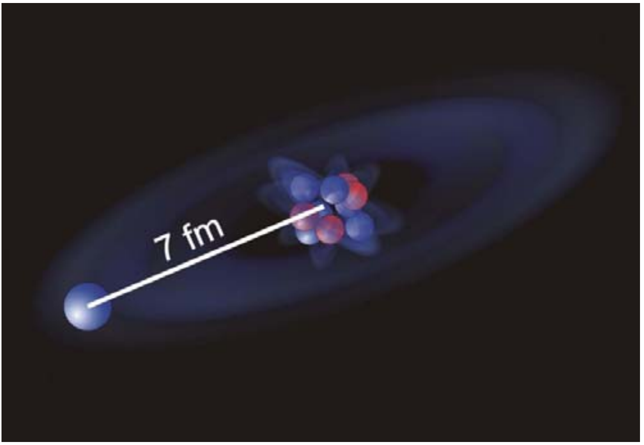
TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

Owned and operated as a joint venture by a consortium of Canadian universities via a
contribution through the National Research Council Canada

Moon Halo



Nuclear Halo

Mass measurements of Halos

Jens Dilling, TRIUMF/ UBC

for the TITAN collaboration

MPI-K Heidelberg Seminar 3 July 2009

UBC THE UNIVERSITY OF BRITISH COLUMBIA

TRIUMF

ISAC

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une
contribution administrée par le Conseil national de recherches Canada

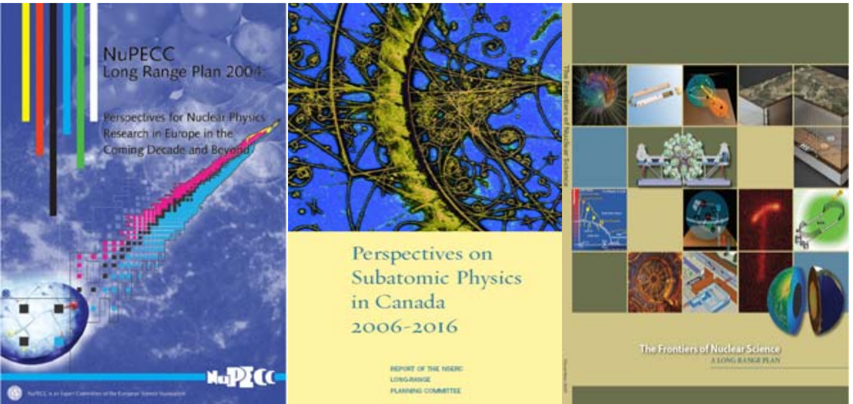
Nuclear Physics: The BIG questions

1. What binds protons and neutrons into stable nuclei and rare isotopes and where are the limits of existence? Fundamental understanding of the strong force and leading to extreme nuclei, as close to neutron stars as we get!
2. When and how did the elements from iron to uranium originate? Can we explain observed element abundances and do we understand reaction processes?
3. What is the origin of simple patterns in complex nuclei? Where does symmetry affect nuclei, and can we use it to understand symmetry concepts that shape the Universe?
4. What causes stars to explode? The life and death of stars, & nuclear reaction fuel stars, and emitted particles (like neutrinos) and light help us understand better how the Universe functions.

Global quest in understanding these questions.

Multi facetted approach with various facilities and experiments

Need combined effort in theory and experimental nuclear physics.



Rare isotopes is what we need

Example regions to study:

1: halo nuclei

2: nuclear structure, ‘Island of Inversion’

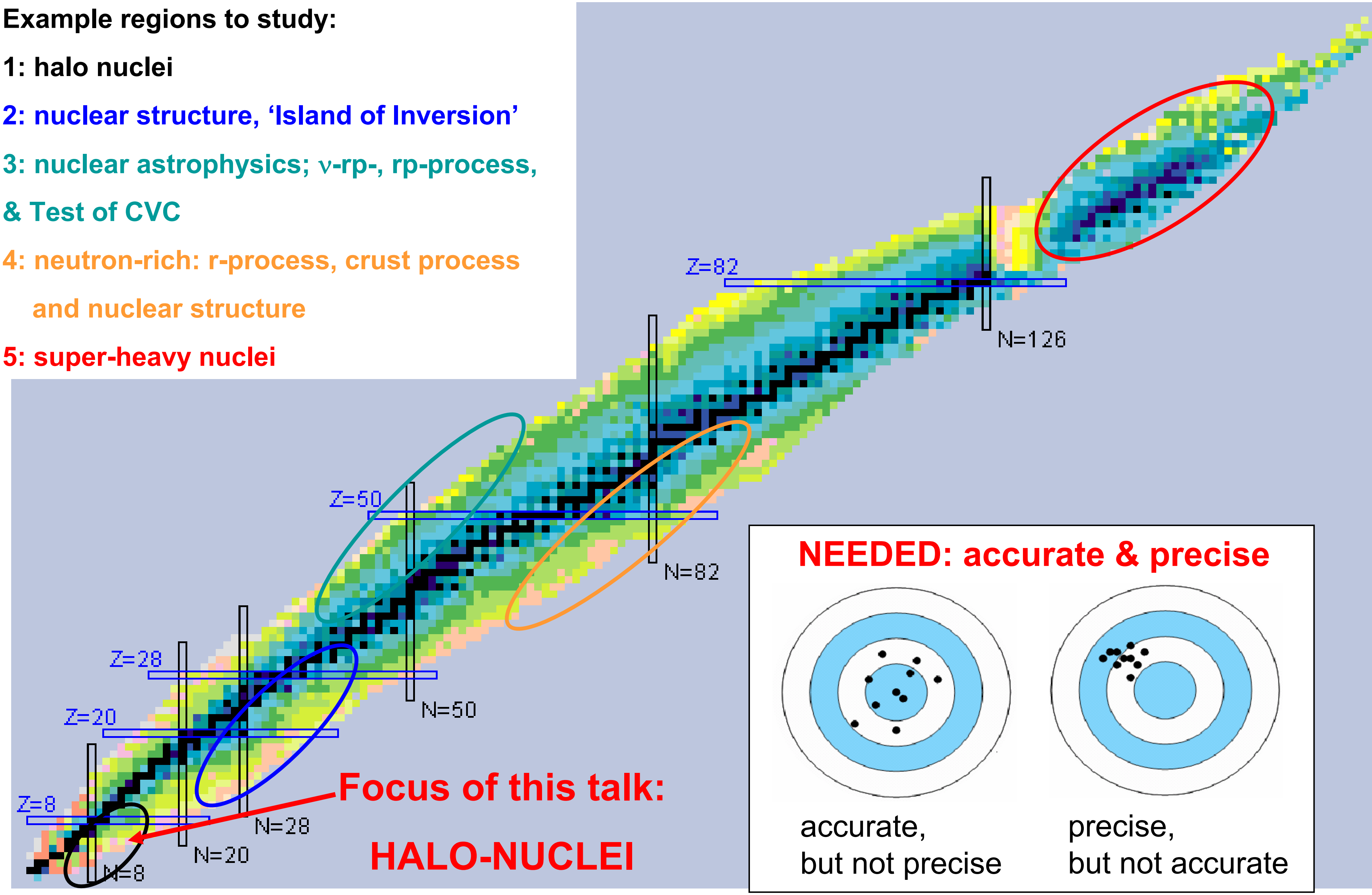
3: nuclear astrophysics; ν-rp-, rp-process,

& Test of CVC

4: neutron-rich: r-process, crust process

and nuclear structure

5: super-heavy nuclei



Focus of this talk:

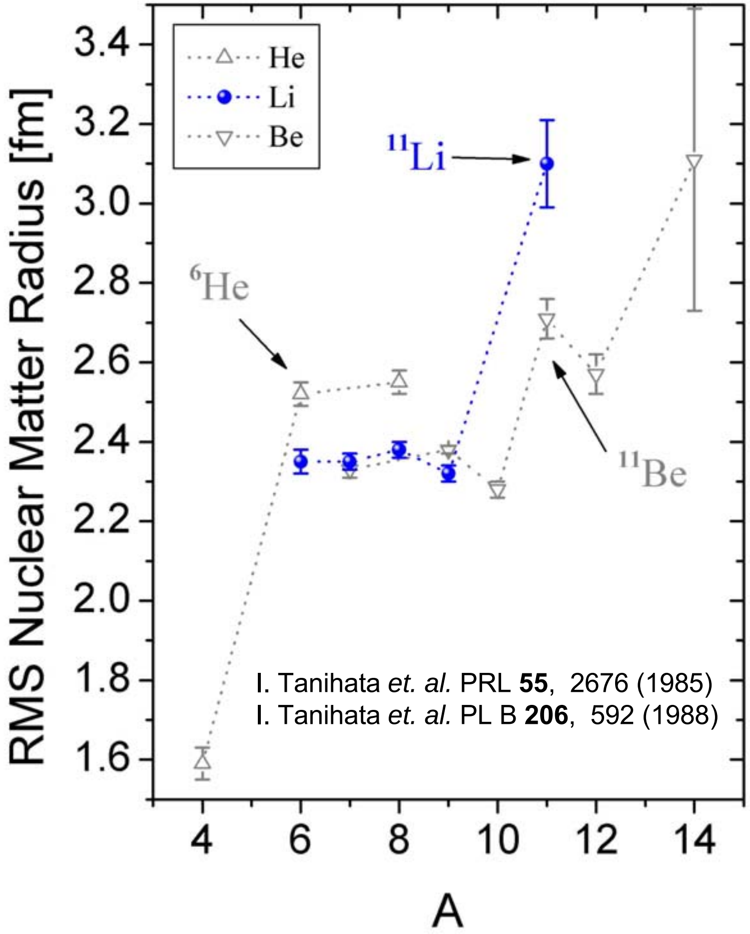
HALO-NUCLEI

NEEDED: accurate & precise

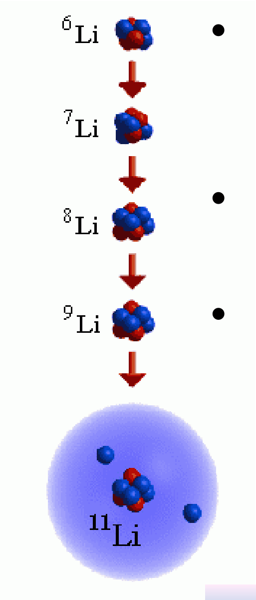
accurate,
but not precise

precise,
but not accurate

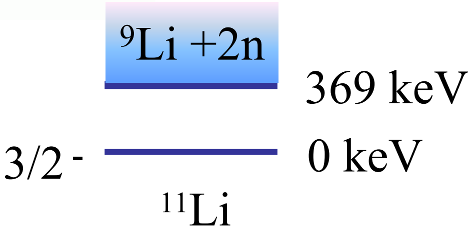
Strange form of matter: Halo nuclei an 'old' phenomena, but new methods



^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{11}Li
∞	∞	838 ms	178 ms	8.6 ms
1	3/2	2	3/2	3/2



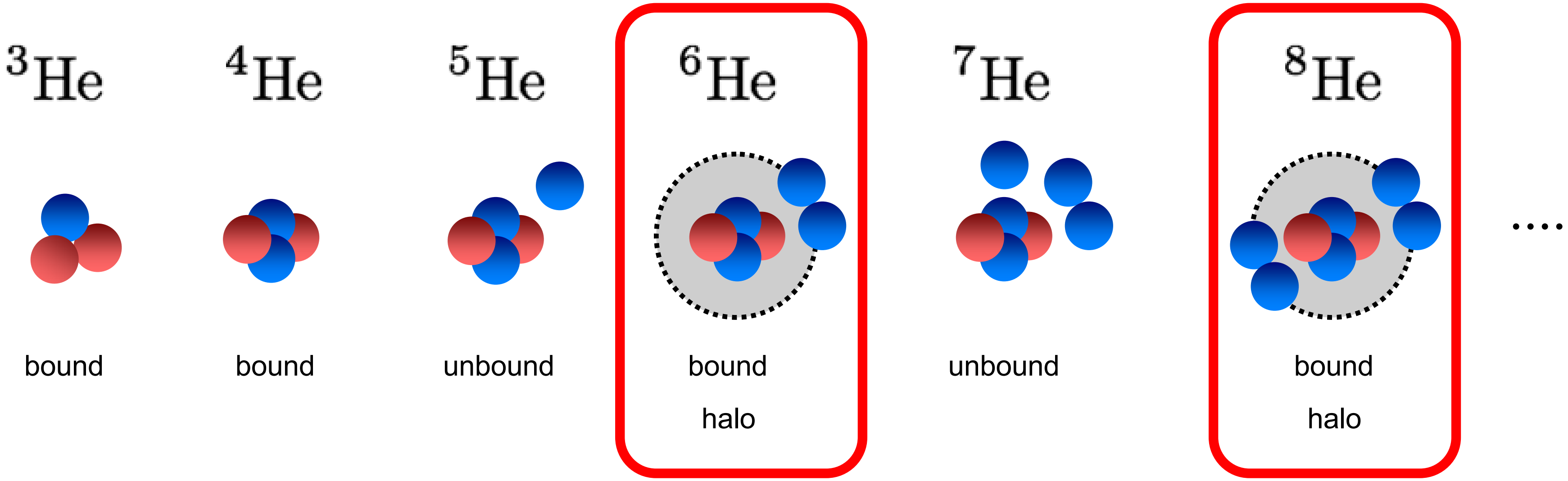
- In 1985 Tanihata et al. fired light nuclei at Beryllium, Carbon and Aluminum targets
- They found the radius of ^{11}Li to be much larger than expected
- Extra neutrons or protons on forbidden orbits



Very low binding of neutrons

The helium isotope chain

Shows many interesting features:



$^{3}\mathrm{He}$	$^{4}\mathrm{He}$	$^{5}\mathrm{He}$	$^{6}\mathrm{He}$	$^{7}\mathrm{He}$	$^{8}\mathrm{He}$	....
bound	bound	unbound	bound	unbound	bound	
			halo		halo	

Borromean system

Most exotic nucleus
“on earth”

$$\frac{N}{Z} = 3$$

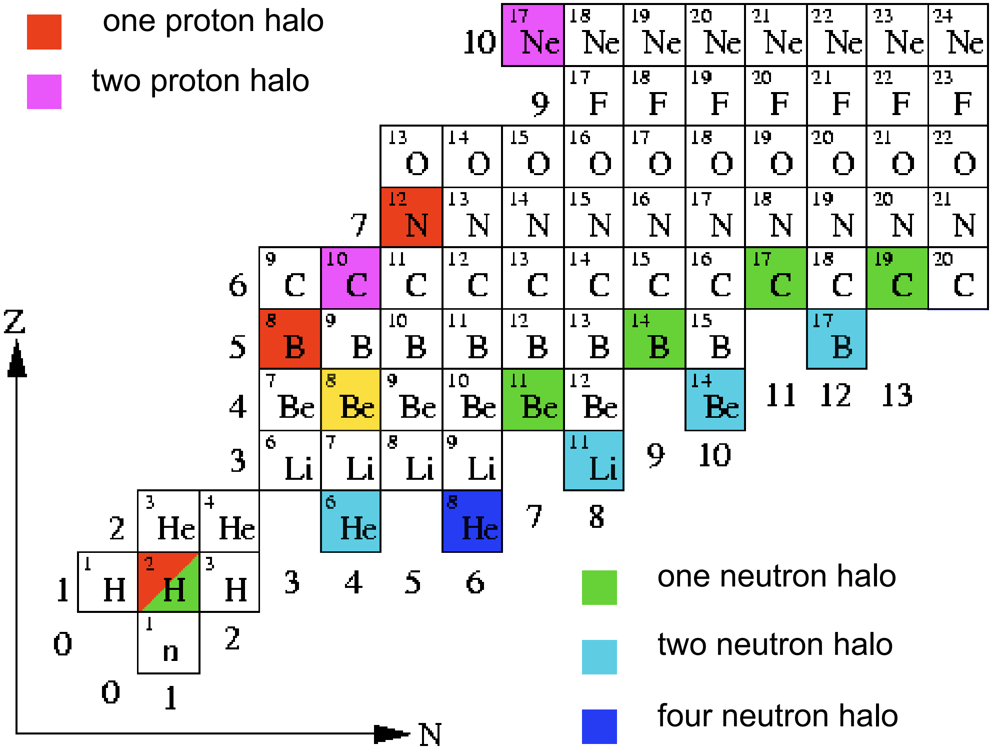
lives 806 ms

lives 108 ms

They are exotic short lived nuclei & they can be investigated experimentally. From a comparison of theoretical predictions with experiment we can test our knowledge on nuclear forces in the most neutron rich region.

Halo Nuclei = extra large nuclei

Know halos (more out there)



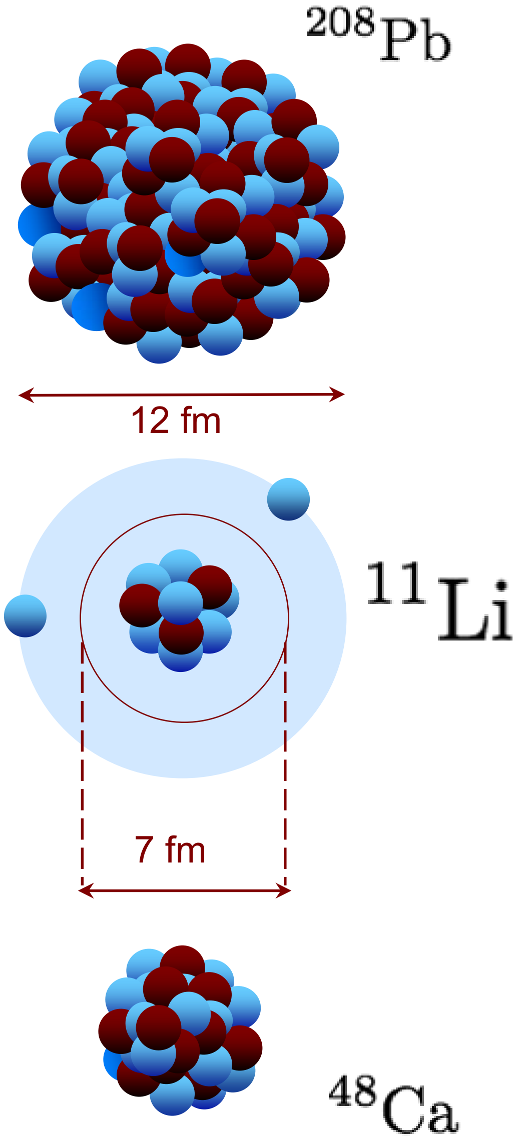
🟥 one proton halo

🟪 two proton halo

🟩 one neutron halo

🟦 two neutron halo

🟦 four neutron halo

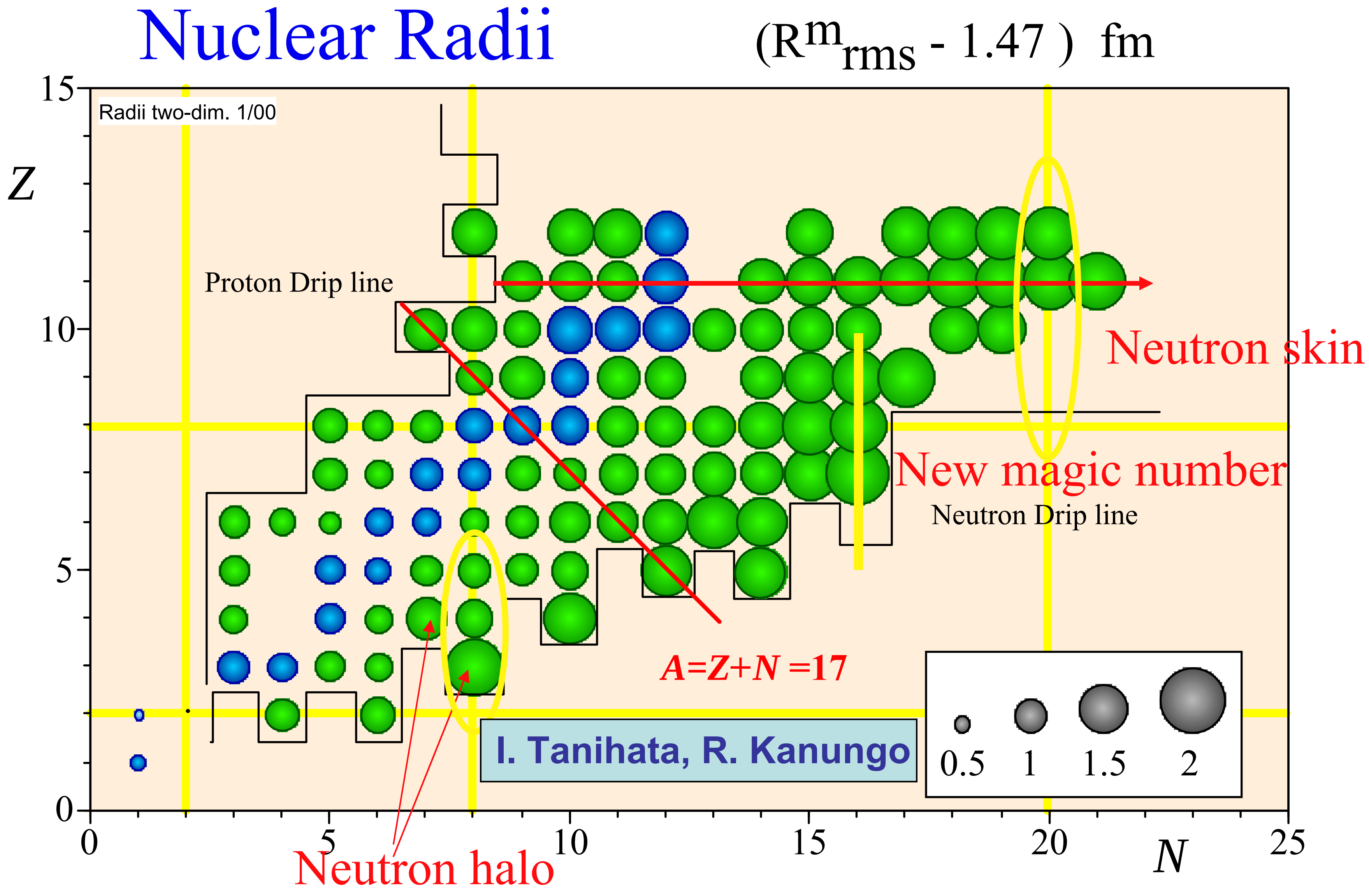


- Short-lived
- few nucleon system
  - **test for theory at extreme conditions**
  - **difficult to produce and measure**
  - **Few have ever been directly measured**

