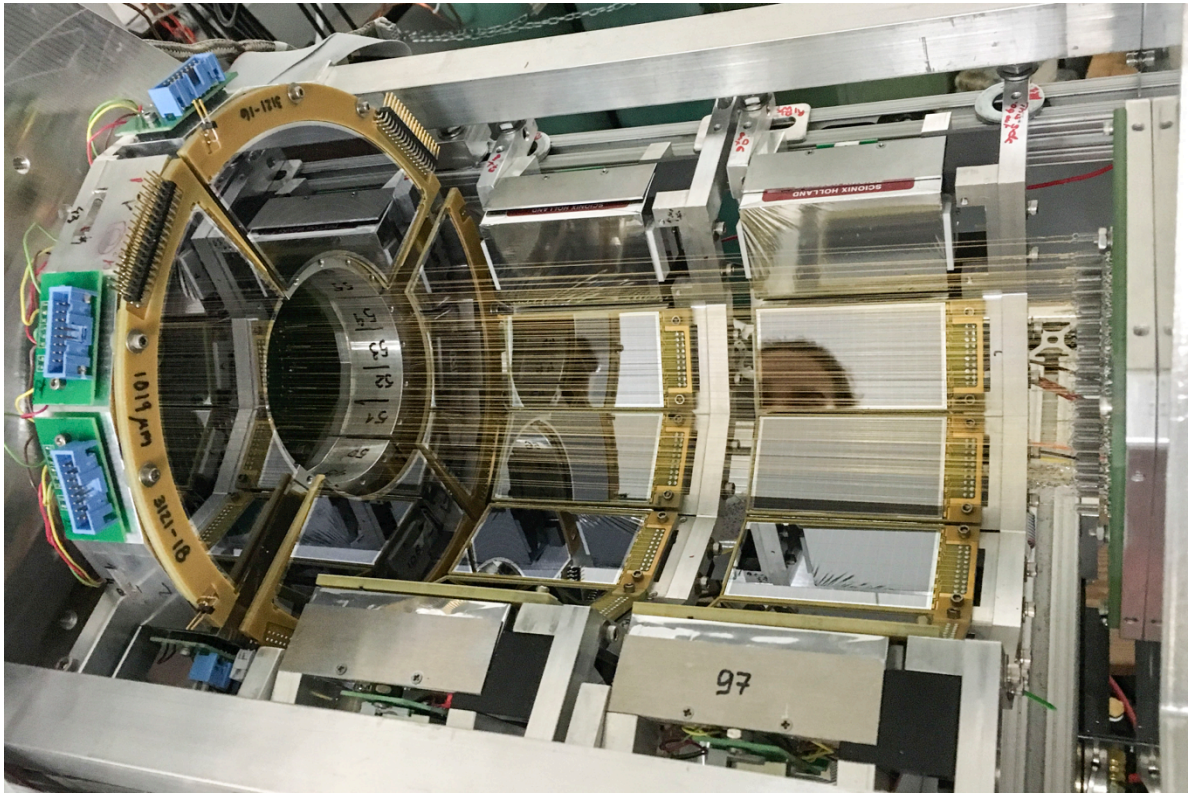
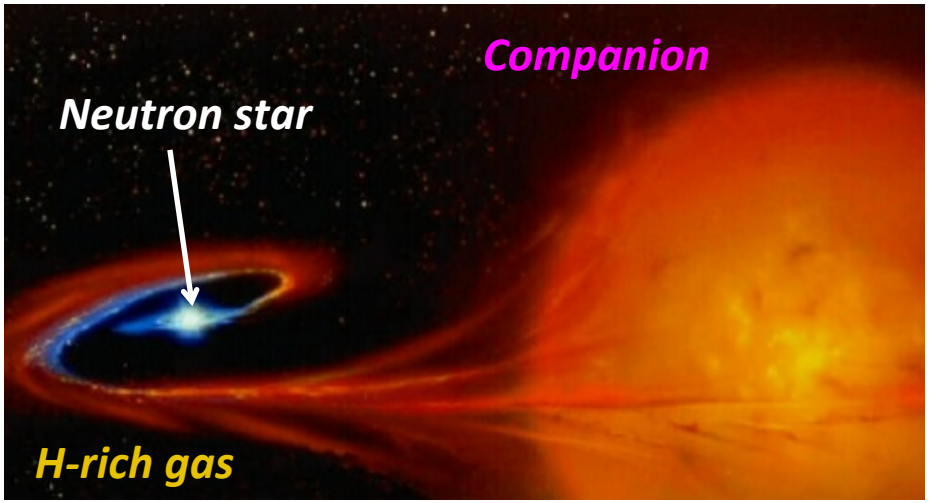
ANASEN at ATLAS:
Current Status and Future Possibilities



Catherine Deibel
Jeffery Blackmon
Louisiana State University

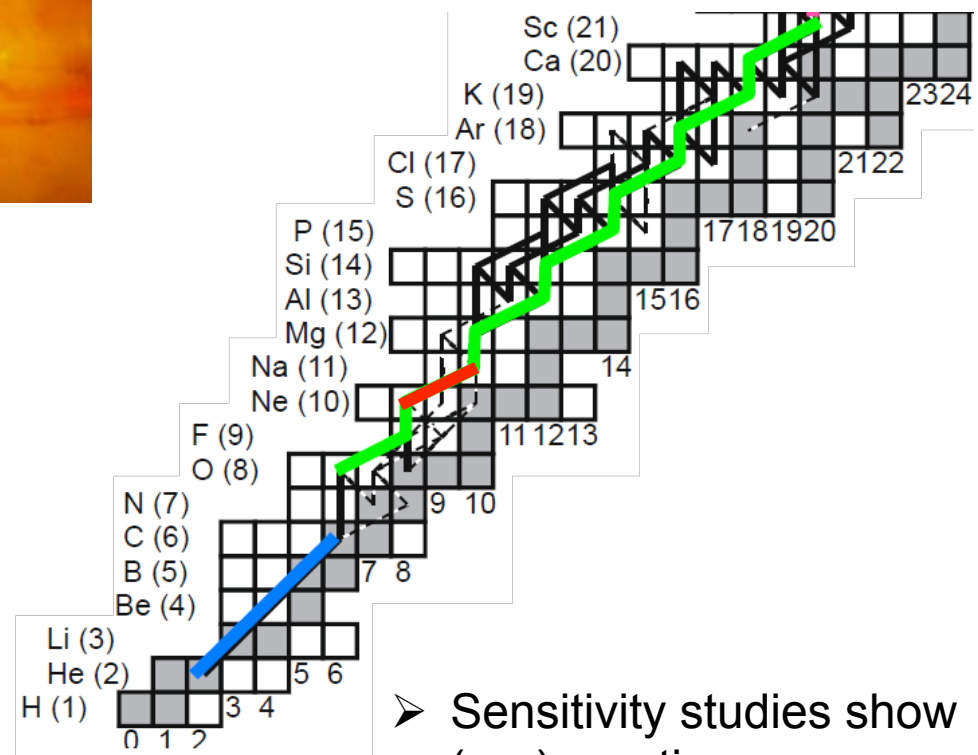
Type I X-ray Bursts



- Most common stellar explosions
  - X-ray binary with periodic bursts
  - 10-100 s bursts recurring ~days
- Thermonuclear explosions

Cyburt et al., APJ (2016)

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha, \gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha, p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p, \gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p, \gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha, p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha, p)^{17}F$	D	5.8	1
7	$^{23}Al(p, \gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha, p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p, \gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p, \alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha, \gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha, p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha, p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha, \gamma)^{28}Si$	U	1.2	2

