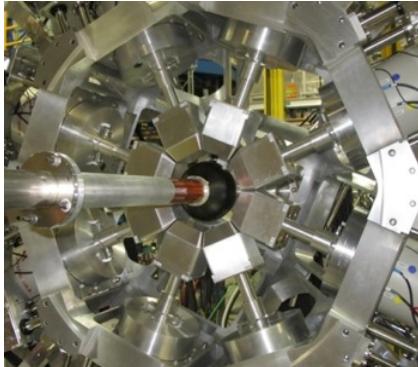
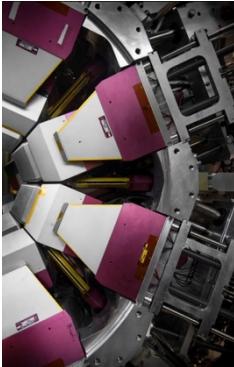


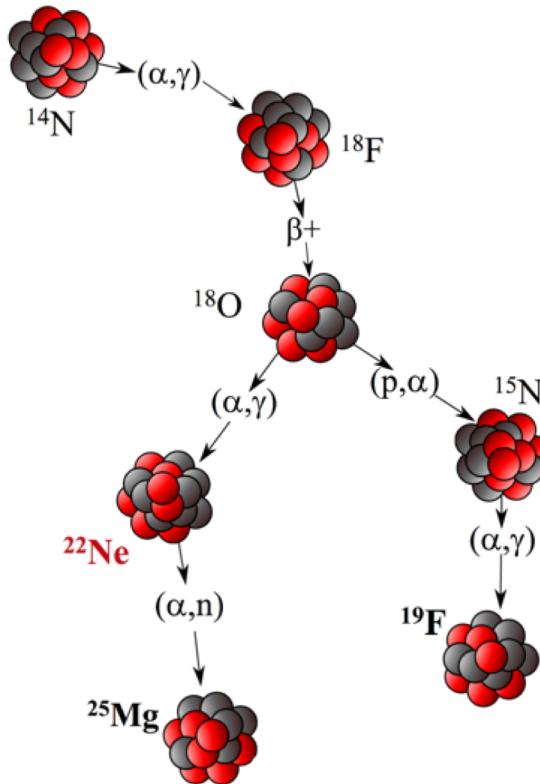
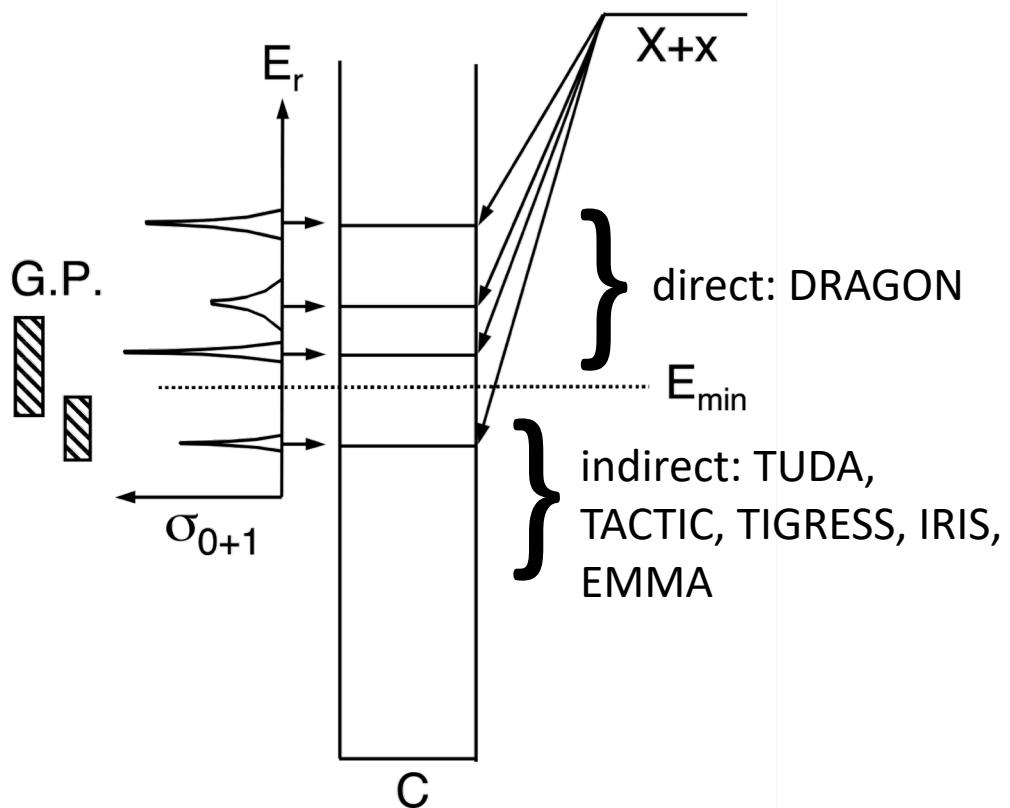
Opportunities for Nucleosynthesis Studies with TI-STAR and TIGRESS at ARIEL

Dennis Mücher, Leyla Atar, Tomer Rockman

University of Guelph + TRIUMF for the TIGRESS and TI-STAR collaborations

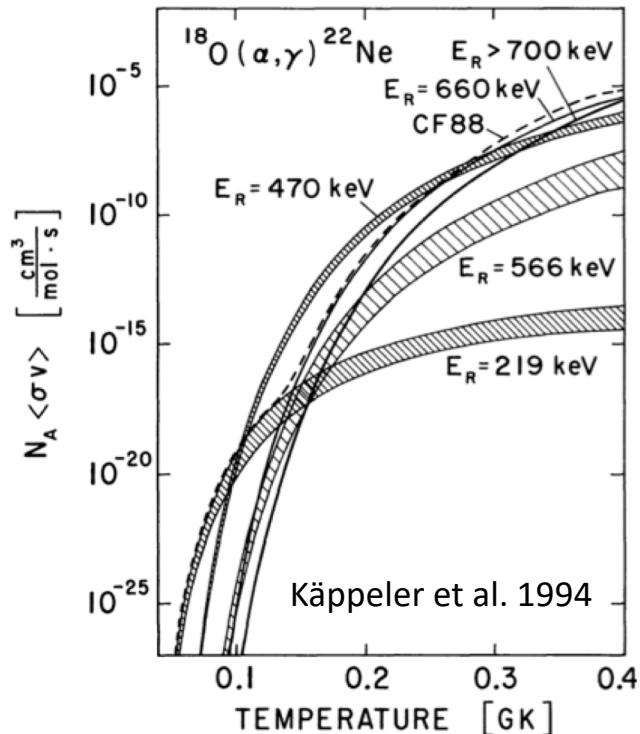
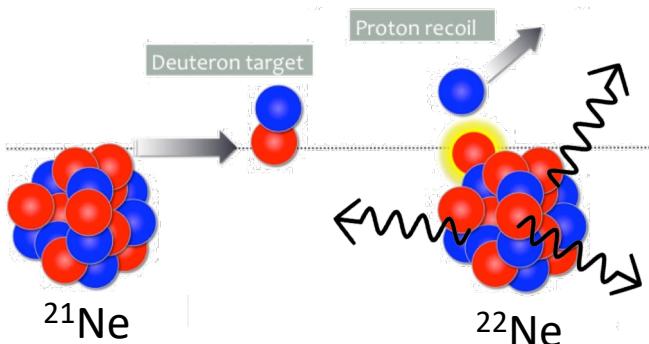


Intro: indirect approaches to nucleosynthesis studies

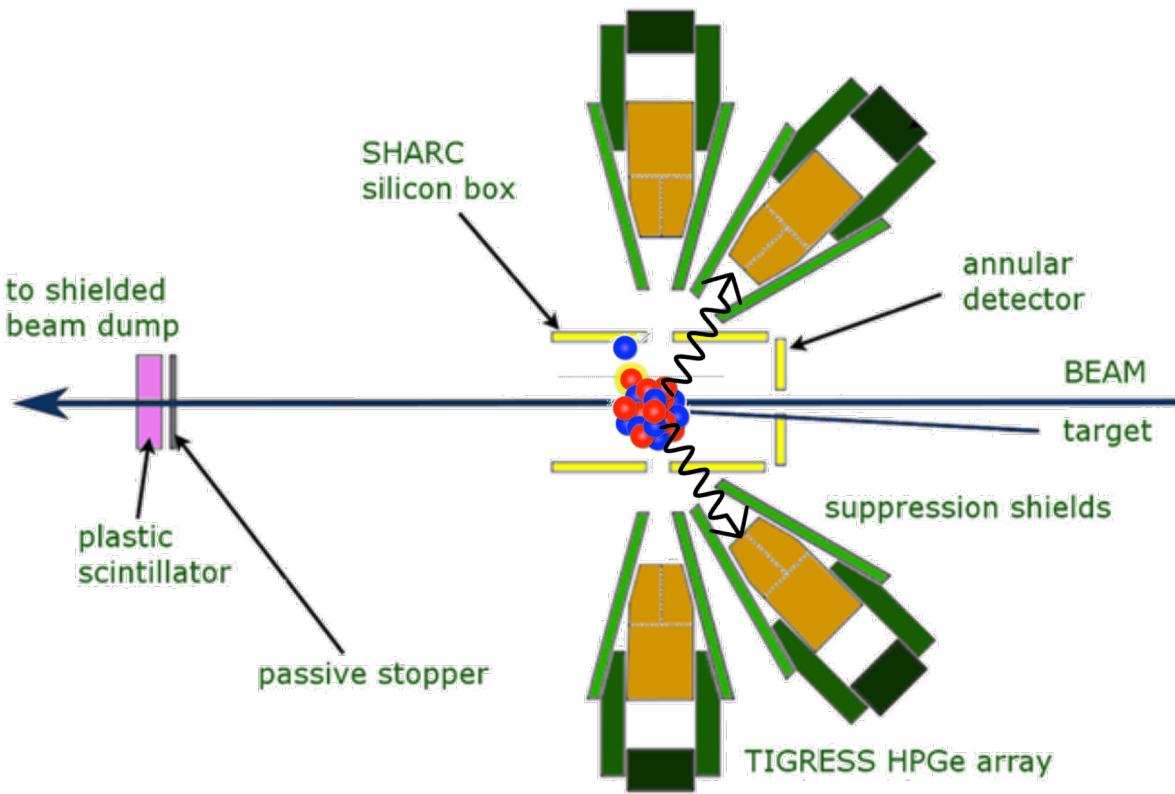


Example: spectroscopy of ^{22}Ne resonances at ISAC-II

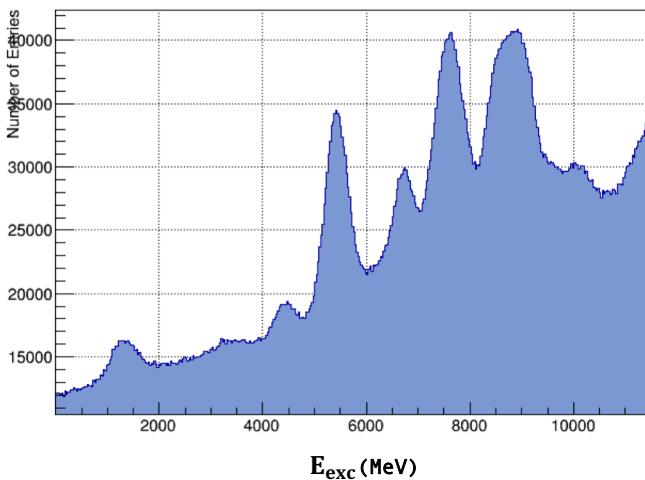
E_r (MeV)	E_x (MeV)	J^π ^a	$\omega_{\gamma(\alpha,\gamma)}$ (μeV) ^b	$\omega_{\gamma(\alpha,n)}$ (μeV) ^b
$^{18}\text{O} + \alpha$				
0.058.....	9.72	3^- (2^+)	4.1×10^{-40} 1.5×10^{-39}	
0.218.....	9.85	2^+ (1^-)	7.1×10^{-12} 5.8×10^{-11}	
0.470.....	10.05	0^+ (1^-)	0.55 0.23	
0.566.....	10.13	4^+ (2^+) (3^-)	7.9×10^{-3} 1.95 0.15	
0.662.....	10.21	1^-	230 ± 25^c	



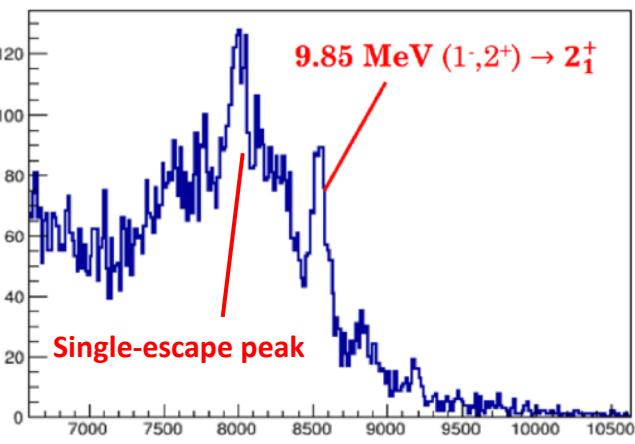
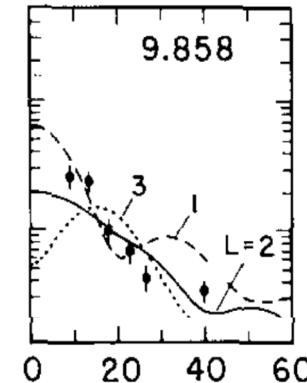
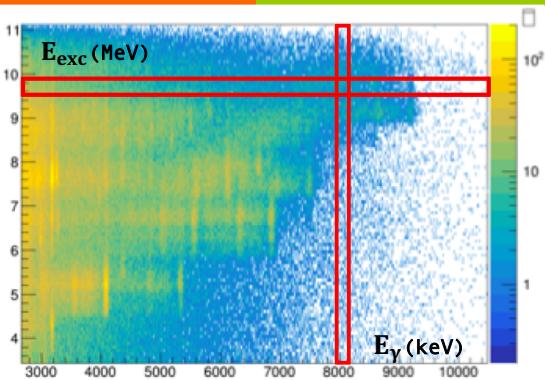
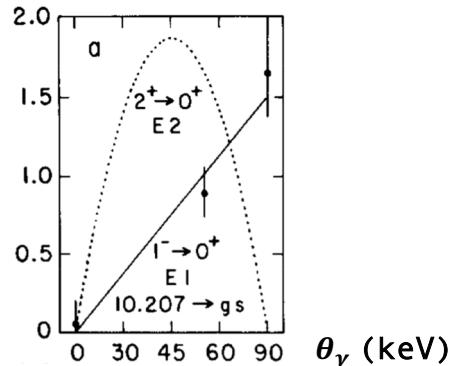
Particle-gamma spectroscopy with TIGRESS



