NEUTRON SOURCES IN STARS

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ONGOING IReNA / ChETEC-INFRA SPONSORED WORKSHOPS

- Nuclear Reaction rates for the s-process workshop, February 22-23, Naples, IT
- Topical meeting of IReNA – FA1 and ChETEC-INFRA Nuclear reaction measurements in Underground Laboratories, Rome, IT April 5-8, 2022
- Virtual workshop on (α,n) reactions for astrophysics, July 14-15, 2021

WHAT ARE THE NEUTRON SOURCE REACTIONS IN STARS?

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]

$^{10}B(\alpha,n)^{13}N$ **First stars**

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

OVERALL NEUTRON FLUX IS MORE COMPLICATED

- Neutron poisons
  - $^{22}Ne(n,\gamma)^{23}Na$, $^{25}Mg(n,\gamma)^{26}Mg$ and $^{16}O(n,\gamma)^{17}O$
- Neutron recycling reactions
  - $^{17}O(\alpha,n)^{20}Ne$, $^{18}O(\alpha,n)^{21}Ne$, $^{25}Mg(\alpha,n)^{28}Si$ and $^{26}Mg(\alpha,n)^{29}Si$

NEW FACILITIES, TECHNOLOGY, AND DETECTOR SIMULATION METHODS HAVE DRIVEN NEW MEASUREMENTS

- Interest has been there, but previous facilities / methods had reached their limits

- LUNA able to run α-beams
- JUNA came online
- Improved neutron detection / analysis technology

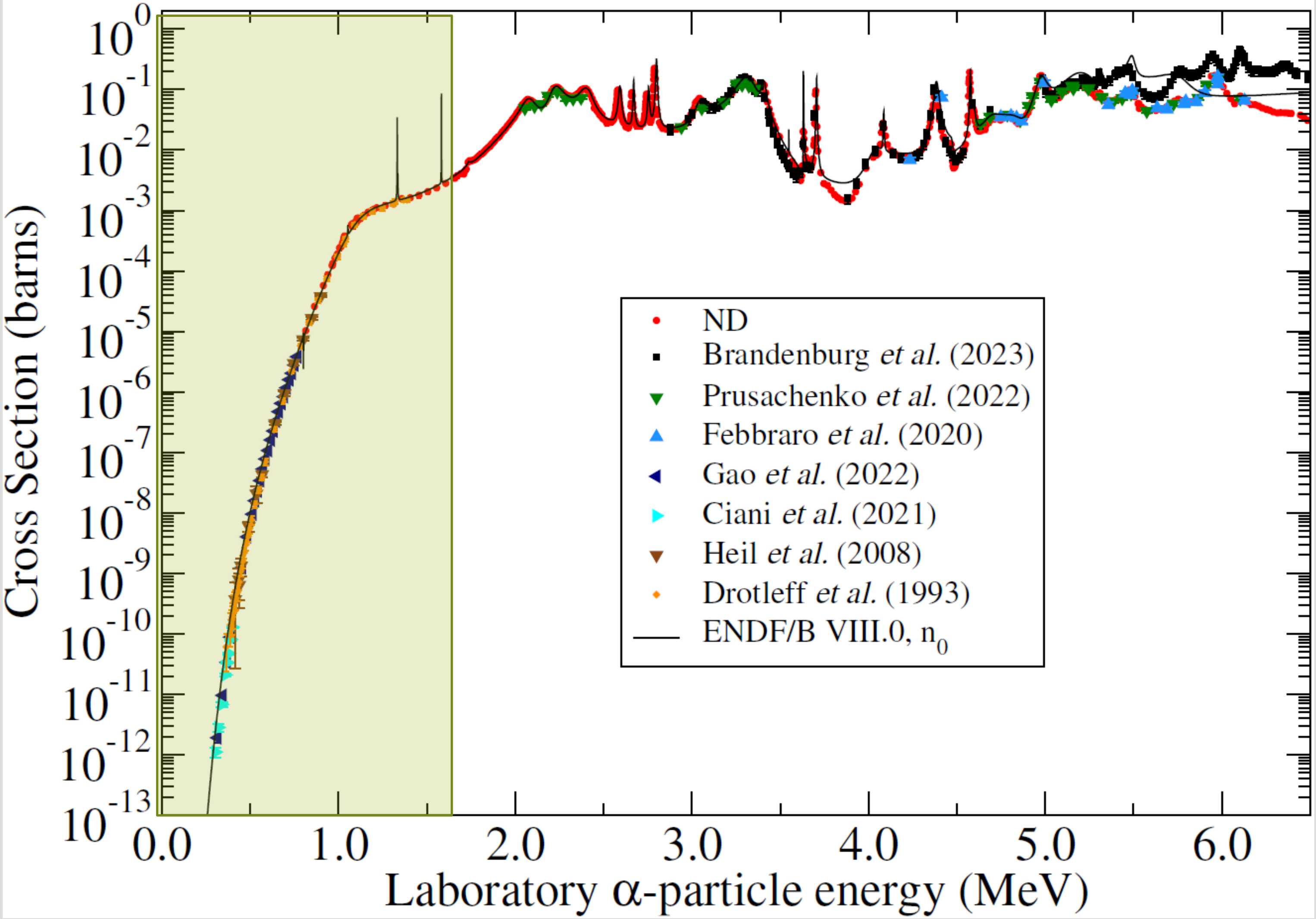
CROSS SECTION OF THE $^{13}C(\alpha,n)^{16}O$ REACTION

- Cross section is very low, but maybe not out of reach
- Not many sources of background because it is a strong reaction
- Level density is medium

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

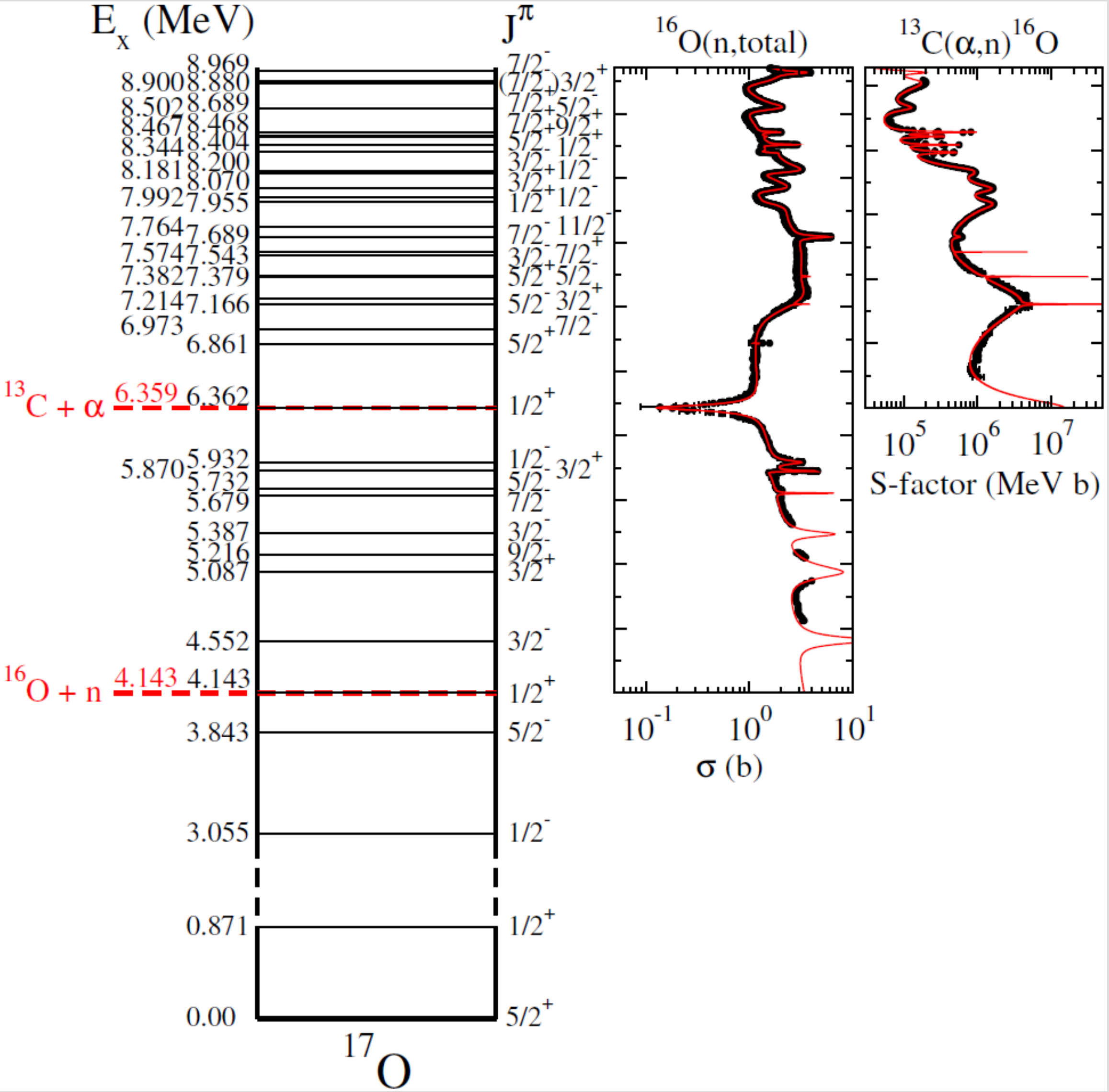
l = 0, Coulomb

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



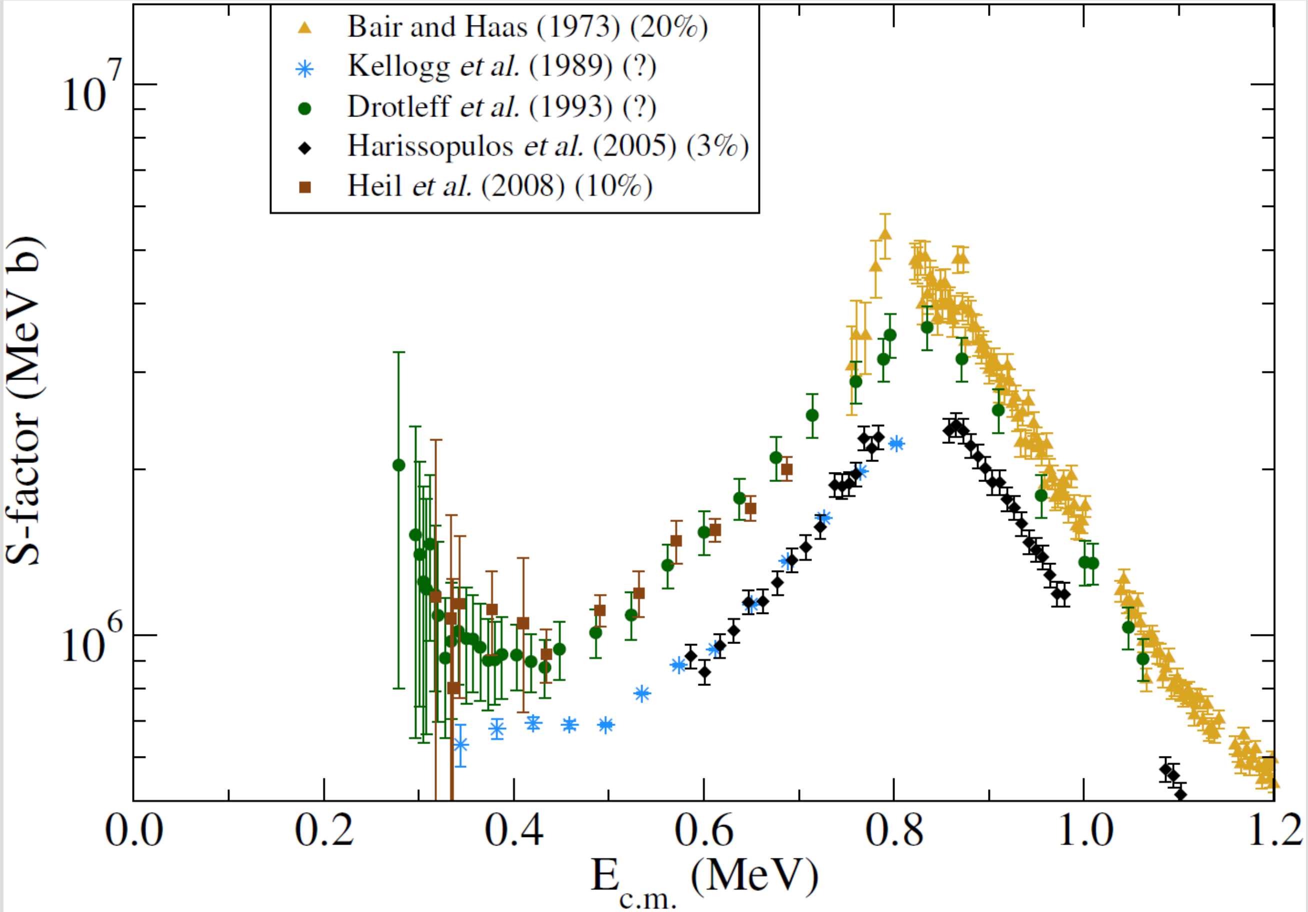
THE $^{13}C(\alpha,n)^{16}O$ REACTION

- Positive 2.2 MeV Q-value
- High precision ^{16}O(n,total) data
- Medium level density
- Strong threshold state
- Neutron total cross section data can provide a lot of useful information



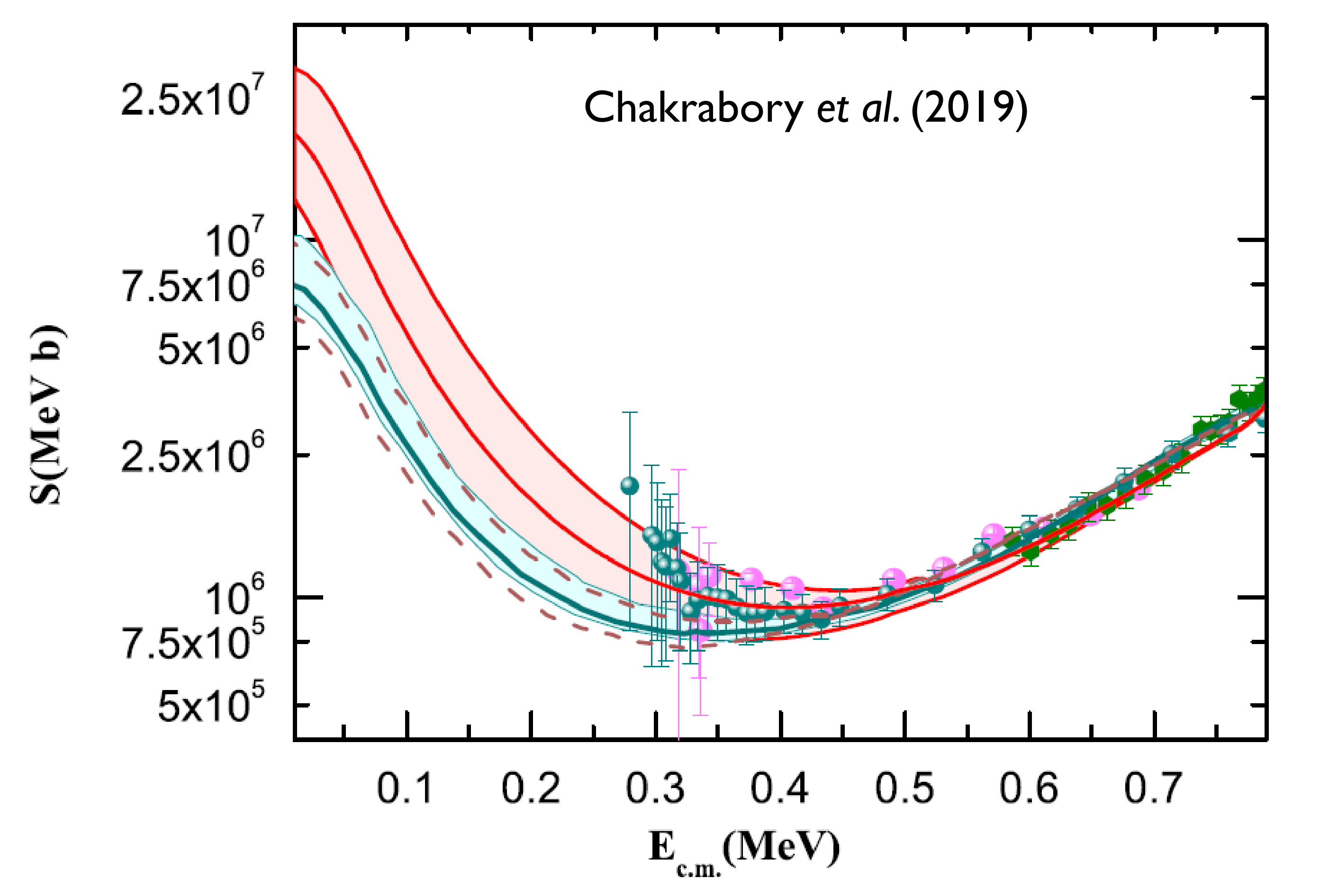
STATE OF THE DATA IN 2020

- 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**



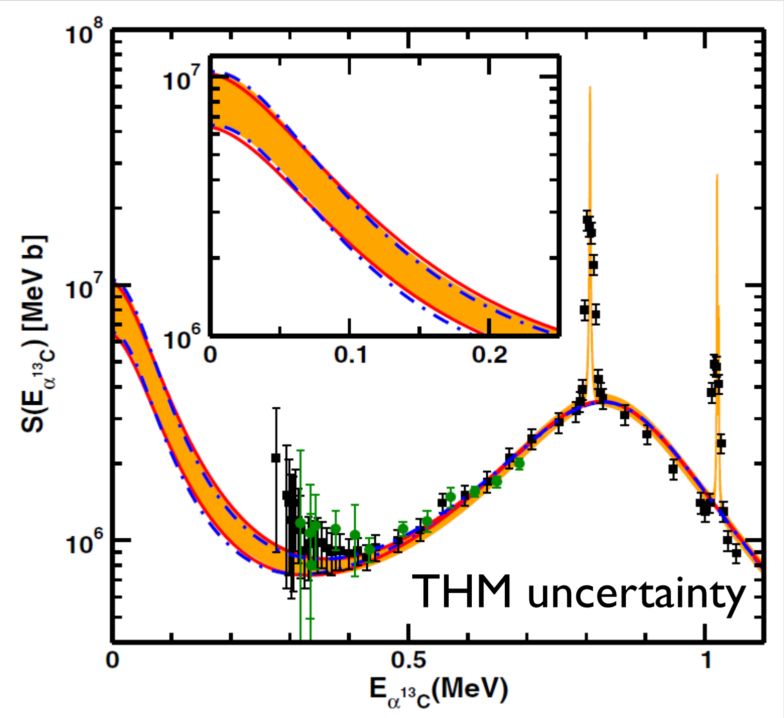
MUST STILL EXTRAPOLATE TO LOW ENERGIES

- Usually phenomenological R-matrix is used to fit data, taking constraints on the properties of the threshold state from α-transfer reactions
- We're using R-matrix because we need to be able to precisely model interference between resonances
  - There are a lot of other motivations for this as well



