The ISAC facility at TRIUMF and TITAN mass measurements on halo nuclei

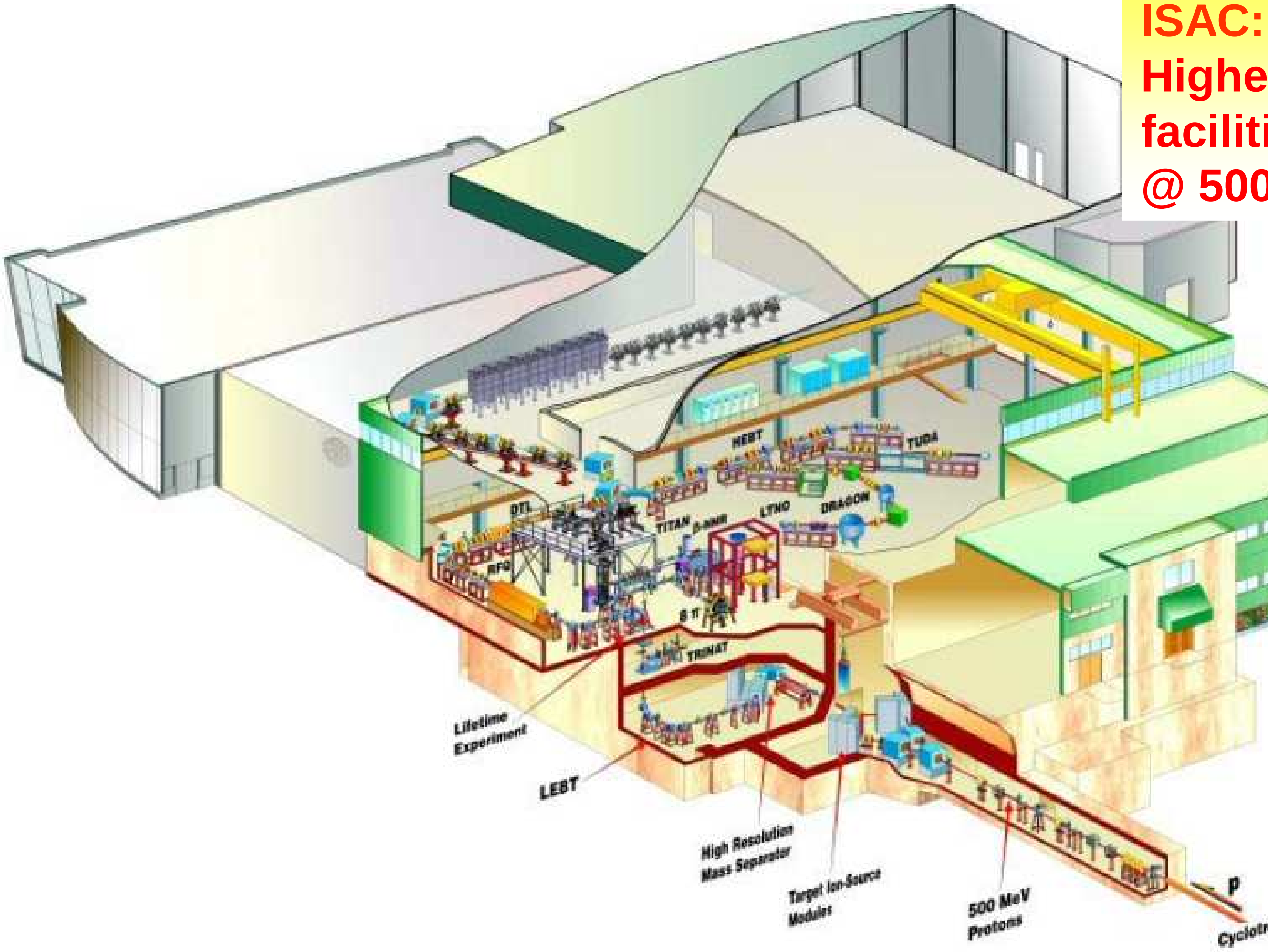
Jens Dilling, TRIUMF & UBC

- ISAC at TRIUMF: Present and future plans
- TITAN system, a new Penning trap mass spectrometer
- Mass measurements for halo-nuclei studies
- He and Li on-line experiments
- Conclusions & Outlook

TRIUMF ISAC

THE UNIVERSITY OF BRITISH COLUMBIA

ISAC @ TRIUMF



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 10 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

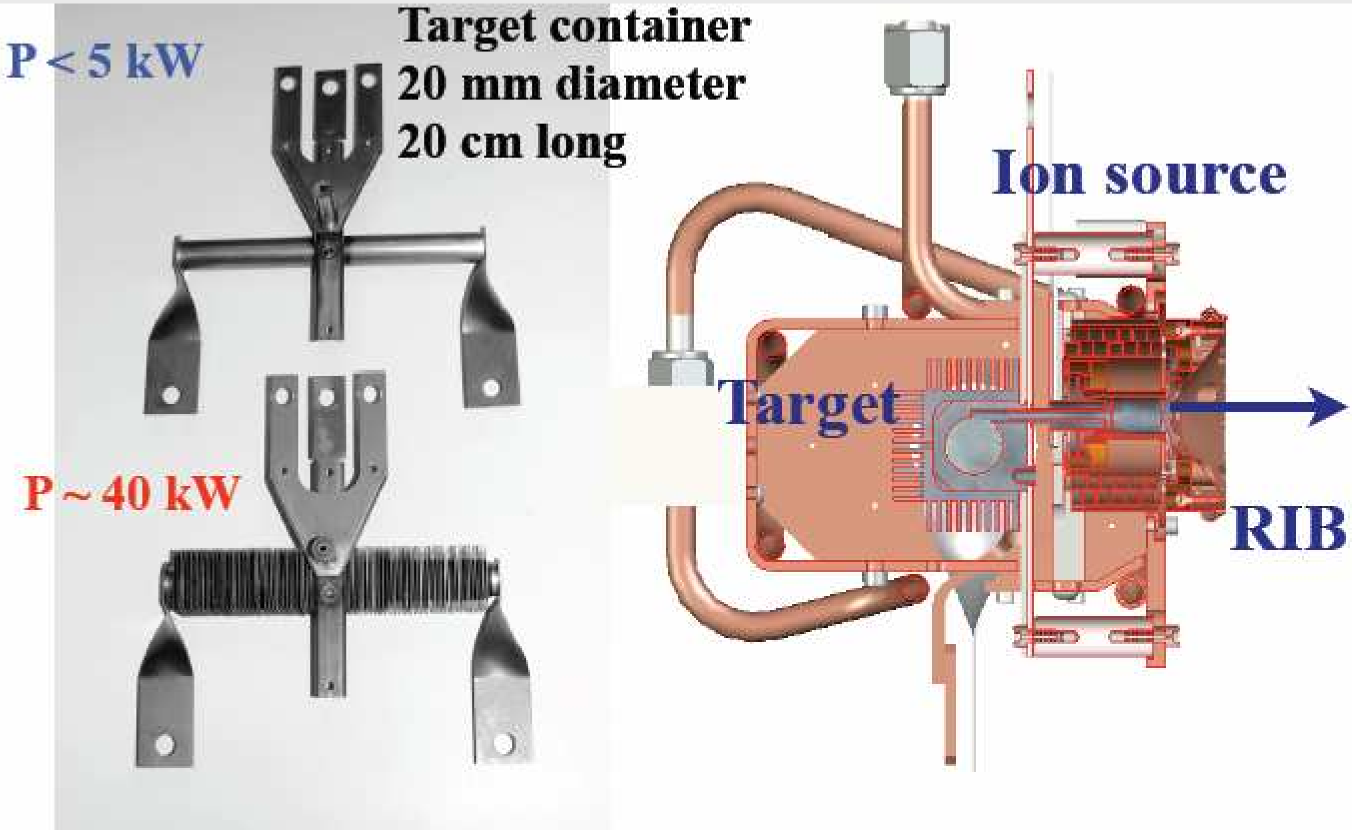
ISAC: Targets and Sources

Ion-sources:

- • Surface ☑
- • Resonant-Laser source on-line ☑
- •Negative, off-line test ☑
- •FEBIAD, on-line ☑
- •ECR, on-line tests and checks ☑ (changes needed)
- •ECR new design (Mystic) to be tested on-line 2008

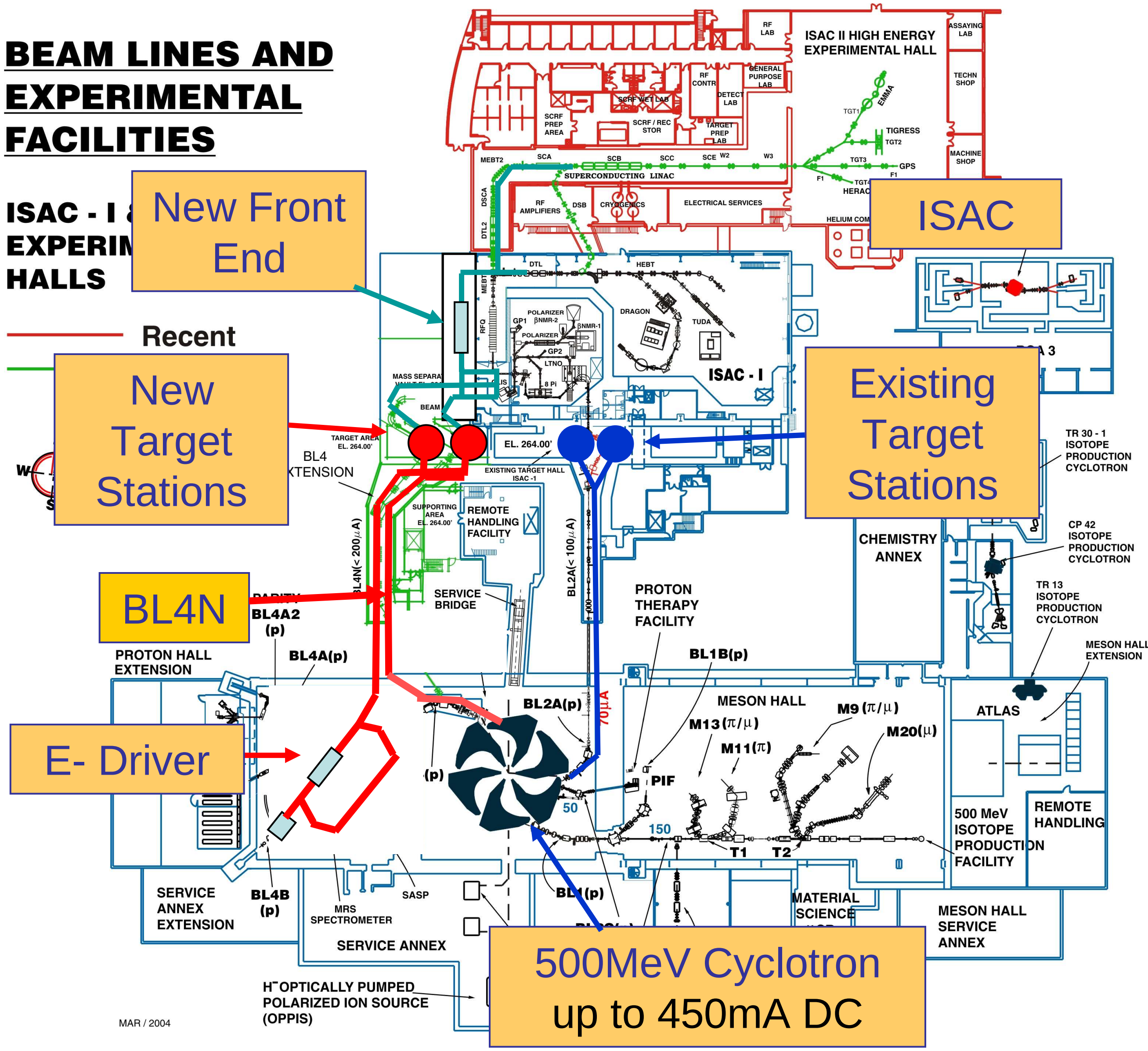
Targets:

- •High power target tested on-line and reached 50kW on target ☑
- •Actinide target: licence test scheduled in summer schedule 2008



- •Targets are typically used for 6 weeks.
- •We have 2 target stations
- •Change of targets takes ~ 10 days
- •Limited by one user facility (science and R&D)

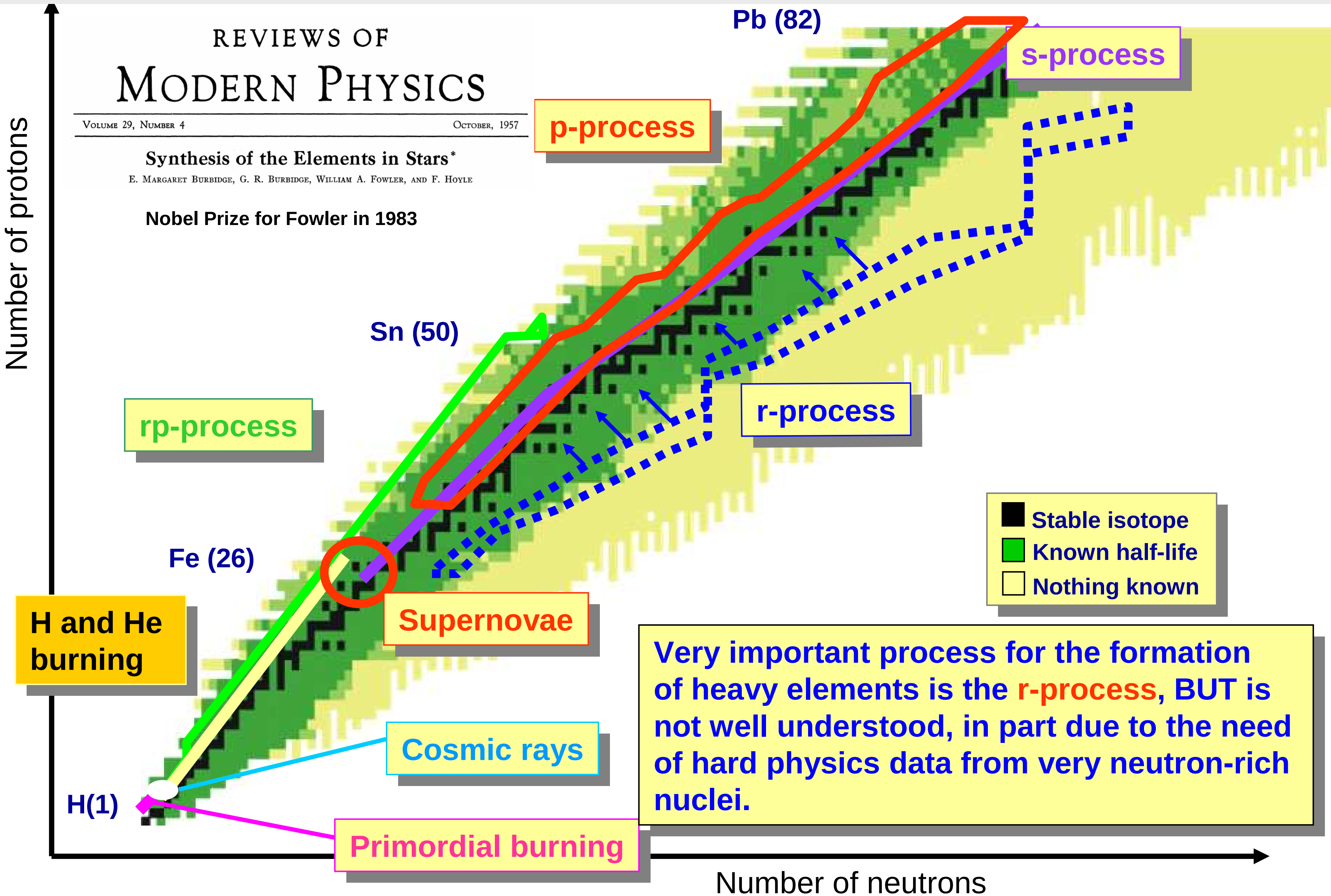
The proposed new facilities for TRIUMF



- A new electron accelerator produces 50 MeV electrons
- Electrons impinge on converter and photons are generated
- Photons hit U-target and photo-fission occurs
- New, very exotic, neutron rich isotopes are produced

- A second proton beam-line from the cyclotron conntects to a new target station.
- Main focus actinide targets
- Go to higher power (~100 kW)
- Have three radioactive beams a the same time.

