THE $^{13}C(\alpha,n)^{16}O$ REACTION RATE

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MOTIVATIONS

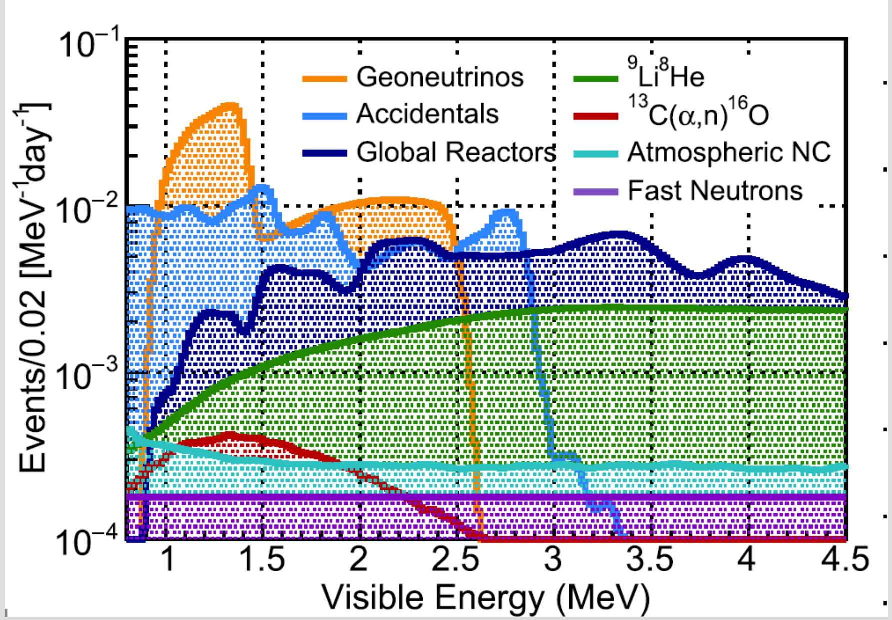
- Neutron sources for nucleosynthesis
- Backgrounds for ton scale detectors

Table 1 The slow, intermediate, neutron, and rapid processes

Name(s)	N_n (cm^{-3})	Neutron source(s)	Astrophysical site(s)
Slow (*s*)	10^6–10^{11}	$^{13}C(\alpha,n)^{16}O$	AGB[b] stars
		$^{22}Ne(\alpha,n)^{25}Mg$	Massive stars[c]
Intermediate (*i*)	10^{12}–10^{15}	$^{13}C(\alpha,n)^{16}O$	Post-AGB stars[d]
			Low-*Z*[e] AGB stars
			Super-AGB stars[f]
			Accreting white dwarfs
			Massive stars[c]
Neutron (*n*) (also called neutron burst)	10^{18}–10^{20}	$^{22}Ne(\alpha,n)^{25}Mg$	He shell of CCSNe[g]
Rapid (*r*)	$>10^{20}$	—	Compact mergers[h] Special CCSNe[i]

Maria Lugaro, Marco Pignatari, Rene Reifarth and Michael Wiescher, Ann. Rev. Nuc. Part. Phys. (2023)

JUNO 20 kT neutrino detector



Abusleme *et al.* (2022)

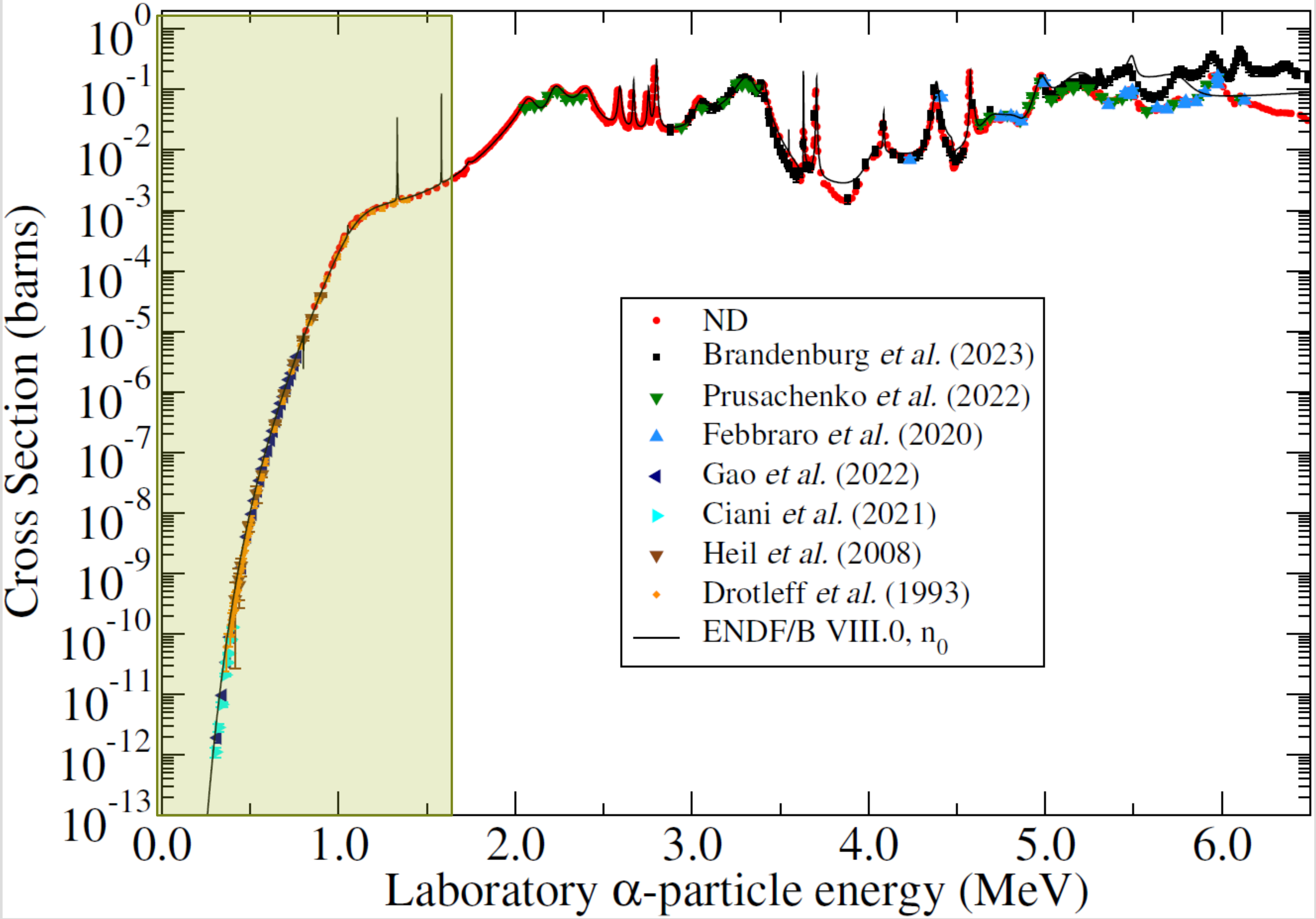
CROSS SECTION AND S-FACTOR OF THE $^{13}C(\alpha,n)^{16}O$ REACTION

