Background (α,n) reactions at low energies: $^{10,11}B(\alpha,n)^{13,14}N$

(Richard) James deBoer

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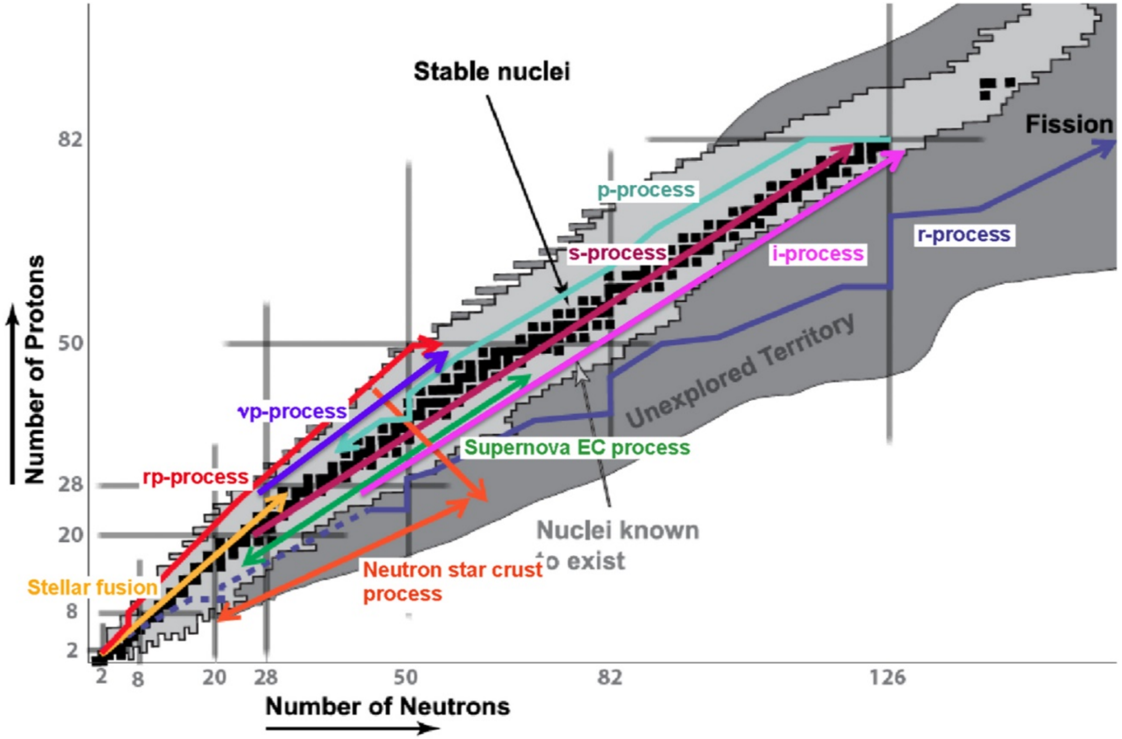
Improved rates for neutron production reactions are key for understanding the *s*-process

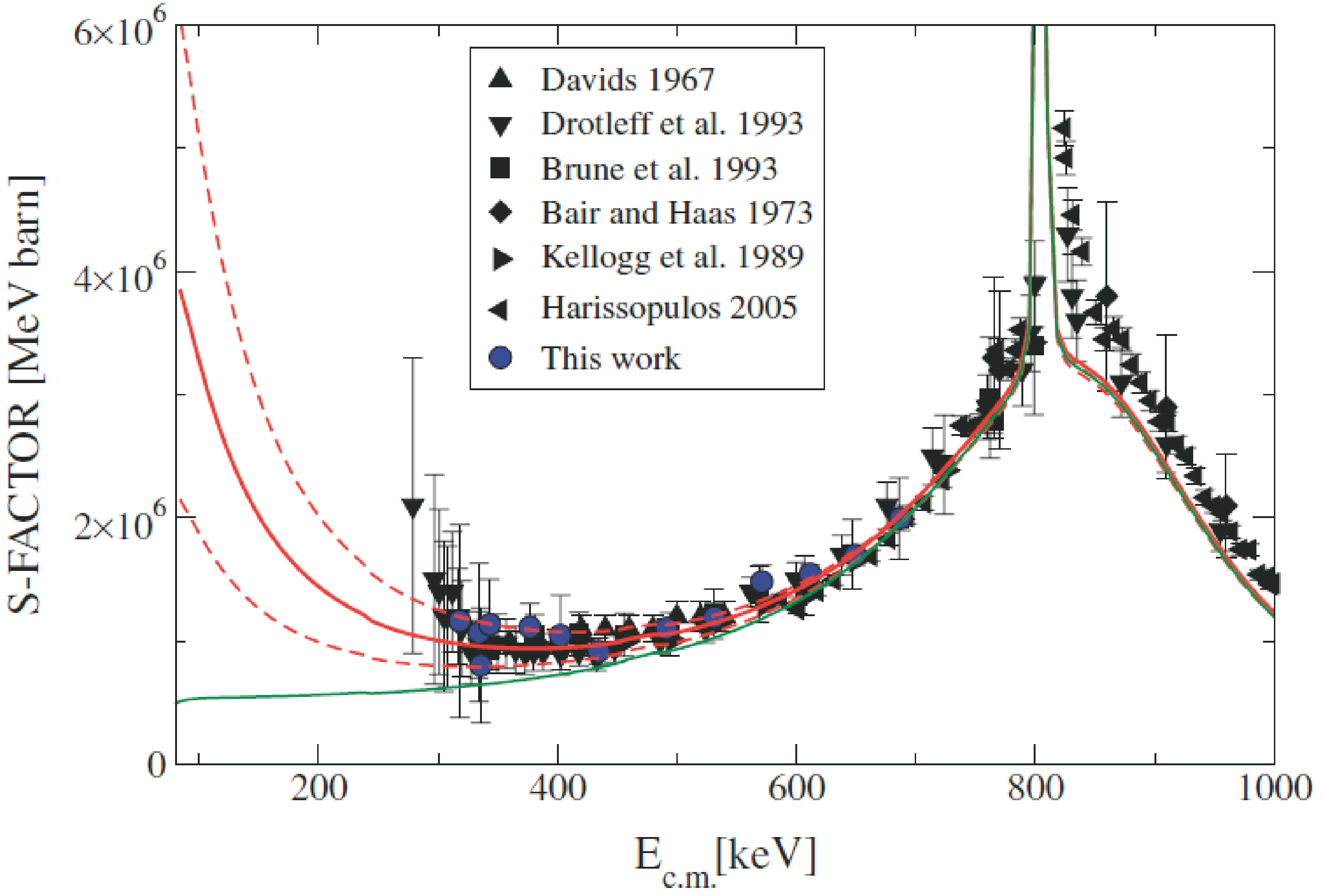
- Main Candidates
  - $^{13}C(\alpha,n)^{16}O$
  - $^{22}Ne(\alpha,n)^{25}Mg$



Hendrik Schatz and Frank Timmes
Schatz, Journal of Physics G **43**, 064001 (2016)

State of the measurements: $^{13}C(\alpha,n)^{16}O$

Heil *et al.* (2008)



Uncertainty at 0.1 GK is about 20%

Indirect studies of $^{13}C(\alpha,n)^{16}O$

- $^{16}O(n,n)^{16}O$, best constraint on energy of ½⁺ threshold state (about 160 keV wide)
- α transfer reactions for ANC or width of threshold state
- Global R-matrix analyses (also can include $^{13}C(\alpha,\alpha)^{13}C$ data)
- Also well studied by the applied community

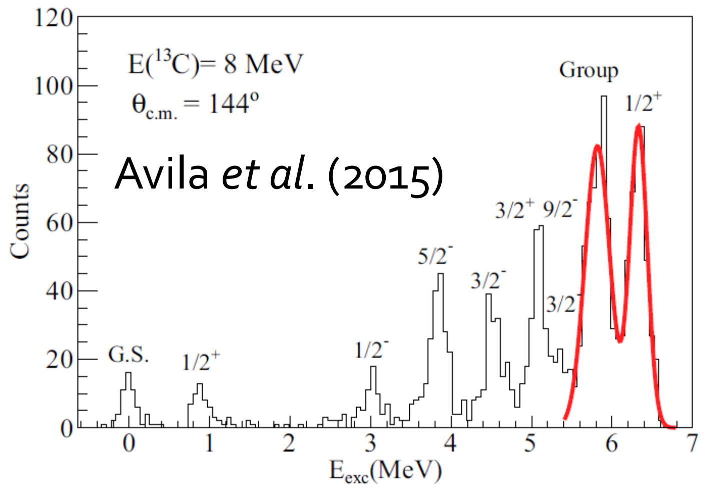
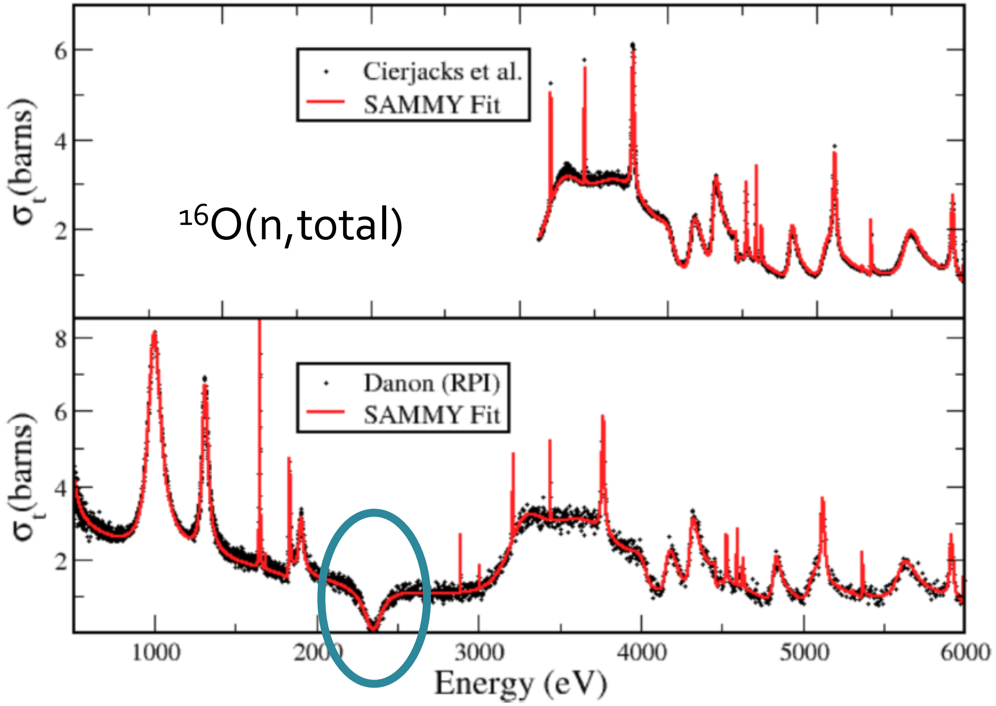