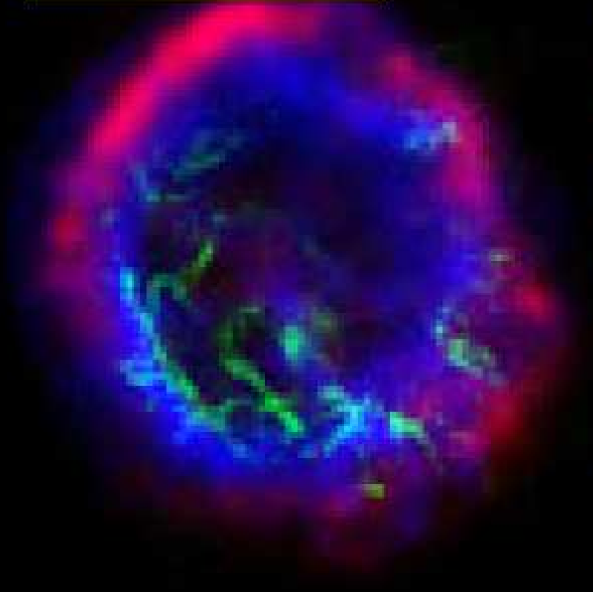
Photo-Fission: Origin of the heavy elements



Very important process for the formation of heavy elements is the r-process, BUT is not well understood, in part due to the need of hard physics data from very neutron-rich nuclei.

The r (apid neutron capture)-process

Supernovae ?

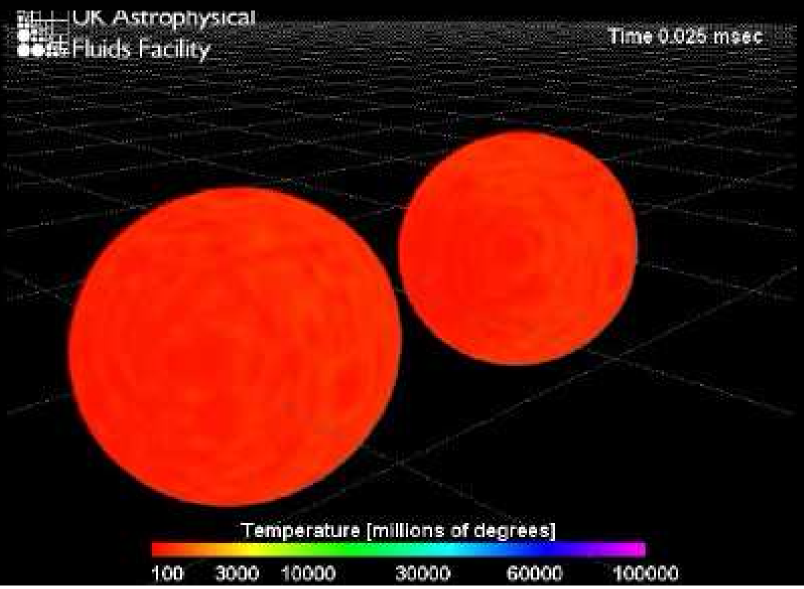


The origin of about half of elements > Fe (including Gold, Platinum, Silver, Uranium)

OPEN QUESTIONS:

- Where does the r-process occur?
- Are there multiple r-processes and are the individual contributions?
- What can the r-process tell us about the physics of extreme environments?

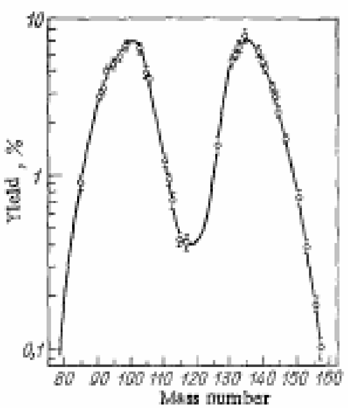
Neutron star mergers ?

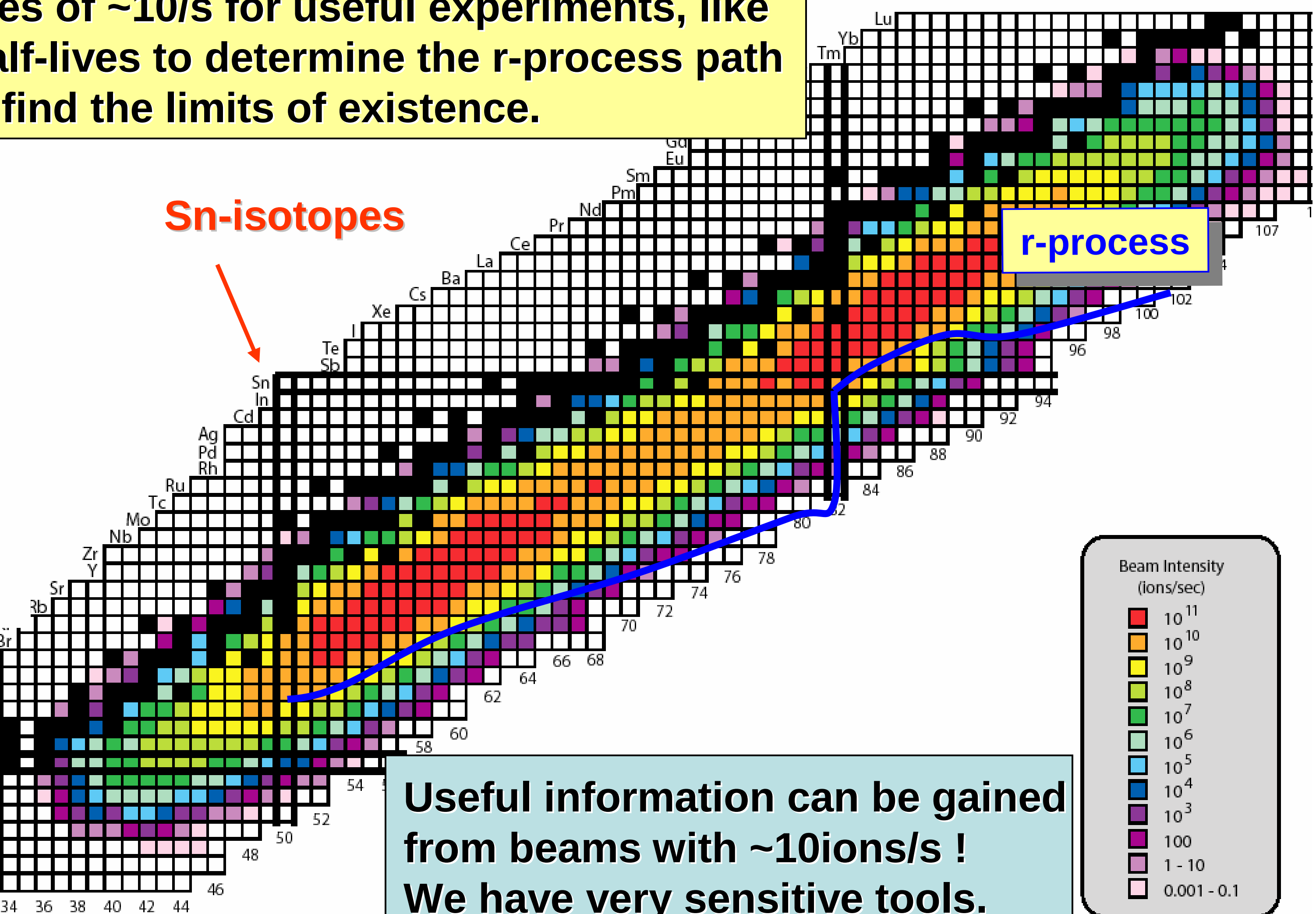


Make ‘new’ isotopes via photo-fission

Calculated isotopes production from 40 MeV, 10μA. populates the important region.
Need intensities of ~10/s for useful experiments, like masses and half-lives to determine the r-process path and find the limits of existence.

Double peak distribution



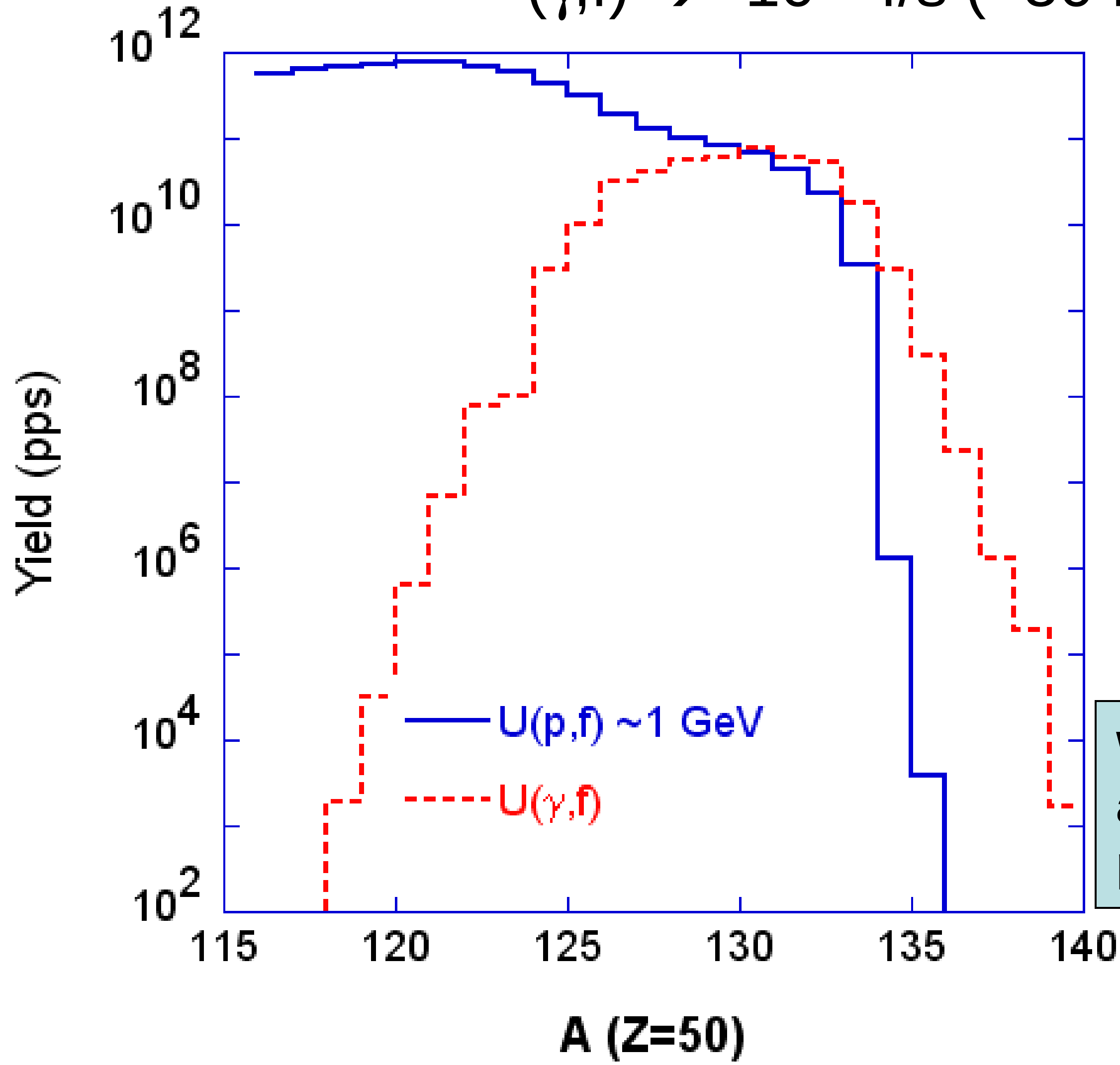


Useful information can be gained from beams with ~10ions/s !
We have very sensitive tools.

