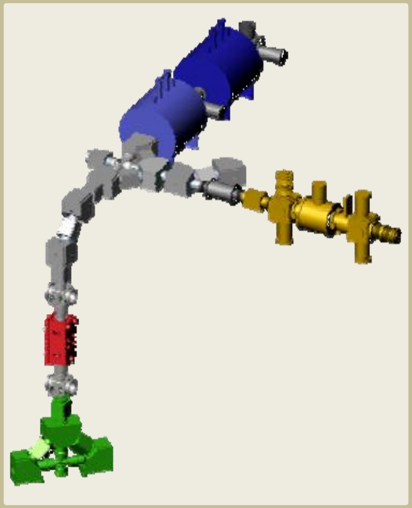
TRIUMF

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

Benchmarks from high-precision mass measurements at TITAN

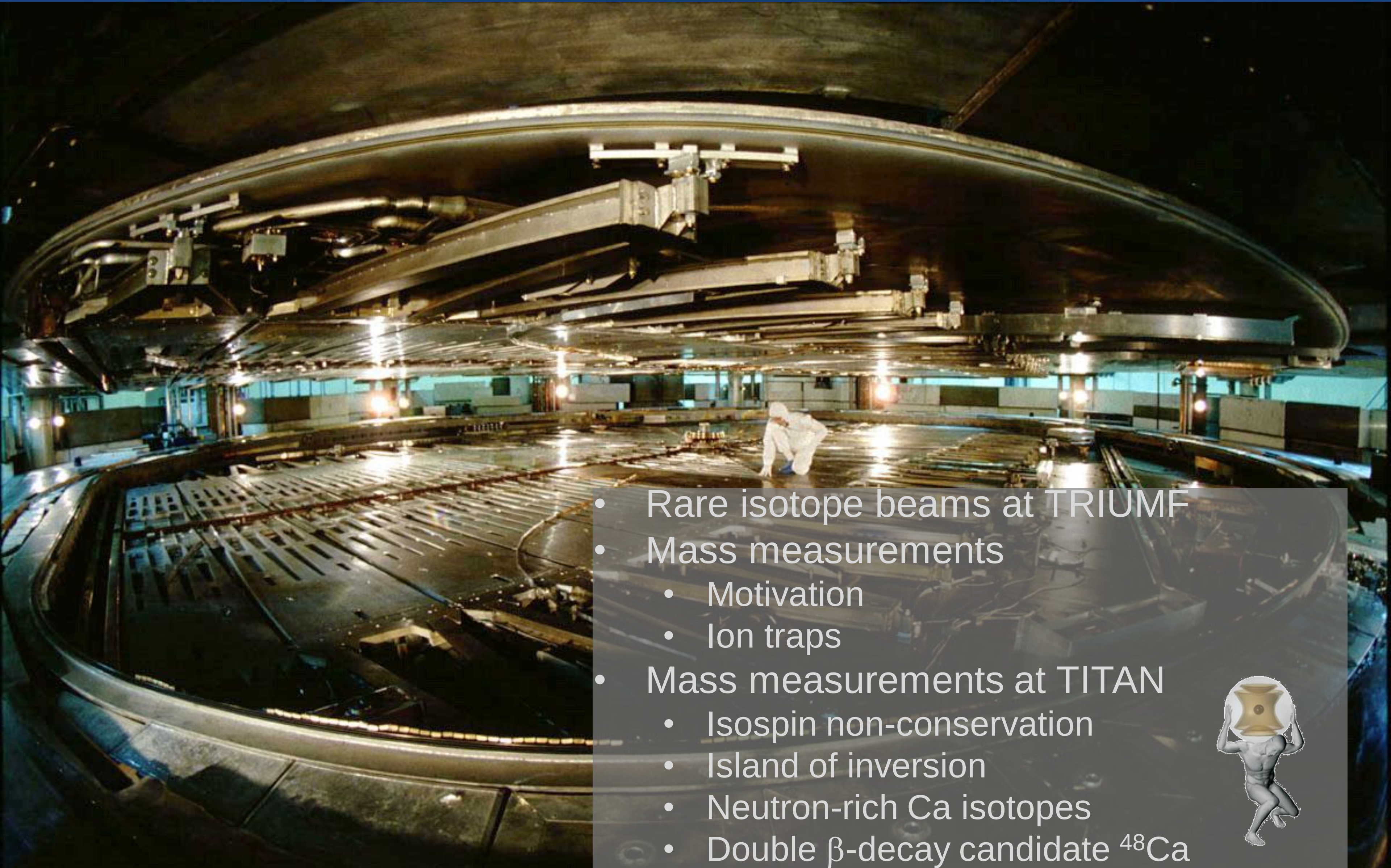
A.A. Kwiatkowski

INT Workshop, Few-body Universality in Atomic and Nuclear Physics
12 May 2014



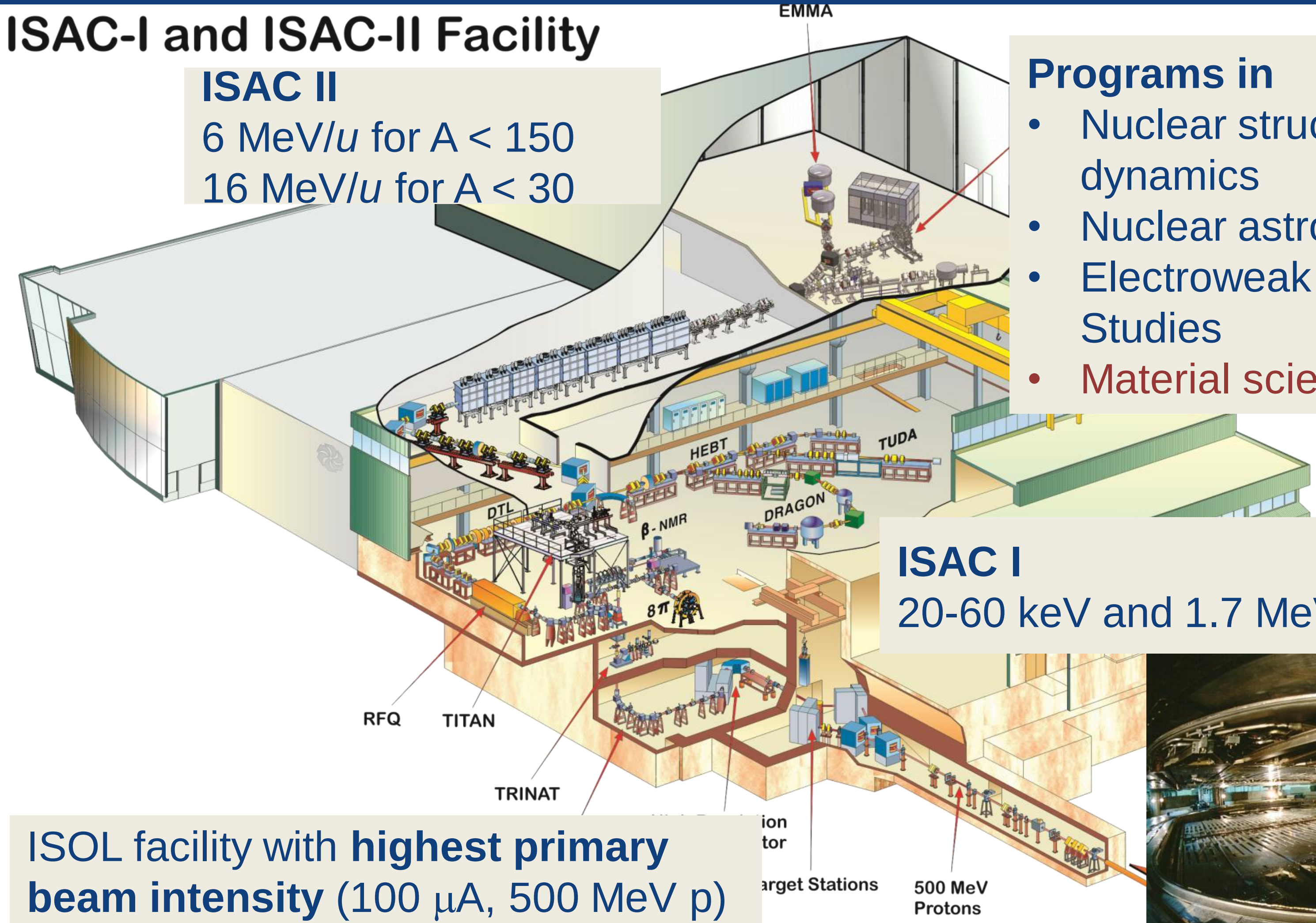
Accelerating Science for Canada
Un accélérateur de la démarche scientifique canadienne

Outline



- Rare isotope beams at TRIUMF
- Mass measurements
  - Motivation
  - Ion traps
- Mass measurements at TITAN
  - Isospin non-conservation
  - Island of inversion
  - Neutron-rich Ca isotopes
  - Double β-decay candidate ^{48}Ca

ISAC RIB Facility



ISAC II
6 MeV/*u* for A < 150
16 MeV/*u* for A < 30

Programs in

- Nuclear structure & dynamics
- Nuclear astrophysics
- Electroweak interaction Studies
- Material science

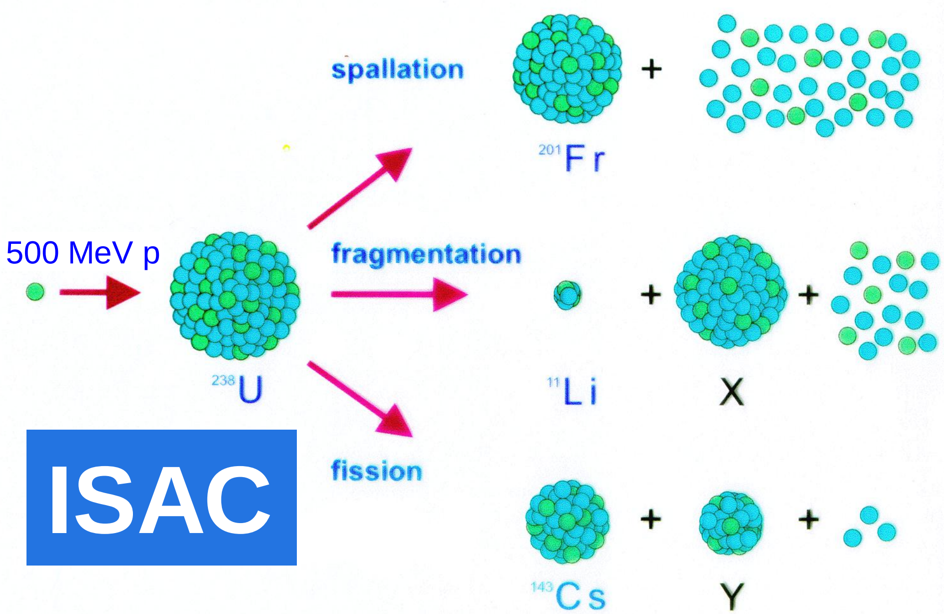
ISAC I
20-60 keV and 1.7 MeV/*u*

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

User facility with ~1000 users

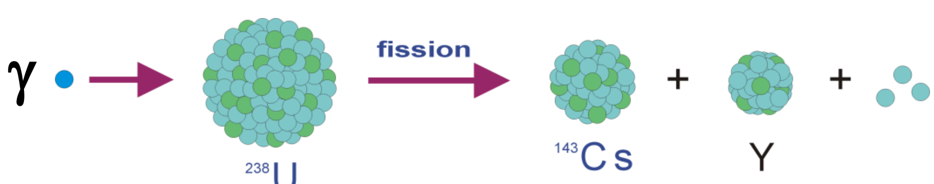
TRIUMF RIB Production

Proton-induced reactions



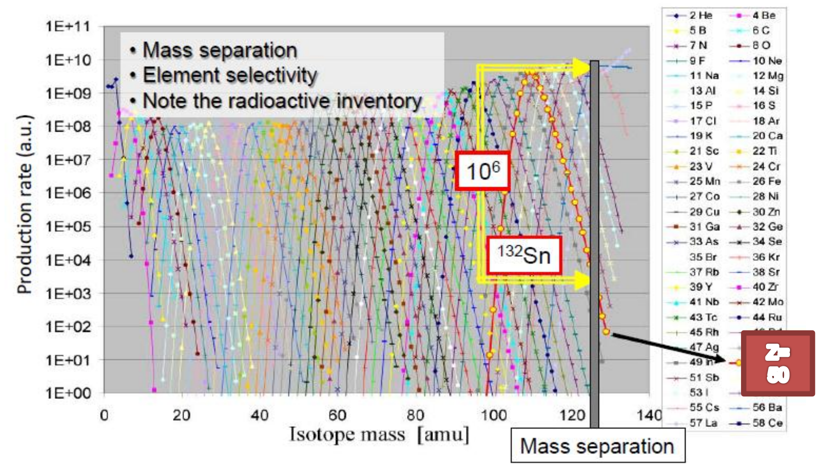
ISAC

Photo-induced fission



ARIEL

• 1 GeV proton beam on a lanthanum (La) target



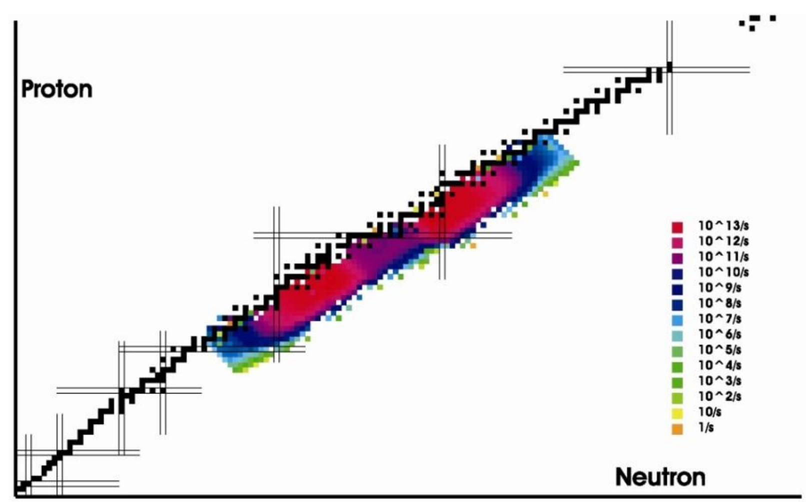
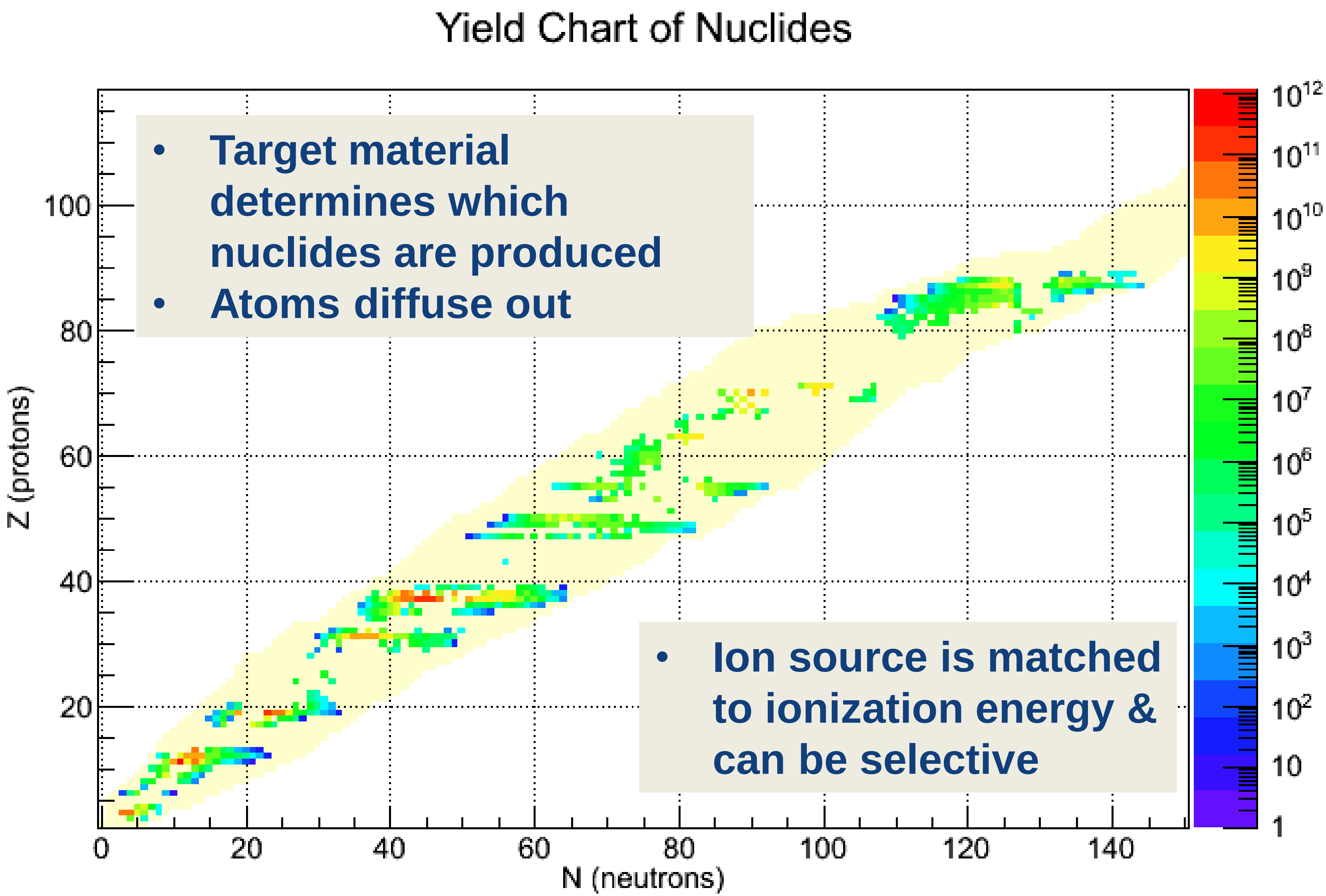


Photo-fission products using 50 MeV 10 mA electrons on to Hg convertor & UC_x target.