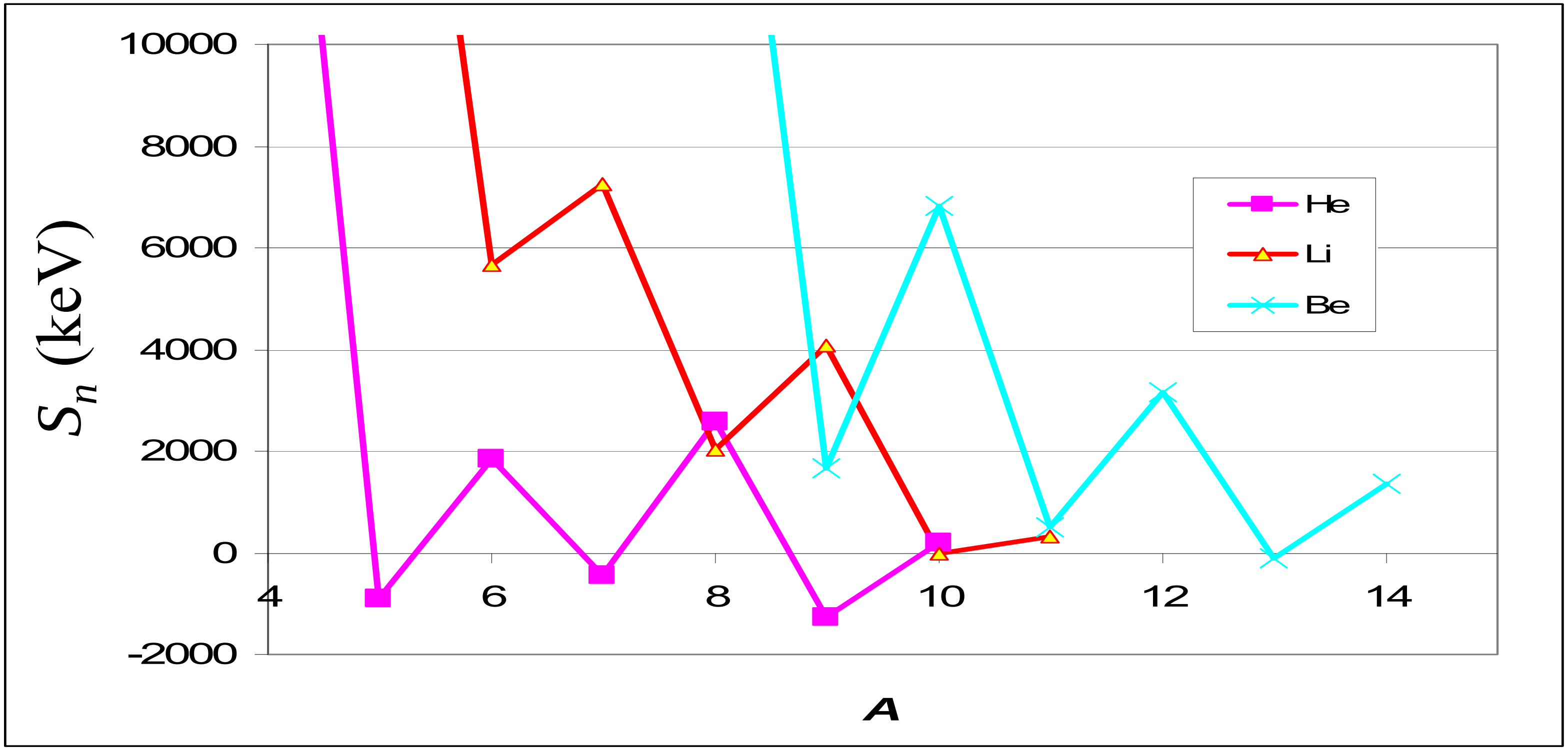
Halo	$T_{1/2}$
^{8}He	119 ms
^{11}Li	8.8 ms
^{14}Be	4.4 ms

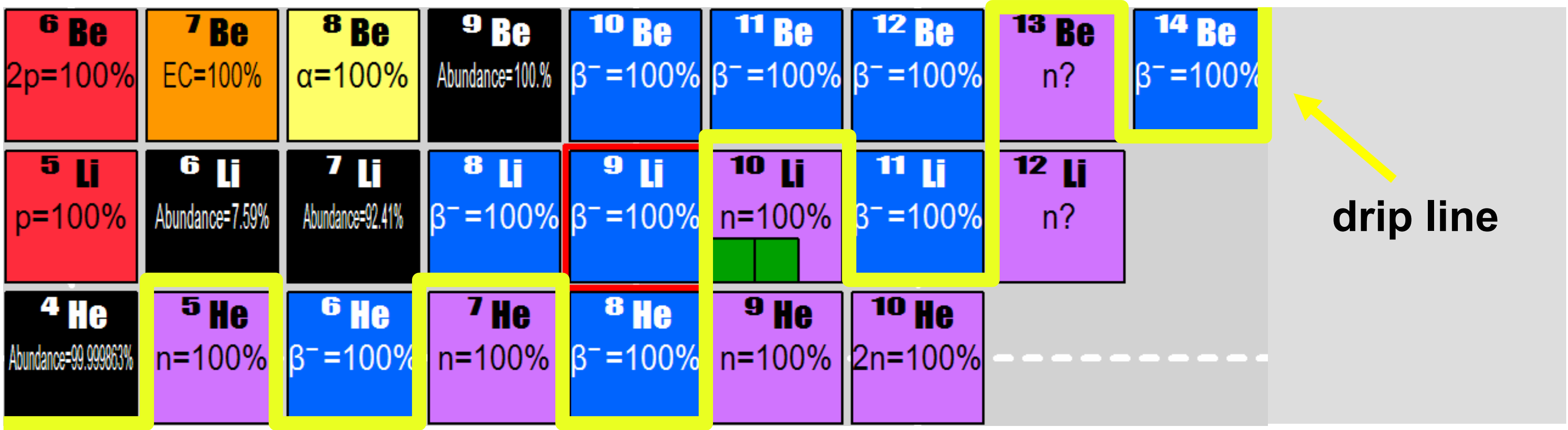
Halo Nuclear: Size

Nuclear radius: $R_N \sim r_0 A^{1/3}$



Halo nuclei = very low binding energies @ the drip lines

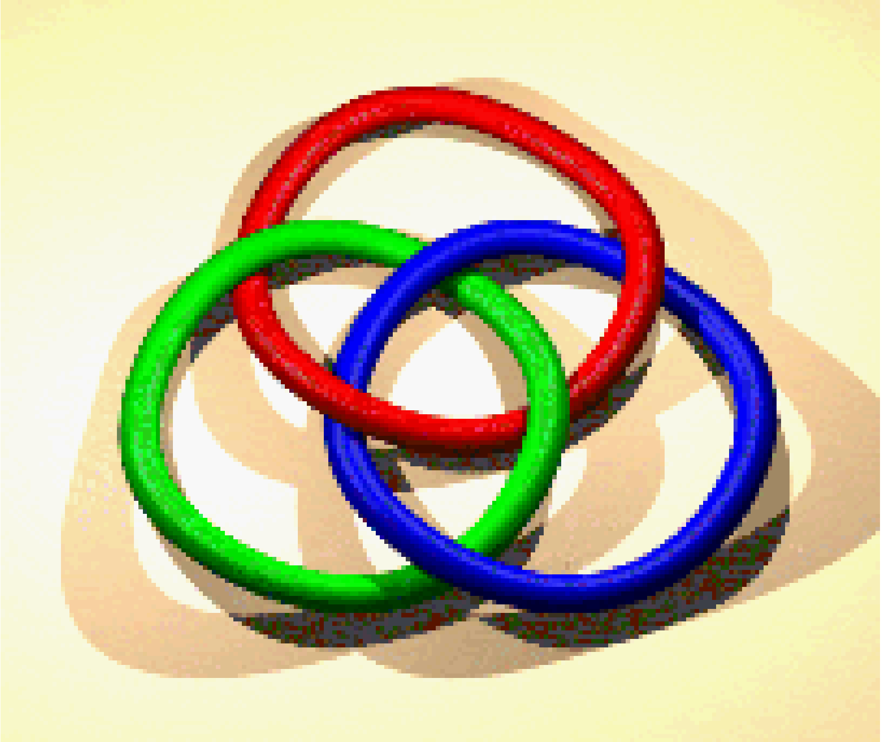




^{6}**Be** 2p=100%	^{7}**Be** EC=100%	^{8}**Be** α=100%	^{9}**Be** Abundance=100.%	^{10}**Be** β^-=100%	^{11}**Be** β^-=100%	^{12}**Be** β^-=100%	^{13}**Be** n?	^{14}**Be** β^-=100%
^{5}**Li** p=100%	^{6}**Li** Abundance=7.59%	^{7}**Li** Abundance=92.41%	^{8}**Li** β^-=100%	^{9}**Li** β^-=100%	^{10}**Li** n=100%	^{11}**Li** β^-=100%	^{12}**Li** n?	
^{4}**He** Abundance=99.999863%	^{5}**He** n=100%	^{6}**He** β^-=100%	^{7}**He** n=100%	^{8}**He** β^-=100%	^{9}**He** n=100%	^{10}**He** 2n=100%		

drip line

Halo Nuclei: Borromean Rings



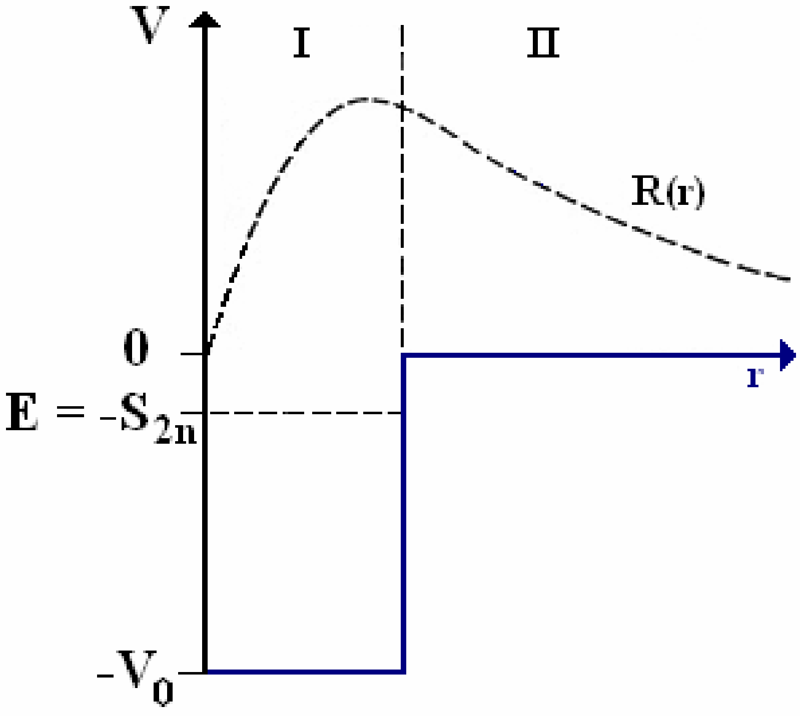
- Three rings interlinked in such a way that
  - All three hold together
  - Remove any one, and the other two fall apart!
  - Like: 9Li + n + n
    - But not 9Li + n
    - Not n + n

Borromean rings, the heraldic symbol of the Princes of Borromeo, are carved in the stone of their castle at Lake Maggiore in northern Italy.

Halo Nuclei: A simple model 9Li + 2n

Schrödinger equation for a spherically symmetric square-well:

$$\left(\frac{\partial^2}{\partial\rho^2}+\frac{2}{\rho}\frac{\partial}{\partial\rho}+1-\frac{l(l+1)}{r^2}\right)R_l(r)=0$$



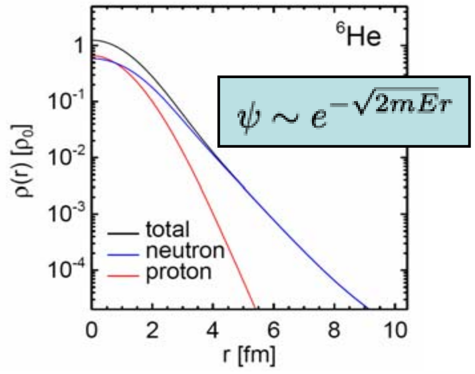
I	II
$\rho=\alpha r$	$\rho=i\beta r$
$\alpha=\sqrt{\frac{2m(V_0-\lvert E\rvert)}{\hbar^2}}$	$\beta=\sqrt{\frac{2m\lvert E\rvert}{\hbar^2}}$
$R_l(r)\propto j_l(\alpha r)$	$R_l(r)\propto h_l^{(1)}(i\beta r)$
$R_0(r)\propto\frac{\sin(\alpha r)}{r}$	$R_0(r)\propto\frac{e^{-\beta r}}{r}$

G.P. Hansen & B. Jonson EPL 4, 409, 1987

Halo Nuclei – ‘real’ theory

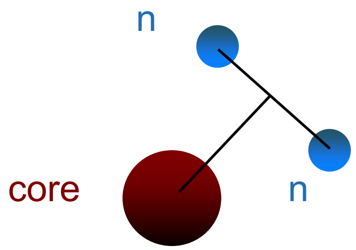
halo nuclei are a challenge to theory

- It is difficult to describe the extended wave function properly
- They test nuclear forces at the extremes, where less has been described theoretically or tested



$$\psi \sim e^{-\sqrt{2mEr}}$$

Cluster models:



3-body models with phenomenological interactions

^{6}He, ^{11}Li - borromean systems

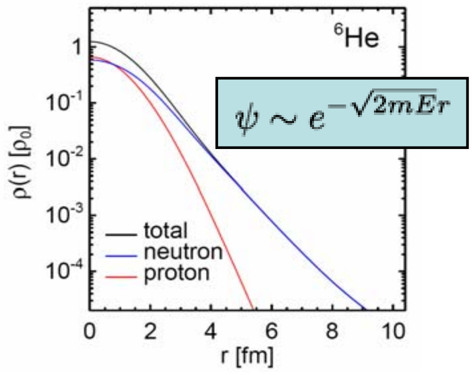
can do reactions, specialized calculations

but difficult to add core polarizations

Halo Nuclei – ‘real’ theory

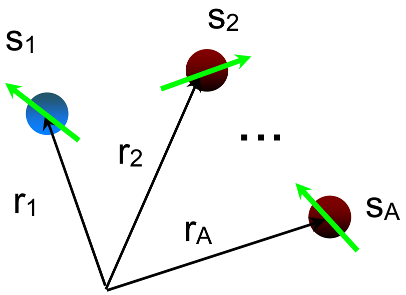
halo nuclei are a challenge to theory

- It is difficult to describe the extended wave function properly
- They test nuclear forces at the extremes, where less has been described theoretically or tested



Ab-initio calculations:

treat the nucleus as an A-body problem



full antisymmetrization of the w.f.

use modern Hamiltonians to predict halo properties

$$H = T + V_{NN} + V_{3N} + \ldots$$

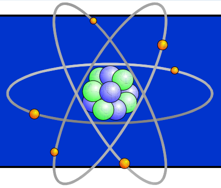
Methods: GFMC, NCSM, CC

Testing and refining theory

- In order to test and improve the theoretical models or approaches we need
  - Experimental data; accurate and precise
  - Data from ground states (moments, masses, size and shapes)
  - Data from excited states and decay
- Data are needed as input for the theory and for testing the predictions

TITAN does precision mass spectroscopy on very short-lived isotopes.

TITAN's mass program:

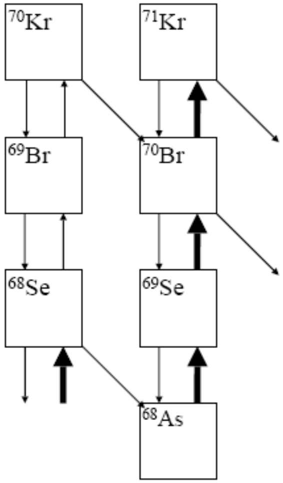


= N · ● + Z · ● + Z · ●

- binding energy

Nuclear Astrophysics

$\delta m/m \approx 1 \cdot 10^{-7/8}$

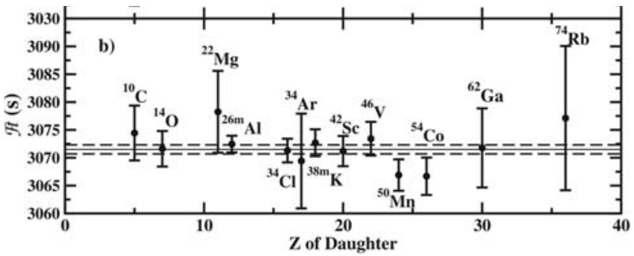


- nucleo-synthesis paths and waiting points
- understanding of stellar processes (e.g. X-ray bursts)

Weak Interaction

$\delta m/m \approx 1 \cdot 10^{-9}$

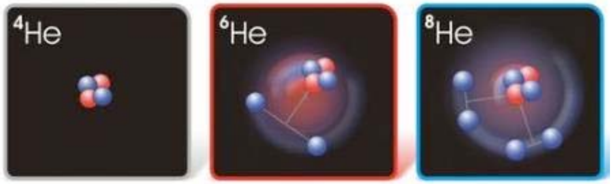
- CKM unitarity test
- CVC hypothesis
- search for scalar currents



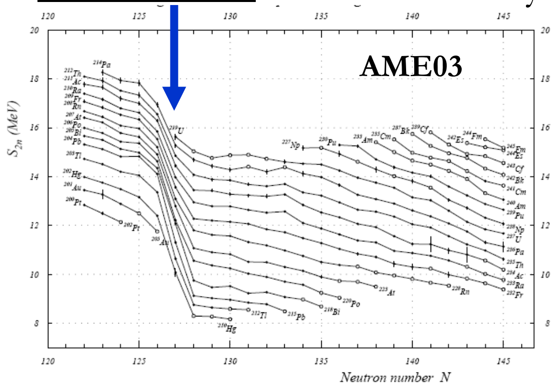
Nuclear Physics

$\delta m/m \approx 1 \cdot 10^{-7/8}$

- halo nuclei



- <u>shell closures</u> far from stability



<u>TITAN can measure</u>

- singly charged ions
- highly charged ions (HCIs)

TITAN
Triumf's Ion Trap for Atomic and Nuclear science

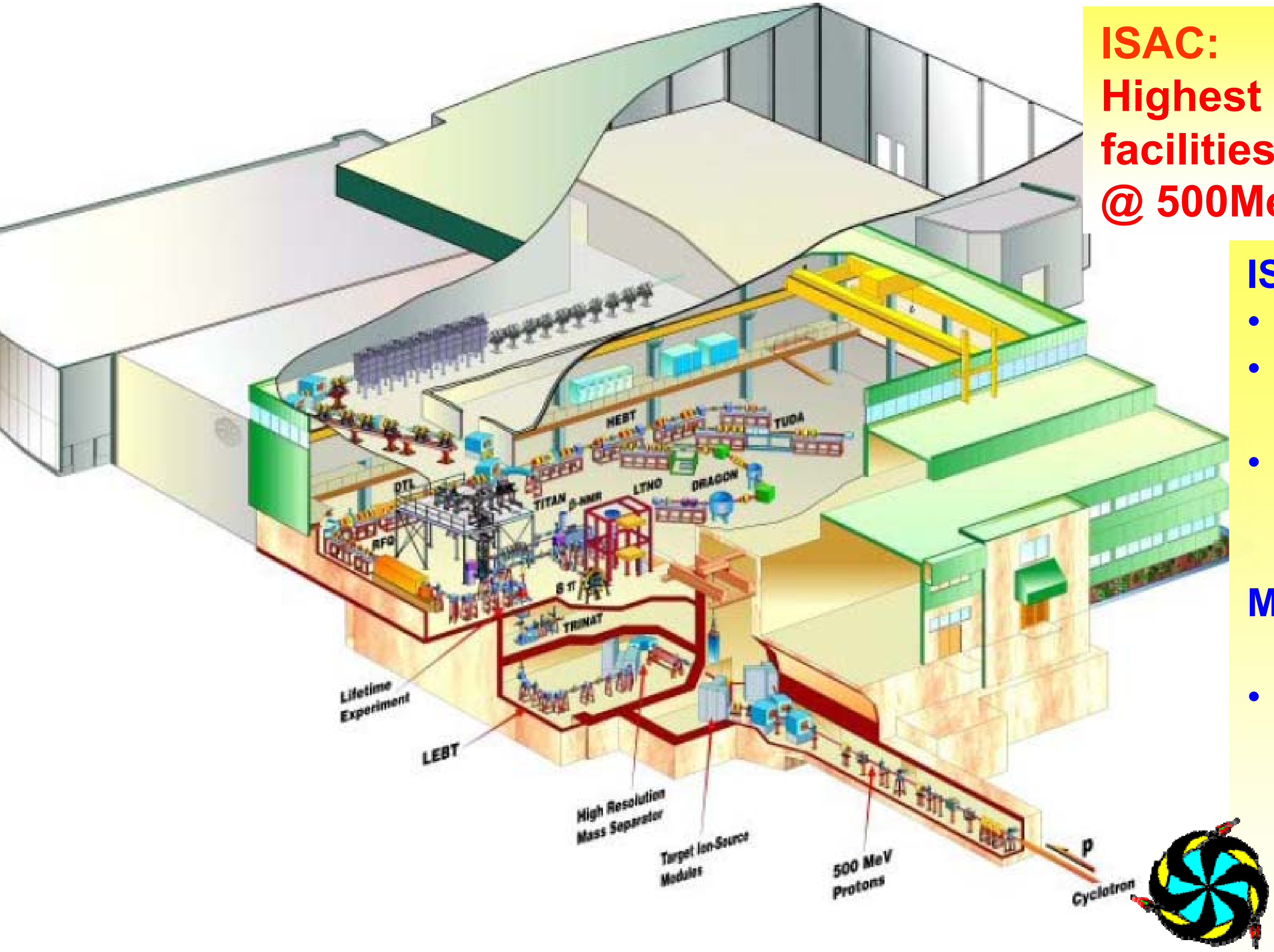
ISAC ion beam → **RFQ cooler & buncher** → **EBIT charge breeder** → **m/q selection** → **Cooler Penning trap** → **Precision Penning trap**

- •Mass measurements on isotopes with short half-life $T_{1/2} \approx 10$ ms and low production yields (≈ 10 ions/s) with high precision $\delta m/m \approx 10^{-8}$.
- •Ideally, uniquely matched to isol-type production mode, only on-line system coupled to breeder to use HCIs.
- •TITAN started April 2003 (NSERC), first on-line mass measurements on singly charged ions carried out in 2007.
- •Set-up optimized for 'fast measurements', can reach half-life limit of ISOL-system.