$^{21}\text{Ne}(\text{d},\text{p})$, 7.9 MeV/u
August 2017



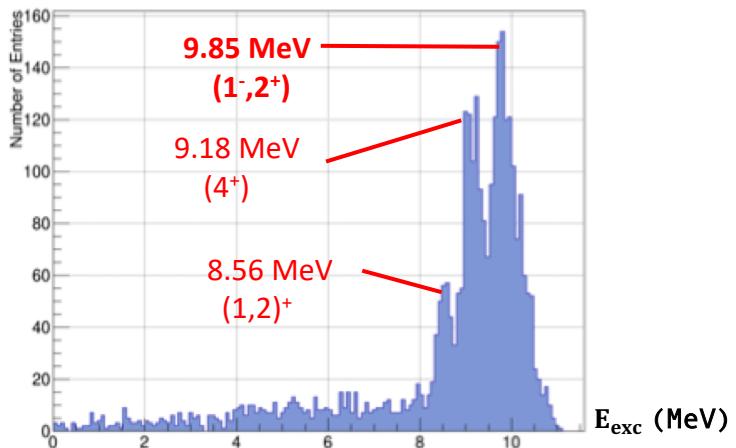
Example: spectroscopy of ^{22}Ne resonances at ISAC-II



Analysis:

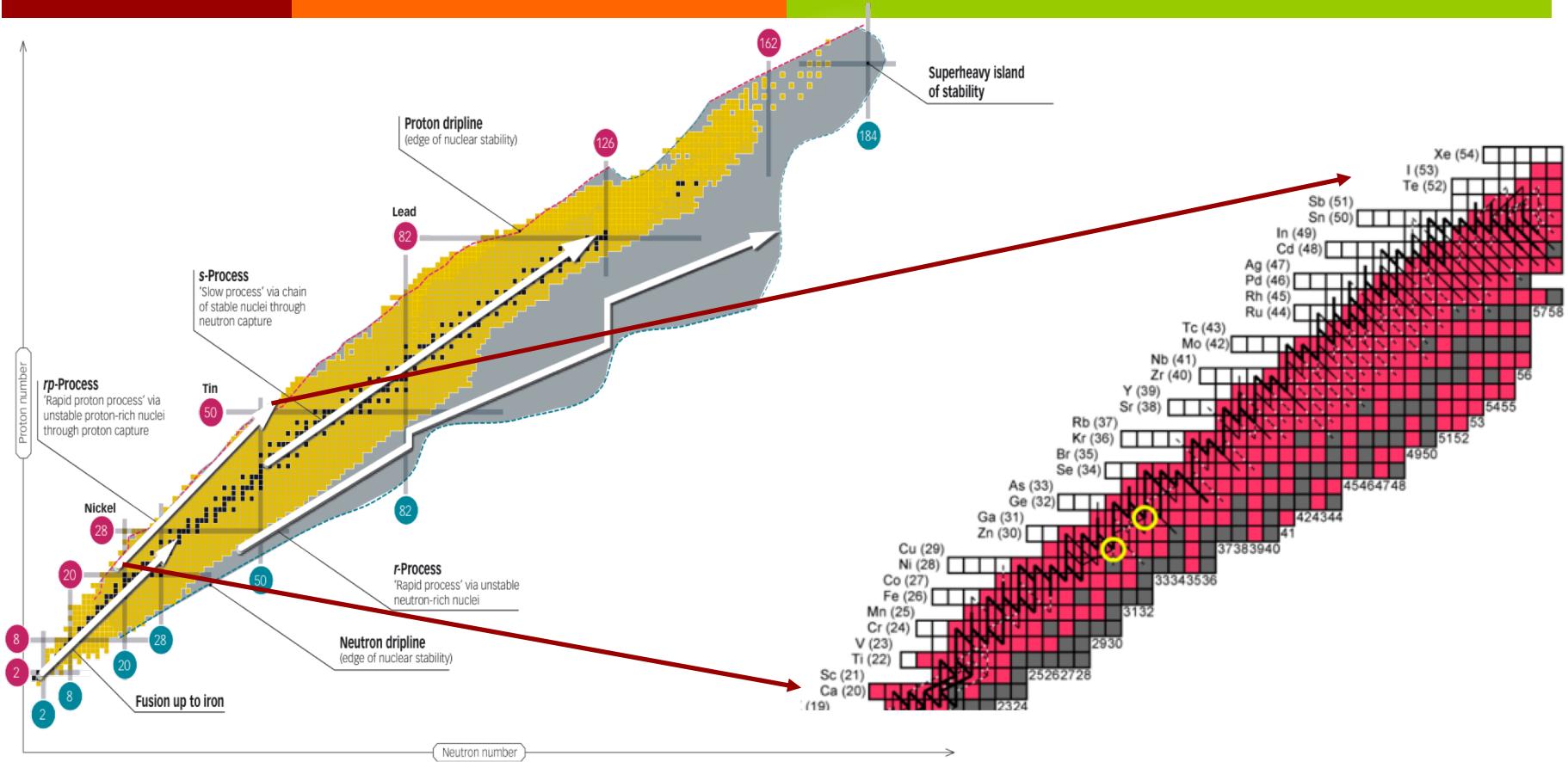
- B. Greaves (UofG)
- S. Gillespie (TRIUMF)

E_γ (keV)



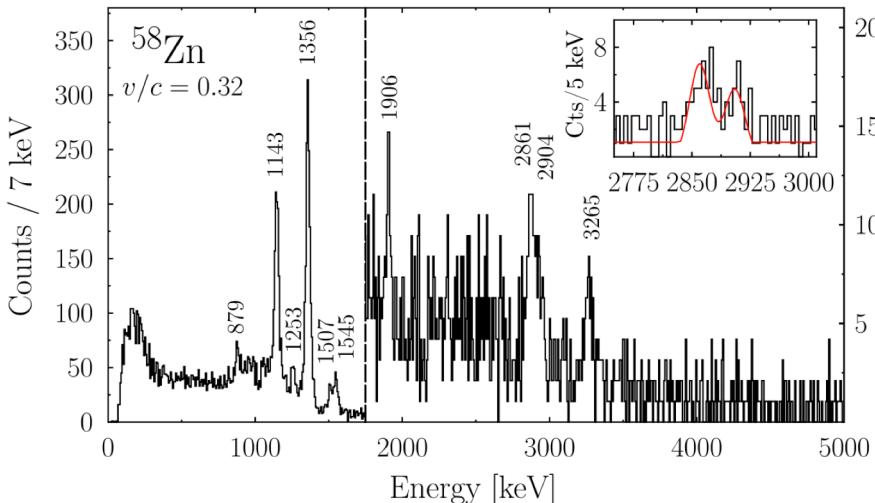
E_{exc} (MeV)

rp-process



Indirect measurements for the rp-process

- $^{57}\text{Cu}(\text{d},\text{n})^{58}\text{Zn}$
- using GRETINA @ NSCL
- **resolution** and **statistics** at the limit



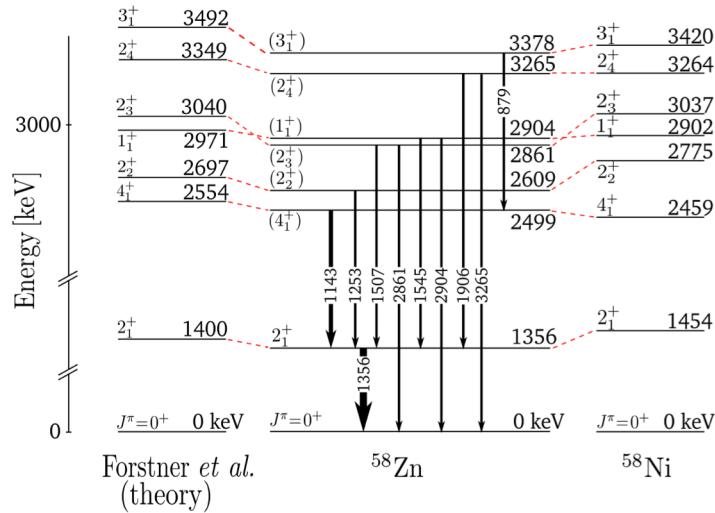
PRL 113, 032502 (2014)

PHYSICAL REVIEW LETTERS

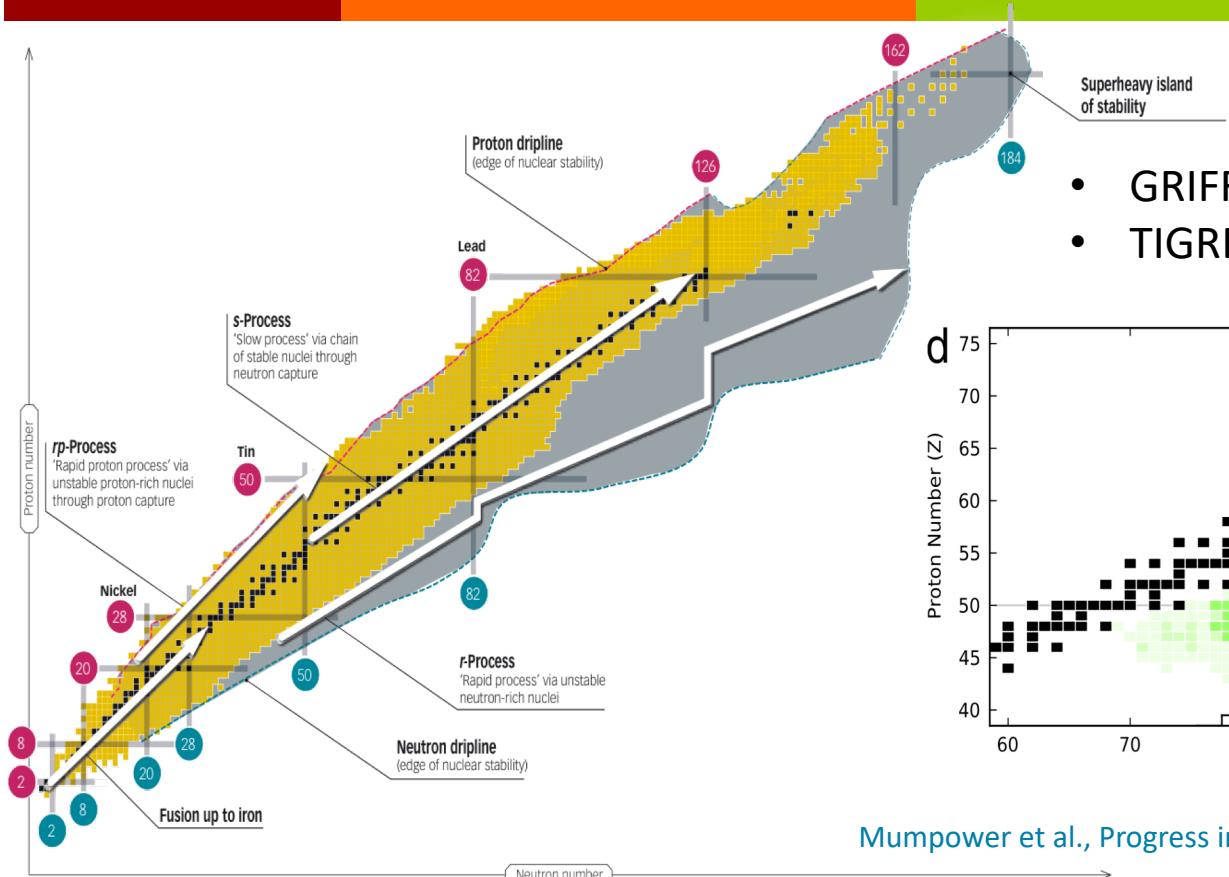
week ending
18 JULY 2014

Determining the *rp*-Process Flow through ^{56}Ni : Resonances in $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$ Identified with GRETINA

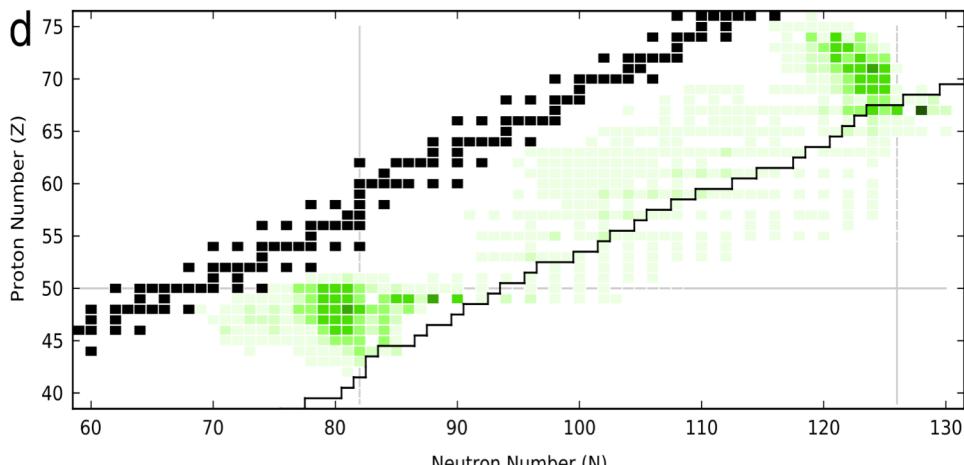
C. Langer,^{1,2,*} F. Montes,^{1,2} A. Aprahamian,³ D. W. Bardayan,^{4,†} D. Bazin,¹ B. A. Brown,^{1,5} J. Browne,^{1,2,5} H. Crawford,⁶