Using protons or photo-fission

U(γ,f) vs U(p,f) @1 GeV

(p,f) → 100 μA on 30 g/cm^2 → 5x10^{13} f/s
(γ,f) → 10^{13} f/s (~50 kW 25 MeV)



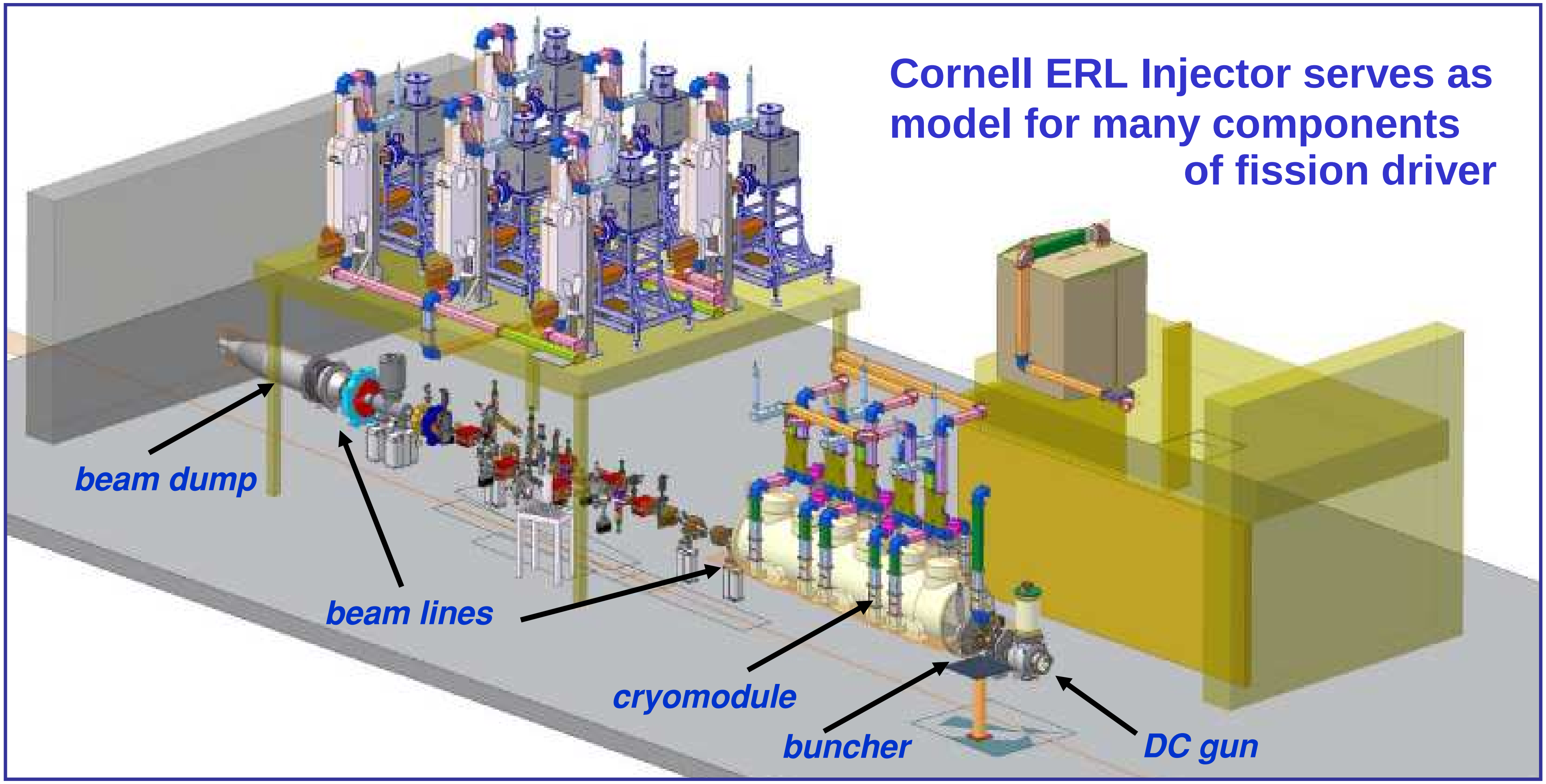
Sn-isotopes:

Clearly higher production via photo-fission.

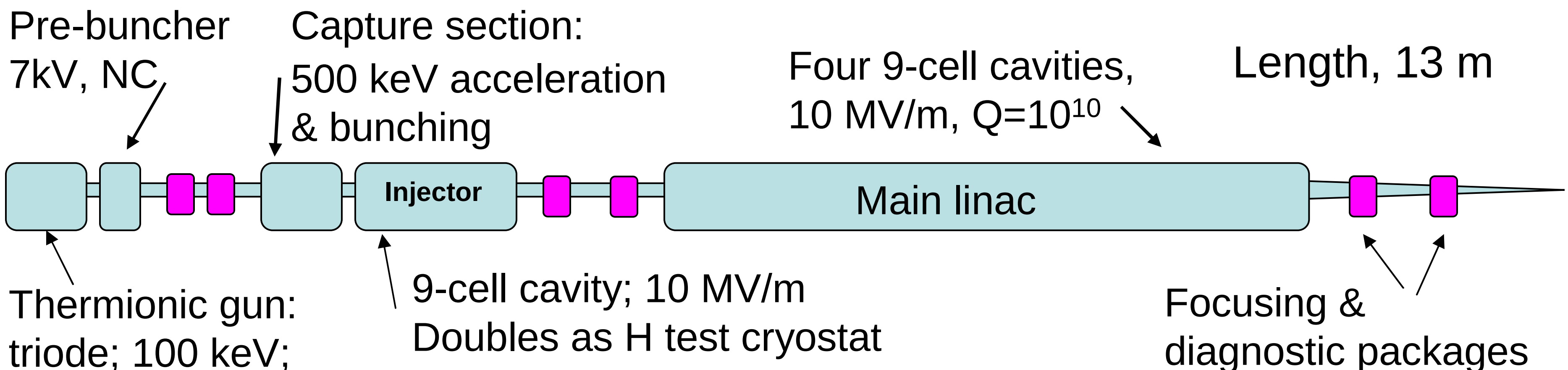
Even better at higher photon-flux. (we assume factor 20 more fission in target)

We can produce comparable, and cleaner beams than p-based. (N-converter?)

E-linac concept for photo-fission



Base-line design for the E-linac



Injector linac	Main linac	
10 mA, 10 MeV 100 kW beam pwr	10 mA, 40 MeV 400 kW beam power	**Fission driver**
Single 9-cell cavity	4 cavities; 9 cell/cavity	All K.E. dumped in target
Two 50 kW input coupler;10 MV/m	Two 50 kW coupler/cavity; 10 MV/m gradient	
Single HOM absorber	1 HOM absorber/cavity	500 kW

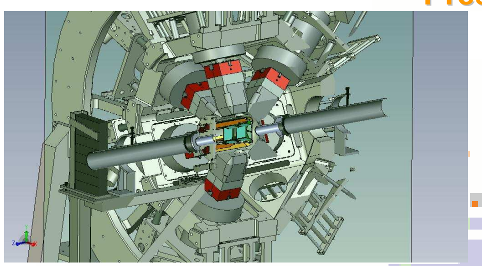
Will put proposal forward in 2008 to CFI

(funded SNOlab), if funded start building in 2009.

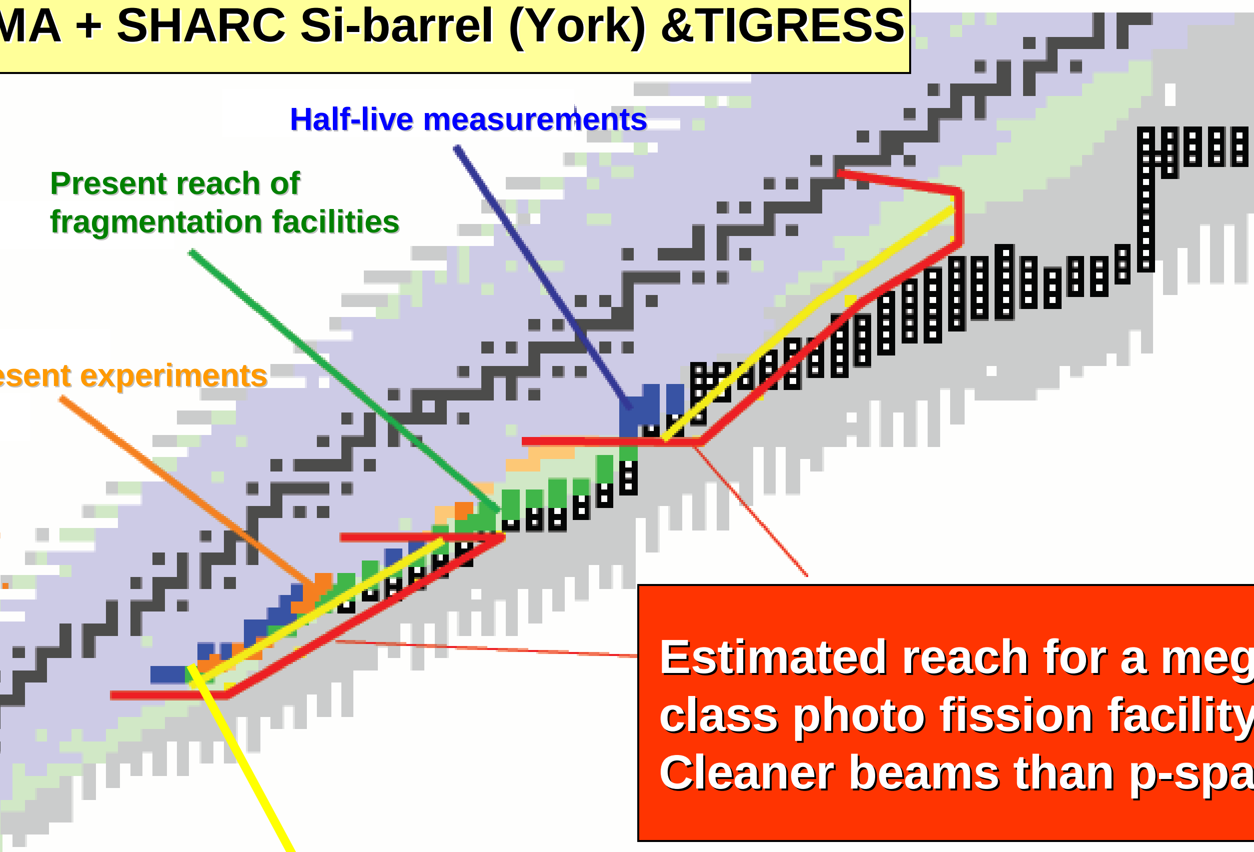
photo-fission @ 1 MW

Half-lives: EMMA + TIGRESS
Neutron emission probability: DESCANT + EMMA
Masses: TITAN
(d,p) reactions: EMMA + SHARC Si-barrel (York) &TIGRESS

TITAN

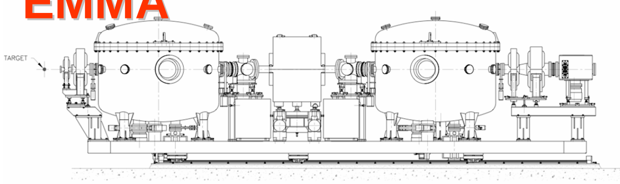


TIGRESS + SHARC



Estimated reach for a mega-watt class photo fission facility at ISAC Cleaner beams than p-spallation.

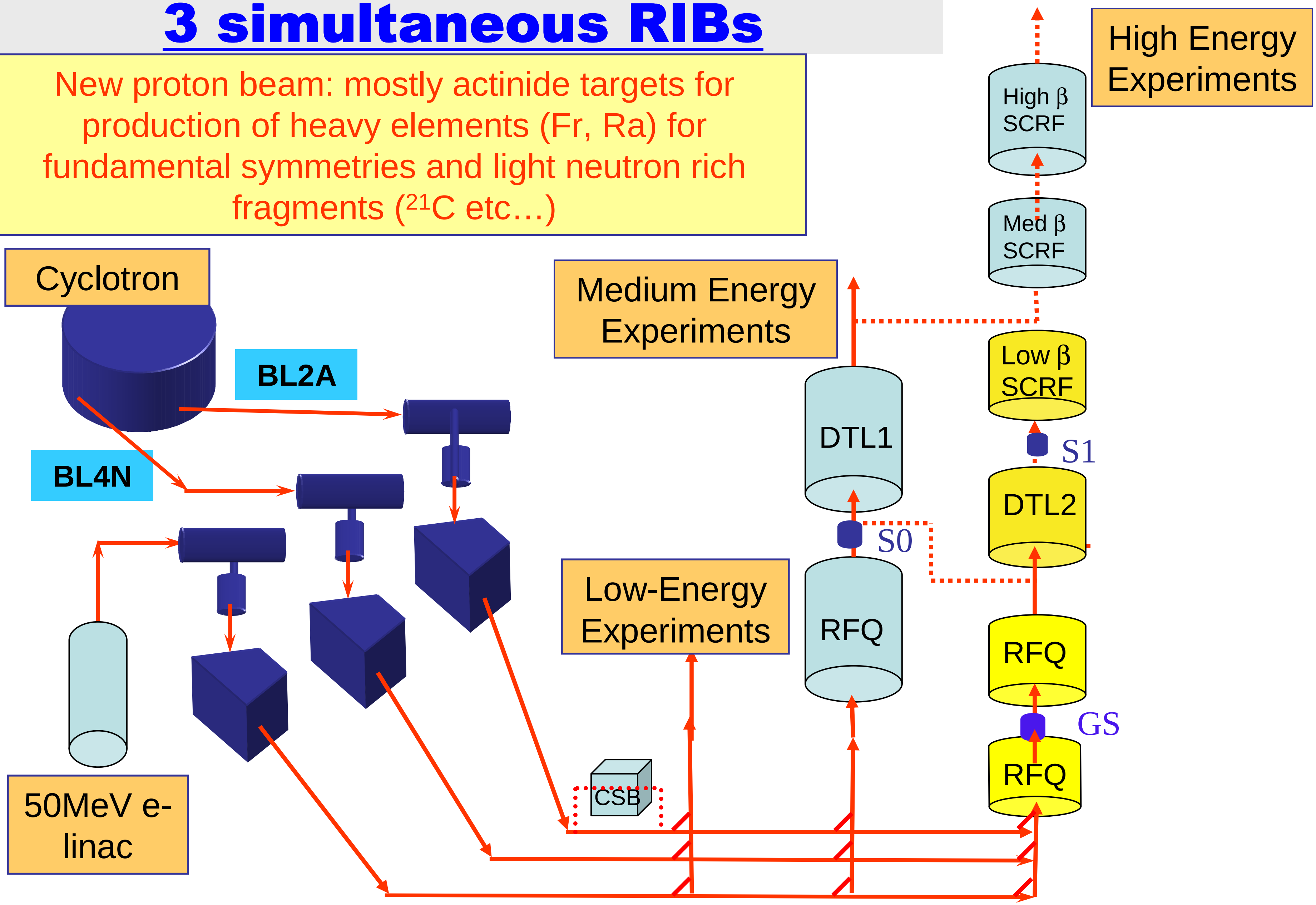
EMMA



Approx. boundary for (d,p) reactions to probe neutron capture rates (during r-process freezout)

