

# The ISAC science program at TRIUMF

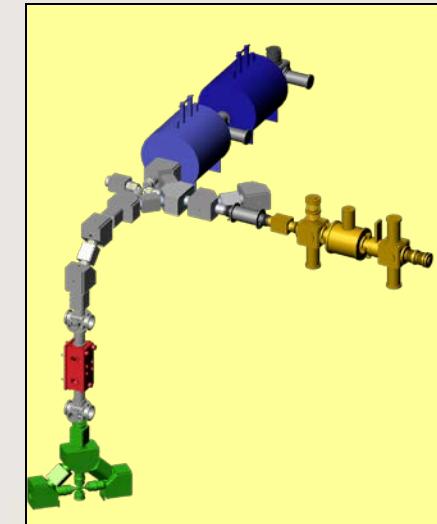
Highlights, status, and future plans



J. Dilling

TRIUMF/University of British Columbia  
Vancouver, Canada

ISOLDE Workshop  
November 25 2013



# TRIUMF's accelerator complex

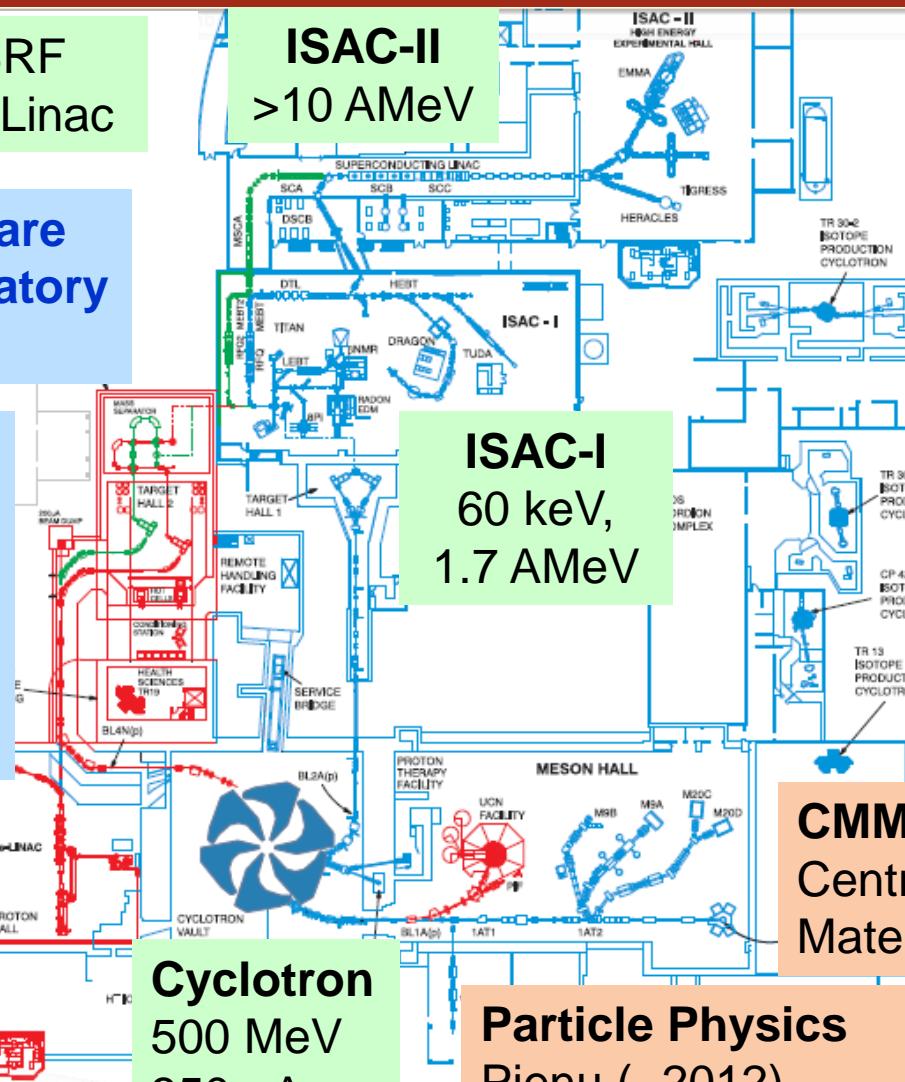
40 MV SRF  
Heavy Ion Linac

**ISAC-II**  
 $>10$  AMeV

Advanced Rare  
Isotope Laboratory  
(ARIEL)

e-LINAC  
300-500 kW  
photo-fission  
driver  
(under  
construction)

**ISAC-I**  
60 keV,  
1.7 AMeV



**Cyclotron**  
500 MeV  
 $350 \mu\text{A}$

## ISAC

Highest Power ISOL RIB facility

- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries
- CMMS ( $\beta$ NMR)

## Nordion

commercial medical  
isotope production  
3 cyclotrons

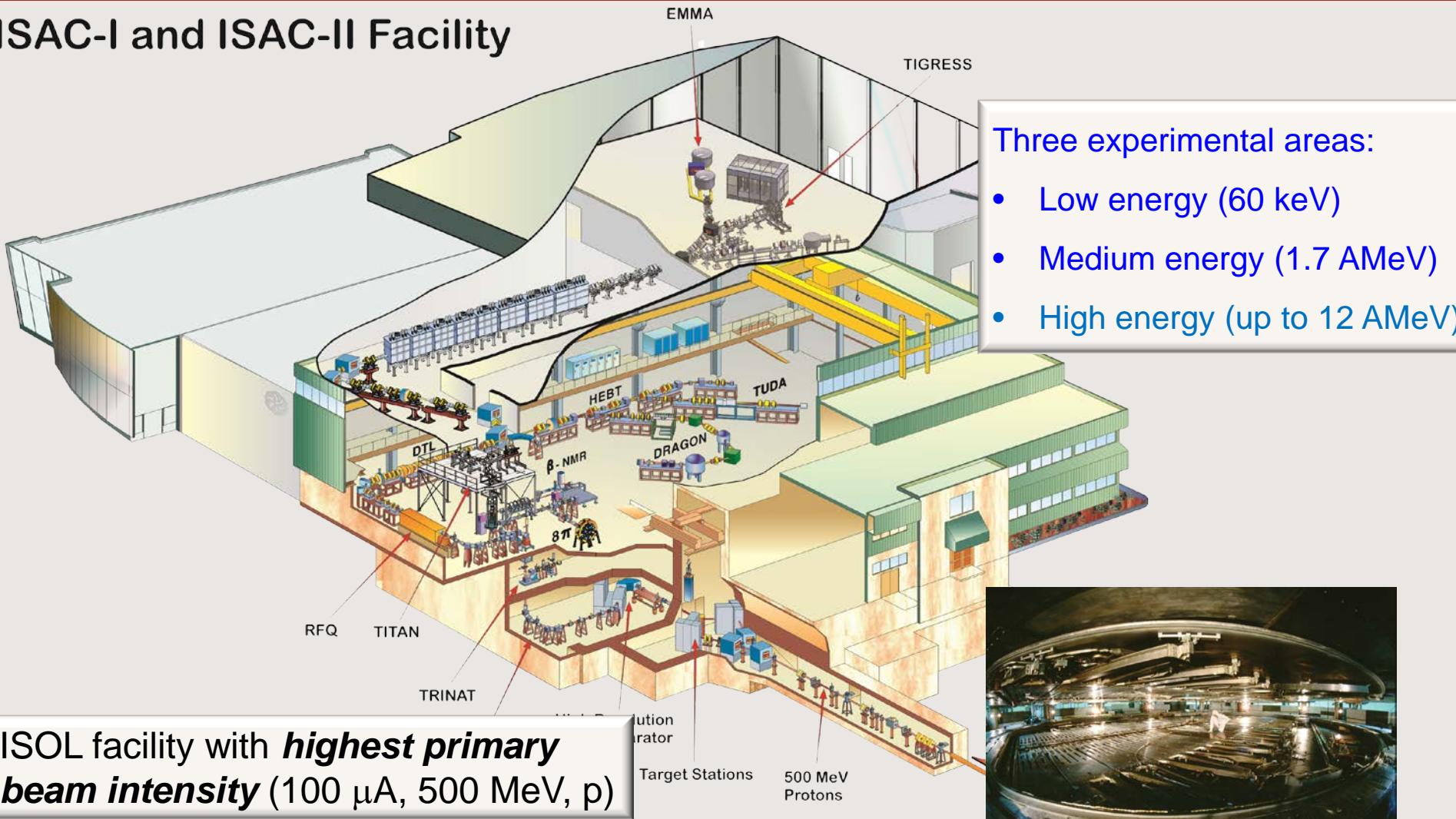
## CMMS

Centre for Molecular and  
Material Science ( $\mu$ SR)

**Particle Physics**  
Pienu (- 2012)  
Ultra Cold Neutrons (2015 -)

# ISAC rare isotope facility

## ISAC-I and ISAC-II Facility



Three experimental areas:

- Low energy (60 keV)
- Medium energy (1.7 AMeV)
- High energy (up to 12 AMeV)



ISOL facility with **highest primary beam intensity** (100  $\mu$ A, 500 MeV, p)

RIB and SIB parallel beam operation

# Experimental facilities and programs in NP

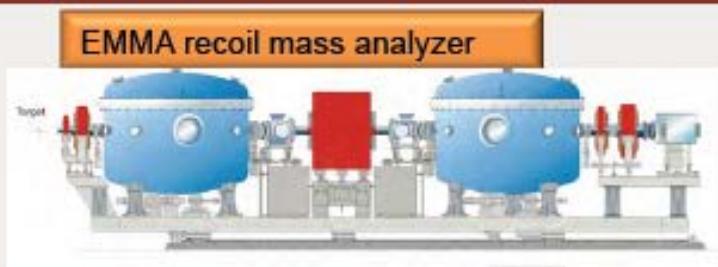
TITAN Penning Trap facility



Francium trapping facility



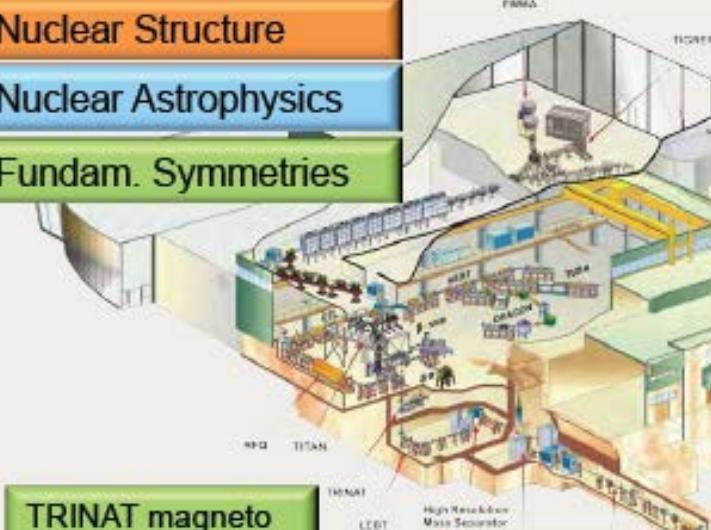
EMMA recoil mass analyzer



Nuclear Structure

Nuclear Astrophysics

Fundam. Symmetries



MTV Mott scattering drift chamber



8pi gamma-ray decay spectrometer



TRINAT magneto optical trap



TIGRESS in-beam gamma-ray spectrometer



IRIS solid hydrogen reaction set-up

DRAGON recoil separator



TUDA reaction setup



Targets and Yield: TRIUMF, SFU

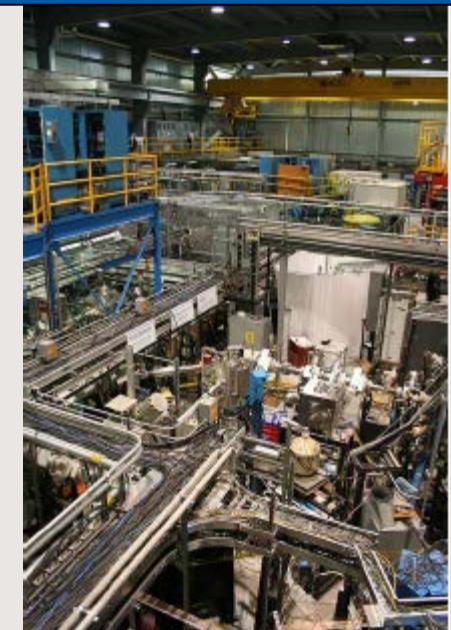
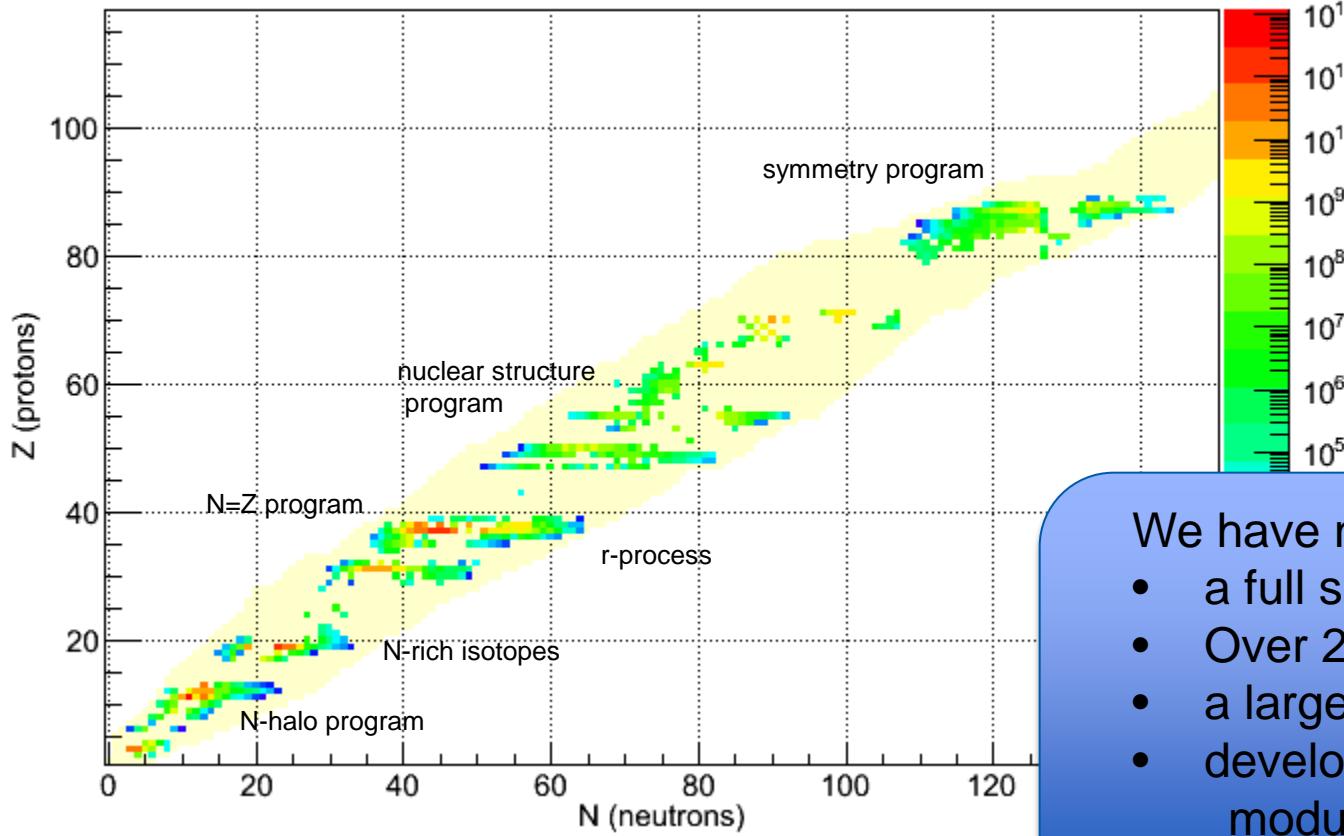
Ion Source: TRIUMF