Isotope production figure from ISOLDE-CERN

RIB Available at ISAC



- **Target material determines which nuclides are produced**
- **Atoms diffuse out**

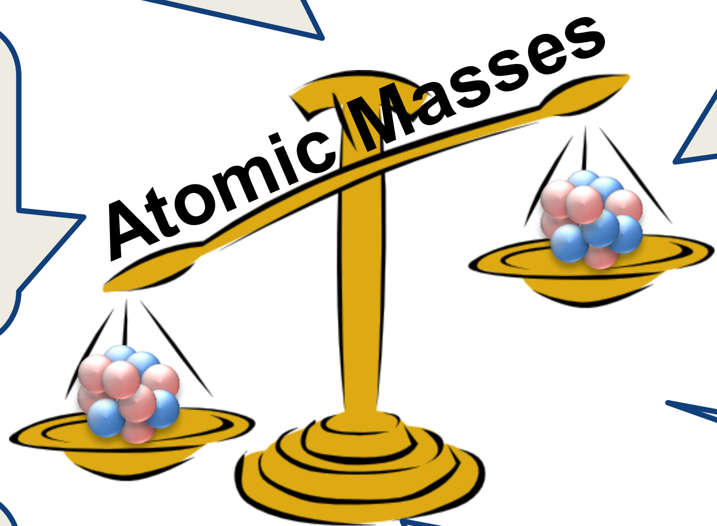
- **Ion source is matched to ionization energy & can be selective**

TRIUMF

Why measure the atomic mass?

Physics & Chemistry
Basic information
$\delta m/m \approx 10^{-6}$

Nuclear Astrophysics
$\delta m/m \leq 10^{-7}$



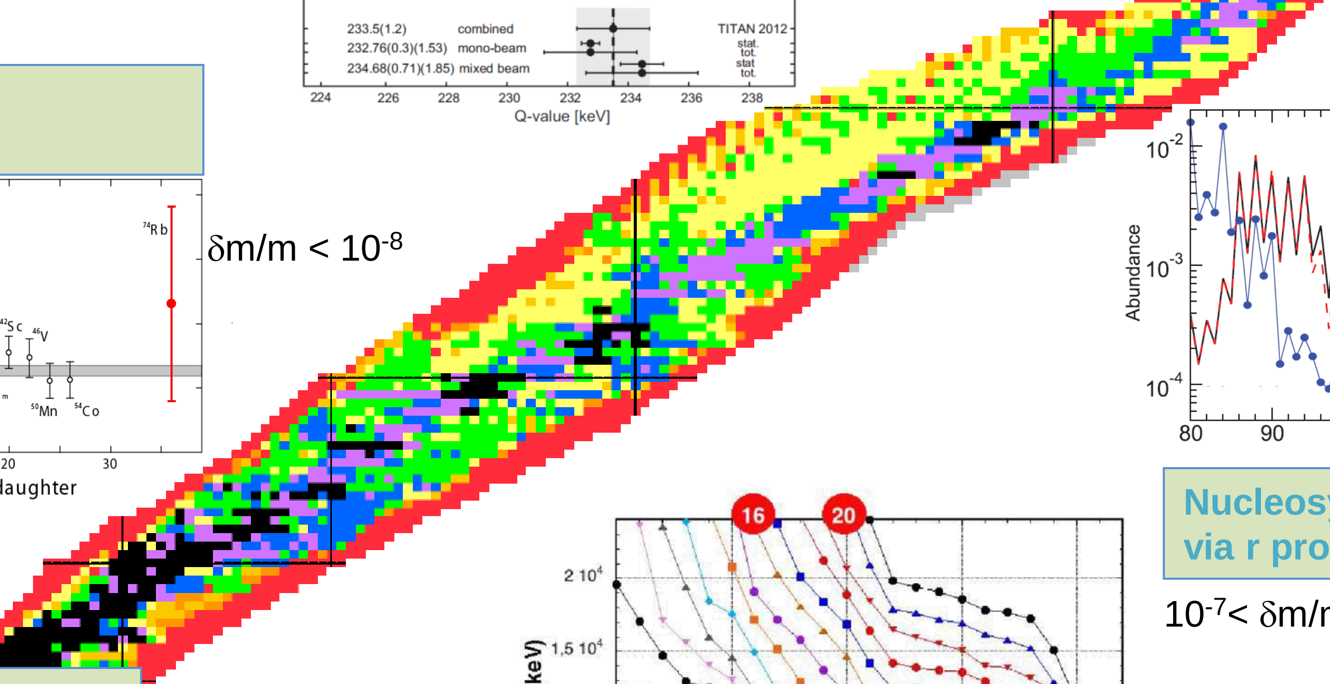
General Physics
Metrology, tests of CPT
$\delta m/m \leq 10^{-10}$

Nuclear Physics
Mass models & formulae
$\delta m/m \approx 10^{-7}$

Weak Interactions
Tests of fundamental symmetries
$\delta m/m \approx 10^{-7}$

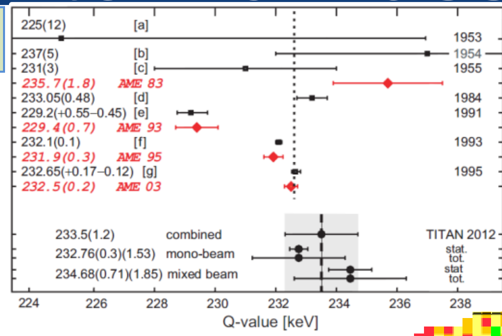
Atomic Physics
Binding energies and tests of QED w/ HCI
$\delta m/m \leq 10^{-9}$

Mining Nuclear Physics from Atomic Mass Measurements

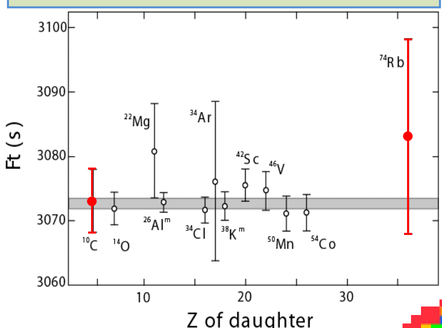


Neutrino physics

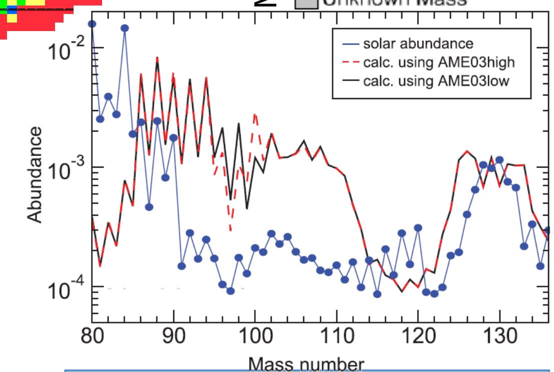
$\delta m/m \leq 10^{-9}$



Test of CVC hypothesis



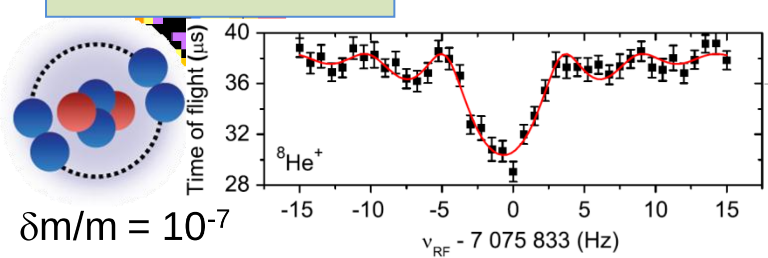
$\delta m/m < 10^{-8}$



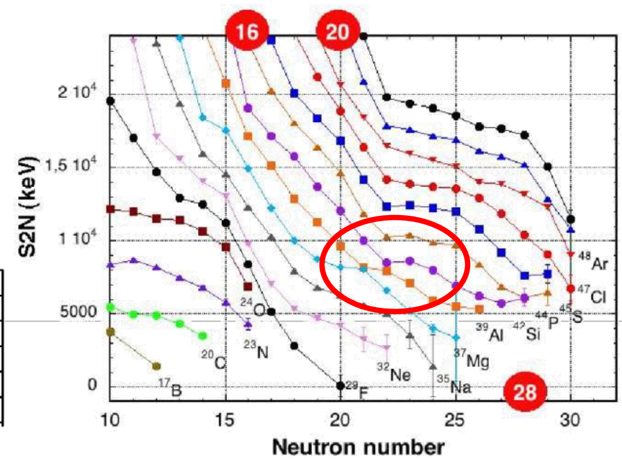
Nucleosynthesis via r process

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

Halos and skins



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

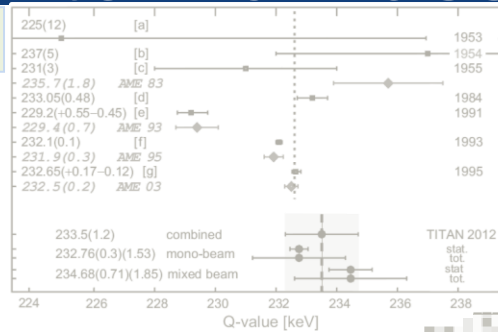


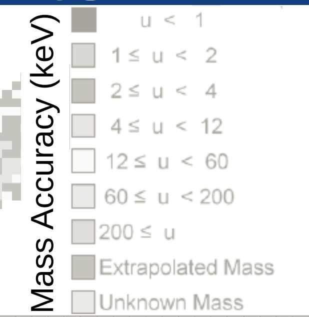
Evolution of nuclear shell structure

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

NUBASE-AME 2012

Mining Nuclear Physics from Atomic Mass Measurements

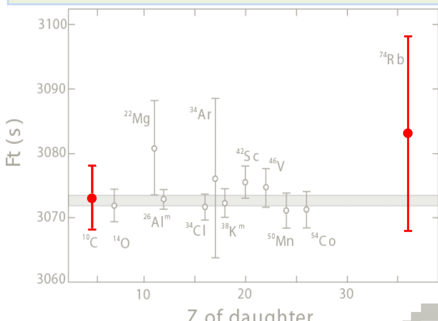




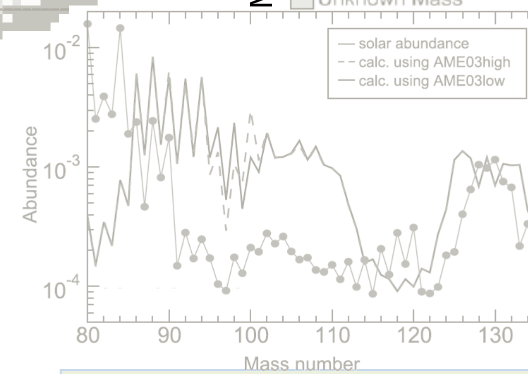
Neutrino physics

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

Test of CVC hypothesis

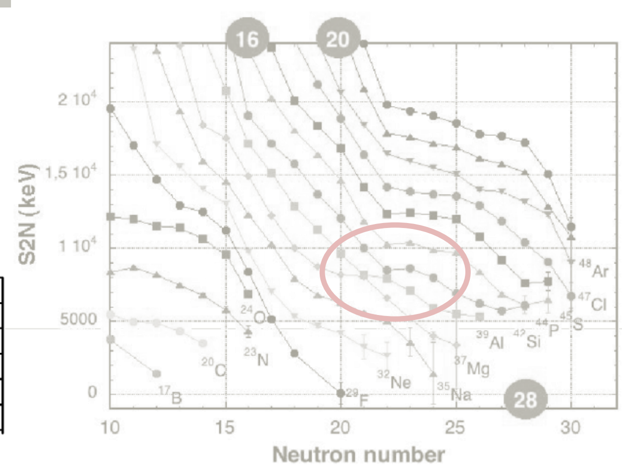


$\delta m/m < 10^{-8}$



Nucleosynthesis via r process

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



Evolution of nuclear shell structure

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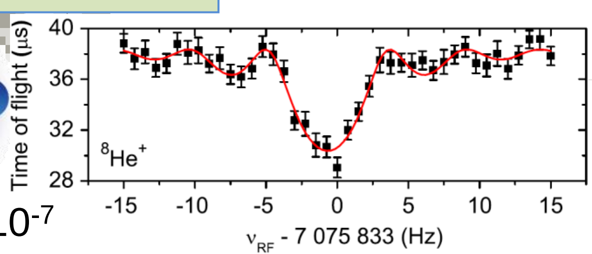
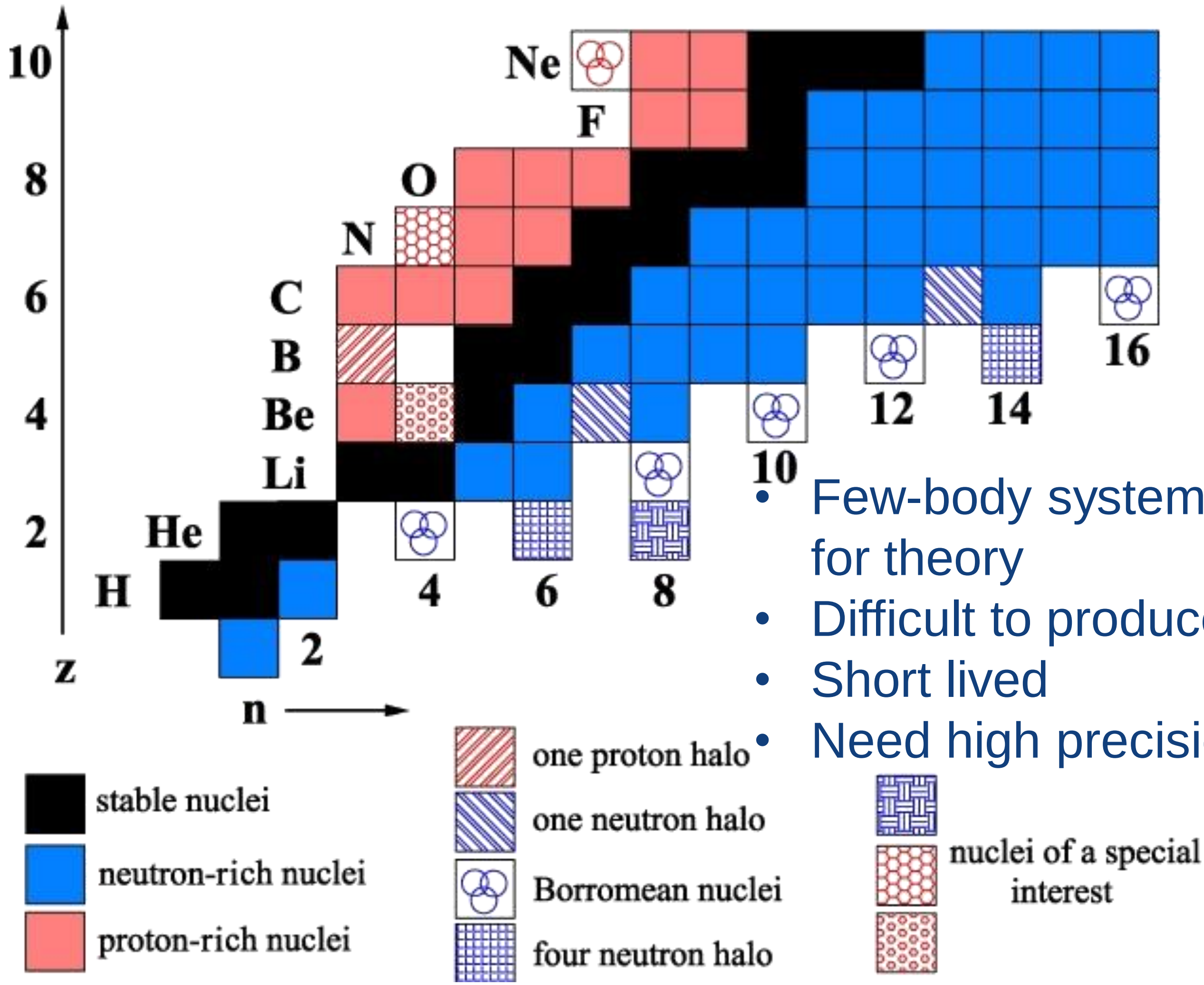


$\delta m/m = 10^{-7}$

NUBASE-AME 2012

Halo nuclei



- Few-body system → good for theory
- Difficult to produce
- Short lived
- Need high precision

challenging experiments!

