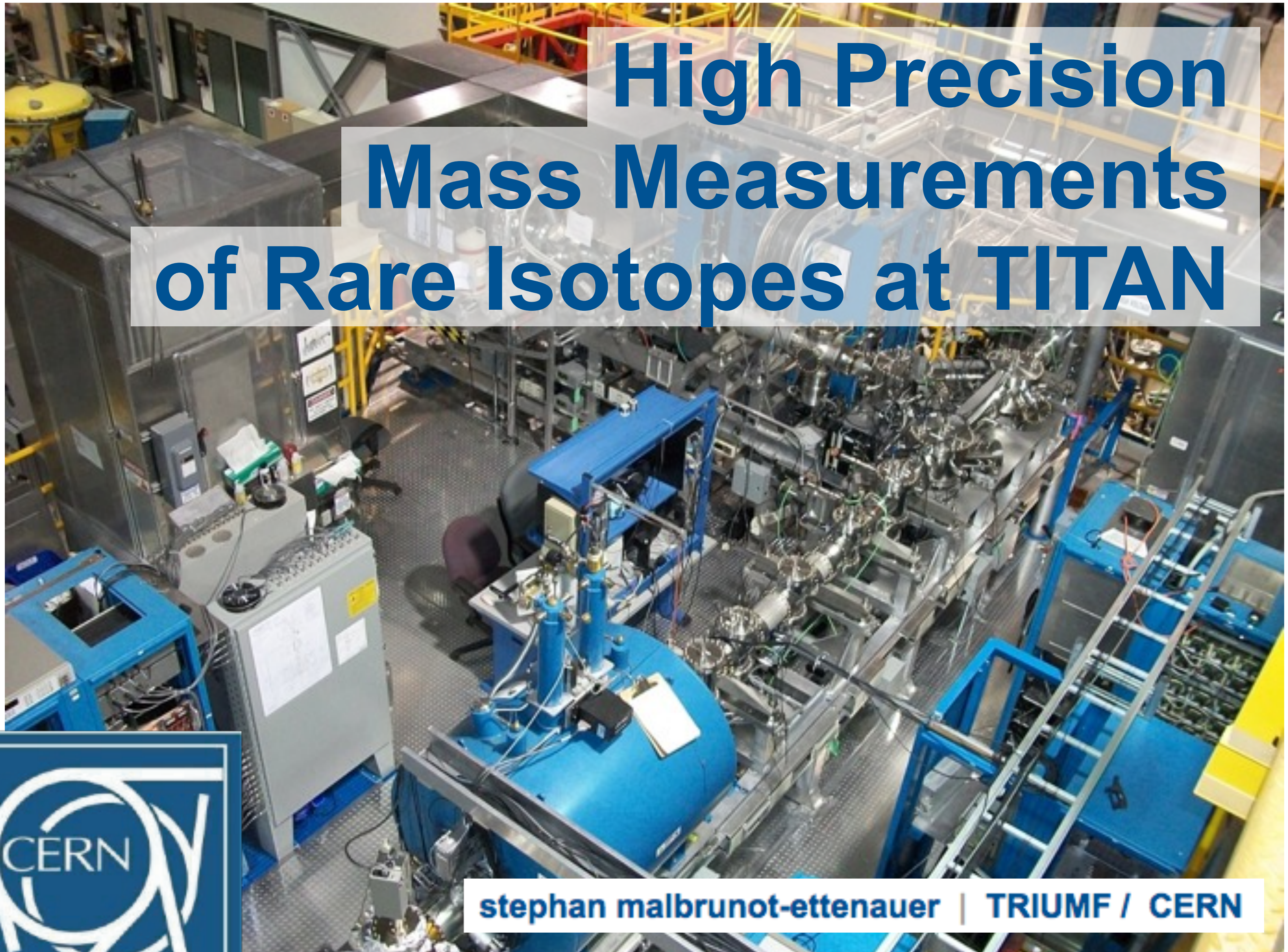
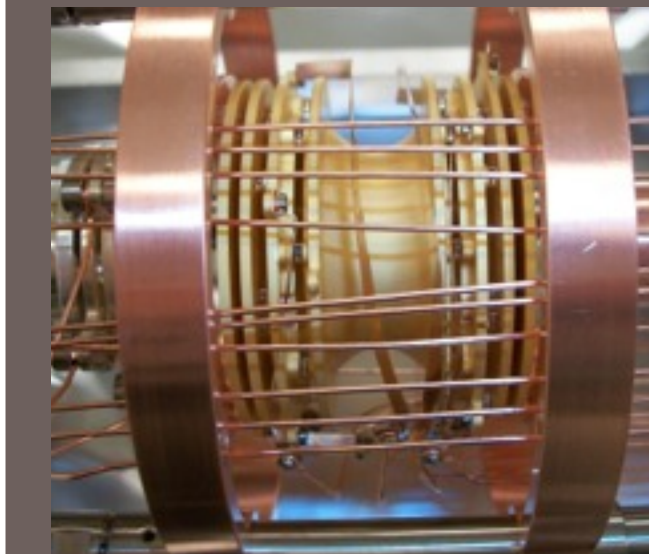
TRIUMF

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

High Precision Mass Measurements of Rare Isotopes at TITAN



stephan malbrunot-ettenauer | TRIUMF / CERN



CERN

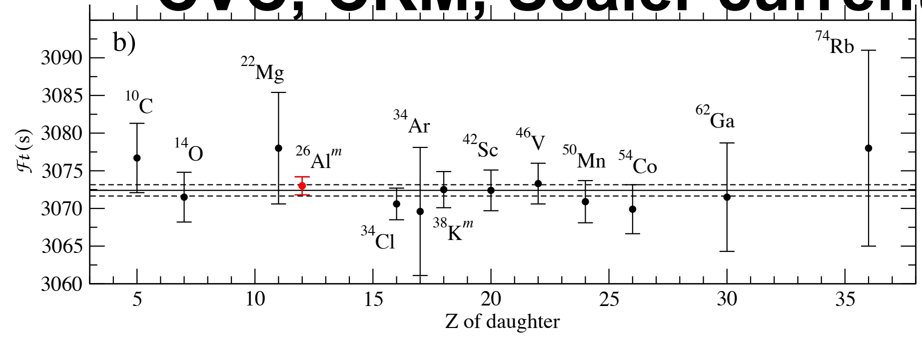
TRIUMF

atomic masses

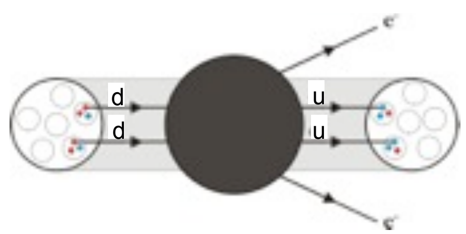
weak interaction

δm/m≈$10^{-8/9}$

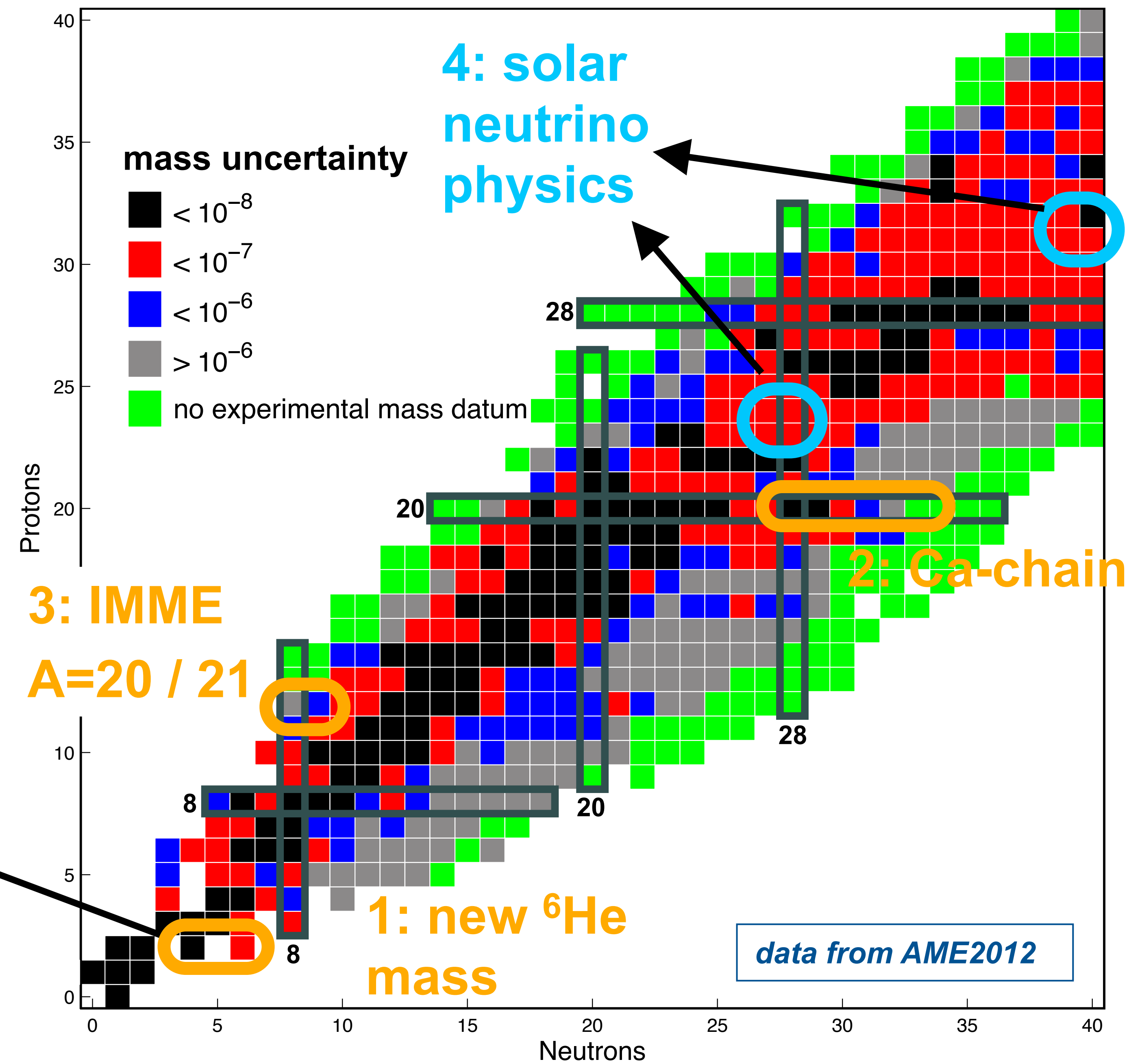
CVC, CKM, Scaler currents



neutrino physics

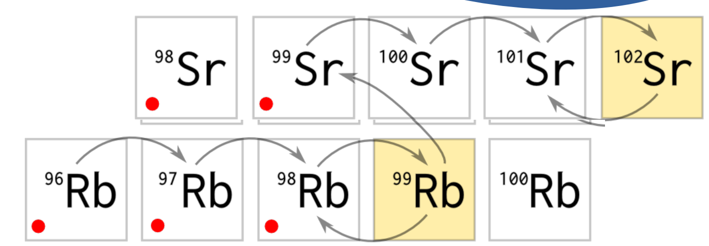


0νββ-decay



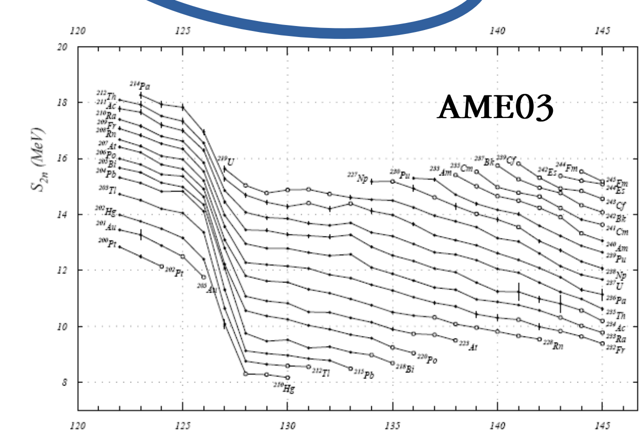
Nuclear Astrophysics

δm/m≈10^{-7}



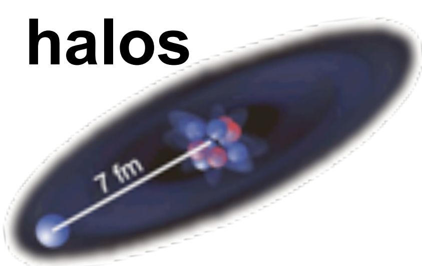
Nuclear Structure

δm/m≈$10^{-6/7}$



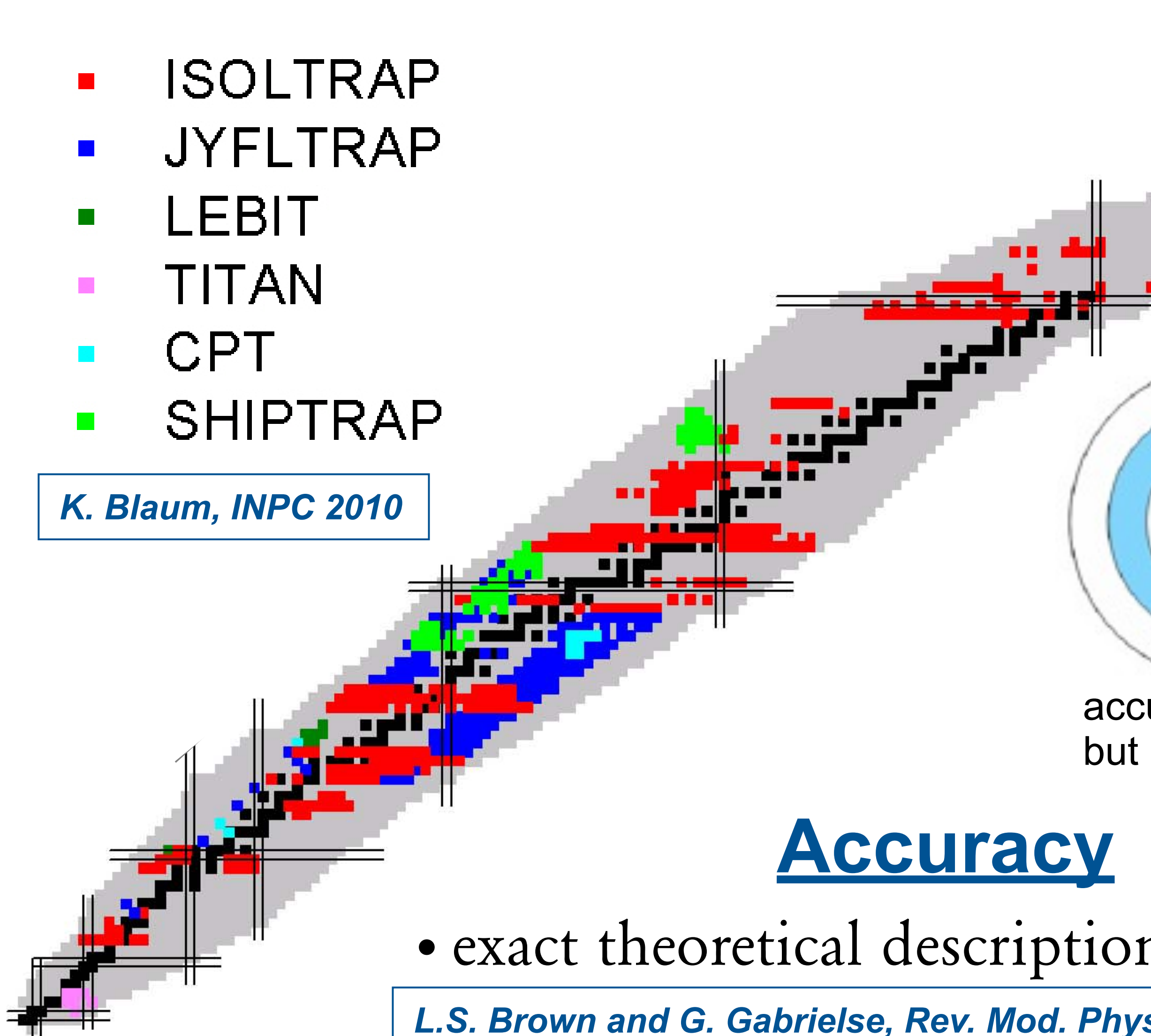
shell evolution

halos



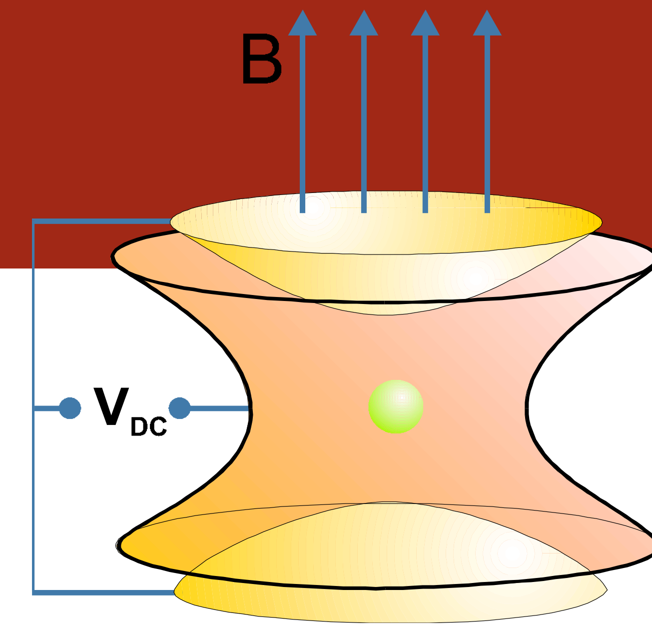
previously@TITAN:
^{11}Li, ^{11}Be, ^{8}He

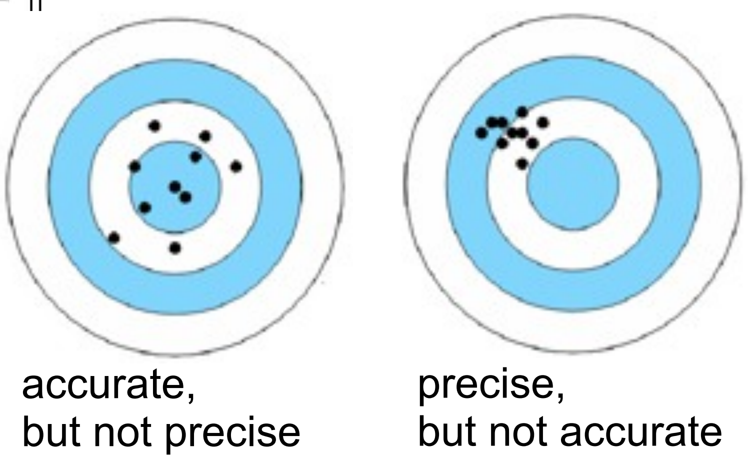
Penning traps



K. Blaum, INPC 2010

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





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

Precision

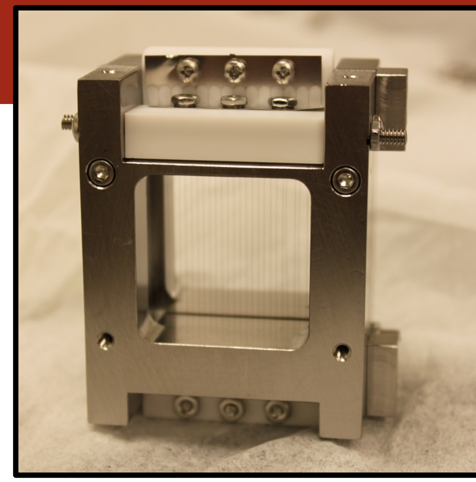
line-width (FWHM):

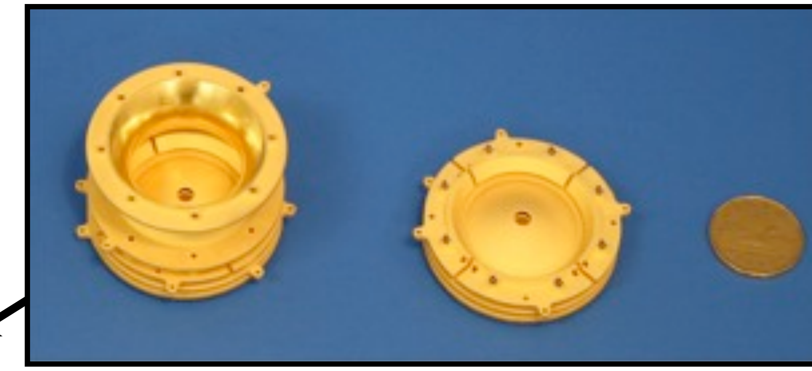
$$\Delta\nu \approx 1/T_{rf}$$

⇒ resolution:

$$R = \frac{m}{\Delta m} = \frac{\nu_c}{\Delta\nu_c} \approx \nu_c T_{rf} \approx \frac{qBT_{rf}}{2\pi m}$$