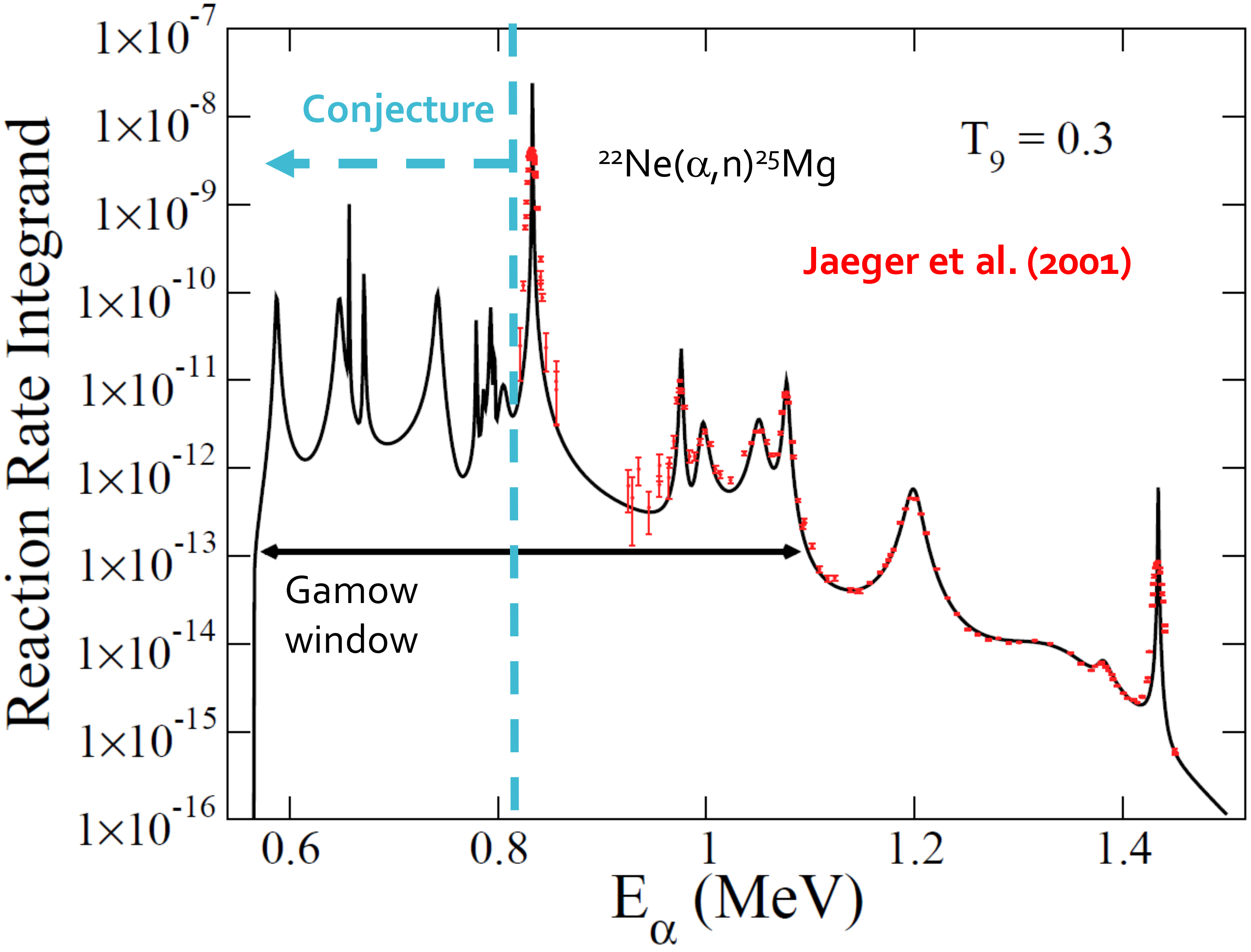
FIG. 2. (Color online) Spectrum of deuterons from the $^{6}Li(^{13}C,d)^{17}O$ reaction at 8 MeV (7.72 MeV effective energy after energy-loss corrections) of ^{13}C beam at 144° in c.m.

Leal *et al.* (2016)



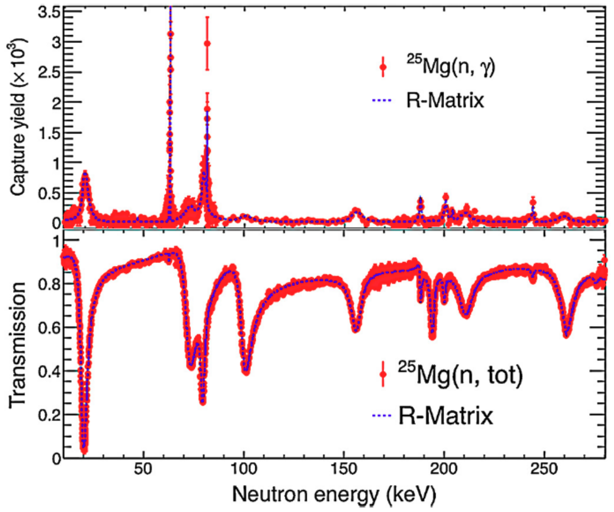
State of the measurements: $^{22}Ne(\alpha,n)^{25}Mg$

$$N_A\langle\sigma v\rangle = N_A \frac{(8/\pi)^{1/2}}{\mu^{1/2}(k_B T)^{3/2}} \int_0^\infty \sigma E \exp(-E/k_B T)\, dE,$$

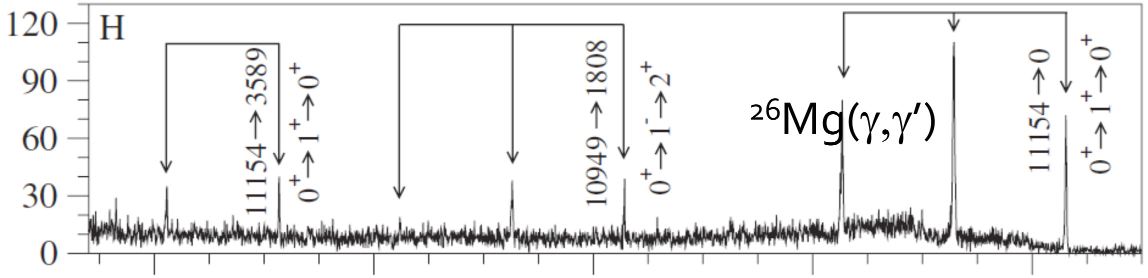


Indirect studies of $^{22}Ne(\alpha,n)^{25}Mg$

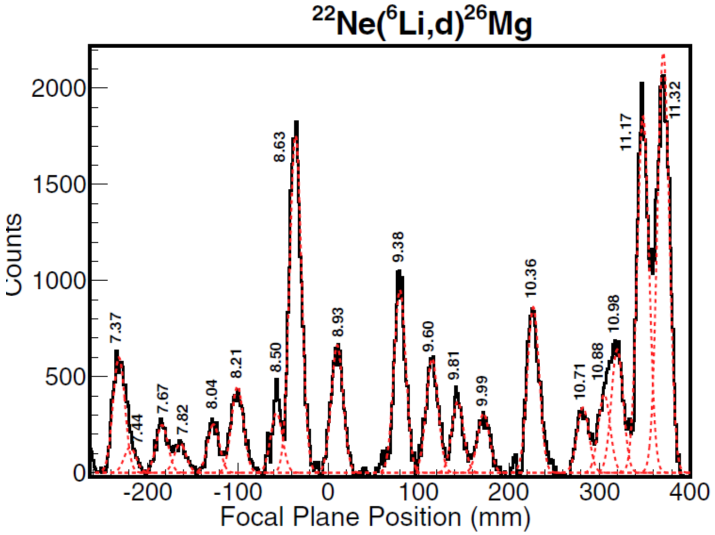
- $^{25}Mg(n,\gamma)$ and (n,total) at n_ToF (CERN)
- $^{26}Mg(\gamma,\gamma)$ and (γ,n) at HIγS
- α transfer at RCNP and TAMU
- Failure to make correspondence between resonances observed in (α,n) reaction!



Massimi *et al.* (2017)

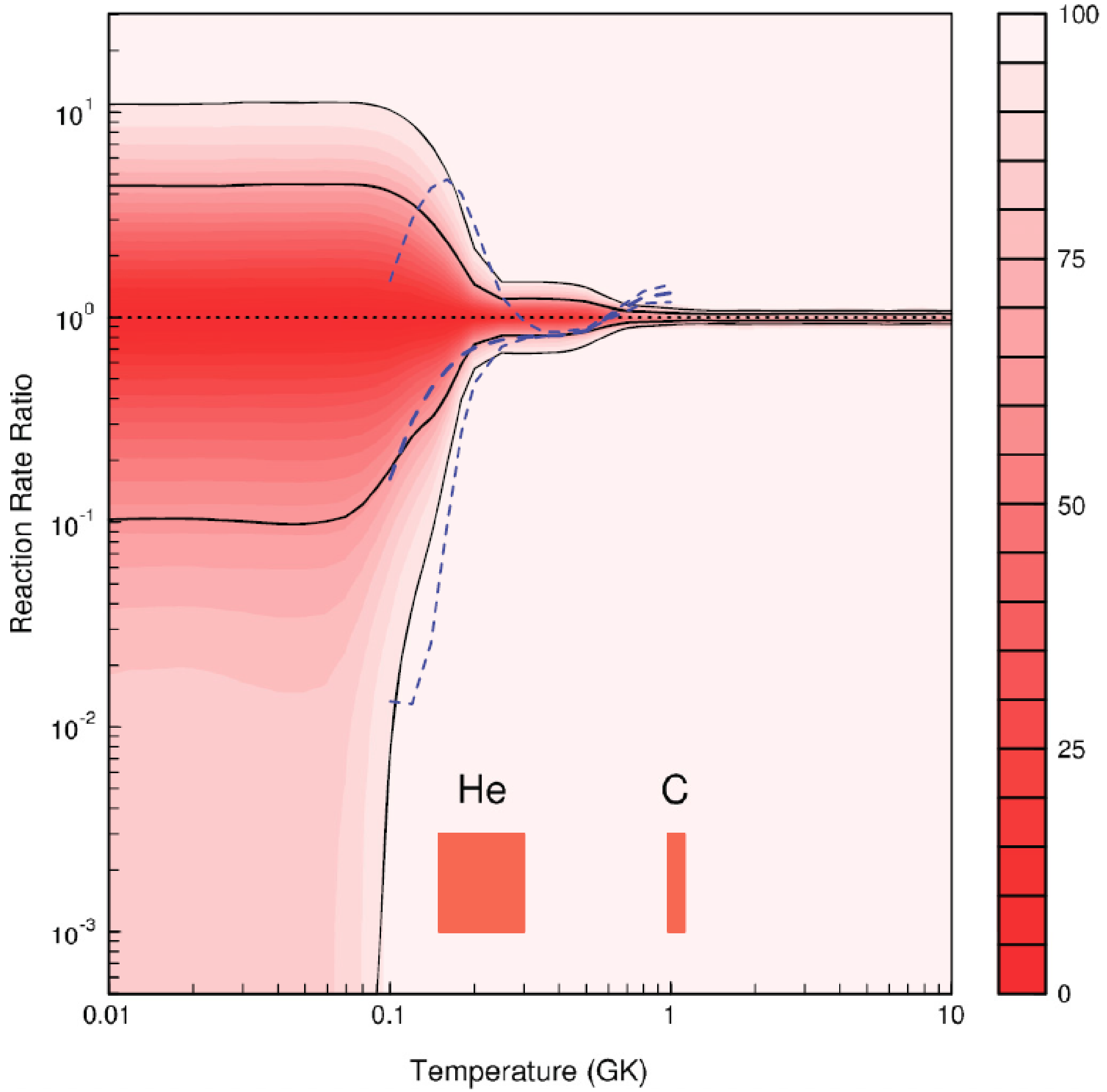


Longland *et al.* (2009)