- A method to help us visualize and extrapolate to low energies

$$S(E) = \sigma(E)E\exp(2\pi\eta)$$

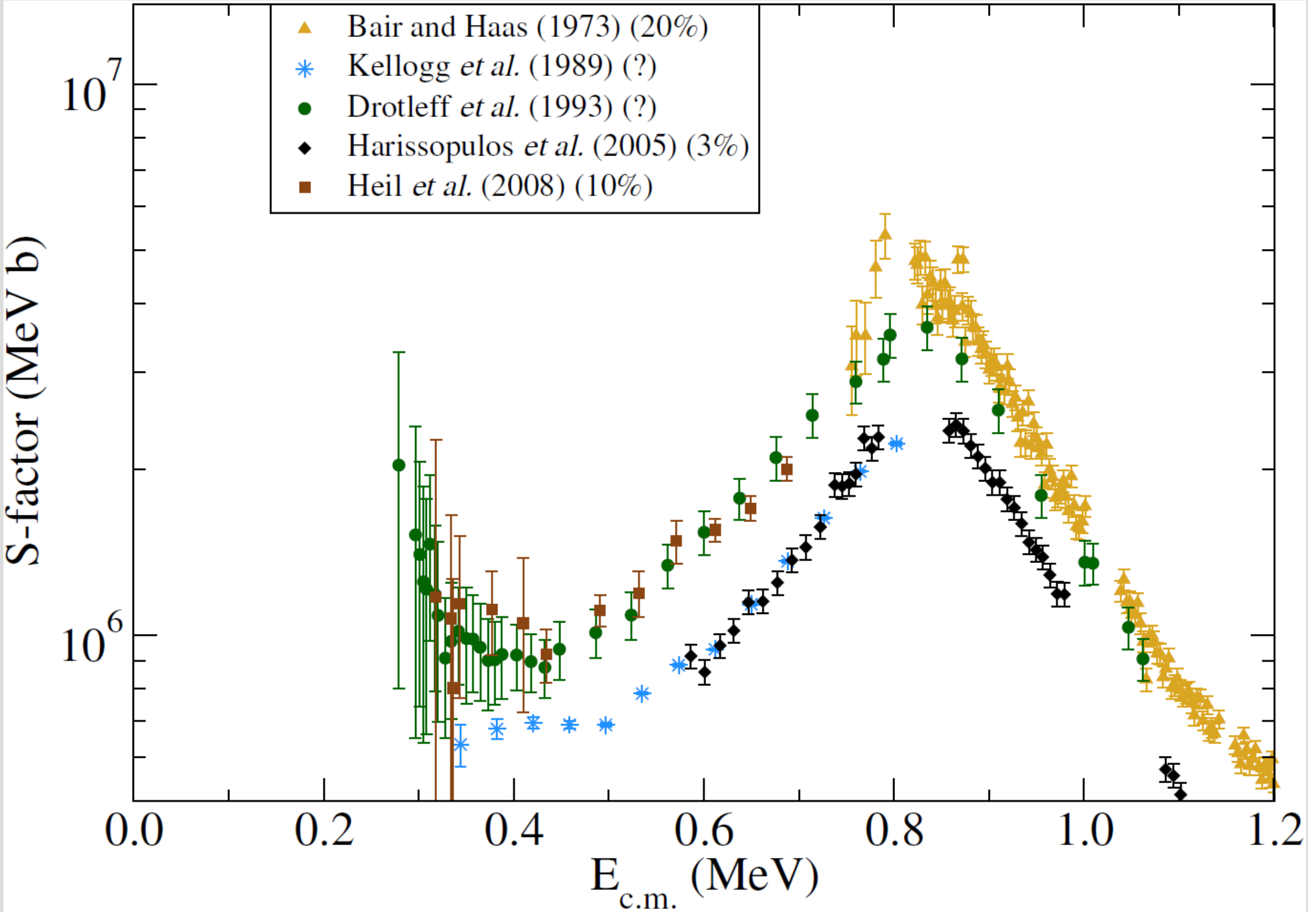
l = 0, Coulomb

$$\eta = \sqrt{\frac{\mu}{2E}}\frac{Z_1 Z_2 e^2}{\hbar^2}$$



STATE OF THE DATA IN 2020

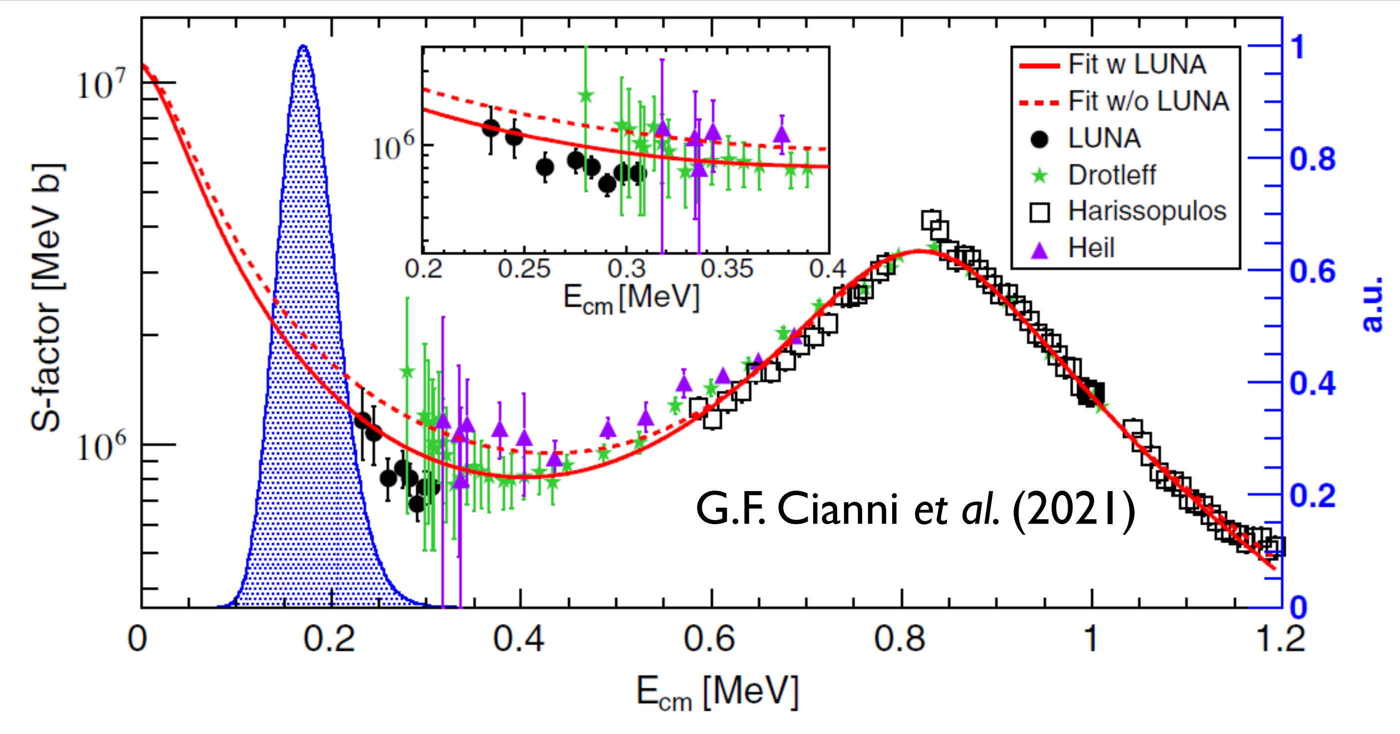
- The normalization issues were the main source of uncertainty until recently
- Some data sets have very little uncertainty information
  - Kellogg *et al.* (1989)
  - Drotleff *et al.* (1993)
- Harissopulos et al. (2005) has unrealistically small uncertainties
- **Around 15 to 20% uncertainty because of data inconsistencies**



NEW MEASUREMENTS AT UNDERGROUND LABORATORIES

- 2021, new measurements at LUNA
- Lower than previous measurements and with greatly reduced uncertainties
- Uncertainties well defined
- Limited overlap with higher energy data
- Thin target measurement

