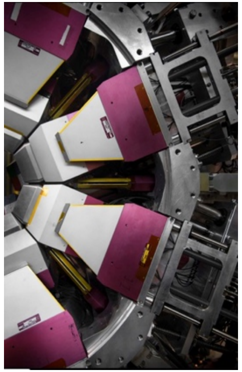
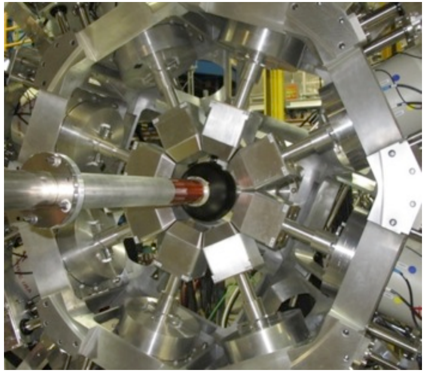
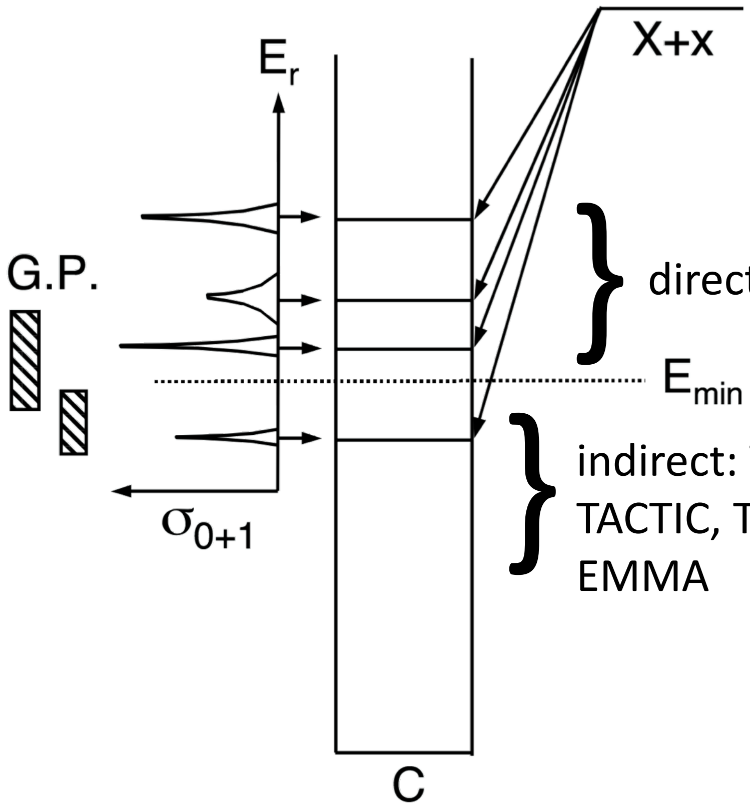
Opportunities for Nucleosynthesis Studies with TI-STAR and TIGRESS at ARIEL

Dennis Mücher, Leyla Atar, Tomer Rockman
University of Guelph + TRIUMF for the TIGRESS and TI-STAR collaborations



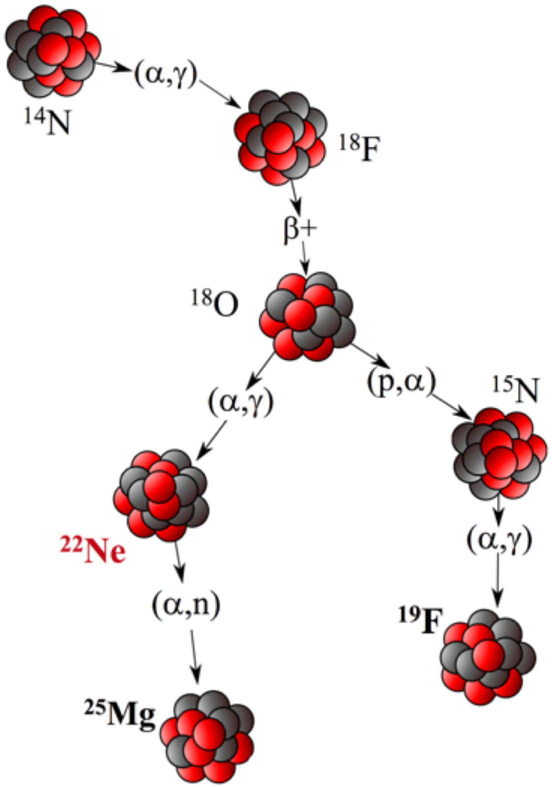



Intro: indirect approaches to nucleosynthesis studies



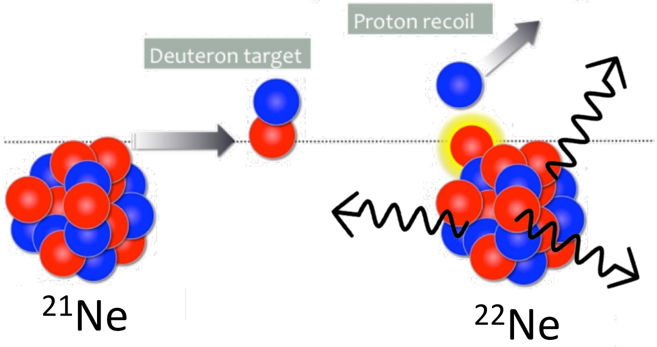
direct: DRAGON

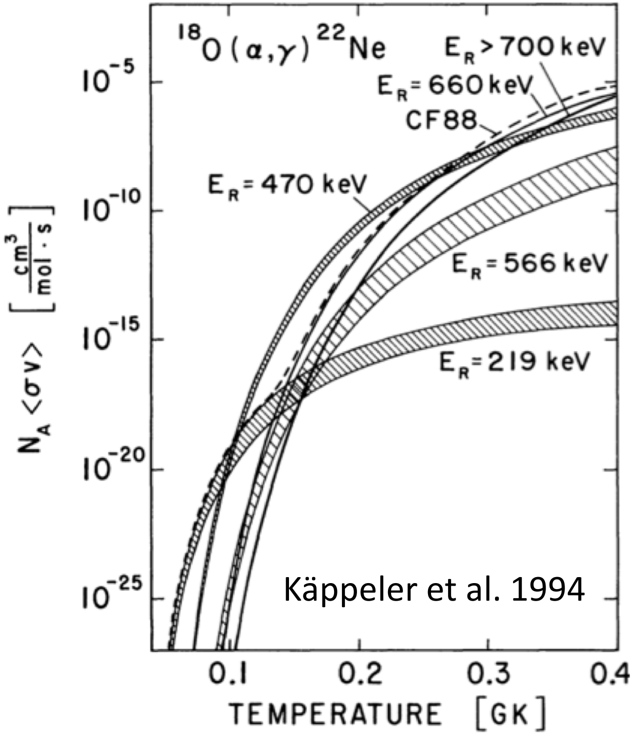
indirect: TUDA, TACTIC, TIGRESS, IRIS, EMMA



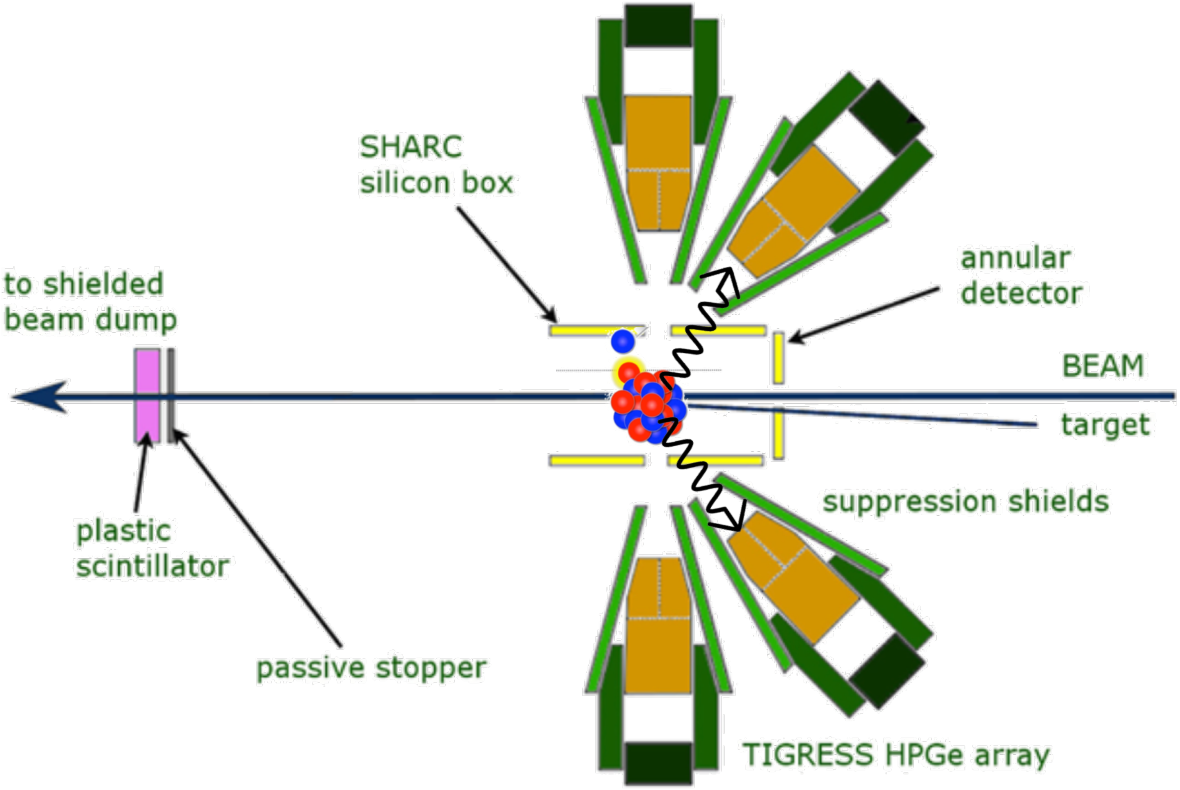
Example: spectroscopy of ^{22}Ne resonances at ISAC-II

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

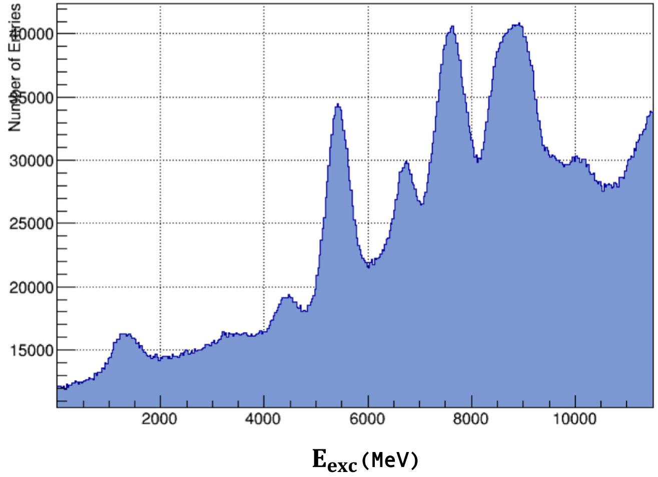




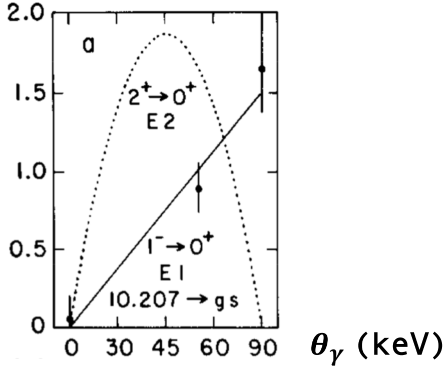
Particle-gamma spectroscopy with TIGRESS

