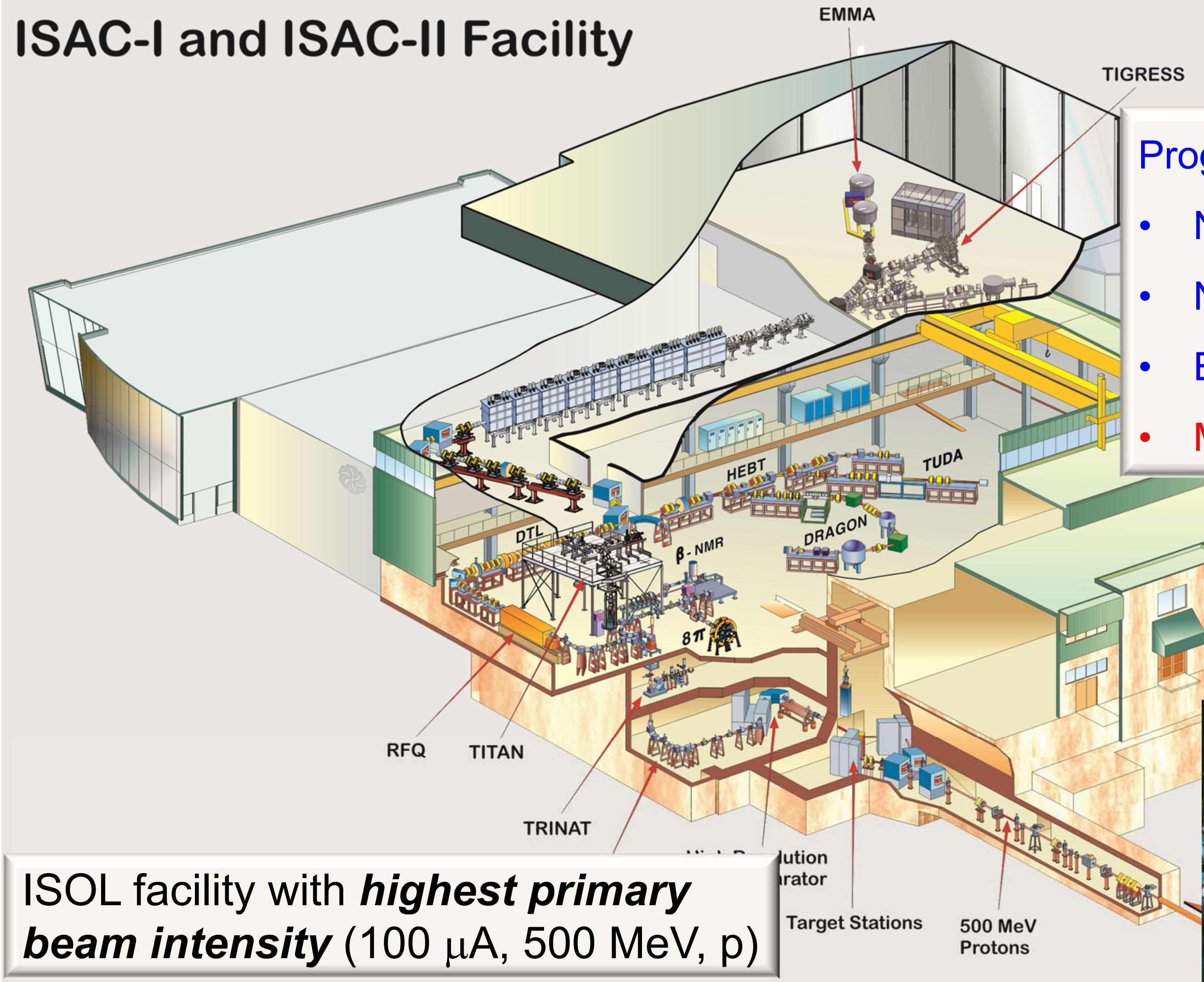
TRIUMF/University of British Columbia
Vancouver, Canada

Theory workshop @ TRIUMF
February 18-21 2014

outline

- Rare beams at ISAC
- Mass measurements
  - Motivation
  - Ion traps
- Examples:
  - Halos
  - ^{20,21}Mg
  - Island of Inversion measurements
  - N-rich Ca isotopes
  - Applications of mass measurements in nuclear-astro

ISAC rare isotope facility

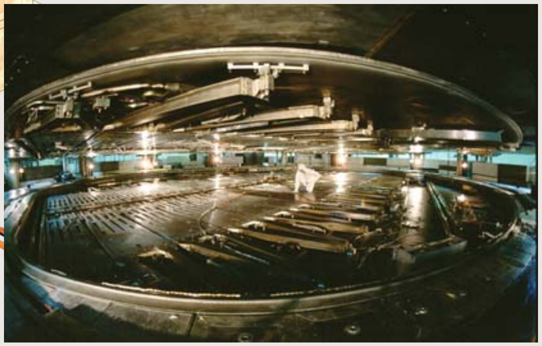


Programs in

- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science

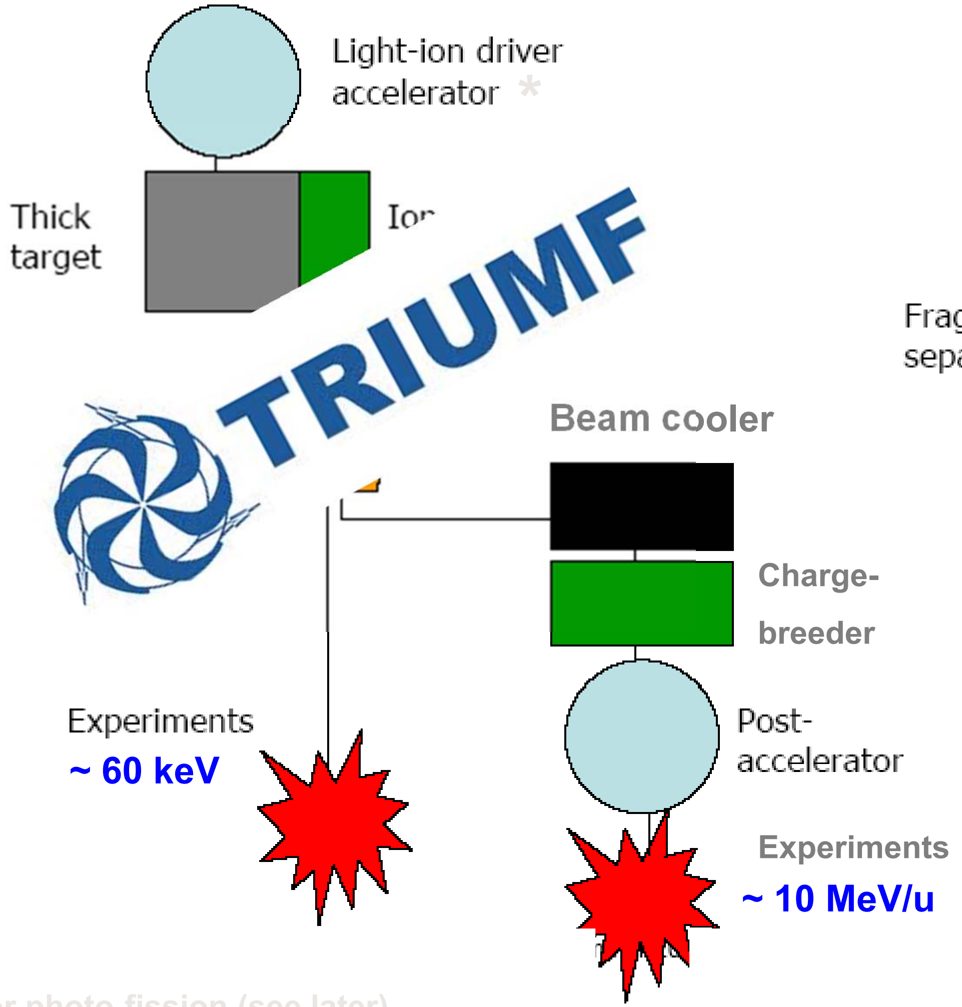
ISOL facility with ***highest primary beam intensity*** (100 μA, 500 MeV, p)

ISOL User facility with ~ 1000 users

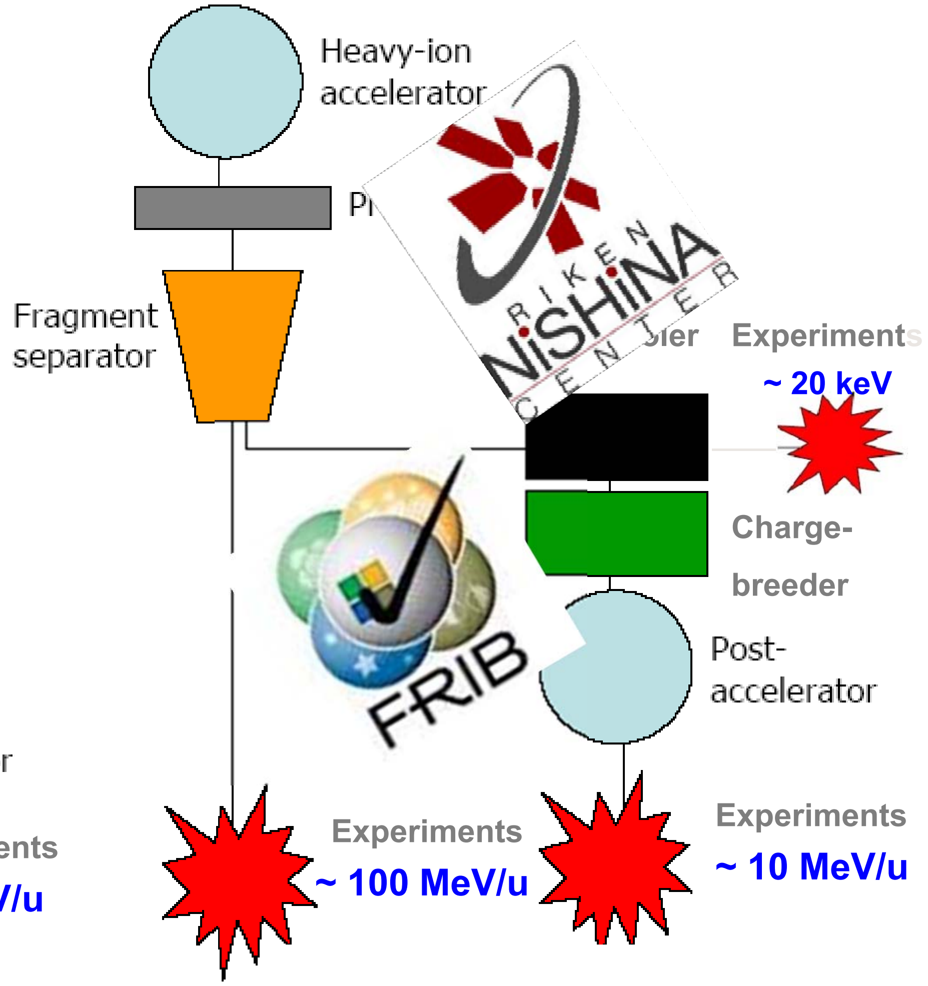


How to get the rare isotopes… rare beam facilities

Isotope Separation On-Line (ISOL)



In-Flight Fragmentation / In-Flight Fission



* or photo-fission (see later)

TRIUMF

TRIUMF's isotopes

Proton-induced reactions

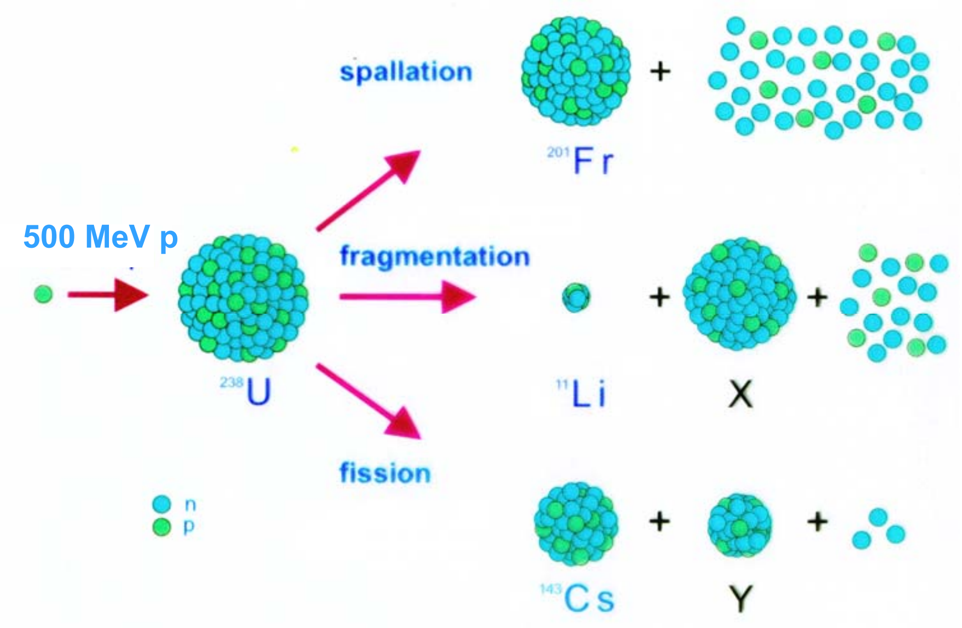
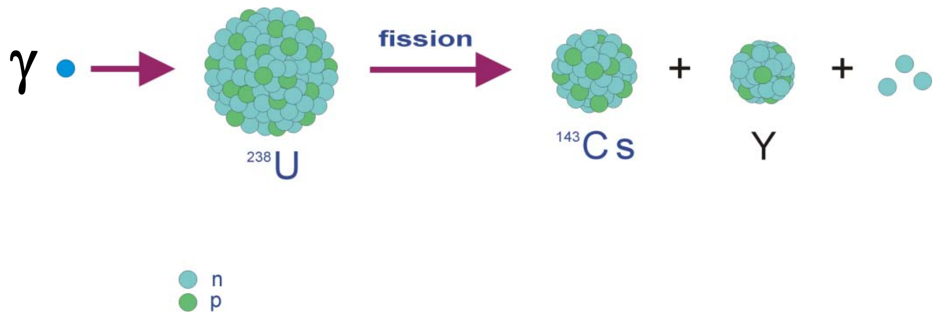
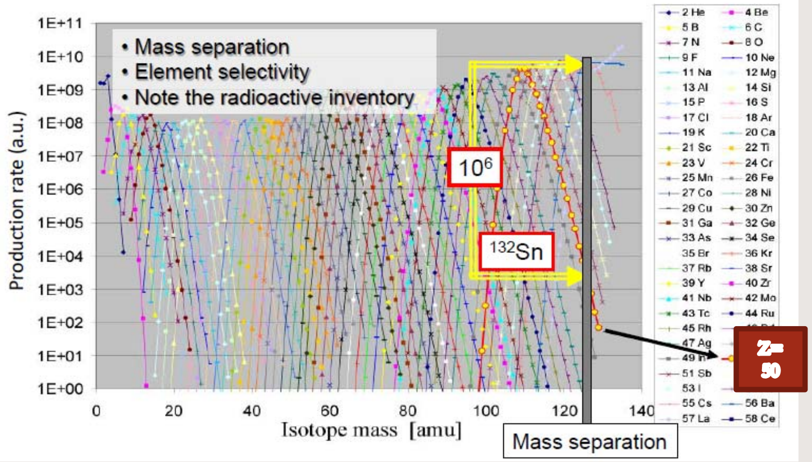


Photo-induced fission





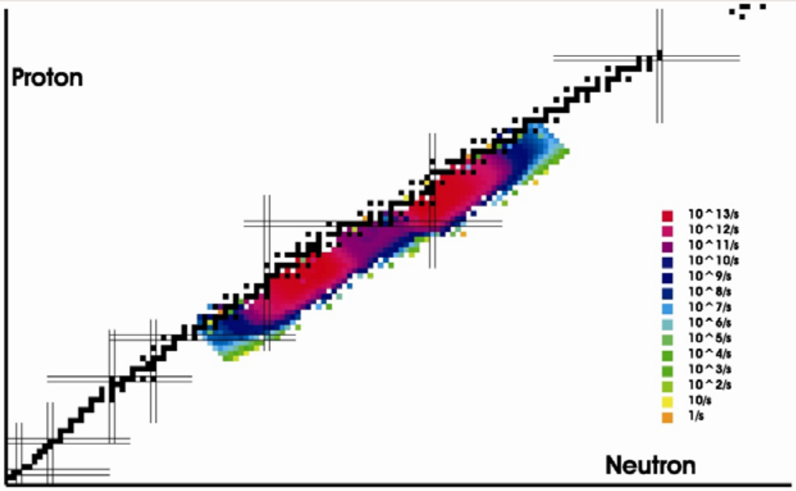
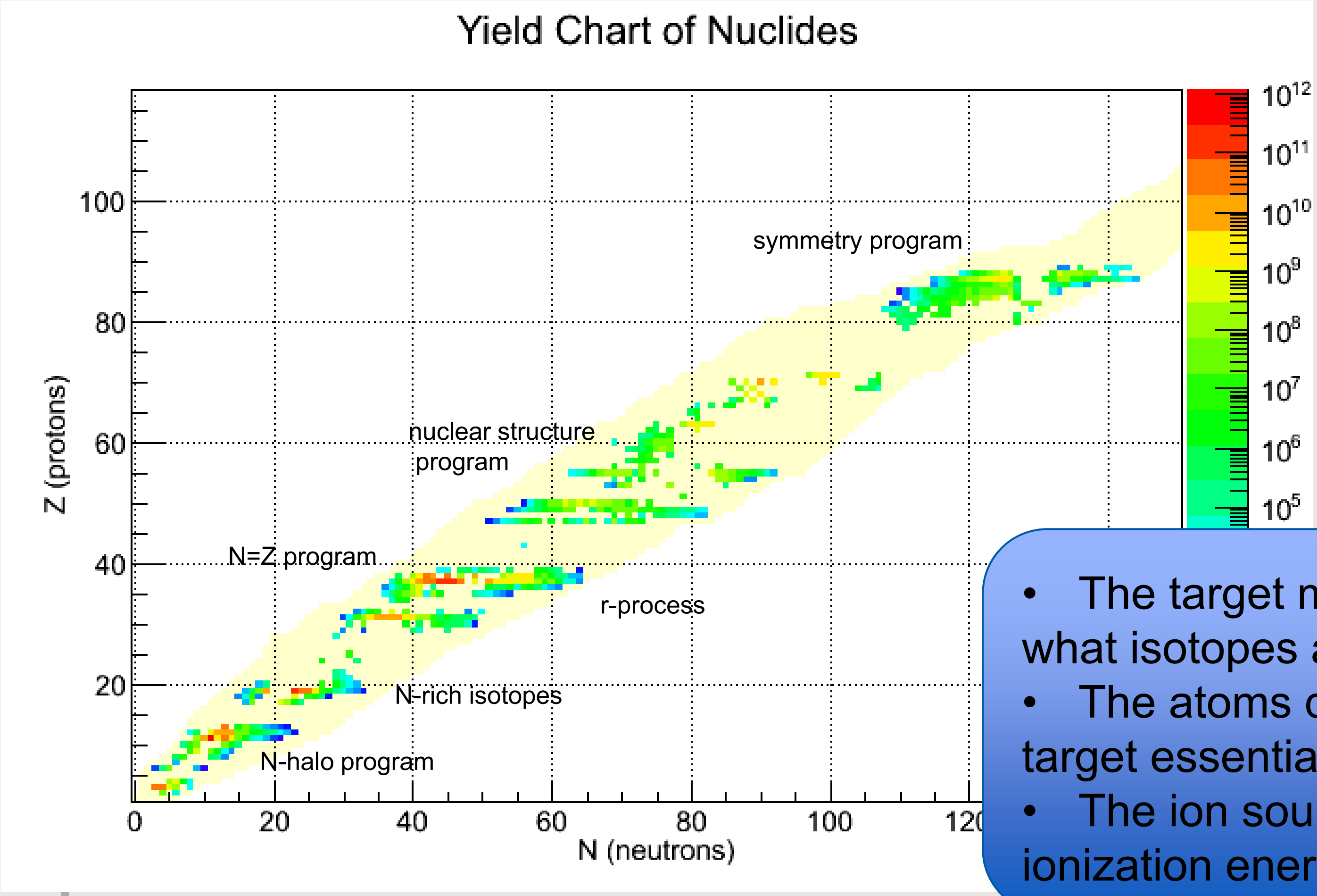
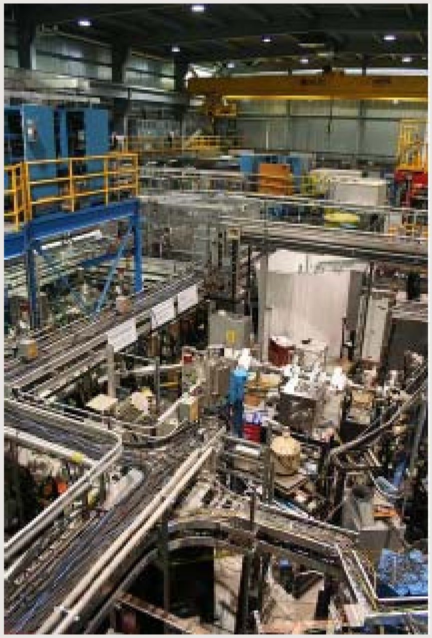


Photo-fission products using 50 MeV 10 mA electrons on to Hg convertor & UC$_x$ target.