TITAN @ TRIUMF





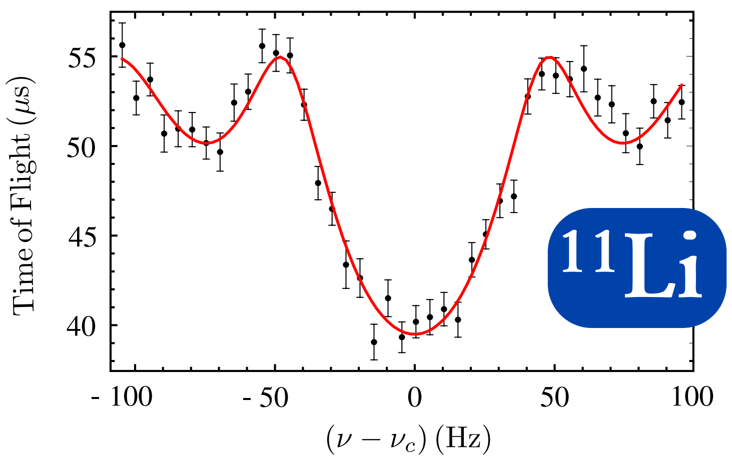
Penning traps:

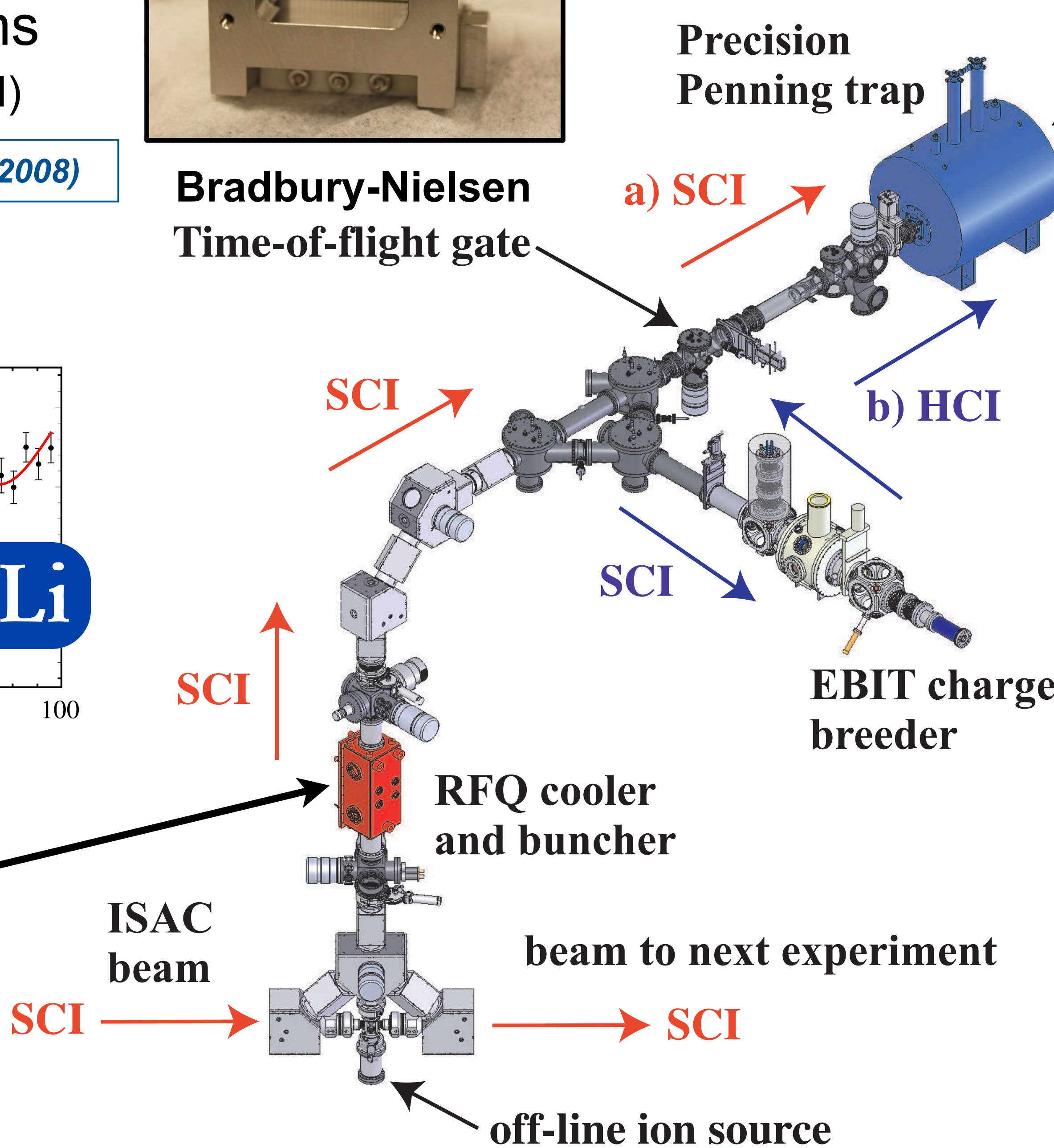
- highest precision
- down to $T_{1/2} < 10$ ms

(^{11}Li $T_{1/2} = 8.8$ ms @ TITAN)

M. Smith et al., PRL 101, 202501 (2008)

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

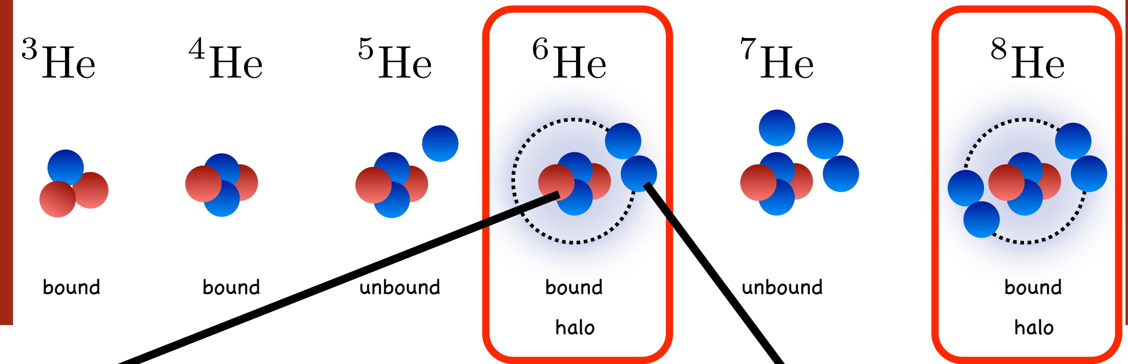




systematics: < 5ppb possible

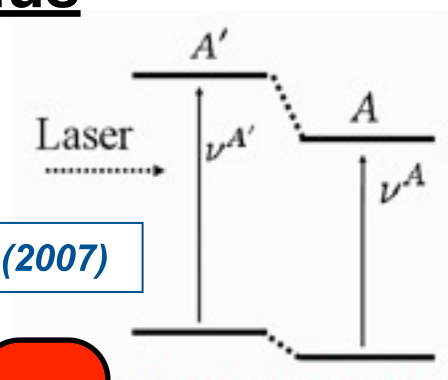
M. Brodeur et al, PRC 80, 044318 (2009)
M. Brodeur et al., IJMS 310, 20 (2012)

^{6}He



core & charge radius

Isotope Shift



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

$$\delta\nu_{A,A'} = \delta^{\mathrm{MS}}_{A,A'} + K_{\mathrm{FS}}\,\delta < r_c^2 >_{A,A'}$$

Mass Shift — Field Shift / Finite Size Shift

high precision atomic physics calculation

G. W. F. Dranke, Nucl. Phys. A737, 25 (2004)
Z.-C. Yan et al., PRL 100, 243002 (2008)

$$E = \mathcal{E}^{(0)}_{\mathrm{NR}} + \lambda\mathcal{E}^{(1)}_{\mathrm{NR}} + \lambda^2\mathcal{E}^{(2)}_{\mathrm{NR}} + \alpha^2(\mathcal{E}^{(0)}_{\mathrm{rel}} + \lambda\mathcal{E}^{(1)}_{\mathrm{rel}}) + \alpha^3(\mathcal{E}^{(0)}_{\mathrm{QED}} + \lambda\mathcal{E}^{(1)}_{\mathrm{QED}}) + \alpha^4(\mathcal{E}^{(0)}_{\mathrm{ho}} + \lambda\mathcal{E}^{(1)}_{\mathrm{ho}}) + \bar{r}_c^2(\mathcal{E}^{(0)}_{\mathrm{nuc}} + \lambda\mathcal{E}^{(1)}_{\mathrm{nuc}}) + \cdots$$

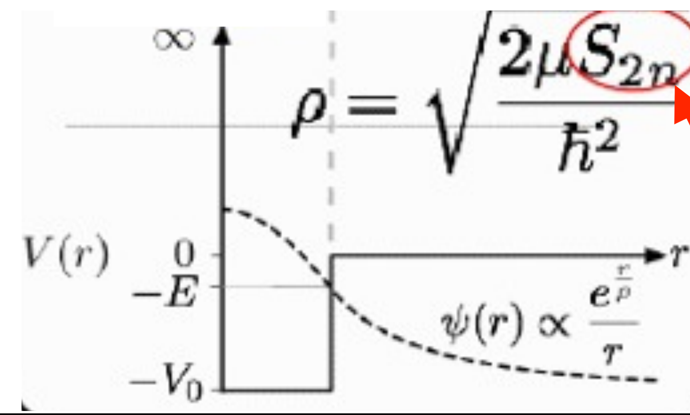
with $\lambda = \frac{\mu}{M} = \frac{m_e}{m_e + M}$

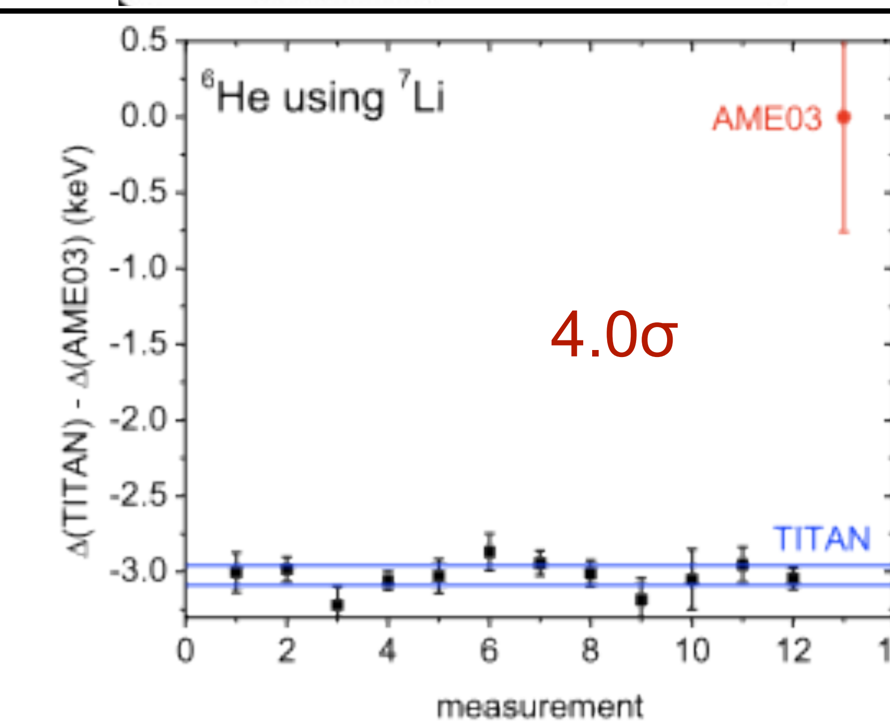
nuclear mass: δm < 1keV

see talks Friday morning

extend of halo formation & S_{2n}

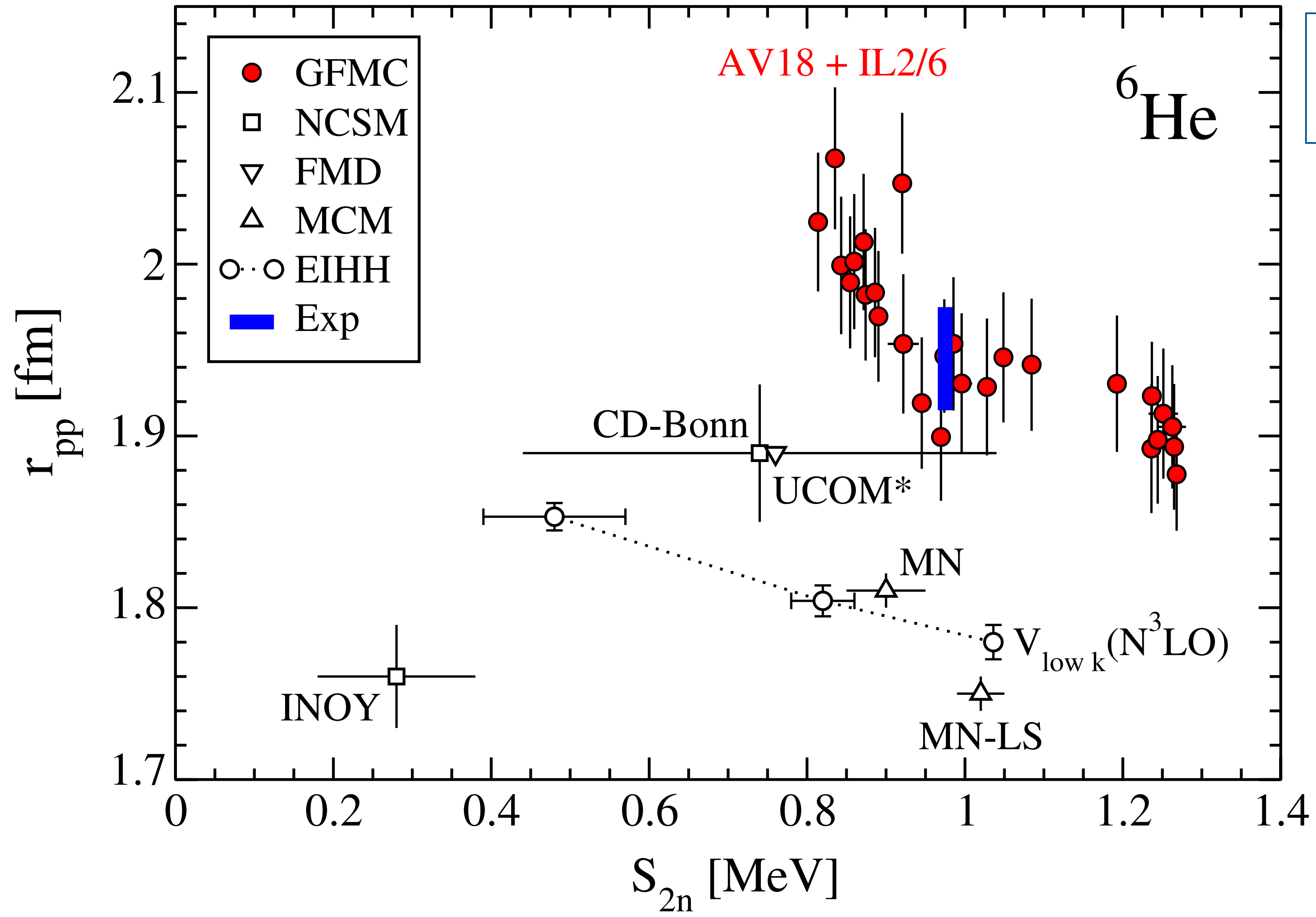
$$S_{2n} = m(Z, N-2) + 2m_n - m(Z,N)$$





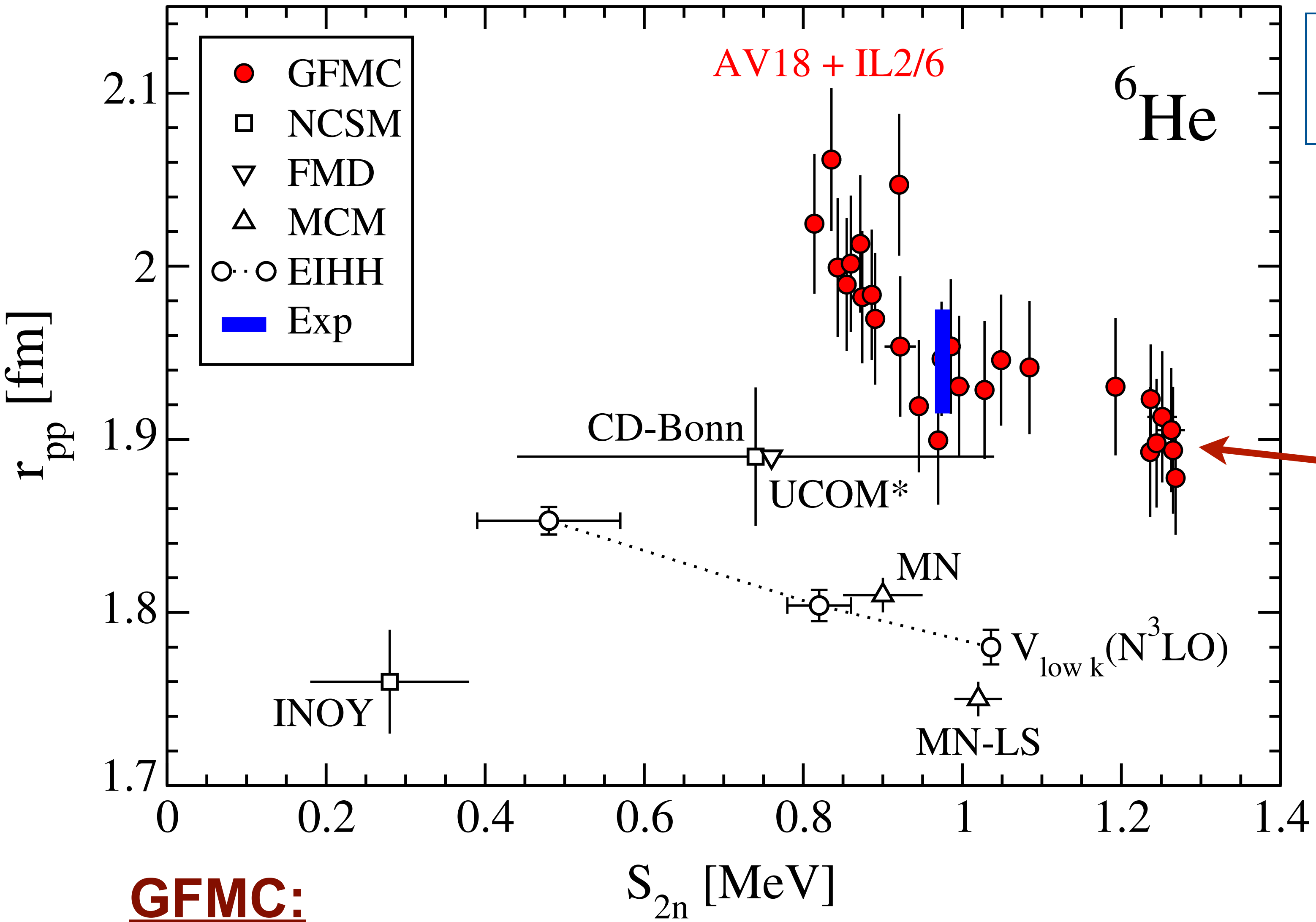
M. Brodeur et al., Phys. Rev. Lett. 108, 052504 (2012)

comparison to ab-inito calculations



NCSM: E. Caurier and P. Navratil, PRC 73, 021302(R) (2006)
FMD: T. Neff and H. Feldmeier, Nucl. Phys. A 738, 357 (2004)
MCM: I. Brida and F. M. Nunes, Nucl. Phys. A 847, 1 (2010)

comparison to ab-inito calculations



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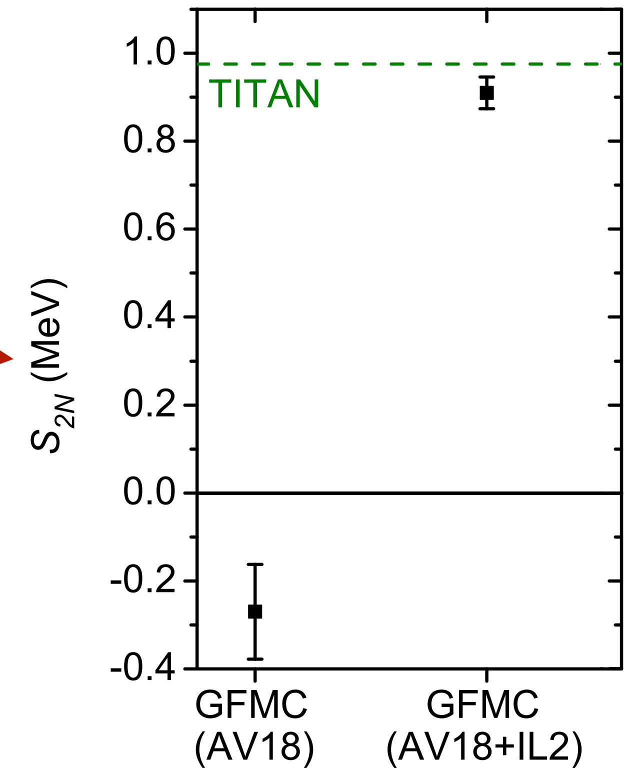


