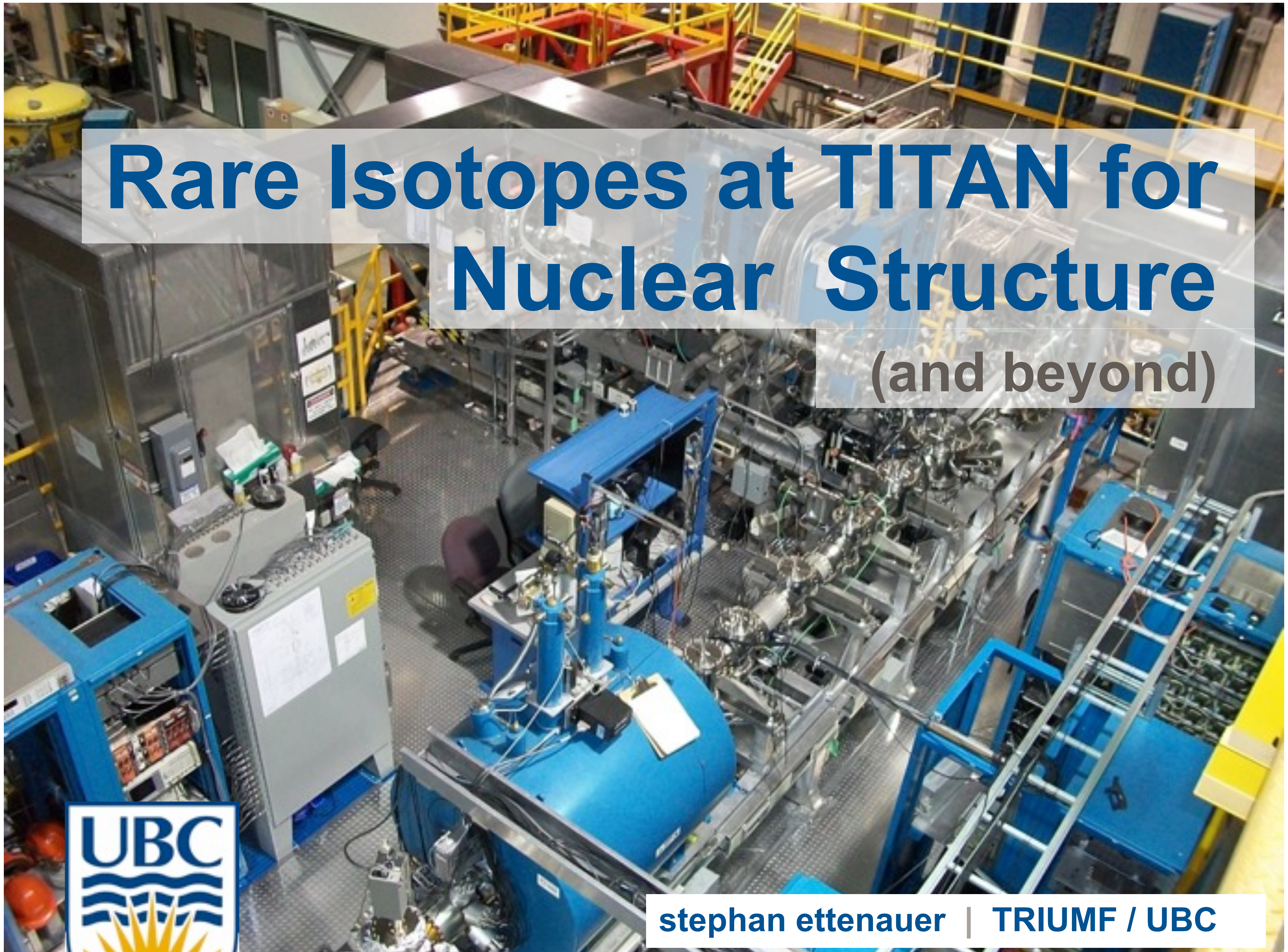
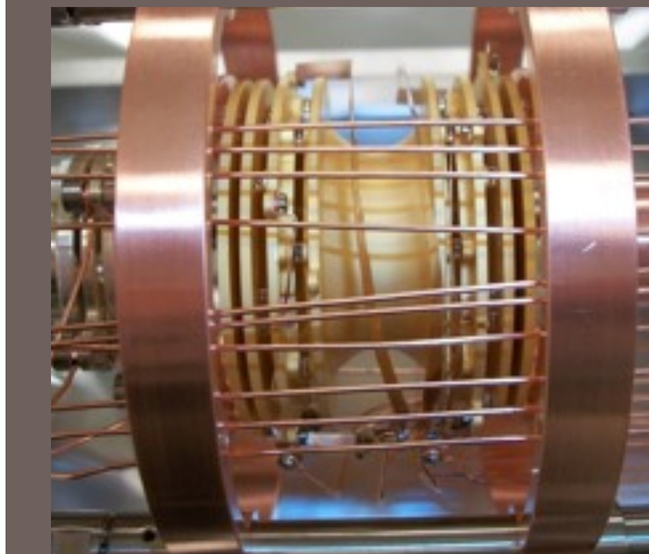
TRIUMF
Canada’s national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules



Rare Isotopes at TITAN for Nuclear Structure

(and beyond)

stephan ettenauer | TRIUMF / UBC



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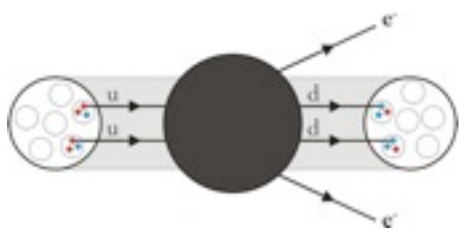
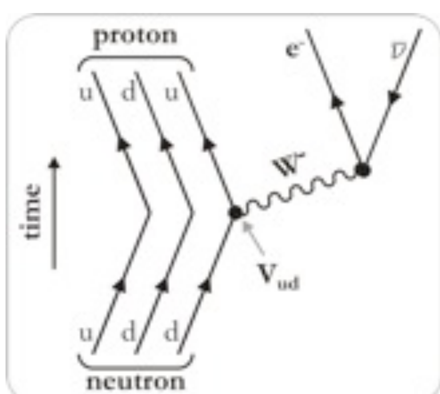
(some) big questions for nucl. structure

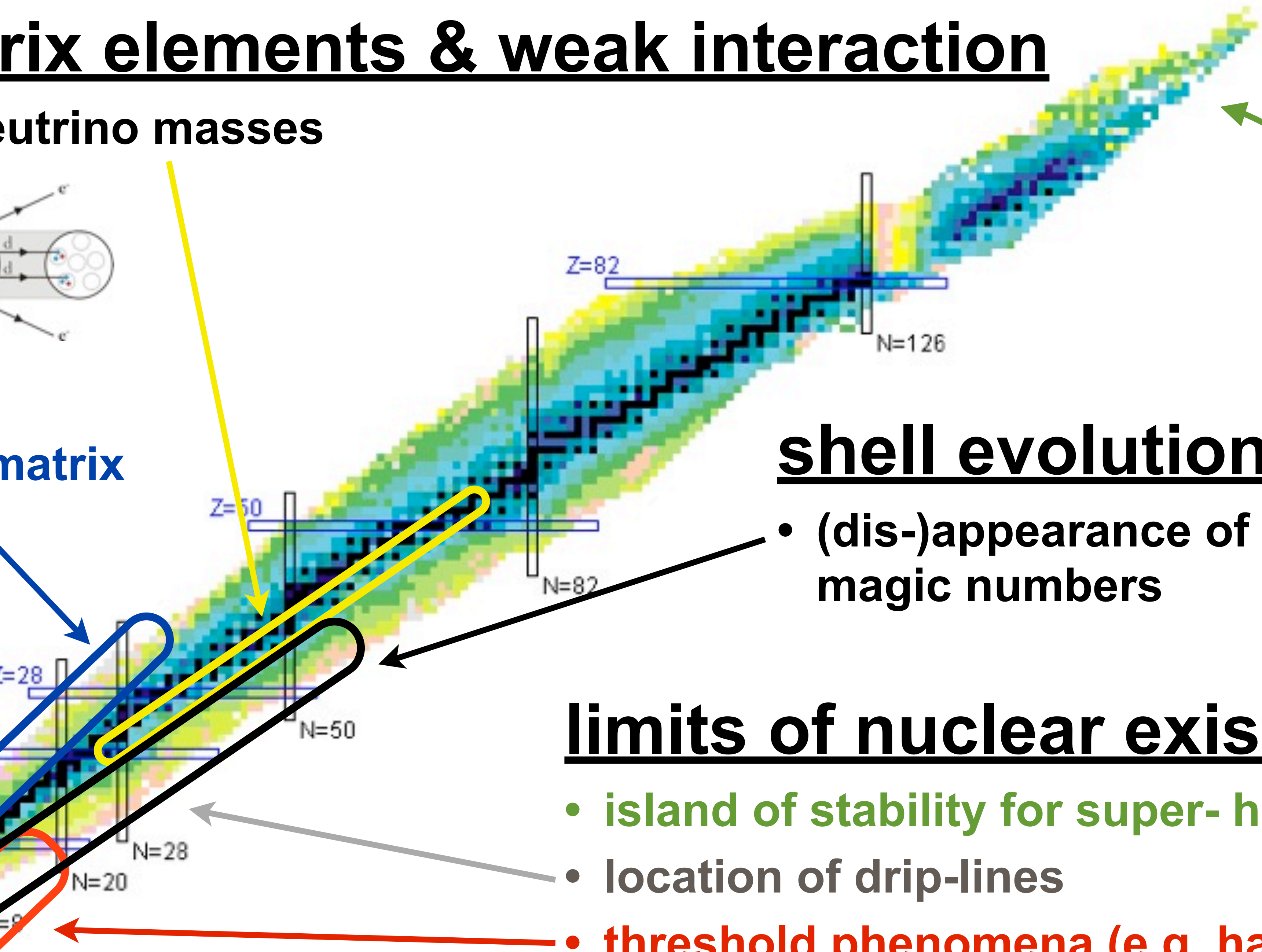
nuclear matrix elements & weak interaction

- **0νββ-decay & neutrino masses**



- **V_{ud} of the CKM matrix**





shell evolution

- **(dis-)appearance of magic numbers**

limits of nuclear existence

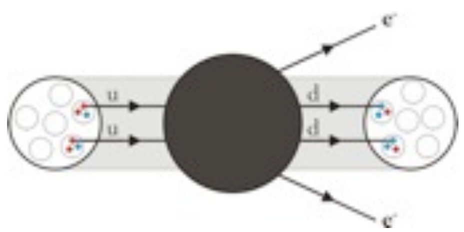
- **island of stability for super- heavies**
- **location of drip-lines**
- **threshold phenomena (e.g. halos, ...)**

⇒ challenges for understanding of nuclear forces & models

(some) big questions for nucl. structure

nuclear matrix elements & weak interaction

- $0\nu\beta\beta$-decay & neutrino masses



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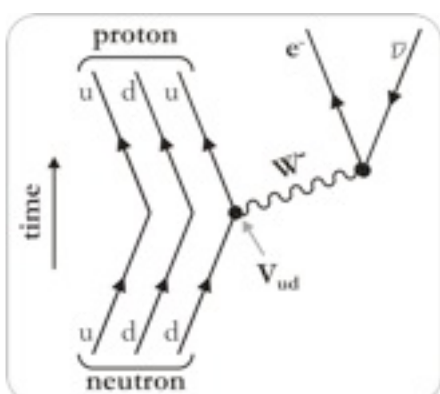
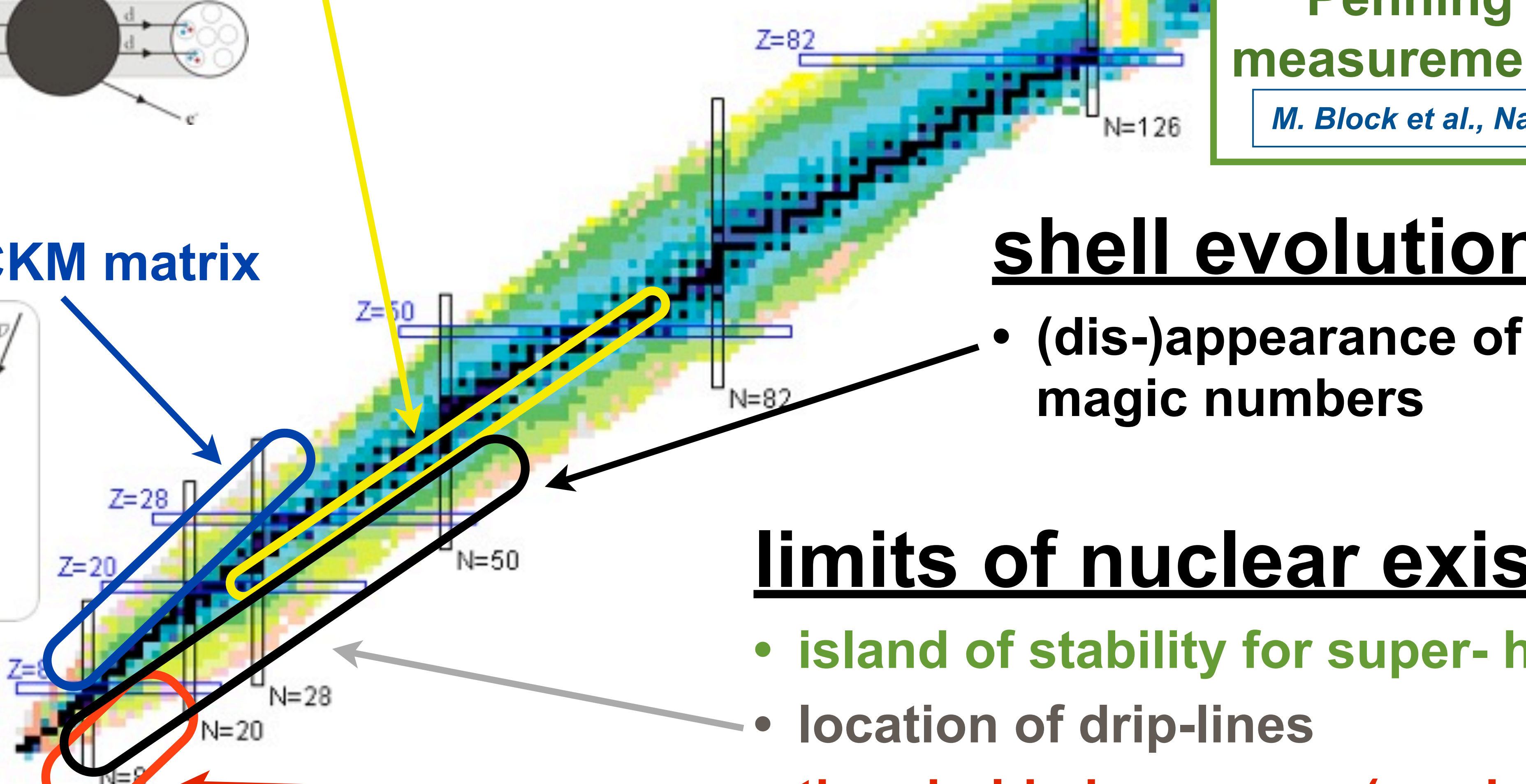




Penning trap mass measurement of $^{252-254}$No

M. Block et al., Nature 463, 785(2010)

shell evolution

- (dis-)appearance of magic numbers

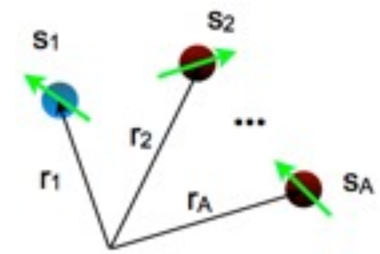
limits of nuclear existence

- island of stability for super- heavies
- location of drip-lines
- threshold phenomena (e.g. halos, ...)

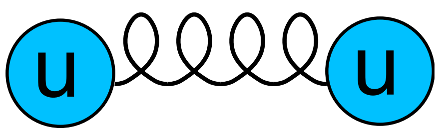
⇒ challenges for understanding of nuclear forces & models

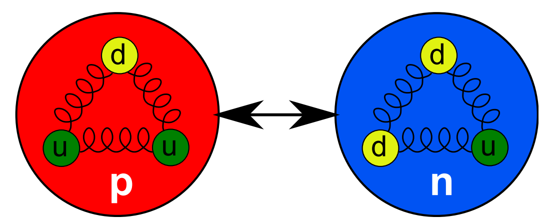
the big challenges

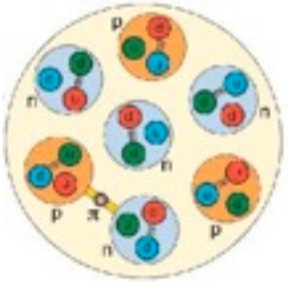
‘ingredients’ well understood, **BUT**



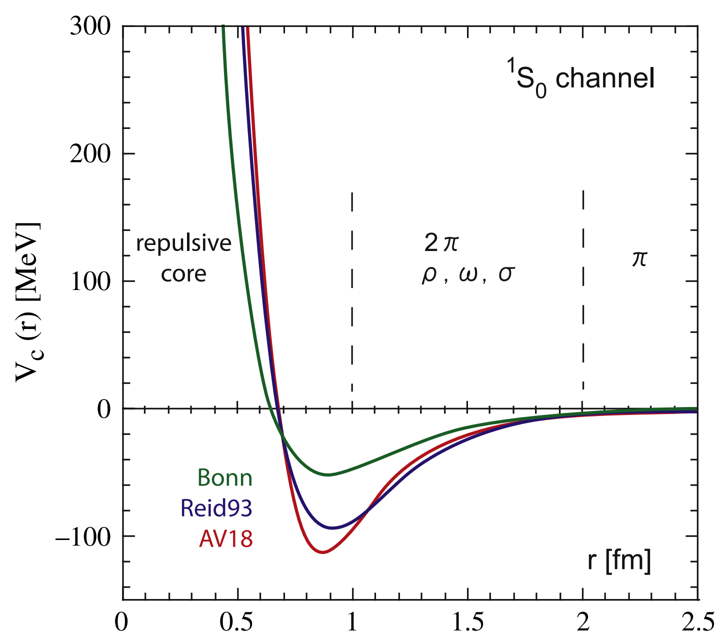
- A! and A generally too small for stat. approach
- nucleons composites of quarks: **force between nucleons?**

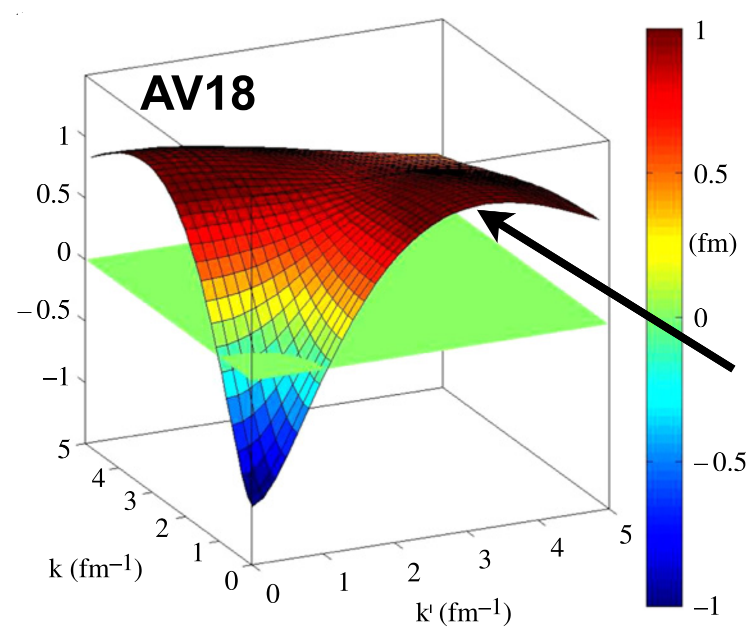






- repulsive core of NN-force





coupling of high and low k

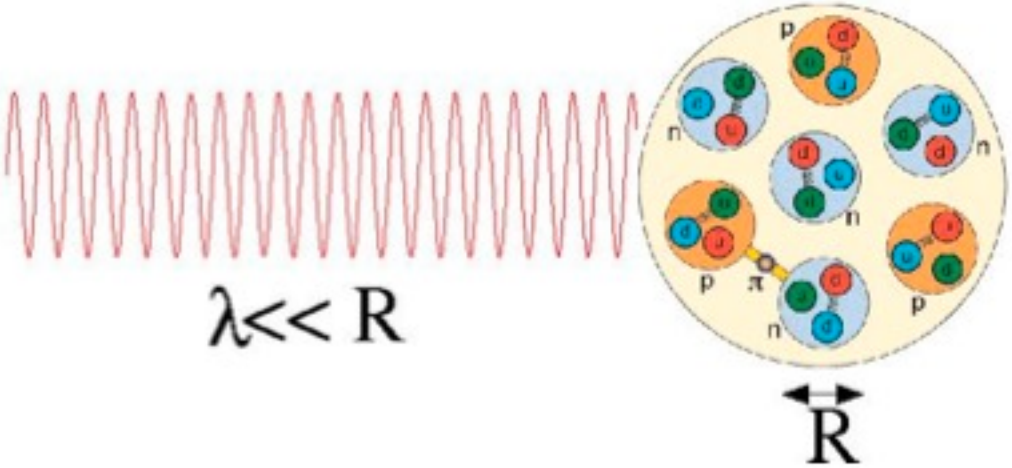
⇒ large model spaces

S.K. Bogner et al, Prog. Par. Nuc. Phys., 65,94, (2010)

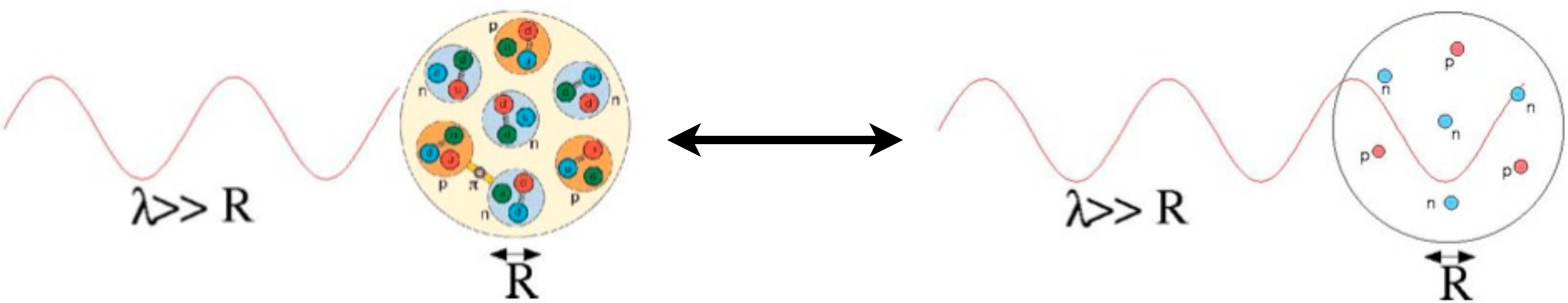
method

nuclear forces

resolution



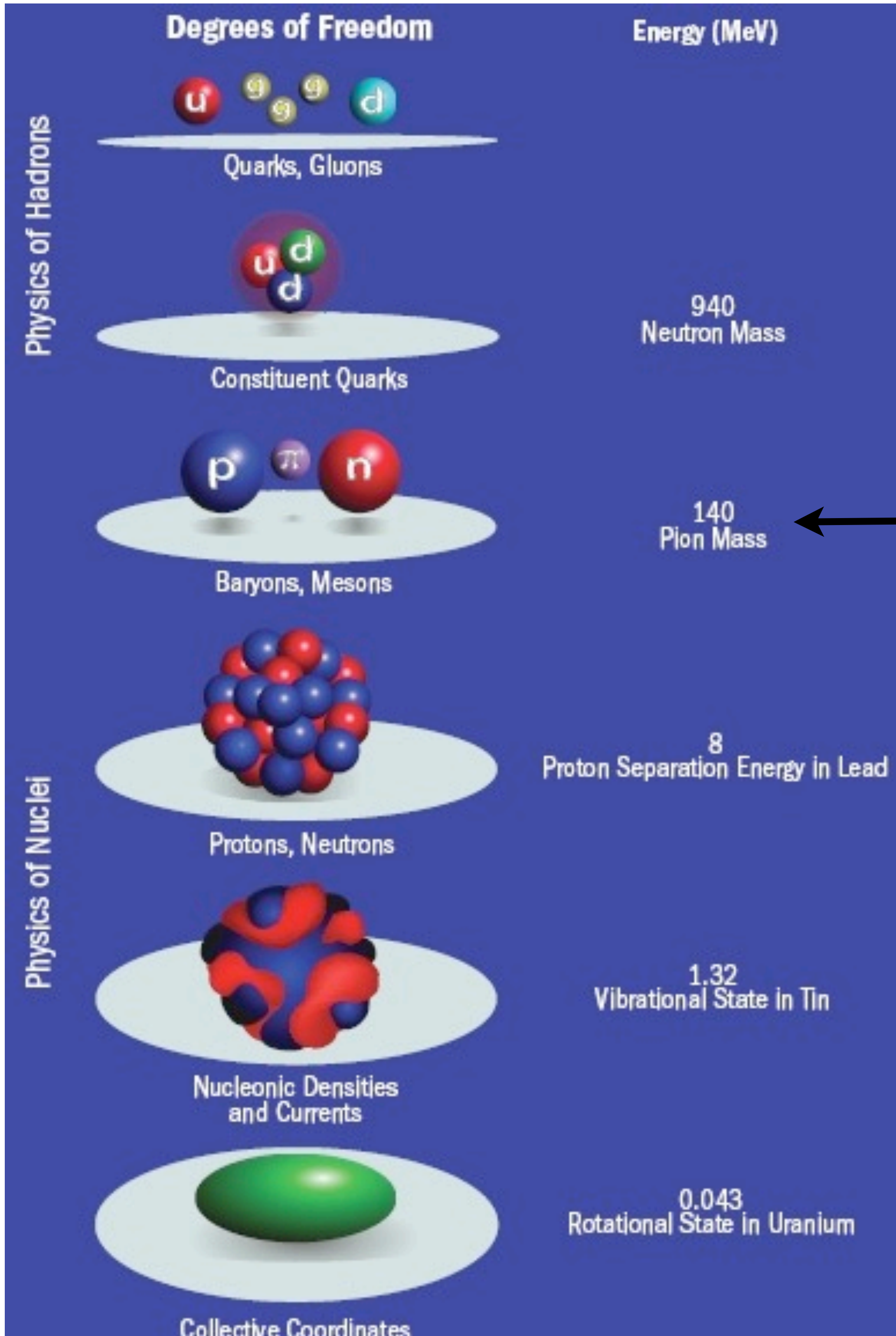
high energy: quarks resolved



<u>probe atomic nucleus at low E</u>

➡ details not resolved

separation of scales



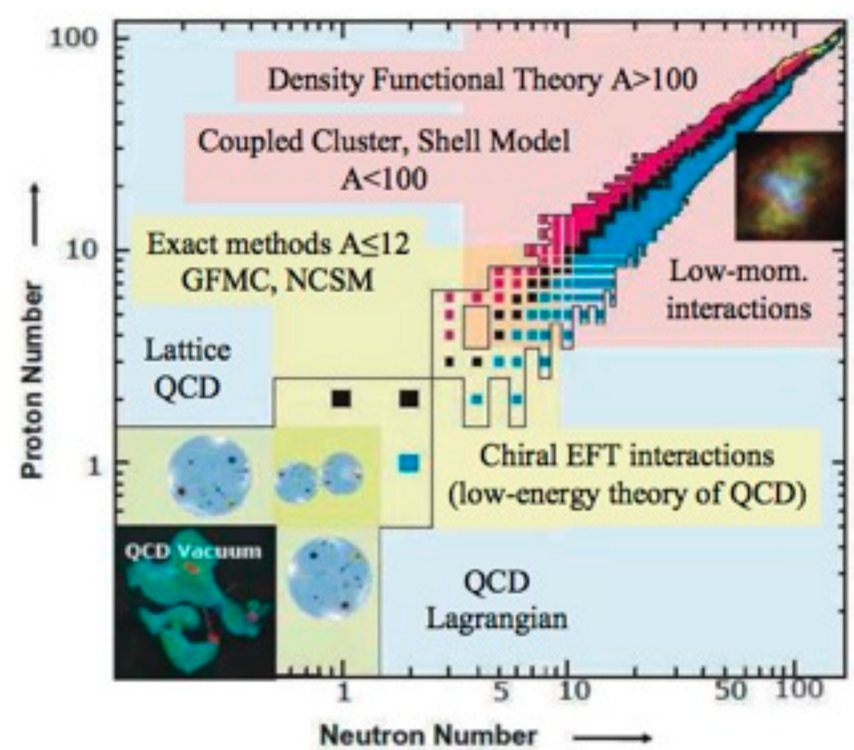
<u>work only with relevant d.o.f:</u>

➡ effective field theory

➡ renormalization group

typical momenta in nuclei ~m_π

bridge QCD to nuclear forces



chiral EFT

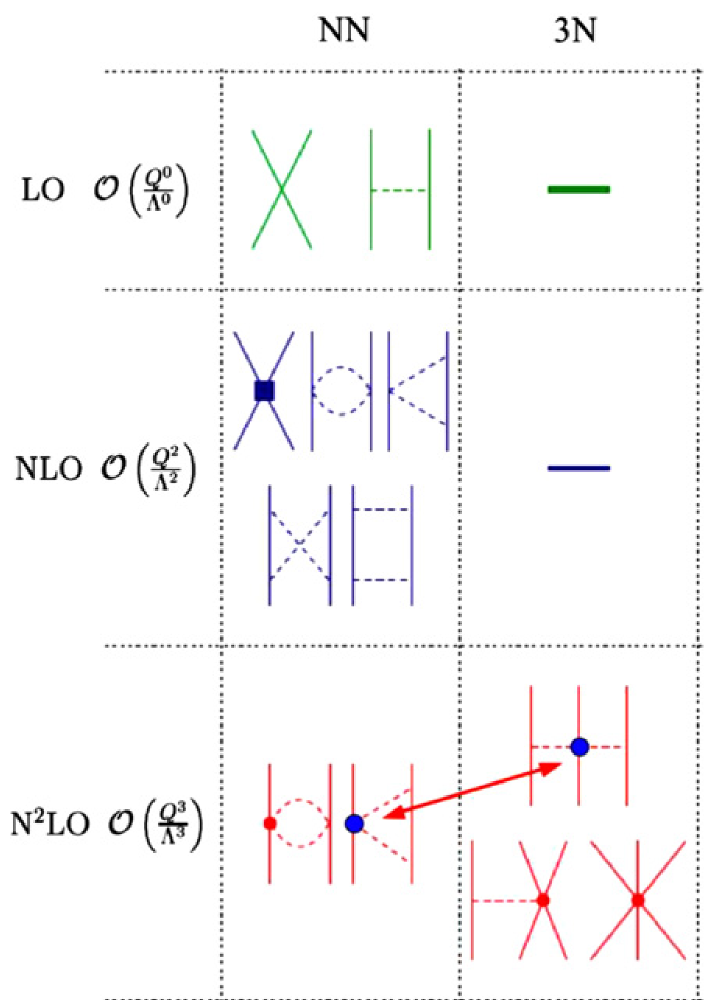
Hamiltonian:

- use p,n, pions
- most general H consistent with QCD

$$H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + V_{4N}(\Lambda) + \ldots$$

resolution scale / cut-off

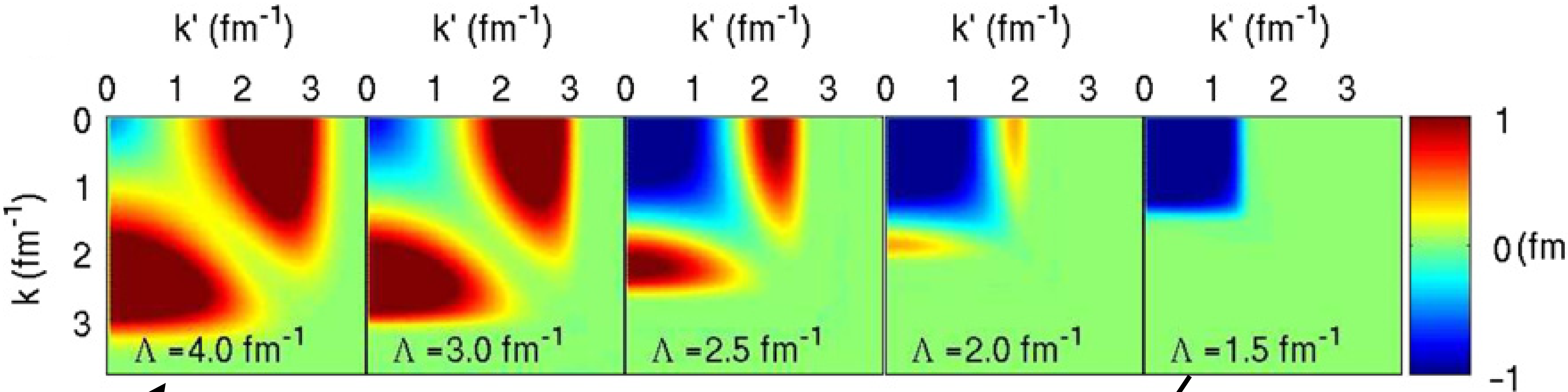
3 body forces!



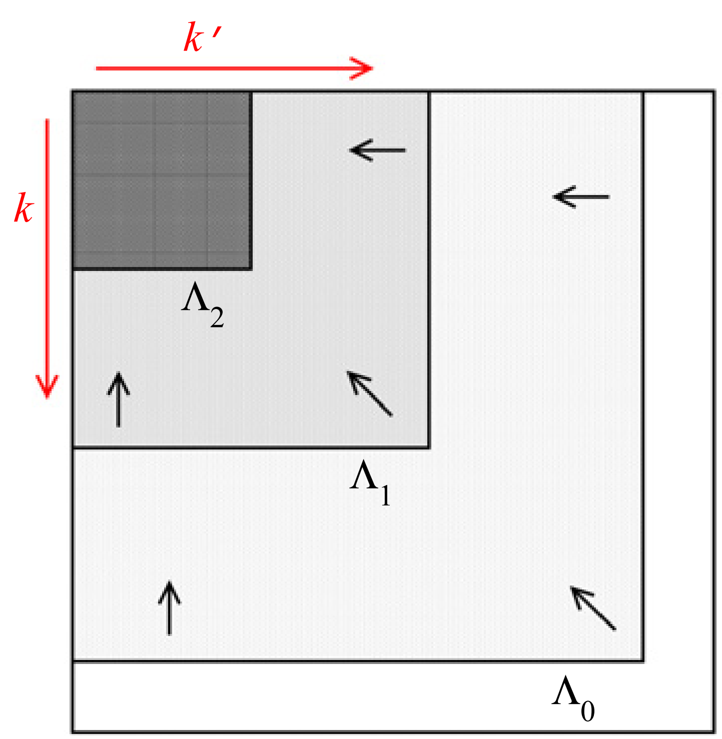
➡ systematic expansion in Q/Λ

E. Epelbaum et al., Rev. Mod. Phys., 81, 1773 (2009)
S.K. Bogner et al., Prog. Par. Nuc. Phys., 65,94, (2010)

example for renormalization: $V_{low,k}$



NN from N³LO



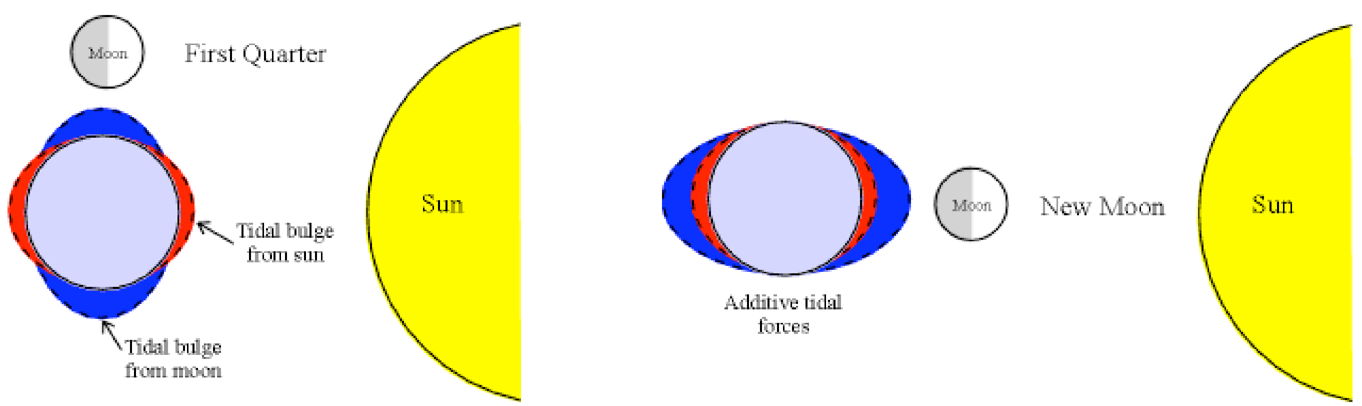
- ➡ decouples high and low momentum modes
- ➡ only low momentum
- ➡ <u>note:</u> potential is NOT an observable!

S.K. Bogner et al, Prog. Par. Nuc. Phys., 65,94, (2010)

origin of 3-body forces

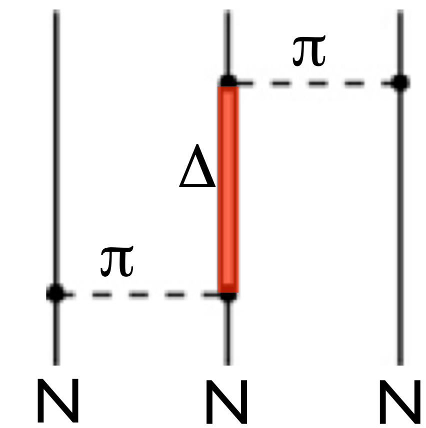
- <u>nucleons: composite particles</u>

<u>example:</u> tidal effects when using moon, earth, and sun as effective d.o.f.