U. of Manitoba
McGill U.
Muenster U.,
Max Plank Inst. für Kernphysik
GANIL
U. of Calgary
U. of Windsor
Colorado School of Mines
TRIUMF
UBC

→ Key collaboration with MPI-K HD

ISAC @ TRIUMF, today



ISAC:
Highest power for On-Line facilities, we go up to 100μA @ 500MeV DC proton

ISAC has 3 exper. areas:
- Low energy (60keV)
- ISAC I (cont. up 1.8 MeV/u)
- ISAC II (up to 18 MeV/u, present licence to 5 MeV/u)

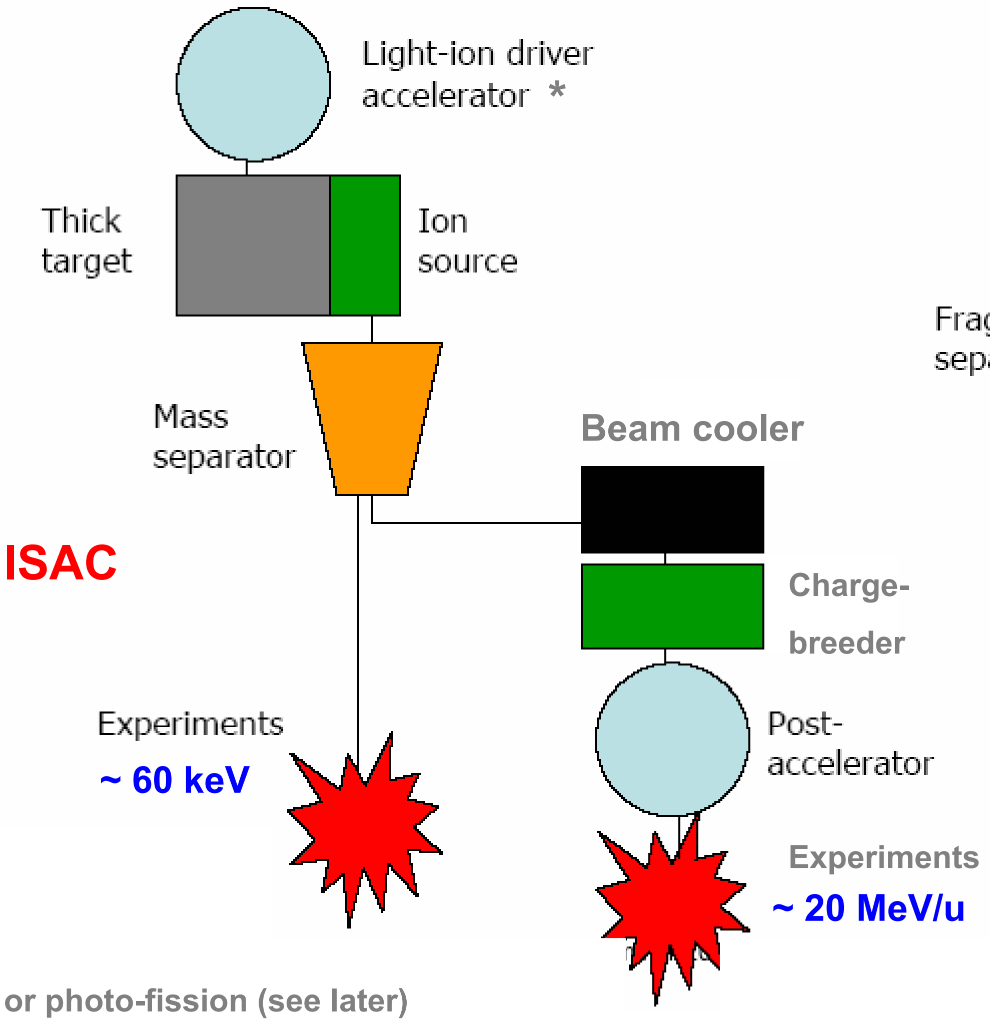
Many experimental stations:
- TRINAT, Beta-NMR, 8pi, tape-station, TITAN, Co-linear laser spec, polarised beam line, etc DRAGON, TUDA, TACTIC, GPS (Leuven)
- TIGRESS, EMMA (2010), GPS (Maya)

Yields: ^{11}Li 4*10^{4}/s, ^{74}Rb 2*10^{4}/s, ^{62}Ga 2*10^{3}/s

Ion sources: surface, laser, FEBIAD, ECR (test)

ISOL VS in-flight

Isotope Separation On-Line (ISOL)



Light-ion driver accelerator *

Thick target

Ion source

Mass separator

Beam cooler

Charge-breeder

Post-accelerator

ISAC

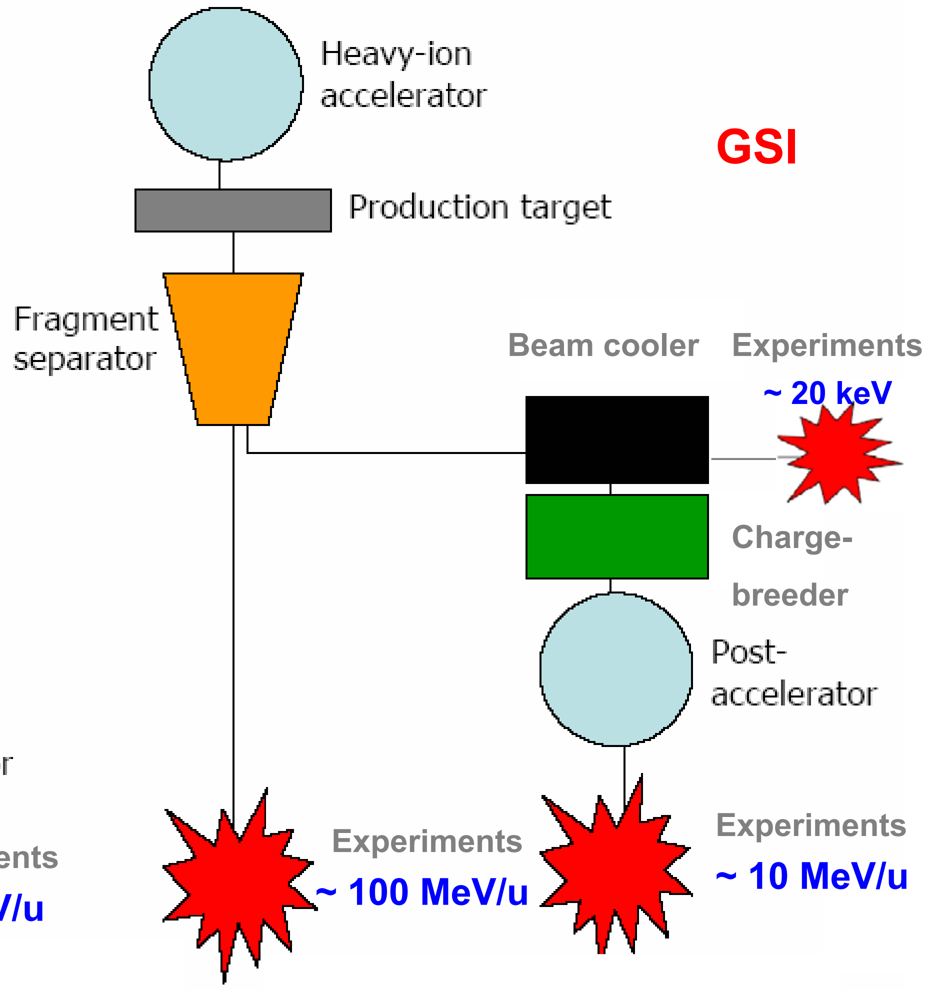
Experiments

~ 60 keV

Experiments

~ 20 MeV/u

In-Flight Fragmentation / In-Flight Fission



Heavy-ion accelerator

GSI

Production target

Fragment separator

Beam cooler

Experiments

~ 20 keV

Charge-breeder

Post-accelerator

Experiments

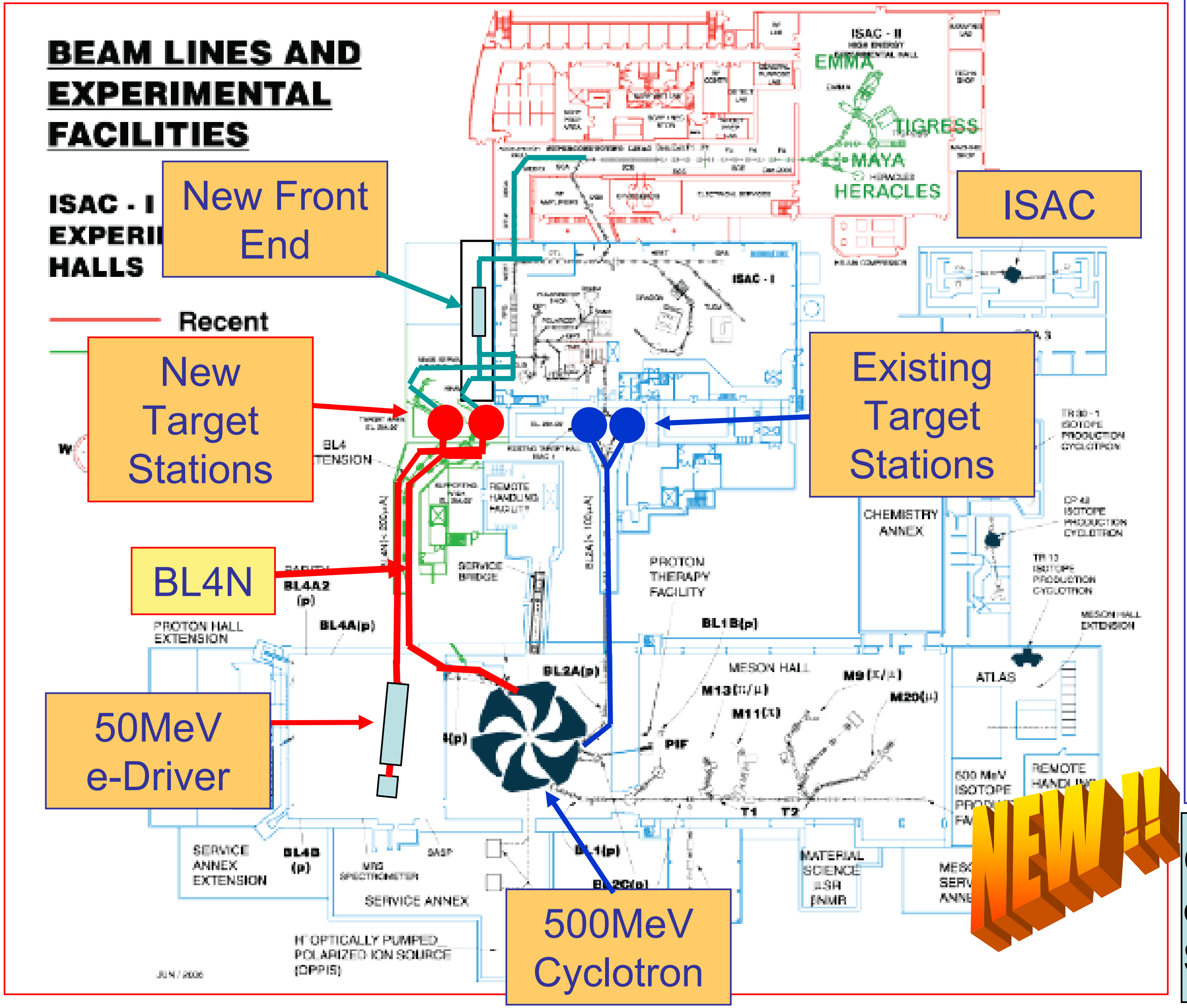
~ 100 MeV/u

Experiments

~ 10 MeV/u

* or photo-fission (see later)

ISOL production @ TRIUMF in the future

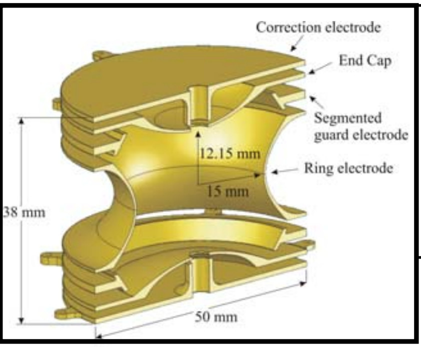


Proposal:

- **BL4N is proposed to deliver 500-MeV protons to two actinide target stations for beam production**
- **Provide independent production for 'new isotopes' and for 12 months running (during cyclotron sgut-down)**
- **Develop new ISAC front end to permit three simultaneous RIB beams (two accelerated)**

CFI proposal for e-linac approved with $M17.7 (+$M17.7)

TITAN system overview



Penning Trap

Mass Measurement
Optimized for fast measurements

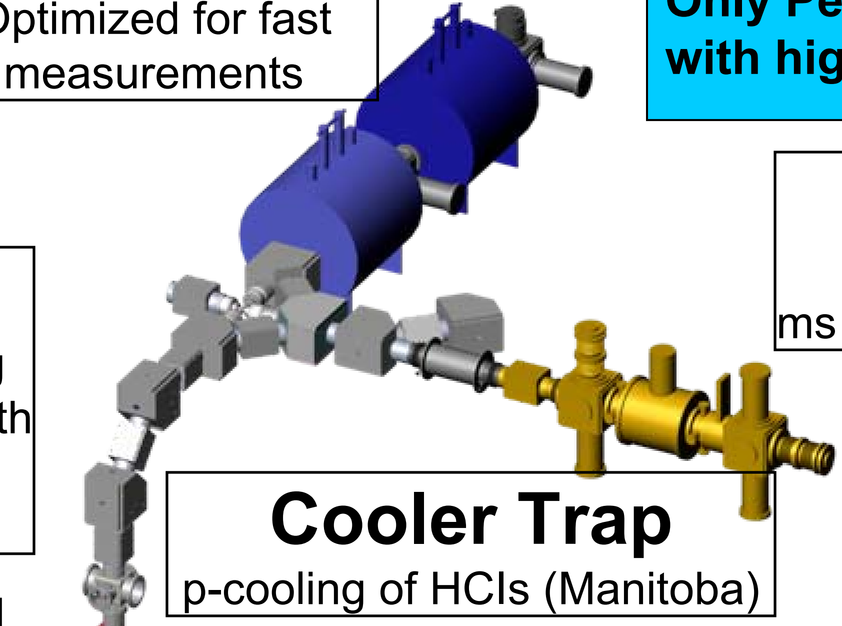
Only Penning trap system on-line with highly charged ions.

EBIT

Charge State Breeding
ms breeding with high efficiency

RFQ

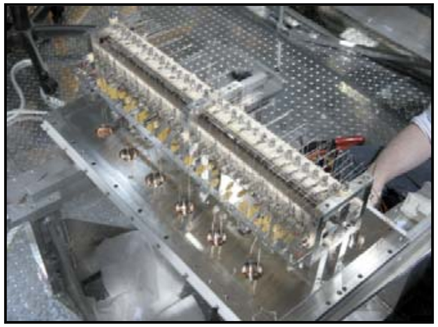
Cooling and Bunching
Sq-W driven system with He or H coolant
reverse extraction



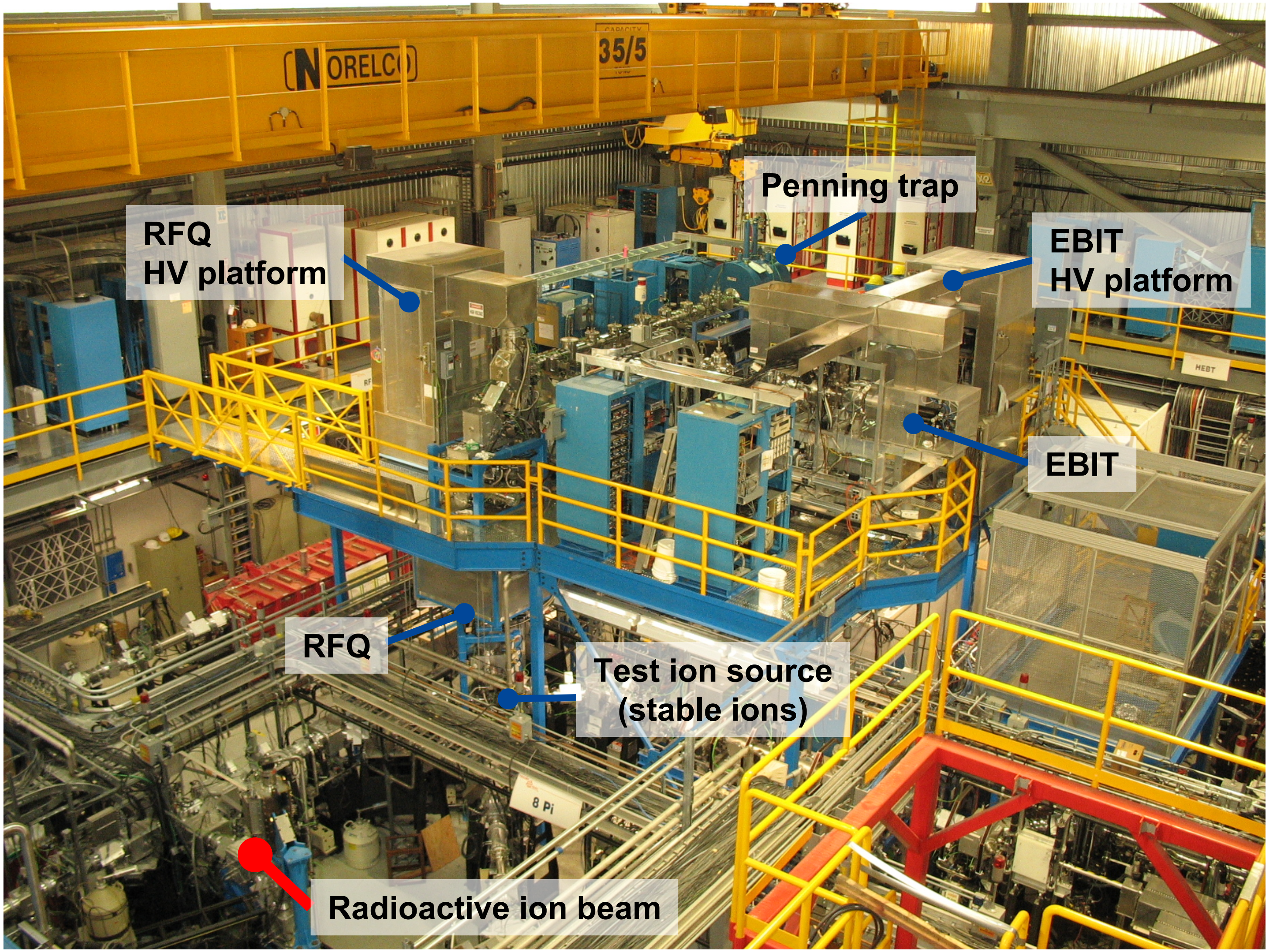
Cooler Trap

p-cooling of HCIs (Manitoba)

ISAC Beam



TITAN set-up @ ISACI

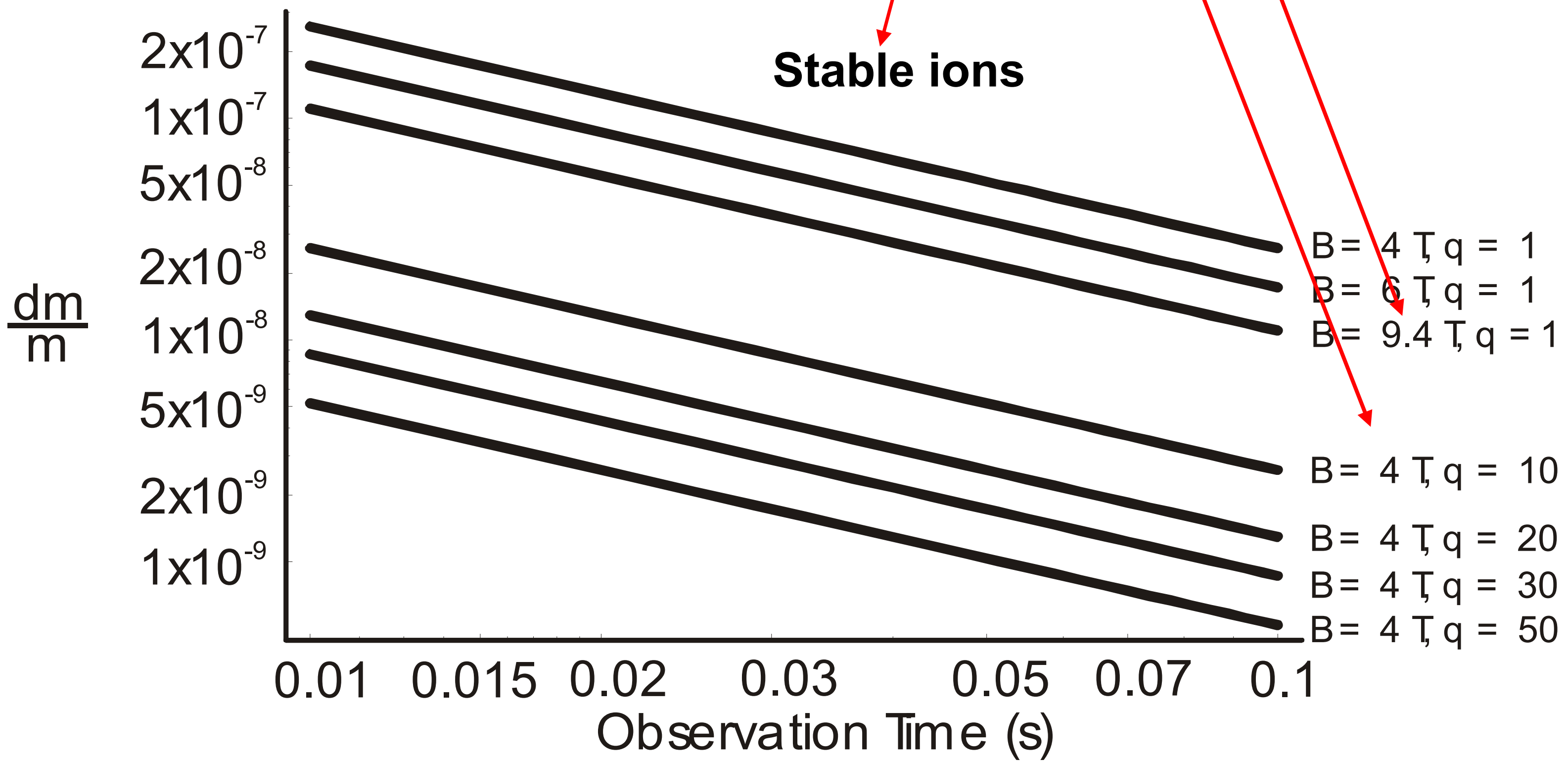


PT Mass accuracy and HCIs

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

Where can we gain something?

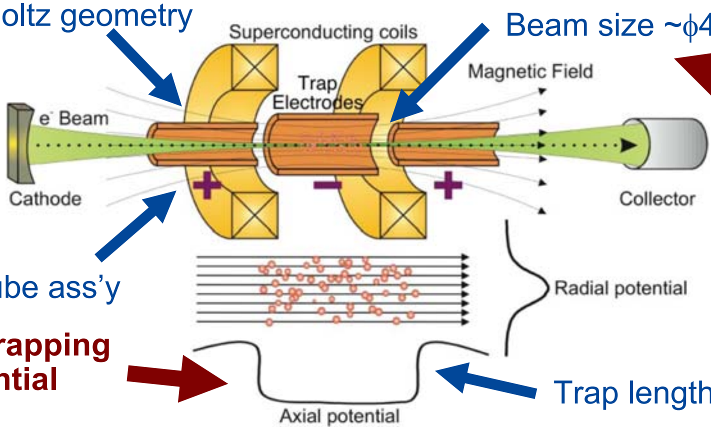
m = 100 u, N = 10, 000



HCIs from the EBIT

Electron Beam Ion Trap

- Ion trap, which **traps & produces highly charged ions (HCI's)** with high-current electron beam compressed to **high current densities** by a **strong (~Tesla) axial magnetic field**.
- The advantage of an EBIT over other charge breeders is the possibility of reaching **well-defined high charge states** and a **rapid breeding process needed for short-lived isotopes**.



Helmholtz geometry

Beam size ~ϕ40 μm @ 5 T

Cause of high-current density!

Drift tube ass'y

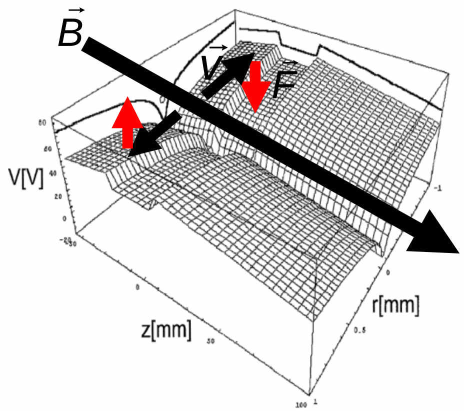
Ion trapping potential

Trap length ~ cm's

HCIs produced by sepwise electron-impact ionization

i.e., 1 HCI → Impact of many e

Electrostatic potential experienced by ions.



HCIs can also be trapped with no electron beam for secondes.