P. Kunz et al.

P. Bricault, F. Ames. J. Lassen et al.,

## Isotopes delivered at ISAC

Yield Chart of Nuclides

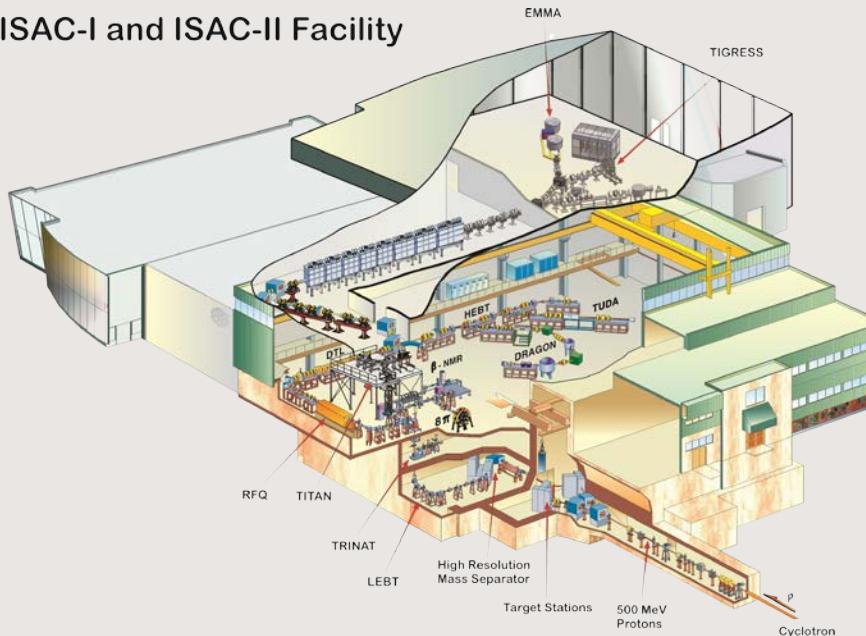


- We have now:
- a full set of targets
  - Over 200 beams
  - a large range of ion sources
  - developing fast target module exchange
  - Off-line test capabilities

# Science highlights

## 1. low energy area

ISAC-I and ISAC-II Facility

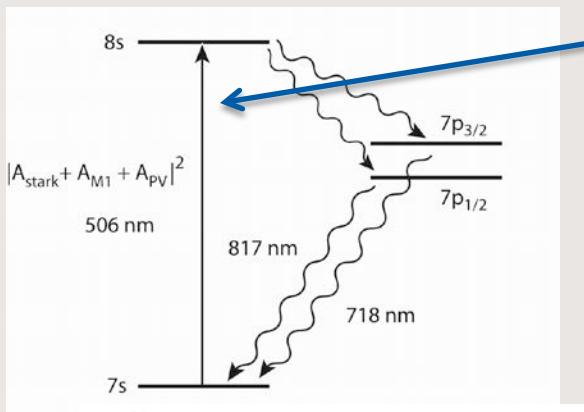


- Fr PNC trap
- Collinear laser spectroscopy
- TITAN mass measurements

# Fr-TRAP: atom trap for weak interaction

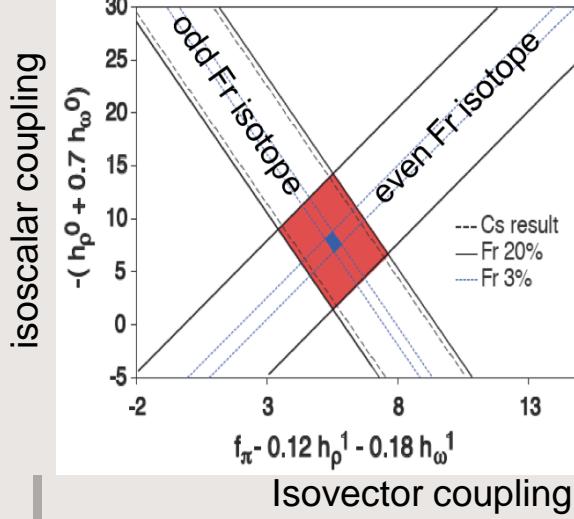
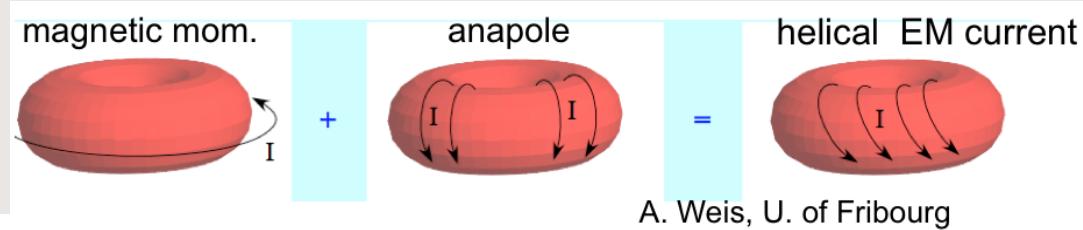
## Fr isotopes: Heavy nucleus, simple atomic structure

- candidate for low-energy tests of hadronic weak interaction (effect scales with  $Z$ )
- search for physics beyond the Standard Model



### Parity-non-conserving (PNC) atomic transition ( $8s \rightarrow 7s$ )

→ Probes strength of the weak neutral current between electron and quarks at very low momentum transfer



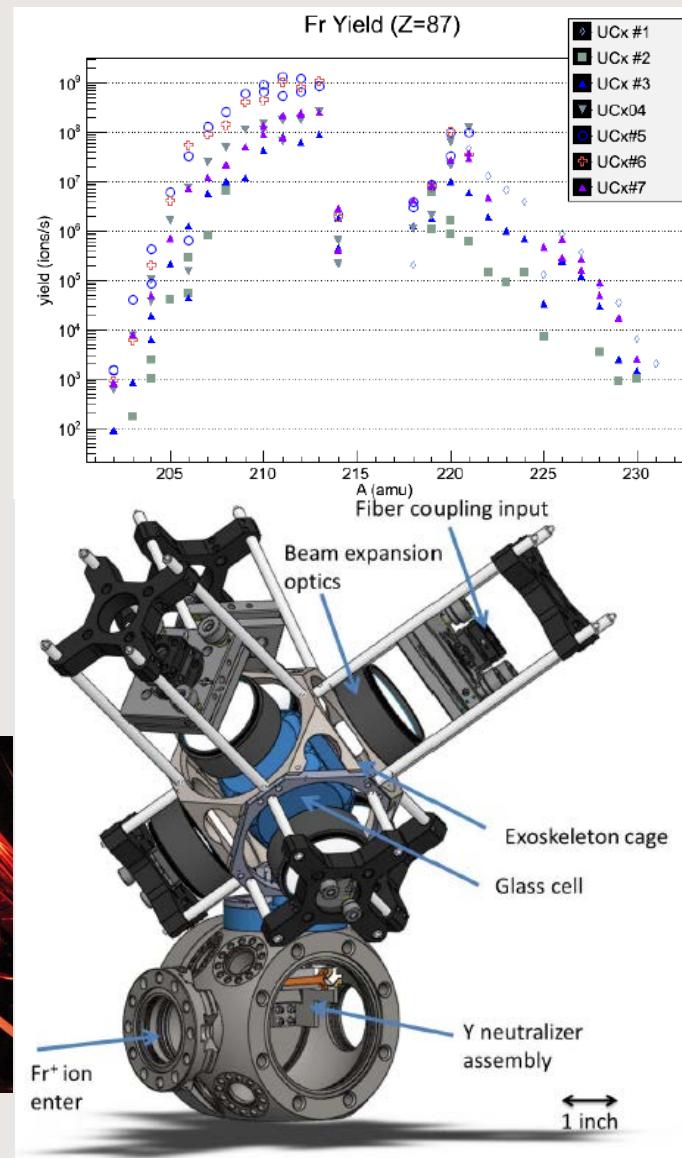
### Anapole moment (parity violating, time reversal conserving):

- arises from the weak interaction between the valence nucleons and the core
- probes isovector and isoscalar weak N-N couplings in the nuclear medium
- Use multiple isotopes

Fr-TRAP: TRIUMF - Maryland - Manitoba - San Luis Potosi - William & Mary Shanxi - Stony Brook - New South Wales  
 L. Orosco, G. Gwinner, M. Tandecki et al.

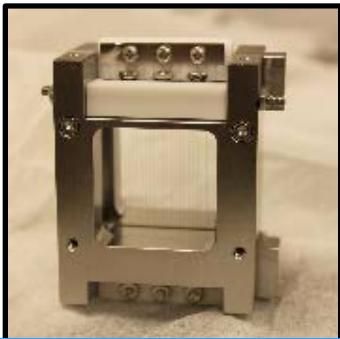
- **2010:**  
 UCx targets, enabling FrPNC program, become routinely available at ISAC
- **Fall 2011:**  
 Construction of facility from scratch
- **September 2012:**  
 Initial commissioning, trapping of  $^{209}\text{Fr}$ ,  $^{221}\text{Fr}$  and  $^{207}\text{Fr}^*$
- **September 2012 (S1336):**  
 Off-line implantation of  $^{225}\text{Ac}$  to trap  $^{221}\text{Fr}$  off-line
- **November 2012:**  
 Measurement of  $7\text{p}_{1/2}$  splitting and isotope shifts for  $^{206}\text{Fr}^*$ ,  $^{207}\text{Fr}$ ,  $^{209}\text{Fr}$ ,  $^{213}\text{Fr}^*$
- **September 2013:**  
 Continued spectroscopic measurements on  $^{206}\text{Fr}^o$ ,  $^{206m}\text{Fr}^*$ ,  $^{208}\text{Fr}$ ,  $^{209}\text{Fr}$ ,  $^{210}\text{Fr}$ ,  
 $^{211}\text{Fr}$ ,  $^{212}\text{Fr}$ ,  $^{221}\text{Fr}$
- **2010-2013:**  
 Collinear laser spectroscopy<sup>2</sup> on  $^{204g,m1,m2}\text{Fr}$ ,  $^{205}\text{Fr}$ ,  $^{206g,m1,m2}\text{Fr}$  w.r.t.  $^{208}\text{Fr}$

Successful Francium trapping of Fr in new Magneto Optical Trap (MOT) and collinear spectroscopy, A. Voss et al PRL (2013)



# TITAN @ TRIUMF

## masses, in-trap spectroscopy, and laser spectroscopy



T. Brunner et al., IJMS 309, 97 (2012)

### BN gate for m/q selection

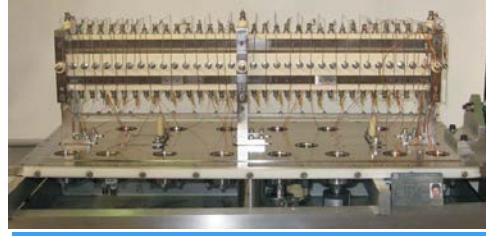
Bradbury-Nielsen

a) SC

SCI

SCI

### RFQ cooler & buncher



T. Brunner et al., NIMA 676 32 (2012)

ISAC beam

RFQ cooler  
and buncher

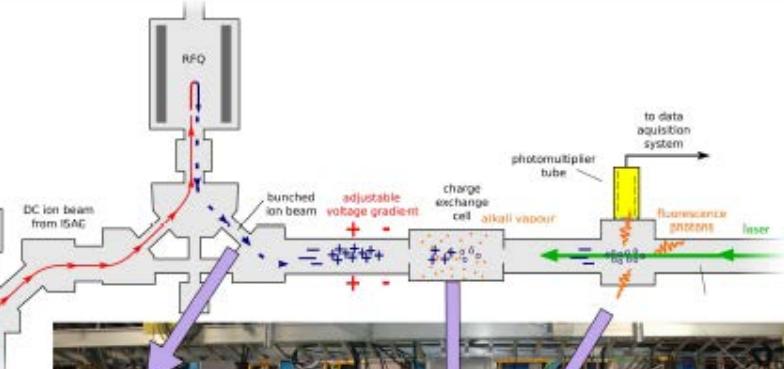
beam to no

off-line ion source

### Mass measurement Penning Trap



Precision  
Penning trap



Laser spec on cooled and  
bunched RIBs

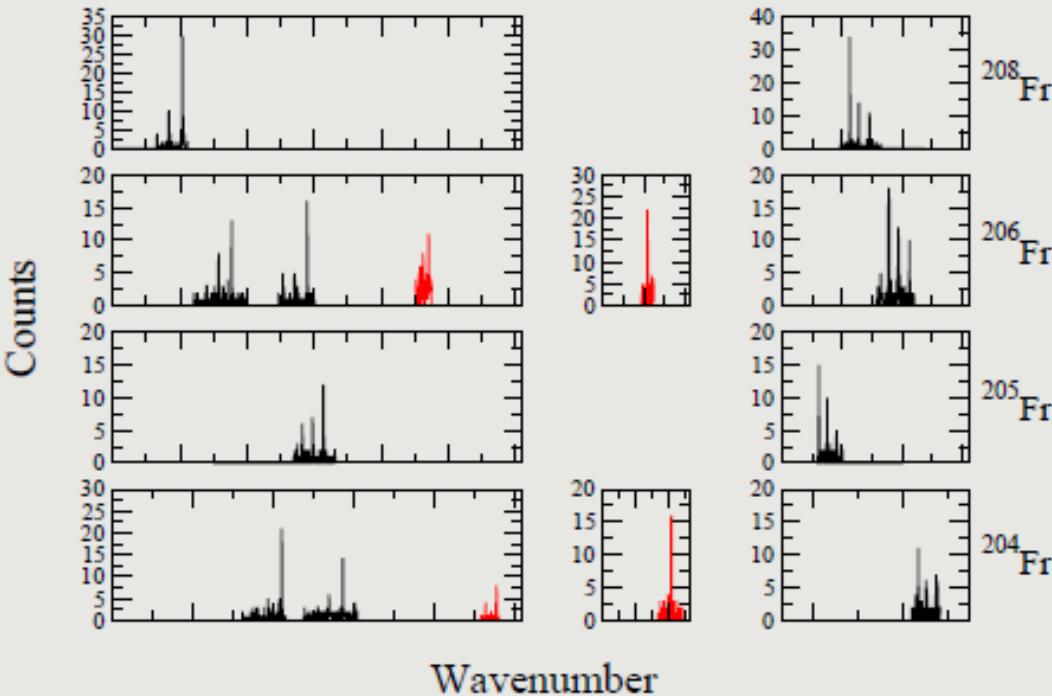
J. Dilling et al., NIM B 204 (2003) 492-496