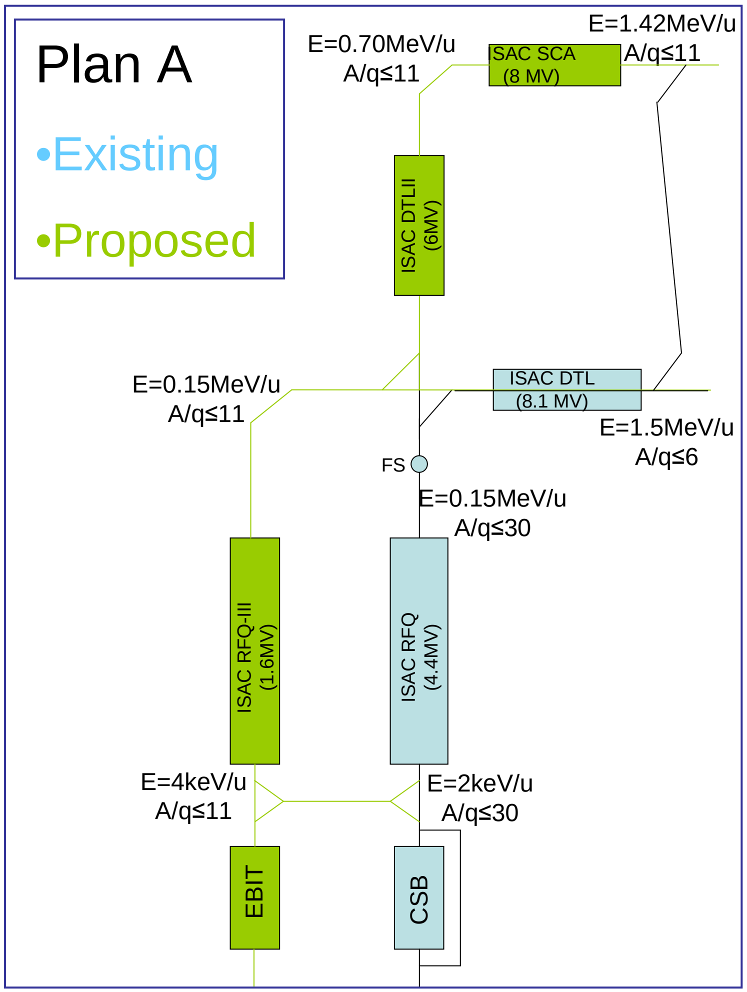
New proton beam line and 3 simultaneous RIBs

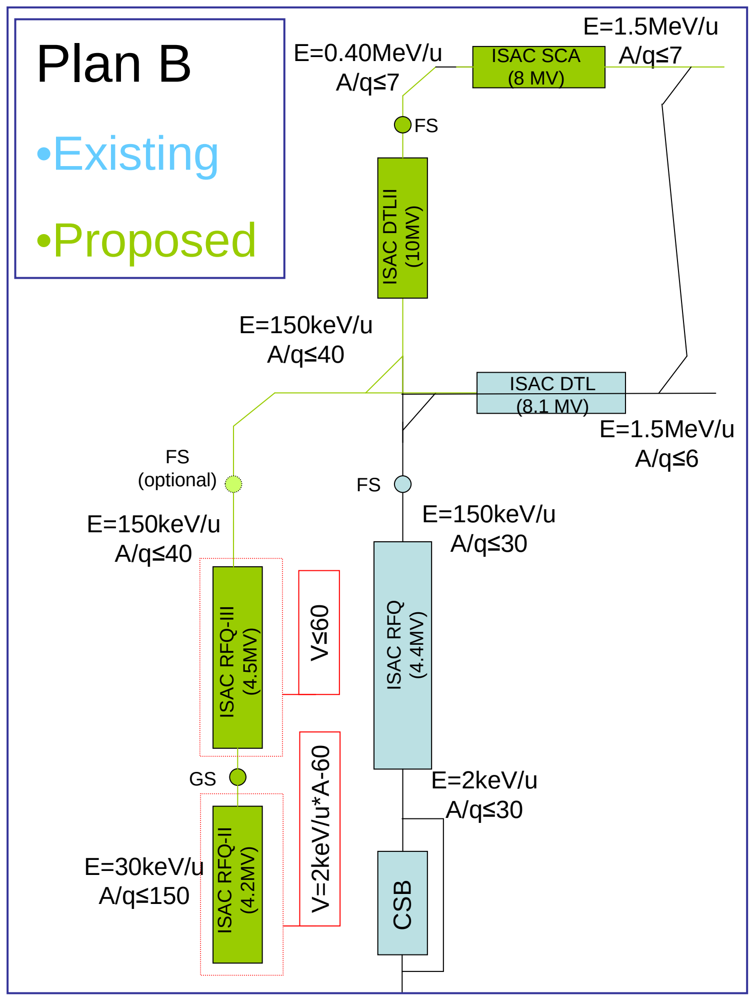
New proton beam: mostly actinide targets for production of heavy elements (Fr, Ra) for fundamental symmetries and light neutron rich fragments (^{21}C etc…)



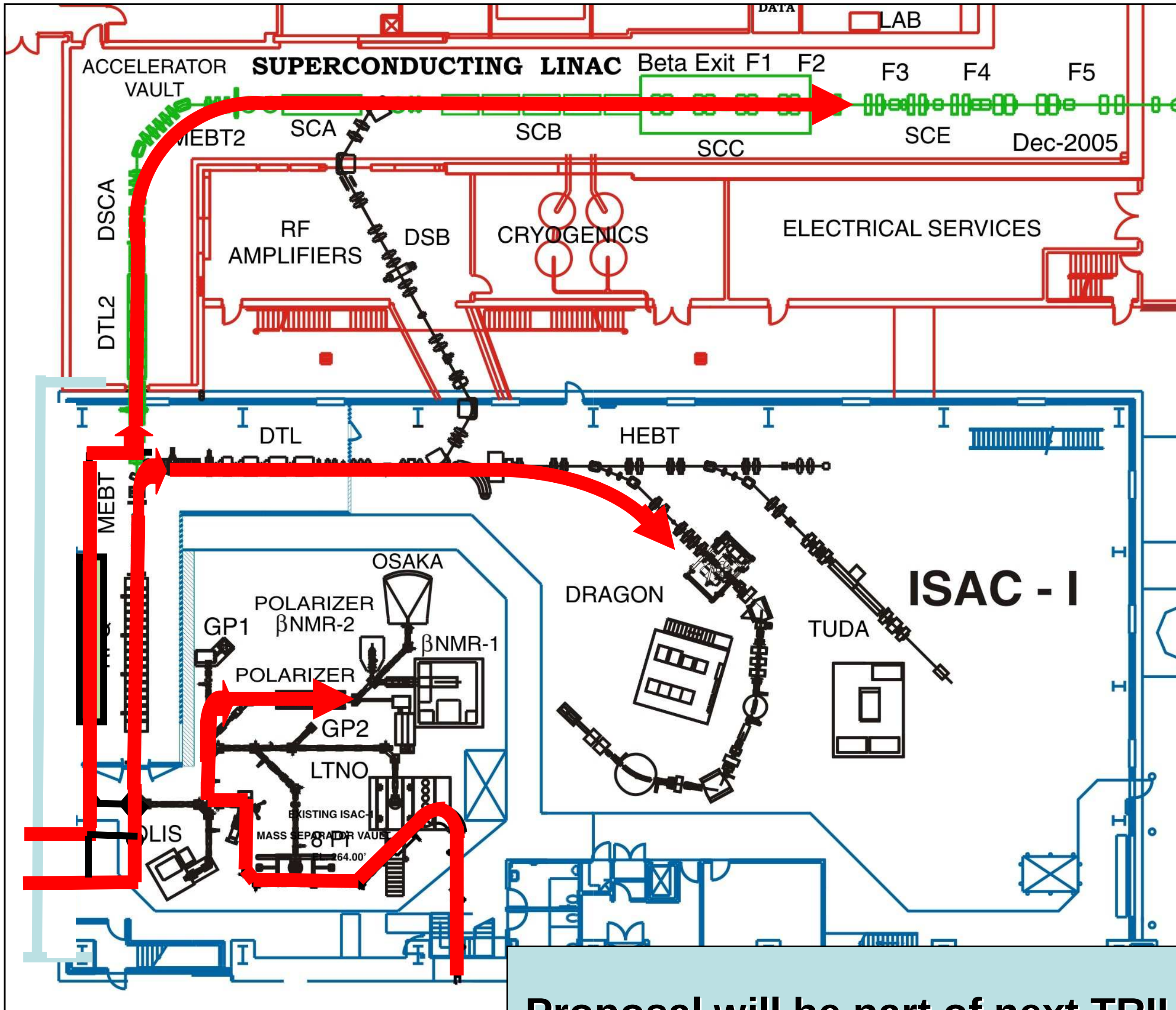
New post-accelerator structure for ISAC

- A new accelerator leg will take advantage of the new targets and provide two simultaneous accelerated beams





3 RIBs to ISAC and ISACII



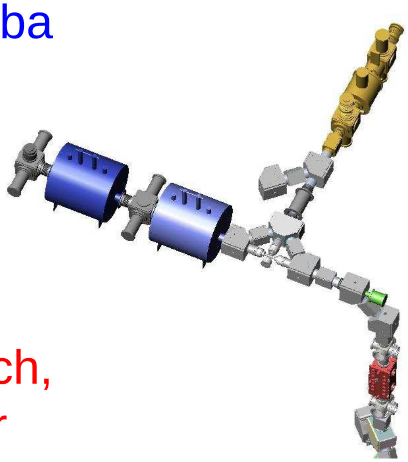
Proposal will be part of next TRIUMF 5 year plan for 2010-2015 (submission Aug 2008).

TITAN and halo nuclei

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**

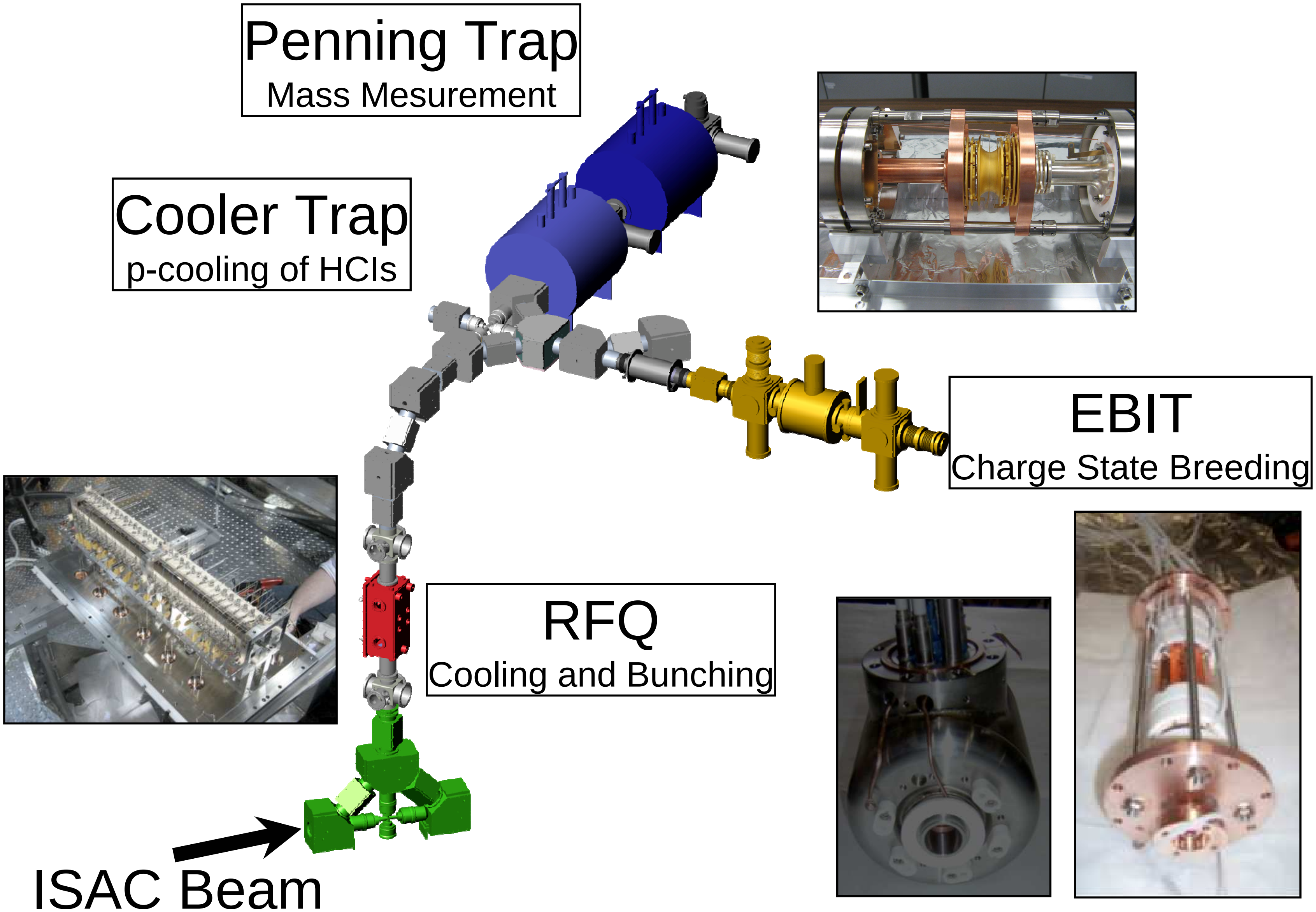
McGill, UBC
U Manitoba
TRIUMF
York
Windsor
Calgary.
MPI-HD
TU Munich,
Muenster
Col. School of Mines,
York,
GANIL
RCNP Osaka



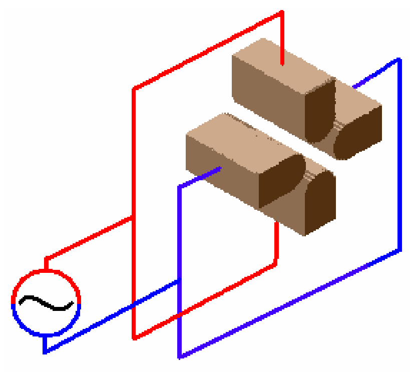
- Mass measurements on isotopes with short half-life $T_{1/2} \approx$ 10 ms and low production yields (≈ 100 ions/s) with high precision $\delta m/m \approx 10^{-8}$.
- Ideally, uniquely matched to isol-type production mode, only system in the world to use HCIs
- TITAN started April 2003 (NSERC), first on-line mass measurements on singly charged ions carried out in 2007.
- TITAN has also a program for other experiments (x-ray spectroscopy, laser spectroscopy, double-beta decay)