ISAC rare isotope facility

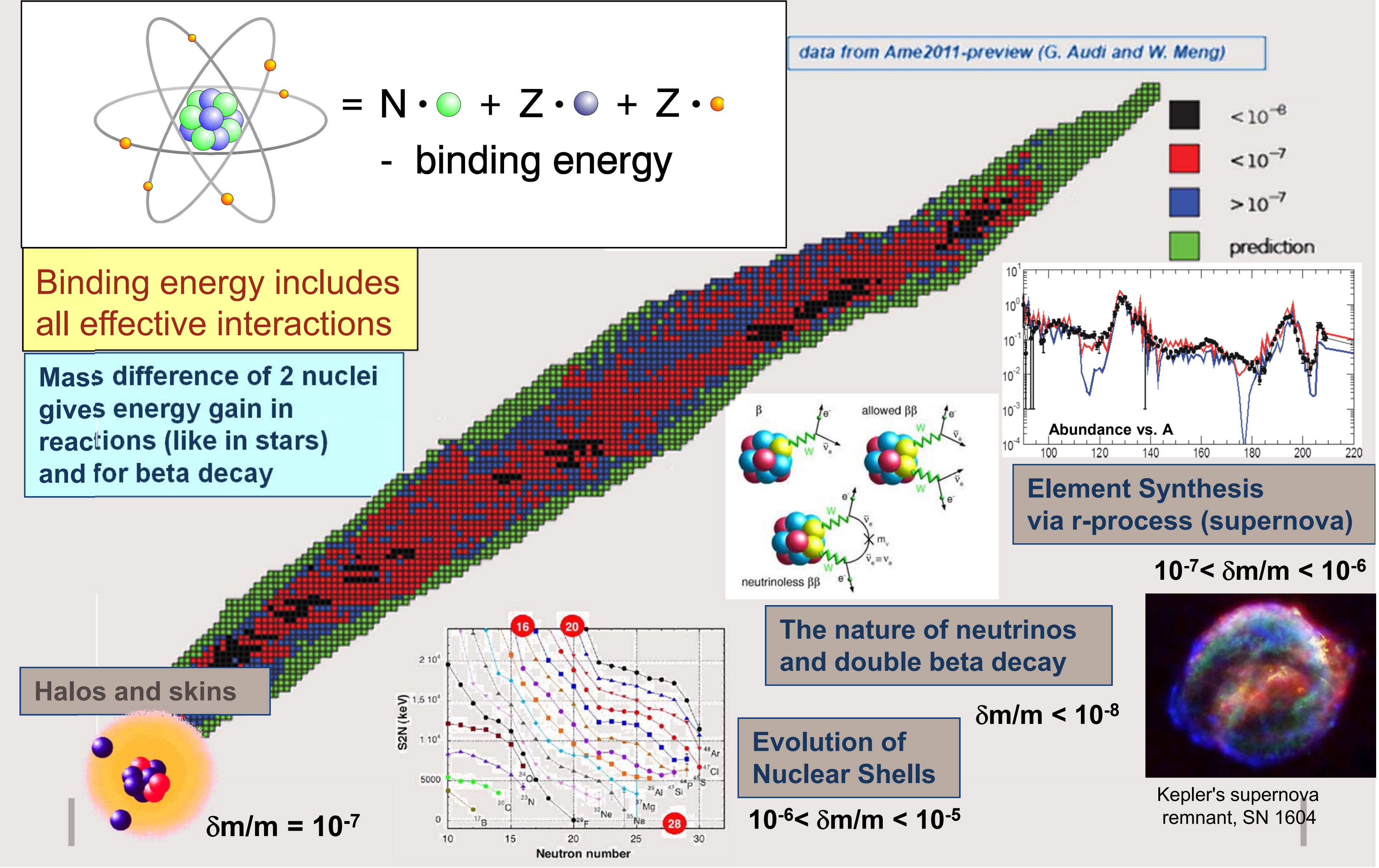
Isotopes delivered at ISAC





- The target material determines what isotopes are produced.
- The atoms defuse out of the target essentially at rest.
- The ion source is matched to the ionization energy, can be selective.

Nuclear physics via atomic mass measurements!



= N • ● + Z • ● + Z • ●

\- binding energy

Binding energy includes all effective interactions

Mass difference of 2 nuclei gives energy gain in reactions (like in stars) and for beta decay

Halos and skins

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

Evolution of Nuclear Shells

$10^{-6} < \delta m/m < 10^{-5}$

The nature of neutrinos and double beta decay

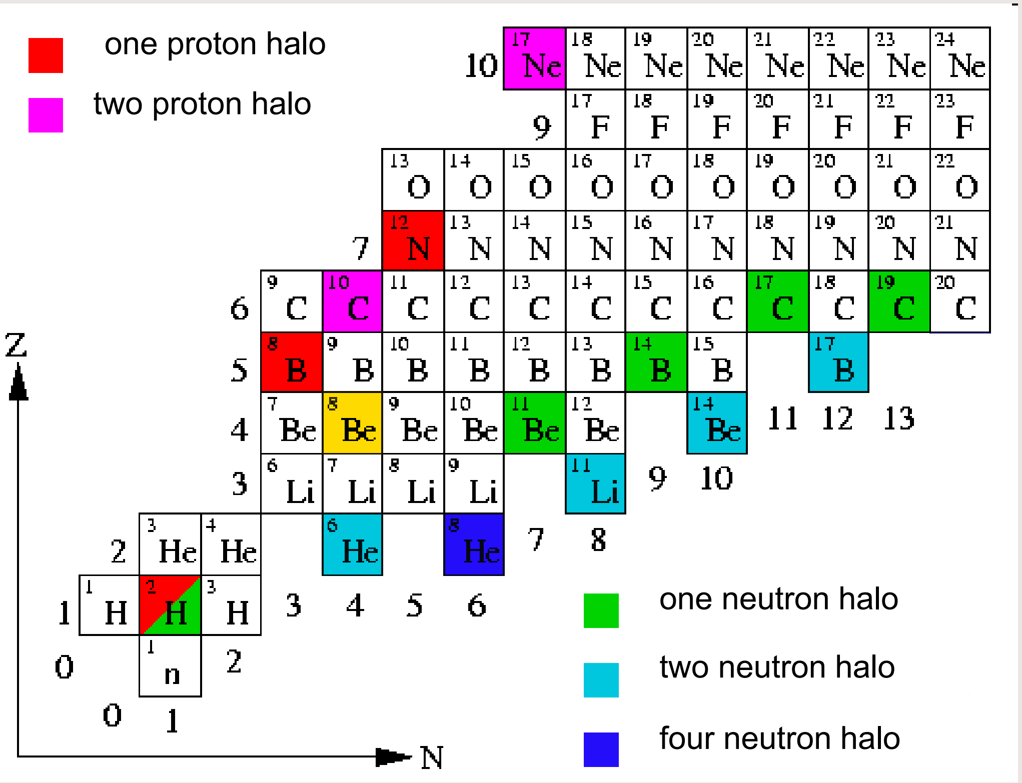
$\delta m/m < 10^{-8}$

Element Synthesis via r-process (supernova)

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

Kepler's supernova remnant, SN 1604

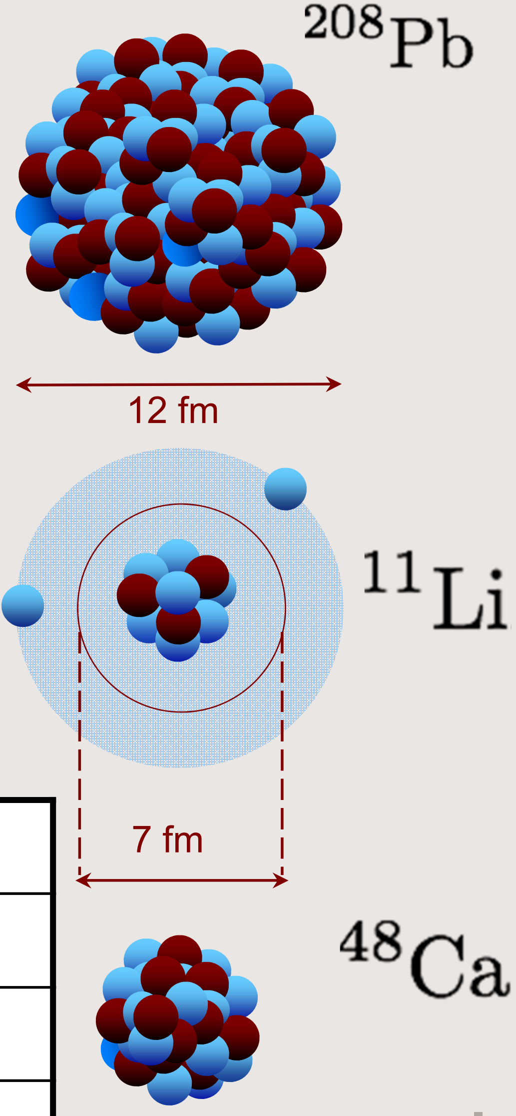
Light neutron rich isotopes: a special breed: but difficult from an experimental point of few.



few nucleon system, good for tests of theory, BUT:

- **Difficult to produce and measure**
- **Production of isotopes is low, typically a few/sec to 1000s/ sec**
- **Short half-lives, but require good precision (~1keV)**
- **A challenge for experiments**

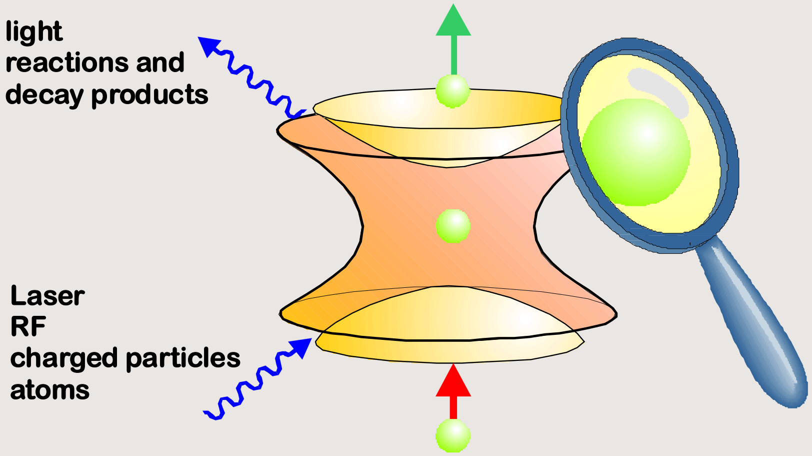
isotope	$T_{1/2}$
^{8}He	119 ms
^{11}Li	8.8 ms
^{14}Be	4.4 ms

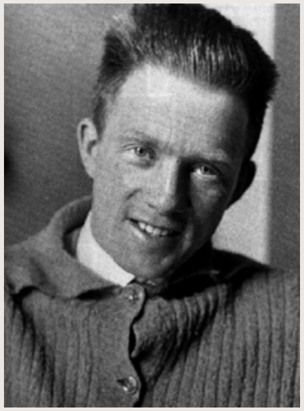


Ion Traps

a well developed tool to get answers : controlled & robust storage:

Precision and maniulation




W. Heisenberg

Long-time storage in well-defined fields ⇒

precisio

MASS measurement

STORAGE

↓

PRECISION

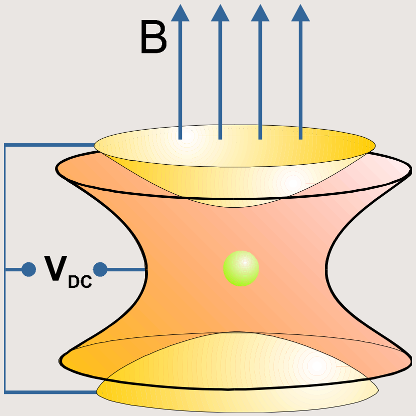
$\Delta t \cdot \Delta E > h / 2\pi$

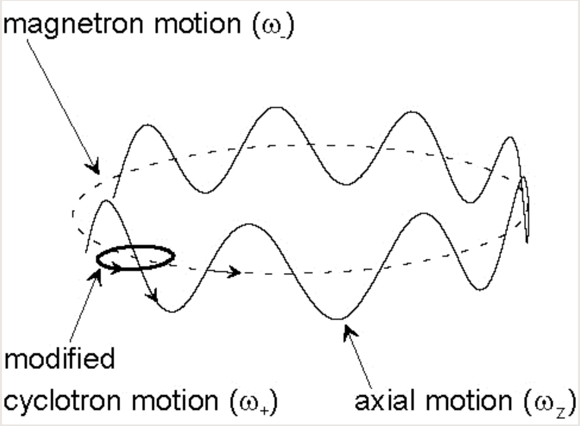
Confinement and interaction with gas or other charged particles (electrons), laser light, … ⇒

ION MANIPULATION

ION TRAPS
invented for stable particles & produced inside the trap

Penning trap:
Static electric quadrupole + magnetic field

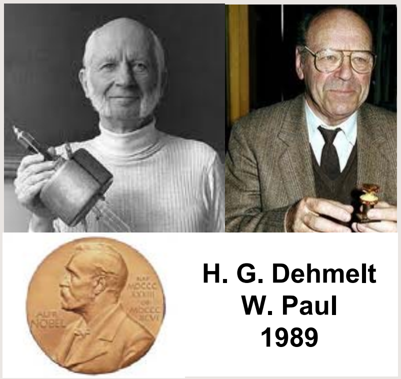




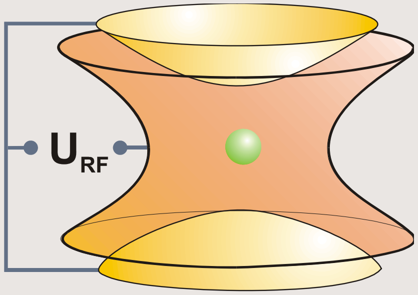
3 harmonic oscillations

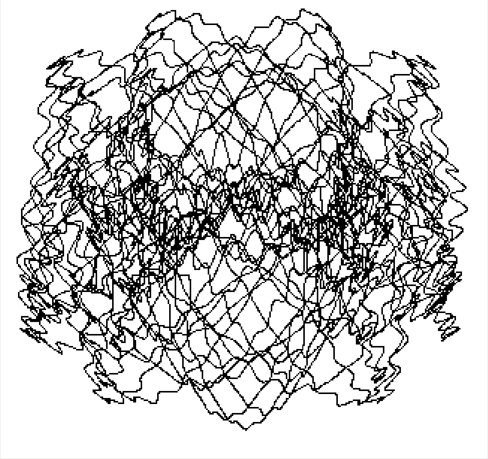
[Suited for precision experiments.]

3D confinement


H. G. Dehmelt
W. Paul
1989

Paul trap:
Oscillating electric quadrupole field

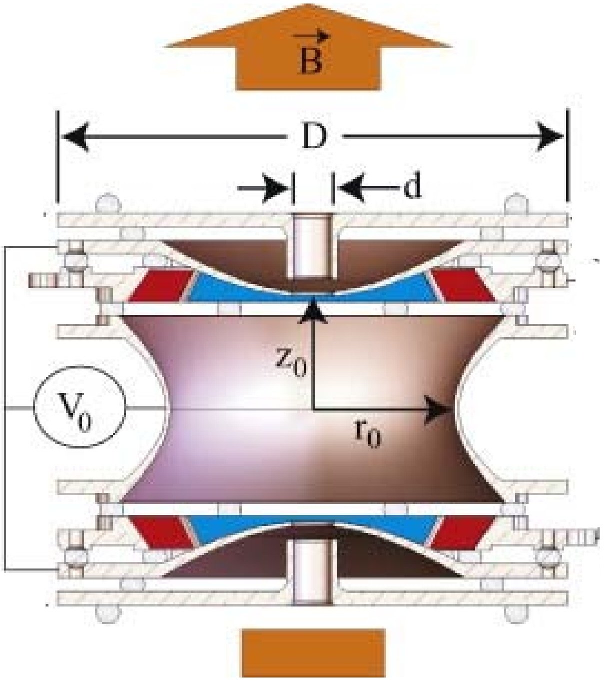




micromotion + macromotion

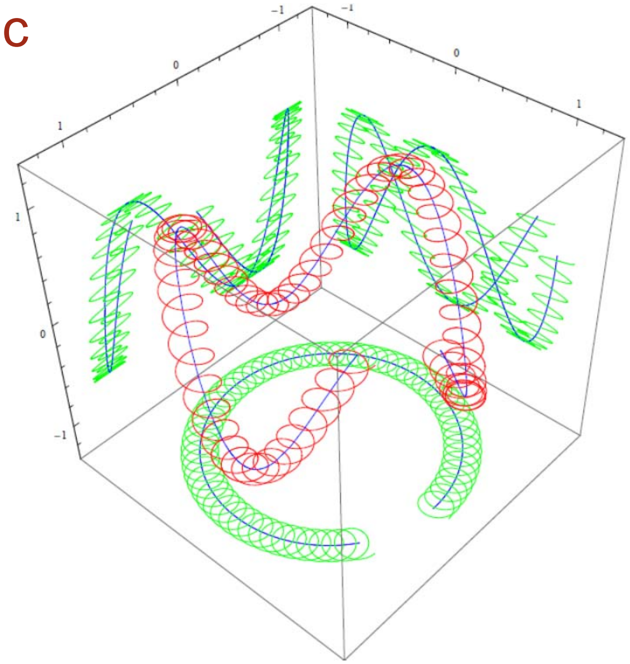
[Suited for manipulation techniques of hot ions.]