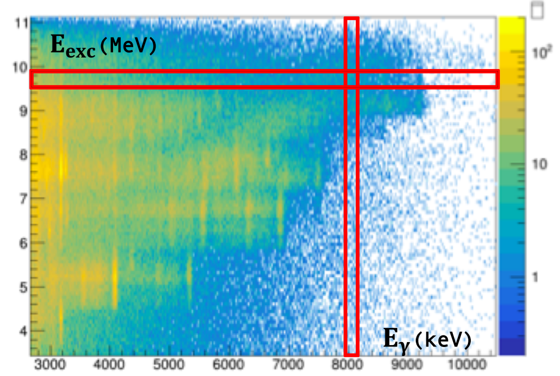


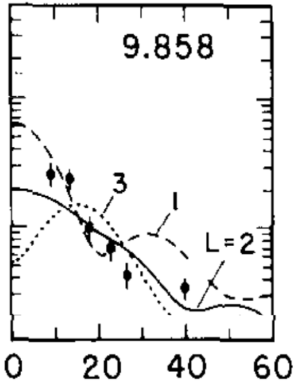
^{21}Ne(d,p), 7.9 MeV/u
August 2017

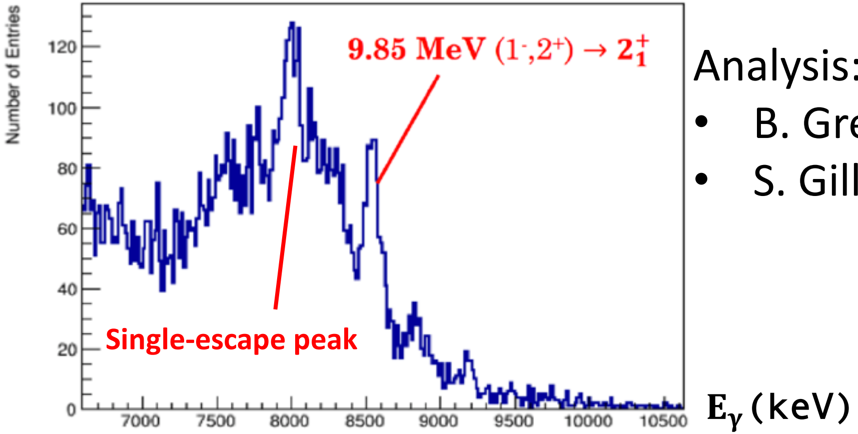


Example: spectroscopy of ^{22}Ne resonances at ISAC-II



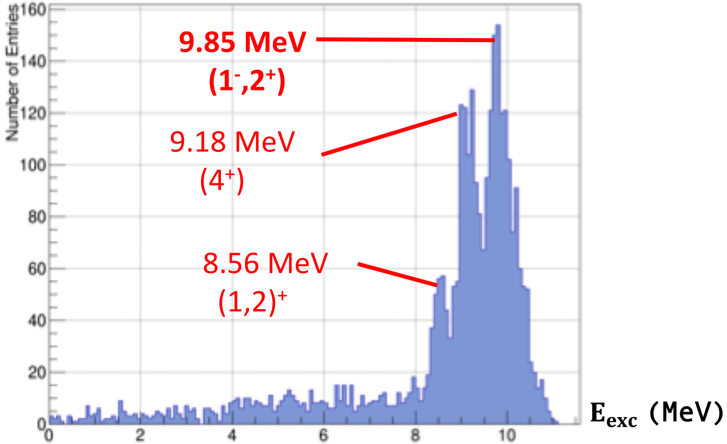




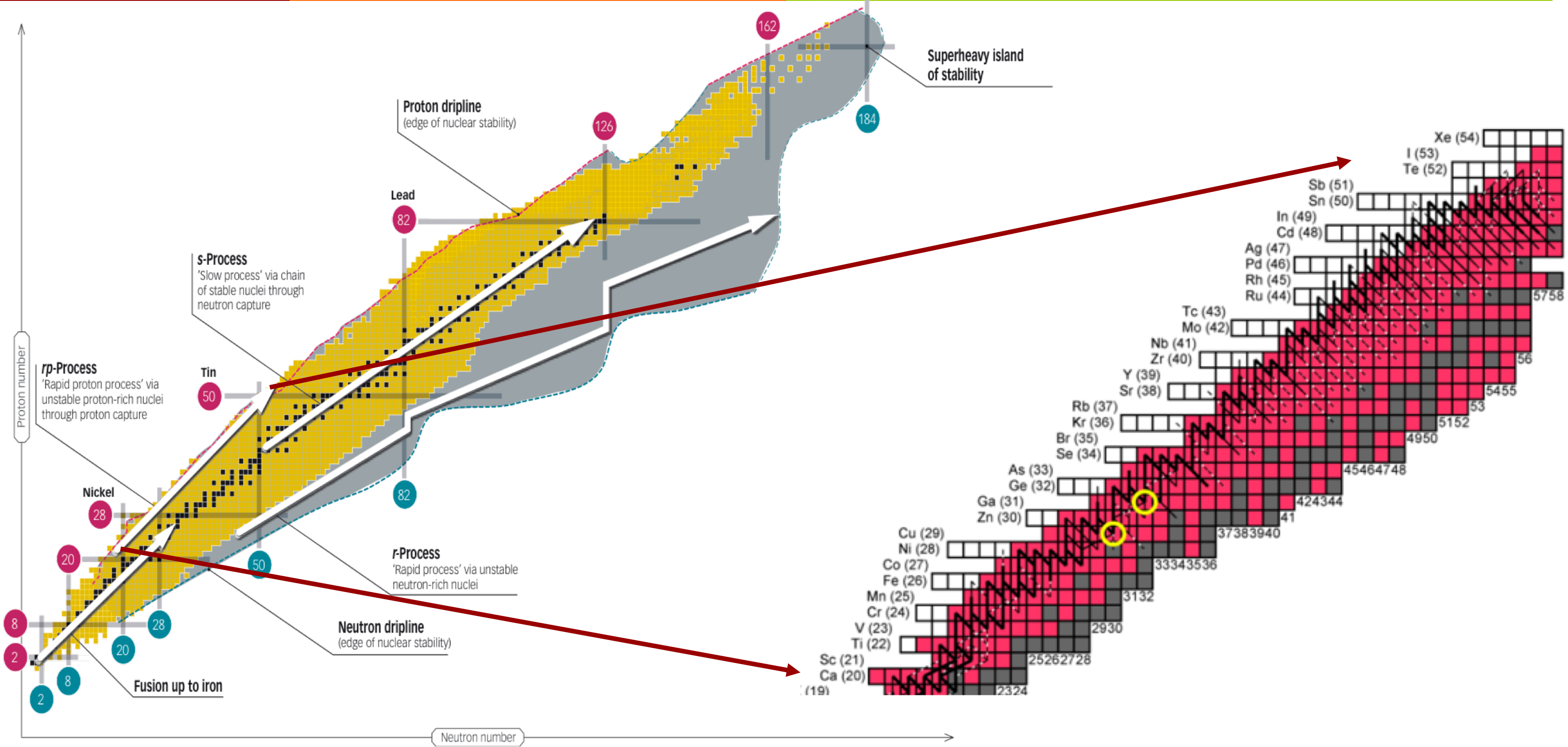


Analysis:

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

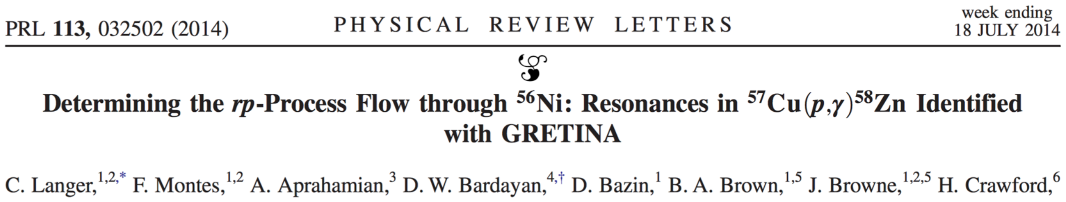


rp-process


Proton dripline
(edge of nuclear stability)
Superheavy island
of stability
162
126
184
Lead
82
s-Process
'Slow process' via chain
of stable nuclei through
neutron capture
Tin
50
rp-Process
'Rapid proton process' via
unstable proton-rich nuclei
through proton capture
Nickel
28
20
8
2
82
50
28
20
8
2
r-Process
'Rapid process' via unstable
neutron-rich nuclei
Neutron dripline
(edge of nuclear stability)
Fusion up to iron
Proton number
Neutron number
Xe (54)
I (53)
Te (52)
Sb (51)
Sn (50)
In (49)
Cd (48)
Ag (47)
Pd (46)
Rh (45)
Ru (44)
Tc (43)
Mo (42)
Nb (41)
Zr (40)
Y (39)
Sr (38)
Rb (37)
Kr (36)
Br (35)
Se (34)
As (33)
Ge (32)
Ga (31)
Zn (30)
Cu (29)
Ni (28)
Co (27)
Fe (26)
Mn (25)
Cr (24)
V (23)
Ti (22)
Sc (21)
Ca (20)
(19)
5758
56
5455
53
5152
4950
45464748
424344
41
37383940
33343536
3132
2930
25262728
2324

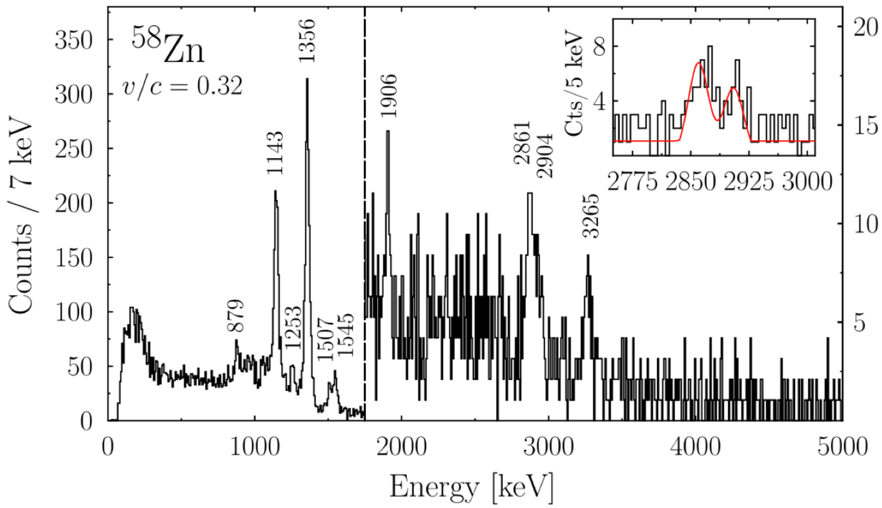
Indirect measurements for the rp-process

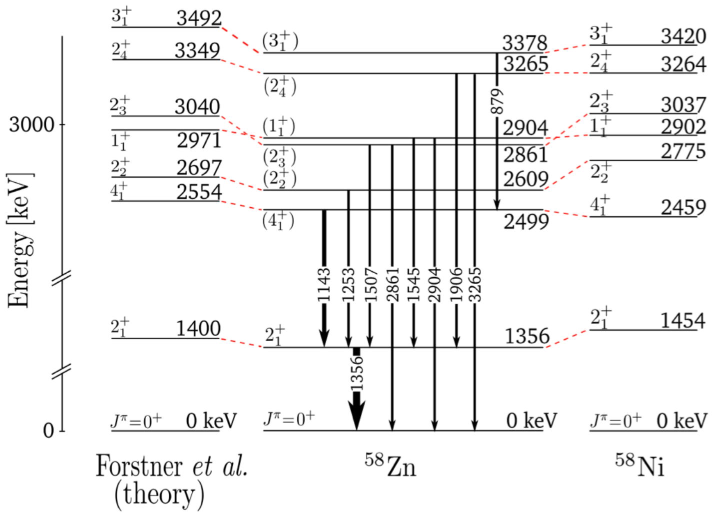
- $^{57}Cu(d,n)^{58}Zn$
- using GRETINA @ NSCL
- **resolution** and **statistics** at the limit


PRL **113**, 032502 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

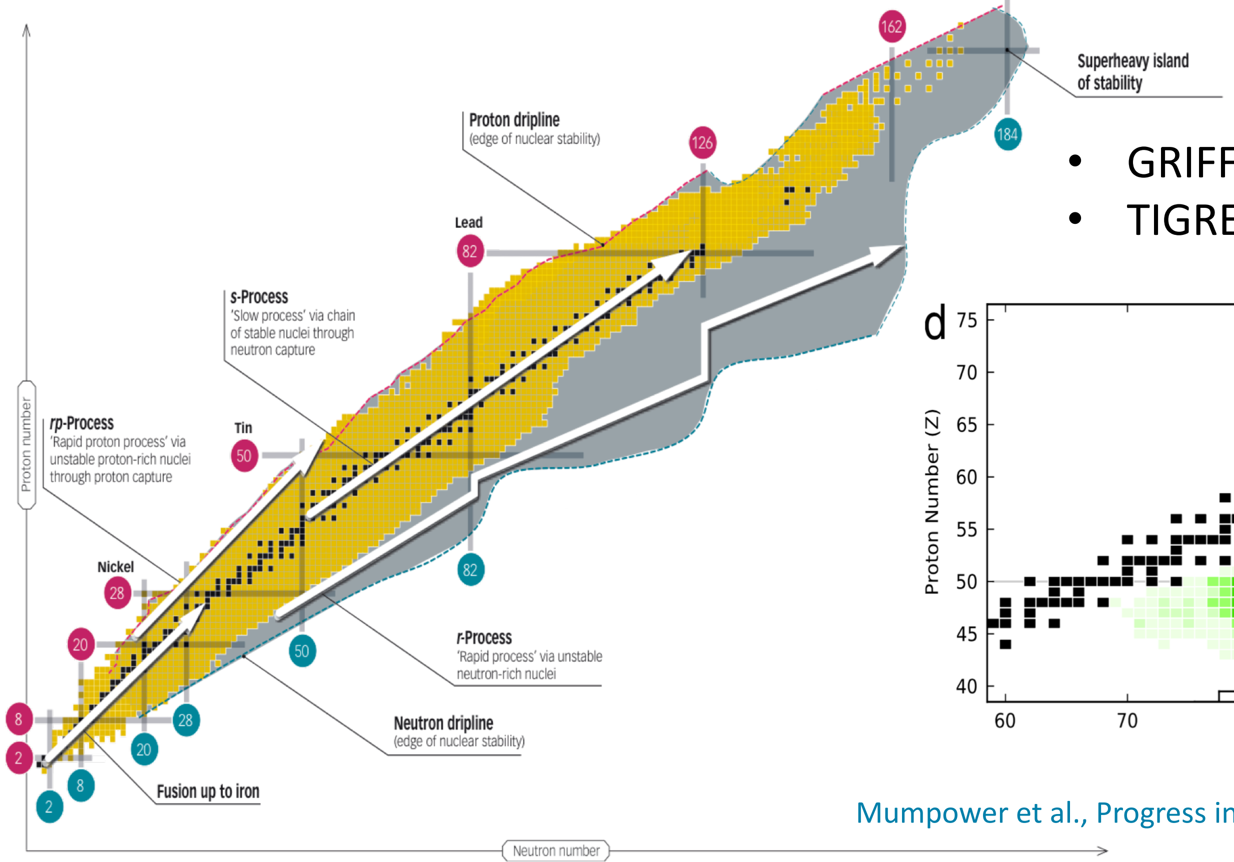
Determining the *rp*-Process Flow through ^{56}Ni: Resonances in ^{57}Cu$(p,\gamma)^{58}$Zn Identified with GRETINA

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]