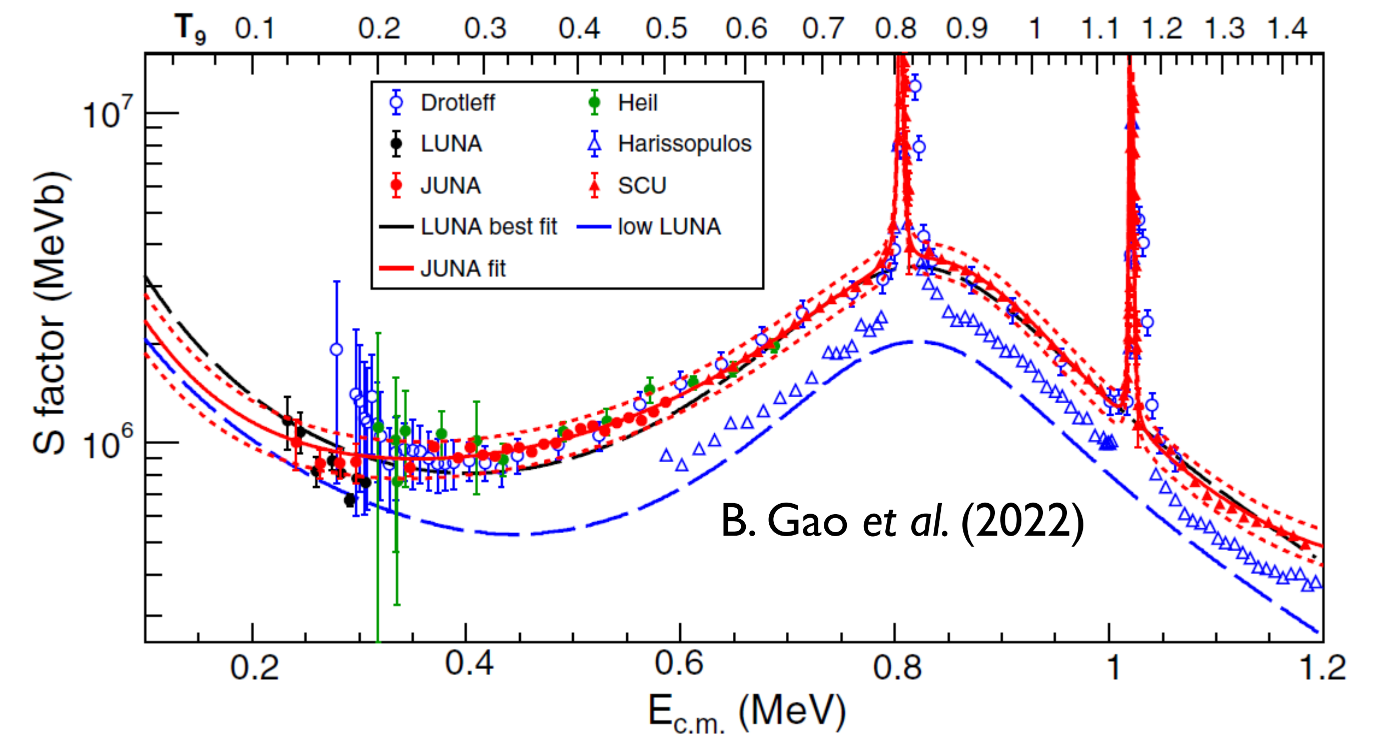
LUNA measurement of $^{13}C(\alpha,n)^{16}O$, PRL



NEW MEASUREMENTS AT UNDERGROUND LABORATORIES

- 2022, new measurements at JUNA
- Measurements extend down to the same energy as LUNA
- Lots of overlap with higher energy data!
- Even higher energy above ground measurements also reported
- Uncertainties well defined
- Thick target measurement

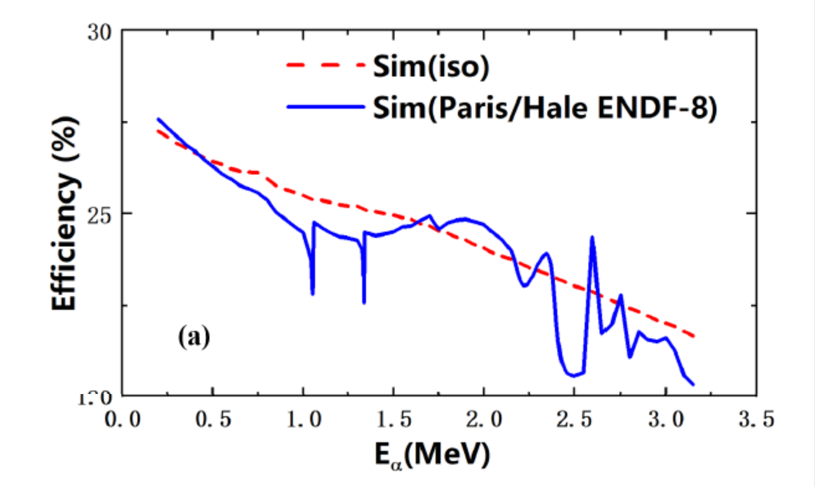
JUNA measurement of $^{13}C(\alpha,n)^{16}O$, PRL



HOW CAN WE COMPLIMENT THESE MEASUREMENTS AT AN ABOVE GROUND LABORATORY?

- Two main areas
  1. High efficiency 4π detectors need to know the underlying angular distributions from the reaction they are measuring to accurately characterize their cross section uncertainties
  2. The phenomenological *R*-matrix description that will be used to extrapolate the data to low energies can be further constrained by differential cross section data since different partial waves are present and there are broad interfering resonances

Y.T. Li *et al.* (2022)



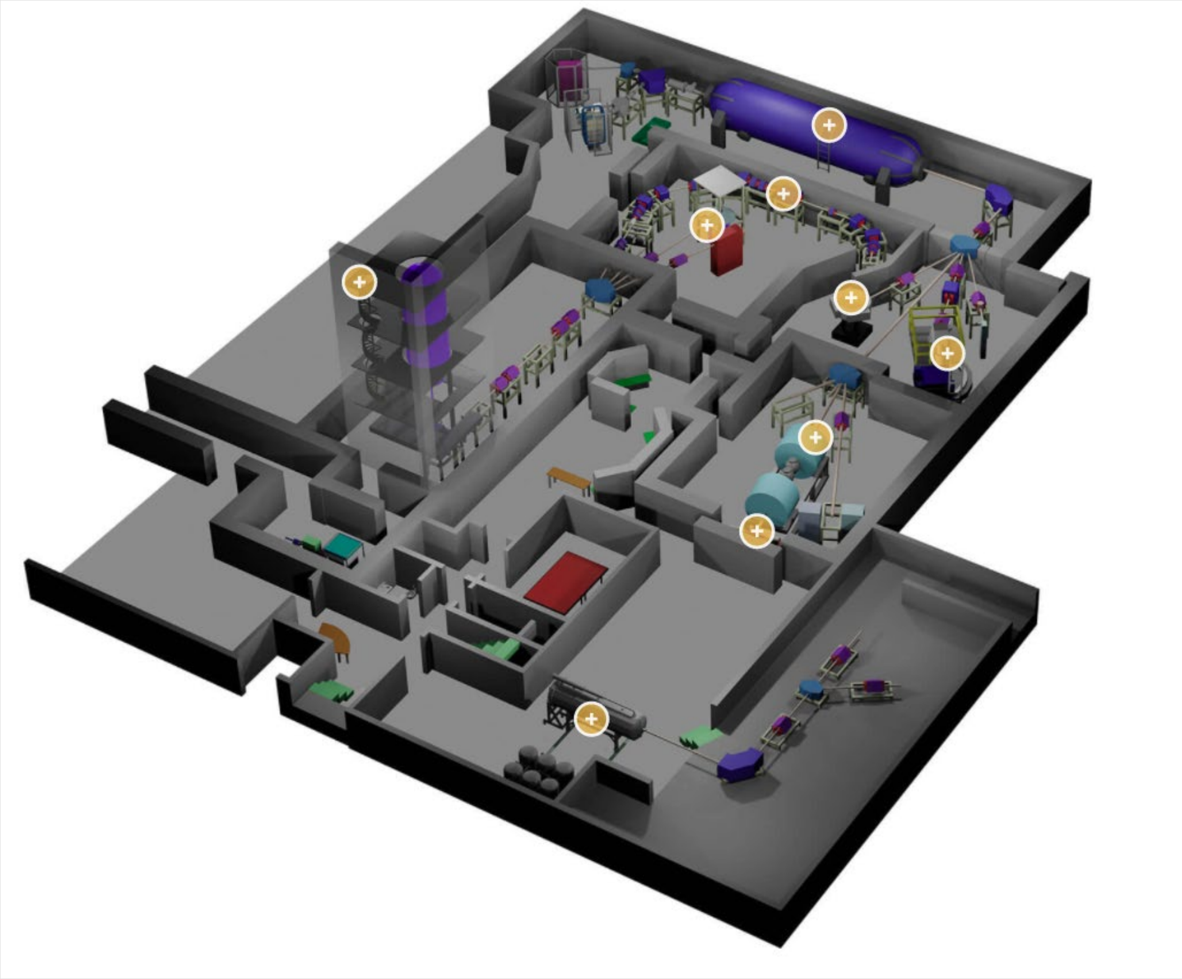
Azuma *et al.* (2010)