Ions are trapped:

Axially (B-field axis)

1) Quadrupole electrostatic potential applied to drift tubes.

Radially

1) Electron beam space charge potential.
2) Axial magnetic field:

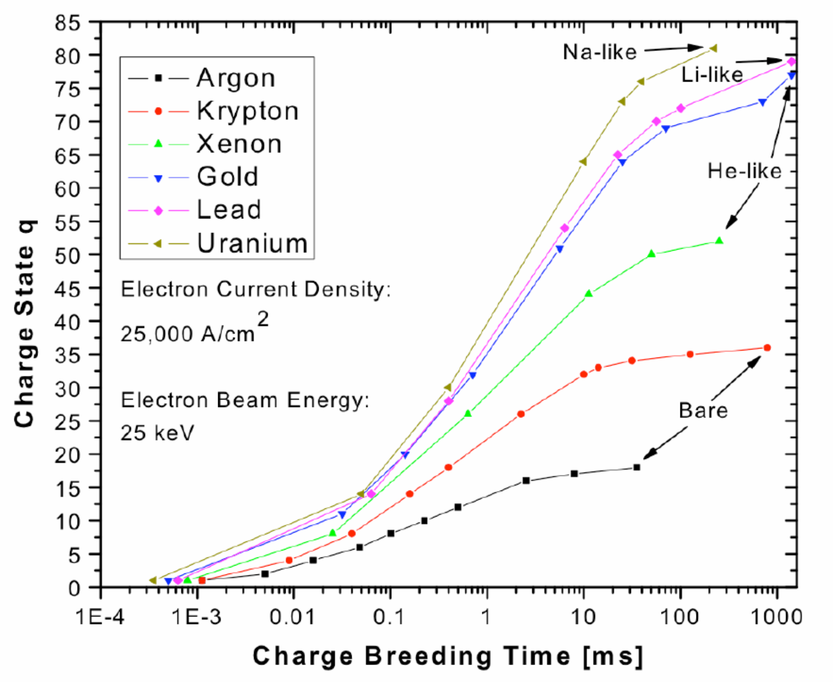
HCIs from the EBIT

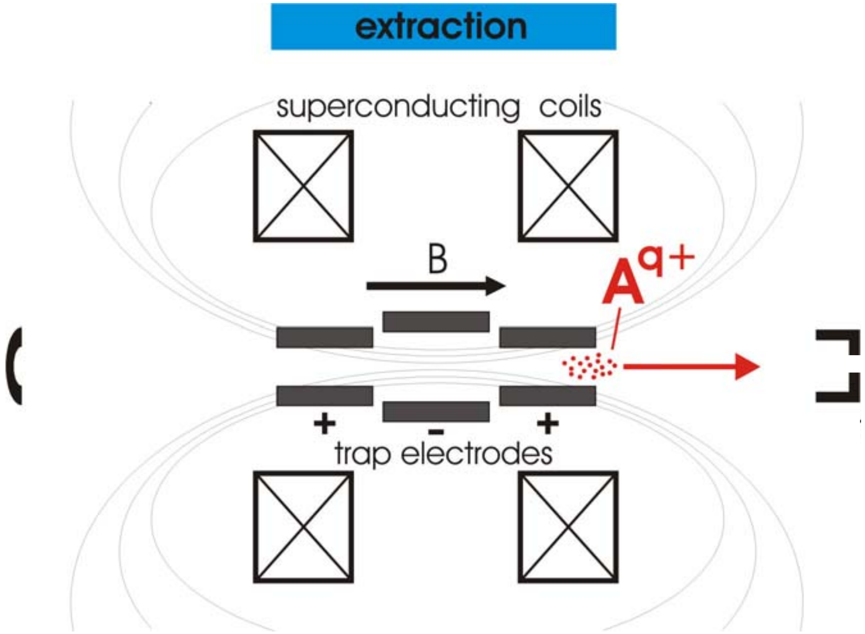
What we expect from 'theory':

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

$\Rightarrow$ e^- density up to 40 000 A/cm^2

$\Rightarrow$ increased ionization rate





requirements for charge breeding:

- efficient
- fast

Built in collaboration the MPI-K Heidelberg

Max-Planck-Institut für Kernphysik

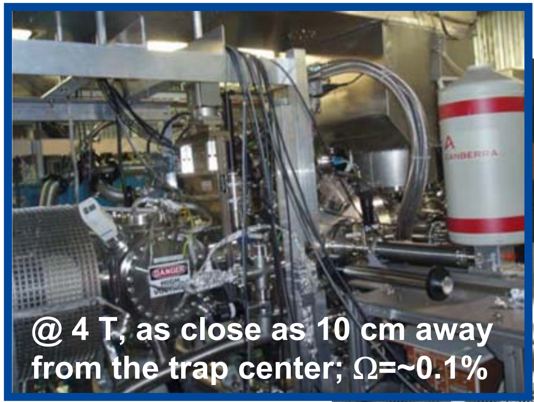
TITAN EBIT on the move from HD

The TITAN EBIT @ TRIUMF

Thanks Jose & Joachim
(and the group)

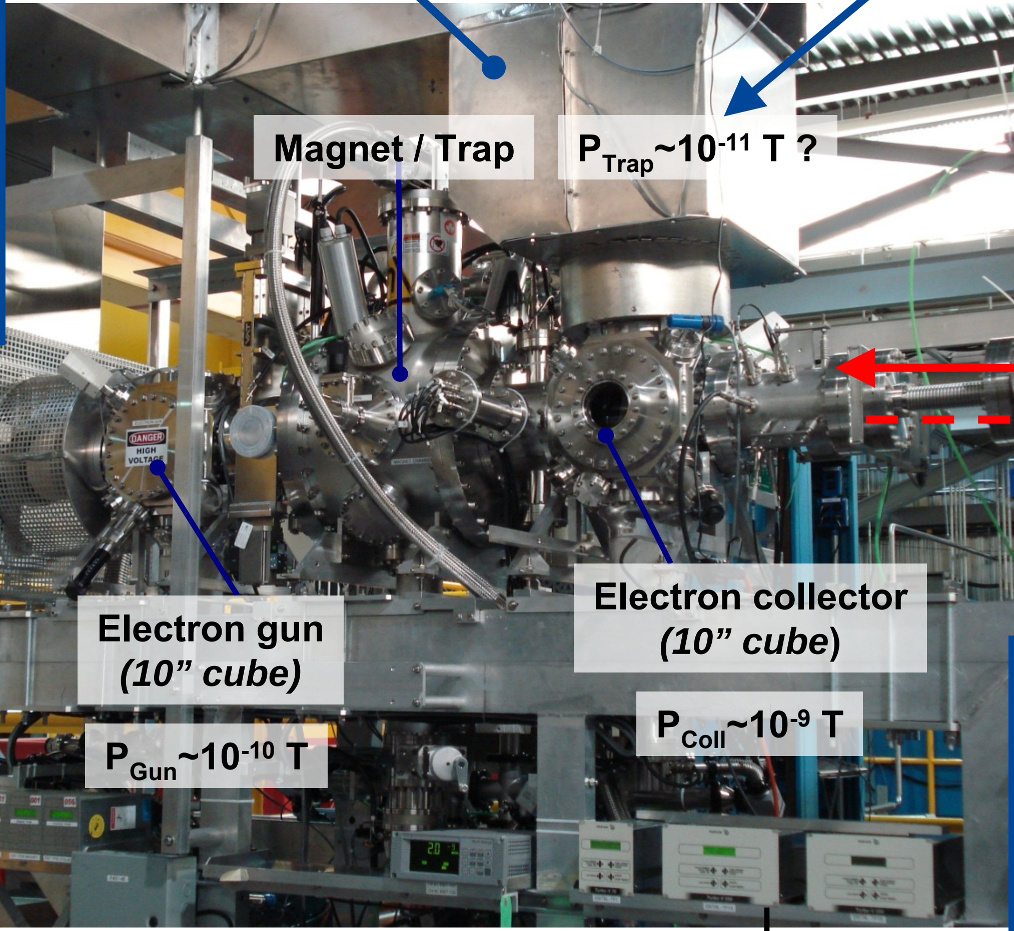
The EBIT @ TITAN (4 weeks later)

LEGe X-ray detector
~3 – 100 keV



@ 4 T, as close as 10 cm away from the trap center; Ω=~0.1%

High res; small size



60 kV high-voltage duct

Cryogenic temperature;
Ideal for a low level of contaminations

Magnet / Trap

P_{Trap}~10^{-11} T ?

Injection A^+
~ 2 keV

Extraction A^{q+}
~ 2 kV_{Ext}*q

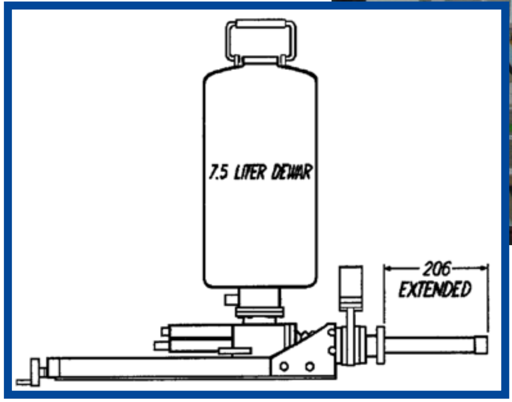
Electron gun
(10" cube)

P_{Gun}~10^{-10} T

Electron collector
(10" cube)

P_{Coll}~10^{-9} T

2.5 m



Low res; large size

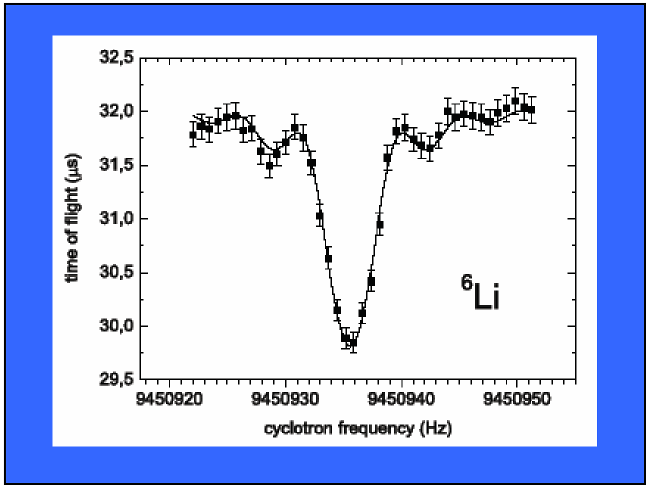
Coax Ge X-ray detector
~ 5 – 100 keV

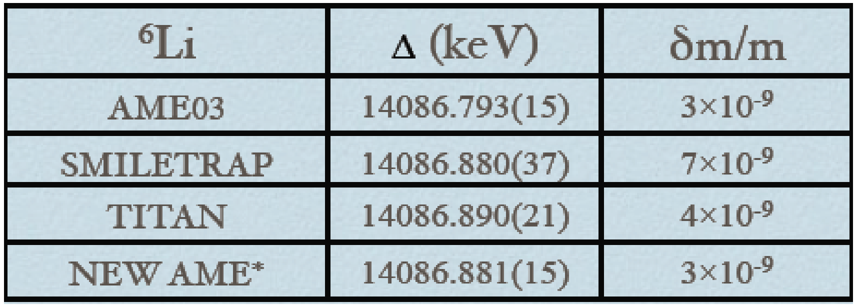
TITAN RESULTS & IMPACT

- In order to test and improve the theoretical models or approaches we need
  - Experimental data; accurate and precise
  - Data from ground states (moments, masses, size and shapes)
  - Data from excited states and decay
- Data are needed as input for the theory and for testing the predictions

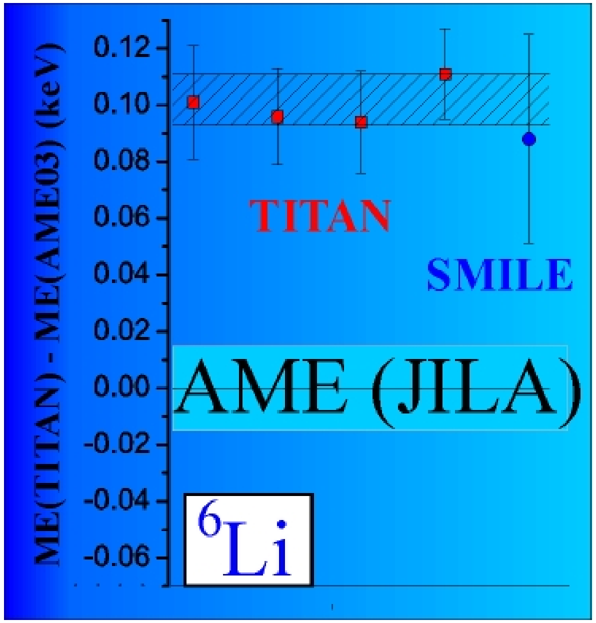
TITAN mass measurements on very short-lived halo isotopes.

TITAN mass measurements on stable Li





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

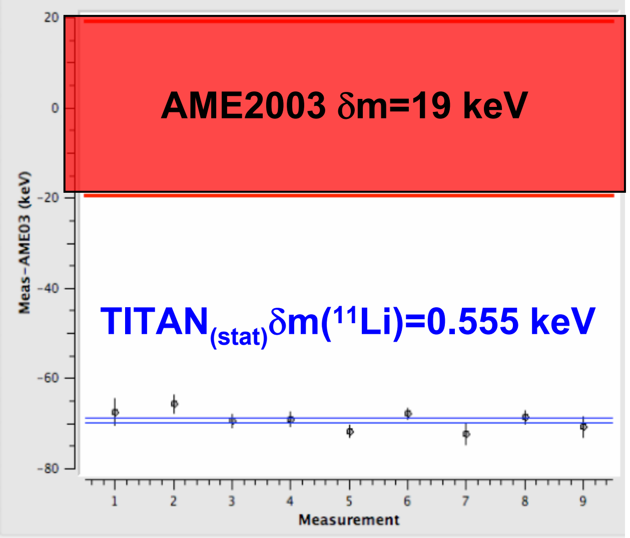


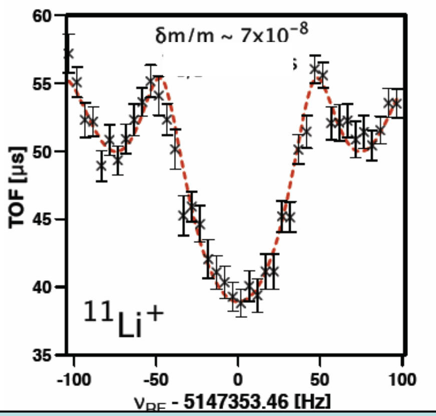
- TITAN mass measurements for Li-6
- solved conflict with AME (SMILETRAP had found different value than JILA-trap)
- M. Brodeur visited G. Audi (Orsay) and performed AME (* private communication)
- TITAN agrees with SMILE-trap value
- TITAN most precise value for new AME
- Submitted to Phys Rev C (M. Brodeur)

TITAN contributes to mass table even for stable ions!

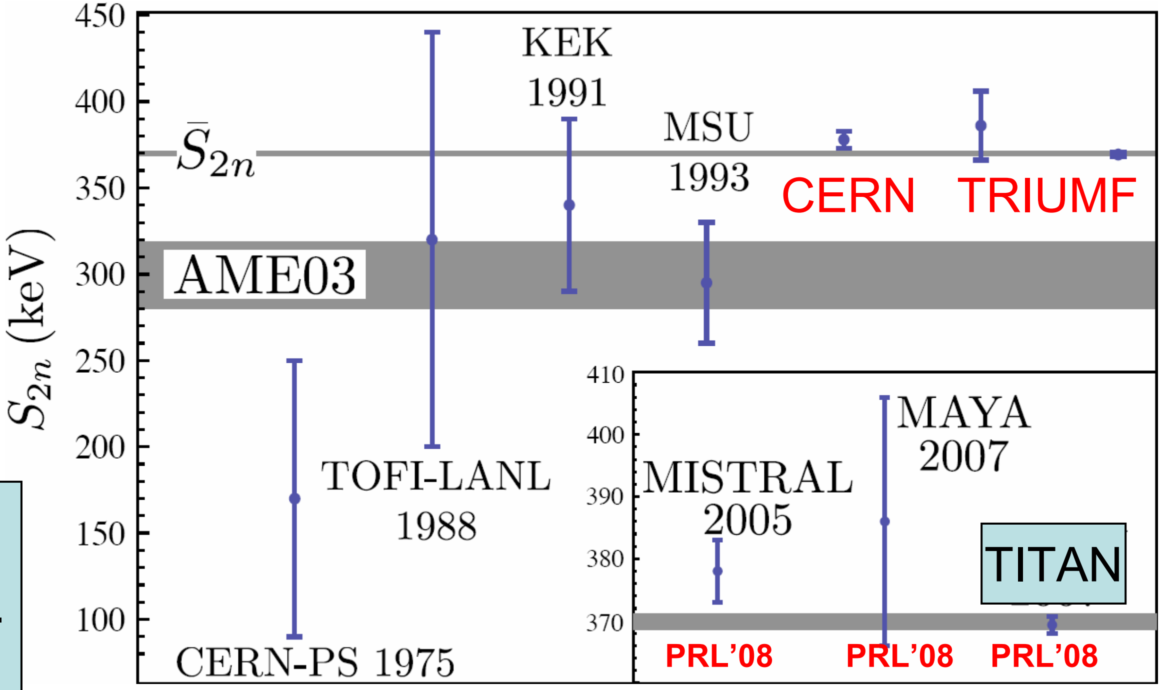
Halo mass measurements

- TITAN mass measurement of ^{6,7,8,9,11}Li
- Improved precision, S_{2n} improved by factor 7
- Shortest-lived isotope ($T_{1/2}$=8.8ms) for Penning trap mass measurement!
- Final analysis δm = 650 eV
- PRL M. Smith et al PRL 101, 202501 (2008)



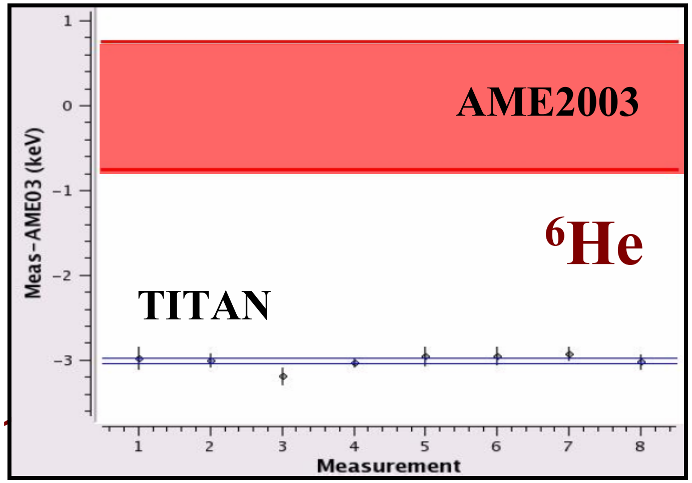


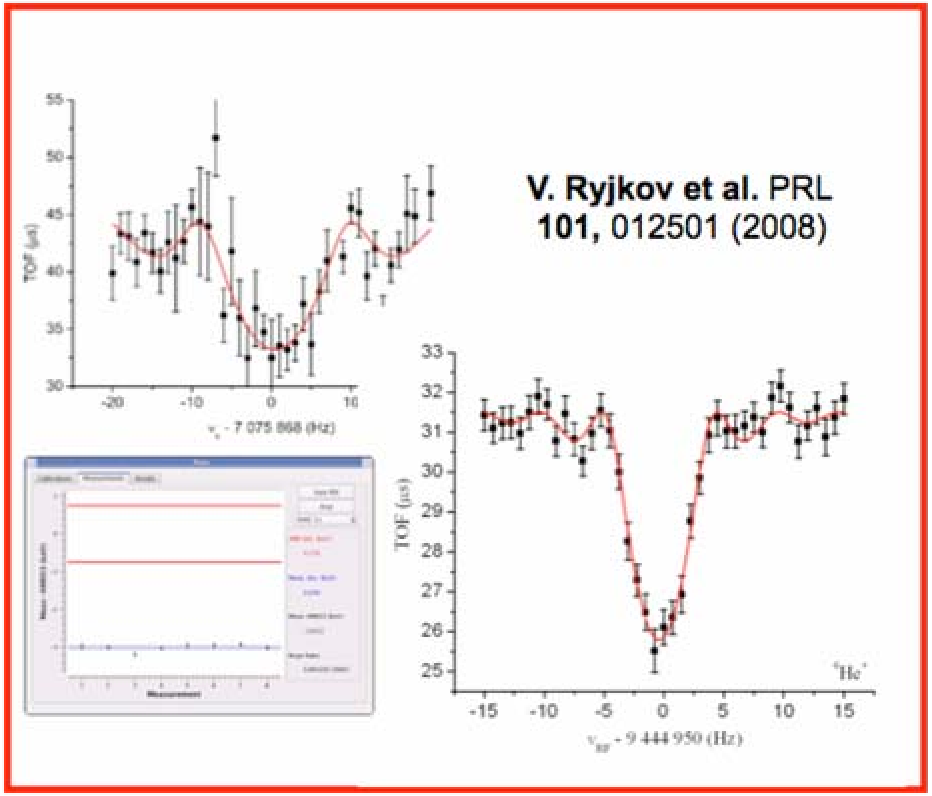
Fastest measurement due to rapid ion preparation with TITAN. Also found deviations at stable 6-Li from AME 2003



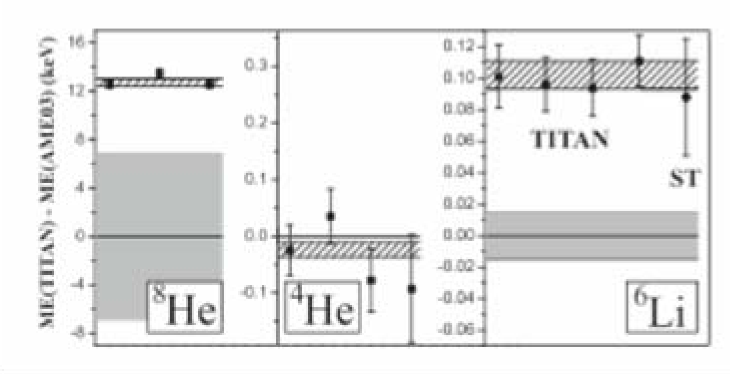
On-line measurements: Helium

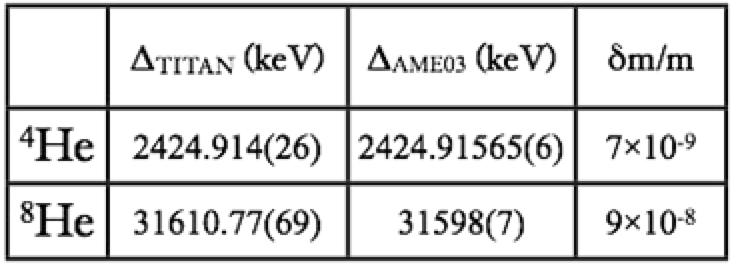
- First direct measurement of ^{6,8}He
- factor 10 improvement in precision over previous indirect result for ^{8}He
- ^{6}He also measured (publication in prep.)