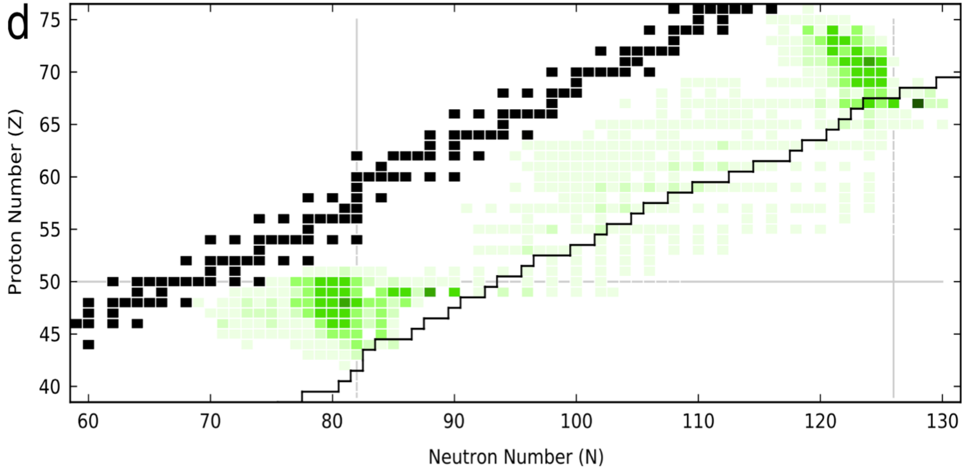




Constraining neutron capture rates

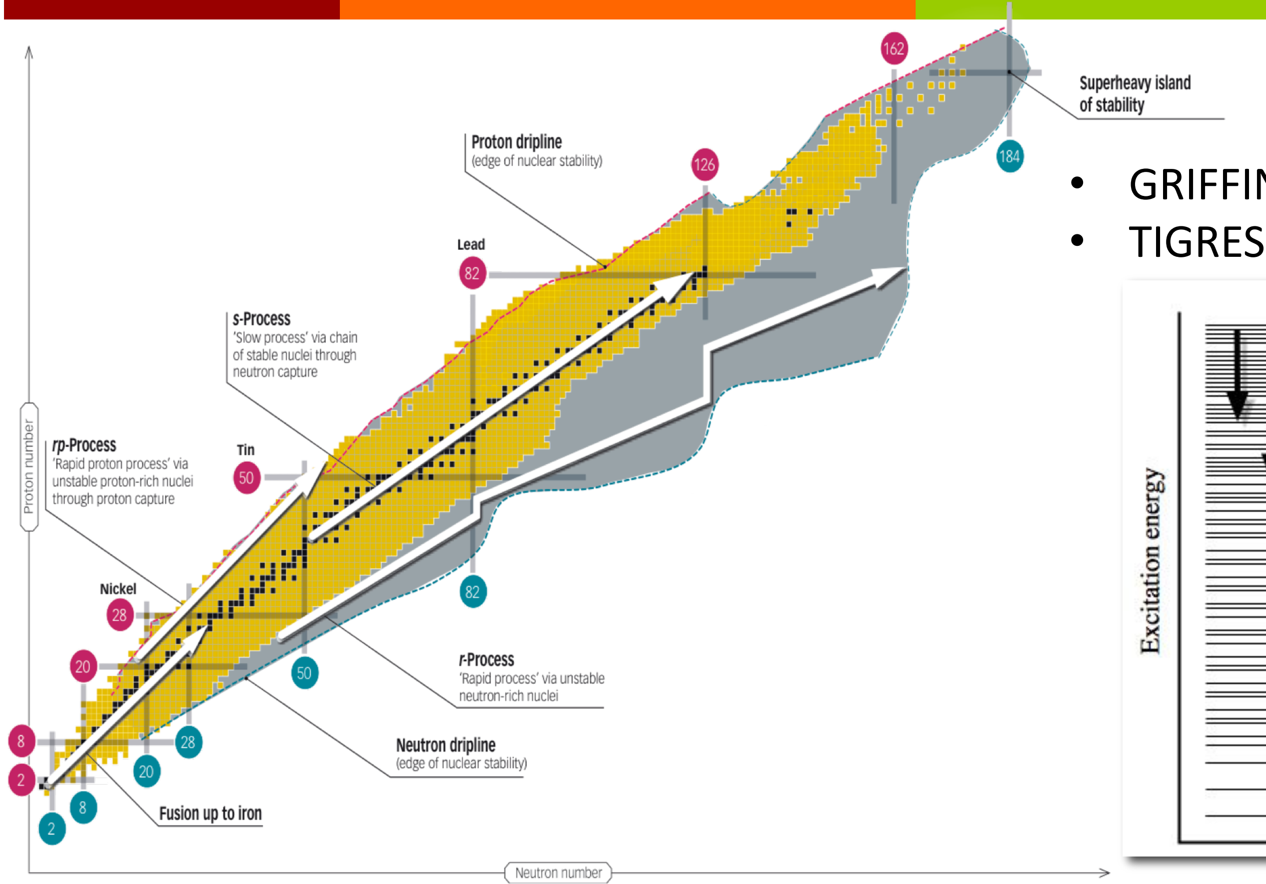


- GRIFFIN: $T_{1/2}$ and β-delayed neutrons
- TIGRESS: neutron capture rates



Mumpower et al., Progress in Particle and Nuclear Physics 86 (2016) 86–126

Constraining neutron capture rates



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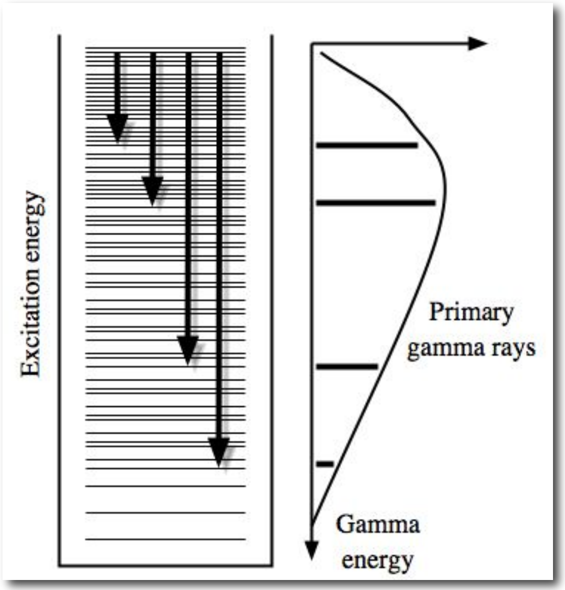
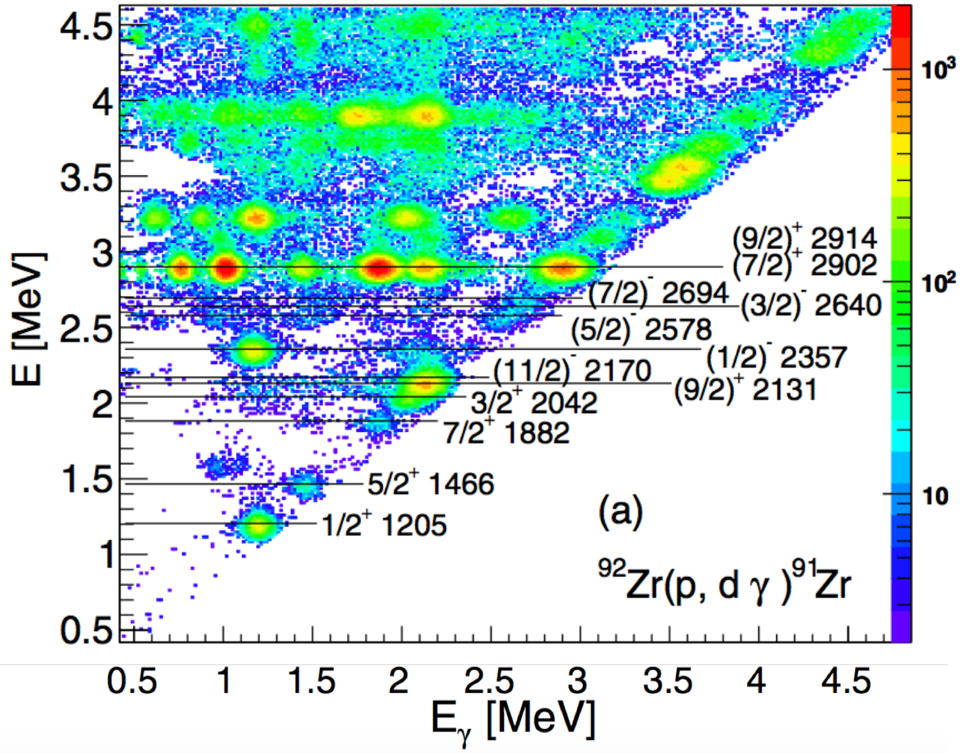
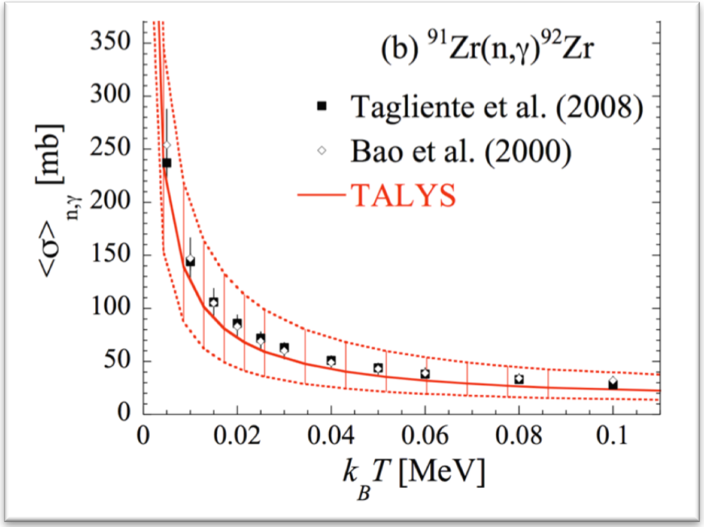