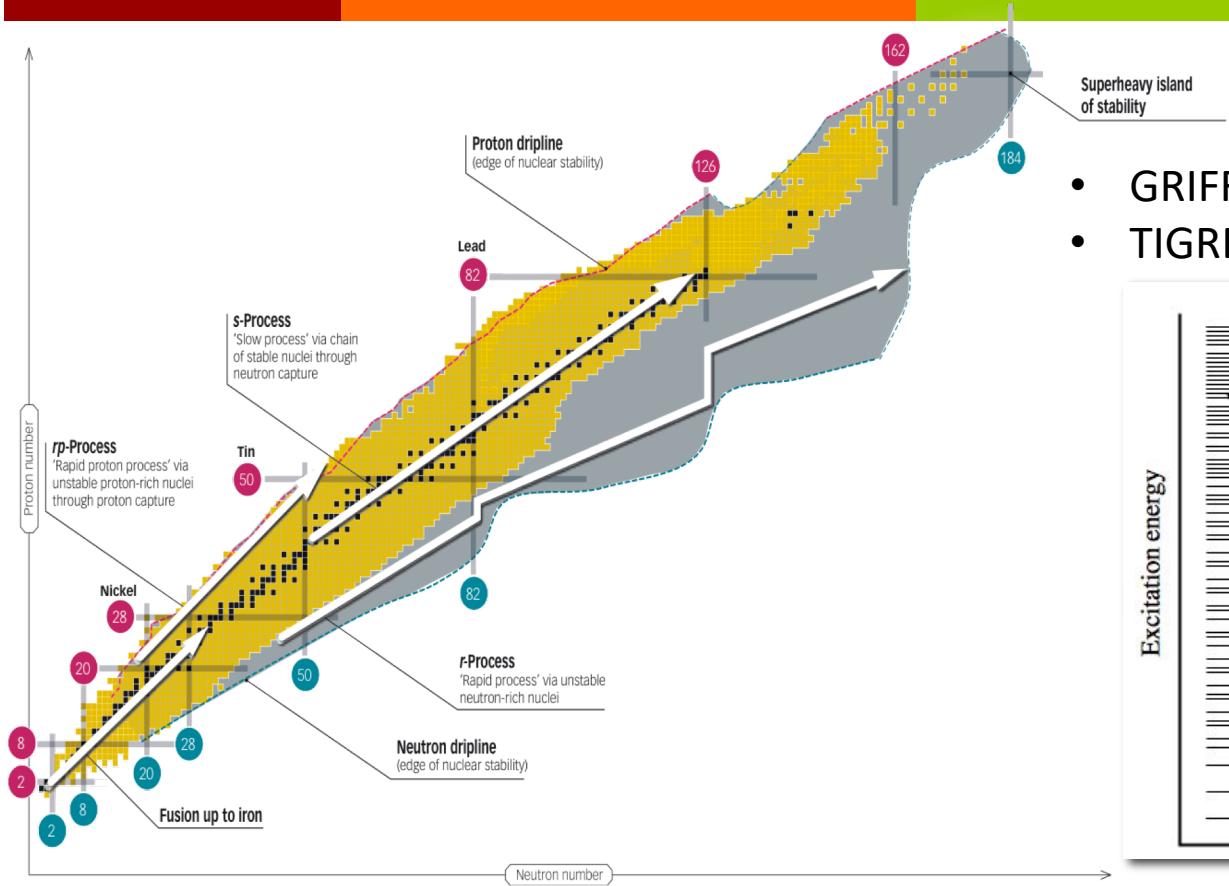
Constraining neutron capture rates



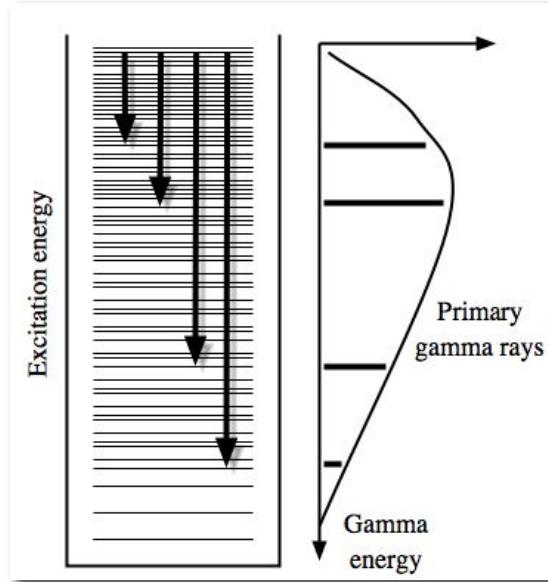
- GRIFFIN: $T_{1/2}$ and β -delayed neutrons
- TIGRESS: neutron capture rates



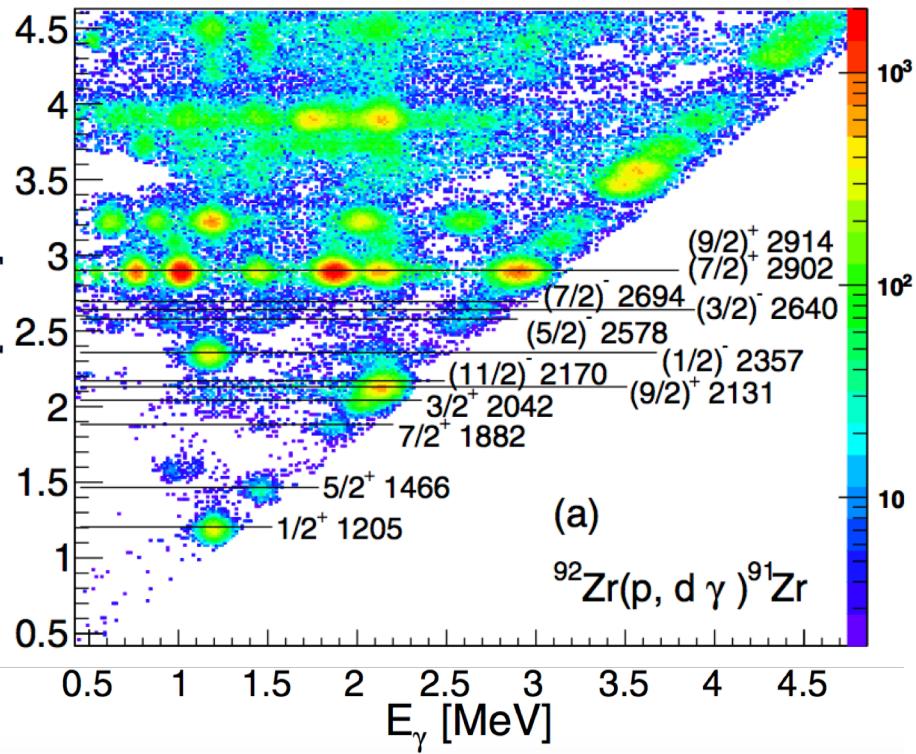
Constraining neutron capture rates



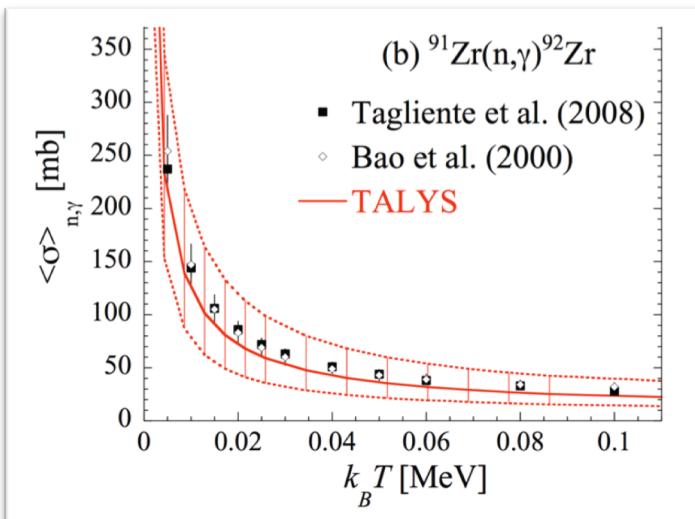
- GRIFFIN: $T_{1/2}$ and β -delayed neutrons
 - TIGRESS: neutron capture rates



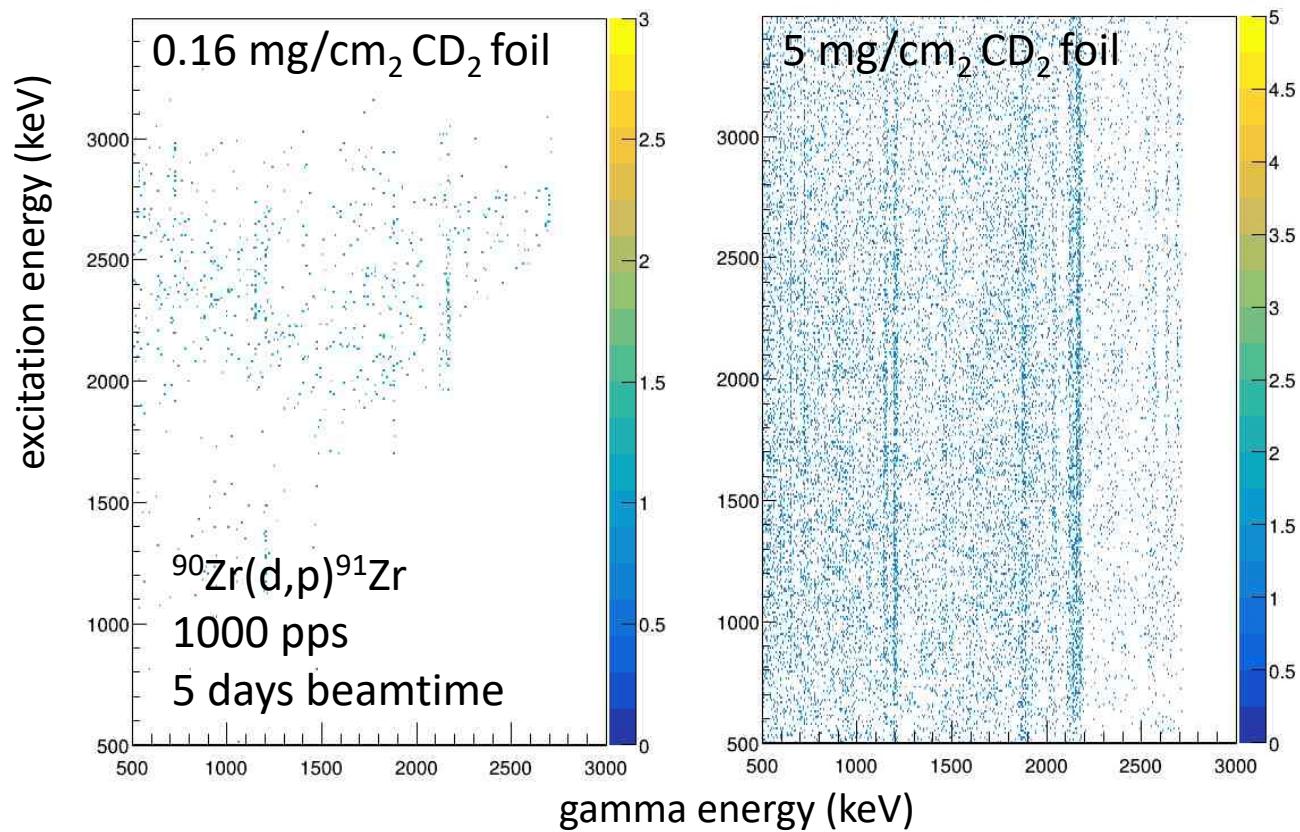
Validation of the “Oslo” method



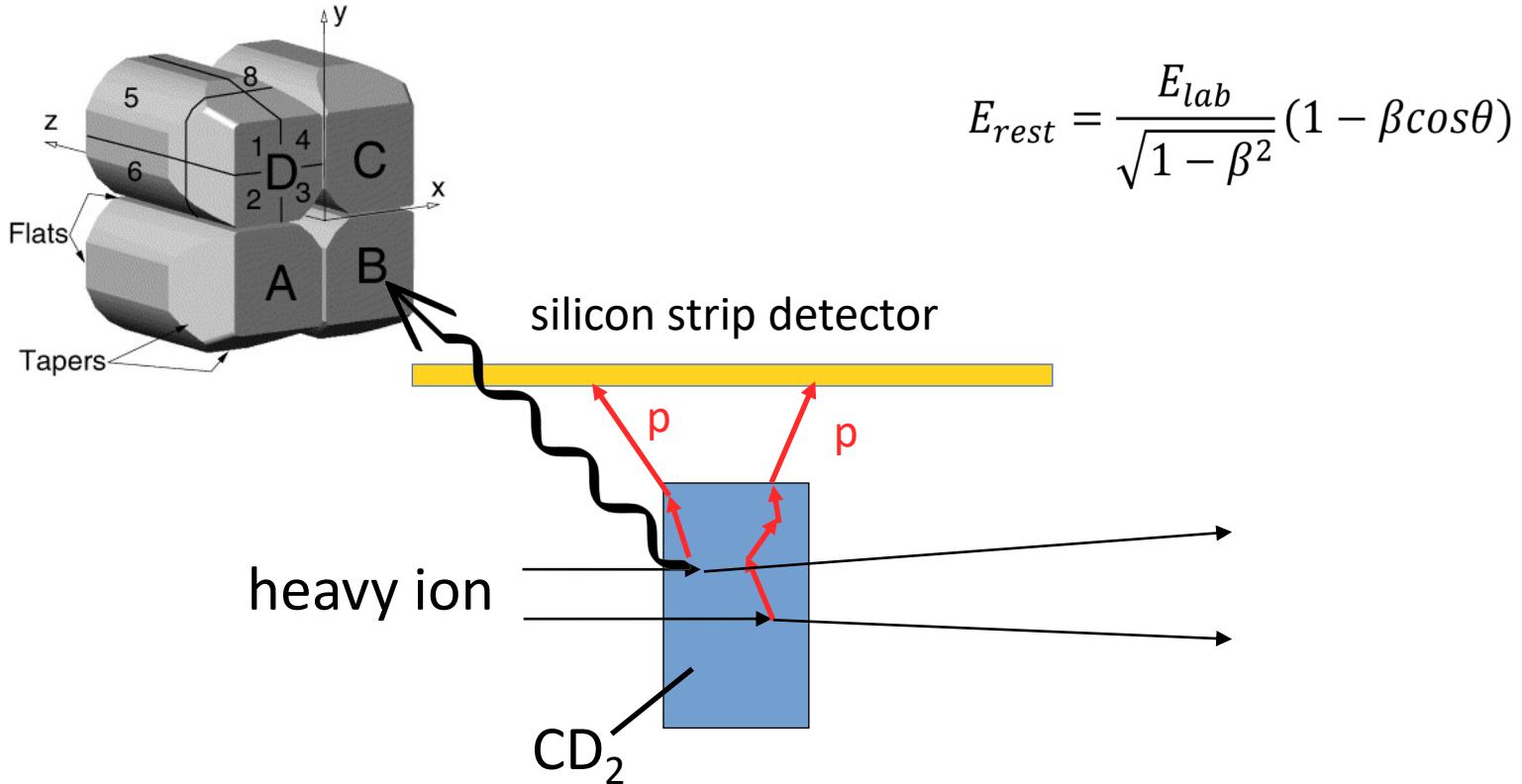
M. Guttormsen et al., PRC **96**, 024313 (2017)



Oslo-method: doable for exotic beams at ARIEL?