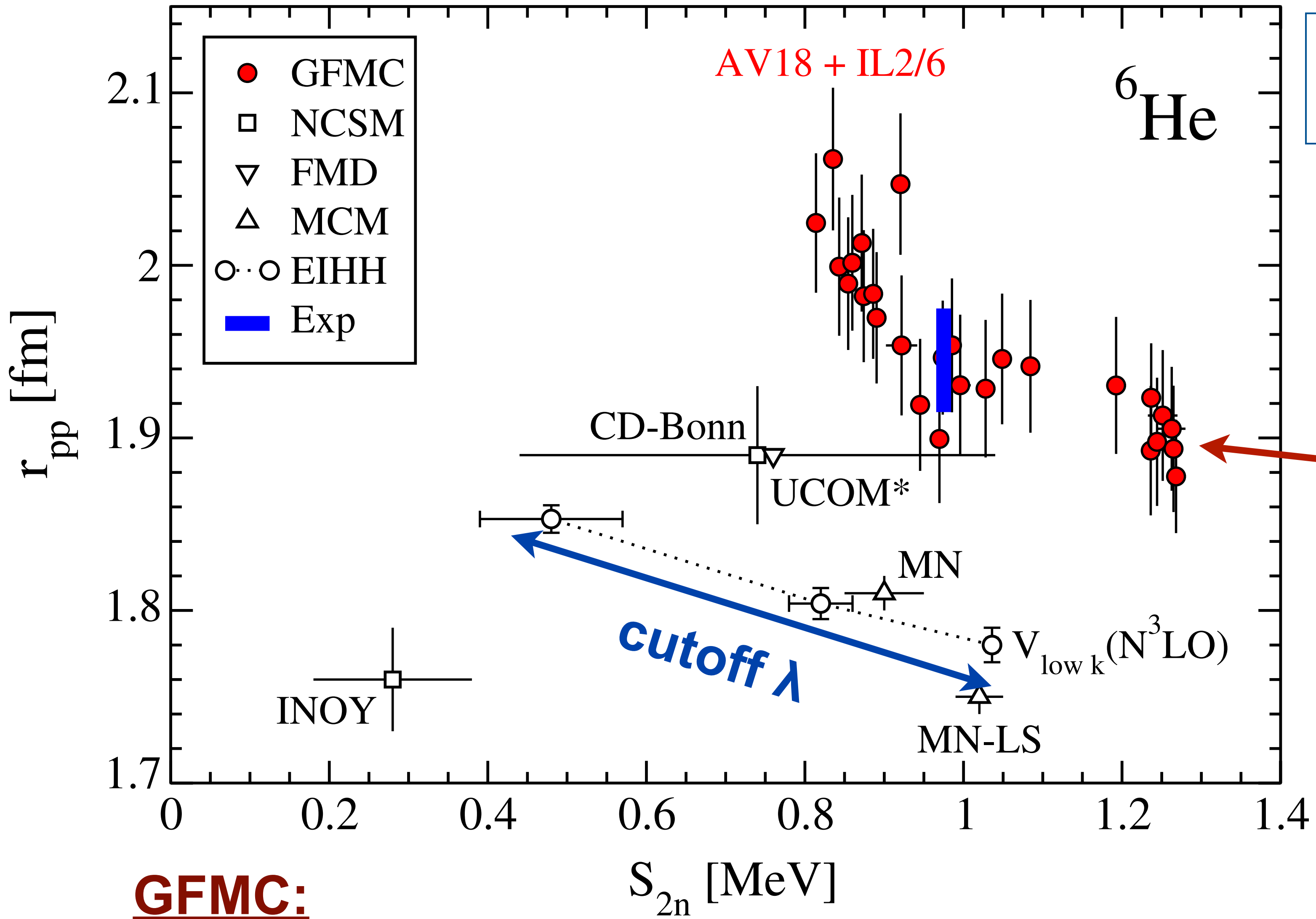
S. C. Pieper et al., C 70, 054325 (2004)

GFMC:

- only calculation with 3N forces
- phenomenological forces

S. C. Pieper, Riv. Nuovo Cimento 31, 709 (2008), arXiv:0711.1500

comparison to ab-inito calculations



NCSM: E. Caurier and P. Navratil, PRC 73, 021302(R) (2006)
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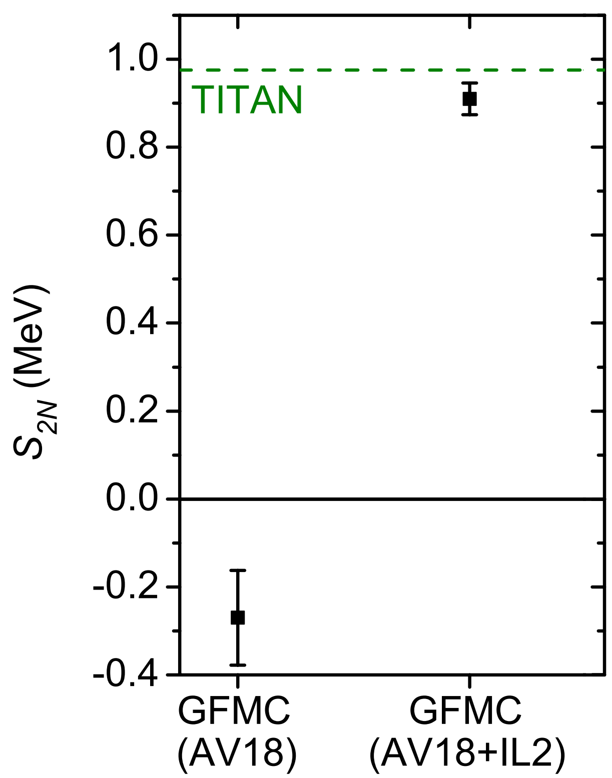

S. C. Pieper et al., C 70, 054325 (2004)

GFMC:

- only calculation with 3N forces
- phenomenological forces *S. C. Pieper, Riv. Nuovo Cimento 31, 709 (2008), arXiv:0711.1500*

hyper-spherical harmonics

M. Brodeur et al., Phys. Rev. Lett. 108, 052504 (2012)
S. Bacca et al., PRC 86, 034321 (2012)

- chiral EFT, but without 3N forces
- running of observables with λ ↔ no many-body forces (analog to Tjon line)

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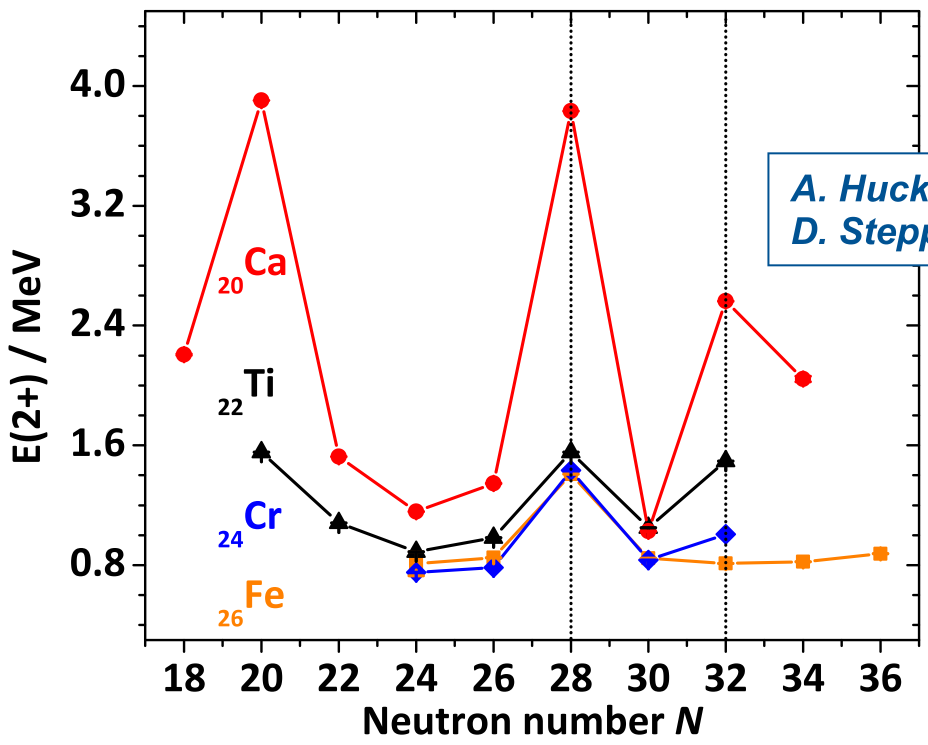
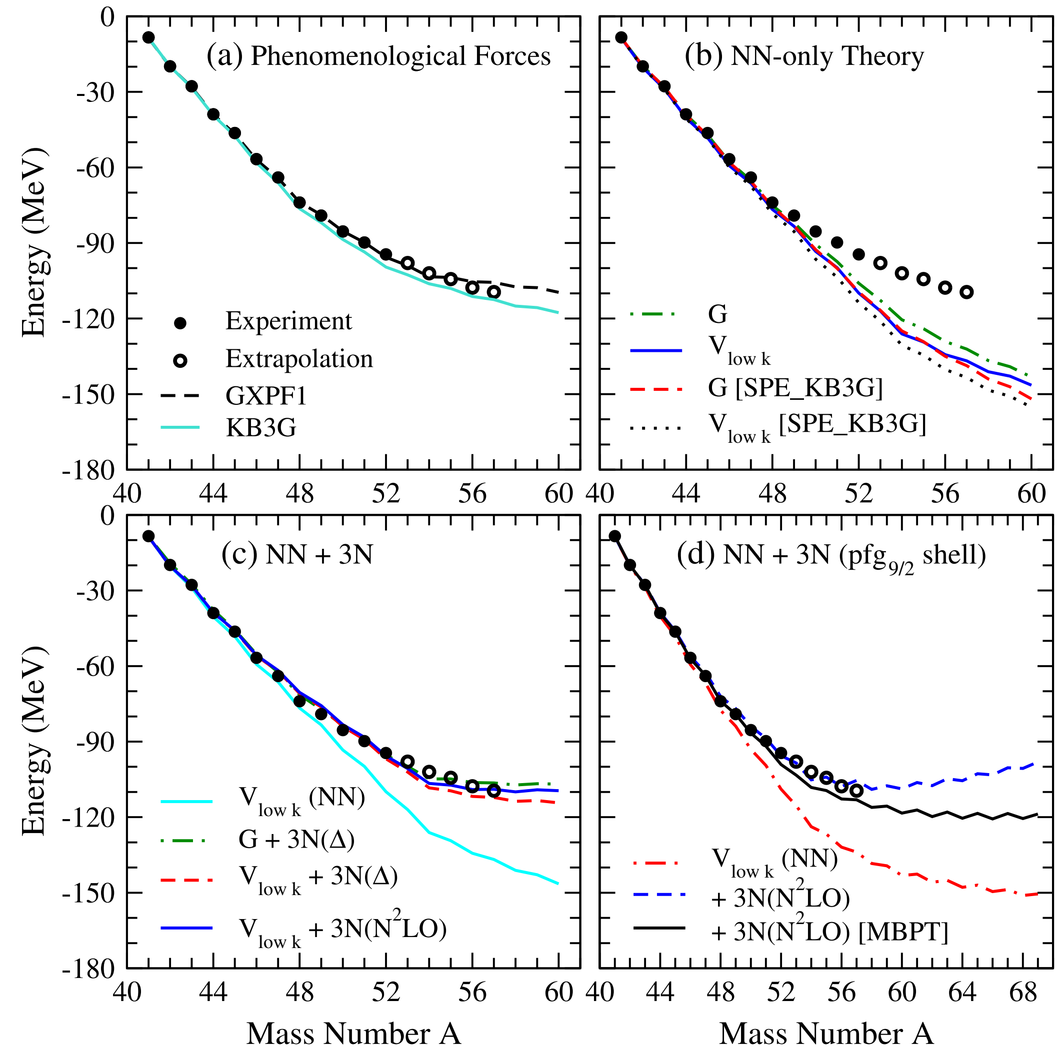
Ca-chain: magic numbers N=32 / 34?



A. Huck et al., Phys. Rev. C 31, 2226–2237 (1985)
D. Steppenbeck et al., Nature 502, 207-210 (2013)

J. D. Holt et al., J. Phys. G: Nucl. Part. Phys. 39 085111 (2012)

shell model with chiral 3N forces



GXPF1/GXPF1A:

predicts shell closure at N=34

M. Honma et al., Phys. Rev. C 65, 061301(R) (2002).
M. Honma et al., Eur. Phys. J. A 25, 499 (2005).

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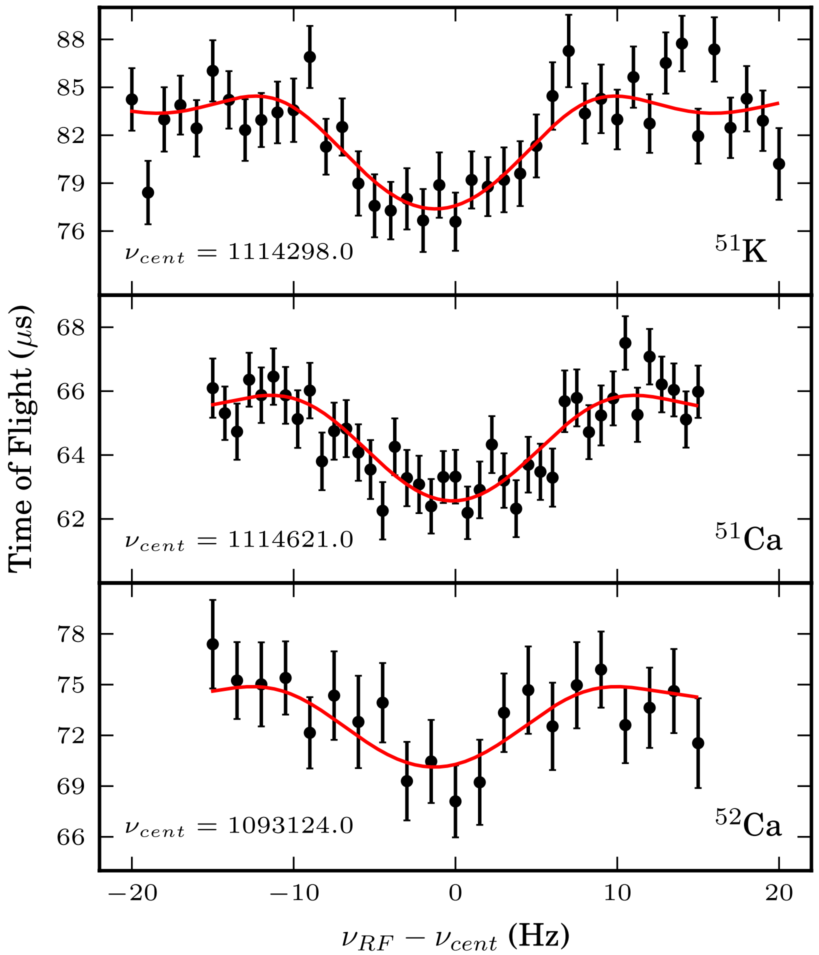
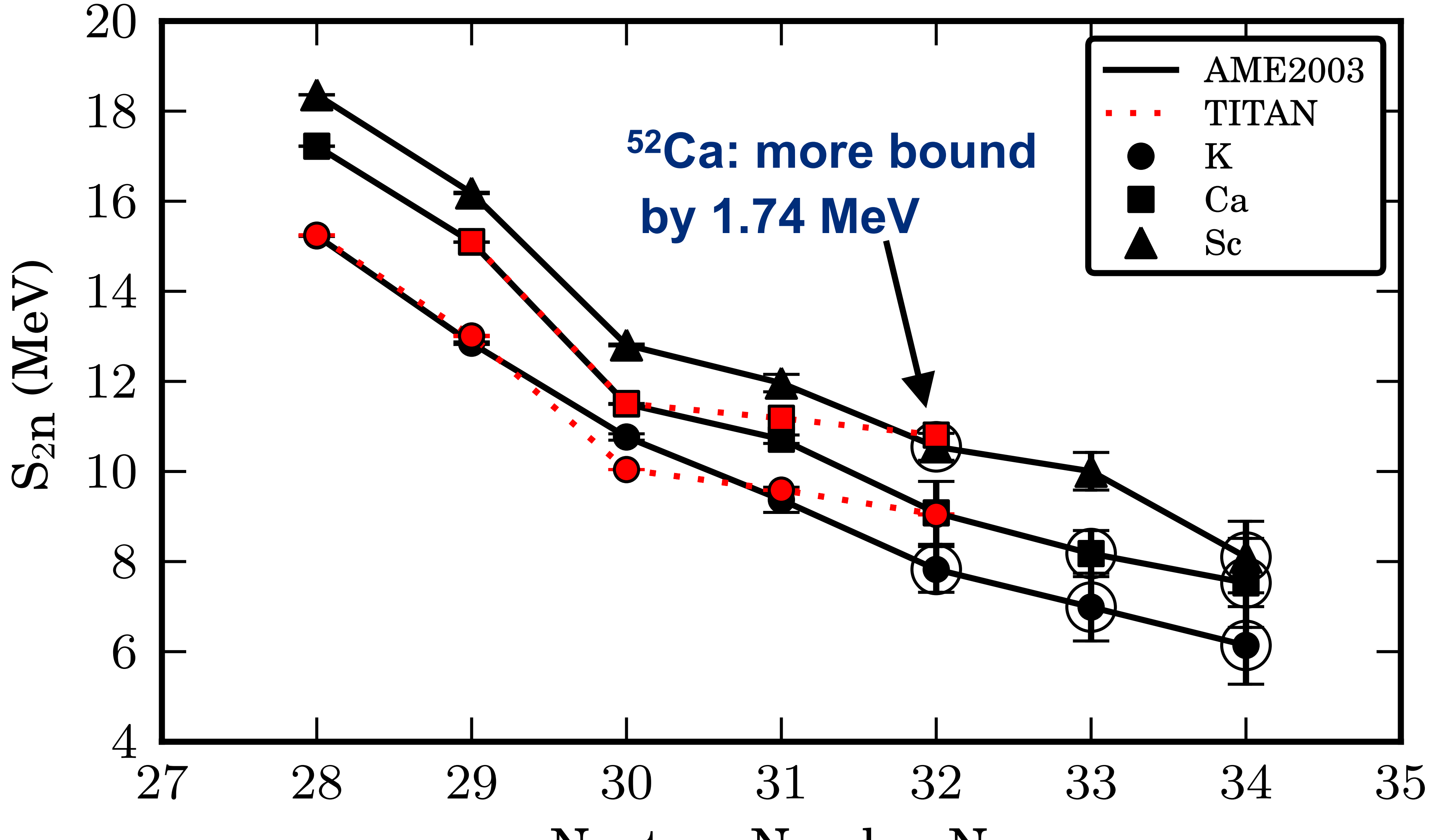
TITAN- measurements