Differential cross section formula of R-matrix theory

$$(2s+1)\frac{k_\alpha^2}{\pi}\frac{d\sigma_{\alpha s,\alpha' s'}}{d\Omega_{\alpha'}} = (2s+1)|C_{\alpha'}(\theta_{\alpha'})|^2\delta_{\alpha s,\alpha' s'} + \frac{1}{\pi}\sum_L B_L(\alpha s,\alpha' s') \times P_L(\cos\theta_{\alpha'}) + \delta_{\alpha' s',\alpha s}(4\pi)^{-1/2}\sum_{Jl}(2J+1) \times 2\mathrm{Re}\left[i\left(T^J_{c'c}\right)^* C_{\alpha'}(\theta_{\alpha'})P_l(\cos\theta_{\alpha'})\right]. \qquad (17)$$

UNIVERSITY OF NOTRE DAME NUCLEAR SCIENCE LABORATORY

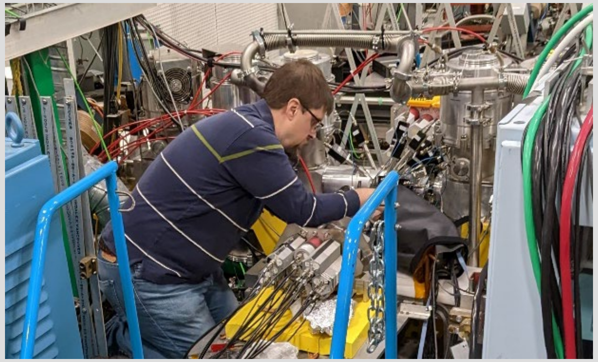
- 5 MV single ended accelerator (5U)
  - dc alpha beam, alphas from 300 keV up to 9 MeV
  - up to 100 uA of beam on target
  - Usually using 10 uA for these studies
  - Energy resolution better than 1 keV at 1 MeV, energy calibration uncertainty of 2 keV at 1 MeV

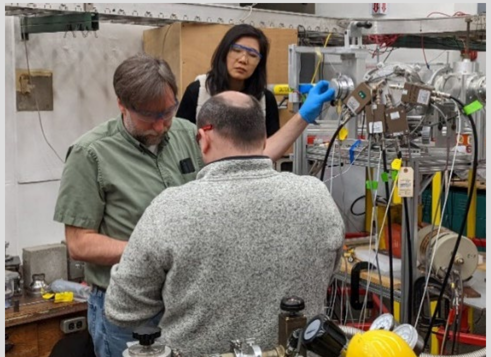


A TEAM EFFORT!

- ND graduate students operate all accelerators
- Research faculty and technicians keep things working

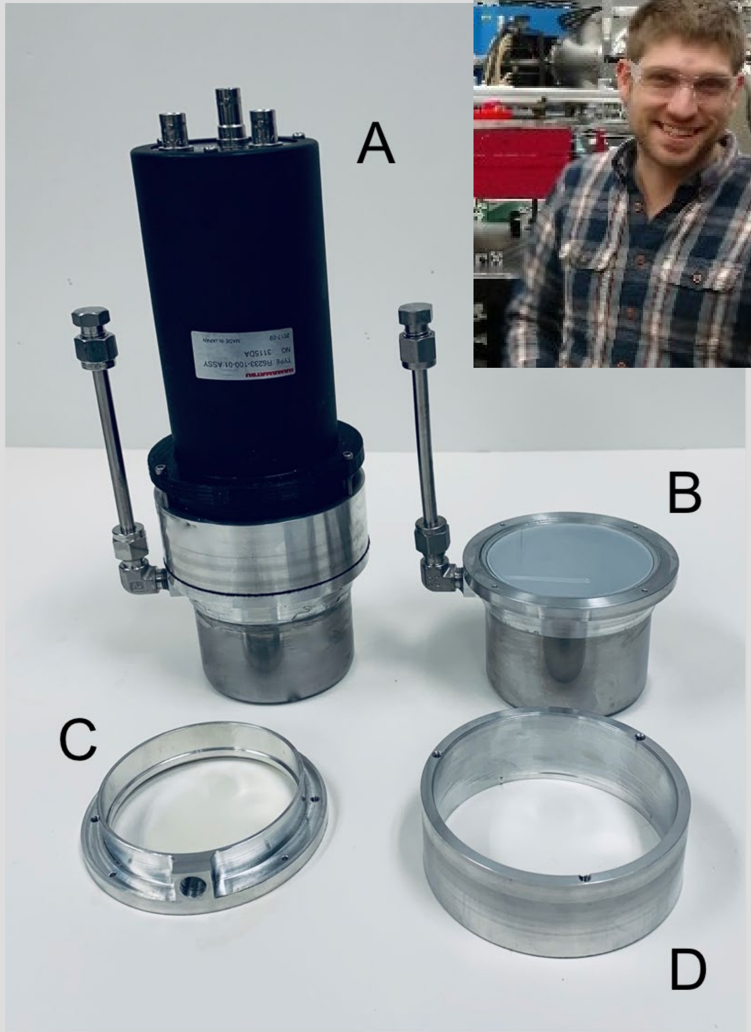





THE ODeSA ARRAY

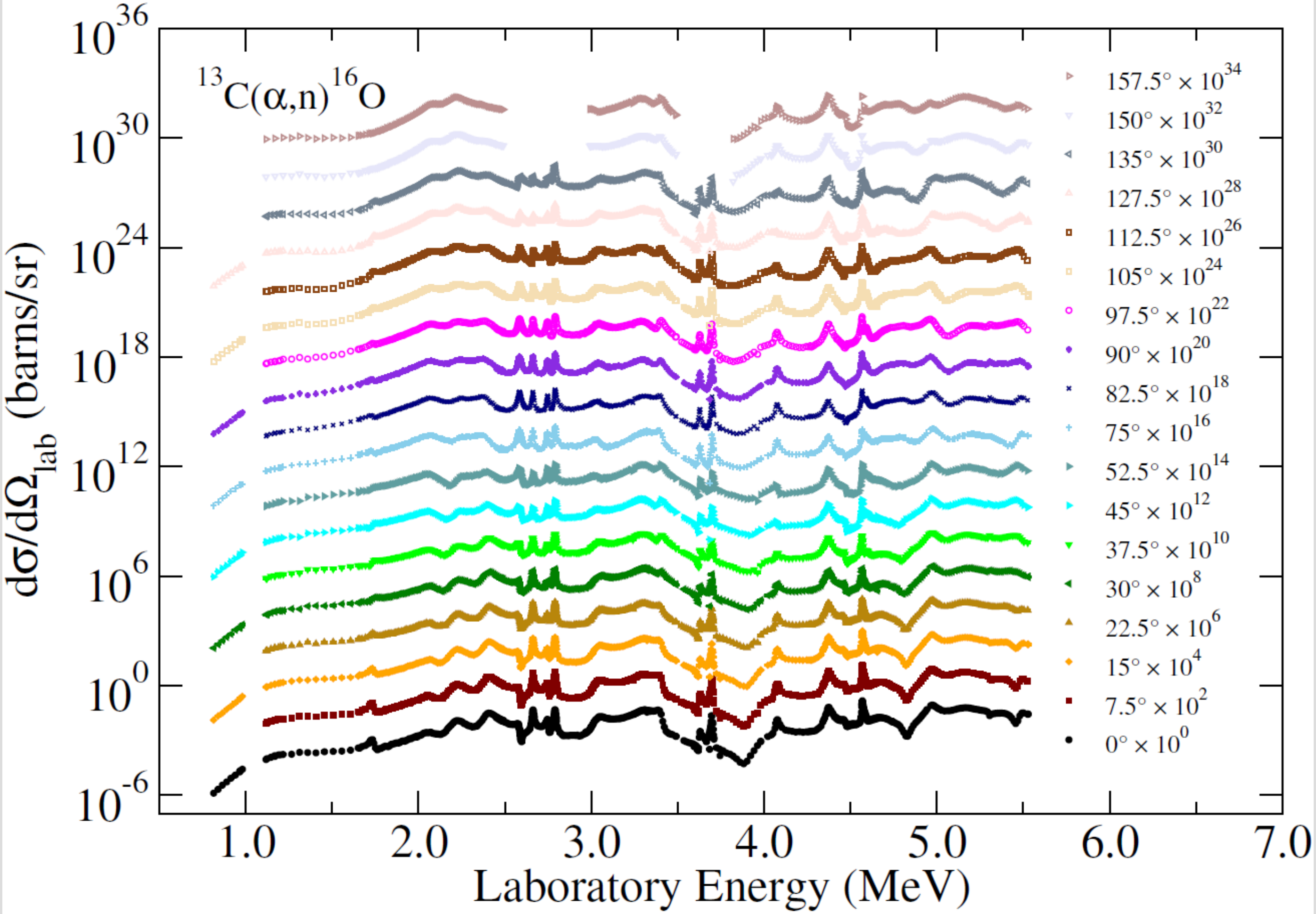
Michael Febbraro (AFIT)