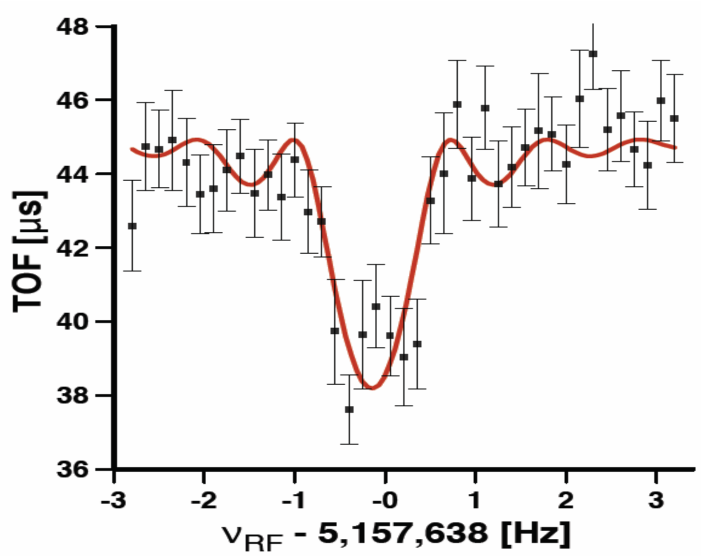
V. Ryjkov et al. PRL 101, 012501 (2008)

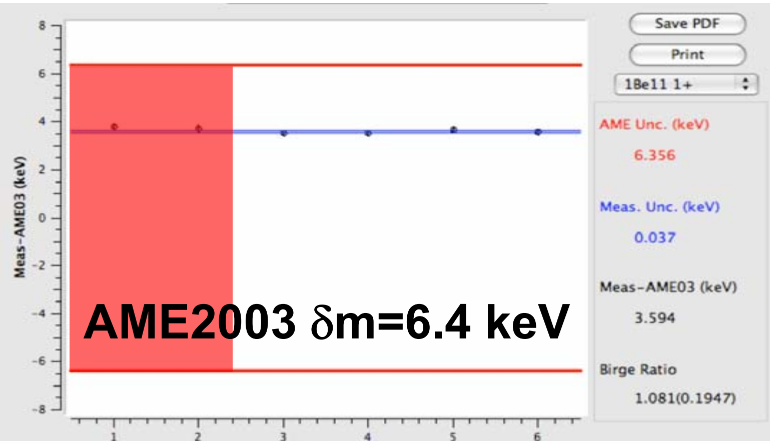




	Δ_{TITAN} (keV)	Δ_{AME03} (keV)	δm/m
^{4}He	2424.914(26)	2424.91565(6)	7×10^{-9}
^{8}He	31610.77(69)	31598(7)	9×10^{-8}

One neutron halo: Beryllium





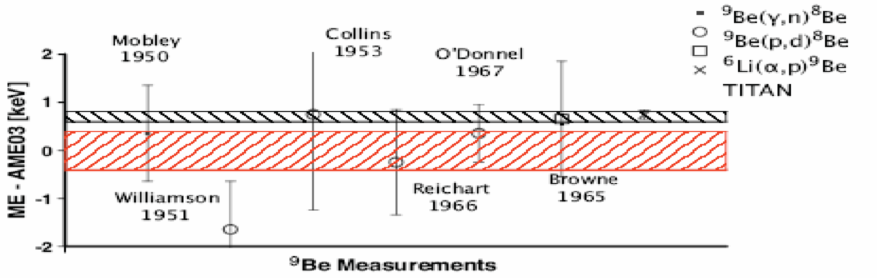
AME Unc. (keV)
6.356

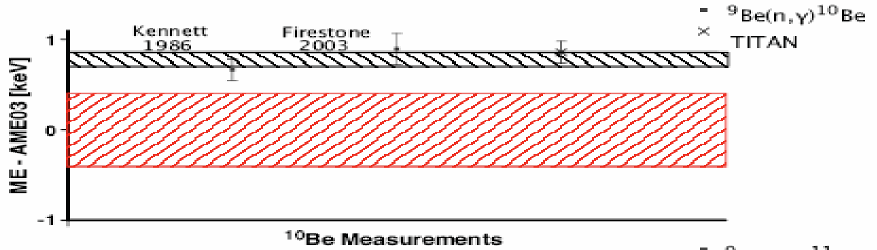
Meas. Unc. (keV)
0.037

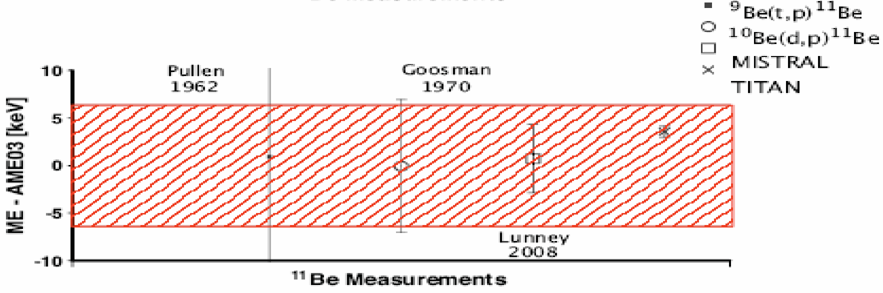
Meas-AME03 (keV)
3.594

Birge Ratio
1.081(0.1947)

AME2003 δm=6.4 keV



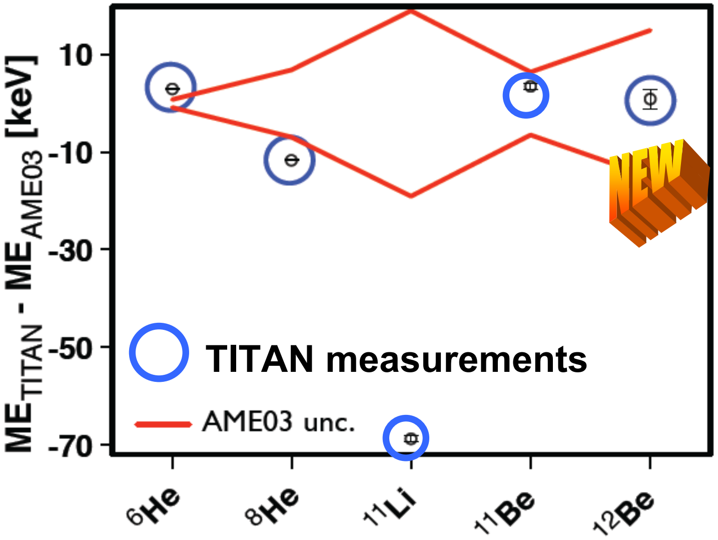




- **New measurements of the mass of ^{9,10,11}Be measured, stable masses changed!**
- **^{11}Be mass improved by over factor 10.**
- **R. Ringle et al., Phys Lett B 675, 170–174 (2009)**

Highest precision halo mass measurement

TITAN halo harvest & one more mass



^{6,8}He: Brodeur et. al., in prep.

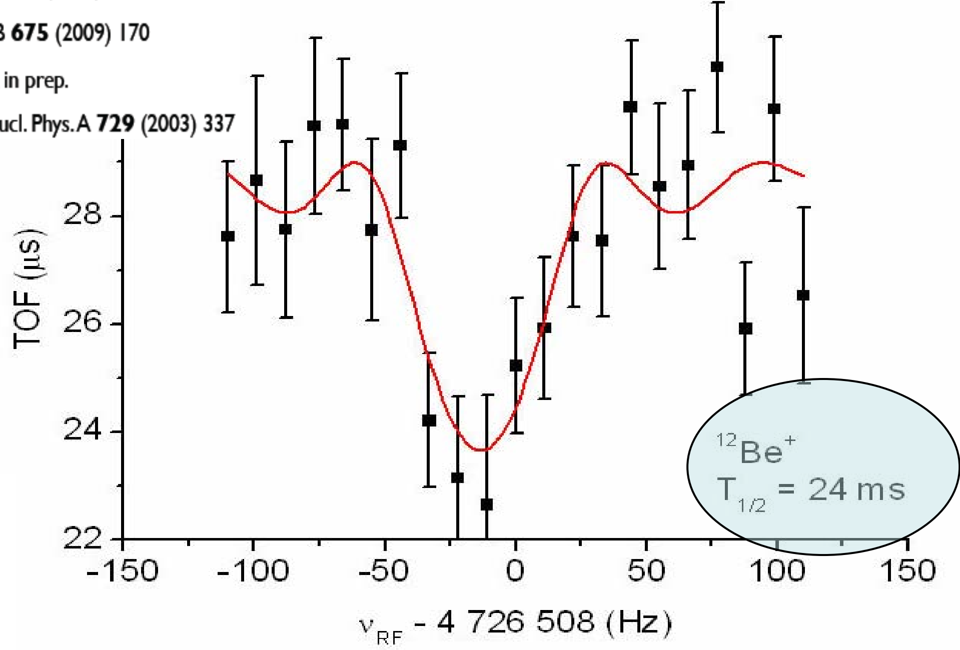
^{8}He: Ryjkov et. al., PRL **101** (2008) 012501

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

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

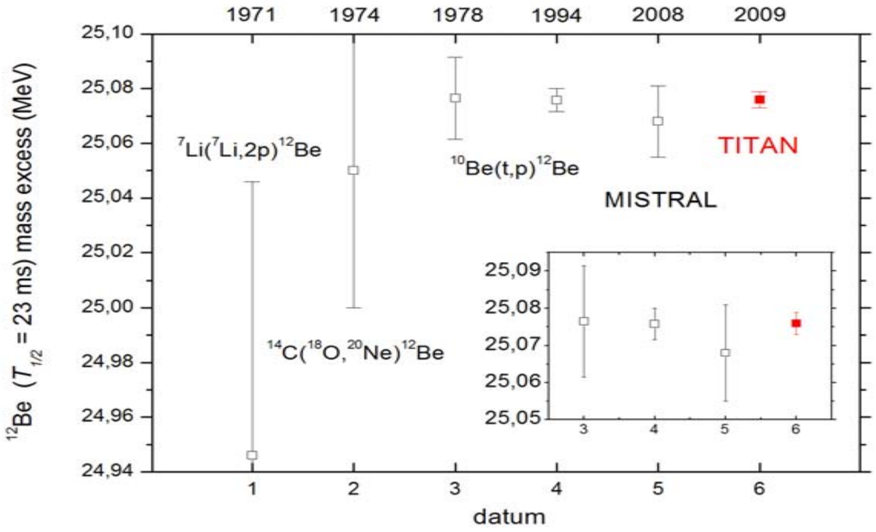
^{12}Be: Ettenauer et. al., in prep.

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



Thanks to the TRILIS group for Be.

New: TITAN measurement @ 30 ions/sec



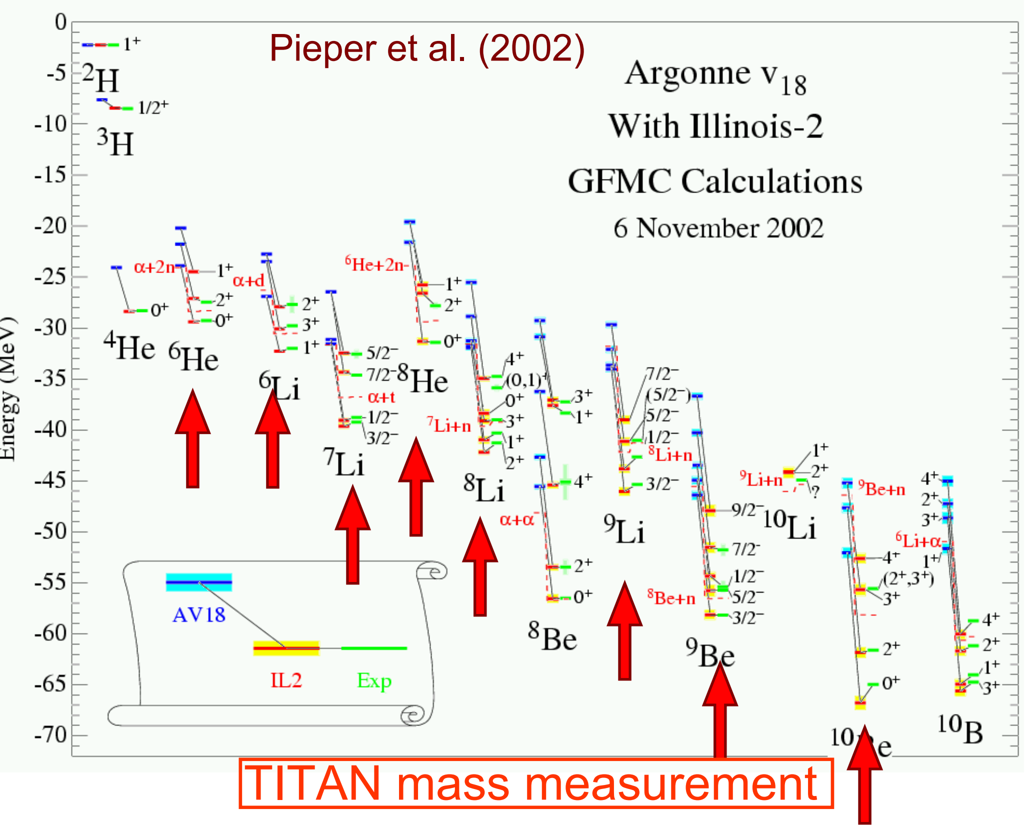
Limit of sensitivity for TITAN:
If the isotope can be ‘seen’ at ISAC yield station, we do can do a mass measurement.
Limit ~ 5-10 ions / sec

What to do with the data: use to understand halos

- test and improve the theoretical models or approaches we need
  - Experimental data; accurate and precise
  - Data from ground states (moments, mass, size and shapes)
  - Data from excited states and decay
- Data are needed as input for the theory and for testing the predictions

Experimental data as input for theory:

GFMC Quantum Monte Carlo Method,
Uses local two- and three-nucleon forces ➡ short range phenomenology



TITAN mass measurement

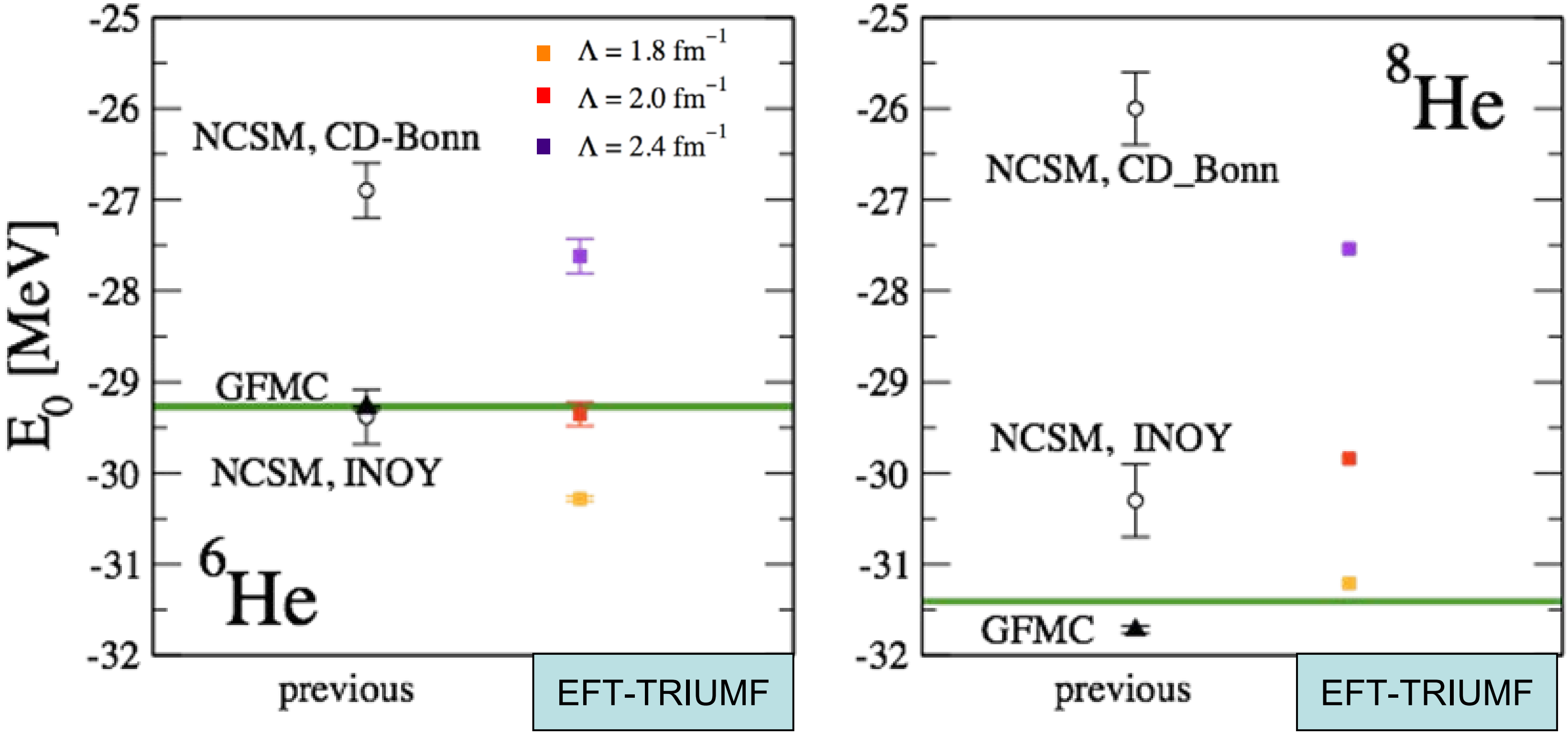
parameters of the IL2 force are obtained from a fit of 17 ground states masses and excitation of $A \leq 10$

TITAN measured 8 ground state masses, found deviations up to 7 σ from AME 2003 and reached for some up to one order of mag. improvements in precision.

Reached precision will not ‘help’ here, BUT check for consistency & needed for charge radius determination

NOW: let’s use theory to PREDICT properties: masses and radii

Binding Energy predictions



S.Bacca et al., arXiv:0902.1696

Experimental data

— TITAN ISAC-TRIUMF

SOME IMPROVEMENT NEEDED:
But very promising progress.

Let's look at Charge Radius

Isotope Shift = Frequency difference in an atomic (electron) transition between two isotopes

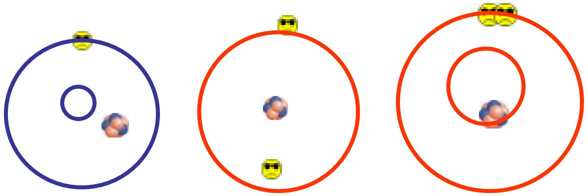
$$\Delta\nu_{IS} = \Delta\nu_{MS} + \Delta\nu_{FS}$$

charge radius difference

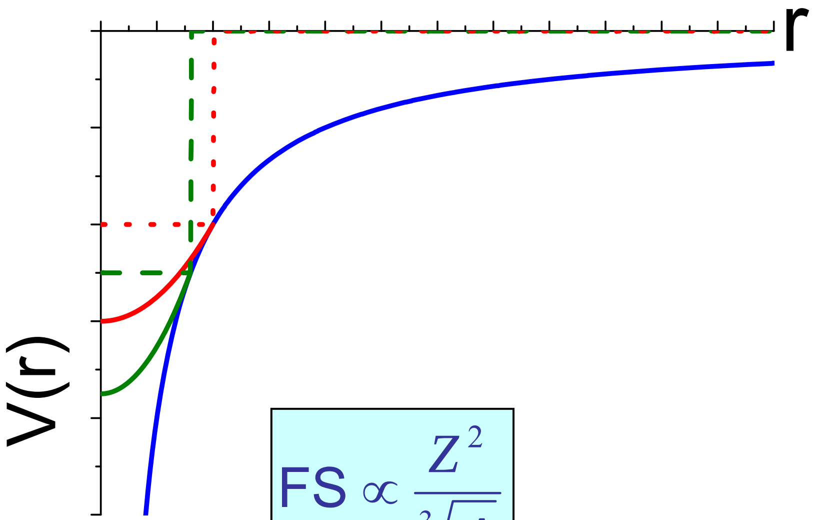
$$\frac{2\pi Z}{3}\Delta|\psi(0)|^2 \boxed{\delta\langle r^2\rangle}$$ **Field Shift**

Mass Effect

$\Delta\nu_{MS} \sim (A-A')/AA'$



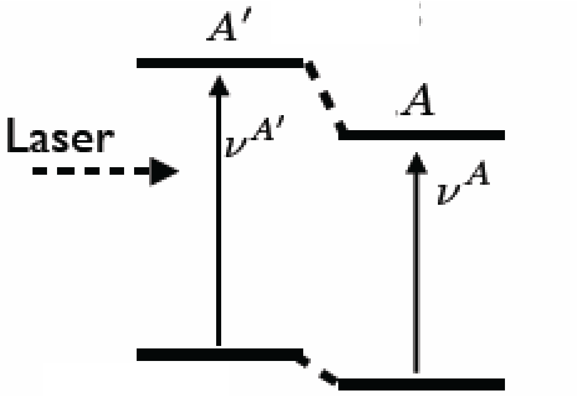
$$\text{MS} \propto \frac{A-A'}{AA'} \xrightarrow{A>>1} \frac{1}{A^2}$$



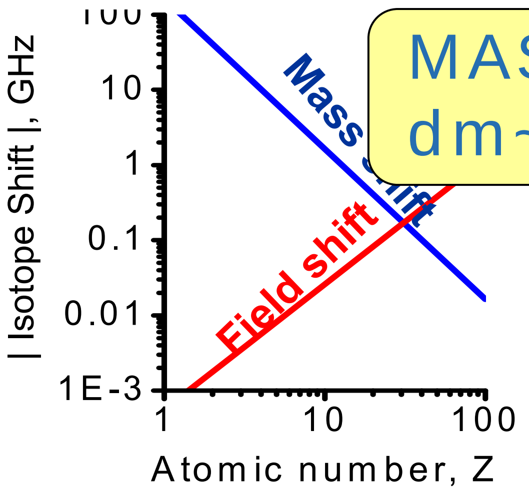
$$\text{FS} \propto \frac{Z^2}{\sqrt[3]{A}}$$

Charge radius predictions

Determination from laser spectroscopy & atomic theory (TopLis @ GSI and Drake & Pachucki et al.

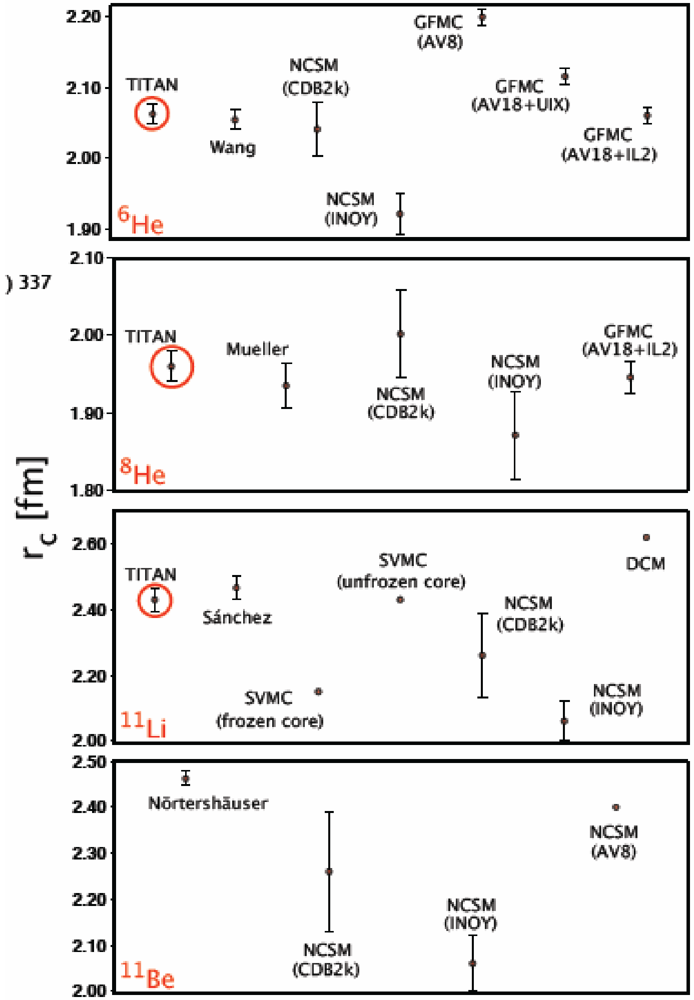


$$\overbrace{\delta\nu^{A,A'} = \nu^{A'} - \nu^{A}}^{\text{Experiment}} = \overbrace{\delta\nu^{A,A'}_{MS} + K_{FS}\cdot\delta < r_c^2 >^{A,A'}}^{\text{Theory}}$$



MASS NEEDED:
dm~ 1 keV

Charge radii using TITAN masses.