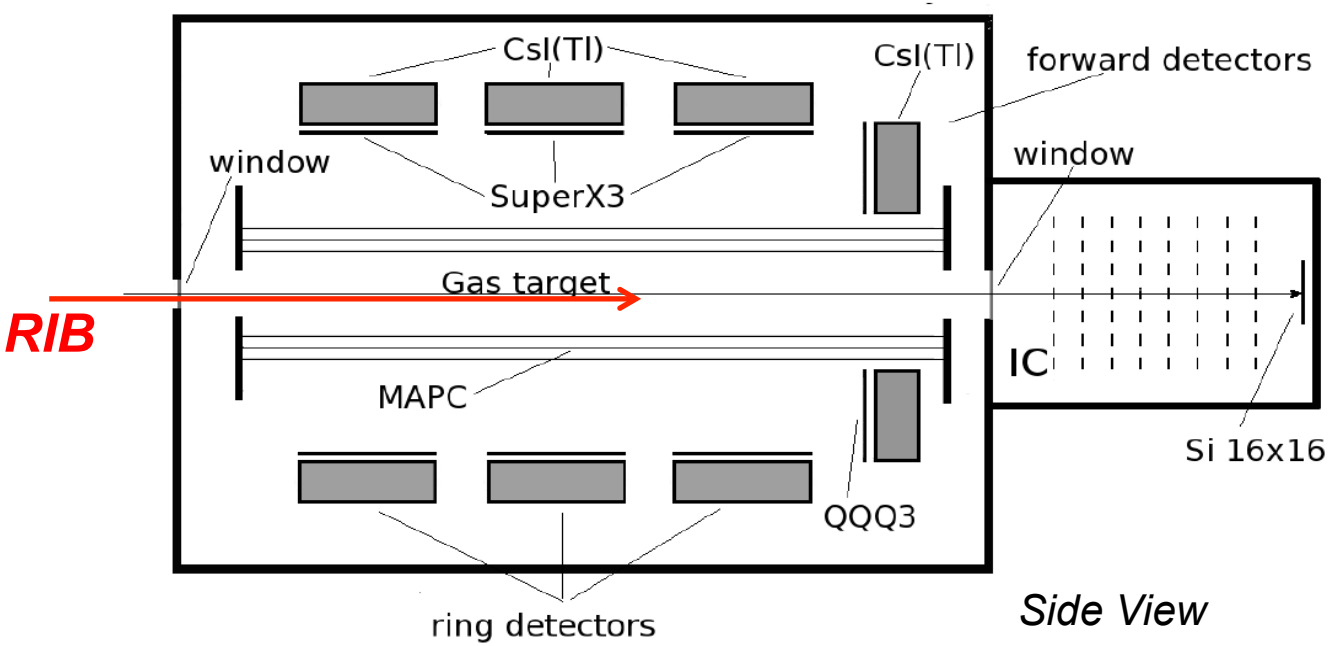


- Sensitivity studies show (α,p) reactions are particularly important

ANASEN

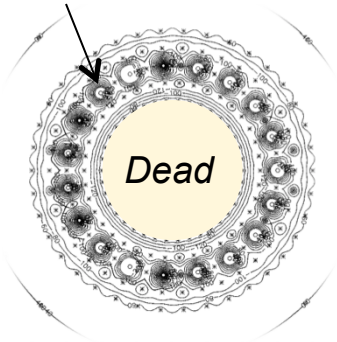
Array for Nuclear Astrophysics and Structure with Exotic Nuclei

- Extended active gas target/detector
- He-CO_2 gas for (α,p) reaction studies
- Cylindrical proportional counter surrounding beam axis
  - *7μm* diam carbon fiber → High Gain
- Over 1000 cm^2 of Si-strip detectors (28+) w/ CsI & ASIC electronics (Sobotka *et al.*)



Side View

PC: individual sensitive volumes

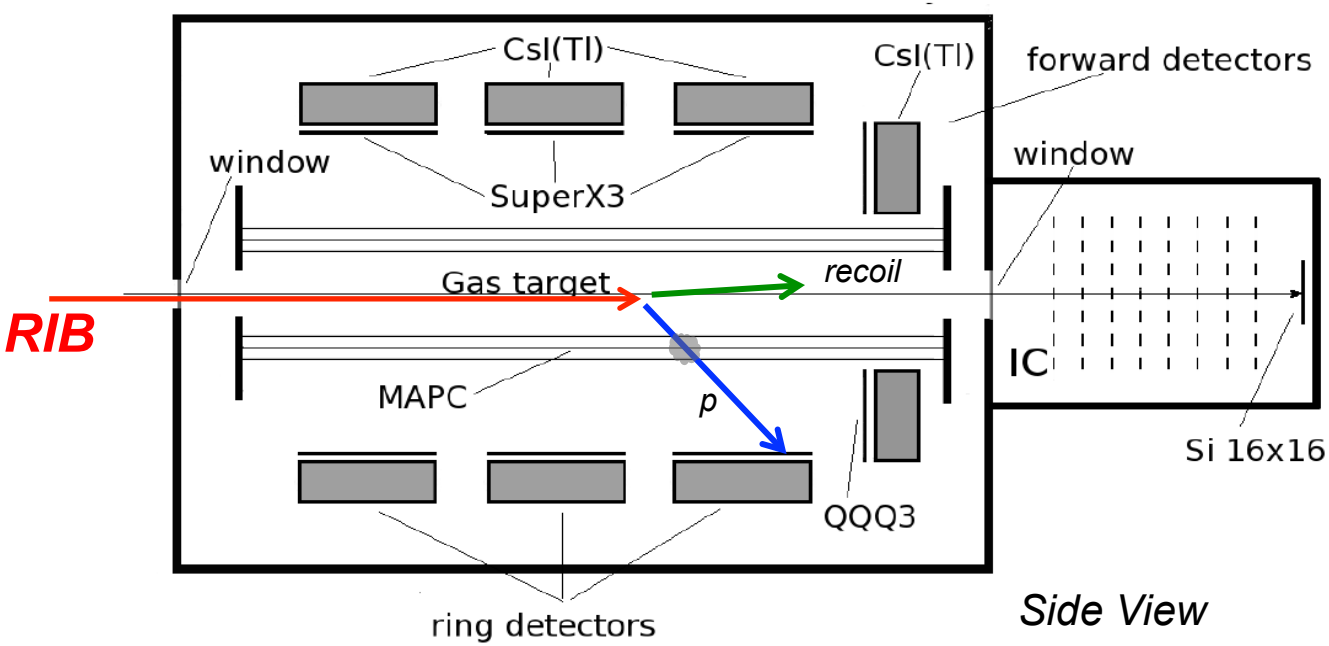


PC End View

ANASEN

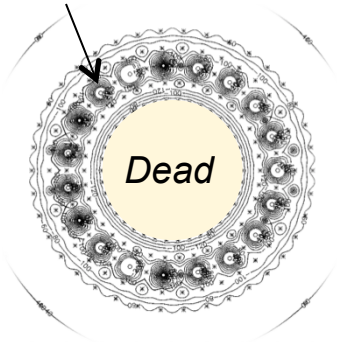
Array for Nuclear Astrophysics and Structure with Exotic Nuclei

- Extended active gas target/detector
- He-CO_2 gas for (α,p) reaction studies
- Cylindrical proportional counter surrounding beam axis
  - *7μm* diam carbon fiber → High Gain
- Over 1000 cm^2 of Si-strip detectors (28+) w/ CsI & ASIC electronics (Sobotka *et al.*)



Side View

PC: individual sensitive volumes

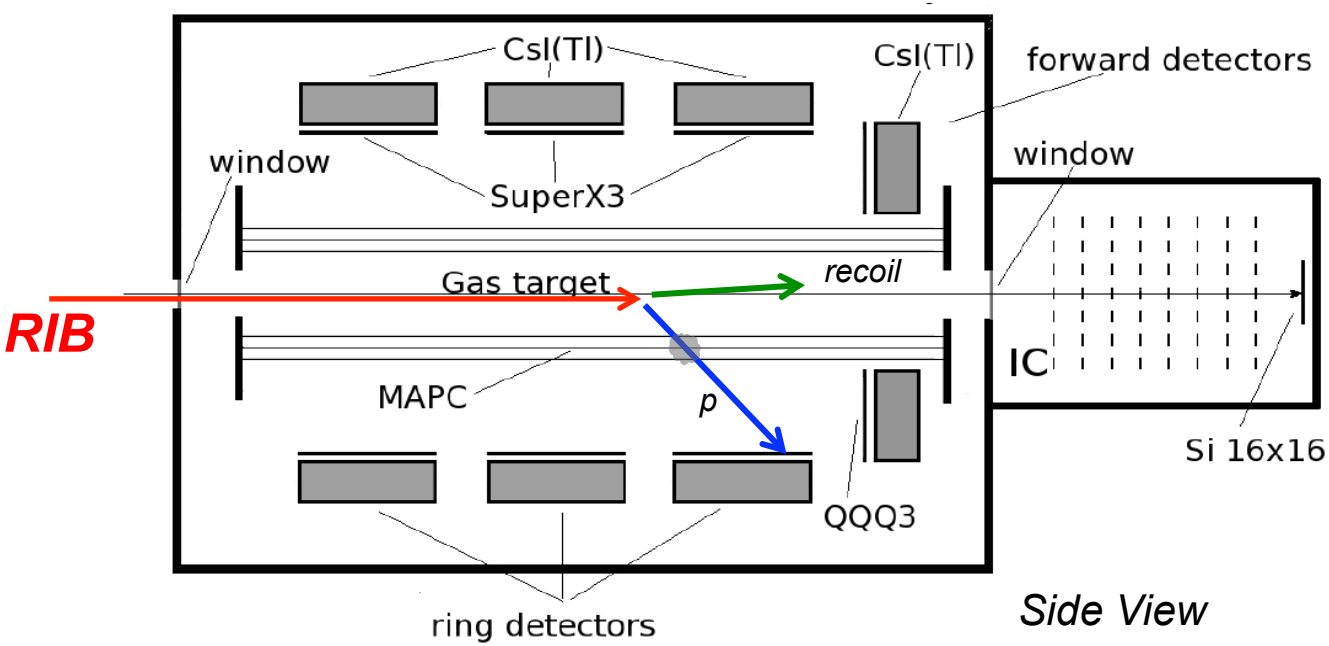


PC End View

ANASEN

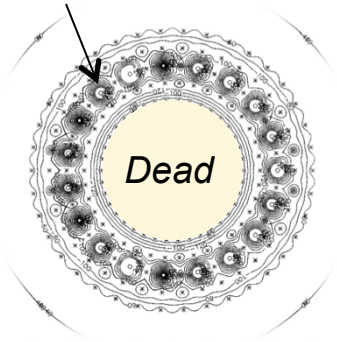
Array for Nuclear Astrophysics and Structure with Exotic Nuclei