ASYMPTOTIC NORMALIZATION COEFFICIENT OF THE NEAR THRESHOLD STATE AND LOW ENERGY TROJAN HORSE MEASUREMENTS

- Threshold state dominates the cross section at very low energies
- ANC & the neutron width of the threshold state determine its contribution to the low energy cross section



Mukhamedzhanov *et al.* (2017)

Ref.	$\widetilde{C}^2$ (fm^{-1})	% unc. in S
Pellegriti *et al.* [43]	4.5(22)	50
La Cognata *et al.* [31][a]	$7.7 \pm 0.3_{\text{stat}}{}^{+1.6}_{-1.5}{}_{\text{norm}}$	20
Guo *et al.* [44]	4.0(10)	25
Avila *et al.* [33]	3.6(7)	20
Mezhevych *et al.* [42]	5.1(15) or 4.5(14)	30
Uncertainty in DWBA fitting [29]		10

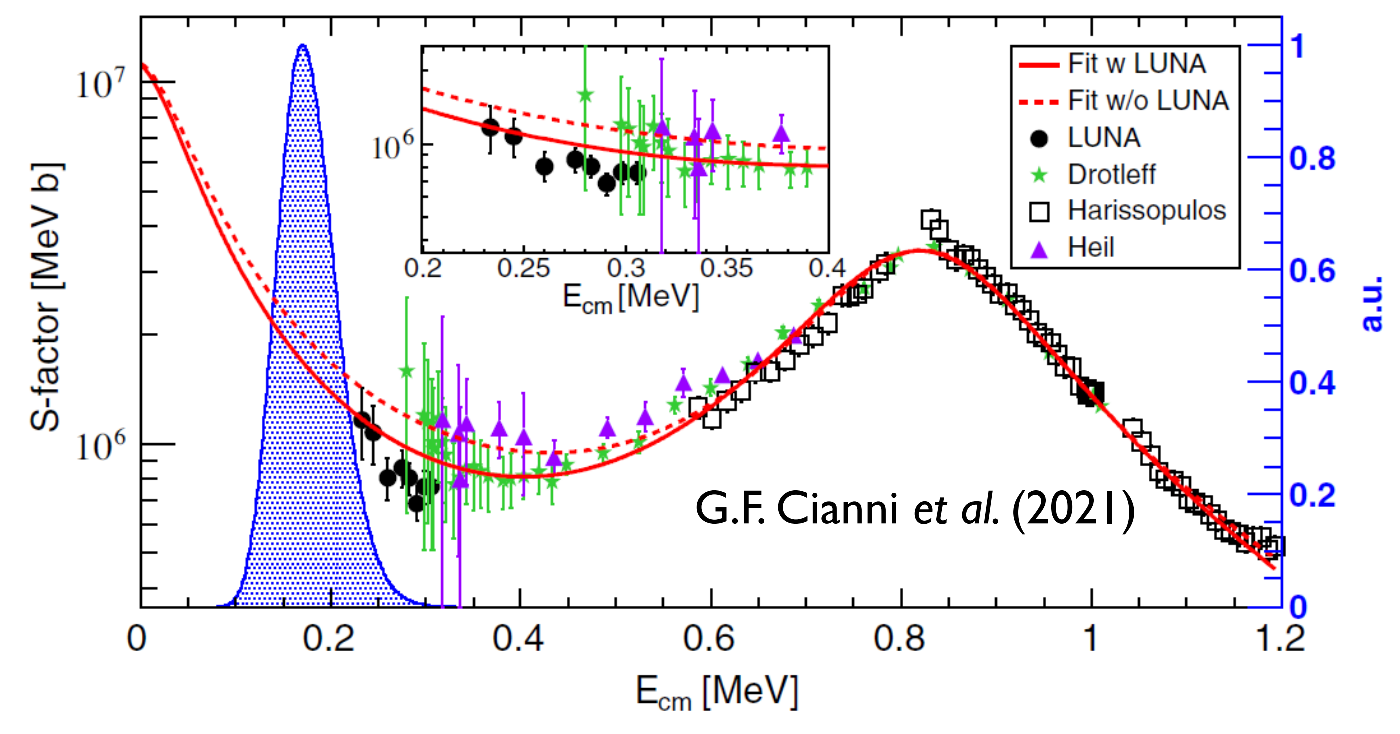
[a]Re-evaluated in Trippella and La Cognata [35].

- At astrophysical energies, the cross section is a mix between the threshold state and a broad higher energy resonance
- ANCs are determined through α-transfer and scattering experiments
  - ^{6}Li(^{13}C,d)^{17}O, ^{13}C(^{11}B,^{7}Li)^{17}O, ^{13}C(^{7}Li,t)^{17}O

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

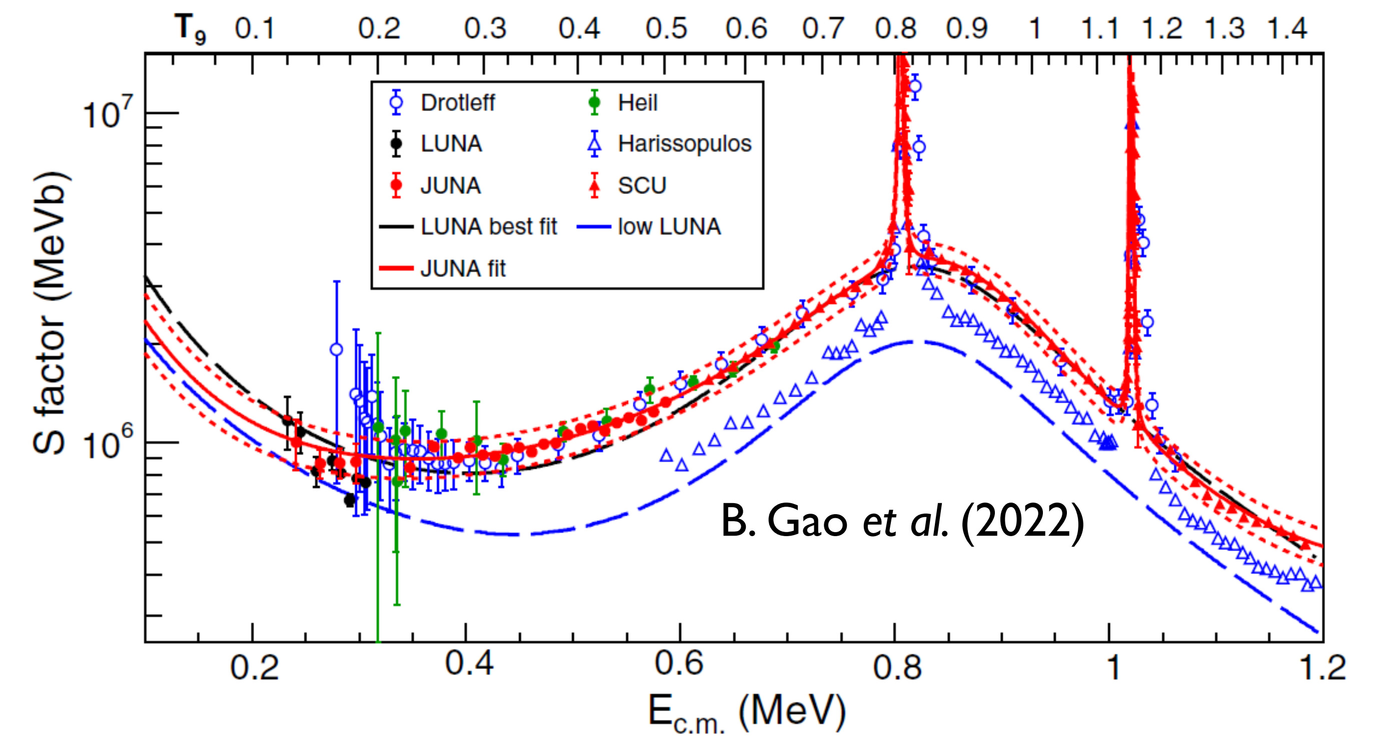
LUNA measurement of $^{13}C(\alpha,n)^{16}O$, PRL



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

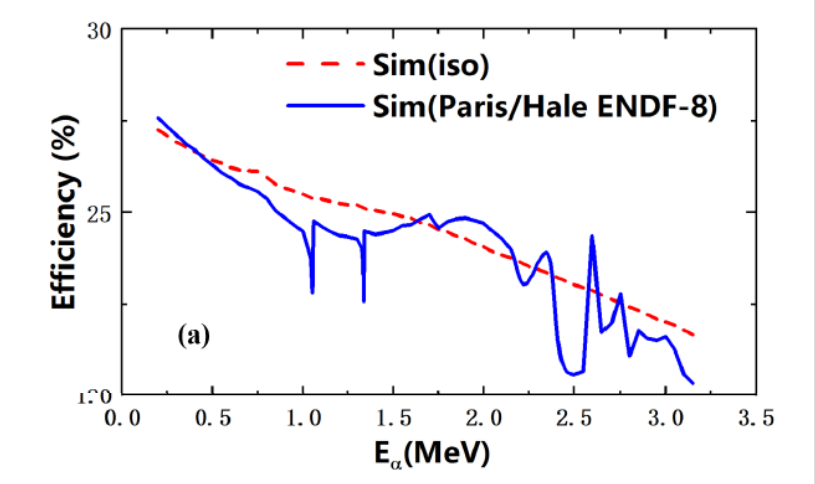
JUNA measurement of $^{13}C(\alpha,n)^{16}O$, PRL



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

- 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)



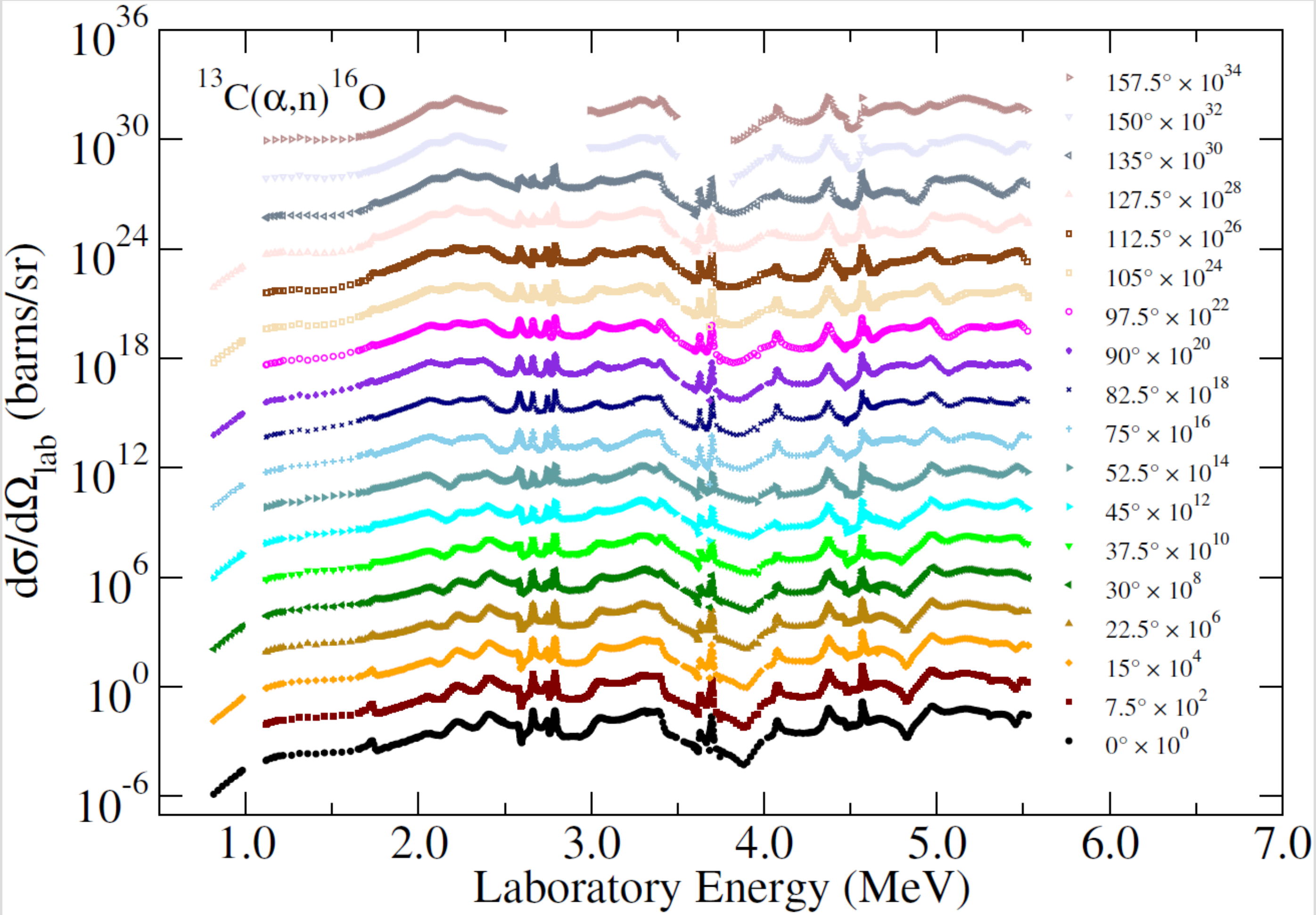
Azuma *et al.* (2010)

Differential cross section formula of R-matrix theory

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

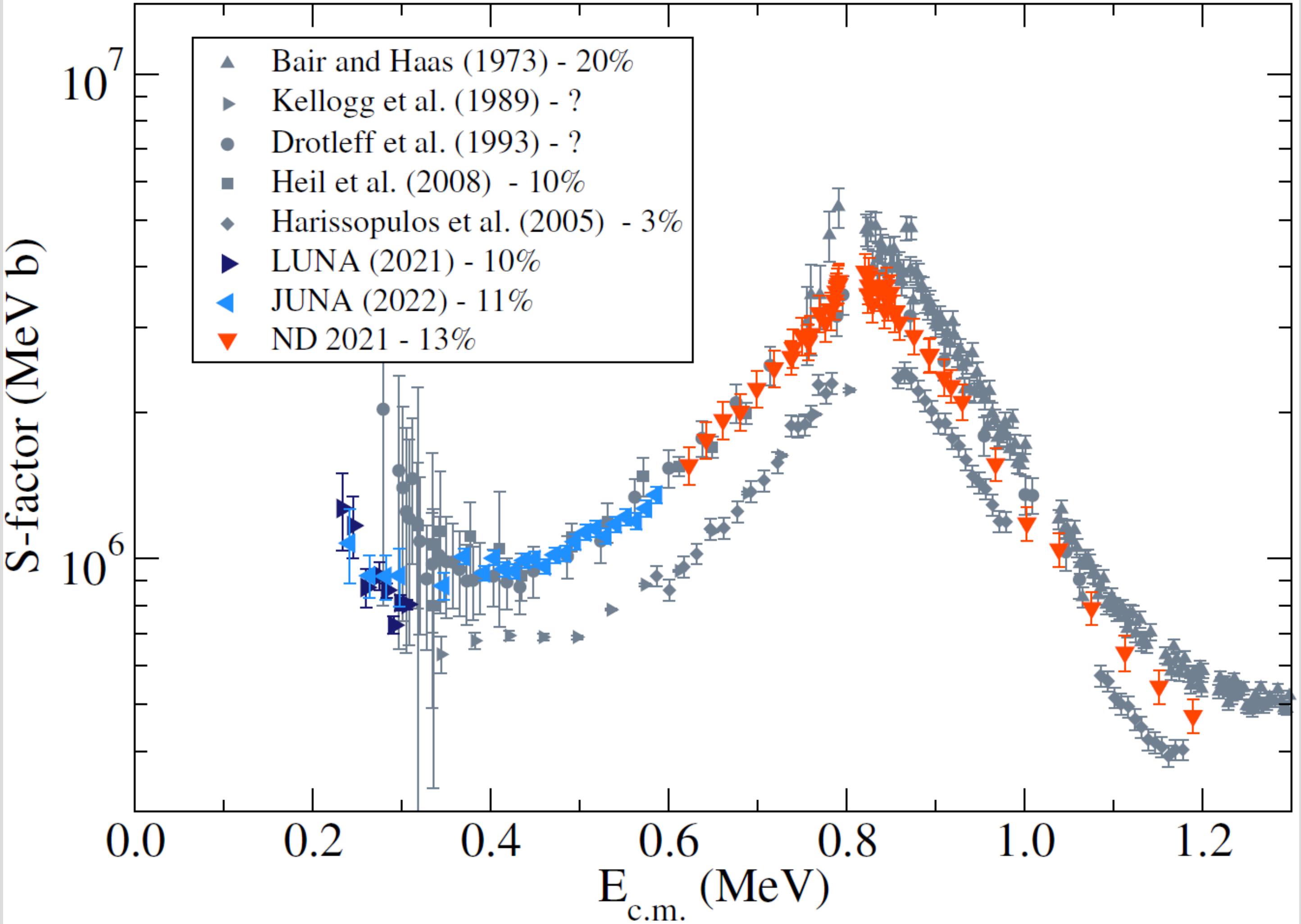
NOTRE DAME DIFFERENTIAL PARTIAL CROSS SECTION FOR $^{13}C(\alpha,n_0)^{16}O$