<u>nuclear forces:</u> excitation to Δ

(also u&d-quarks, but I=J=3/2)



m_p= 938 MeV

m_n= 940 MeV

m_Δ=1232 MeV

- <u>induced 3N forces</u>

χEFT non-renormalizable

➡ at each order: counter terms + **<u>new interaction terms</u>** in Lagrangian

➡ new, free coupling constants

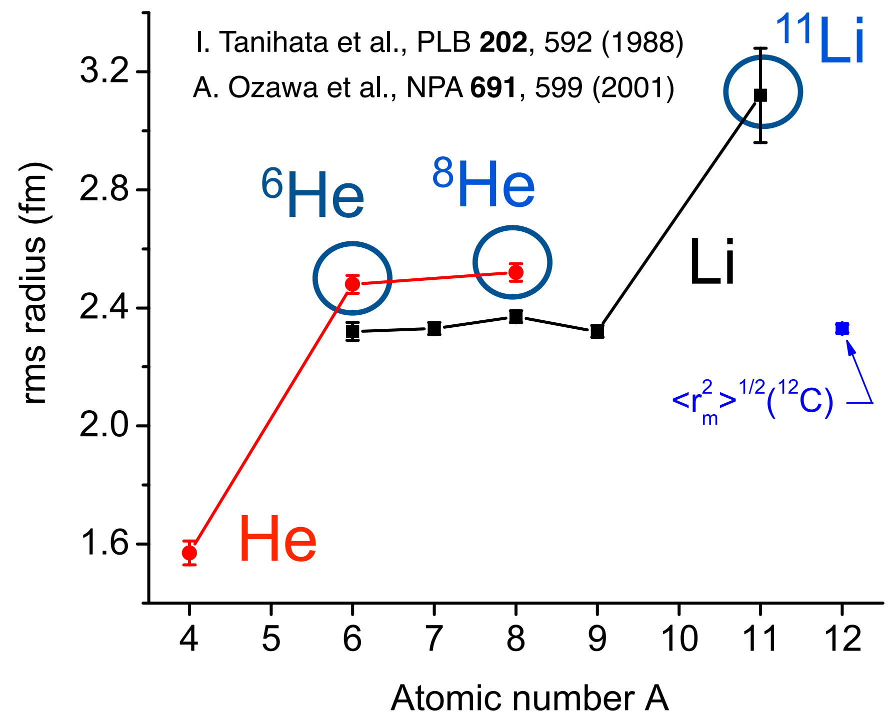
➡ but as cut-off is 'physical' (=true separation of scales) suppressed by $(Q/\Lambda)^n$

benchmark for EFTs: halo nuclei

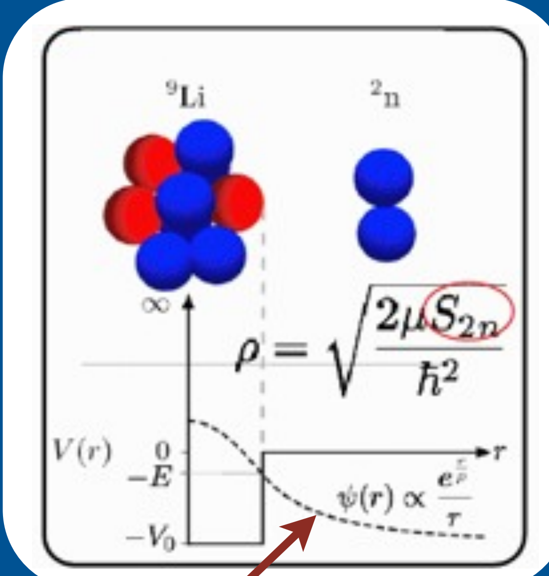
extreme n/p ratios

Halo	n/p
^{6}He	2
^{8}He	3
^{11}Li	2.66
^{14}Be	2.5
^{22}C	2.66
^{12}C	1

large radii

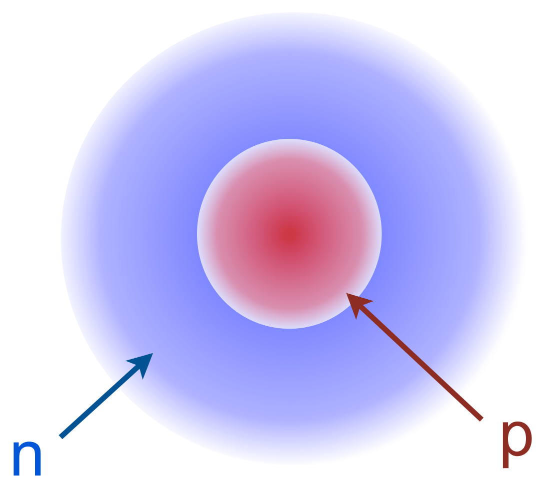


nucleons in classically forbidden region

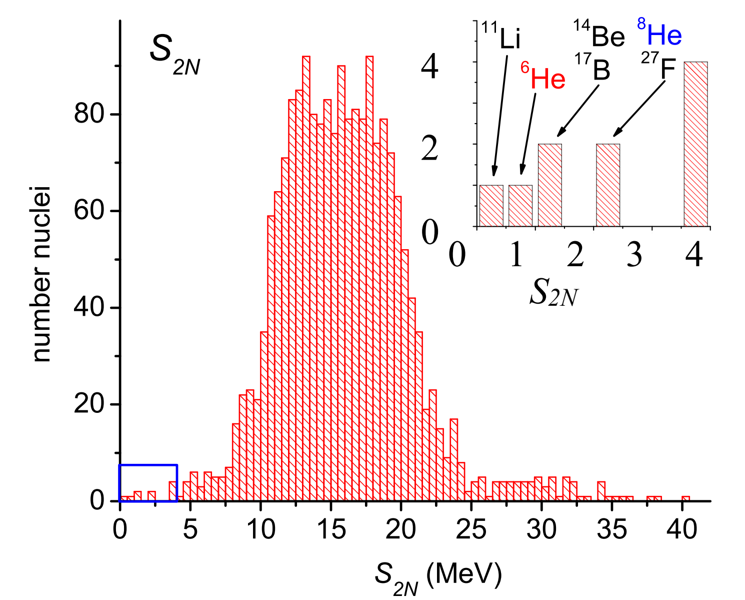


exp. fall off

but R_{matter} ≠ R_{charge}



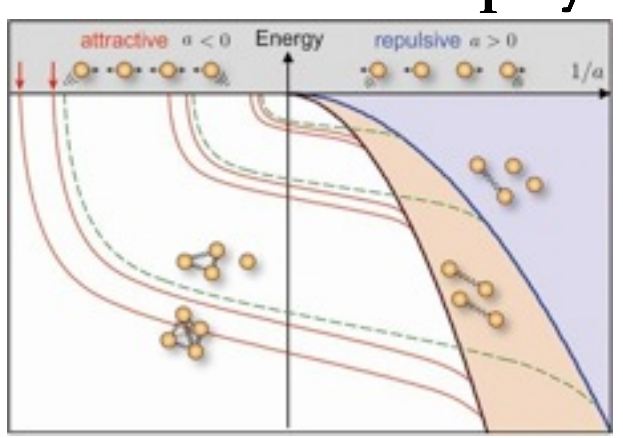
tiny separation energies



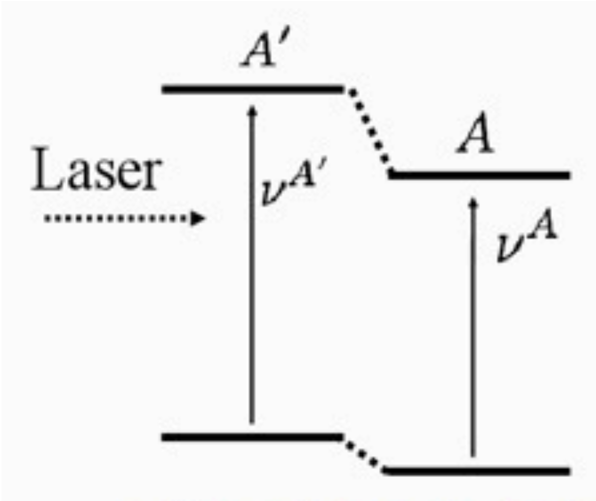
loosely bound

⇒ large scattering length

⇒ link to Effimov physics

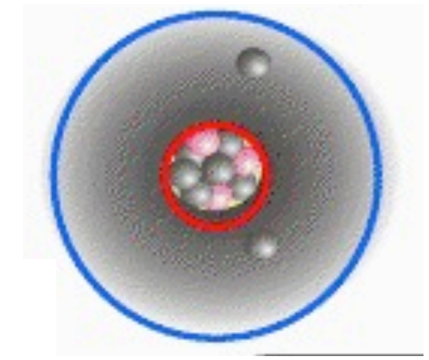


charge radius



Isotope Shift

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



$r_c \neq r_m$

Mass shift — Field Shift / Finite Size Shift

atomic laser spectroscopy

relative measurement

⇒need reference:

electron scattering

(only possible with stables)

Techniques:

- (anti)collinear LS } in-beam
- two photon resonant LS } in-beam
- LS of individual atoms in MOT
- LS of trapped ions

high precision atomic physics calculation

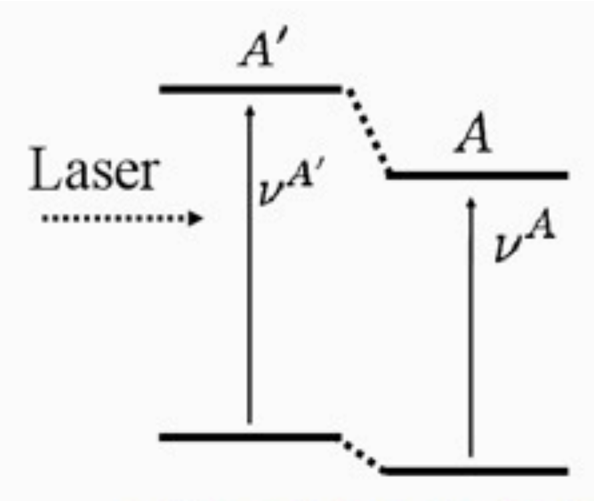
Z.-C. Yan et al., PRL 100, 243002 (2008)

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

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

for He, Li, Be: MS ~10 GHz ⇔ FS ~1 MHz

charge radius



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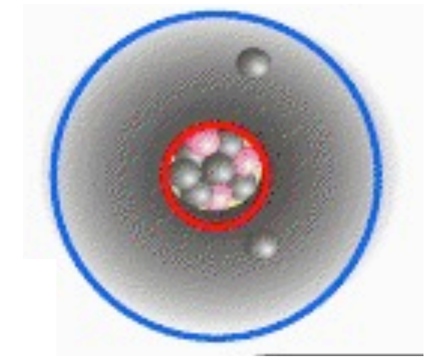

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$$\text{with } \lambda = \frac{\mu}{M} = \frac{m_e}{m_e + M}$$

nuclear mass:

- need δm < 1keV
- short lived (<10 ms)

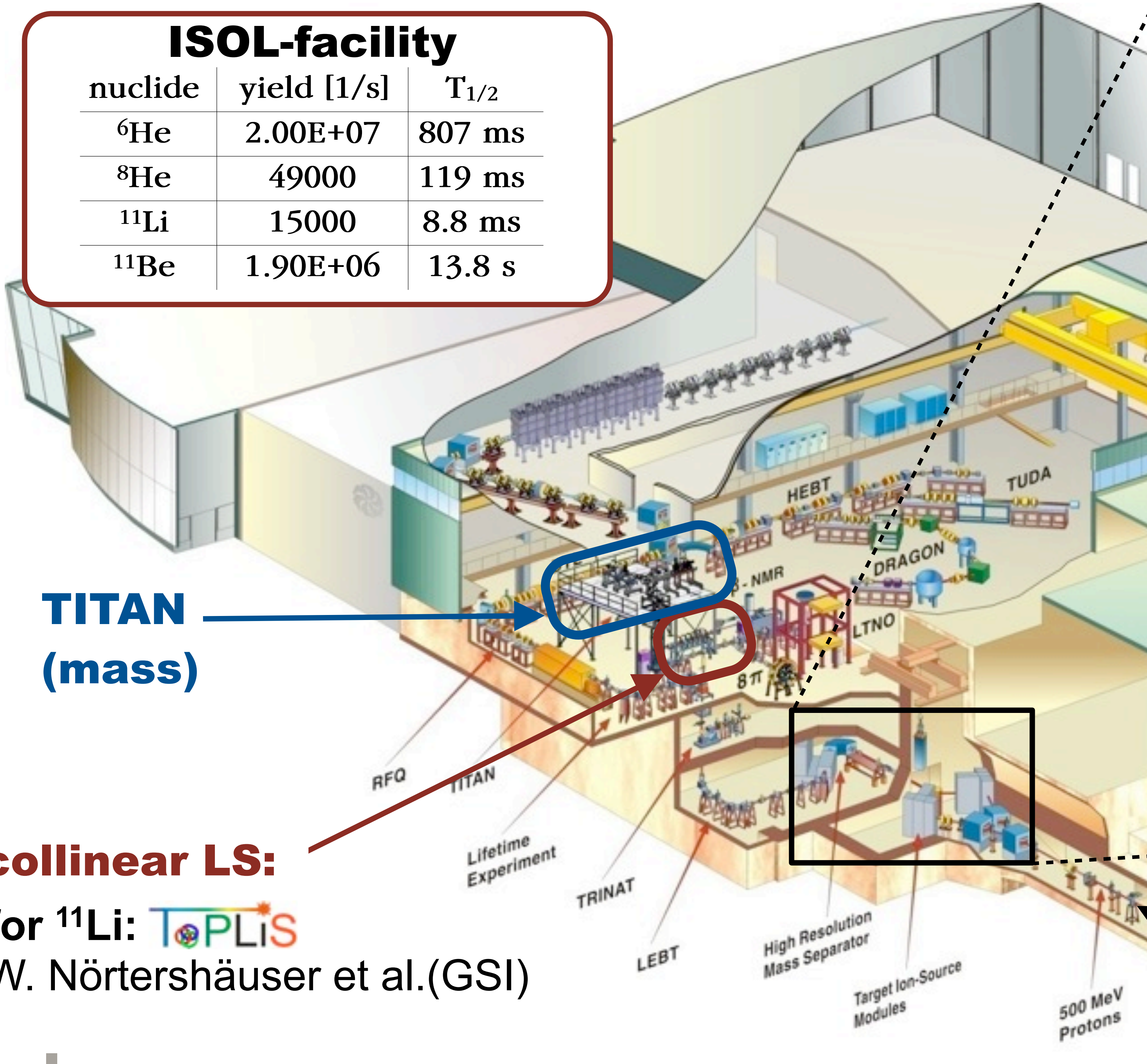
⇒ Penning Traps

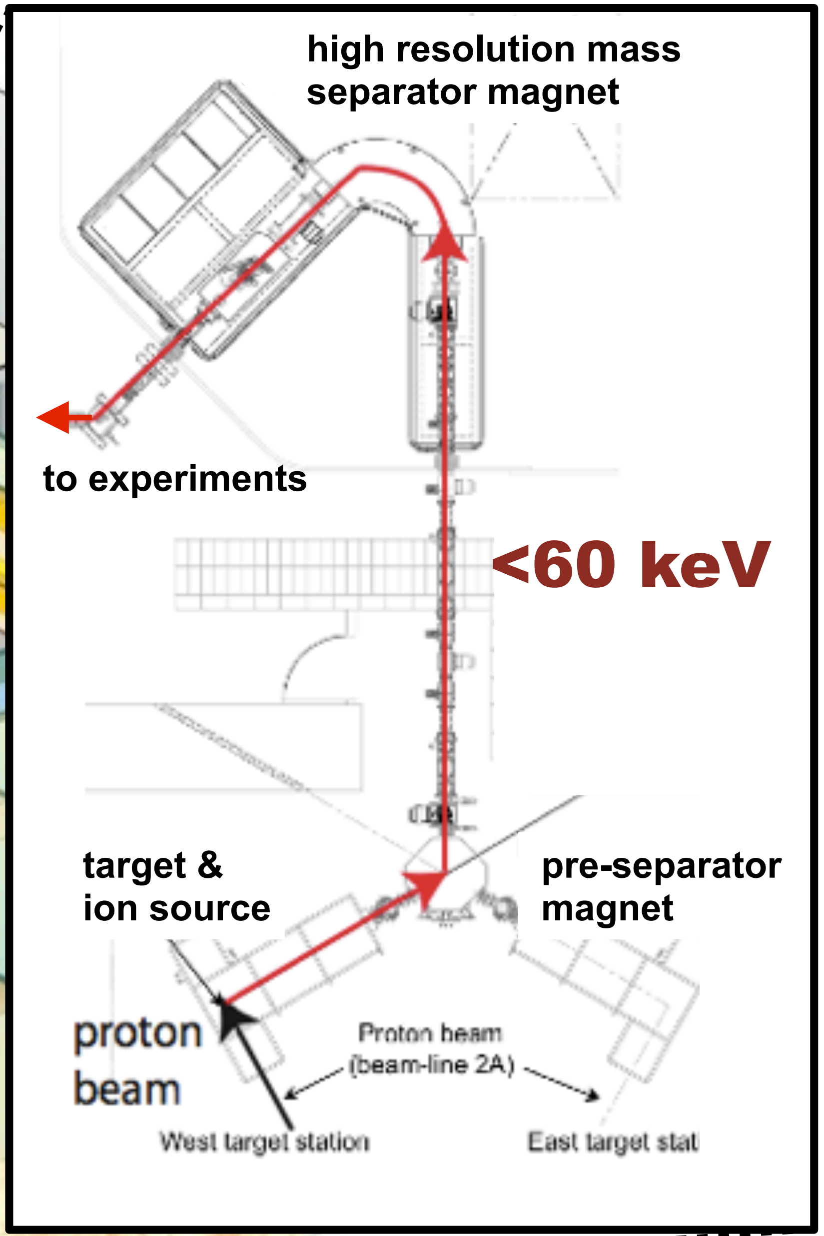
for He, Li, Be: MS ~10 GHz ⇔ FS ~1 MHz

ISAC@ TRIUMF

ISOL-facility

nuclide	yield [1/s]	$T_{1/2}$
^{6}He	2.00E+07	807 ms
^{8}He	49000	119 ms
^{11}Li	15000	8.8 ms
^{11}Be	1.90E+06	13.8 s





for ^{11}Li: ToPLiS
W. Nörtershäuser et al.(GSI)

^{11}Li: charge radius

TOPLiS

isotope shifts ^{7}Li-^{A}Li:

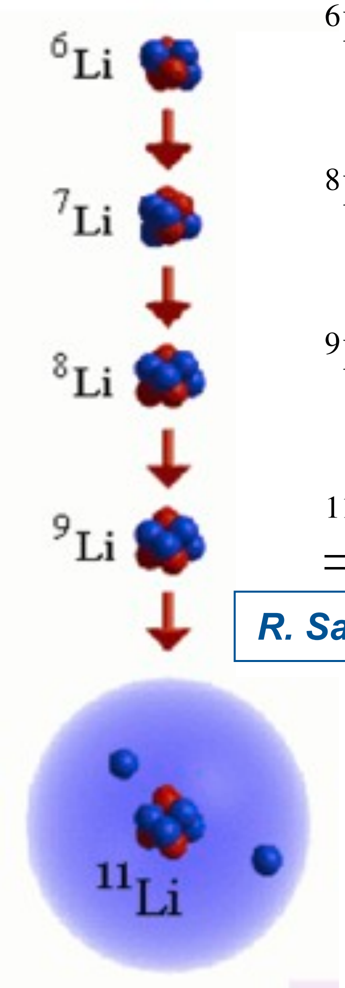
- 2s→3s
- reference $r_c(^7Li)$ = 2.39(3) fm

At. Data Nucl. Data Tables 14, 479 (1974)

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

Isotope		Isotope Shift, kHz
^{6}Li	TRIUMF	−11 453 984(20)
	GSI	−11 453 950(130)
	avg	−11 453 983(20)
^{8}Li	TRIUMF	8 635 781(46)
	GSI	8 635 790(150)
	avg	8 635 782(44)
^{9}Li	TRIUMF	15 333 279(40)
	GSI	15 333 140(180)
	avg	15 333 272(39)
^{11}Li	TRIUMF	25 101 226(125)[a]

R. Sanchez et al., PRL 96, 033002 (2006)



mass shifts

Isotopes	$2\,^2P_{1/2} - 2\,^2S$	$2\,^2P_{3/2} - 2\,^2S$	$3\,^2S - 2\,^2S$
^{7}Li − ^{6}Li	−10 532.111(6)	−10 532.506(6)	−11 452.821(2)
^{7}Li − ^{8}Li	7940.627(5)	7940.925(5)	8634.989(2)
^{7}Li − ^{9}Li	14 098.840(14)	14 099.369(14)	15 331.799(13)
^{7}Li − ^{11}Li[a]	23 082.642(24)	23 083.493(24)	25 101.470(22)
^{9}Be − ^{7}Be	−49 225.765(19)	−49 231.814(19)	−48 514.03(2)
^{9}Be − ^{10}Be	17 310.44(6)	17 312.57(6)	17 060.56(6)
^{9}Be − ^{11}Be	31 560.01(6)	31 563.89(6)	31 104.60(6)

Z.-C. Yan et al., PRL 100, 243002 (2008)

M. Puchalski et al., PRL 97,133001 (2006)

$r_c(^{11}Li)$ = 2.423(17)(30) fm

reference r_c

^{11}Li: charge radius

TOPLiS

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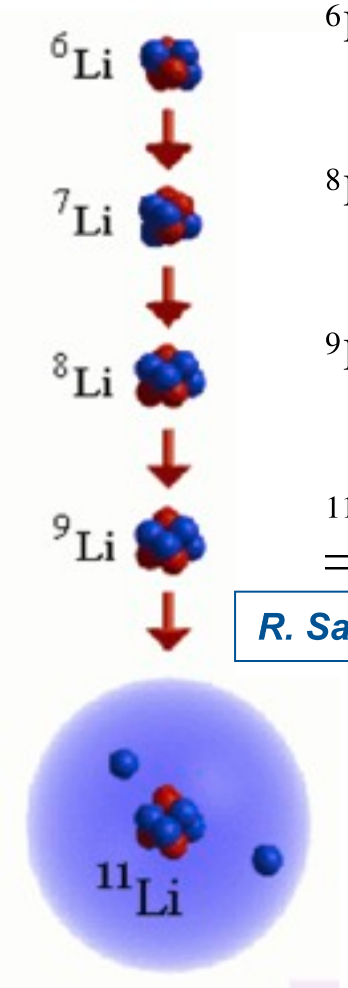

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	GSI	8 635 790(150)
	avg	8 635 782(44)
^{9}Li	TRIUMF	15 333 279(40)
	GSI	15 333 140(180)
	avg	15 333 272(39)
^{11}Li	TRIUMF	25 101 226(125)[a]

R. Sanchez et al., PRL 96, 033002 (2006)

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^{9}Be − ^{7}Be	[illegible]	[illegible]	−48 514.03(2)
^{9}Be − ^{10}Be	[illegible]	[illegible]	17 060.56(6)
^{9}Be − ^{11}Be	31 560.01(6)	31 563.89(6)	31 104.60(6)

mass: MISTRAL (2005)

! need mass !

243002 (2008)

M. Pucha[illegible]ki et al., PRL 97,133001 (2006)

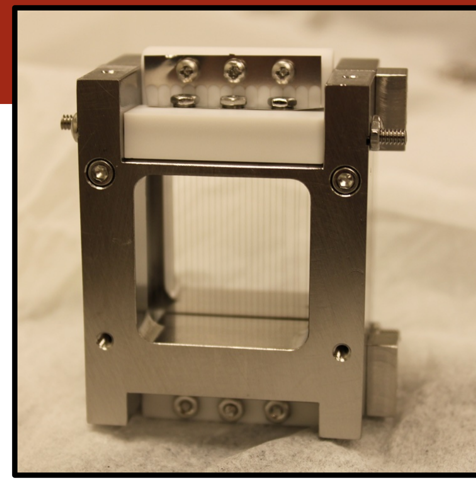
mass: AME'03

$r_c\,(^{11}Li) = 2.423(17)(30)$ fm

reference r_c

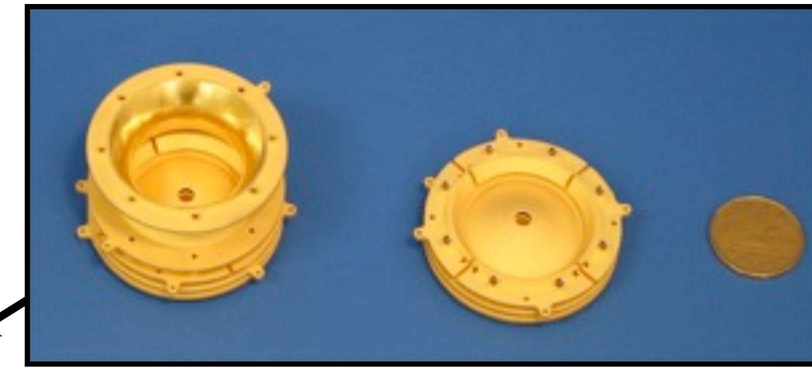
$r_c\,(^{11}Li) = 2.465(19)(30)$ fm

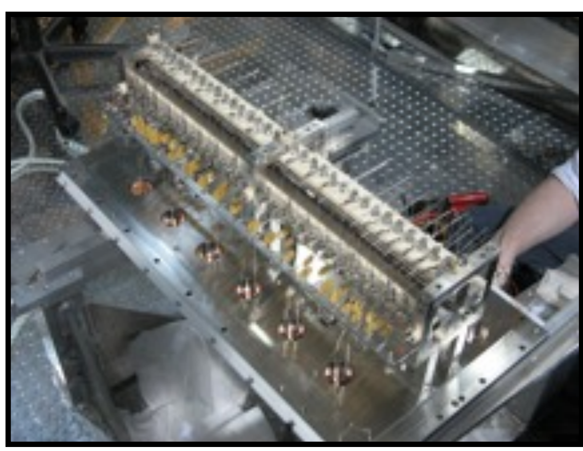
TITAN

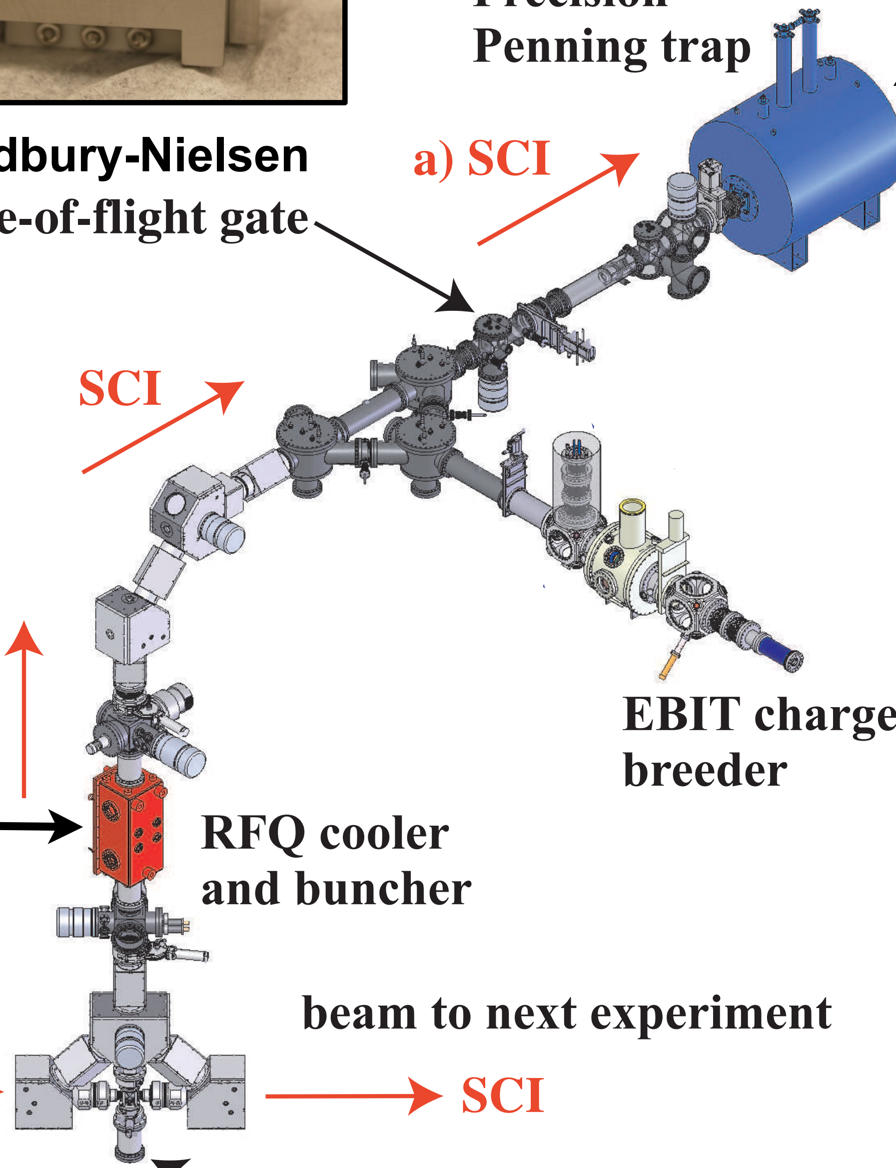


masses of halos:

- reflect binding energy
- separation energy: S_n, S_p
- input to extract physical quantities from exp. (e.g. r_c)







Penning traps:

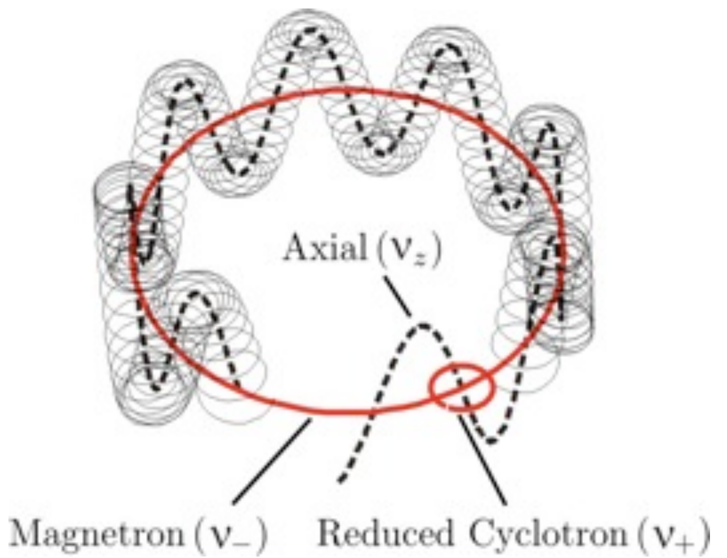
- highest precision
- previously shortest ^{74}Rb with $T_{1/2}$=65 ms ISOLTRAP @ CERN

A. Kellerbauer et al., PRL 93, 072502 (2004)

- but ^{11}Li $T_{1/2}$ = 8.8 ms

measurement principle

3 Eigen motions



L.S. Brown and G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986)
G. Bollen et al., J. Appl. Phys. 88, 4355 (1990)

relevant frequencies

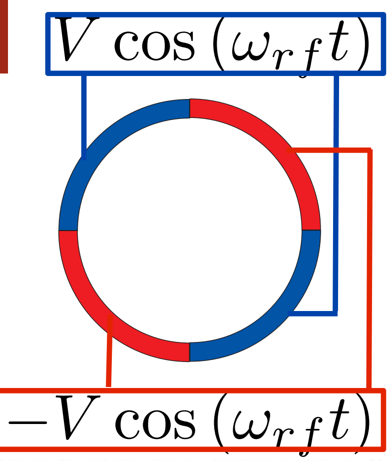
$$\nu_c = \nu_+ + \nu_- = \frac{1}{2\pi}\frac{q}{m}B$$

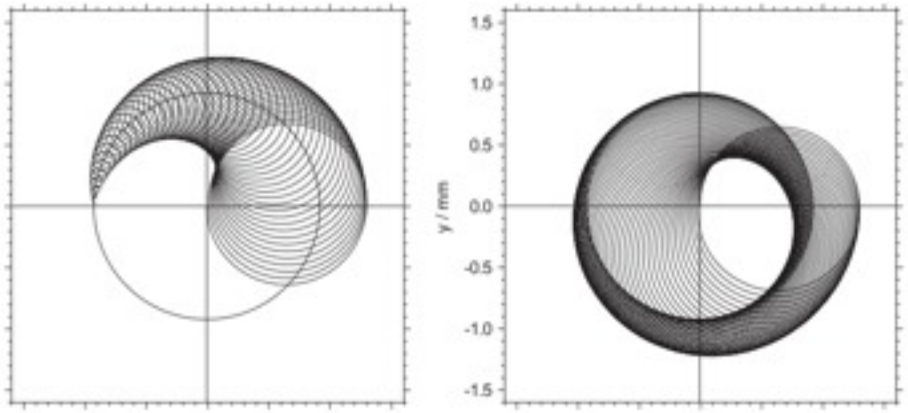
$$\nu_+ \gg \nu_z \gg \nu_-$$

radial energy:

$$E_r \propto \nu_+^2\rho_+^2 + \nu_-^2\rho_-^2 \approx \nu_+^2\rho_+^2$$

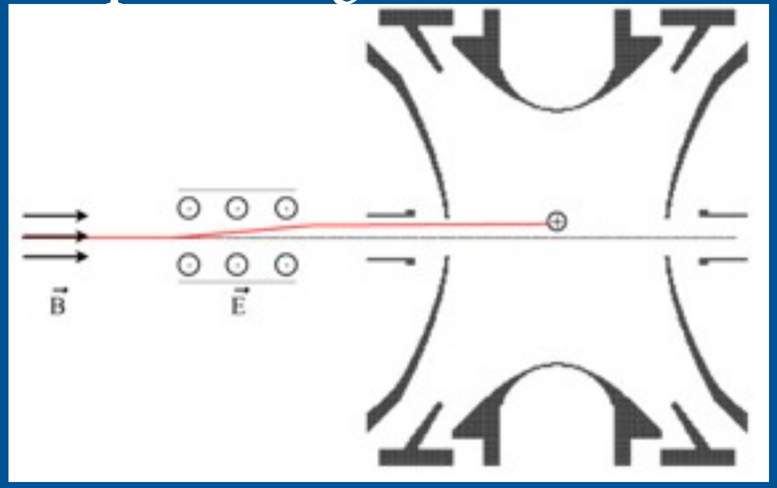
quad. azimuthal RF couples radial motions





Lorentz-steerer

=> pure magnetron motion

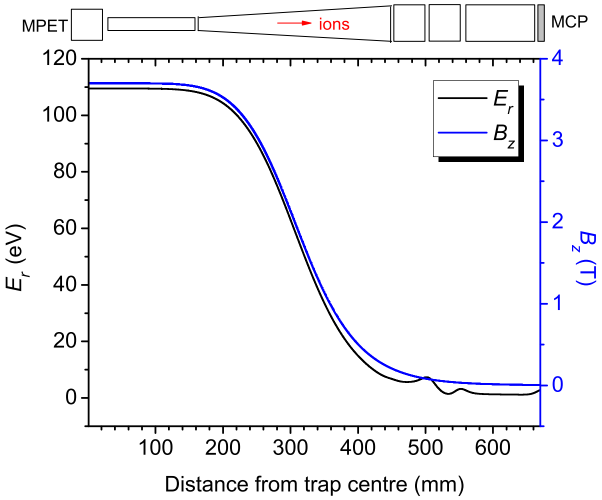


R. Ringle et al., IJMS 263, 38 (2007)

full conversion for

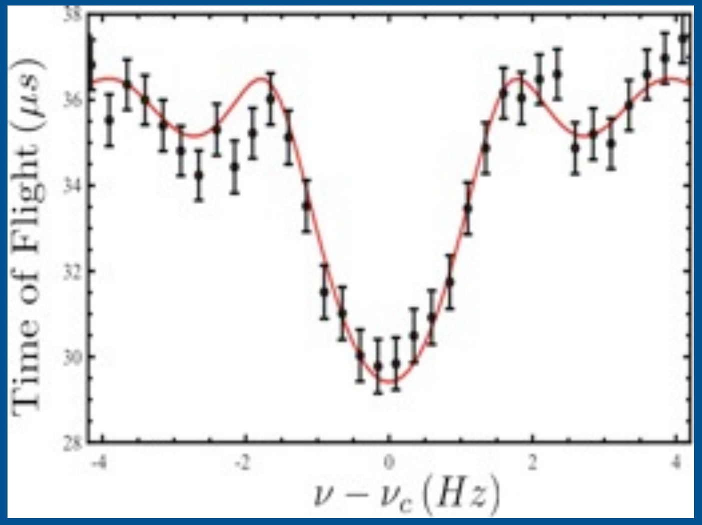
$$\nu_{rf} = \nu_c$$

=> max. energy gain



scan ν_{rf}

one ν_{rf} per ion shot



Precise & Accurate

line width (FWHM):

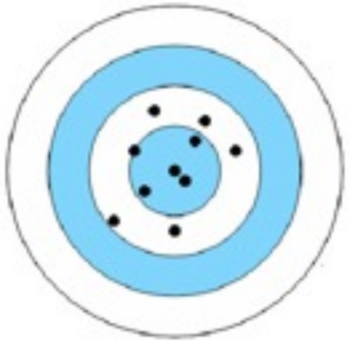
$$\Delta\nu \approx 1/T_{rf}$$

⇒ resolution:

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

⇒ even for T_{rf} ~ 10ms

$$(\delta m/m)_{\mathtt{stat}} < 10^{-7}$$



accurate,
but not precise

precise,
but not accurate

- 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)

'protected' by invariance theorem

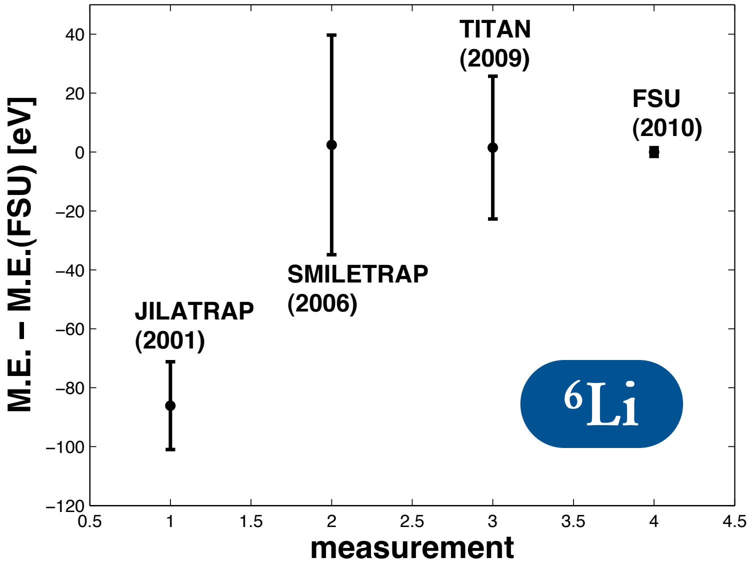
$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

G. Gabrielse, PRL 102, 172501 (2009)

- off-line tests with stables

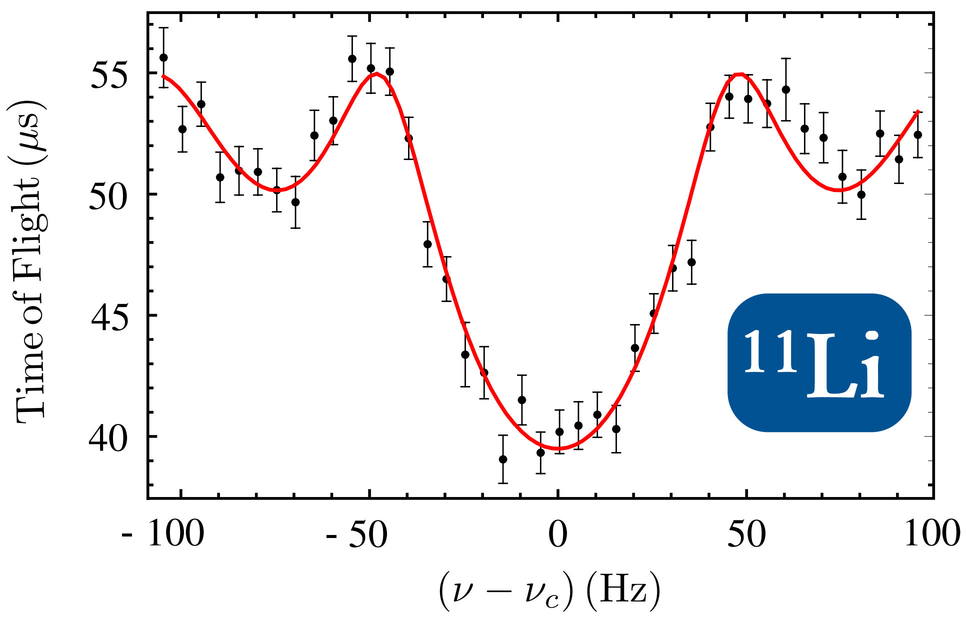
⇒ control over systematics

<u>for TITAN:</u> < 5 ppb possible



M. Brodeur et al, PRC 80, 044318 (2009)

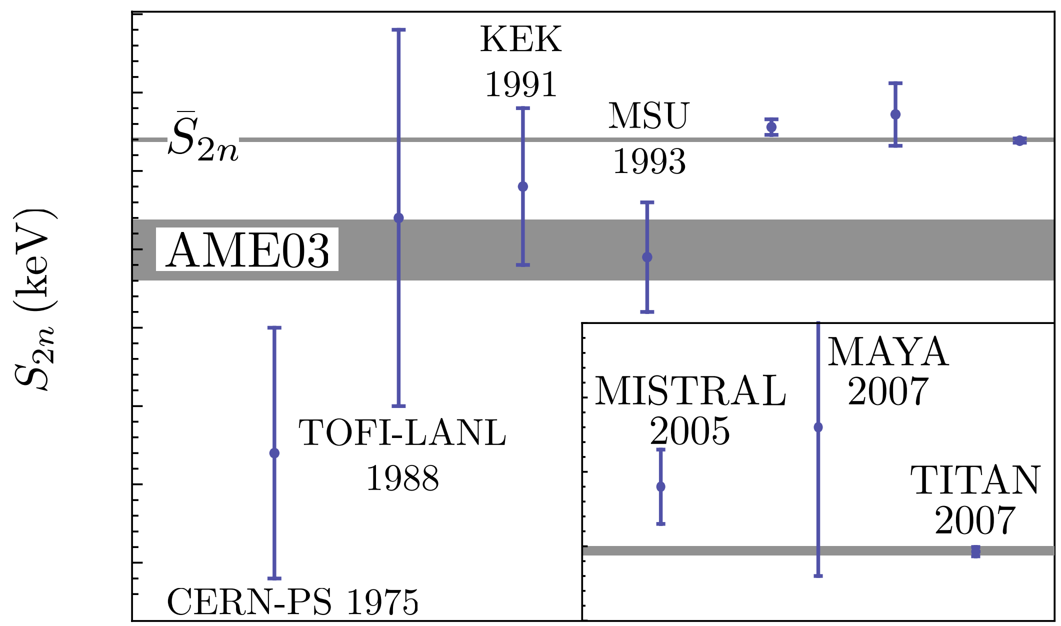
mass of ^{11}Li

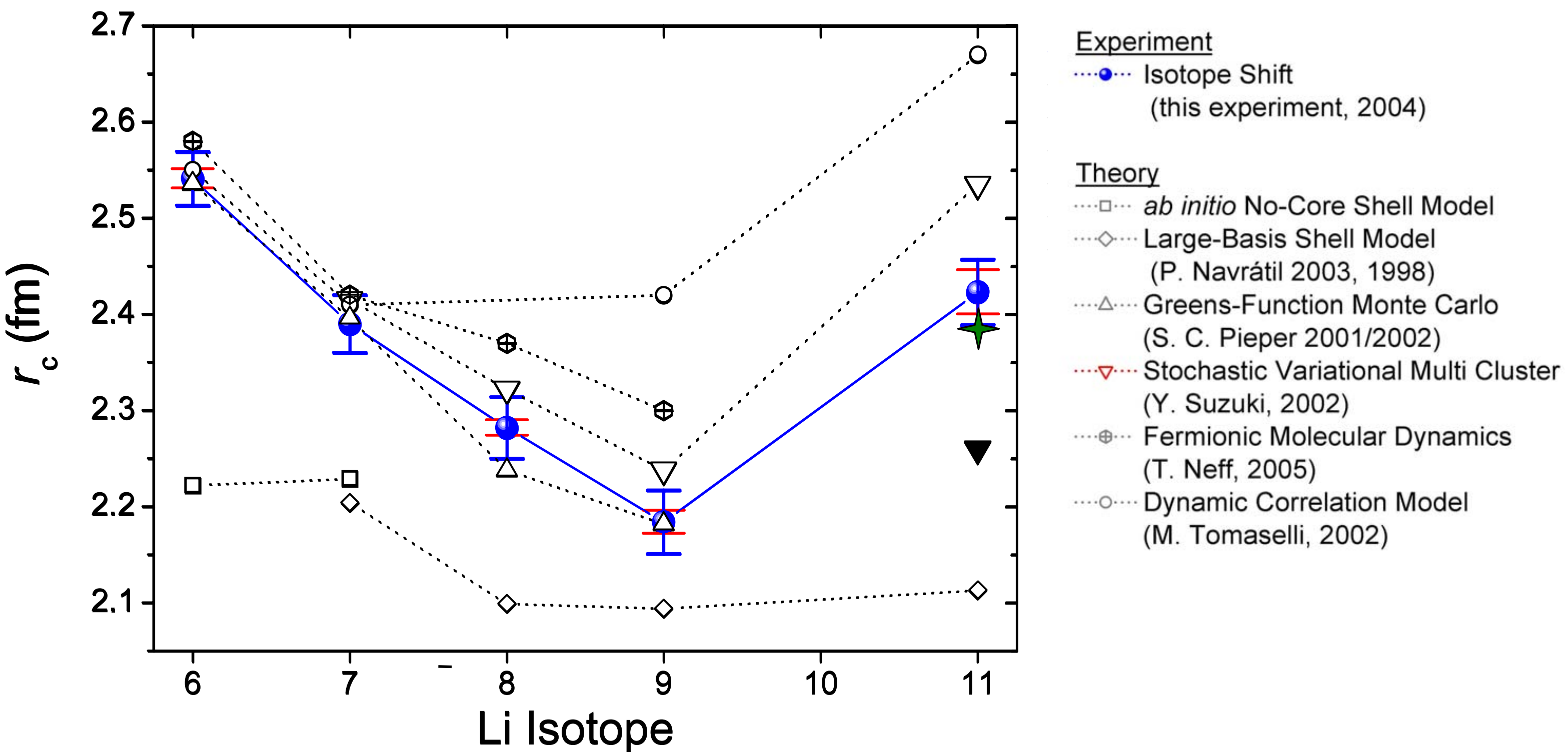


Reference	Mass [u]
AME'03	11.043 798(21)
MISTRAL 2005	11.043 715 7(54)
TITAN 2007	11.043 723 61 (69)

$r_c\ (^{11}Li) = 2.427(16)(30)$ fm

eliminates mass as source of uncertainty!