Talwar *et al.* (2016)

Uncertainty of $^{22}Ne(\alpha,n)^{25}Mg$



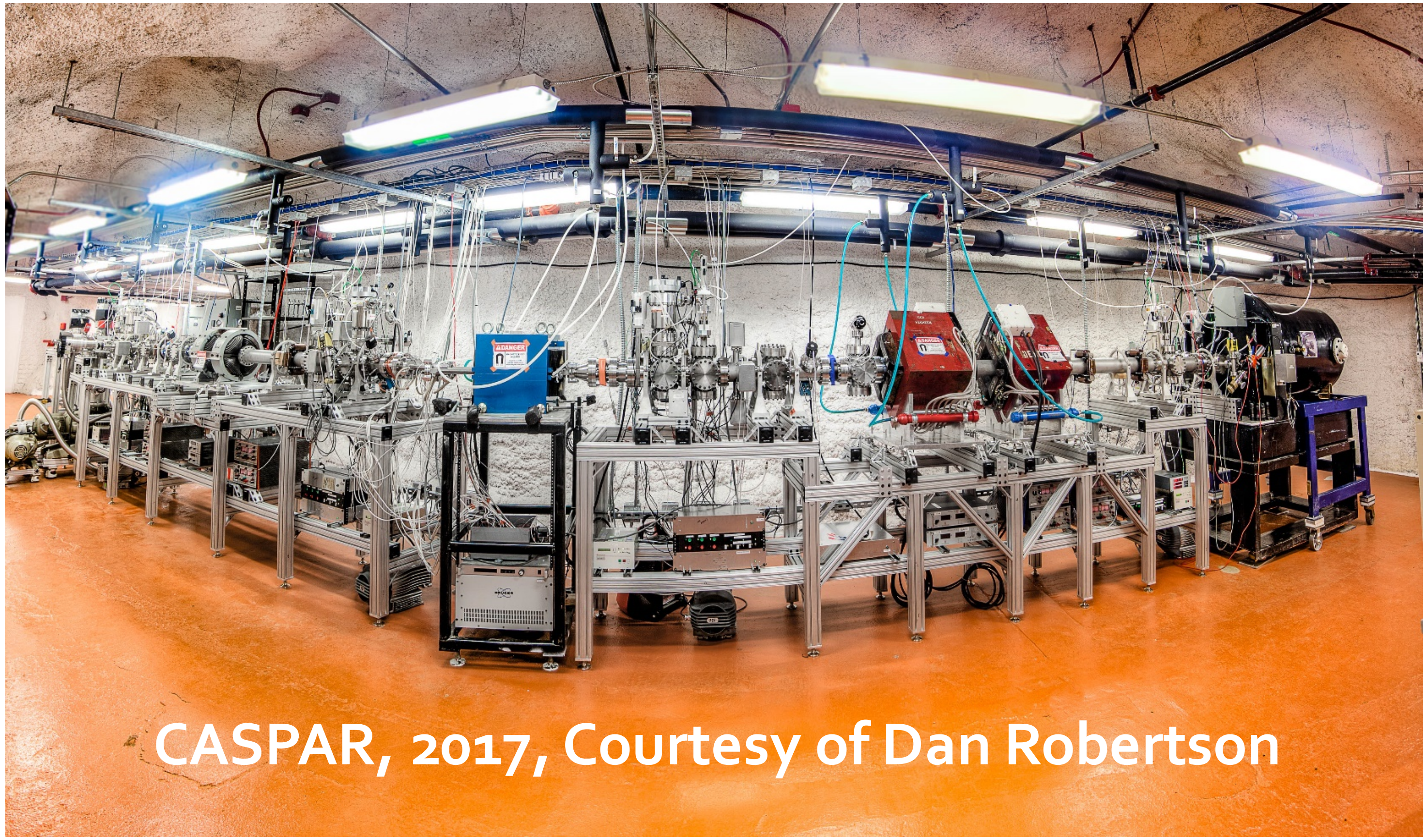
High level density, hard to find corresponding states from different experiments

Uncertainty 20%+

Longland *et al.* (2012)

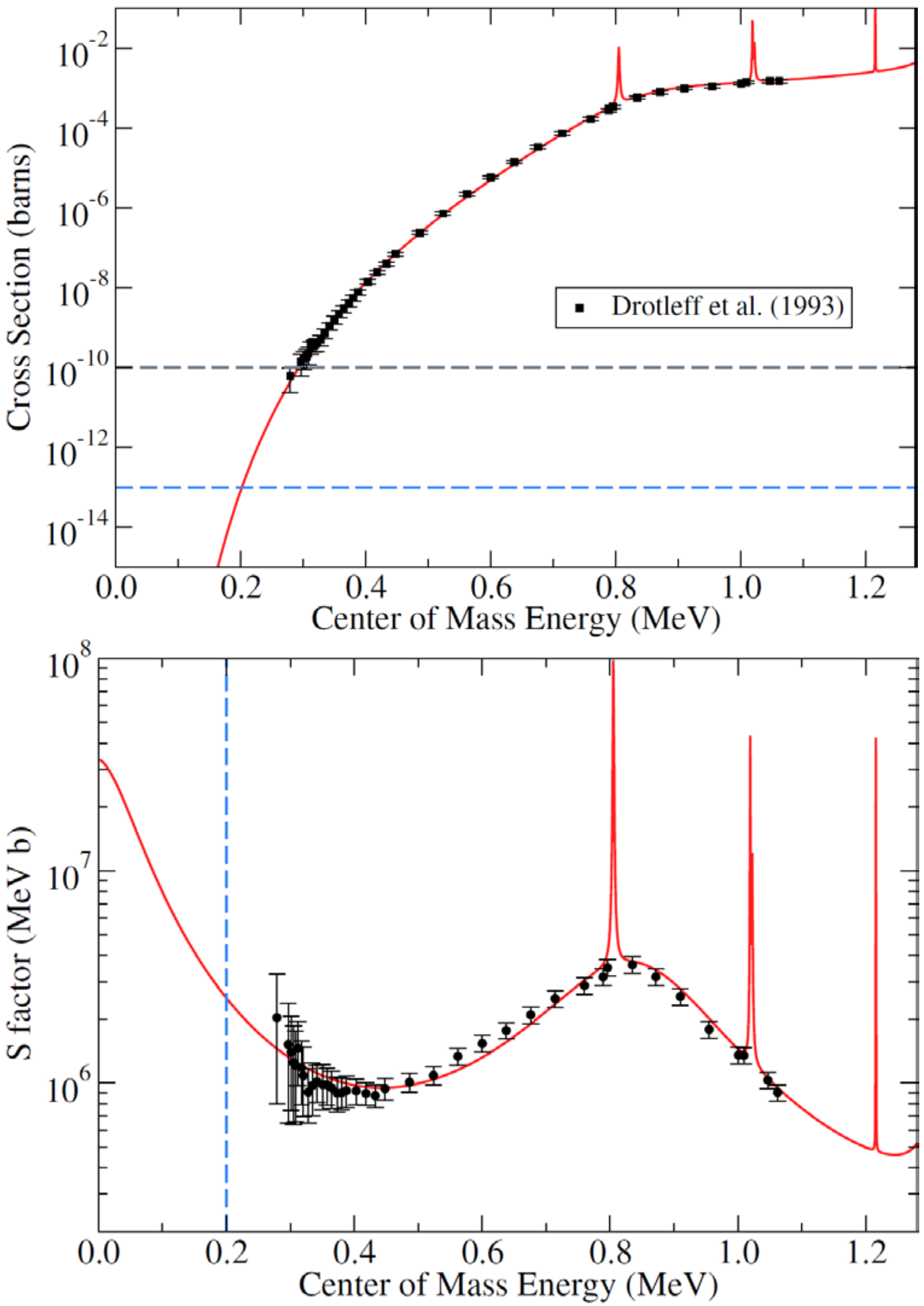
Low energy studies: Underground

- $^{13}C(\alpha,n)^{16}O$, can extrapolate with *R*-matrix, but lower energy measurements are practical and will add further constraint
- $^{22}Ne(\alpha,n)^{25}Mg$, must be measured, indirect methods have failed
- Where can these be measured?
- CASPAR, LUNA MV, JUNA
- Neutron background reduced by perhaps 3 orders of magnitude from surface levels