- Extended active gas target/detector
- He-CO_2 gas for (α,p) reaction studies
- Cylindrical proportional counter surrounding beam axis
  - *7μm* diam carbon fiber → High Gain
- Over 1000 cm^2 of Si-strip detectors (28+) w/ CsI & ASIC electronics (Sobotka *et al.*)



Side View

PC: individual sensitive volumes



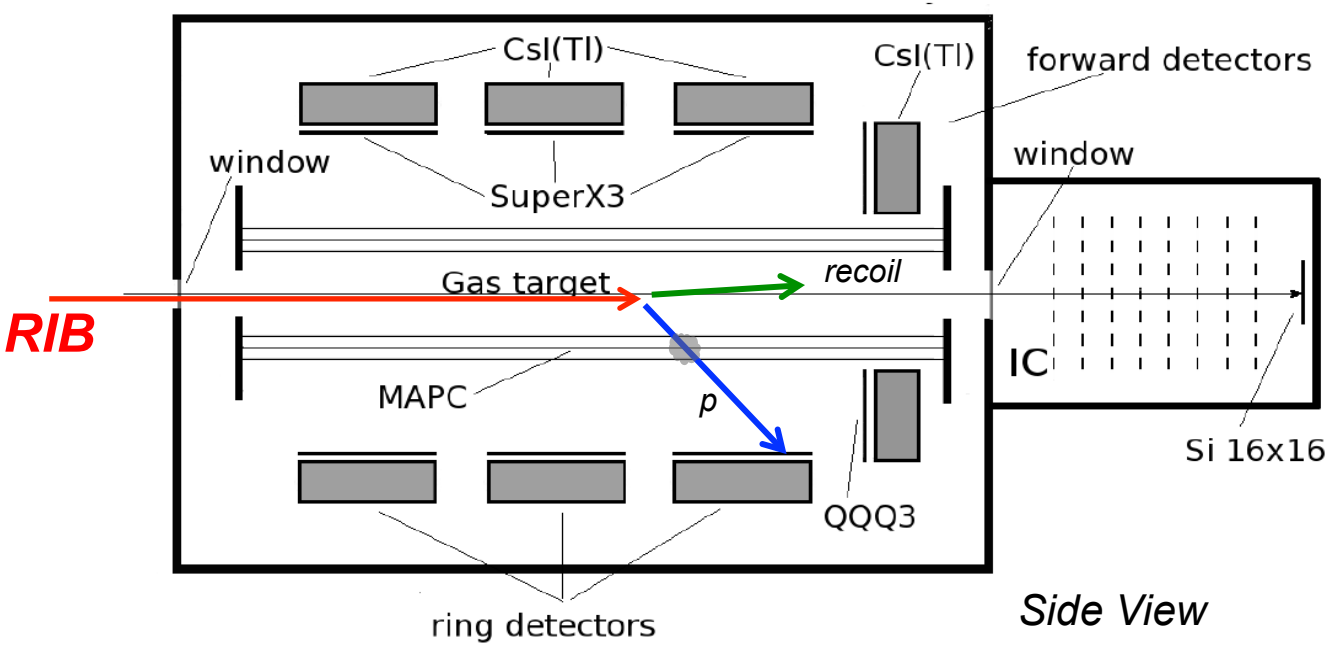
PC End View

1. ΔE in PC → particle identification
2. Position Si + Position PC → θ_{lab}
3. Energy Si +θ_{lab} → E_{cm}

ANASEN

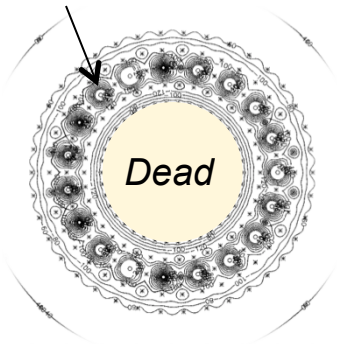
Array for Nuclear Astrophysics and Structure with Exotic Nuclei

- Extended active gas target/detector
- He-CO_2 gas for (α,p) reaction studies
- Cylindrical proportional counter surrounding beam axis
  - *7μm* diam carbon fiber → High Gain
- Over 1000 cm^2 of Si-strip detectors (28+) w/ CsI & ASIC electronics (Sobotka *et al.*)



Side View

PC: individual sensitive volumes



PC End View

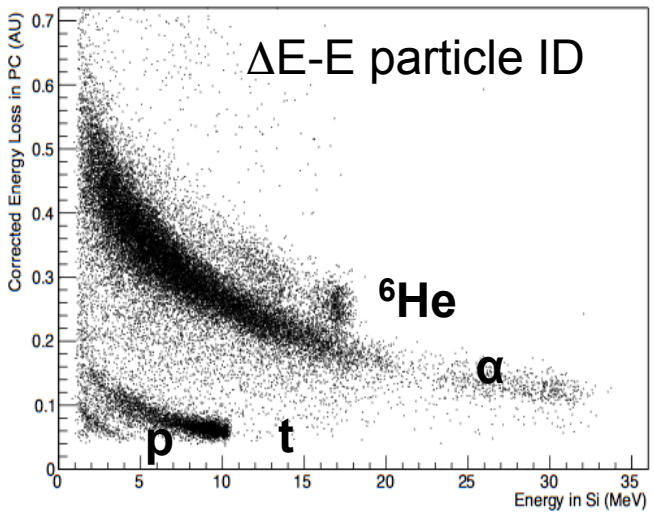
1. ΔE in PC → particle identification
2. Position Si + Position PC → θ_{lab}
3. Energy Si +θ_{lab} → E_{cm}

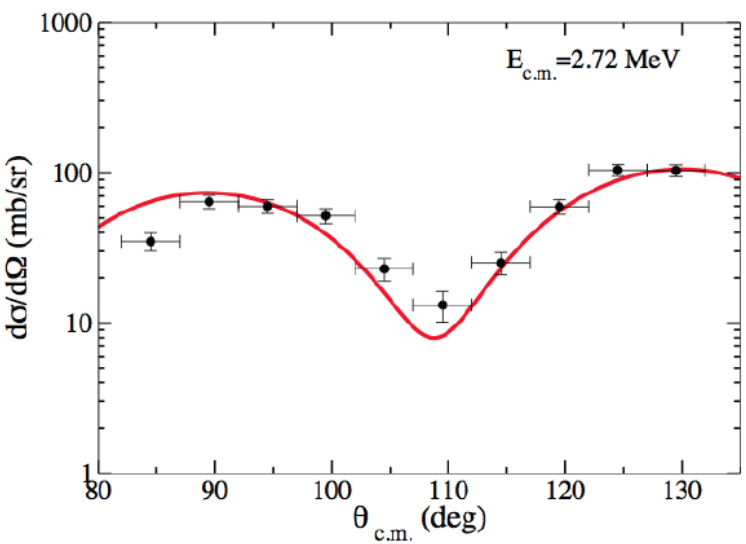
Entire excitation function simultaneously measured