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

other halos: ^{6}He and ^{8}He

Laser spectroscopy

- Argonne Lab / GANIL
- LS in MOT

all in MHz

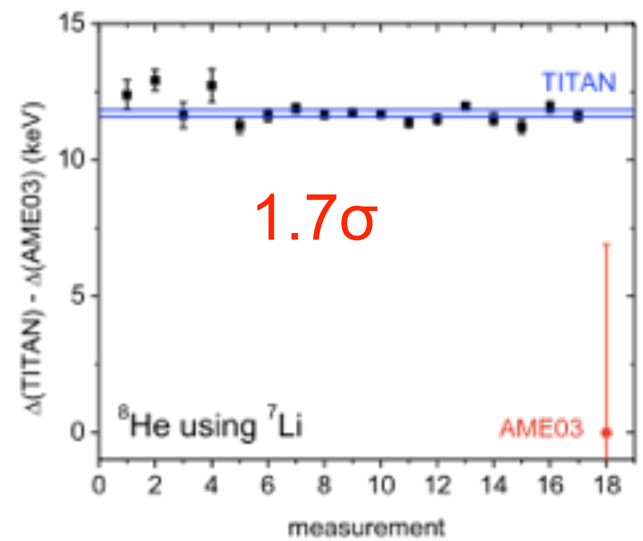
	^{6}He Value	^{6}He Error	^{8}He Value	^{8}He Error
Statistical				
Photon counting		0.008		0.032
Probing laser alignment		0.002		0.012
Reference laser drift		0.002		0.024
Systematic				
Probing power shift				0.015
Zeeman shift		0.030		0.045
Nuclear mass		0.015		0.074
Corrections				
Recoil effect	0.110	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

mass: dominating uncertainty

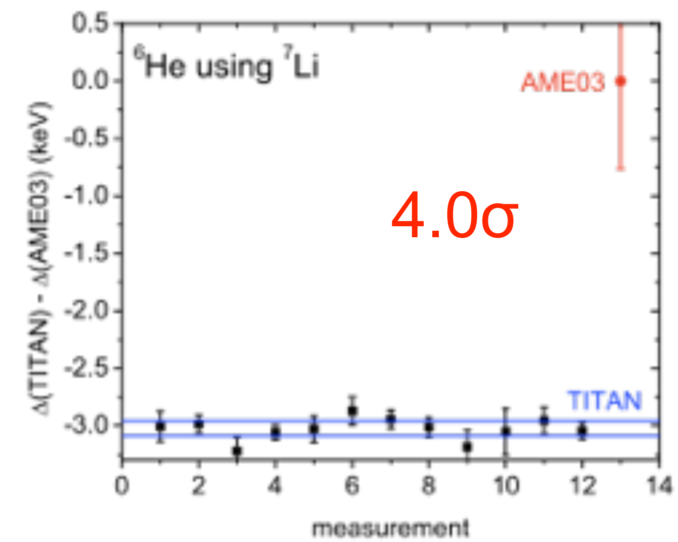
P. Mueller et al., PRL 99, 252501 (2007)

Mass measurement @ TITAN

2nd ^{8}He mass meas.



^{6}He mass meas.

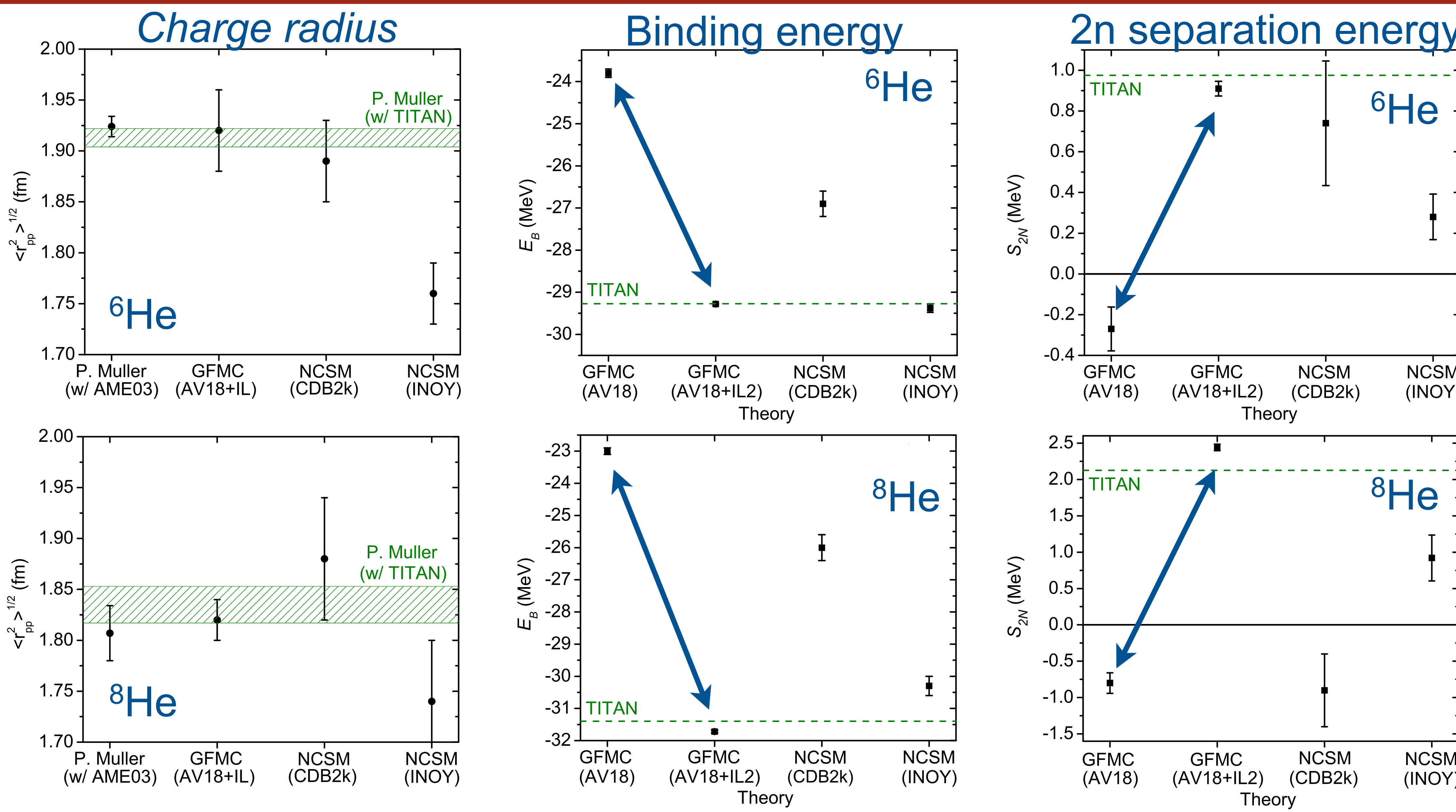


Isotope	mass ($\times 10^6$ u)	M.E. (keV)
^{6}He	6 018 885.883(70)	17 592.087(65)
^{8}He (1^{st})	8.033 935 669(722)	31 610.872(673)
^{8}He (2^{nd})	8.033 934 410(128)	31 609.700(120)
^{8}He (average)	8.033 934 449(126)	31 609.736(118)

V. L. Ryjkov et al., PRL 101, 012501 (2008)

M. Brodeur et al., PRL in prep.

^{6}He and ^{8}He: comparison to theory



➡ **GFMC:** 3N -forces essential *S.C. Pieper, Nucl. Phys. A 751,516 (2005)*

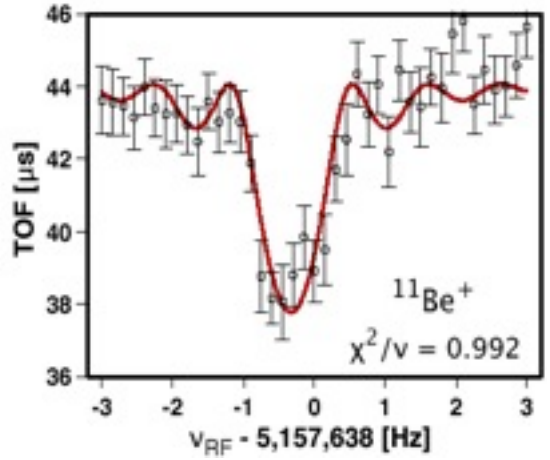
➡ **NCSM (CDB2k):** ^{8}He is unbound: lack of 3N ? Gaussian fall-off in wave-fn?

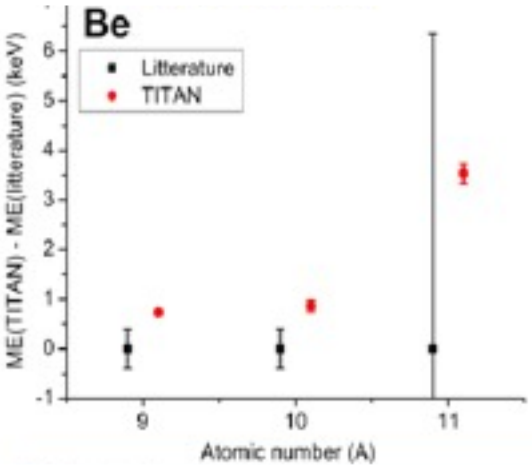
E. Caurier et al, PRC 73, 021302(R), (2006); P. Navrátil et al., J. Phys. G: Nucl. Part. Phys. 36, 083101 (2009)

^{11}Be

Laser spectroscopy: *W. Nörtershäuseret al., PRL 102, 062503 (2009)*

Mass:



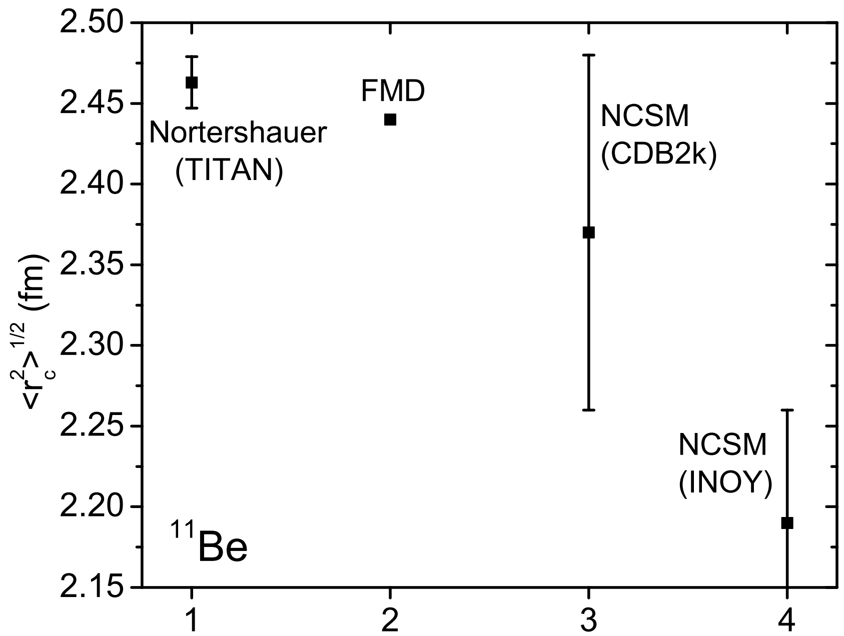


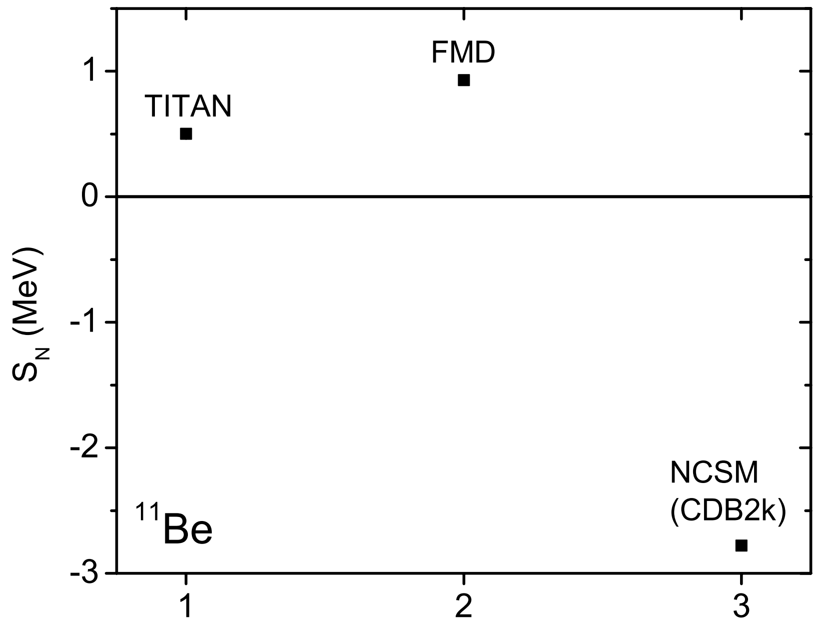
⇒confirms AME & improves precision

⇒uncertainty of mass negligible for r_c

R. Ringle et al., Phys. Lett. B 675, 170 (2009)

Theory:



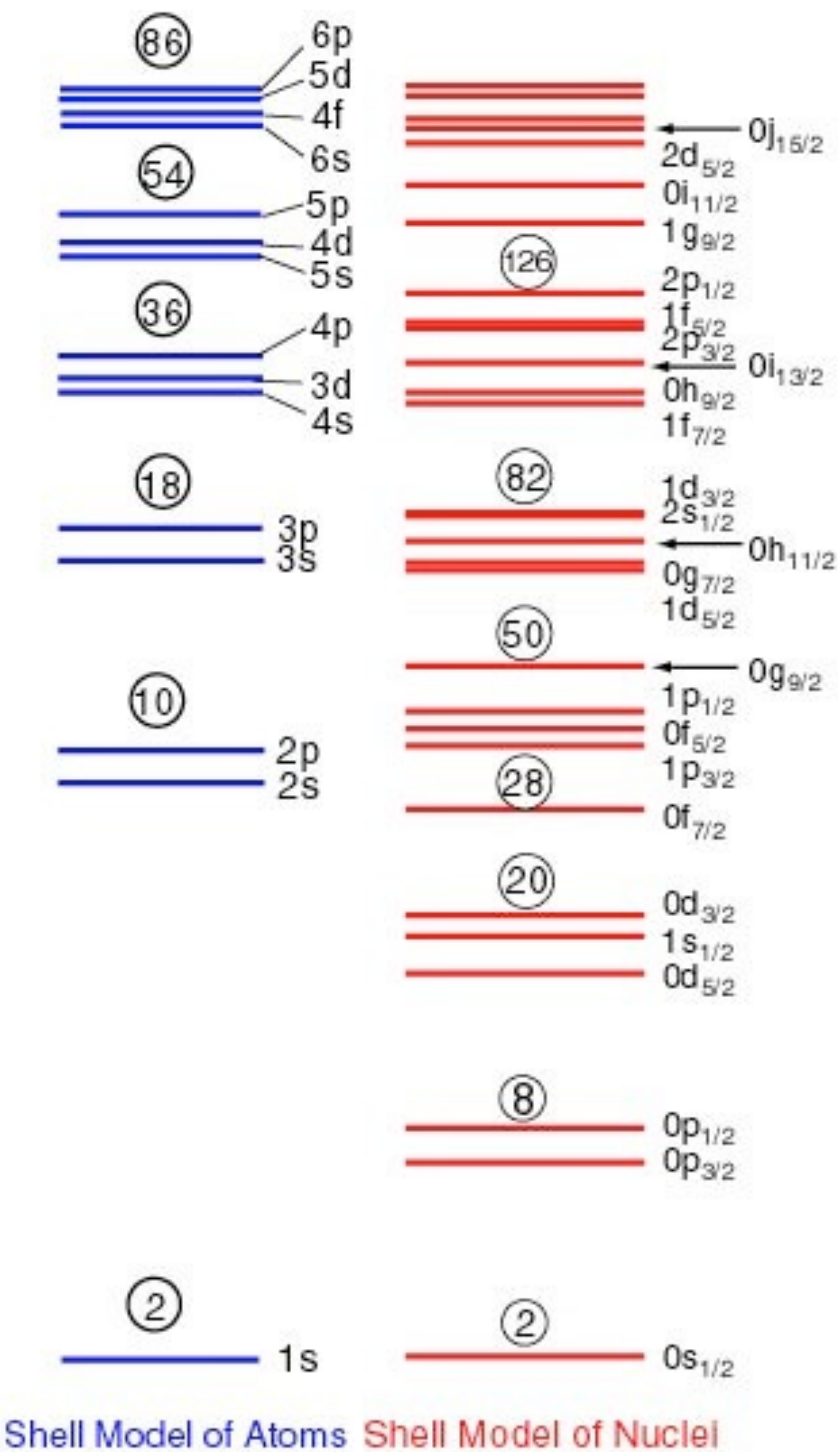


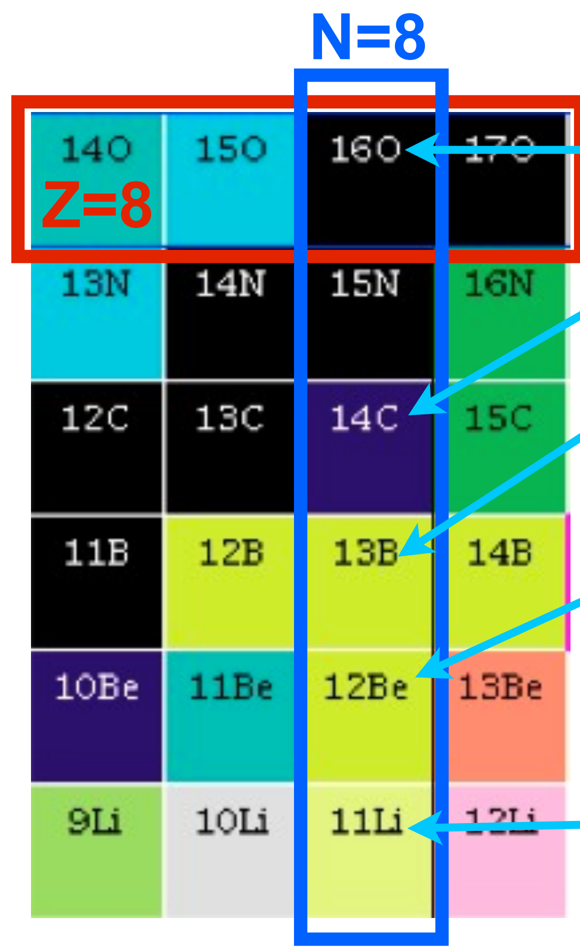
➡ **NCSM:** ^{11}Be is unbound — *Forssén et al., PRC 79,021303(R) (2009) ; Quaglioni et al., PRL 101, 092501 (2008)*

➡ **FMD:** good agreement for both

phenomenological potential mimicking 3N forces — *B.R. Torabi, Ph.D. thesis, TU Darmstadt (2010)*

^{12}Be: from halos to shell quenching





doubly magic

semi magic

excited state: intruder

H. Iwasaki et al., PRL 102, 202502 (2009)

$\nu(1s,0d)^2$ intruder dominance in ground state

A. Navin et al., PRL 85, 266 (2000)
S. D. Pain et al., PRL 96, 032502 (2006)

g.s.: strong $\nu(1s)^2$ admixture

H. Simon et al., PRL 83, 496 (1999)

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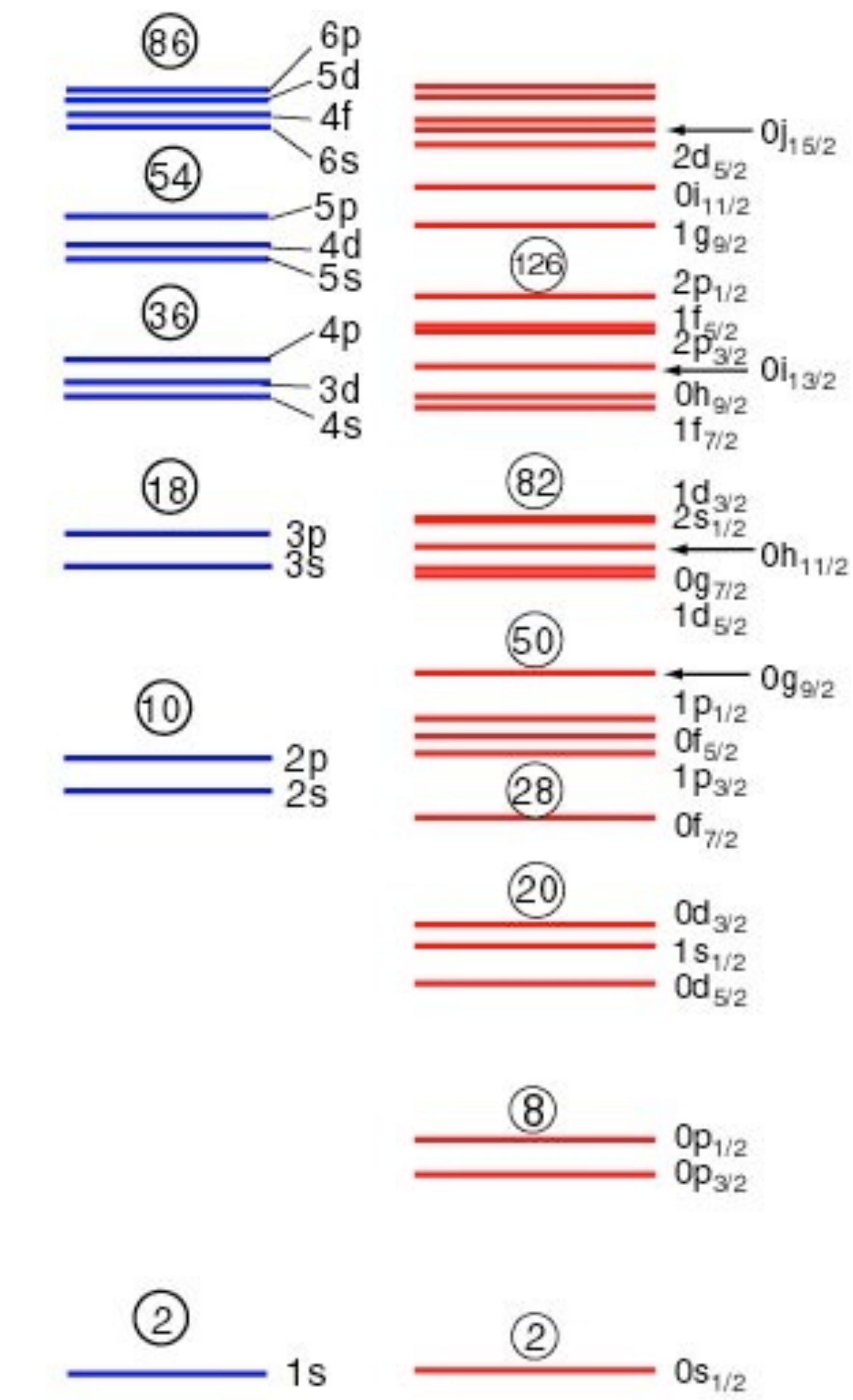
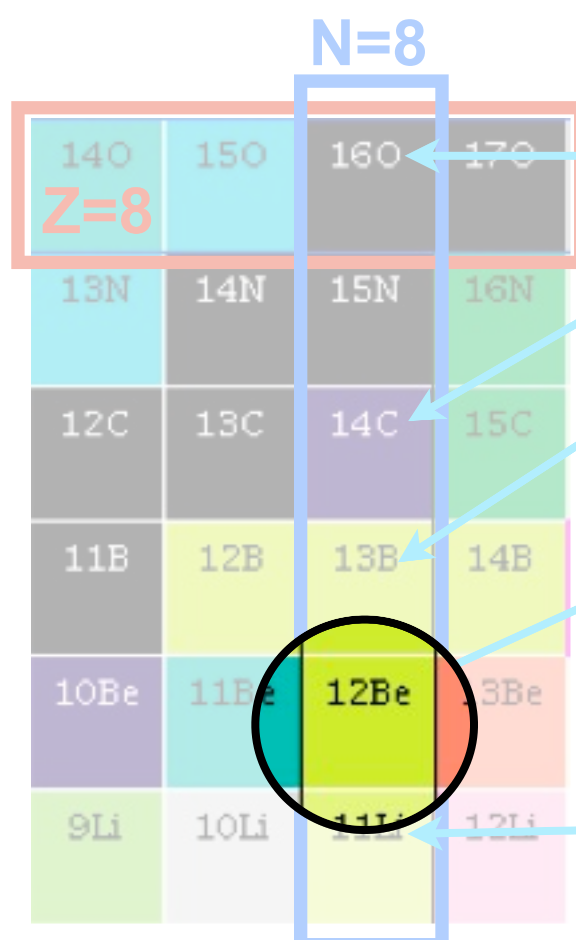


Shell Model of Atoms Shell Model of Nuclei



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g.s.: strong $\nu(1s)^2$ admixture

H. Simon et al., PRL 83, 496 (1999)

R. Kanungo et al., Phys. Lett. B682, 391 (2010)

⇒ neutron halo-like structure ?

$$S_n^{eff} = S_n - E^*$$

g.s. mass

known to 1 keV

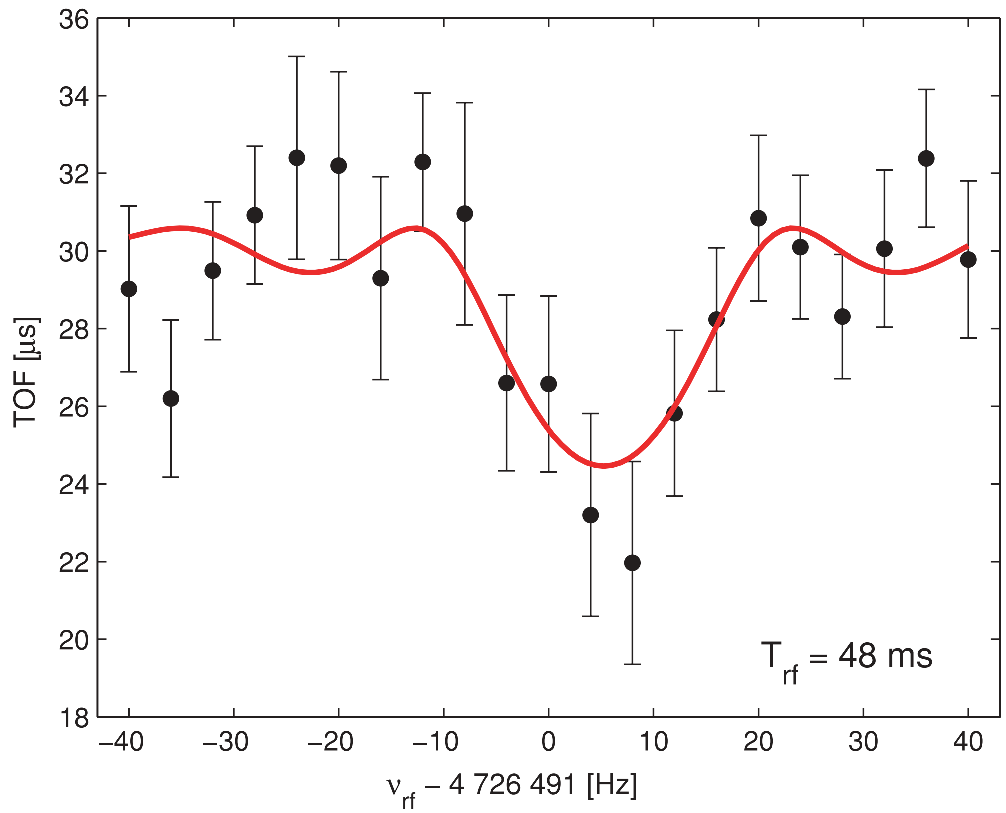
S. Shimoura et al., Phys. Lett. B654, 87 (2007)

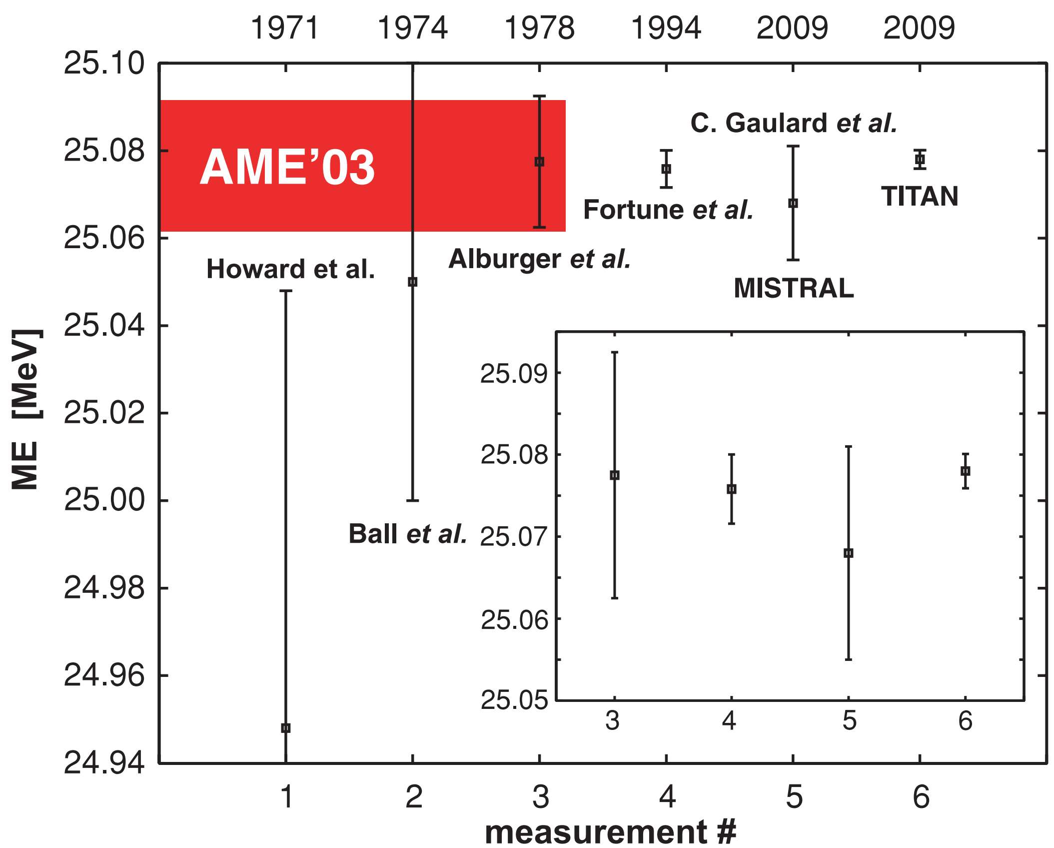
TRIUMF

mass of ^{12}Be

experimental challenges:

- $T_{1/2}$ = 24 ms ⇒ never measured in a Penning trap before
- yield: ~30-300 ions/s





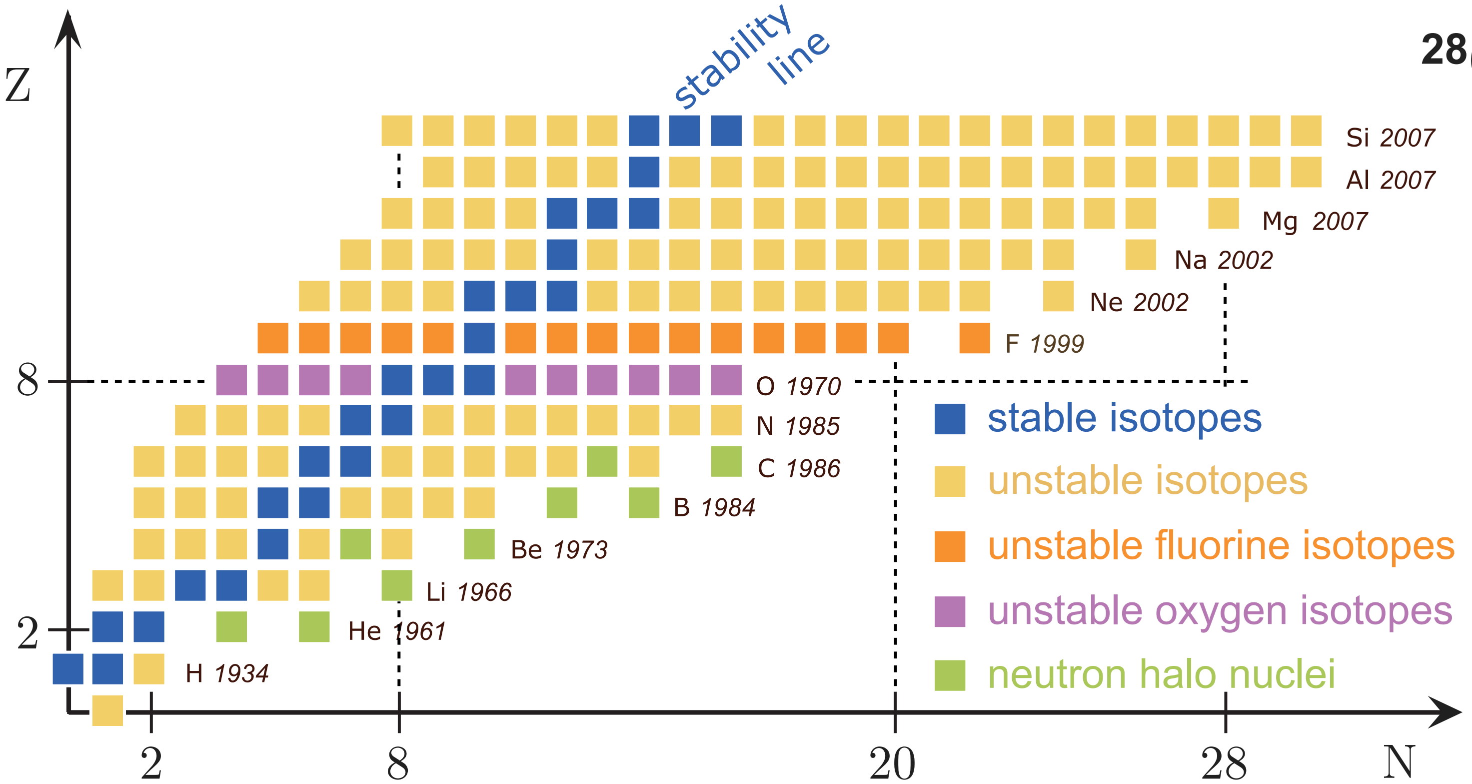
TITAN: m.e.=25 078.0(2.1) keV

➡ halo: confirms low S_n^{eff} ⇒ possibility for halo-like structure

➡ shell quenching: due to near-degeneracy of $\nu(0p)^2$ - $\nu(1s,0d)^2$ conclusion from m($^{9-12}$Be) alone difficult

S. Ettenauer et al., PRC 81, 024314 (2010)

magic numbers & n-drip line



^{28}O: expected to be

- doubly magic
- at drip line

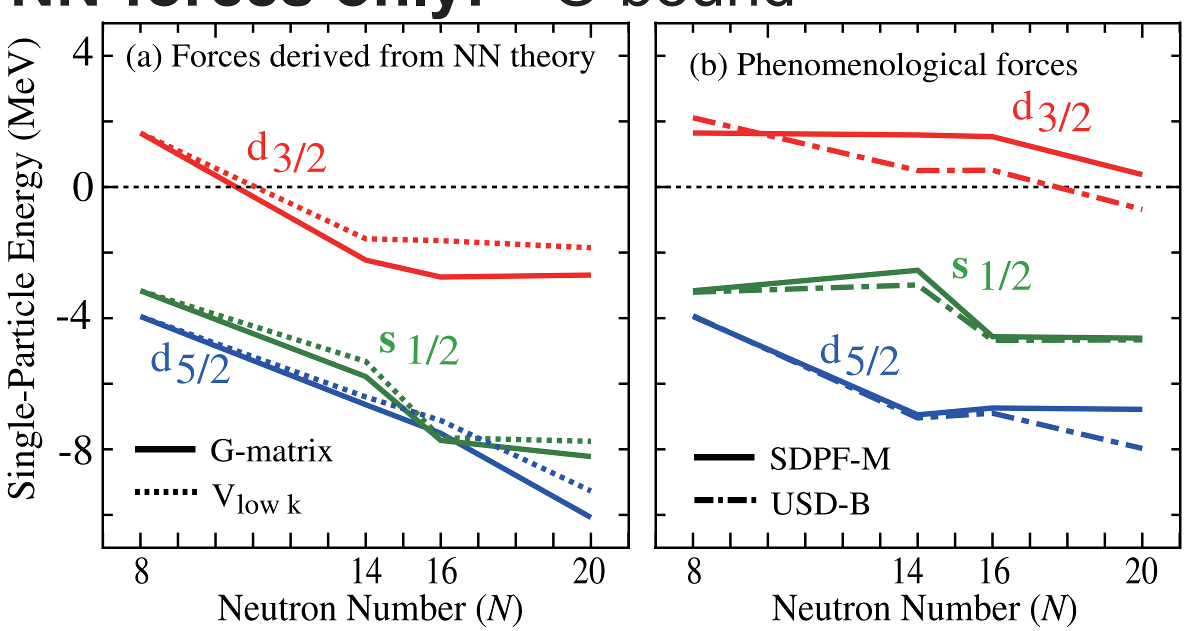
experiment:

- **^{24}O has both features**

R. V. F. Janssens, Nature 459, 1069 (2009)

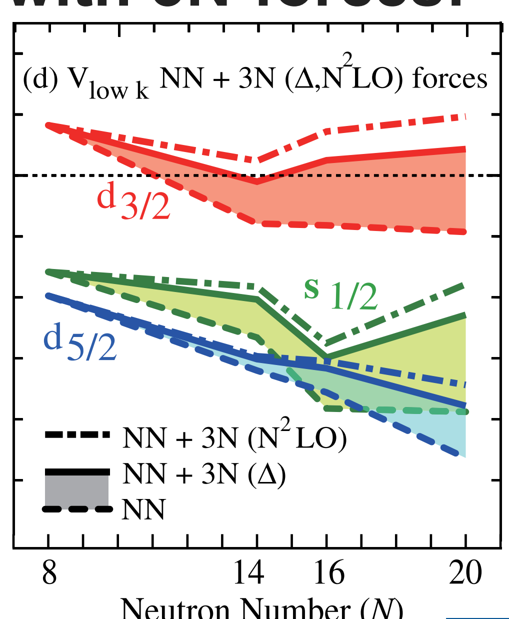
- drip-line anomaly for O-isotopes

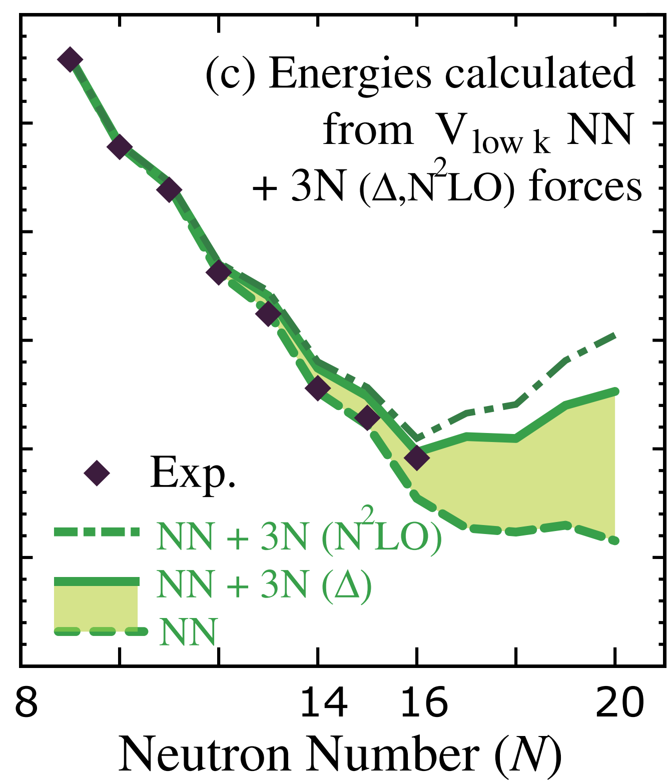
NN-forces only: ^{28}O bound



^{28}O

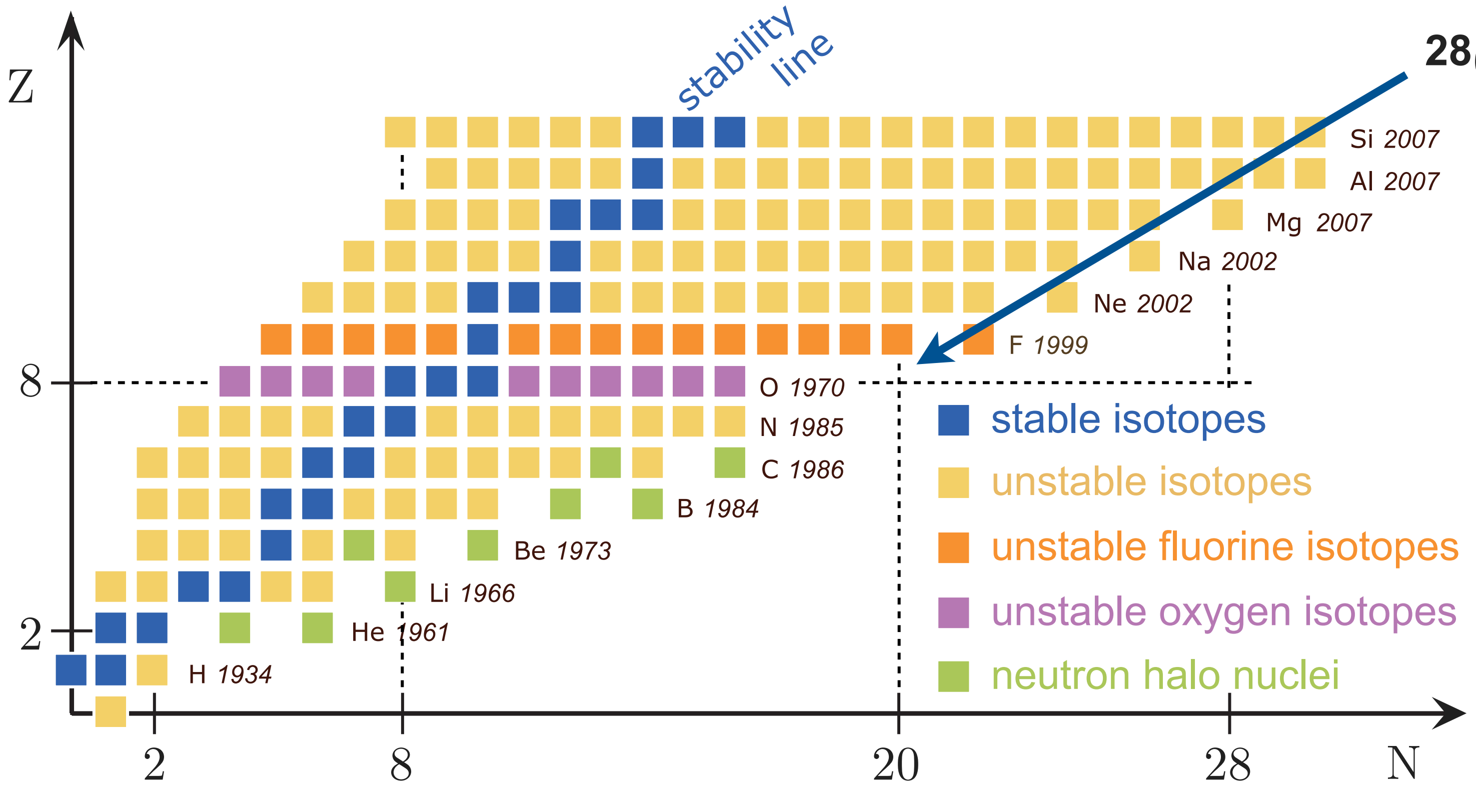
with 3N-forces:





T. Otsuka et al., PRL 105, 032501 (2010)

magic numbers & n-drip line



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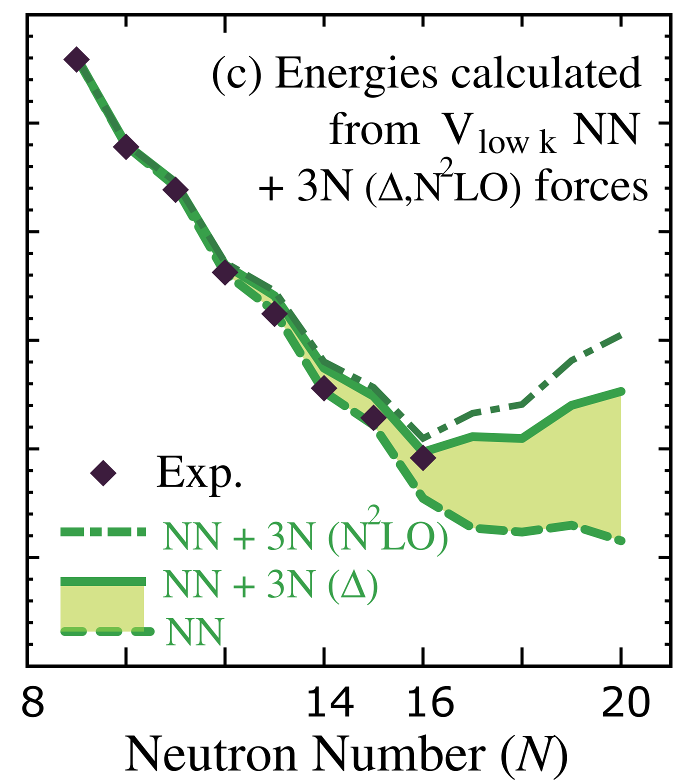
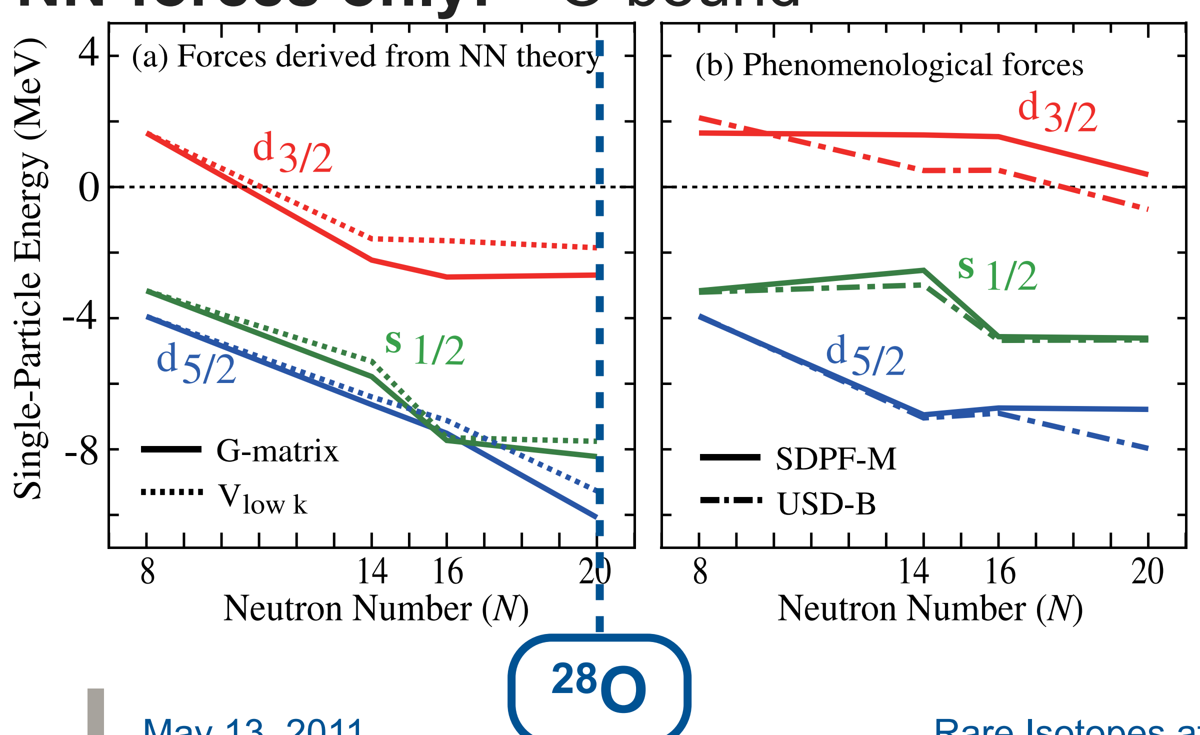
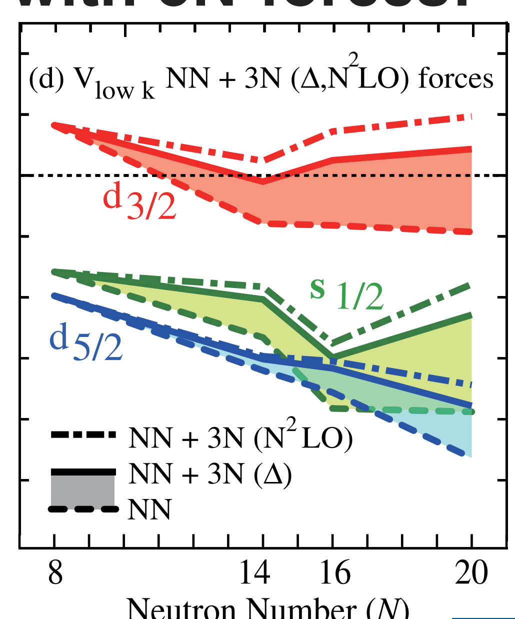


NN-forces only: ^{28}O bound



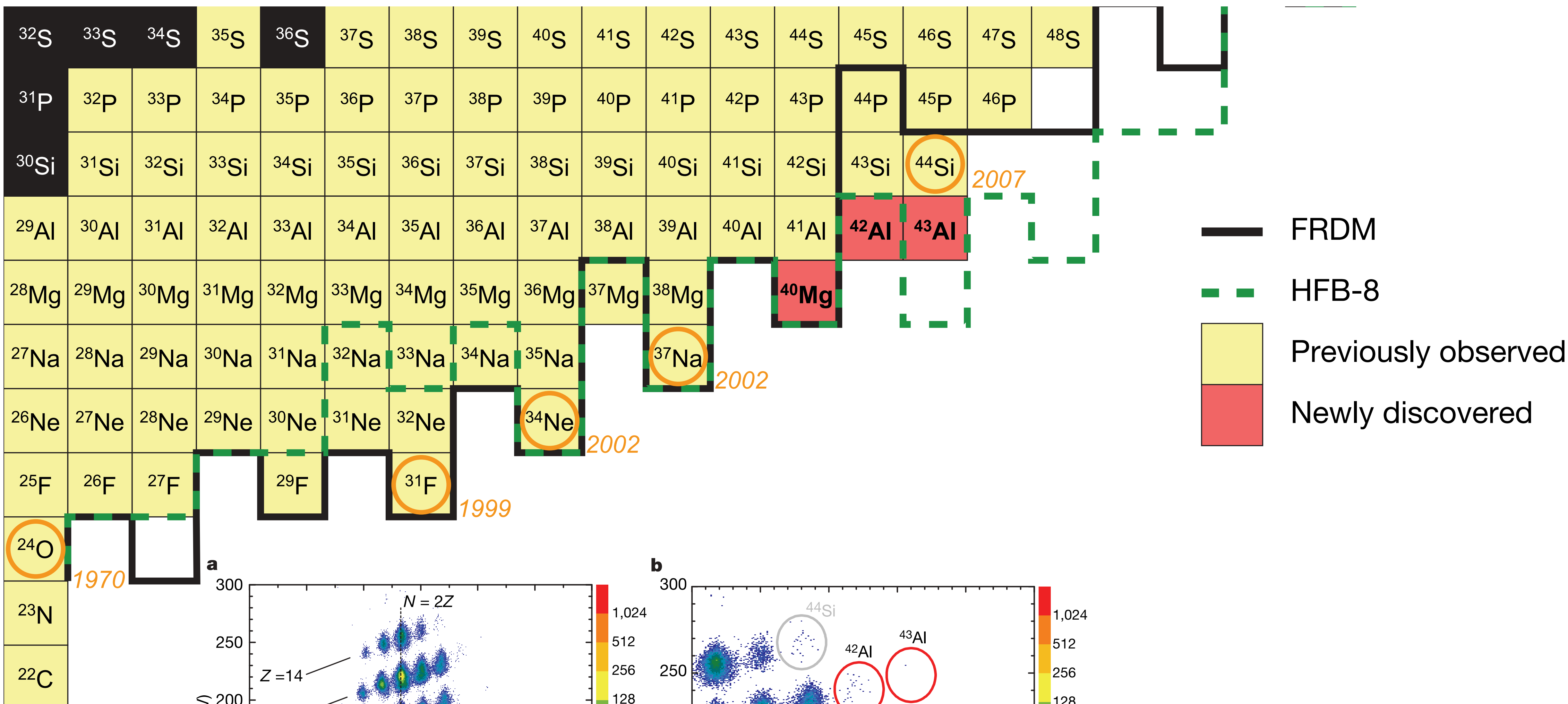
with 3N-forces:

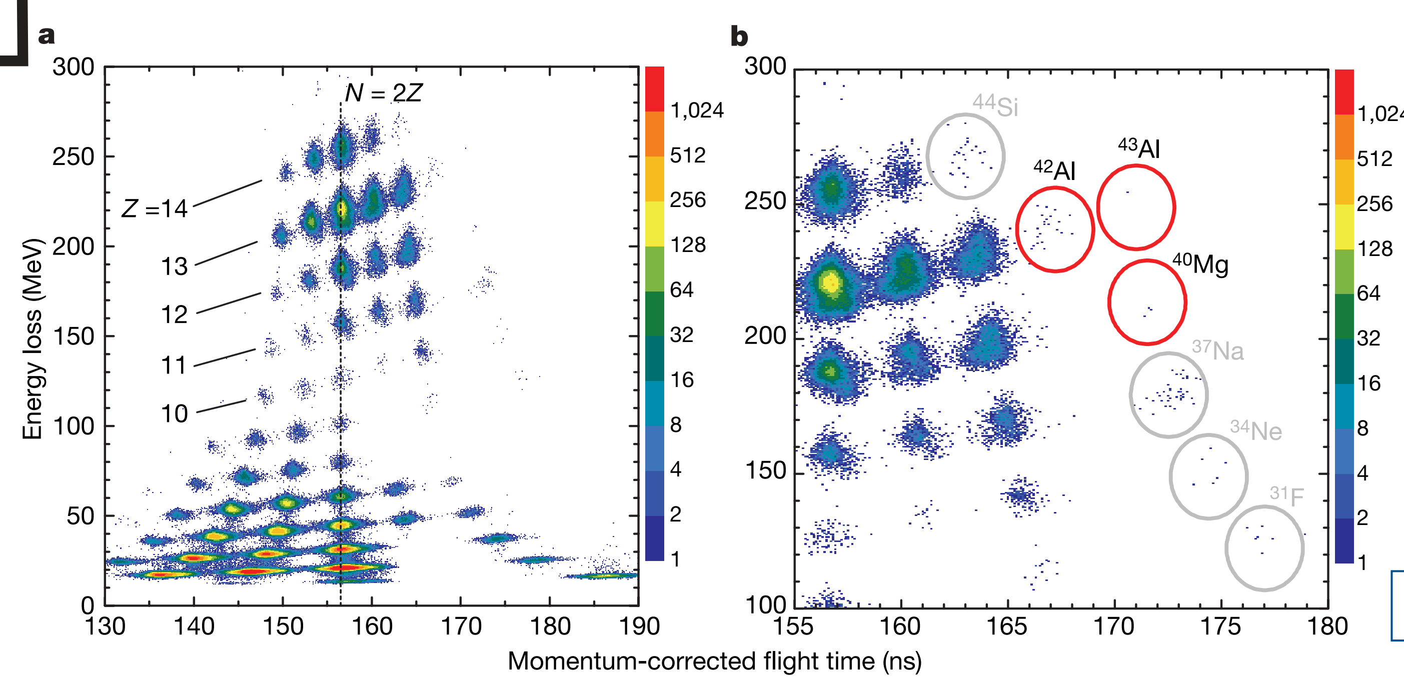


T. Otsuka et al., PRL 105, 032501 (2010)

TRIUMF

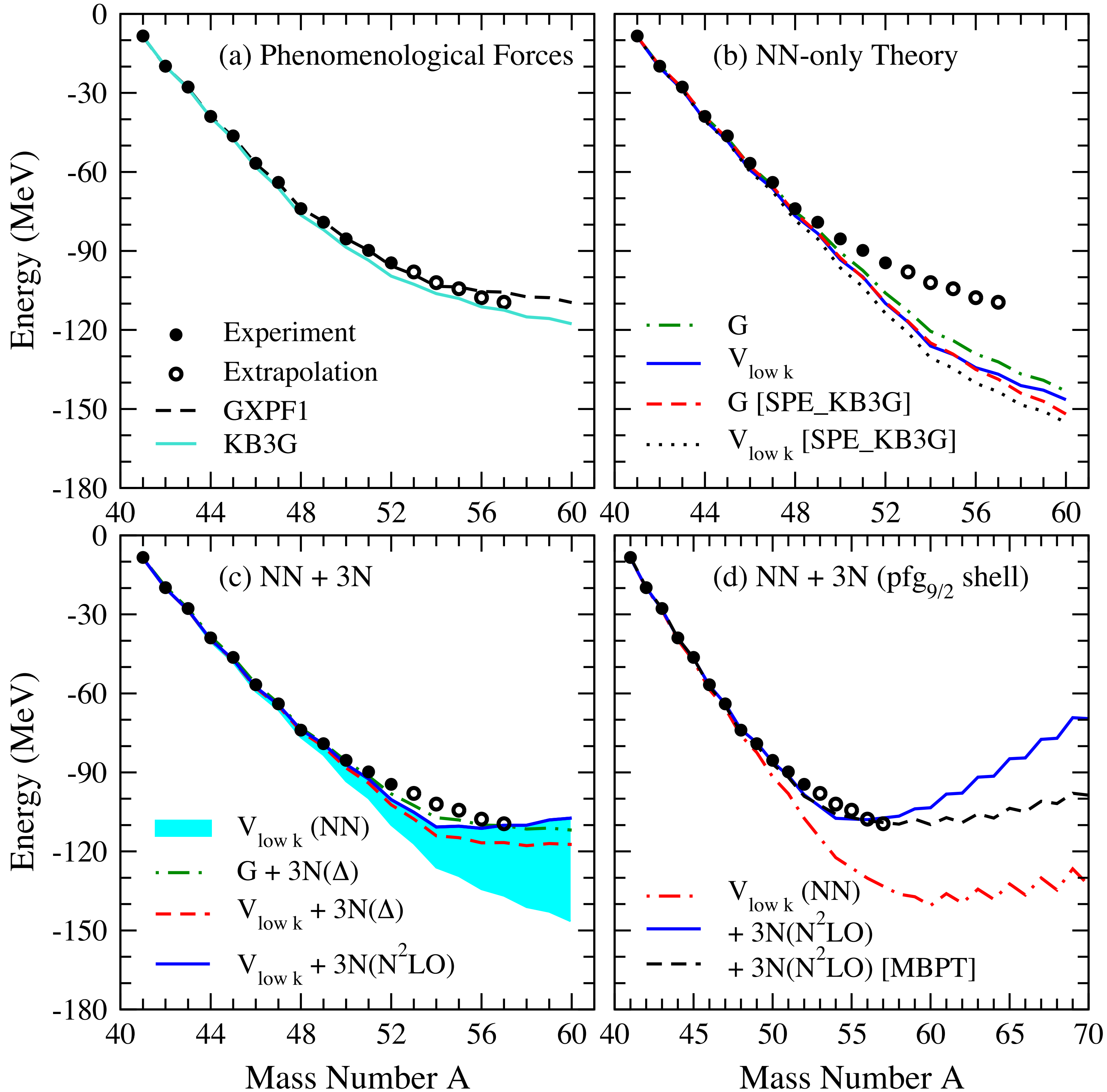
new discoveries at the drip-line





T. Baumann et al., Nature 449, 1022(2007)

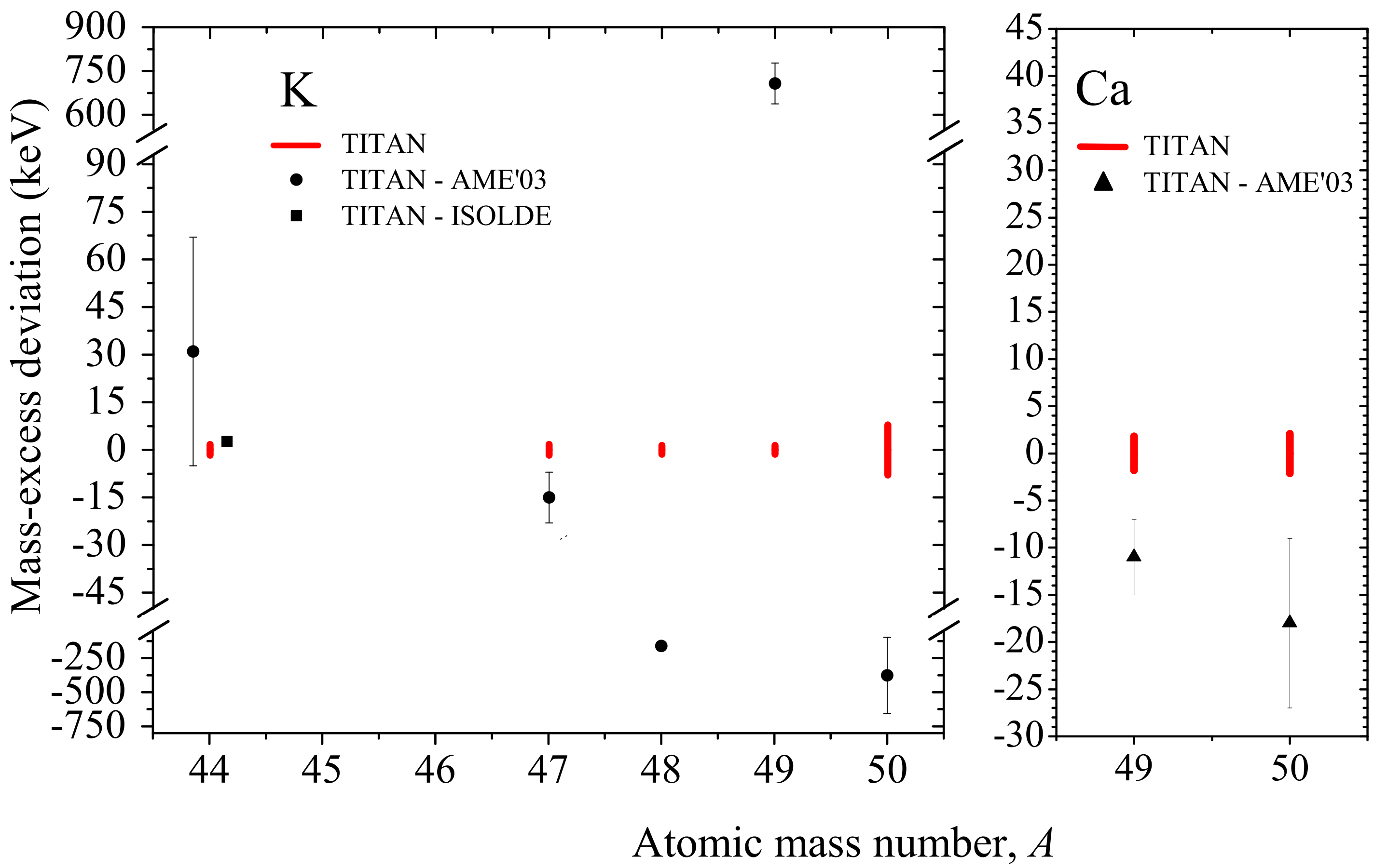
3N-forces and Ca-isotopes

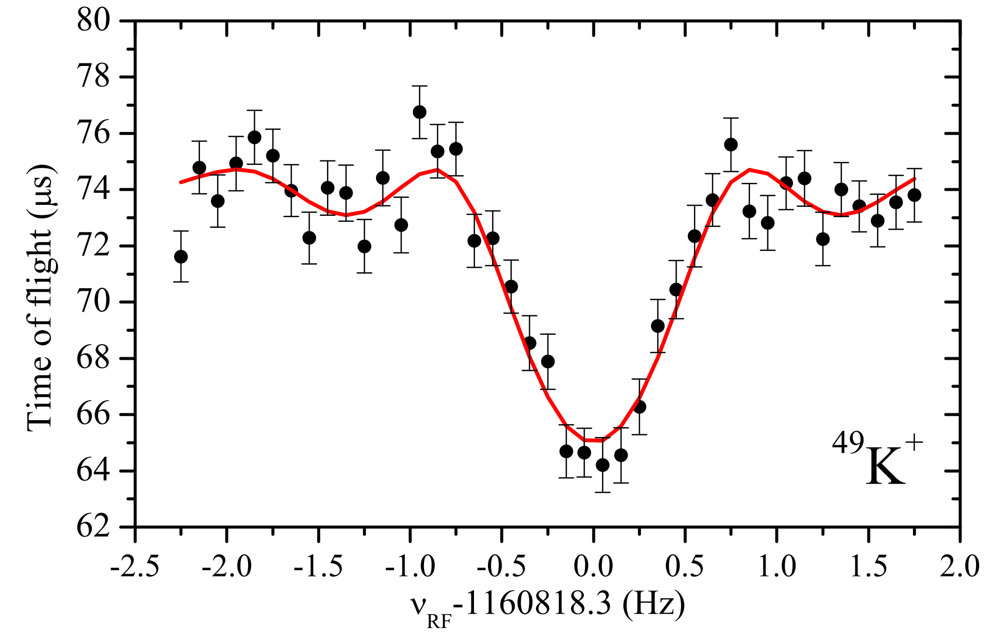


- correctly describes ^{48}Ca as a magic nucleus
- predicts shell closure at N = 34 (^{54}Ca)

J. D. Holt et al., arXiv:1009.5984

TITAN: towards N=34 with K & Ca





- large deviations from previous measurements up to 10 σ
- N=28 shell gap in fact ≈1 MeV larger
- later this year:

A. Lapierre et al., to be submitted to PRC

current exp. uncertainties [keV]

A	K	Ca
51	unknown	93.7
52	unknown	698.6
53	unknown	unknown

TRIUMF

Weak Interaction
and
Nuclear Matrix Elements

V_{ud}

interaction Lagrangian quarks - W^+ and W^-

$$g\,\bar{u}_{Li}\gamma^{\mu}d_{Li}W_{\mu}^{+} + h.c. = g\,\bar{u}'_{Li}U_L D_L^{+}\gamma^{\mu}d'_{Li}W_{\mu}^{+}$$

$$V = U_L D_L^{+} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo–Kobayashi –Maskawa matrix → test unitarity!

V_{ud}

interaction Lagrangian quarks - W^+ and W^-

$$g\,\bar{u}_{Li}\gamma^{\mu} d_{Li} W_{\mu}^{+} + h.c. = g\,\bar{u}'_{Li} U_L D_L^{+} \gamma^{\mu} d'_{Li} W_{\mu}^{+}$$

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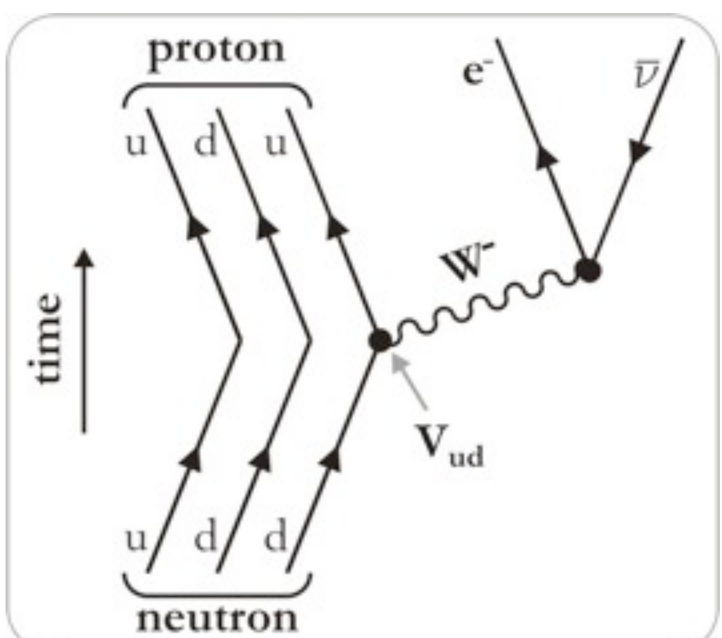
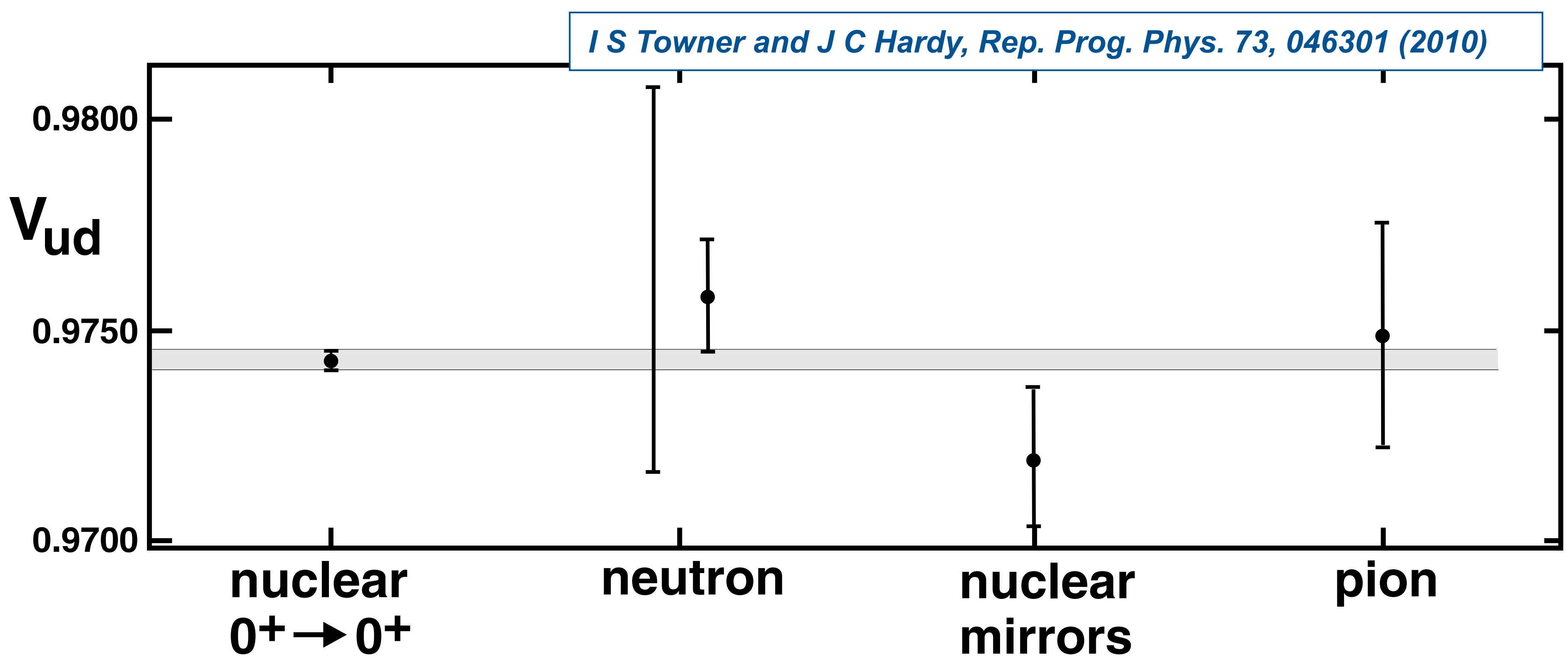
Cabibbo–Kobayashi –Maskawa matrix → test unitarity!

β - decay





superallowed $0^+ \rightarrow 0^+$ beta decays

⇒ superallowed $0^+ \rightarrow 0^+$ decays most precise way to extract V_{ud}

due to $\Delta J = \Delta T = \Delta L = \Delta S = 0$:

- pure Fermi decay (only vector part)
- transition between isobaric analog states
- only total Isospin Ladder Operator $T^{\pm}$ alters wave-function

⇒ for T = 1: matrix element: $$\left|\overline{M}\right|^2 = \frac{G_V^2}{g^2}\left|M(F)\right|^2 = \frac{2G_V^2}{g^2}$$

experimental input

K … numerical constant

t … „partial halflife (dep on. BR and $T_{½}$)

f … phase space integral (dep. on **Q-value**)

$$ft = \frac{K}{2G_V^2} = \text{const}$$

superallowed $0^+ \rightarrow 0^+$ beta decays

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t … „partial halflife

f … phase space integral

experimental input

(dep on. BR and $T_{1/2}$)

(dep. on **Q-value**)

$$ft = \frac{K}{2G_V^2} = \text{const}$$

recent mass measurements in Penning taps:

^{22}Mg, ^{26m}Al, ^{34}Cl, ^{38m}K, ^{38}Ca, ^{42}Sc, ^{46}V, ^{50}Mn, ^{54}Co, ^{74}Rb

➡ discovered&resolved discrepancy to reaction meas.

M. Mukherjee et al., PRL 93, 150801(2004)
A. Kellerbauer et al., PRL 93, 072502 (2004)
G. Savard et al., PRL 95, 102501 (2005)
G. Bollen et al., PRL 96, 152501 (2006)
T. Eronen et al., PRL 97, 232501 (2006);
PRL100, 132502 (2008); PRL 103, 252501 (2009)

corrected Ft-values

$$Ft = ft(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} = \text{const}$$ **(assuming CVC)**

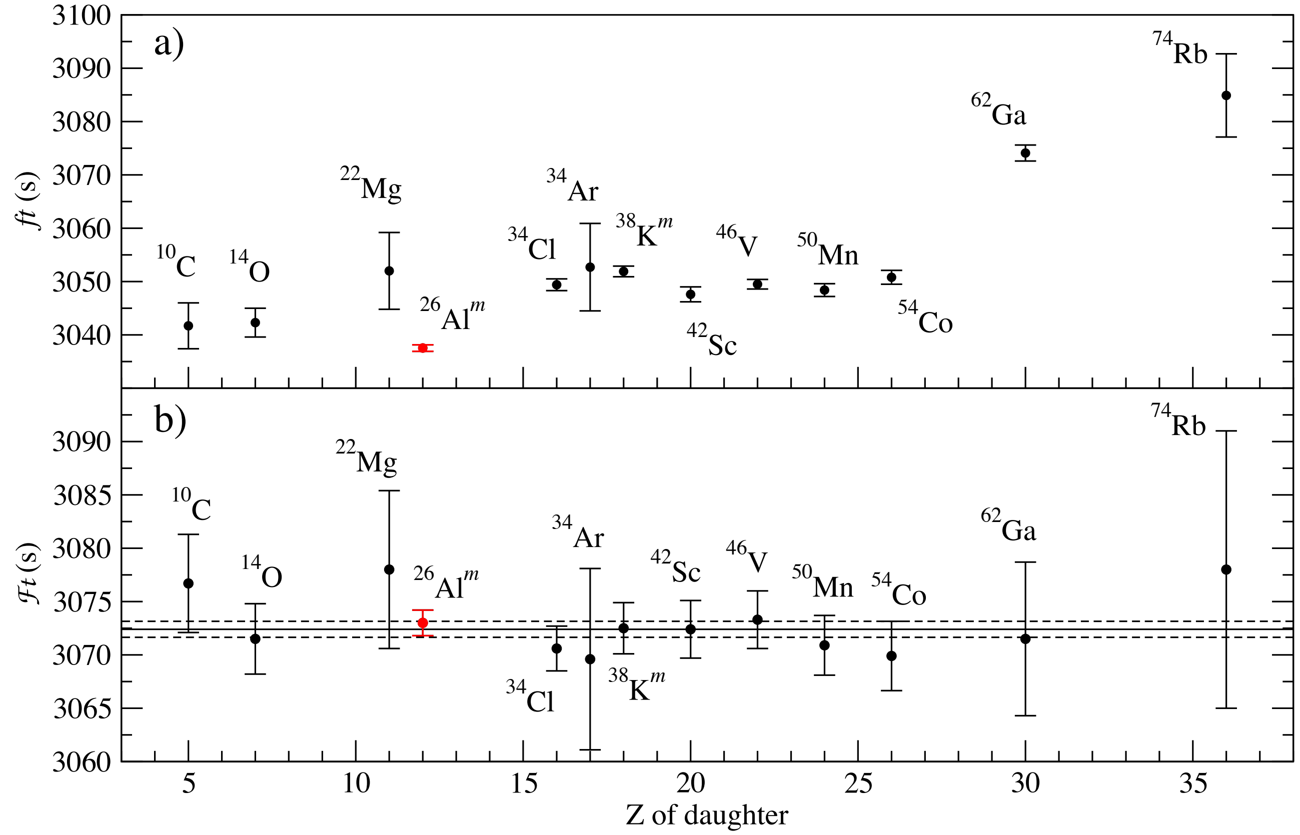
Δ^V_R … transition indep.

δ_R and δ_{NS} ….transition dep.

δ_C … isospin symmetry breaking (tans. dep.)

Corrections: small (about a few %),

BUT generally dominating uncertainty



discrepancies between different models

- Woods-Saxon
- Hartree-Fock (2 different calculations)
- perturbation theory
- self-consistent RPA
- **NEW: DFT**

→ $$|V_{ud}| = \frac{G_V}{G_F}$$

corrected Ft-values

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discrepancies between different models

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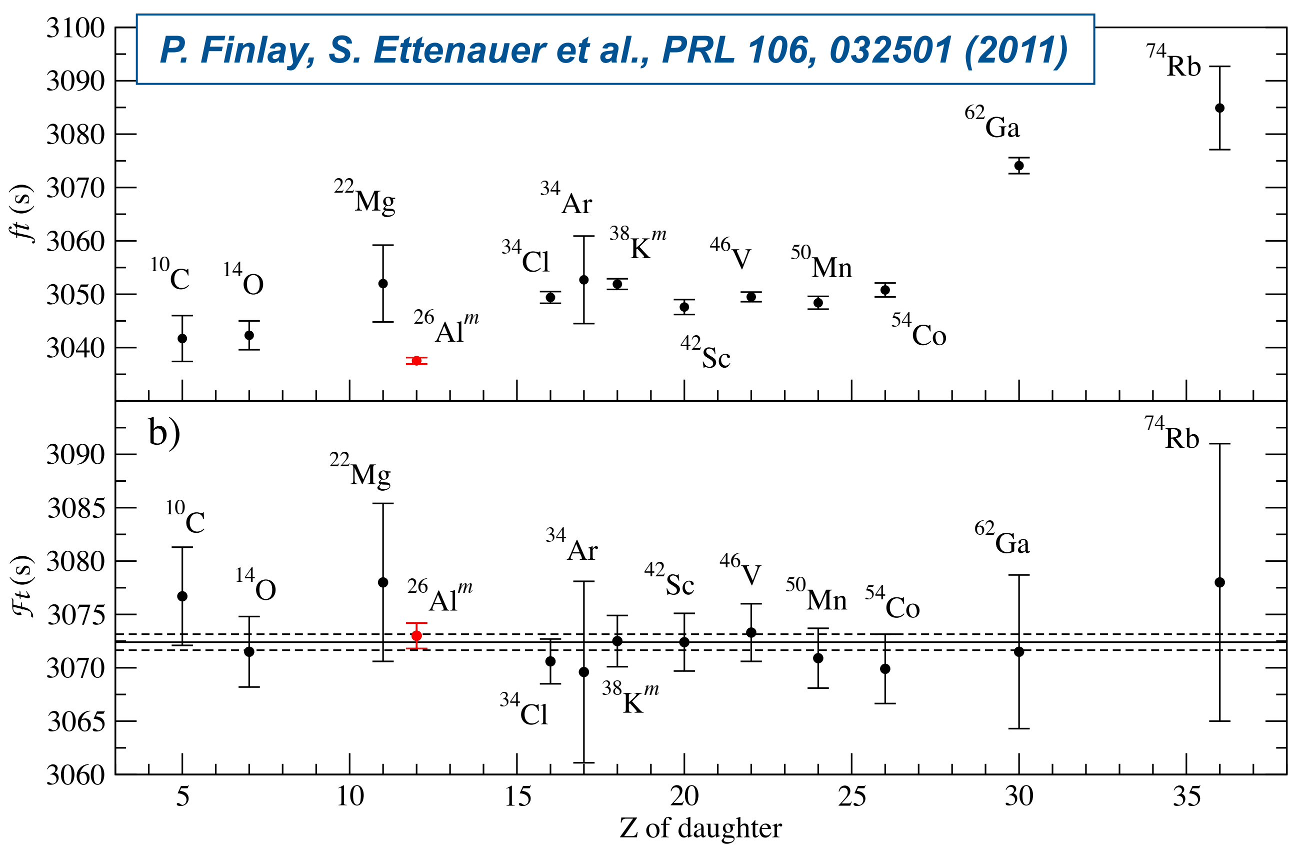
- Hartree-Fock (2 different calculations)
- perturbation theory
- self-consistent RPA
- **NEW: DFT** *W. Satuła et al., PRL 106, 132502 (2011)*

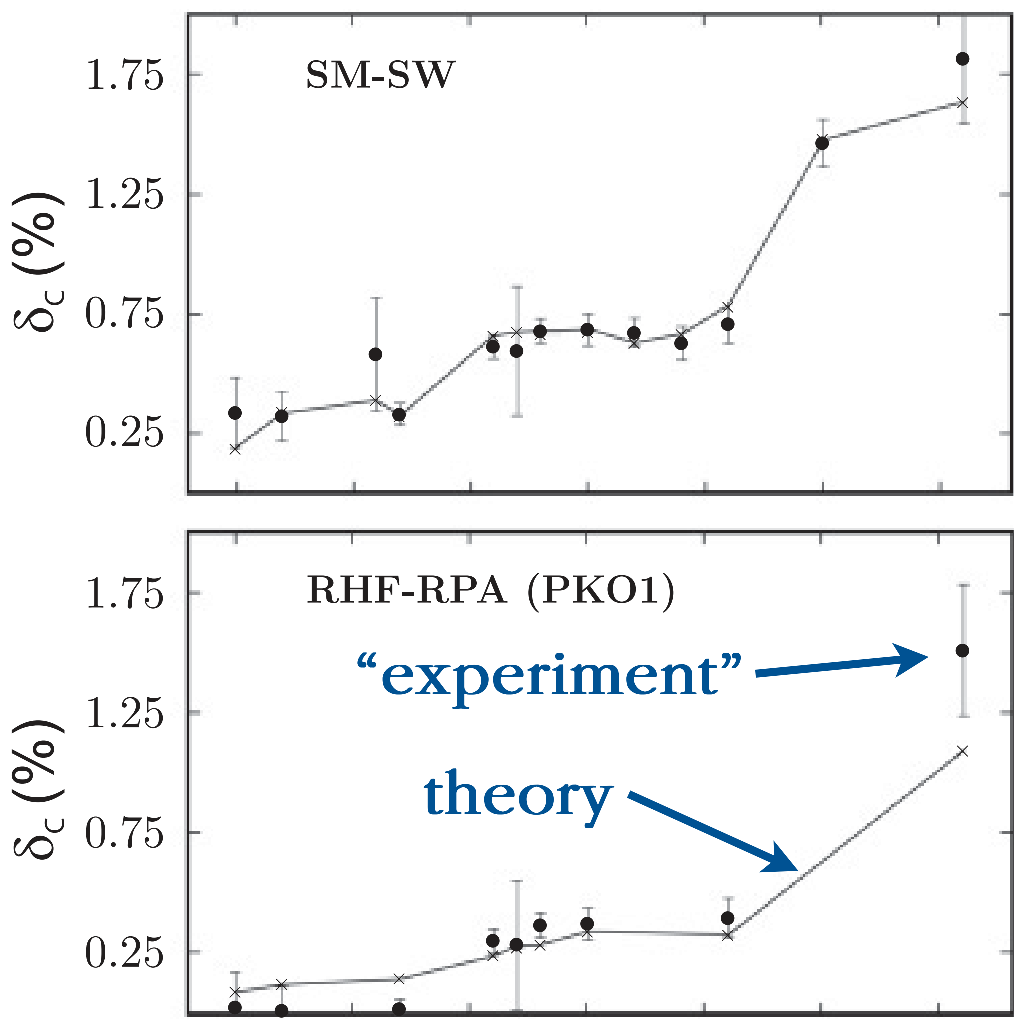


$$|V_{ud}| = \frac{G_V}{G_F}$$

experimental “tests” of δ_c

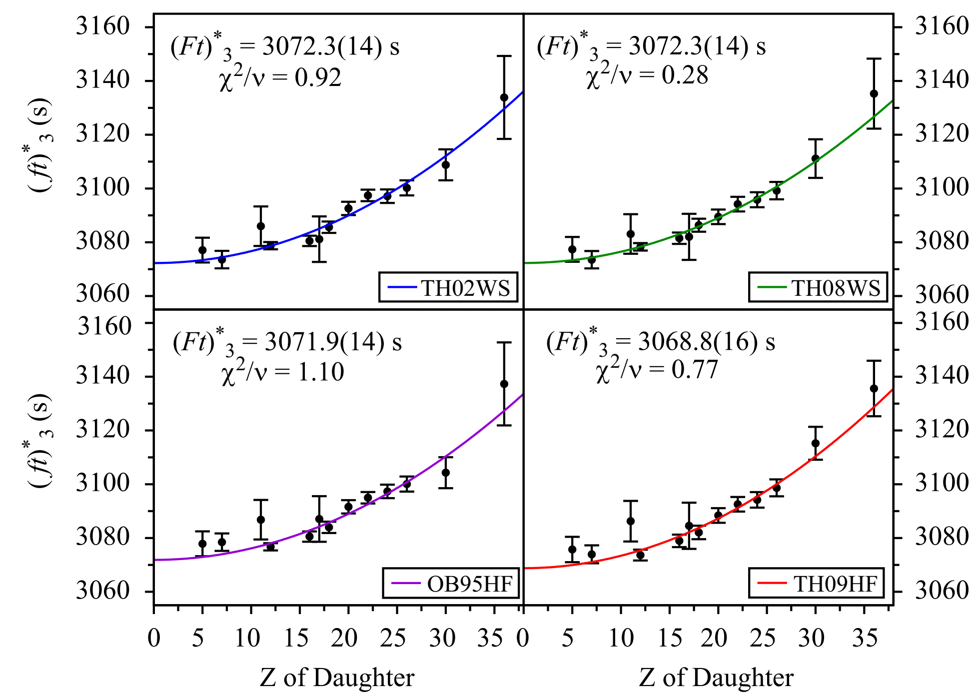
$$\delta_C = 1 + \delta_{NS} - \frac{\overline{\mathcal{F}t}}{ft(1+\delta'_R)}.$$

χ^2 minimization



I. S. Towner and J. C. Hardy, PRC 82, 065501 (2010)

- extrapolate to charge-independent limit $\propto Z^2$
- subtract non Z^2 components from models