Penning Trap: Single ion quantum manipulation



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

Superposition
- strong magnetic field
- weak electrostatic quadrupole field



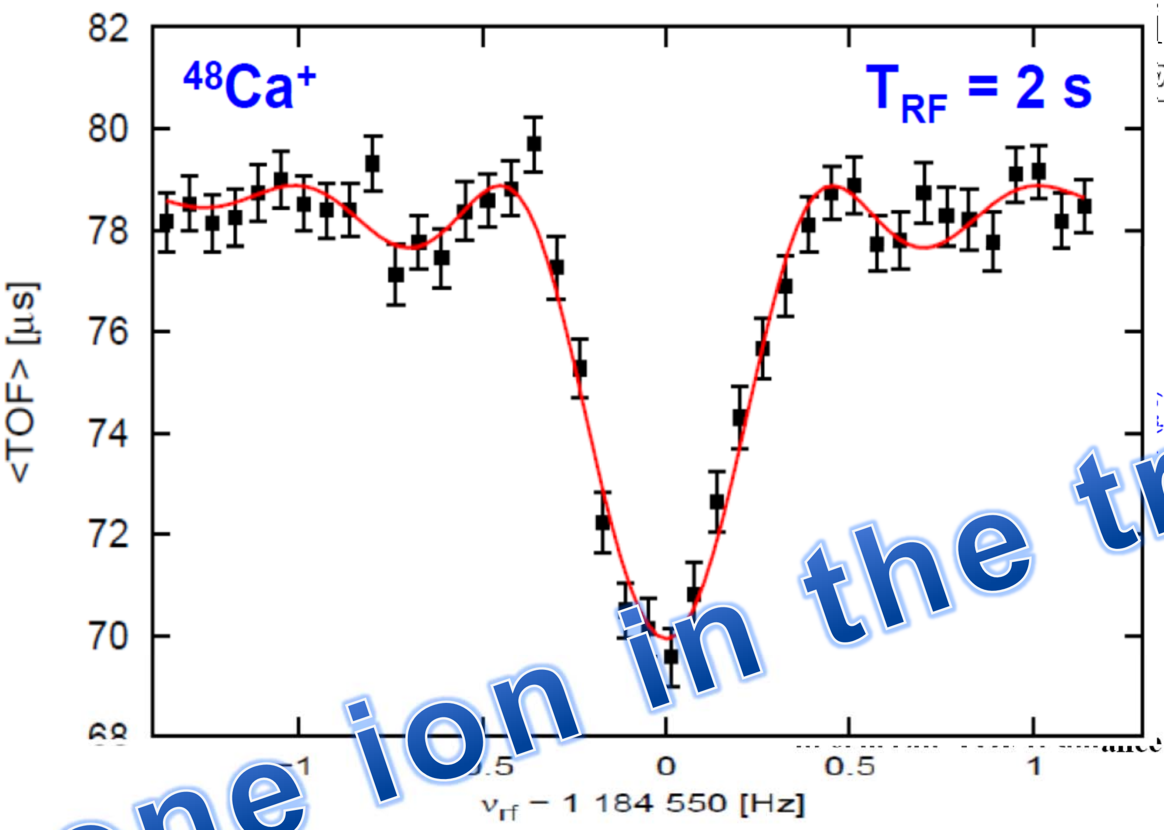
Mass measurement via the determination of the cyclotron-frequency:
Measurement is done with one ion in the trap,
repeat to scan over frequency range.
Total number of ions for mass spectrum ~200.

Mass determination

Time-of-Flight Ion Cyclotron Resonance (TOF-ICR)

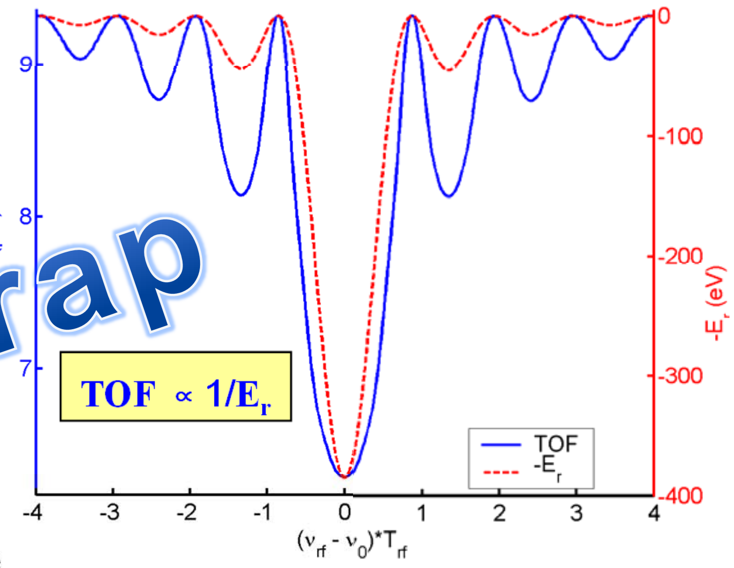
Ions in the trap are

G. Gräff *et al.* Z. Phys. A, 297 (1980)



genmotions

$$\frac{E_r(\omega_{rf})}{B}\frac{\partial B(z)}{\partial z}\hat{z}$$



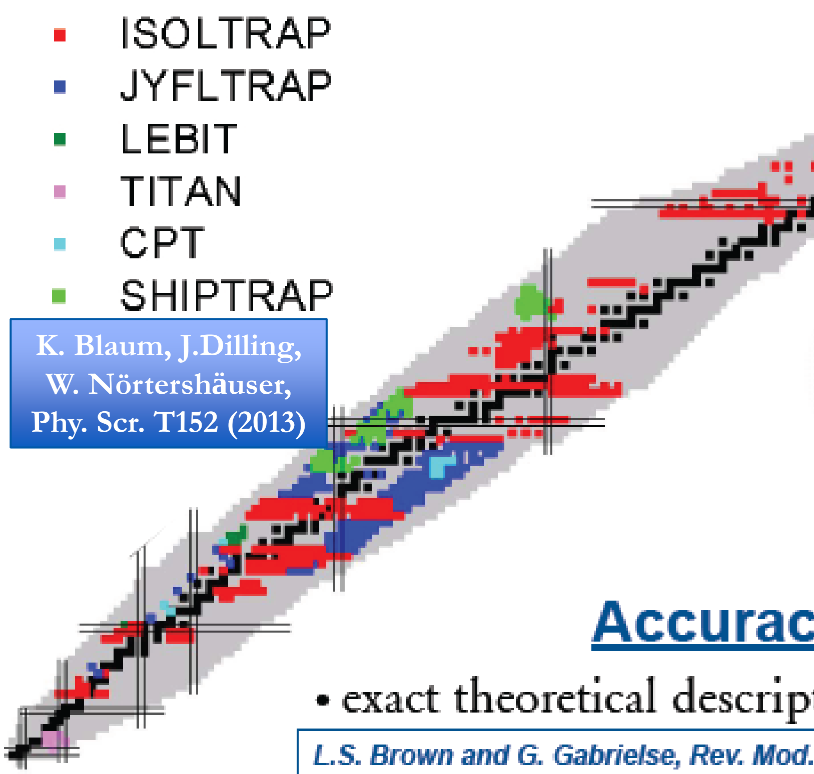
one ion in the trap

$$\delta m \approx \frac{1}{T_{RF} \cdot q \cdot B \cdot \sqrt{N}}$$

The mass is determined by a scan of ω_{rf} around the resonance: $\omega_{rf} = \omega_c = \frac{qB}{m}$

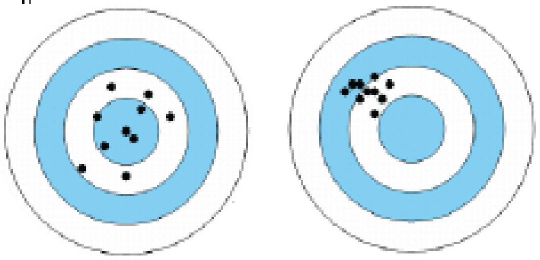
then compare to well known reference!

Precision and accuracy
PT are a widespread mature application



K. Blaum, J.Dilling, W. Nörtershäuser, Phy. Scr. T152 (2013)

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


accurate, but not precise

precise, but not accurate

Accuracy

- exact theoretical description

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986)
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)
M. König et al., Int. J. Mass Spect. 142, 95 (1995)
M. Kretzschmarr, Int. J. Mass Spect. 246, 122 (2007)

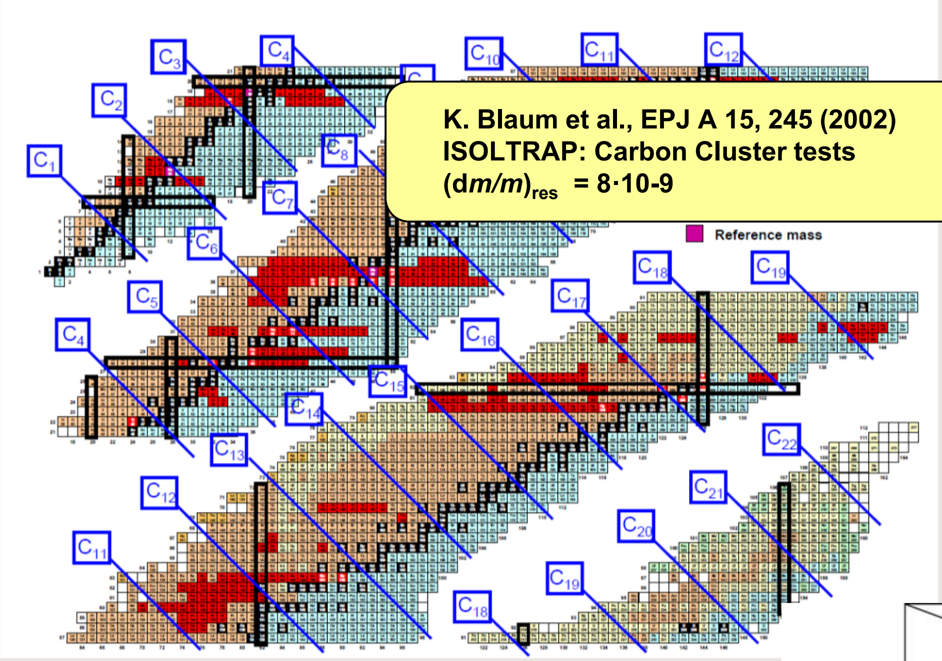
- even for non-ideal traps

G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)

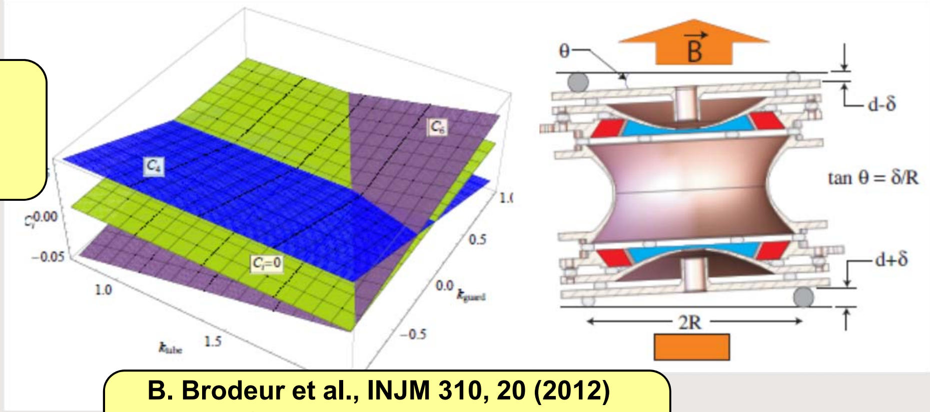
- off-line tests with stables

Since PT were developed for ions, they behave the same way for stable or unstable particles!
Ideal for systematic test and optimizations

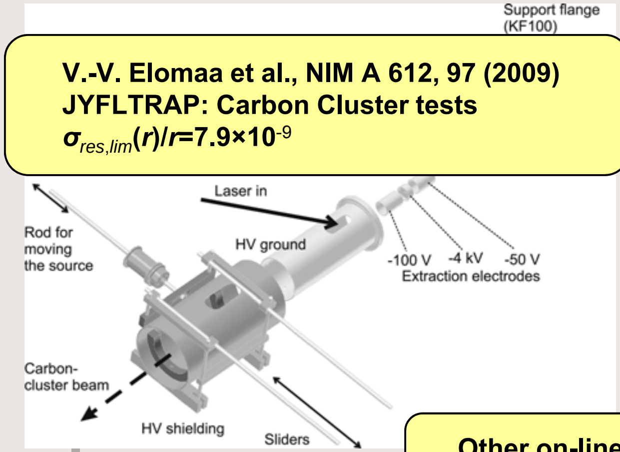
Verification of performance using stable masses (or standard ^{12}C)



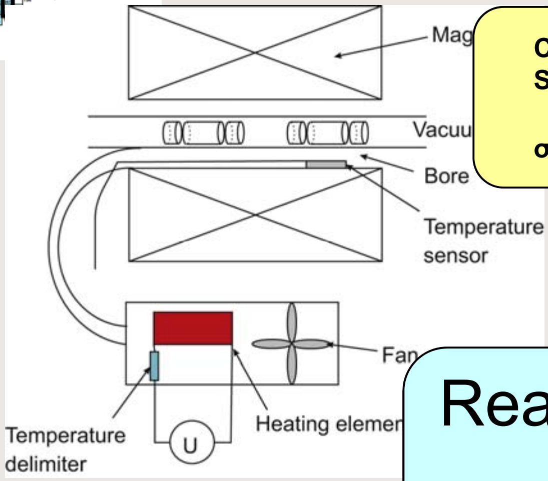
K. Blaum et al., EPJ A 15, 245 (2002)
ISOLTRAP: Carbon Cluster tests
$(dm/m)_{res}$ = 8·10-9



B. Brodeur et al., INJM 310, 20 (2012)
TITAN: Global compensation method
$\Delta R/R_{total} = -4(6) \times 10^{-12} \cdot \Delta(m/q) \cdot V_0$



V.-V. Elomaa et al., NIM A 612, 97 (2009)
JYFLTRAP: Carbon Cluster tests
$\sigma_{res,lim}(r)/r$=7.9×10^{-9}



C. Droese et al., NIM A 632, 157 (2011)
SHIPTRAP: Temperature stability

σ_o=1.3(3)×10^{-9}/h

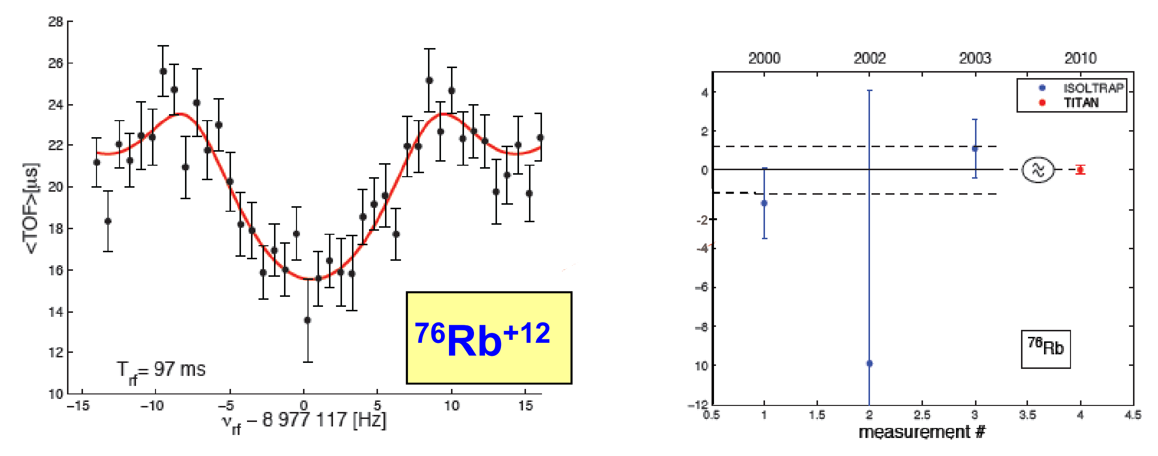
Other on-line trap systems do this as well…CPT, LEBIT…

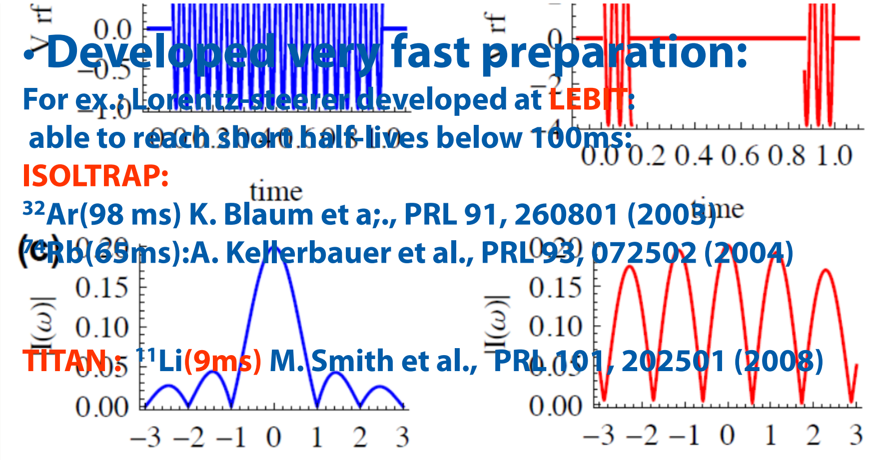
Reached high accuracy
and precision:
Excellent reliability

Fast and efficient (but keeping the precision)

$$\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B \quad \delta m \approx \frac{1}{\nu_c} \propto \frac{1}{T_{RF} \cdot q \cdot B \cdot \sqrt{N}}$$