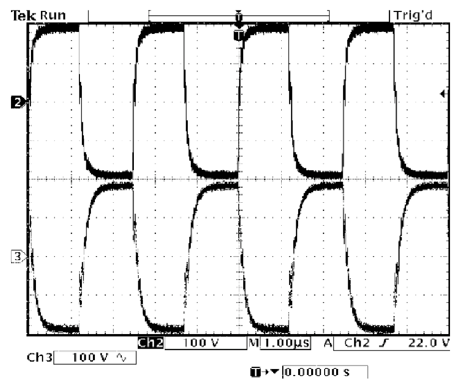
J.Dilling Dec 2007

TITAN system

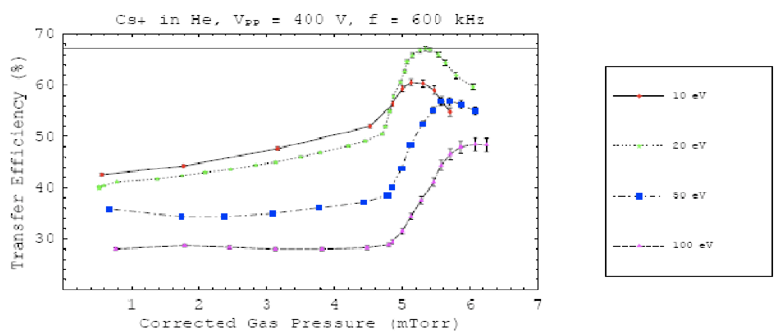


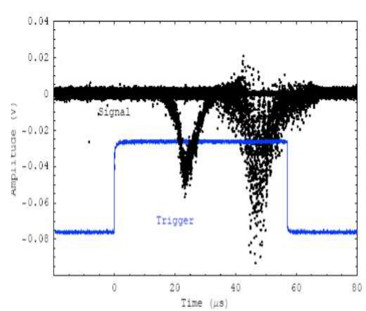
TITAN RFCT

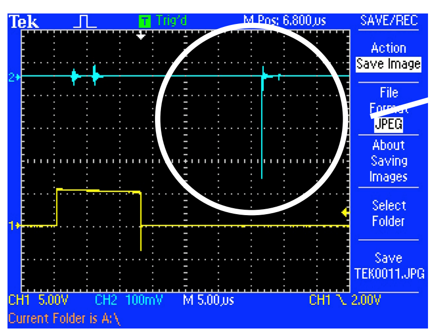


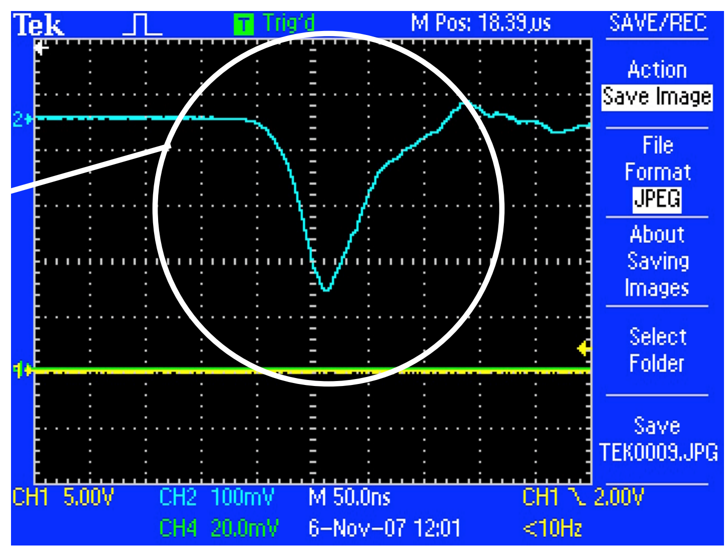


- 400 V_{pp} applied RF at up to 3 Mhz
- 68% DC efficiency for $^{133}Cs^{+}$ in He
- 15% DC efficiency for $^{6,7}Li^{+}$ in He
- 60% DC efficiency for $^{6}Li^{+}$ in H_2
- Pulses as short as 50 ns FWHM @ up to 1 kHz
- Reversed extraction successfully demonstrated with ^{136}Xe from OLIS

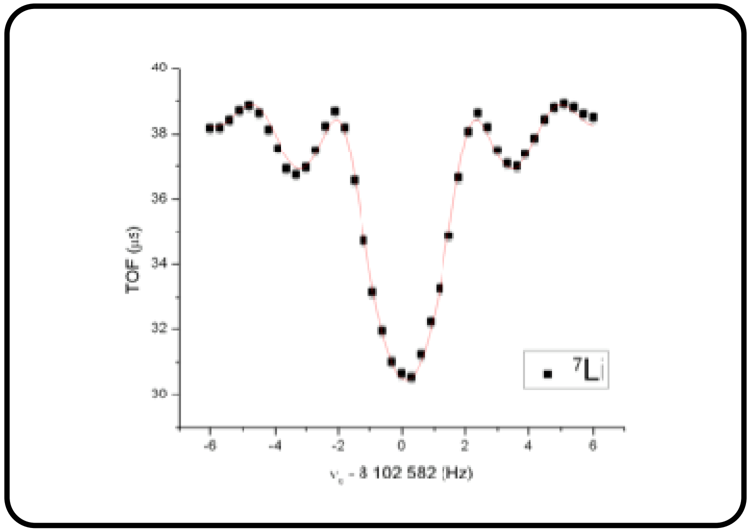




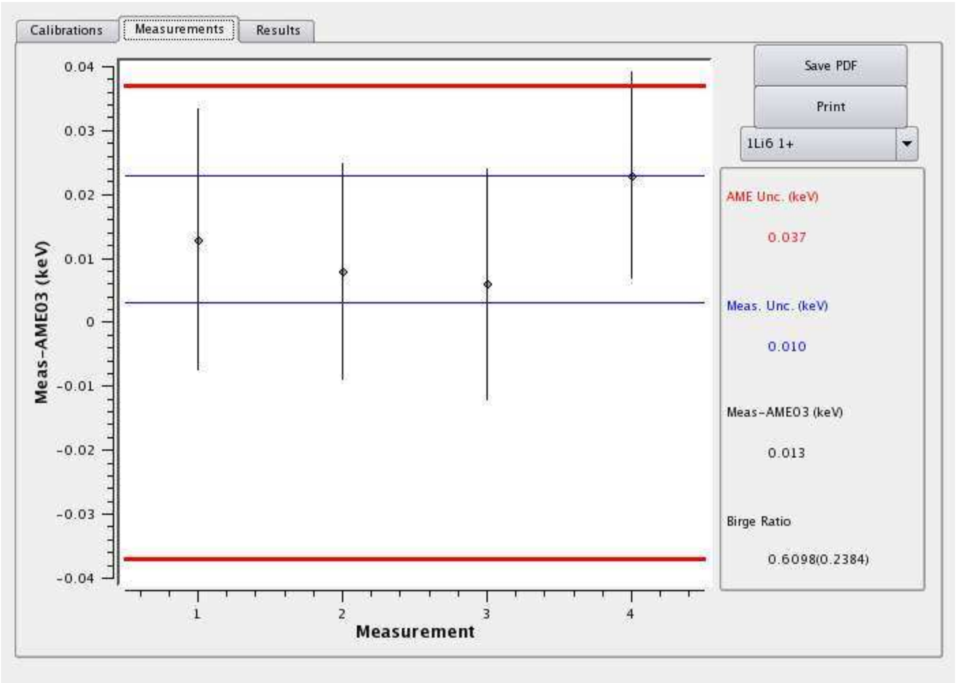




Off-line mass measurements

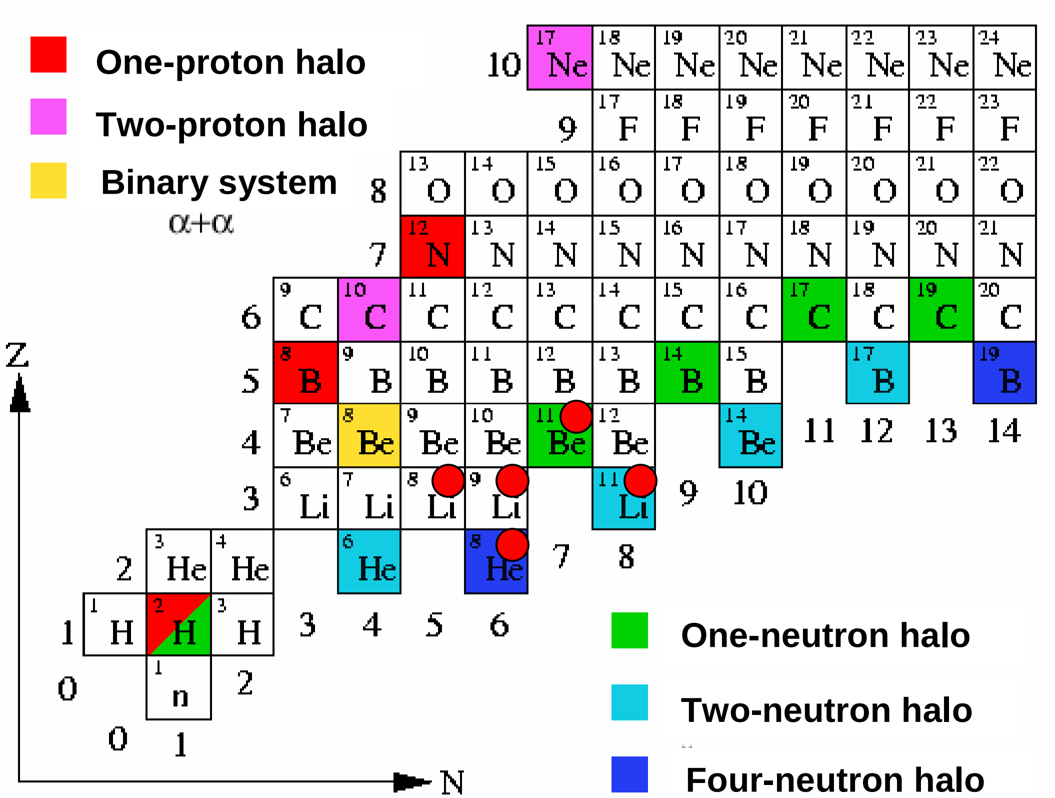


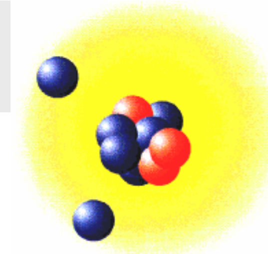
	Mass Excess (keV)	δm/m
AME03	14908.14(79)	1.1×10^{-8}
SMILETRAP	14907.0951(42)	6.4×10^{-10}
TITAN	14907.053(44)	3.2×10^{-9}



- ✶ Confirmation of recent SMILETRAP measurement and agreement with ^{6,7}Li
- ✶ Systematic tests confirm system at the level of ~10^{-9}
- ✶ Systematic tests with C-12 as reference.

Halo-nuclei

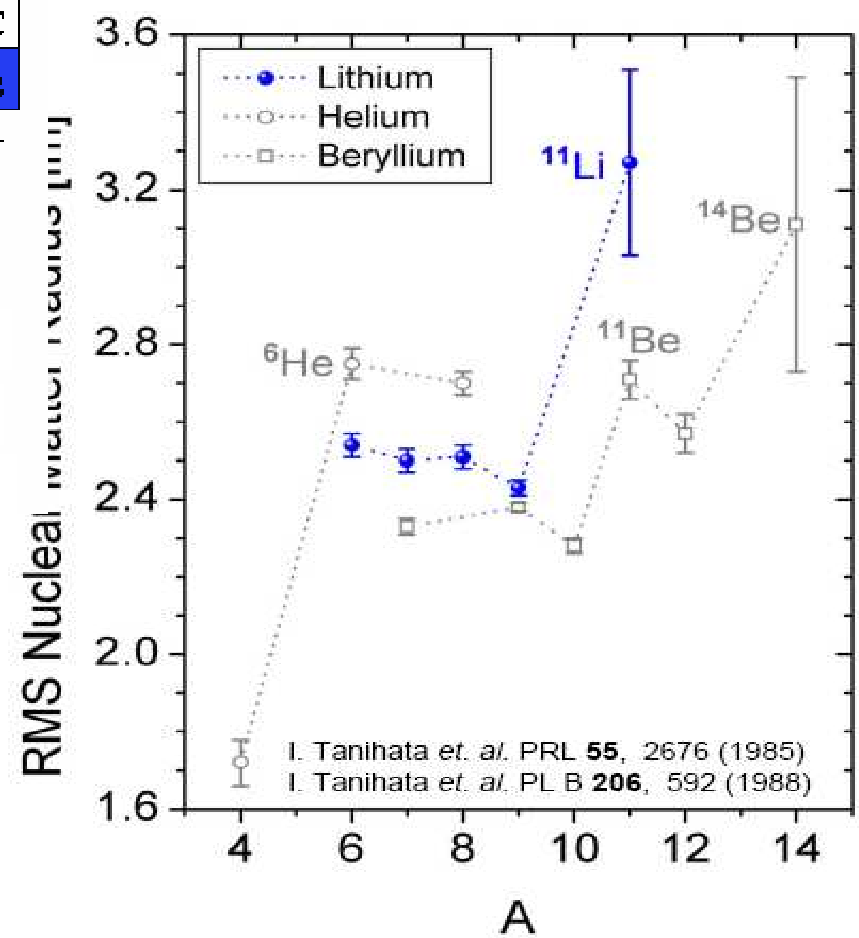




HALO-nuclei: ^{11}Li

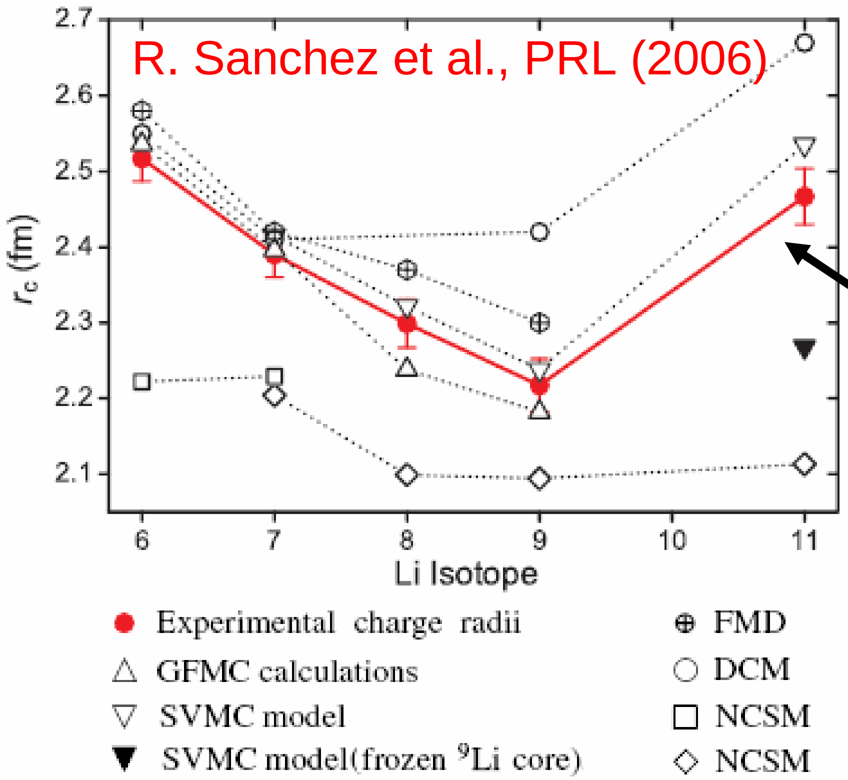
$T_{1/2} \approx 8.6$ ms

Borromean three body halo nuclei.