Theory still needs to be improved before it can predicts BOTH energy and radius.
BUT: New development underway.

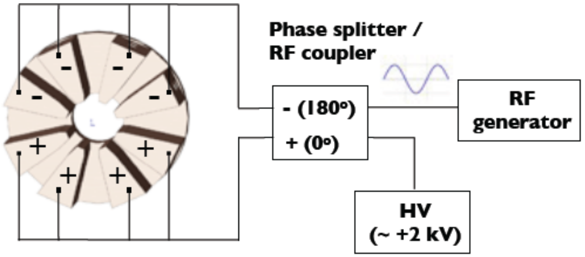
TITAN: first Highly Charged Ions

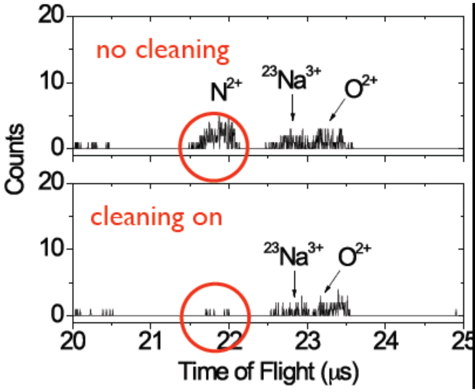
EBIT can charge breed to high charge states: A $^{n+}$

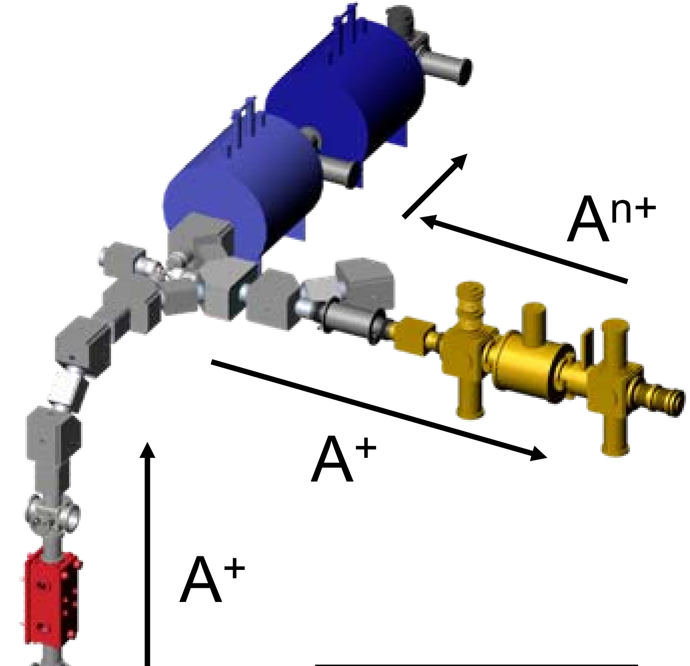
Contamination from residual gas in EBIT!

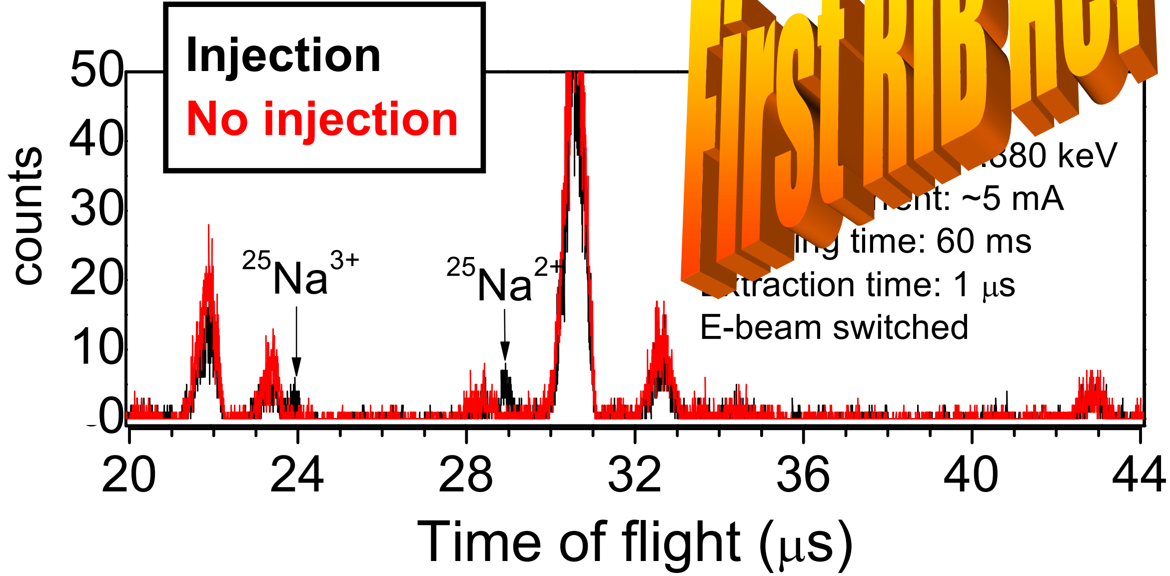
New cleaning method using ion trap techniques:

standard dipole excitation used to clean contaminants









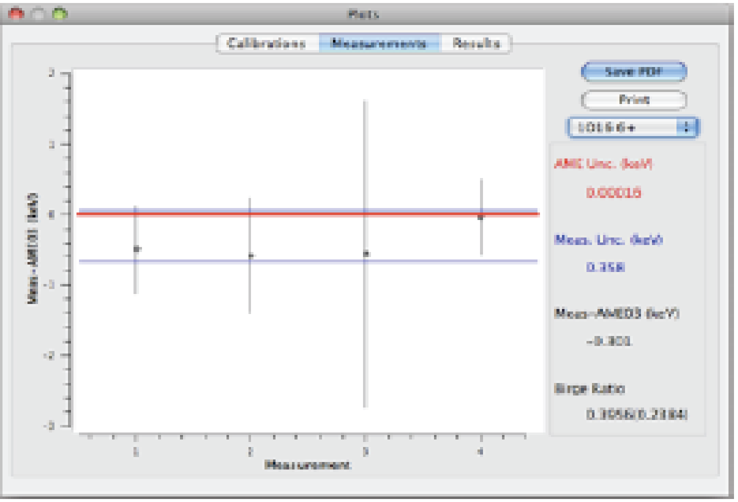
First RIB HCI

First charge bred RIB with TITAN EBIT.

ToF of injected RIB.

TITAN: stable HCI mass measurements

Preliminary



AME Unc. (keV)
0.00016

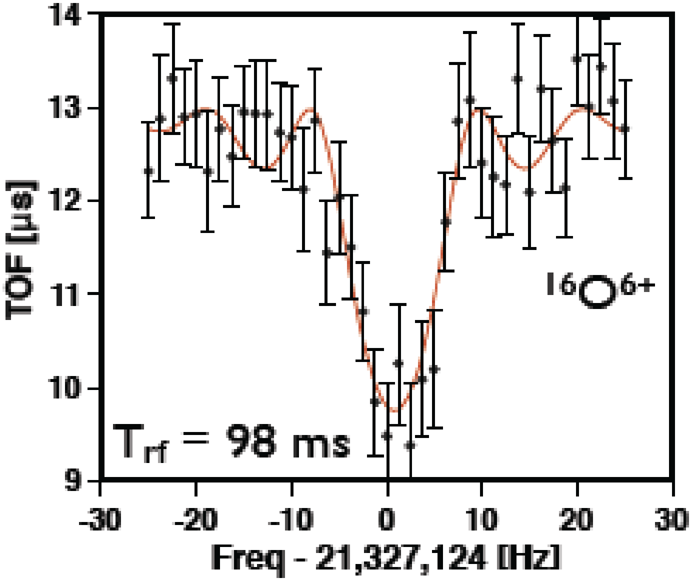
Meas. Unc. (keV)
0.358

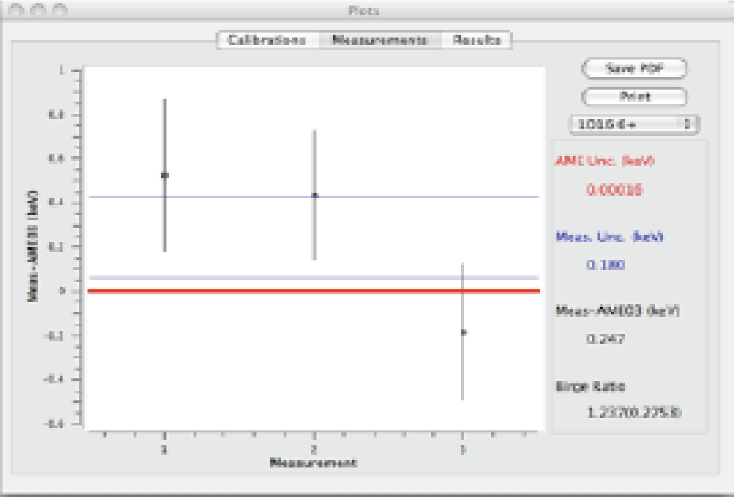
Meas-AME03 (keV)
-0.301

Birge Ratio
0.3056/0.2184

$^{16}O^{6+}$ vs. $^{6}Li^{+}$

($^{6}Li^{+}$ from surface ion s





AME Unc. (keV)
0.00016

Meas. Unc. (keV)
0.180

Meas-AME03 (keV)
0.247

Birge Ratio
1.2370/0.2758

$^{16}O^{6+}$ vs. $^{1}H^{+}$

- TITAN ready for HCI on-line mass measurements.
- Vacuum okay for 500 ms excitation times
- Go to higher EBIT currents
- This needs better vacuum.

Scheduled for TITAN:
July 16-20 Cs-beam time
Sept 11-14 K, Ca beam time

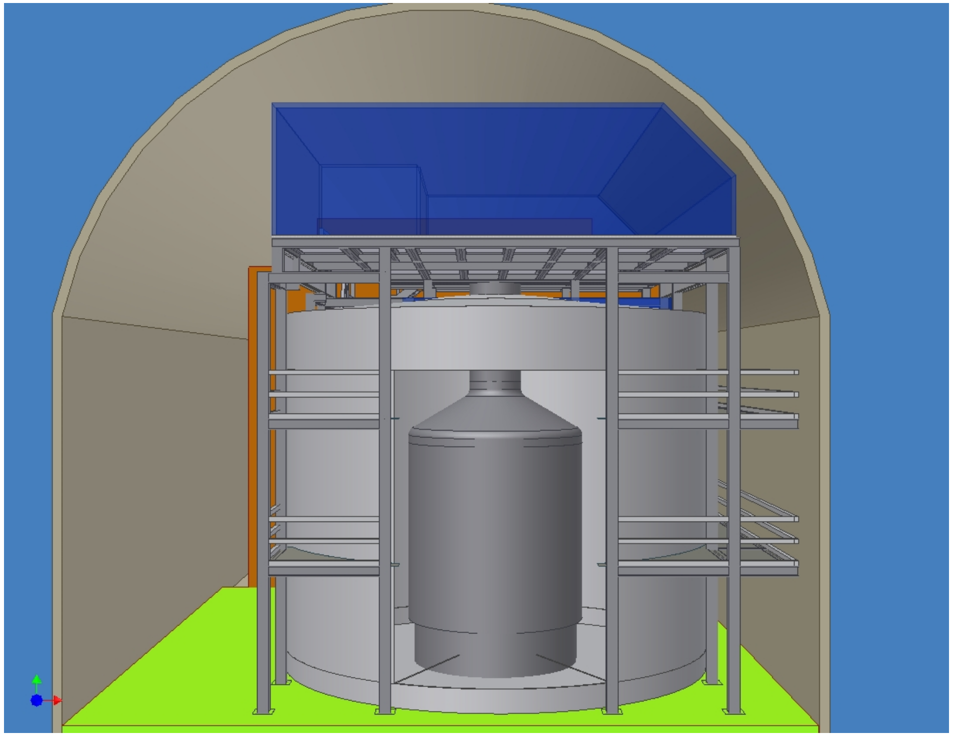
must account for electron binding energies (~ 433 eV)

Summary for Halos

- **TITAN mass measurement program underway for accurate and precise mass measurements on short-lived isotopes**
  - **Li-11 shortest-lived isotope every measured in PT, resolved conflict in mass measurements with existing data. Our precision leads to charge radius re-evaluation and reduced error.**
  - **Be-11, 12 tremendous improvement of precision in mass. New atomic physics calculation and our mass leads to exclusion of systematic uncertainty due to mass.**
  - **He-6,8 measured. Lightest isotopes ever mass measured at on-line PT**
- **TITAN is performing very well, systematic studies with stable ions to check precision and accuracy, confirmed 2ppb-level precision**
- **More measurements planned for Halo- and neutron-skin program: Be, C, Ne,…**
- **Fastest PT system coupled to on-line facility**
- **EBIT for high charge states is operational, coupled to TITAN and on-line run carried out, mass measurements to be done this year....**
- **Stay tuned**
- **New cooler trap system for HCIs, planned for installation in Winter 2009 (V. Simon, MPI-K, will work on system)**

Other TITAN experiments: 2ν2β-decay for nuclear matrix elements

- Help nuclear theory to aid the neutrino physics community understand the neutrino-mass problem (for example:



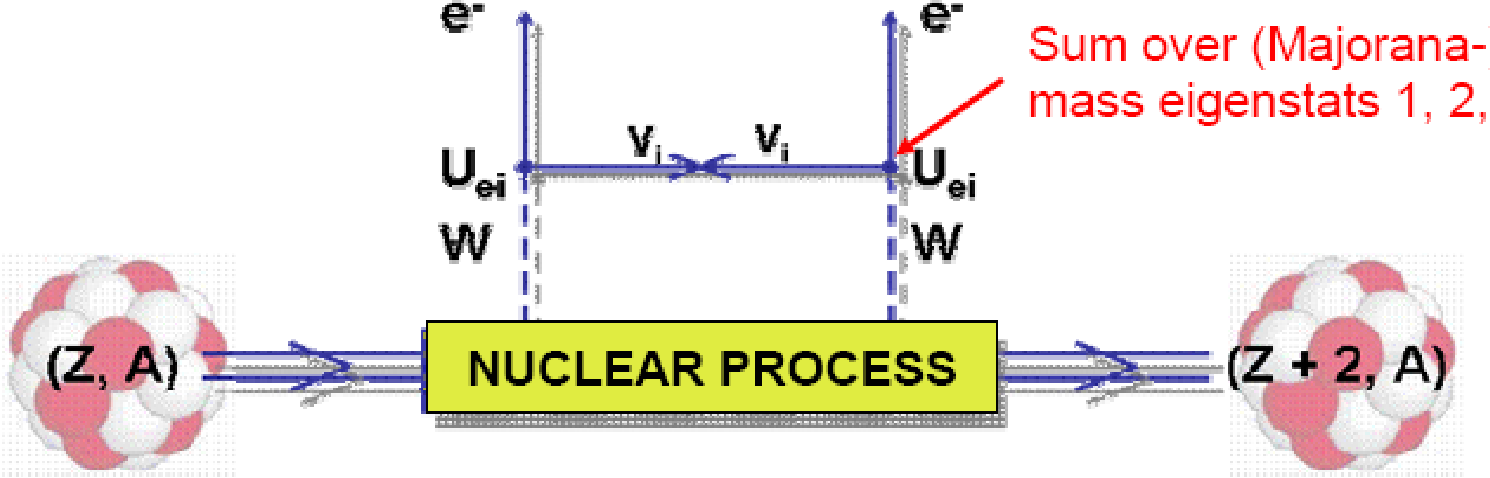
Double-beta decay

Rare, spontaneous nuclear reaction:

$2\nu\beta\beta$: $(Z, A) \rightarrow (Z+2, A) + e^- + e^- + 2\nu$ $\Delta L = 0$ *$(T_{1/2} \sim 10^{21}$ y)*

$0\nu\beta\beta$: $(Z, A) \rightarrow (Z+2, A) + e^- + e^-$ $\Delta L = 2$ *$(T_{1/2} > 10^{25}$ y)*

Lepton number violation (unexpected in the SM)



Sum over (Majorana-) neutrino mass eigenstats 1, 2, 3

Neutrino physics open questions

- What is the nature of neutrinos? Dirac or Majorana?
- Which mass hierarchy is realized in nature?
- What is the absolute mass-scale for neutrinos?

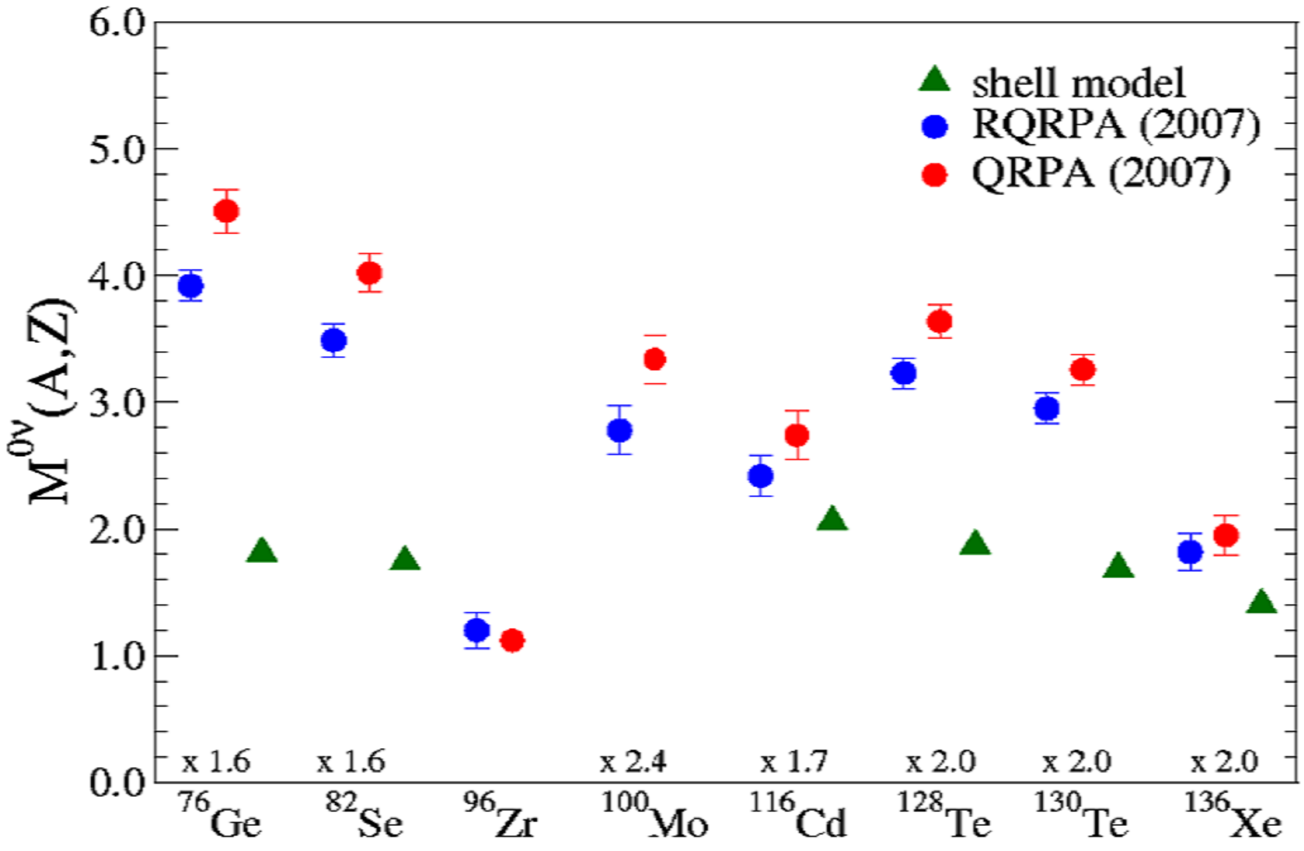
A neutrinoless double beta decay experiment, like GERDA
has the potential to answer all three questions,
but ‘rocky road’ via nuclear physics!

Double beta decay

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 m_{\beta\beta}^2$$

Linking decay rate to effective neutrino mass via Nuclear Matrix Element $M^{0\nu}$

PROBLEM: need $M^{0\nu}$ to ~ 20% to make useful statements F. Deppisch and H. Päs *PRL 98 232501 (2007)*
& models are often in conflict with experimental results (single branch).



QRPA, RQRPA: V.Rodin, A. Faessler, F. Š., P. Vogel, Nucl. Phys. A 793, 213 (2007)
Shell model: E. Caurieratal. Rev. Mod. Phys. 77, 427 (2005).