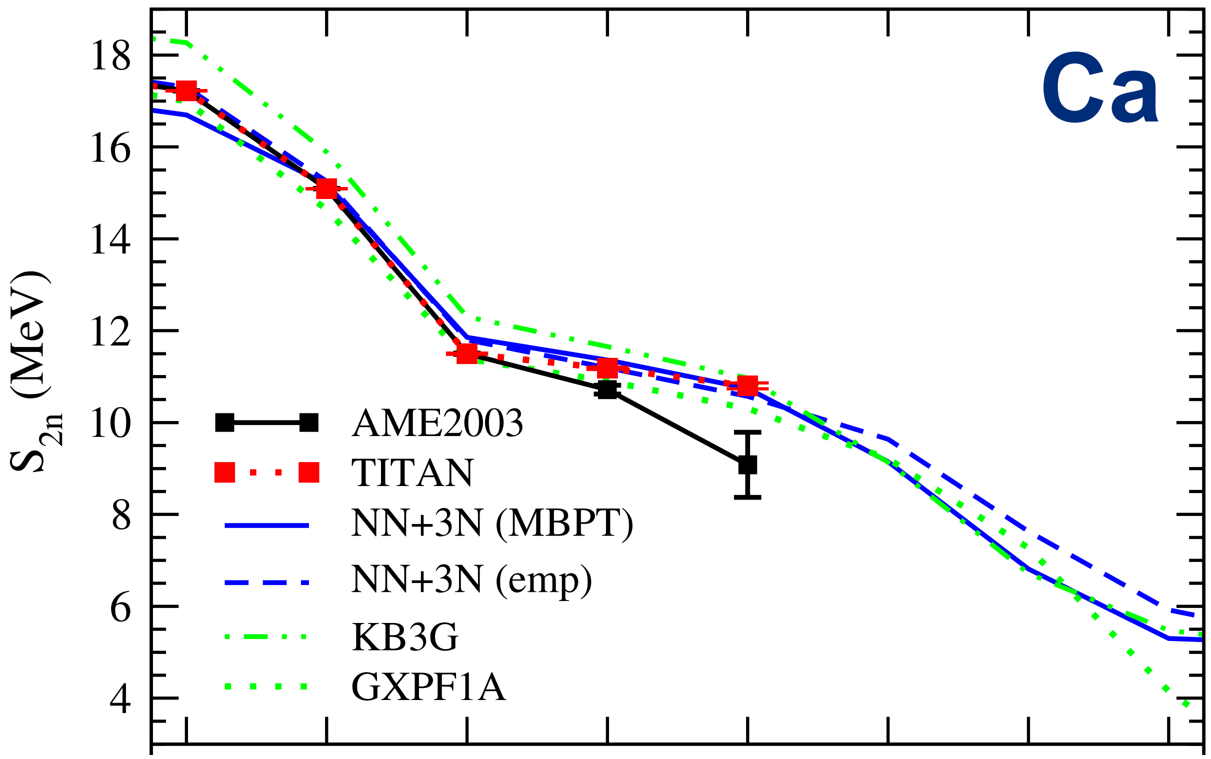


A. T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012)
A. Lapierre et al., Phys. Rev. C 85, 024317 (2012)



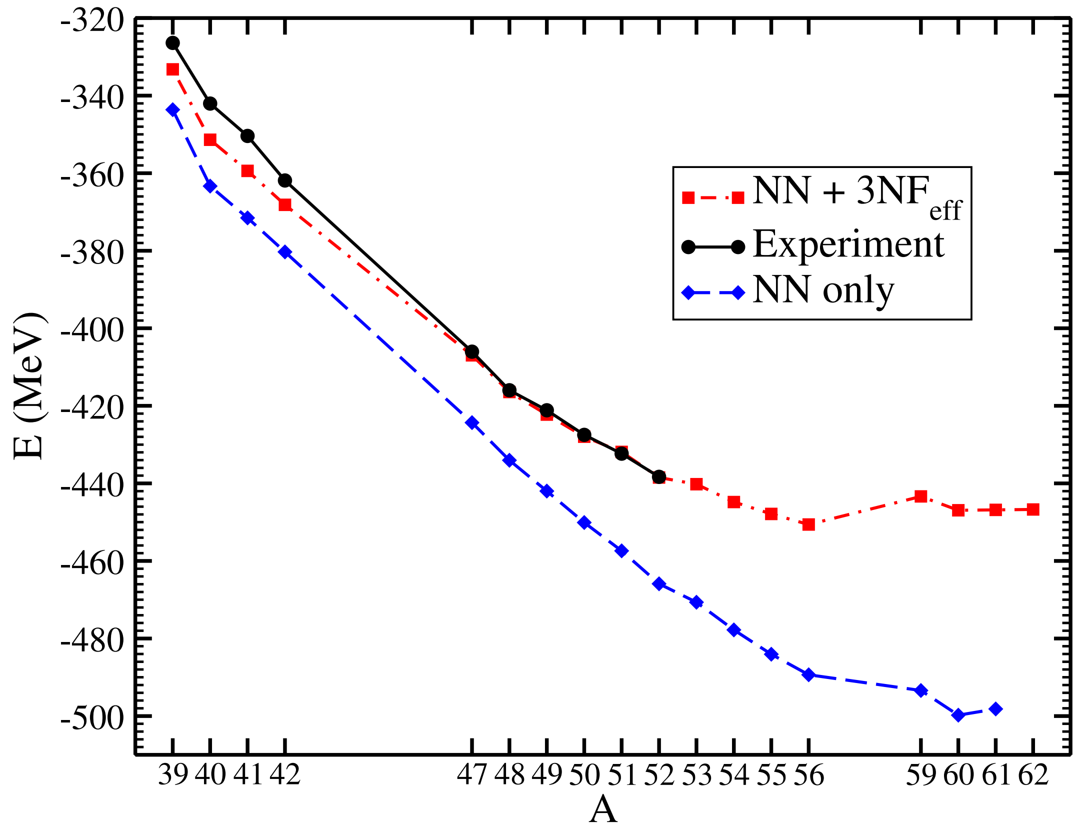
Ca: comparison to theory

shell model + chiral forces



A. T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012)
J. D. Holt et al., J. Phys. G 39, 085111 (2012).

coupled-cluster method + chiral NN forces + phenomenological 3n forces

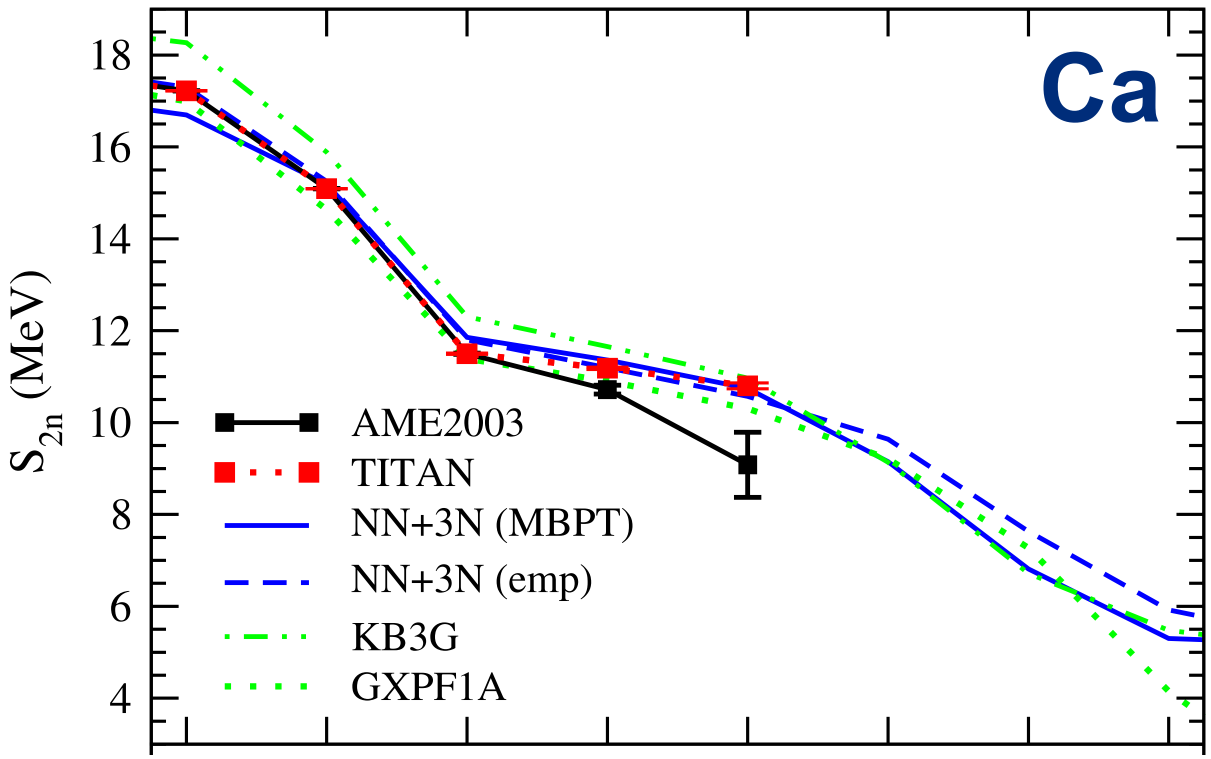


G. Hagen et al., Phys. Rev. Lett. 109, 032502 (2012)

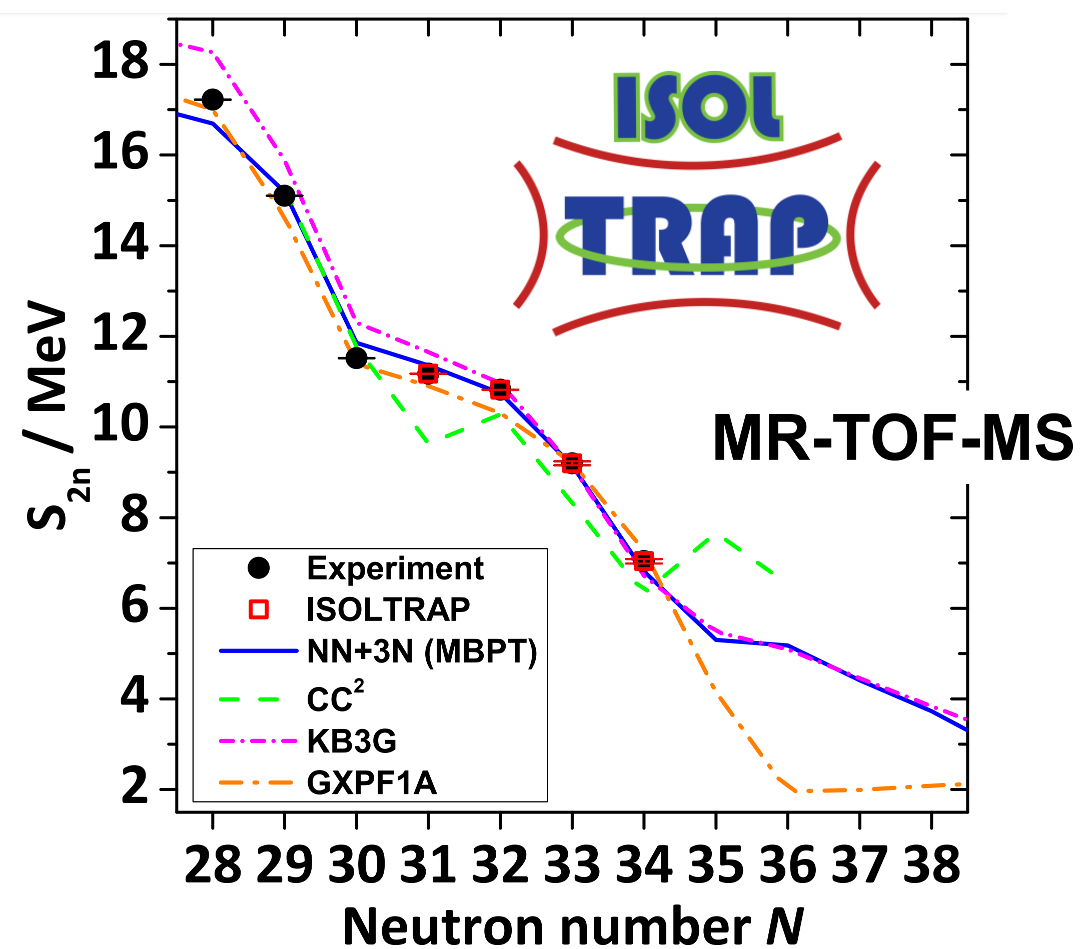
excellent agreement between experiment and theory

Ca: comparison to theory

shell model + chiral forces



A. T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012)
J. D. Holt et al., J. Phys. G 39, 085111 (2012).



F. Wienholtz et al., Nature 498, 346 (2013)

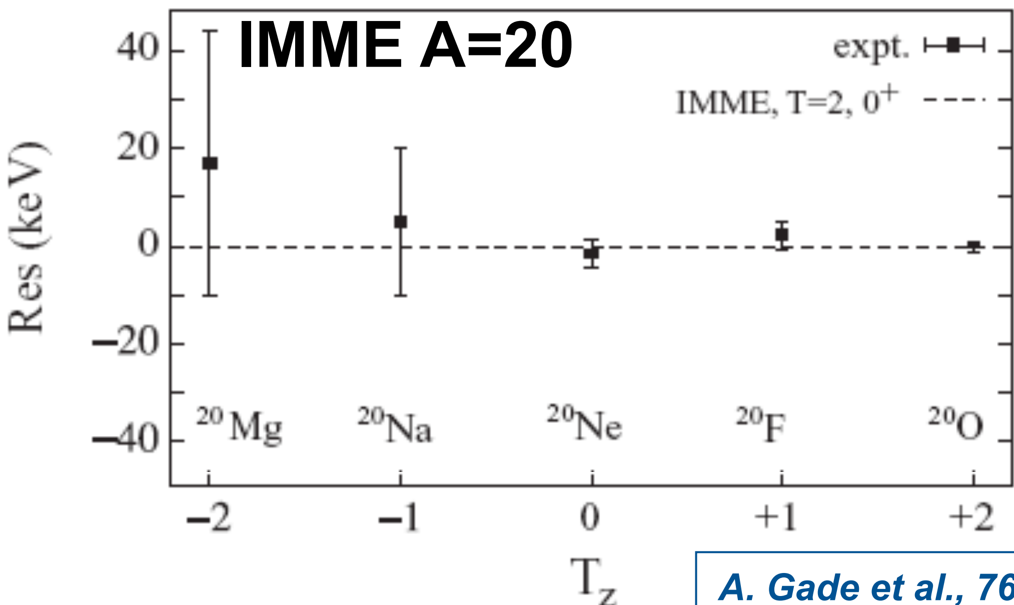
see talk by F. Wienholtz

excellent agreement between experiment and theory

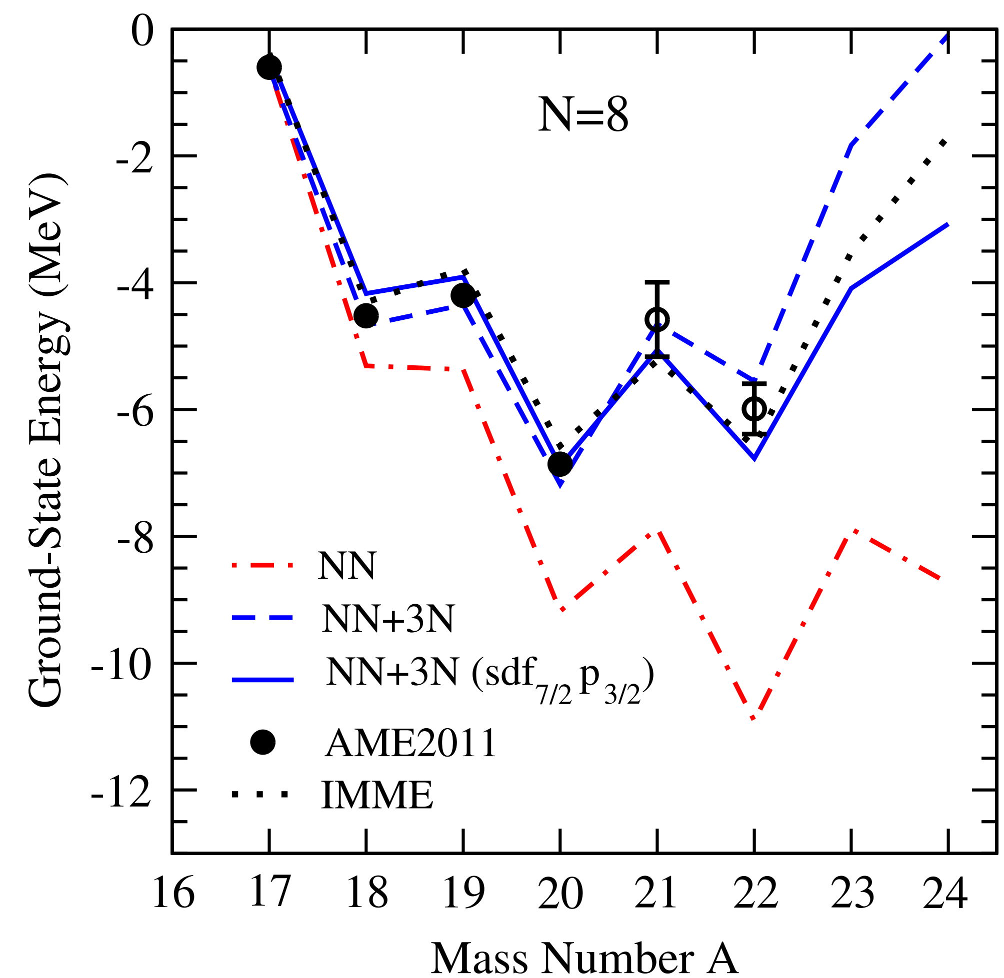
IMME, 3N-forces & proton rich nuclei

IMME

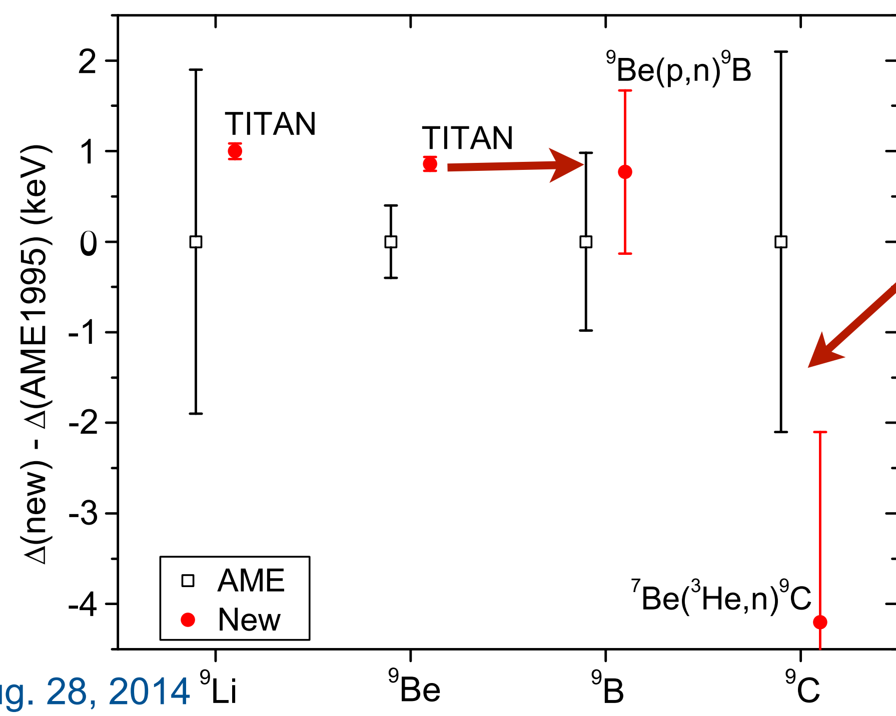
$$M(A,T,T_z) = a(A,T) + b(A,T) \cdot T_z + c(A,T) \cdot T_z^2$$



A. Gade et al., 76, 024317 (2007)



J.D. Holt et al., PRL 110, 022502 (2013)



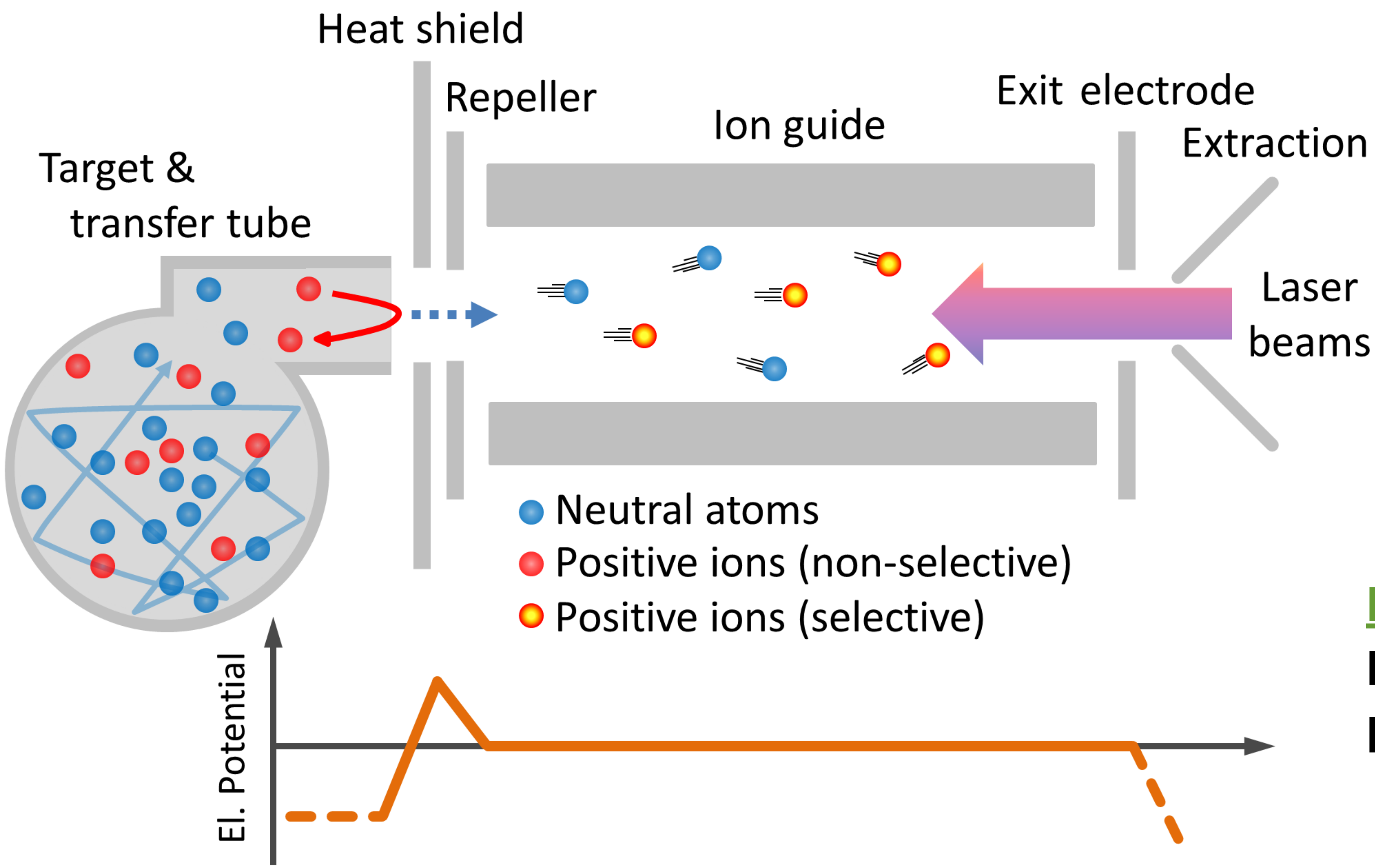
^{7}Li$(p,n)^7$Be & new mass of ^{7}Li (SMILETRAP)

IMME breakdown at A=9 explained by isospin mixing with neighboring states in ^{9}Be and ^{9}B (SM by B. A. Brown)

M. Brodeur et al., PRL 108, 212501 (2012)

Ion Guide Laser Ion Source (IG-LIS)

Laser ion source group: TRIUMF, Laval, U Manitoba, Oldenburg
J. Lassen, H. Heggen, A. Teigelhoefer et al.