- 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



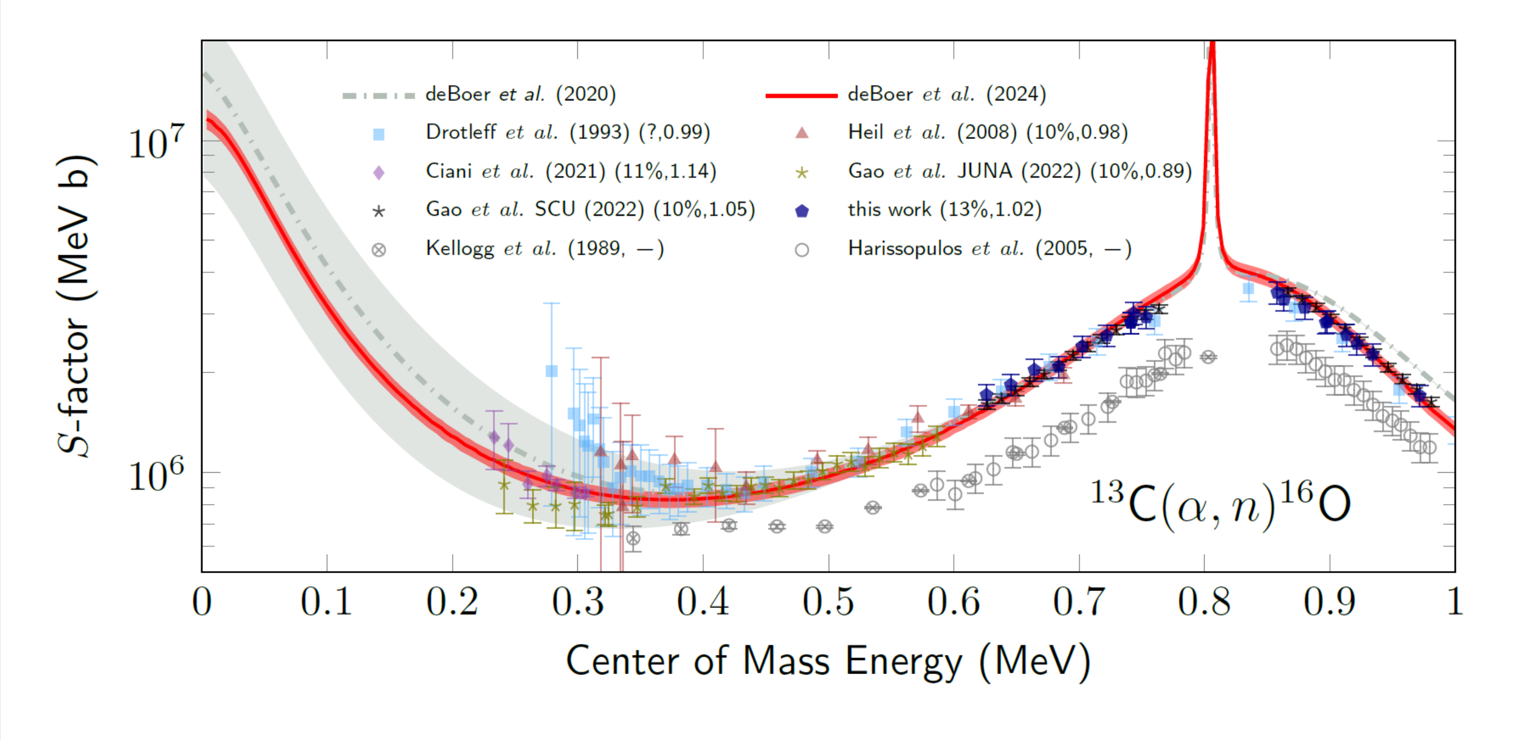
NEW MEASUREMENTS FAVOR LARGER NORMALIZATION FACTOR

- 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



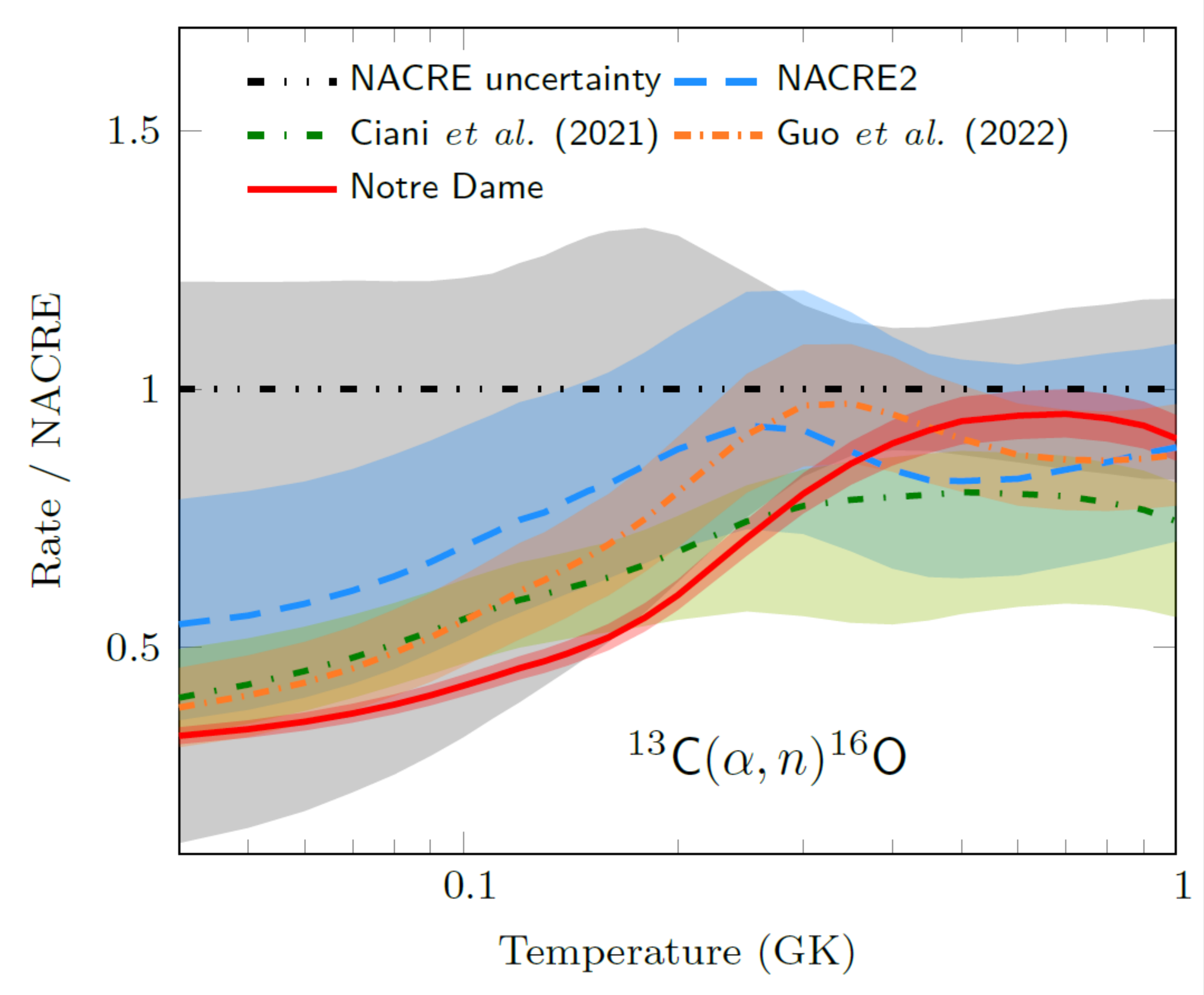
NOTRE DAME R-MATRIX FIT

- R-matrix fit based on extensive previous efforts by Gerry Hale and others at LANL for the ^{16}O+n evaluation
- 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

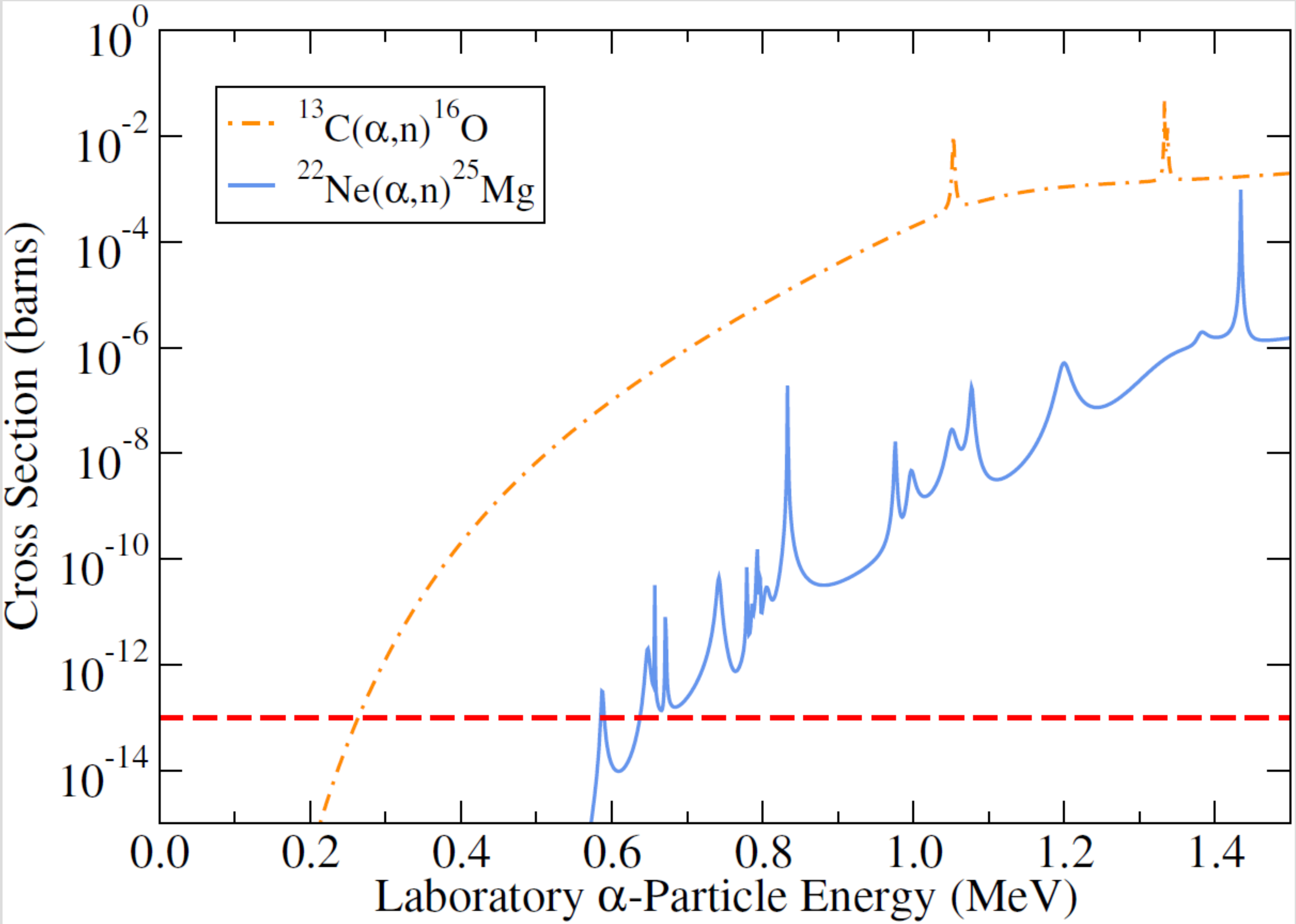


NOW WE WILL TRY TO COMBINE RESULTS TO GIVE A RECOMMENDED REACTION RATE

- With the uncertainties greatly reduced from the recent experiments, an IReNA / ChETEC supported 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