- 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 its neighboring nuclei

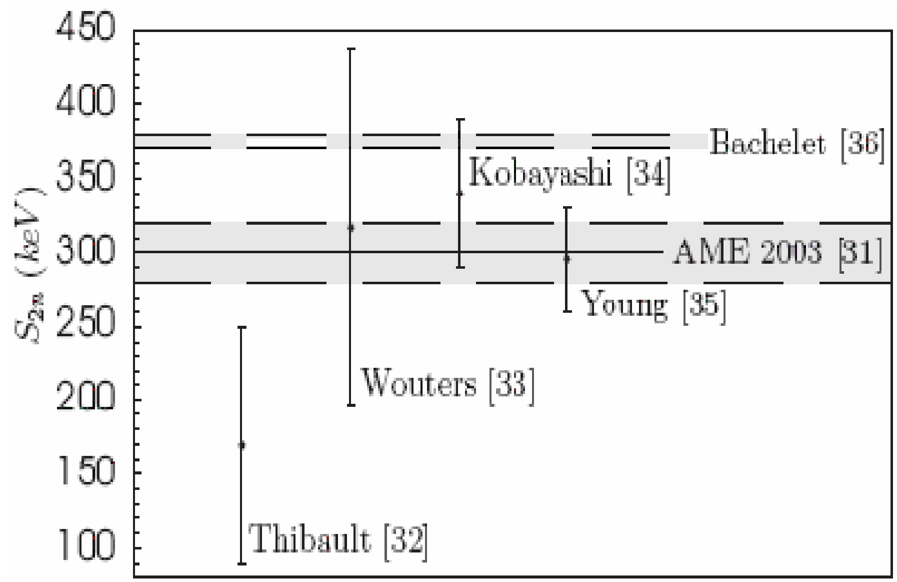
Halo-nuclei



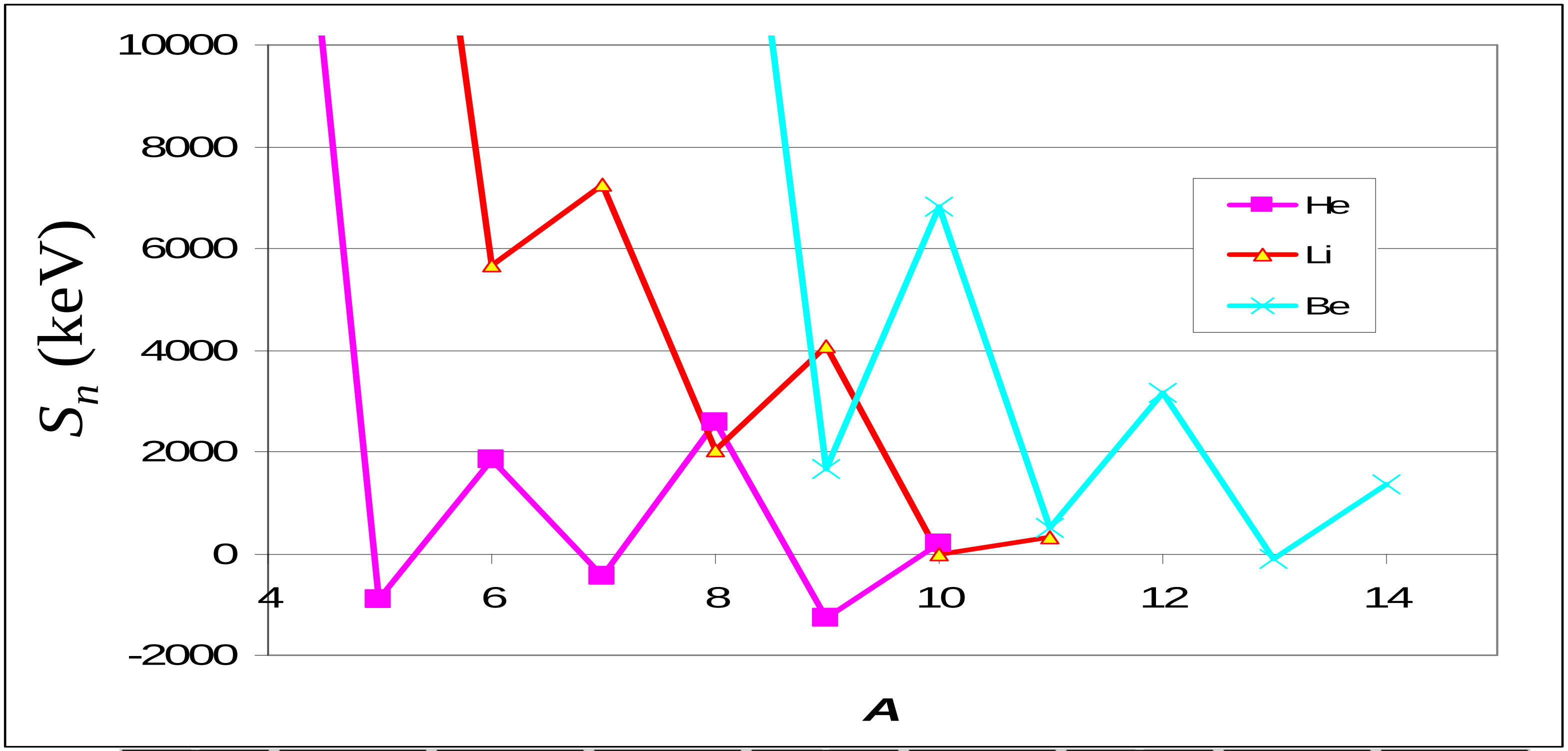
- ToPLiS collaboration @ ISAC measured laser frequency shifts for the Lithium isotopes
- G. W. Drake et al. did the calculations for the mass shifts, and extracted the charge radius.
- A source of error in the calculations is the mass of ^{11}Li

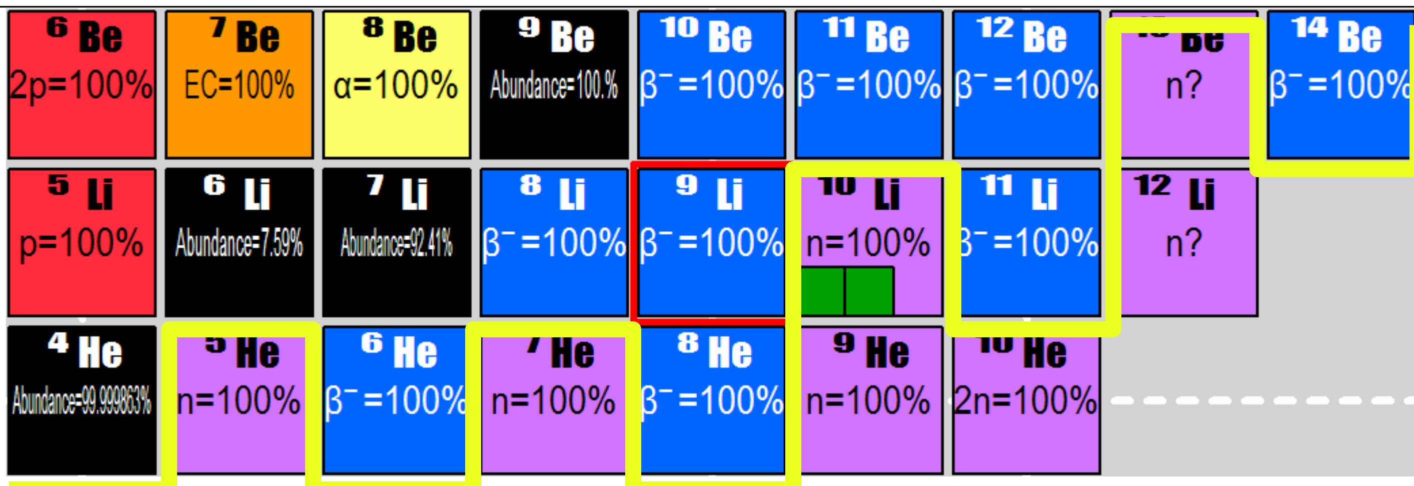
Five Previous measurements of the mass of ^{11}Li:

- Need precision of $\delta m \leq 1$ keV/c^2 for charge radius calculations
- Need precision of $\delta m \leq 5$ keV/c^2 to confirm accuracy of MISTRAL 2003 experiment
- A value of S_{2n} with 1% error, $\delta m \leq 3$ keV/c^2, would provide a solid test for nuclear theory

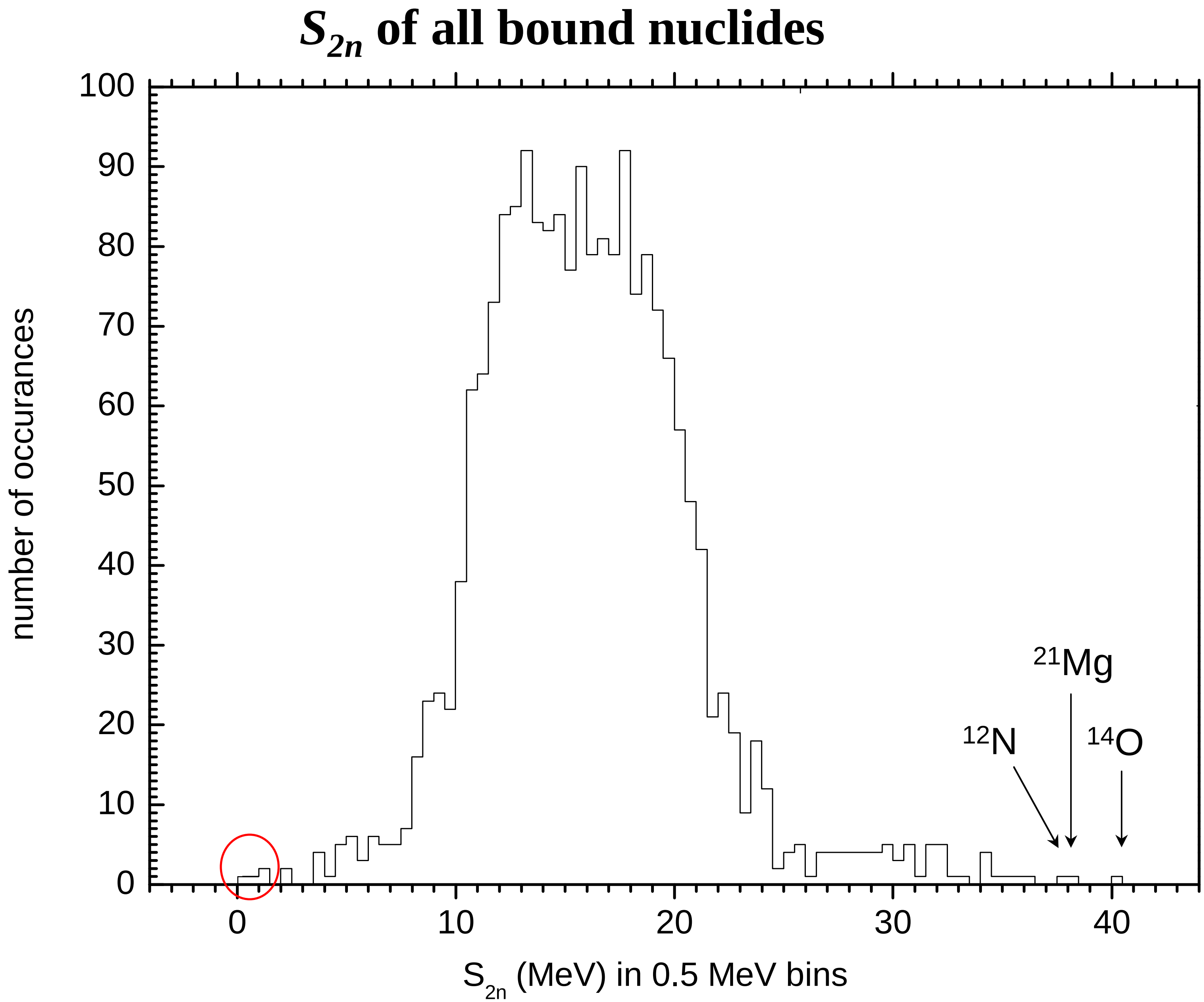


Two Neutron separation





Halo-nuclei



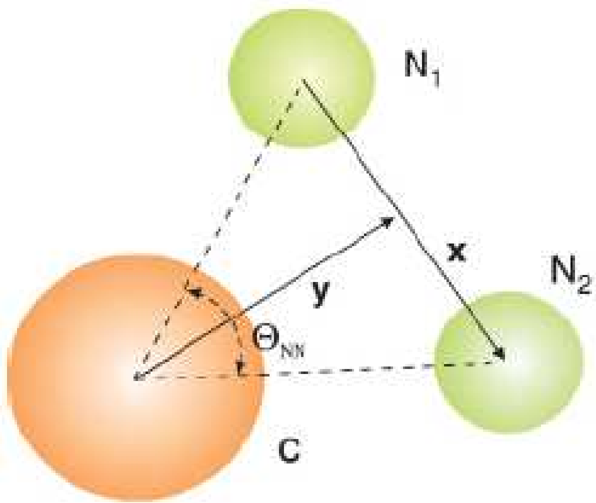
S2n of all bound nuclides
100
90
80
70
60
50
40
30
20
10
0
number of occurances
0
10
20
30
40
S2n (MeV) in 0.5 MeV bins
21Mg
12N
14O

Halo-nuclei: theory

PHYSICAL REVIEW C **76**, 051602(R) (2007)

Geometry of Borromean halo nuclei

C. A. Bertulani[1,2] and M. S. Hussein[3,4]



	r_{NN} (fm)	$r_{c\text{-}2N}$ (fm)	$R_{\rm rms}$ (fm)	$\bar{\theta}_{NN}$
^{6}He	5.9±1.2 [4]	3.36 (39) [16]	2.67 (2.48)	$83^{\circ+20}_{-10}$
		3.71(07) [21]	2.78	$78^{\circ+13}_{-18}$
^{11}Li	6.6±1.5 [4]	5.01 (32) [2]	3.17 (3.12)	$66^{\circ+22}_{-18}$
		5.97(22) [20]	3.4	$58^{\circ+10}_{-14}$
^{14}Be	5.60±1.0 [5]	4.50 [17]	3.10 (3.16)	$64^{\circ+9}_{-10}$
^{17}Ne	4.45 [9]	1.55 [9]	2.70 (2.75)	110°

TABLE I. The average distance between the two nucleons in the halo and the core-2N average distance shown in the first and second columns, respectively. The values of $r_{c\text{-}2N}$ and the rms radii for ^{6}He and ^{11}Li are obtained both from the $B(E1)$'s values, [16] and [2], and from [20,21] with

How big is ^{8}He?