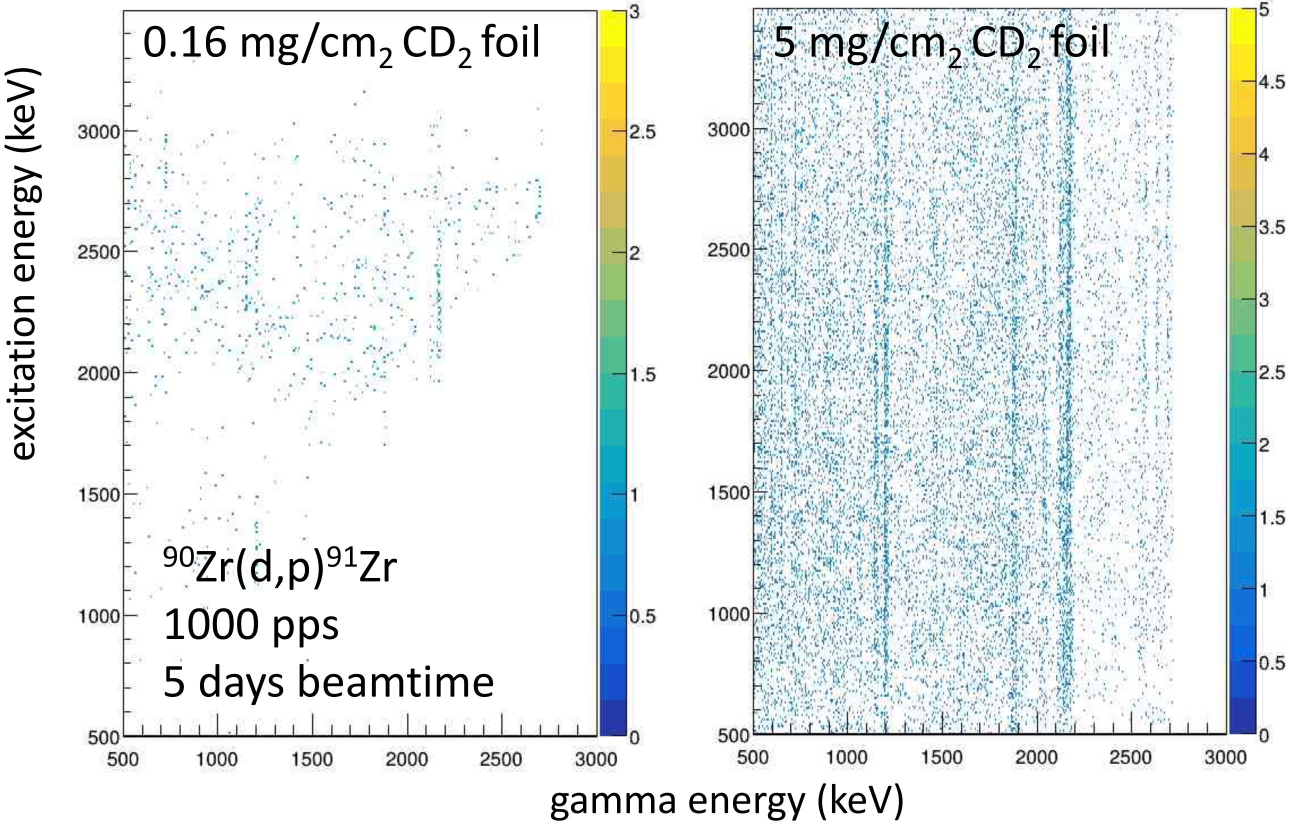
Validation of the "Oslo" method



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

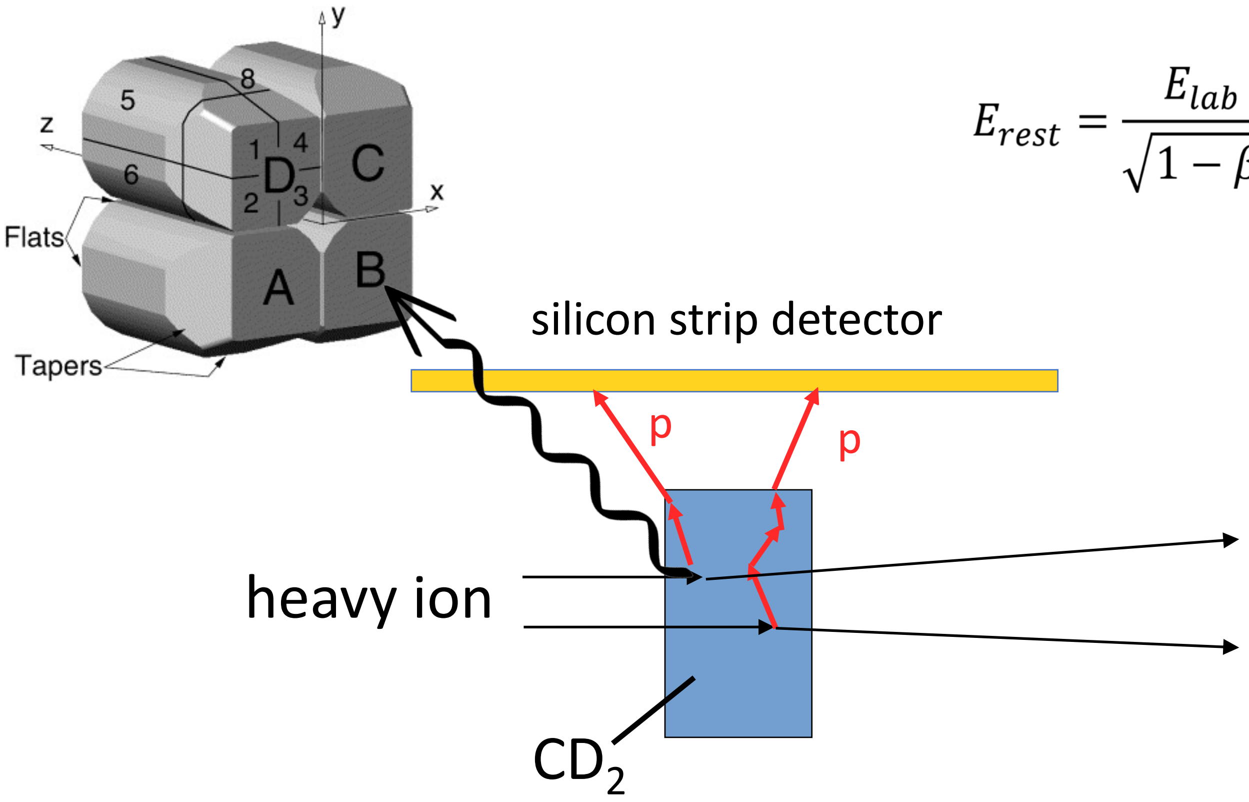


Oslo-method: doable for exotic beams at ARIEL?



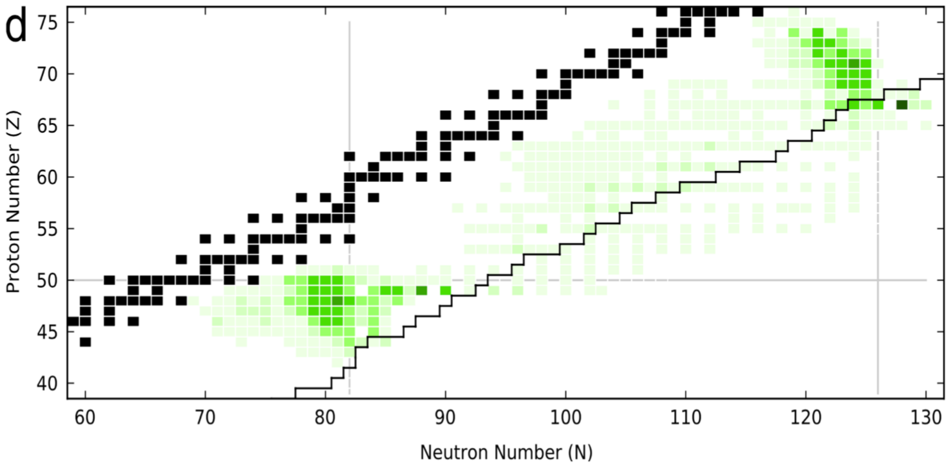
resolution vs. target thickness

$$E_{rest} = \frac{E_{lab}}{\sqrt{1-\beta^2}}(1 - \beta cos\theta)$$

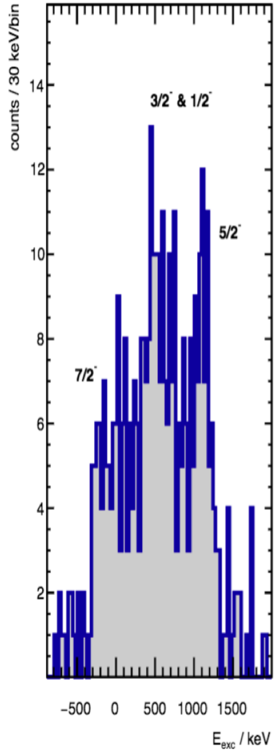


$^{136}Sn(d,p)$ at ARIEL and CD_2 targets

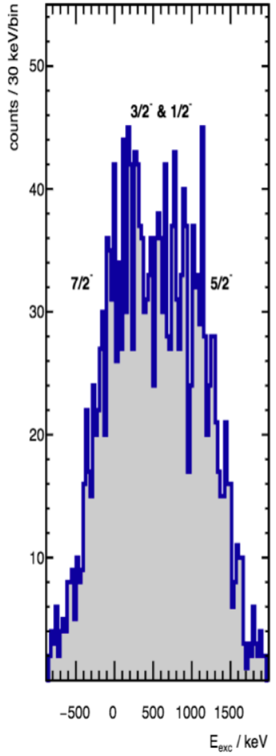
Target thickness becomes a critical issue with increasing Z of the beam: $\Delta E \sim Z^2$



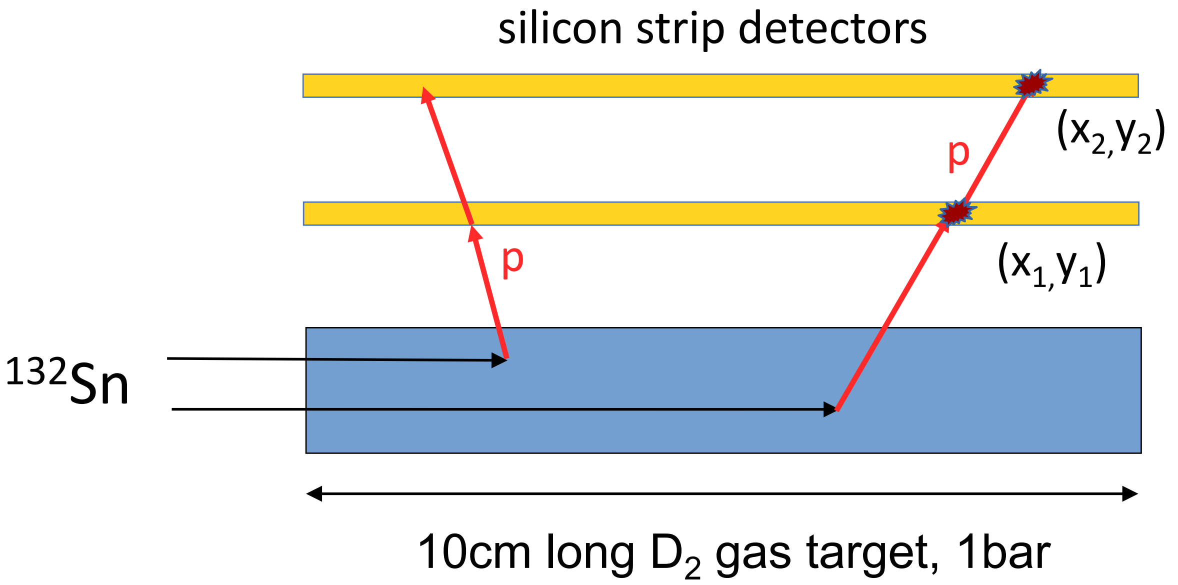
foil: 0.1 mg/cm^2



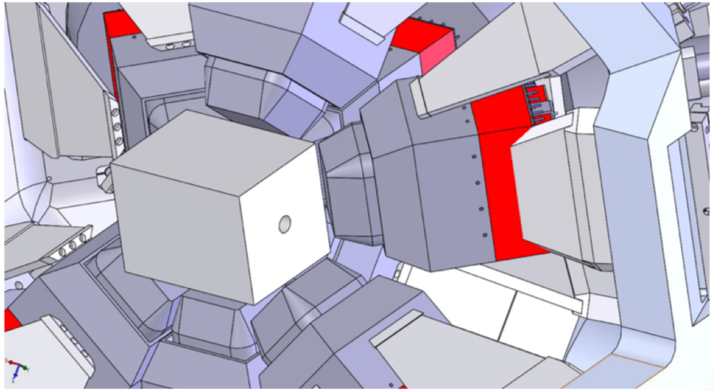
foil: 0.5 mg/cm^2



Idea:vertex tracking at ISOL energies using Si detectors

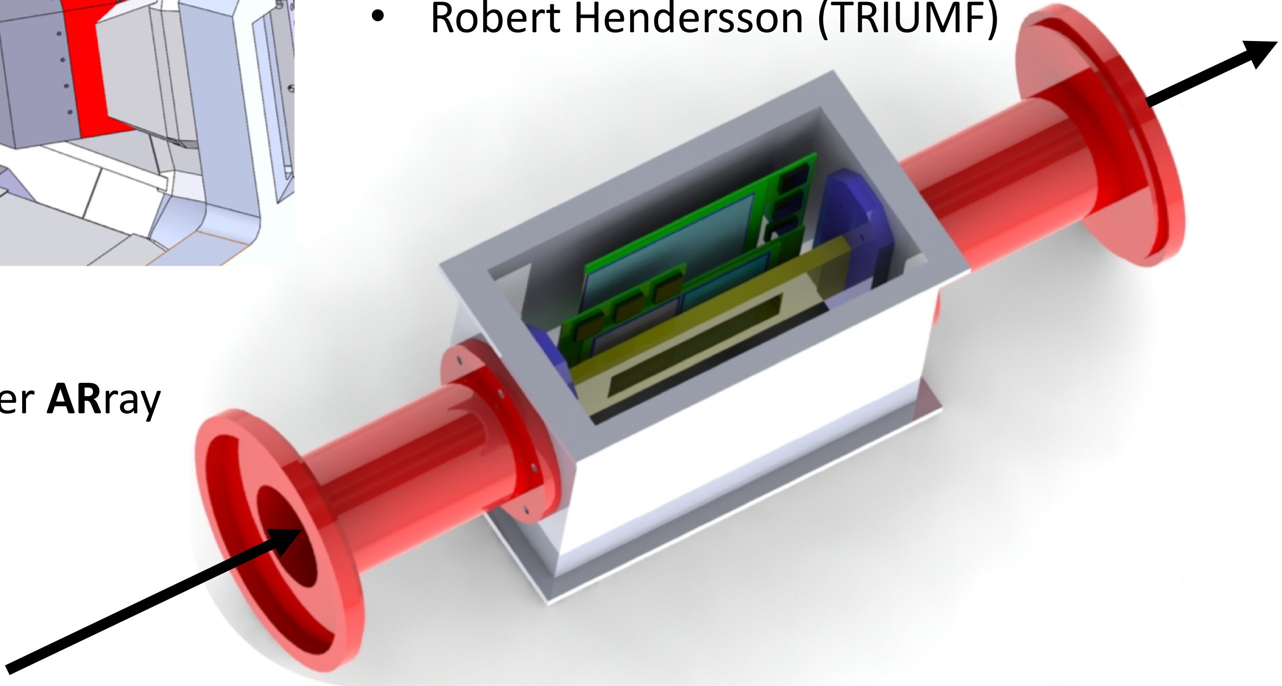


Layout of TI-STAR



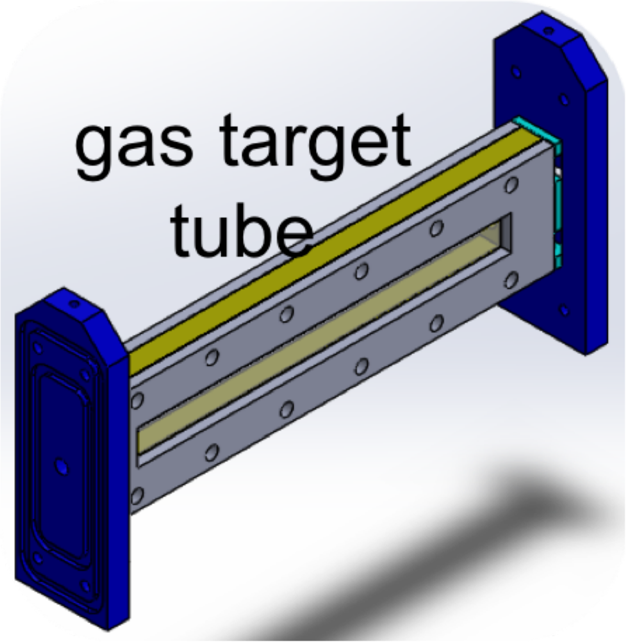
Mechanical Design:

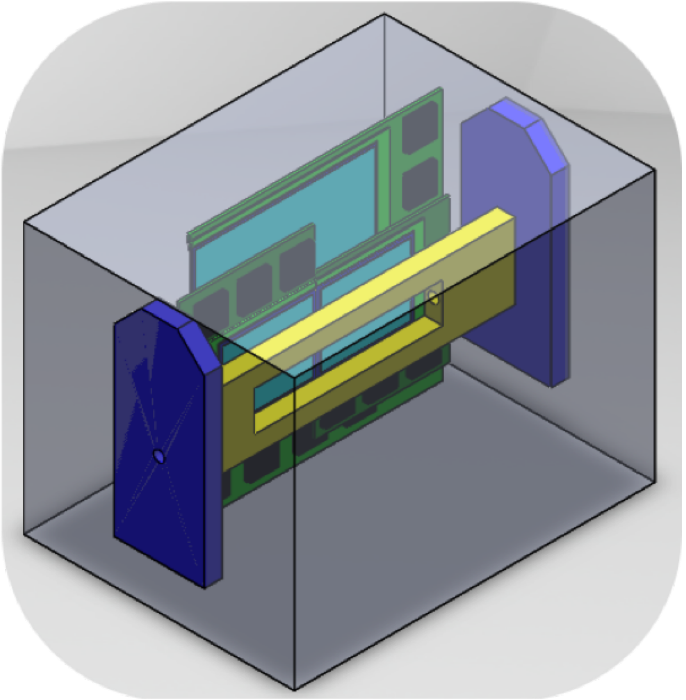
- Fred Sarazin (Colorado School of Mines)
- Robert Hendersson (TRIUMF)



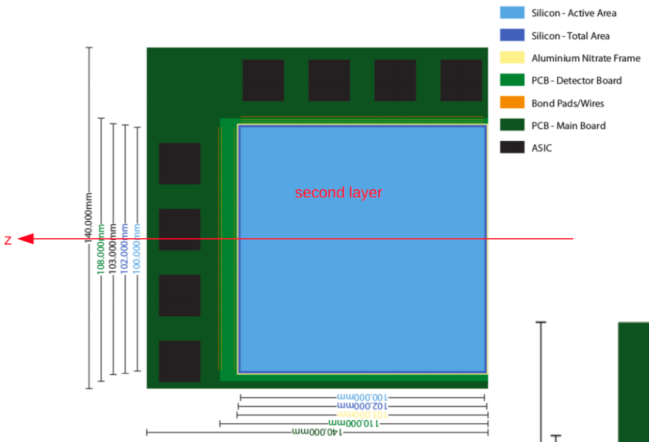
TI-STAR =
TIGRESS **S**ilicon **T**racker **AR**ray

Layout of TI-STAR



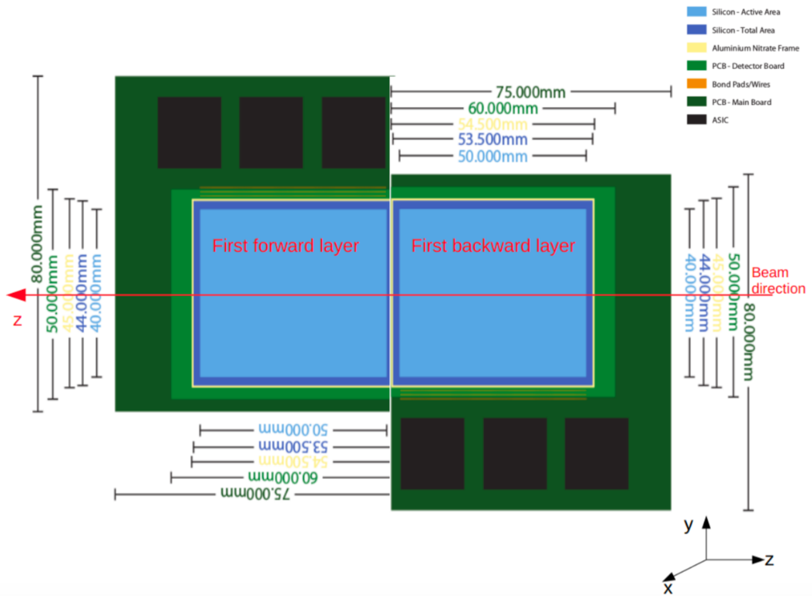


SKIROC-2 ASICs

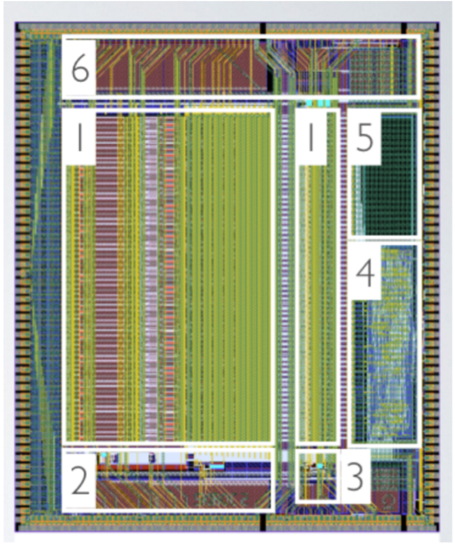


Second layer PCB

First layer PCBs



- 64 chn, designed for Si-PIN (5mm²; 20 pF)
- dyn. range: 0.1 MIP/4 fC … 2500 MIPs/10 pC
- charge PA (positive), slow & fast shaper, 15 depth SCA, TDC & ADC (12 bit), 4kbytes RAM
- PowerPulsing: ~ 25 μW/chn, ENC < 0.4 fC

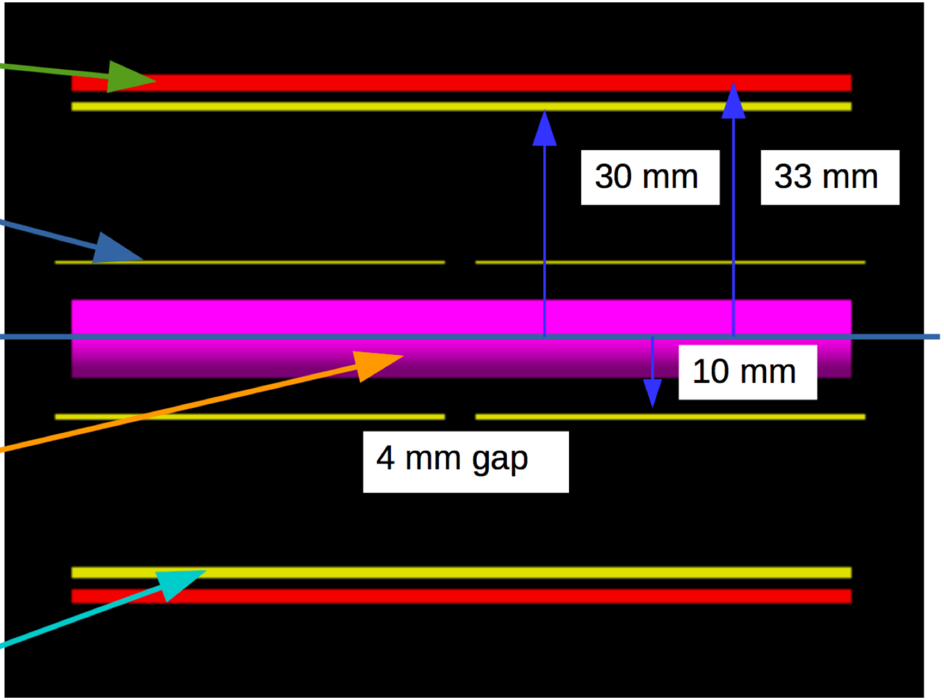


TI-STAR simulation

2 mm thick pad det.
pitch size: 0x3 mm
size: 10x10 cm

first layers 20 um thin, single-sided, double det.
pitch size: 260 um
size: 5x4 cm (2 items)

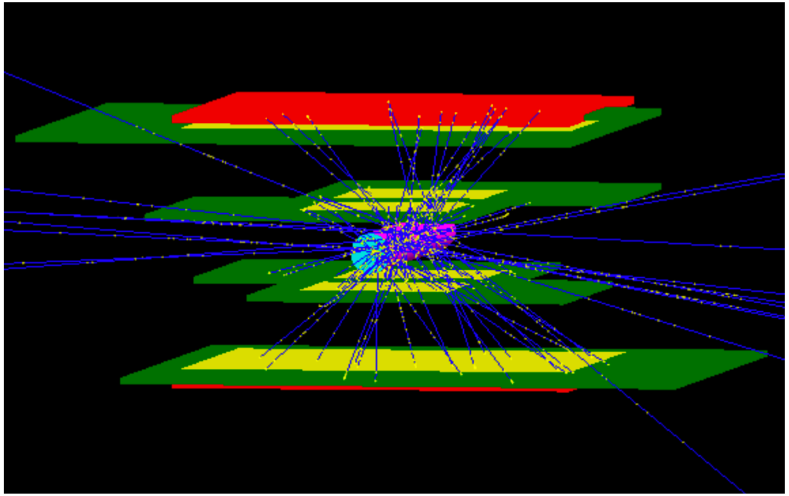
beam

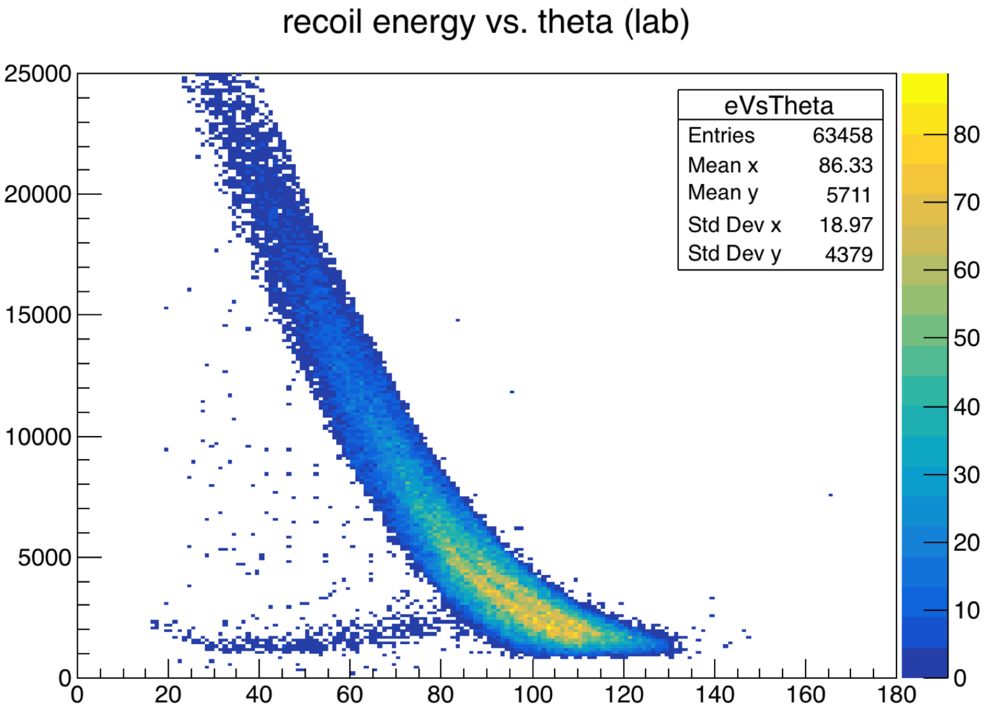


Gas target 10 cm length, 10 mm diameter, surrounded by 2 um Mylar, 8 um Be foil @ exit/entrance

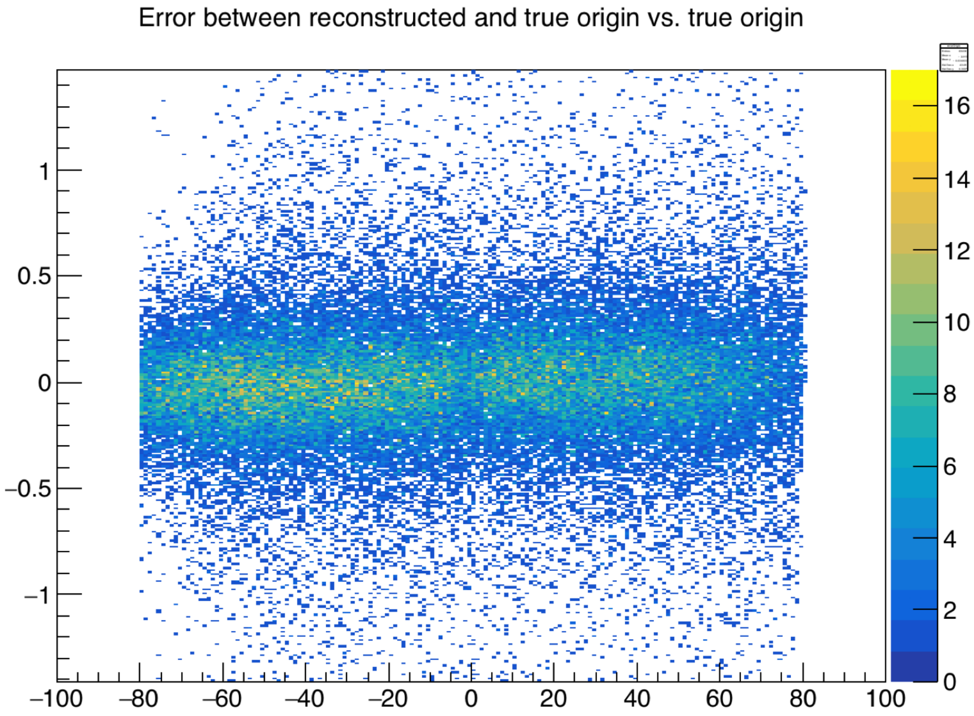
second layers 150 um thin, double-sided, single det.
pitch size: 512x512 um
size: 10x10 cm