CASPAR, 2017, Courtesy of Dan Robertson

$^{13}C(\alpha,n)^{17}O$

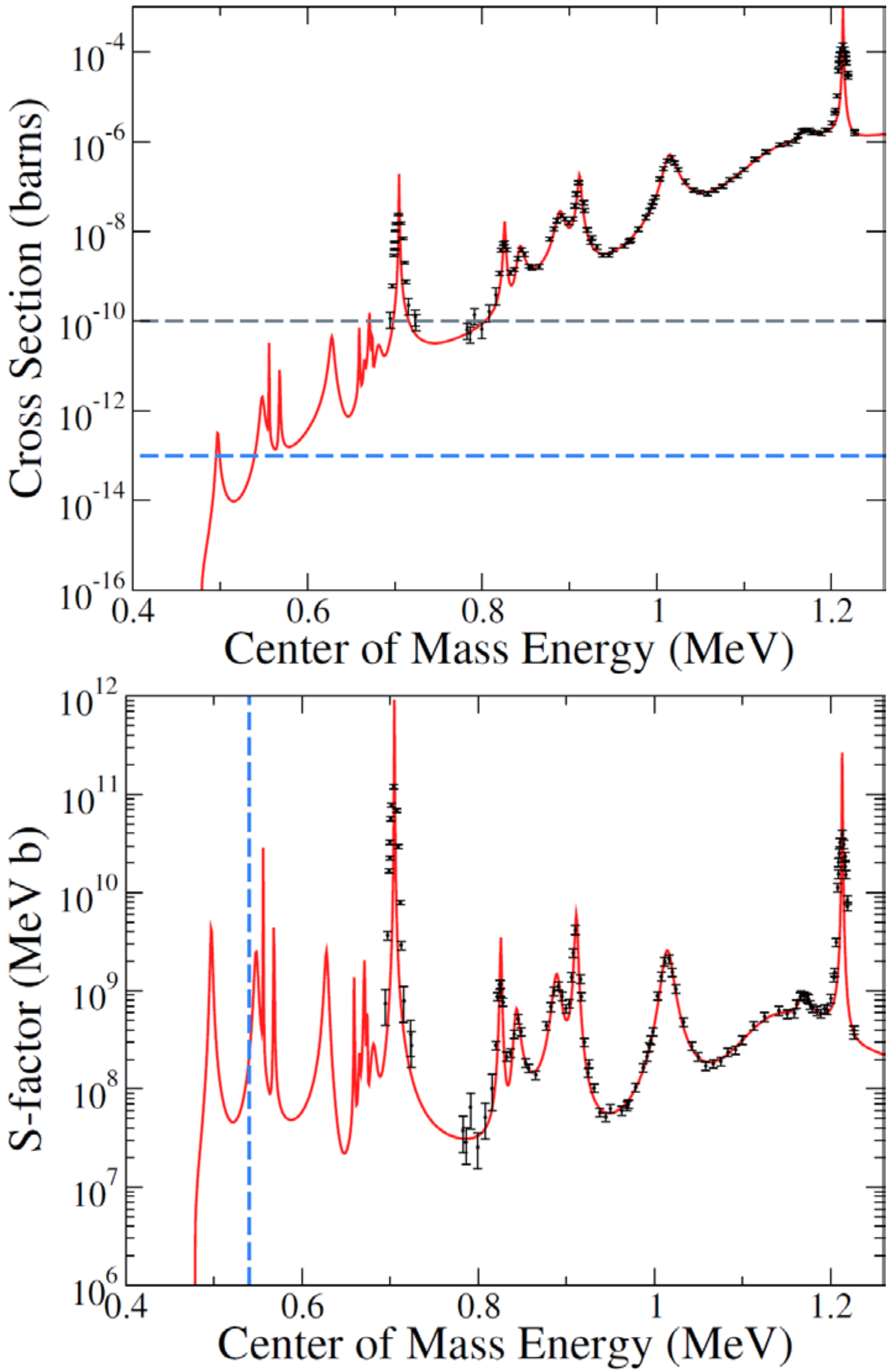


E_{lab} (Current) = 390 keV

E_{lab} (Expected) = 260 keV

R-matrix can be used to extrapolate confidently because level structure is known

$^{22}Ne(\alpha,n)^{25}Mg$

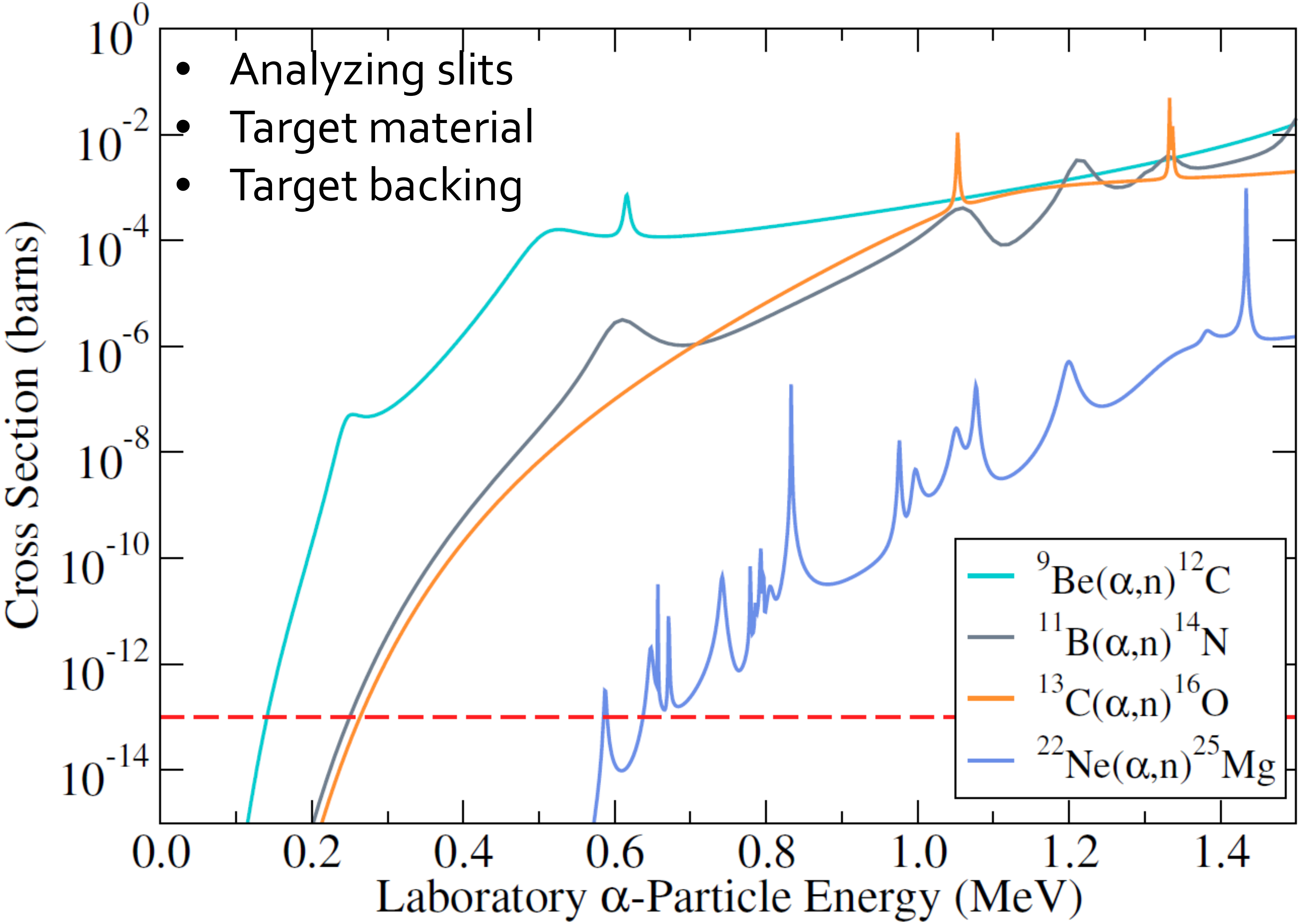


E_{lab} (current) = 830 keV

E_{lab} (expected) = 640 keV

R-matrix is less useful because (dense) level structure is unknown, interferences unknown

Natural background sources reduced underground, but what about beam induced background?



Light elements are a problem: lower Coulomb barrier

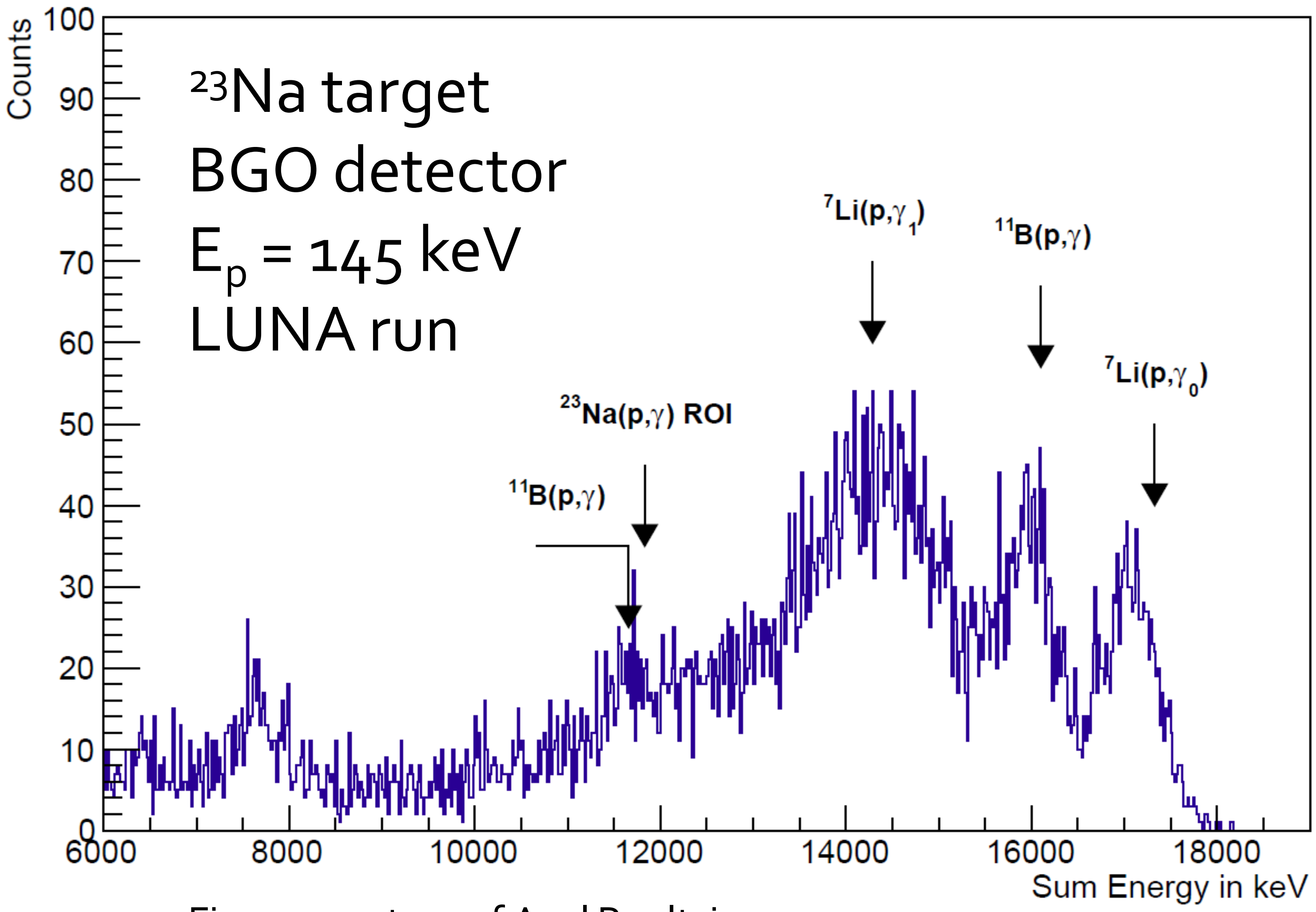
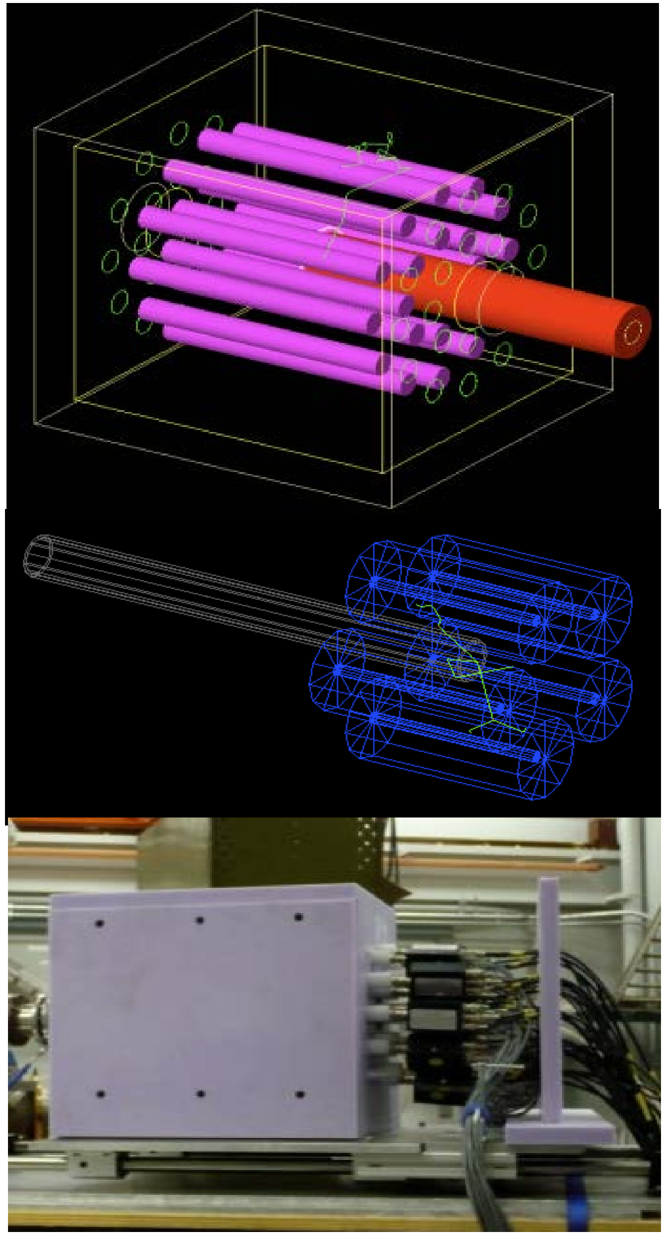