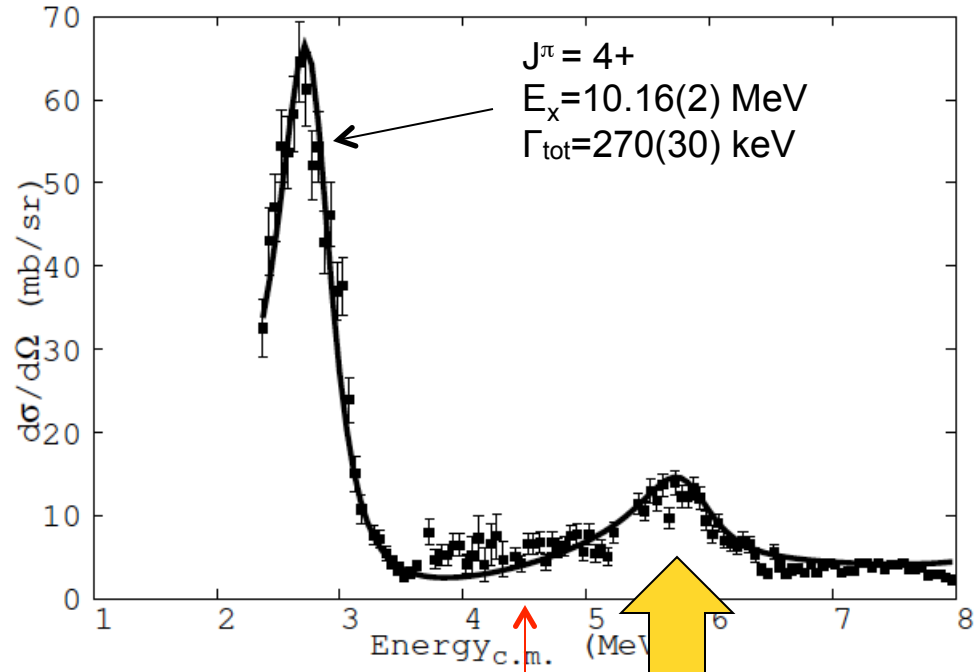
$^6He+\alpha$ Scattering

A. Kuchera et al.

First ANASEN RIB active target measurement with ^4He gas





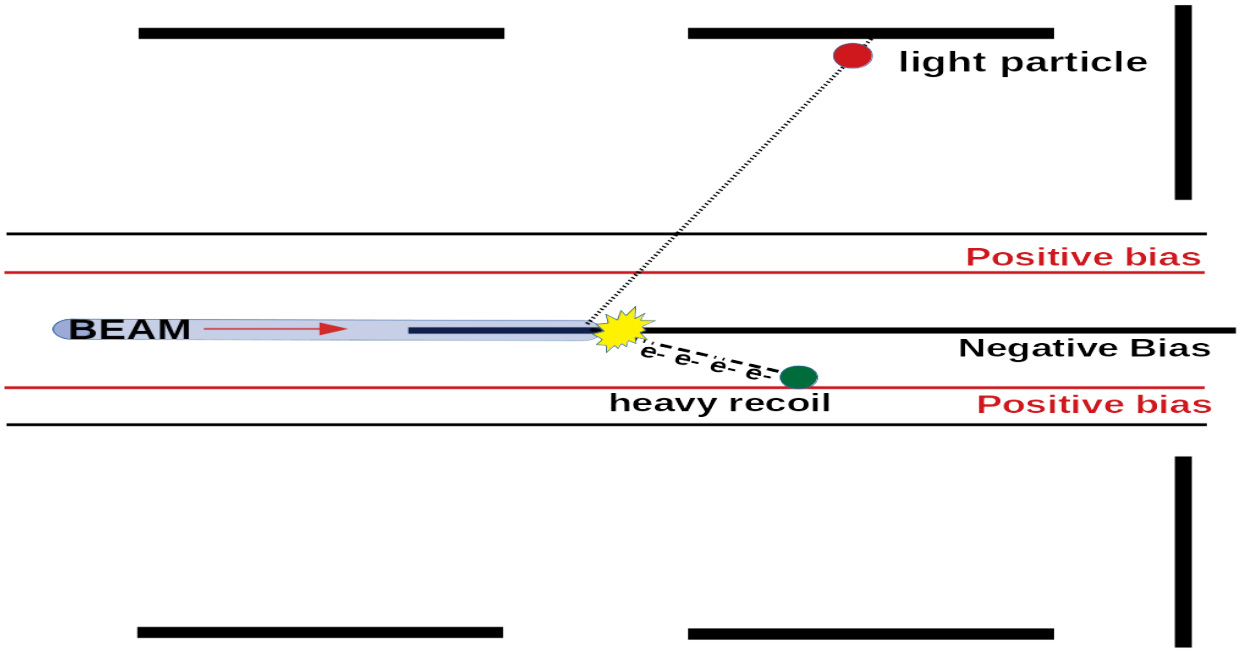


Expected position of 2nd 4^+

New resonance observed with properties consistent with 6^+ assignment

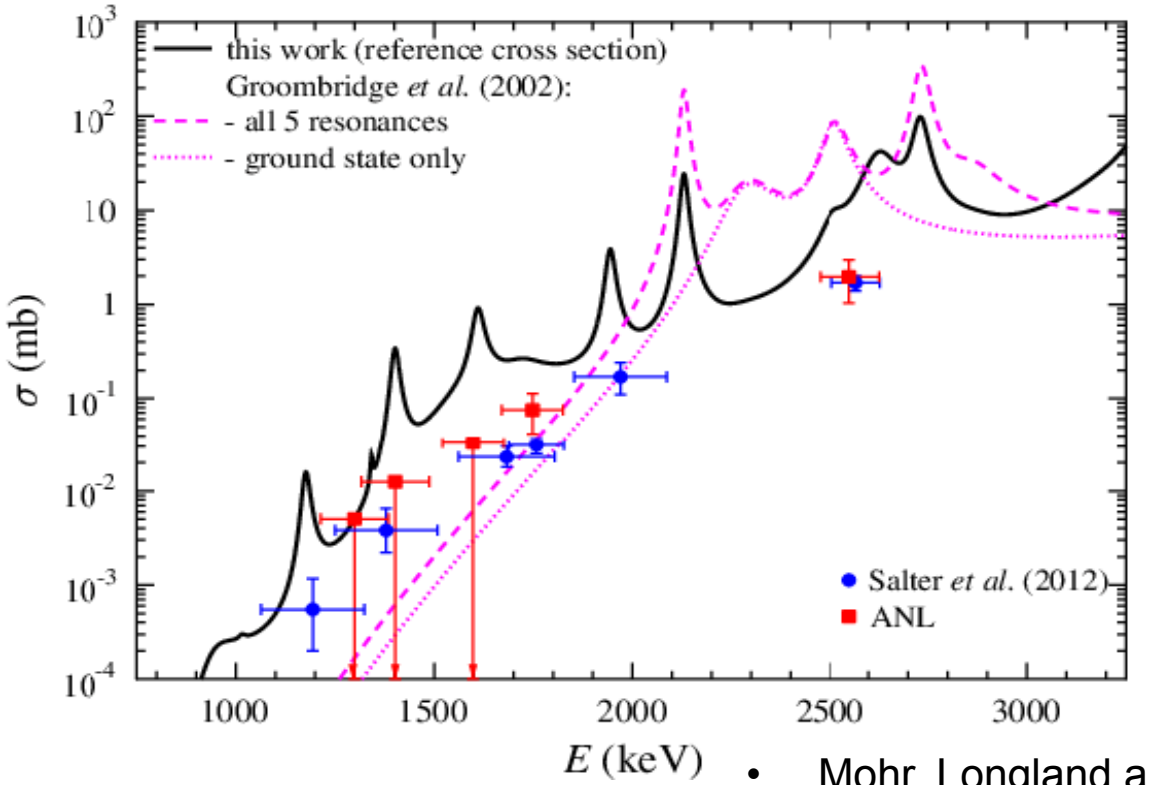
$^{18}Ne(\alpha,p)^{21}Na$ with ANASEN

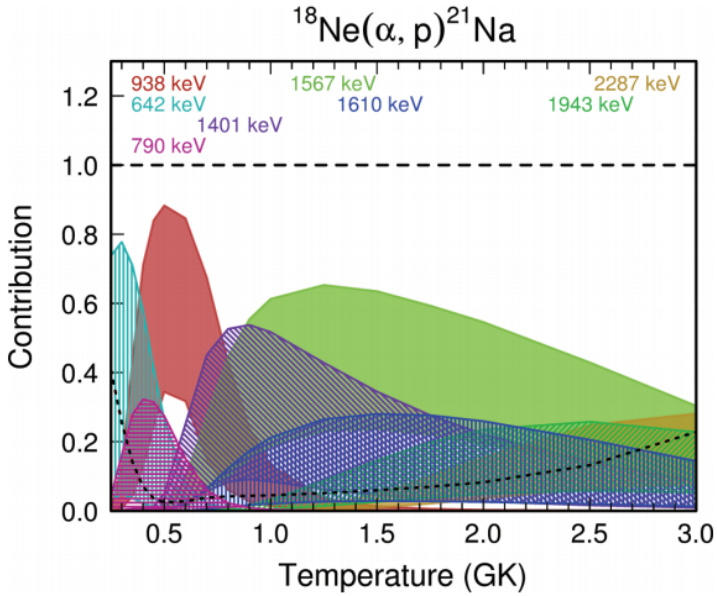
- Run in 2016 and 2018 at FSU
- $^{16}O(^{3}He,n)^{18}Ne$, $E_{beam}(^{16}O)$=112.5 MeV
- $E_{beam}(^{18}Ne)$= 72.34 MeV (4 MeV/A)
- Target : 96% ^{4}He & 4% CO_2
- Intensity ~3,000 pps Purity ~14%