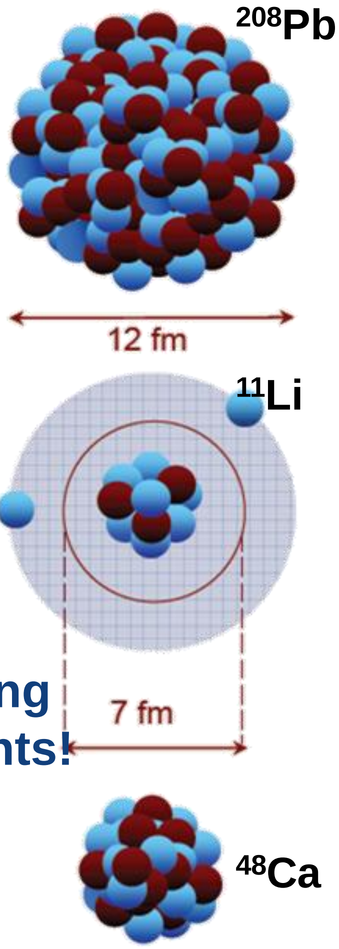


Figure: http://www.ph.surrey.ac.uk/npg/confs/ecthalo.html

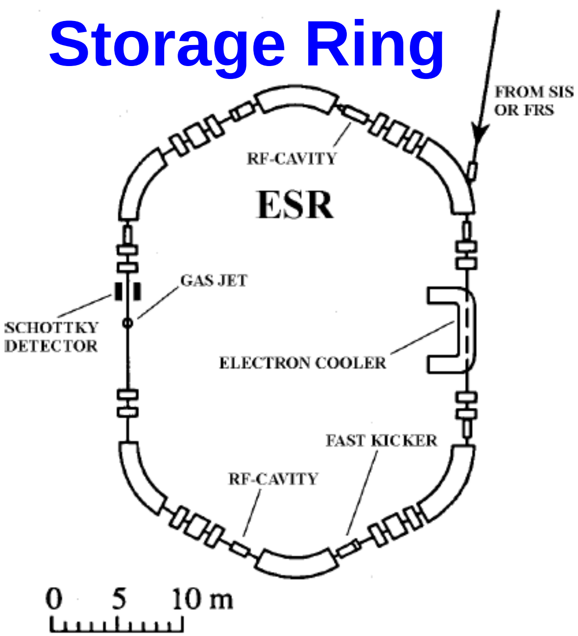
TRIUMF

Storage and Trapping Devices

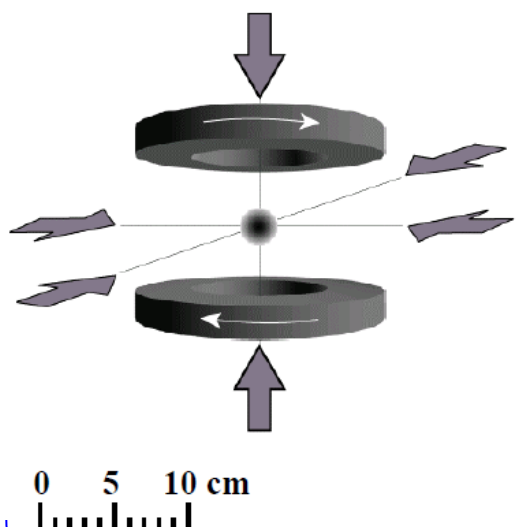
Wish list:

- Confine rare nuclide to a well-defined volume
- “Infinite” observation time (or at least as long as $T_{1/2}$)
- Use well-defined fields → careful manipulation
- Lead to high-accuracy, -precision, -sensitivity experiments

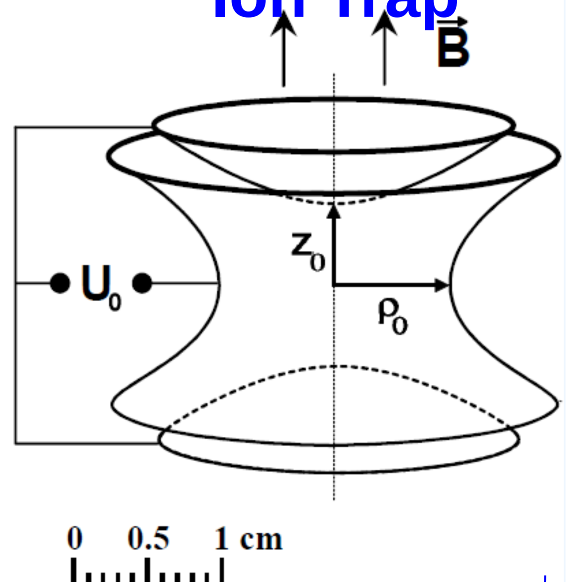
Storage Ring



Atom Trap



Ion Trap



Relativistic Particles

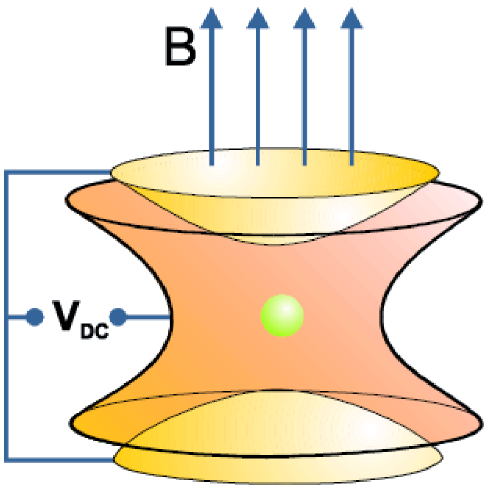
Particles at “rest”

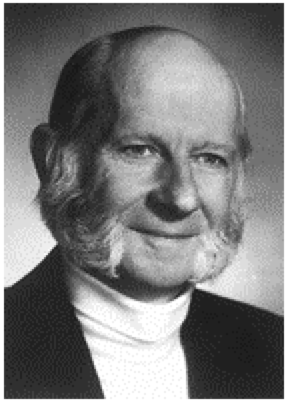
Figure: H.-J. Kluge *et al.*, Phys. Scrip. T104 (2003) 176

Ion Traps

Penning Traps

= electrostatic + magnetic

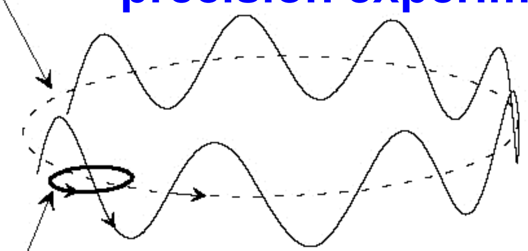




H. G. Dehmelt

magnetron motion (ω_-)

precision experiments



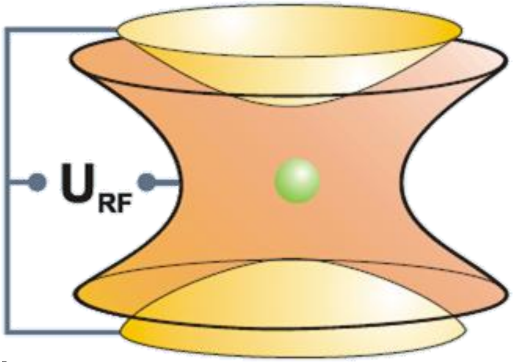
micromotion

1989

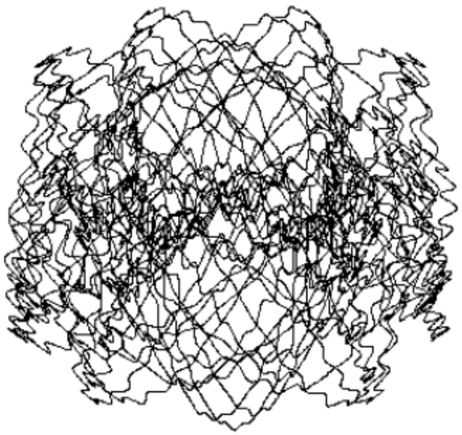
Paul Traps

= oscillating electric field

W. Paul



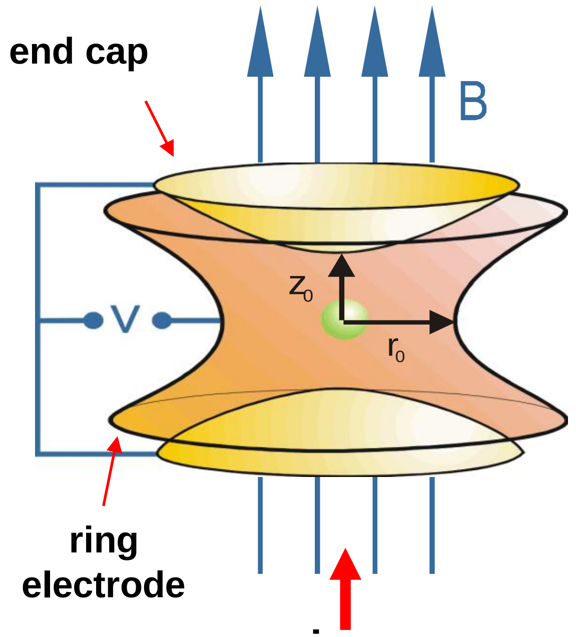
beam preparation

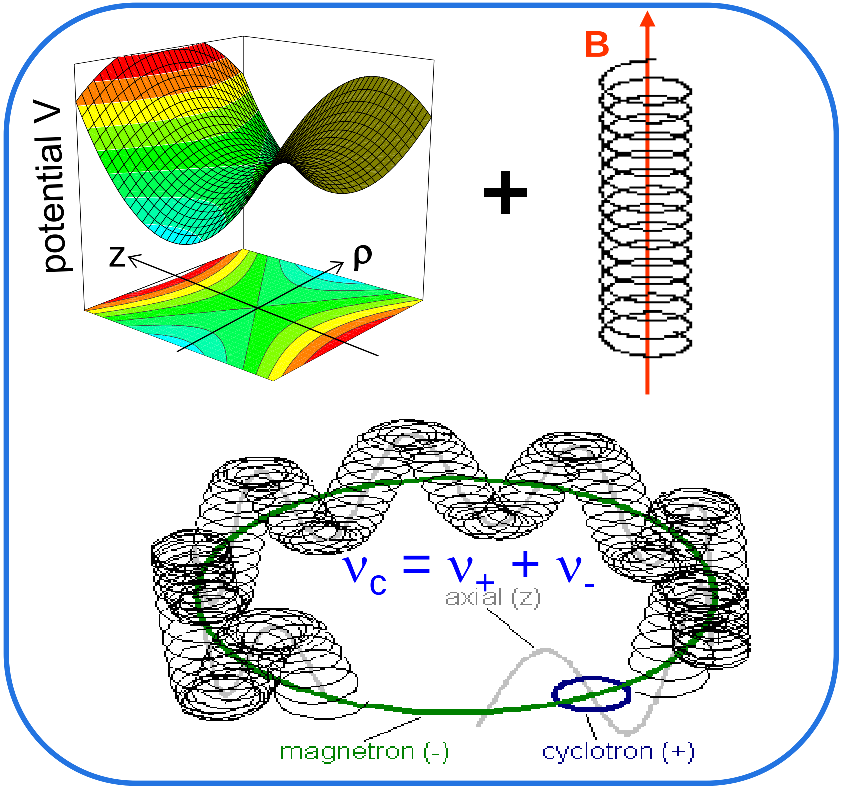


micromotion + macromotion

Penning Trap

Single-ion Quantum Manipulation





$$2\pi\nu_c = (q/\mathbf{m}) \cdot B$$

Mass determination via cyclotron-frequency determination:

- Measurement performed with single ion at a time
- Repeat over a range of frequencies
- Total number of ions per spectrum ~ 100

Mass Determination

- Measure

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

measure time of flight (q)

calibrate with reference ion (B)

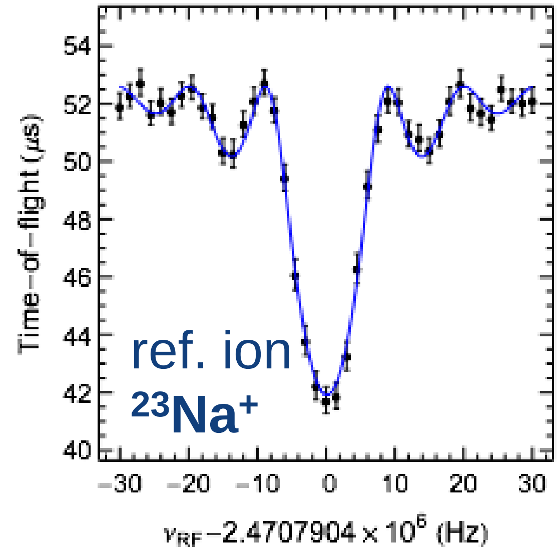
ion's mass (m)