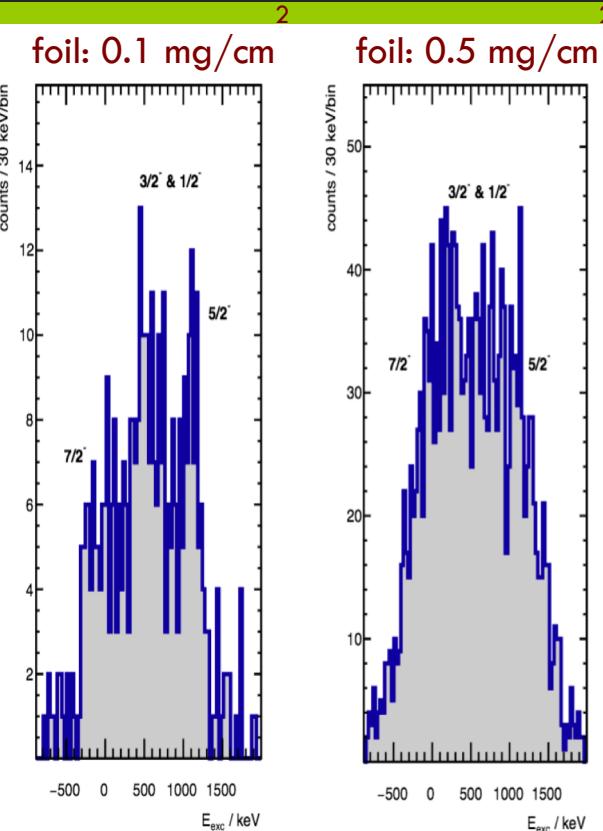
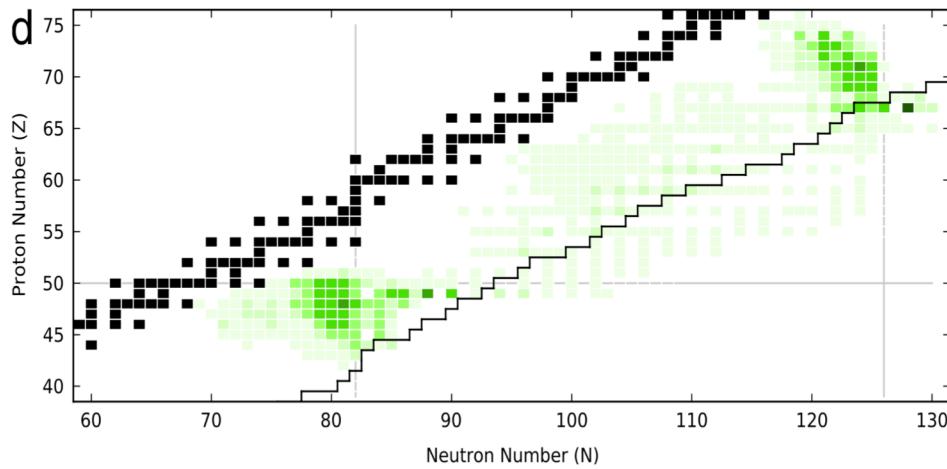


resolution vs. target thickness

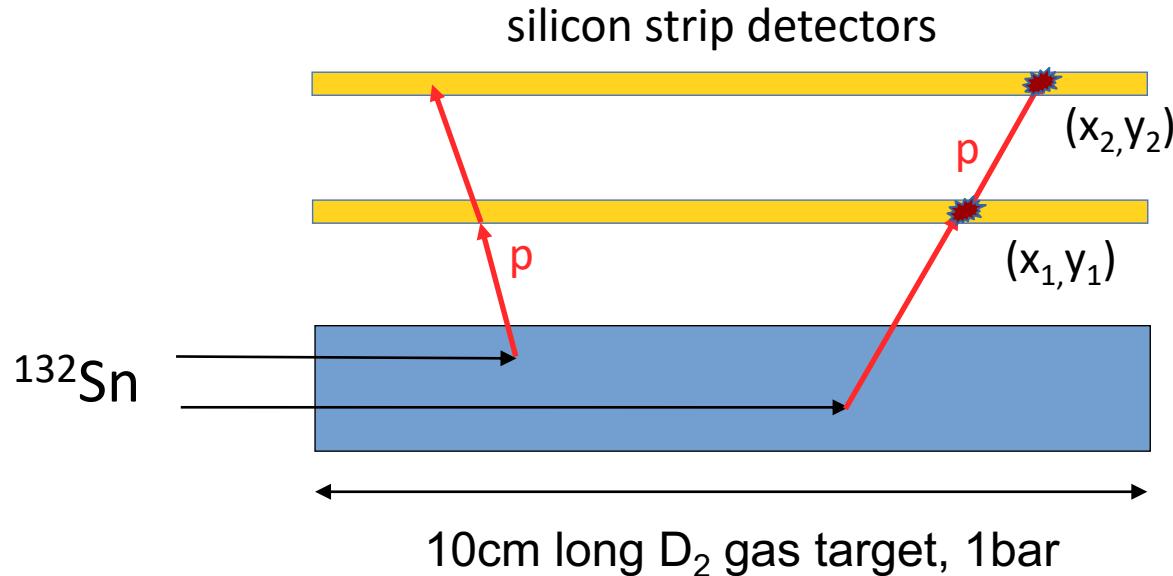


$^{136}\text{Sn}(\text{d},\text{p})$ at ARIEL and CD_2 targets

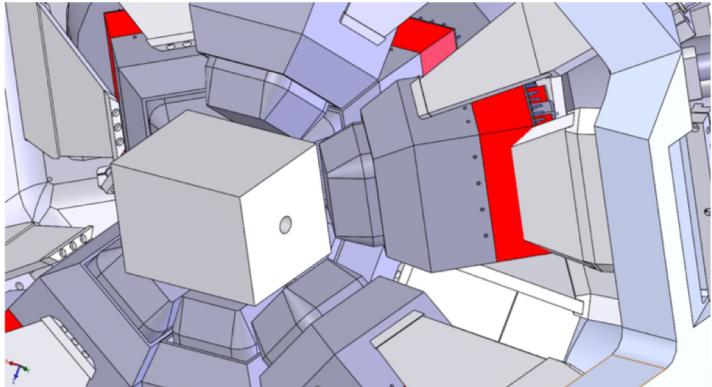
Target thickness becomes a critical issue
with increasing Z of the beam: $\Delta E \sim Z^2$



Idea: vertex tracking at ISOL energies using Si detectors



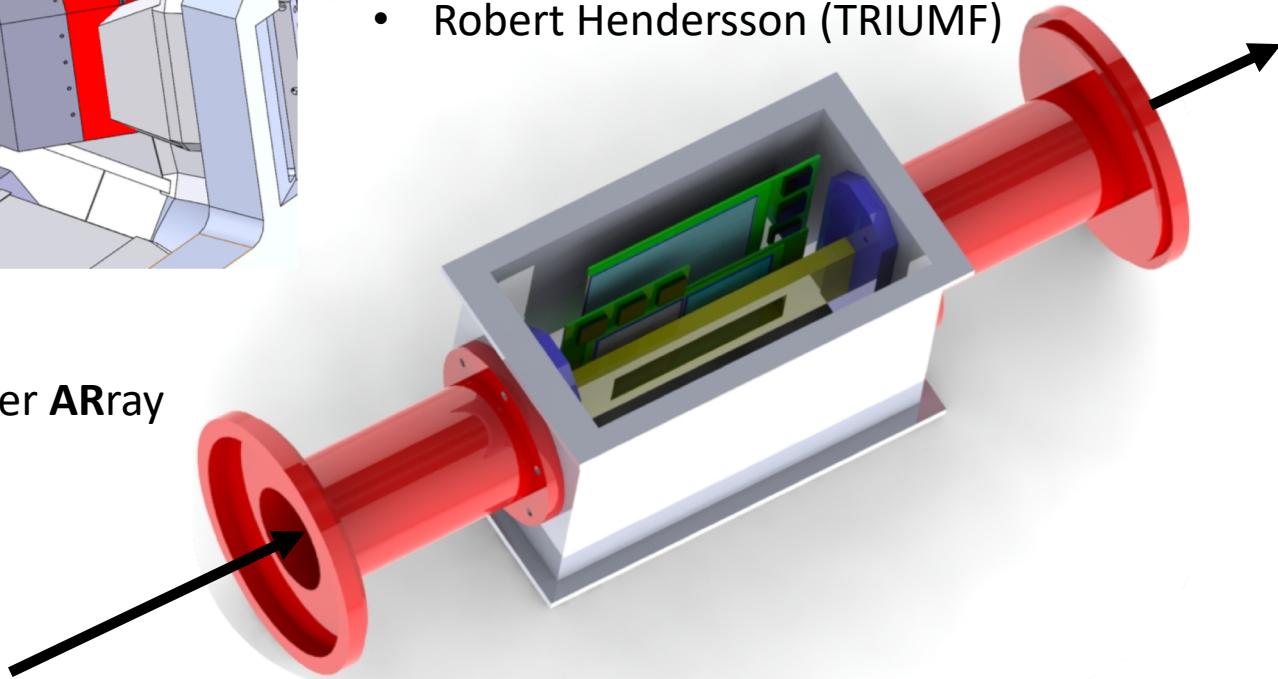
Layout of TI-STAR



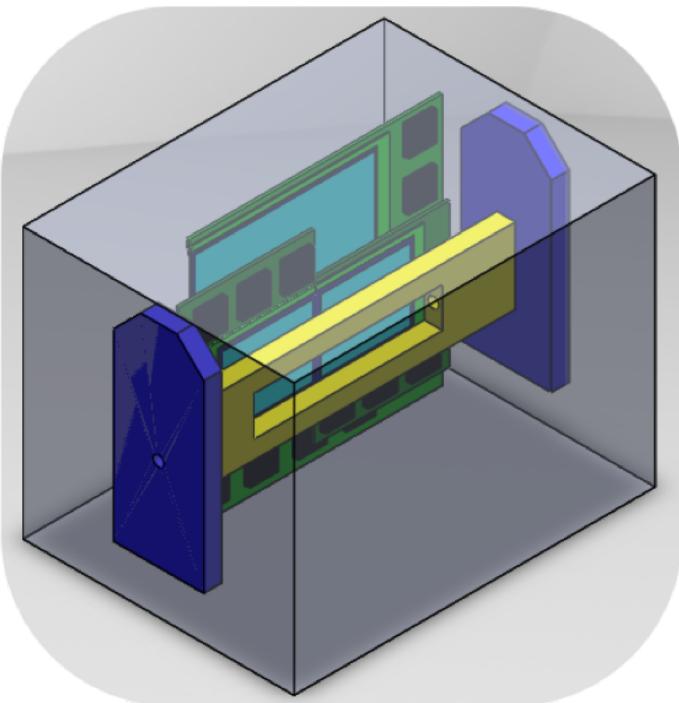
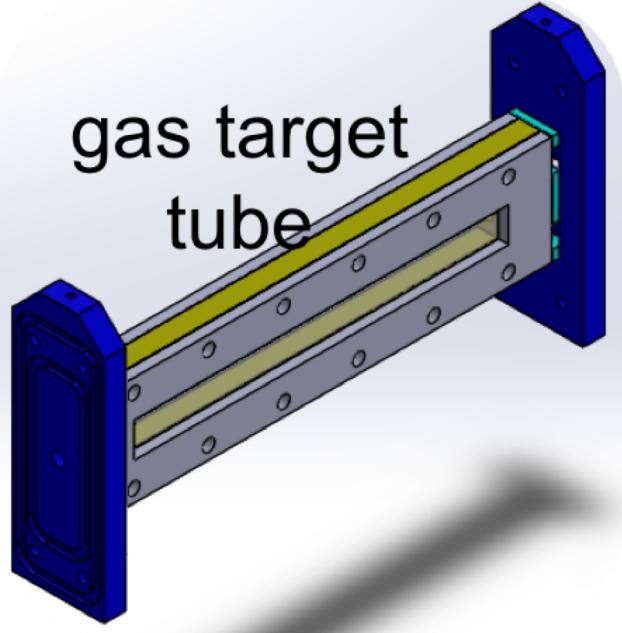
TI-STAR =
TIGRESS Silicon Tracker ARray

Mechanical Design:

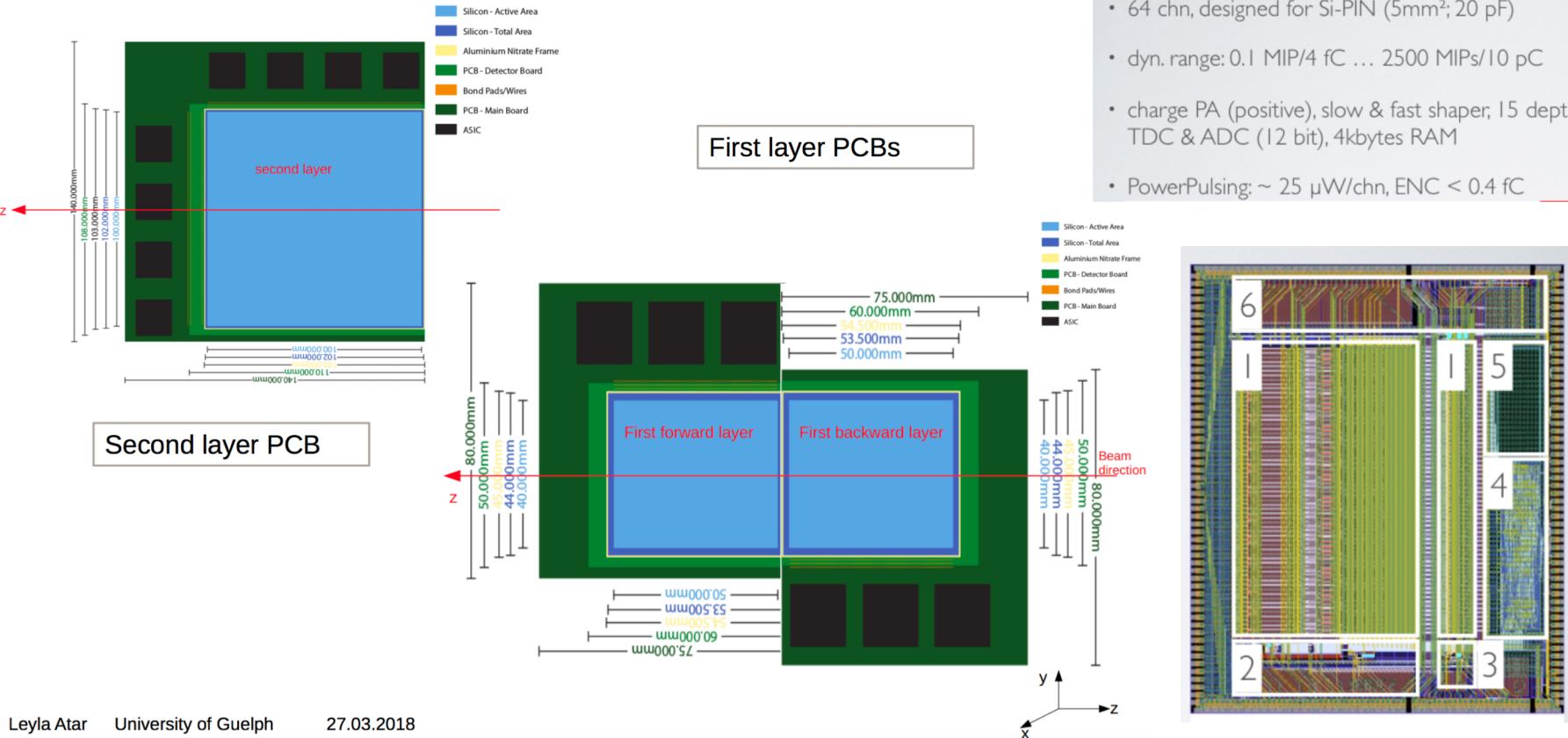
- Fred Sarazin (Colorado School of Mines)
- Robert Hendersson (TRIUMF)