Figure courtesy of Axel Boeltzig

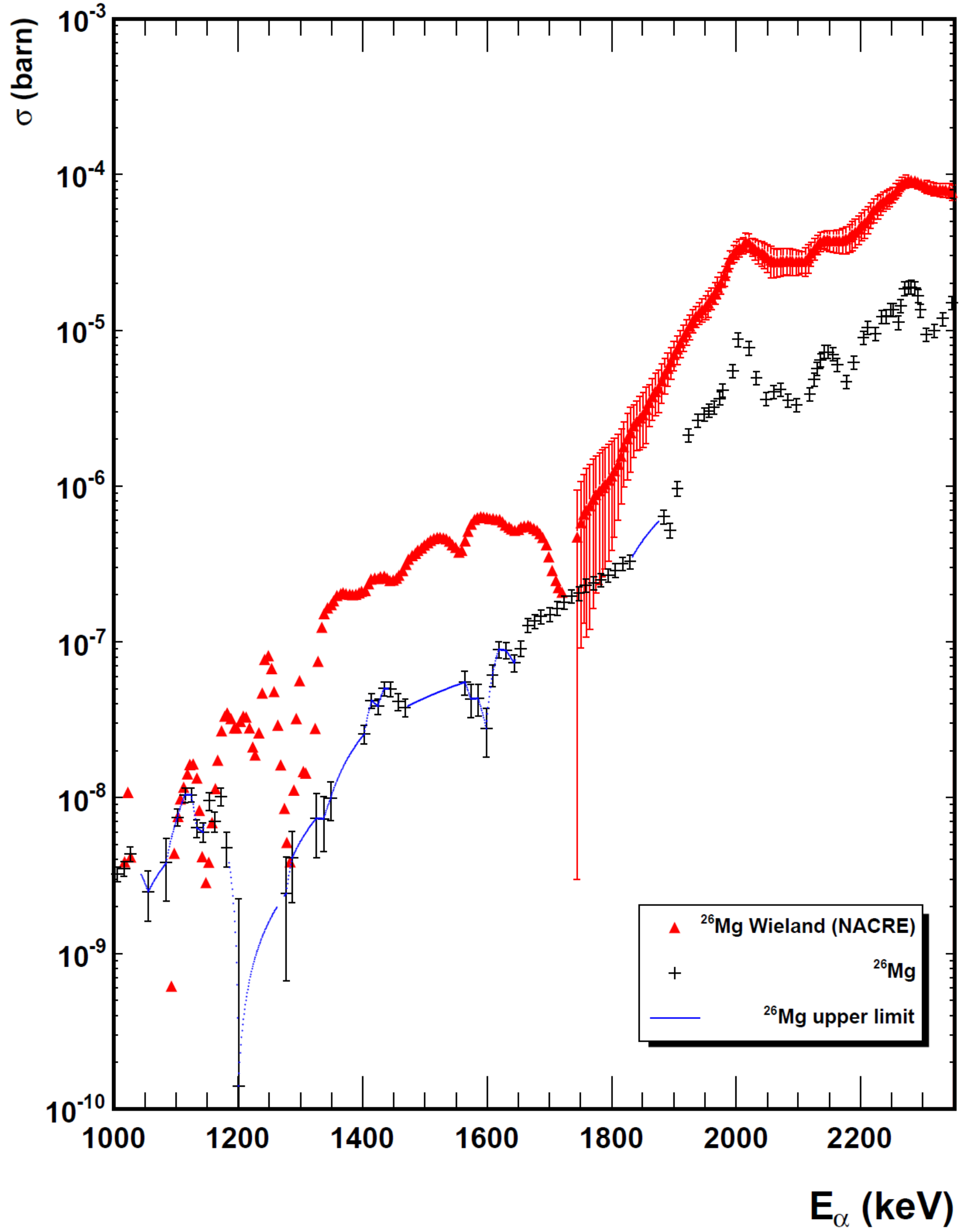
Measuring low energy (α,n) reactions: ^{3}He counters

- Advantages
  - High efficiency
  - 4π coverage
- Disadvantages
  - No energy information
  - Hard to distinguish signal from background
  - Hard to separate ground state from excited state reactions
- Can couple with γ-ray detectors to measure excited state reactions
  - Hard to measure simultaneously
  - Complicated subtraction
- Finding that previous measurements with these detectors have unaccounted for uncertainties



Courtesy of Sasha Falahat

$^{25}Mg(\alpha,n)^{28}Si$



Measuring low energy (α,n) reactions: Deuterated Scintillators

- Advantages
  - Energy information without time-of-flight
  - Can cut out low energy background
  - Well defined far geometry or close geometry
  - Angular distributions can be measured
- Disadvantages
  - **Spectrum unfolding required**
  - Only high energy neutrons (> 1 MeV), PSD threshold
  - Energy resolution is about 0.5 MeV
  - Digital DAQ extremely helpful ($$)
  - **Positive Q-value with wide energy spacing**

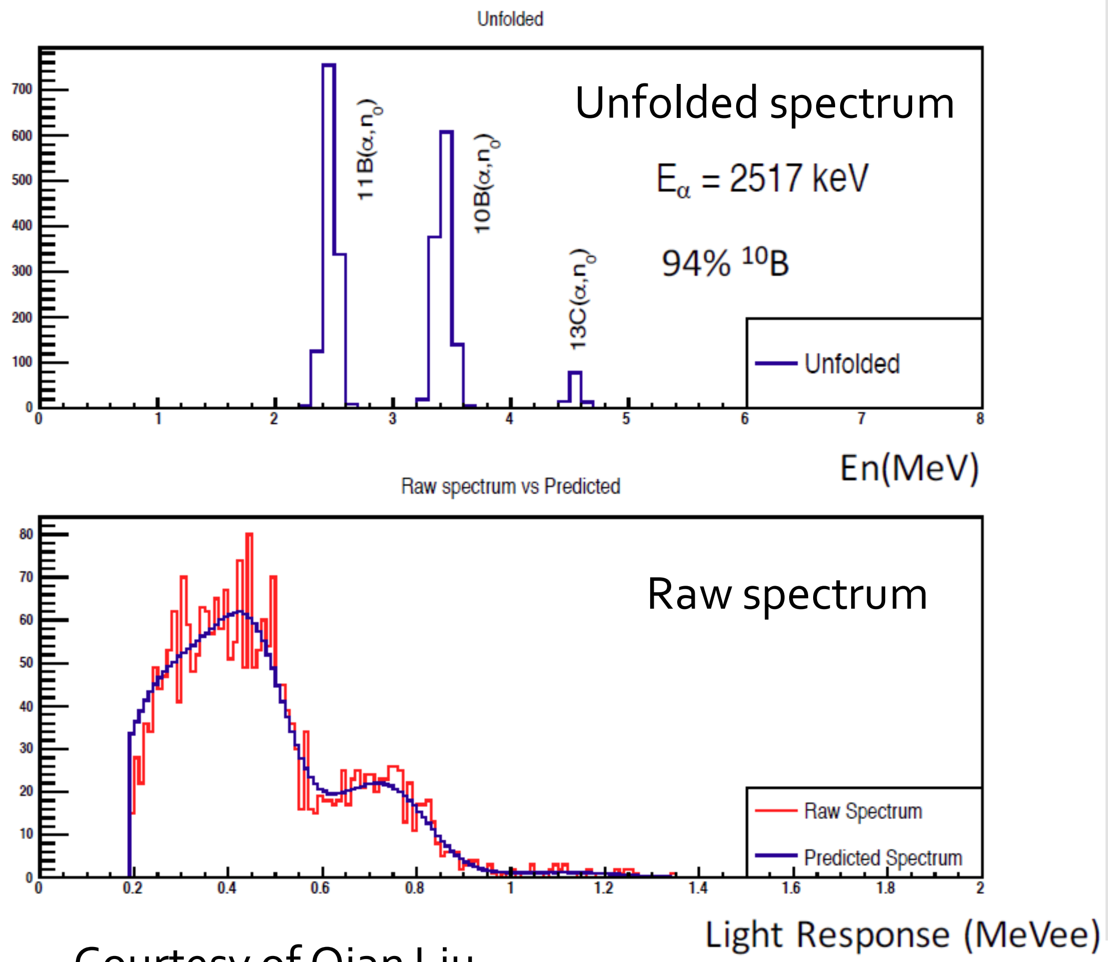
Types of detectors

- Stilbene detectors (hydrogen based)
  - See Van der Zwan and Gieger (1970's)
  - Expensive
  - Delicate
- Deuterated Benzene (EJ-315)
  - More durable
  - Better light response
  - Deuteron collision kinematics gives "peak" that helps with spectrum unfolding
  - Neutron / γ-ray pulse shape discrimination down to about 1 MeV neutron energy
  - Febbraro et al. (2015) NIM