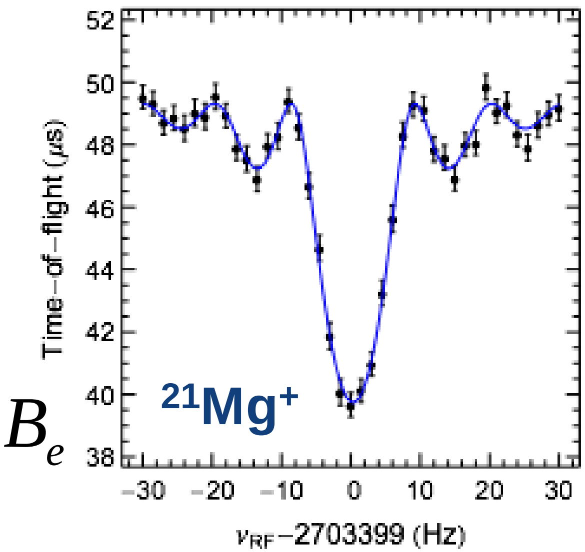
- Experimental result:

$$R = \frac{\nu_{c,ref}}{\nu_c} = \frac{q_{ref}}{q}\cdot\frac{m}{m_{ref}}$$

- Atomic mass:

$$M = R\cdot(m_{ref} - q_{ref}m_e + B_{e,ref}) + qm_e - B_e$$





Maturing Field: High Precision and Accuracy

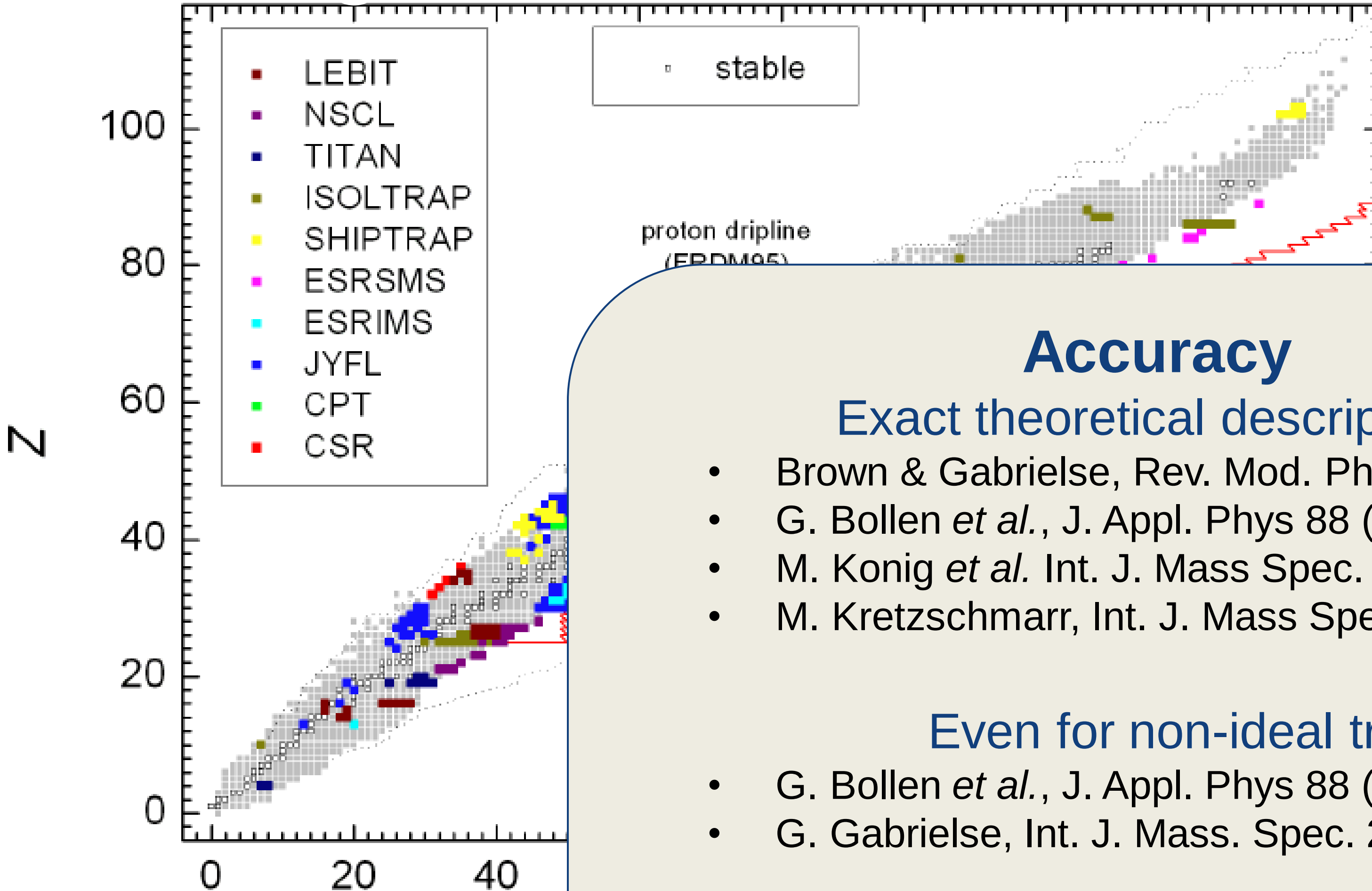


Figure courtesy of D. Lunney

Accuracy

Exact theoretical description:

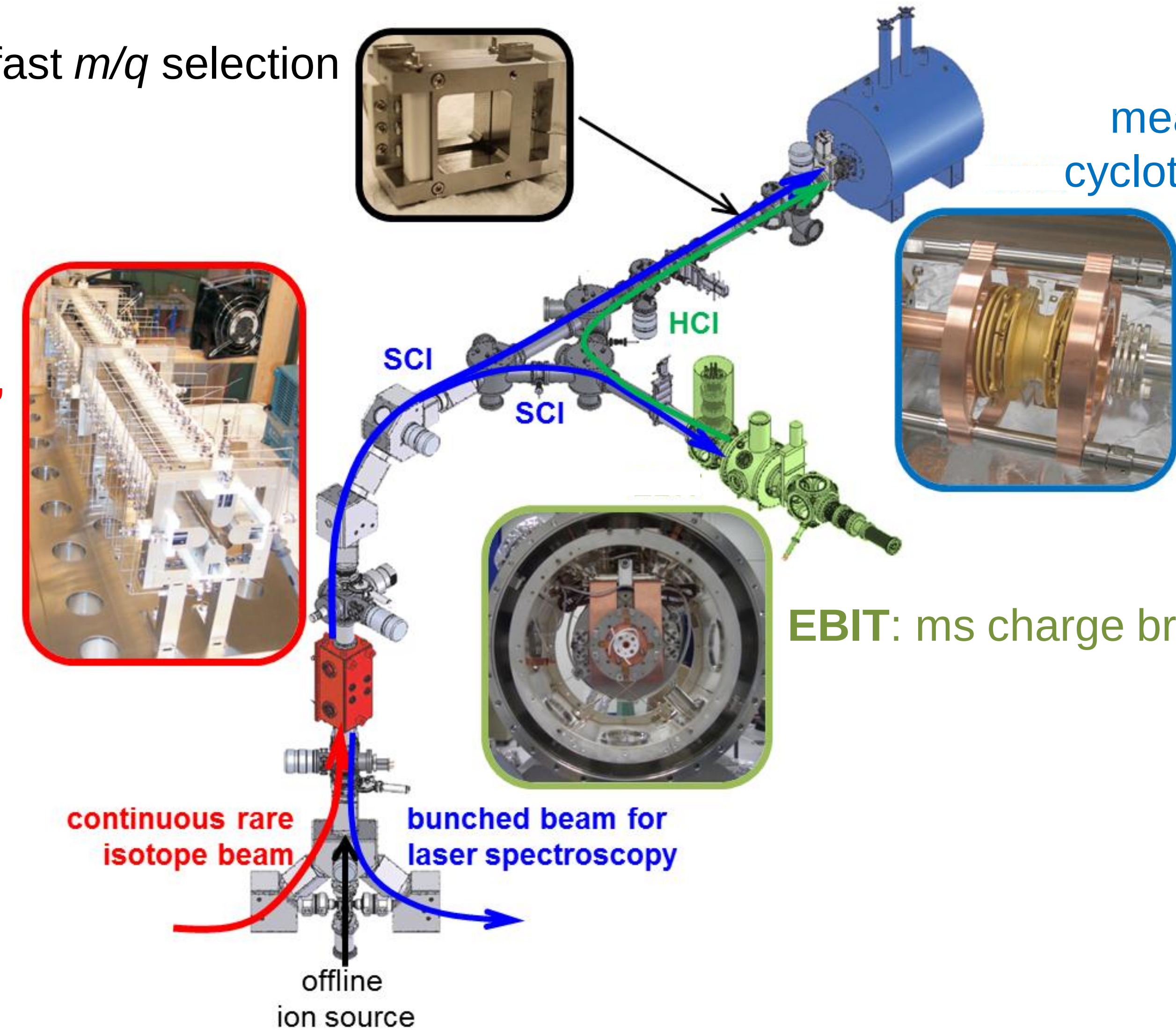
- Brown & Gabrielse, Rev. Mod. Phys. 58 (1986) 233
- G. Bollen *et al.*, J. Appl. Phys 88 (1990) 4355
- M. Konig *et al.* Int. J. Mass Spec. 142 (1995) 95
- M. Kretzschmarr, Int. J. Mass Spec. 246 (2007) 122

Even for non-ideal traps:

- G. Bollen *et al.*, J. Appl. Phys 88 (1990) 4355
- G. Gabrielse, Int. J. Mass. Spec. 279 (2009) 107

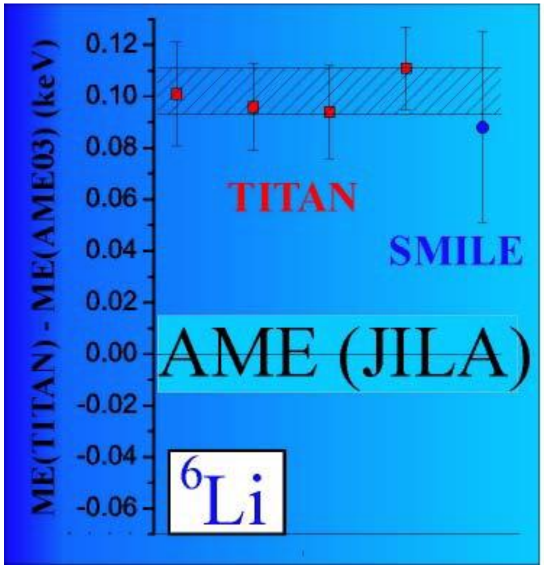
Verify with off-line tests of stable nuclides

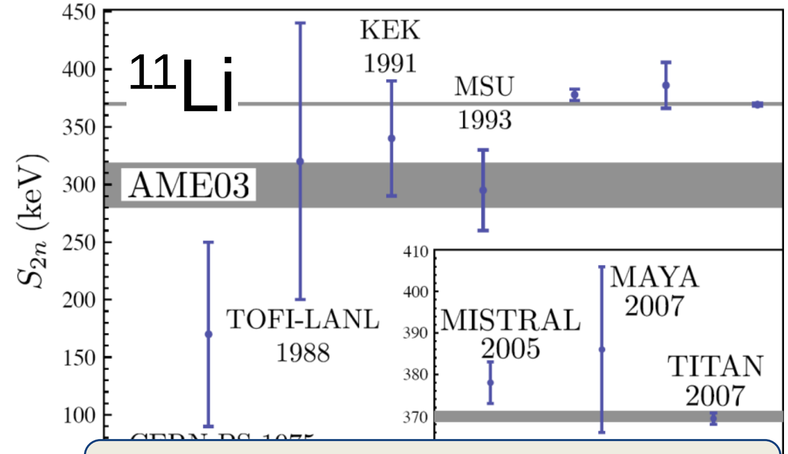
TRIUMF's Ion Trap for Atomic and Nuclear science



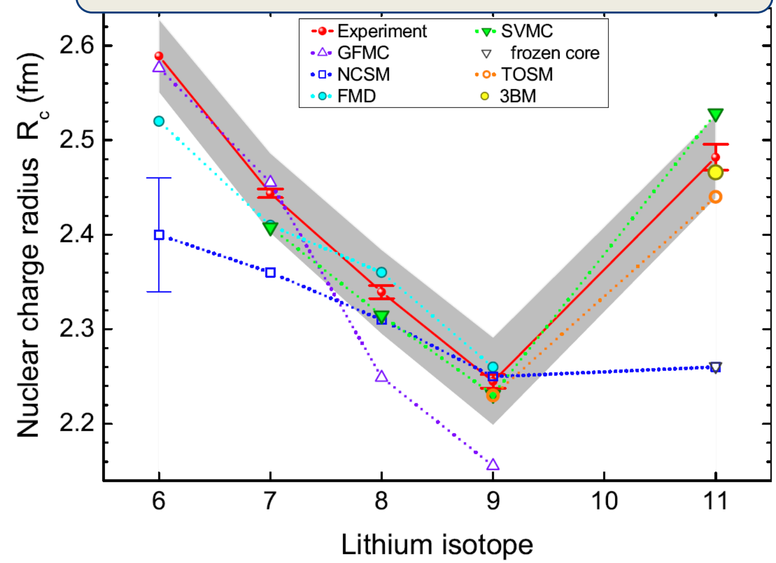
J. Dilling *et al.*, NIMB **204** (2003) 492

^{6,8,9,11}Li Isotopes with TITAN





shortest-lived ($T_{1/2}$ = 9 ms)



- Measured ^{6,8,9,11}Li
- TITAN confirmed ^{6}Li deviation from Atomic Mass Evaluation (AME) 2003 found at SMILETRAP

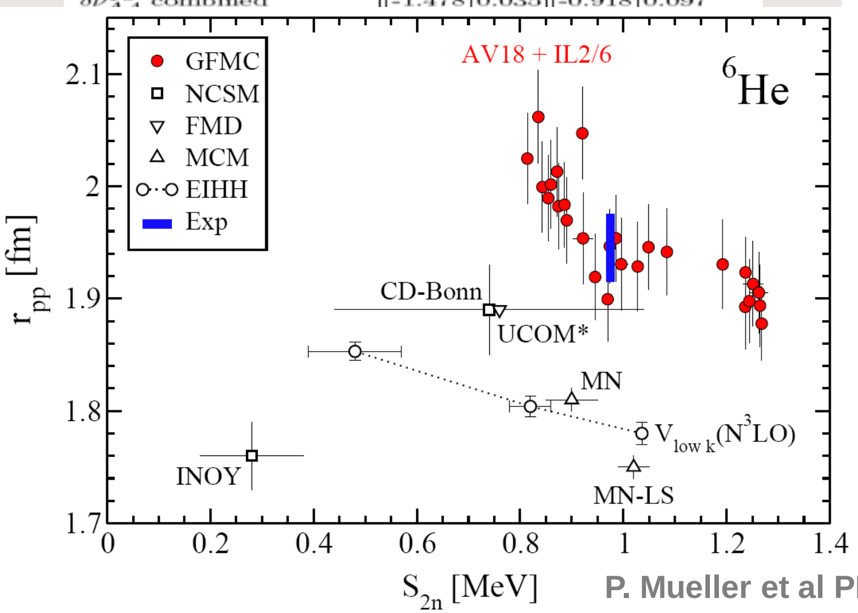
S. Nagy *et al*. PRL 96 163004
M. Brodeur et al, PRC 80 (2009) 044318;
M. Smith et al PRL 101, 202501 (2008)
R. Sánchez *et al.*, PRL 96, 033002 (2006);
Nature Physics 2, 145 (2006);; W. Nörtershäuers *et al*., PRC 84, 024307 (2011); G. W. Drake *et al.* PRL. 100, 243002 (2008)