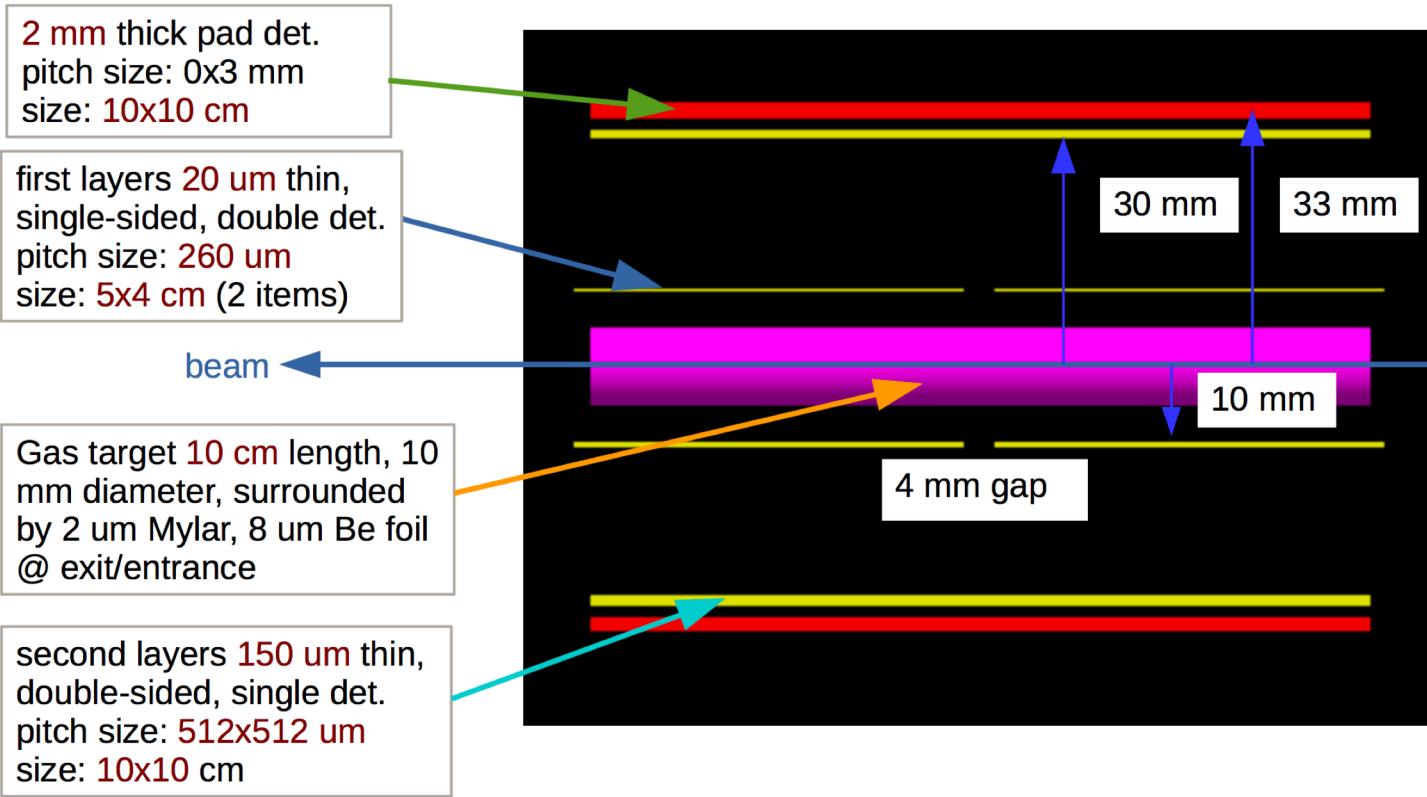
Layout of Ti-STAR



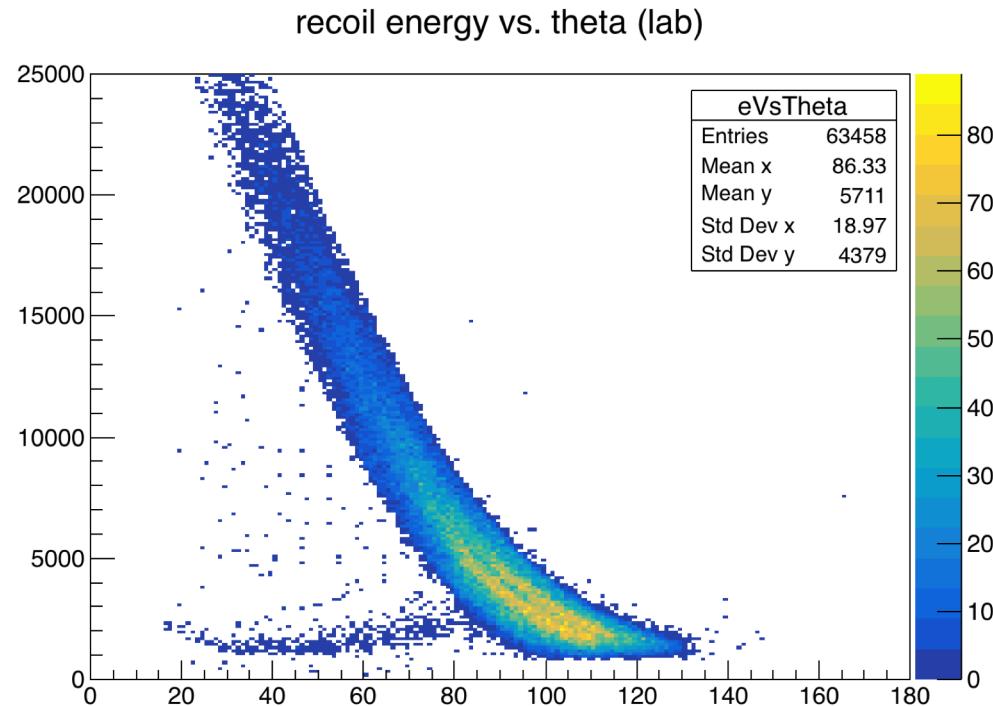
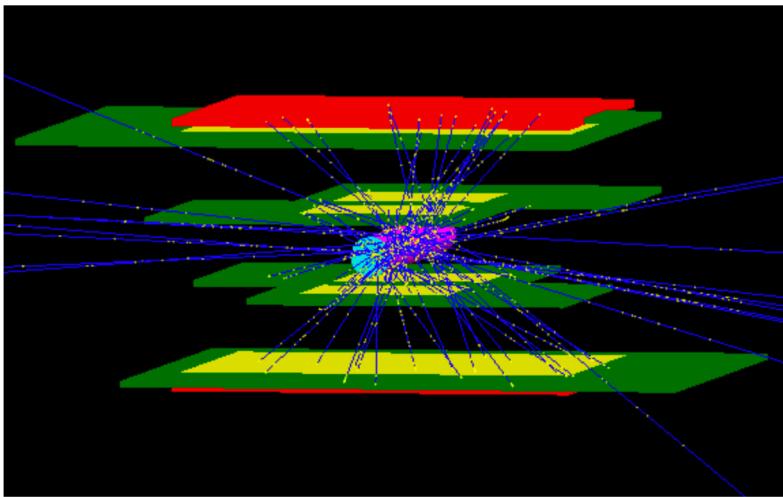
SKIROC-2 ASICs