Nuclear Matrix Element

$$\boxed{\Gamma = G\,|M|^2\,\langle m_{\nu e}\rangle^2}$$

0νββ decay rate:

phase space factor

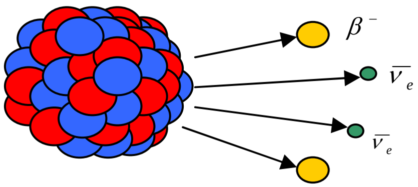
nuclear matrix element:

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

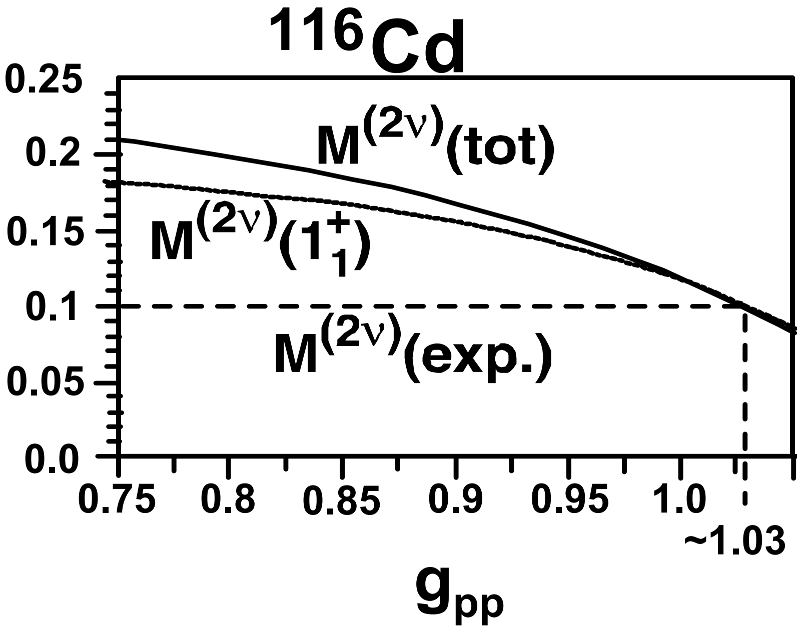
theoretical models:

- proton-neutron Quasiparticle Random Phase Approximation (pnQRPA)
- nuclear shell model
- interacting boson model

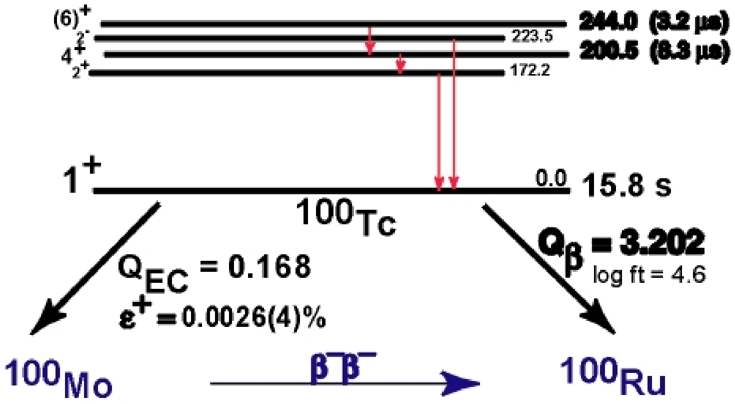
- adjustable particle-particle parameter $\mathbf{g_{pp}}$
- fix $\mathbf{g_{pp}}$ with 2νββ decay (very sensitive on $\mathbf{g_{pp}}$)



- 0νββ decay much less dependent on $\mathbf{g_{pp}}$



Branching ratio determination



EC-signature: X-ray after electron capture

β-signature: electrons

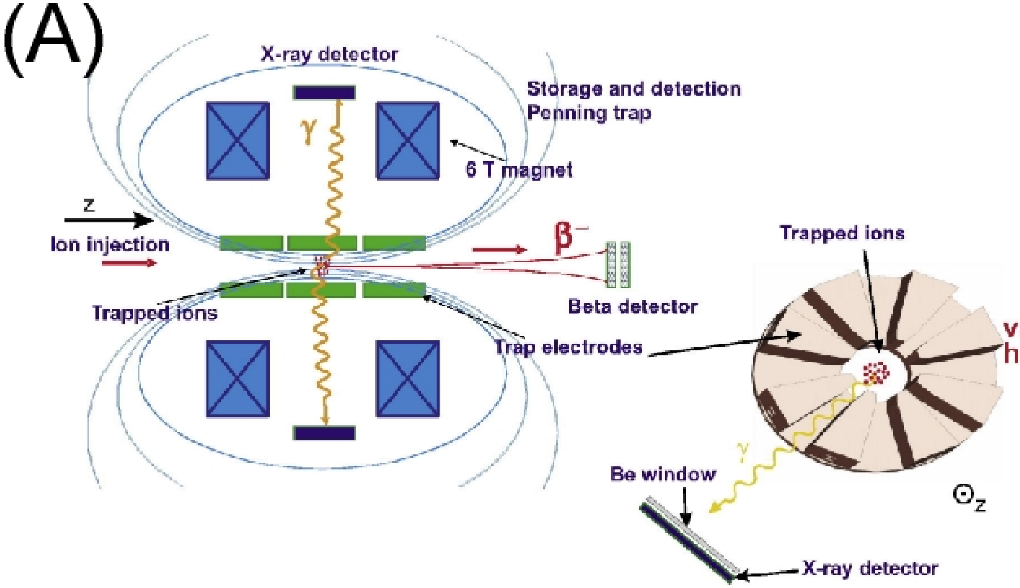
BUT:

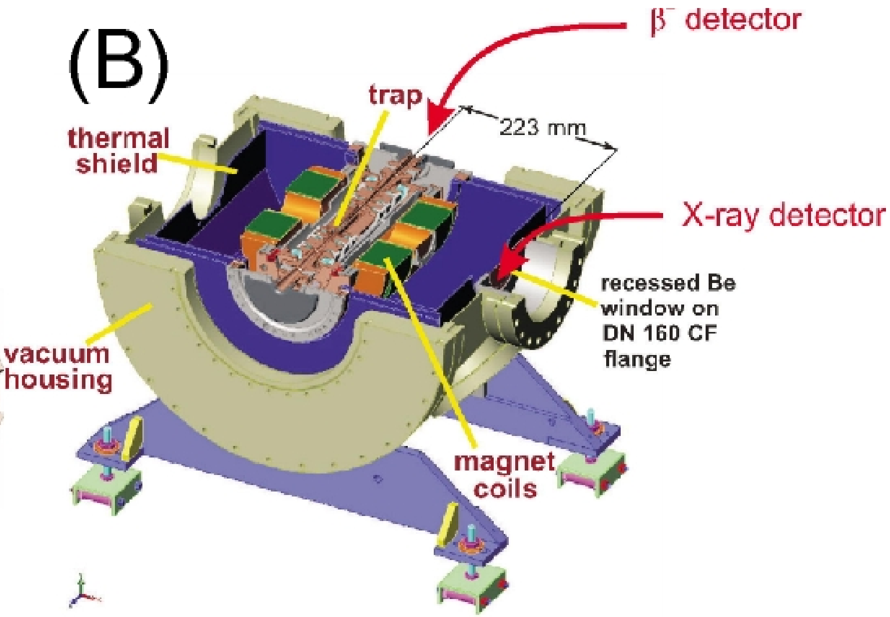
small BR ($10^{-4/5}$) and difficult signature of low-energy X-ray in gamma background

possible bremsstrahlung background

isobar and decay daughter contamination

Novel concept: use Penning trap





EBIT in Penning trap mode

confinement:

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

β- background √
absorption backing material √

in-trap spectroscopy:

strong B field → spatial separation of X-ray and b-particles

segmented trapping electrodes → close placement of X-ray detectors

extract ions after observation time → low background β-dectector → anti-coincidence

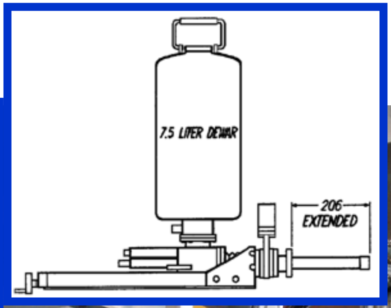
TITAN-EC Set-up

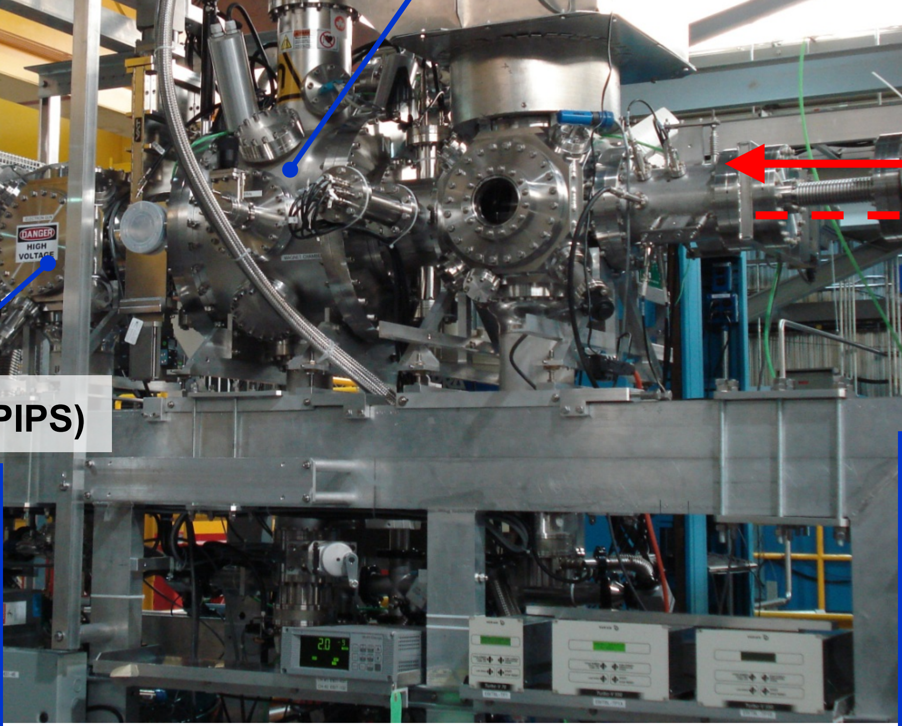
total solid angle: 0.7 %

final: 2.1 %

LEGe X-ray detector in vacuum

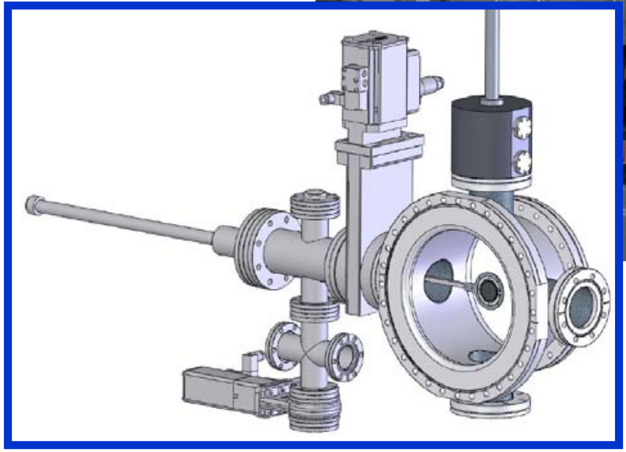
@ 4 T, 10 cm away from the trap center





Injection
~ 2 keV

Extraction



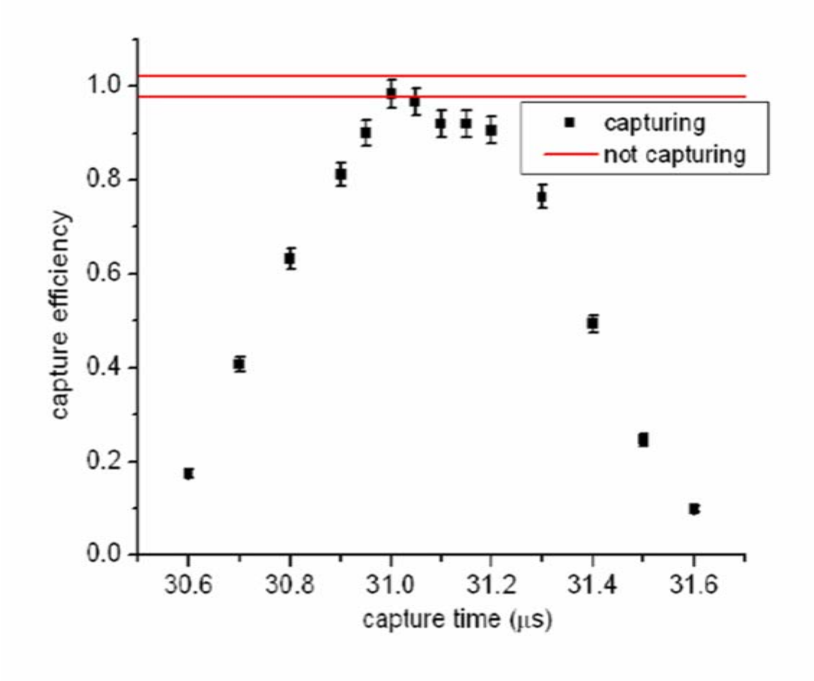
20 % **Coax Ge** external

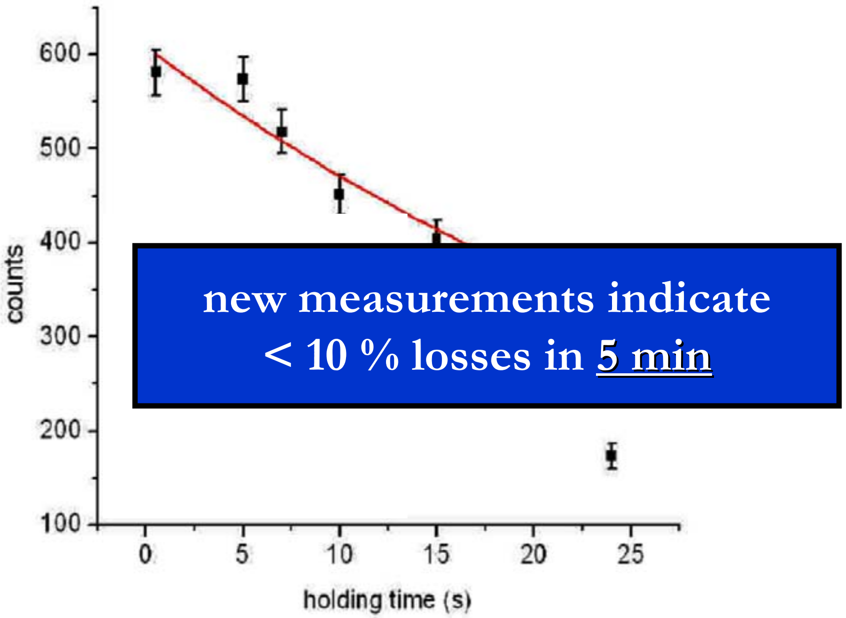
Test run with 107-In

^{107}In well known X-ray (mainly due to EC) and γ intensities

Main Goals:
- can we trap and store ions? (done with stable ions)
- do the β – detector (PIPS) and X-ray detectors work in B- field?
- can we detect X-ray and γ –rays?
- can we detect β from trap?

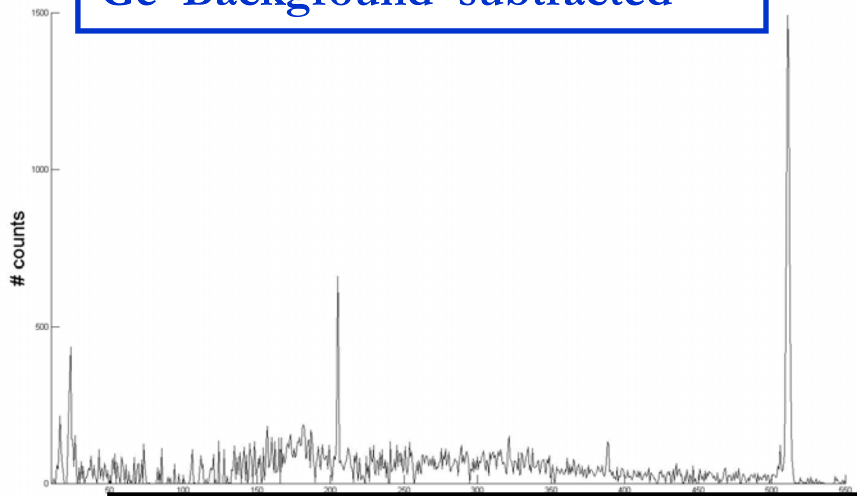
Optimistic Goal: can we reproduce X-ray, γ –ray intensities and EC-BR?



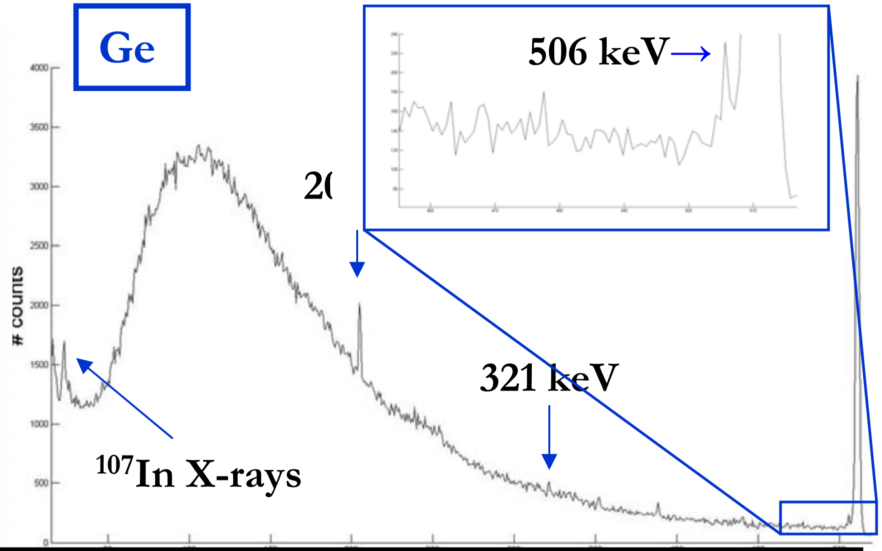


new measurements indicate
< 10 % losses in **5 min**

Detector performance in B-field



Ge ‘Background’ subtracted



Ge

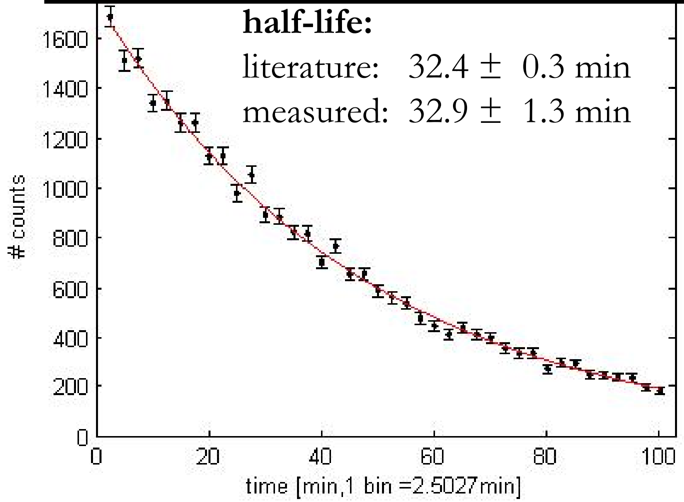
506 keV→

2(

321 keV

^{107}In X-rays

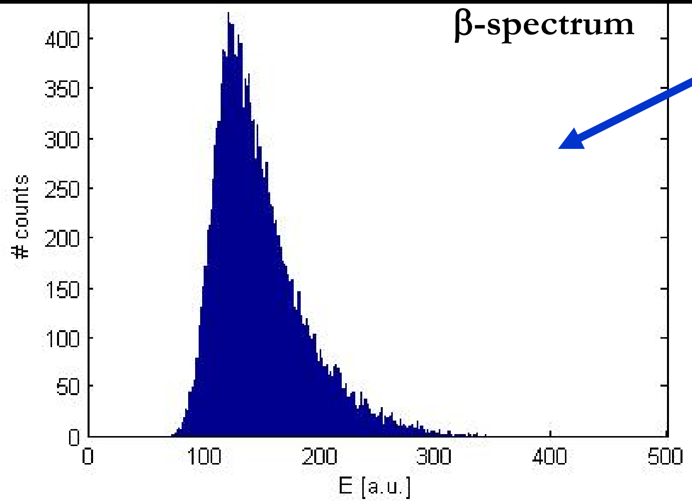
very first in-trap spectroscopy of EC



half-life:

literature: 32.4 ± 0.3 min

measured: 32.9 ± 1.3 min

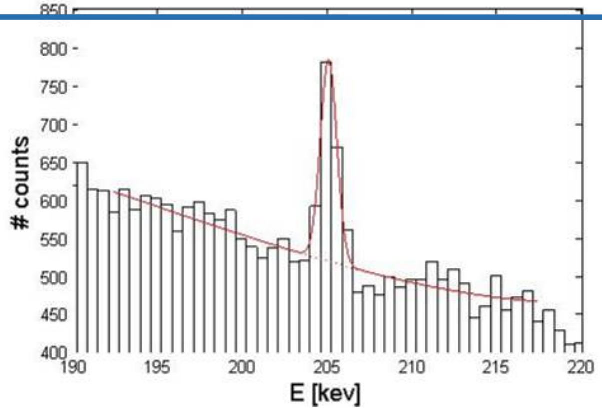


β-spectrum

observation of on Al-foil implanted ^{107}In

Relative Intensities

use 205 keV with I = 47.2% as a reference



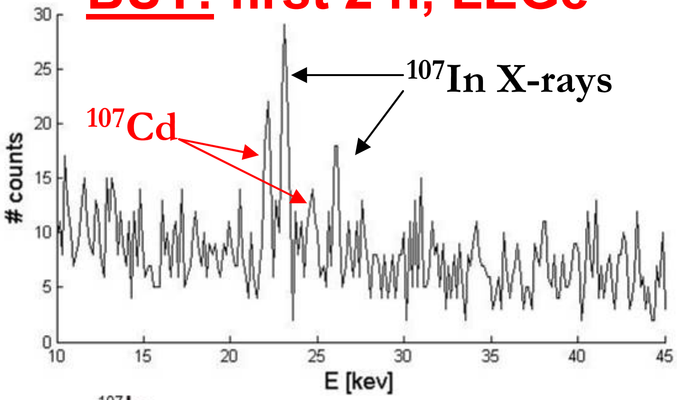
Ge 1st h: γ-rays

peak [keV]	intensity [%]	uncertainty [%]	
321	10.3	2.6	
	10.2	0.3	literature
506	13.6	4.2	
	11.9	0.4	literature

Ge 1st h: X-rays:

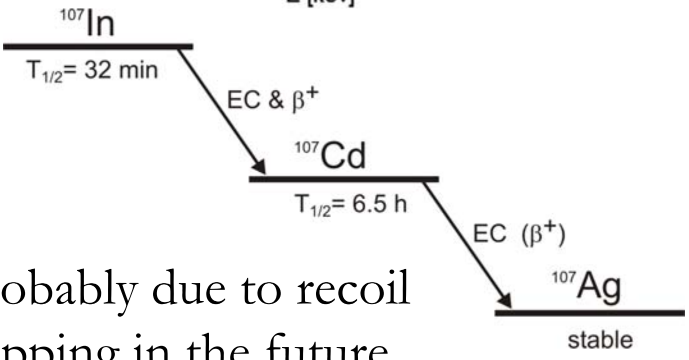
peak [keV]	intensity [%]	uncertainty [%]	
23	35.1	10.5	
	40.5	1.48	literature
26	10.0	3.2	
	7.84	0.24	literature

BUT: first 2 h, LEGe



? ⇒ BR(EC) = (58 ± 16) % ?

Ge: not resolved; **LeGe:** too few counts



⇒ **losses!** probably due to recoil

⇒ deeper trapping in the future

First proof-of-principle experiment

- Can we load ions in trap and store efficiently for long time? ☑
- How many ions can we load? Need to do more off-line work; want 10^6 in the trap.
- Can we put X-ray detectors near the trap (hence into the B-field)? ☑

  need to check resolution.
- Can we use beta Si(Li) detector in the B-field? ☑

  looks go, we did systematic tests and did not see change in resolution for 0,2,3,5 Tesla for x-ray lines (question for γ-energy?)

  Complete digital read-out system (Tig10-units)
- Can we suppress background nuclei be extracting trap content backwards? ☑

  we extracted the beam backwards and could see some contribution from the daughter isotopes Cd. Need to investigate looses (maybe deeper trap?)

- Overall very successful run, good proof of principle experiment for first in-trap gamma spectroscopy.
- Next test scheduled for Summer 2009, and full detector system in Fall 2009.

TRIUMF

TITAN Conclusions

- Rare isotopes provide a unique window into some of the most pressing questions in understanding the universe:
  - Strong force
  - Symmetries
  - Neutrinos
  - Nucleo-synthesis
  - Life and death of stars
  - …
- TITAN carries our precise and accurate mass measurements on halo nuclei, breaking a number of PT records.
- TITAN offers other unique experimental opportunities, like double beta-decay (and more…)
- ISAC @ TRIUMF is one of the world leader in rare isotope physics, with bright future, much, much more to come.