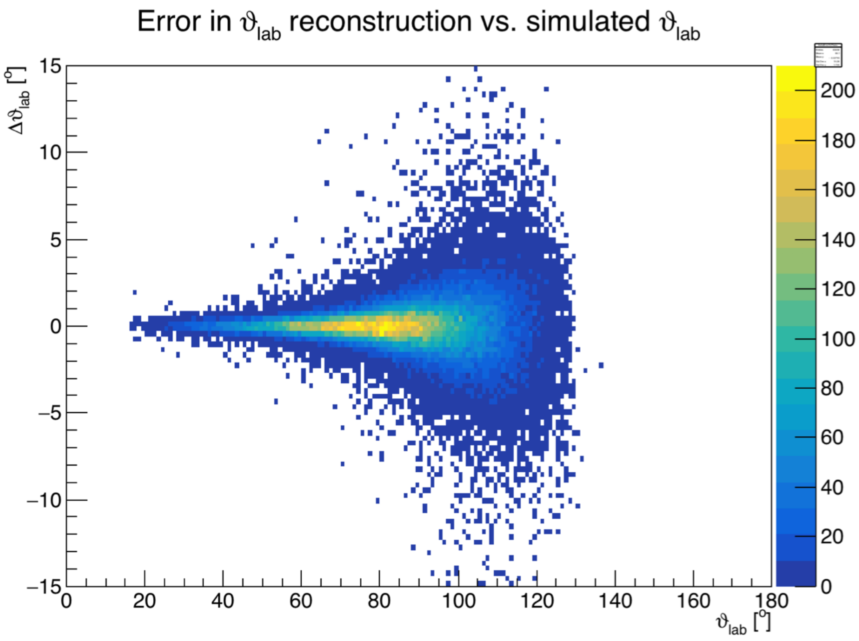
Silicon Tracker: Geant4 simulations



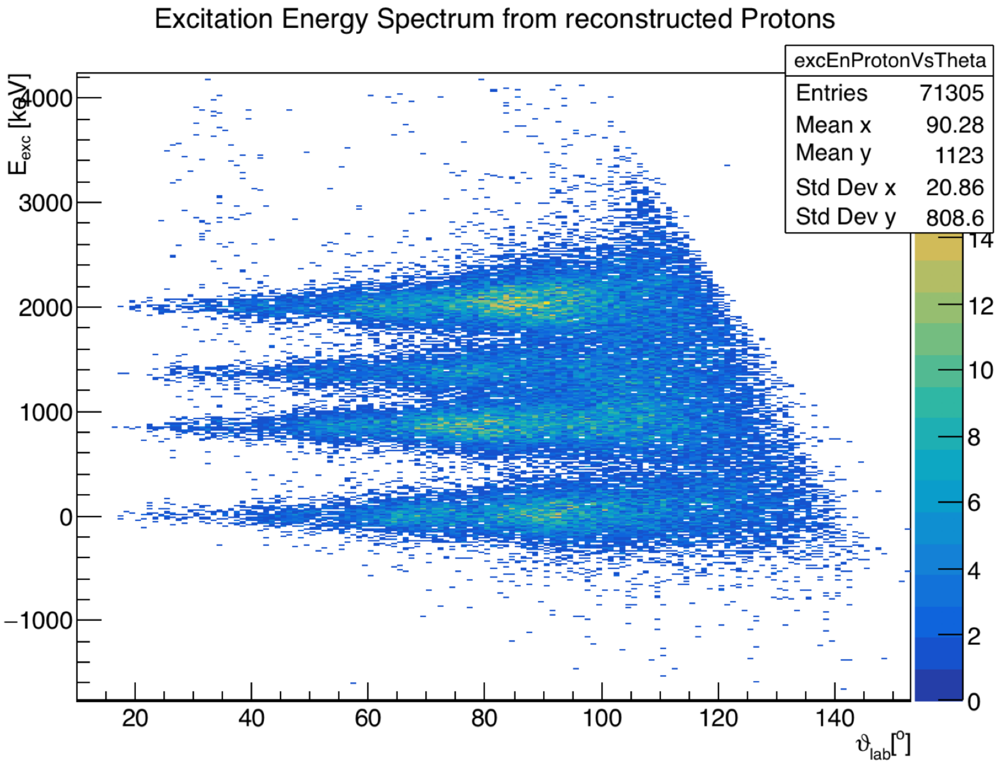


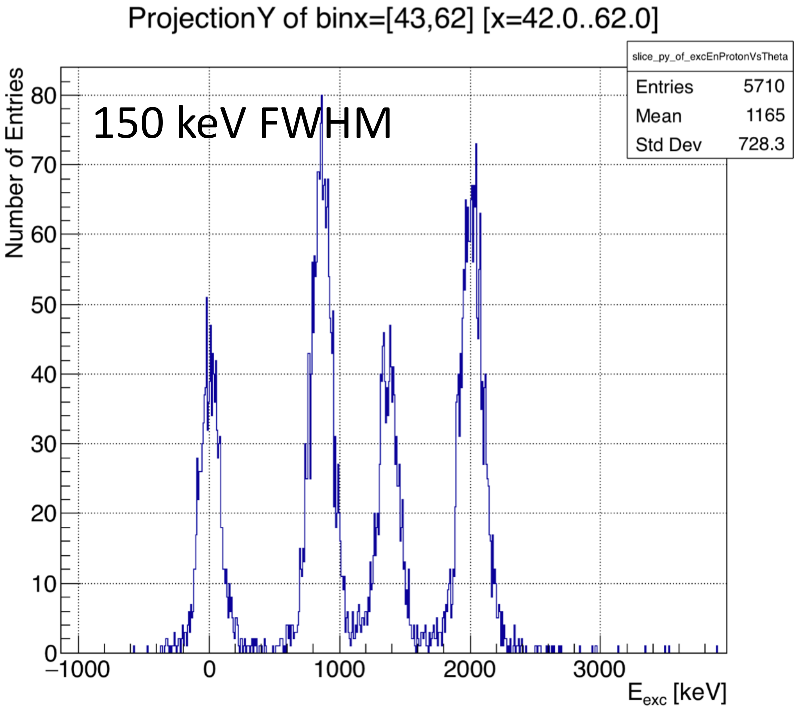
Silicon Tracker: Geant4 simulations



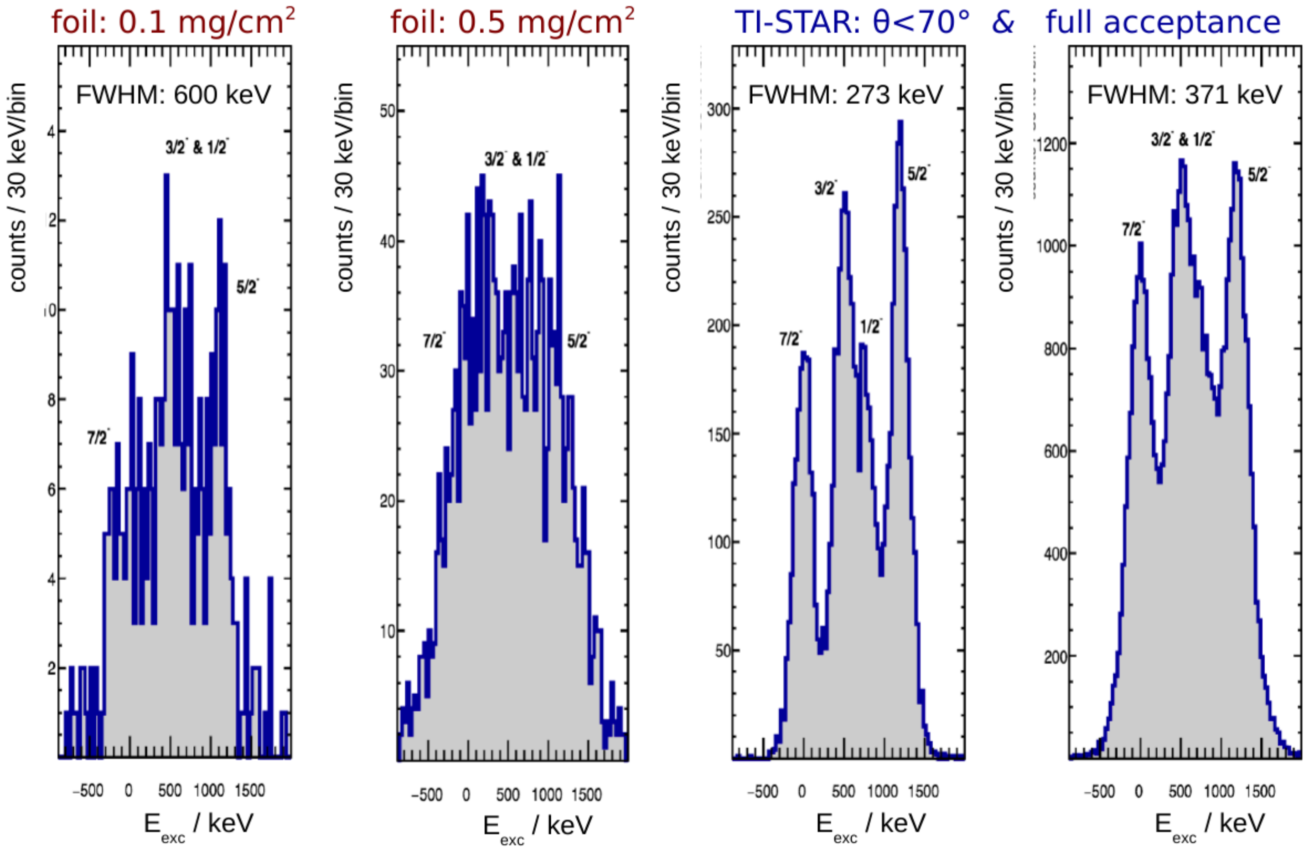


Silicon Tracker: Geant4 simulations



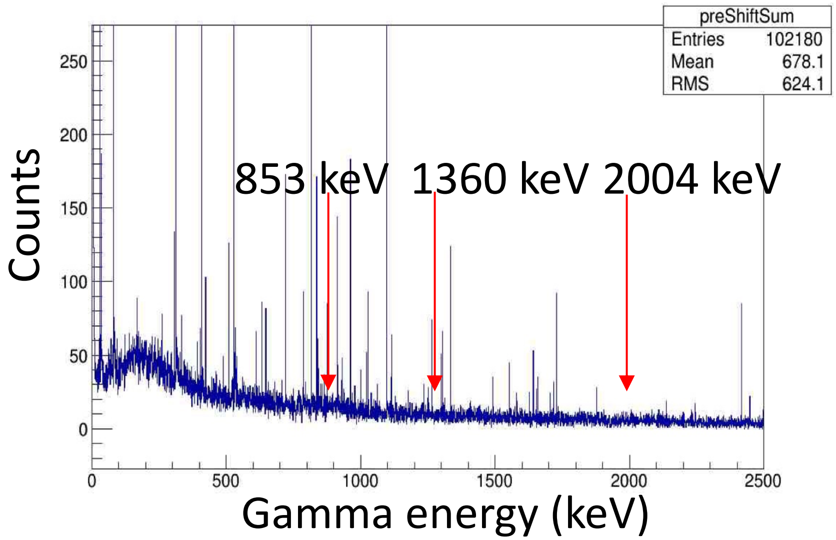


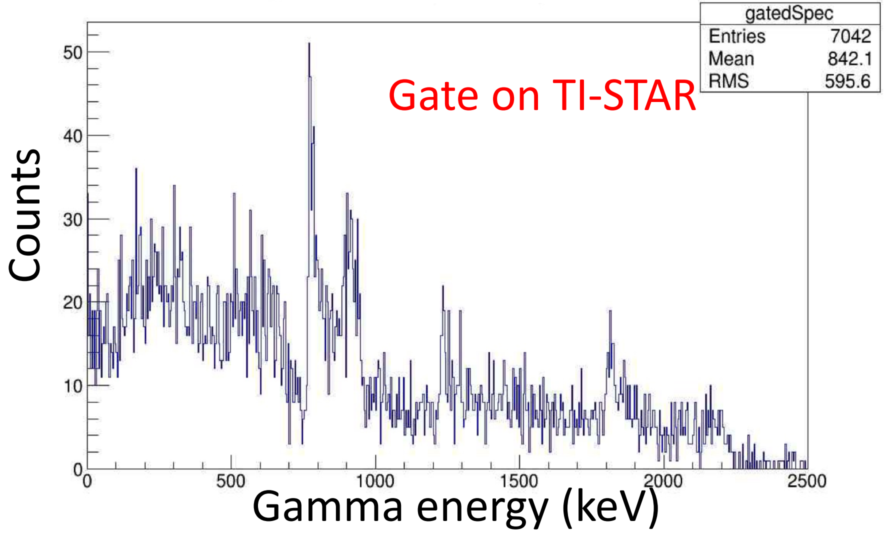
TI-STAR performance: $^{136}Sn(d,p)$



Implementing Realistic Beam Physics

- $^{132}Sn(d,p)$ @ 6 MeV/u
- TI-STAR gas target (2.84 mg/cm^2 D2) with foils





Implementing Realistic Beam Physics