TI-STAR simulation

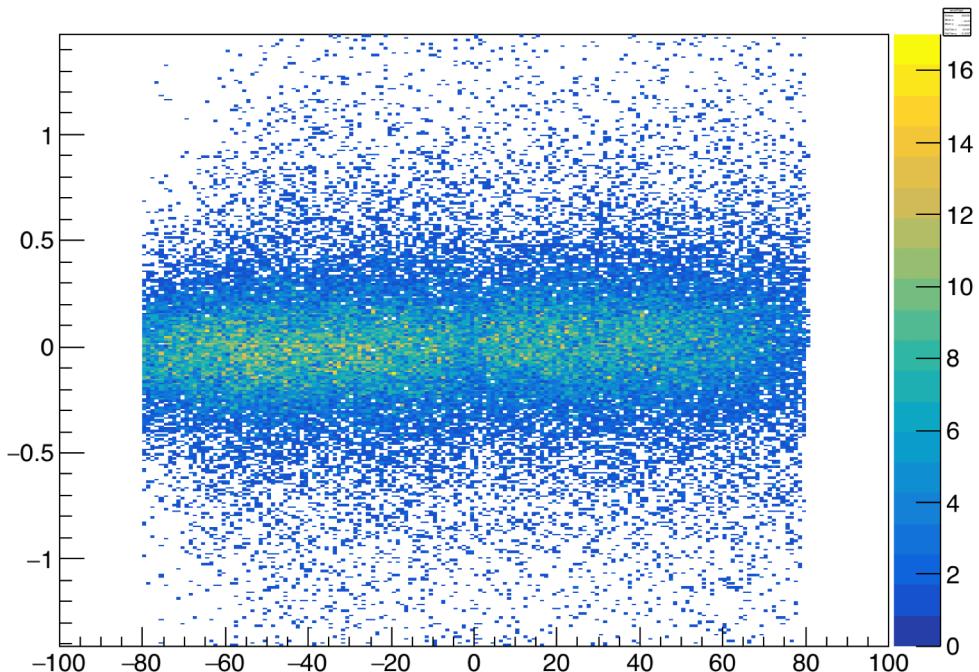


Silicon Tracker: Geant4 simulations

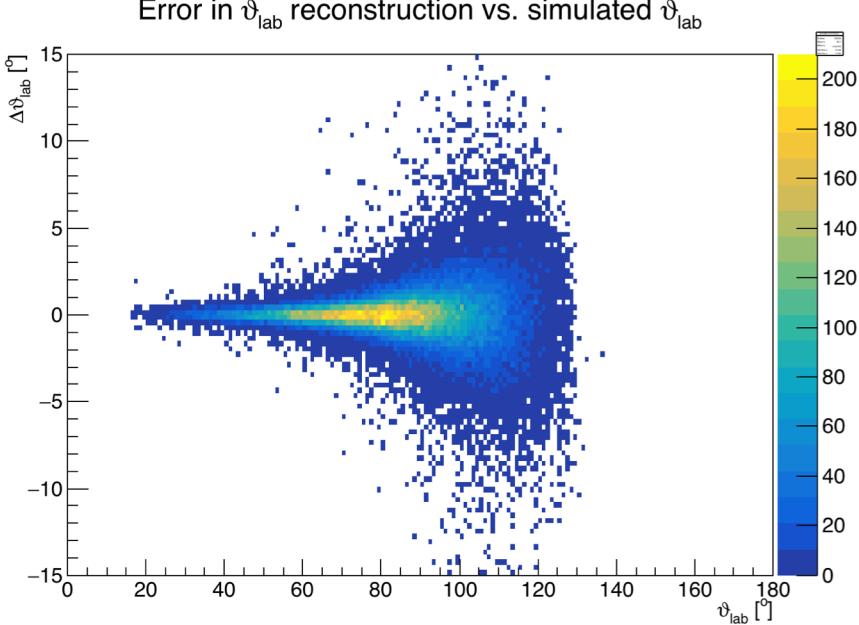


Silicon Tracker: Geant4 simulations

Error between reconstructed and true origin vs. true origin

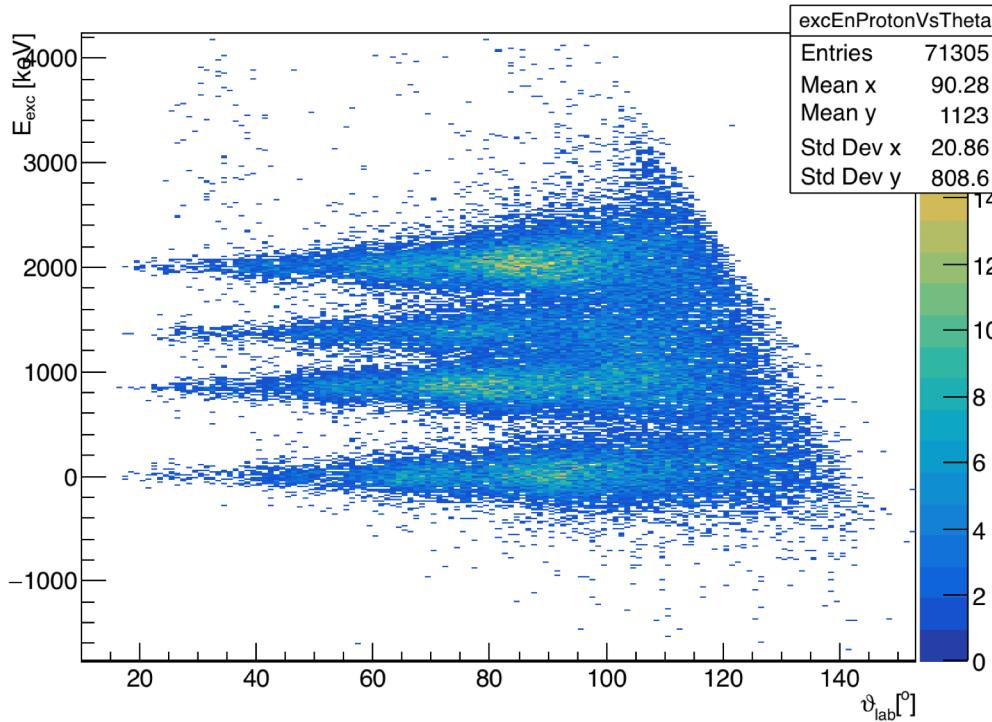


Error in ϑ_{lab} reconstruction vs. simulated ϑ_{lab}

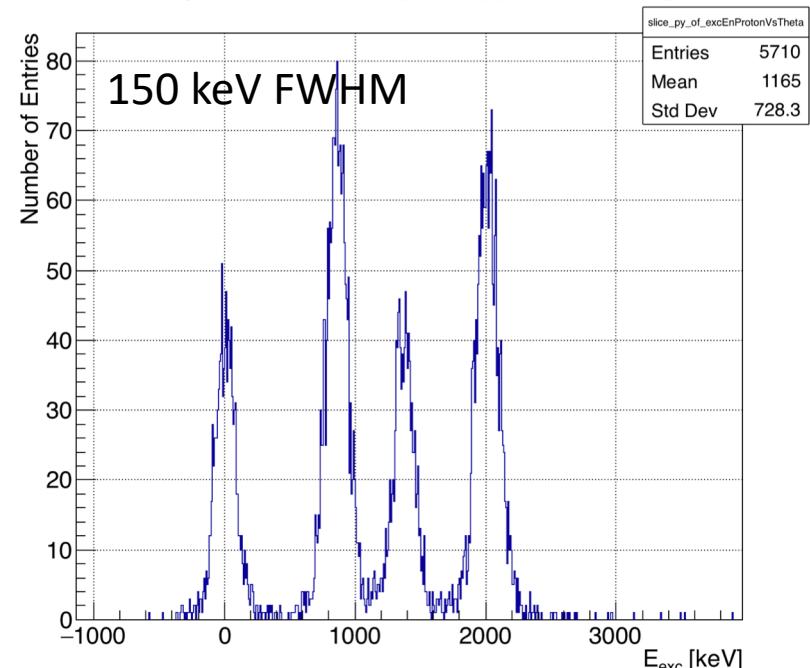


Silicon Tracker: Geant4 simulations

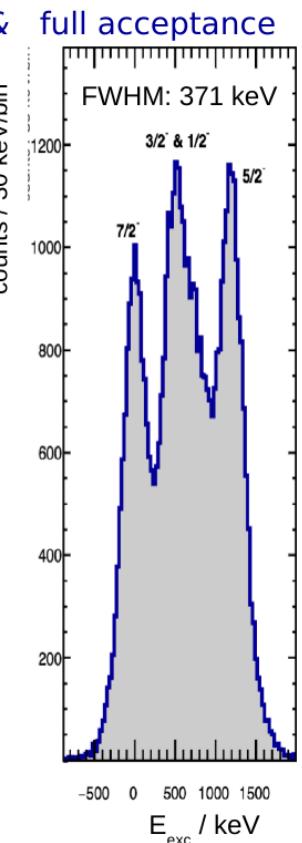
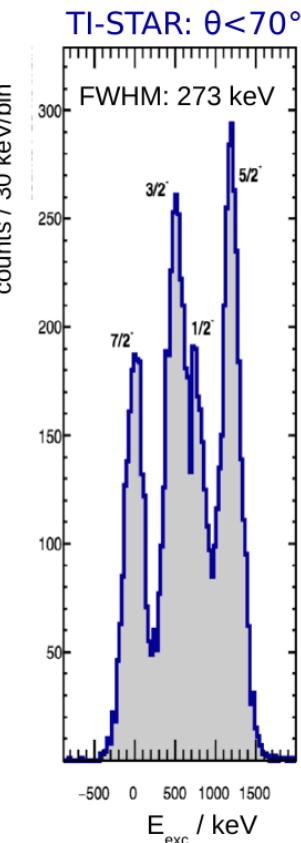
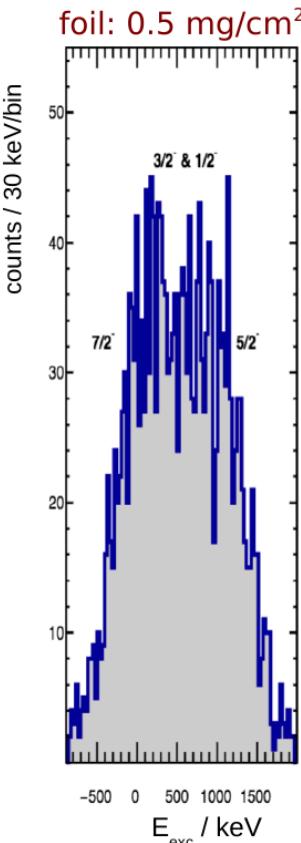
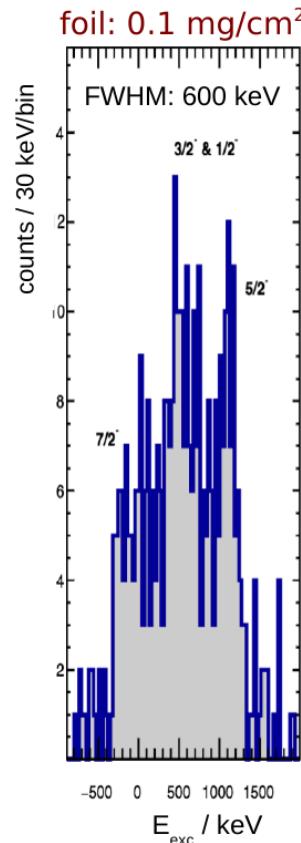
Excitation Energy Spectrum from reconstructed Protons



ProjectionY of binx=[43,62] [x=42.0..62.0]

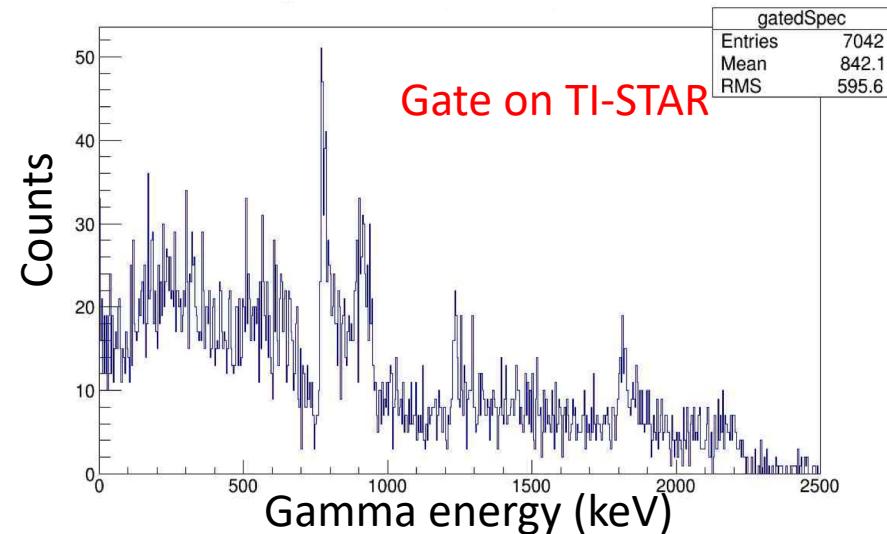
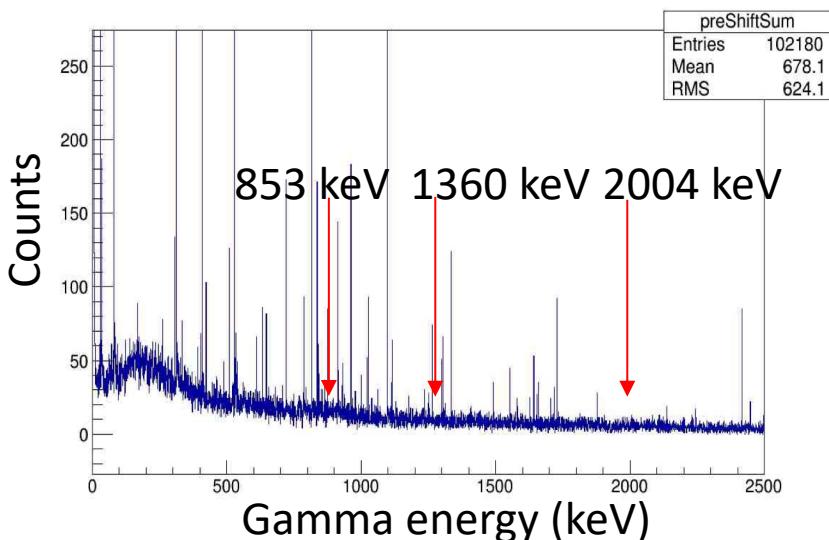


TI-STAR performance: $^{136}\text{Sn}(\text{d}, \text{p})$



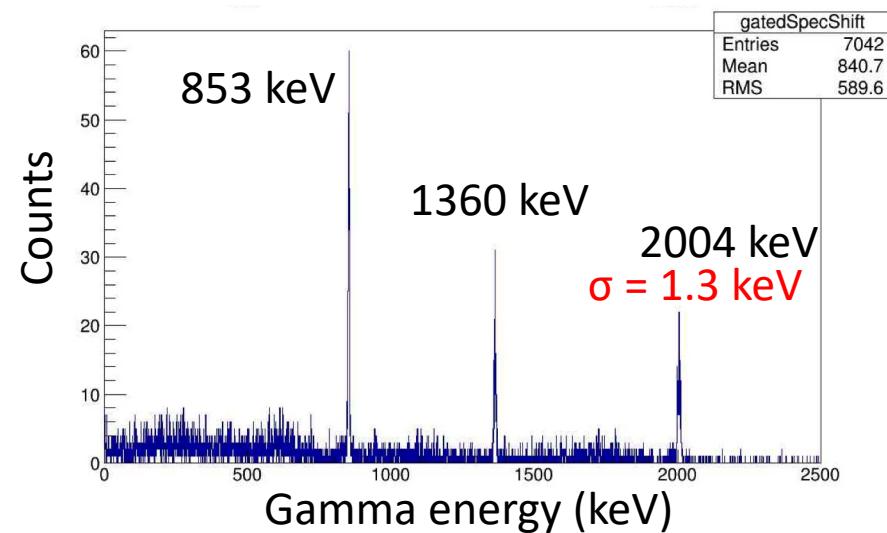
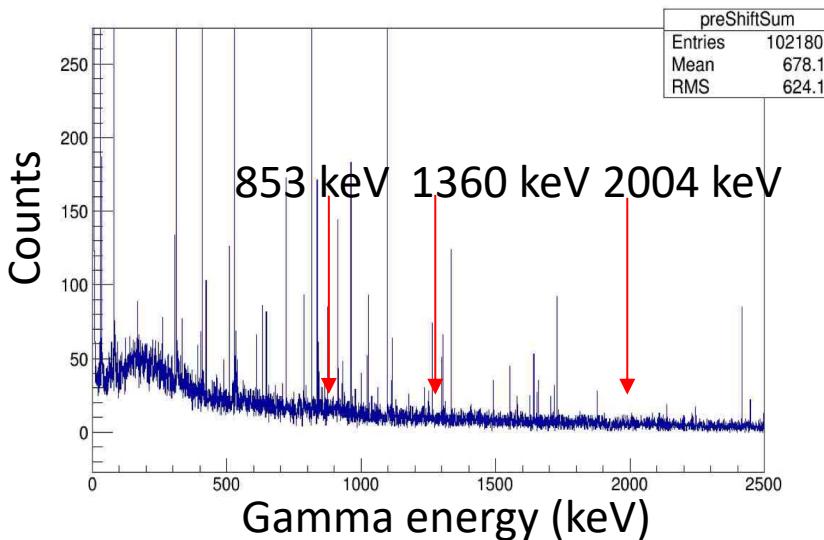
Implementing Realistic Beam Physics

- $^{132}\text{Sn}(\text{d},\text{p})$ @ 6 MeV/u
- TI-STAR gas target (2.84 mg/cm² D2) with foils



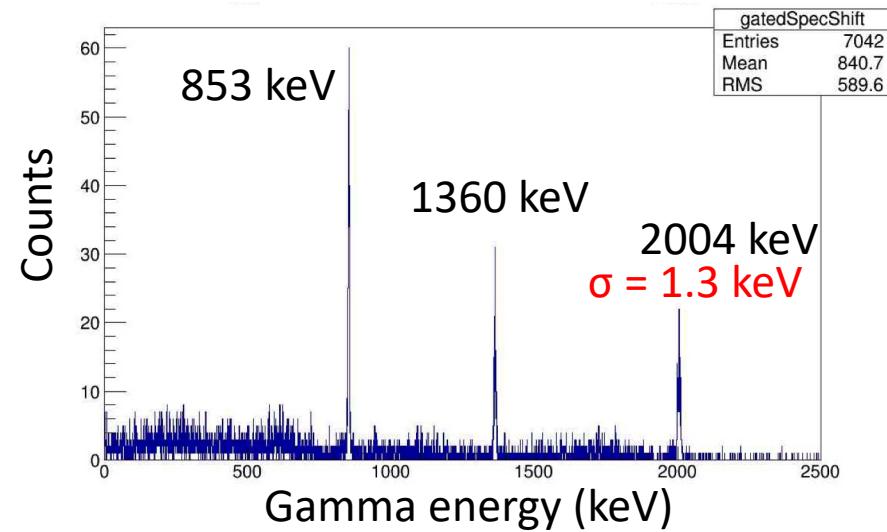
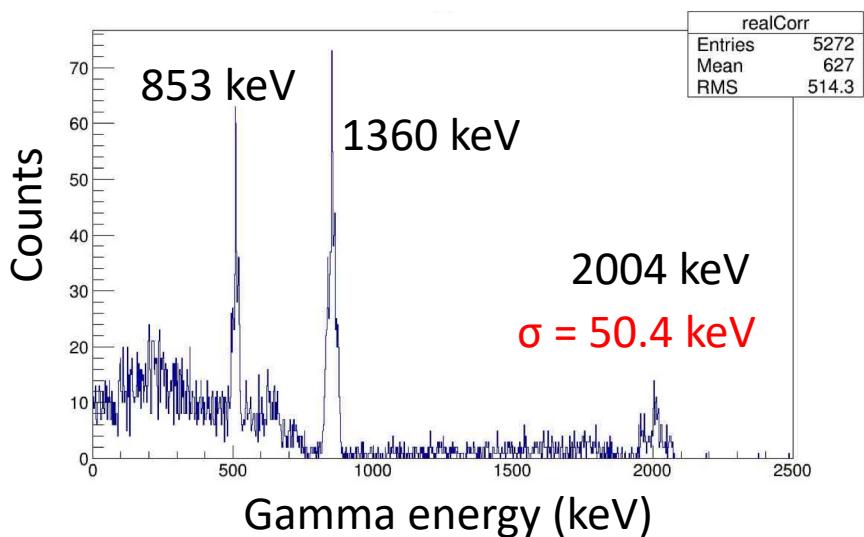
Implementing Realistic Beam Physics

- $^{132}\text{Sn}(\text{d},\text{p})$ @ 6 MeV/u
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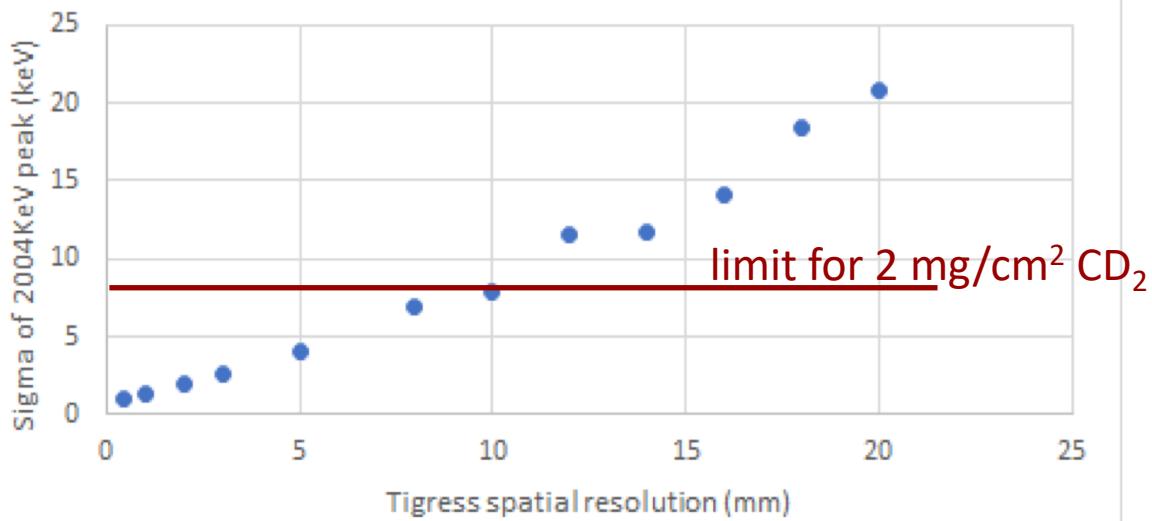
Implementing Realistic Beam Physics

- $^{132}\text{Sn}(\text{d},\text{p})$ @ 6 MeV/u
- comparison: CD₂ foil; 10mg/cm²