- **Improve precision using different excitation mod Ramsey (gain factor ~2)**
- **Precision depends on ν_c, boosting the frequency i key.**
  - Can be done with highe excitation modes:
    - Octupole excitation: JYFLTRAP, LEBIT, SHIPTRAP: S. Eliseev et al., PRL. 107, 152501 (2011)
  - Using highly charged ions: developed at SMILETRAP, now also for radioactive beams: TITAN : S. Ettenauer et al., PRL 107, 272501 (2011)





•Developed very fast preparation:

For ex.: Lorentz steerer developed at LEBIT: able to reach short half-lives below 100ms:

ISOLTRAP:

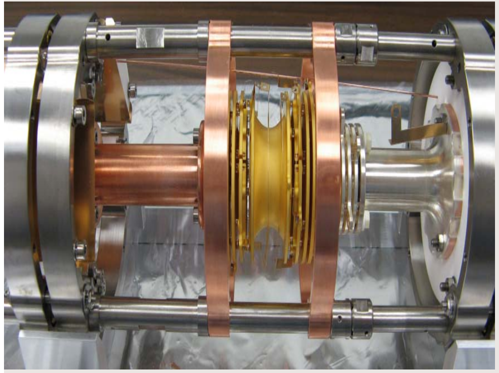
^{32}Ar(98 ms) K. Blaum et a;., PRL 91, 260801 (2003)

^{74}Rb(65ms):A. Kellerbauer et al., PRL 93, 072502 (2004)

TITAN : ^{11}Li(9ms) M. Smith et al., PRL 101, 202501 (2008)

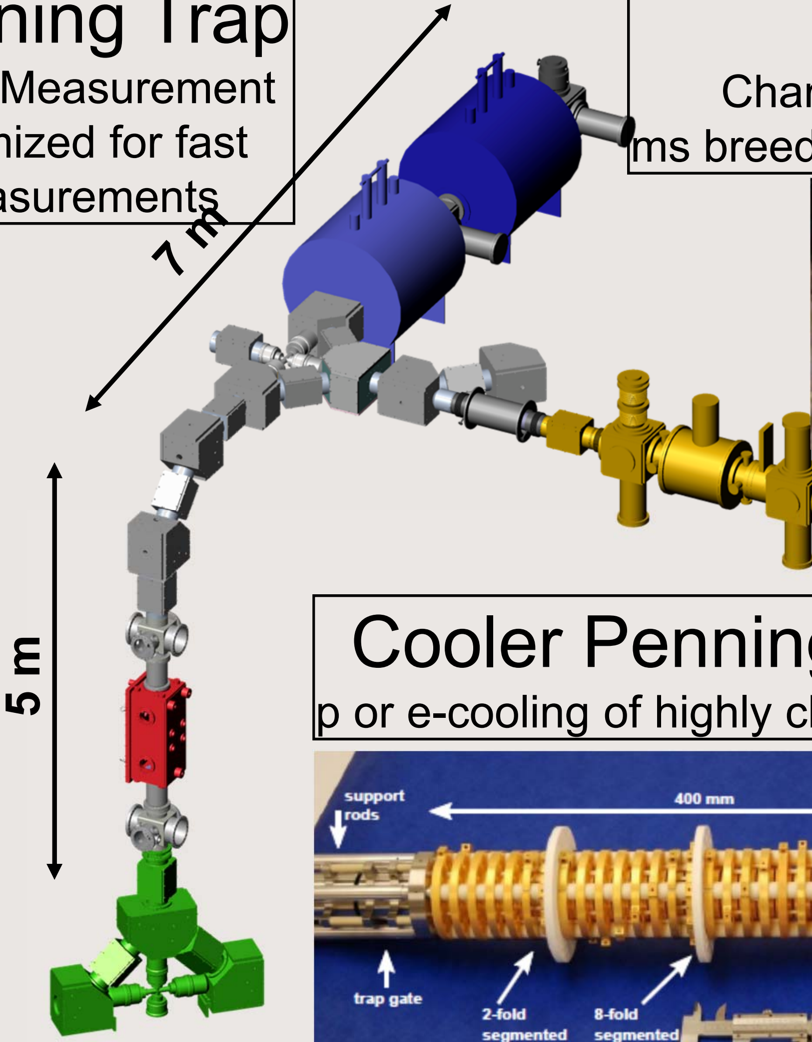
TITAN

Triumf's Ion Trap for Atomic and Nuclear science



Penning Trap

Mass Measurement
Optimized for fast measurements

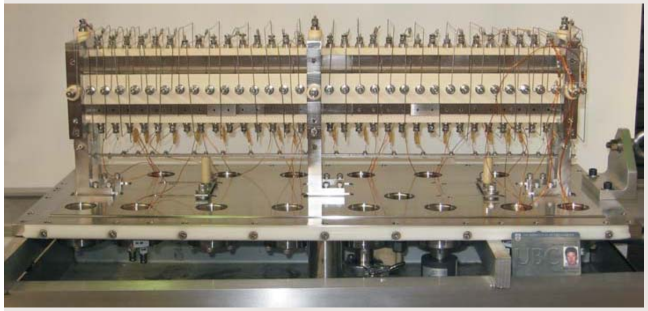


EBIT

Charge State Breeding
ms breeding with high efficiency

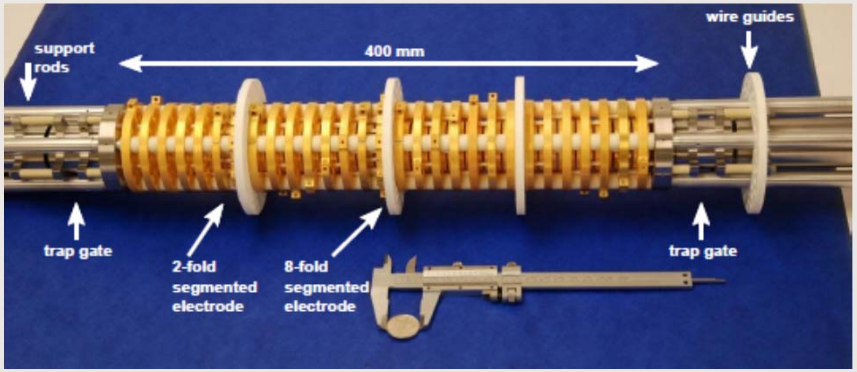
RFQ

Cooling and Bunching
Sq-W driven system with He or H coolant
reverse extraction



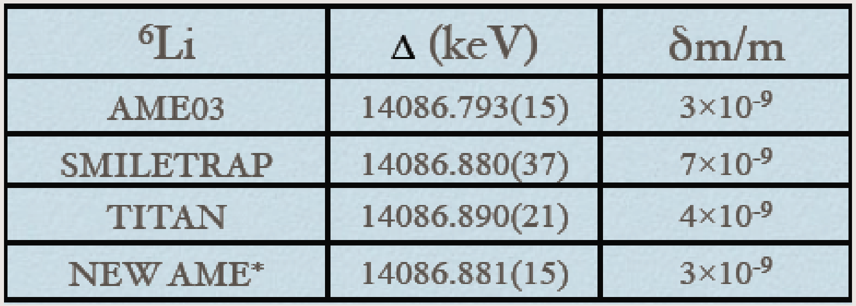
Cooler Penning Trap

p or e-cooling of highly charged ions

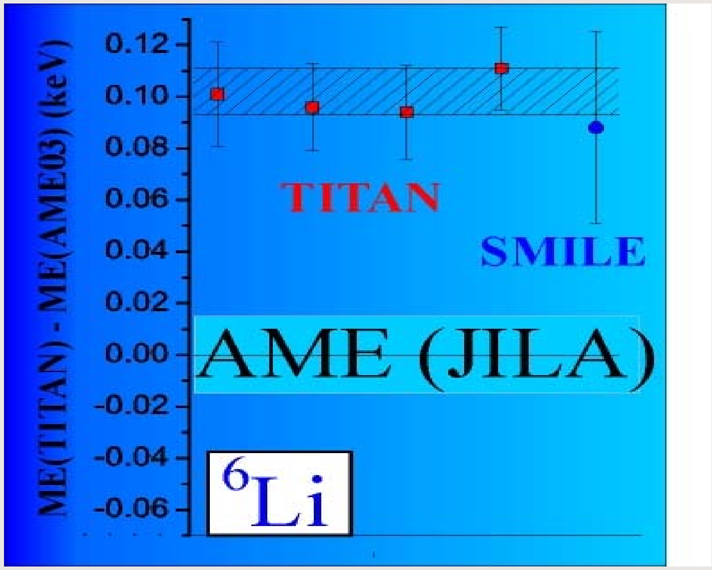


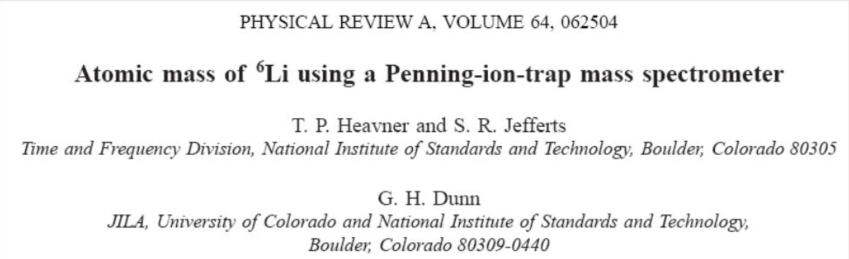
ISAC Beam

Testing the theory (or provide extra input)
stable Li as start: to check precision and accuracy



^{6}Li	Δ (keV)	δm/m
AME03	14086.793(15)	3×10^{-9}
SMILETRAP	14086.880(37)	7×10^{-9}
TITAN	14086.890(21)	4×10^{-9}
NEW AME*	14086.881(15)	3×10^{-9}





PHYSICAL REVIEW A, VOLUME 64, 062504

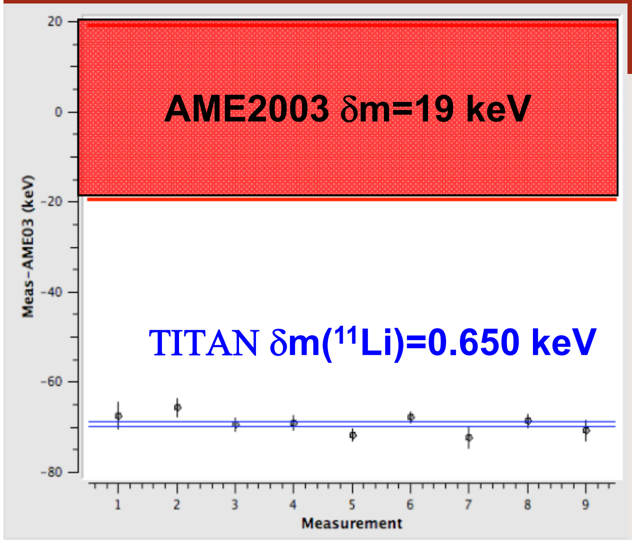
Atomic mass of ^{6}Li using a Penning-ion-trap mass spectrometer

T. P. Heavner and S. R. Jefferts
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305

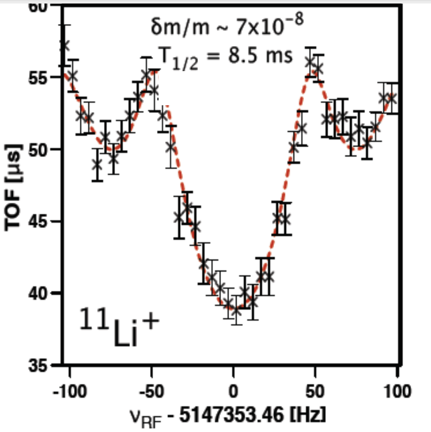
G. H. Dunn
JILA, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440

- TITAN mass measurements for Li-6
- solved conflict with AME (SMILETRAP had found different value than JILA-trap)
- TITAN agrees with SMILETRAP value S. Nagy PRL **96**, 163004
- TITAN now most precise value for new AME
- M. Brodeur et al, PRC 80 (2009) 044318

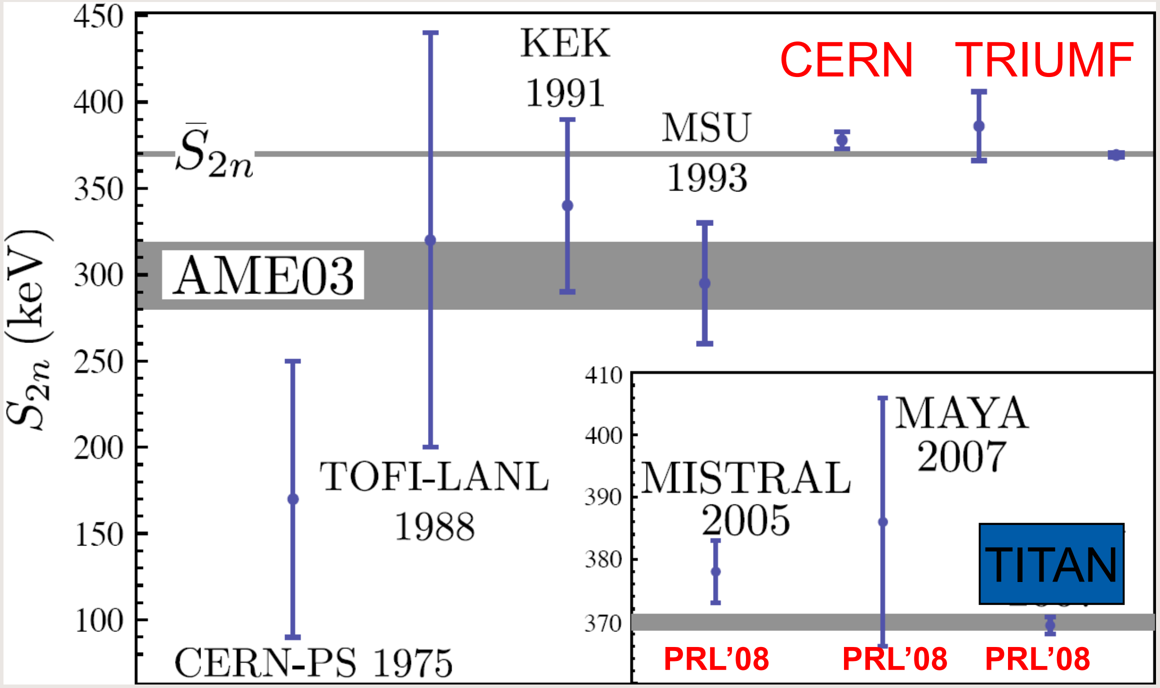
Lithium halo mass measurements



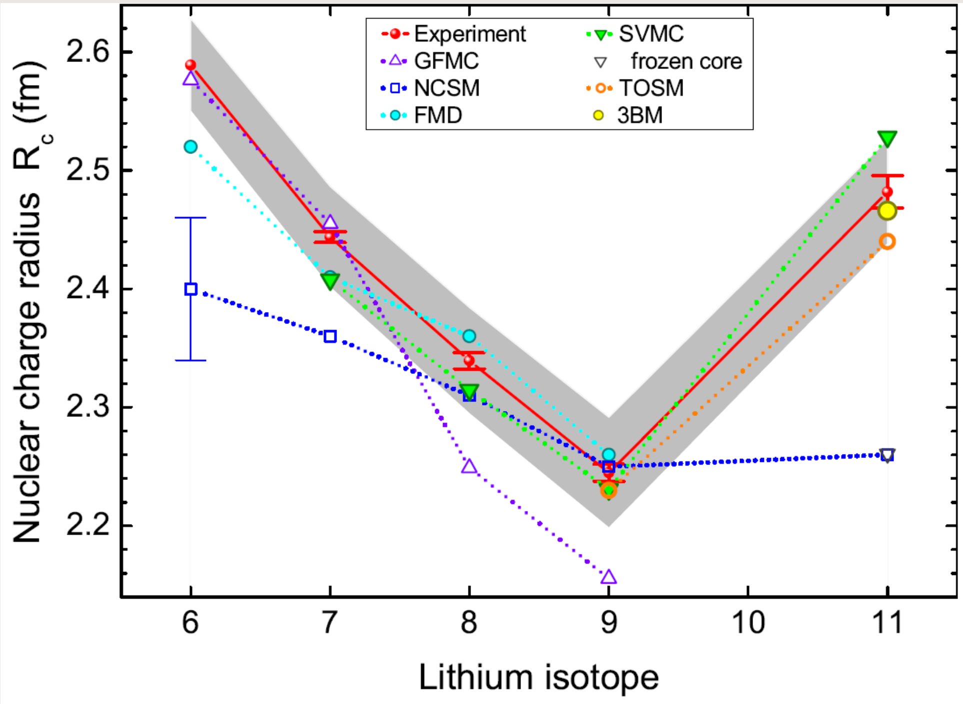
- **TITAN mass measurement of ^{8,9,11}Li**
- **Improved precision, S_{2n} improved by factor 7**
- **Shortest-lived isotope ($T_{1/2}$=8.8ms) for Penning trap mass measurement!**
- **Final analysis δm = 650 eV**
- **Agrees with MISTRAL and MAYA, but more precise.**
- **M. Smith et al PRL 101, 202501 (2008)**
- **→new charge radius**



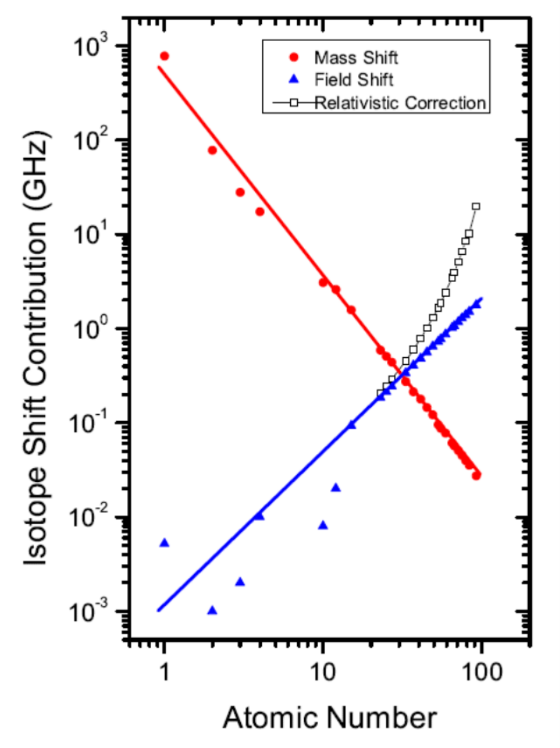
Fastest measurement due to rapid ion preparation with TITAN.