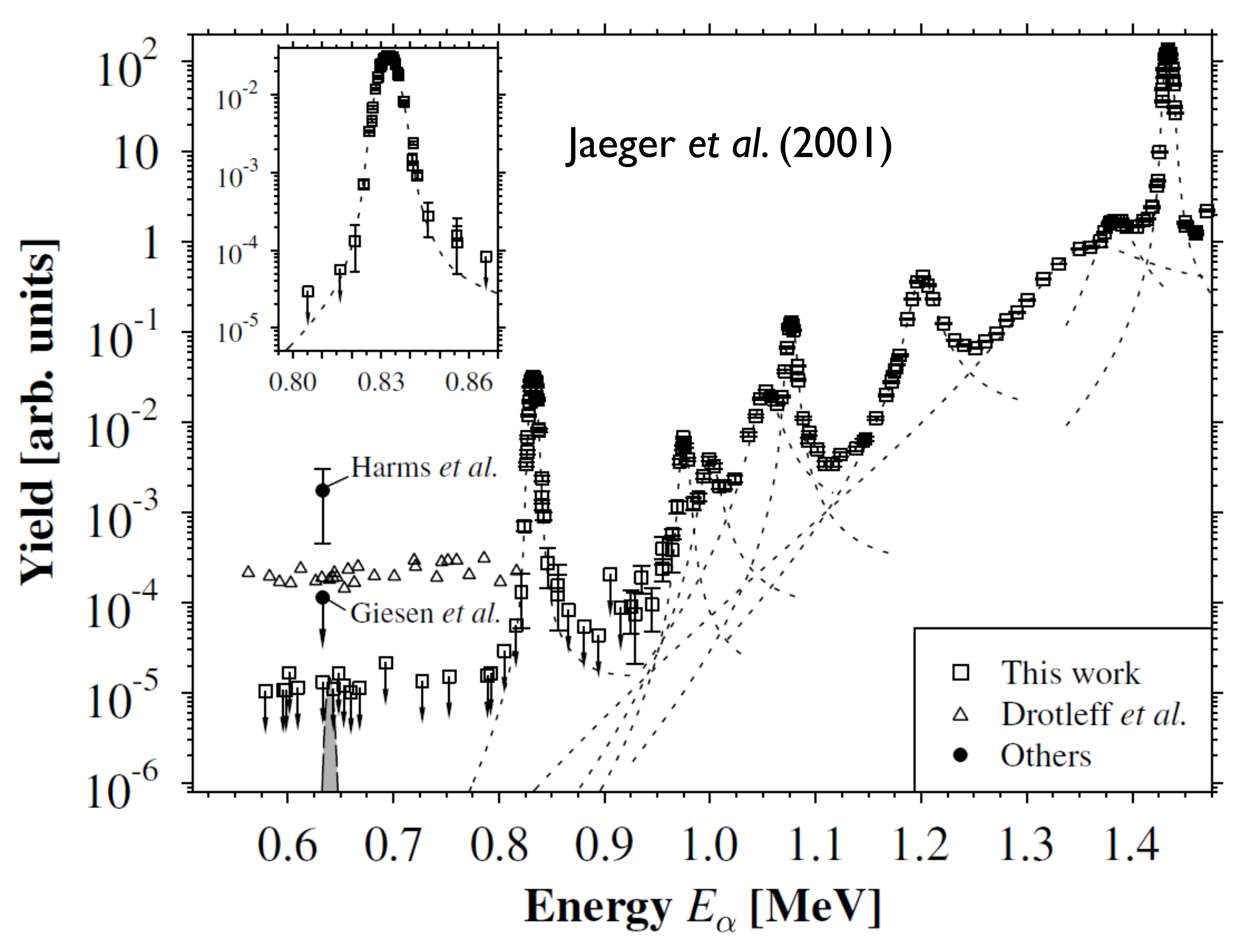


$^{13}C(\alpha,n)^{16}O \rightarrow {}^{22}Ne(\alpha,n)^{25}Mg$

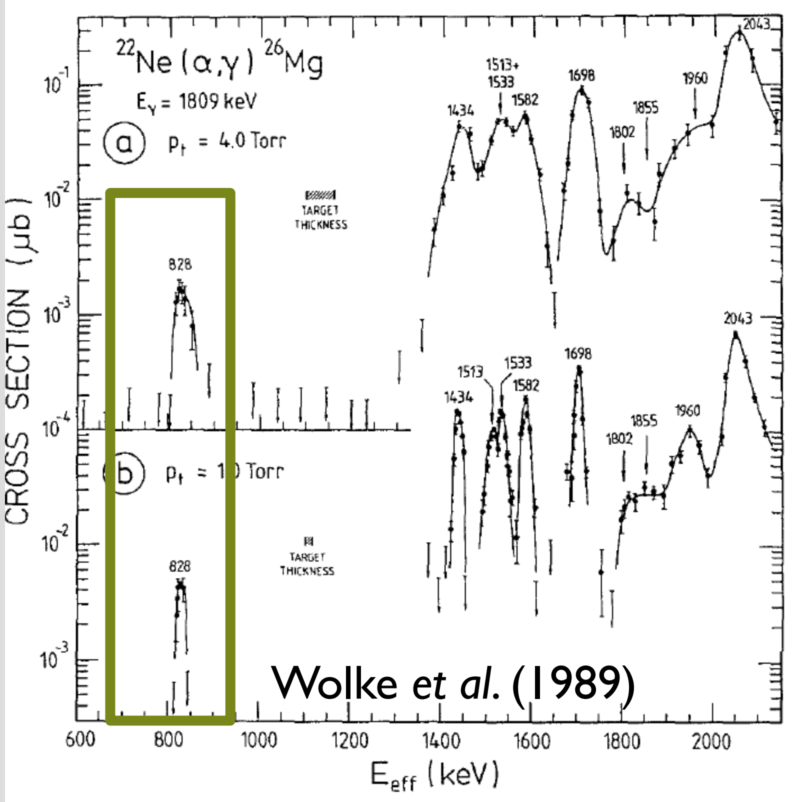


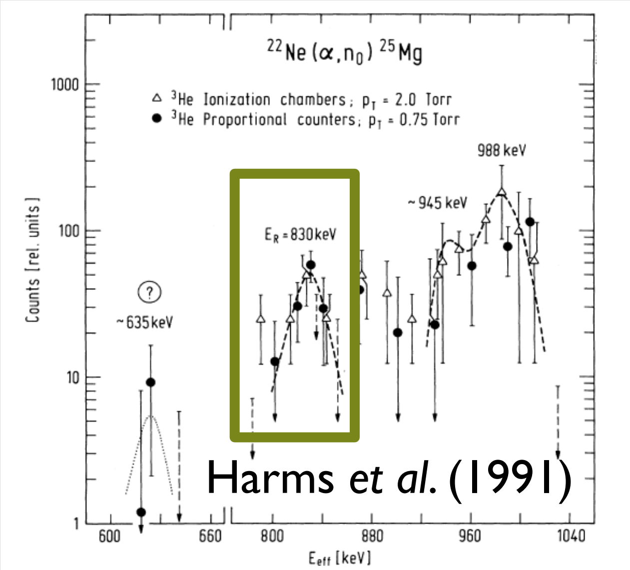
$^{22}Ne(\alpha,n)^{25}Mg$

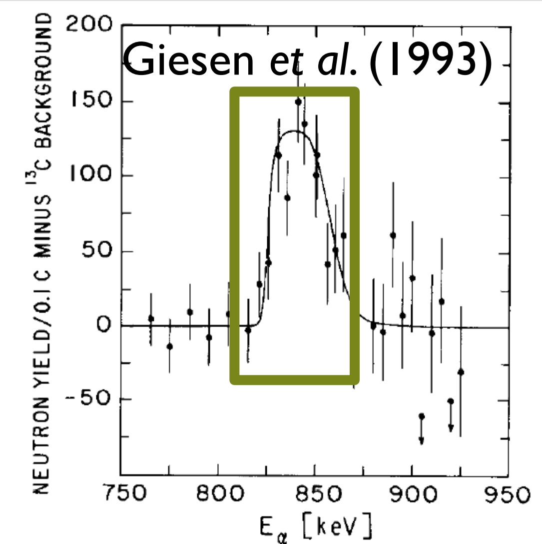
- Negative Q-value: -478 keV
- Low energy cross section is dominated by a resonance at **830 keV**
  - **Reaction rate is dominated by its strength**
- This cross section is low enough in energy and strong enough that it probably dominates the reaction rate at astrophysical energies
- Jaeger *et al.* (2001) was sort of the capstone measurement for a period of measurements
- Recent reviews by Adsley *et al.* (2021) and Wiescher *et al.* (2023)

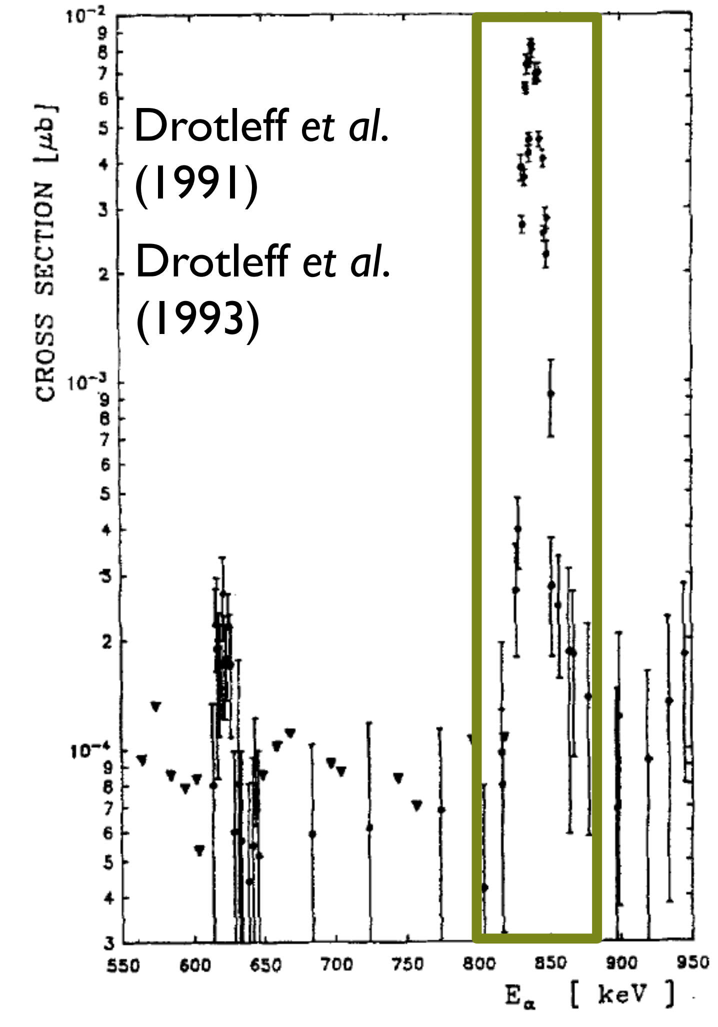


FIRST LOW ENERGY MEASUREMENTS THAT MADE IT TO 830 keV RESONANCE









$^{22}Ne(\alpha,\gamma)^{26}Mg$

- Positive Q-value
- The competing reaction rate is also needed because it may deplete ^{22}Ne at lower temperatures be $^{22}Ne(\alpha,n)^{25}Mg$ can turn on
- Strength of 830 keV resonance is very consistent across several measurements

TABLE I. Comparison of the previous literature resonance strength values with the present work for the $E_\alpha^{lab} = 830$-keV resonance.

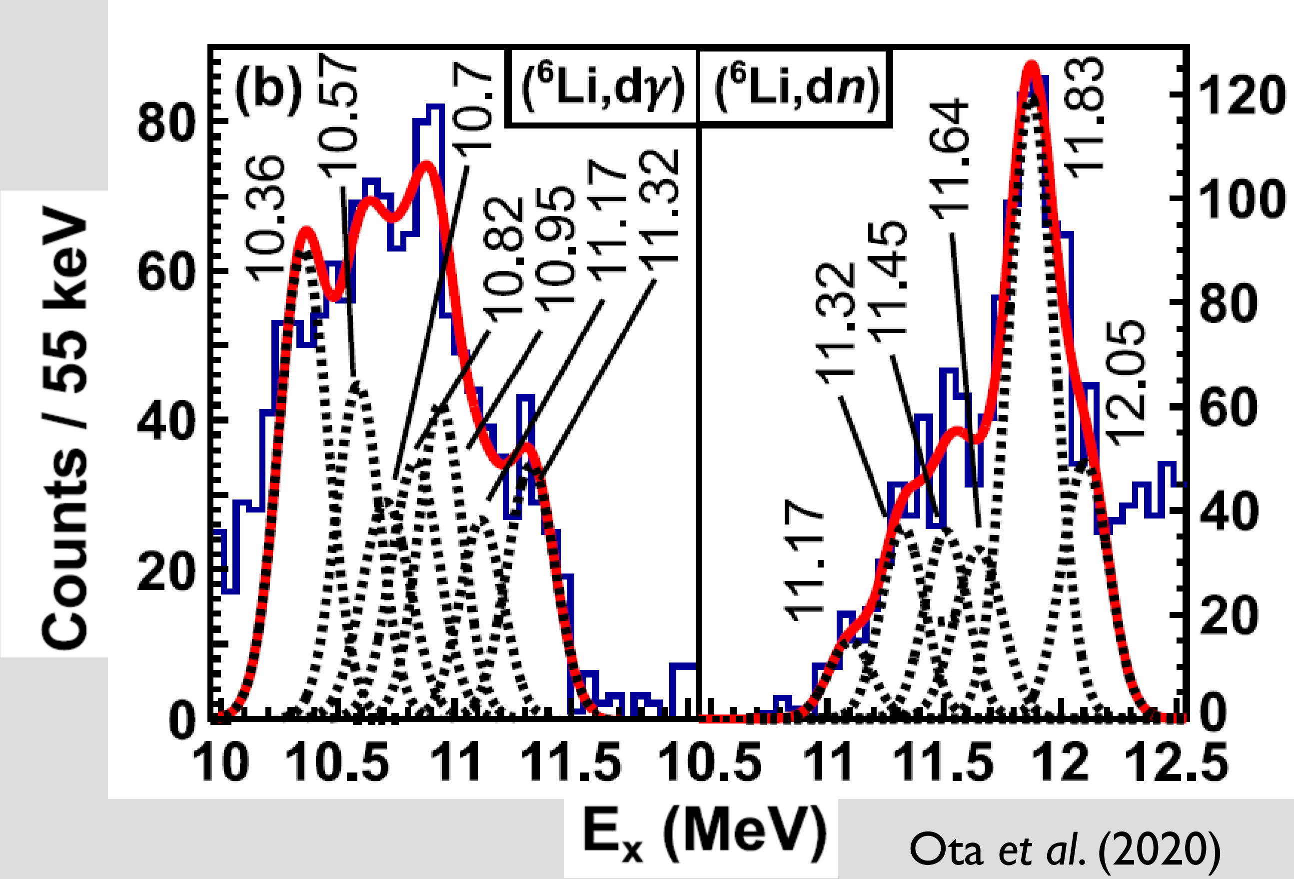
Work	$\omega\gamma$ (μeV)
Wolke *et al.* [5]	36 ± 4
Jaeger (Thesis) [26]	33 ± 4
Hunt *et al.* [6]	46 ± 12
This work	35 ± 4
Weighted average [a]	35 ± 2

[a]Common uncertainties of the individual values are negligible (for details see text).

Shahina *et al.* (2022)

TEXAS A&M n/γ BRANCHING RATIO

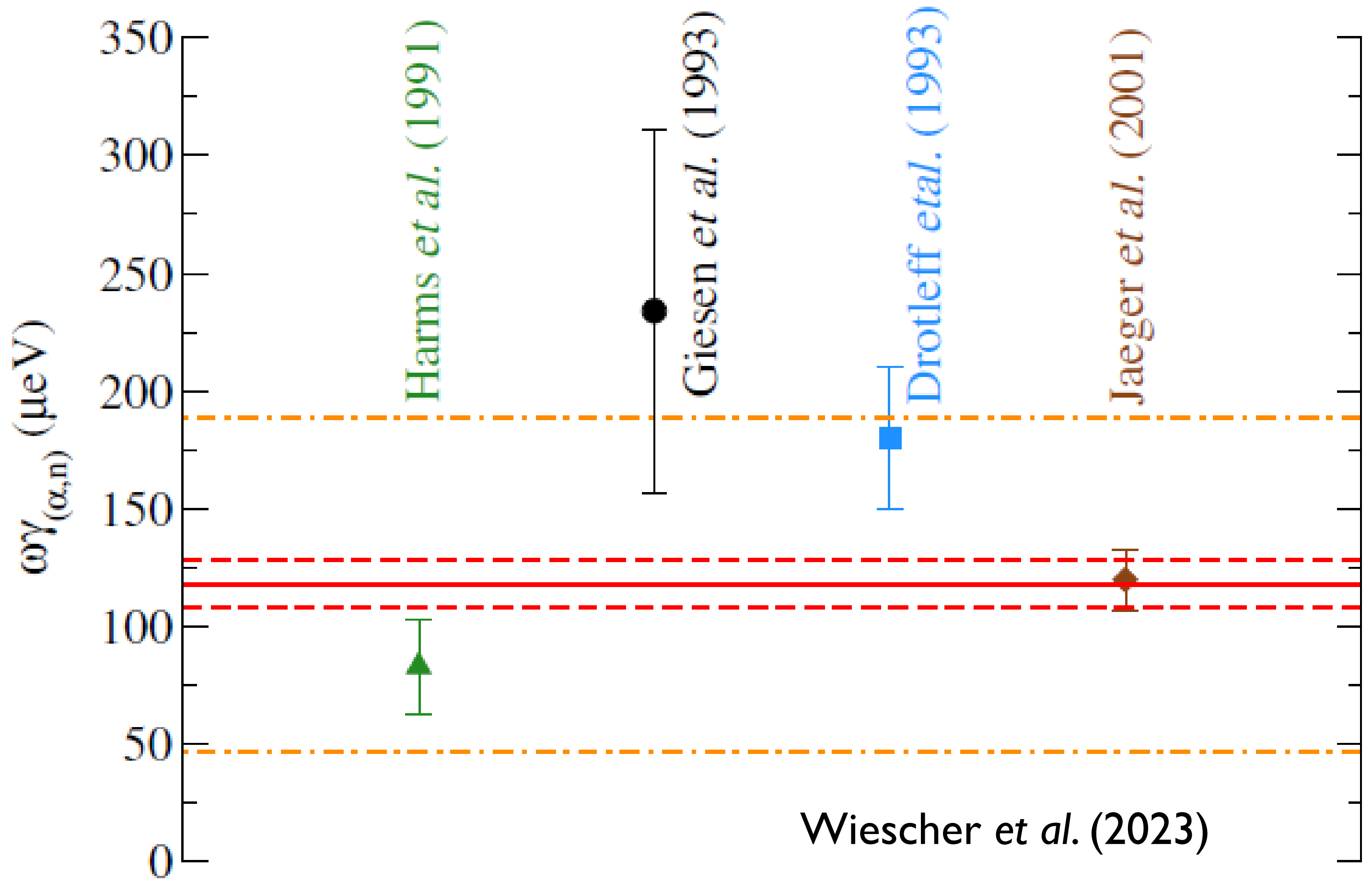
- Ota *et al.* (2020)
- n/γ = 1.14(26)
- Implies that $\omega\gamma_{(\alpha,n)}$ = **42(11) ueV**



Ota *et al.* (2020)

DIRECTLY MEASURED (α,n) STRENGTHS

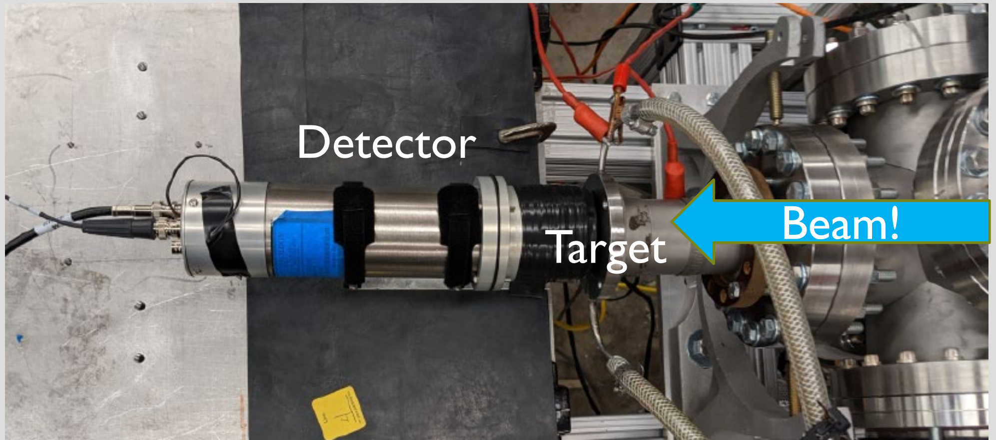
- $\omega\gamma_{(\alpha,n)}$ = 118 ± 10_{stat} ± 71_{syst} ueV
- Large spread of somewhat inconsistent values