Spectrum unfolding

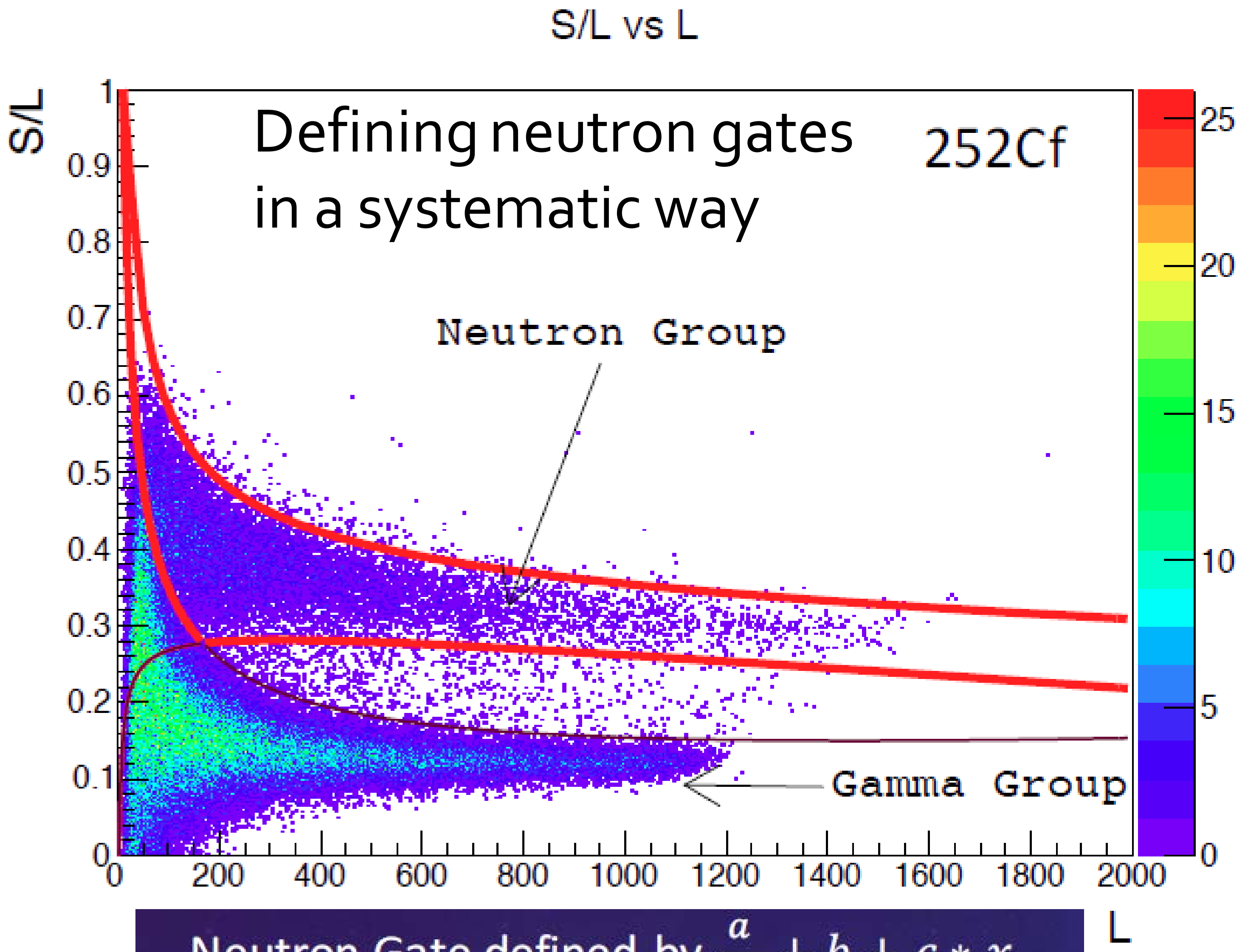
- Must characterize a detector response matrix
- Must do calibration runs over a wide range of neutron energies
  - $^{13}C(a,n)^{16}O$
  - $^{7}Li(p,n)^{7}Be$
- GEANT4 or MCNP simulations must be used
- Deuterium gives "peak" at highest energy
- Once it is done it is fairly robust, minor tuning for geometry and setup changes

Example: $^{10}B(\alpha,n)^{14}N$ run at Notre Dame
Large $^{11}B(\alpha,n)$ cross section
$^{13}C(\alpha,n)$ background from trace amounts



Courtesy of Qian Liu

Pulse Shape Discrimination calibration

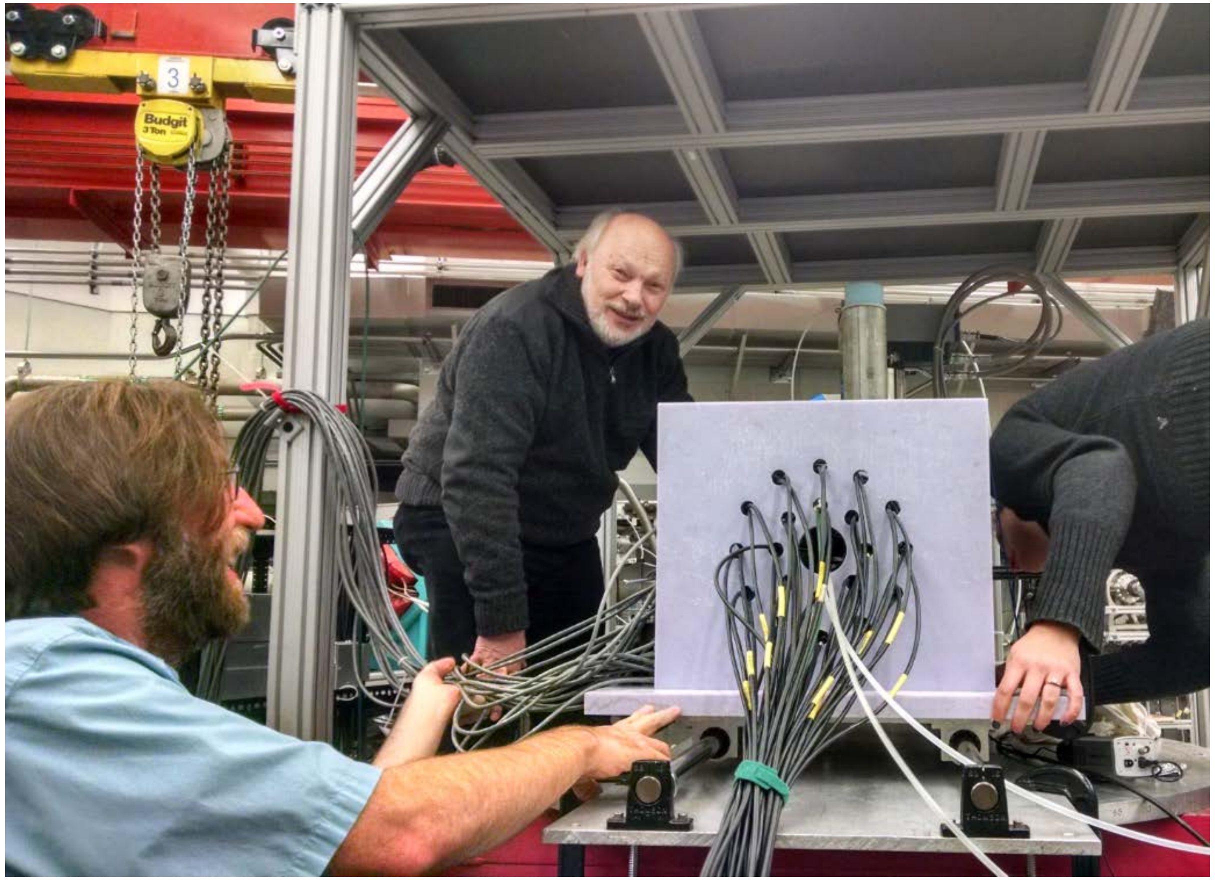


Neutron Gate defined by $\frac{a}{\sqrt{x}} + b + c * x$

Courtesy of Qian Liu

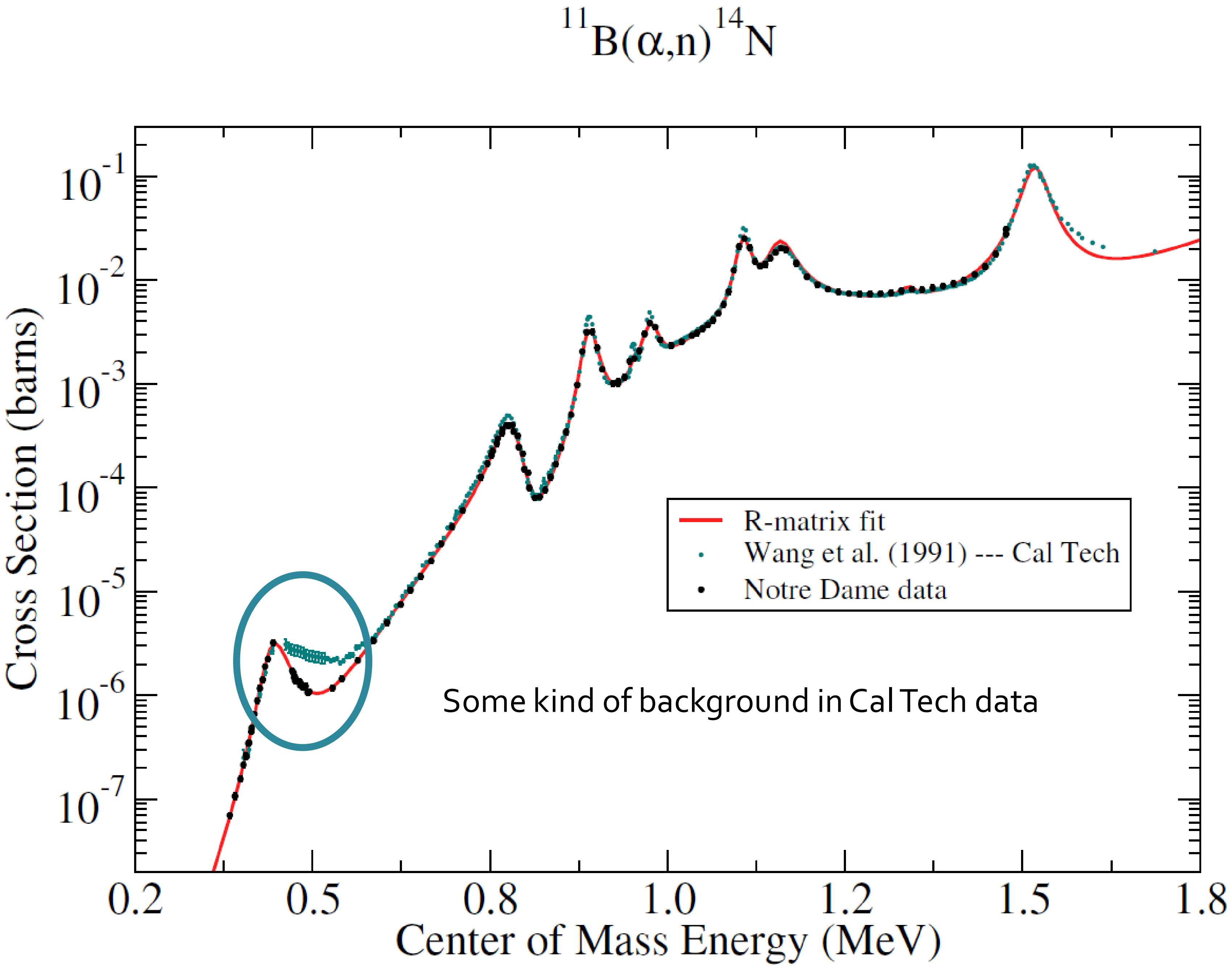
Recent experiments at ND: $^{11}B(a,n)^{15}N$ with ^{3}He counter