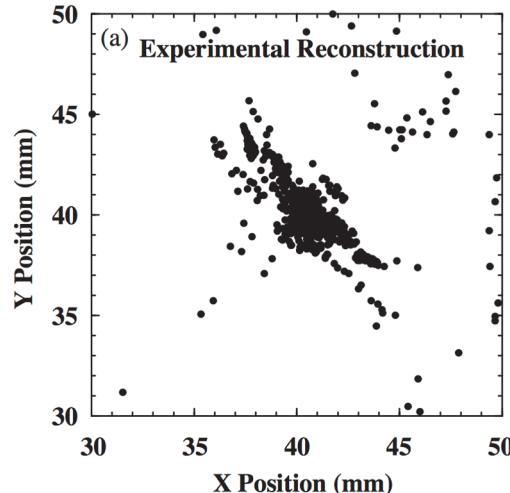


TIGRESS energy resolution using TI-STAR

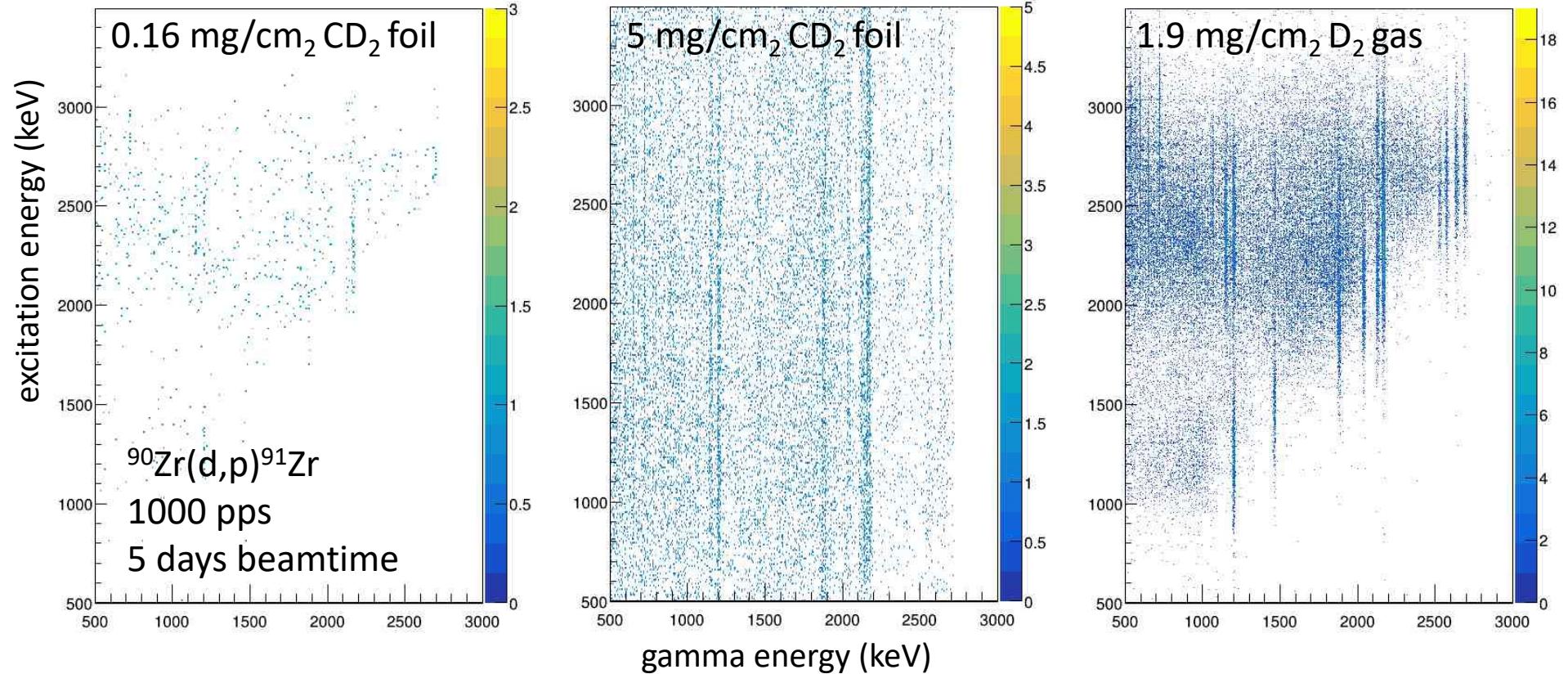
Sigma of gamma peak vs TIGRESS spatial resolution



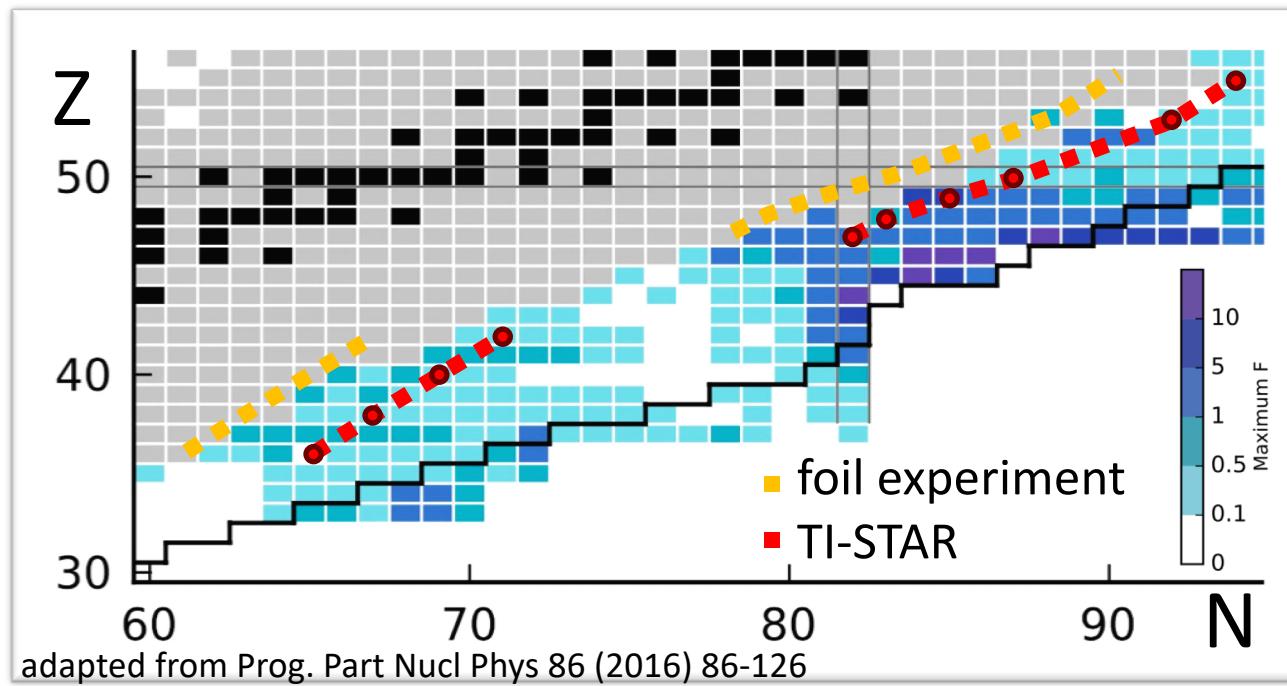
- Gamma ray resolution not limited by target thickness
- PSA and gamma ray tracking limiting factors



Oslo-method using TI-STAR and TIGRESS



Neutron capture rates accessible using ARIEL beams

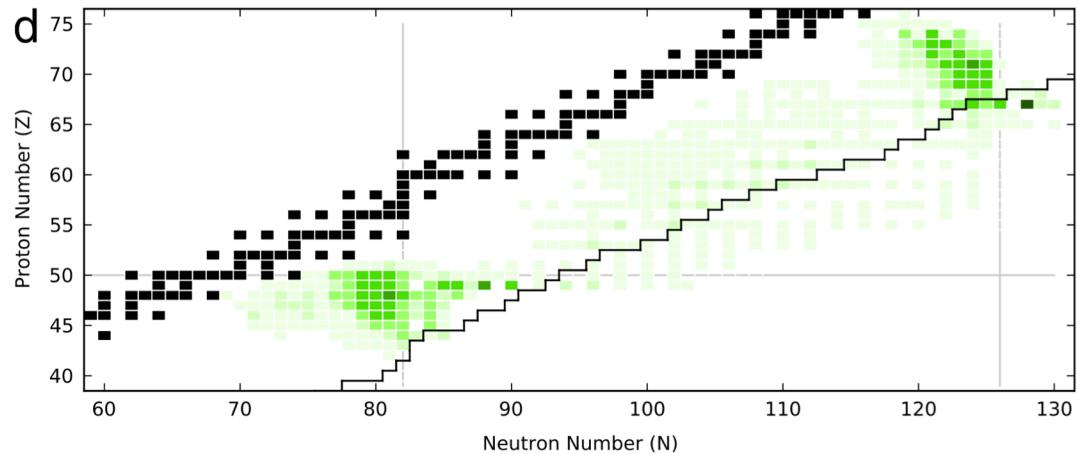


A systematic physics program at ARIEL

reproduce known n-capture cross sections using stable beams

- targeted towards future RIB experiments
- possible first experiments: Sn, In, Lu, Yb stable beam
- (d,p), (p, alpha) and other reactions
- different beam energies
- (d,p) for thin (0.5 mg/cm^2) and thick target (5 mg/cm^2 ?)
- understand role of EMMA

Lu 174 142 d γ^{45} β^- α^{16} γ^{1992} β^{273}	Lu 175 97.41 γ^{45} β^- α^{16} γ^{1992} β^{273}	Lu 176 2.59 $\gamma^{1.2}$ $\beta^-^{0.8}$ α^{16} γ^{138} β^{207} γ^{208} α^{2100}	Lu 177 50.1 d $\gamma^{0.5}$ $\beta^-^{0.5}$ α^{16} γ^{139} β^{120} γ^{113} α^{100}	Lu 178 22.7 m $\gamma^{2.0}$ $\beta^-^{1.2}$ α^{16} γ^{134} β^{132} γ^{131} α^{100}	Lu 179 4.6 h $\beta^-^{1.4}$ γ^{214} α^{9}	Lu 180 5.7 m $\beta^-^{1.5}$ γ^{408} ; 1199; α^{1107} ; 215...	Lu 181 3.5 m β^- γ^{652} ; 206; α^{575}
Yb 173 16.13 α^{16} $\alpha_n, \alpha < 1E-6$	Yb 174 31.83 α^{83} $\alpha_n, \alpha < 0.00002$	Yb 175 4.2 d $\beta^-^{0.5}$ γ^{7396} ; 283; α^{14}	Yb 176 12 s $\beta^-^{0.5}$ γ^{293} α^{390} ; 190; α^{98}	Yb 177 6.5 s $\beta^-^{1.4}$ γ^{104} α^{1000} ; 122; α^{1241}	Yb 178 74 m $\beta^-^{0.6}$ γ^{391} ; 348; α^{9}	Yb 179 7.9 m β^- γ^{592} ; 612; α^{181} ; 654...	Yb 180 2.4 m β^- γ^{173} ; 375; α^{120} ; 386...
Tm 172 63.6 h $\beta^-^{1.8}$; 1.9... γ^{79} ; 1094; 1387; 1530; 1466; 1609...	Tm 173 8.2 h $\beta^-^{0.9}$; 1.3... γ^{399} ; 461...	Tm 174 2.29 s $\beta^-^{1.2}$ γ^{100} α^{152}	Tm 175 15.2 m $\beta^-^{0.9}$; 1.9... γ^{190} ; 1069; α^{304}	Tm 176 15.9 m $\beta^-^{2.0}$; 2.8... γ^{151} ; 941; α^{382}	Tm 177 85 s β^- γ^{105} ; 518... α^{9}		
						$2.8E-10$	$7.8E-11$
							110



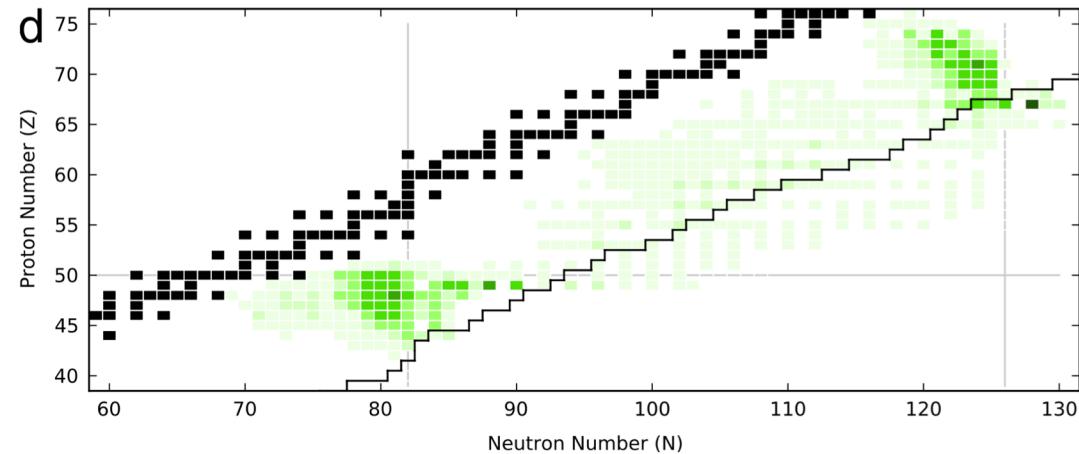
Step 1: establish
 γ -Oslo at
TIGRESS

A systematic physics program at ARIEL

first new data a few steps away from stability

- a few selected cases of largest interest, likely Yb – Lu region
- gain experience for post-acceleration of such heavy, RIB at ISAC-II
- probably using thick CD₂ target in SHARC
- understand delta electrons in SHARC when using thick targets
- beam impurities will be a challenge, maybe EMMA can help

Lu 174 142 d 3.31 s β^+ : 45... β^- : 1... ϵ^- : 4... γ : 1992; 31... 273...	Lu 175 97.41 β^+ : 0.6... β^- : 0.5... ϵ^- : 12... γ : 138... 208... 220...	Lu 176 2.59 β^+ : 0.2... β^- : 0.5... ϵ^- : 12... γ : 319; 122... 113... 131... 1341... 1332... 1310... 1298... 9	Lu 177 160.1 d 6.71 d β^+ : 1.2... β^- : 1.2... ϵ^- : 12... γ : 1341... 1332... 1310... 1298... 9	Lu 178 22.7 m 294.4 m β^+ : 1.2... β^- : 1.4... ϵ^- : 12... γ : 1341... 1298... 9	Lu 179 4.6 h β^+ : 1.4... β^- : 1.4... ϵ^- : 12... γ : 1298... 9	Lu 180 5.7 m β^+ : 1.5; 2.7... T40B; 1199;... 1107; 215... 9	Lu 181 3.5 m β^- : 1652; 206;... 575...
Yb 173 16.13 σ 16 $\sigma_{n,\alpha} < 1E-6$	Yb 174 31.83 σ 83 $\sigma_{n,\alpha} < 0.00002$	Yb 175 4.2 d β^- : 0.5... 7396; 283;... 1414...	Yb 176 12 s 12.76 β^+ : 0.5... 1293... 390; 190;... 98... ϵ^- : 3.1 $\sigma_{n,\alpha} < 1E-6$	Yb 177 6.5 s β^+ : 1.4... 104; 122;... 1241... 9	Yb 178 74 m β^- : 0.6... 391; 348;... 9	Yb 179 7.9 m β^- : 1692; 812;... 831; 654;... 110	Yb 180 2.4 m β^- : 173; 375;... 120; 385...
Tm 172 63.6 h β^+ : 1.8; 1.9... 1387; 1094;... 1466; 1609;...	Tm 173 8.2 h β^- : 0.9; 1.3... 1387; 1530;... 1466; 1609;...	Tm 174 2.29 s 5.4 m β^+ : 1.2... 100; 152;... 177...	Tm 175 15.2 m β^- : 0.9; 1.9... 190; 1069;... 364;... 9	Tm 176 1.9 m β^+ : 2.0; 2.8... 190; 1069;... 362... 9	Tm 177 85 s β^- : 105; 518;... g; m		
						2.8E-10	7.8E-11