- 8 ORNL deuterated spectroscopic array (**ODeSA**)
- 1 EJ315

DIFFERENTIAL PARTIAL CROSS SECTION FOR $^{13}C(\alpha,n_0)^{16}O$

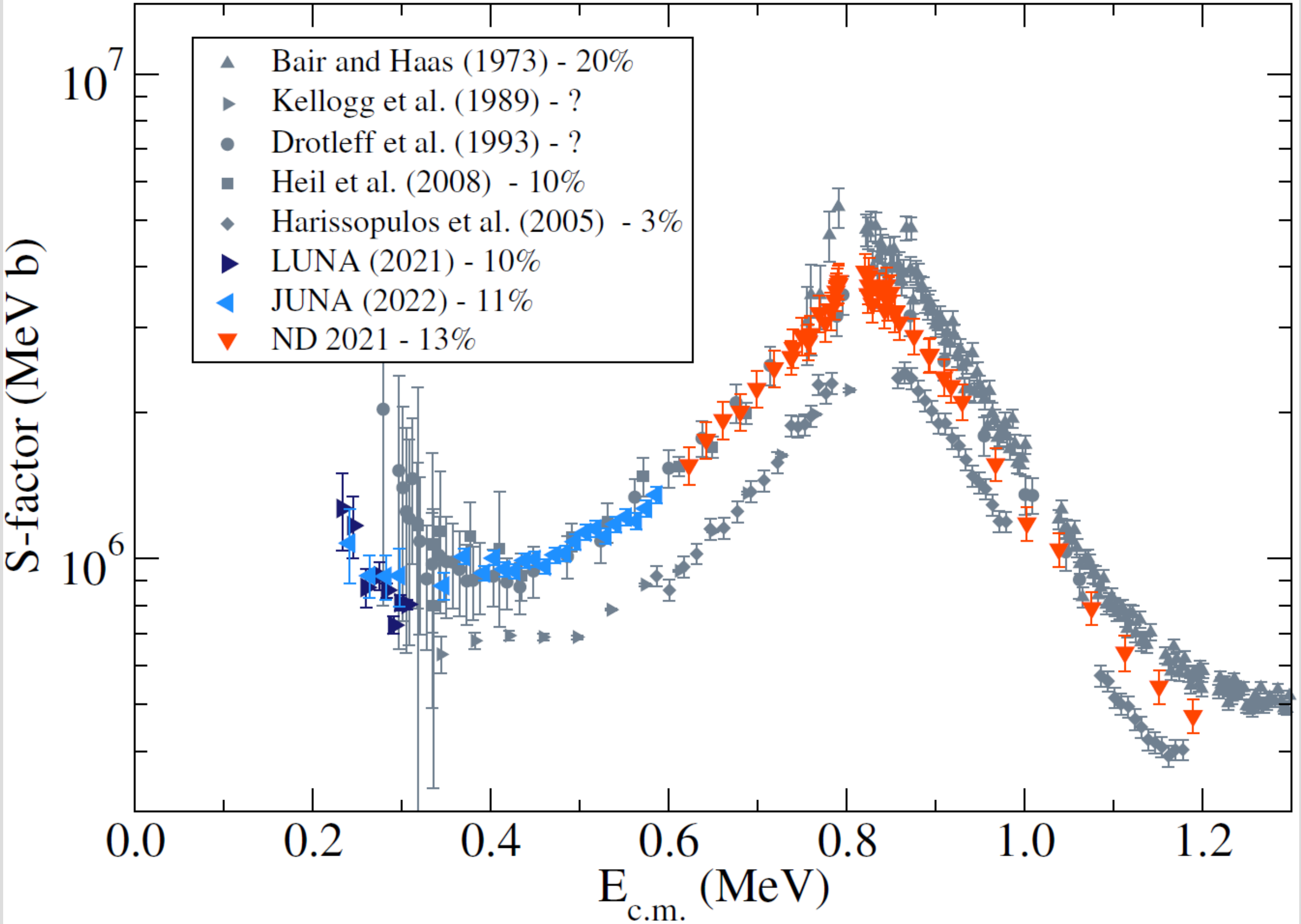
- Thin target, about 5 and 10 ug/cm²
- Resolution better than 10 keV (target energy loss)
- 10 keV or smaller energy steps
- More than 700 different energy steps
- angular coverage
  - 0 to 157.5 degrees
  - 18 point angular distributions



NEW MEASUREMENTS FAVOR LARGER NORMALIZATION FACTOR

- New measurements highly favor the larger normalization factor

- New measurements point towards issues with the neutron detection efficiency for the Harissopulos and Kellogg data sets



THE 1.05 MEV RESONANCE

- The 1.05 MeV resonance in $^{13}C(\alpha,n)$ should be a good calibration point for normalization
- E_{lab} = 1.0563(15) MeV, $\Gamma_{c.m.}$ = 1.5(2) keV
- Problem: resonance strength in the literature seems to be too low!
  - Values from Bair and Haas (1973), Brune *et al.* (1993) and Harissopulos *et al.* (2005)

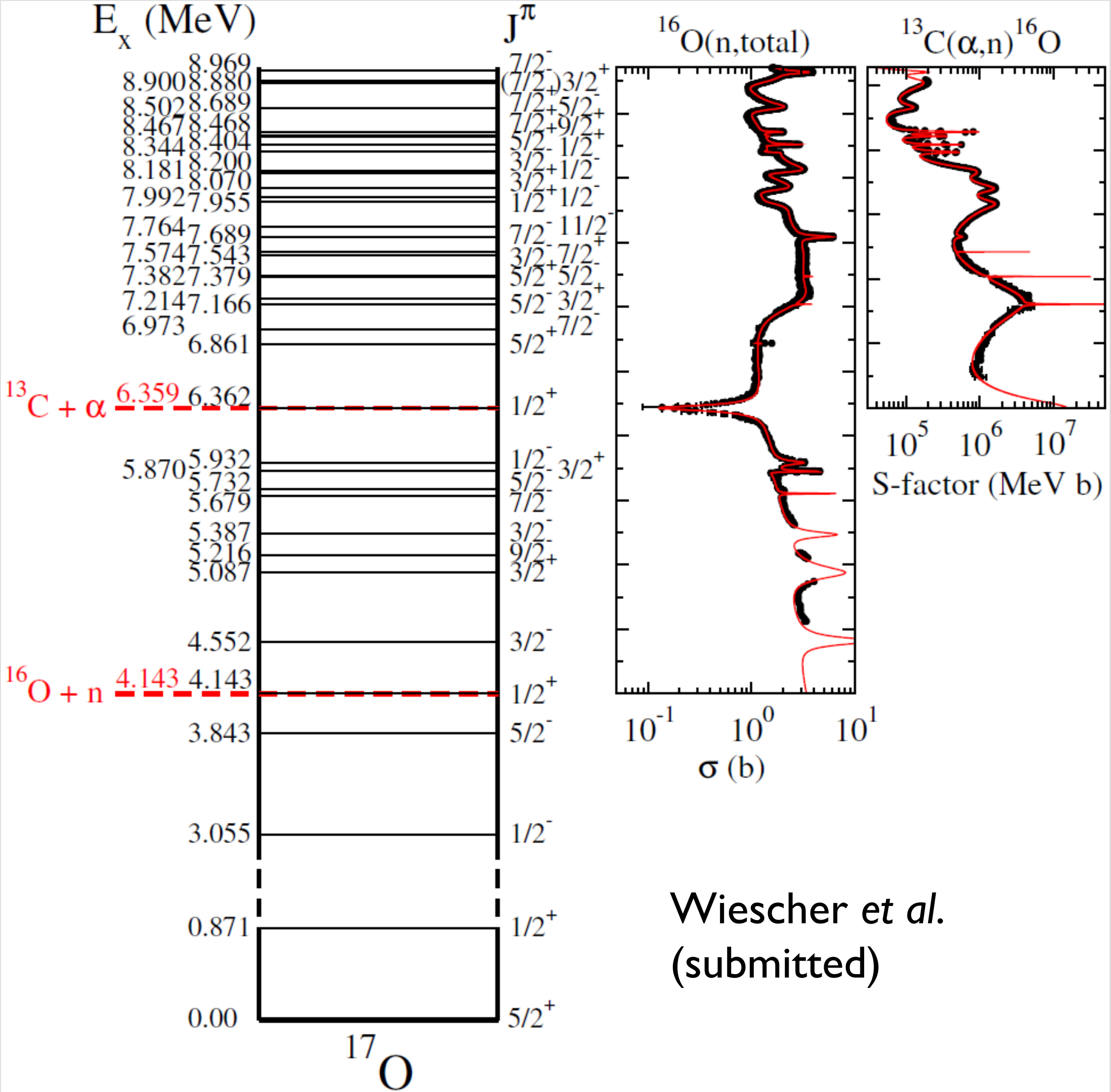
L.H. Ru *et al.* (2023)