Charge radius determination



- **Isotope shift measurements: ToPLiS (GSI) collaboration @ ISAC measured laser frequency shifts for the Lithium isotopes**
- **G. W. Drake (Windsor) PRL. 100, 243002 (2008) atomic theory calculations for the mass shifts => extract the charge radius**
- **Isotope shift = modification of electron binding energy =Mass Shift (mass effect) + Field shift (finite size of nucleus)**

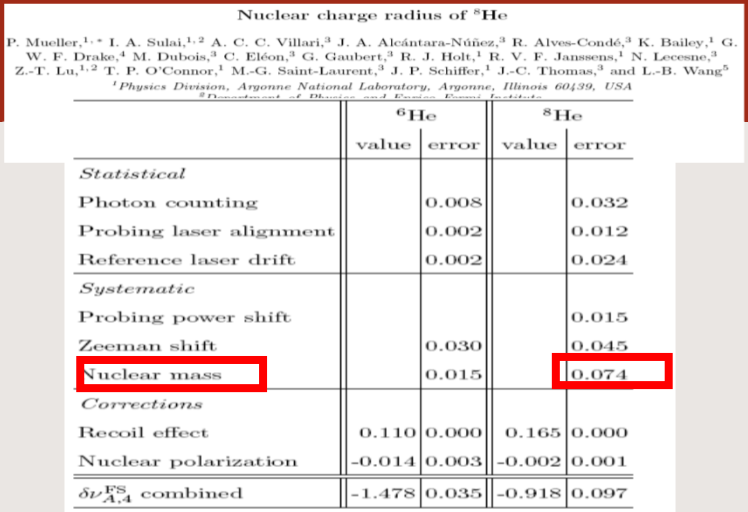


Requirements:

- Need precision of **δm ≤ 1 keV** for charge radius calculations for atomic physics theory

R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
W. Nörtershäuers et al., Phys. Rev. C 84, 024307 (2011)

Mass measurements of helium



Nuclear charge radius of ^{8}He

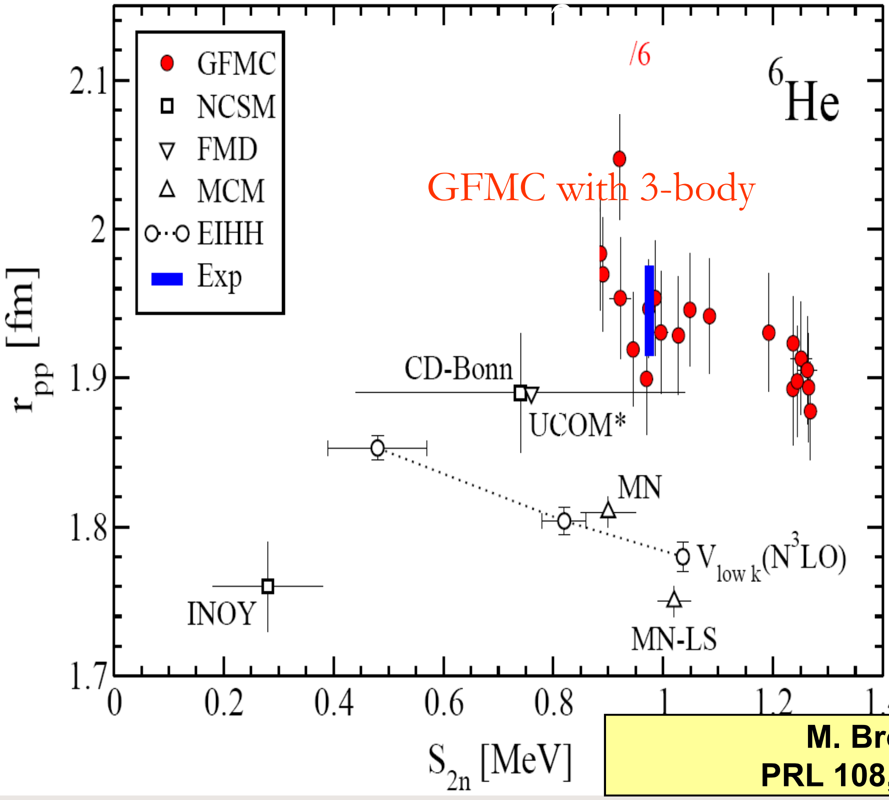
P. Mueller,[1,*] I. A. Sulai,[1,2] A. C. C. Villari,[3] J. A. Alcántara-Núñez,[3] R. Alves-Condé,[3] K. Bailey,[1] G. W. F. Drake,[4] M. Dubois,[3] C. Eléon,[3] G. Gaubert,[3] R. J. Holt,[1] R. V. F. Janssens,[1] N. Lecesne,[3] Z.-T. Lu,[1,2] T. P. O'Connor,[1] M.-G. Saint-Laurent,[3] J. P. Schiffer,[1] J.-C. Thomas,[3] and L.-B. Wang[5]

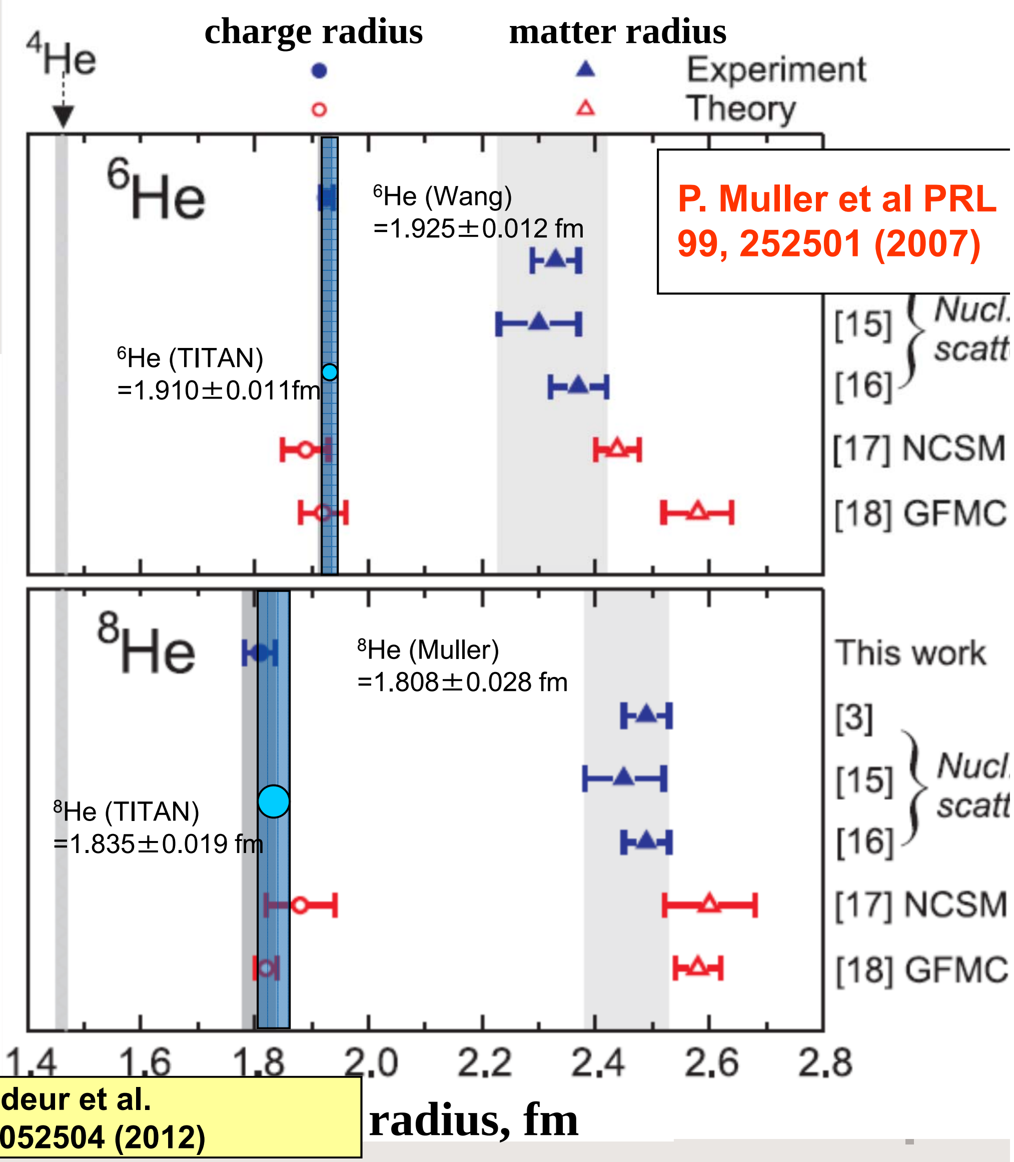
[1] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

[2] *Department of Physics and Enrico Fermi Institute*

	^{6}He		^{8}He	
	value	error	value	error
Statistical				
Photon counting		0.008		0.032
Probing laser alignment		0.002		0.012
Reference laser drift		0.002		0.024
Systematic				
Probing power shift				0.015
Zeeman shift		0.030		0.045
Nuclear mass		0.015		0.074
Corrections				
Recoil effect	0.110	0.000	0.165	0.000
Nuclear polarization	-0.014	0.003	-0.002	0.001
$\delta\nu^{FS}_{A,4}$ combined	-1.478	0.035	-0.918	0.097

Revised charge radius calculation G. Drake et al

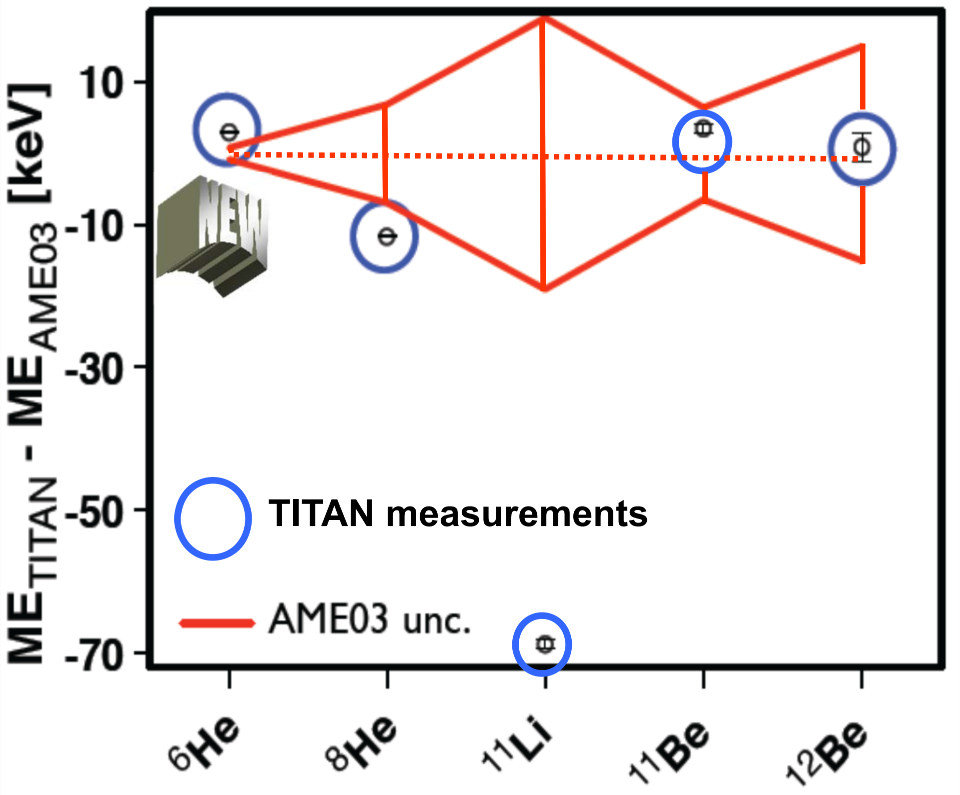




P. Muller et al PRL 99, 252501 (2007)

M. Brodeur et al. PRL 108, 052504 (2012)

TITAN harvest for very neutron-rich light isotopes



^{6}Li: Brodeur et al, PRC 80 (2009) 044318

^{6}He: Brodeur et al, PRL 108, 052504 (2012)

^{9}Li :Brodeur et al, PRL 108.212501 (2012)

^{8}He: Ryjkov et. al., PRL **101** (2008) 012501

^{11}Li: Smith et. al., PRL **101** (2008) 202501

^{11}Be: Ringle et. al., PLB **675** (2009) 170

^{12}Be: Ettenauer et. al PRC 81, 024314 (2010)

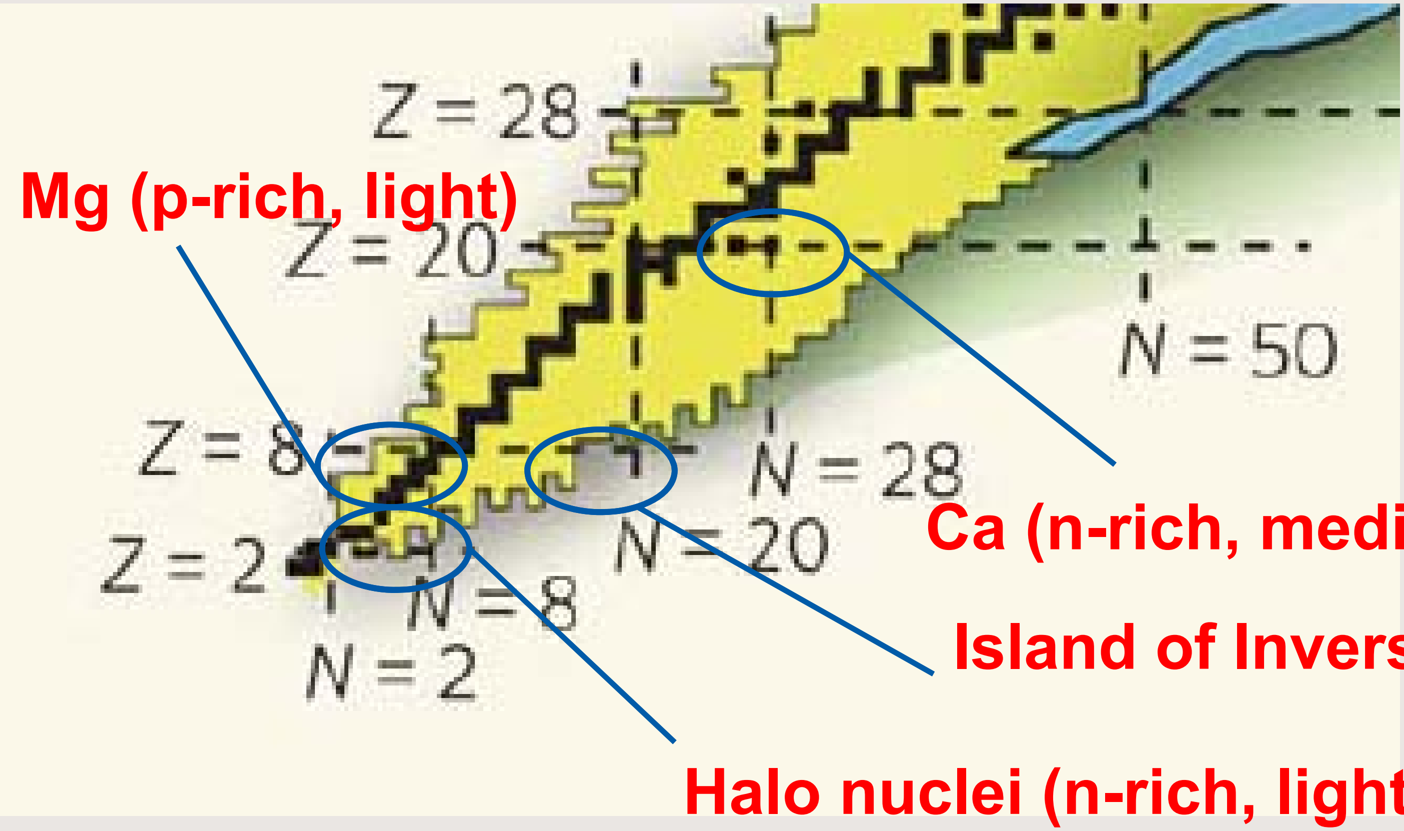
AME03: Audi *et. al.*, Nucl. Phys. A **729** (2003) 337

Mass measurements possible due to fastest on-line PT.

Reached highest precision for short-lived isotopes.

Limit of sensitivity ~ 5-10 ions / sec

Going heavier: A=20,21 Mg



Mg (p-rich, light)

Ca (n-rich, medium)

Island of Inversion

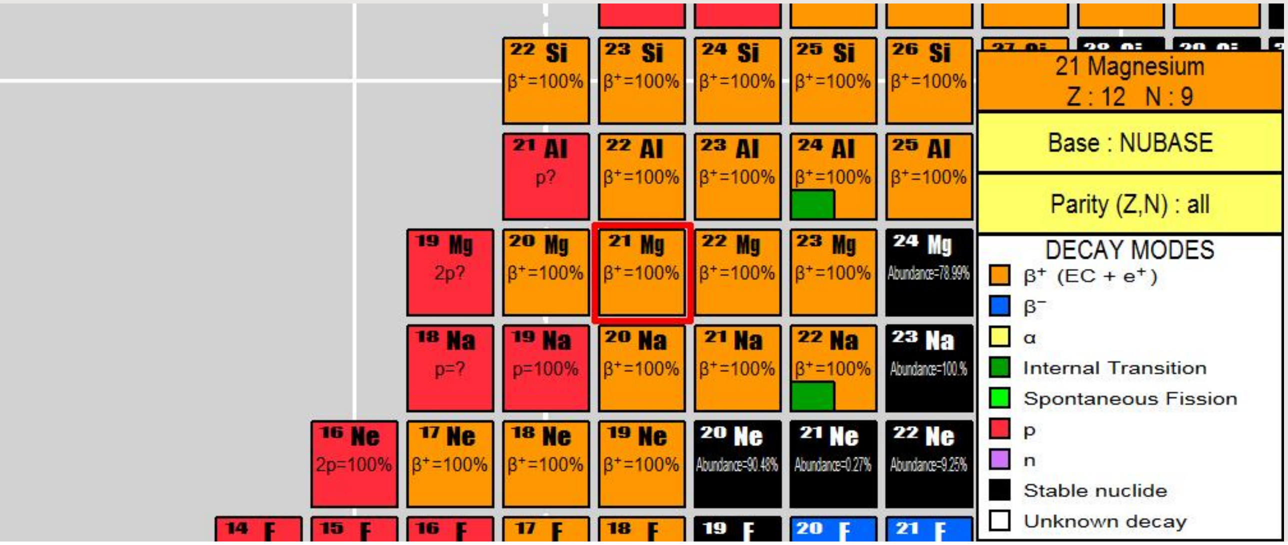
Halo nuclei (n-rich, light)

Mass measurements at A=20,21
Proton rich isotopes
& some more tricks for clean beams