J. Dilling et al., IJMS 251, 198 (2006)

TITAN/Laser-spectroscopy: TRIUMF, McGill, Manchester UK

J. Crawford, F. Buchinger, B. Cheal, M. Pearson et al.

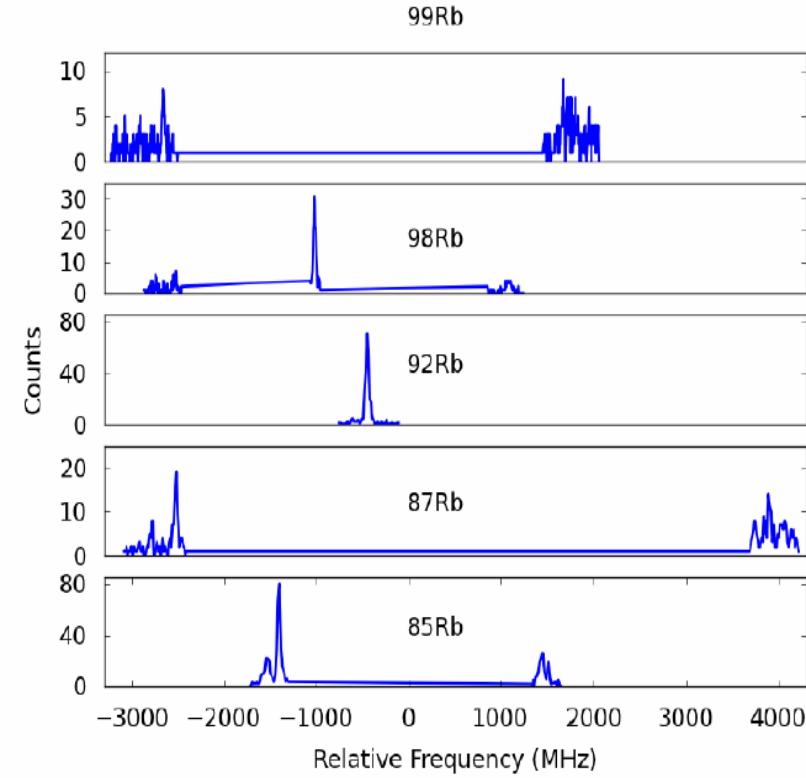
## Francium spectroscopy



Wavenumber

- Fully resolved spectra scanning over 60GHz with a single laser locking point allowed two isomers to be found in each of  $^{204,206}\text{Fr}$ .
- A. Voss et al., PRL 111 122501 (2013)
- Spins, moments and charge radii are currently being determined.

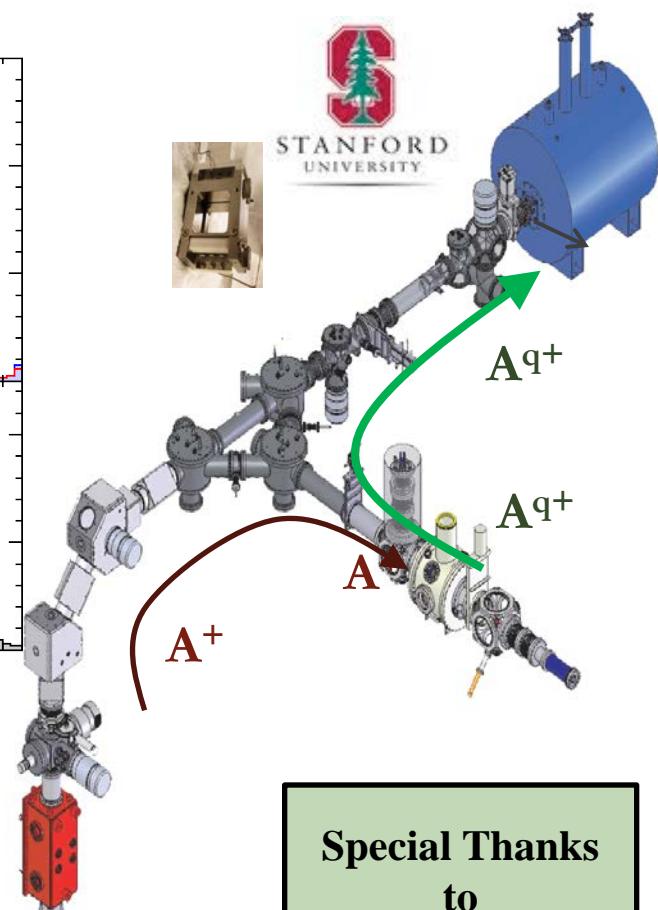
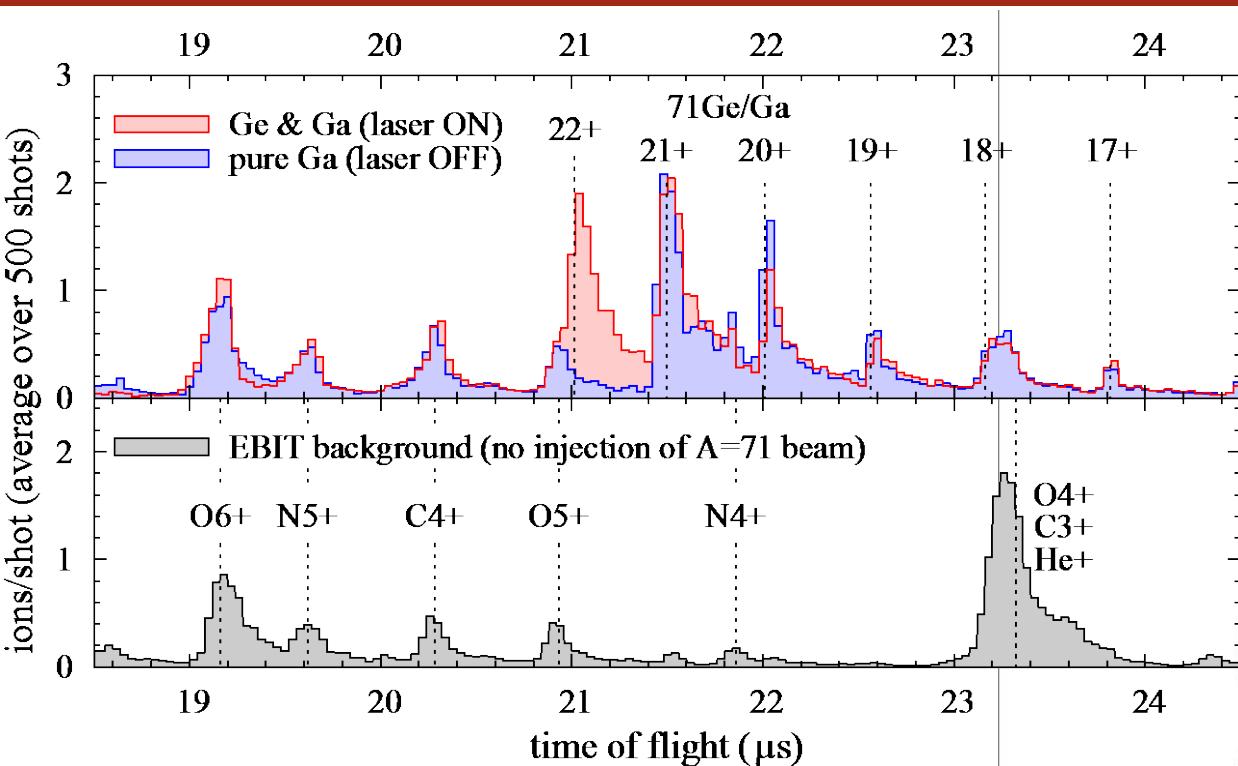
## Rubidium spectroscopy



- Spectroscopy of N-rich Rb isotopes
- Identification of isomer
- More studies needed to do full assignments

# $^{71}\text{Ge}$ - $^{71}\text{Ga}$ mass measurements

solar neutrino measurements: gallium anomaly

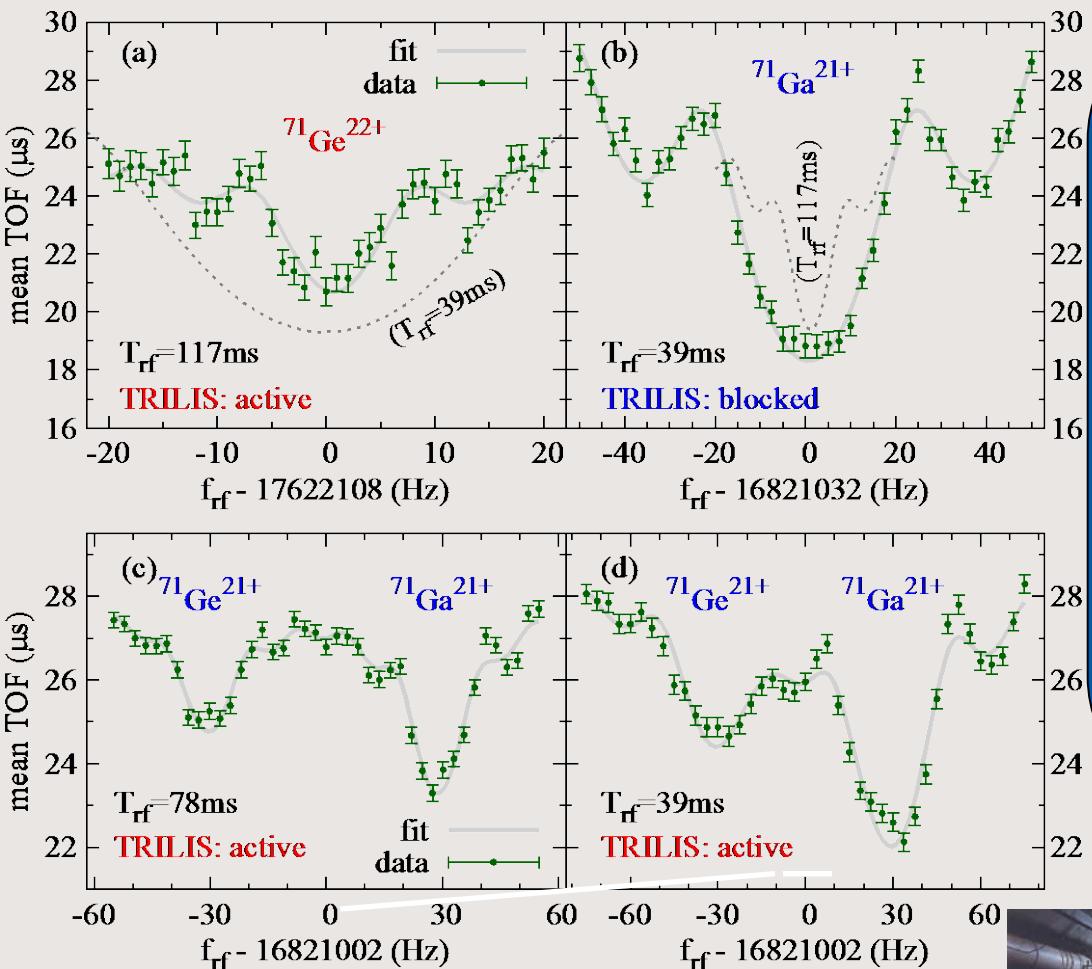


Ge delivery from ISAC required Laser Ionization  
 → clean  $^{71}\text{Ga}^{21}$  if Laser OFF (Ga surface ionization)  
 → clean  $^{71}\text{Ge}^{22}$  if Laser ON (Ga not bred to  $q=22+$ )

- Selection of species via laser and electron energy
- Different ionization energy, depends on chemical element (and Z)

Special Thanks  
to  
Jens Lassen &  
the TRILIS team

# Separation of isobars by use of threshold charge breeding: Z of Ge and Ga is different and e-binding is Z-dependent (both Ne-like)



Q-value confirmed:  
Found value sits outside  
'needed' range to explain  
the gallium anomaly for SAGE  
and GALLEX.  
Need different explanation  
for  $\nu$ -event disagreement  
(like sterile neutrinos!)