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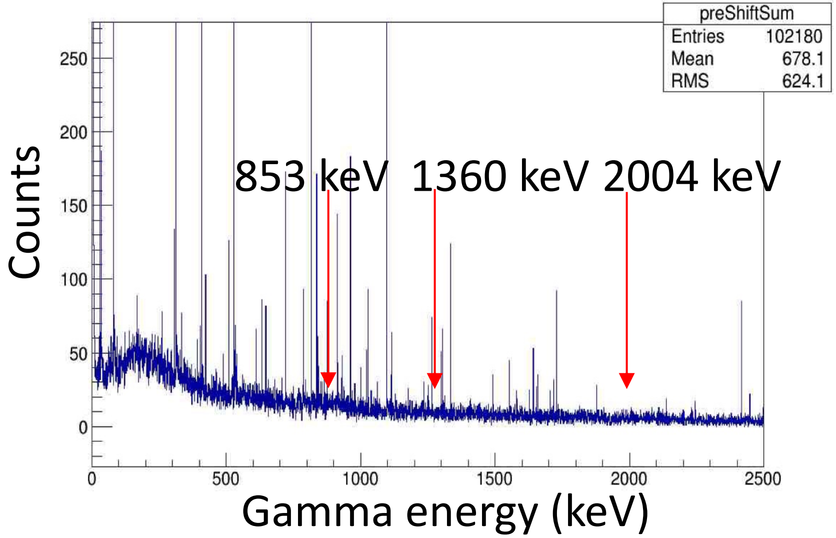
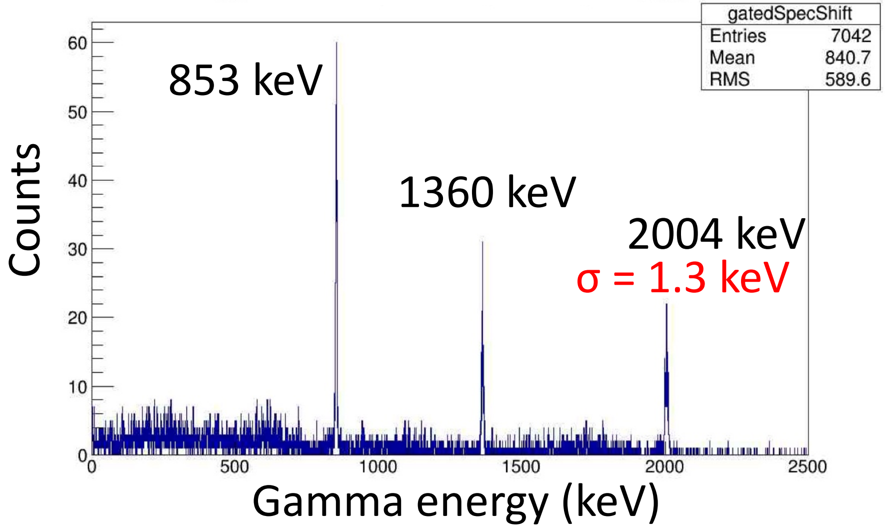
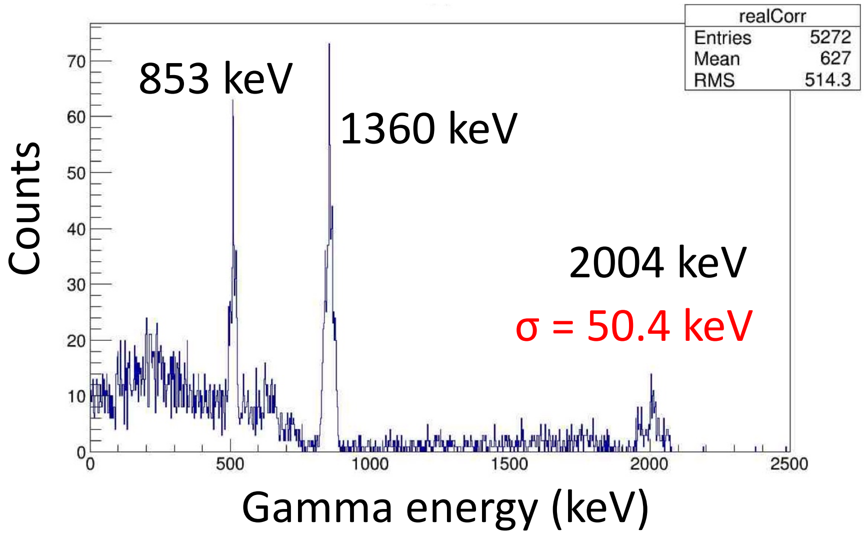
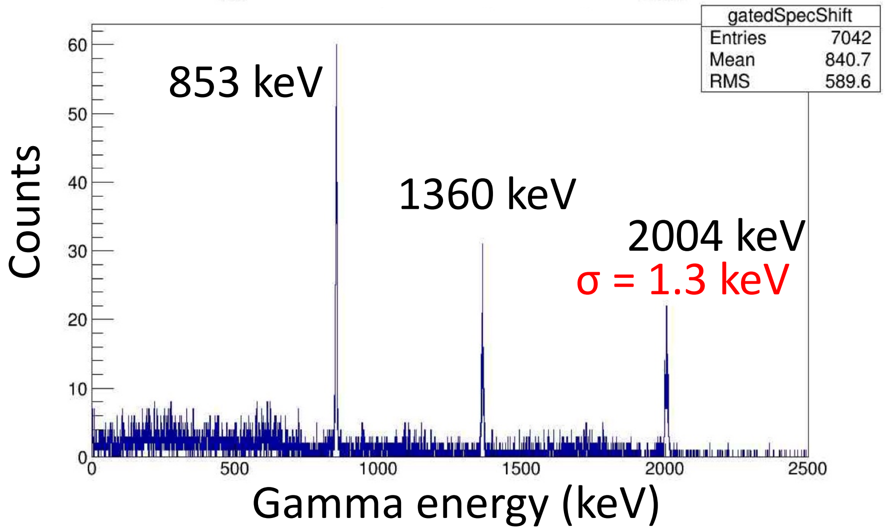




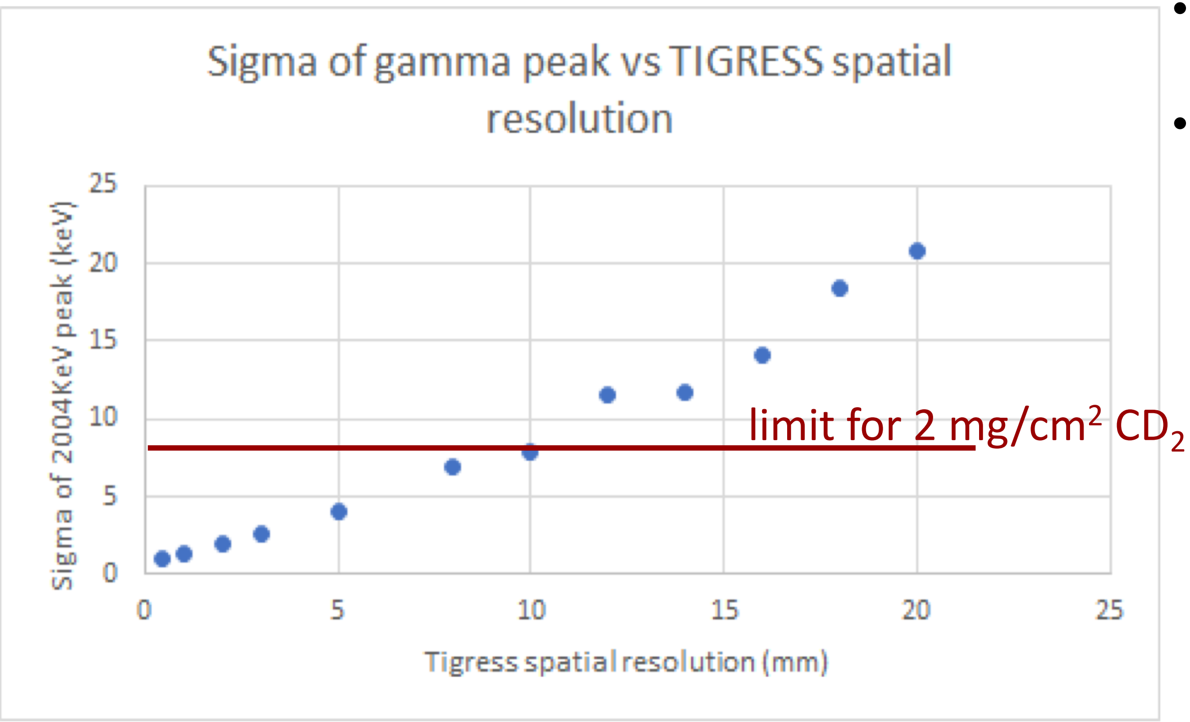
Implementing Realistic Beam Physics

- $^{132}Sn(d,p)$ @ 6 MeV/u
- comparison: CD_2 foil; 10mg/cm^2

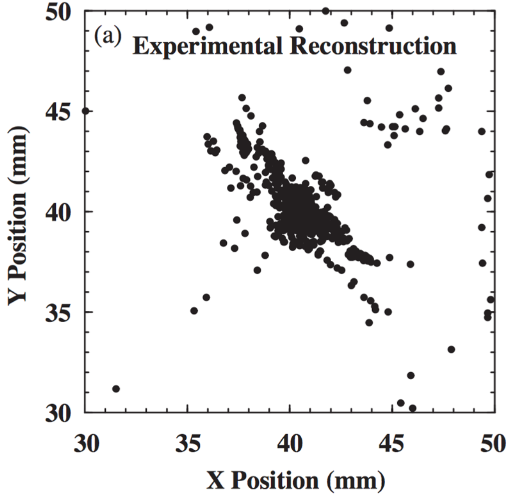




TIGRESS energy resolution using TI-STAR

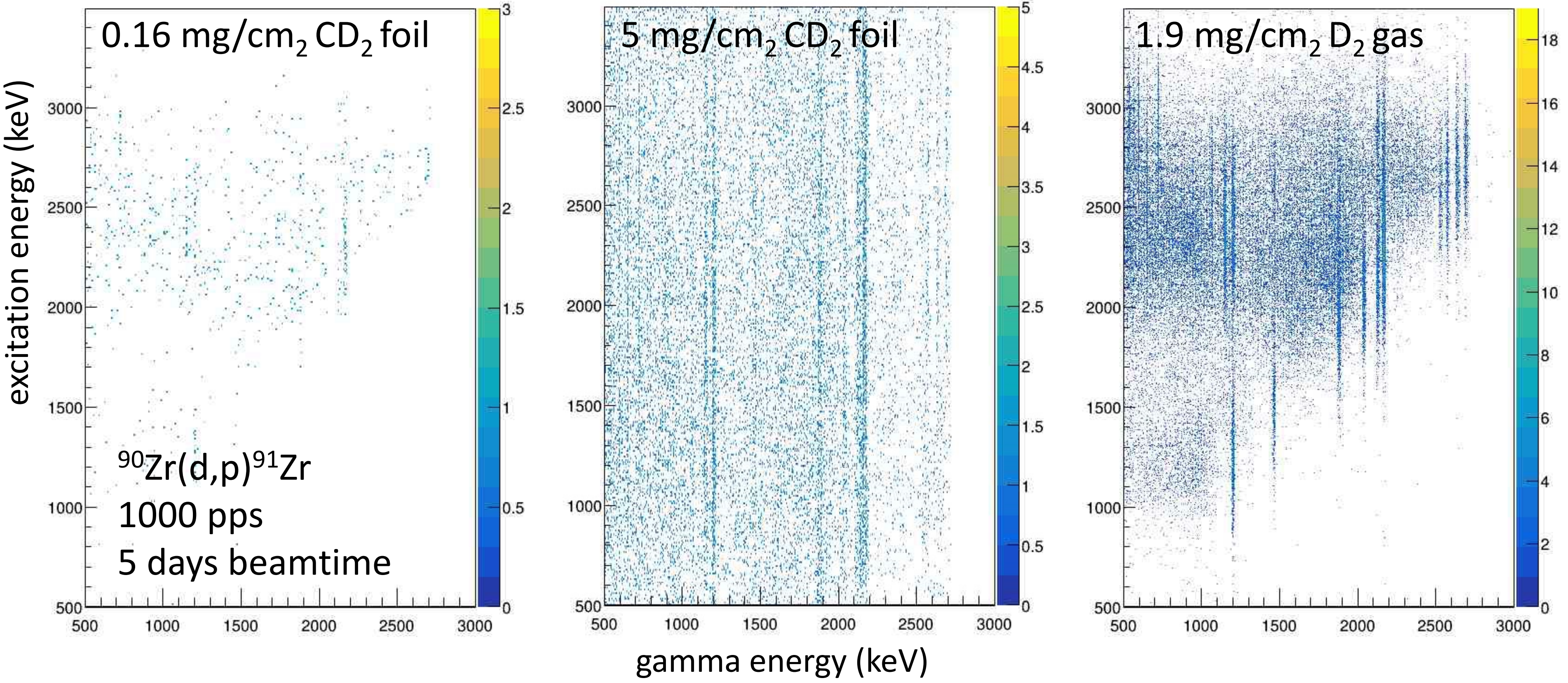


- Gamma ray resolution not limited by target thickness
- PSA and gamma ray tracking limiting factors