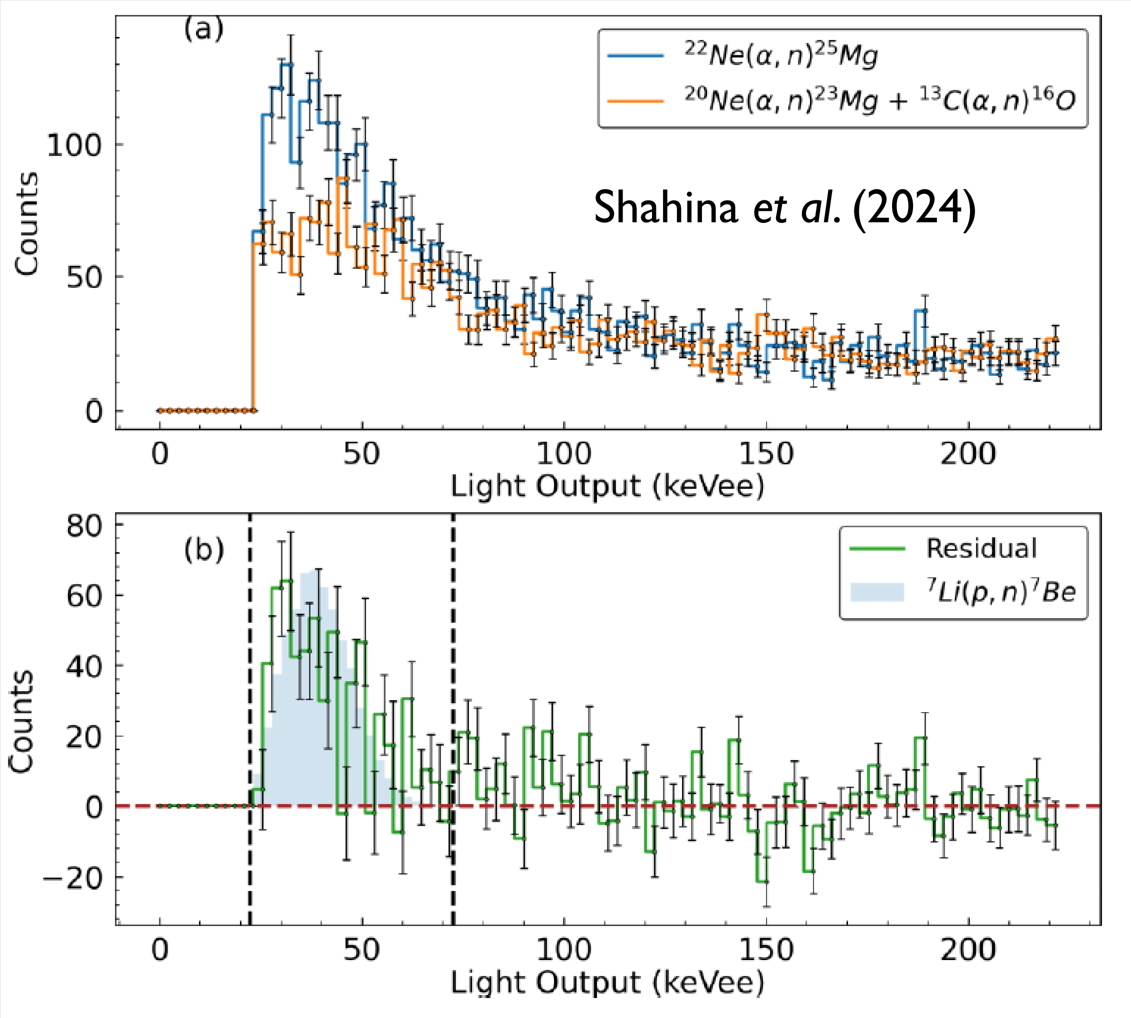


Wiescher *et al.* (2023)

DIRECT MEASUREMENT OF THE 830 keV RESONANCE STRENGTH AT NOTRE DAME

- Stilbene scintillator
  - Low discrimination threshold for gammas and neutrons of about 200 keV
  - Response is a continuous spectrum, but highest energy cutoff corresponds to full neutron energy
  - Provides a way to distinguish between $^{13}C(\alpha,n)^{16}O$ background
    - $Q(^{22}Ne(\alpha,n)^{25}Mg) = -478$ keV
    - $Q(^{13}C(\alpha,n)^{16}O) = 2.2$ MeV

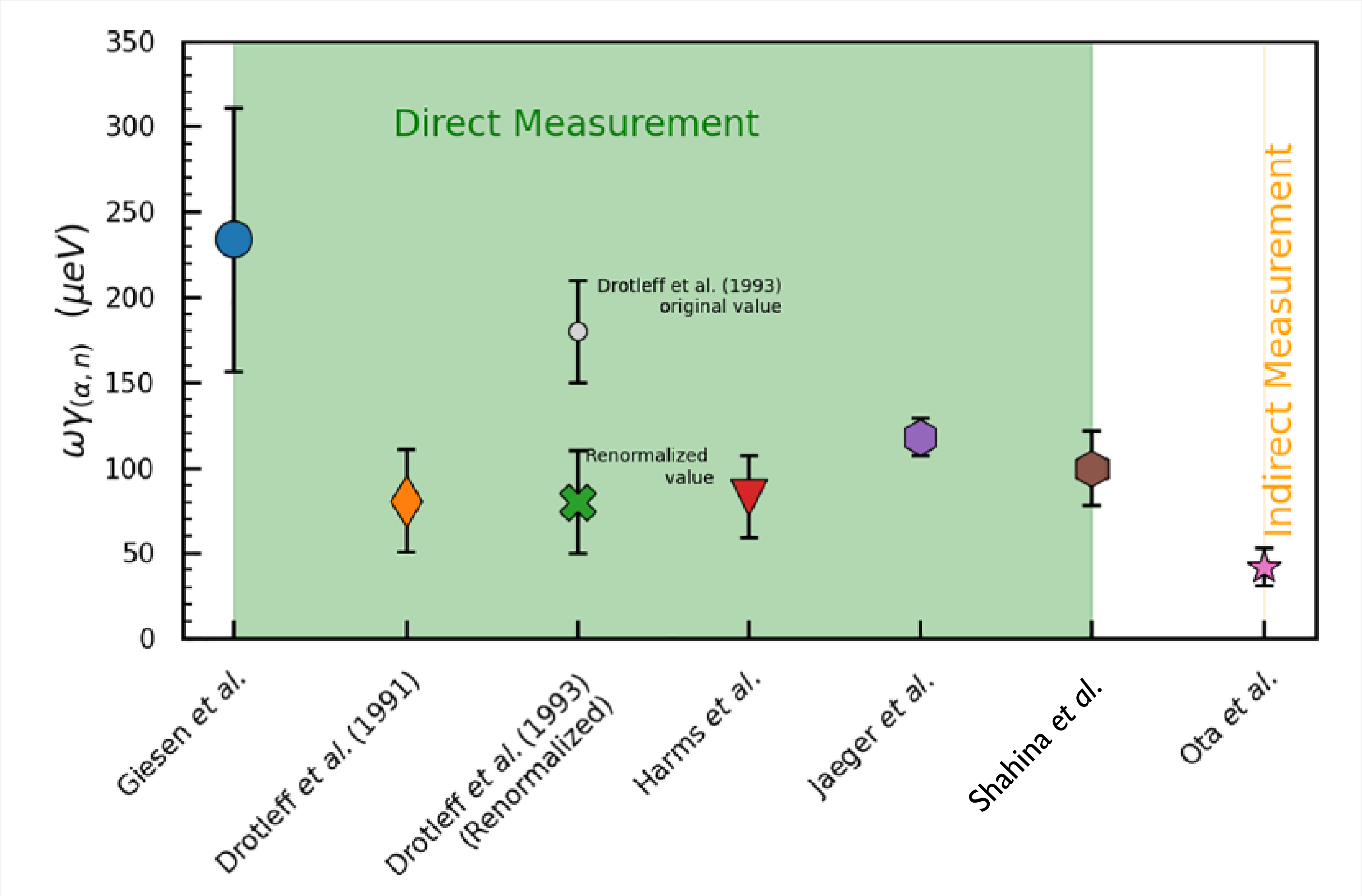




DIRECT MEASUREMENTS BECOMING MORE CONSISTENT

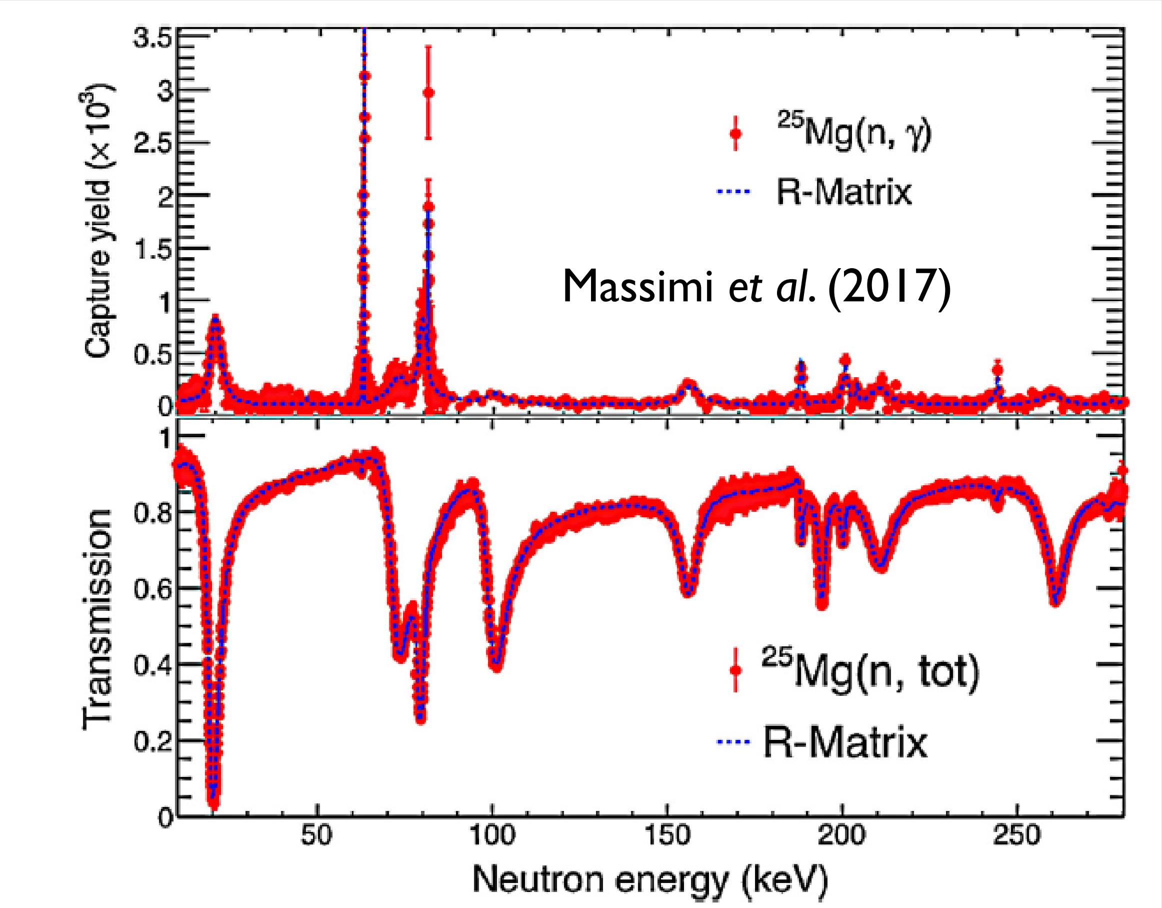
- Found a value of $\omega\gamma_{(\alpha,n)}$ = **100(22) ueV**
- We think that Drotleff *et al.* (1991) is actually correct over Drotleff *et al.* (1993)
- Still much higher than that implied by Ota et al. of $\omega\gamma_{(\alpha,n)}$ = **42(11) ueV**

Shahina *et al.* (2024)



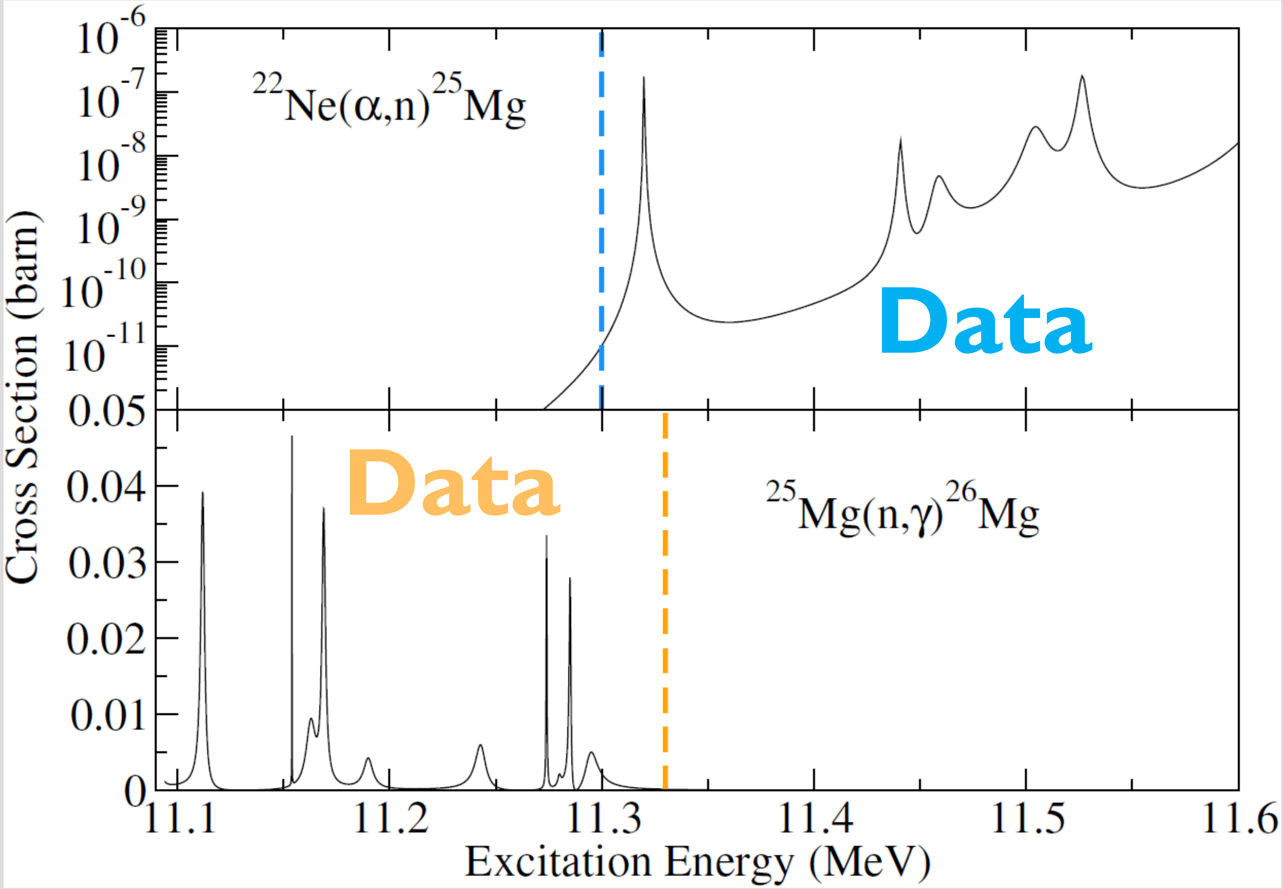
INDIRECT MEASUREMENTS HAVE PROVEN VERY DIFFICULT AS WELL

- Like $^{13}C(\alpha,n)^{16}O$, we can look at the inverse reaction because ^{25}Mg is stable
- Unfortunately things don't work out as well
- Limited to low neutron energy
- Not much overlap with (α,n) measurements



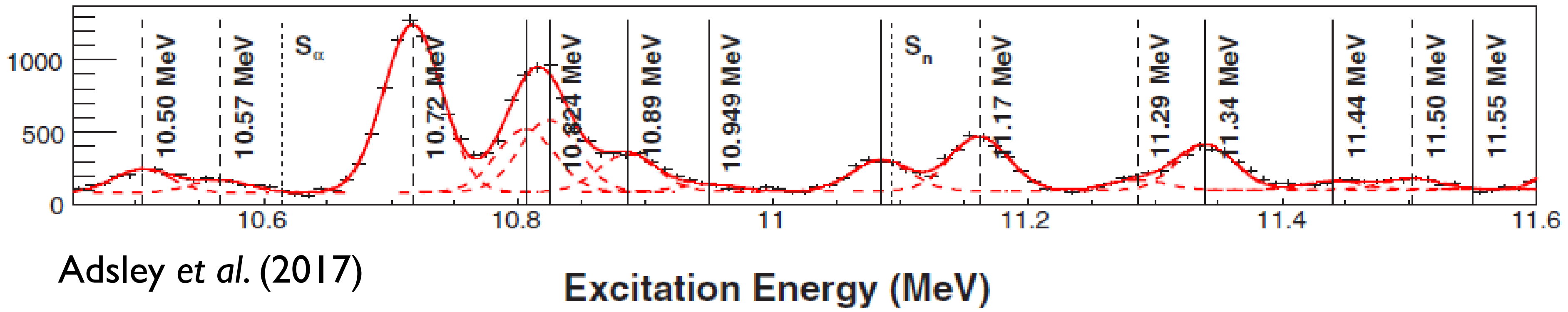
INDIRECT MEASUREMENTS HAVE PROVEN VERY DIFFICULT AS WELL

- In particular, the strong 830 keV resonance in $^{22}Ne(\alpha,n)^{25}Mg$ doesn't show up in $^{25}Mg(n,\gamma)$ or (n,total)!