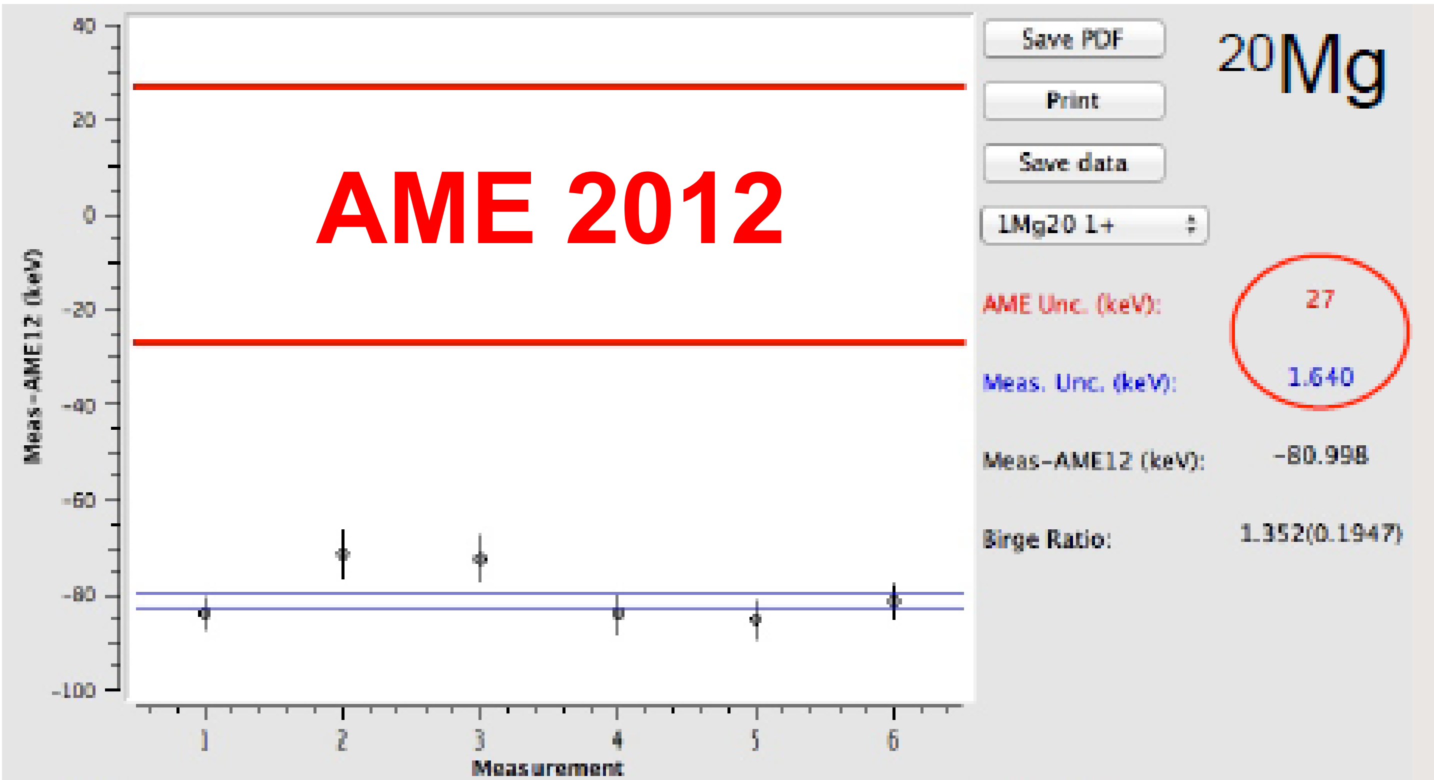
Na-contamination

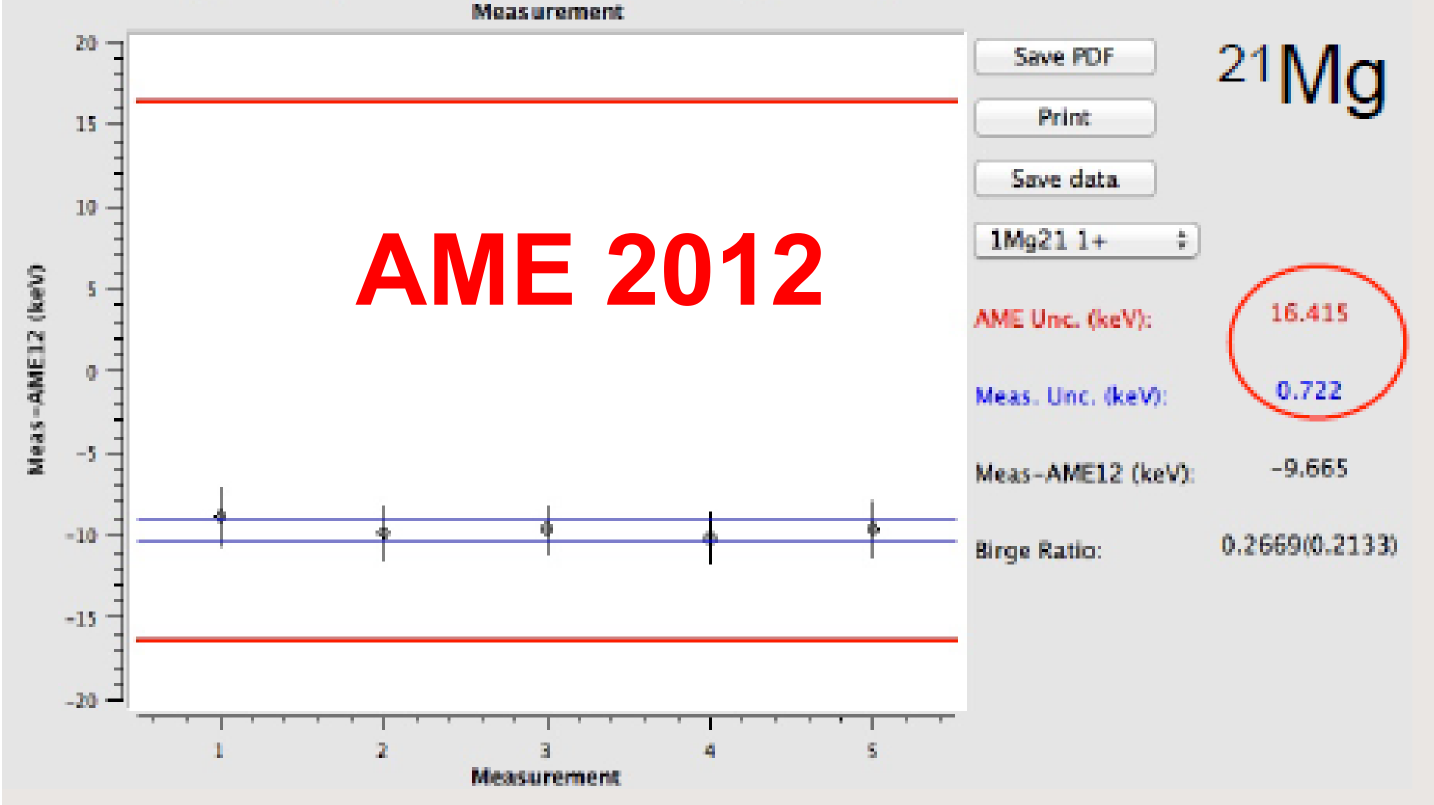
Na suppressed by 10^6

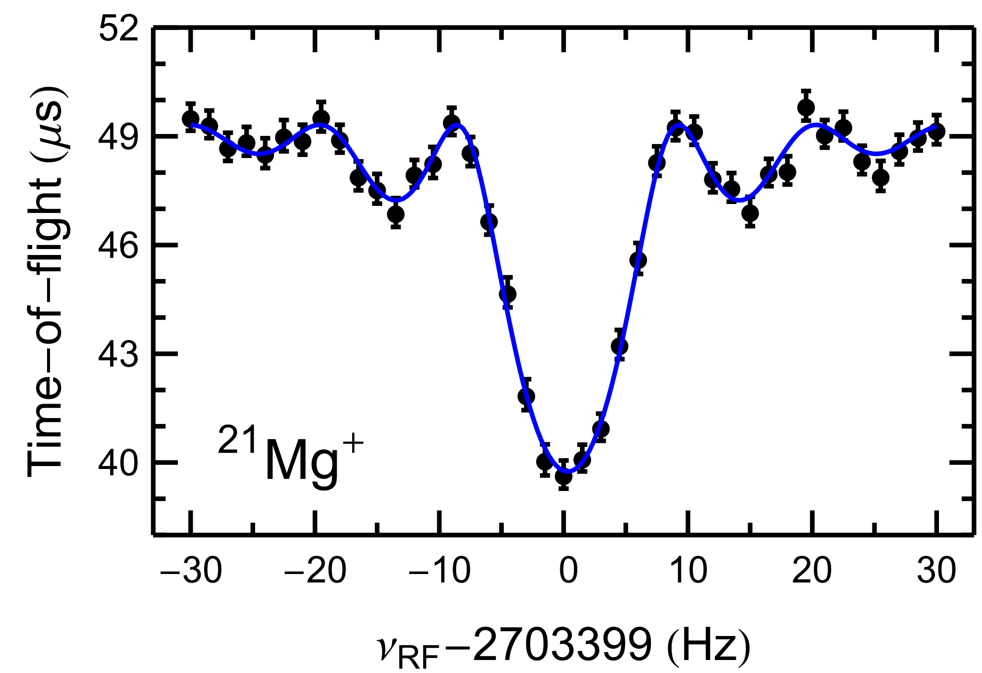
Mg reduced by 50

A. T. Gallant et al., PRL 113, 082501 (2014)

$^{20,21}Mg$ measurement at TITAN







Nuclide	Exp.	USDA	USDB	NN + 3N
^{20}Mg	−6.94	−6.71	−6.83	−6.89
^{21}Mg	−21.59	−21.79	−21.81	−23.18

A. T. Gallant et al., PRL 113, 082501 (2014)

IMME: A=20 / 21 multiplets

Nuclide	T_z	ME(g.s.) (keV)	E_x (keV)
$A = 20,\ J^\pi = 0^+,\ T = 2$			
^{20}O	+2	3796.17 (89)	0.0
^{20}F	+1	-17.45 (3)	6519.0 (30)
^{20}Ne	0	-7041.9306 (16)	16732.9 (27)
^{20}Na	-1	6850.6 (11)	6524.0 (97) [a]
^{20}Mg	-2	17477.7 (18) [b]	0.0

Fit	d (keV)	e (keV)	χ^2
Quadratic	-	-	10.4
Cubic	2.8 (11)	-	3.7
Quartic Only	-	0.89 (12)	9.9
Quartic	5.4 (17)	−3.5 (18)	-
USDA	−0.1	-	
USDA	-	−1.7	
USDB	−0.1	-	
MBPT	−18		

Nuclide	T_z	ME(g.s.) (keV)	E_x (keV)
$A = 21,\ J^\pi = 5/2^+,\ T = 3/2$			
^{21}F	+3/2	-47.6 (18)	0.0
^{21}Ne	+1/2	-5731.78 (4)	8859.2 (14)
^{21}Na	-1/2	-2184.6 (3)	8976.0 (20)
^{21}Mg	-3/2	10903.85 (74) [b]	0.0

Fit	d (keV)	χ^2
Quadratic	-	28
Cubic	6.7 (13)	-
USDA	−0.3	
USDB	0.3	
MBPT	−38	

again breakdown of the IMME

prediction of required cubic d coefficients:

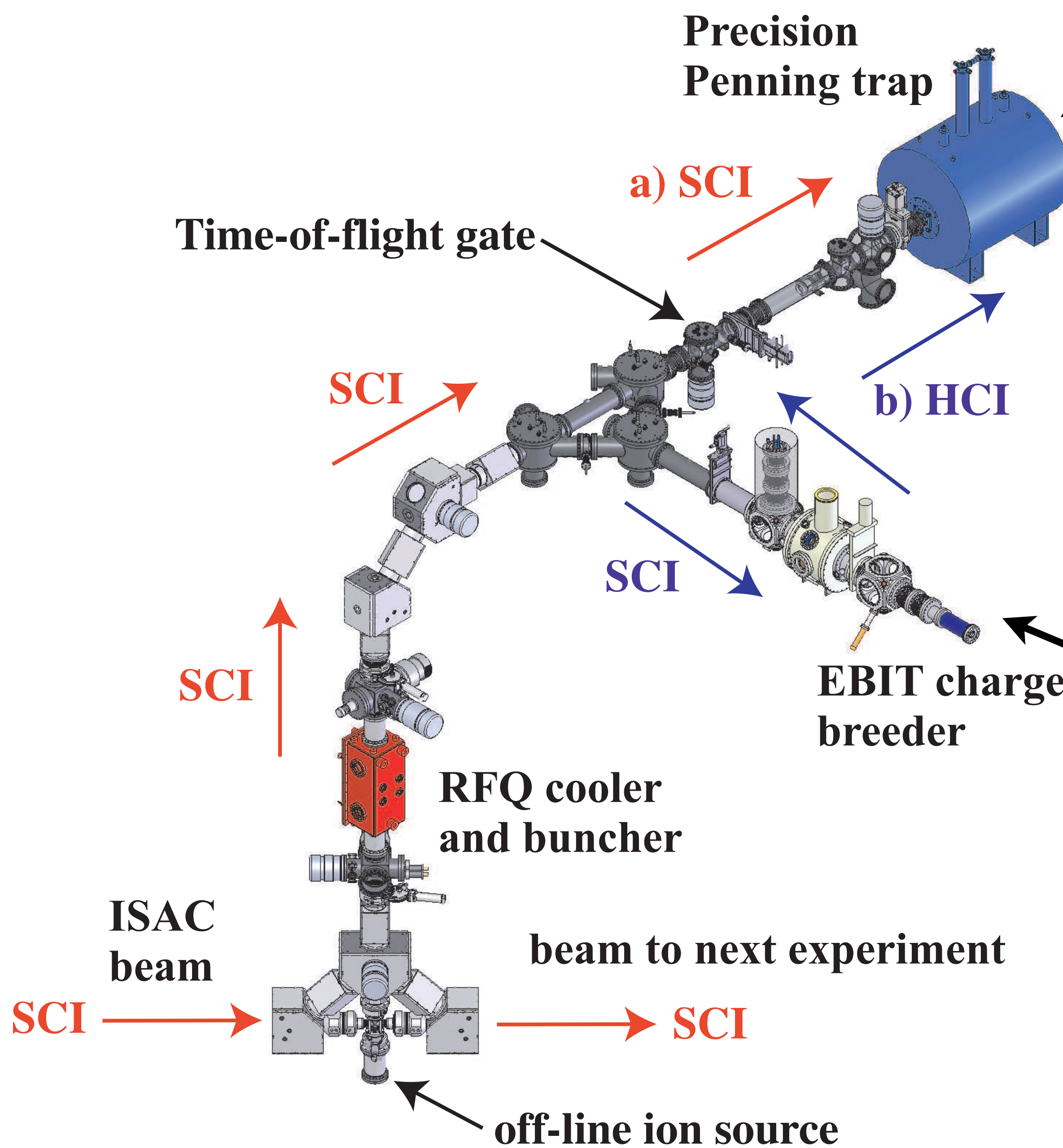
challenge for shell-model calculations

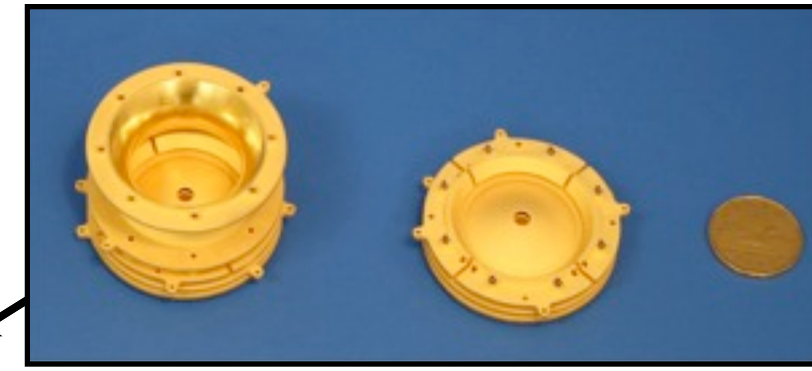
A. T. Gallant et al., PRL 113, 082501 (2014)

highly charged ions @ TITAN

$$\frac{\delta m}{m} \propto \frac{m}{q}\frac{1}{BTN^{1/2}}$$

Advantages:
- ➡ precision
- ➡ resolving power
- ➡ new separation schemes

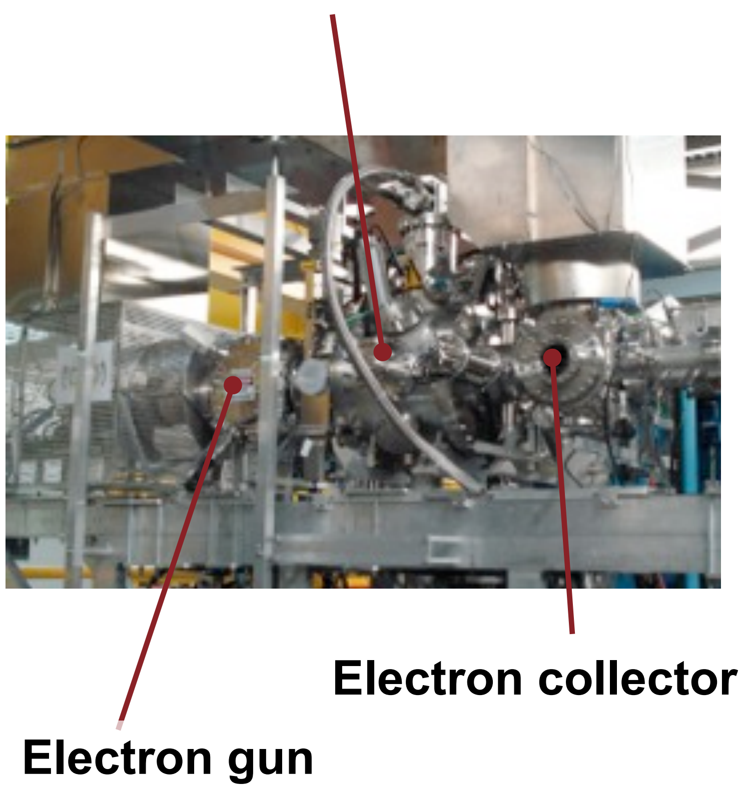


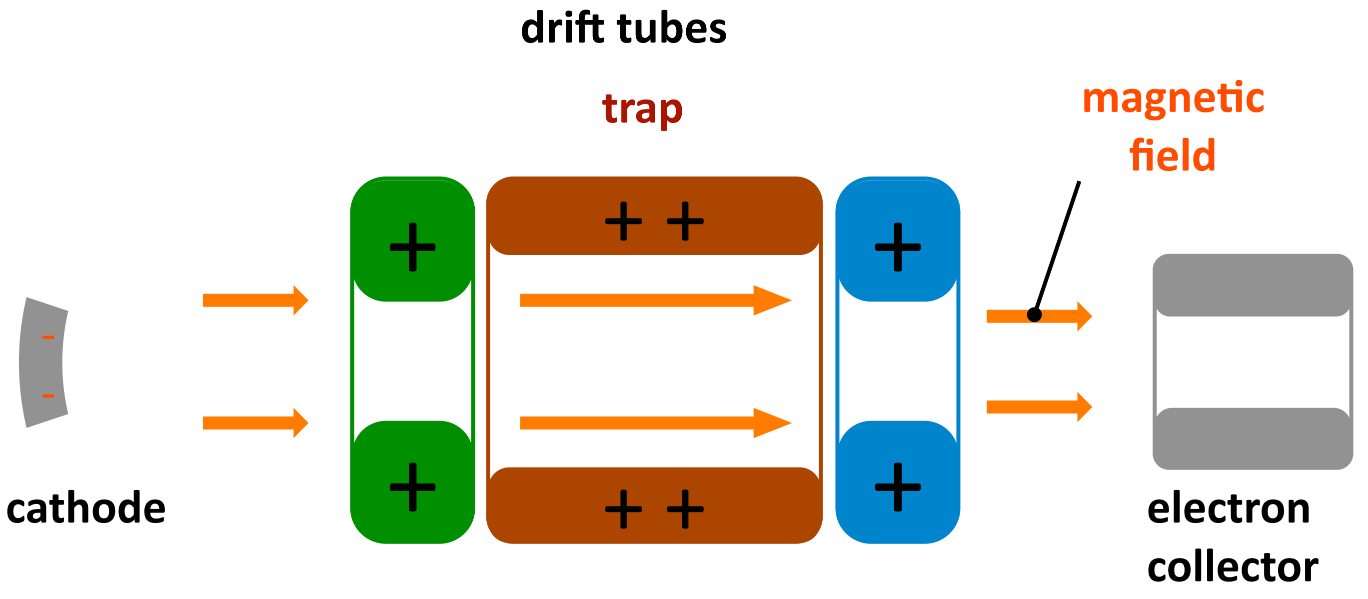


first demonstrated with ^{74}Rb ($T_{1/2}$=65 ms)