D. Frekers et al.,  
PLB 722 (2013) 233

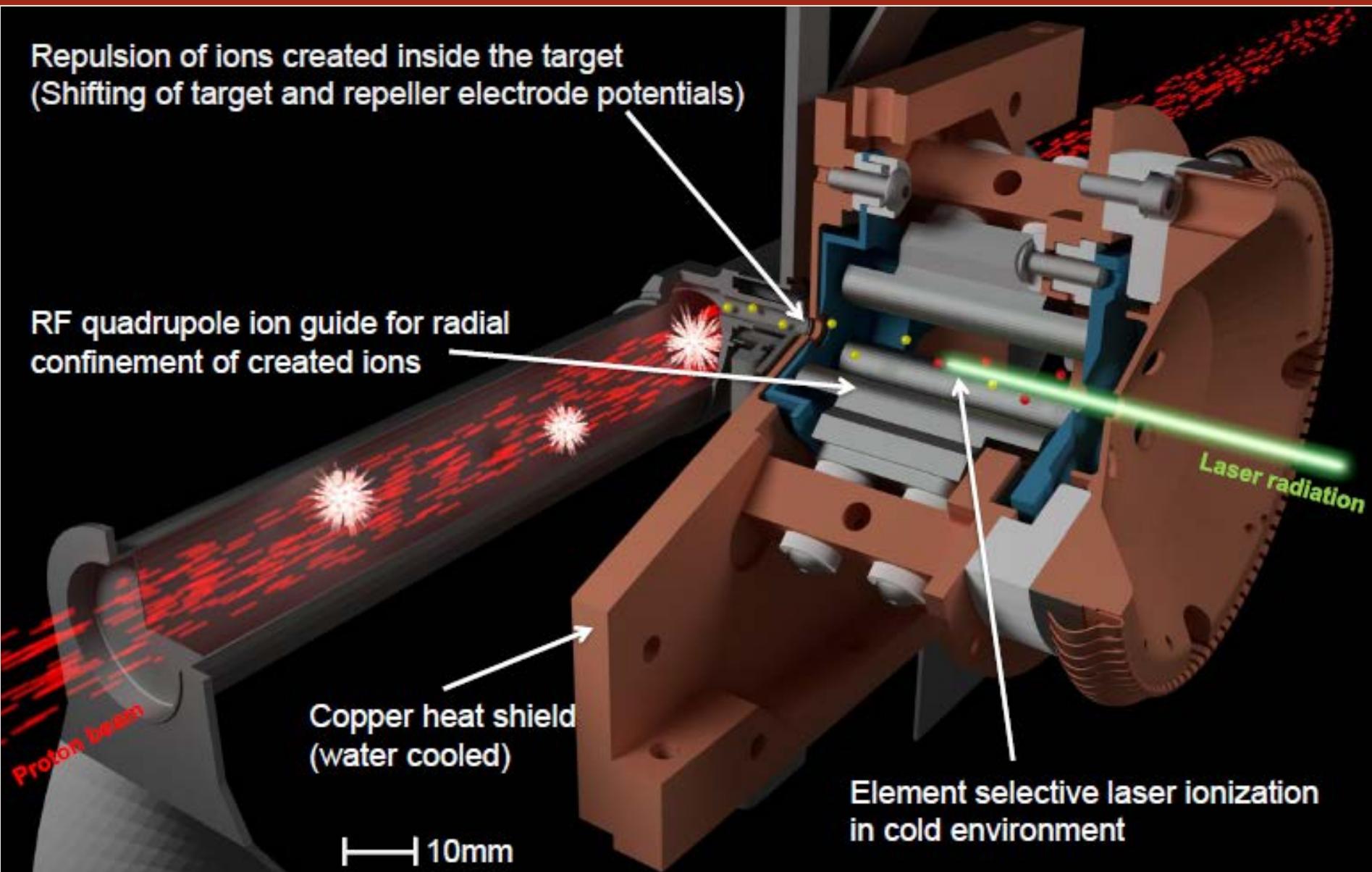


# Mass measurements at A=20,21 IMME and test of theory & some more tricks for clean beams

- Mass measurements of p-rich Mg masses
- Isobars are co-produced with the isotopes of interest!
- Na, closer to stability, and longer-lived
- Much more extracted and delivered to experiment (1.000.000-1 ratio)
- Cleaning system required!

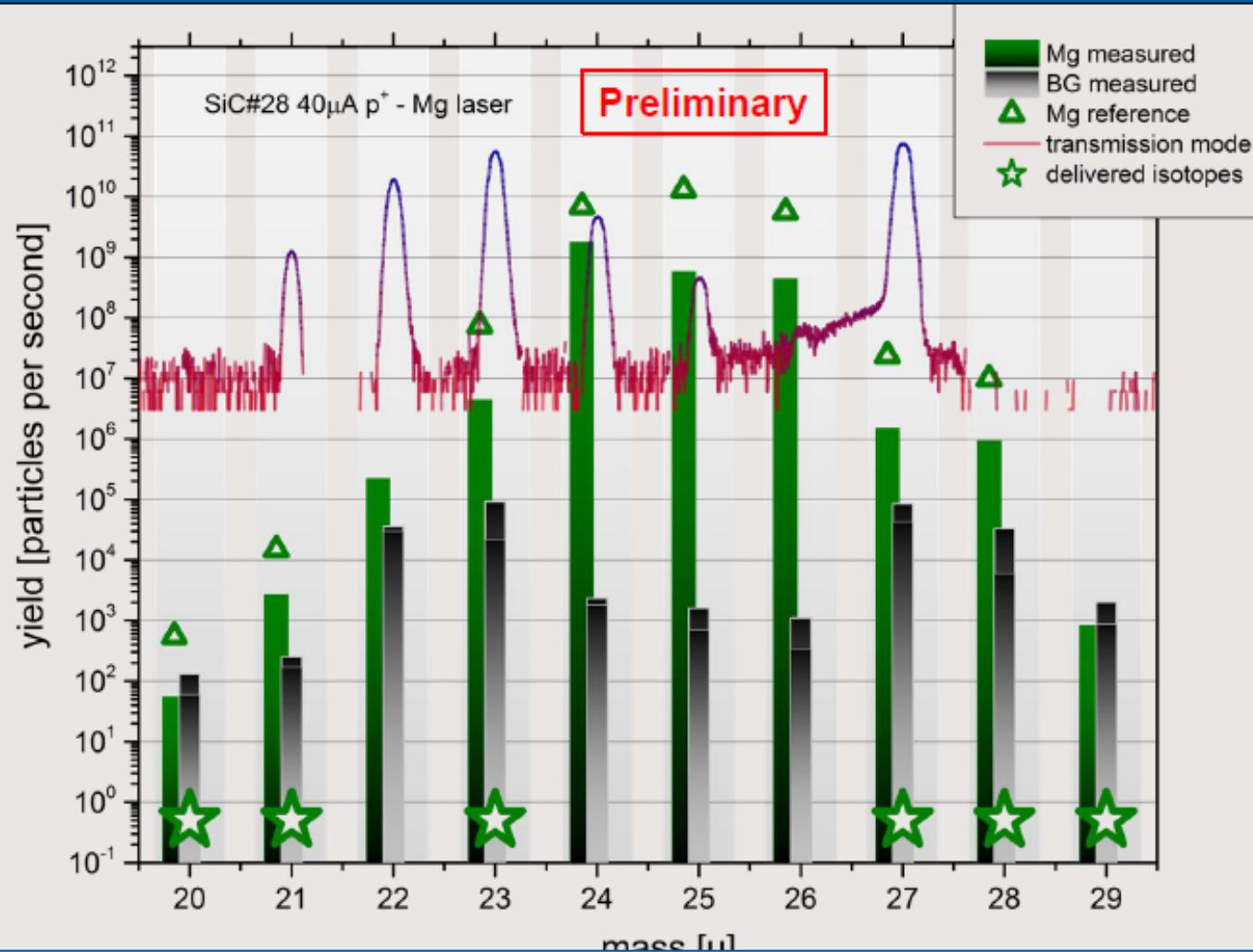
		M 20120# (300#) p?	$\beta^+ = 100\%$ $\beta^+ p = 44 (3)\%$ ...	$\beta^+ = 100\%$ $\beta^+ p = 8 (4)\%$	IT=82 (3)% $\beta^+ = 18 (3)\%$ $\beta^+ \alpha = 0.035 (6)\%$ ...	$\beta^+ = 100\%$ $\beta^+ = 100\%$	M 89162 (0.5) $\beta^+ = 100\%$								
		<b>19</b> <b>12</b> Mg 7	1/2 <sup>-</sup> # M 33040 (250) 2p?	<b>20</b> <b>12</b> Mg 8	90 ms 0 <sup>+</sup> M 17570 (27) $\beta^+ = 100\%$ $\beta^+ p = 30.4 (16)\%$	<b>21</b> <b>12</b> Mg 9	122 ms (5/2,3/2) <sup>+</sup> M 10911 (16) $\beta^+ = 100\%$ $\beta^+ p = 32.6 (10)\%$ ...	<b>22</b> <b>12</b> Mg 10	3.857 s 0 <sup>+</sup> M ~397.0 (1.3) $\beta^+ = 100\%$	<b>23</b> <b>12</b> Mg 11	11.317 s 3/2 <sup>+</sup> M ~5473.8 (1.3) $\beta^+ = 100\%$	<b>24</b> <b>12</b> Mg 12	stable 0 <sup>+</sup> M ~13933.567 (0.013) Abundance=78.99 (4)%		
		<b>18</b> <b>11</b> Na 7	1.3 zs 1 <sup>-</sup> # M 24190 (50) $\beta^+ ?$	<b>19</b> <b>11</b> Na 8	<40 ns 5/2 <sup>+</sup> # M 12927 (12) $\beta^+ = 100\%$	<b>20</b> <b>11</b> Na 9	447.9 ms 2 <sup>+</sup> M 6848 (7) $\beta^+ = 100\%$ $\beta^+ \alpha = 25.0 (4)\%$	<b>21</b> <b>11</b> Na 10	22.49 s 3/2 <sup>+</sup> M ~2184.2 (0.7) $\beta^+ = 100\%$	<b>22</b> <b>11</b> Na 11	244 ns 1 <sup>+</sup> Ex 583.03 (0.09) IT=100% 2.6019 y 3 <sup>+</sup> M ~51824 (0.4) $\beta^+ = 100\%$	<b>23</b> <b>11</b> Na 12	stable 3/2 <sup>+</sup> M ~9529.8536 (0.0027) Abundance=100.0%		
		<b>16</b> <b>10</b> Ne 6	9 zs 0 <sup>+</sup> M 23996 (20) 2p=100%	<b>17</b> <b>10</b> Ne 7	109.2 ms 1/2 <sup>-</sup> M 16461 (27) $\beta^+ = 100\%$ $\beta^+ p = 96.0 (9)\%$ ...	<b>18</b> <b>10</b> Ne 8	1.672 s 0 <sup>+</sup> M 5317.17 (0.28) $\beta^+ = 100\%$	<b>19</b> <b>10</b> Ne 9	17.296 s 1/2 <sup>+</sup> M 1751.44 (0.29) $\beta^+ = 100\%$	<b>20</b> <b>10</b> Ne 10	stable 0 <sup>+</sup> M ~7041.9313 (0.0018) Abundance=90.48 (3)%	<b>21</b> <b>10</b> Ne 11	stable 3/2 <sup>+</sup> M ~5731.78 (0.04) Abundance=0.27 (1)%	<b>22</b> <b>10</b> Ne 12	stable 0 <sup>+</sup> M ~8024.715 (0.018) Abundance=9.25 (3)%

# Tricks for clean beams: Go to the source! Ion Guide Laser Ion Source (IG-LIS)



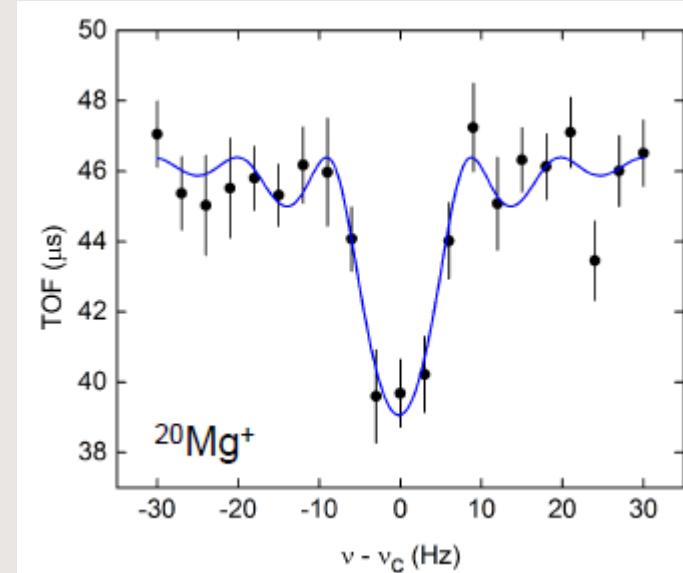
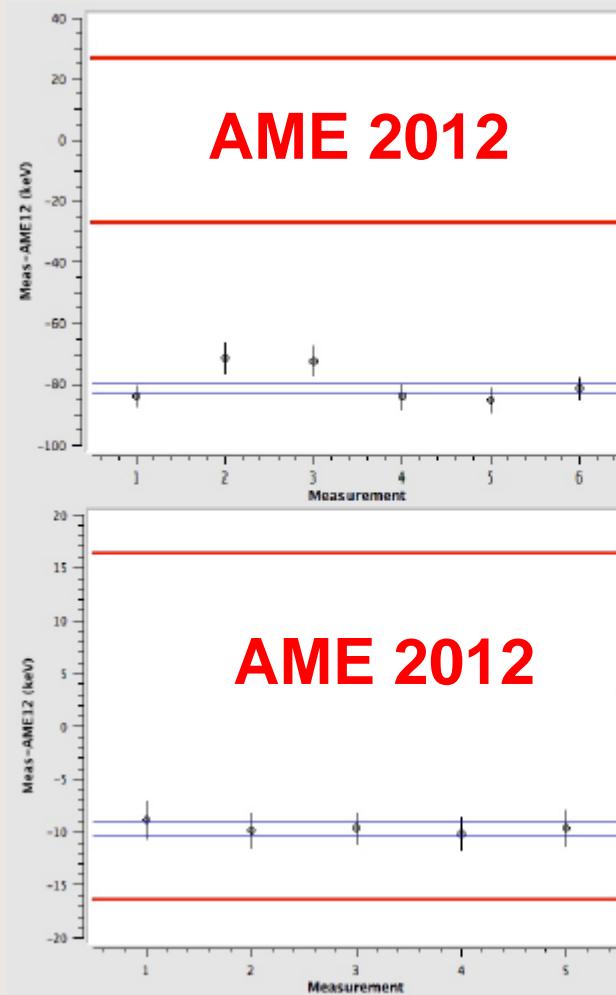
Laser ion source group: TRIUMF, Laval, U Manitoba, Oldenburg

J. Lassen, H. Heggen, A. Teigelhoefer et al.



Background reduction by 6 orders of magnitude!