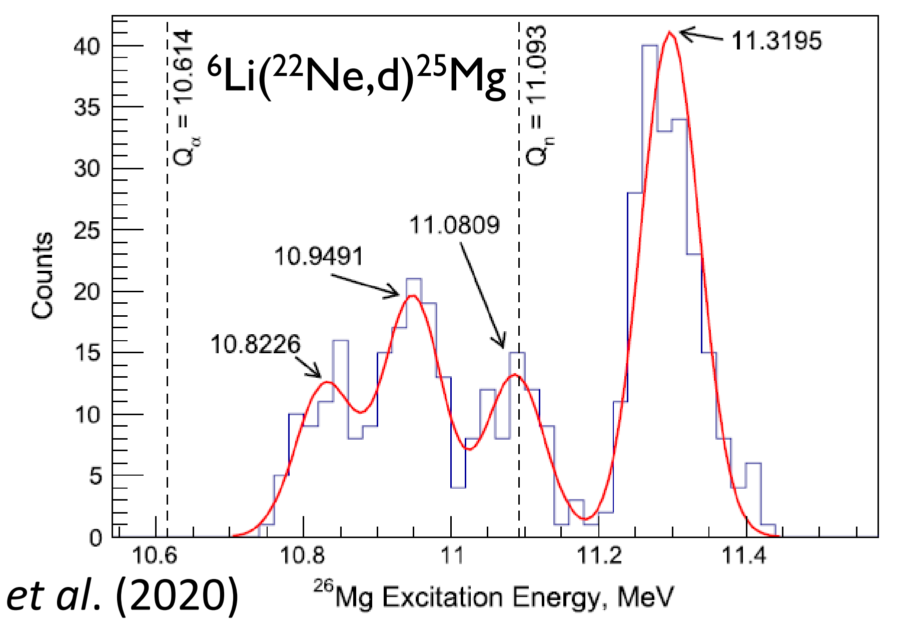
A TRANSFER STUDIES ARE HAMPERED BY RESOLUTION

$^{26}Mg(\alpha,\alpha')$



Adsley *et al.* (2017)

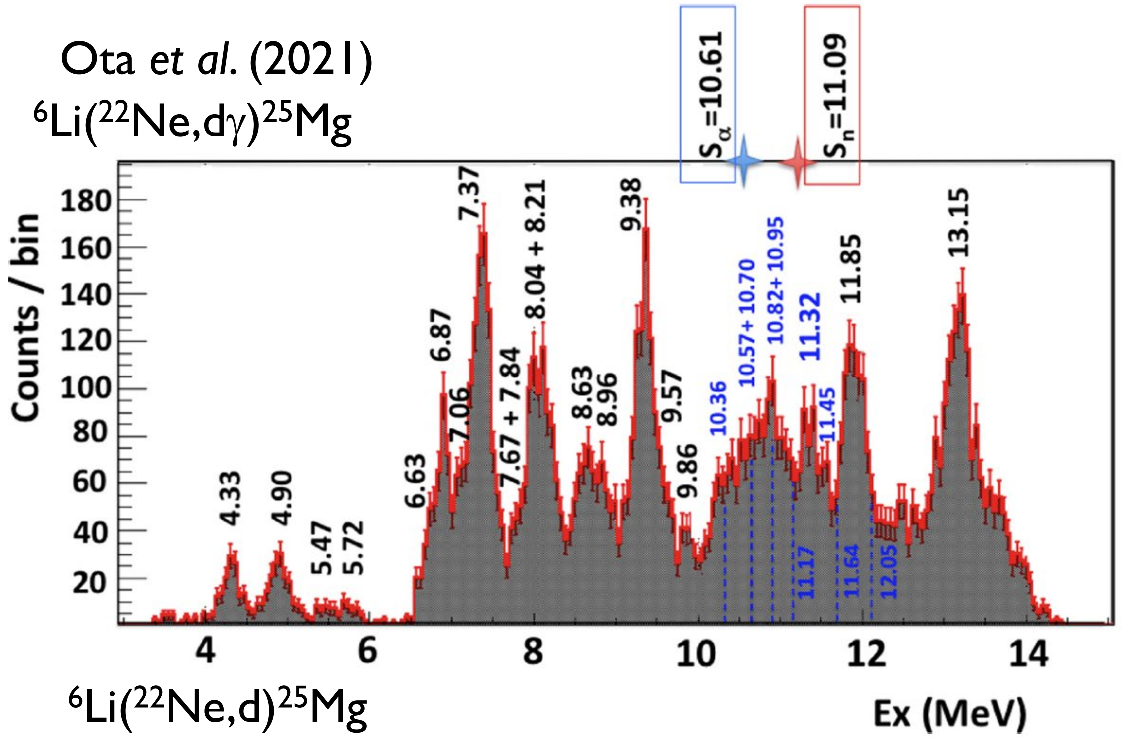
See Phil Adsley's talk later today



Jayatissa *et al.* (2020)

Ota *et al.* (2021)

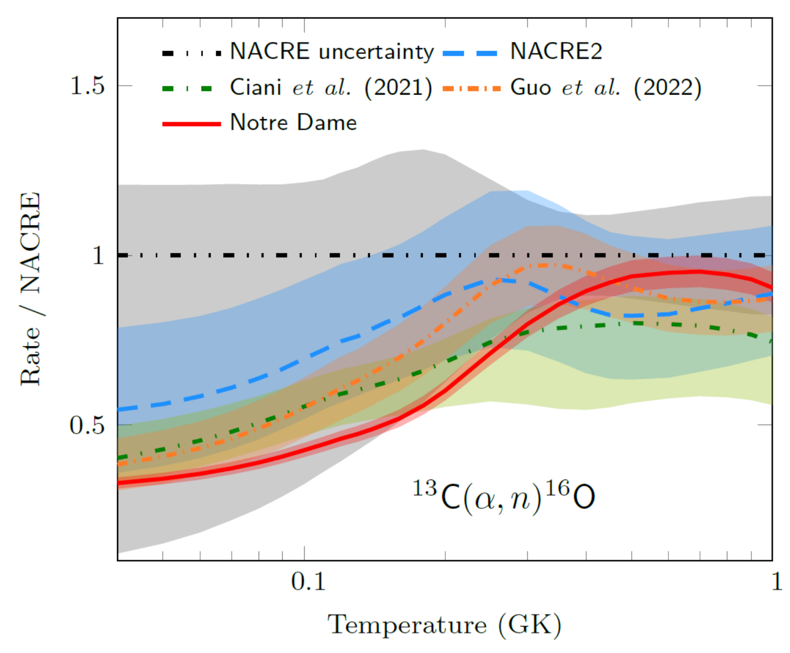
$^6Li(^{22}Ne,d\gamma)^{25}Mg$

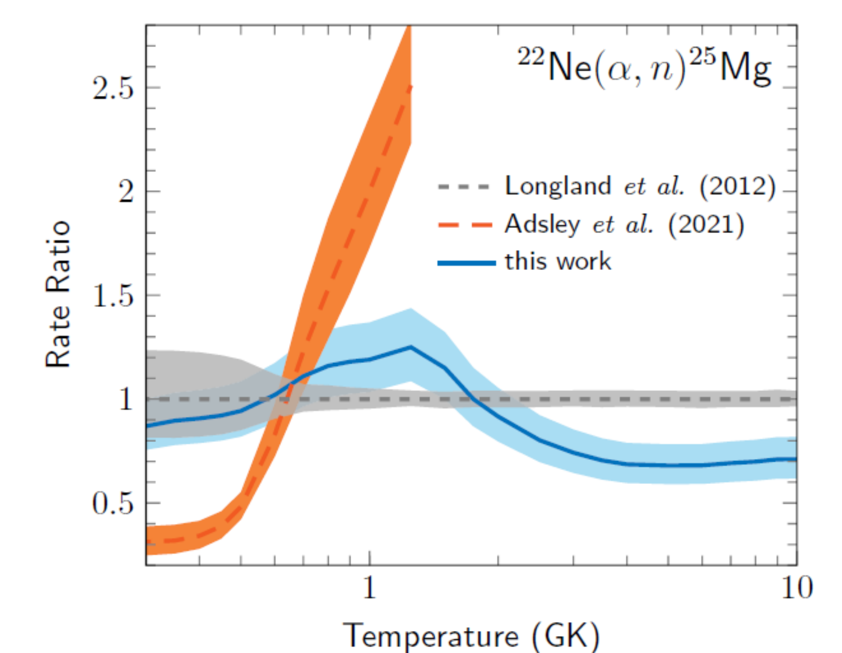


$^6Li(^{22}Ne,d)^{25}Mg$

SUMMARY

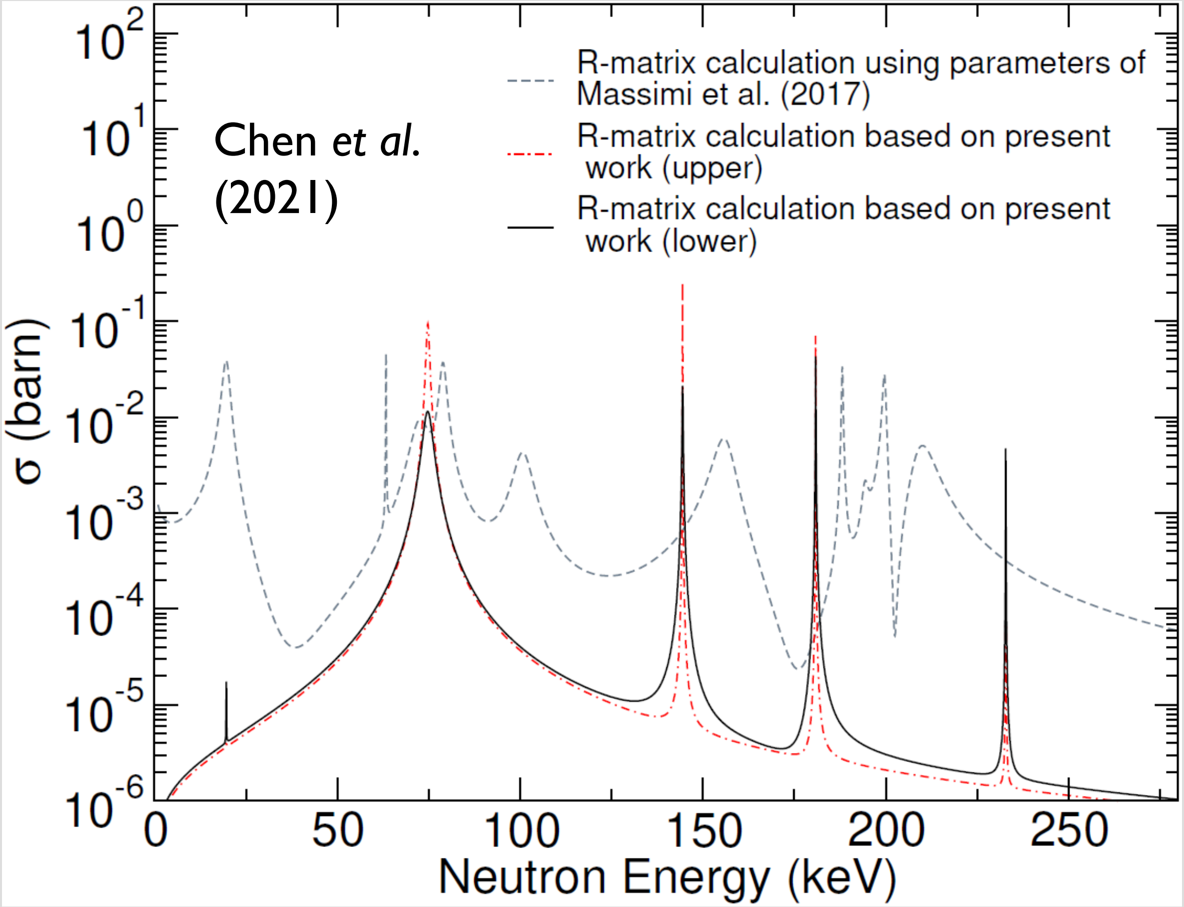
- For $^{13}C(\alpha,n)^{16}O$, **everything works**
- For $^{22}Ne(\alpha,n)^{25}Mg$, **nothing works**
  - Andreas' job to fix everything at LUNA MV
  - JUNA will also give it a try
- IReNA and ChETEC have provided great opportunities for the communities to come together and discuss these reactions





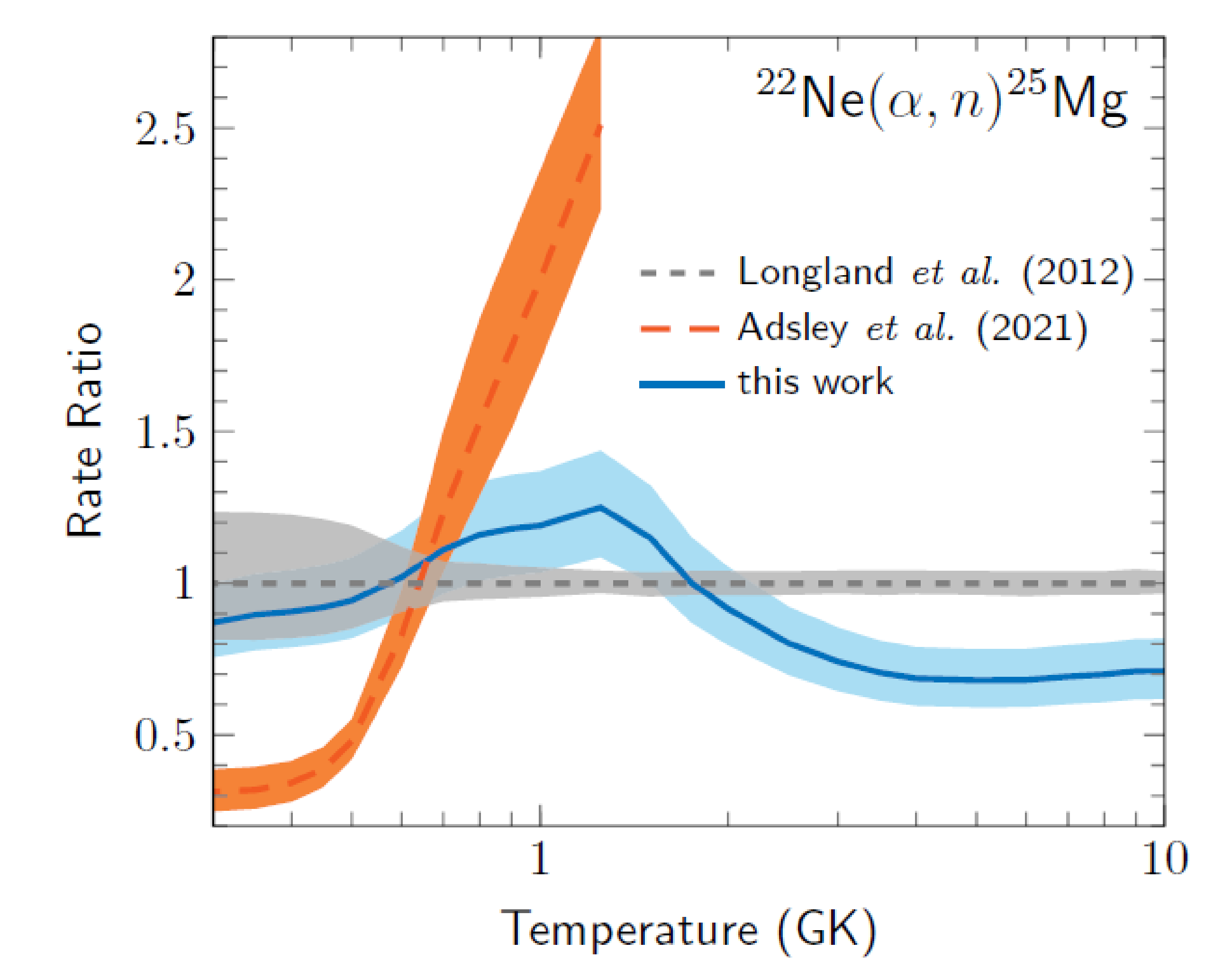
INDIRECT MEASUREMENTS HAVE PROVEN VERY DIFFICULT AS WELL

- Transfer reaction studies, which can overlap with ^{25}Mg+n data at lower energies, also don't seem to populate the same states



REACTION RATE CALCULATIONS

- Lots of difficult in quantifying uncertainties
  - Very different rate estimates based on different assumptions by different groups
- Probably the issue was largely in determining the neutron detection efficiency
- A new generation of measurements are needed, just to get the 830 keV resonance strength determined with confidence



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)

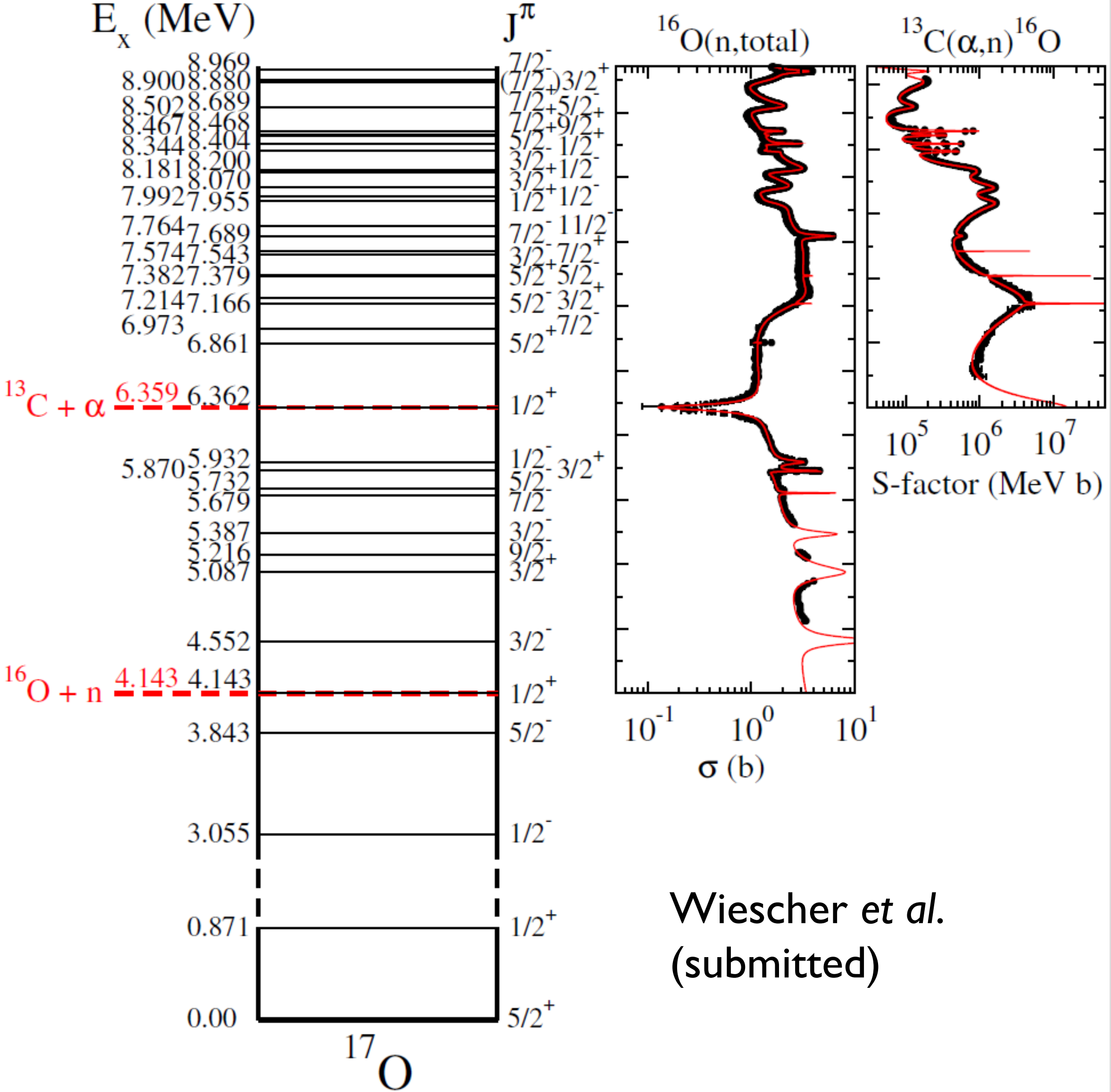
L.H. Ru *et al.* (2023)

TABLE II. Resonance strength and the thick target yield of the $E_\alpha = 1055.63$ keV resonance.