G.F. Grinyer,et al. NIM A 622, 236 (2010)

study <u>new cases</u>: e.g. T=2

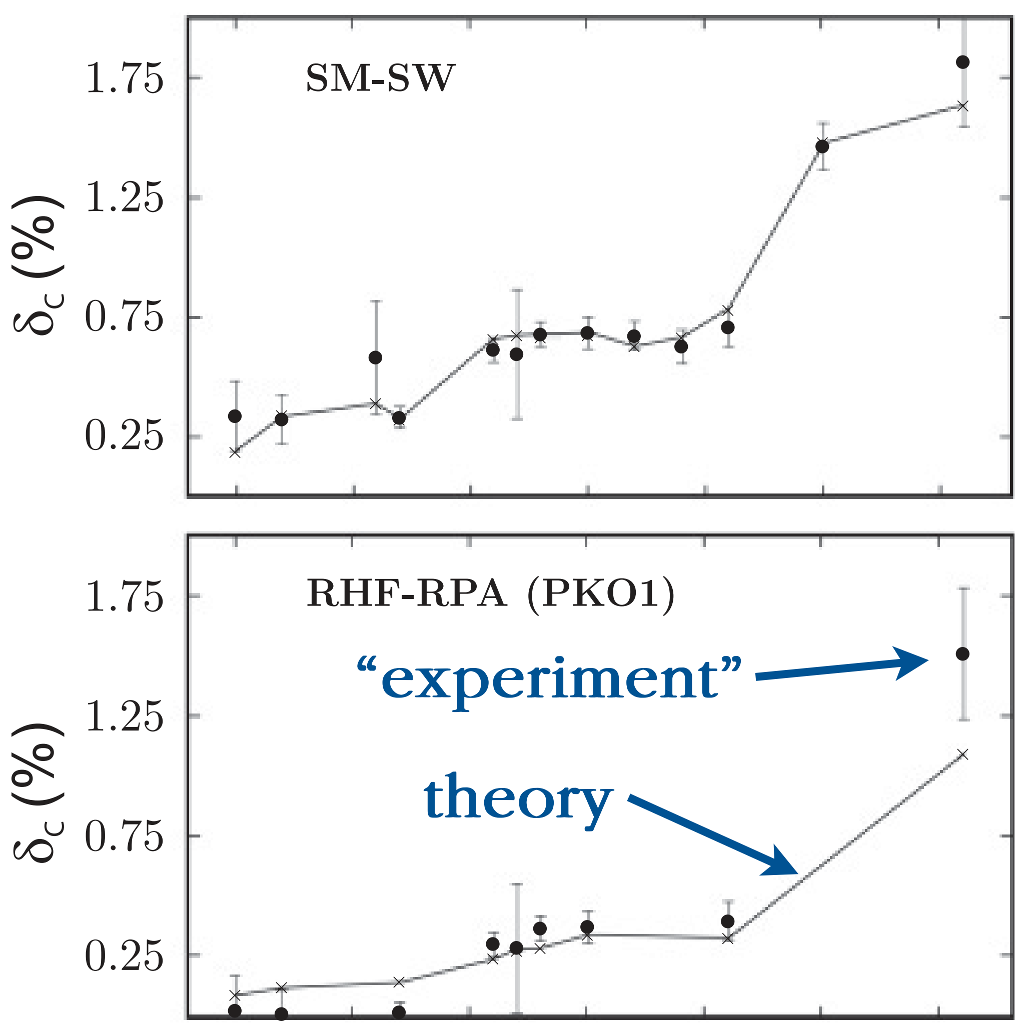
$$ft = \frac{\overline{\mathcal{F}t}}{(1+\delta_R)(1-\delta_c+\delta_{NS})}$$

mean value of T=1

experimental "tests" of δ_c

$$\delta_C = 1 + \delta_{NS} - \frac{\overline{\mathcal{F}t}}{ft(1+\delta'_R)}.$$

χ^2 minimization



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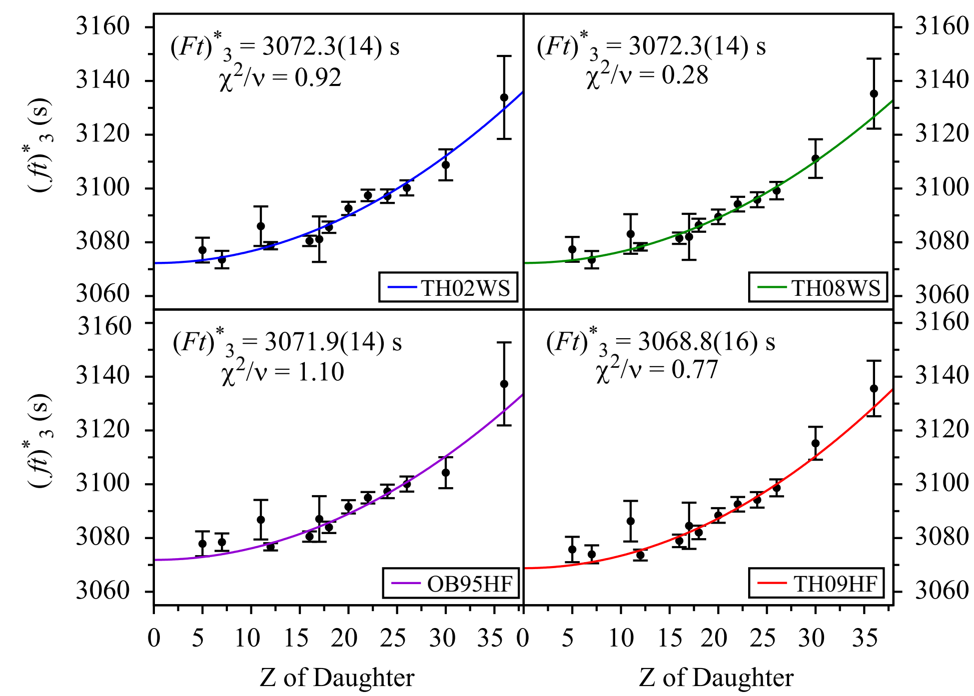

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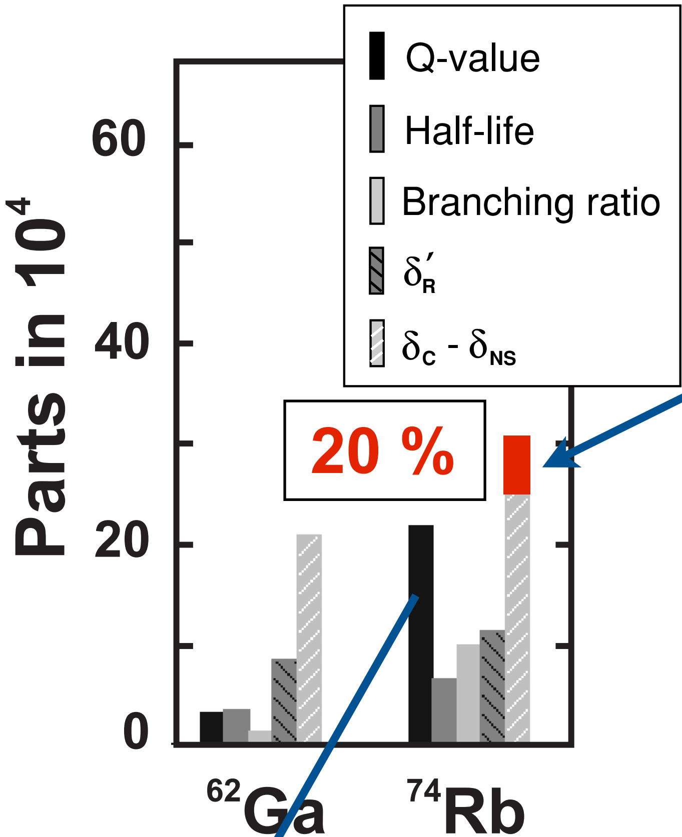
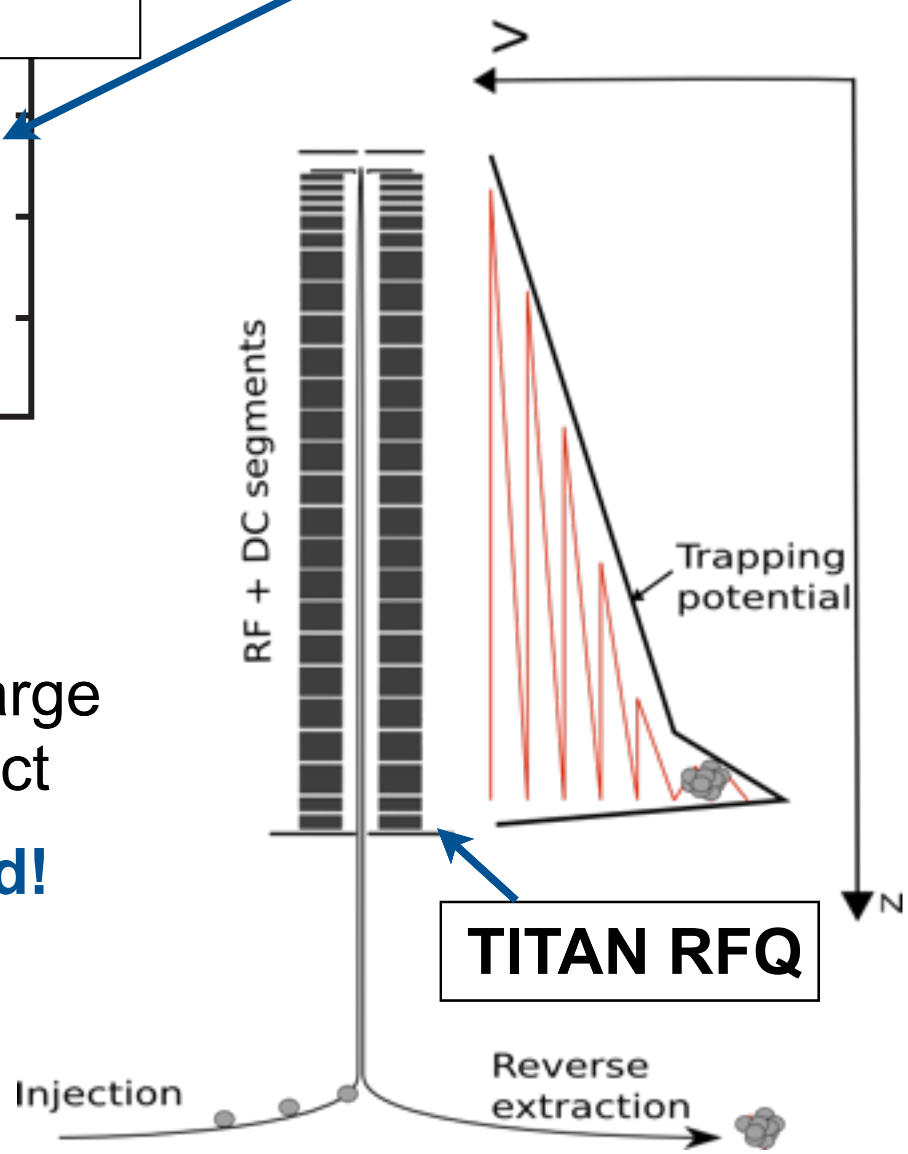
TRIUMF proposal S1242

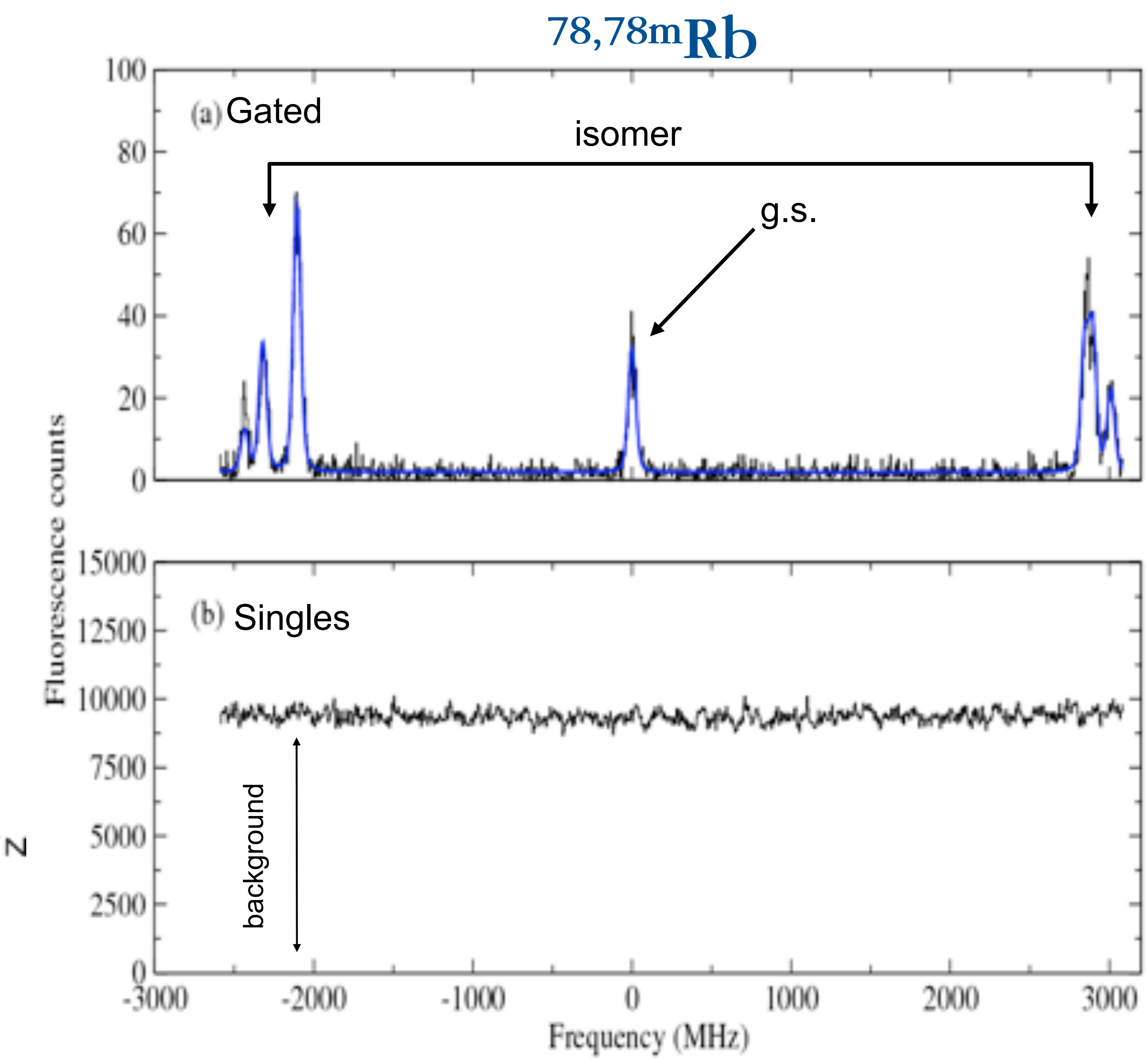
δ_C and the charge radius of ^{74}Rb



Laser spectroscopy of bunched beams

uncertainty of δ_C due to charge radius





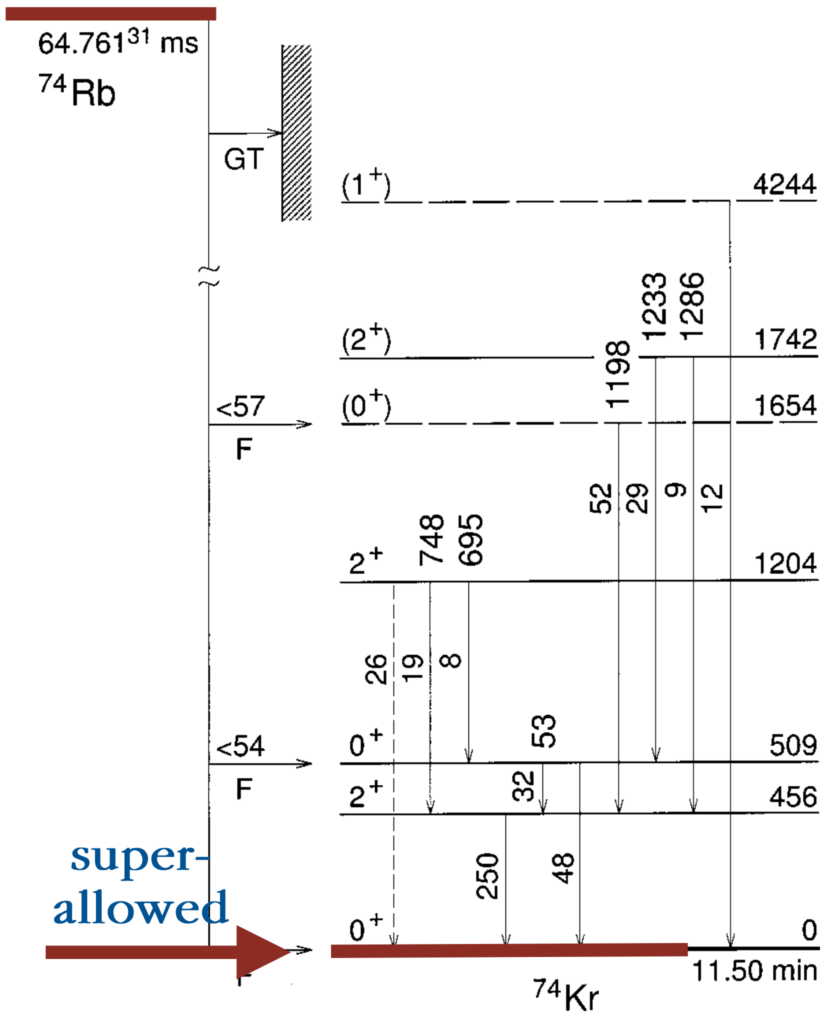
exp. contribution large

⇒ direct exp. impact

⇒ Q-value needed!

E. Mané et al., submitted to PRL

Q-value for ^{74}Rb



A. Piechaczek et al., PRC 67, 051305(R) (2003)

direct mass measuremnts in Penning trap:

- highest precision
- ISOLTRAP @ CERN

A. Kellerbauer et al., PRL 93, 072502 (2004)
PRC 76, 045504 (2007)

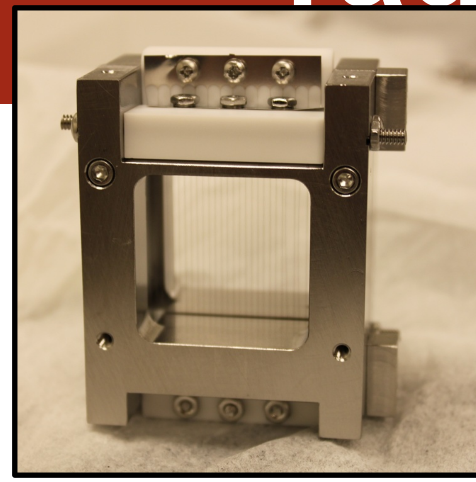
Nuclide	D_{exp} (keV)			
	2000	2002	2003	mean
^{64}Zn		−65 998.6(7.8)		−65 998.6(7.8)
^{71}Ga		−70 137.5(1.2)		−70 137.5(1.2)
^{74}Ga	−68 047(21)		−68 019(32)	−68 041(18)[a]
^{74}Rb	−51 905(18)[b]	−51 917.3(4.8)[c]	−51 910.7(7.0)[c]	−51 914.7(3.9)

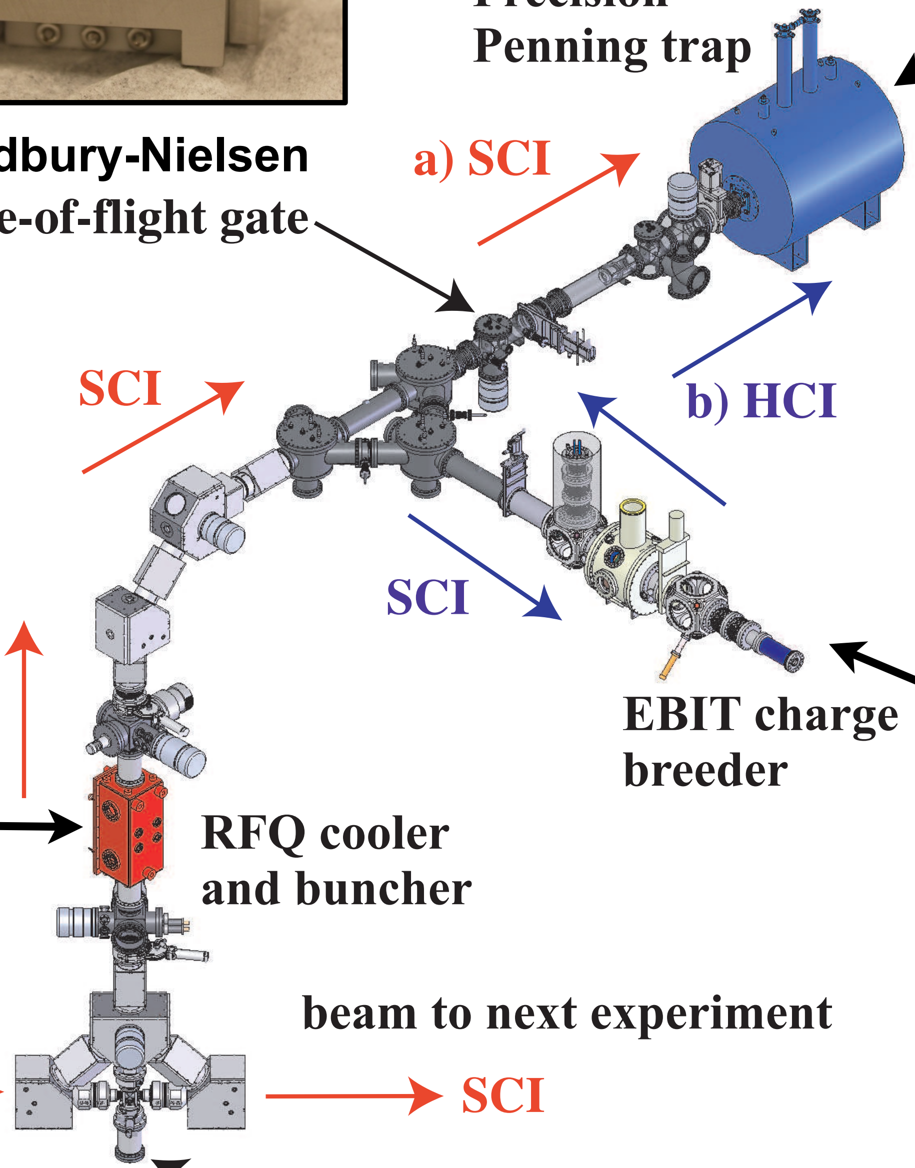
- limitation due to $T_{1/2}$

$$\frac{\delta m}{m} \propto \frac{m}{q} \frac{1}{B T N^{1/2}}$$

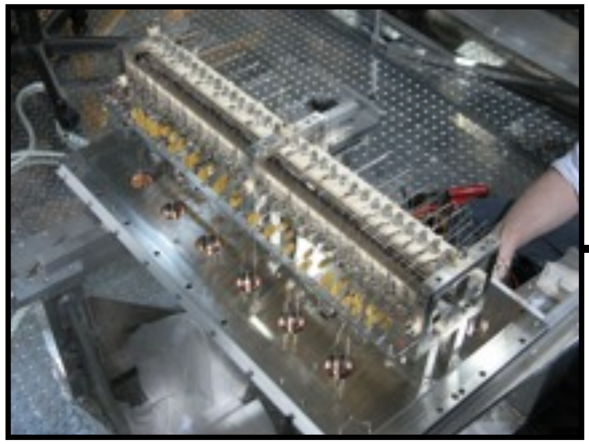
- to improve precision further: HCI
- **TITAN only online facility to use HCI**

radioactive HCI @ TITAN





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



Electron Beam Ion Trap

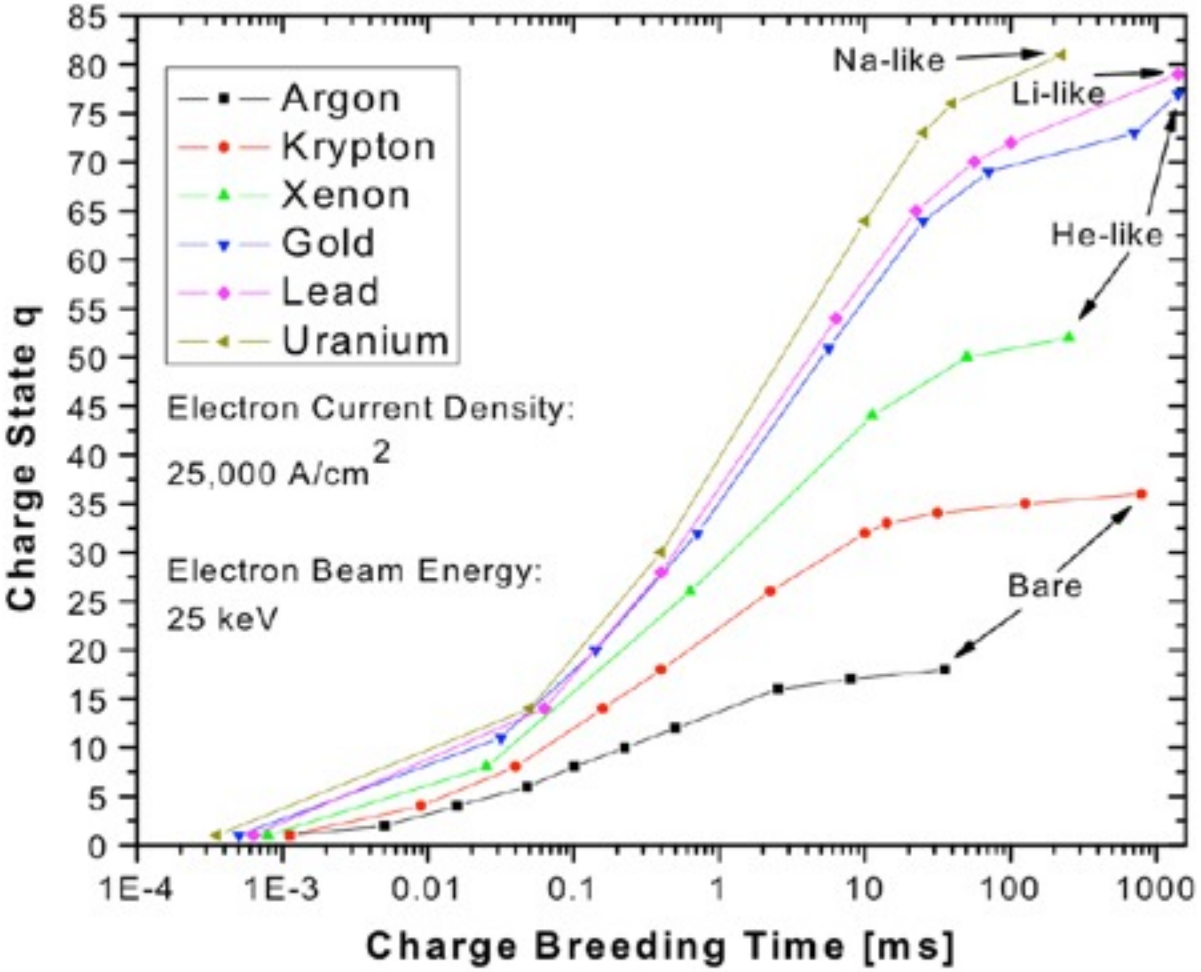
confinement:

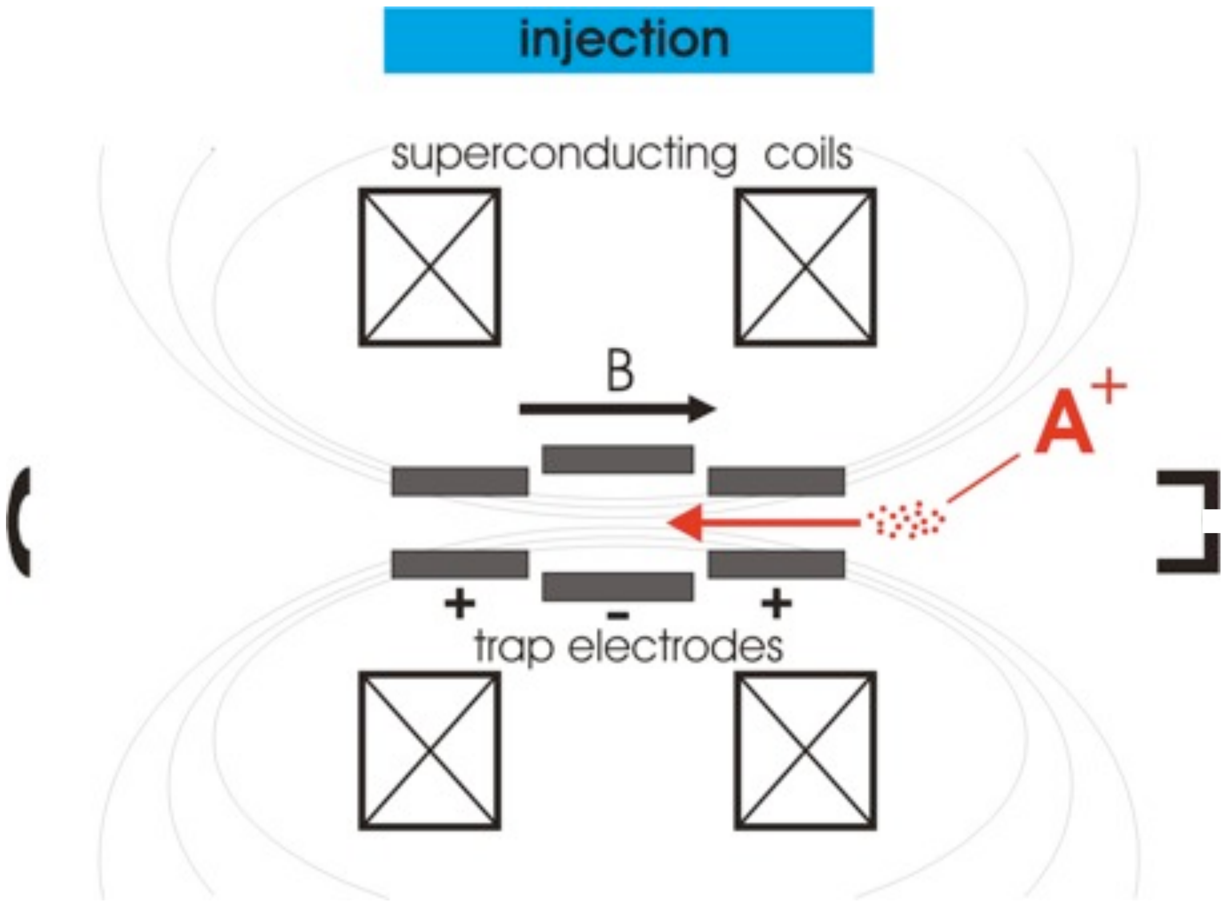
- axial by electrostatic field
- radial by electron beam + B- field

B-field (up to 6 T) compresses e^- beam

$\Rightarrow e^-$ density up to 10 000 A/cm^2

$\Rightarrow$increased ionization rate





requirements for charge breeding:

- efficient
- fast

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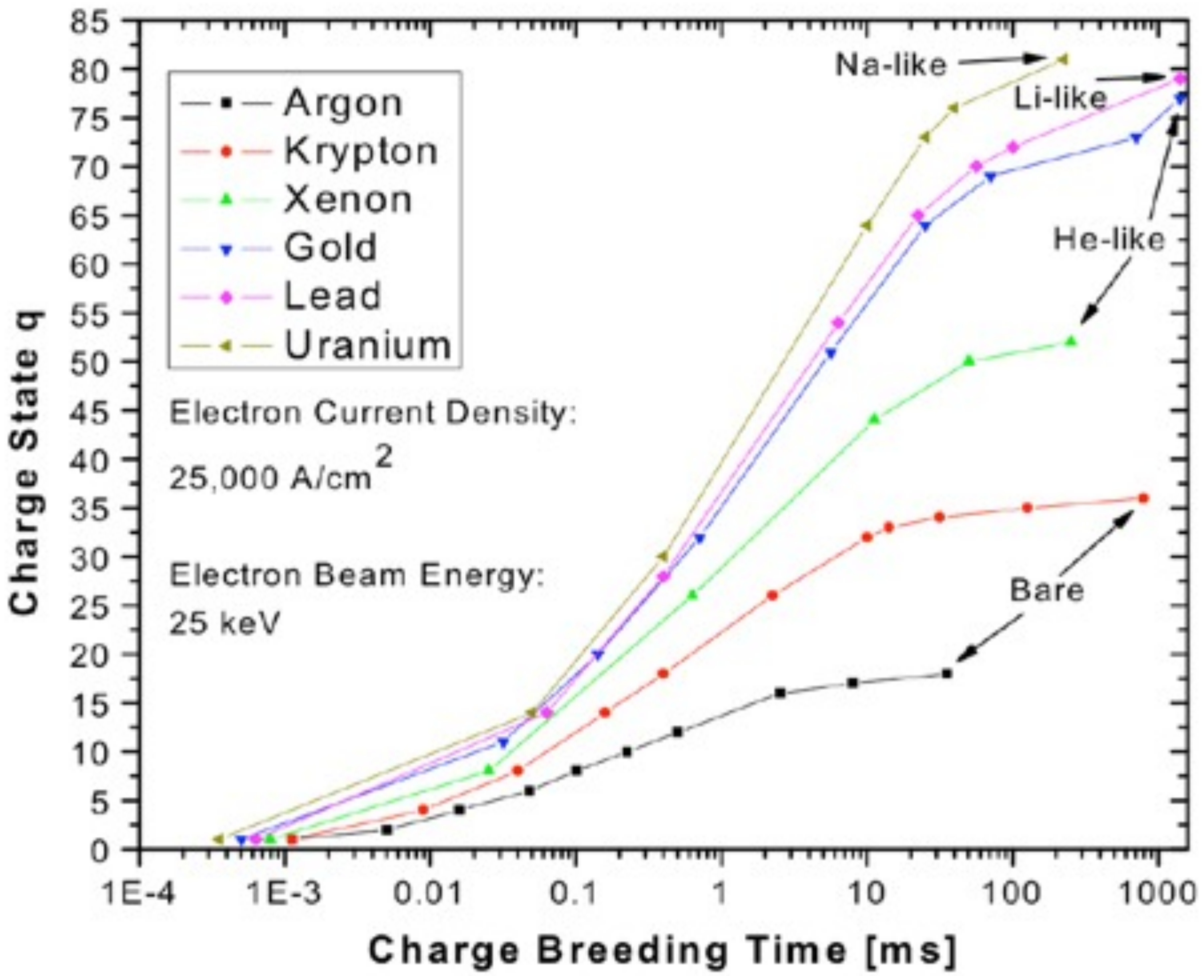

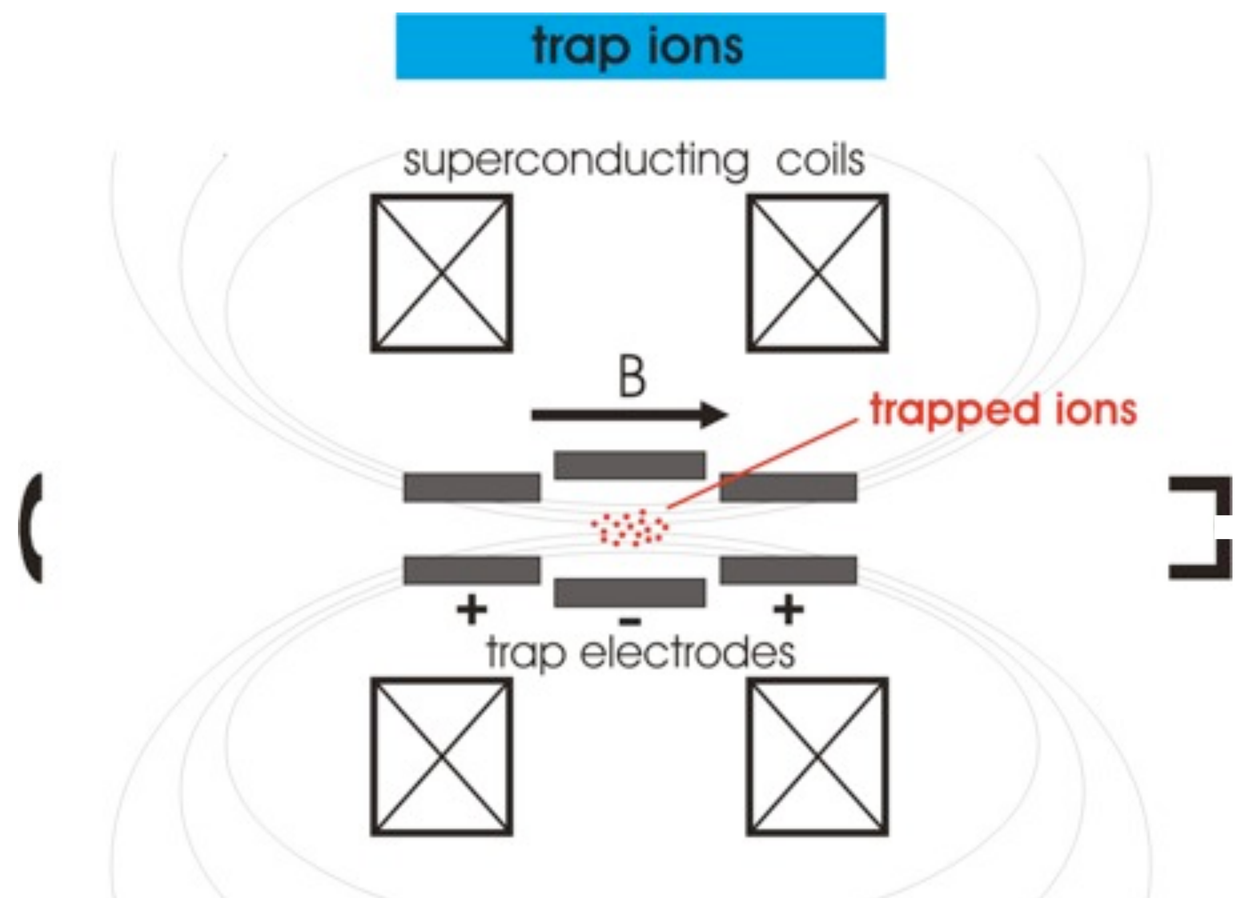

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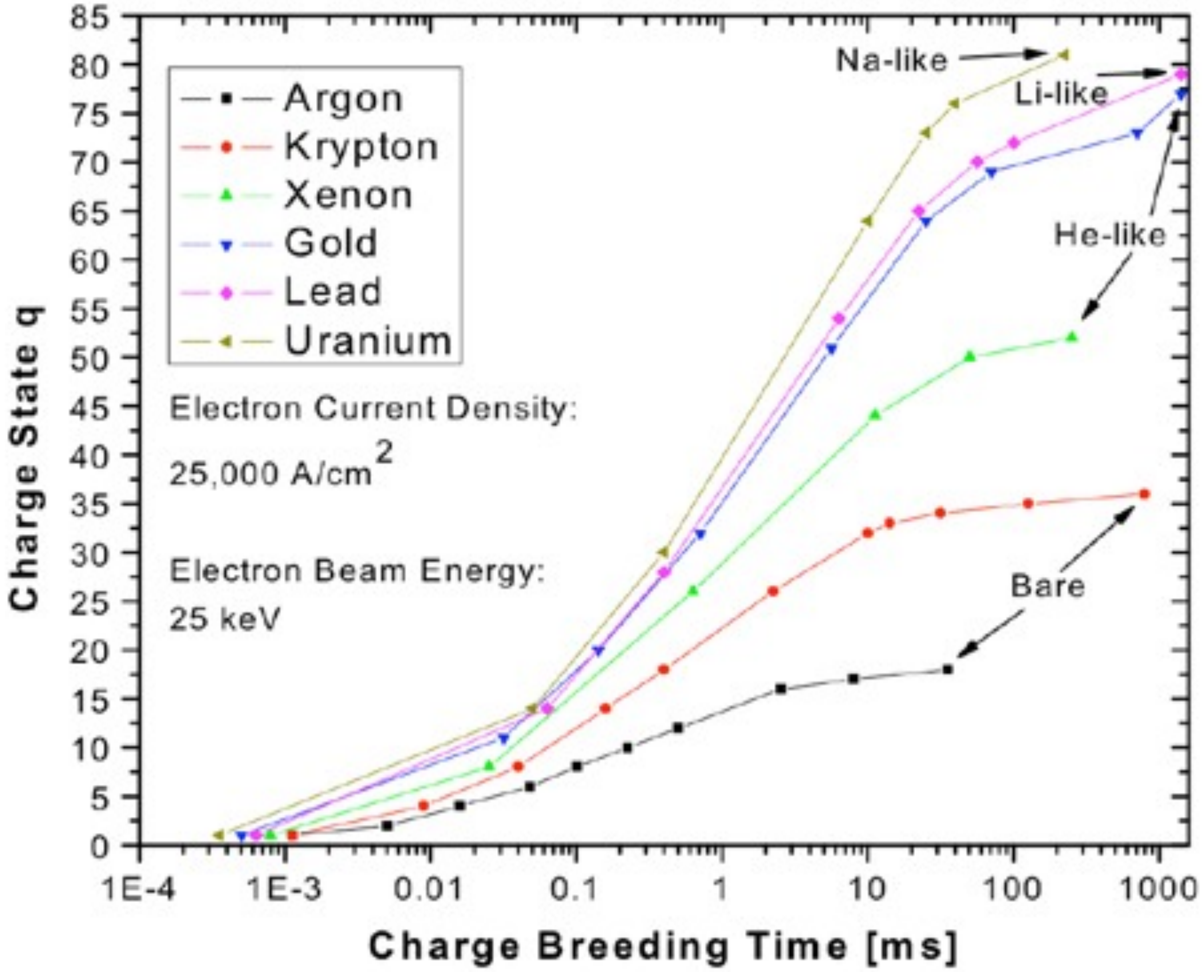