Encouraging Analysis So Far

- Strongest $^{18}Ne(\alpha,p)^{21}Na_{gs}$ resonance in LLN data clearly observed
- Possible yields extractable down to almost E_{cm}>1.5 MeV (low statistics)?
- Working now on efficiencies for 1p and 2p channels

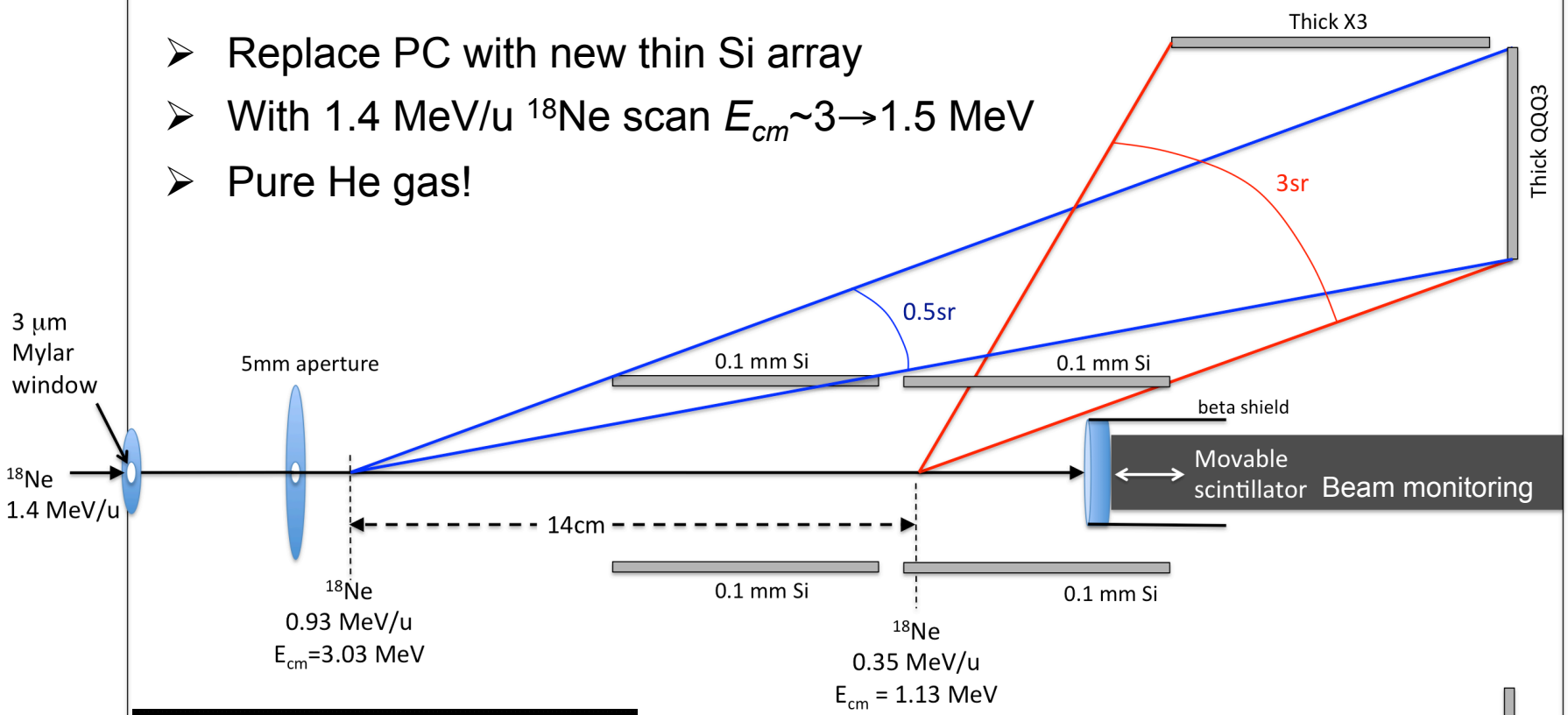


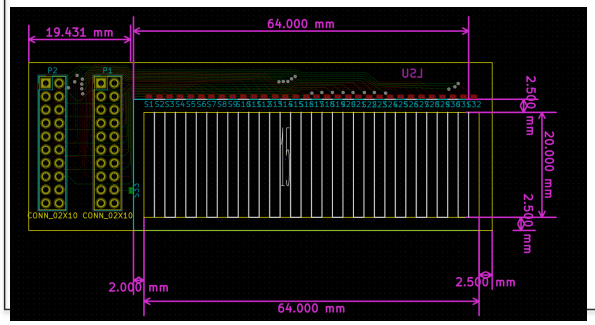


- Mohr, Longland and Iliadis, PRC 90 (2014)
- Mohr and Matic, PRC 87 (2013)
- Maria Anastasiou's (successfully defended!) PhD thesis

S1773: $^{18}Ne(\alpha,p)^{21}Na$ @ TRIUMF-ISAC

- Replace PC with new thin Si array
- With 1.4 MeV/u ^{18}Ne scan E_{cm}~3→1.5 MeV
- Pure He gas!

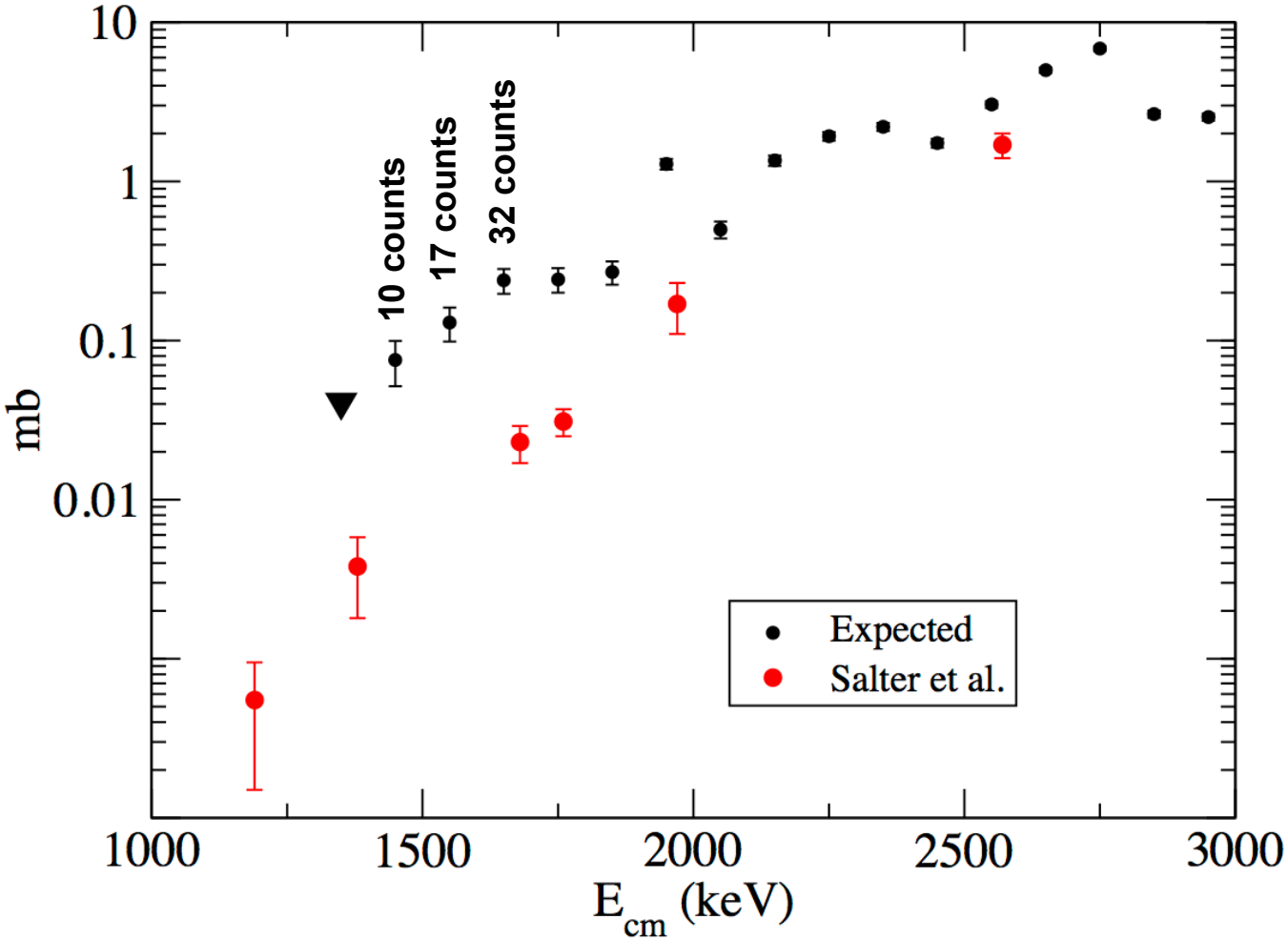




New ΔE Si design
32 strips (2mm wide) X 20 mm
(Univ. Autonoma de Barcelona)