# Results of the mass measurements possible with the IG-LIS

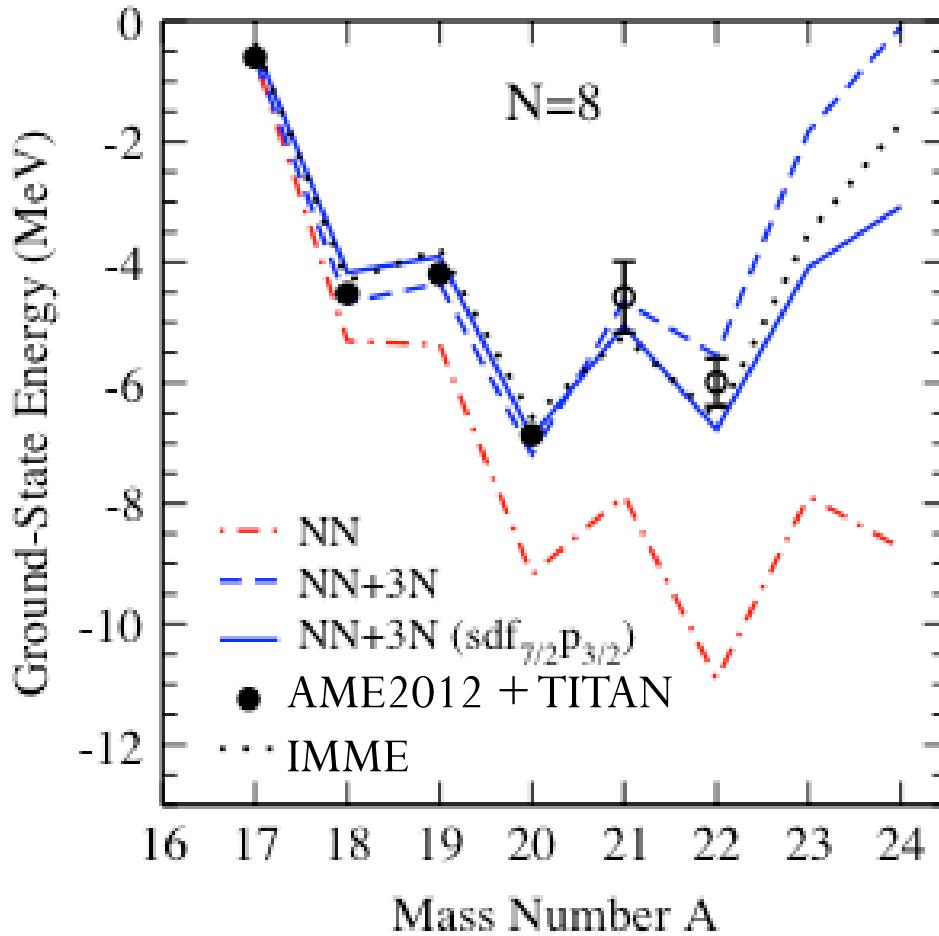


Clean beam delivered to TITAN  
Excellent mass measurements possible, background-free.

# Results of the mass measurements

TITAN: TRIUMF, UBC, SFU, Manitoba, U Muenster, MPI-K HD, Stanford, Dresden

A. Gallant, A. Kwiatkowski, J. Dilling et al.



Direct data improved – but also use phenomenological isobaric multiplet mass equation (IMME), improved by TITAN

**NN-only**: over-bound

**NN+3N**: improved agreement with experiment/IMME

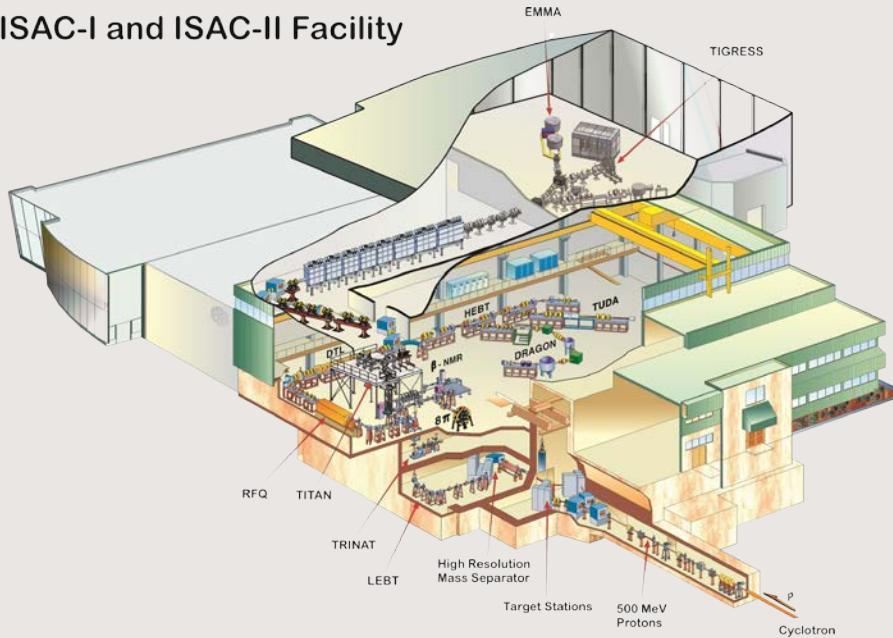
Adopted from J.Holt, Menendez, Schwenk, PRL (2013)

Mass values can be described by theory when including 3N forces. A. Gallant et al., submitted to PRL.

# Science highlights

## 2. medium energy area

ISAC-I and ISAC-II Facility



- Nuclear Astrophysics with DRAGON
- Energy quasi-continuously up to 1.7 AMeV

# Direct capture measurements for nuclear astrophysics: the DRAGON facility

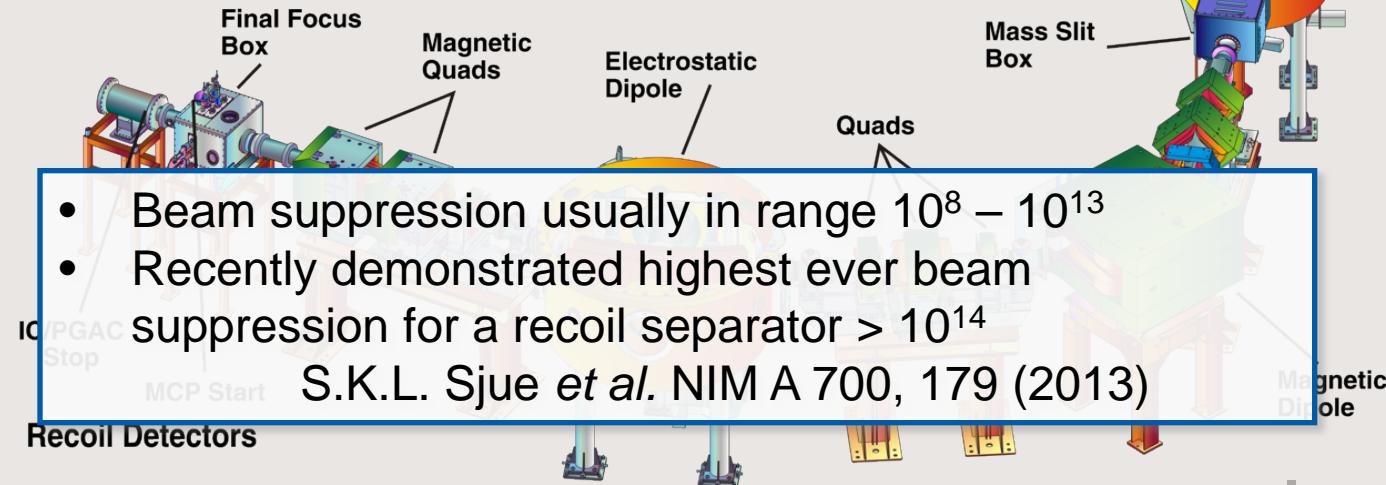
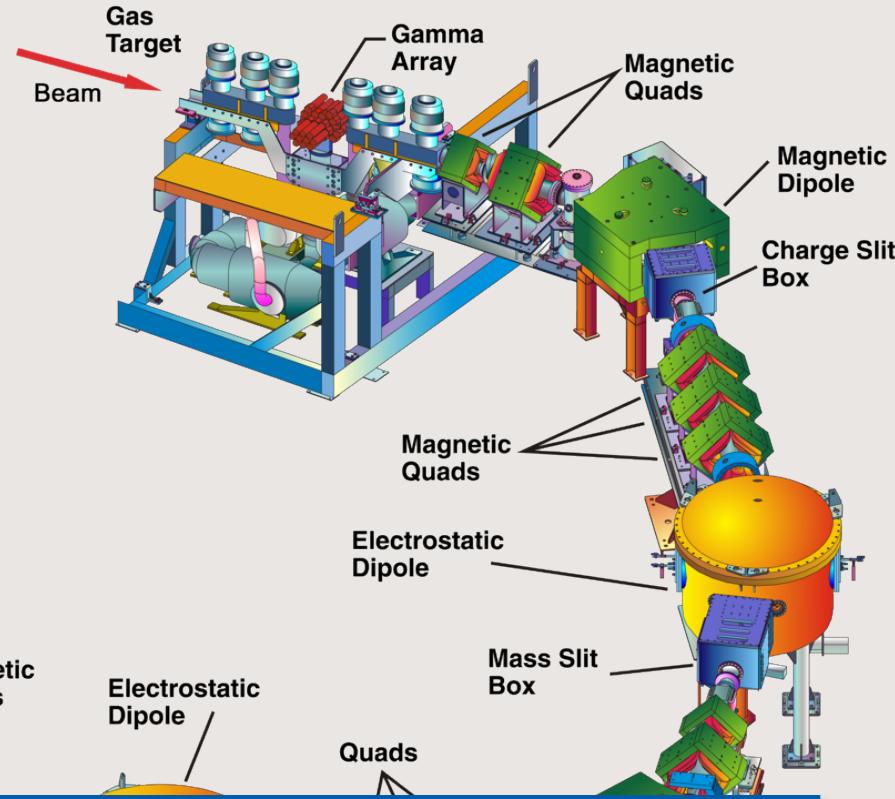
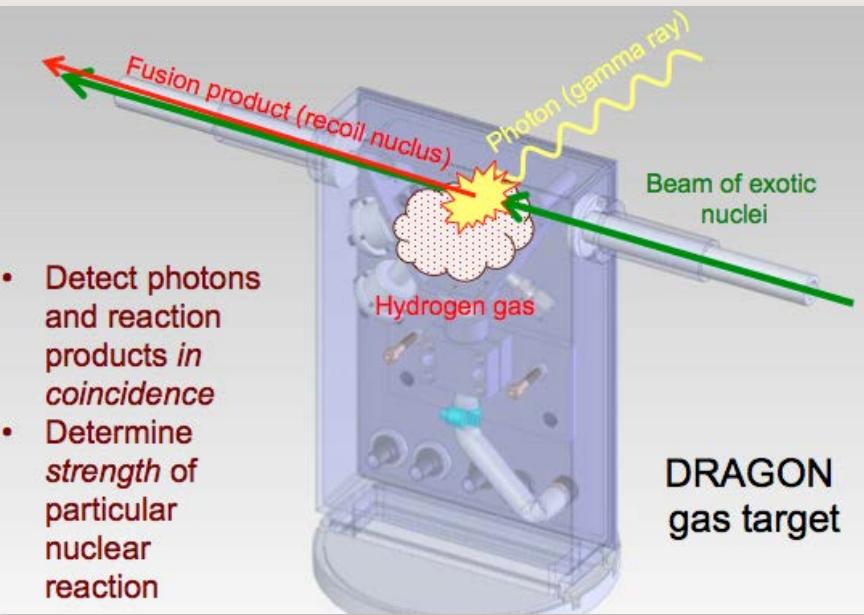
- Detect photons and reaction products *in coincidence*
- Determine *strength* of particular nuclear reaction

## DRAGON:

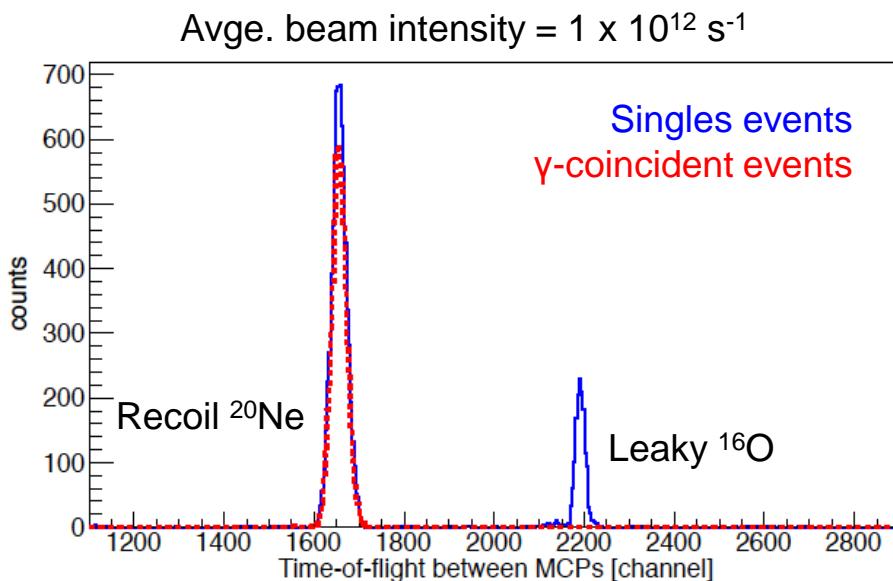
Direct measurement of proton- or  $\alpha$ - radiative capture e.g.