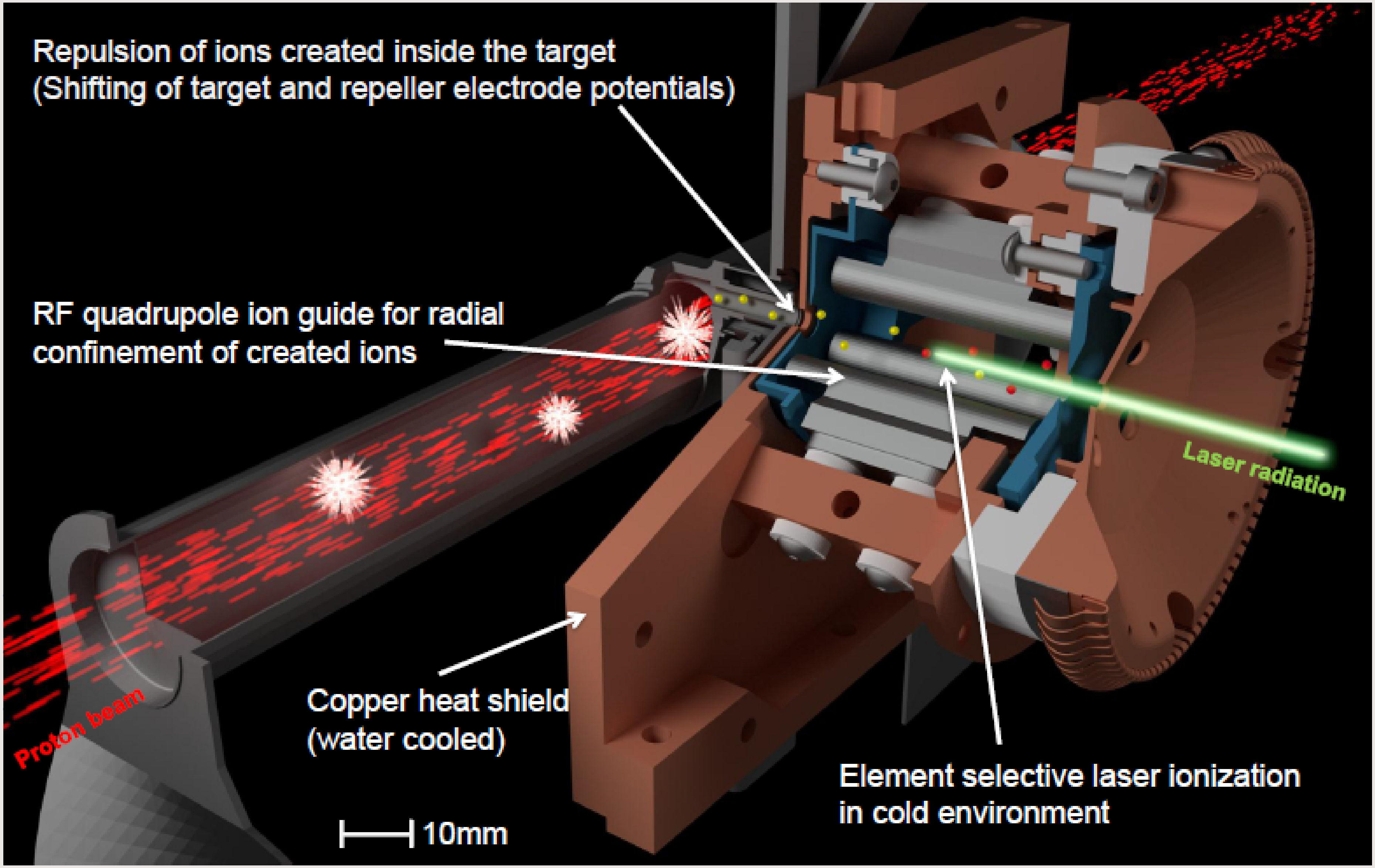
- Mass measurements of Mg masses

Technical difficulty: ISOL production is not selective:

- isobars are co-produced with the isotopes of interest!
- Na, closer to stability, and longer-lived
- much more extracted and delivered to experiment (1.000.000-1 ratio)
- cleaning system required!



Tricks for clean beams: Go to the source! Ion Guide Laser Ion Source (IG-LIS)



Repulsion of ions created inside the target (Shifting of target and repeller electrode potentials)

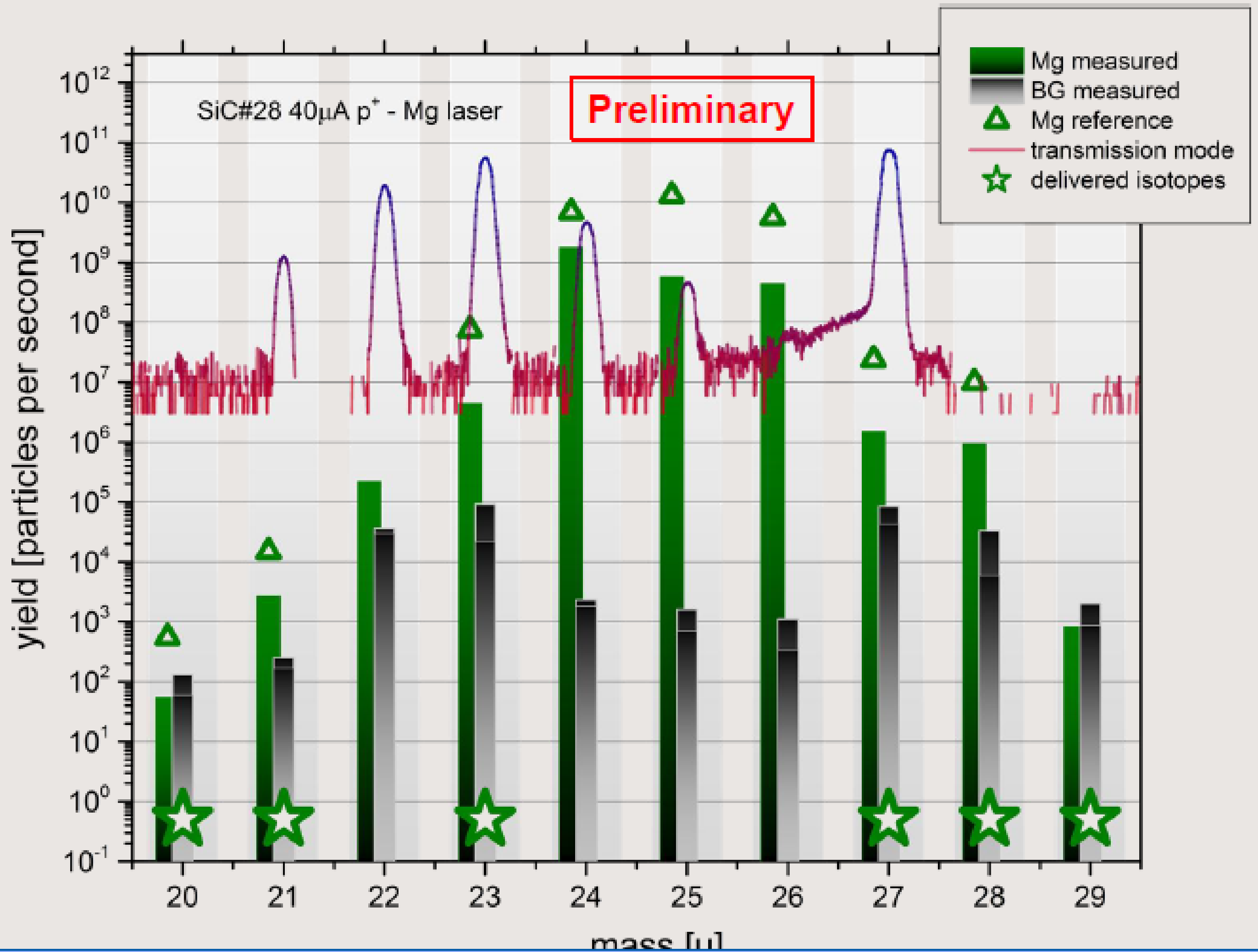
RF quadrupole ion guide for radial confinement of created ions

Copper heat shield (water cooled)

Element selective laser ionization in cold environment

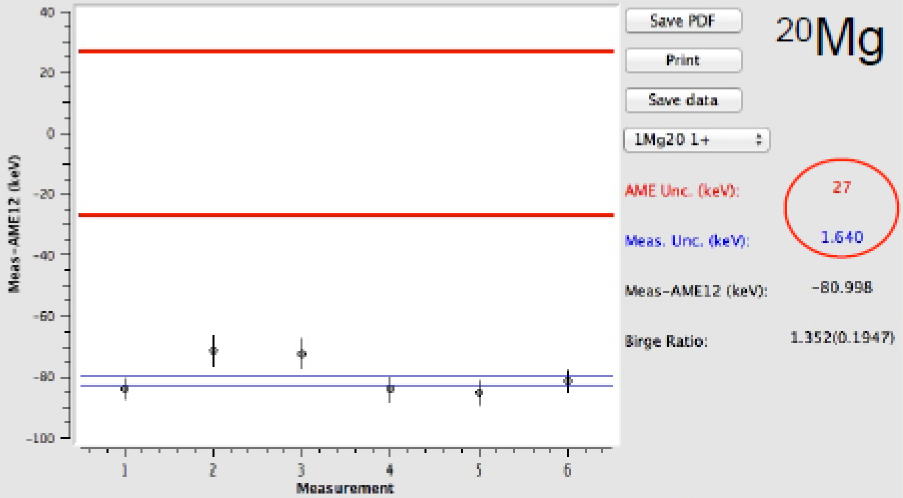
TRIUMF

Performance of the source: IG-LIS



Background reduction of 6 orders of magnitude!

Results of the mass measurements possible with the IG-LIS



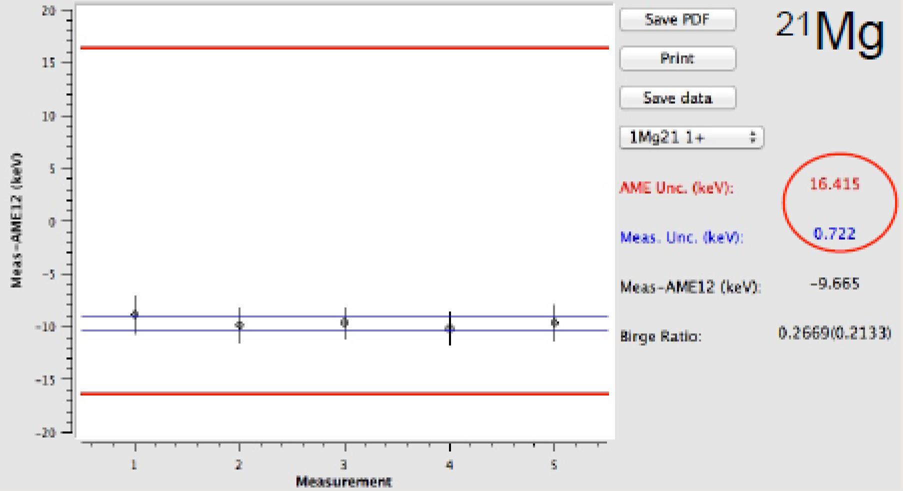
^{20}Mg

AME Unc. (keV): 27

Meas. Unc. (keV): 1.640

Meas-AME12 (keV): -80.998

Birge Ratio: 1.352(0.1947)



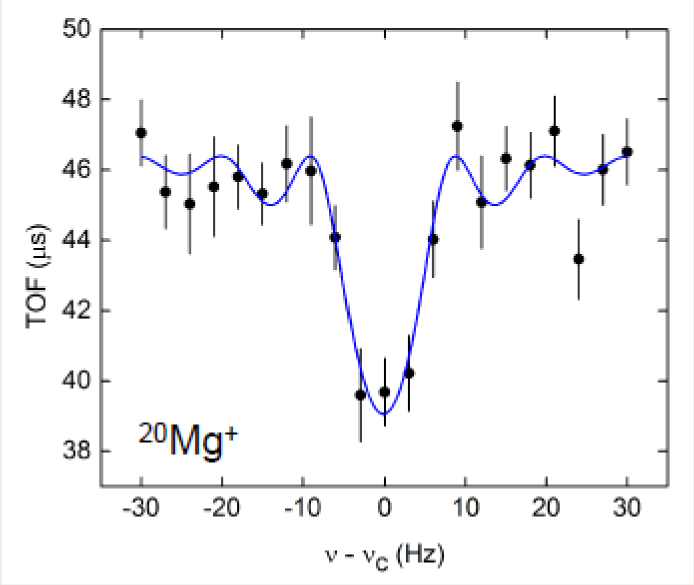
^{21}Mg

AME Unc. (keV): 16.415

Meas. Unc. (keV): 0.722

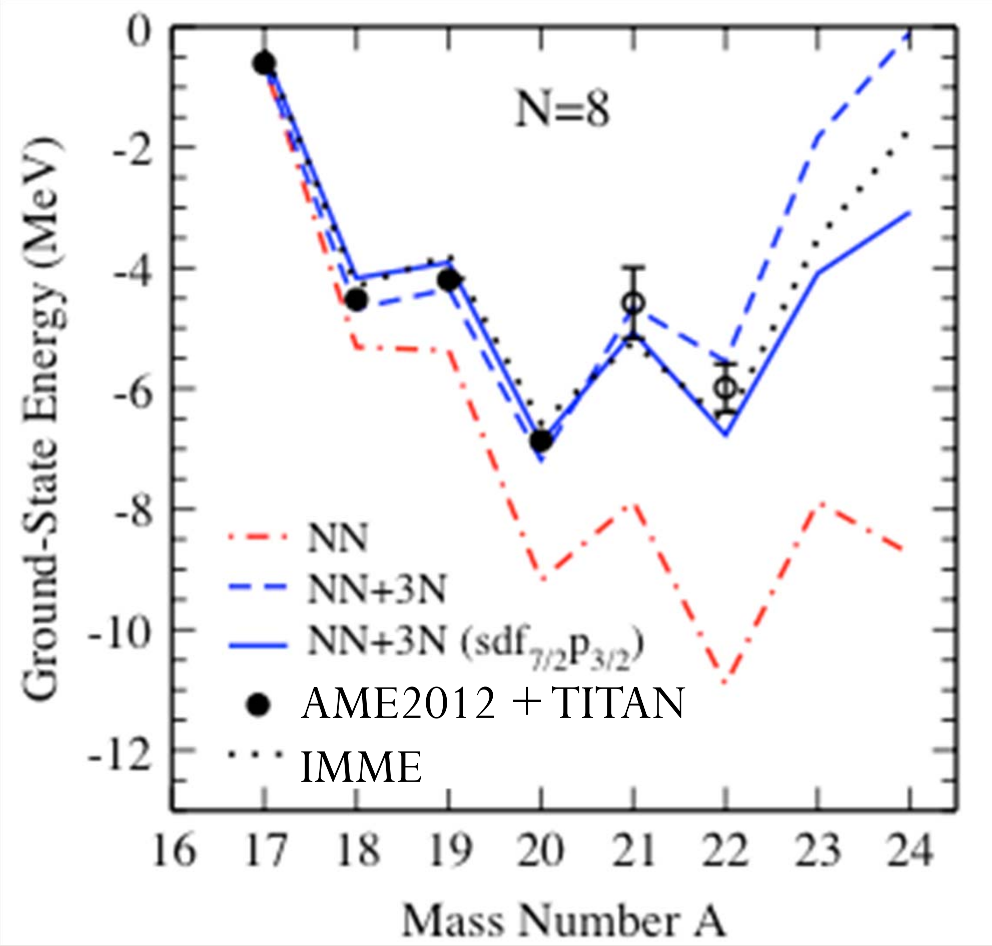
Meas-AME12 (keV): -9.665

Birge Ratio: 0.2669(0.2133)



Clean beam delivered to TITAN
Excellent mass measurements possible, only minor background.

Results of the mass measurements



Direct data improved – but also use phenomenological isobaric multiplet mass equation (IMME), improved by TITAN

NN-only: over-bound

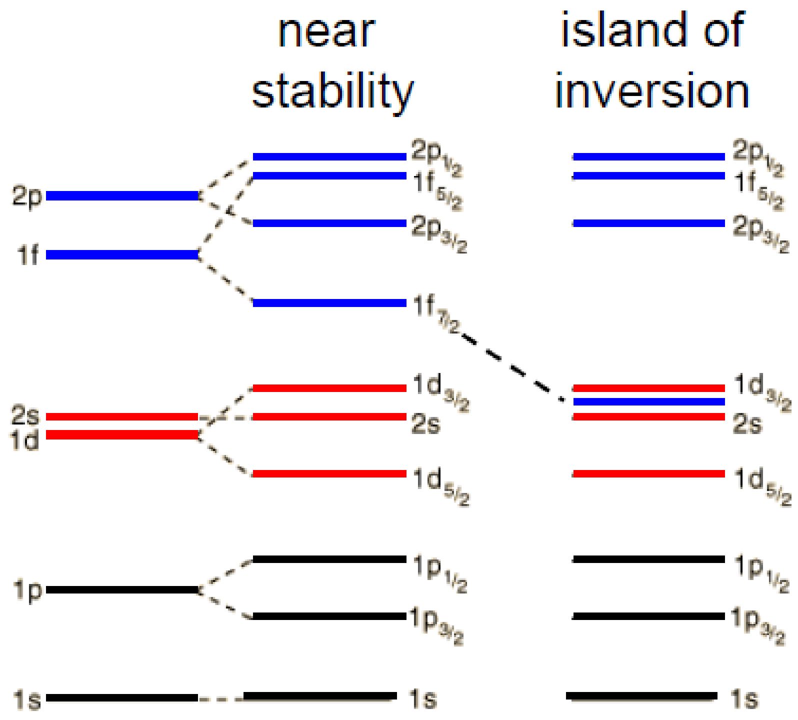
NN+3N: improved agreement with experiment/IMME

Adopted from J.Holt, Menendez, Schwenk, PRL (2013)

Mass values can be described by theory when including 3N forces. A. Gallant et al., submitted to PRL.

