(α,n) studies at the University of Notre Dame and Ohio University

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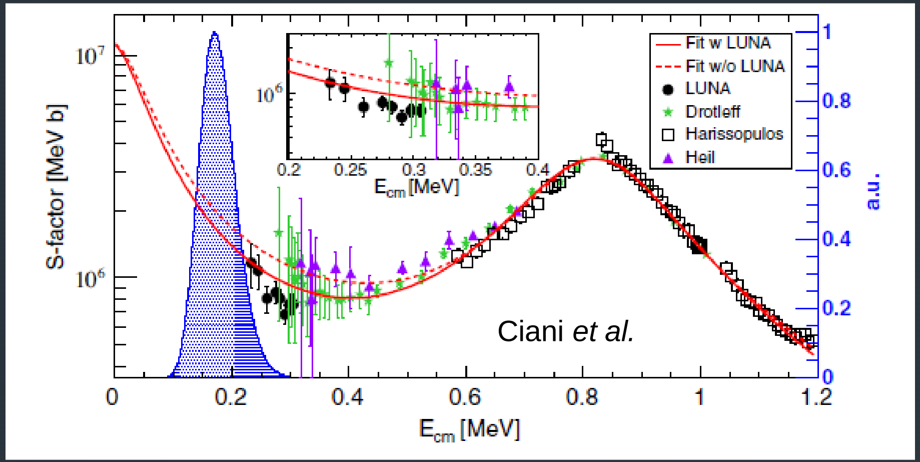
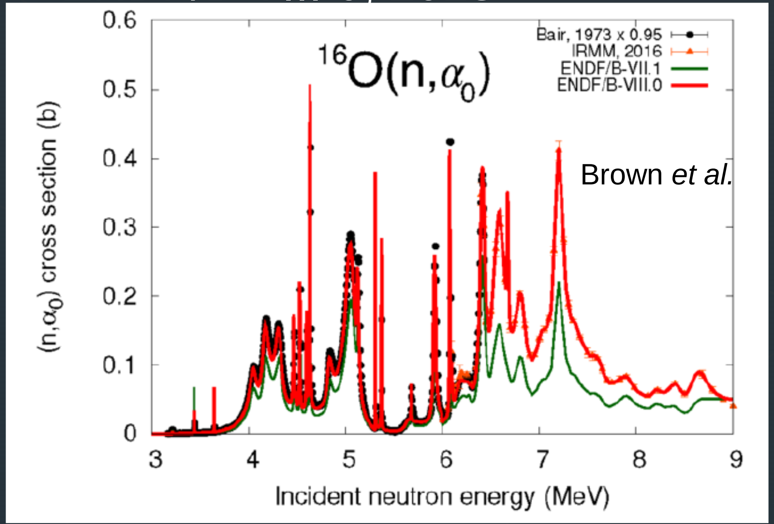
Quick background

- (α,n) reactions on light nuclei are neutron sources in various different astrophysical sites
  - In particular, during core helium burning of an Asymptotic Giant Branch Star (AGB)
  - Main site of the slow neutron capture process (s-process), which creates about half of the heavy elements above iron
  - $^{13}C(\alpha,n)^{16}O$, $^{17}O(\alpha,n)^{20}Ne$, $^{18}O(\alpha,n)^{21}Ne$, $^{25}Mg(\alpha,n)^{28}Si$, $^{26}Mg(\alpha,n)^{29}Si$, etc.
- (α,n) reactions are also major background sources in any type of large volume detector system (neutrino, dark matter, neutrinoless double beta decay)
- They are also needed to model the neutron energy spectra of light element – actinide compounds
  - $^{17}O(\alpha,n)^{20}Ne$, $^{18}O(\alpha,n)^{21}Ne$, $^{19}F(\alpha,n)^{22}Na$
- Modeling many types high neutron flux environments requires the inverse reactions
  - $^{16}O(n,\alpha)^{13}C$