- 5U accelerator
- 0.55 to 2.0 MeV
- 99%+ enriched 11B target on tantalum backing
- ^{3}He counter with 20 helium tubes
- PhD project of **Qian Liu** at ND



Left to right: Ed Stech, Michael Wiescher, Stephanie Lyons

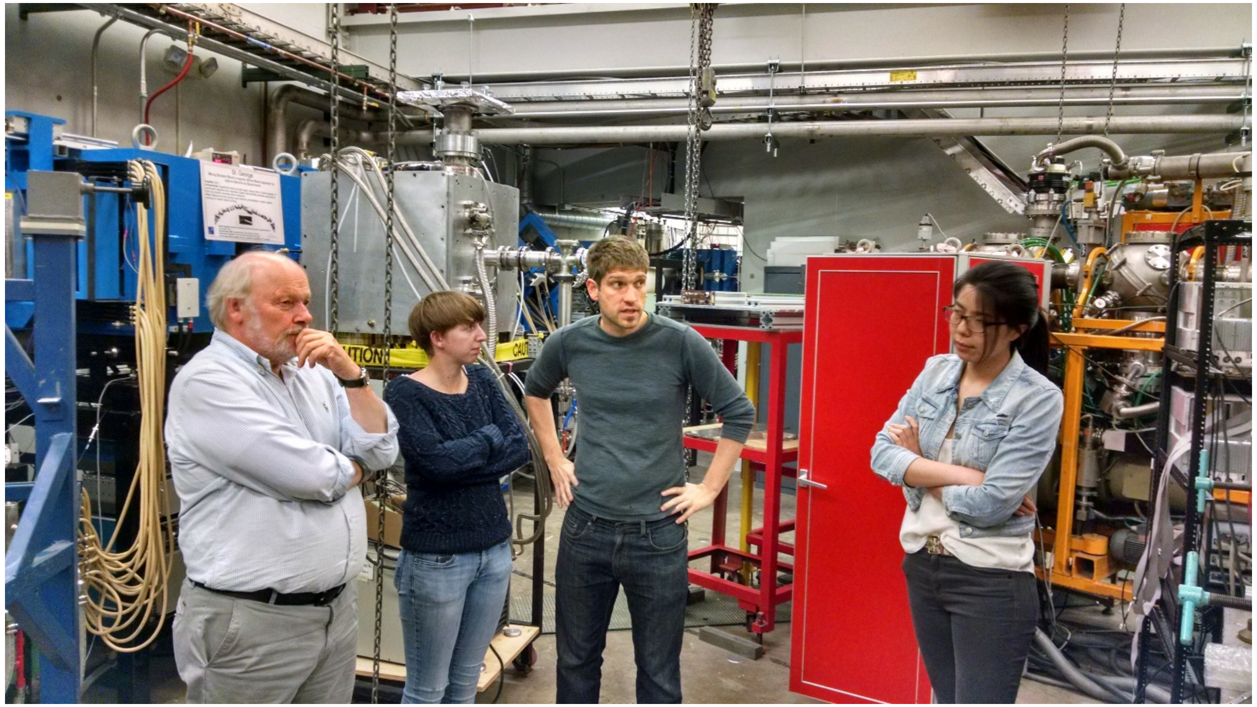
Results



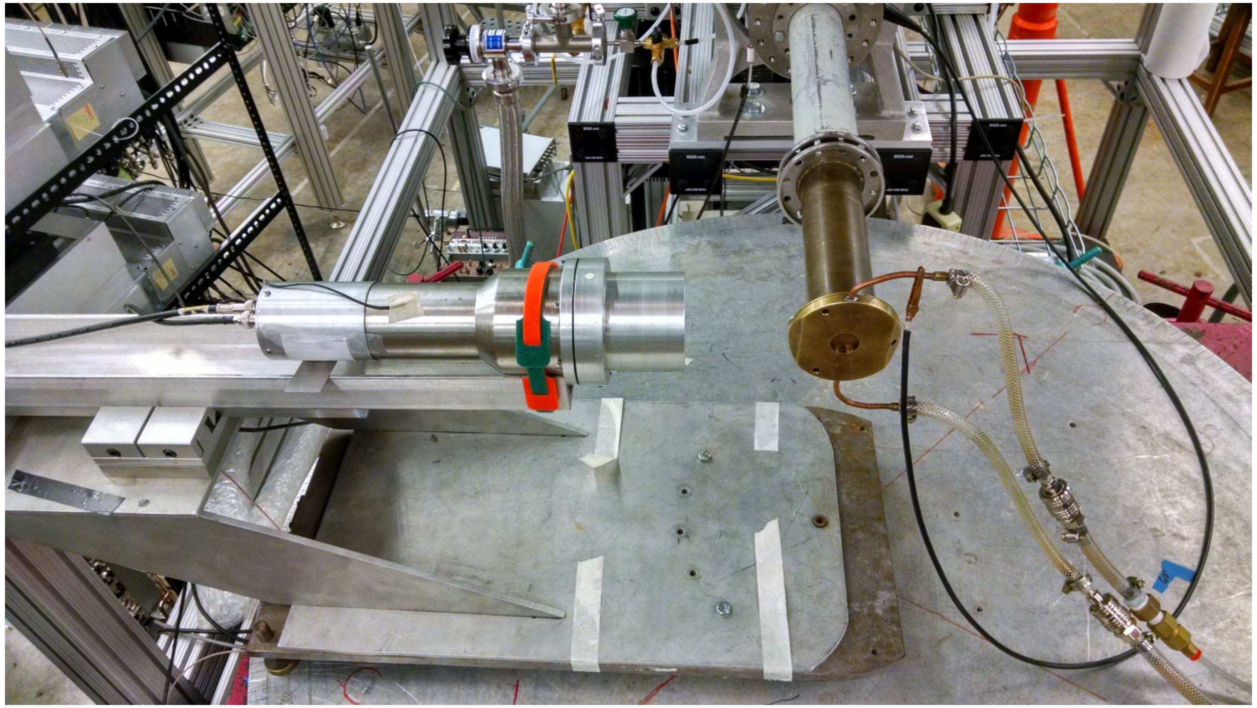
$^{11}B(\alpha,n)^{14}N$
Cross Section (barns)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.2
0.5
0.8
1.0
1.2
1.5
1.8
Center of Mass Energy (MeV)
R-matrix fit
Wang et al. (1991) --- Cal Tech
Notre Dame data
Some kind of background in Cal Tech data

Recent experiments at ND: $^{10}B(\alpha,n)^{14}N$ with deuterated liquid detectors

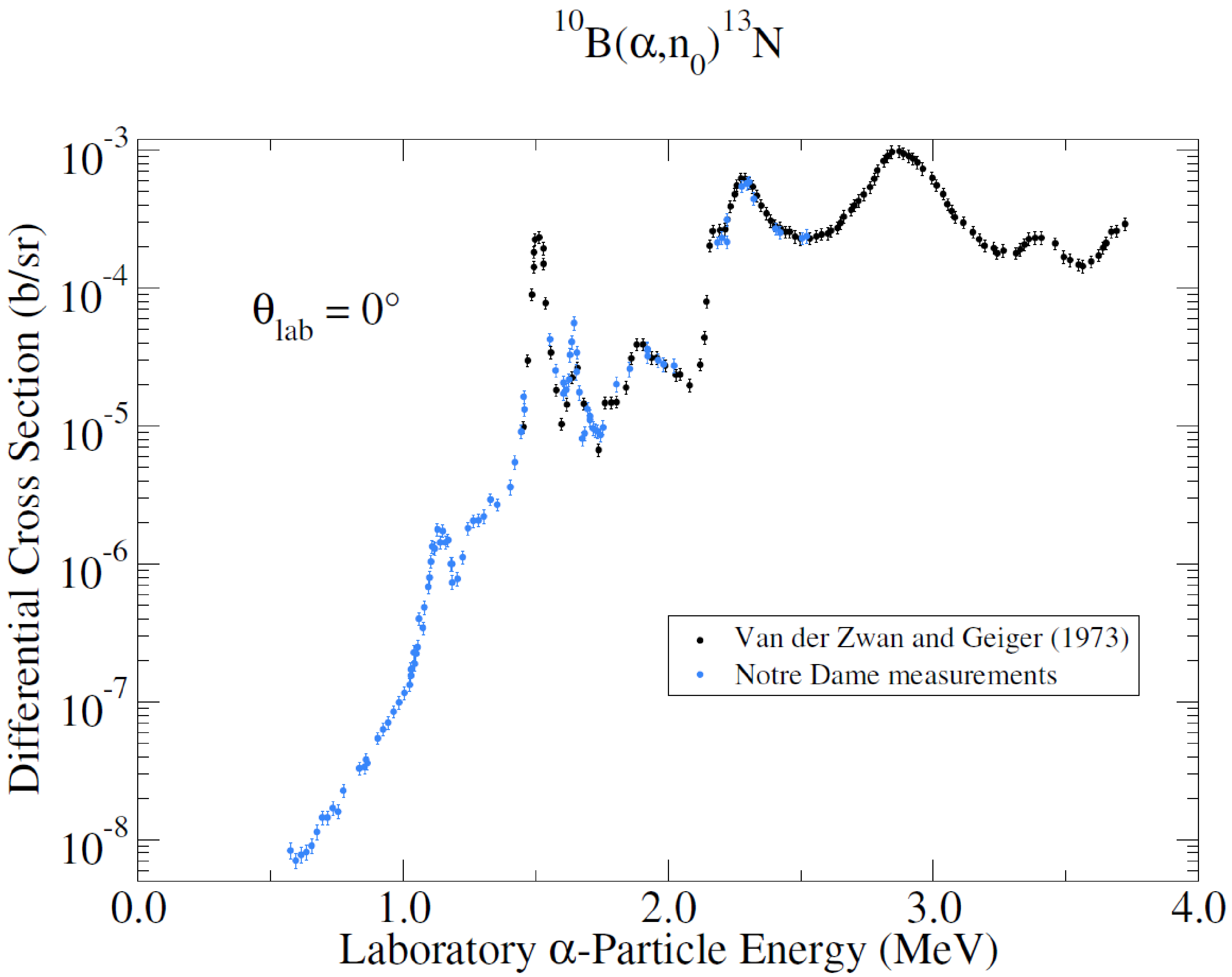
Left to right: Michael Wiescher, Becca Toomie, Mike Febbraro, and Qian Liu