$^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ ,  
 $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$ ,  $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$ ,  
 $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ ,  $^3\text{He}(\alpha,\gamma)^7\text{Be}$ ,  
 $^{26\text{g,m}}\text{Al}(p,\gamma)^{27}\text{Si}$ ,

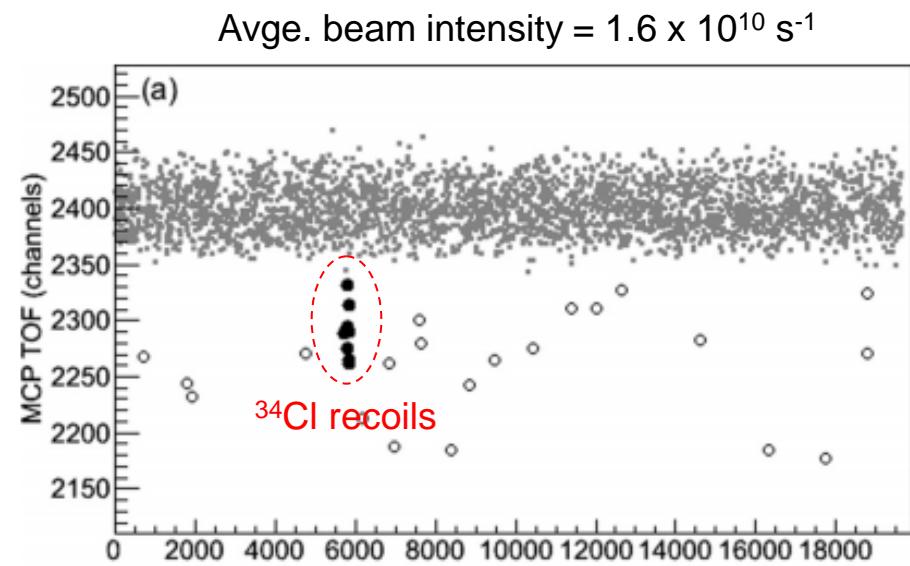
- First isomeric beam



- Resonance strengths as small as  $\sim 10 \text{ } \mu\text{eV}$
- Measure in presence of strong isobaric contaminant backgrounds (1000:1)
- Competitive stable beam measurements  $\rightarrow 1 \text{ } \mu\text{A}$  level using offline ECR
- High mass capture measurements for the p-process e.g.  $^{76}\text{Se}(\alpha, \gamma)^{80}\text{Kr}$



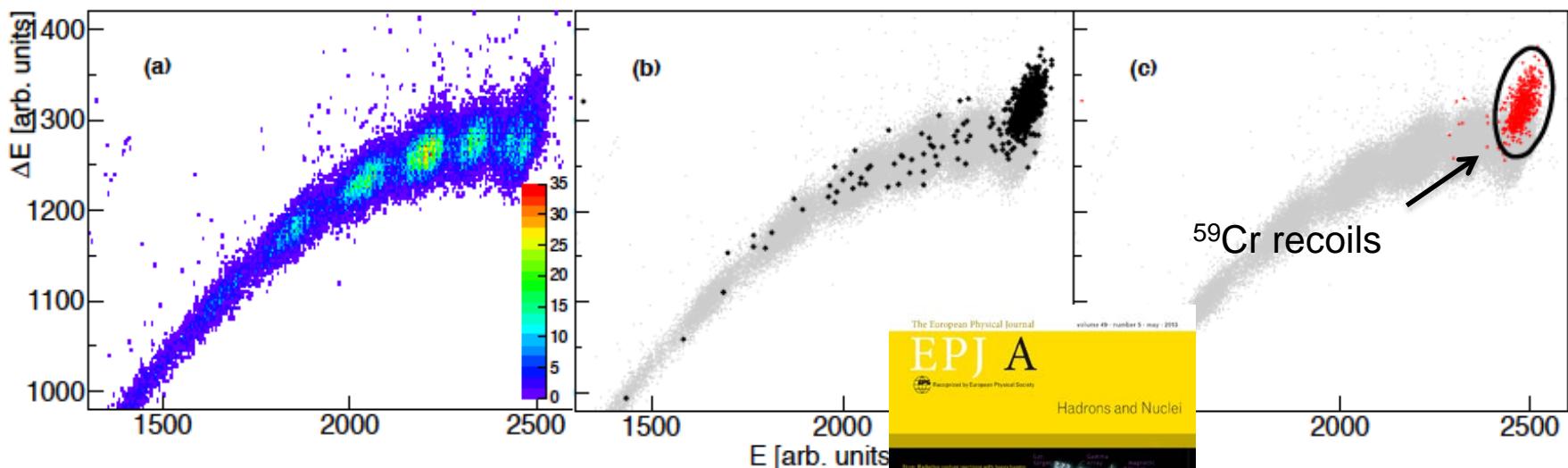
$^{16}\text{O}(\alpha, \gamma)^{20}\text{Ne}$ : U. Hager *et al.*, Phys. Rev. C 86 (2012) 055802



$^{33}\text{S}(p, \gamma)^{34}\text{Cl}$ : J. Fallis *et al.*, Phys. Rev. C 88 (2013) 045801

- Resonance strengths as small as  $\sim 10 \text{ } \mu\text{eV}$
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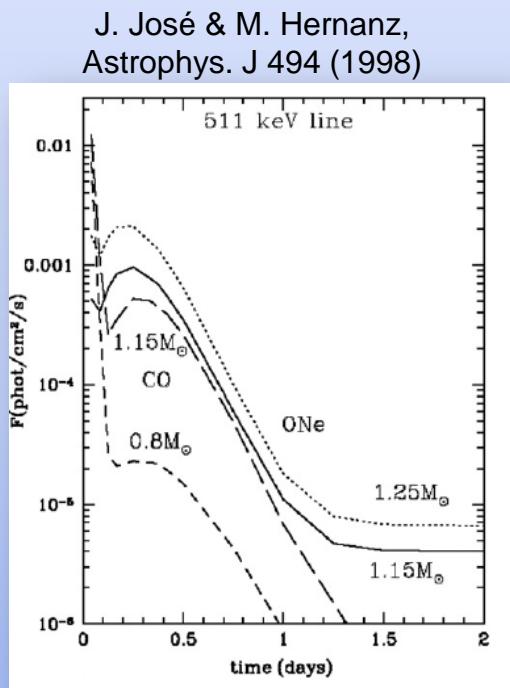
### $^{58}\text{Ni}(p, \gamma)^{59}\text{Cr}$ demonstrator experiment



A. Simon et al., Eur. Phys. J A 49 (2013)

DRAGON: TRIUMF, York, School of Mines, Edinburgh, Notre Dame  
 A. Laird, A. Murphy, C. Ruiz et al.,

- $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$  reaction partially determines 511-keV line emission from O-Ne novae (strongest and earliest signal)



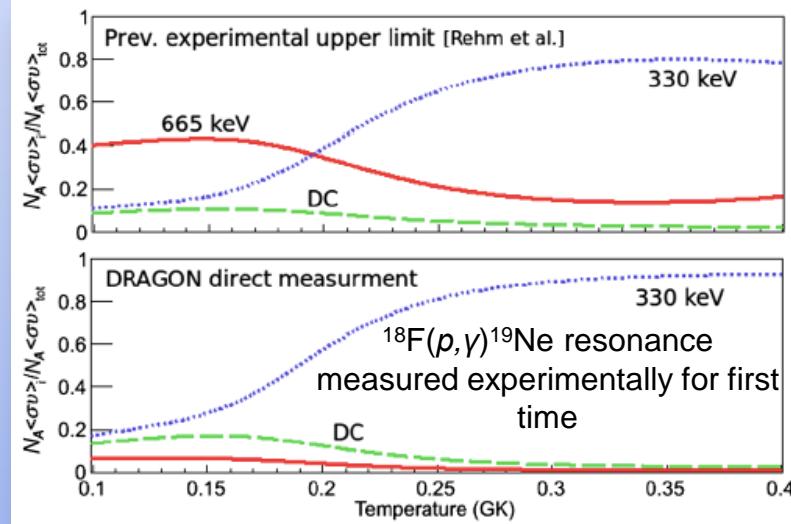
PRL 110, 262502 (2013)

PHYSICAL REVIEW LETTERS

Week ending  
28 JUNE 2013

### Measurement of Radiative Proton Capture on $^{18}\text{F}$ and Implications for Oxygen-Neon Novae

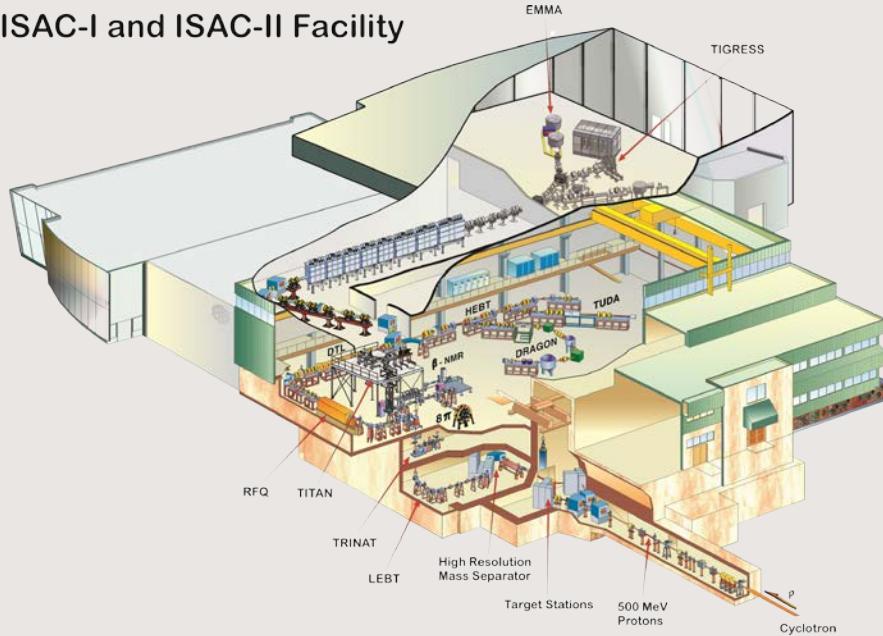
C. Akers,<sup>1,2</sup> A. M. Laird,<sup>2</sup> B. R. Fulton,<sup>2</sup> C. Ruiz,<sup>1</sup> D. W. Bardayan,<sup>3</sup> L. Buchmann,<sup>1</sup> G. Christian,<sup>1</sup> B. Davids,<sup>1</sup> L. Erikson,<sup>4</sup> J. Fallis,<sup>1</sup> U. Hager,<sup>5</sup> D. Hutcheon,<sup>1</sup> L. Martin,<sup>1</sup> A. St. J. Murphy,<sup>6</sup> K. Nelson,<sup>7</sup> A. Spyrou,<sup>8,9</sup> C. Stanford,<sup>10</sup> D. Ottewell,<sup>1</sup> and A. Rojas<sup>1</sup>



# Science highlights

## 3. high energy area

ISAC-I and ISAC-II Facility



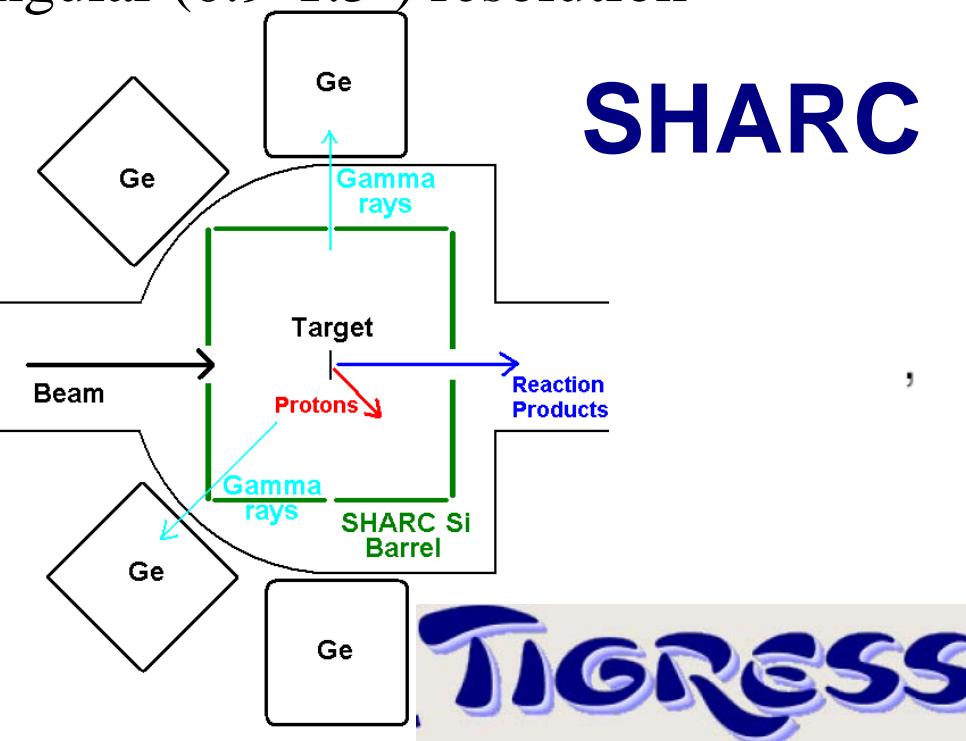
- TIGRESS/ SHARC
- IRIS
- Energy up to 12 AMeV
- Demonstrated post accel for charge bred with  $A > 30$

University of York, UK  
Colorado School of Mines, USA  
Louisiana State University, USA  
TRIUMF

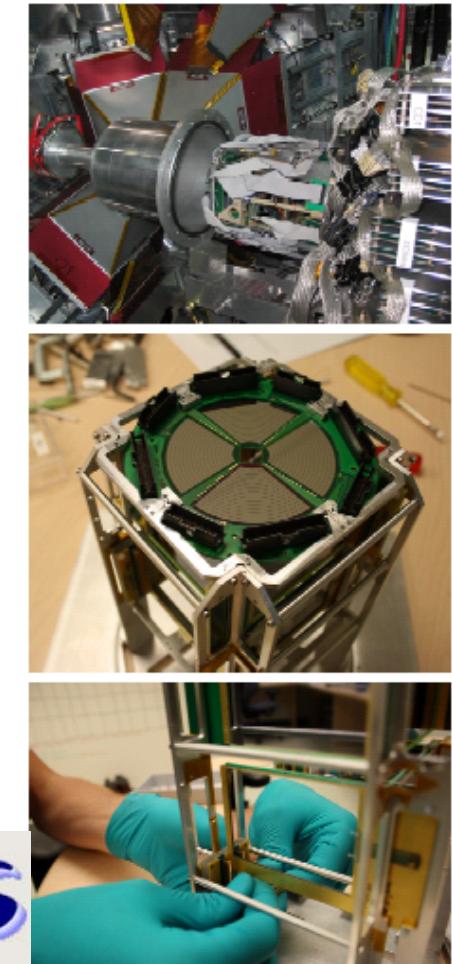
# Silicon Highly-segmented Array for Reactions and Coullex