Reference	$\omega\gamma/eV$	Y_{max} $(n/\mu C)$[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)

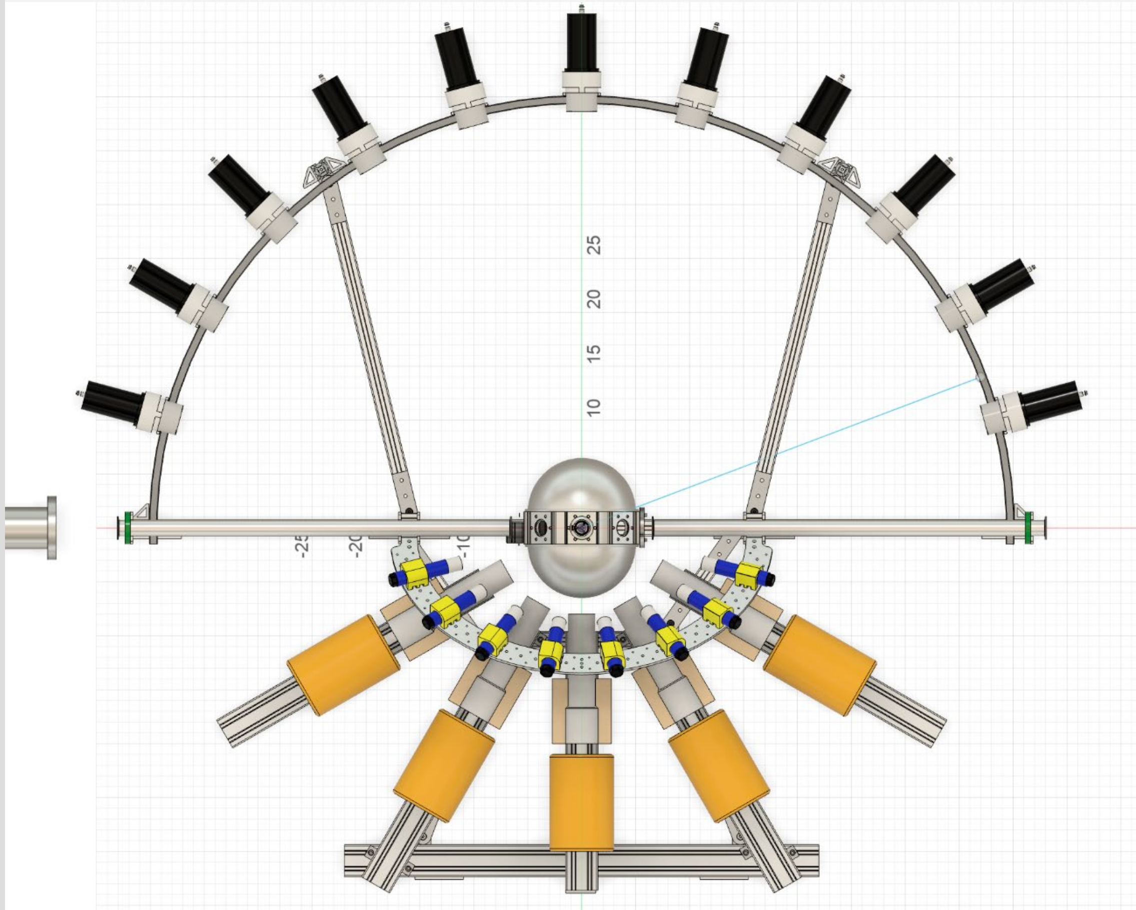


Wiescher *et al.* (submitted)

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(α,n)^{11}B
  - ^{10}B(α,n)^{13}N
  - ^{11}B(α,n)^{14}N
  - ^{13}C(α,n)^{16}O
  - ^{19}F(α,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



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- John McDonaugh (ND)
- Kristyn Brandenburg (OU)
- Nisha Singh (OU)
- Joseph Derkin (OU)
- Adam Fritch (OU)
- Yenuel Jones-Alberty (OU)
- Gula Hamad (OU)
- Shane Moylan (ND)
- Brennan Hackett (UTK)
- Chevelle Boomershine (ND)
- Khachatur Manukyan (ND)
- Michael Wiescher (ND)
- C. Feathers (OU)
- D.C. Ingram (OU)
- D. Soltesz (OU)

UNIVERSITY OF NOTRE DAME

OHIO UNIVERSITY

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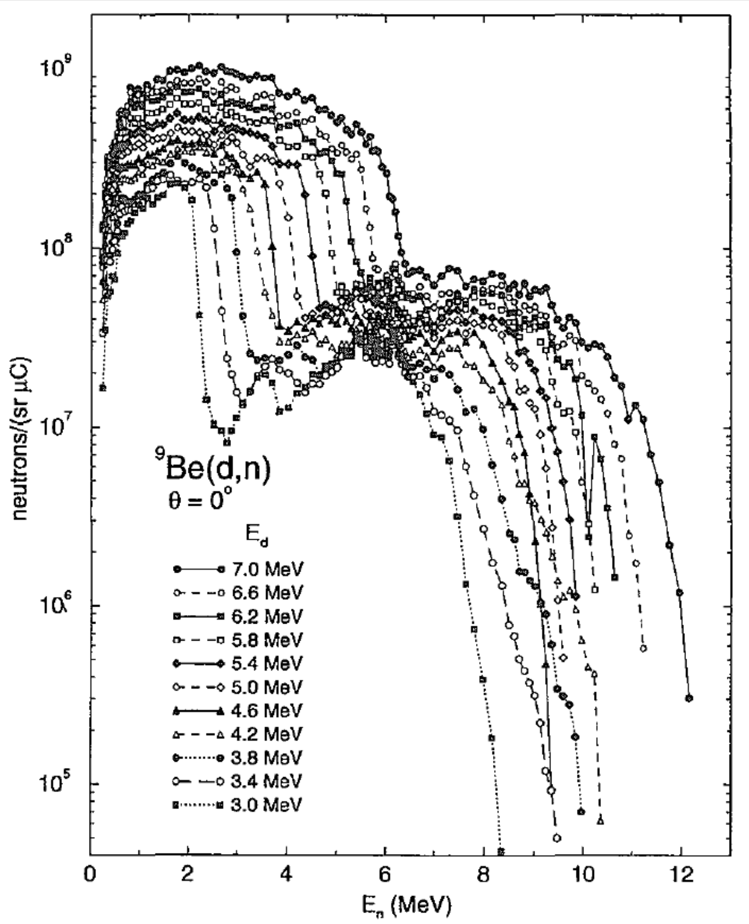
SOME UNIQUE CAPABILITIES AT ND

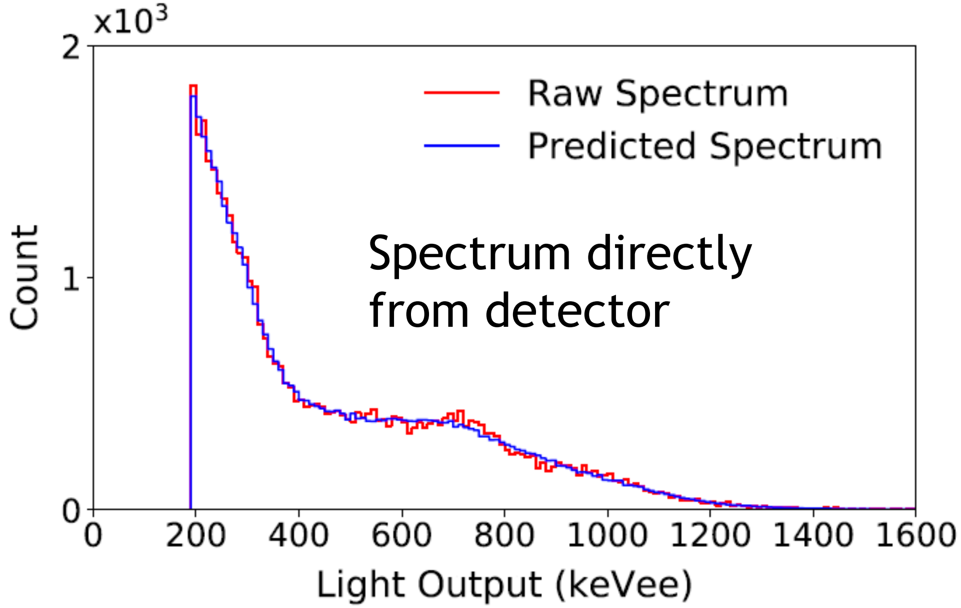
- **Accelerator (ND 5U)**
- Array of deuterated liquid scintillators (ORNL)
- Response Matrix (OU) and Spectrum Unfolding (ORNL)

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

=

Febbraro *et al.* (2019)

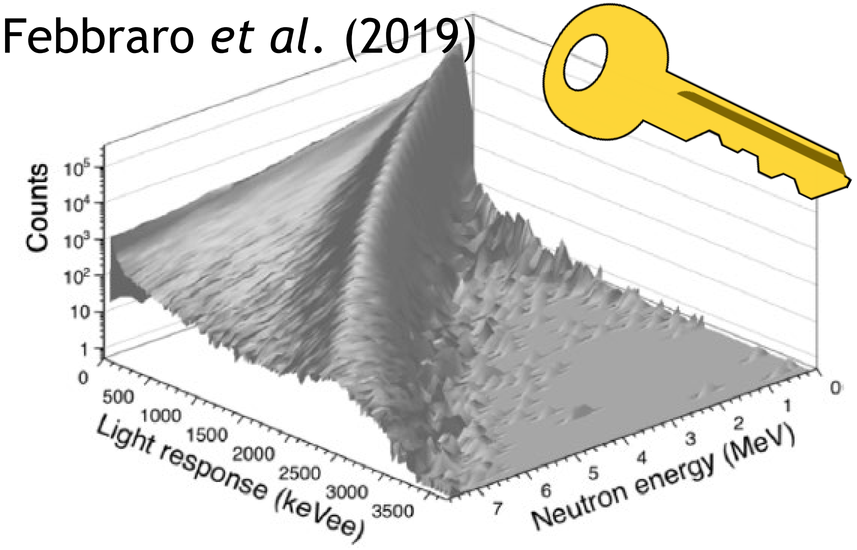
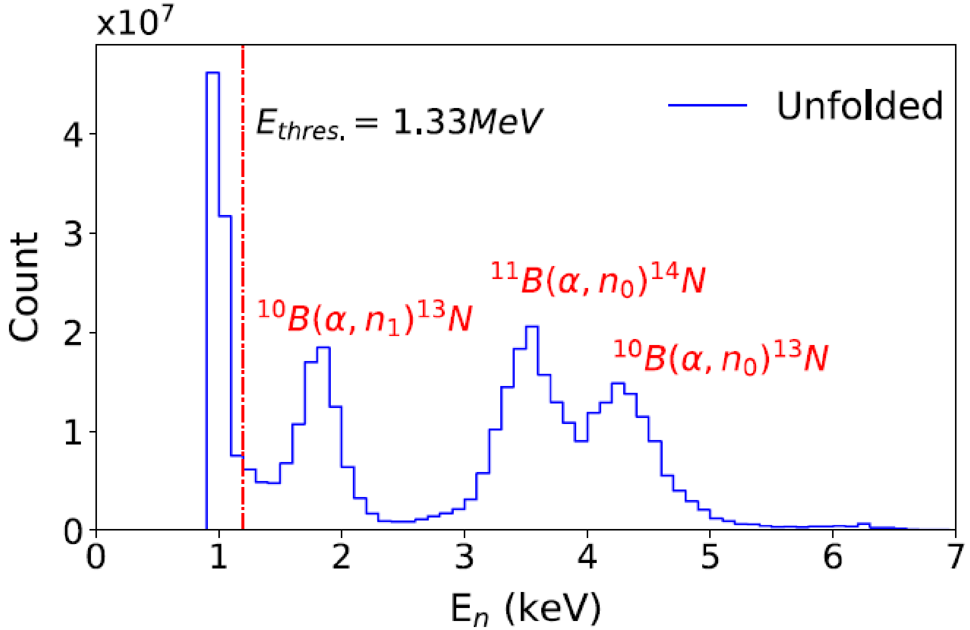


Fig. 9. Response matrix generated using a broad energy neutron source from a thick target $^{27}Al(d,n)$ reaction at E_d = 7.44 MeV [12].

Response matrix (experimentally measured)