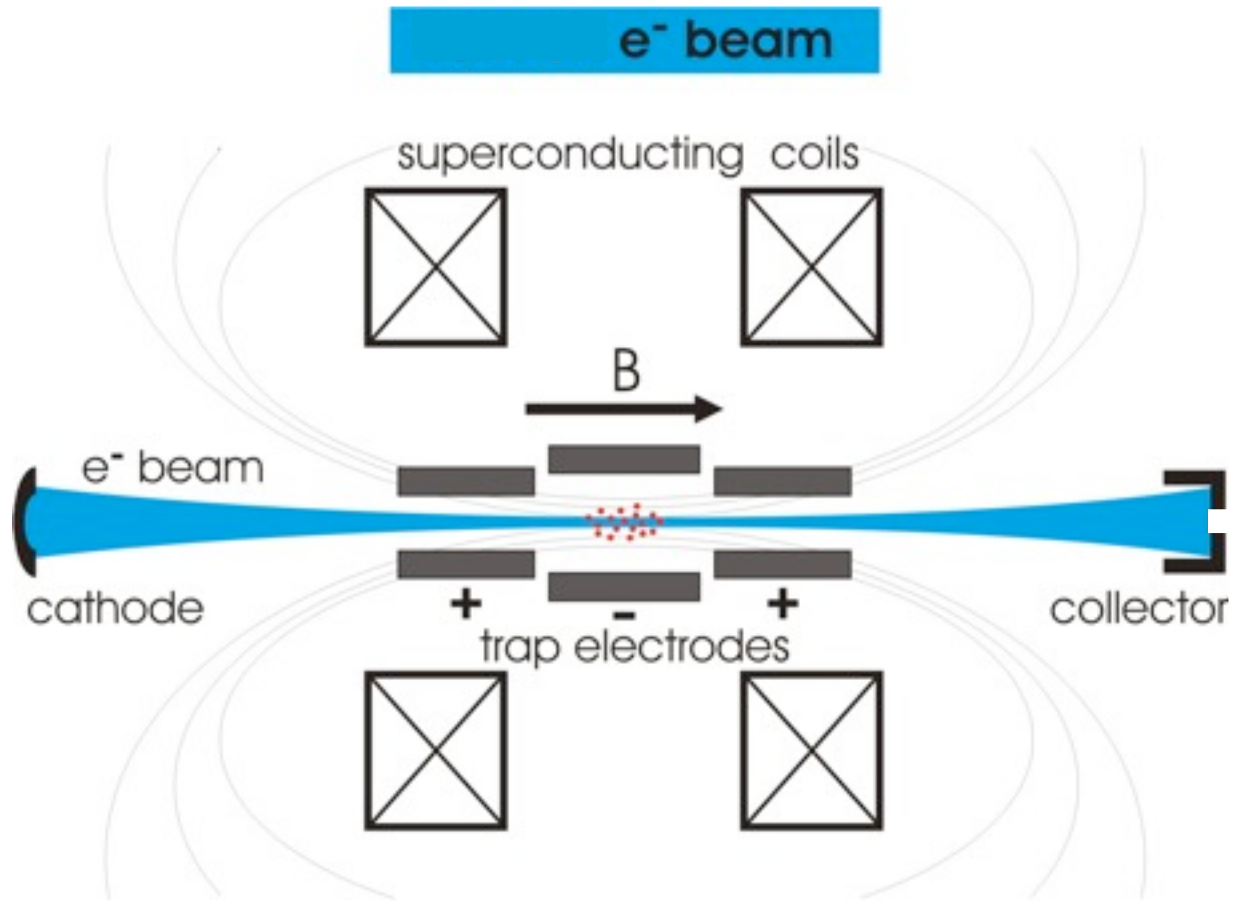

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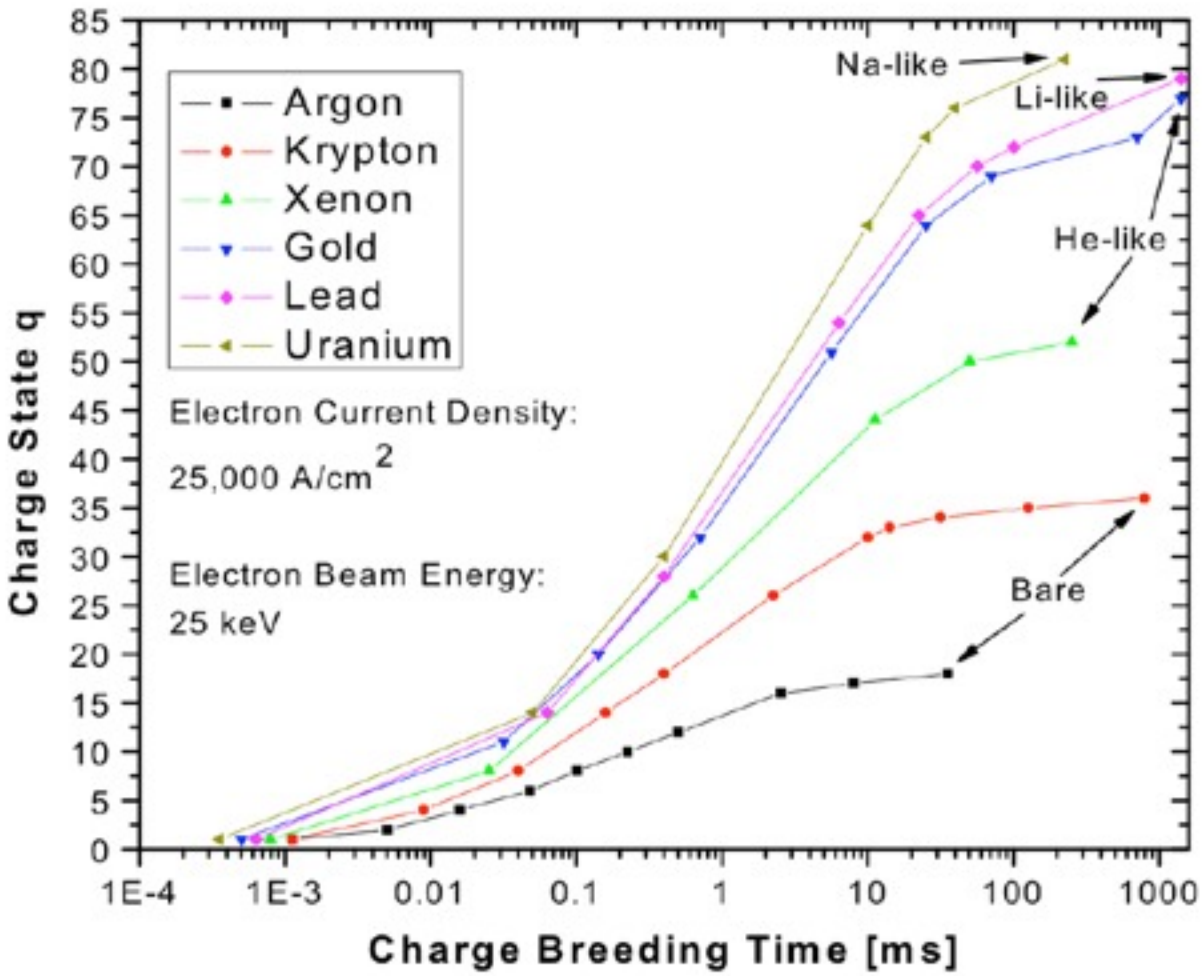

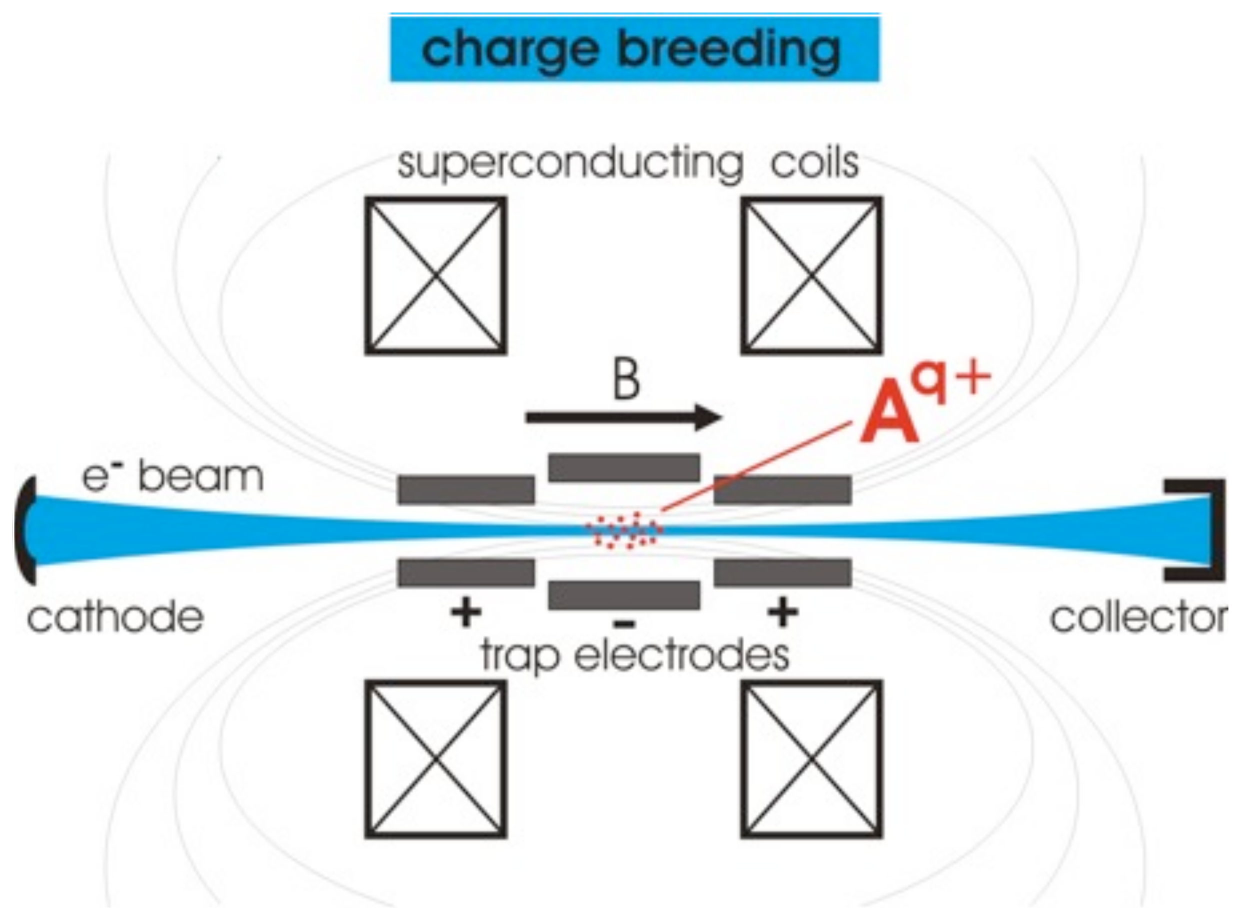

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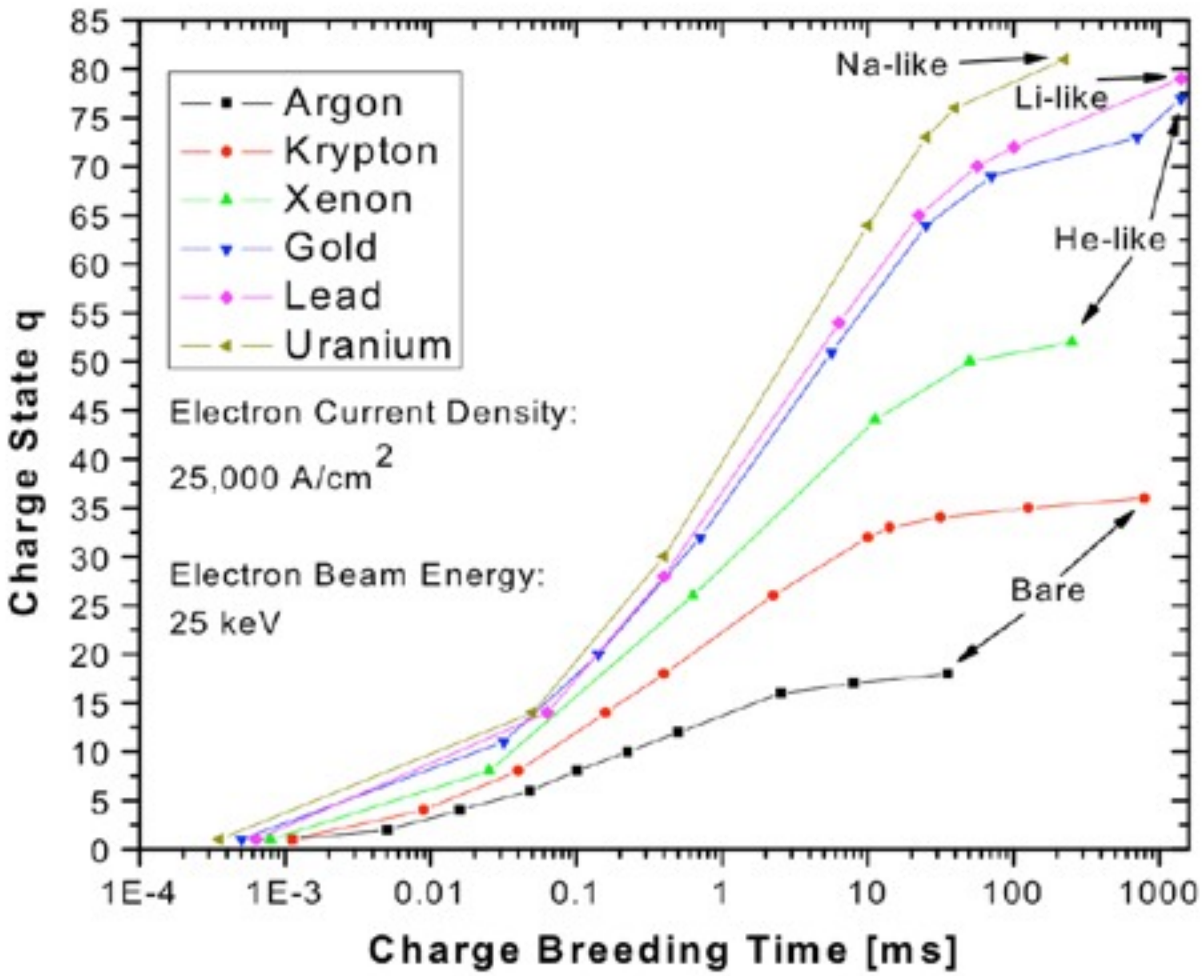

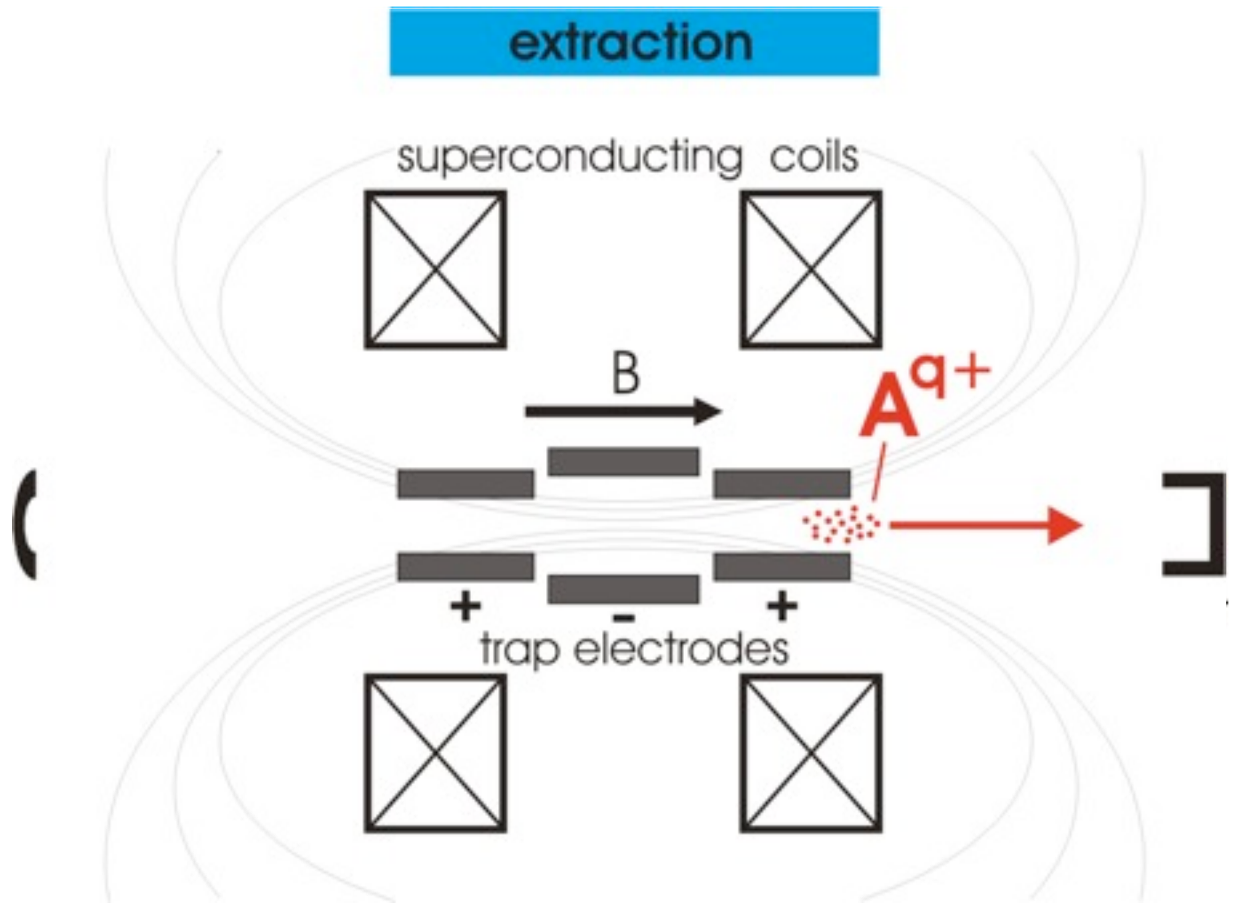

<u>requirements for charge breeding:</u>

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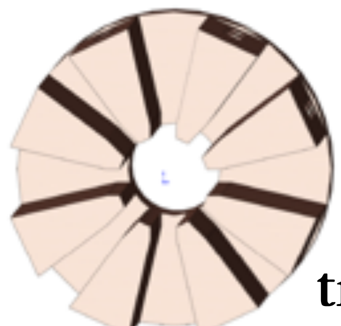
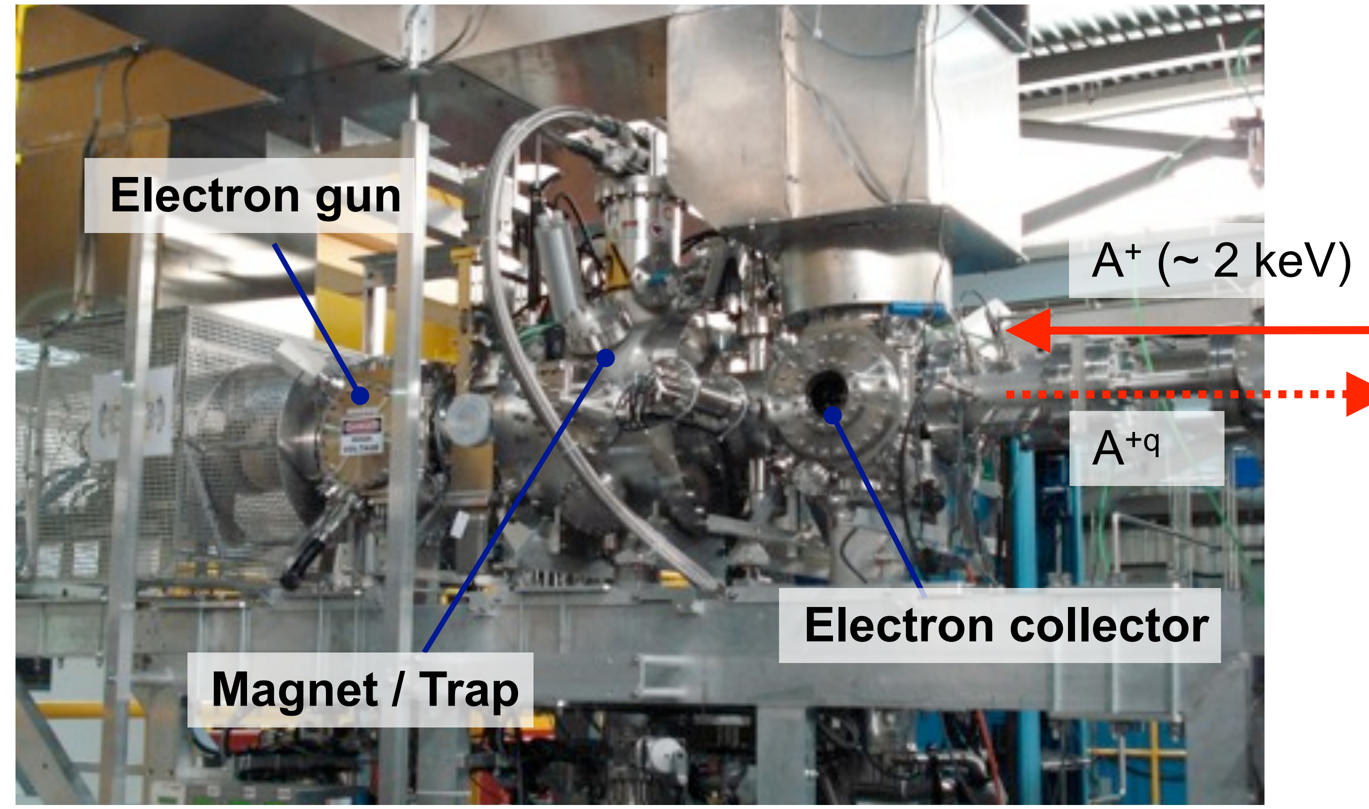
TITAN's EBIT

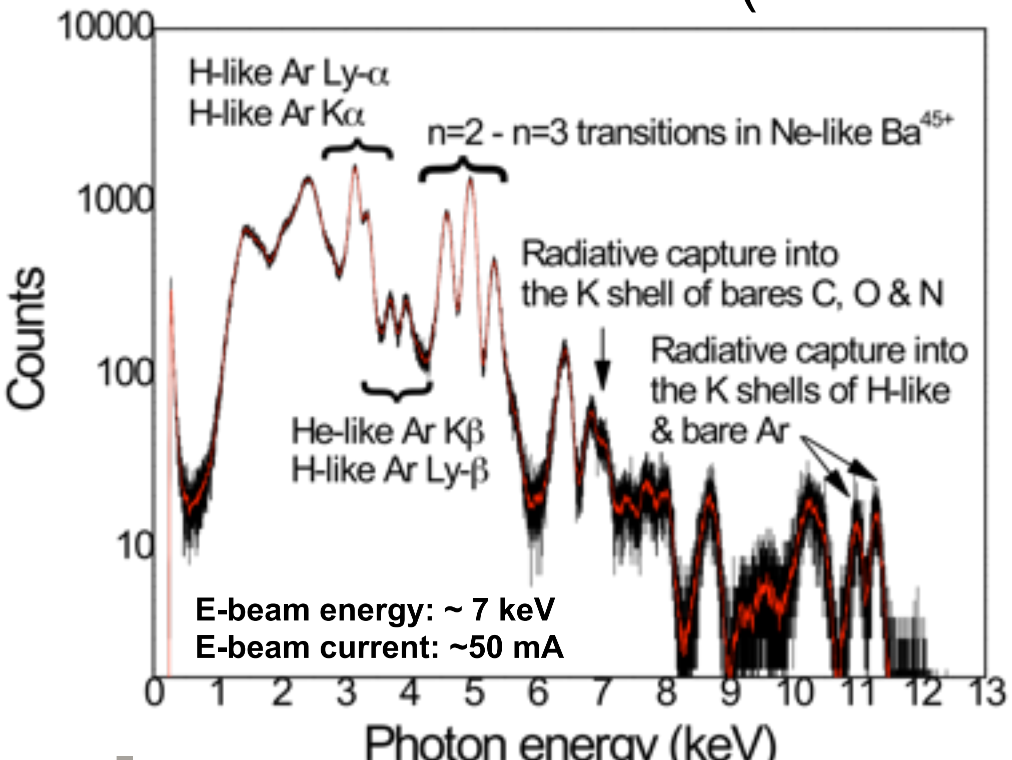


trap electrode



X-ray spectroscopy:

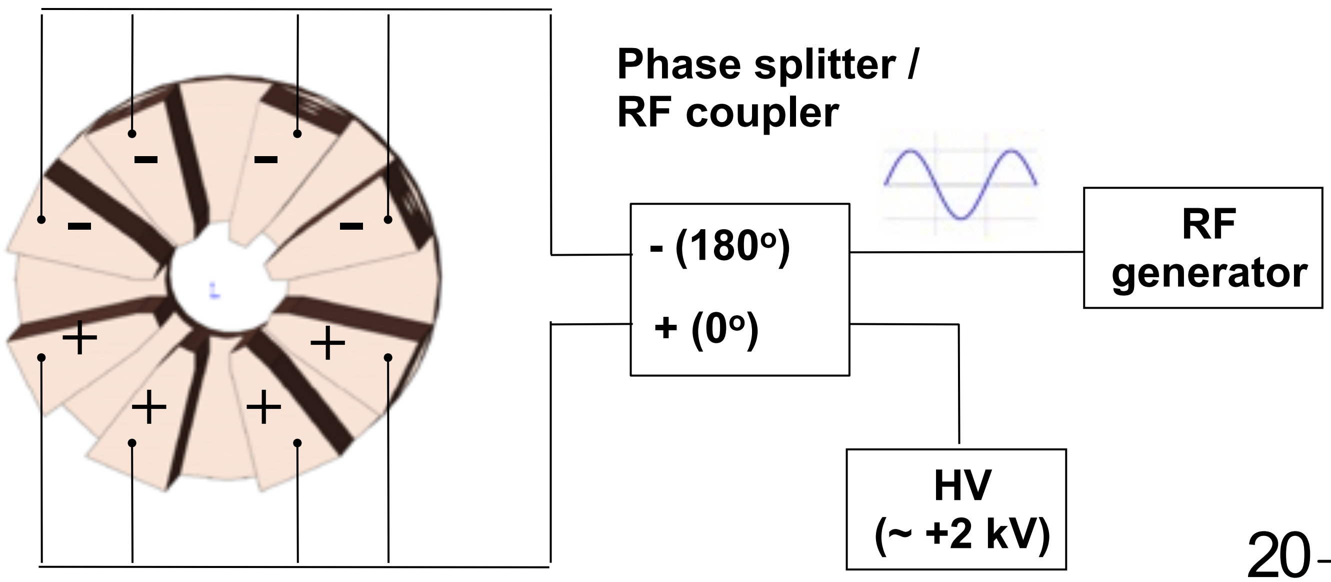
- diagnostics tool for charge breeding
- EC-BR measurement (discussed later)

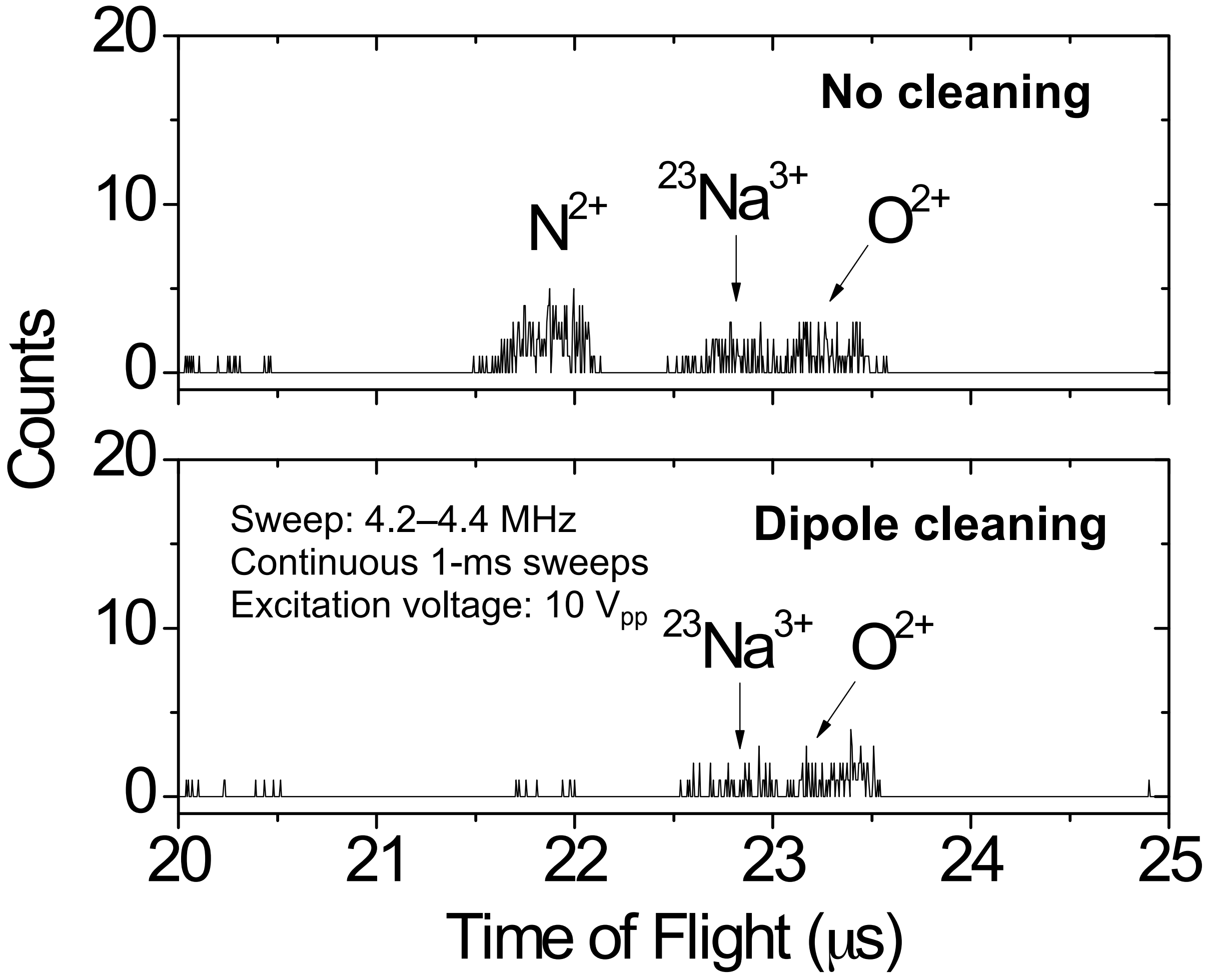


Design values

Max. e-beam energy	~70 keV [demonstr.: 25 keV]
Max. e-beam current	500 mA [demonstr.: 400 mA]
Max. magnetic field strength	6 T
Beam diameter (FWHM)	~40 μm+
Electron beam current density	~10^4 A/cm^2
Number of trapped ions	10^6-10^8 (depending on charge)
Beam energy spread	~50 eV
Highest charge state	~ He-like U, q=90+

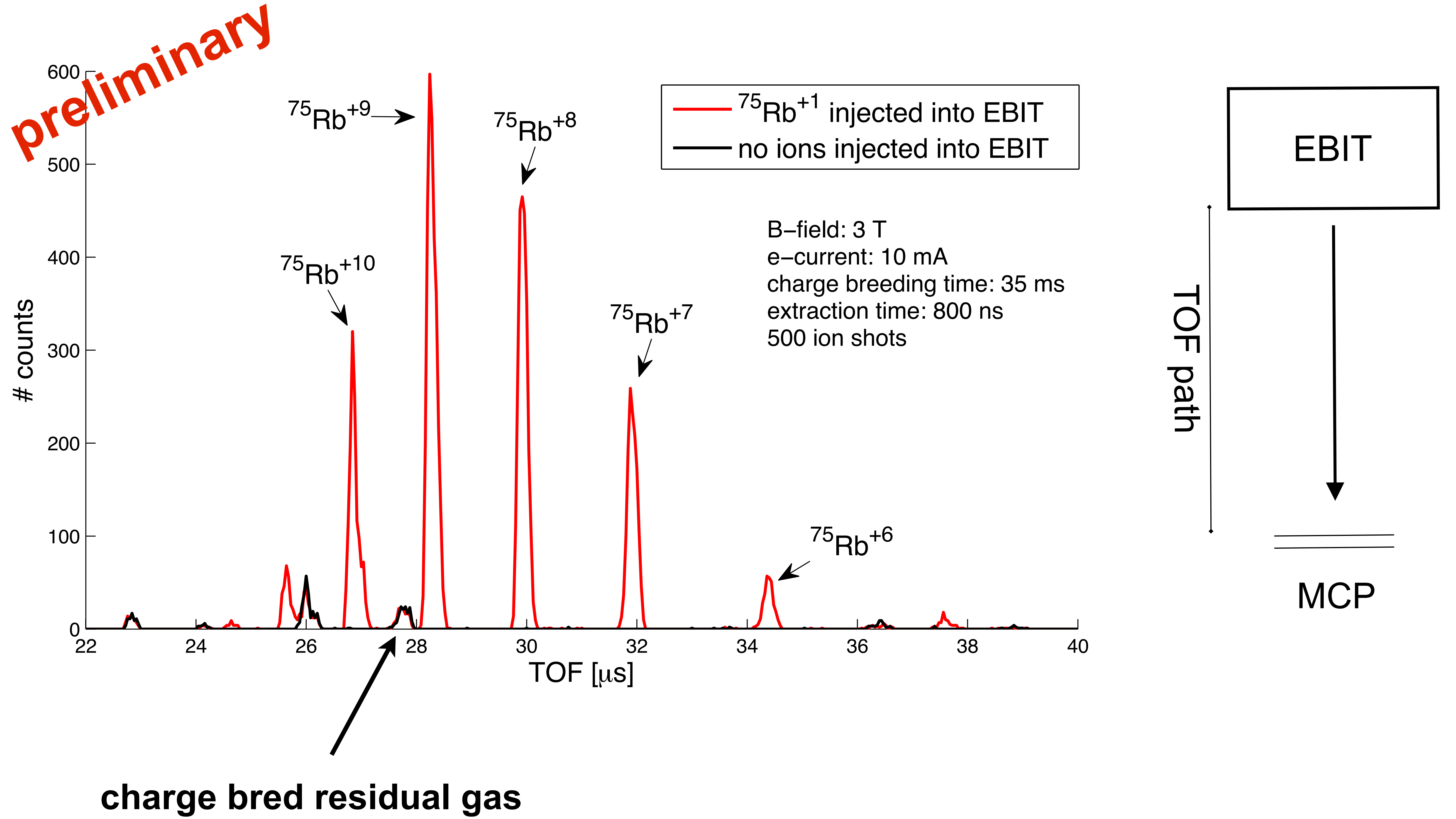
Dipole Cleaning in EBIT



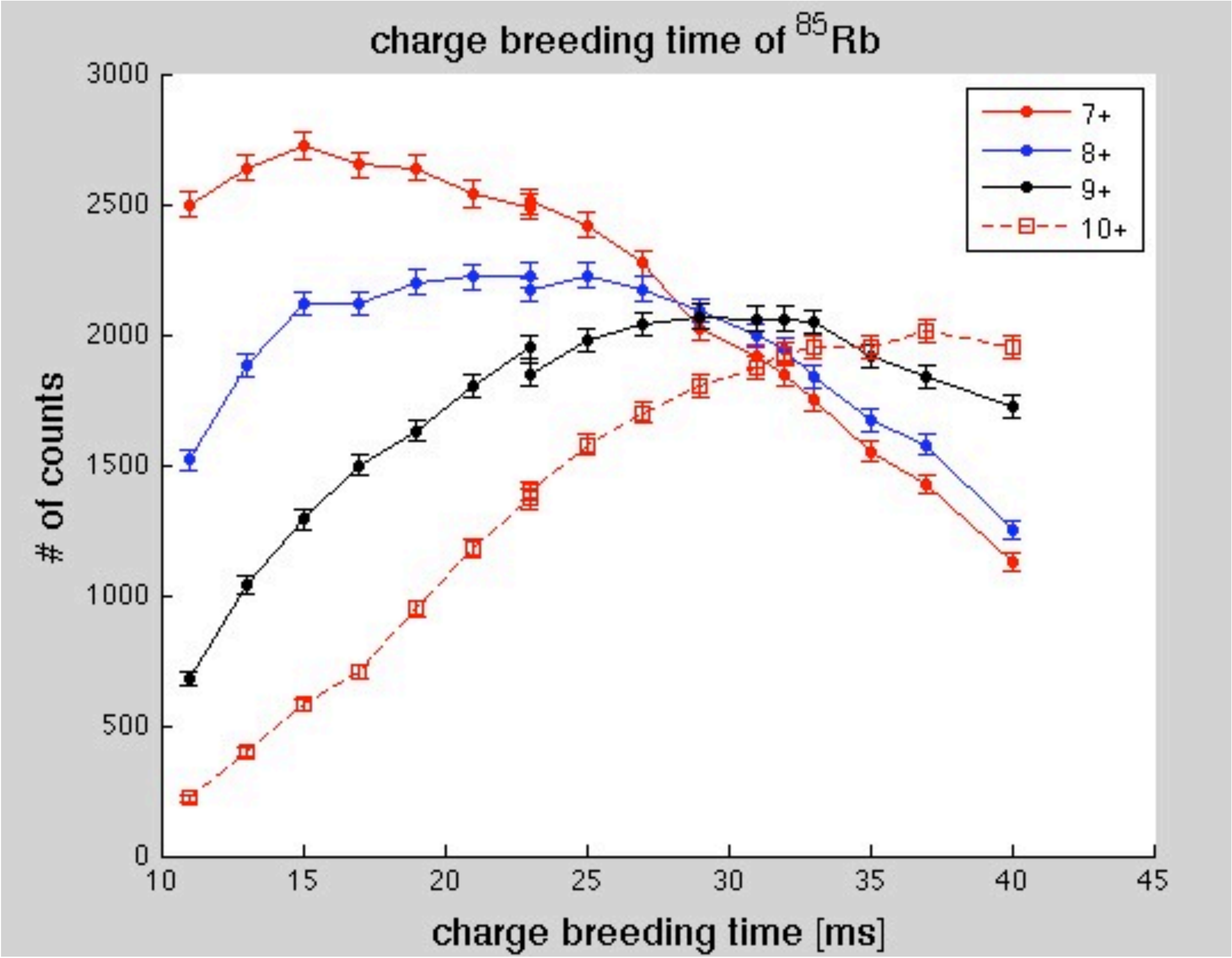


E-beam energy: 3.880 keV
E-beam current: ~5 mA
Breeding time: 100 ms
Extraction (dump) time: 1 ms
(E-beam switched)