Close to  $4\pi$  solid angle coverage of silicon

Excellent energy (25keV) and  
angular ( $0.9$ - $1.5^\circ$ ) resolution



## SHARC



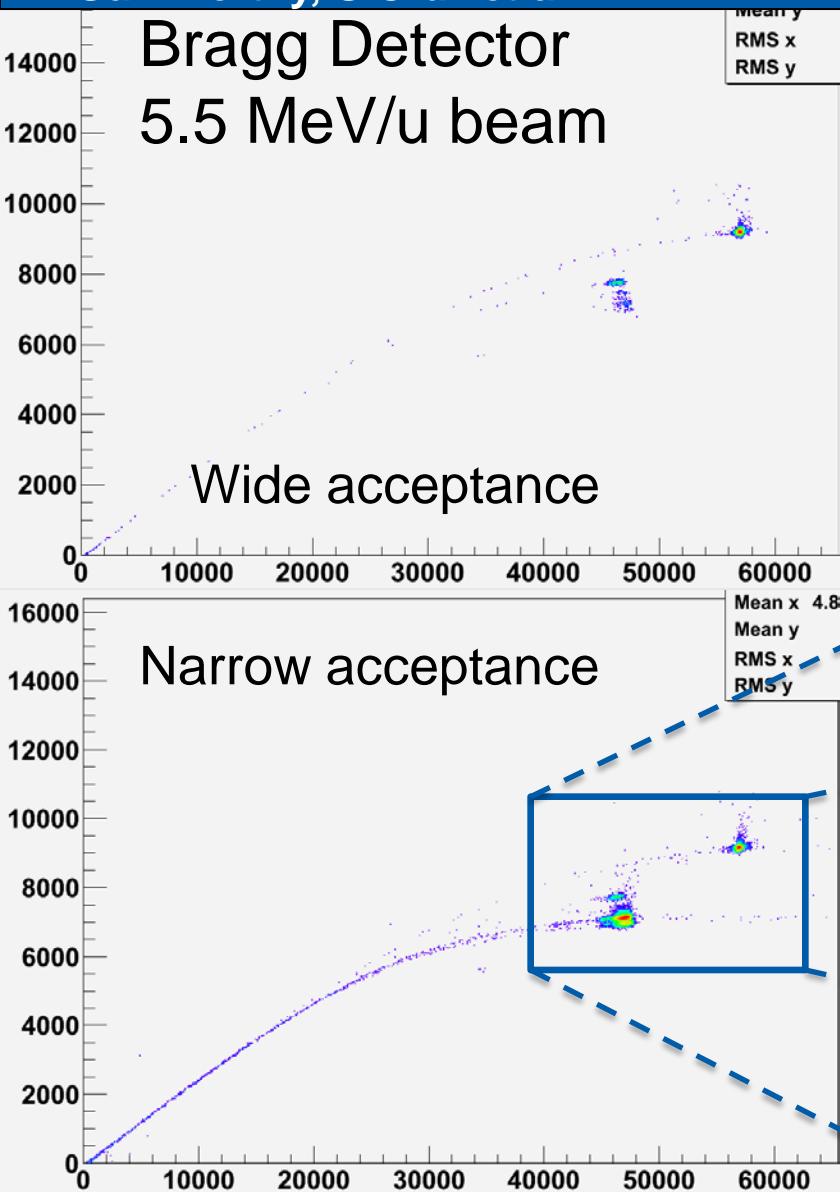
## TIGRESS

Optimized for transfer and coulomb excitation studies  
for Nuclear Structure and Nuclear Astrophysics

# High-mass delivery for d(94Sr,95Sr)p beam at 5.5 AMeV

SHARC: TRIUMF, SFU, Louisiana, York, Colorado School of Mines

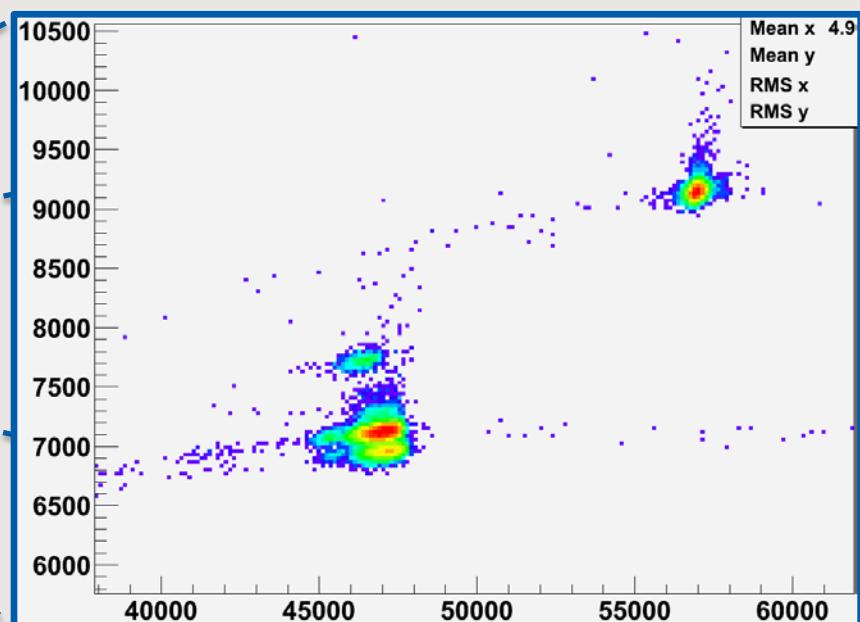
A. Garnworthy, S Cruz et al.



$^{94}\text{Sr}^{15+}$  from CSB breeder  
Stripped to 22+ at 1.5 AMeV

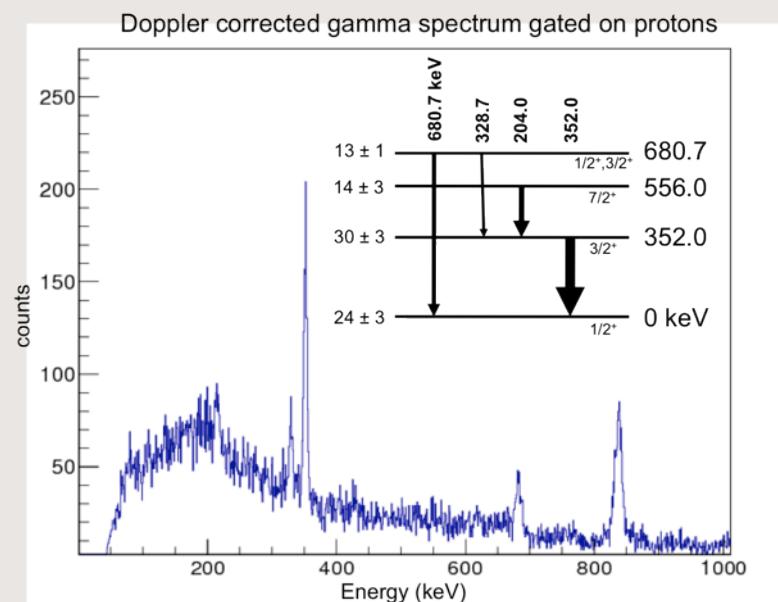
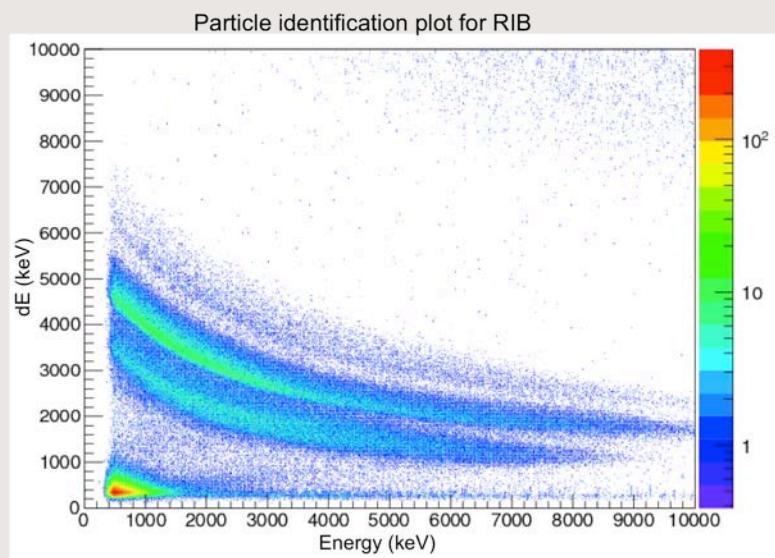
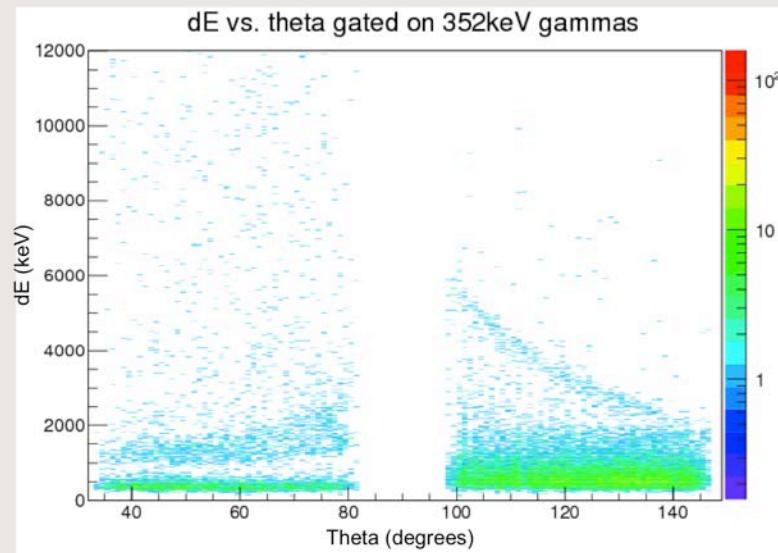
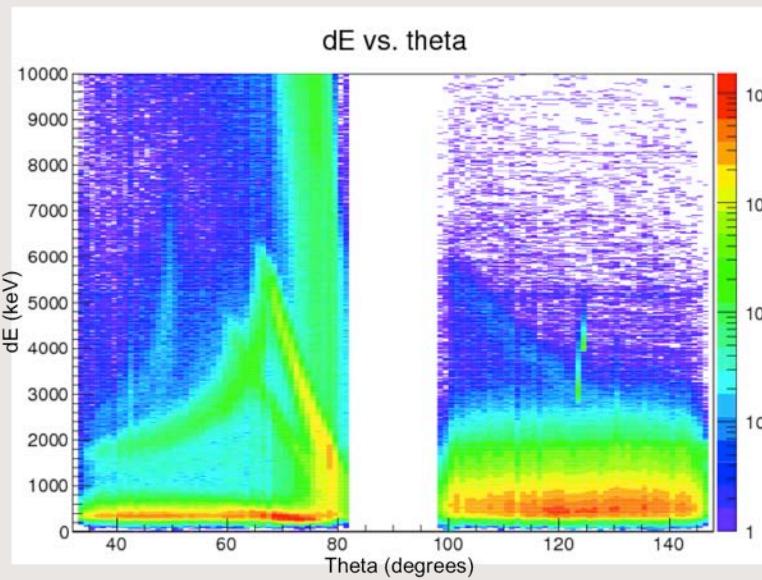
Stable beam contaminants  
dramatically reduced through two-  
stage time-of-flight separation

$^{119}\text{Sn}^{19/28+}$  and A=94 isobars

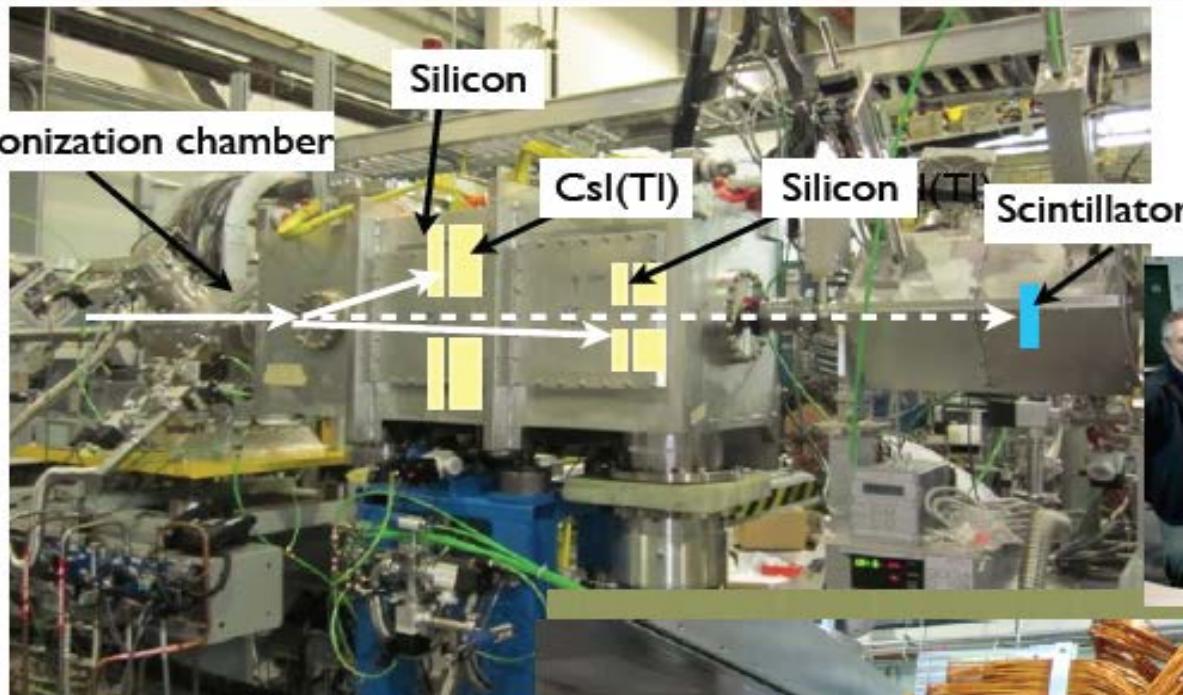


# d(94Sr,95Sr)p

## shape coexistence and transition at N=60



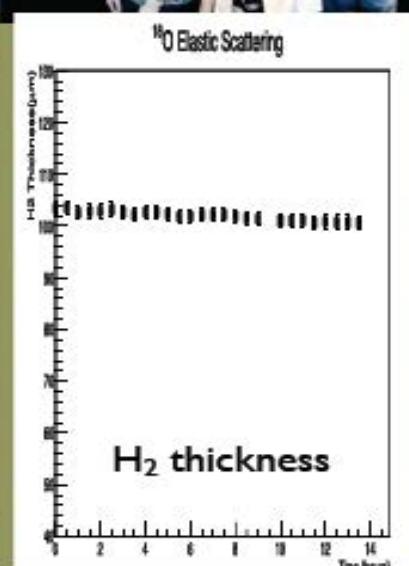
IRIS: TRIUMF, St Mary's, SFU, Manitoba, RCNP Osaka, GANIL, Edinburgh  
Ritu Kanungo et al.,