S. Ettenauer et al., PRL 107, 272501 (2011)

Electron Beam Ion Trap





requirements for charge breeding:

- efficient
- fast

Electron Beam Ion Trap

Magnet / Trap

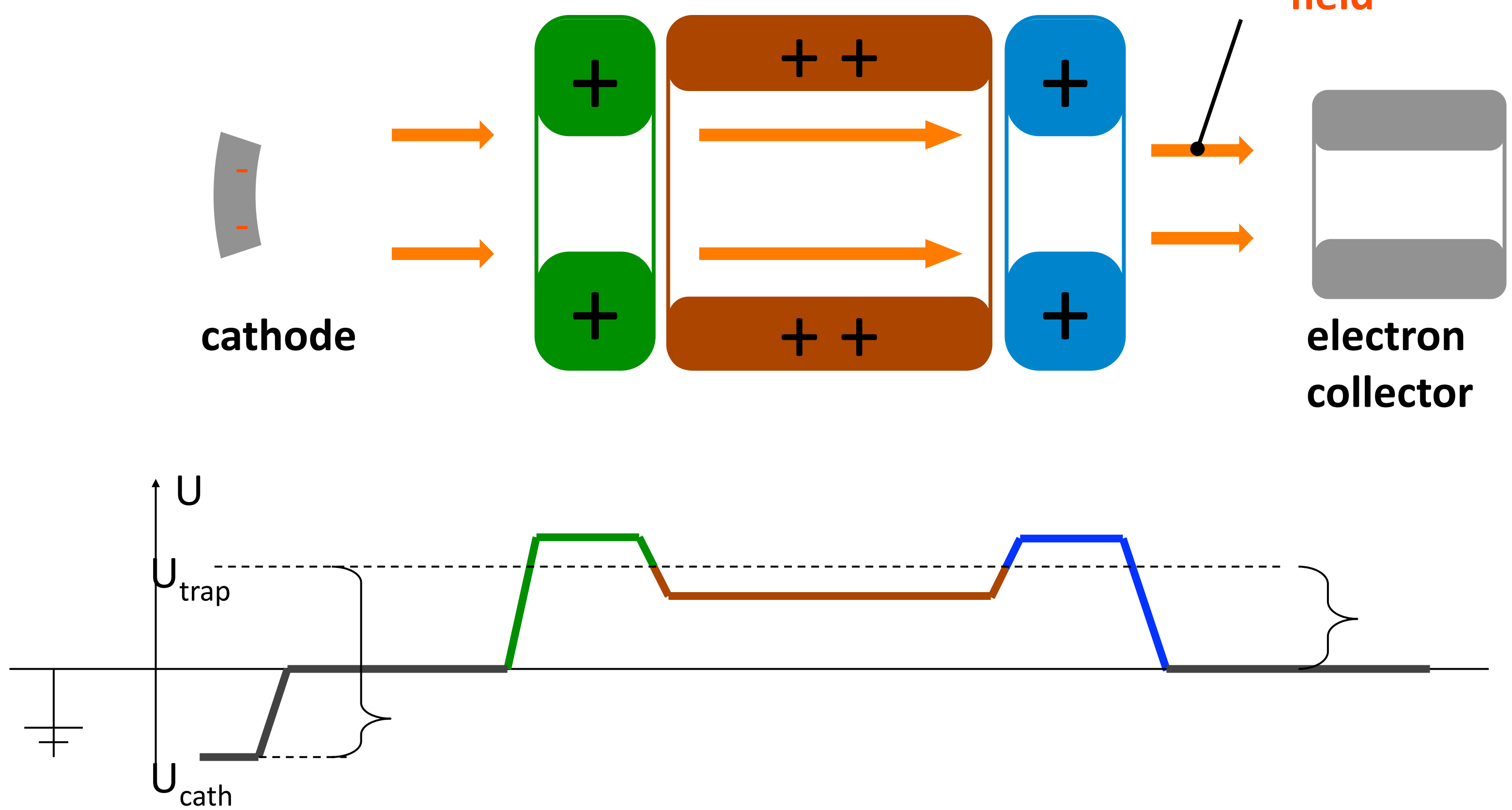
Electron collector

Electron gun

drift tubes

trap

magnetic field



requirements for charge breeding:

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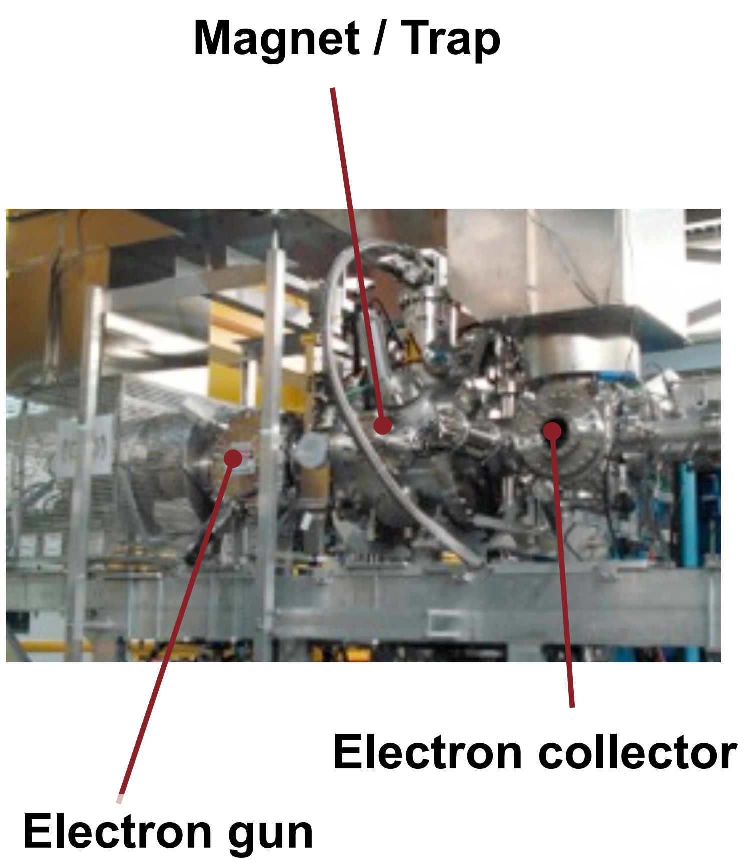
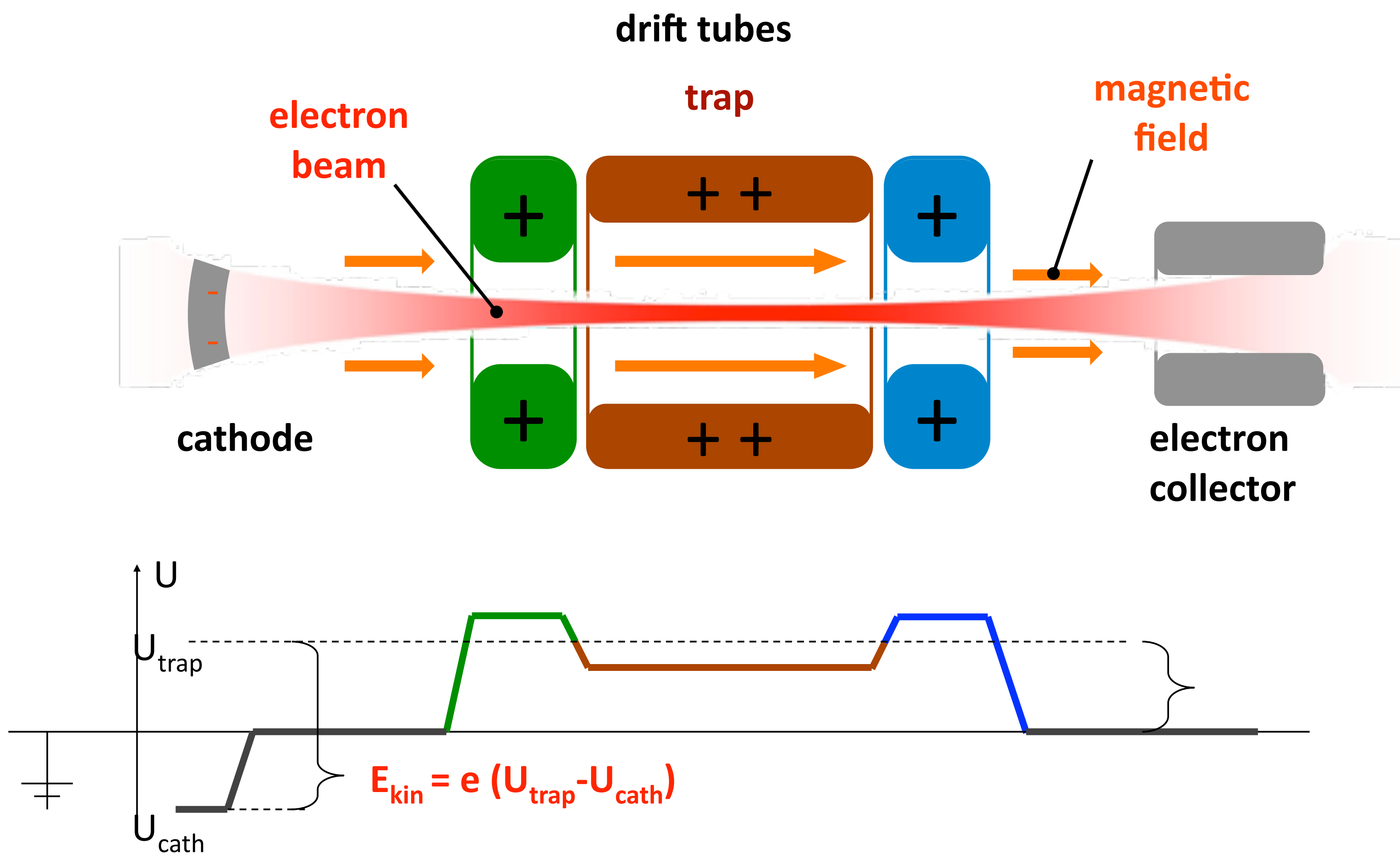
Electron Beam Ion Trap





requirements for charge breeding:

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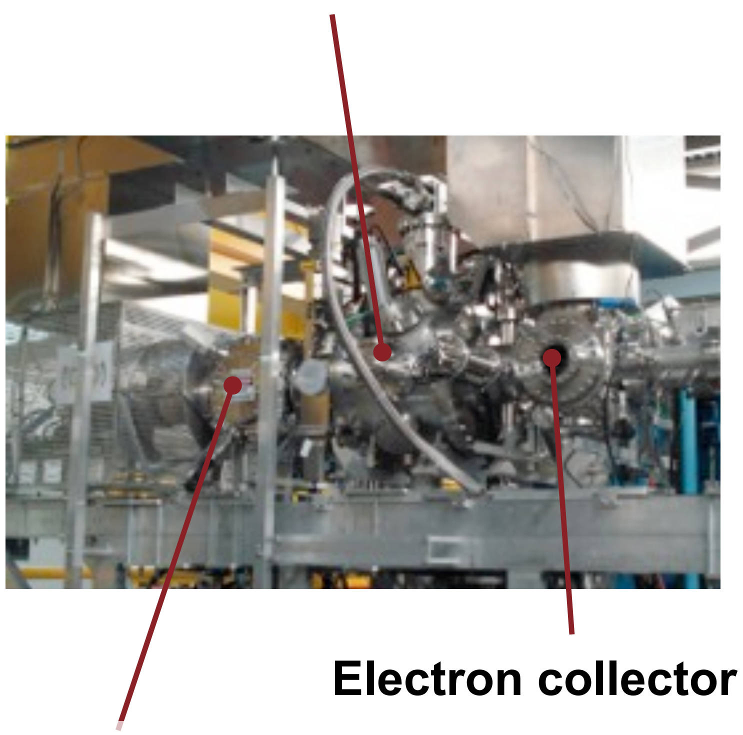
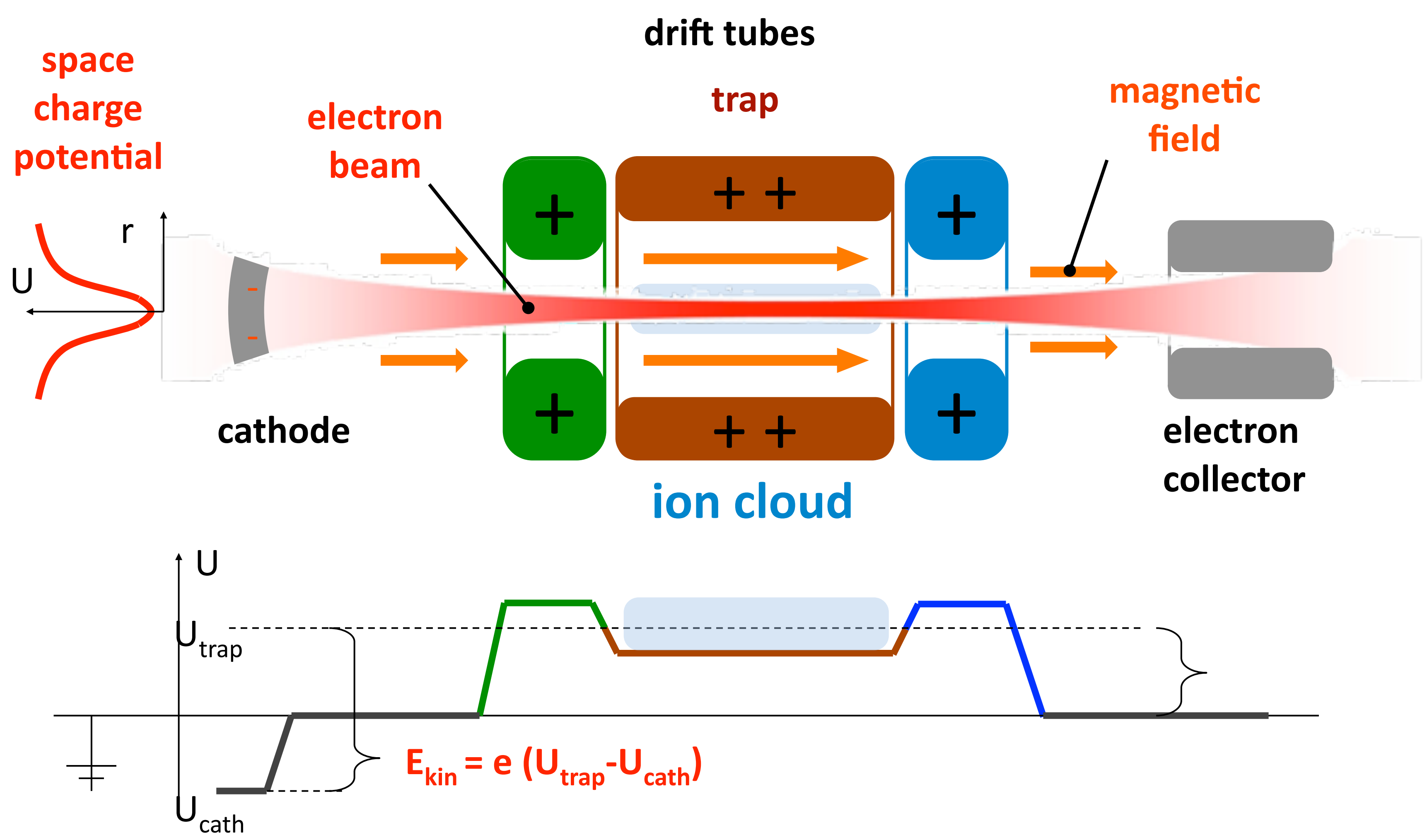
Electron Beam Ion Trap

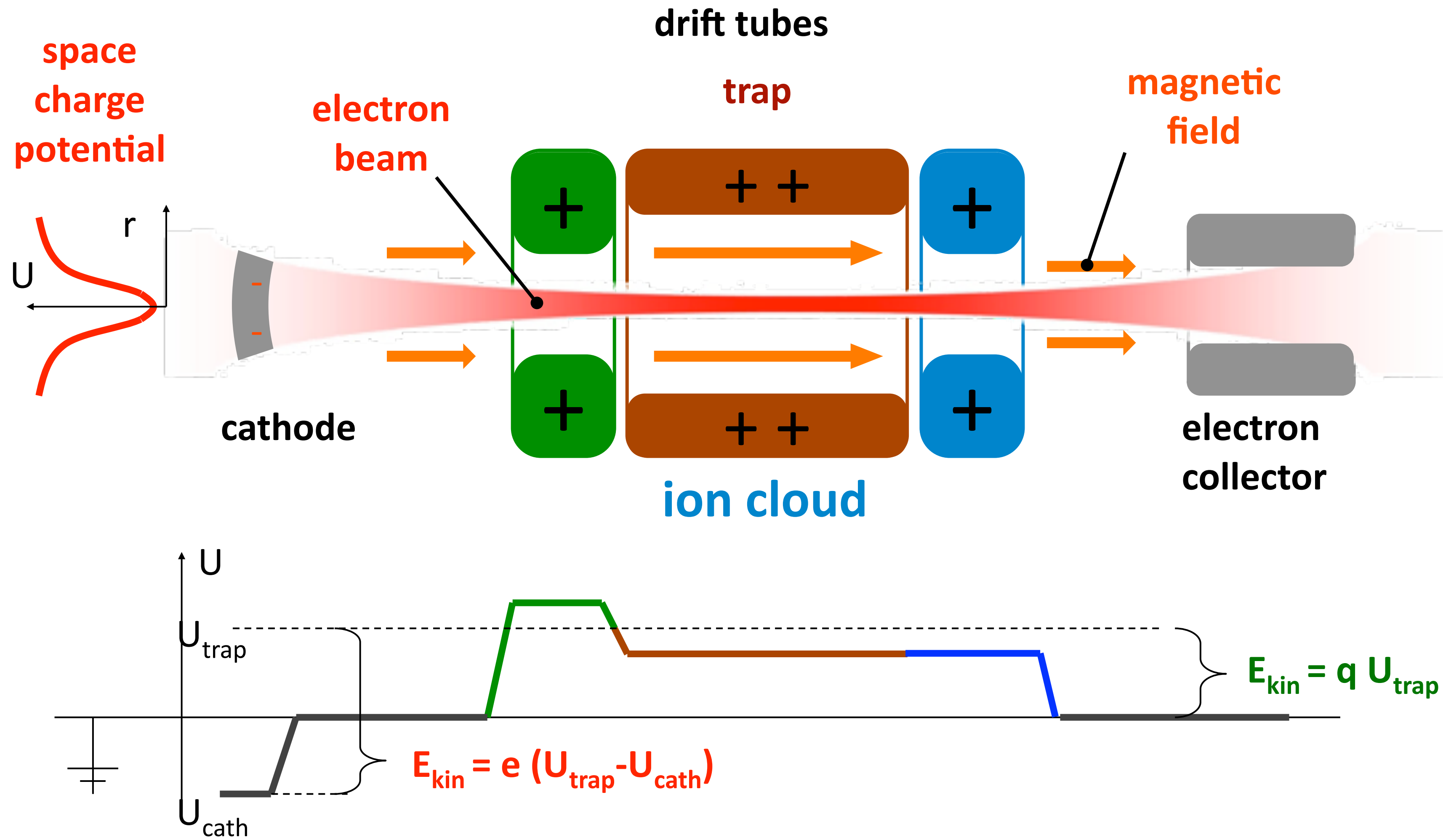




requirements for charge breeding:

- efficient
- fast

Electron Beam Ion Trap



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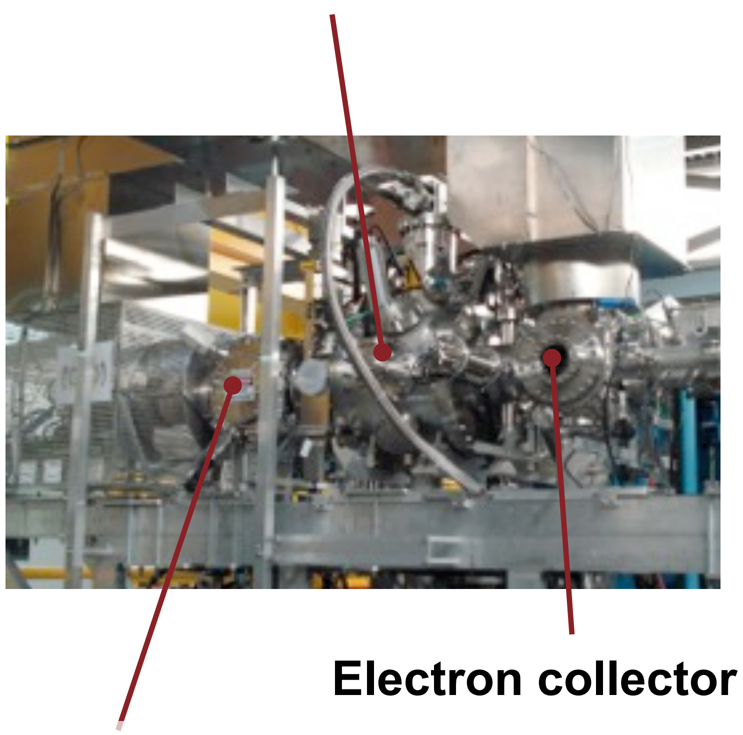