Nuclear charge radius of ^{8}He

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

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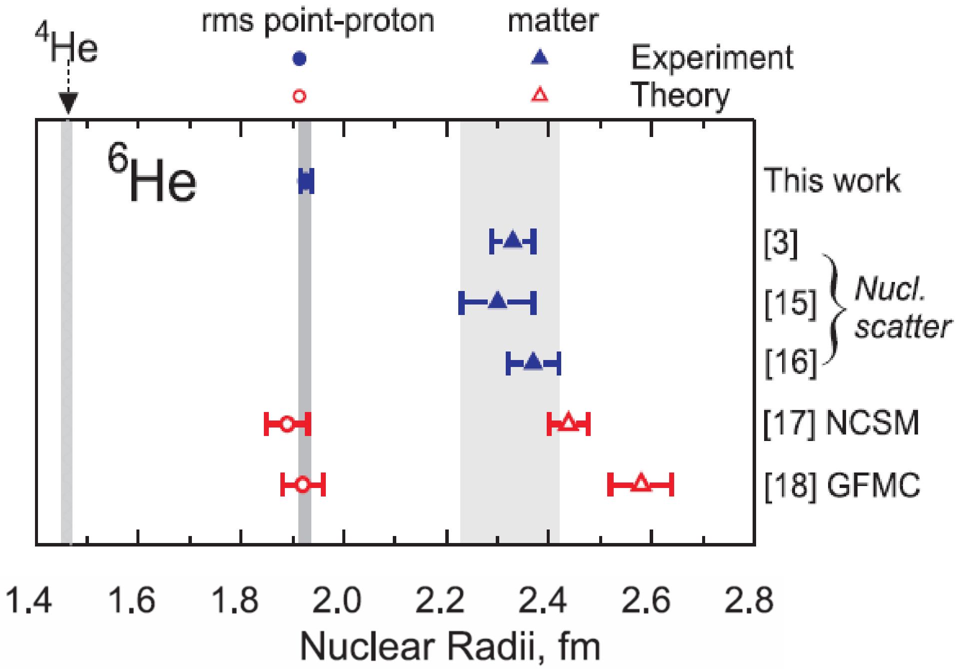
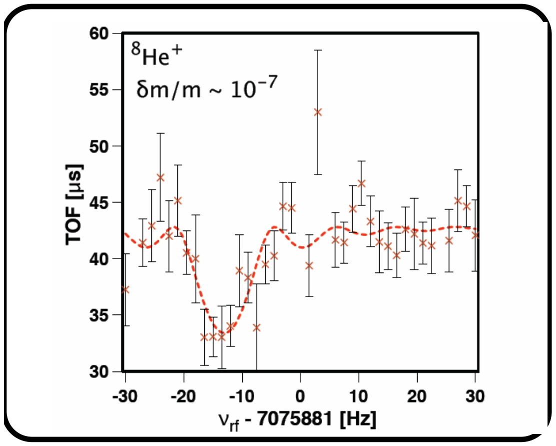
[4]*Physics Department, University of Windsor, Windsor, Ontario, Canada N9B 3P4*
[5]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
(Dated: November 21, 2007)

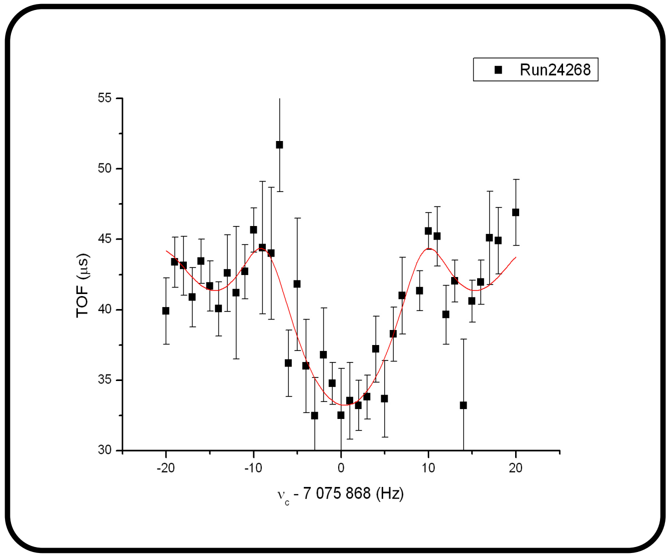


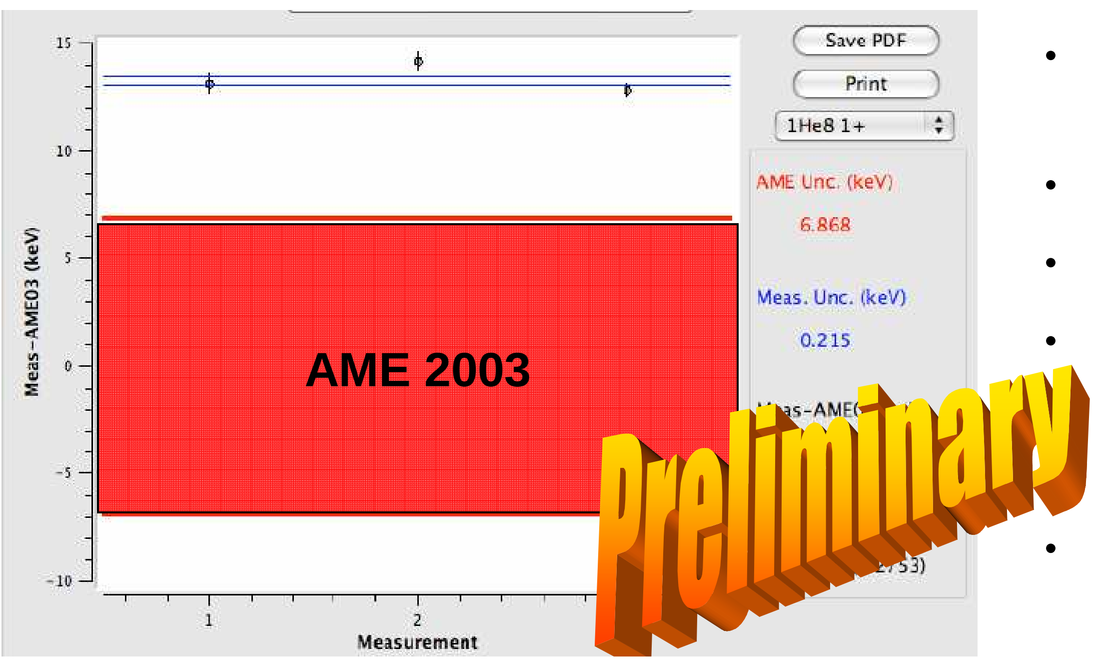
accepted PRL (Dec. 21, 2007)

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

On-line mass measurements (Nov. run He)

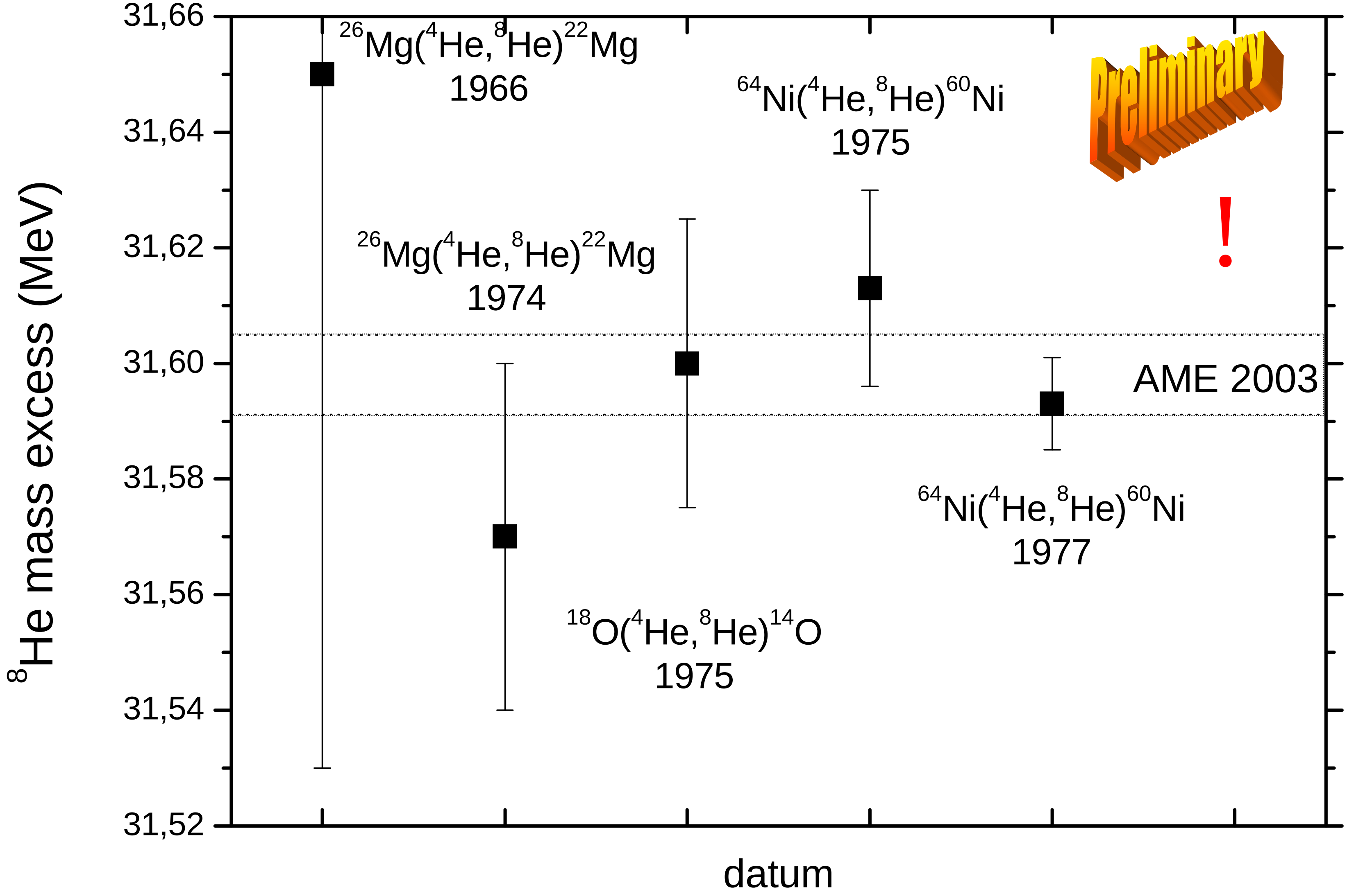




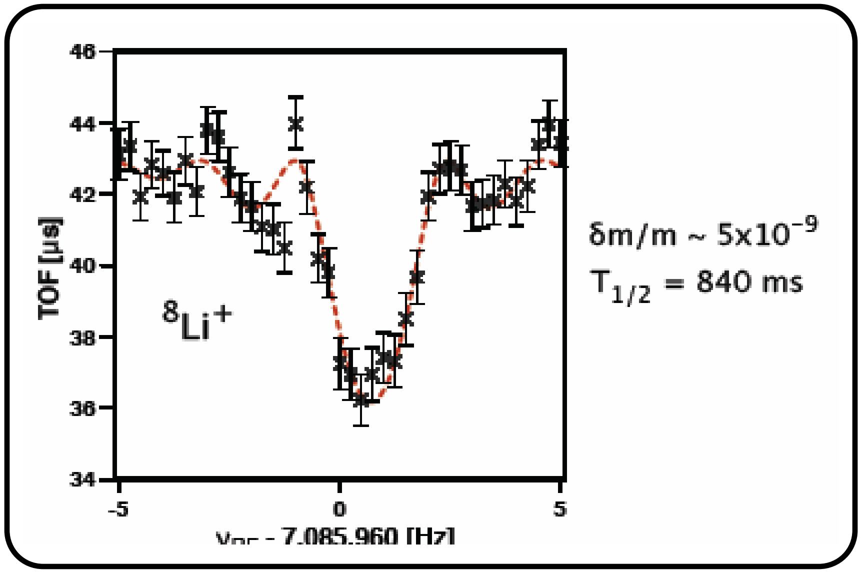


- Measurements of the mass of ^8He
- First direct mass measurement
- Used H2 in RFQ
- Carried out with 3100/ions sec beam
- Final uncertainty ~ 300eV.
- Used stable Li as reference

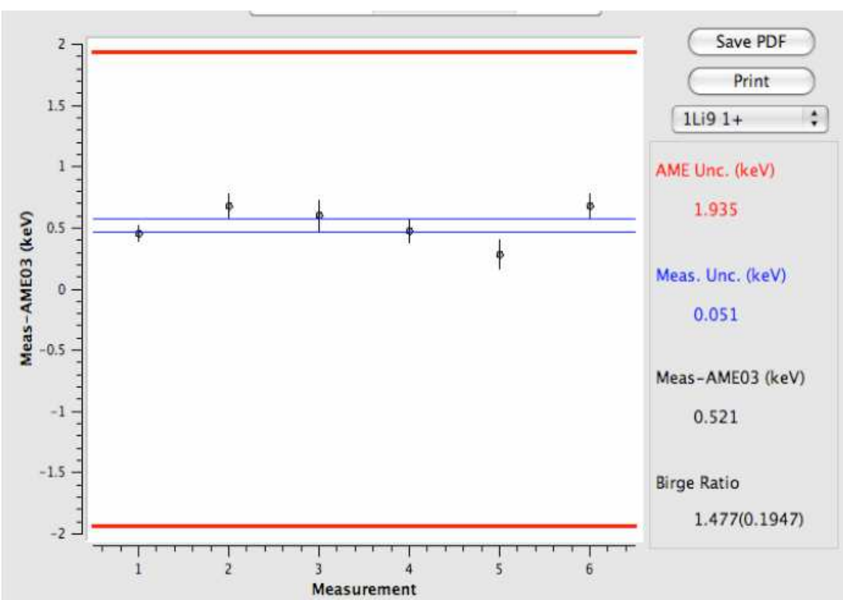
On-line mass measurements (Nov. run He)