- 5U accelerator
- 55% HPGe
- EJ315 on rotating arm

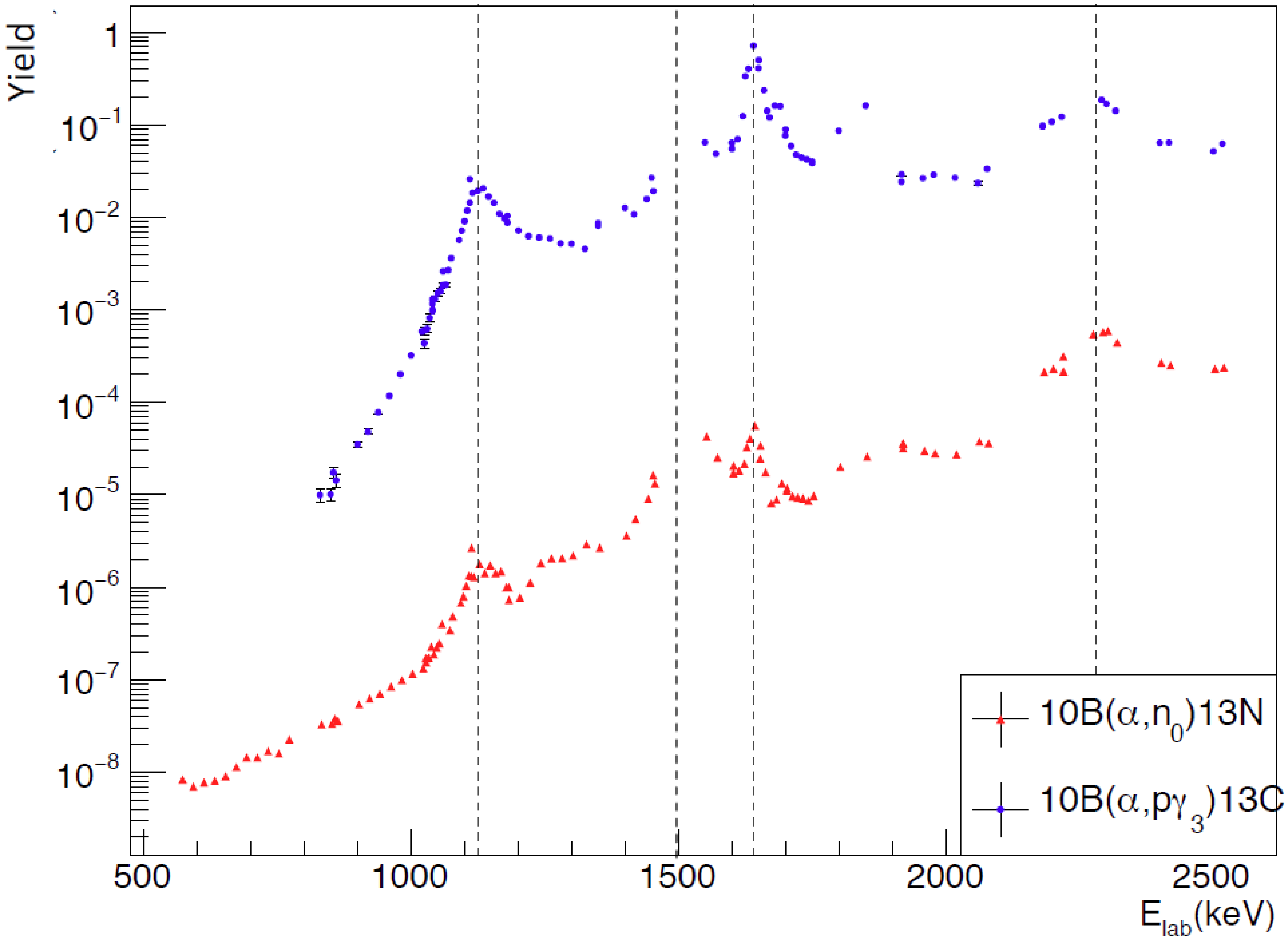


Results



$^{10}B(\alpha,n_0)^{13}N$
$\theta_{lab} = 0°$
Differential Cross Section (b/sr)
Laboratory α-Particle Energy (MeV)
Van der Zwan and Geiger (1973)
Notre Dame measurements
0.0
1.0
2.0
3.0
4.0
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

$^{10}B(\alpha,p\gamma)^{13}C$ measured simultaneously

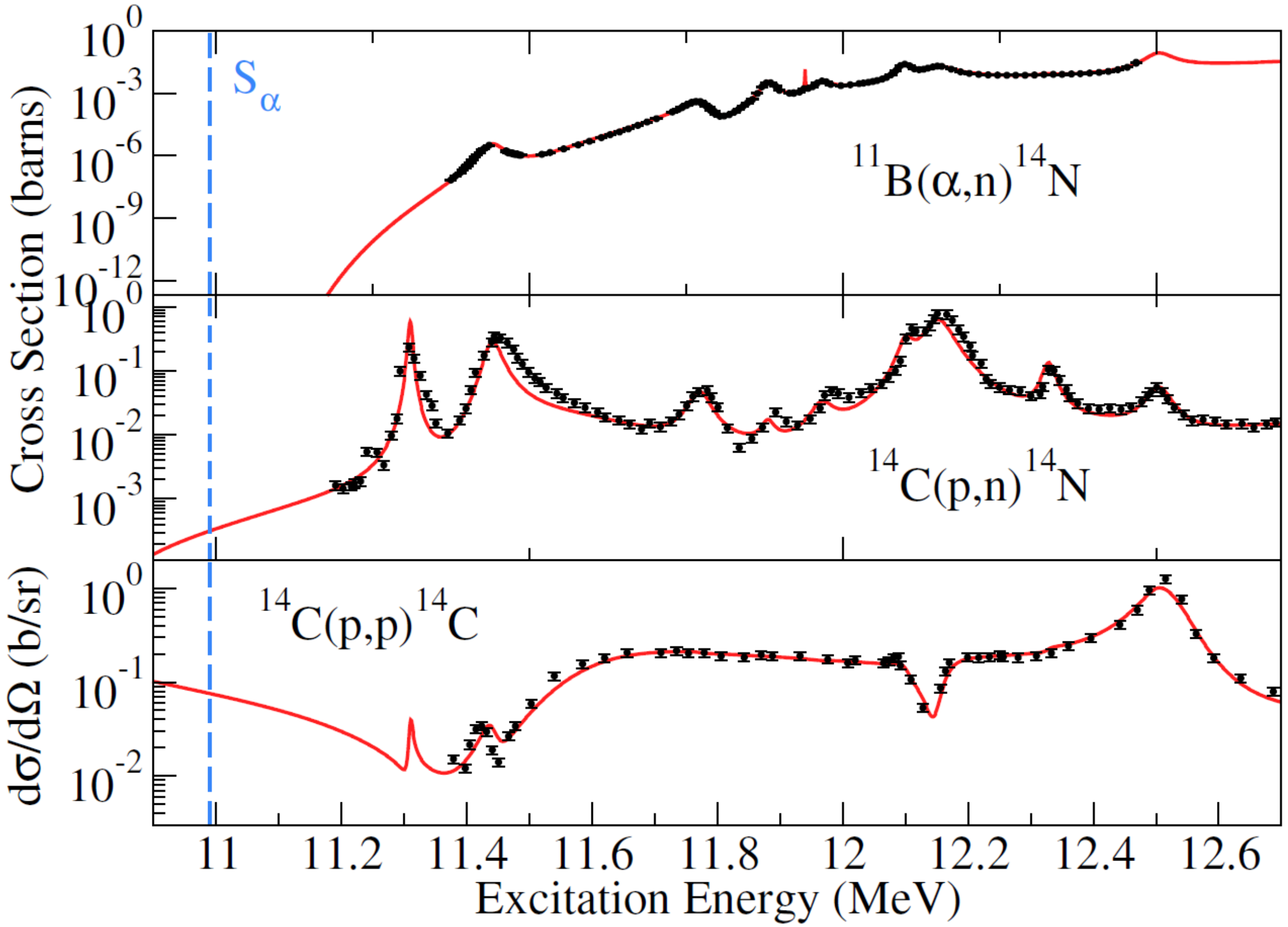


Courtesy of Qian Liu

R-matrix fits: ^{14}N compound nucleus

Preliminary

- 3 open channels
  - $^{11}B+\alpha_0$
  - $^{14}C+p_0$
  - $^{14}N+n_0$
- S_p = 10.21 MeV
- S_n = 10.83 MeV
- S_α = 10.99 MeV



Will also add ^{14}N(n,total), (n,n), (n,p), and (n,α) data

R-matrix fits: ^{15}N compound nucleus

- 9 open channels
  - $^{10}B+\alpha_0, \alpha_1$
  - $^{13}C+p_0, p_1, p_2, p_3$
  - $^{13}N+n_0, n_1$
  - $^{12}C+d_0$

  - Initial attempts have been challenging
  - Not as much data in other channels
  - No ^{13}N+n data

Future work

- $^{17}O(\alpha,n)^{20}Ne$ (re: Peter Mohr's HF comparisons)
- $^{25}Mg(\alpha,n)^{28}Si$, $^{9}Be(\alpha,n)^{12}C$

- Array of neutron detectors to improve measurement efficiency of angular distributions
- Combine with Hagrid $LaBr_3$ array (Kate Jones, UTatK) for measurement of excited state γ-rays

Collaborators

- **Mike Febbraro** (ORNL)
- Becca Toomey (Surrey)
- Steve Pain (ORNL)
- Bill Peters (ORNL)
- Jay Riggins (UofM)

- **Qian Liu** (UND)
- Yingying Chen (ND)
- Stephanie Lyons (ND, MSU)
- Ed Stech (ND)
- Chris Seymour (ND)
- Bryant Vande Kolk (ND)
- Michael Wiescher (ND)

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