TABLE II. Resonance strength and the thick target yield of the E_α = 1055.63 keV resonance.

Reference	$\omega\gamma$ /eV	Y_{max} (n/μC)[a]
This work	16.9 ± 0.4[b]	6460 ± 152[c]
Bair *et al.*	12.9 ± 0.6[d]	4475 ± 223
Brune *et al.*	11.9 ± 0.4[e]	4410 ± 170
Harissopulos *et al.*	12.1 ± 0.6	
Notre Dame (unpublished)	**16.5 ± 2.1**	**6320 ± 316**

COMBINED R-MATRIX ANALYSIS

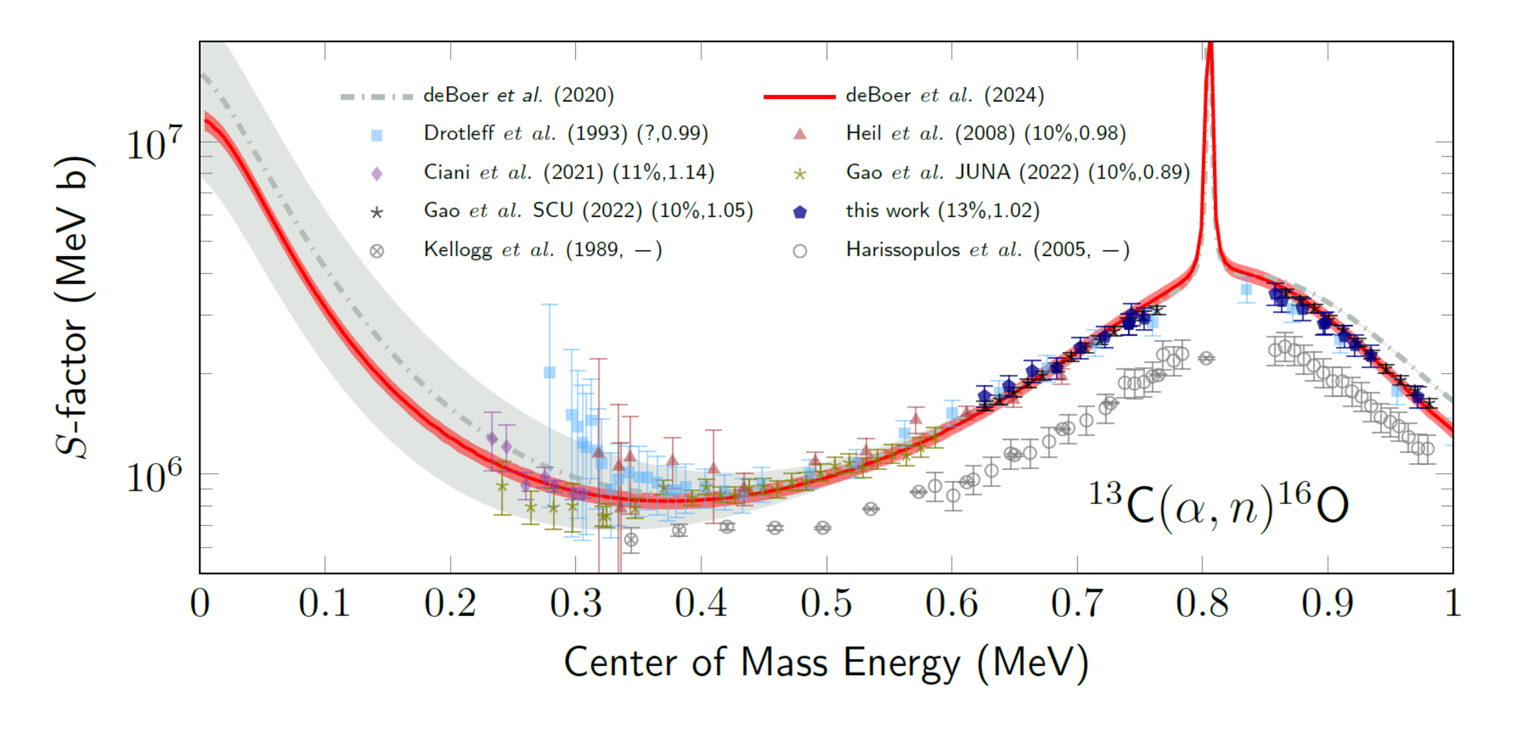
- Independent R-matrix analyses have been made by JUNA, LUNA and ND groups
- All based, at least in some part, on the LANL R-matrix fit of Gerry Hale and Mark Paris that is used for the ENDF/B evaluations
- See also Chakraborty *et al.* (2019)



Wiescher *et al.* (submitted)