S1773: $^{18}Ne(\alpha,p)^{21}Na$ @ TRIUMF-ISAC

- Use evaluated cross section of Mohr *et al.*
- Assume 5×10^5 ^{18}Ne/s for 18 shifts



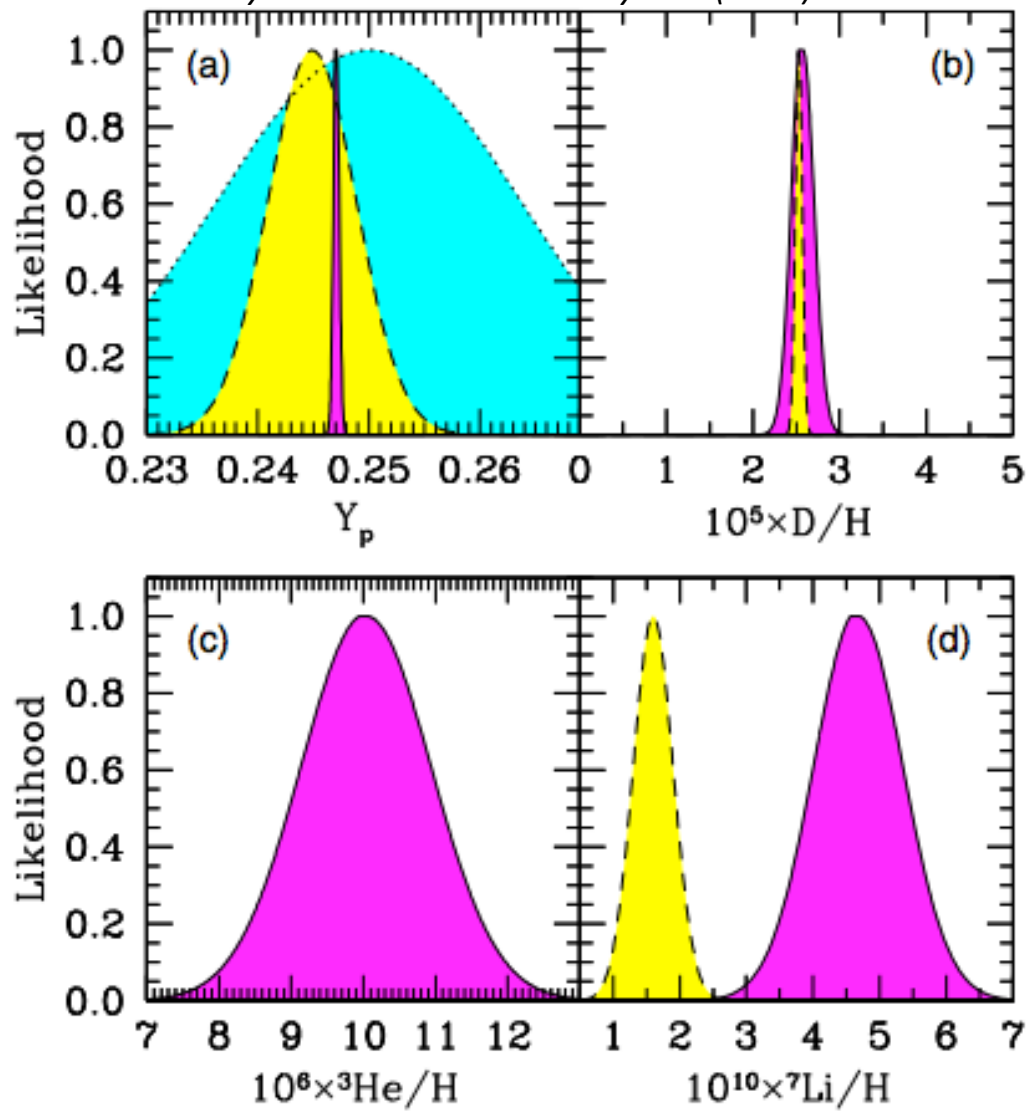
The Cosmological Lithium Problem

- ^{1}H, ^{2}H, ^{4}He in good agreement
- Li disagrees by more than 3σ

"All of the reactions that are ordinarily the most important for BBN have been well measured at the energies of interest. Typically, cross sections are known to ~10% or better, and these errors are already folded in."

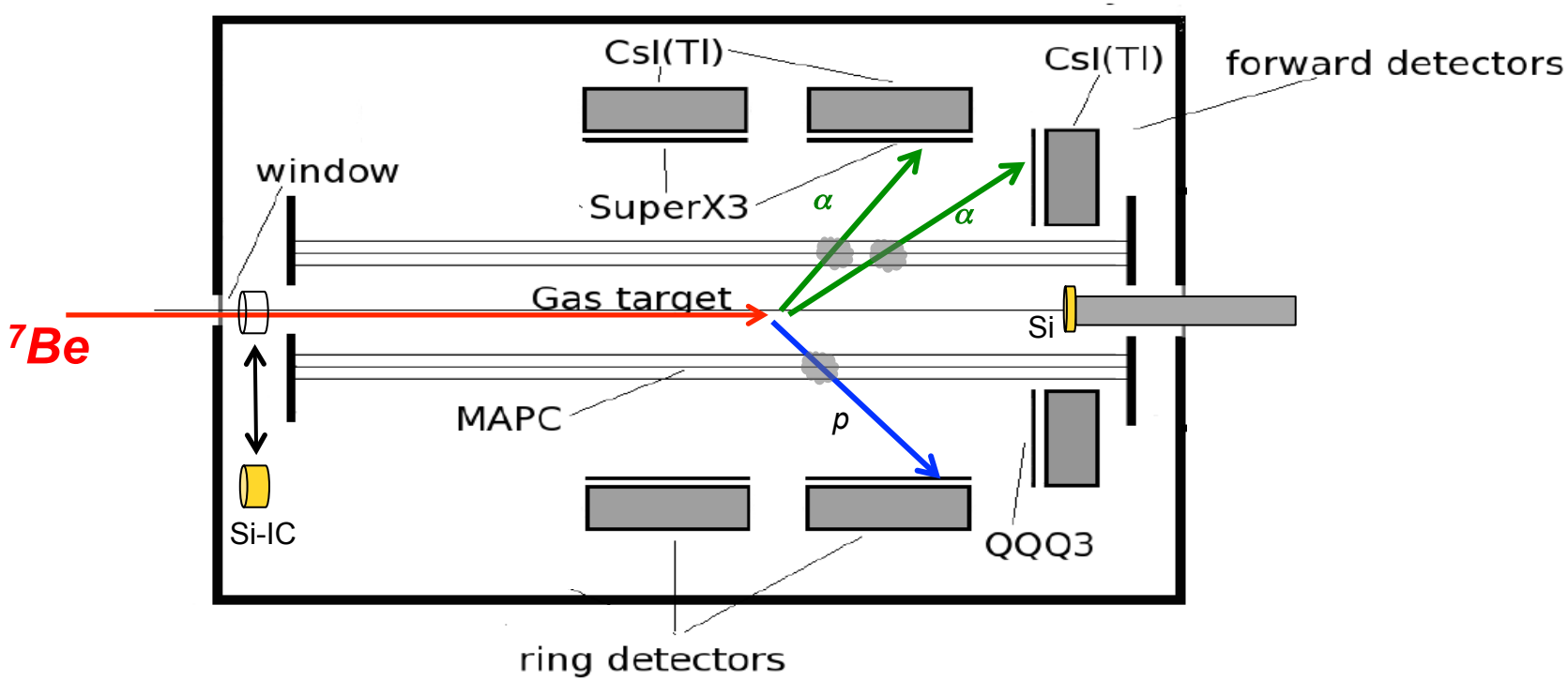
Cyburt et al. (2016)