He Halos with TITAN

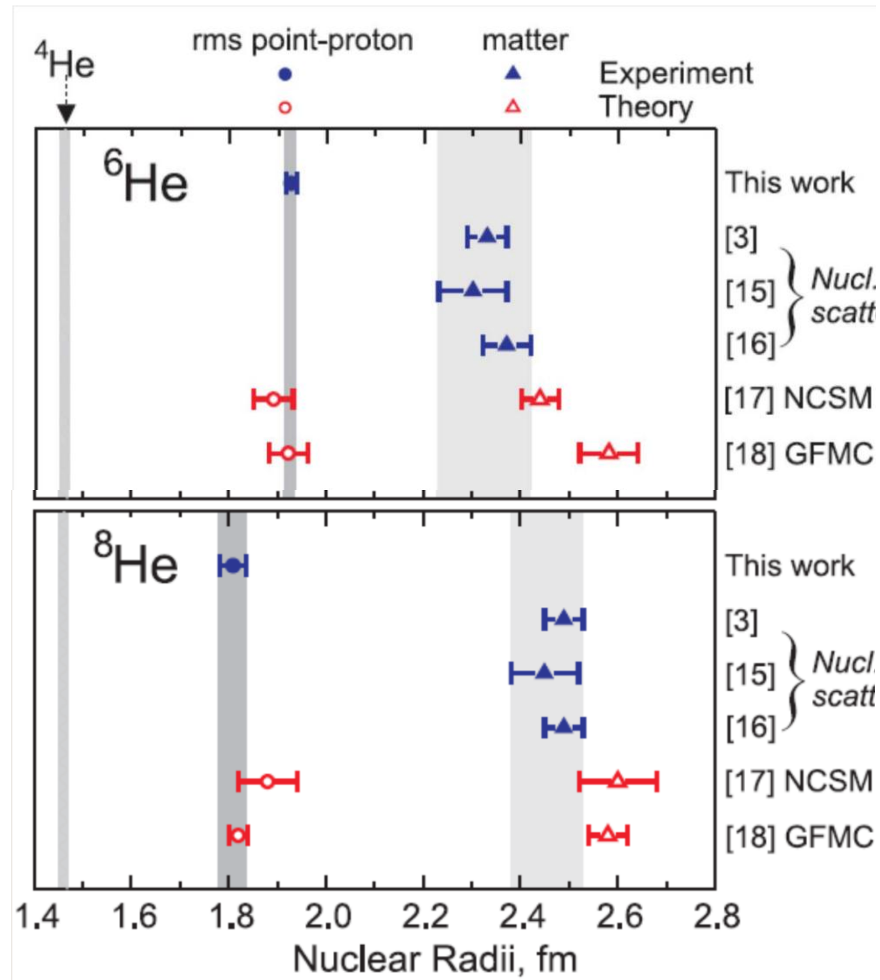
Nuclear charge radius of ^{8}He

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

	^{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		[illegible]		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



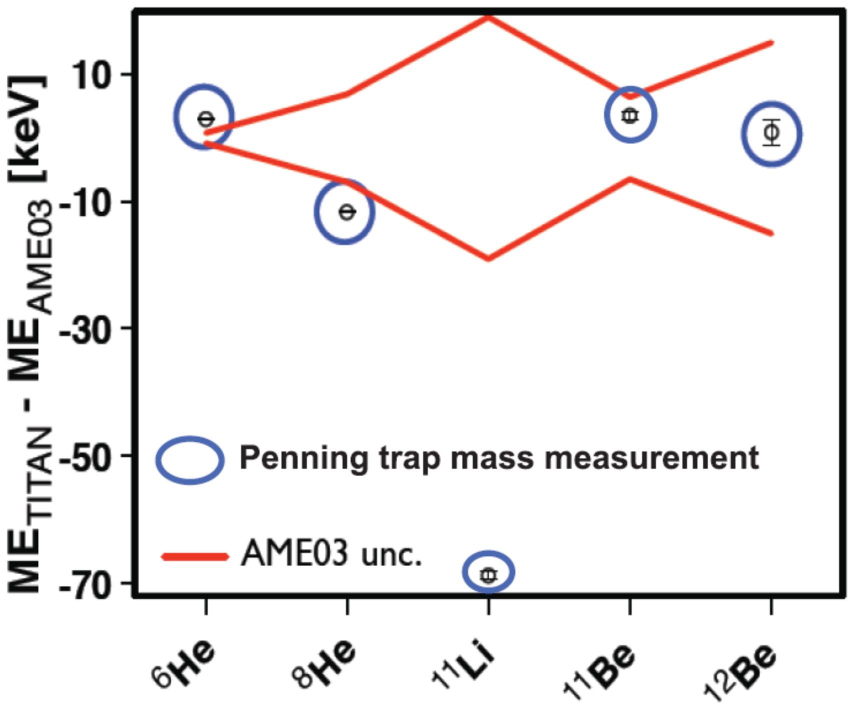
G. Drake *et al.*



P. Mueller et al PRL 99, 252501 (2007); M. Brodeur *et al.* PRL 108, 052504 (2012)

TITAN Halo Harvest

- Highest precision for such short-lived nuclides
- Shortest-lived (^{11}Li $T_{1/2}$ = 9 ms) measured with Penning trap mass spectrometry
- Limits of sensitivity (5-10 ions/sec)



V. Ryjkov et al., PRL 101 (2008) 012501
M. Brodeur et al., PRL108 (2012) 052504
M. Smith et al PRL 101, 202501 (2008)
R. Ringle et al., PLB 675 (2009) 170
S. Ettenauer et al., PRC 81 (2010) 024314

Plot: K. Blaum *et al.*, Phys. Scrip. T152 (2013) 014017

Moving heavier: ^{20,21}Mg

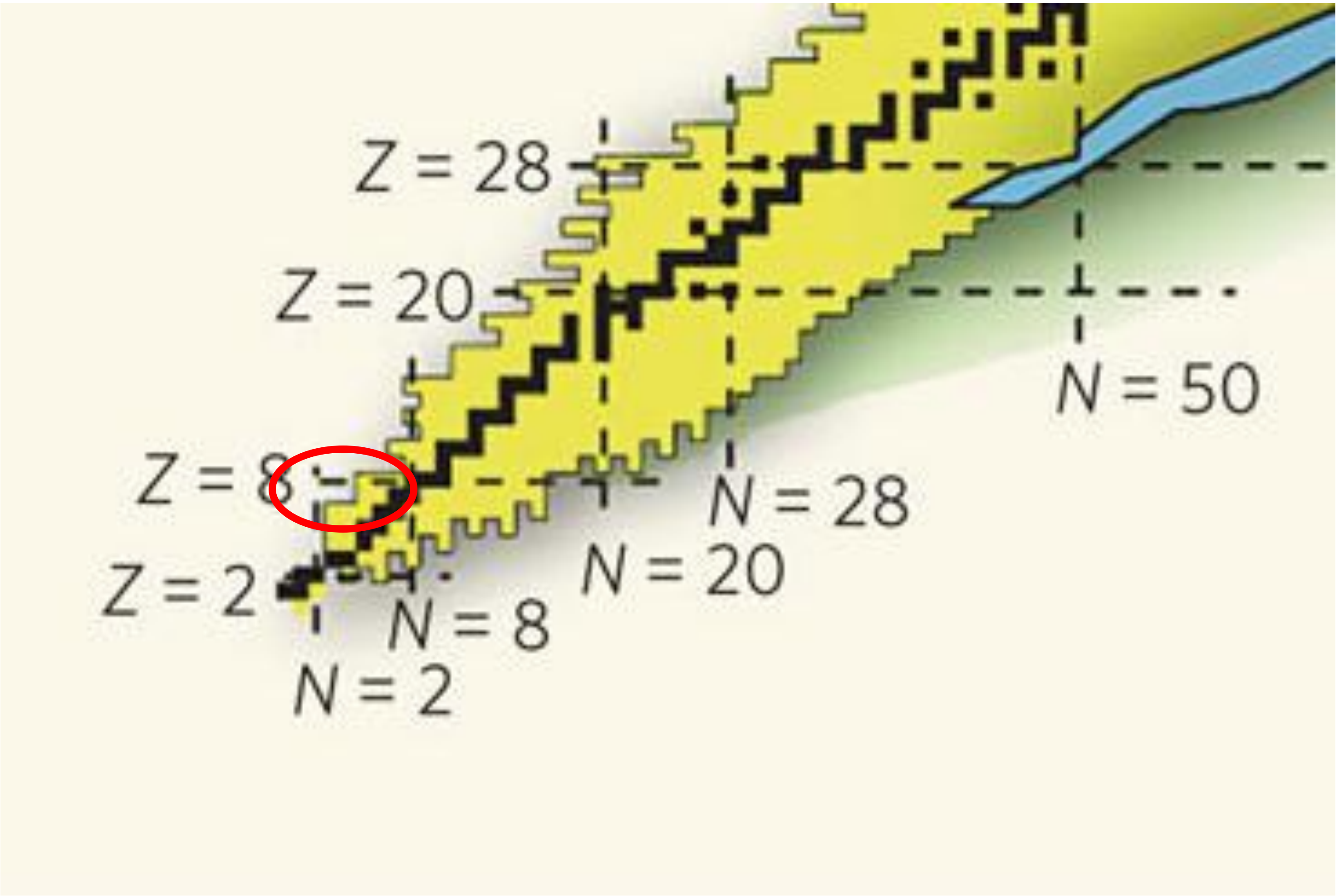
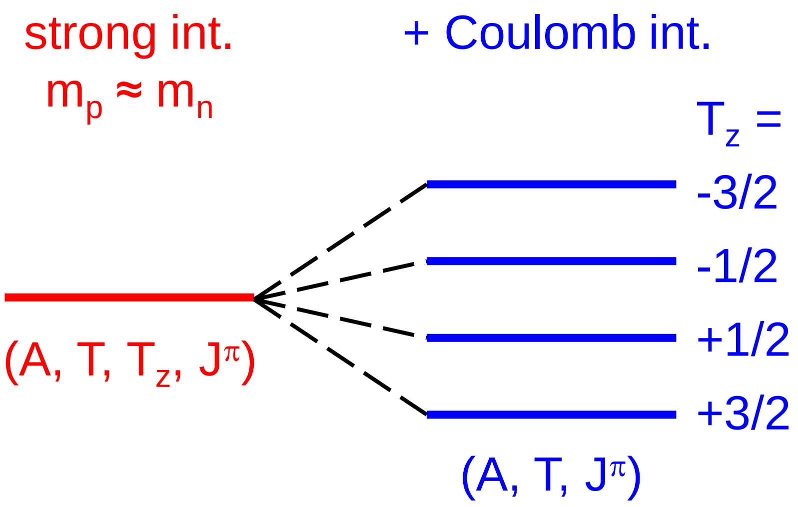


Figure: P. Cottle, *Nature* 465 (2010) 430

Isobaric Multiplet Mass Equation

- Assume charge-independent strong interaction
- Isobaric analog states (IAS) are degenerate & share same mass
- Coulomb interaction breaks symmetry
- Using two-body charge-dependent interaction, the sum of isoscalar, isovector, and isotensor operators is



$$M(A,T,T_z) = a(A,T) + b(A,T)\,T_z + c(A,T)\,T_z^2$$

How robust is IMME?

- 29 of 35 multiplets obey quadratic form
- 6 outliers: A = 8, 9, 11, 32, 33, 35
  - Problem with experimental data or requires
    dT_z^3 or eT_z^4
- Sources of *d* term:
  - Unbound nuclei
  - Isospin mixing with nearby states of same J^{π} → usually observed in shell model calculations

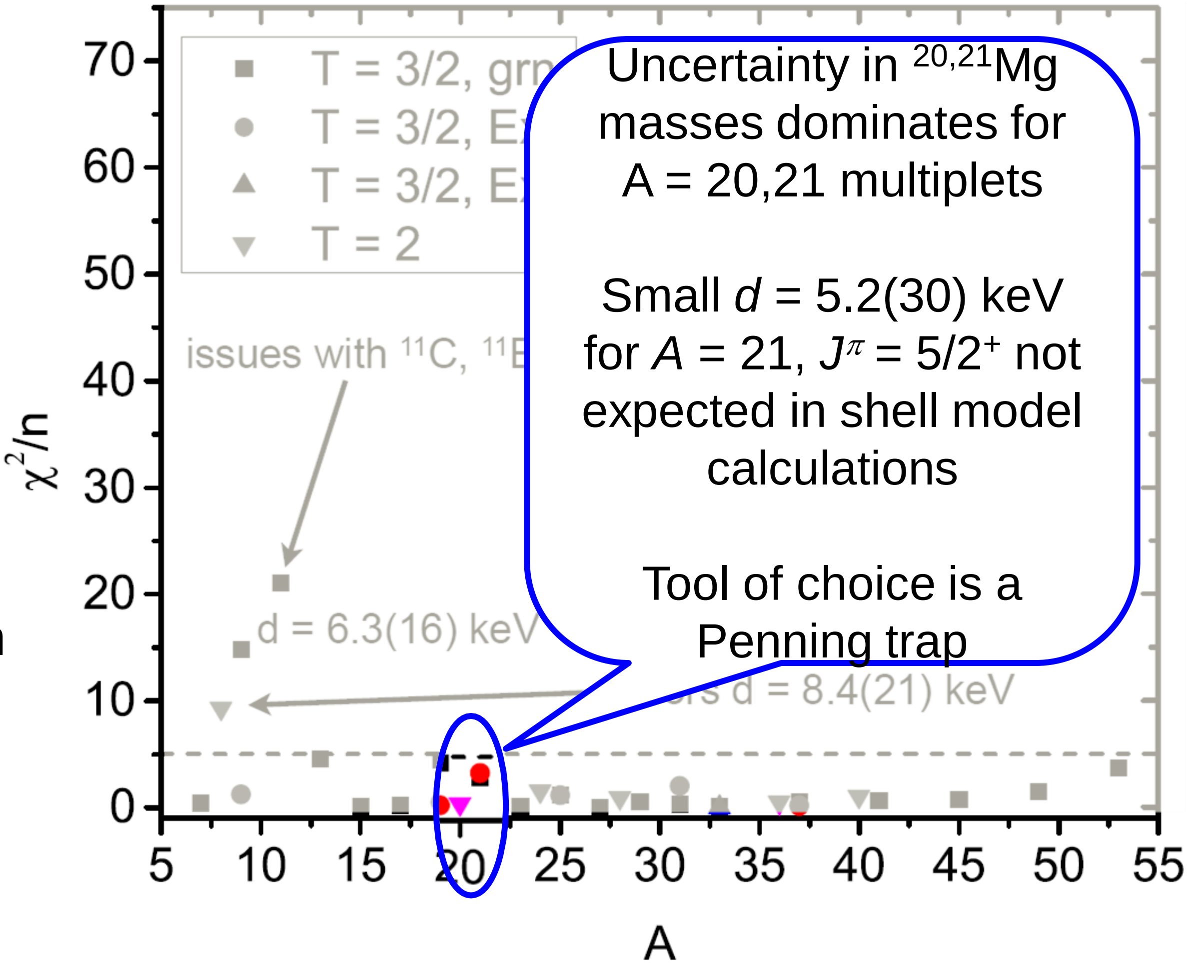
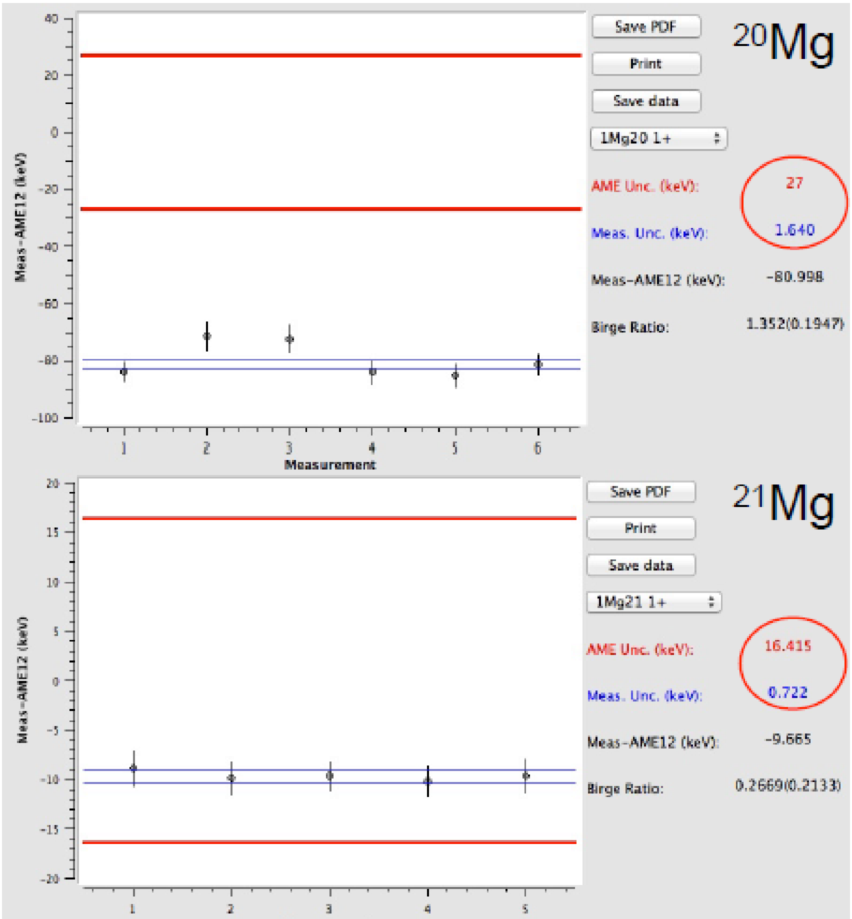
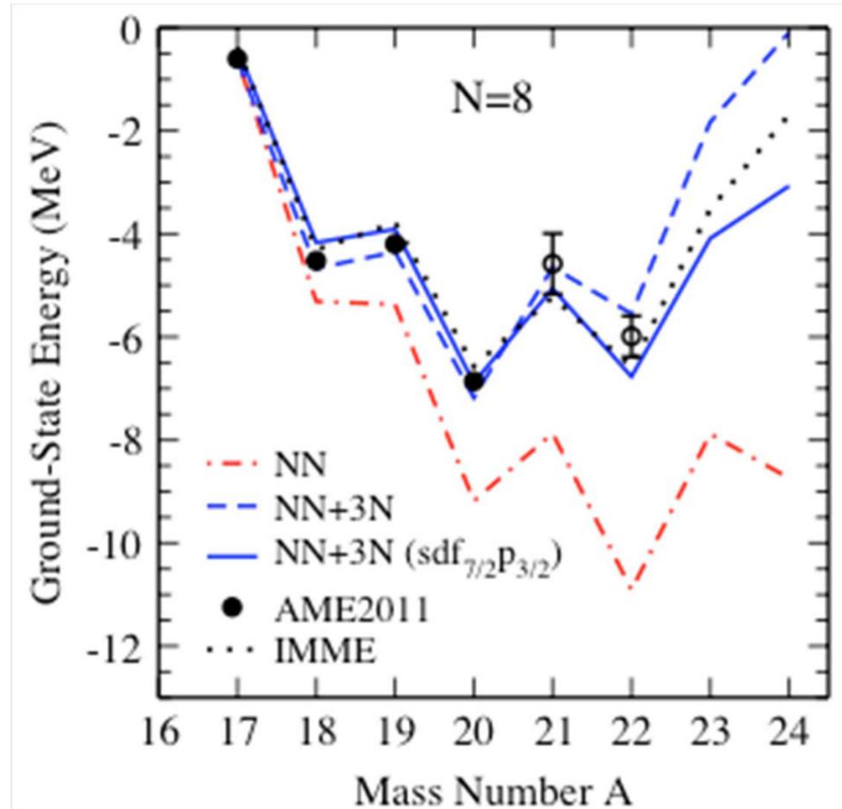