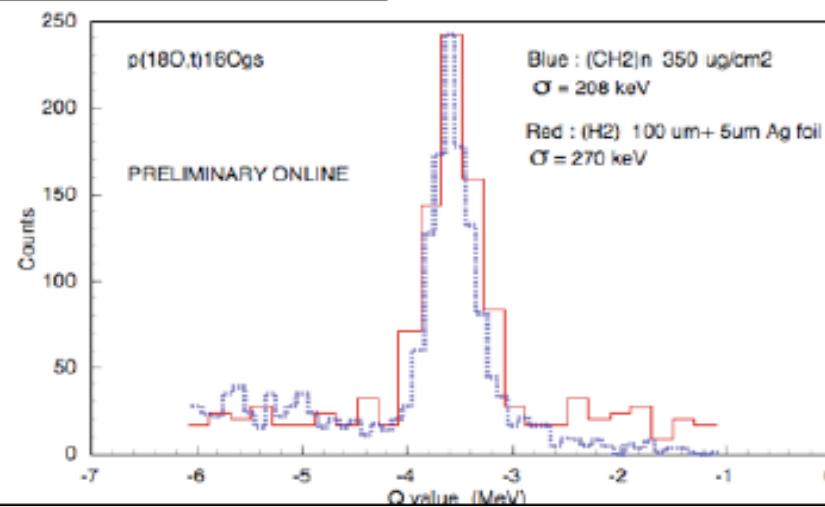
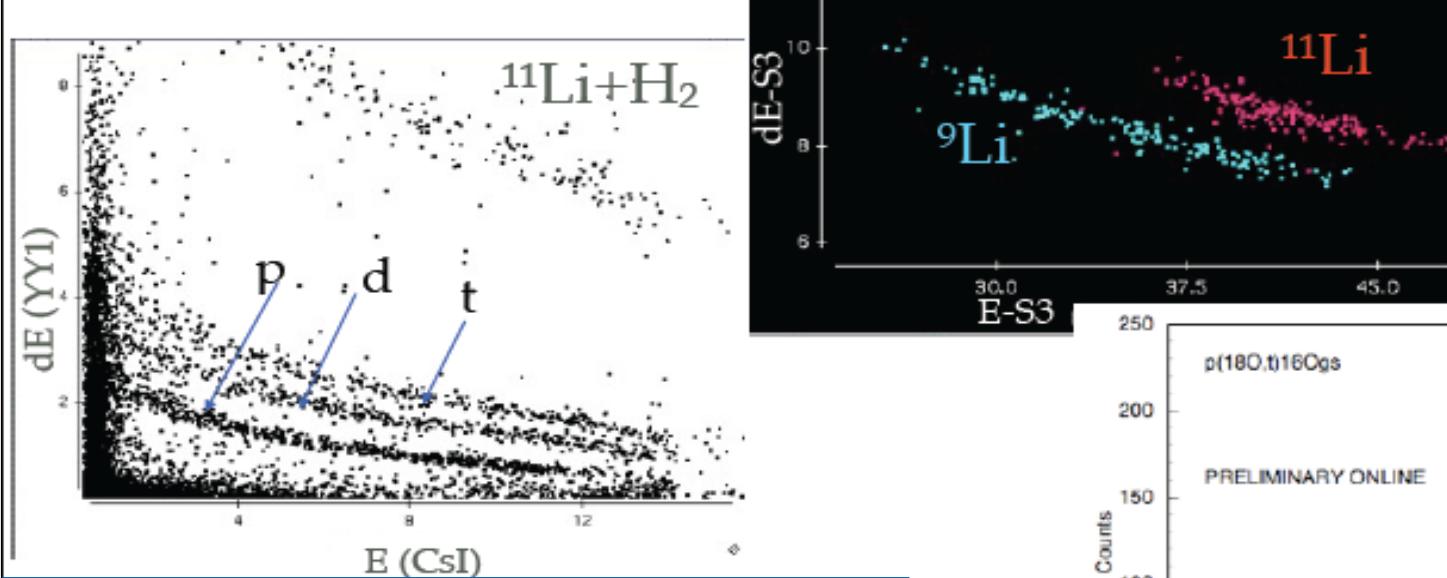
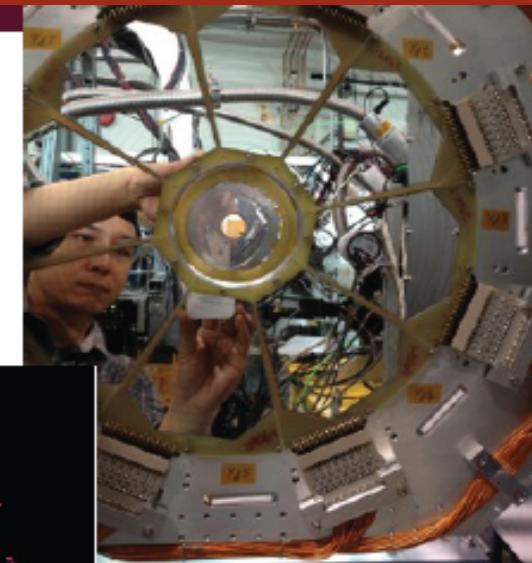
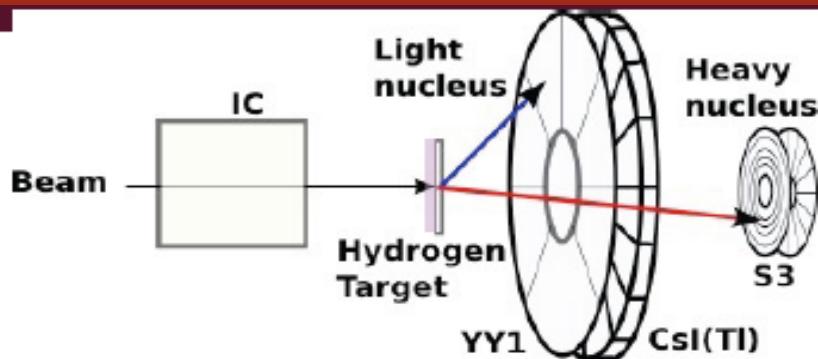
Overview of IRIS beamline

Solid H<sub>2</sub>

- Higher reaction yield
- Low background

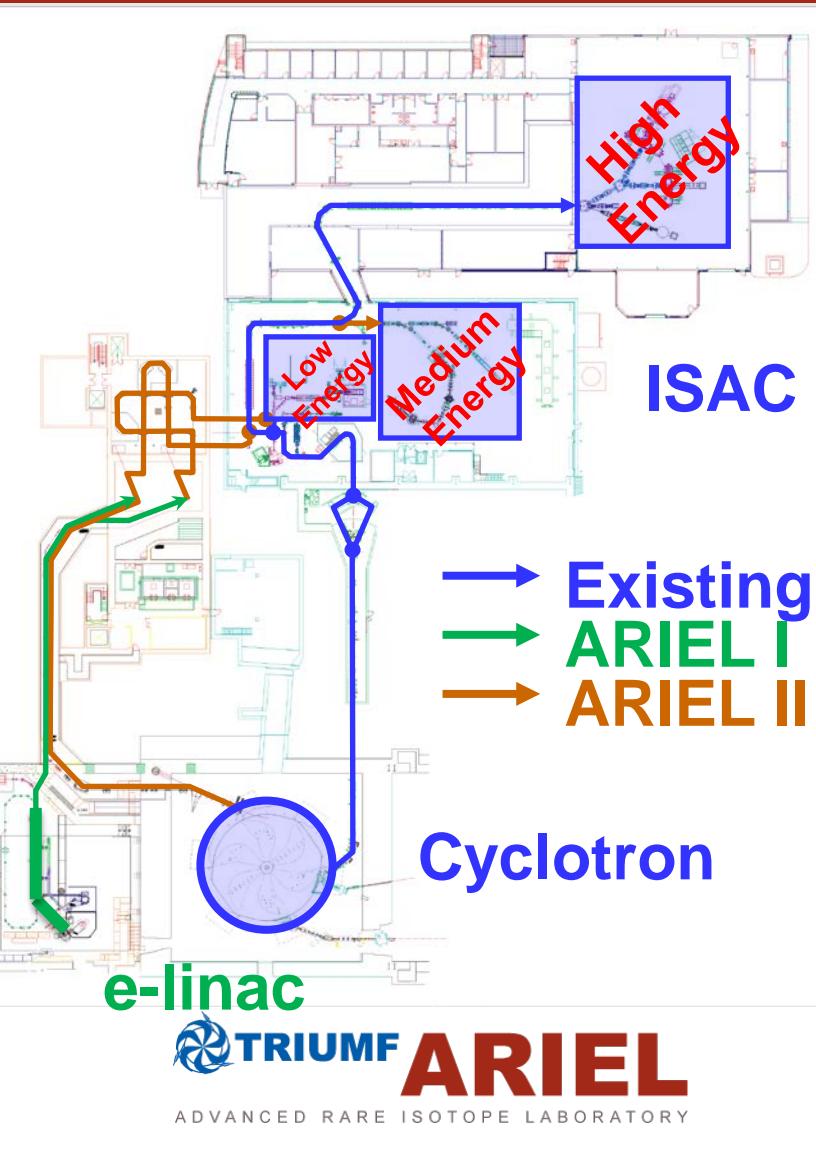


# First on-line experiments: ${}^{9,11}\text{Li}$ @ 5 AMeV



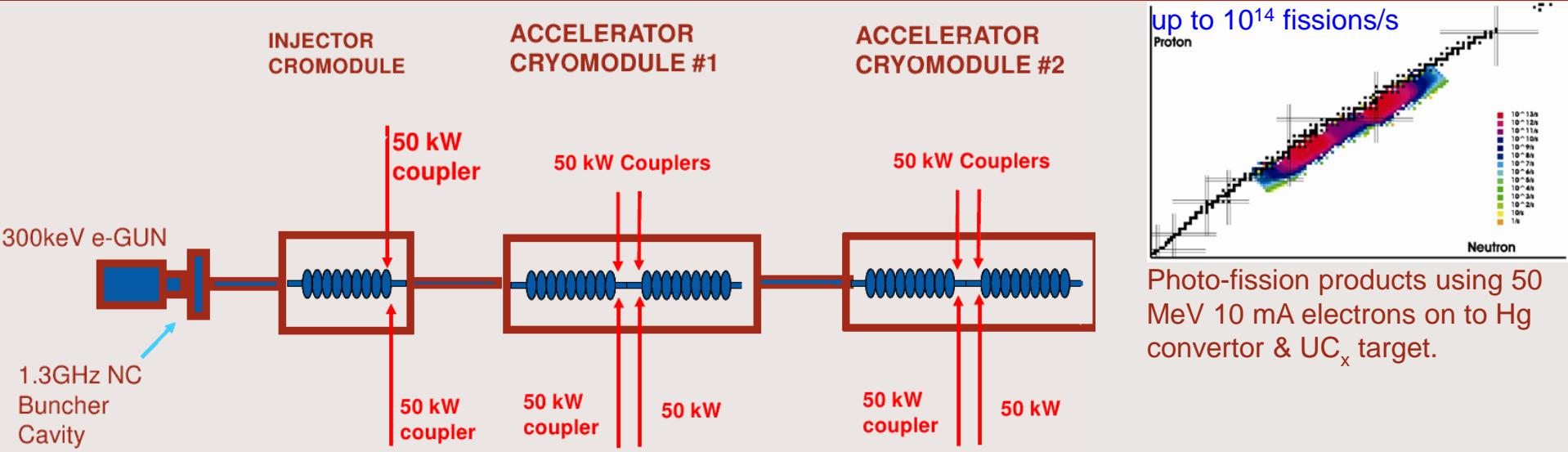
Solid hydrogen target scattering facility for  
 $(p,d)$ ,  $(p,t)$ ,  $(d,p)$ ,  $(d,n)$ , ...  
Commissioned 2013, now fully operational  
→ solid deuterium target and  ${}^{11}\text{Li}(d,p){}^{12}\text{Li}$

# The future at ISAC: ARIEL



- expand RIB program with:
  - three simultaneous beams
  - increased number of hours delivered per year
  - new beam species
  - enable long beam times (nucl. astro, fund. symm.)
  - increased beam development capabilities
- New electron linac driver for photo-fission
- New proton beamline
- New target stations and front end

# ARIEL: MW-class e-linac: ready to go



## TIMELINE:

- 2014 first beam, target R&D
- 2017 new front end
- 2017 physics production  $^8\text{Li}$
- 2018 photo fission
- 2019 proton beam (3 beams)



# conclusions

ISAC is operating on high level with extensive programs in:

- Nuclear structure
- Nuclear astrophysics
- Test of fundamental symmetries

We have three experimental areas, all three are fully operational:

- First experiments with heavy ( $A > 30$ ) mass post accelerated
- More separation and breeding capabilities with the new front end for ARIEL (funded) which will couple to ISAC

- Exciting times for nuclear physics
- ARIEL will bring new capabilities
- More opportunities for collaborations



# Thank you!

# Merci!

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 M. Tandecki, M. Pearson, A. Gallant, C. Ruiz, R. Kanungo, L. Mermanga,**

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