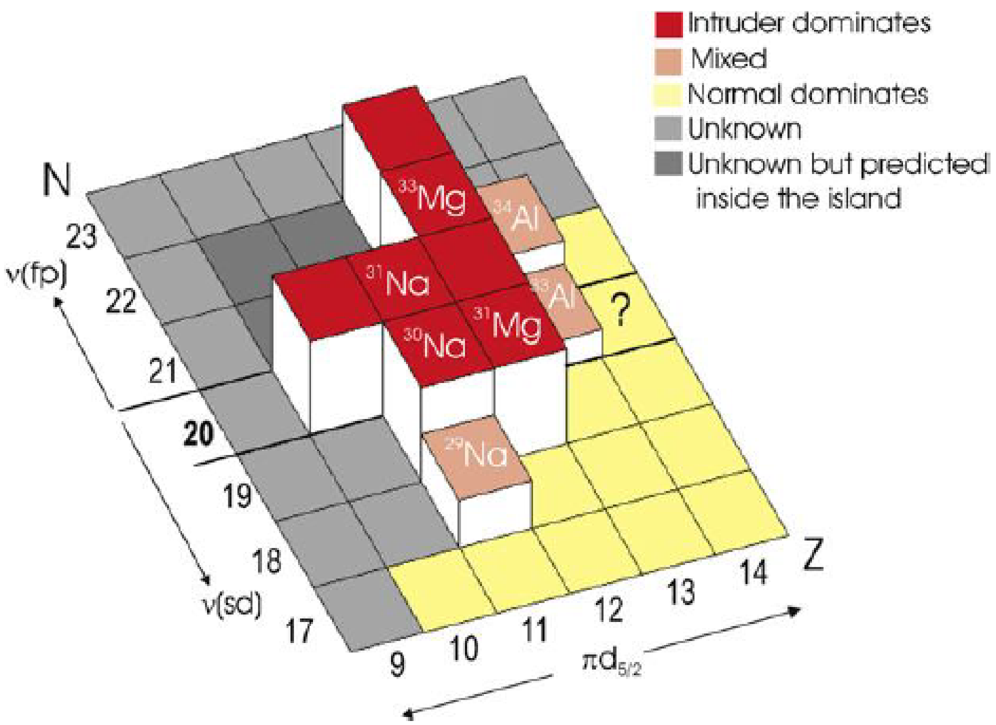
Island of Inversion mass cartography

Name arises from the *pf* orbitals which “intrude” into the *sd* shell



TITAN’s campaign of mass measurements:

- Na: A = 29-31
- Mg: A = 30-34
- Al: A = 29-34



A.Chaudhuri *et al*, accepted in PRC; AAK *et al*, in preparation; figure from Himpe *et* al, PLB 658 (2008) 203

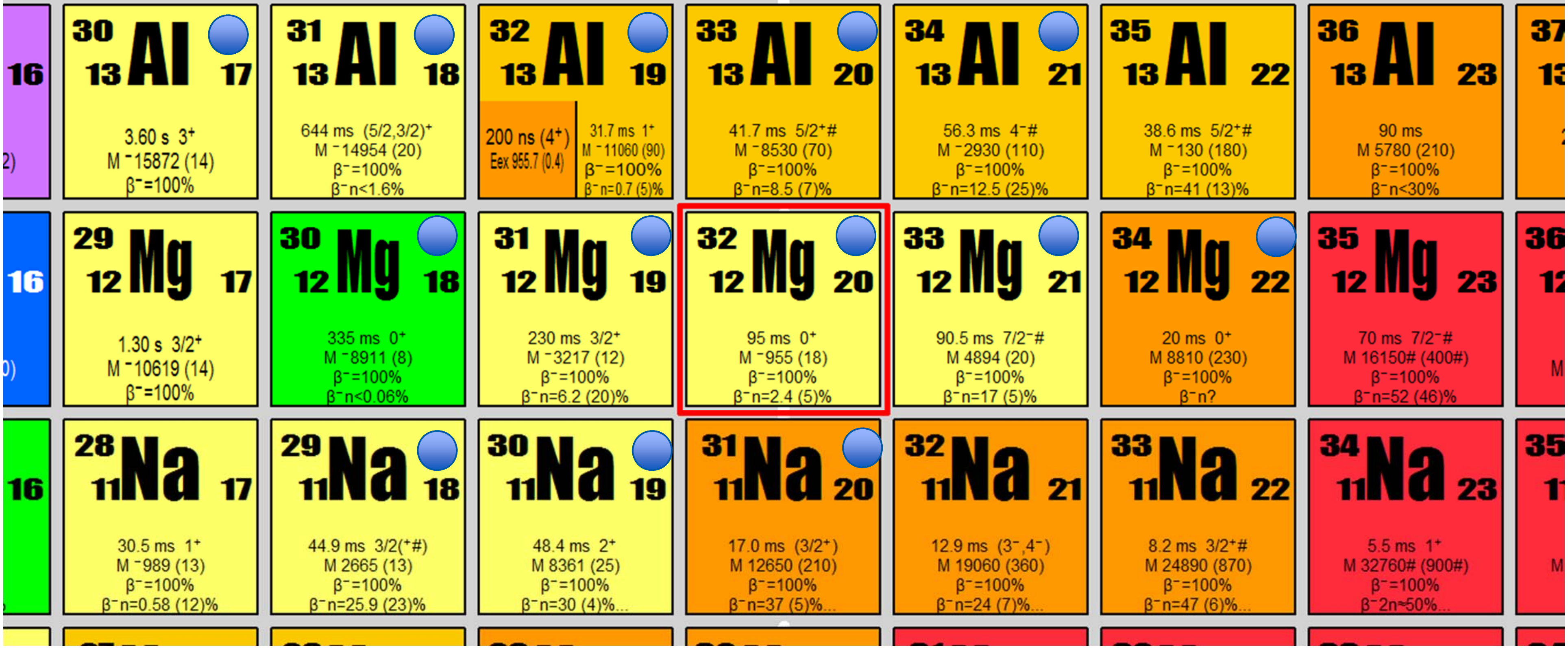
TRIUMF

Island of Inversion mass cartography

Mass measurements with TITAN:

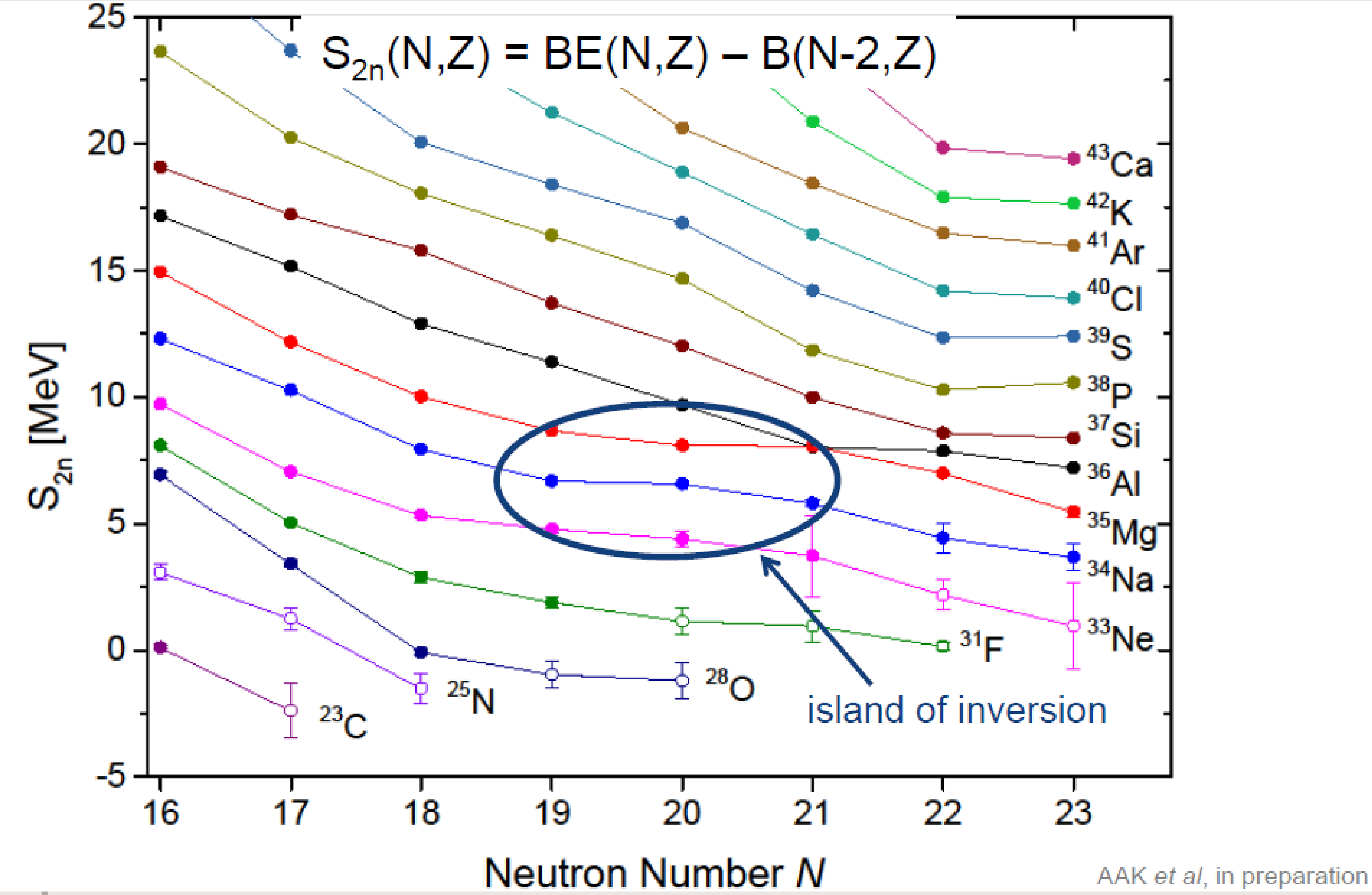
- Fast (short half-lives)
- Precise
- Accurate

Na: 29-31
Mg: 30-34
Al: 30-34



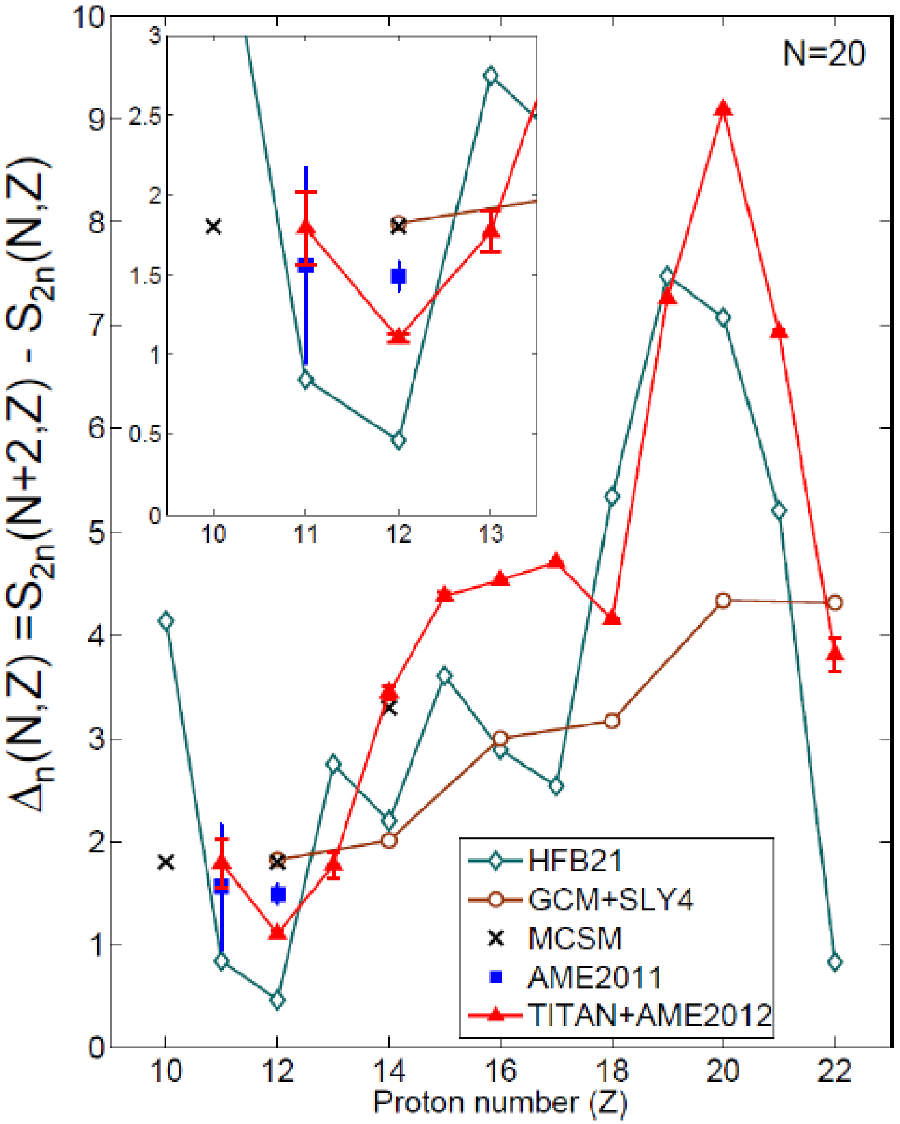
16 2)	$^{30}_{13}$Al 17 3.60 s 3^+ M −15872 (14) β^-=100%	$^{31}_{13}$Al 18 ● 644 ms $(5/2,3/2)^+$ M −14954 (20) β^-=100% β^-n<1.6%	$^{32}_{13}$Al 19 ● 200 ns (4^+) Eex 955.7 (0.4) 31.7 ms 1^+ M −11060 (90) β^-=100% β^-n=0.7 (5)%	$^{33}_{13}$Al 20 ● 41.7 ms $5/2^+$# M −8530 (70) β^-=100% β^-n=8.5 (7)%	$^{34}_{13}$Al 21 ● 56.3 ms 4^-# M −2930 (110) β^-=100% β^-n=12.5 (25)%	$^{35}_{13}$Al 22 ● 38.6 ms $5/2^+$# M −130 (180) β^-=100% β^-n=41 (13)%	$^{36}_{13}$Al 23 90 ms M 5780 (210) β^-=100% β^-n<30%	37 13
16 0)	$^{29}_{12}$Mg 17 1.30 s $3/2^+$ M −10619 (14) β^-=100%	$^{30}_{12}$Mg 18 ● 335 ms 0^+ M −8911 (8) β^-=100% β^-n<0.06%	$^{31}_{12}$Mg 19 ● 230 ms $3/2^+$ M −3217 (12) β^-=100% β^-n=6.2 (20)%	$^{32}_{12}$Mg 20 ● 95 ms 0^+ M −955 (18) β^-=100% β^-n=2.4 (5)%	$^{33}_{12}$Mg 21 ● 90.5 ms $7/2^-$# M 4894 (20) β^-=100% β^-n=17 (5)%	$^{34}_{12}$Mg 22 ● 20 ms 0^+ M 8810 (230) β^-=100% β^-n?	$^{35}_{12}$Mg 23 70 ms $7/2^-$# M 16150# (400#) β^-=100% β^-n=52 (46)%	36 12 M
16	$^{28}_{11}$Na 17 30.5 ms 1^+ M −989 (13) β^-=100% β^-n=0.58 (12)%	$^{29}_{11}$Na 18 ● 44.9 ms 3/2(+#) M 2665 (13) β^-=100% β^-n=25.9 (23)%	$^{30}_{11}$Na 19 ● 48.4 ms 2^+ M 8361 (25) β^-=100% β^-n=30 (4)%...	$^{31}_{11}$Na 20 ● 17.0 ms $(3/2^+)$ M 12650 (210) β^-=100% β^-n=37 (5)%...	$^{32}_{11}$Na 21 12.9 ms $(3^-,4^-)$ M 19060 (360) β^-=100% β^-n=24 (7)%...	$^{33}_{11}$Na 22 8.2 ms $3/2^+$# M 24890 (870) β^-=100% β^-n=47 (6)%...	$^{34}_{11}$Na 23 5.5 ms 1^+ M 32760# (900#) β^-=100% β^-2n≈50%...	35 11 M

Island of Inversion mass cartography



AAK *et al*, in preparation

Island of Inversion mass cartography
Looking at the shell gap…



- $\Delta_n(^{31}Na)$ = 1.79(23) MeV
- $\Delta_n(^{32}Mg)$ = 1.10(3) MeV
- $\Delta_n(^{33}Al)$ = 1.82(7) MeV

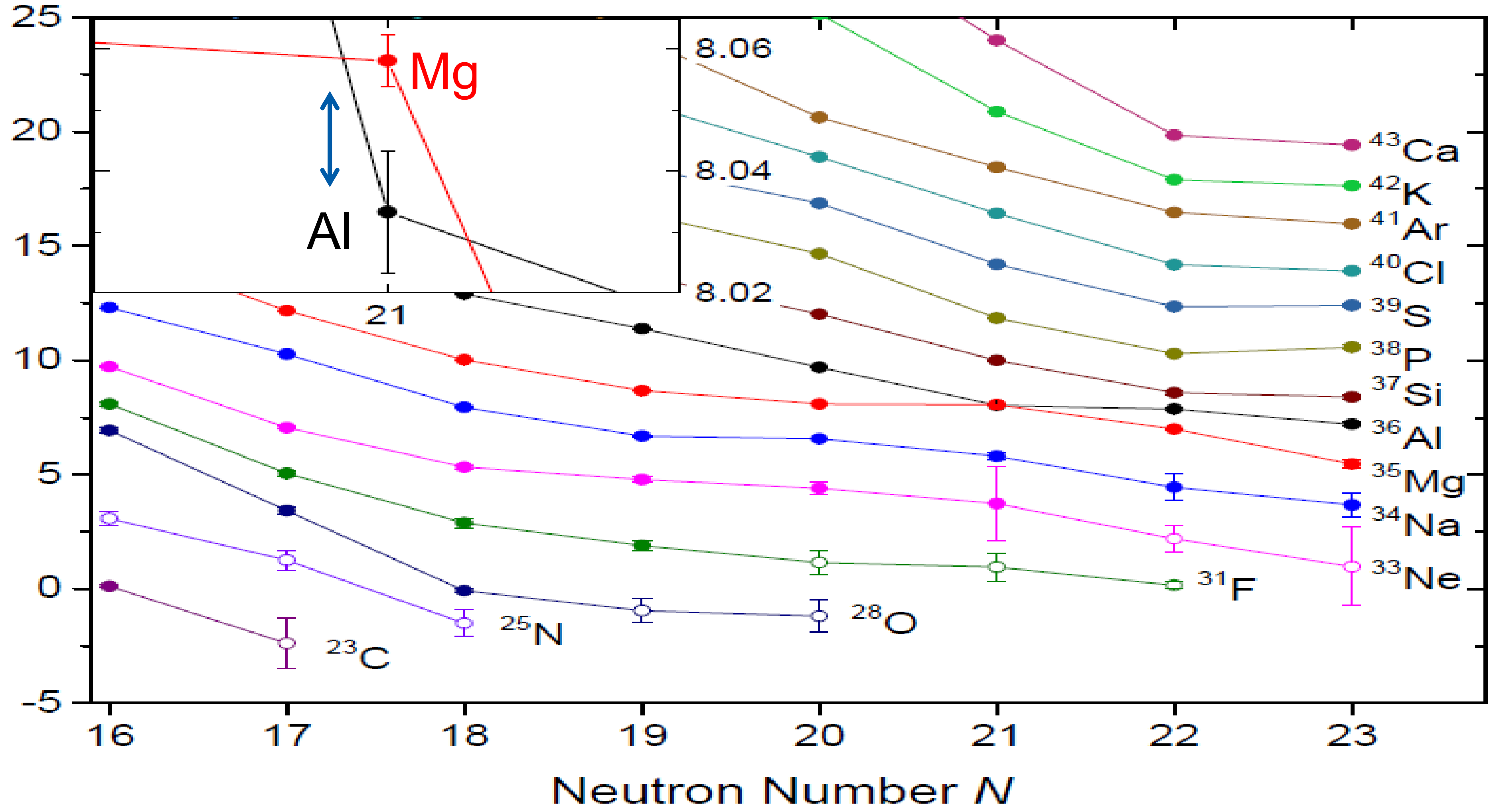
lowest known of any magic nuclide

Limited guidance from theory:

- Models tend to overestimate “shell gap” Δ_n in ^{32}Mg
- Mean-field models predict shape incorrectly
- Only conventional shell model indicates breaking of N = 20 shell closure but it predicts $\Delta_n<0$
- Out of reach for energy-density functional and *ab-initio* methods?