Figure: courtesy of M. Brodeur

TITAN ^{20,21}Mg Masses





Phenomenological approach:

NN: over-bound

NN + 3N: improved agreement with exp.

A.T. Gallant *et al.*, submitted to PRL; figure : J.D. Holt *et al.*, PRL **110 (2013) 022502**

IMME: Comparison to Theory

A = 20 quintet

term	exp (keV)	USDA (keV)	USDB (keV)	$V_{low\,k}$ (keV)
d	2.8(11)	-0.1(10)	-0.1(10)	-18(13)
e	0.9(12)	-1.7(10)	degenerate	-49(17)

- Observed d term cannot be explained by USDA/B
- e term close to USDA result
- Uncertainty in $V_{low\,k}$ calculation too large

A = 21 quartets

J^p	d exp (keV)	d USDA (keV)	d USDB (keV)	d $V_{low\,k}$ (keV)
$5/2^+$	6.7(13)	-0.3(10)	0.3(10)	-38(37)
$1/2^+$	-4.4(14)	1.2(10)	1.9(10)	6(37)

- Observed d term cannot be explained by USDA/B
- Inadequate data or new effects not included in calculation
- Uncertainty in $V_{low\,k}$ calculation too large

A.T. Gallant *et al.*, submitted to PRL

Moving heavier: Island of Inversion

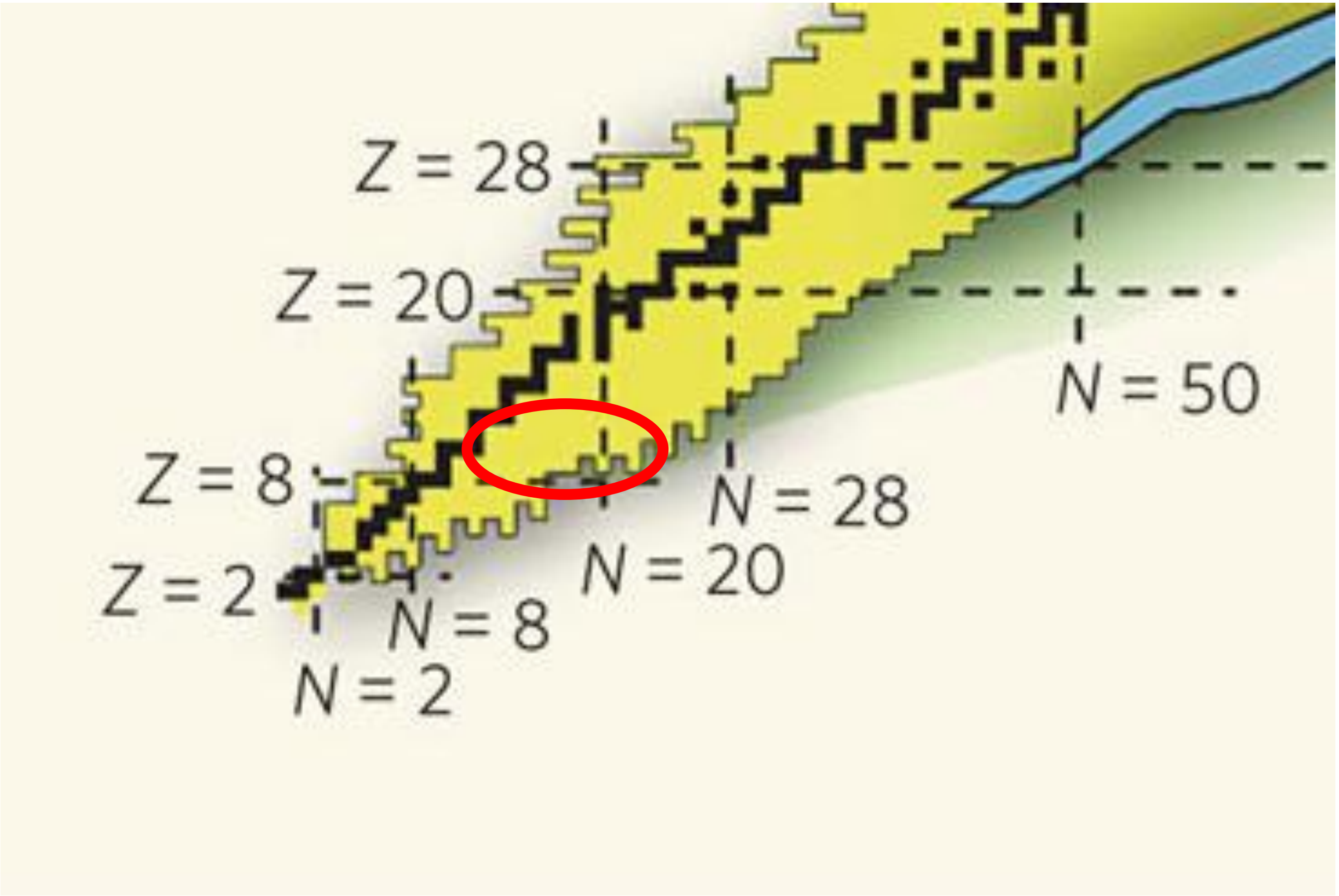
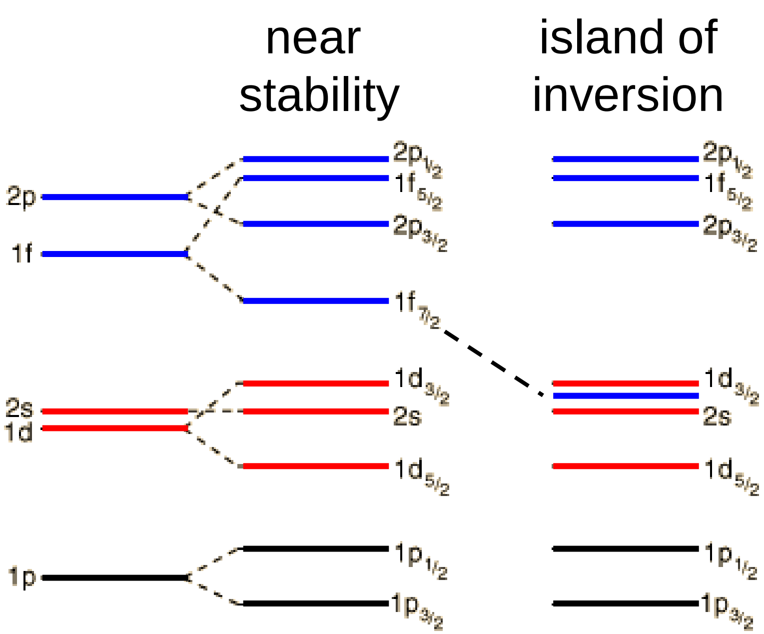


Figure: P. Cottle, *Nature* 465 (2010) 430

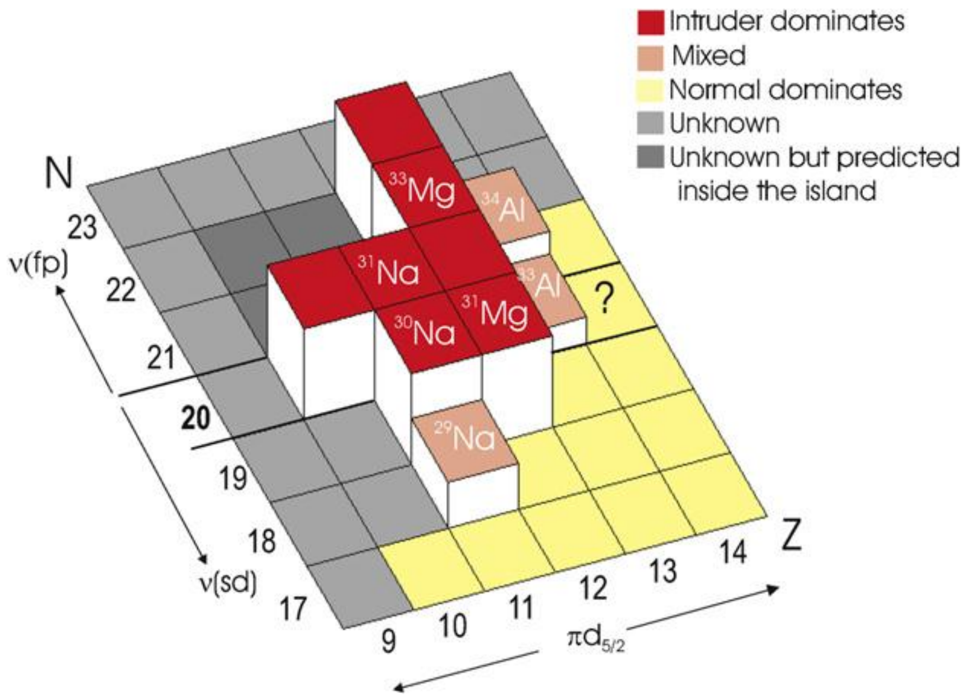
Island-of-inversion Mass Cartography

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



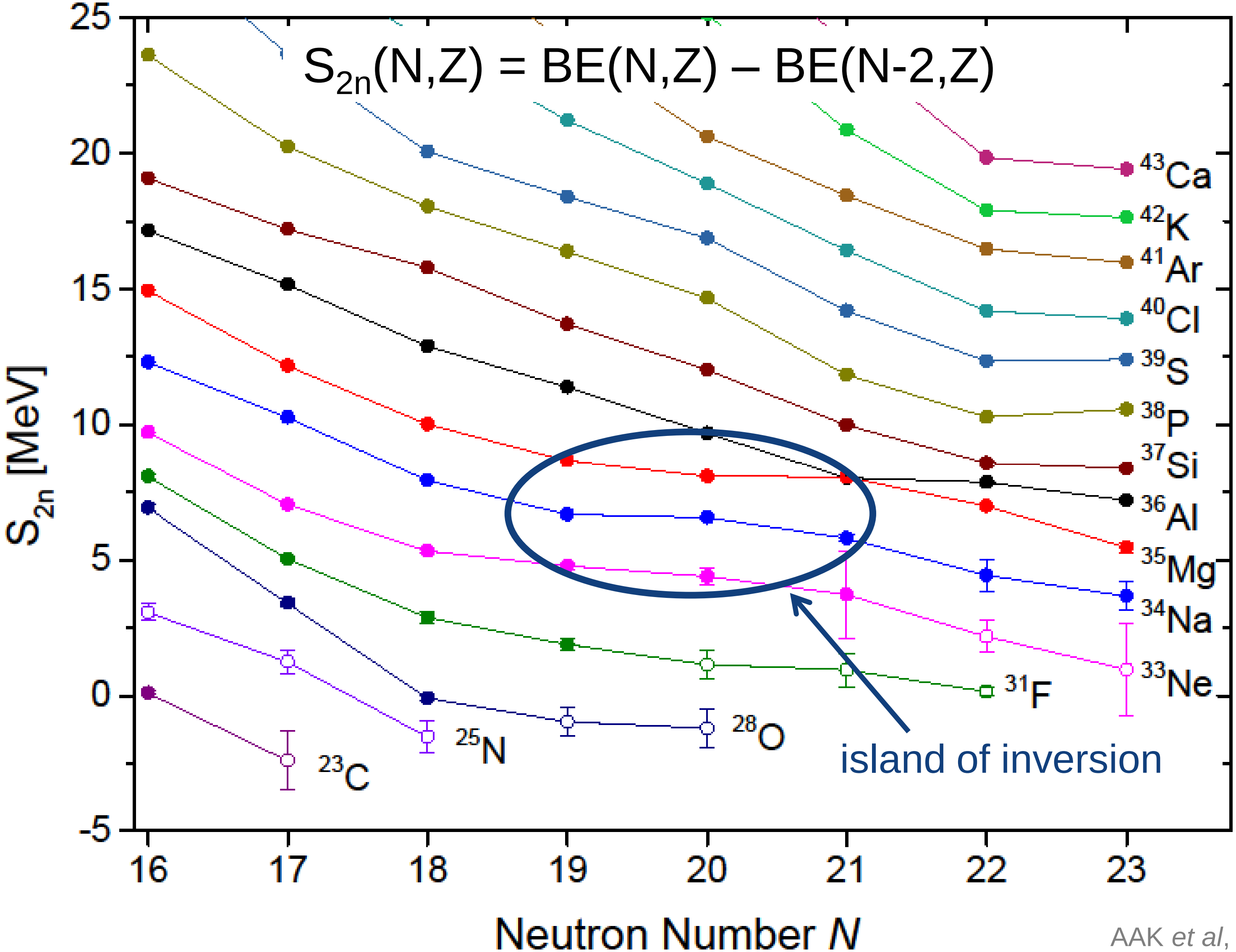
TITAN's campaign of mass measurements:

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



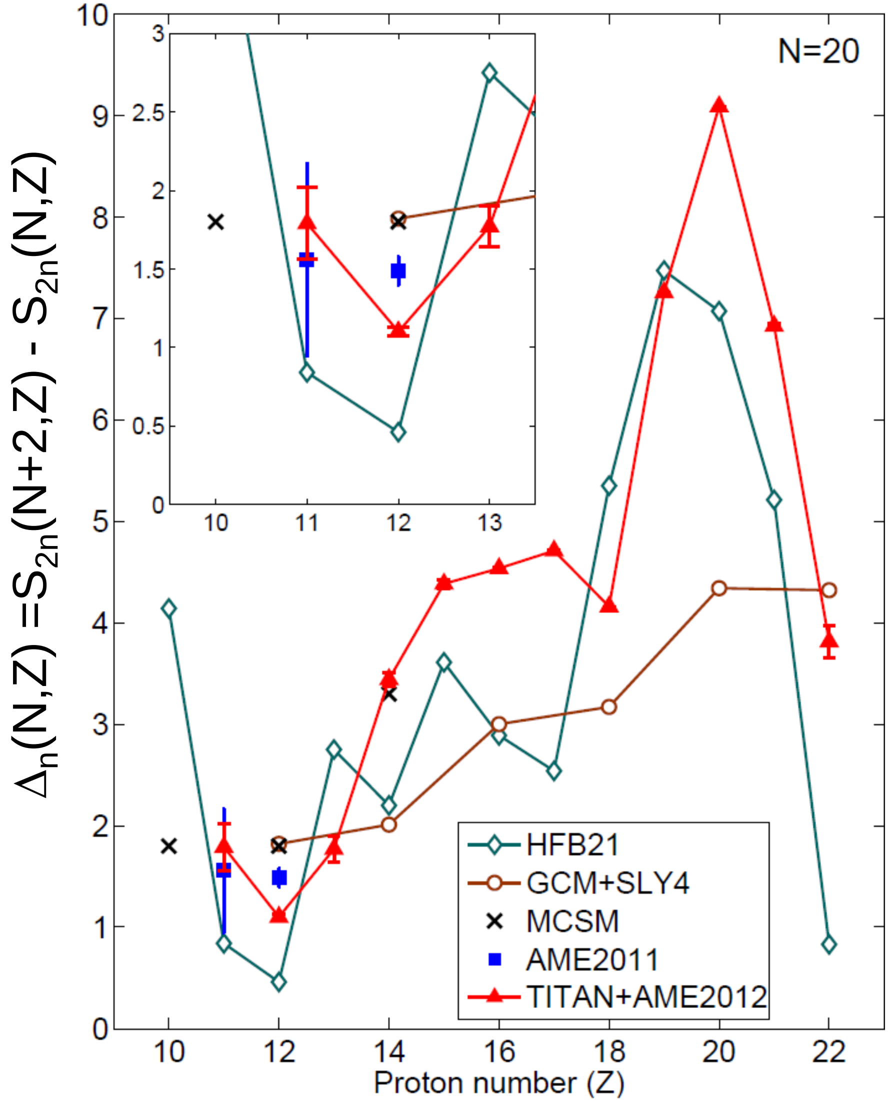
A.Chaudhuri *et al*, PRC 88 (2013) 054317; AAK *et al*, submitted to PLB; figure from Himpe *et* al, PLB 658 (2008) 203

Island of Inversion: S_{2n} Cartography



AAK *et al*, submitted to PLB

Vanishing N = 20 Shell



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

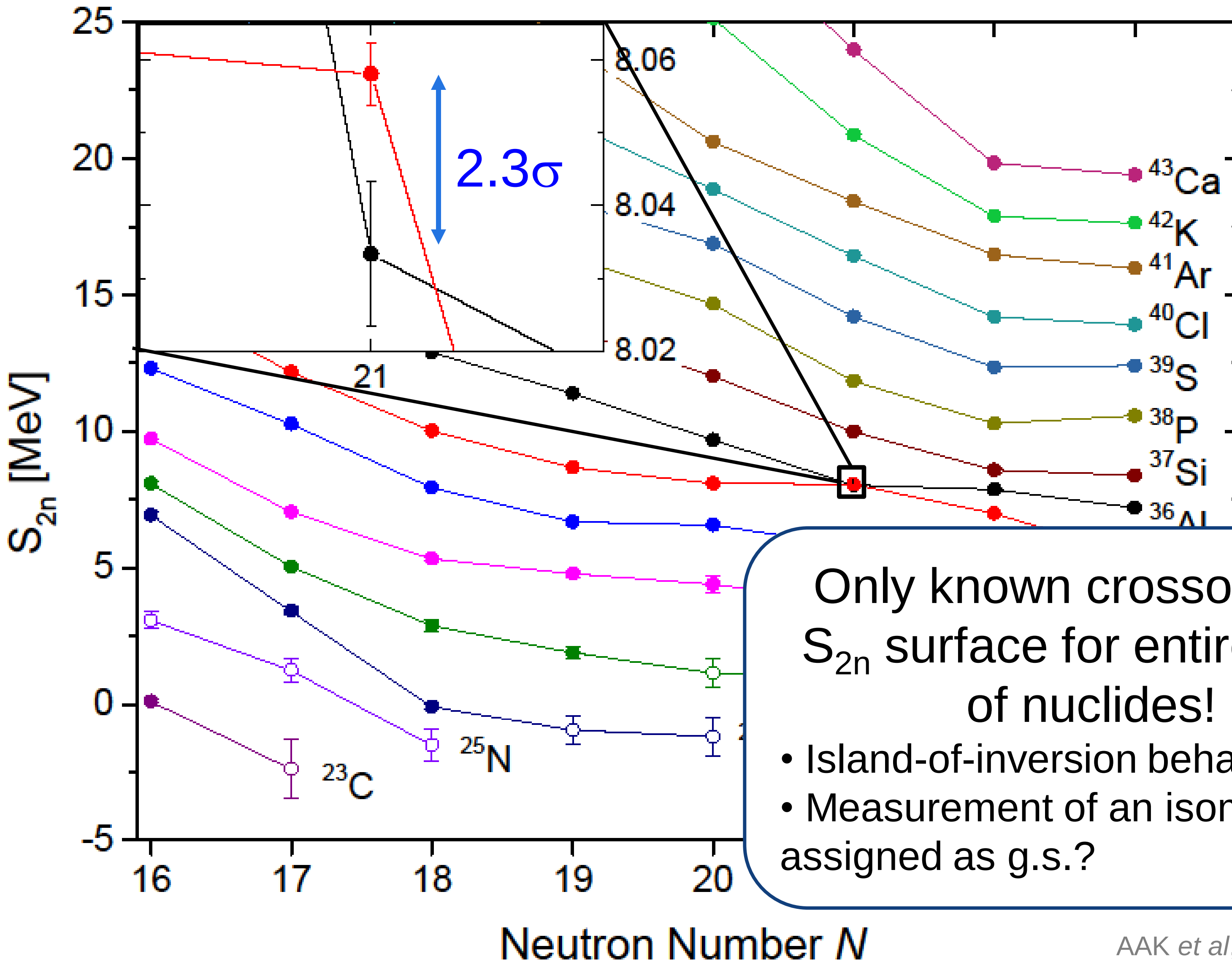
lowest known of any magic nuclide

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 Δ_n<0
- Out of reach for energy-density functional and *ab-initio* methods

A.Chaudhuri *et al*, PRC 88 (2013) 054317

N = 21 S_{2n} Crossover



Only known crossover on S_{2n} surface for entire chart of nuclides!

- Island-of-inversion behavior?
- Measurement of an isomer assigned as g.s.?

AAK *et al*, submitted to PLB

Moving heavier: ^{51,52}Ca

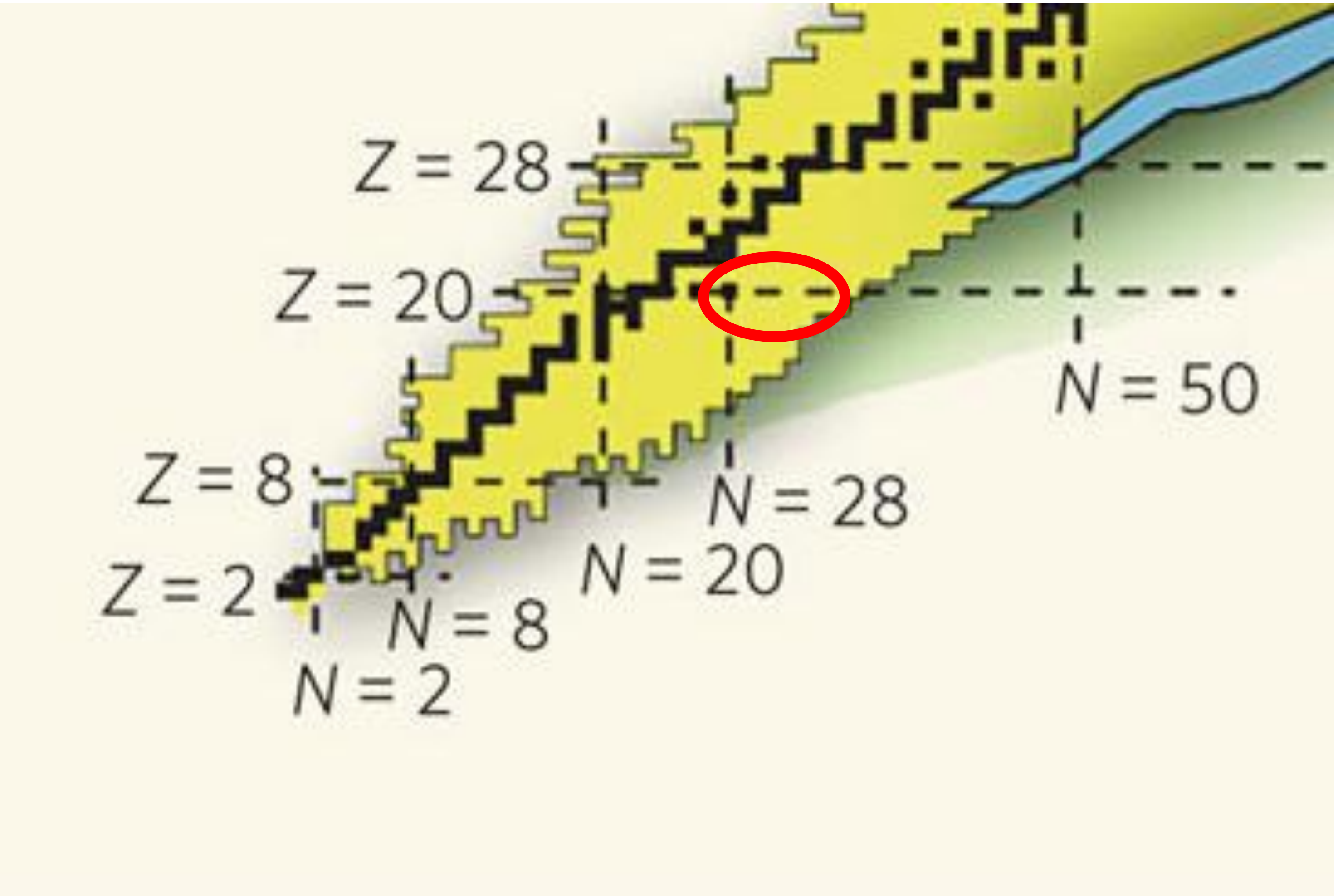
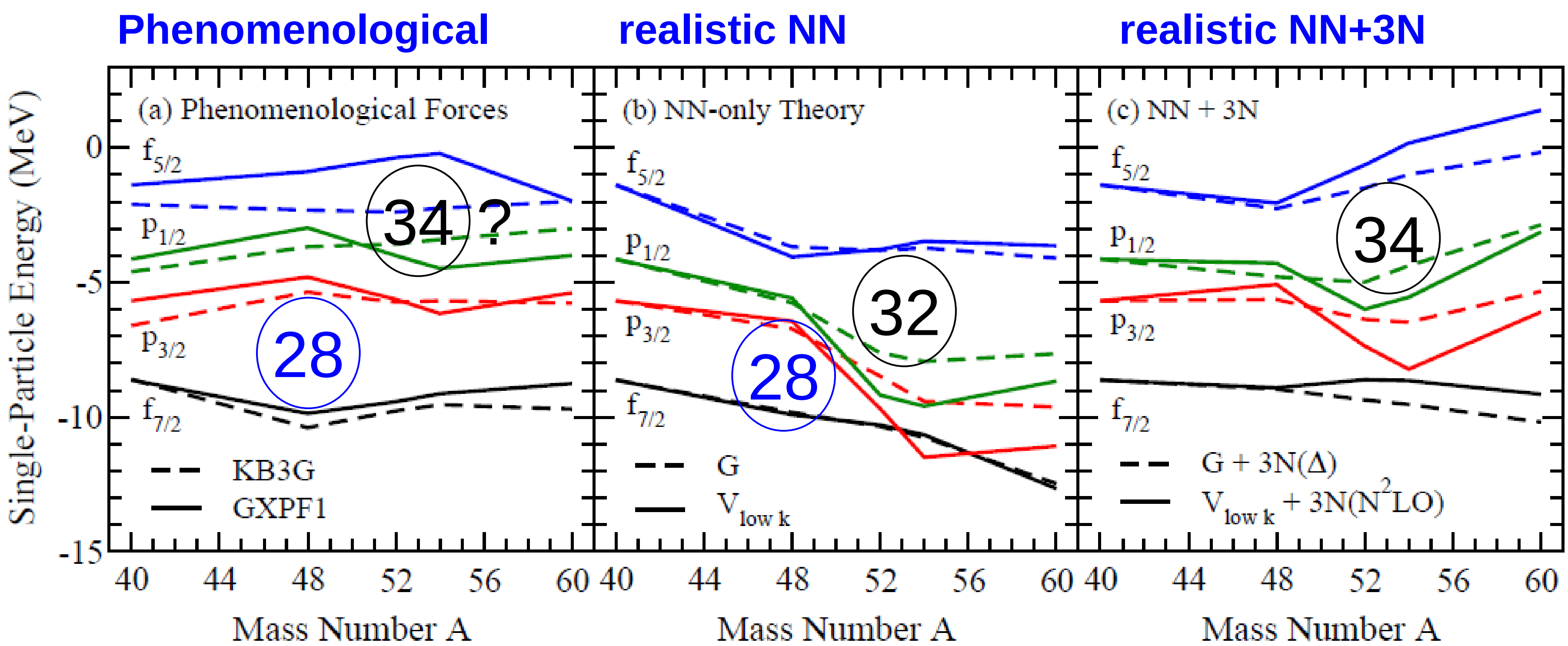


Figure: P. Cottle, *Nature* 465 (2010) 430

Extending Theory to Heavier Nuclides

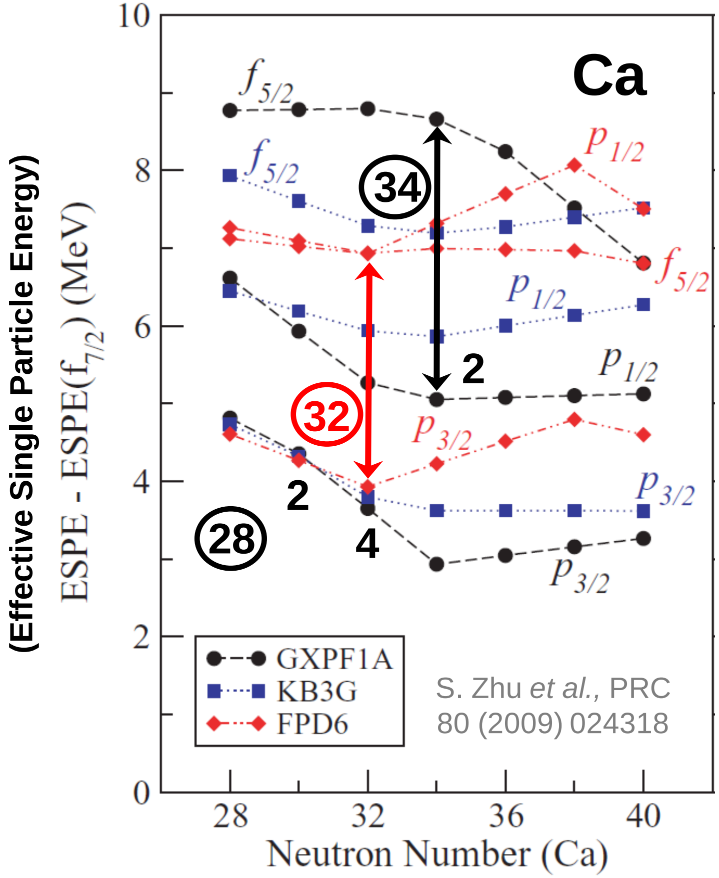


Ca theory with realistic NN interaction & 3N forces:

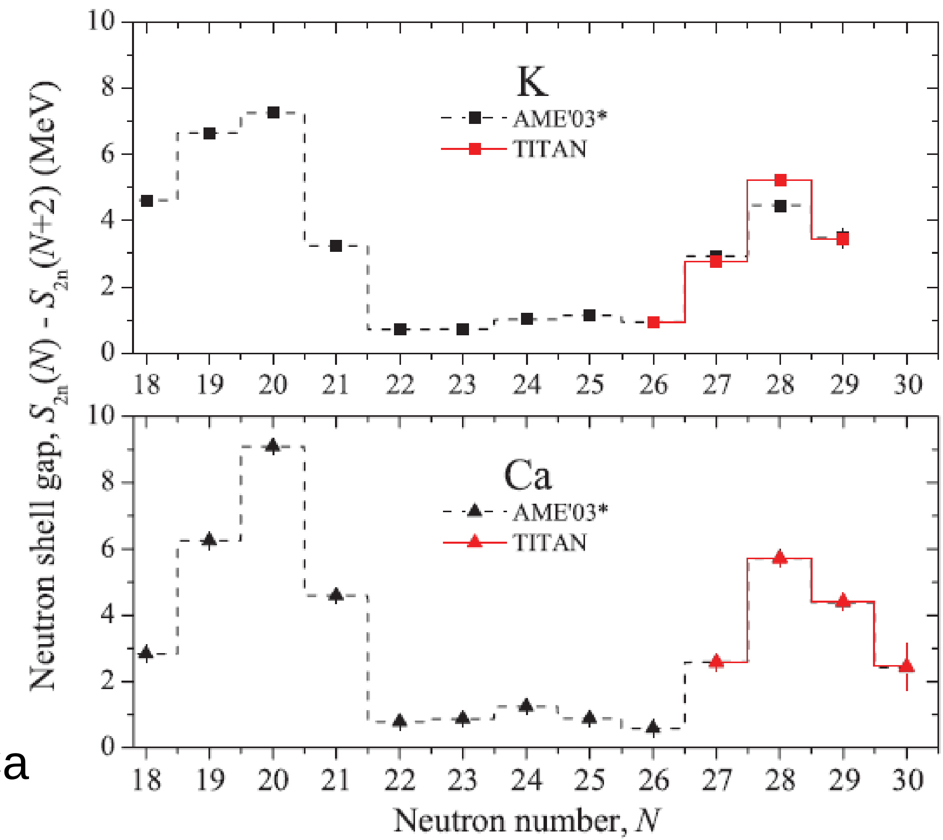
- Substantially different trend for single-particle energies & S_{2n}
- Quenching of N=28 shell gap around A=50-54

New magic shell closure at N = 32, 34 in Ca?

Neutron-rich K and Ca isotopes



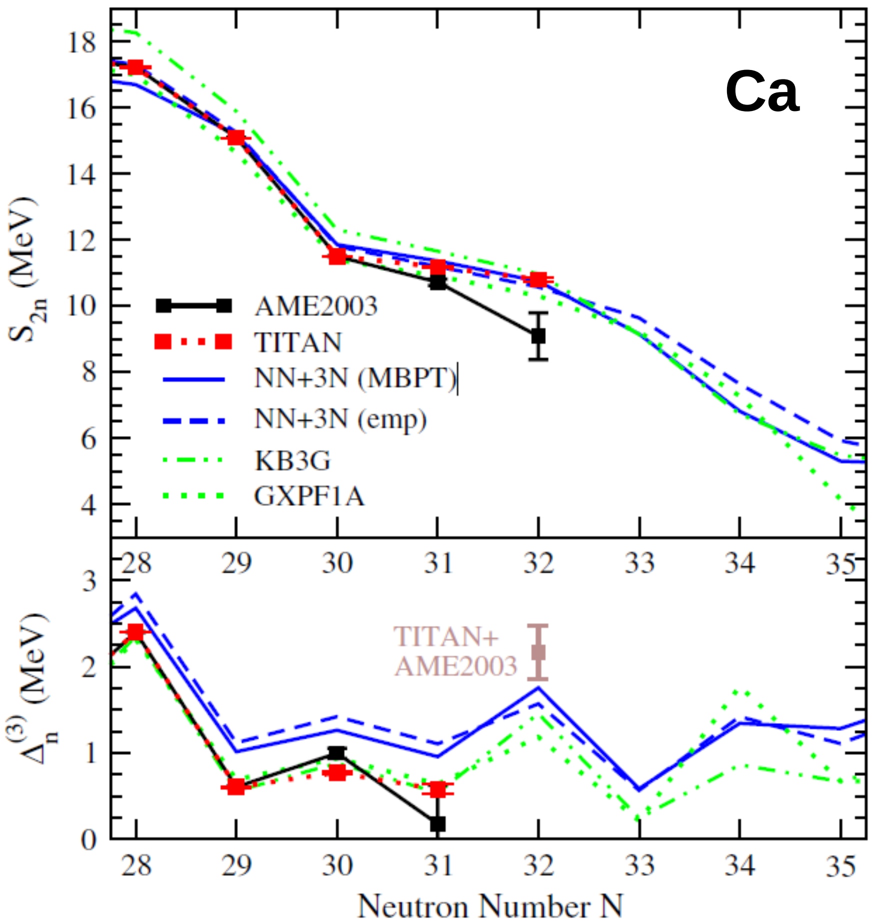
Found that the N = 28 shell is 1 MeV stronger than previously believed



- Measured mass of $^{44,47-50}$K and $^{49-50}$Ca
- TITAN value deviated 7σ & 10σ from AME 2003 for ^{48,49}K respectively

A. Lapierre *et al.*, PRC **85** (2012) 024317

Is N = 32 magic for K, Ca isotopes?



Measured ^{51}K and ^{51,52}Ca masses

- Found ^{52}Ca 1.74 MeV more bound than expected from AME 2003

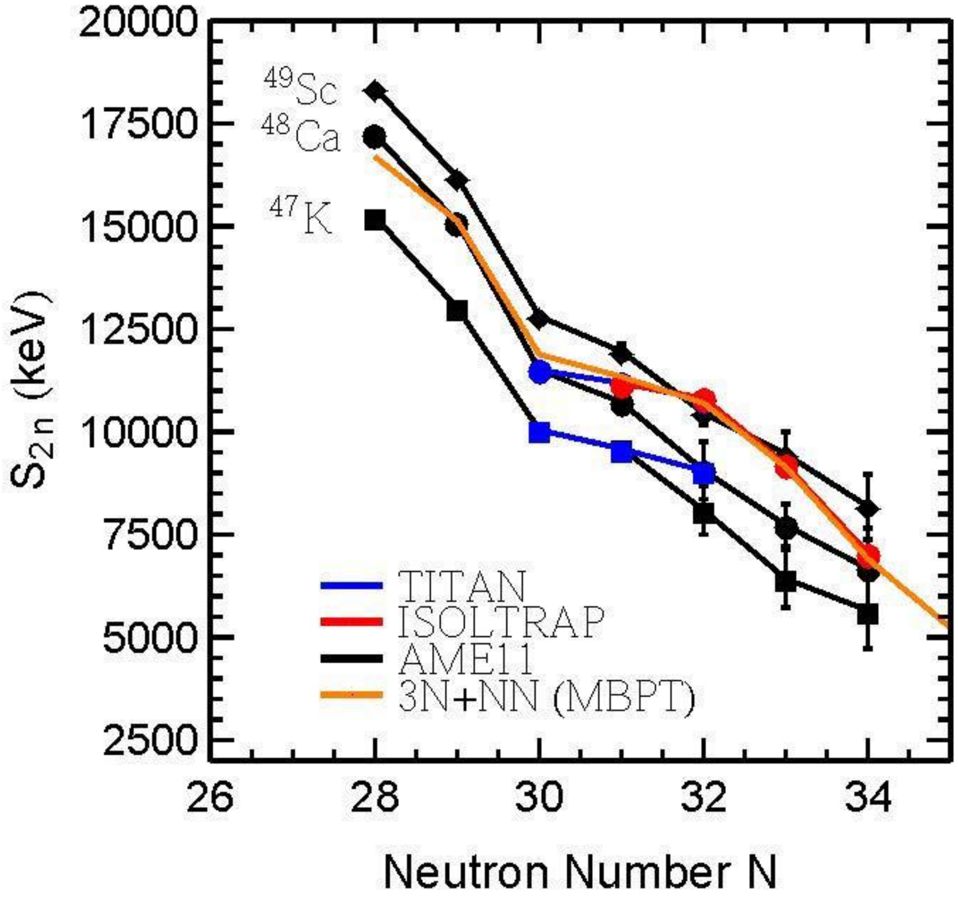
Calculations based on chiral NN and 3N force predict increased binding at N ≈ 32

- Repulsive 3N contributions critical for Ca g.s. properties & require further investigation
- ^{51,52}Ca S_{2n} & $\Delta_n^{(3)}$ differences with experiment ≤ 200 & 500 keV

KB3G & GXPF1A phenomenological models also predict behavior well

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

N = 34 Subshell Closure?



- ISOLTRAP extended high-precision mass measurements to ^{54}Ca
- Experiments agree well with this theory, confirming trend, and other theories (e.g. CC PRL 109, 032502).

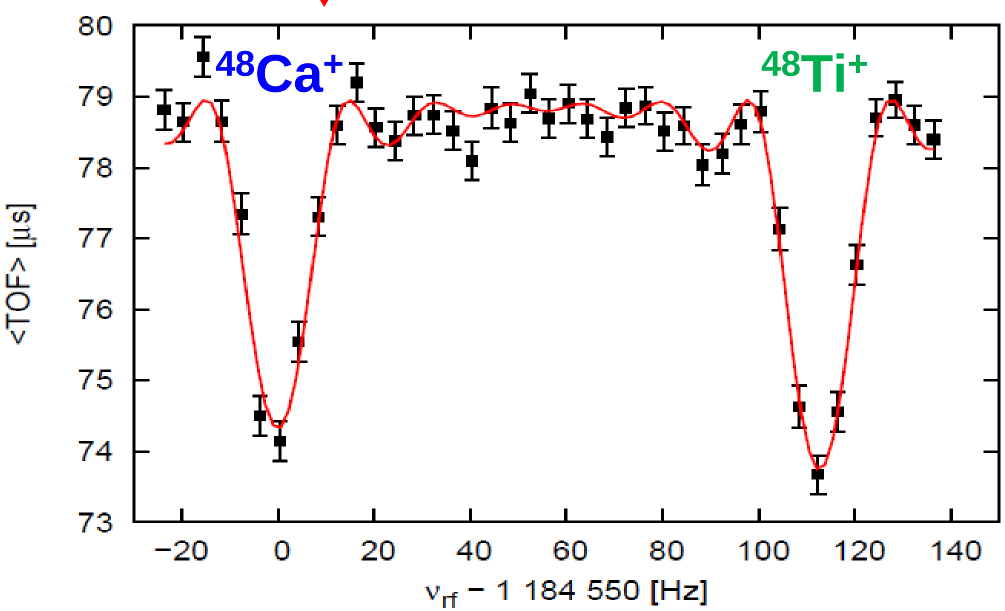
Weinholtz *et al.*, Nature 493 (2013) 346; A.T. Gallant *et al.*, PRL **109** (2012) 032506

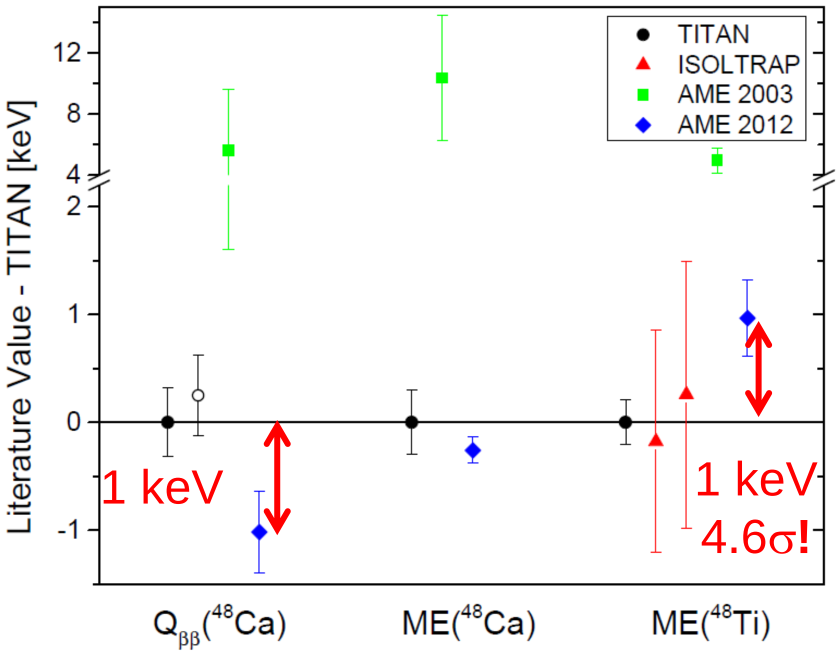
Q-value of $^{48}Ca \rightarrow {}^{48}Ti$

$$T_{1/2}^{0\nu} = G_{0\nu}(Q_{\beta\beta}, Z) |M_{0\nu}| \frac{\langle m_{\beta\beta} \rangle}{m_e}$$

measured at TITAN

$T_{1/2}^{0\nu}$	half-life
$G_{0\nu}(Q_{\beta\beta}, Z)$	phase-space factor
$\lvert M_{0\nu} \rvert$	nuclear matrix element
$\langle m_{\beta\beta} \rangle$	effective ν Majorana mass
m_e	electron mass





A.A. Kwiatkowski *et al.*, PRC 89 (2014) **045502**

TRIUMF

Q-value of ^{48}Ca → ^{48}Ti

$$T_{1/2}^{0\nu} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|\,\frac{\langle m_{\beta\beta}\rangle}{m_e}$$

$T_{1/2}^{0\nu}$ half-life

$G_{0\nu}(Q_{\beta\beta}, Z)$ phase-space factor

$|M_{0\nu}|$ nuclear matrix element

$\langle m_{\beta\beta}\rangle$ effective ν Majorana mass

m_e electron mass

χEFT + MBPT
w/ J.D. Holt (TU Darmstadt)

$$M_{0\nu} = M_{0\nu}^{GT} - \frac{g_V^2}{g_A^2} M_{0\nu}^{F} + M_{0\nu}^{T}$$

	M^{GT}_{0n}	$-g_a/g_v\ M^F_{0n}$	M^T_{0n}	Sum
Bare $M_{0\nu}$	0.675	0.130	-0.072	0.733
1st order $\tilde{X}$-box no 3p-1h	1.340	0.225	-0.064	1.501
Full 1st order $\tilde{X}$-box	00.61 6	0.12		
Full 2nd-order $\tilde{X}$-box	1.822	0.2		
Final $M_{0\nu}$	**1.221**	**0.16**		

1 keV shift in $Q_{\beta\beta}$ & 75% increase in NME make ^{48}Ca more attractive for 0ν2β exp

Summary

- **Isospin non-conservation**
  - Mass determinations of ^{20,21,21m}Mg
  - Most stringent test of IMME to date
  - Some USD issues
  - Some χEFT issues
- **Role of three-body forces**
  - At ^{52}Ca , confirm prediction of N = 32 subshell closure
  - In ^{48}Ca, determined 75% larger $0\nu2\beta$ NME and1 keV higher measured Q-value
- **Island of inversion**
  - Mass determinations of n-rich Na, Mg, Al
  - Lowest shell gap of any (traditionally) magic nuclide
  - S_{2n} (N=21) crossover is a singularity on mass surface
- **Outlook**
  - Continue mass-measurement campaign in island of inversion → will there be more surprises?
  - IMME: most imprecise are ^{24,25}Si, ^{27}P, ^{28,29}Si, ^{31}Cl, and ^{36}Ca

TITAN

ISAC-TRIUMF

Thank you!

Merci

U. Chowdhury, A.T. Gallant, R. Klawitter, AAK, K.G. Leach, A. Lennarz, T.D. Macdonald, B.E. Schultz, J. Dilling and the TITAN Collaboration

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