Charge Breeding of ^{75}Rb

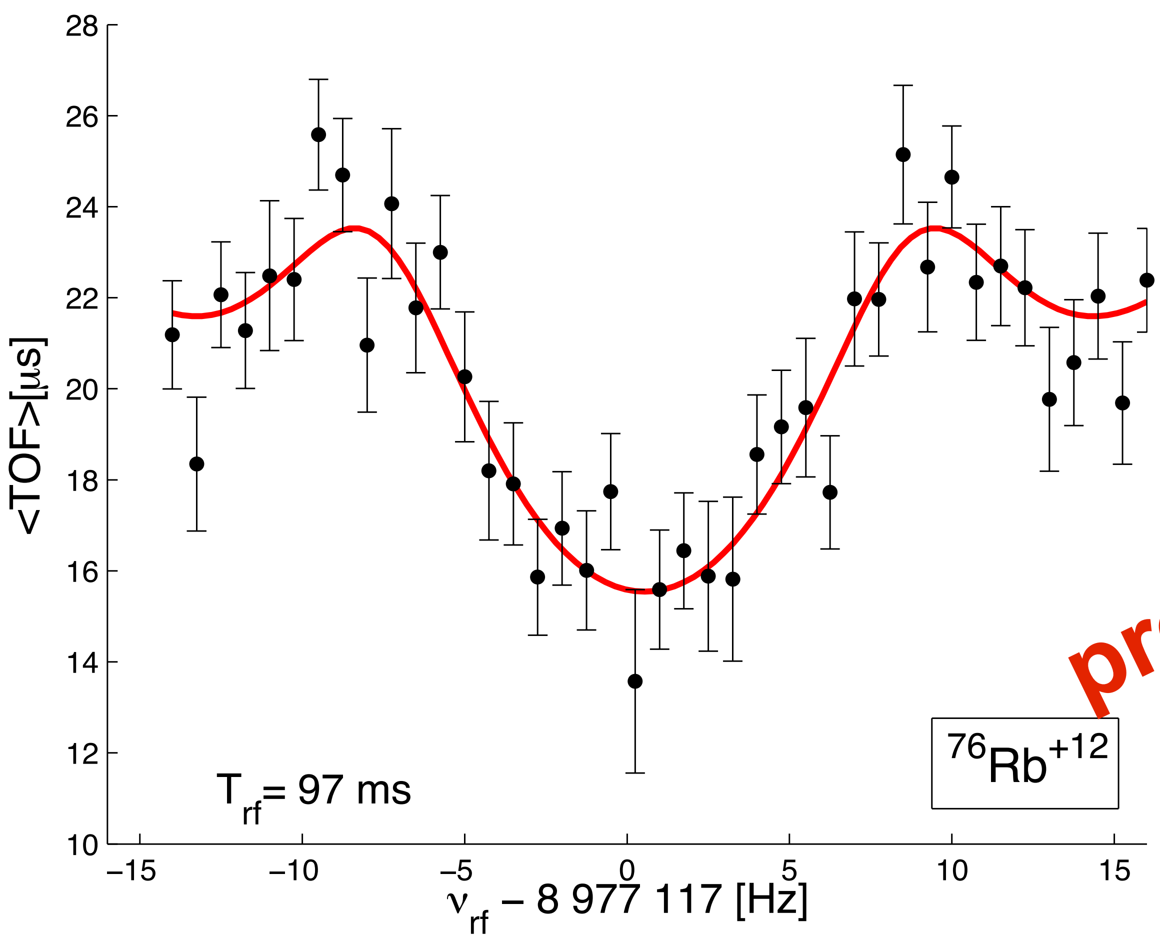


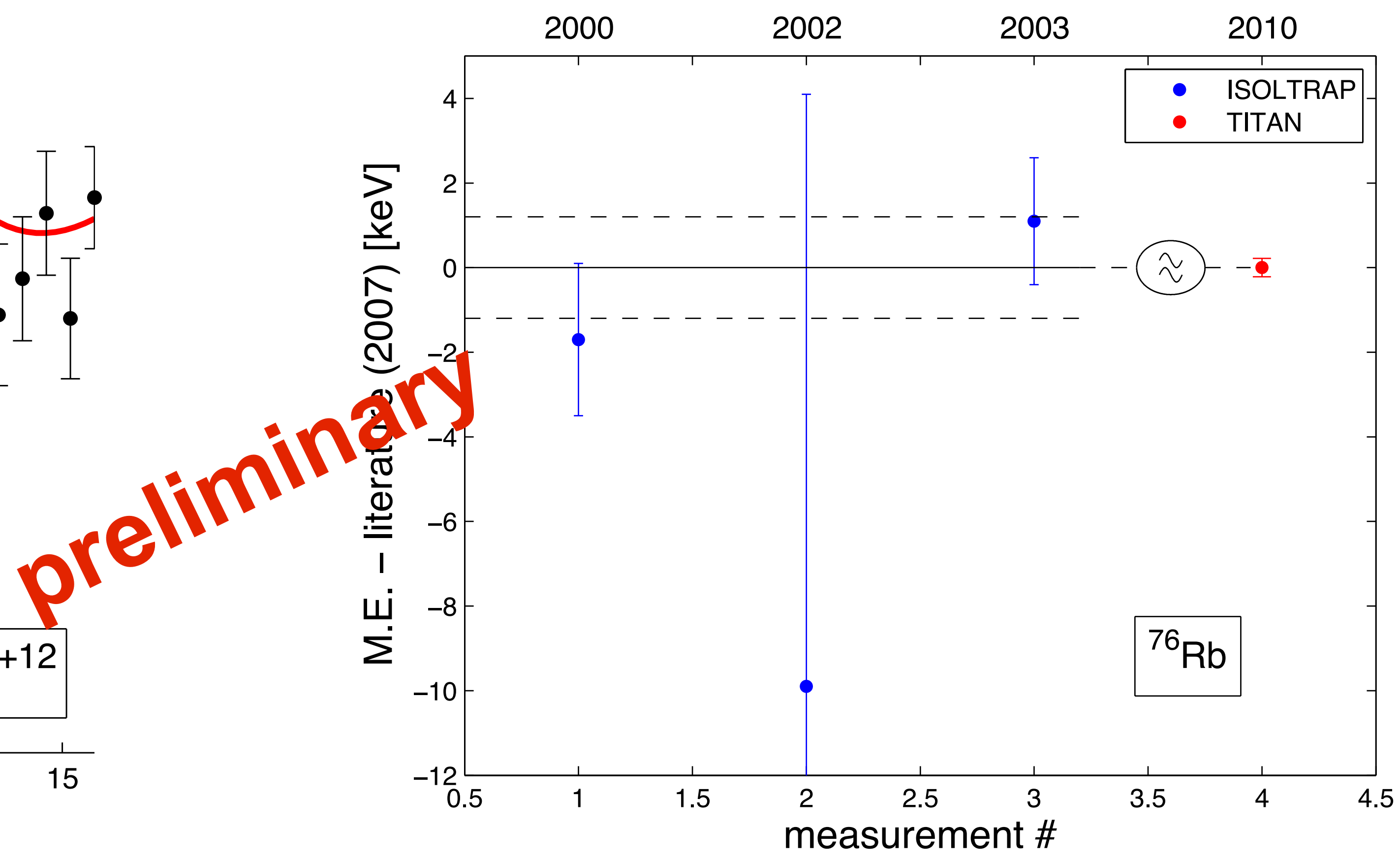
charge breeding time



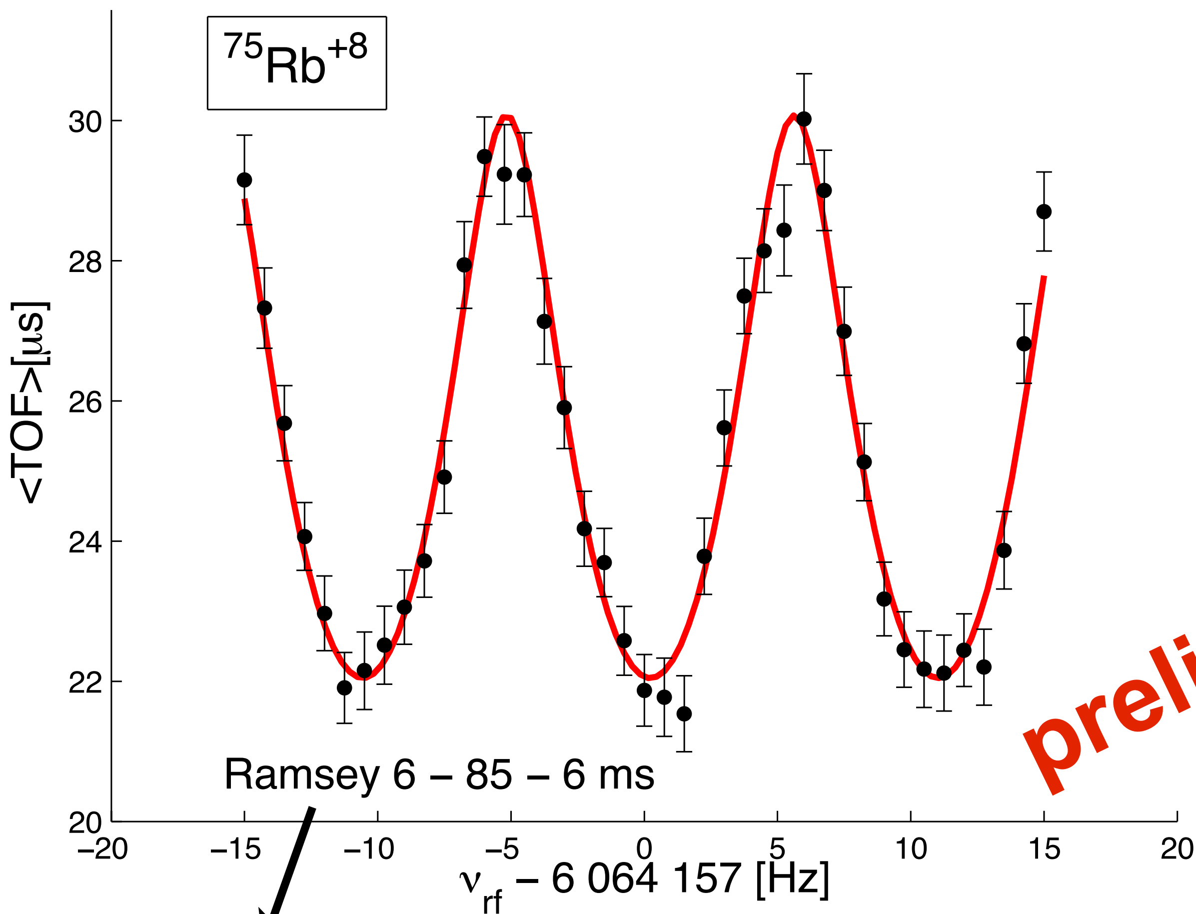
^{76}Rb

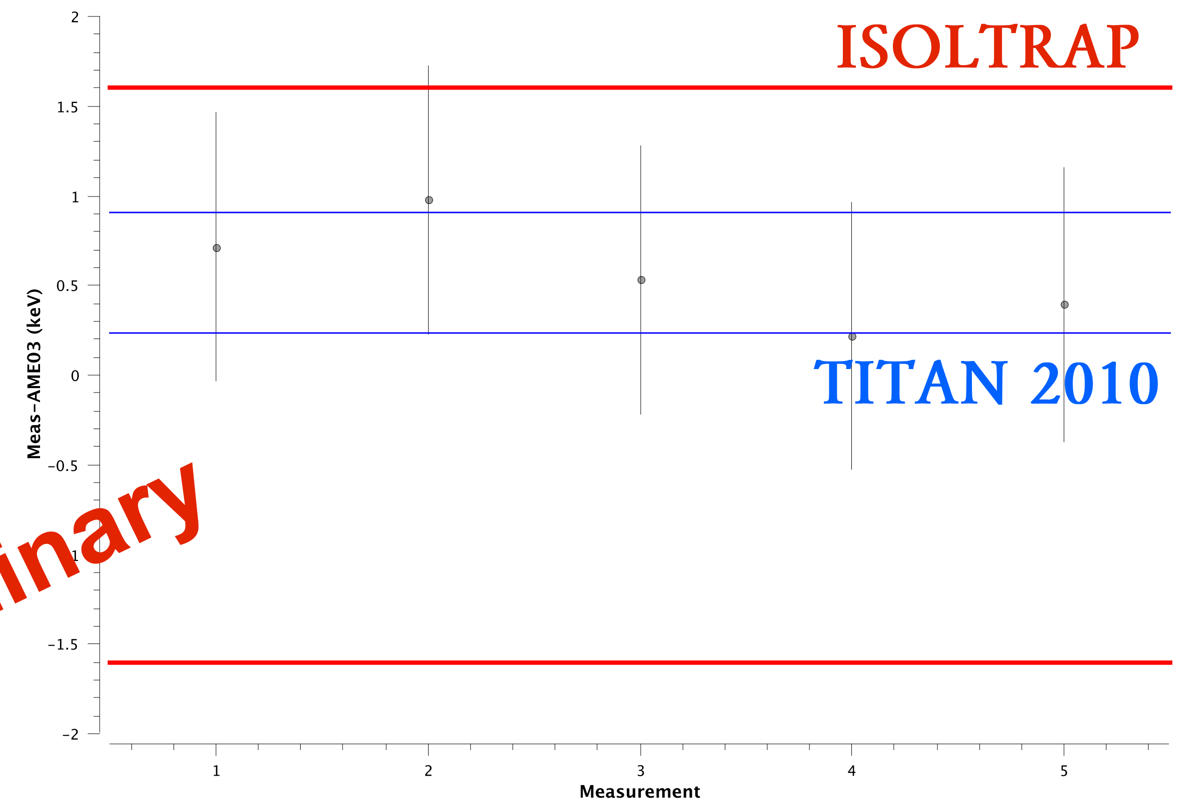
- very first mass measurement of radioactive HCIs
- stat. uncertainty of < 300 eV achieved in a few hours





Ramsey excitation of ^{75}Rb





preliminary

Ramsey excitation:

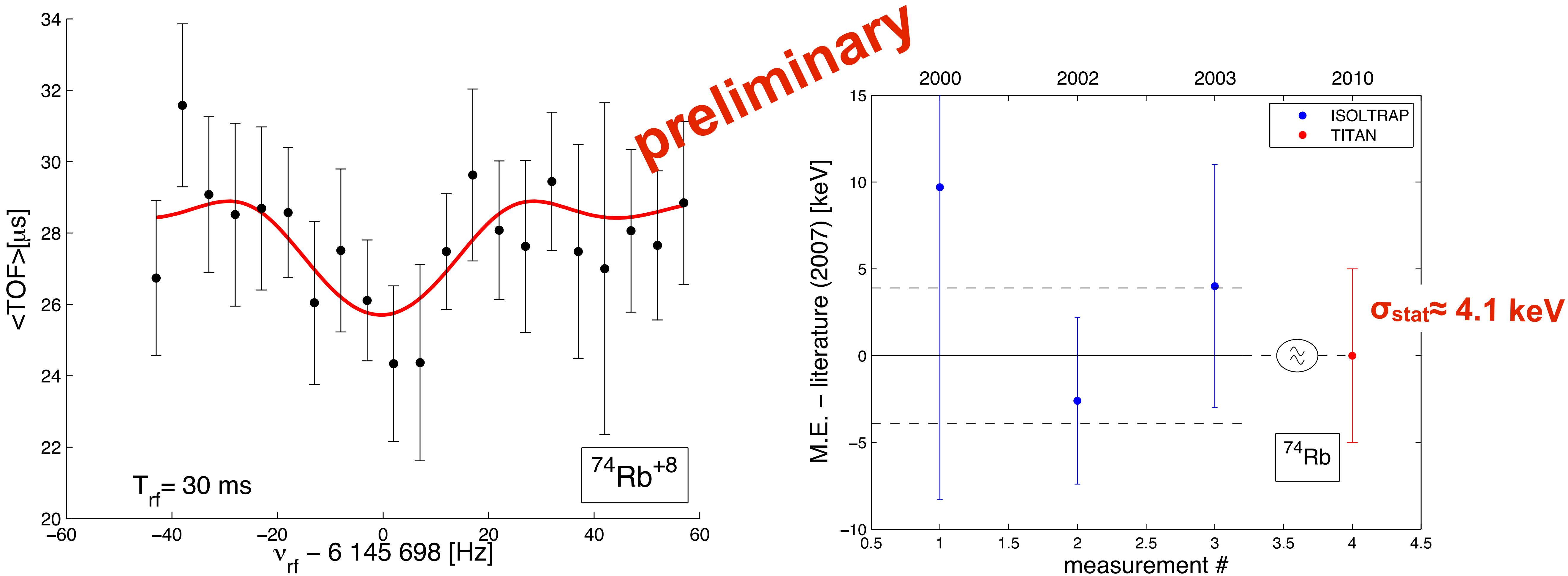
- 2 excitation pulses
- improves precision by a factor 2 - 3

HCI

during this beamtime demonstrated up to q=12+

compared to conventional method: improvement by factor >24

^{74}Rb



^{74}Rb:

- Yield: around 2000/s + contamination from ^{74}Ga
- precision already comparable to ISOLTRAP (2007)

BUT

- data of < 20 hours
- power outage during ^{74}Rb => reconditioning of EBIT => lower efficiency

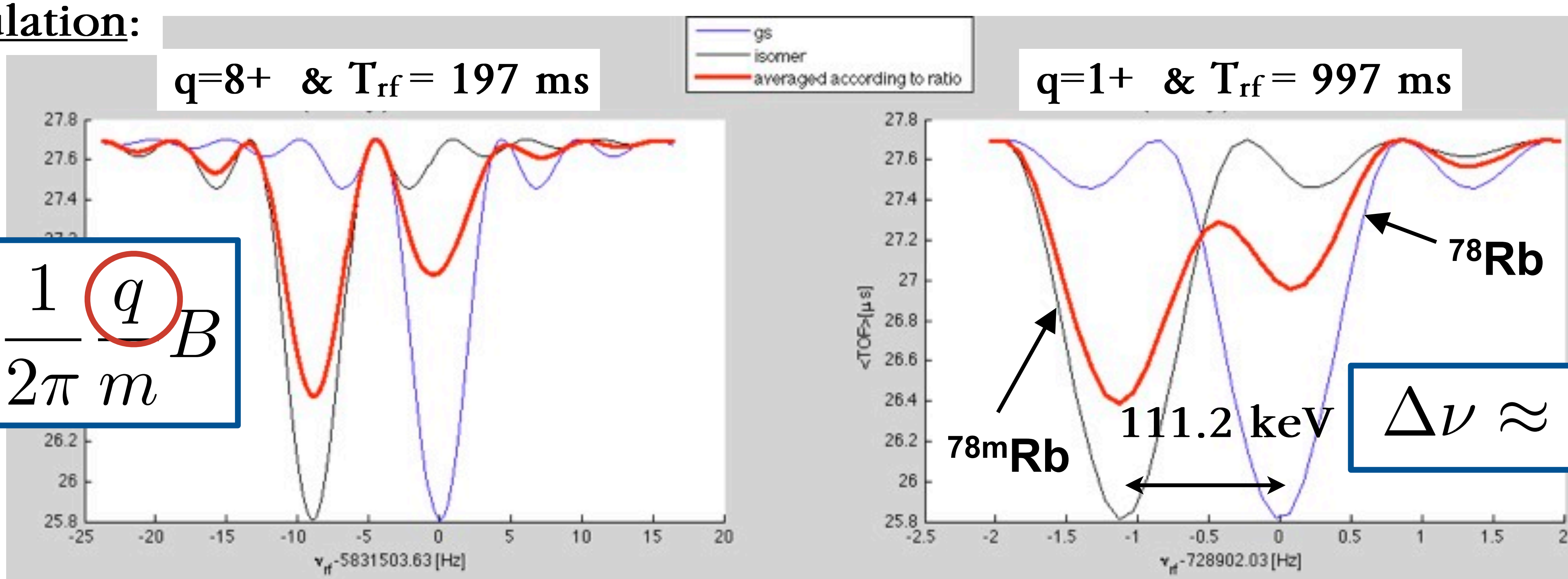
=> “easy” improvement next time

S. Ettenauer et al., in preparation

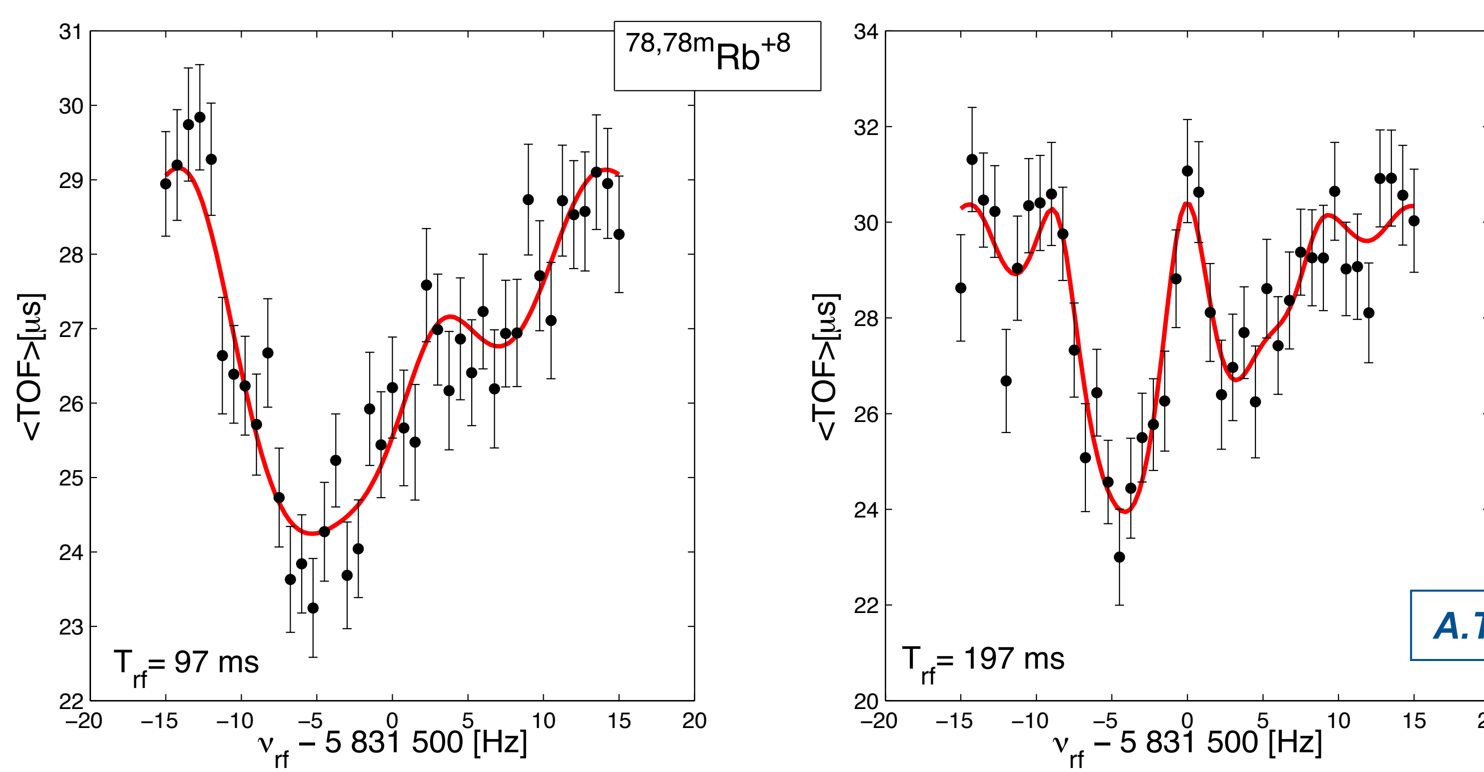
HCI and Isomers

Calculation:

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



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



A.T. Gallant et al., in preparation

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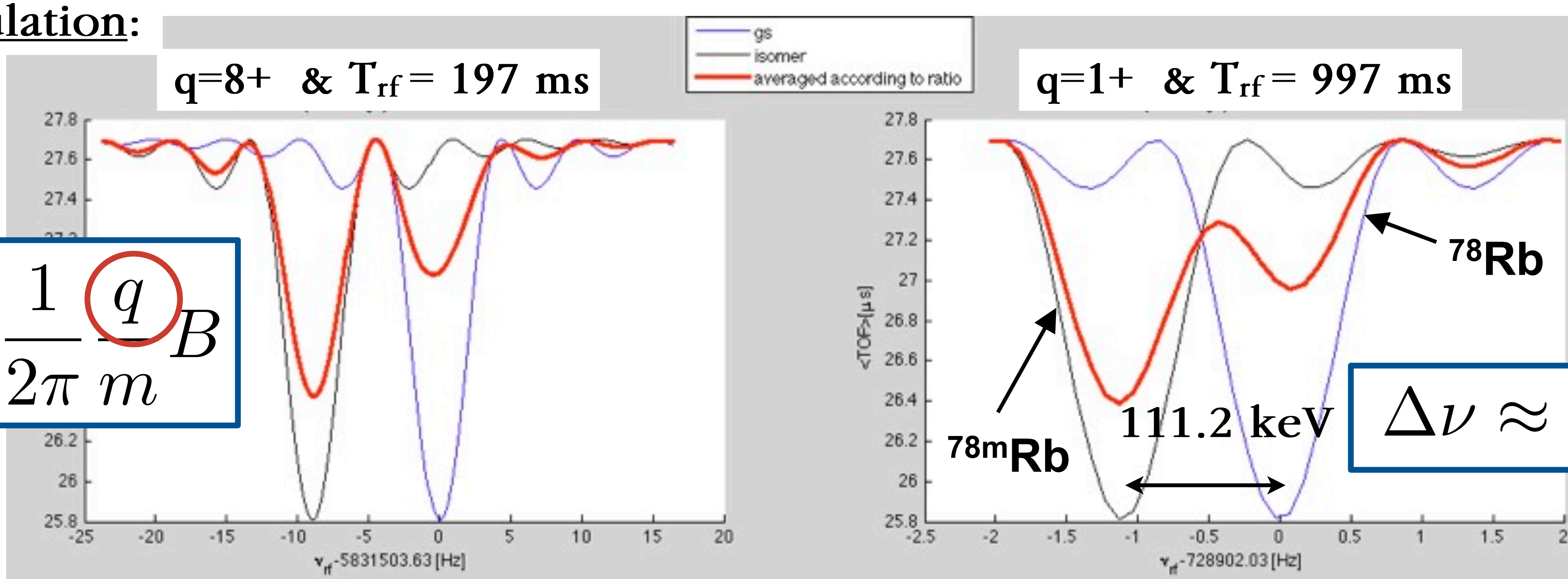

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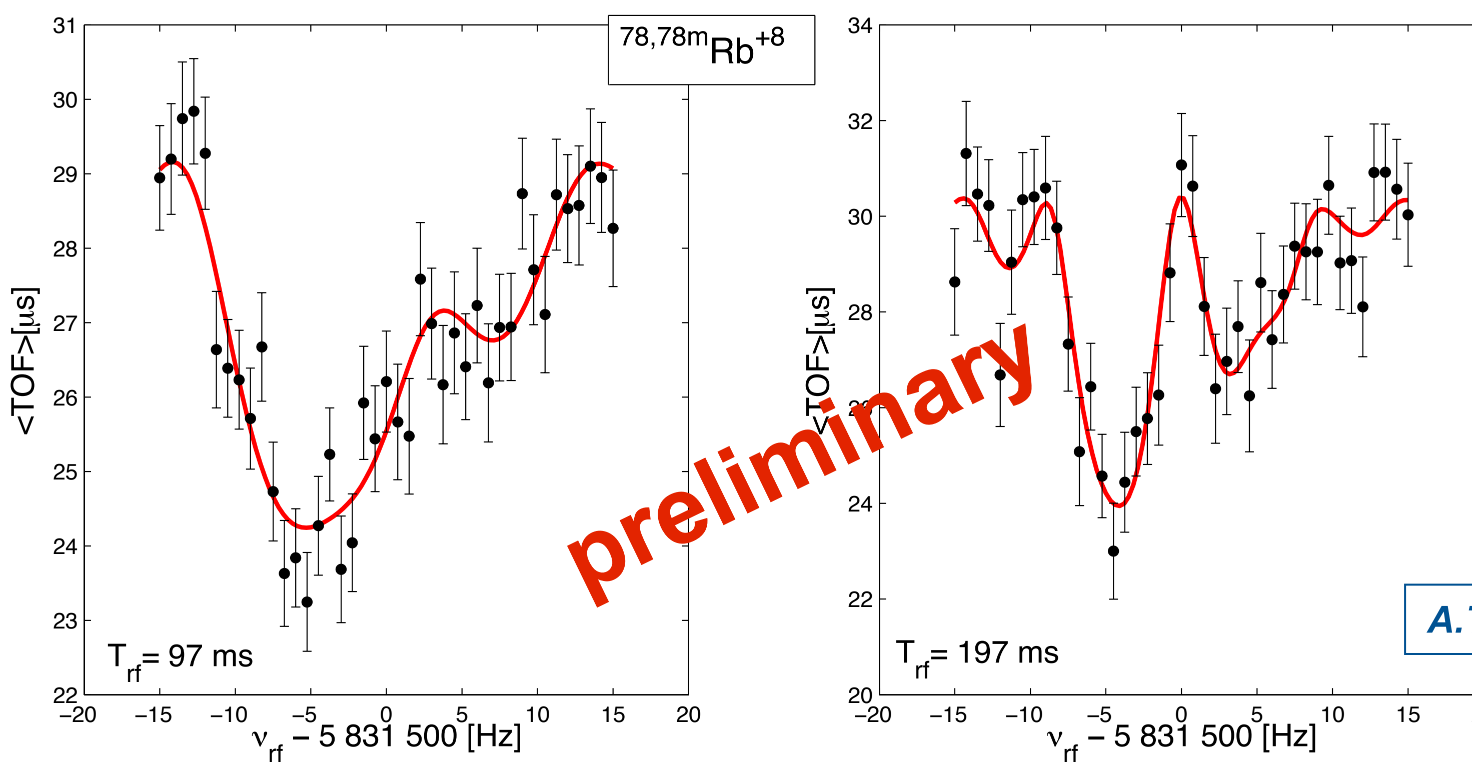
Measurement:



A.T. Gallant et al., in preparation

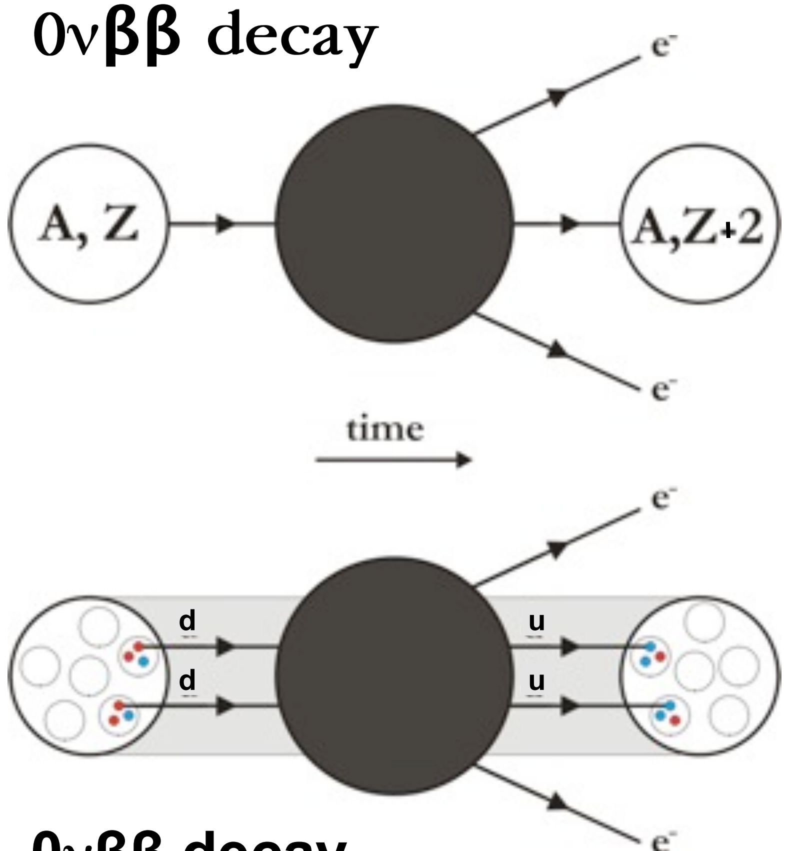
EC-BR measurements and 2νββ Matrix Elements

neutrino oscillation experiments:

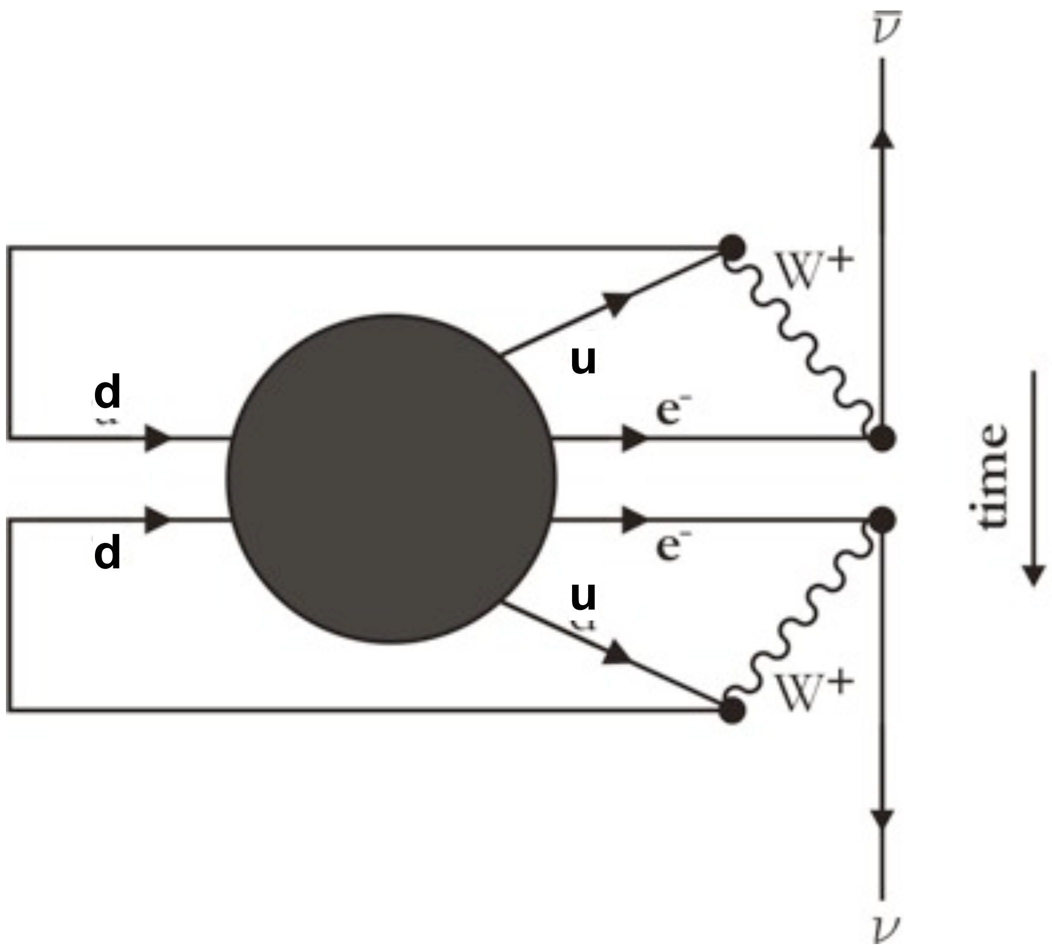
- neutrino massive
- BUT: no information about absolute mass scale & type of mass

absolute scale:

- electron endpoint energy in beta decay
- astrophysical limit
- 0νββ decay



0νββ decay



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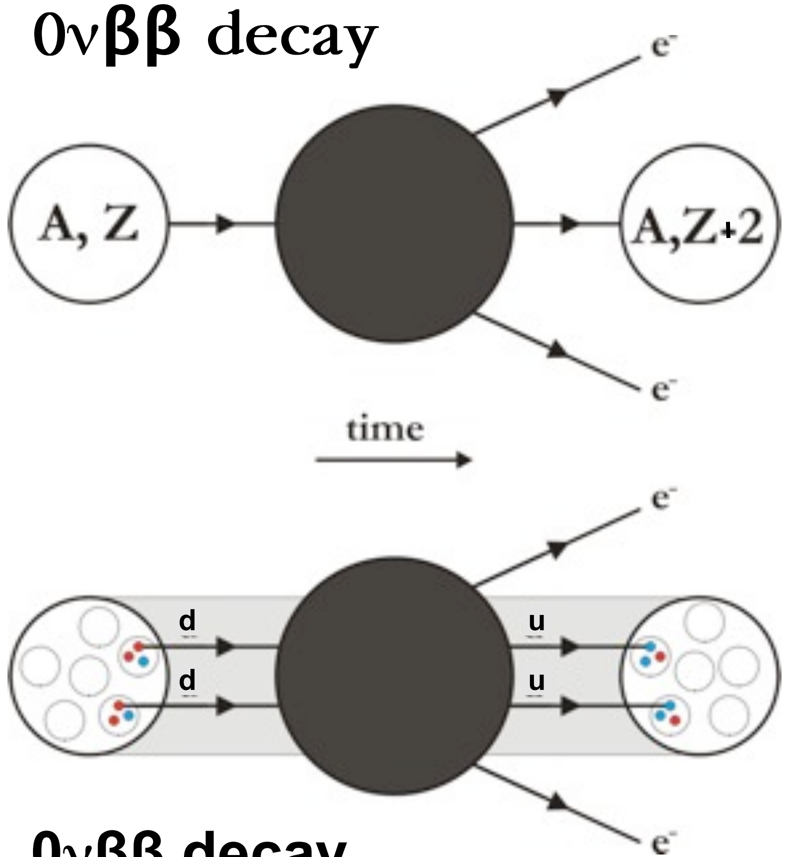
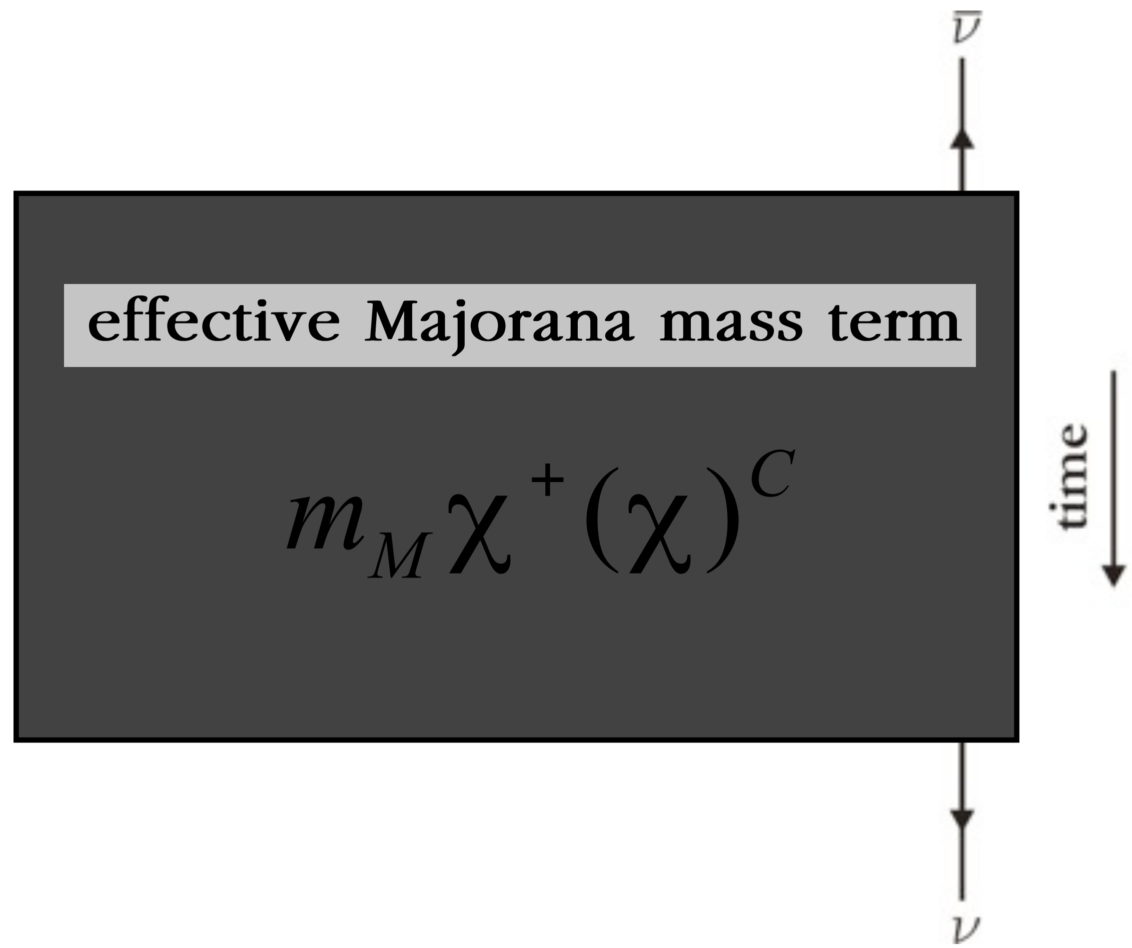


0νββ decay



Nuclear Matrix Element

$0\nu\beta\beta$ decay rate: $\Gamma = G\,|M|^2 \langle m_{\nu e} \rangle^2$

phase space factor

nuclear matrix element:

effective Majorana mass $\langle m_{\nu e} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$

theoretical models:

- proton-neutron Quasiparticle Random Phase Approximation (pnQRPA)
- nuclear shell model
- interacting boson model
- !! NEW: χEFT !!

J. Menéndez et al., arXiv:1103.3622

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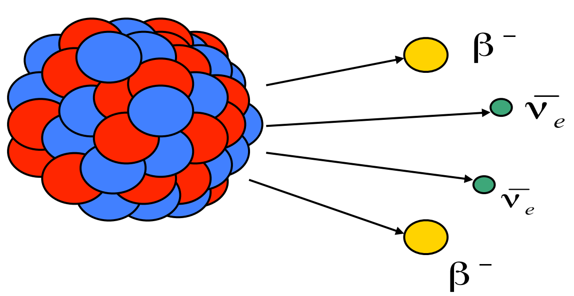
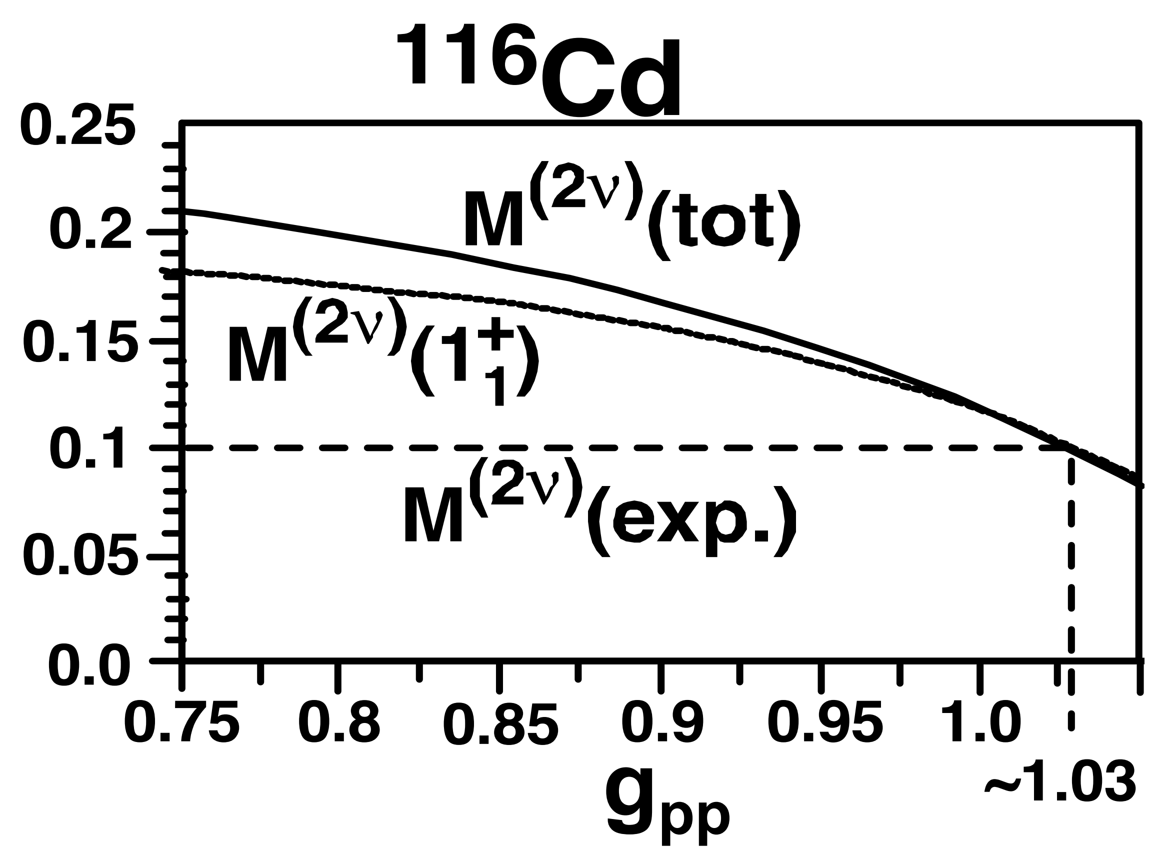
- !! NEW: χEFT !! J. Menéndez et al., arXiv:1103.3622

- adjustable particle-particle parameter g_{pp}
- fix g_{pp} with $2\nu\beta\beta$ decay (very sensitive on g_{pp})





- $0\nu\beta\beta$ decay much less dependent on g_{pp}

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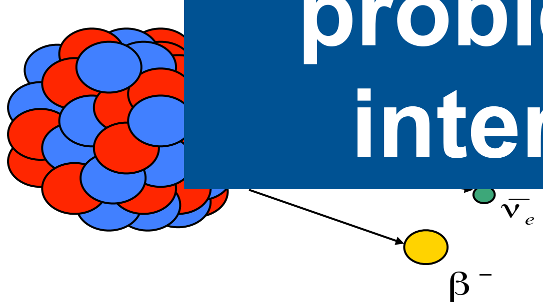
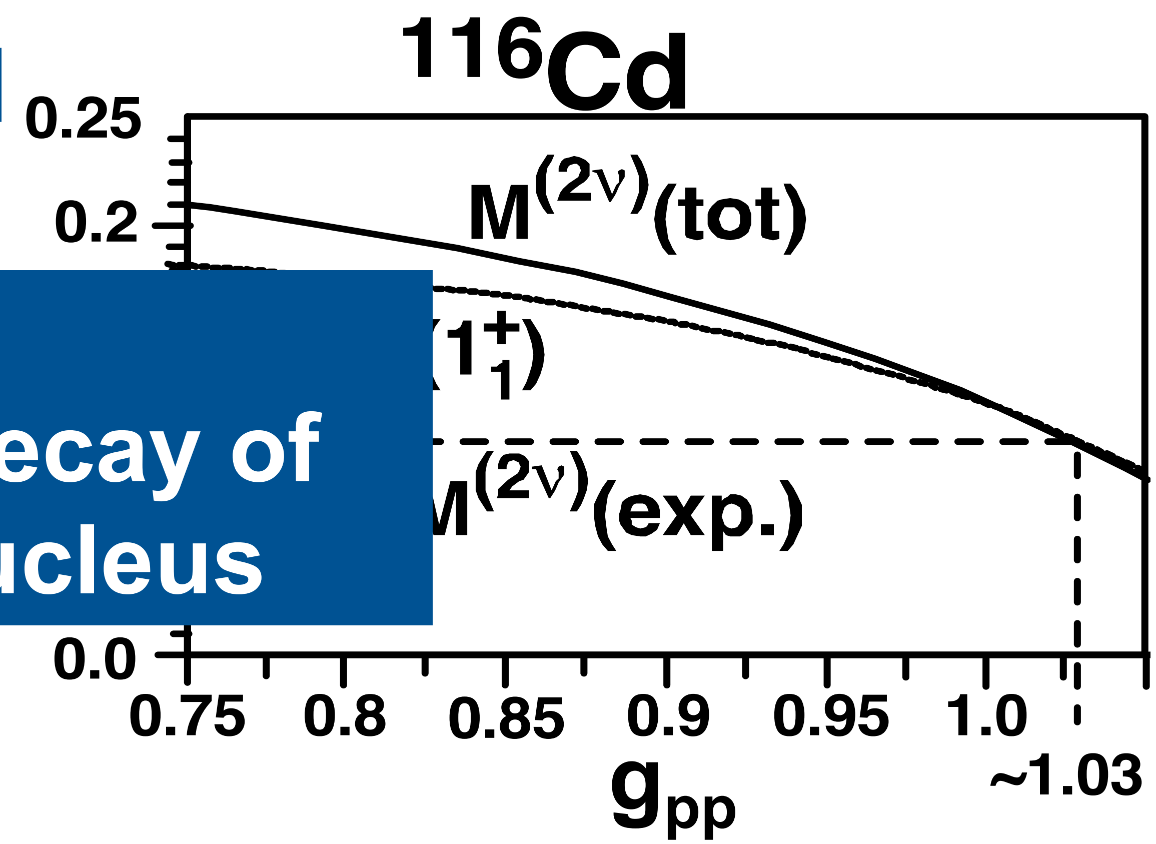