NOTRE DAME R-MATRIX FIT

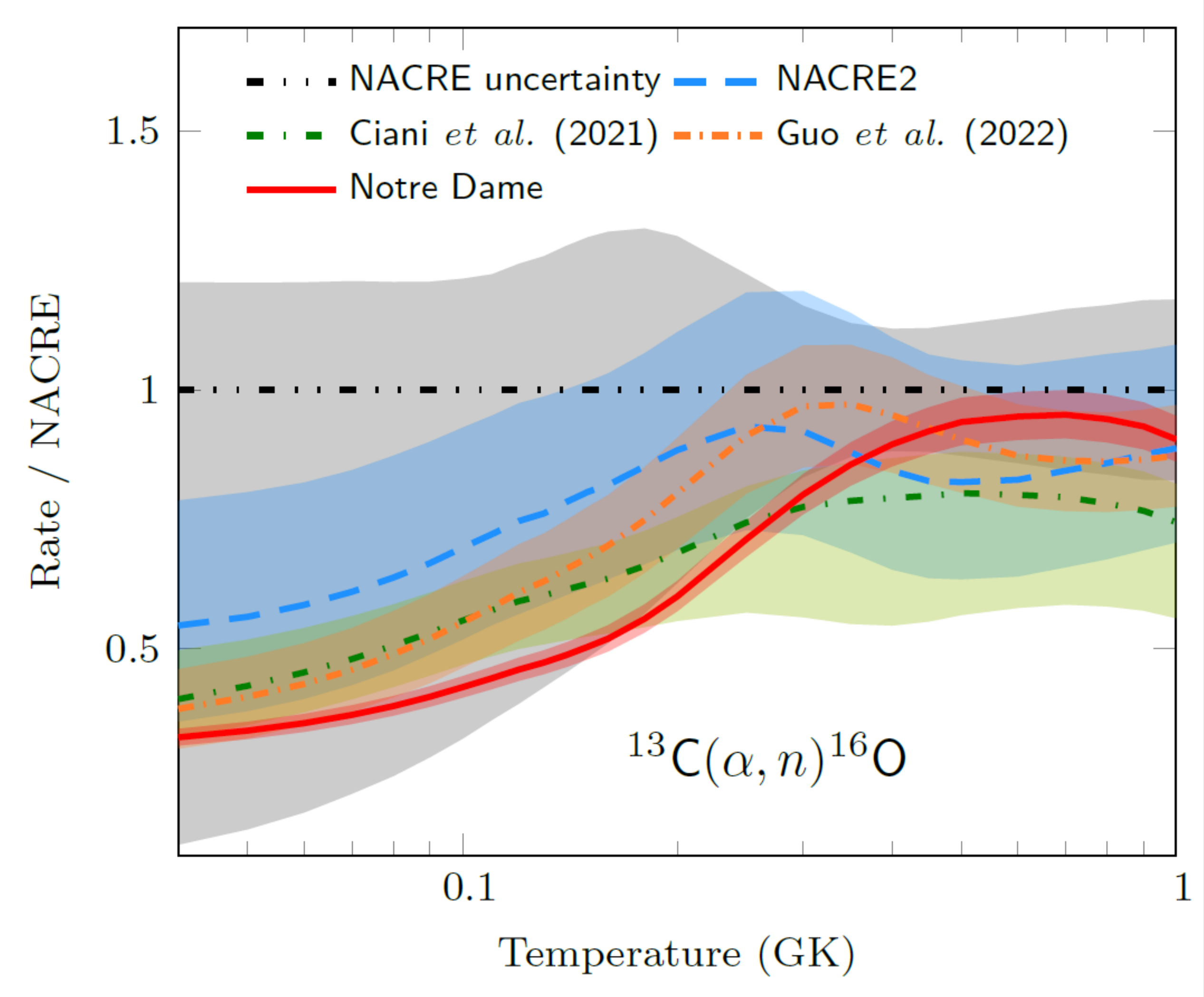
- Quite a small uncertainty found from our "best fit", about 5% over much of the energy range, even at low energies
- Angular distribution data provide a lot of additional constraint on the model
- However, some systematic uncertainties in the angular distribution data were hard to correct
  - Out scattered neutrons from target holder



NOW WE WILL TRY TO COMBINE RESULTS TO GIVE A RECOMMENDED REACTION RATE

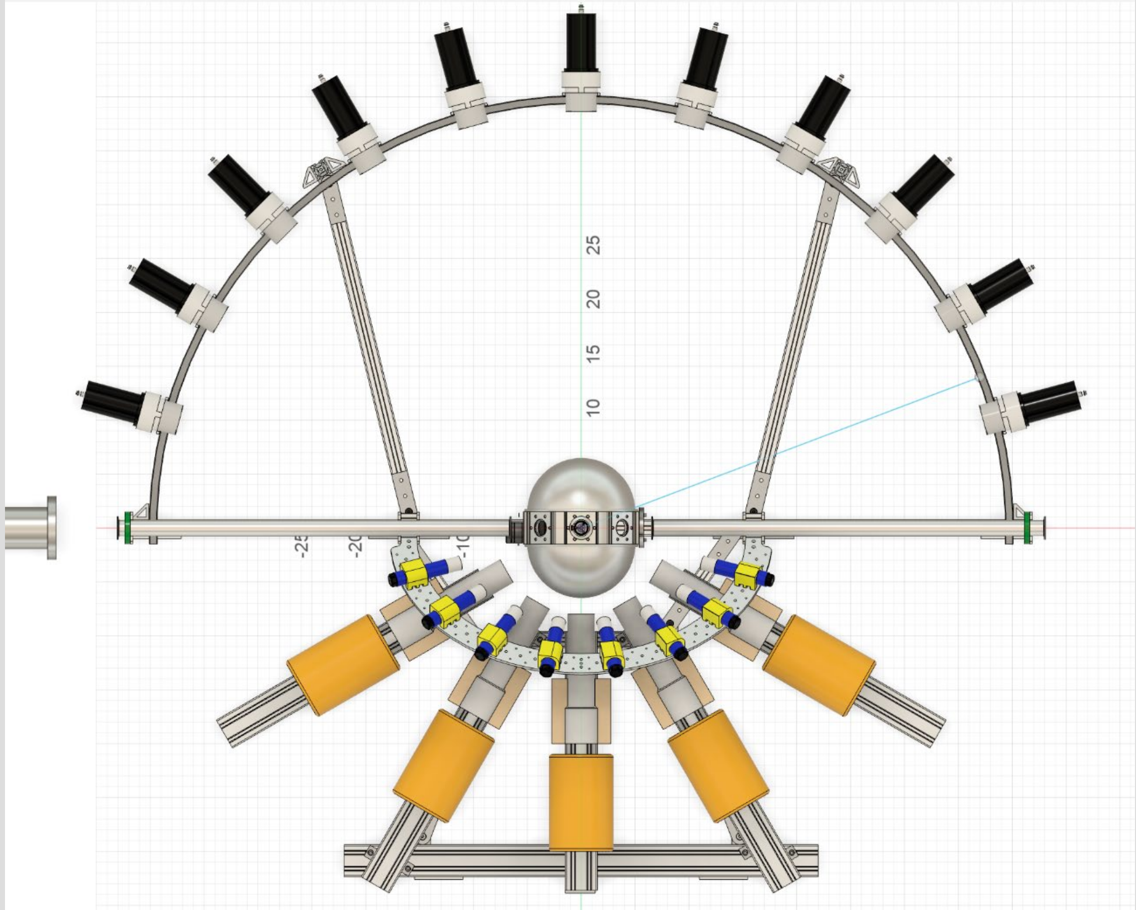
IReNA
International Research Network for Nuclear Astrophysics

- With the uncertainties greatly reduced from the recent experiments, an IReNA funded project is now being led by David Rapagnani at University of Naples to produce an updated rate for the community
- Some systematics still not accounted for that are probably quite significant
  - Ambiguity in the way different data sets are fit
  - Some discrepancy remain between different data sets, although greatly reduced from pre 2020
- Treatment of indirect data
  - ANCs for threshold state
  - ^{16}O+n data
- Bringing together experts in all of these areas to provide a best estimate of the rate



MORE (α,n) ON THE HORIZON AT ND:
A COMPREHENSIVE SELF-CONSISTENT CAMPAIGN TO DETERMINE REACTION CROSS SECTIONS, SECONDARY GAMMA-RAY YIELDS, AND MEASURED NEUTRON SPECTRA FOR ALPHA-INDUCED REACTIONS ON LIGHT NUCLEI

- PIs
  - Hye Young Lee (LANL)
  - James deBoer (ND)
  - Michael Febbraro (AFIT)
- (α,n) reactions to study from 2 to 8 MeV
  - $^{7}Li(\alpha,n)^{11}B$
  - $^{10}B(\alpha,n)^{13}N$
  - $^{11}B(\alpha,n)^{14}N$
  - $^{13}C(\alpha,n)^{16}O$
  - $^{19}F(\alpha,n)^{21}Na$
- Trying to measure neutrons, charged particles and γ-rays in order to reduce systematic uncertainties
- The ODeSA array + array of stilbene + photodiode array + HPGe array