Thank you for your attention!

Jens Dilling for the

TITAN collaboration:

M. Smith, M. Brodeur, S. Ettenauer, T. Brunner, C. Champagne, Z. Ke, A. Gallant, R. Ringle, A. Lapierre, W. Chi, V. Ryjkov, P. Delheij, M. Pearson, G. Gwinner, D. Lunney, F. Buchinger, J. Crawford, R. Krücken, D. Frekers, F. Sarazin, I. Tanihata, J. Crespo, J. Ullrich

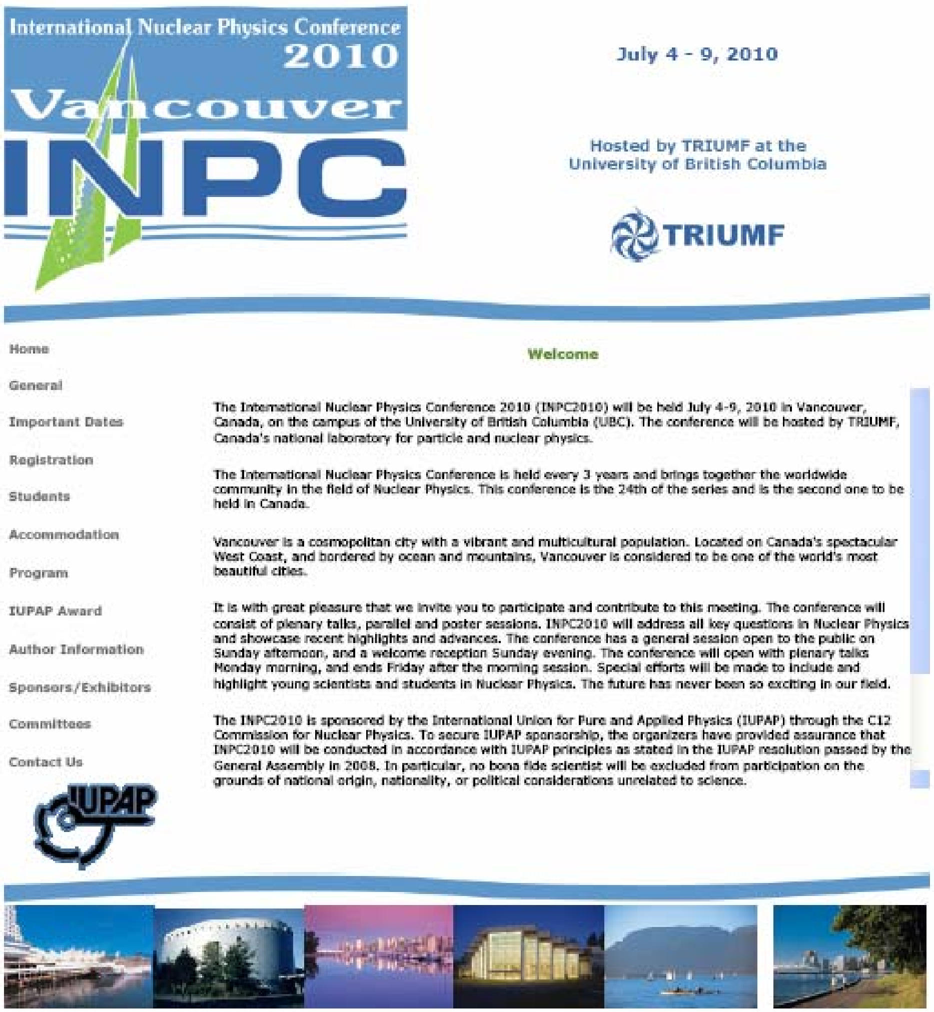
UBC, TRIUMF, TU Munich, U Münster, Colorado SoM, McGill, RCNP Osaka, MPI-K Heidelberg

TRIUMF

THE UNIVERSITY OF BRITISH COLUMBIA

www.triumf.ca/TITAN

www.inpc2010.triumf.ca



July 4 - 9, 2010

Hosted by TRIUMF at the University of British Columbia

Welcome

The International Nuclear Physics Conference 2010 (INPC2010) will be held July 4-9, 2010 in Vancouver, Canada, on the campus of the University of British Columbia (UBC). The conference will be hosted by TRIUMF, Canada's national laboratory for particle and nuclear physics.

The International Nuclear Physics Conference is held every 3 years and brings together the worldwide community in the field of Nuclear Physics. This conference is the 24th of the series and is the second one to be held in Canada.

Vancouver is a cosmopolitan city with a vibrant and multicultural population. Located on Canada's spectacular West Coast, and bordered by ocean and mountains, Vancouver is considered to be one of the world's most beautiful cities.

It is with great pleasure that we invite you to participate and contribute to this meeting. The conference will consist of plenary talks, parallel and poster sessions. INPC2010 will address all key questions in Nuclear Physics and showcase recent highlights and advances. The conference has a general session open to the public on Sunday afternoon, and a welcome reception Sunday evening. The conference will open with plenary talks Monday morning, and ends Friday after the morning session. Special efforts will be made to include and highlight young scientists and students in Nuclear Physics. The future has never been so exciting in our field.

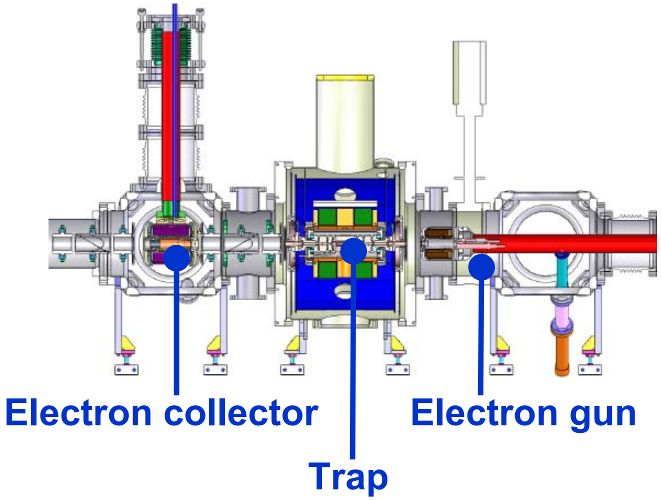
The INPC2010 is sponsored by the International Union for Pure and Applied Physics (IUPAP) through the C12 Commission for Nuclear Physics. To secure IUPAP sponsorship, the organizers have provided assurance that INPC2010 will be conducted in accordance with IUPAP principles as stated in the IUPAP resolution passed by the General Assembly in 2008. In particular, no bona fide scientist will be excluded from participation on the grounds of national origin, nationality, or political considerations unrelated to science.

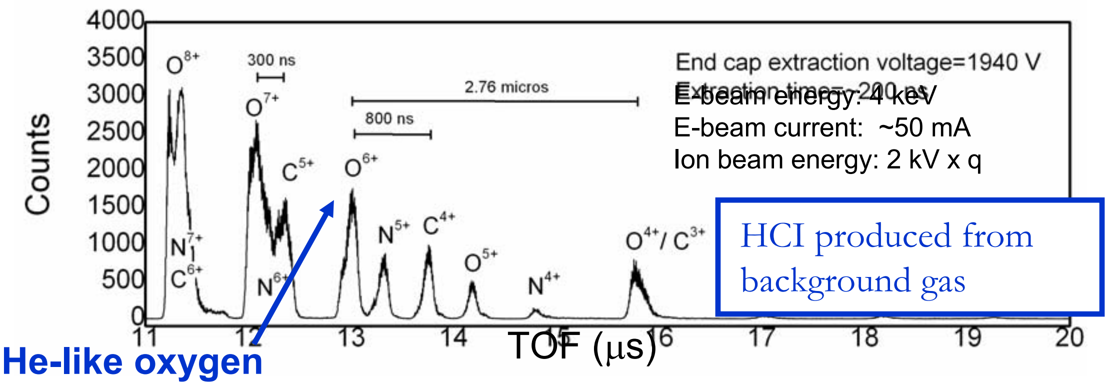
See you in Vancouver!

TITAN EBIT

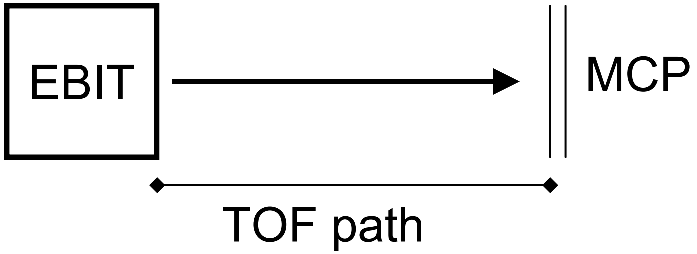
Design values

Max. e-beam energy	**~70 keV [reached 25 keV]**
Max. e-beam current	**500 mA [reached: 400 mA]**
Max. magnetic field strength	**6 T**
Beam diameter (FWHM)	**~40 µm**
Electron beam current density	**~10^5 A/cm^2**
Number of trapped ions	**10^6-10^8**
Beam energy spread	**~50 eV**
Highest charge state	**~ He-like U, q=90+**





HCI produced from background gas

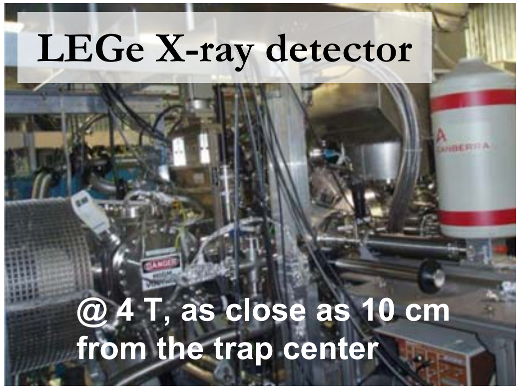

EBIT

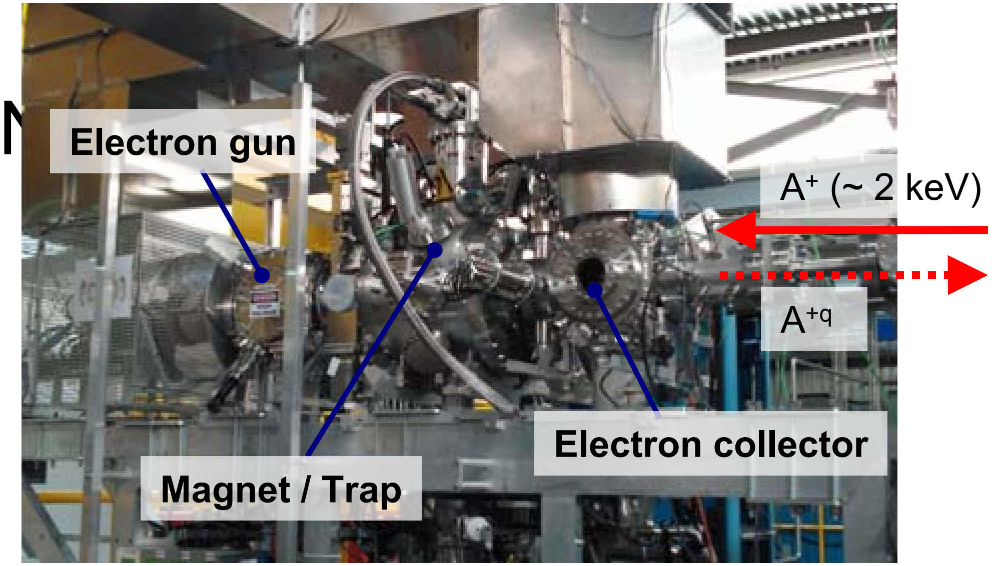
MCP

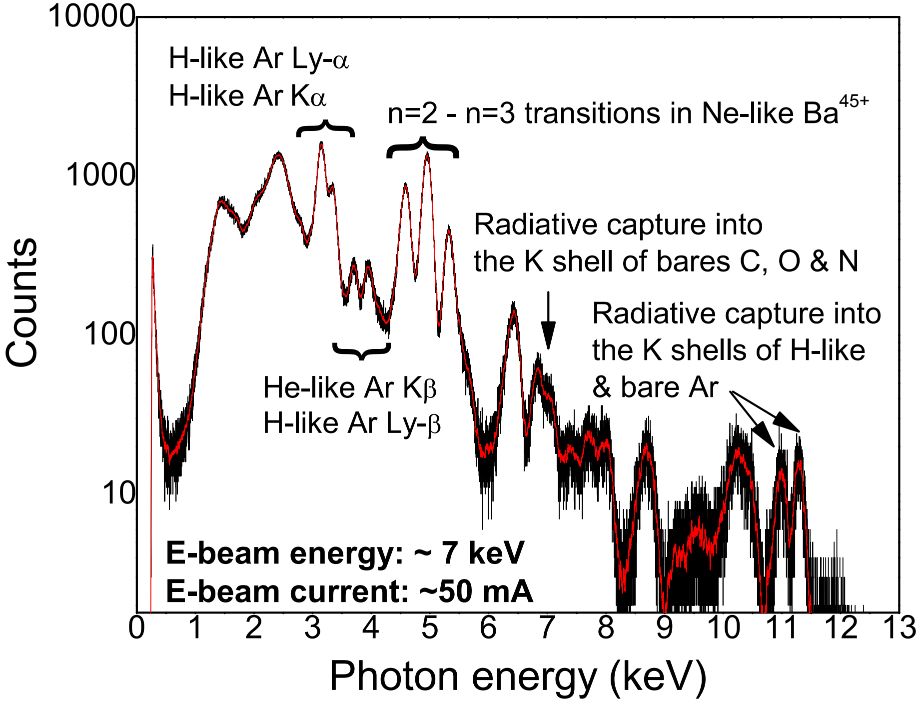
TOF path

TOF: starts with extraction from EBIT

TITAN



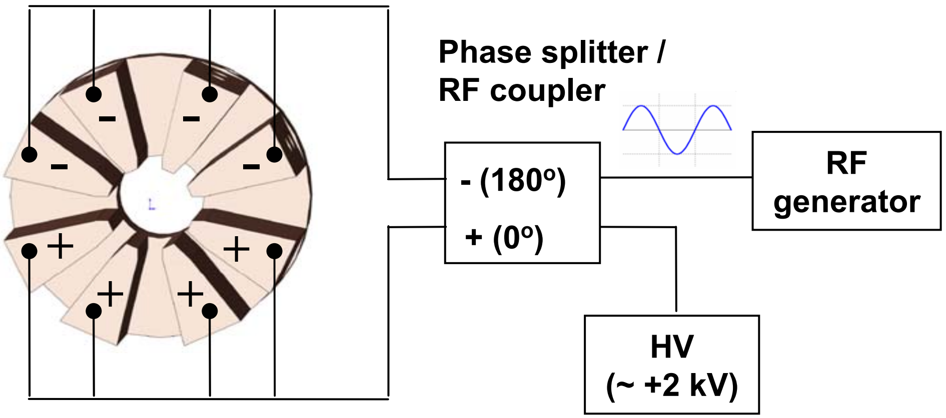




X-ray spectroscopy:

- diagnostics tool for charge breeding
- EC-BR measurement
  (approved proposal S1066)

Dipole Cleaning in EBIT



Phase splitter / RF coupler

- (180°)

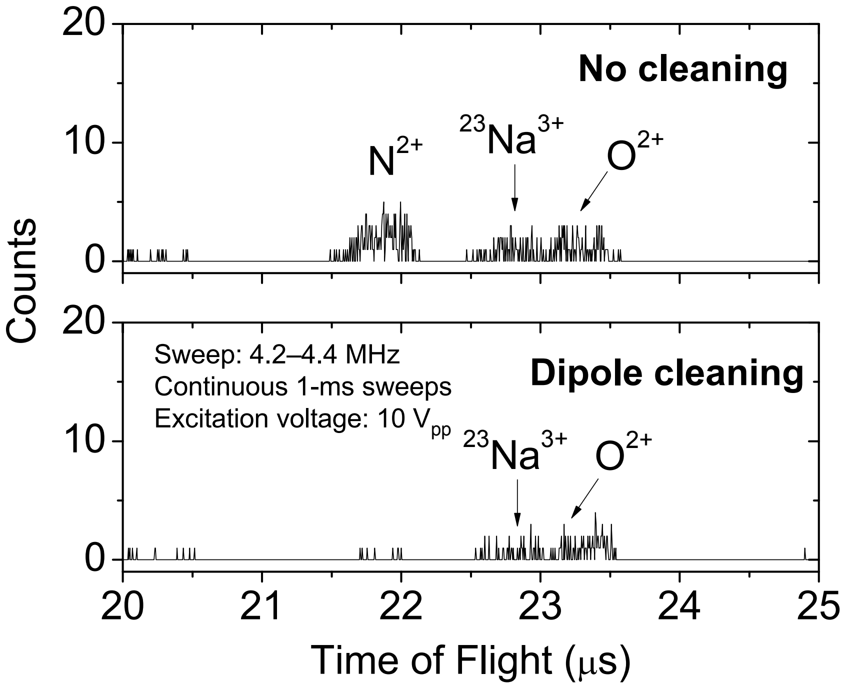
+ (0°)

RF generator

HV (~ +2 kV)

ion trap technique to get rid of unwanted species:

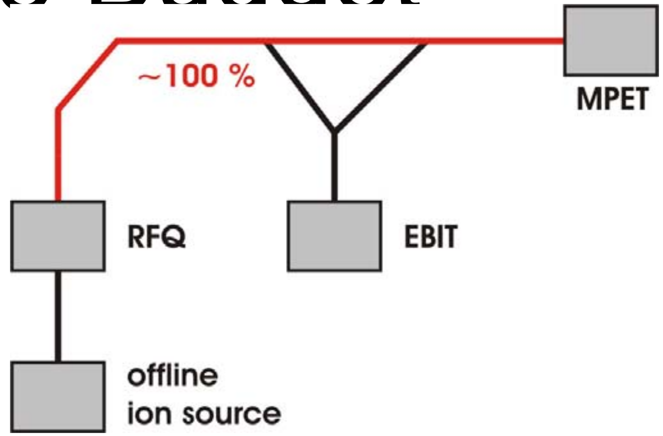
- apply RF at reduced cyclotron frequency of species (↔ eigen-motion)
- increases radius until ions leave the trap



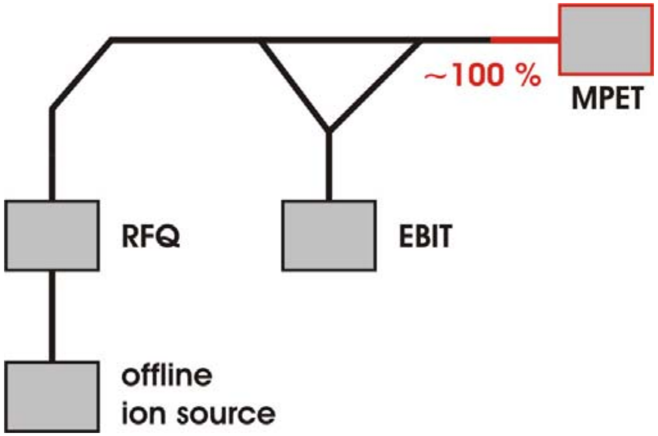
E-beam energy: 3.880 keV
E-beam current: ~5 mA
Breeding time: 100 ms
Extraction (dump) time: 1 ms
(E-beam switched)

Efficiency & Time Budget

A^+	Efficiency	time
RFQ	~65 %	10ms – 1s
RFQ to MPET	~100%	
MPET	~ 100% (?)	10ms – 1s
Total	~65 %	10ms – 1s

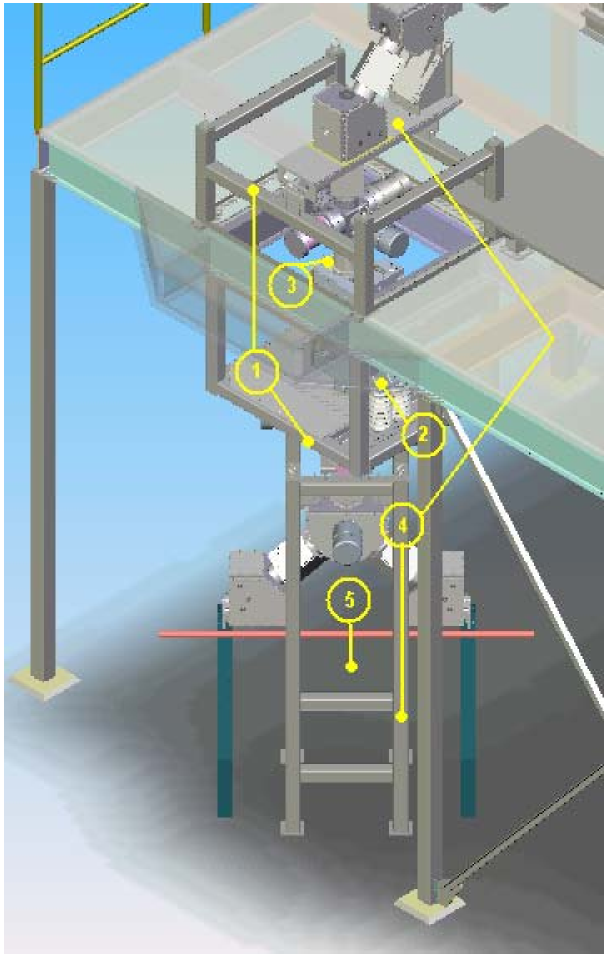


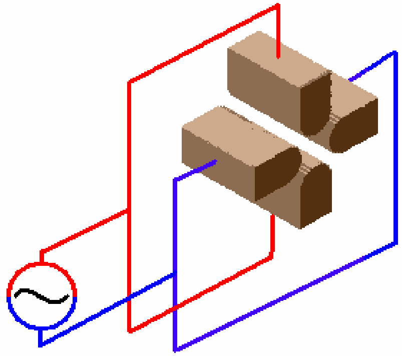
A^{+q}	Efficiency	time
RFQ	~65 %	10ms – 1s
RFQ to EBIT	~100%	
charge breeding (He or Ne-like)	~50% (simulations)	< 200 ms (dep. on e^- current)
EBIT to MPET (A^+)	50-60 %	
EBIT to MPET (A^{+q})	not measured	
MPET	~ 100% (?)	10ms – 1s
Total	~16-20 %	30ms - 1.2s

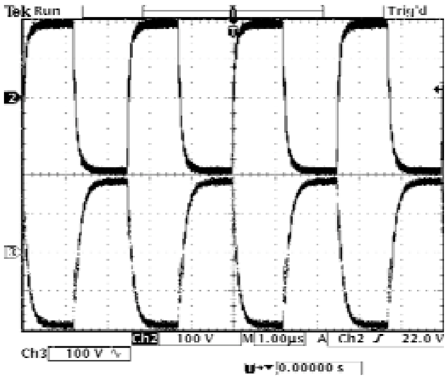


Coupling to ISAC: TITAN RFQ

Linear gas filled Paul trap, to convert 'hot' DC ISAC beam into cool bunches.
Uses fast switches to generate RF-field (broad-band, no amplifier needed)







TITAN RFQ

- Emittance $\varepsilon_{95\%} = 6.1\ \pi$ mm mrad
- 68% DC efficiency for $^{133}Cs^{+}$ in He
- 15% DC efficiency for $^{6,7}Li^{+}$ in He
- 60% DC efficiency for $^{6}Li^{+}$ in H_2
- Pulses as short as 50 ns FWHM @ up to 1 kH
- Reversed extraction successfully demonstrated with ^{136}Xe from OLIS
- Will be used for laser spectroscopy to improve S/N ratio using cooled bunches