Cyburt et al. Rev. Mod. Phys. ***88*** *(2016)*

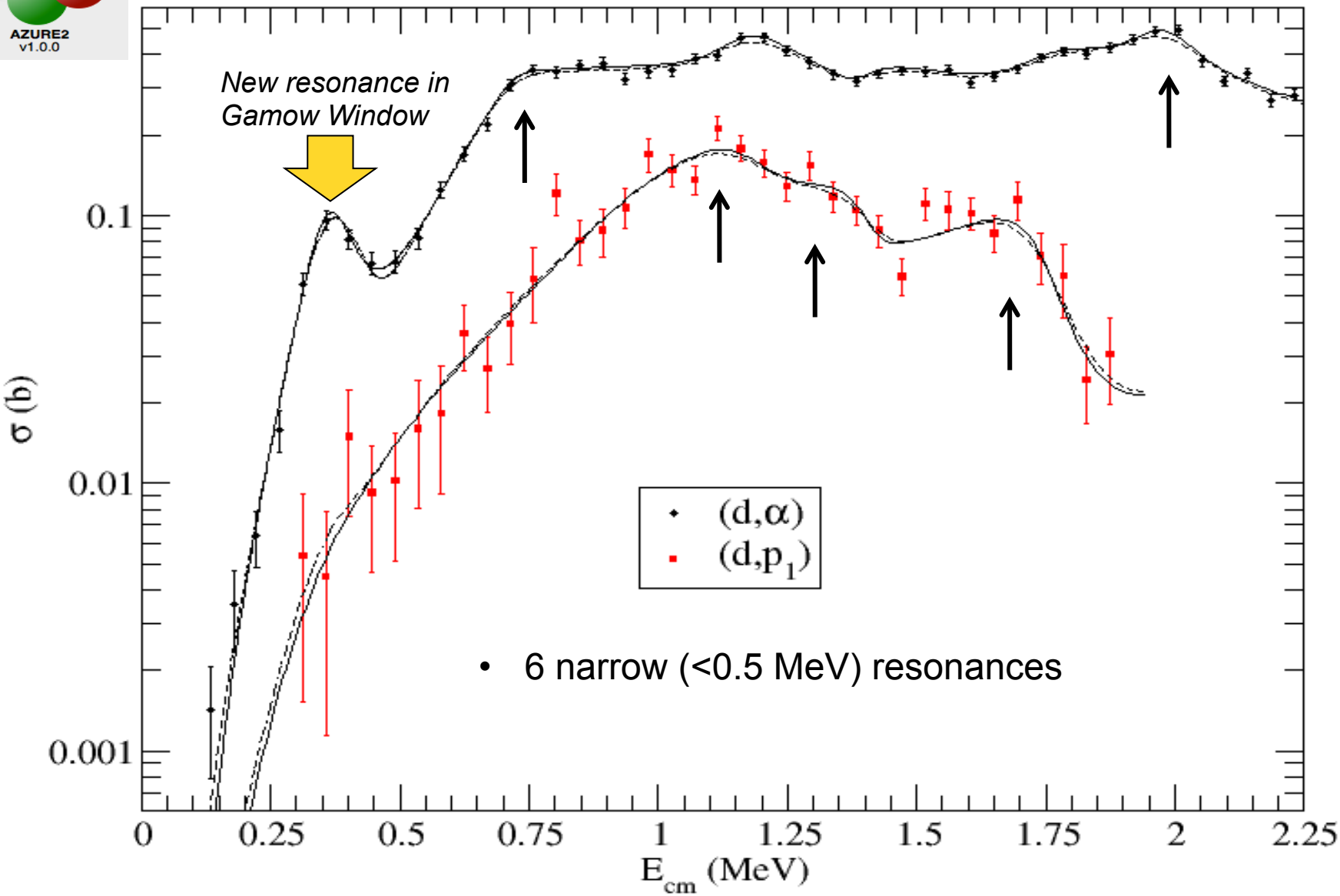


Early 2016: $^7Be+d \rightarrow \alpha+\alpha+p$

- Triple coincidence of light ions
- Gas IC – Si hybrid detector for beam characterization
- Si detector at zero degrees
  - diagnostic
  - stopping power measurement