National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

Office of Science

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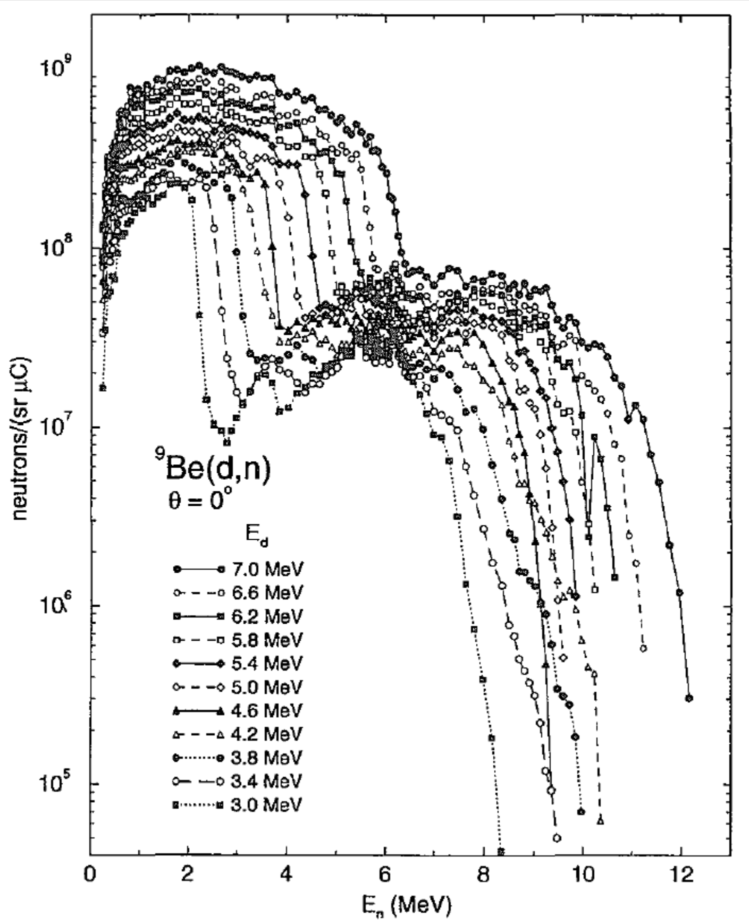
SOME UNIQUE CAPABILITIES AT ND

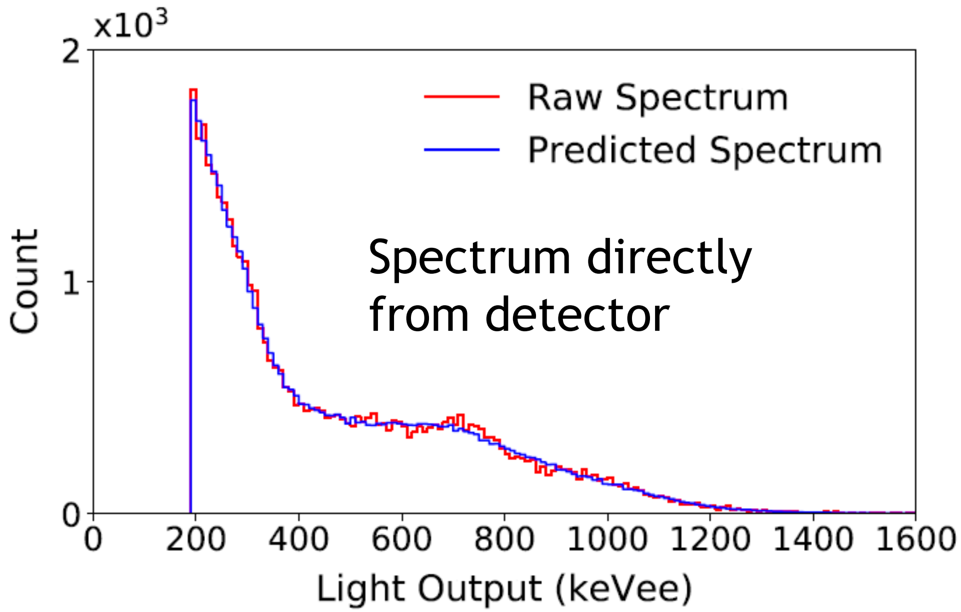
- **Accelerator (ND 5U)**
- Array of deuterated liquid scintillators (ORNL)
- Response Matrix (OU) and Spectrum Unfolding (ORNL)

RESPONSE MATRIX AND EFFICIENCY

- Massey *et al.* (2002)
- We perform a high statistics run using time-of-flight and a deuteron beam on a thick ^{9}Be target
- Takes a day or so of running for each detector to get enough stats, but only needs to be done once
- Thick target yield is known to about 5% uncertainty
- Gets us both the detector response to "monoenergetic" (about 100 keV bins) and the absolute efficiency
- Calibrations done at Ohio University



Spectrum Unfolding



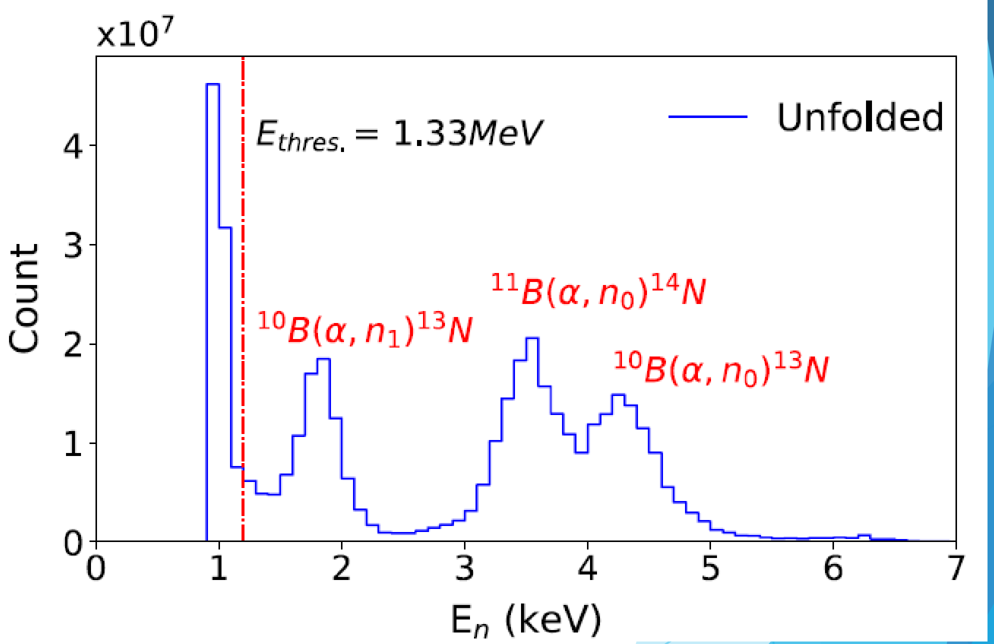
Light output spectrum

\+

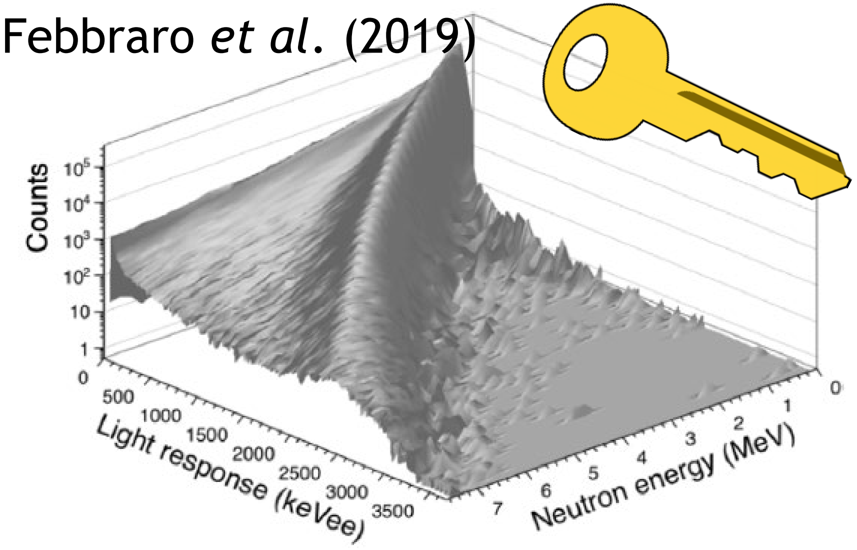
Maximum Likelihood

=

Neutron Energy Spectrum



Febbraro *et al.* (2019)



Response matrix (experimentally measured)

Fig. 9. Response matrix generated using a broad energy neutron source from a thick target $^{27}Al(d,n)$ reaction at E_d = 7.44 MeV [12].

Calibrations preformed at the **Edwards Accelerator Laboratory** at OU and now also **LANSCE** at LANL

LEGENDRE FIT, COMPARE WITH 4Π DATA

- Good agreement between ND and OU data!
- Independent measurements at independent facilities
- OK agreement with recent Prusachenko measurements, but there are some inconsistencies