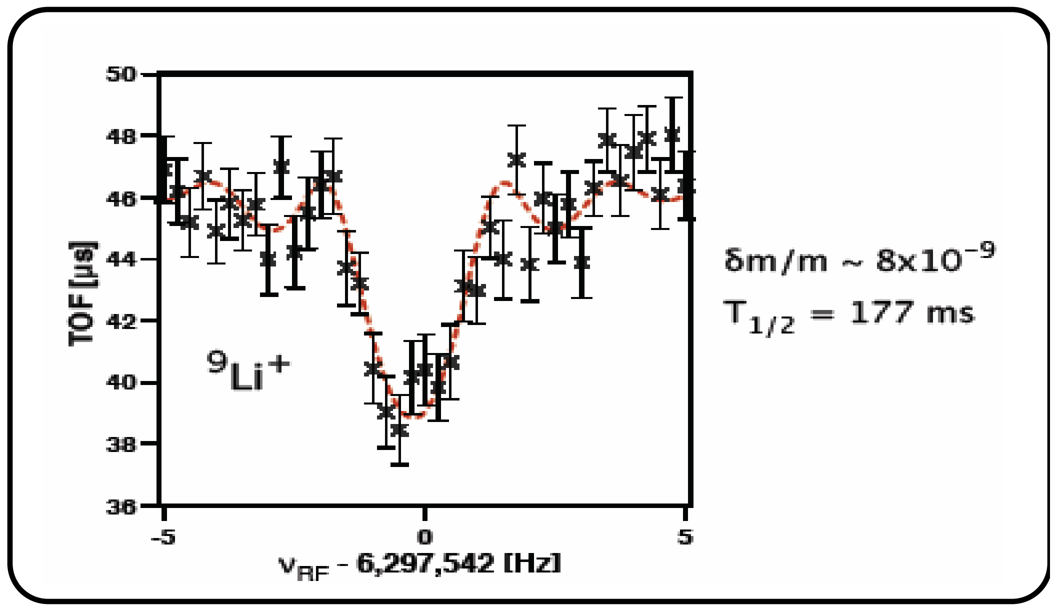


On-line mass measurements (Dec. run Li)

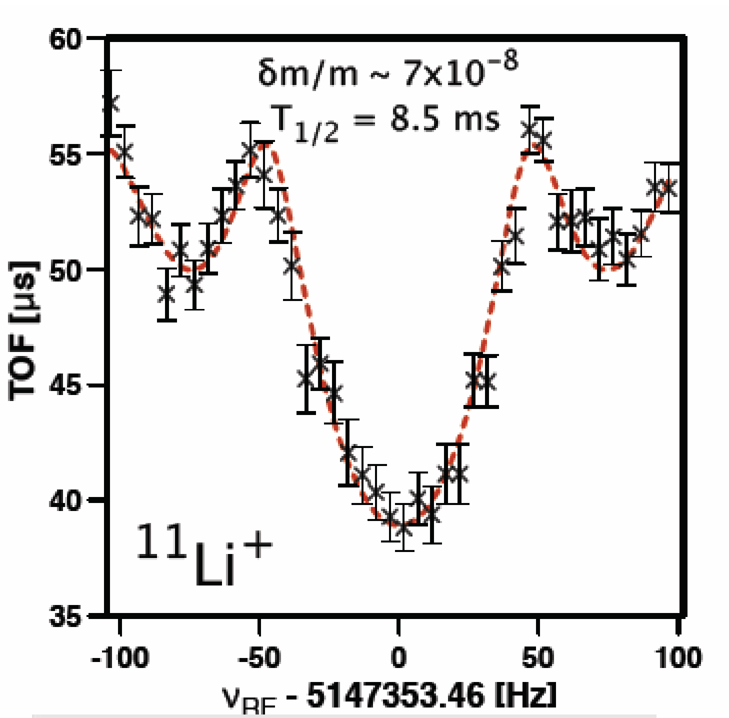


- Measurements of the mass of Li isotopes
- First direct Penning trap mass measurement
- Used H2 in RFQ
- Carried out at three different beam times/targets+ion source
- Final uncertainty ~ 100eV.
- Used Li stable Li as reference

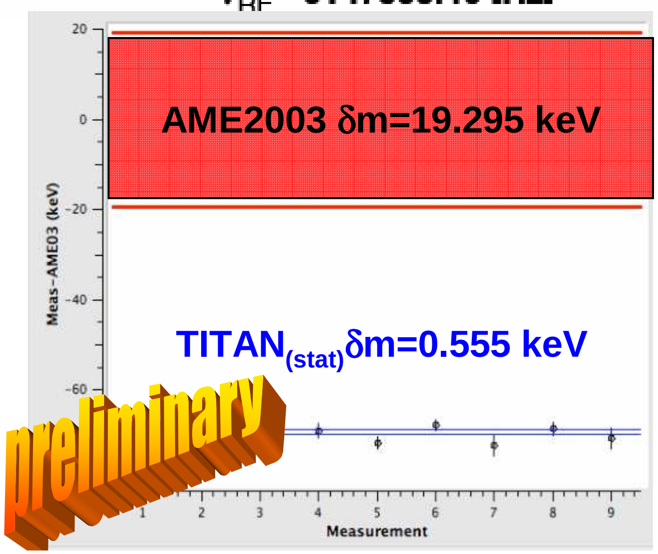


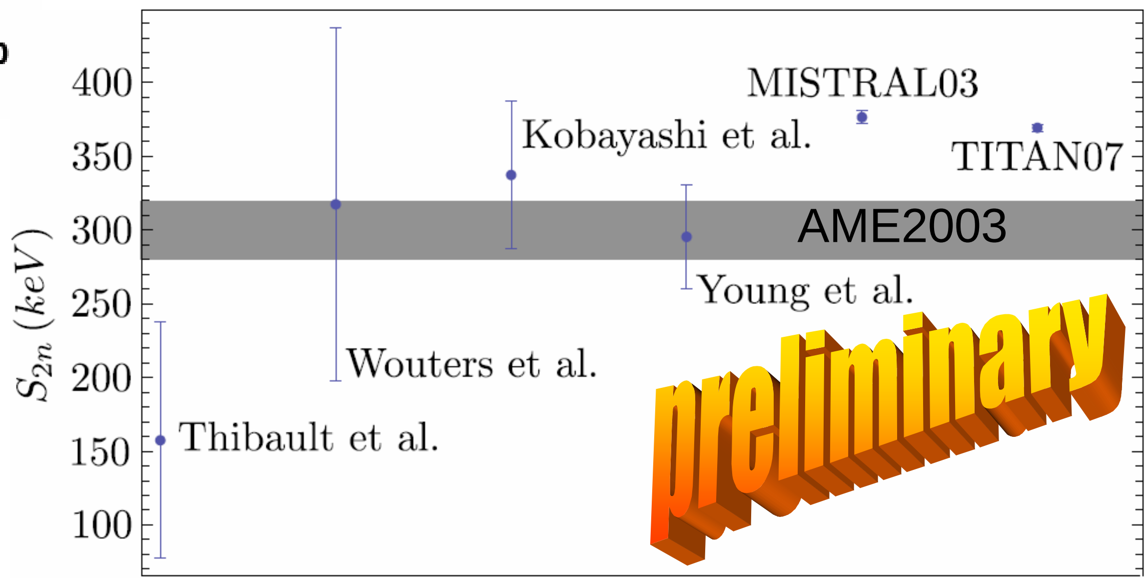


On-line mass measurements (Dec. run Li)



- TITAN direct mass measurement of ^{11}Li
- Shortest-lived isotope ever trapped!
- Run @ 50 Hz and 20ms excitation
- ISAC yield of 1200 ions/s.
- Preliminary analysis shows δm = 0.555 keV + systematic needed for final analysis.
- Reference measurement done with $^{6,7}Li$ and ^{12}C.
- Best precision achieved.

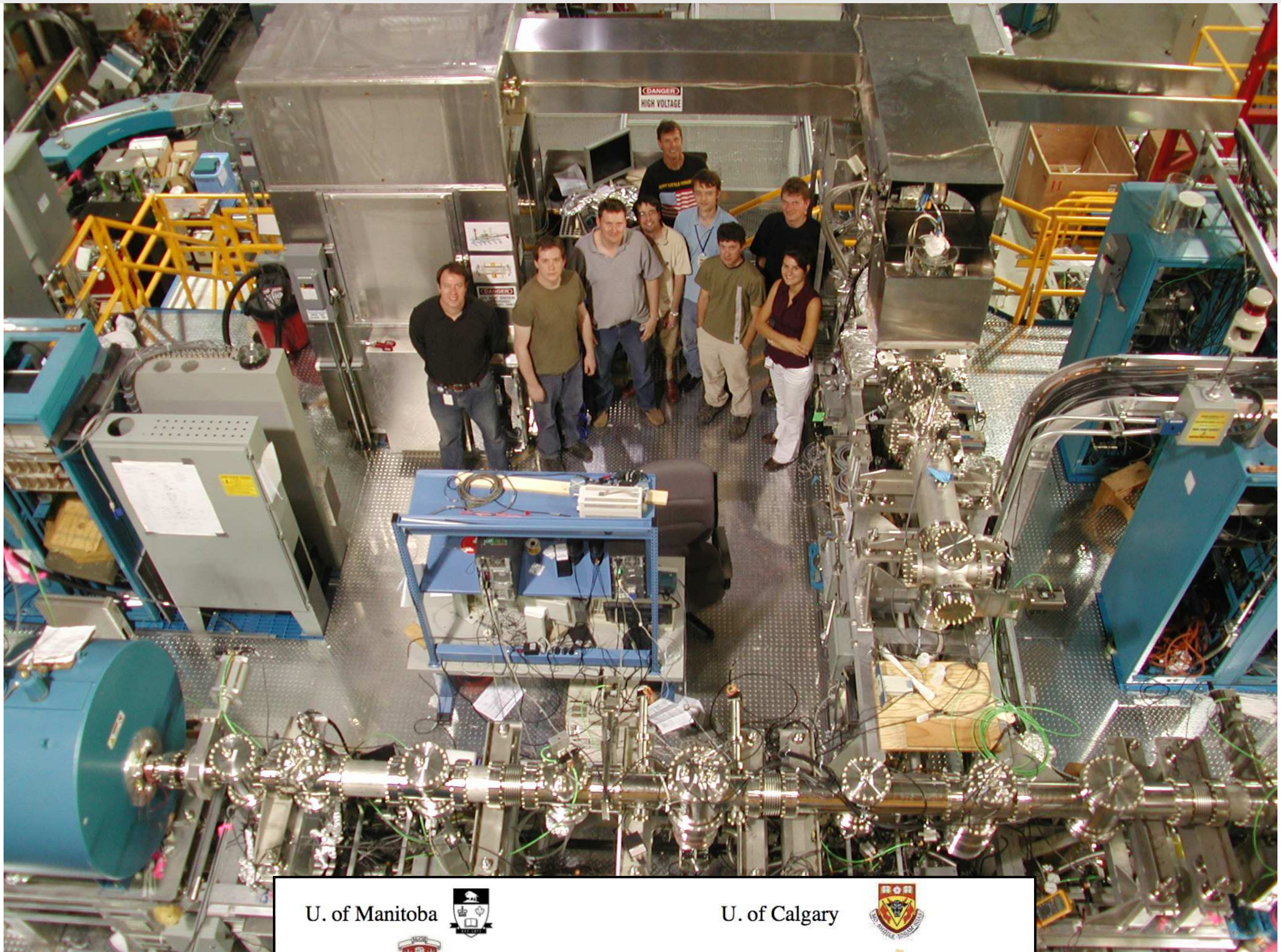




Conclusion:

- ISAC has a very strong science program with state-of-the-art experimental facilities.
- By adding a photo-fission facility a unique niche of physics for nuclear structure and nuclear astro-physics is accessible in the near term (~ 3 years).
- Additional p-beam line will benefit the fundamental symmetries program and n-rich nuclear structure.
- TITAN is a powerful mass spectrometer, well suited for light halo nuclei mass measurements with low production rates.
- TITAN performed precision mass measurements of He, Li, and Be halo nuclei, final analysis pending.
- Will allow refined charge radius determinations and shed new light on the structure of halo nuclei.
- There is more to come from TITAN (halo, CKM, structure…) incl. mass measurements on HCIs.

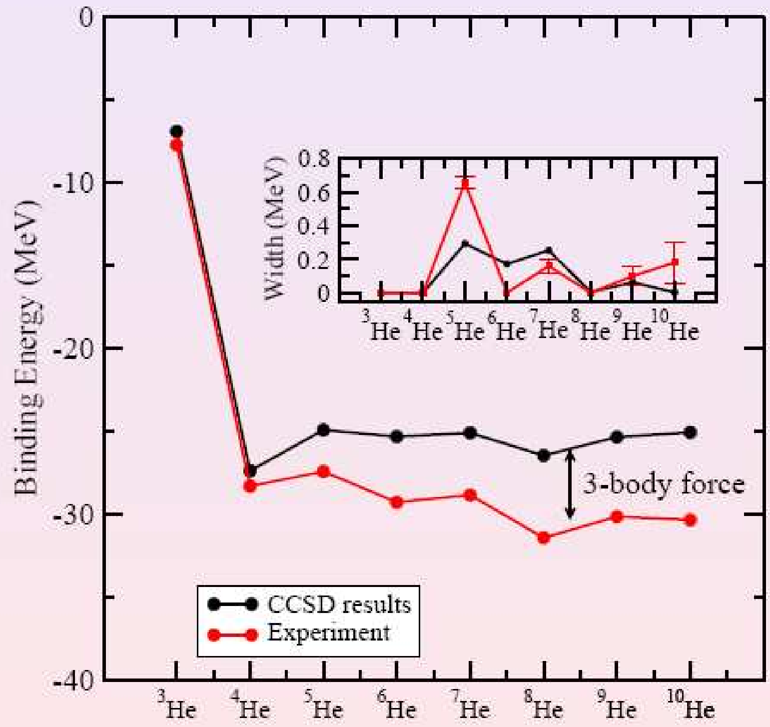
The TITANs:



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

CCSD results for Helium chain using $V_{\mathrm{low}-k}$

A. Schwenk/TRIUMF



- $V_{\mathrm{low}-k}$ from N3LO with $\Lambda = 1.9\mathrm{fm}^{-1}$.
- G. Hagen et al., Phys. Lett. B 656, 169 (2007). arXiv:nucl-th/0610072.

- First *ab-initio* calculation of decay widths !
- CCM unique method for dripline nuclei.
- ~ 1000 active orbitals
- Underbinding hints at missing 3NF

Coupled-cluster model (*j*-scheme) with 3-body forces for open systems – on a laptop!