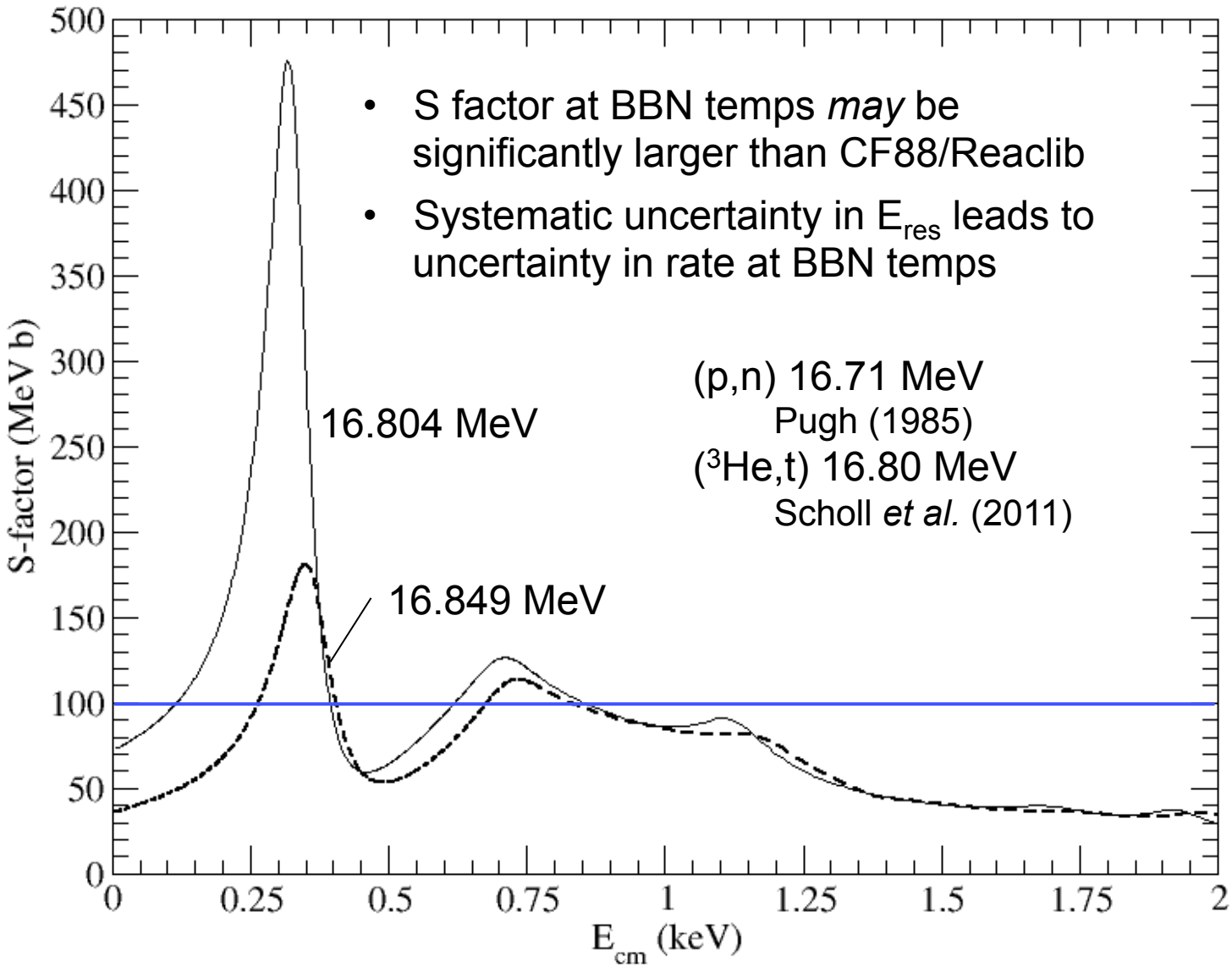


R-matrix Analysis of Total Cross Sections



- 6 narrow (<0.5 MeV) resonances

S factors

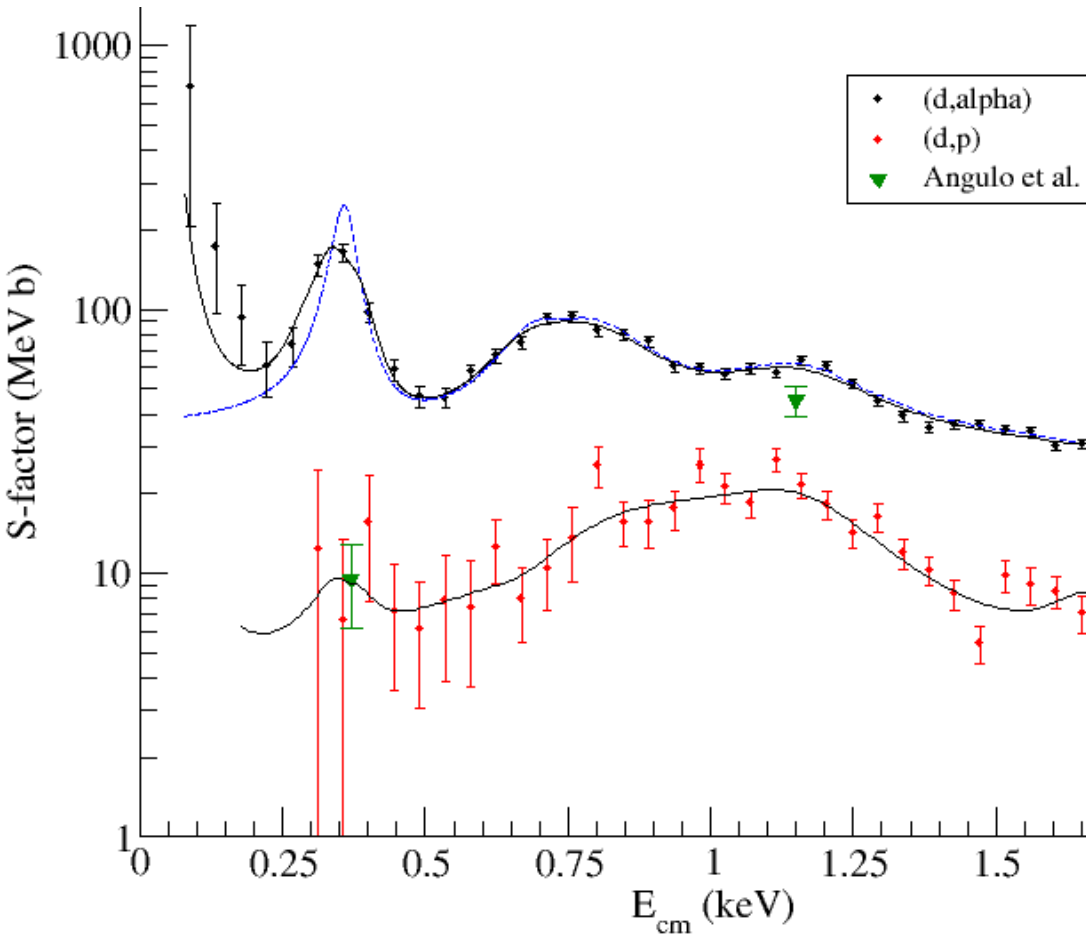


- S factor at BBN temps *may* be significantly larger than CF88/Reaclib
- Systematic uncertainty in E_{res} leads to uncertainty in rate at BBN temps

(p,n) 16.71 MeV
Pugh (1985)
(^{3}He,t) 16.80 MeV
Scholl *et al.* (2011)

$^7Be+d \rightarrow \alpha+\alpha+p$ @ TRIUMF-ISAC

- Propose to measure at 10 different bombarding energies
- Request 2×10^6 ^7Be/s post-stripped to 4^+
- Assume cross section from ANASEN measurement

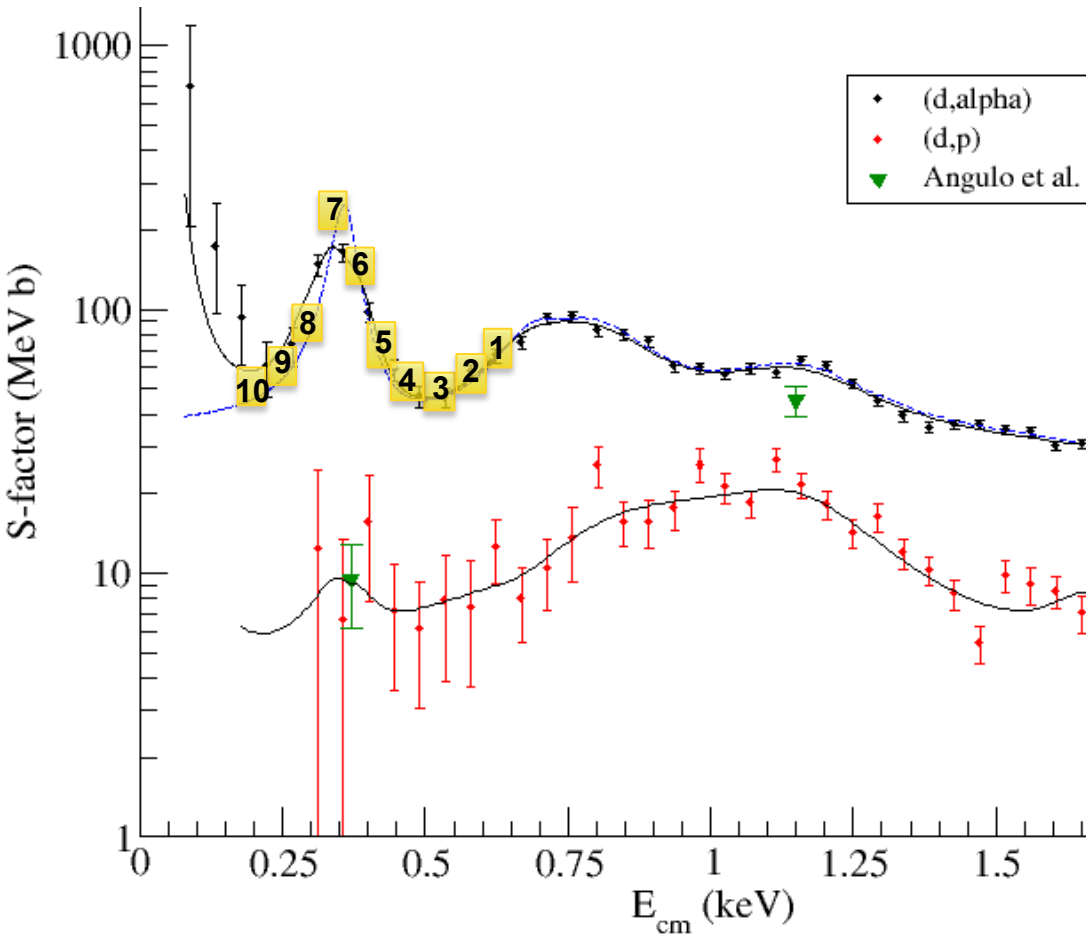


Run #	E_7 MeV	E/u keV	E_{cm} keV	σ mb	Counts per 8 hr
1	2.8	400	626-572	201	23200
2	2.6	371	581-527	143	16500
3	2.4	343	536-481	104	12000
4	2.2	314	492-435	86	9850
5	2.0	286	447-389	96	11100
6	1.8	257	402-344	122	14000
7	1.6	229	358-299	89	10300
8	1.4	200	313-253	39	4500
9	1.2	171	268-209	15	1700
10	1.05	150	234-177	6.7	770

- Sufficient statistics for angular distribution in one shift at each energy (confirm J^π of state)

$^7Be+d \rightarrow \alpha+\alpha+p$ @ TRIUMF-ISAC

- Propose to measure at 10 different bombarding energies
- Request 2×10^6 ^7Be/s post-stripped to 4^+
- Assume cross section from ANASEN measurement



Run #	E_7 MeV	E/u keV	E_{cm} keV	σ mb	Counts per 8 hr
1	2.8	400	626-572	201	23200
2	2.6	371	581-527	143	16500
3	2.4	343	536-481	104	12000
4	2.2	314	492-435	86	9850
5	2.0	286	447-389	96	11100
6	1.8	257	402-344	122	14000
7	1.6	229	358-299	89	10300
8	1.4	200	313-253	39	4500
9	1.2	171	268-209	15	1700
10	1.05	150	234-177	6.7	770

- Sufficient statistics for angular distribution in one shift at each energy (confirm J^π of state)

ANASEN at ATLAS

- ANASEN is (relatively) easy to transport
  - measurements performed at FSU, NSCL, and (soon) TRIUMF
  - all inclusive device – chamber, detectors, electronics, DAQ

- Possible first experiment: $^{17}F(\alpha,p)^{20}Ne$
  - previously measured at FSU with 10^5 ^{17}F/s (data under analysis)
  - RAISOR beam of 10^6 ^{17}F/s will allow for more statistics at astrophysically relevant energies

- Other direct (α,p) measurements?
  - RAISOR beams need further development

- Indirect measurements
  - α scattering to determine resonant properties (e.g. ^{14}O for $^{14}O(\alpha,p)^{17}F$)
  - transfer reactions

Cyburt et al., APJ (2016)

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha,\gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha,p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p,\gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p,\gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha,p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha,p)^{17}F$	D	5.8	1
7	$^{23}Al(p,\gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha,p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p,\alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha,\gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha,p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha,p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha,\gamma)^{28}Si$	U	1.2	2

Summary

- Active target techniques like ANASEN are powerful for radioactive ion beam experiments
- Multiple successful experimental campaigns, including:
  - ^{7}Be+d study shows reaction helps (but does not solve) the cosmological Li problem
  - ^{18}Ne(α,p)^{21}Na measured at FSU for E_{cm} >2 MeV
- TRIUMF campaign planned for 2019 – 2020
  - S1849: ^{7}Be+d measurement at and below new resonance
  - S1773: ^{18}Ne(α,p)^{21}Na at TRIUMF will measured down to ~1.4 MeV
- Possibilities for ANASEN @ ATLAS:
  - ^{17}F(α,p)^{20}Ne direct measurement
  - α-scattering studies with RIBs
  - other reaction studies . . .
- Sincere thanks to:
  - Collaborators and Faculty/Staff at FSU
  - The U.S. National Science Foundation and U.S. Department of Energy Office of Nuclear Physics