A. Chaudhuri et al., Phys. Rev. C **88**, 054317 (2013)

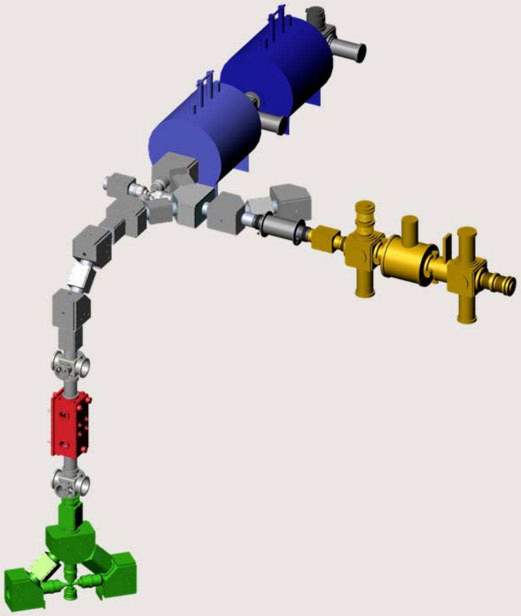
Island of Inversion mass cartography: The unusual case of the cross-over.

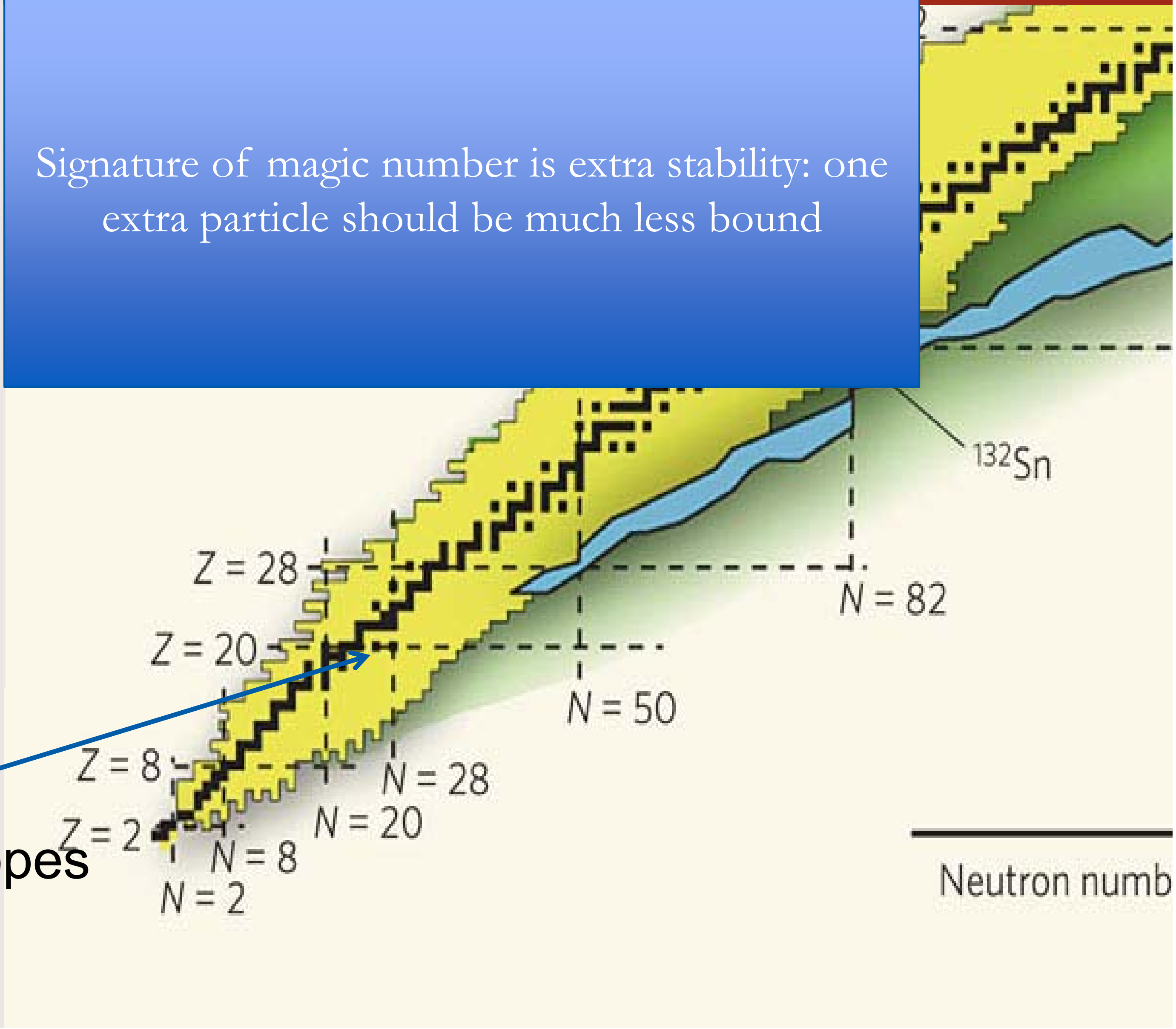


The cross over could be due to and non-identified isomer!
A.A. Kwiatkowski et al., submitted to PRL

N-rich Ca isotopes

Signature of magic number is extra stability: one extra particle should be much less bound

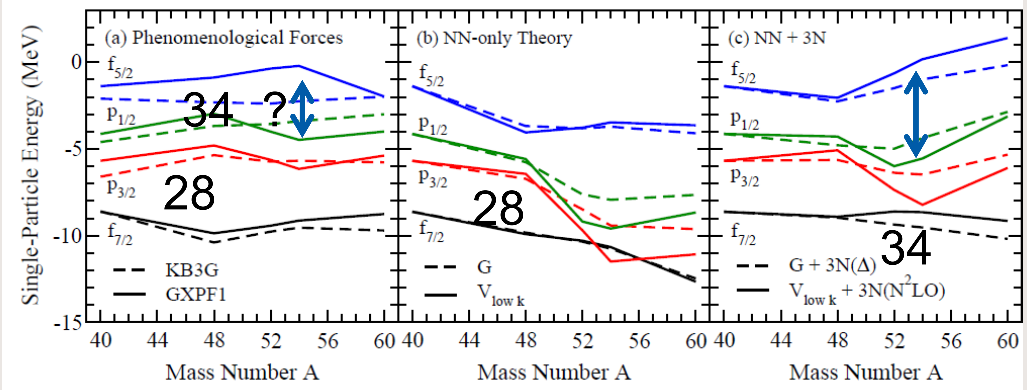


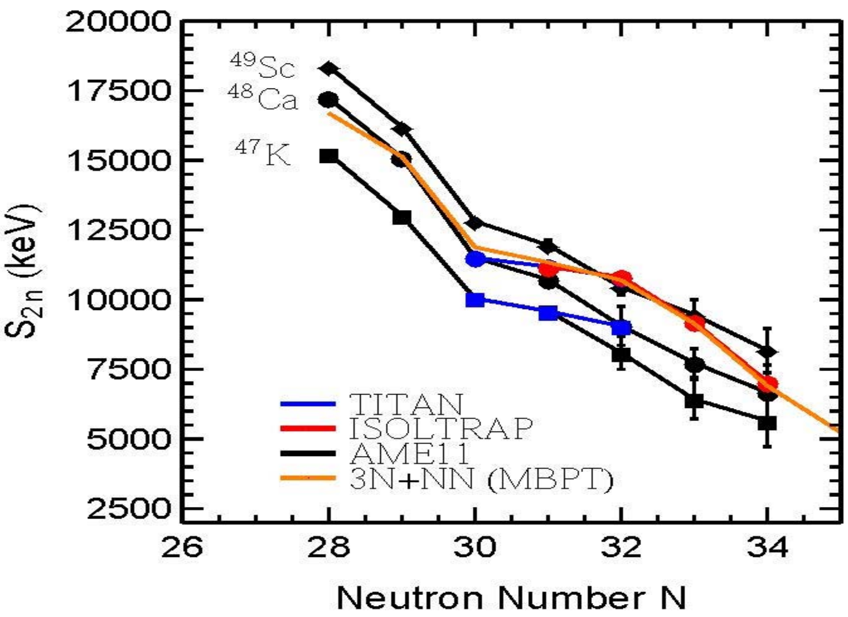


N-rich Ca isotopes

Extension of theory approach to heavier isotopes: n-rich Ca

phenomenology | realistic 2N | realistic 2N + 3N





Theory with realistic NN interaction & 3N forces:

- substantially different trend for single-particle energies and separation energies
- quenching of N=28 shell gap around A=50-54
- **New magic shell closure at N=32/34?**

Mass measurement of ^{51,52}Ca with TITAN

➔ confirms theoretical trends

Experiments agrees well with this theory, but also with others (CC-theory PRL 109, 032502).

Further extension to ^{54}Ca with ISOLTRAP

Old Measurements AME11

A.T. Gallant, PRL **109, 032506** (2012)

Wienholtz et al., Nature (2013)
ISOLTRAP/CERN

Mass measurements for Astrophysics

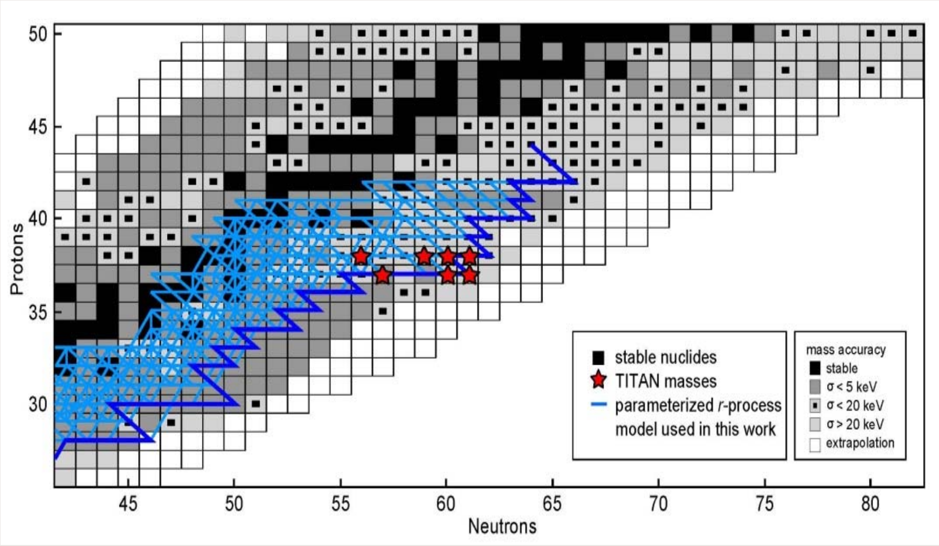
- Parameterized r-process model

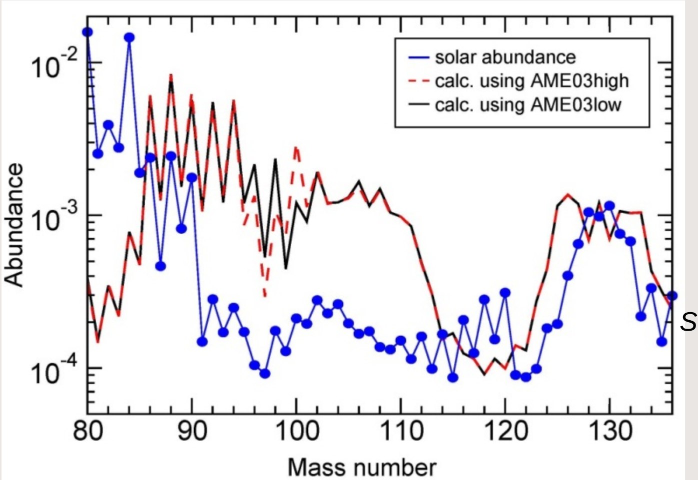
Following C. Freiburghaus et al., AstrophysJ 516, 381 (1999)

  - Fluid element (p, n, Y_e) heated to high temperature 9GK
  - Undergoes rapid expansion at const. velocity, Y_e, S

P. Hosmer et al., PRC 82, 025806 (2010)

  - Model coupled to full reaction network (~5400 nuclei)
  - For full range of entropies → isotopic abundance added up





- model inspired by conditions in high entropy winds from neutron stars in core collapse supernovae
- just 2 free parameters!

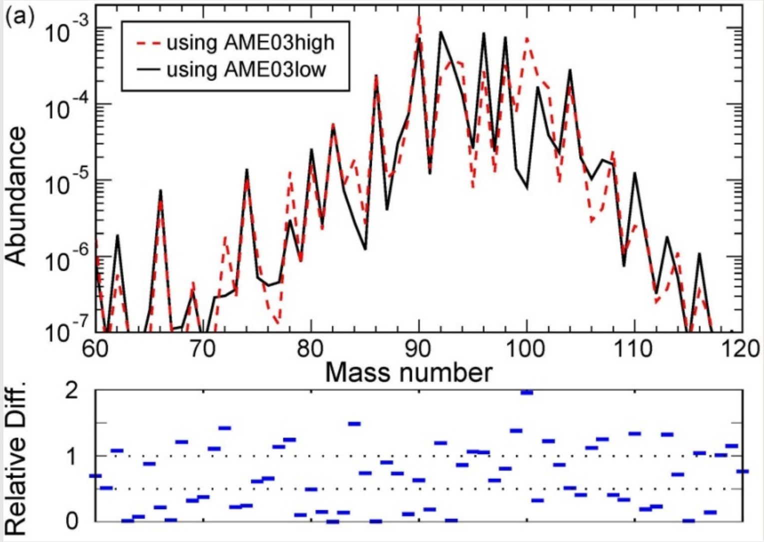
Solar system r-process abundance from C. Travaglio et al., AstrophysJ 601, 864 (2004)

V.V. Simon et al. PRC 85, 064308 (2012)

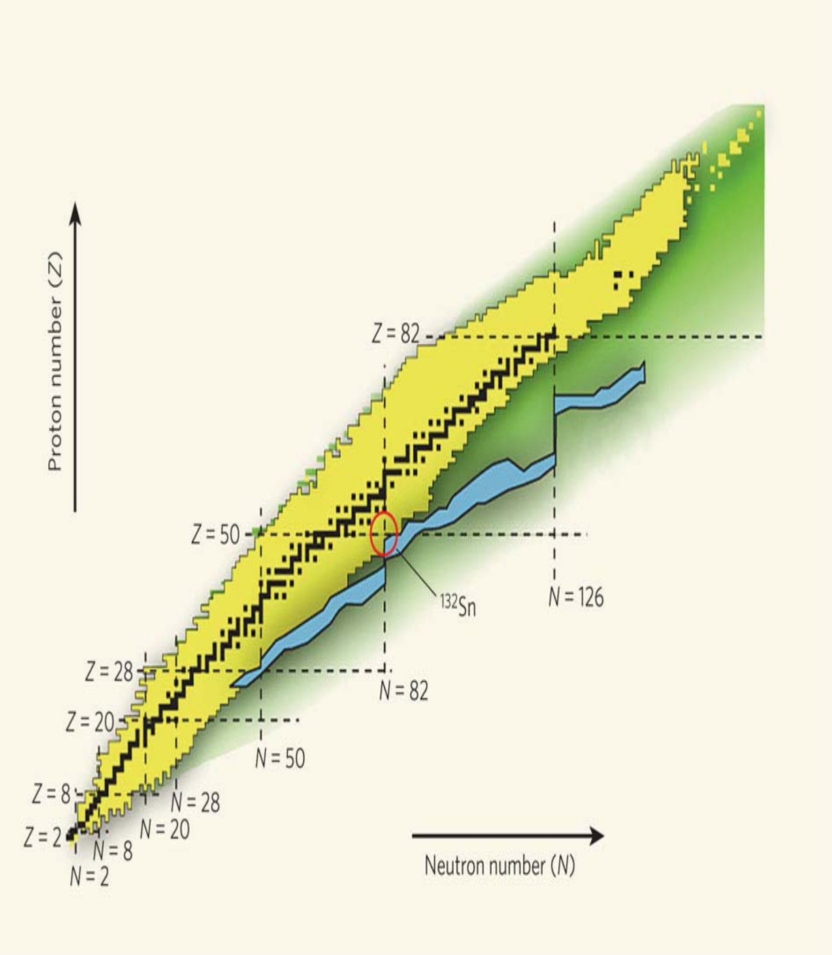
r-process model calculations

- **Include AME03 S_n values varied either 3σ up ('high') or down ('low')**
  - **found up to 6σ deviations in S_n to AME03**
- **S=100 component most affected**

G. Audi, M. Weng, AME2010,pr. comm. (2010)
U. Hager et al., PRL 96, 3 (2006)
J. Hakala et al., EPJA 47, 129 (2011)



outlook



- Extend halo measurements
    - Be, C,…
- Island of Inversion
    - (complete the picture)
- N-rich isotopes (light/medium)
    - F, Ne,..Ar, K, Ca, Sc
- N-rich isotopes (heavier)
    - Cd, In,…^{136}Sn…

- In trap decay spectroscopy
    - Double beta decay studies

TITAN is fast (5ms) and sensitive (5-10 ions/s) and has capability to reach high resolution, precision and accuracy.

TRIUMF

Thank You!

Thanks to the TITAN graduate students:

S. Ettenauer* (Vanier & Killiam),
A. Gallant (NSERC A.G. Bell fellowship),
T. Macdonald
V. Simon* (DAAD + Deutsche Studienstiftung),
T. Brunner *(Villigst fellowship)
U. Chowdhury, J. Bale
B. Eberhard* (Deutsch Kanadische Gesellschaft)
A. Lennarz (DAAD) , R. Klawitter, A. Bader, D. Short

and the post docs:

B. Schultz, A. Chowdhury,

- A. Grossheim, A. Kwiatkowski, K. Leach

long term collaborators:

D. Lunney (Orsay), R. Ringle (MSU), M. Brodeur (ND),
D. Frekers (Muenster) G. Gwinner (Manitoba),
C. Andreoiu (SFU)

theory colleagues:

S. Bacca (TRIUMF), A. Schwenk, J. Holt, J. Menendez (all TU Darmstadt) and B.A. Brown (MSU)

* Have graduated (now at Harvard, Stanford, and Mainz)

titan.triumf.ca   JDilling@triumf.ca

U. of Manitoba
McGill U.
Muenster U.,
Max Plank Inst. für Kernphysik
GANIL
CNRS/Orsay
Yale
Giessen

Uni Mainz
U. of Windsor
TU Dresden
TRIUMF
UBC
SFU
TU Munich
St Mary's