BUT: problems with decay of intermediate nucleus



- $0\nu\beta\beta$ decay much less dependent on g_{pp}

New Approach for ECBR

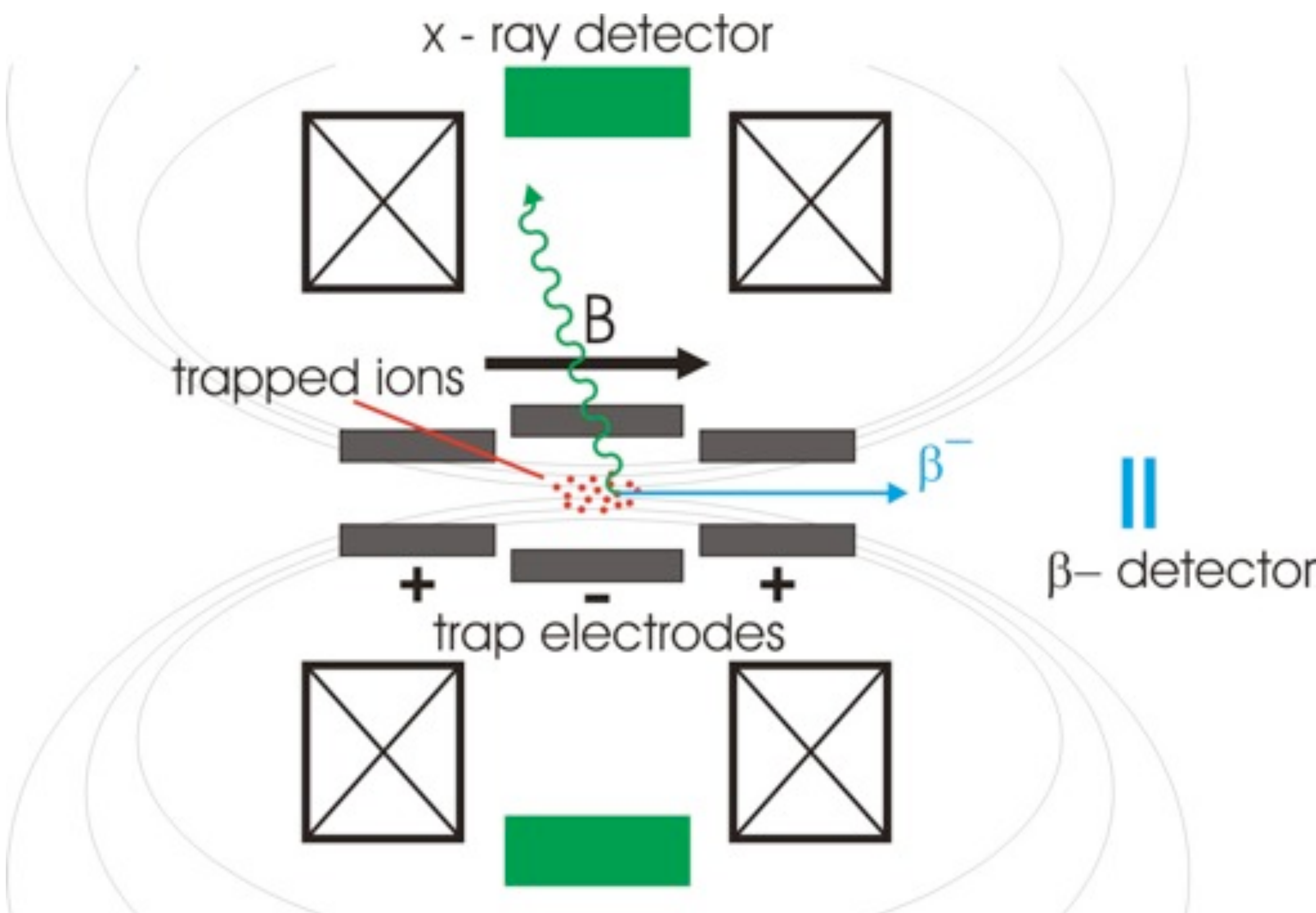
EBIT in Penning trap mode

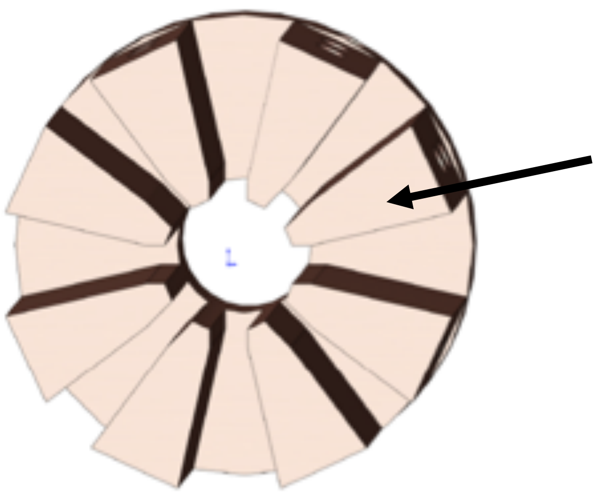
confinement:

- axial by electrostatic field
- B-field (6 T)

in-trap spectroscopy:

- strong B field spatial separation of X-ray and β-particles
- segmented trapping electrodes → close placement of X-ray detectors
- extract ions after observation time low background
- β-dectector: anti-coincidence



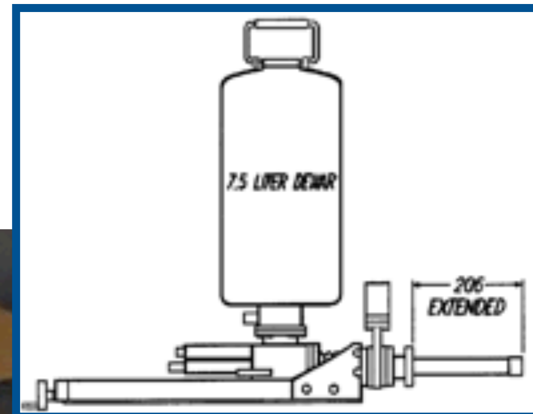


no β - background
no absorption in backing material

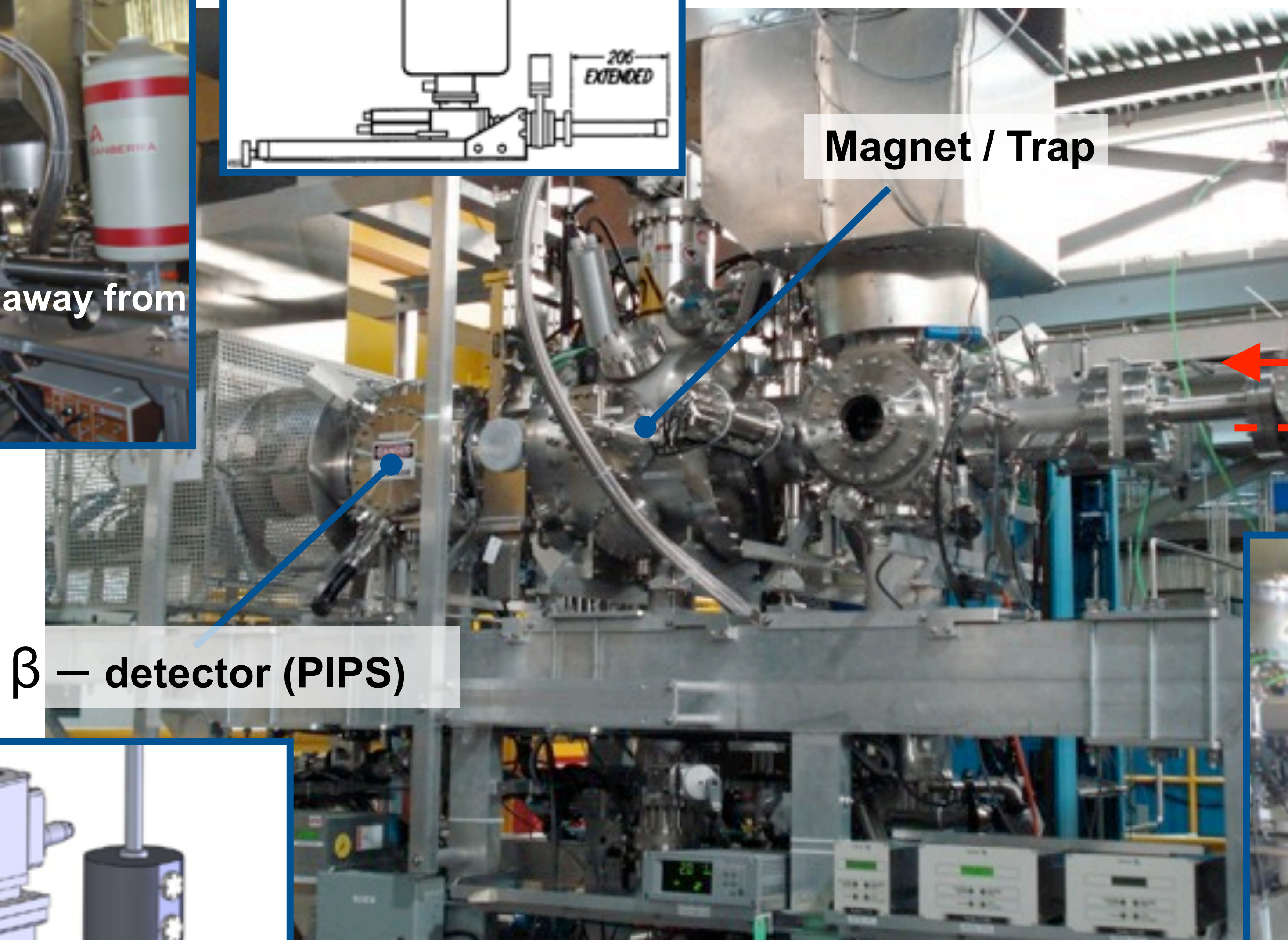
J. Dilling et al., Can. J. Phys. 85, 57 (2007)
T. Brunner et al., NIM B 266, 4643 (2008)

Detector Positions

LEGe X-ray detector
in vacuum

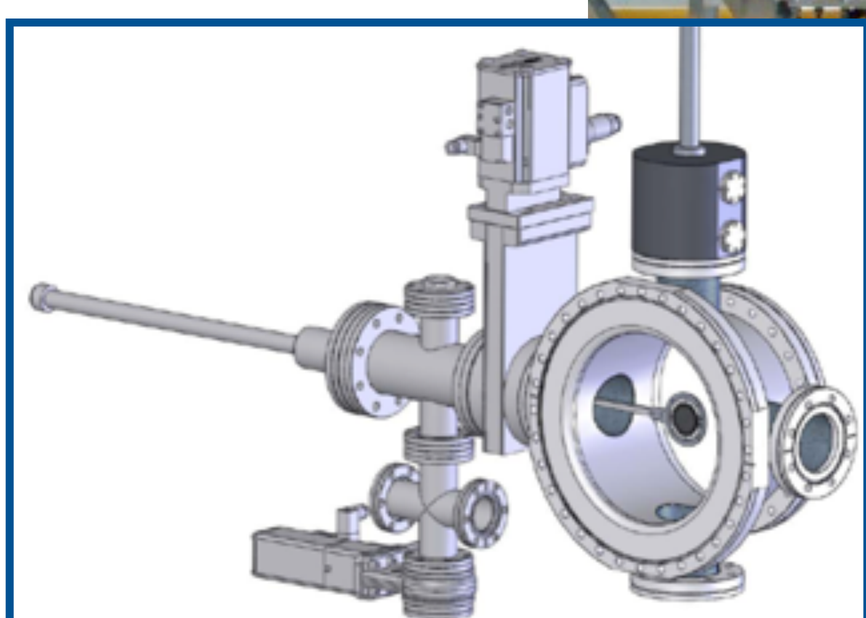


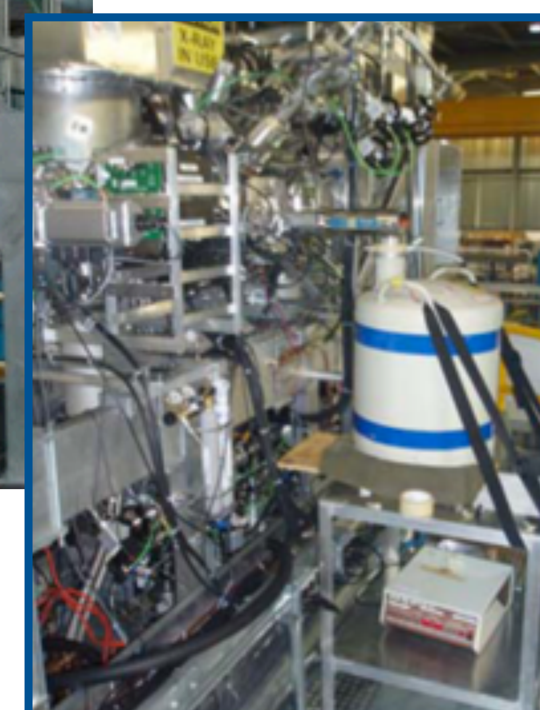
total solid angle: 0.7 %
<u>final: 2.1 %</u>



Injection

Extraction





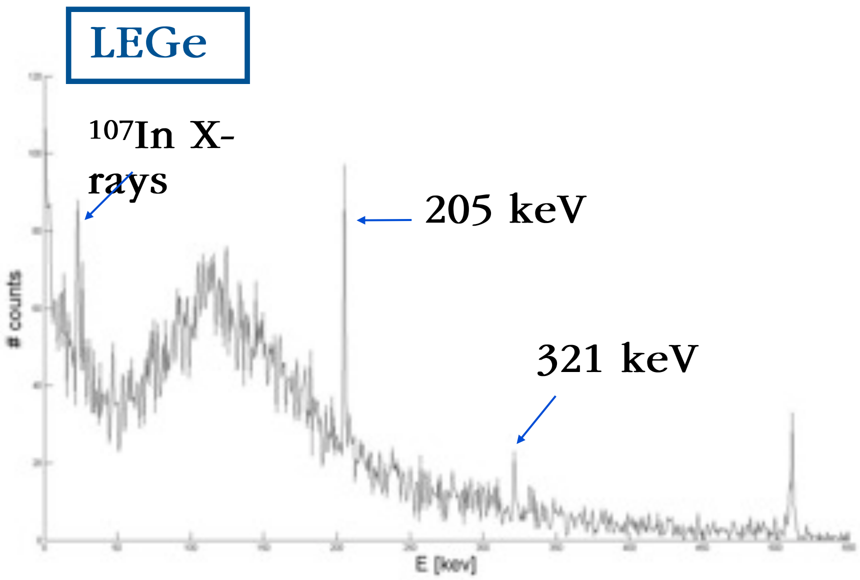
20 % **Coax Ge** external

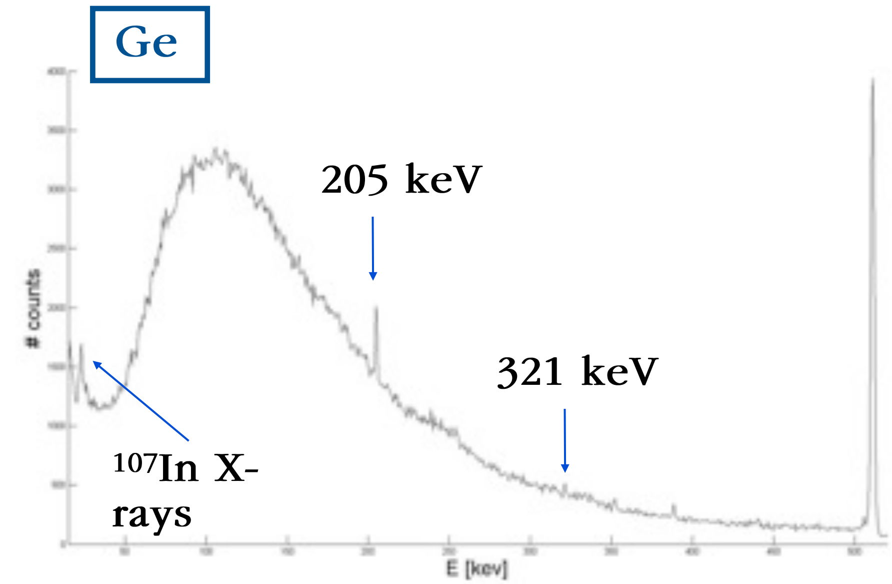
Proof-of-Principle

^{107}In

BR(EC)=(55 ± 20) %
lit =(64 ± 3) %

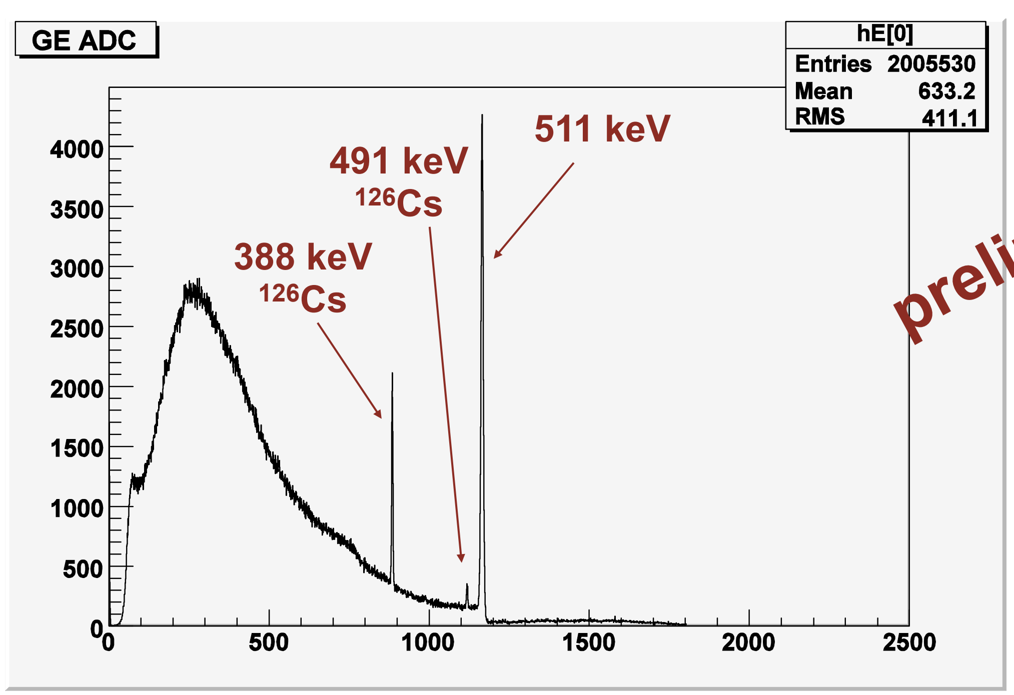
but problems with ion losses in trap

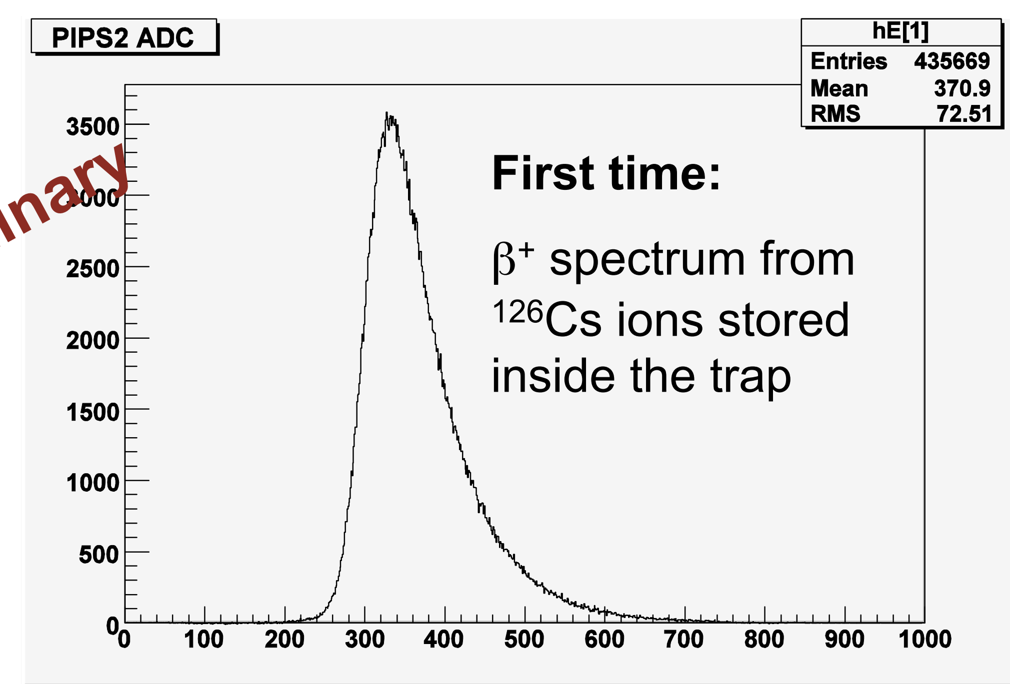




S. Ettenauer et al., AIP Conf. Proc. 1182(2009)100

^{126}Cs





First time:

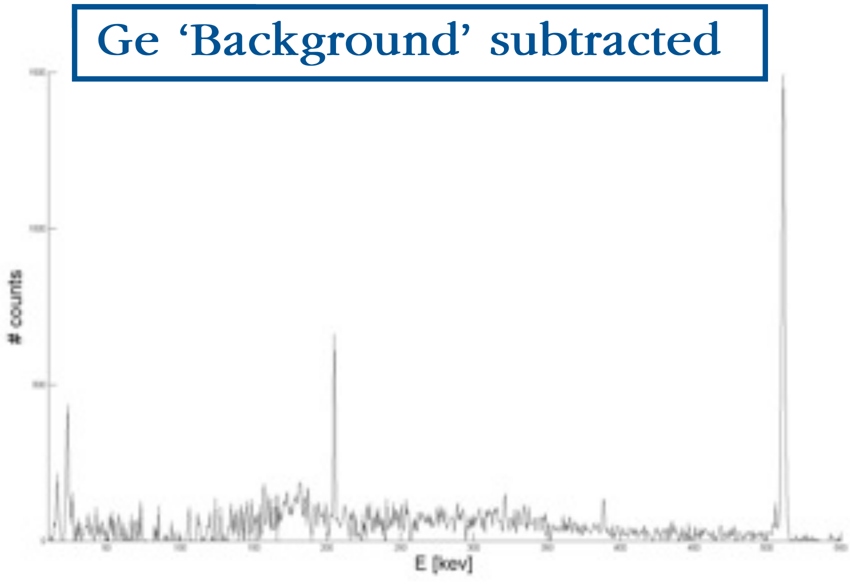
β^+ spectrum from ^{126}Cs ions stored inside the trap

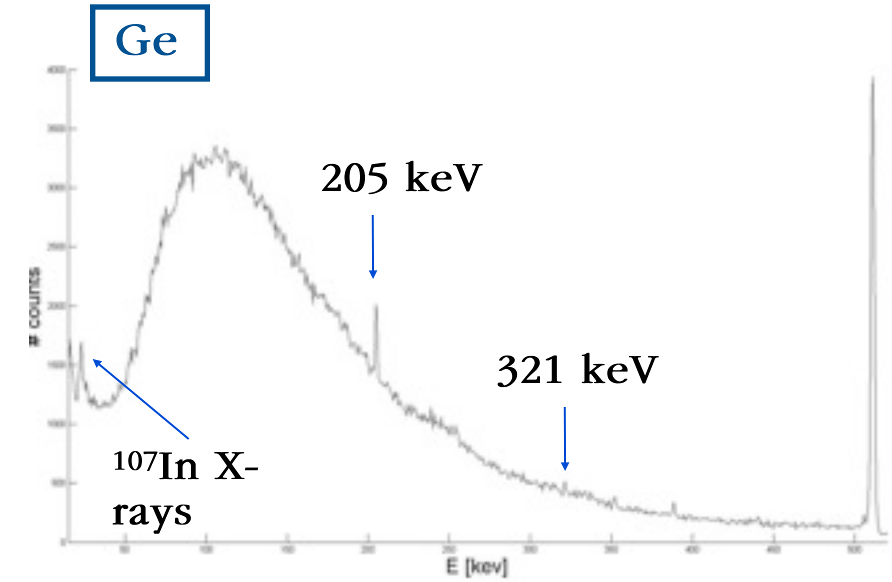
Proof-of-Principle

^{107}In

BR(EC)=(55 ± 20) %
lit =(64 ± 3) %

but problems with ion losses in trap





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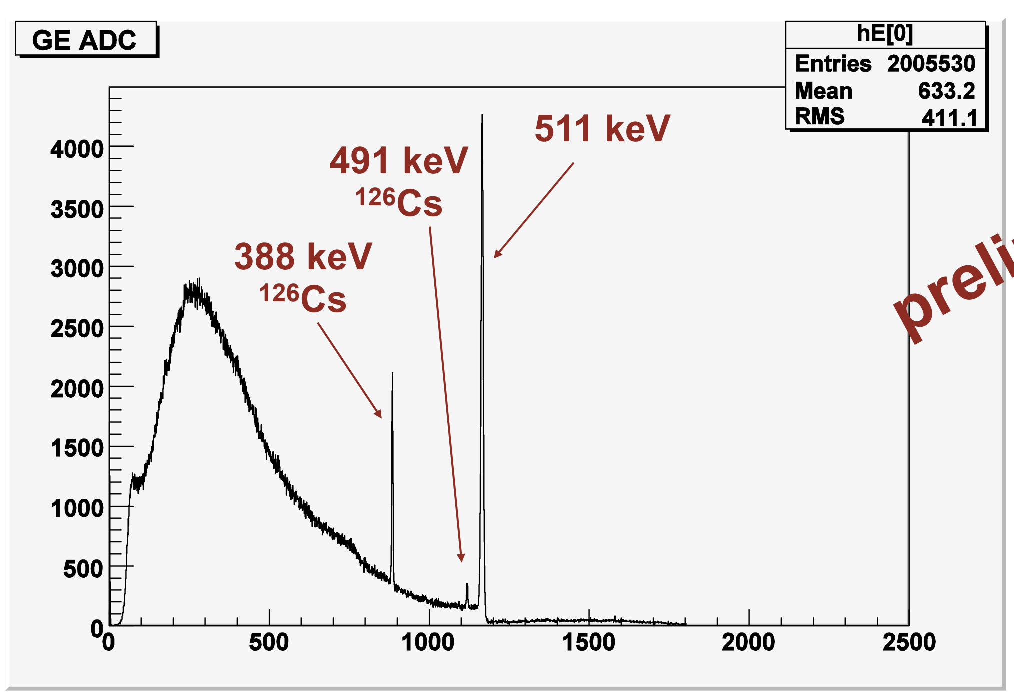
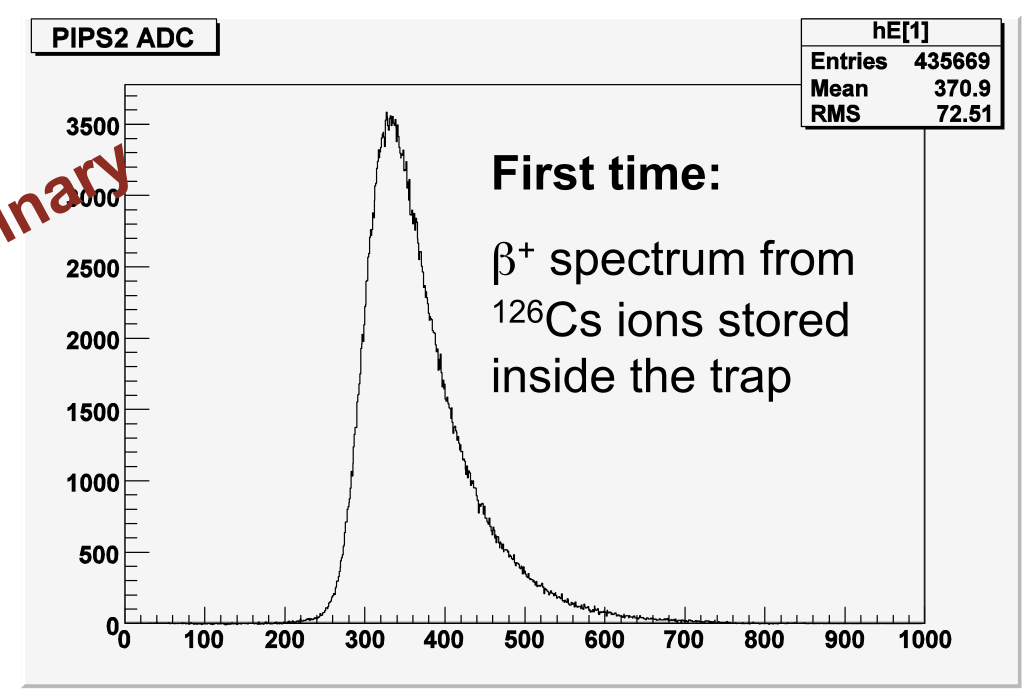
^{126}Cs





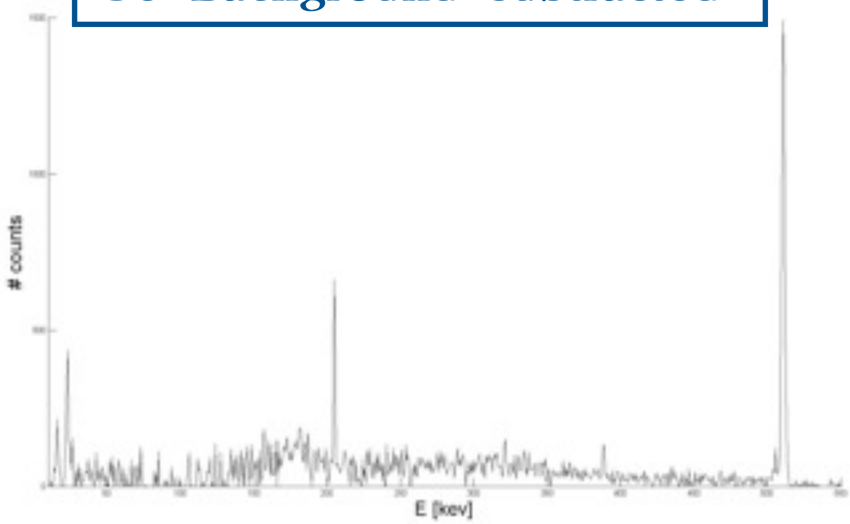
Proof-of-Principle

^{107}In

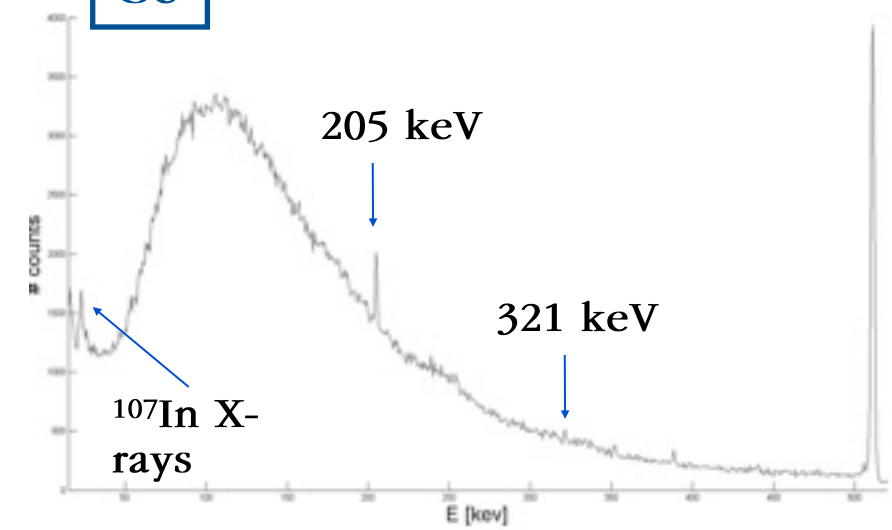
BR(EC)=(55 ± 20) %
lit =(64 ± 3) %

but problems with ion losses in trap

Ge 'Background' subtracted



Ge



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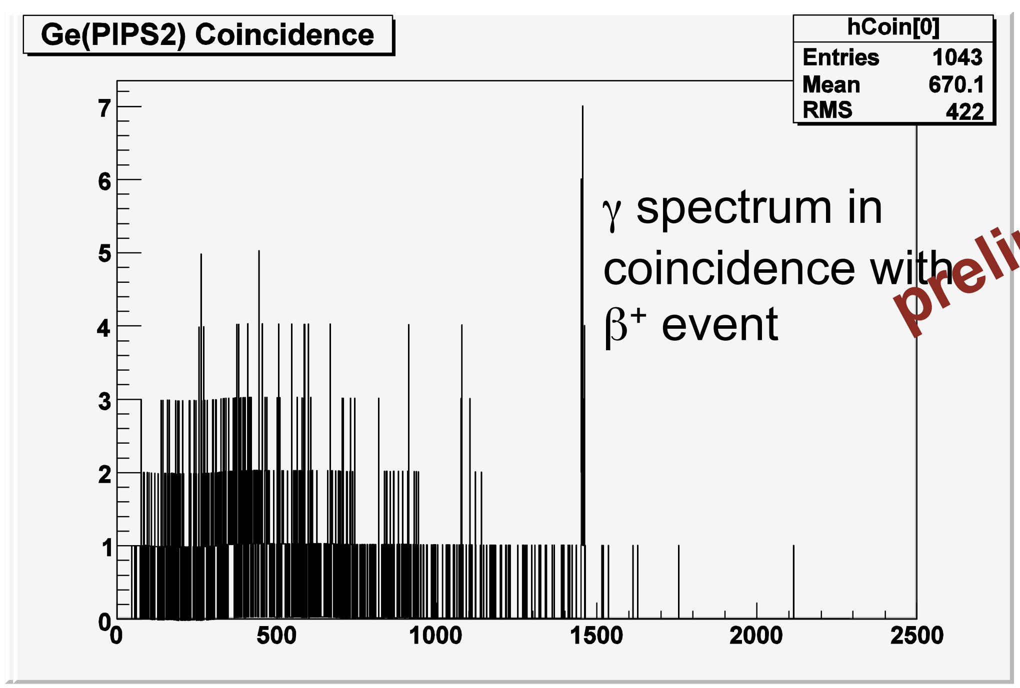
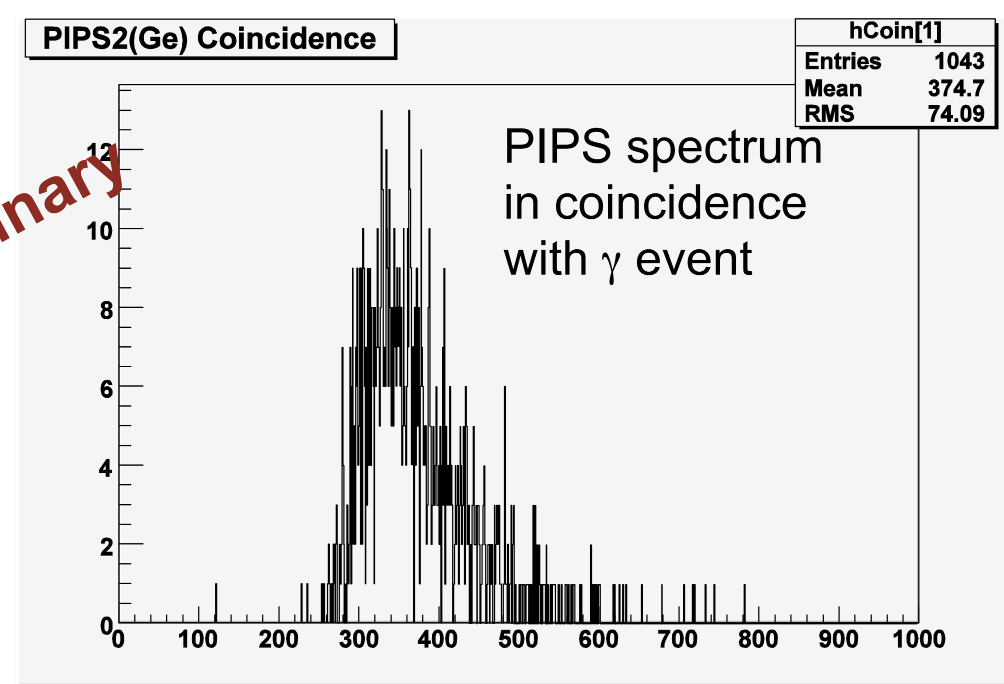
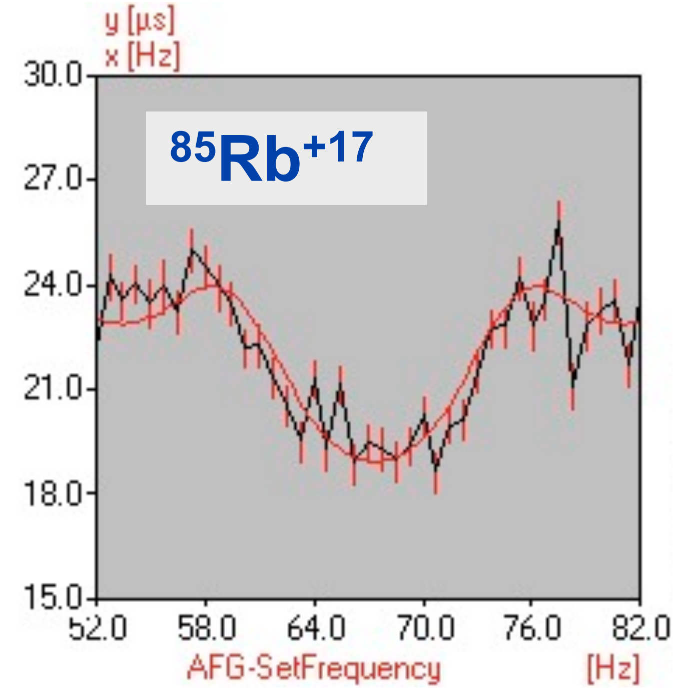
^{126}Cs





Summary & Conclusions

- Halo nuclei
  - benchmark for theory: (3N-) forces & methods
  - mass essential, but experimentally challenging: ^{6,8}He, ^{11}Li, ^{11,12}Be @ TITAN
- new magic numbers
  - again importance of 3N-forces
  - TITAN: towards N=34
- δ_c in NME for V_{ud} from superallowed β decays
  - exp. support to theory: e.g. charge radius from LS (^{74}Rb)
  - TITAN: first online mass measurements with HCI



- NME for 0νββ-decays
  - in-trap decay spectroscopy TITAN: new approach to measure EC-BR
- χEFT: consistent framework of nucl. forces (+ bridges to QCD)
- use of these nucl. forces in various methods all over nuclear chart

Thank you! Merci!

- The TITAN Group: Jens Dilling, Paul Delheij, Gerald Gwinner, Melvin Good, Alain Lapierre, David Lunney, Mathew Pearson, Ryan Ringle, Corina Andreoiu, Maxime Brodeur, Ankur Chaudhuri , Alexander Grossheim, Ernesto Mané, Brad Schultz, Martin C. Simon, Thomas Brunner, Usman Chowdhury, Benjamin Eberhart, Stephan Ettenauer, Aaron Gallant, Vanessa Simon, Mathew Smith
- TRIUMF Staff: Pierre Bricault, Ames Friedhelm, 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
- TRIUMF Theory: Sonia Bacca, Petr Navratil, Achim Schwenk

And the rest of the TITAN collaboration....

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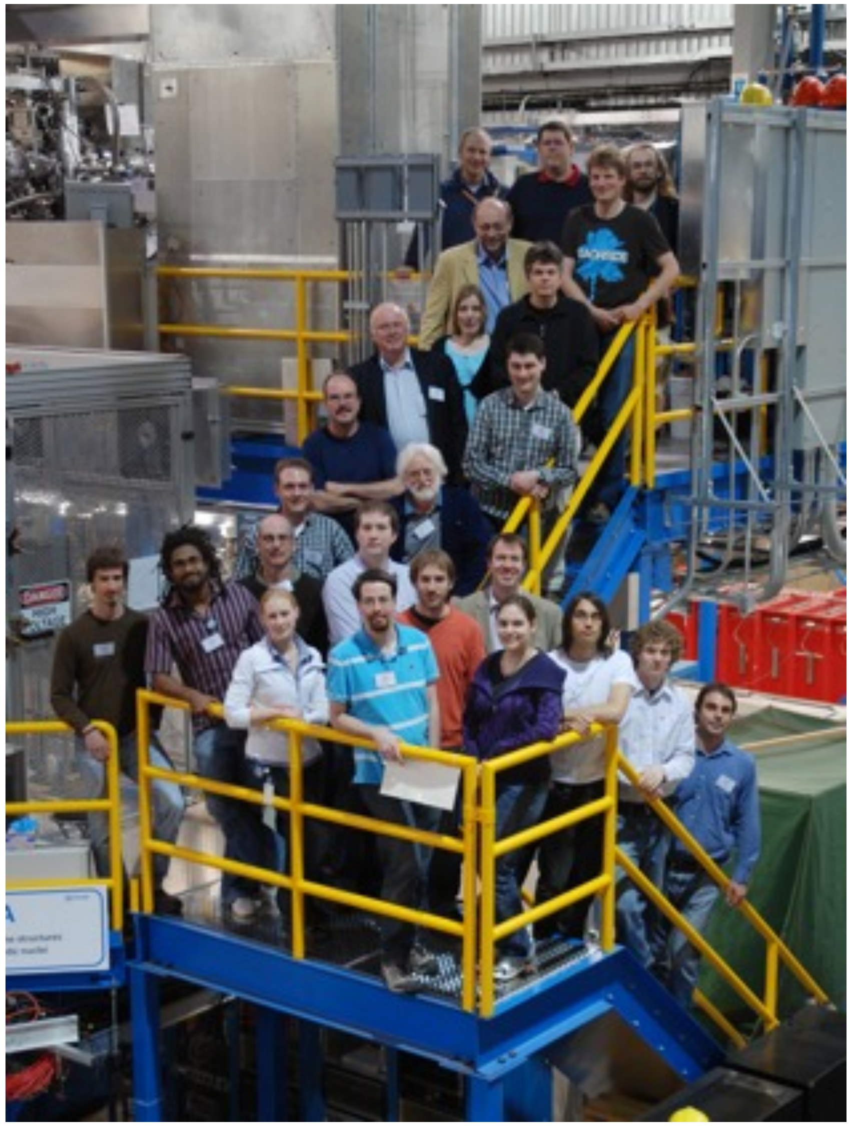
Muenster U.,	Colorado School of Mines
Max Plank Inst. of Heidelberg	TRIUMF
GANIL	UBC



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