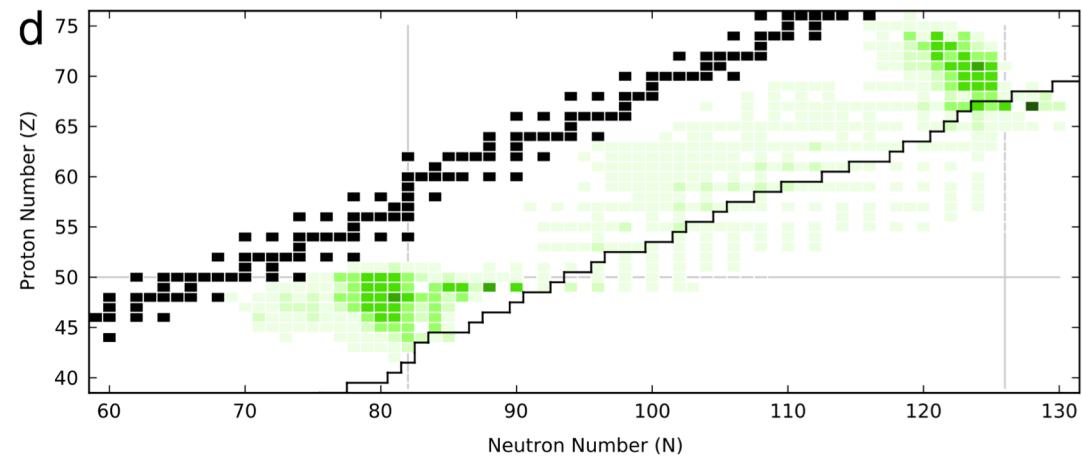
**Step 2: pre-CANREB
beams**

A systematic physics program at ARIEL

CANREB will allow to continue the systematic program:

- Significant boost in intensity and purity of heavy beams
- first r-process relevant data
- comparison to beta-Oslo (e.g. SUN)

Lu 174 142 d 3.31 s β^- : 45... γ : 124C... γ : 1992... γ : 273... $\sigma_{n,a} < 1E-6$	Lu 175 97.41 β^- : 1.2... γ : 38-109... γ : 396... γ : 738... γ : 992... $\sigma_{n,a} < 1E-6$	Lu 176 2.59 β^- : 0.2... γ : 0.5... γ : 100... γ : 319-122... γ : 320... γ : 113... γ : 1341... $\sigma_{n,a} < 1E-6$	Lu 177 160.1 d 6.71 d β^- : 1.2... γ : 123... γ : 130... γ : 1341... γ : 1341... γ : 1341... $\sigma_{n,a} < 1E-6$	Lu 178 22.7 m 28.4 m β^- : 2.0... γ : 121... γ : 132... γ : 1310... γ : 1398... $\sigma_{n,a} < 1E-6$	Lu 179 4.6 h 4.6 h β^- : 1.4... γ : 211... γ : 211... γ : 9 $\sigma_{n,a} < 1E-6$	Lu 180 5.7 m 5.7 m β^- : 1.5; 2.7... γ : 408; 1199... γ : 1107; 215... γ : 1652; 206... γ : 575... $\sigma_{n,a} < 1E-6$	Lu 181 5.5 m 5.5 m β^- : 1.5; 2.7... γ : 408; 1199... γ : 1107; 215... γ : 1652; 206... γ : 575... $\sigma_{n,a} < 1E-6$
Yb 173 16.13 $\sigma_{n,a} < 1E-6$	Yb 174 31.83 $\sigma_{n,a} < 0.00002$	Yb 175 4.2 d β^- : 0.5... γ : 7396; 283; 144... $\sigma_{n,a} < 1E-6$	Yb 176 12 s 12.76 β^- : 1.4... γ : 123... γ : 1000; 122... γ : 1241... $\sigma_{n,a} < 1E-6$	Yb 177 6.5 s 6.5 s β^- : 1.4... γ : 104; 228... γ : 391; 348... $\sigma_{n,a} < 1E-6$	Yb 178 74 m 74 m β^- : 0.6... γ : 391; 348... $\sigma_{n,a} < 1E-6$	Yb 179 7.9 m 7.9 m β^- : 1.5; 2.7... γ : 692; 812; 831; 654... $\sigma_{n,a} < 1E-6$	Yb 180 2.4 m 2.4 m β^- : 1.73; 375; 380; 386... $\sigma_{n,a} < 1E-6$
Tm 172 63.6 h β^- : 1.8; 1.9... γ : 79; 1094; 1387; 1530; 1466; 1609... $\sigma_{n,a} < 1E-6$	Tm 173 8.2 h β^- : 0.9; 1.3... γ : 399; 461... $\sigma_{n,a} < 1E-6$	Tm 174 2.29 s 5.4 m β^- : 1.2... γ : 366... γ : 992; 273; 152... $\sigma_{n,a} < 1E-6$	Tm 175 15.2 m 1.9 m β^- : 0.9; 1.9... γ : 190; 1069; 382... γ : 941; 364... $\sigma_{n,a} < 1E-6$	Tm 176 1.9 m 1.9 m β^- : 2.0; 2.8... γ : 105; 518... γ : g; m $\sigma_{n,a} < 1E-6$	Tm 177 85 s 2.8E-10 β^- : 1.05; 518... γ : g; m $\sigma_{n,a} < 1E-6$		
							110



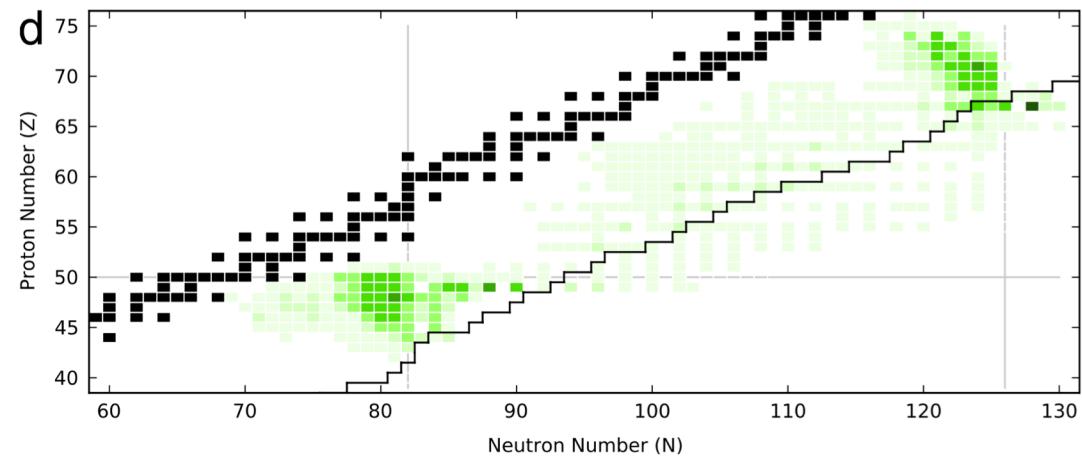
Step 3: experiments with CANREB and SHARC

A systematic physics program at ARIEL

CANREB will allow to continue the systematic program:

- Significant boost in intensity and purity of heavy beams
- first r-process relevant data
- comparison to beta-Oslo (e.g. SUN)

Lu 174 142 d 3.31 s β^- : 45... γ : 124C... γ : 1992... γ : 273... σ : 16	Lu 175 97.41 β^- : 1.2... γ : 120... γ : 138... γ : 208... γ : 2100... σ : 16 + 8	Lu 176 2.59 β^- : 0.2... γ : 0.5... γ : 100... γ : 319; 122... γ : 113... σ : 3.2	Lu 177 160.1 d 3.68 h β^- : 0.2... γ : 1.2... γ : 130... γ : 319; 122... γ : 113... σ : 9 + 1000	Lu 178 22.7 m 6.71 d β^- : 2.0... γ : 1.2... γ : 1341... γ : 1332... γ : 1310... σ : 9	Lu 179 4.6 h 28.4 m β^- : 1.4... γ : 211... γ : 1208... σ : 9	Lu 180 5.7 m 5.7 m β^- : 1.5; 2.7... γ : 408; 1199... γ : 1107; 215... σ : 9	Lu 181 5.5 m β^- : 1.5; 2.7... γ : 652; 206... γ : 575... σ : 9
Yb 173 16.13 σ : 16 $\sigma_{n, \alpha}$: <1E-6	Yb 174 31.83 σ : 83 $\sigma_{n, \alpha}$: <0.00002	Yb 175 4.2 d β^- : 0.5... γ : 739; 283; 144... σ : 16	Yb 176 12 s 12.76 β^- : 1.4... γ : 293; 390; 190; < 3.1... σ : 1.2	Yb 177 6.5 s 1.9 h β^- : 1.4... γ : 104; 220; 1000; 122; 1241... σ : 9	Yb 178 74 m 7.9 m β^- : 0.6... γ : 391; 348; 9... σ : 9	Yb 179 7.9 m β^- : 1.5; 2.7... γ : 652; 612; 281; 654... σ : 9	Yb 180 2.4 m β^- : 1.5; 2.7... γ : 173; 375; 280; 386... σ : 9
Tm 172 63.6 h β^- : 1.8; 1.9... γ : 79; 1094; 1387; 1530; 1466; 1609... σ : 16	Tm 173 8.2 h β^- : 0.9; 1.3... γ : 399; 461... σ : 16	Tm 174 2.29 s 5.4 m β^- : 1.2... γ : 100; 992; 273; 152... σ : 1.2	Tm 175 15.2 m 1.9 m β^- : 0.9; 1.9... γ : 190; 1069; 382... σ : 9	Tm 176 1.9 m 2.0; 2.8... γ : 515; 941; 364... σ : 9	Tm 177 85 s 2.8E-10 β^- : 1.05; 518... γ : 9; m σ : 9		
							110

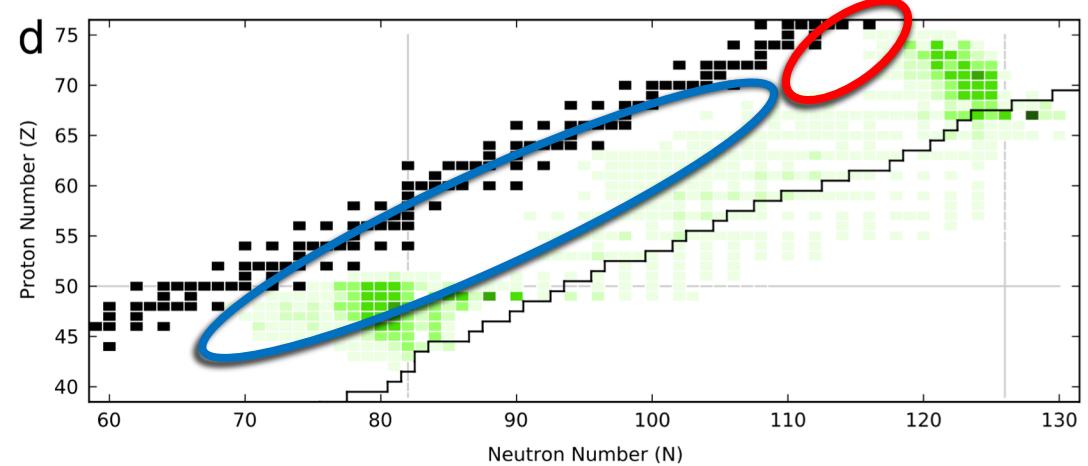


Step 3: experiments with CANREB and SHARC

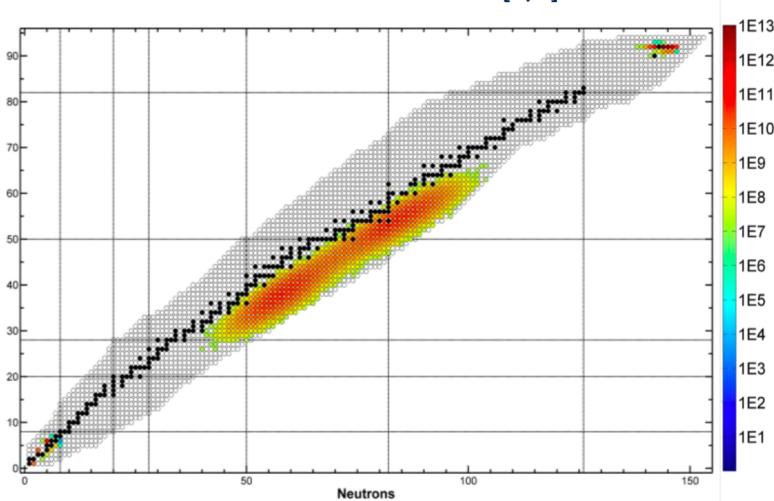
A systematic physics program at ARIEL

pushing towards the limits using TI-STAR

- measure all accessible dominant n-capture cross sections
- at the same time: studies on nuclear structure
- also allows a systematic program on halo features of heavy nuclei



50 MeV x 10 mA electrons [1/s]



**Step 4: experiments with
ARIEL and TI-STAR**

Silicon Tracker: Team

- **L. Atar, T. Rockman** (both UofG): Geant4
 - **Hadi Behnamian** (Iranian lightsource facility): new postdoc to start in the fall:
detector development, cooling
 - **Vinzenz Bildstein**, UofG: essential for this project
 - **R. Gernhäuser, M. Böhmer** (both TU Munich): ASICs, PCBs
 - **F. Sarazin** (Mines), **R. Hendersson** (TRIUMF): mechanical design, mechanics
 - **F. Retiere** (TRIUMF) + team: FPGA
 - **R. Openshow, P. Lu** (TRIUMF): gas system
- gate-0 at TRIUMF:
 - October 2016: meeting w. TRIUMF detector + electronics experts
 - May 2017: CFI JELF envelope at U. of Guelph (\$400k)
 - January 2018: submission to CFI-JELF (total budget \$750k)
 - gate 1+2: in preparation
 - CFI results expected soon