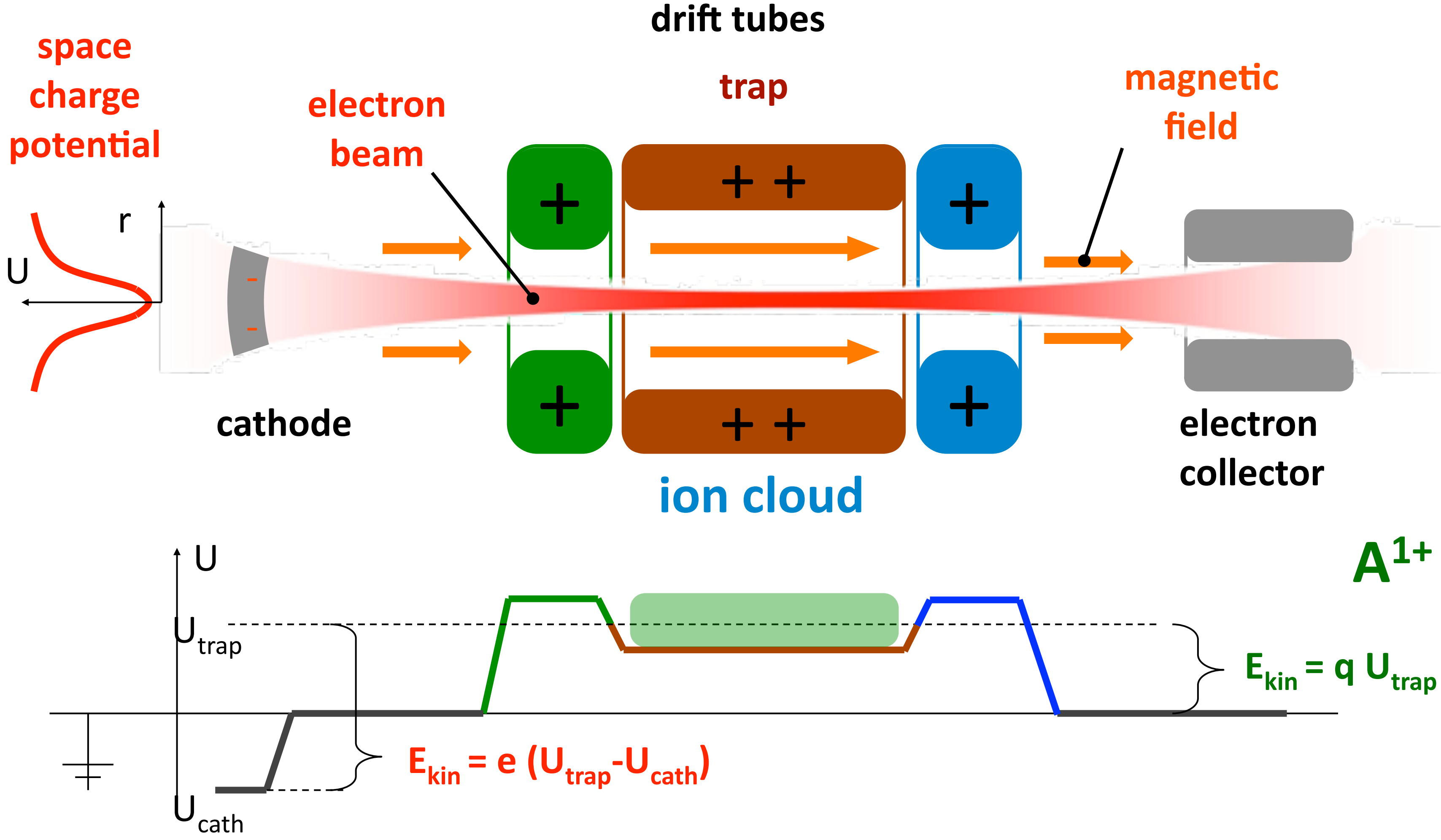

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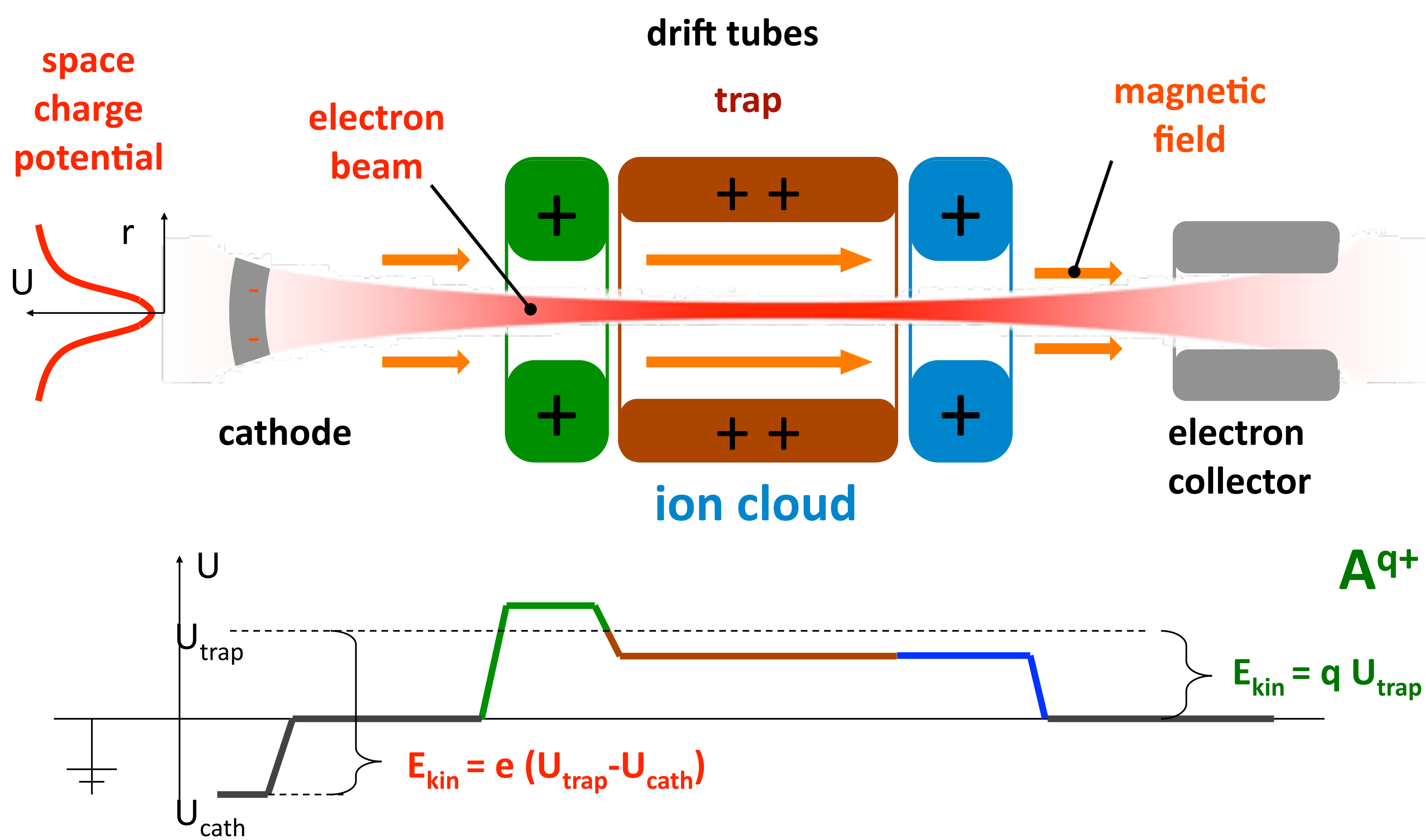

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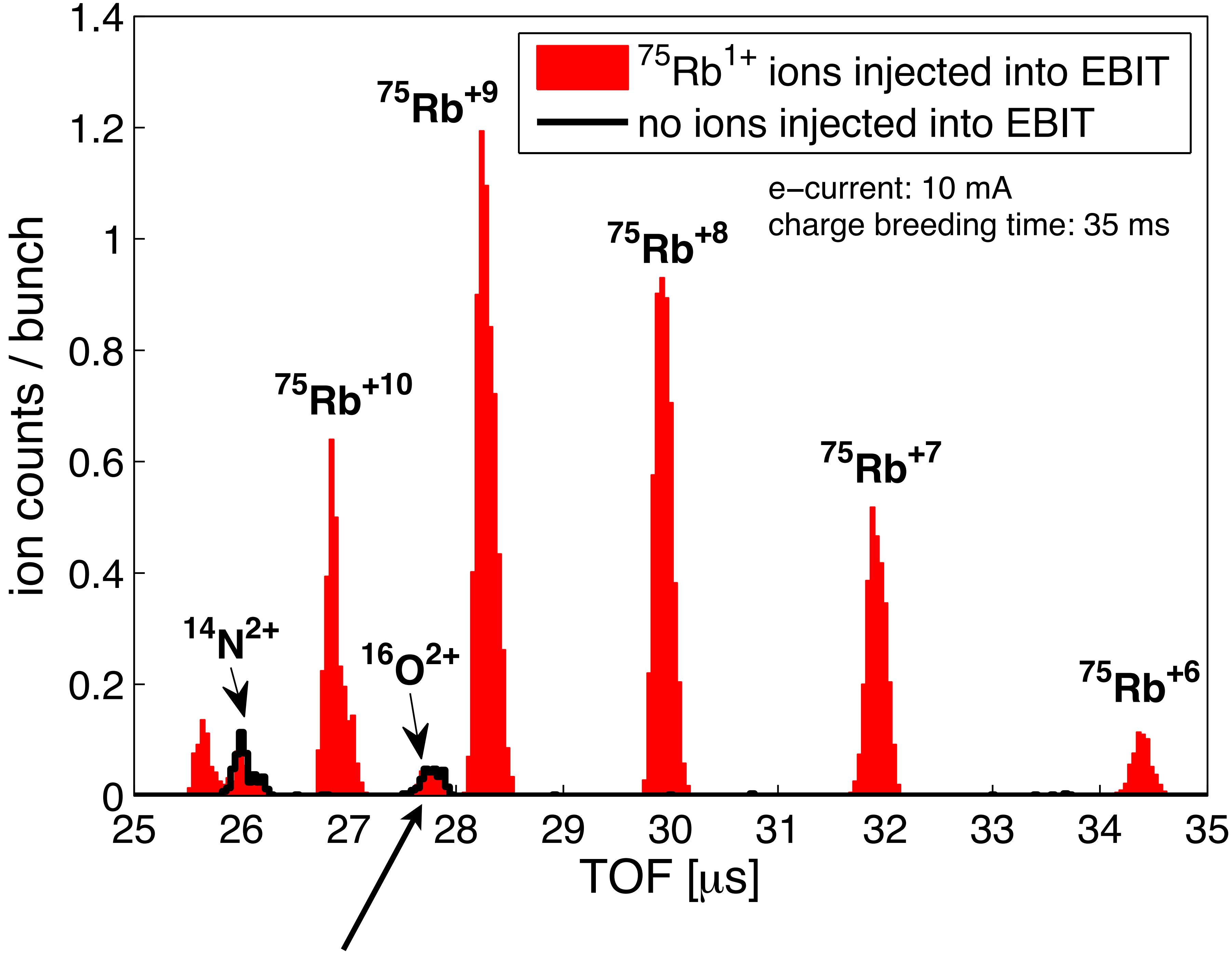
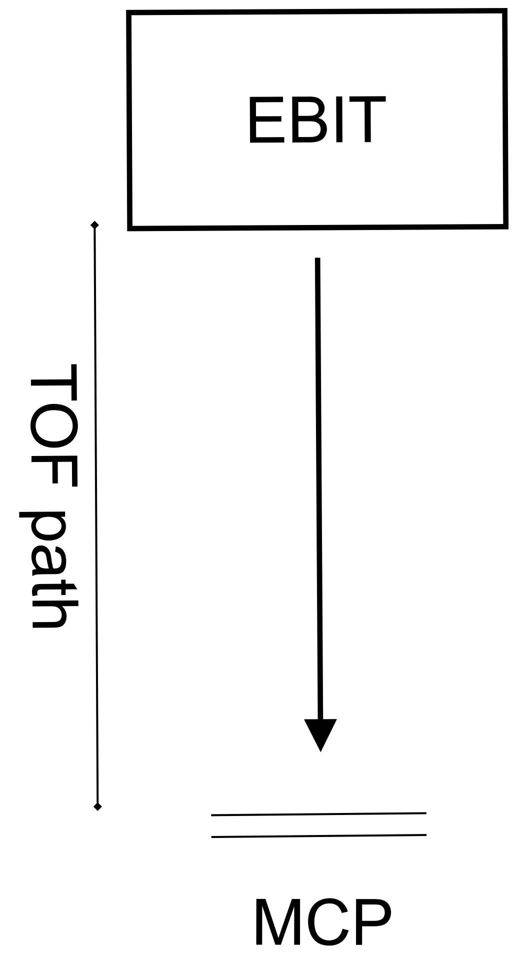
charge breeding of ^{75}Rb

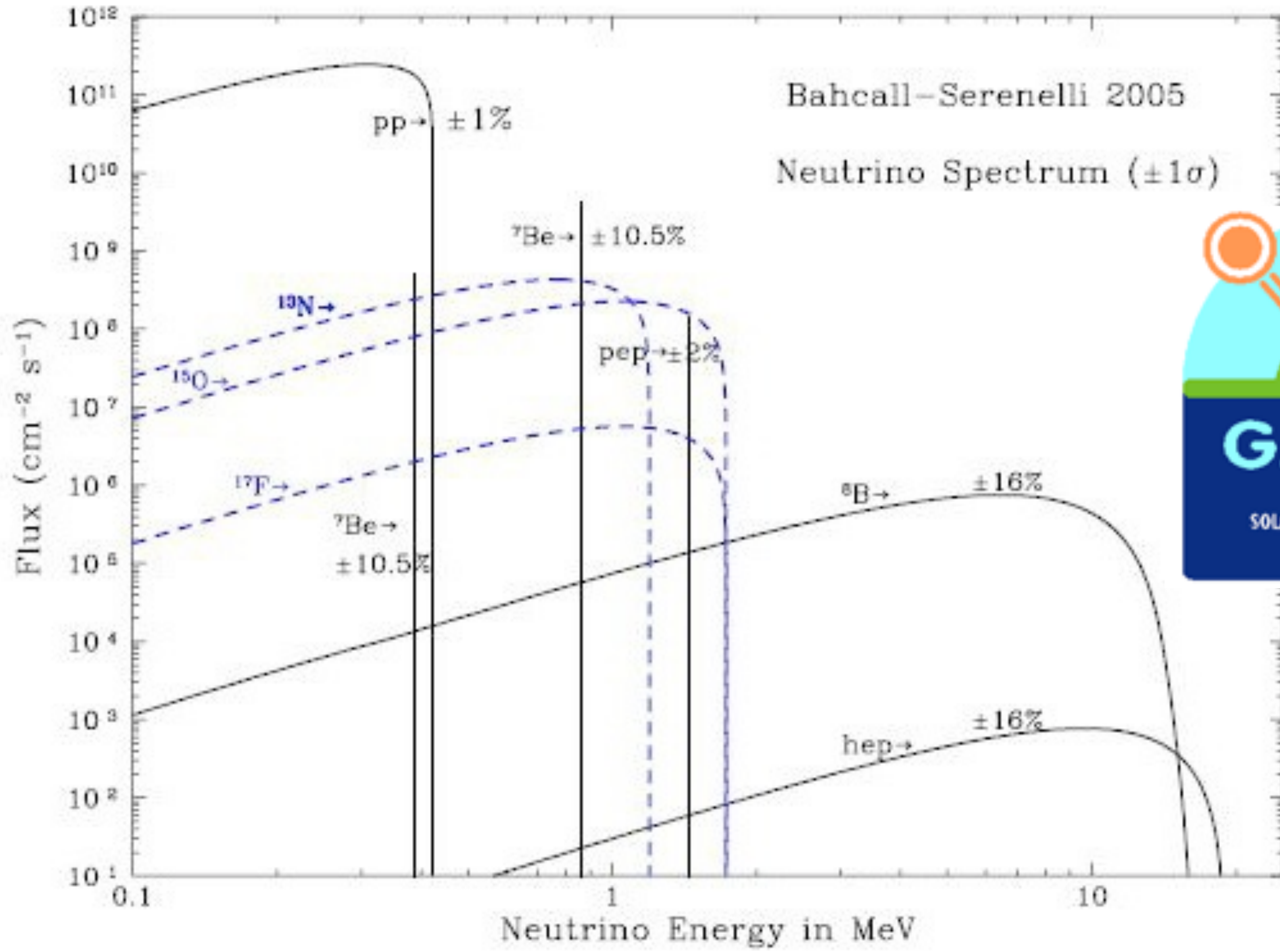




charge bred residual gas

S. Ettenauer et al., PRL 107, 272501 (2011) Int. J. Mass Spectrom. 349, 74 (2013)

Solar Neutrino Physics



Exp.	source	ratio
GALLEX	^{51}Cr-1	0.95 ± 0.11
GALLEX	^{51}Cr-2	0.81 ± 0.11
SAGE	^{51}Cr	0.95 ± 0.12
SAGE	^{37}Ar	0.79 ± 0.10
Average	^{51}Cr, ^{37}Ar	0.87 ± 0.05

measured to expected events ?!?

cross section depends on Q_{EC} of ^{71}Ge !

Detection reaction: $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$

Detector calibration: EC of ^{51}Cr and ^{37}Ar

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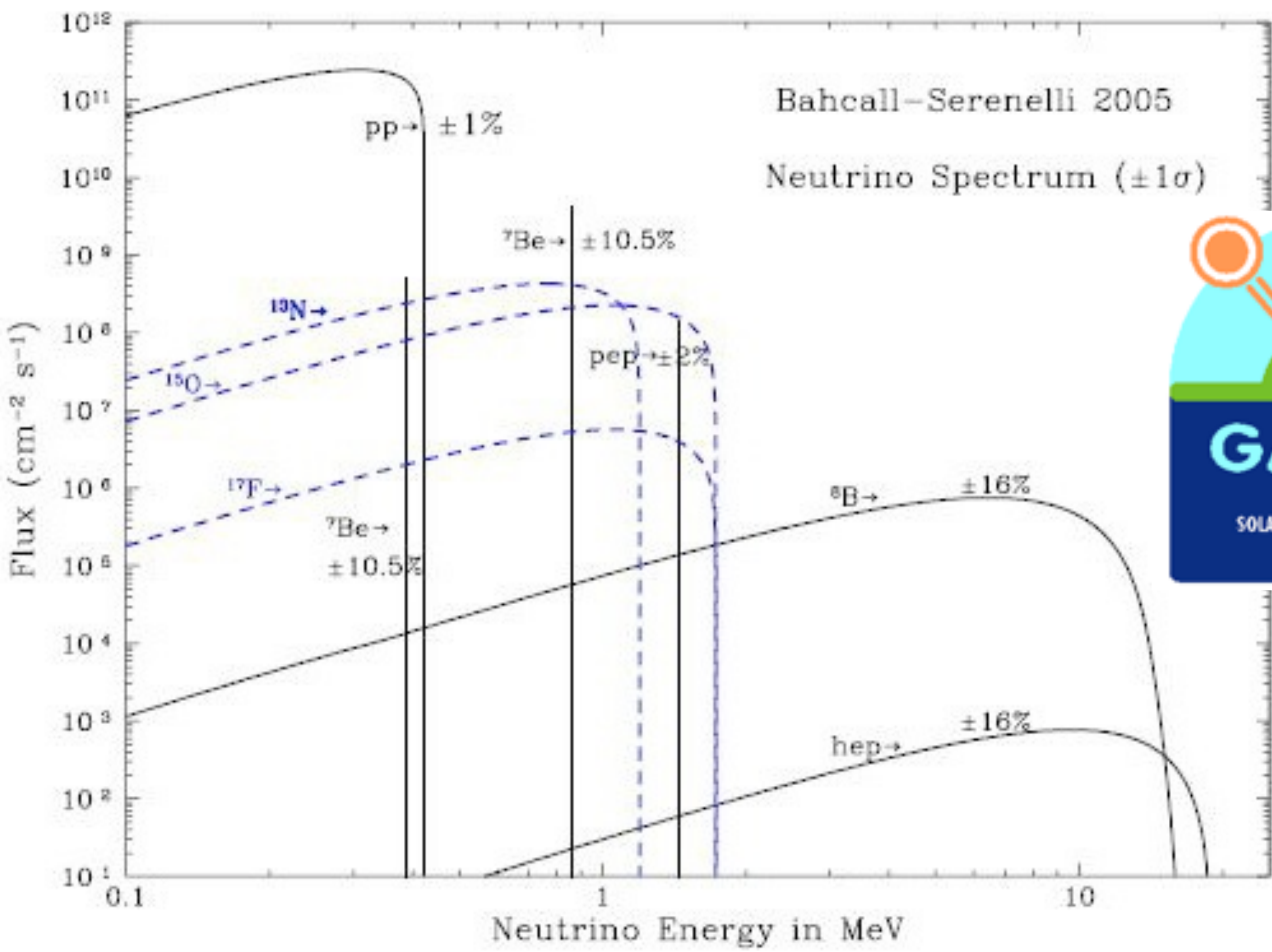

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HCI measurement of Q_{EC} of ^{51}Cr & ^{71}Ge