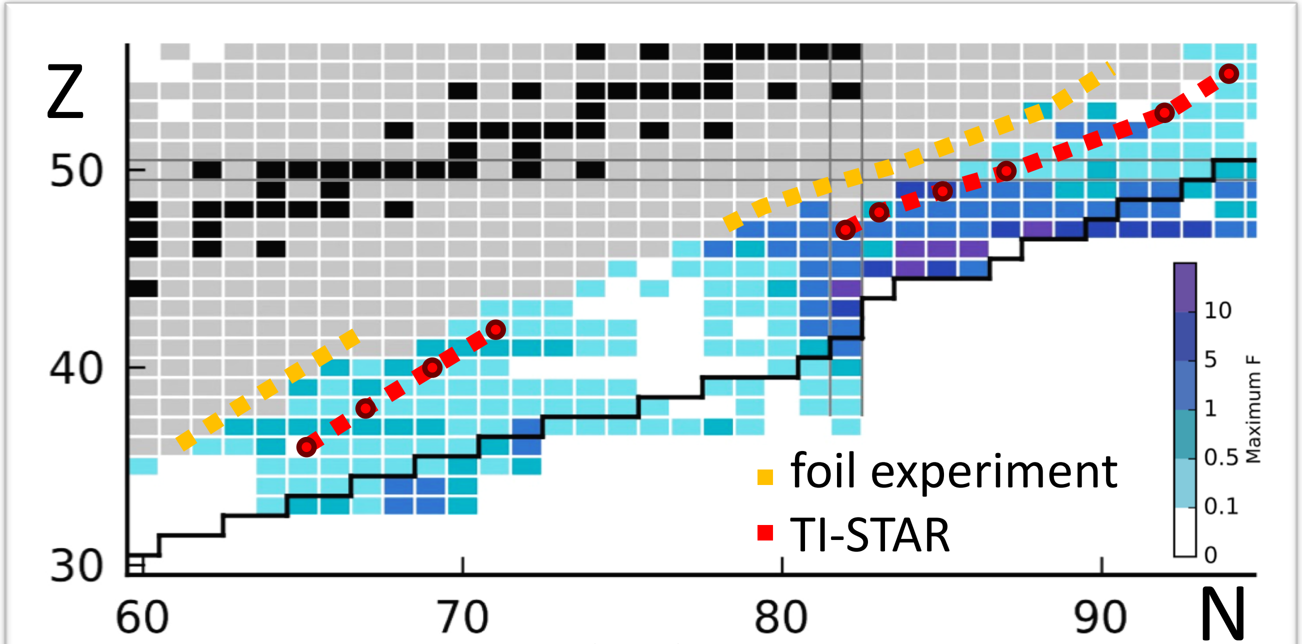


C.E. Svensson et al. / NIM A 540 (2005) 348–360

Oslo-method using TI-STAR and TIGRESS



Neutron capture rates accessible using ARIEL beams

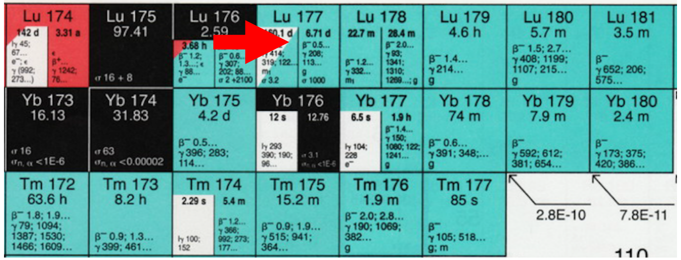


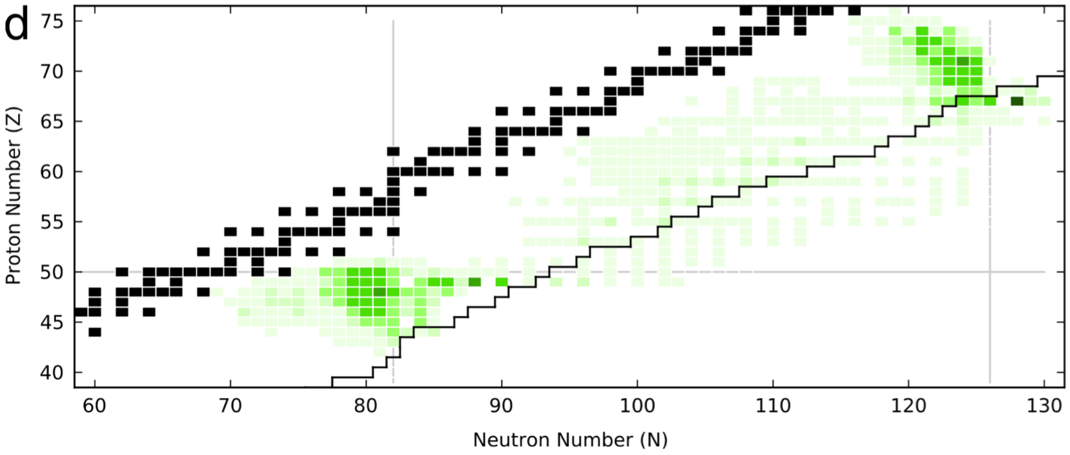
adapted from Prog. Part Nucl Phys 86 (2016) 86-126

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



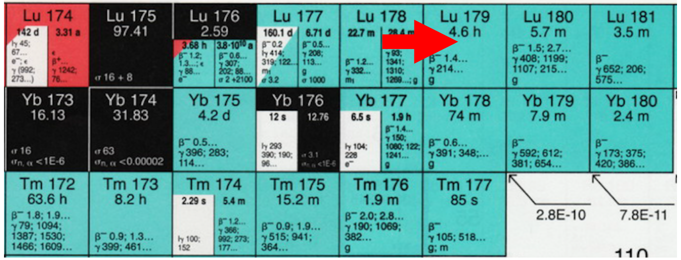


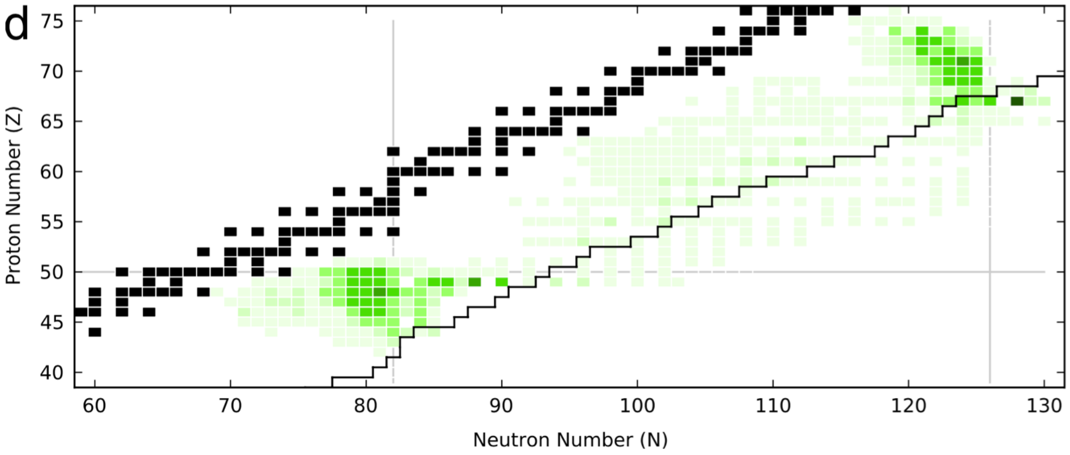
Step 1: establish γ-Oslo at TIGRESS

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 CD_2 target in SHARC
- understand delta electrons in SHARC when using thick targets
- beam impurities will be a challenge, maybe EMMA can help



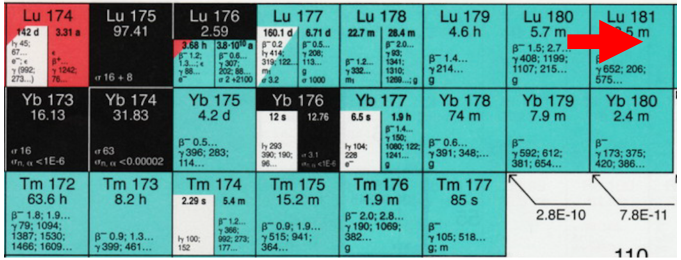


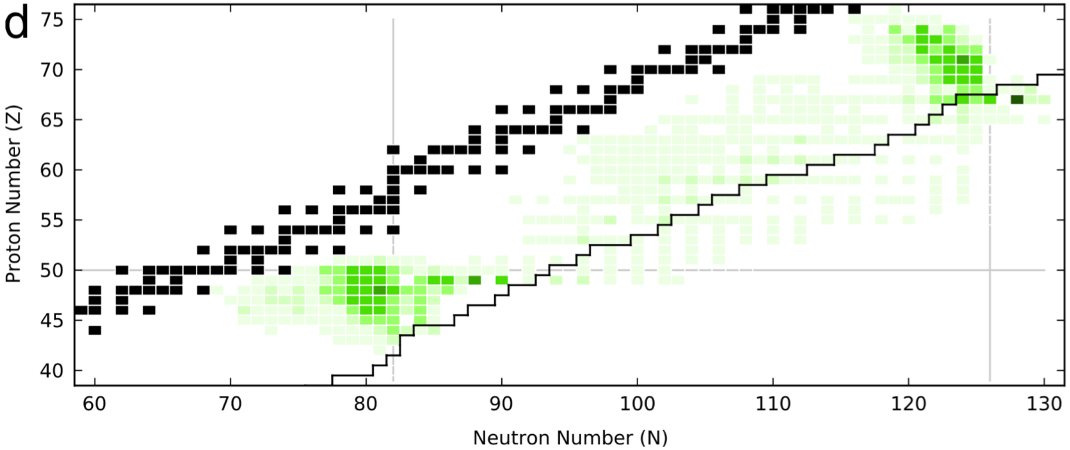
Step 2: pre-CANREB beams

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)



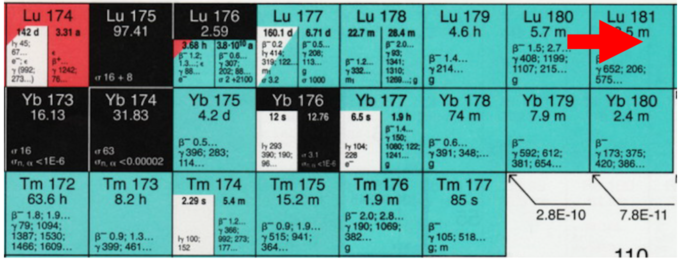


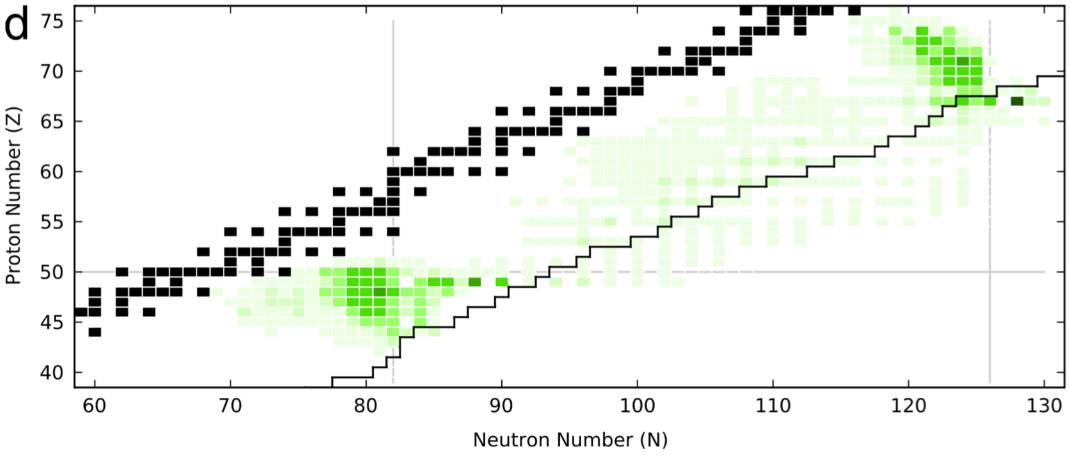
Step 3: experiments with CANREB and SHARC

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)





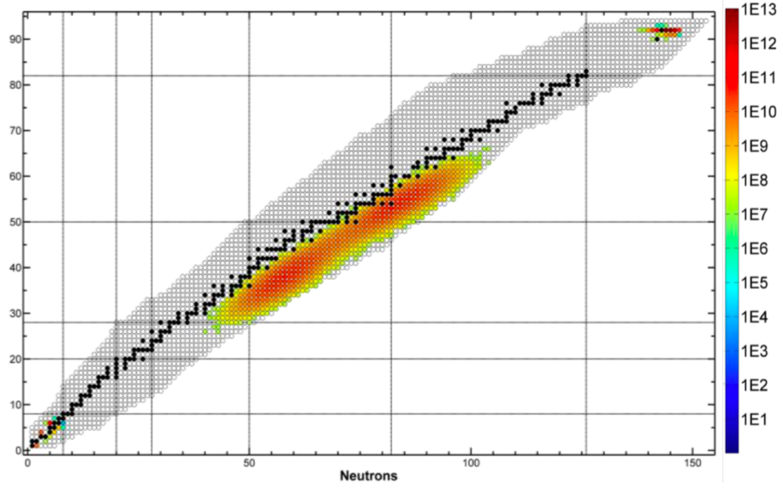
Step 3: experiments with CANREB and SHARC

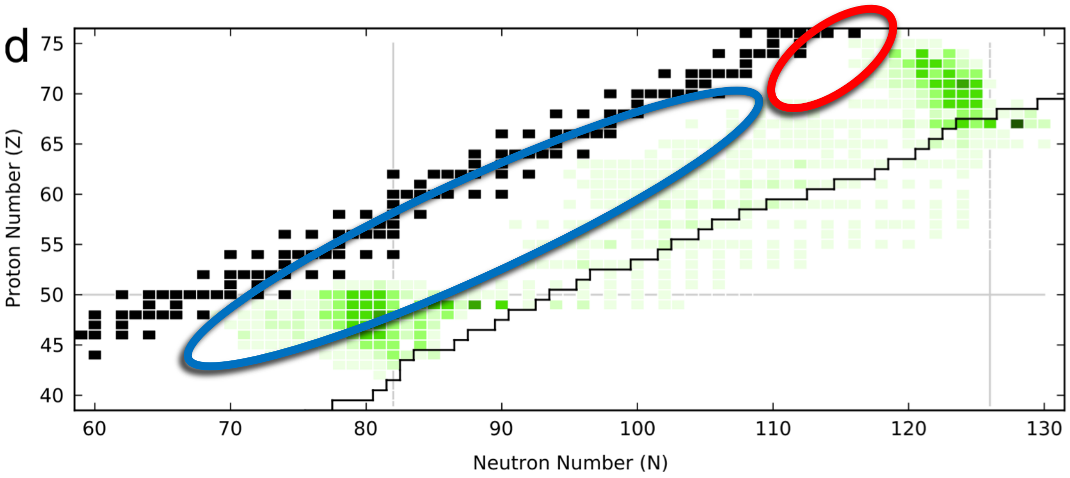
A systematic physics program at ARIEL

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