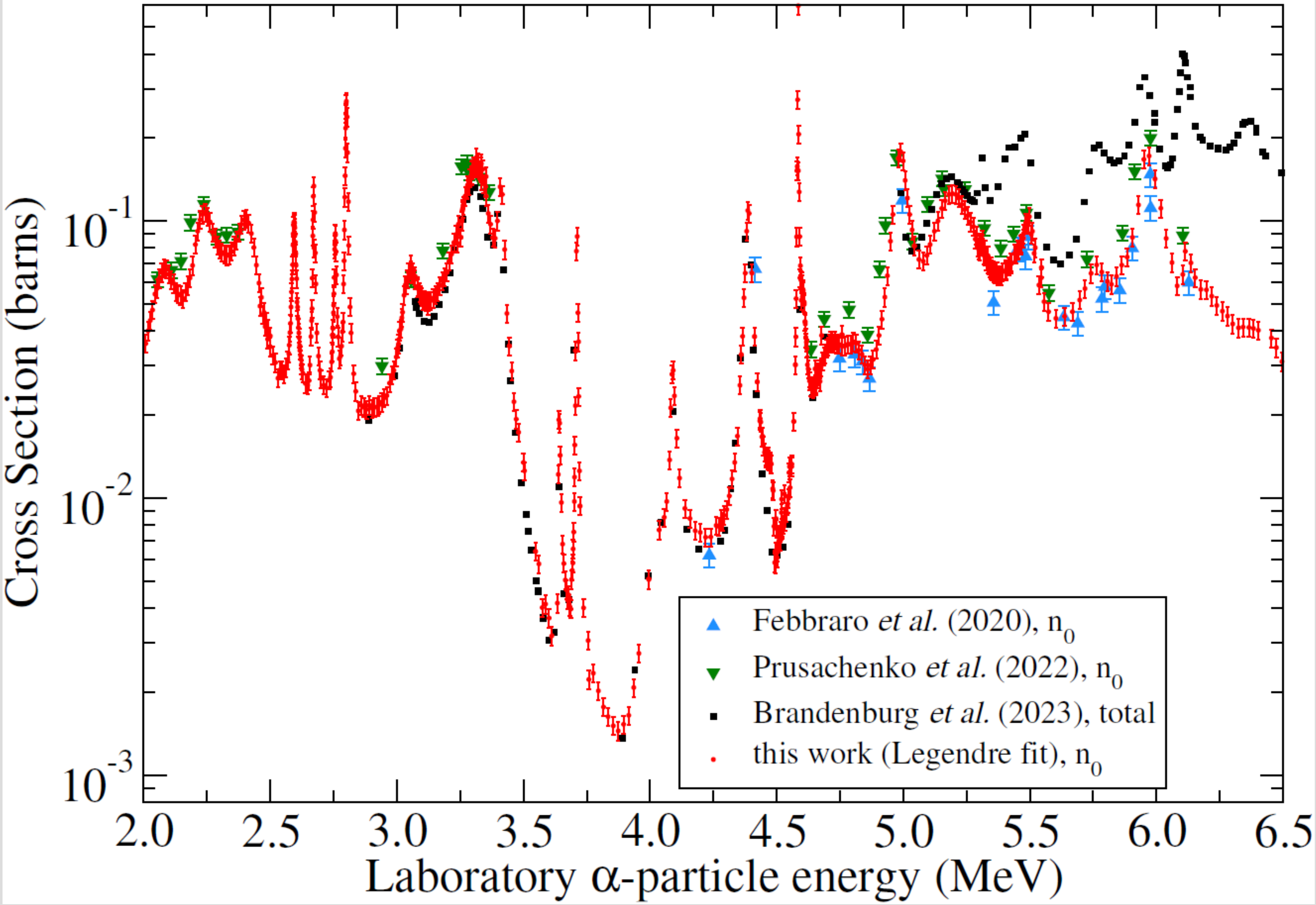
Neutron Energy Spectrum



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

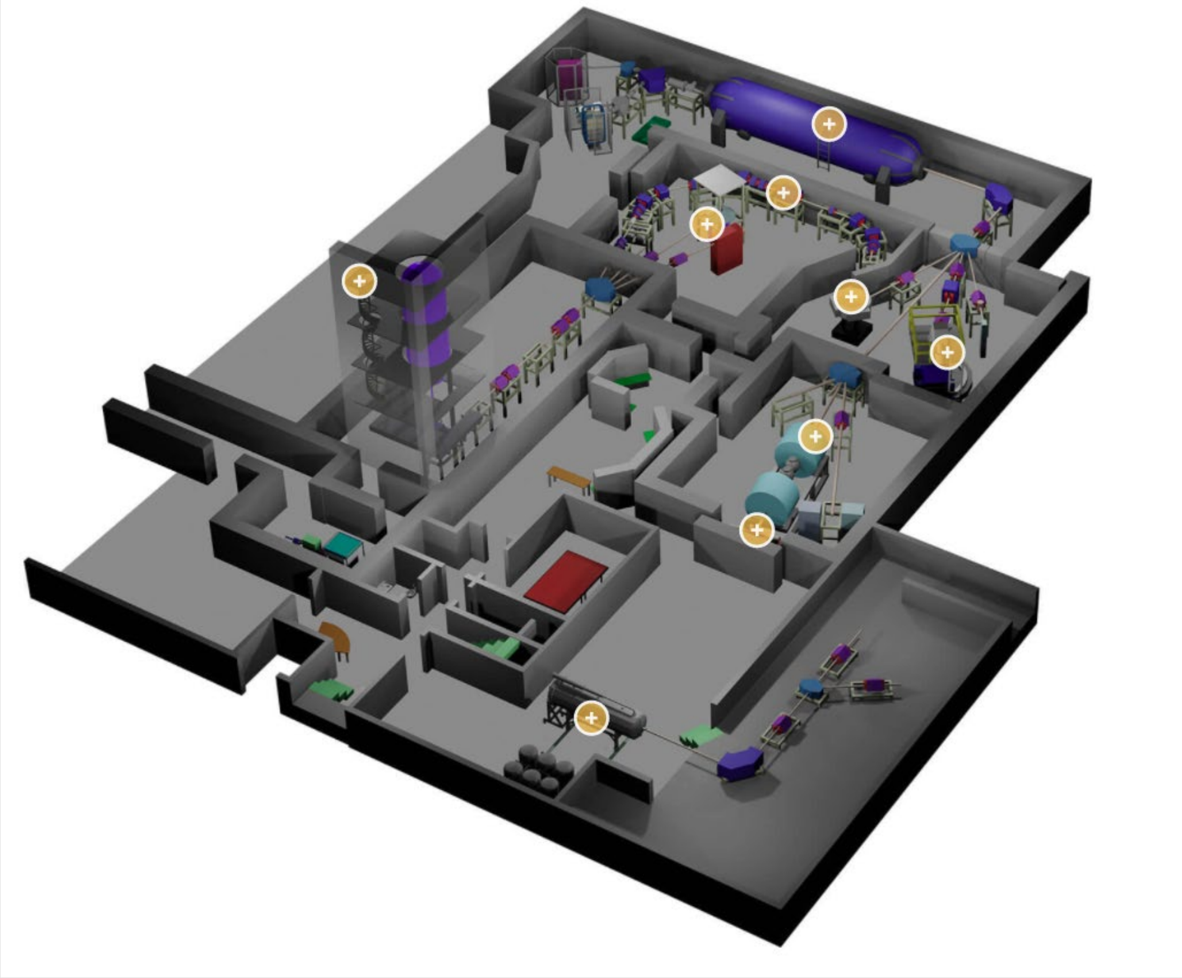
LEGENDRE FIT, COMPARE WITH 4Π DATA

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



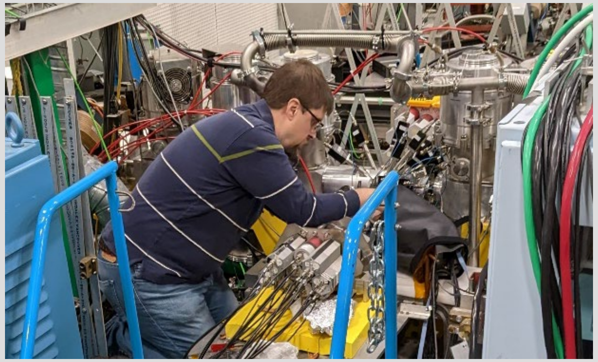
UNIVERSITY OF NOTRE DAME NUCLEAR SCIENCE LABORATORY

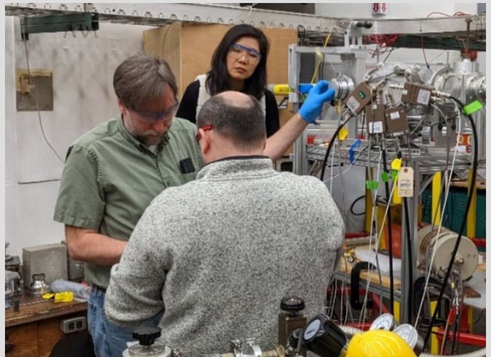
- 5 MV single ended accelerator (5U)
  - dc alpha beam, alphas from 300 keV up to 9 MeV
  - up to 100 uA of beam on target
  - Usually using 10 uA for these studies
  - Energy resolution better than 1 keV at 1 MeV, energy calibration uncertainty of 2 keV at 1 MeV



A TEAM EFFORT!

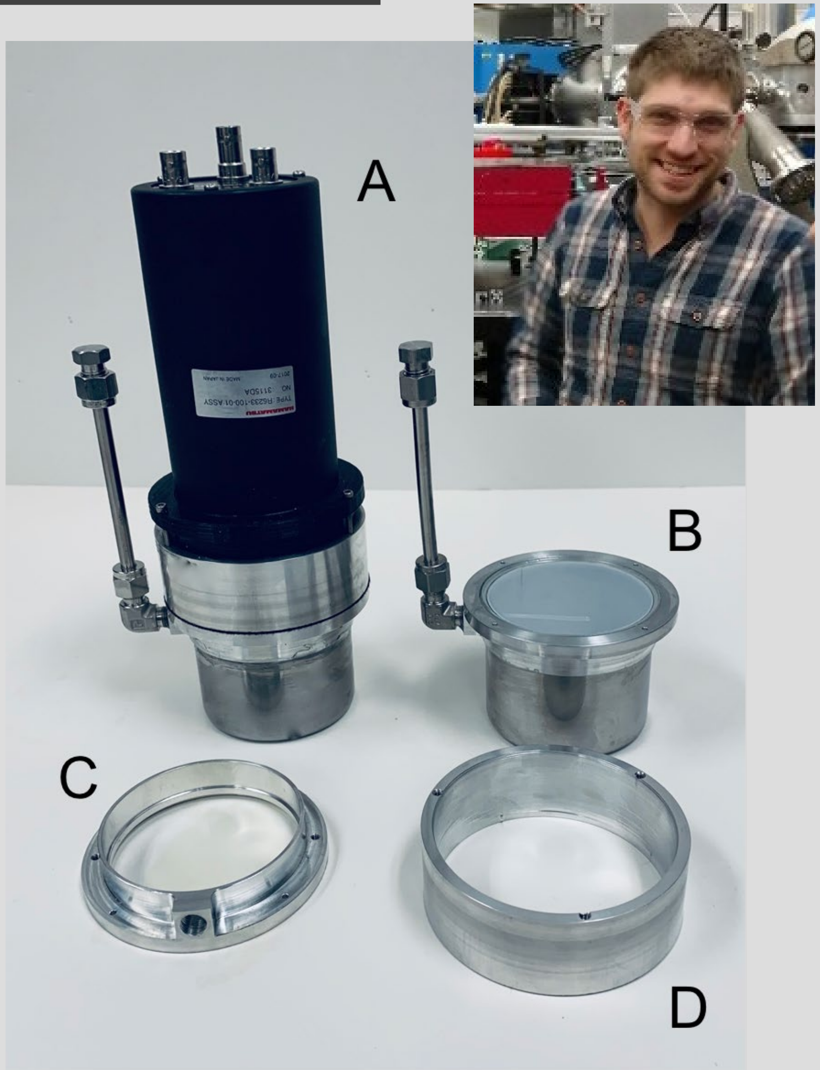
- ND graduate students operate all accelerators
- Research faculty and technicians keep things working





THE ODeSA ARRAY

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

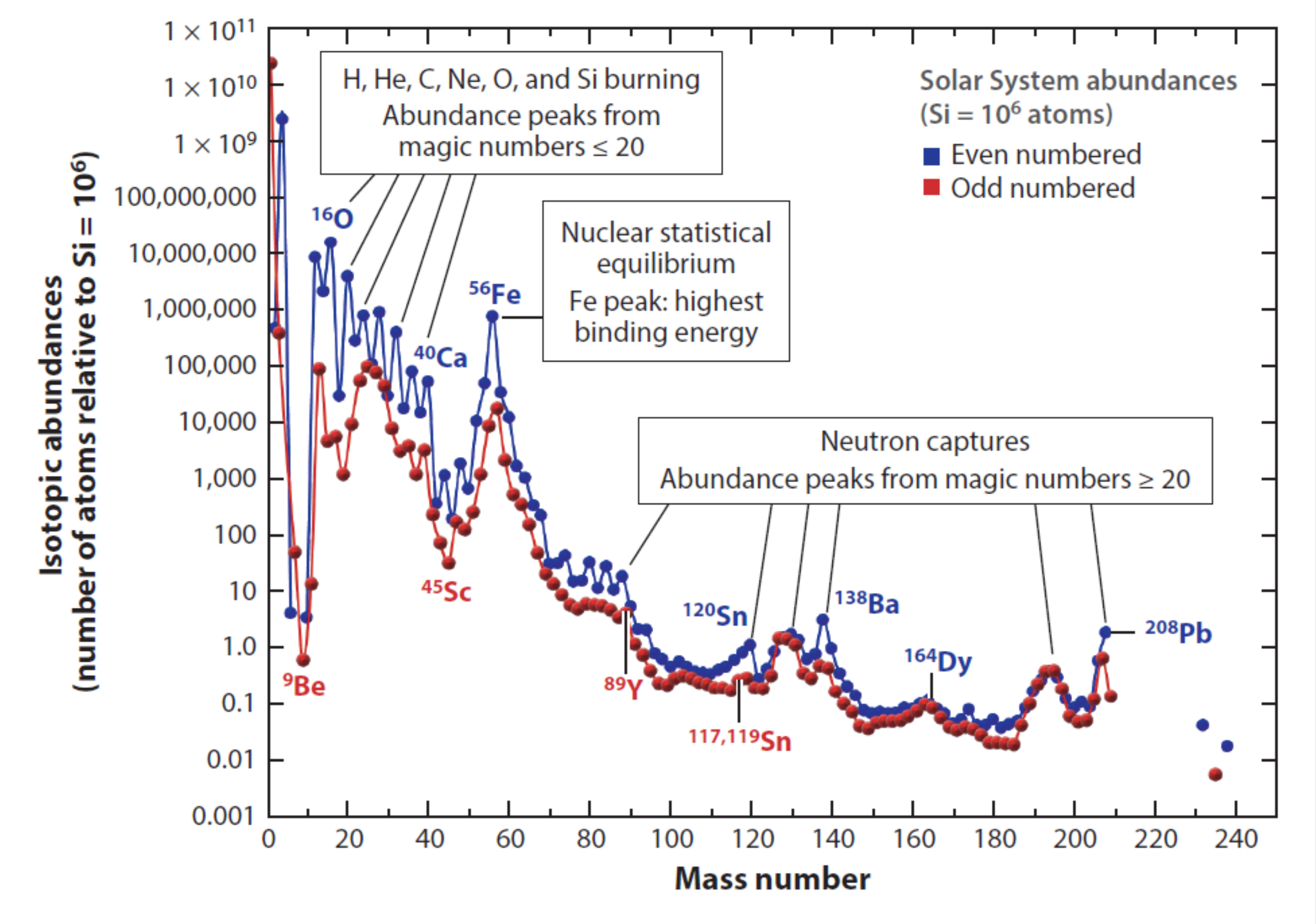


Michael Febbraro (AFIT)

WHY ARE WE INTERESTED IN NEUTRON SOURCES IN STARS?

- Because of the large Coulomb repulsion between charged particles, most of the elements beyond the iron peak are produced through neutron capture
- However, since they have a half life of about 10 minutes, neutrons aren't just hanging out in stars
- There must be some source reaction(s) in the star

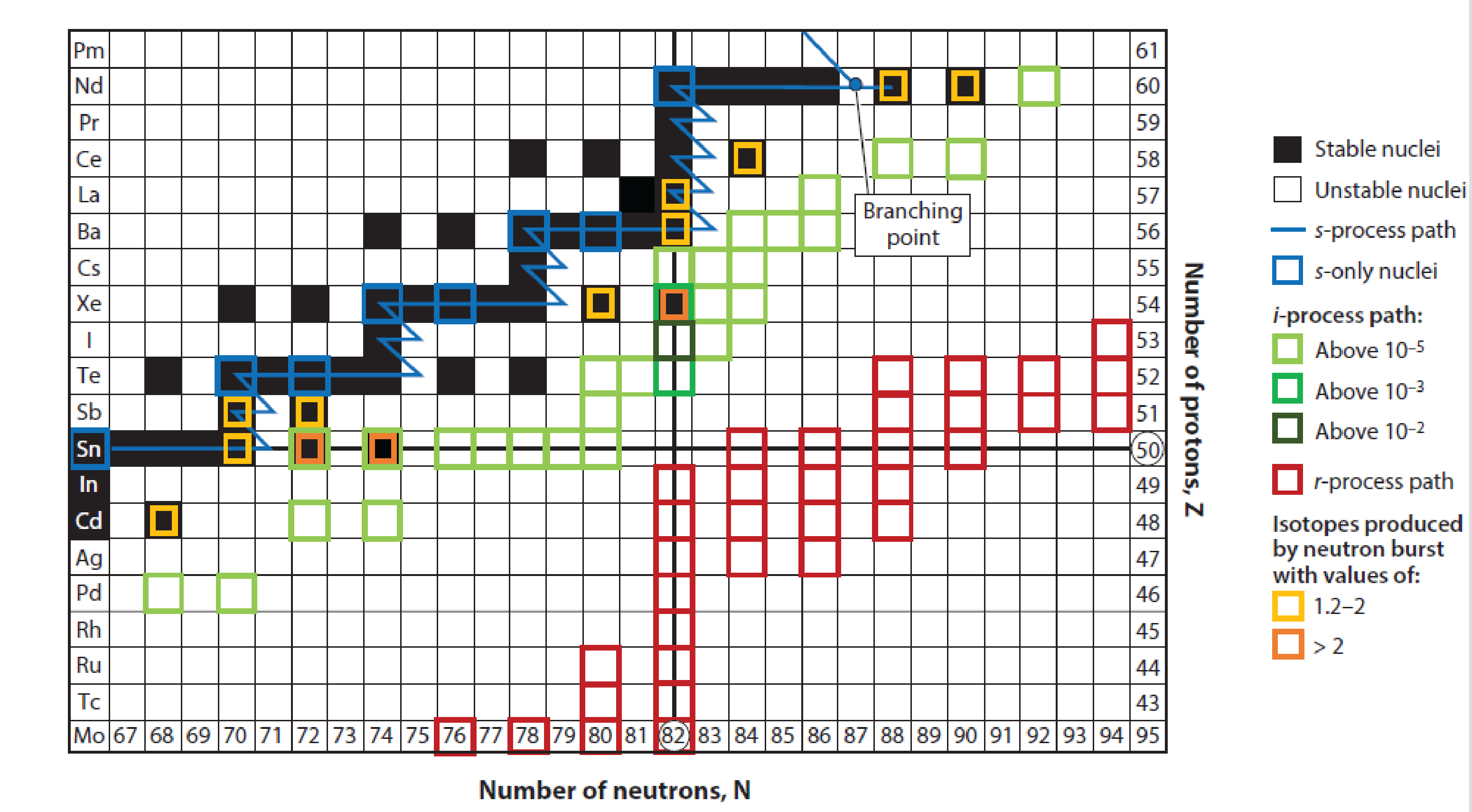
- First few slides barrow figures from the recent review of Lugaro *et al.* (2023)
  - informative and succinct summer of our current understanding of "The s-Process and Beyond"



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

WHAT RATES DO WE NEED TO MODEL THIS TYPE OF NUCLEOSYNTHESIS?

- Depending on the neutron flux, the synthesis path moves away from stability towards the neutron drip line
- The neutron induced reaction rates on these heavier elements (usually radiative neutron capture)
- β-decay rates
- The amount of neutrons available, that is, the rates of the reactions that are producing the neutrons



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