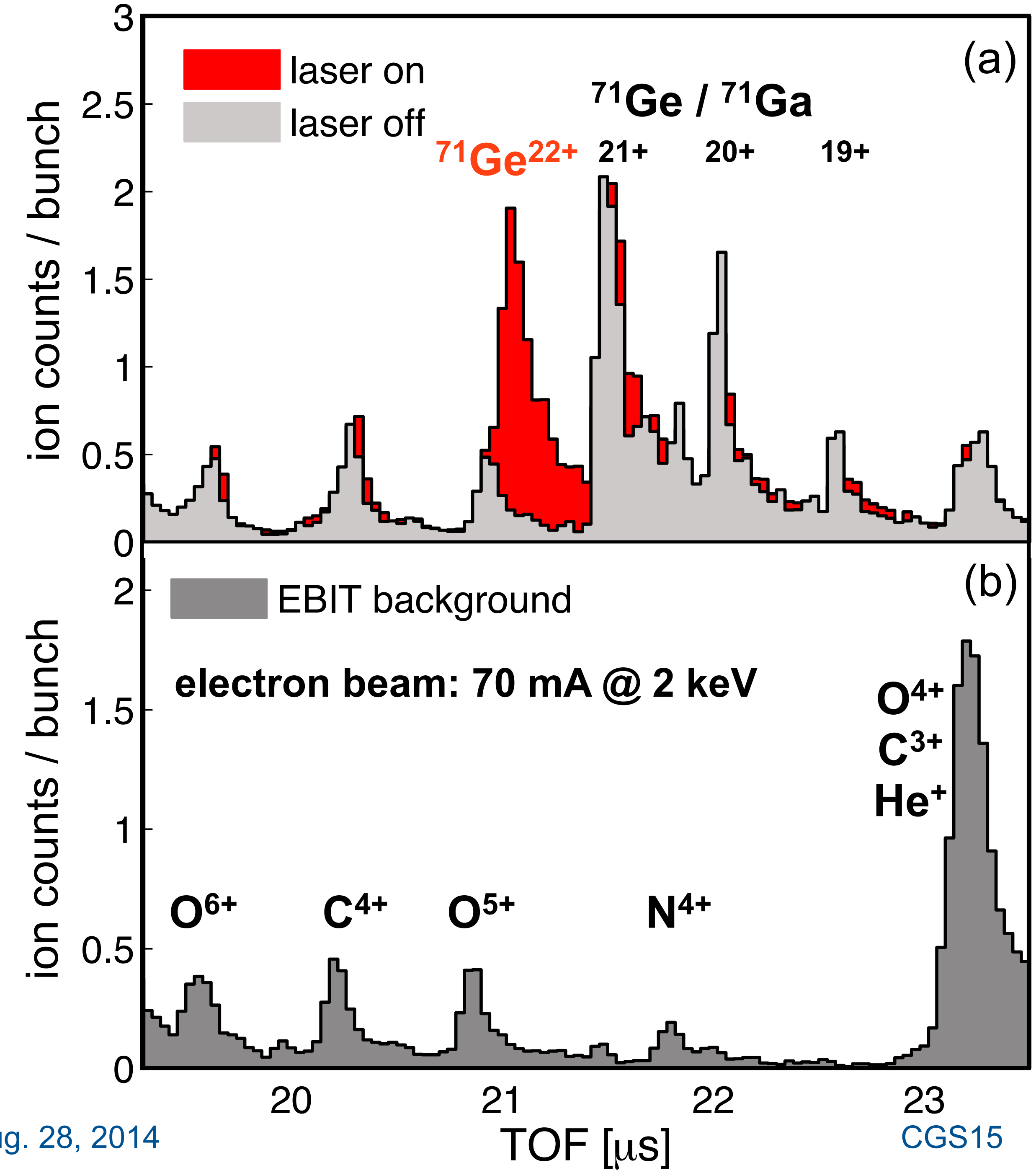
other nuclear physics uncertainties already excluded in *D. Frekers et al., Phys. Lett. B 706, 134 (2011)*

isobaric separation of ^{71}Ga-^{71}Ge

Ge delivery from ISAC required Laser Ionization:

clean $^{71}Ga^{21+}$ if Laser OFF (Ga produced through surface ionization)

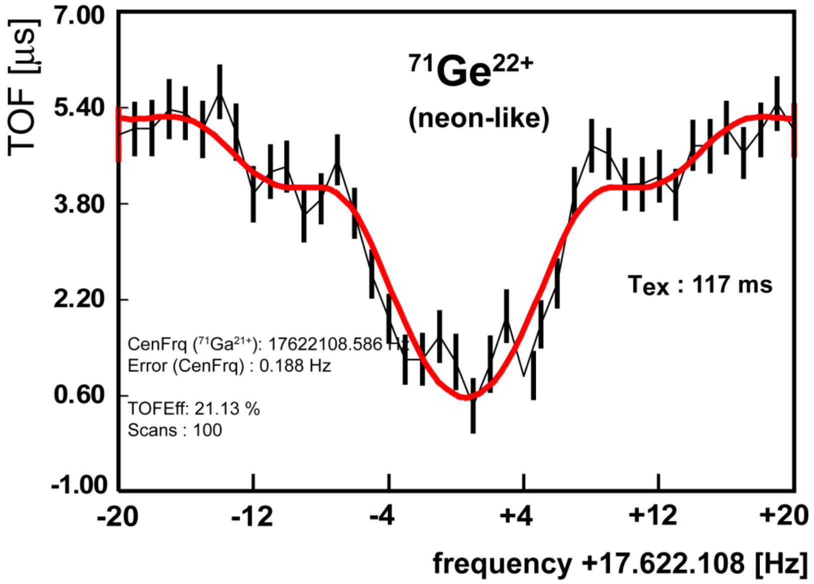
clean $^{71}Ge^{22+}$ if Laser ON (Ga not bred to q=22+)

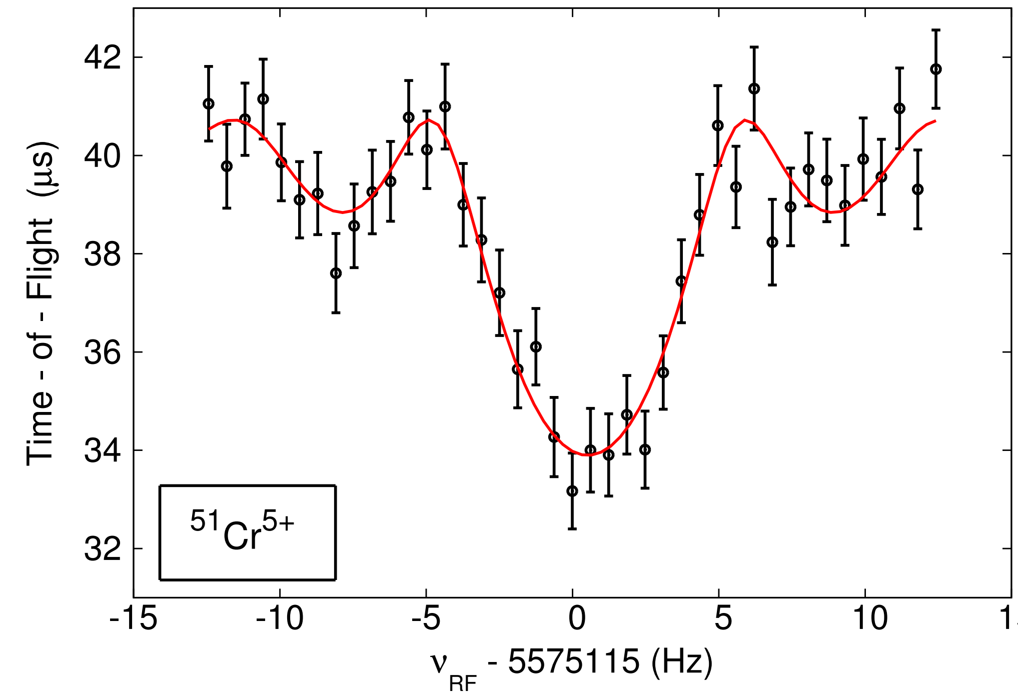


- ➡ **separation based on atomic properties**
- ➡ **no δm/m-limit in resolving power**

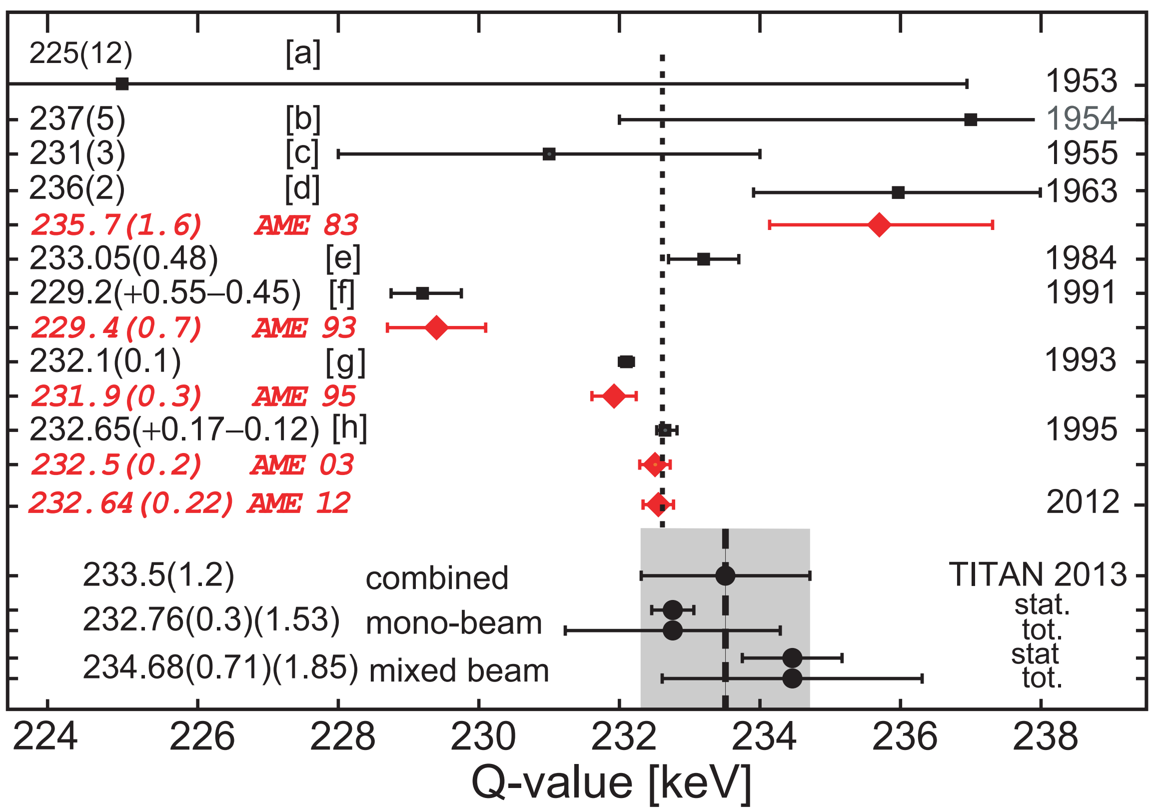
D. Frekers et al., Physics Letters B 722, 233 (2013)

results





Ion	Ref.	$R = \widetilde{\nu}_c^{\,V} / \nu_c^{Cr}$	Q-value (keV)
$^{51}Cr^{5+}$	$^{51}V^{5+}$	1.000015851(14)	752.14(64)
$^{51}Cr^{6+}$	$^{51}V^{6+}$	1.000015827(23)	751.05(108)
		Average Q-value:	751.86(55)
		AME:	752.63(24)



D. Frekers et al., Physics Letters B 722, 233 (2013)
T. D. Macdonald et al., Phys. Rev. C 89, 044318 (2014)

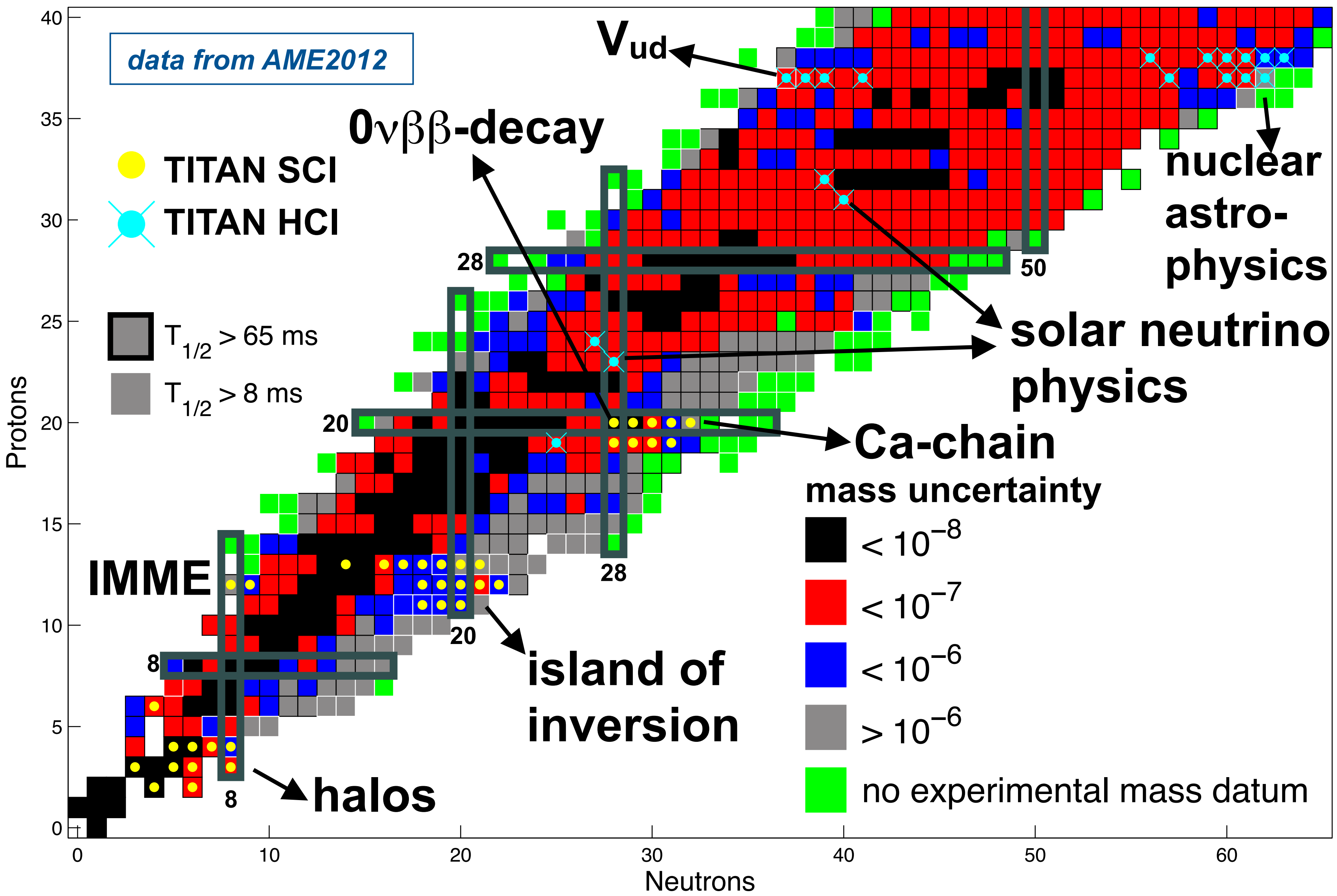
confirms previous Q_{EC} measurements

⇒ GALEX - SAGE discrepancy unresolved!

summary

TITAN:

- ➡ only PT for nuclides with $T_{1/2}$=10 ms
- ➡ unique in use of radioactive HCI
  - precision
  - resolution
  - separation



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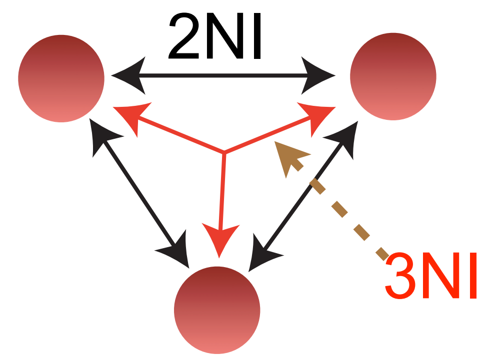
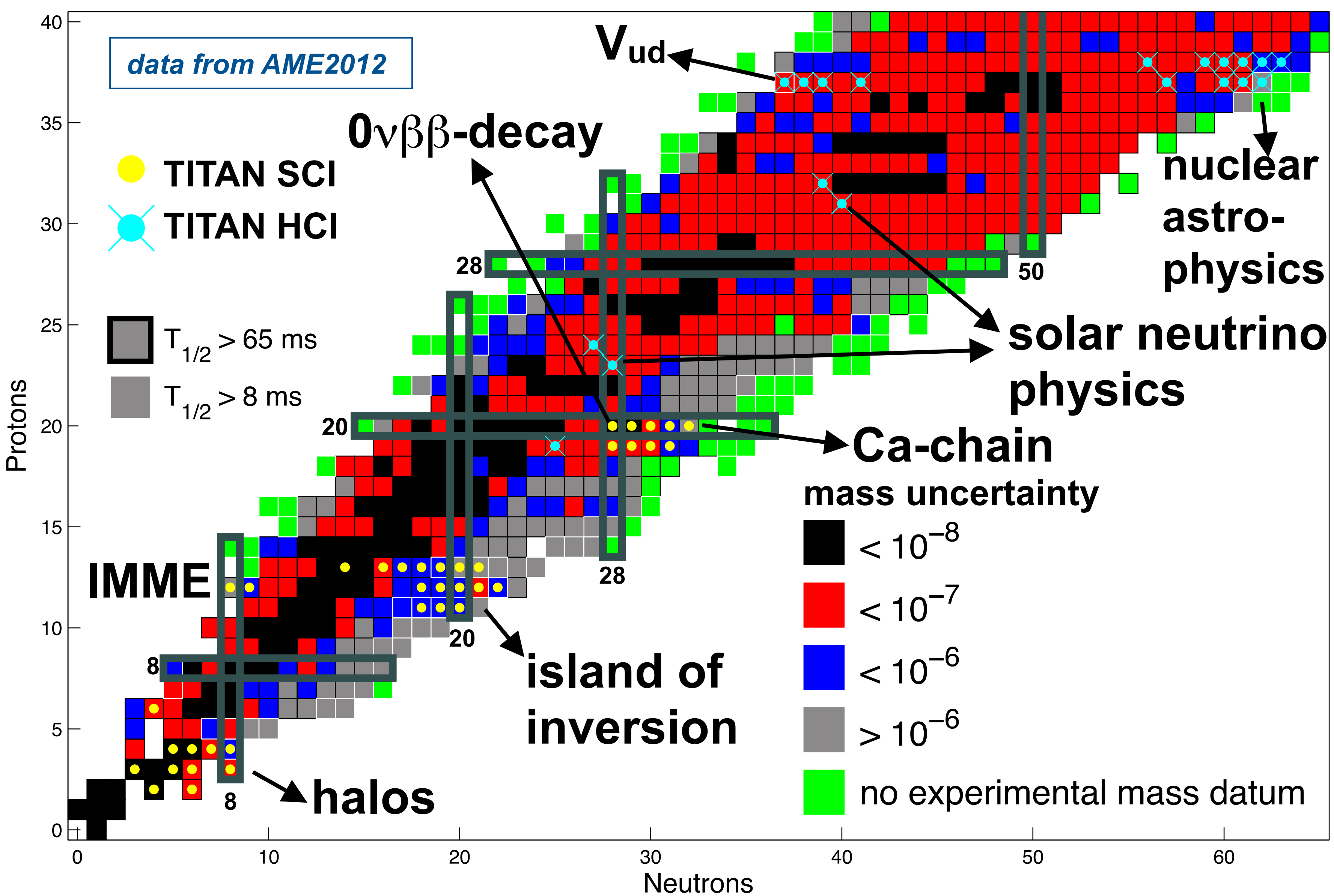


3-body forces:

- new mass of ^{6}He
- masses of Ca-isotopes
- ^{20,21}Mg for tests of IMME

➡ highlights successes and challenges of theory



Ga-anomaly:

- confirmed Q_{EC}-values of ^{51}Cr & ^{71}Ge

➡ discrepancy unresolved

➡ eliminates nuclear physics uncertainties

TRIUMF

TITAN

- The TITAN Group: Jens Dilling, Dieter Frekers, Gerald Gwinner, Melvin Good, Alain Lapierre, David Lunney, Mathew Pearson, Ryan Ringle, Corina Andreoiu, Maxime Brodeur, Thomas Brunner, Ankur Chaudhuri, Stephan Malbrunot-Ettenauer, Alexander Grossheim, Ania Kwiatkowski, Kyle Leach Ernesto Mané, Brad Schultz, Martin C. Simon, Usman Chowdhury, Benjamin Eberhart, Aaron Gallant, R. Klawitter, Annika Lennarz, Tegan Macdonald, Vanessa Simon, Mathew Smith

- TRIUMF Staff: Pierre Bricault, Friedhelm Ames, Jens Lassen, Marik Dombsky, Peter Kunz, Rolf Kietel, Don Dale, Hubert Hui, Kevin Langton, Mike McDonald, Raymond Dubé, Tim Stanford, Stuart Austin, Zlatko Bjelic, Daniel Rowbotham, Daryl Bishop

And the rest of the TITAN collaboration....

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Muenster U.,
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CNRS- CSNSM
U. of Windsor
Colorado School of Mines
TRIUMF
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