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



ENDF/B VIII.0, 2018

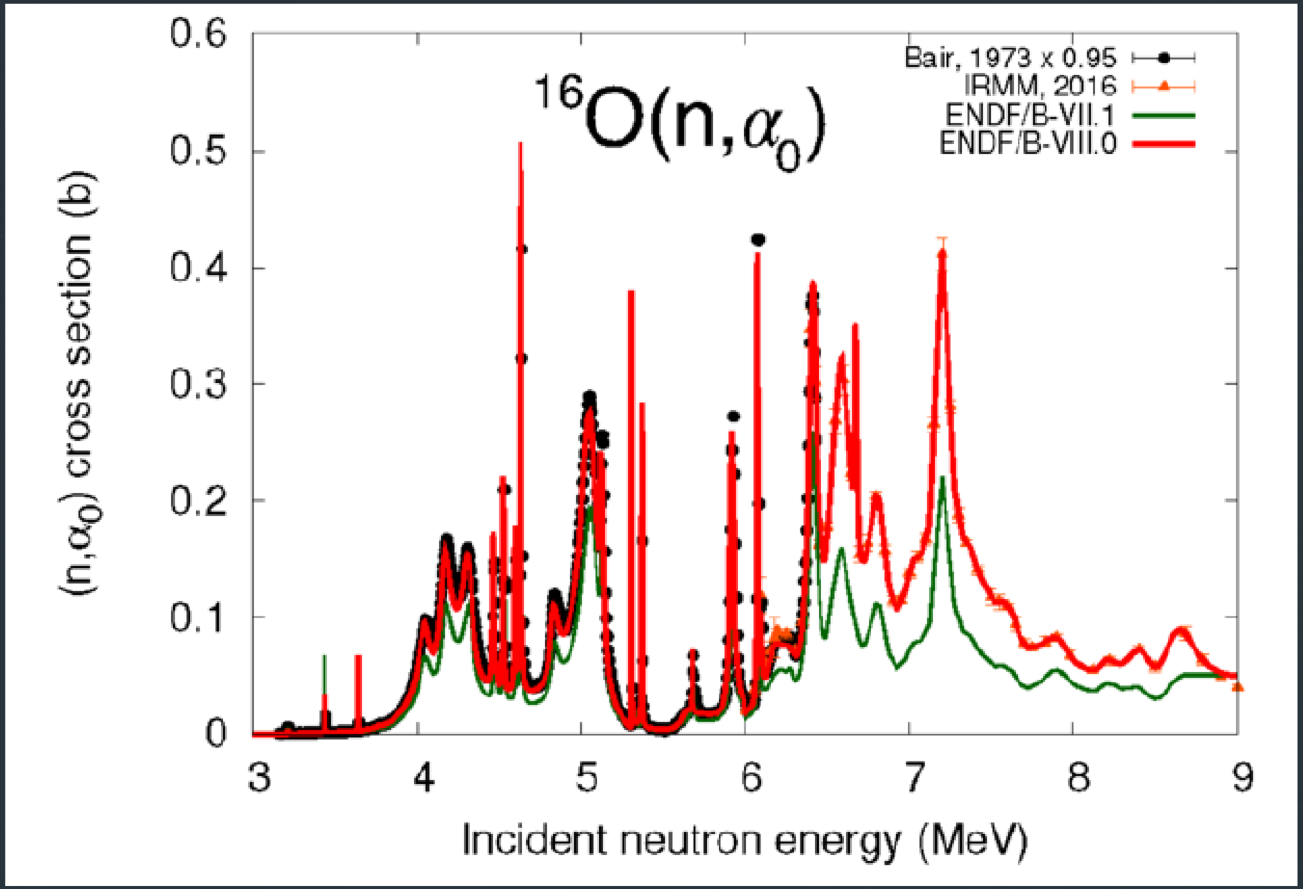


Communication with evaluators

- IAEA workshops
  - R-matrix codes for charged-particle reactions in the resolved resonance region (2016 - merged into INDEN-LE in 2021)
  - International Nuclear Data Evaluation Network (INDEN) on the Evaluation of Light Elements (LE) (2018-present)
- For these types of low mass reactions where resolved resonances dominate, R-matrix theory is used to evaluate data
- Experimentalists ask: What data is needed to improve evaluations (i.e. the phenomenological R-matrix fit)?
  - Partial cross sections (cross sections to each individual final state)
  - Differential cross sections
  - Polarization cross sections

Focus of this talk will be on $^{13}C(\alpha,n)^{16}O$ or $^{16}O(n,\alpha)^{13}C$

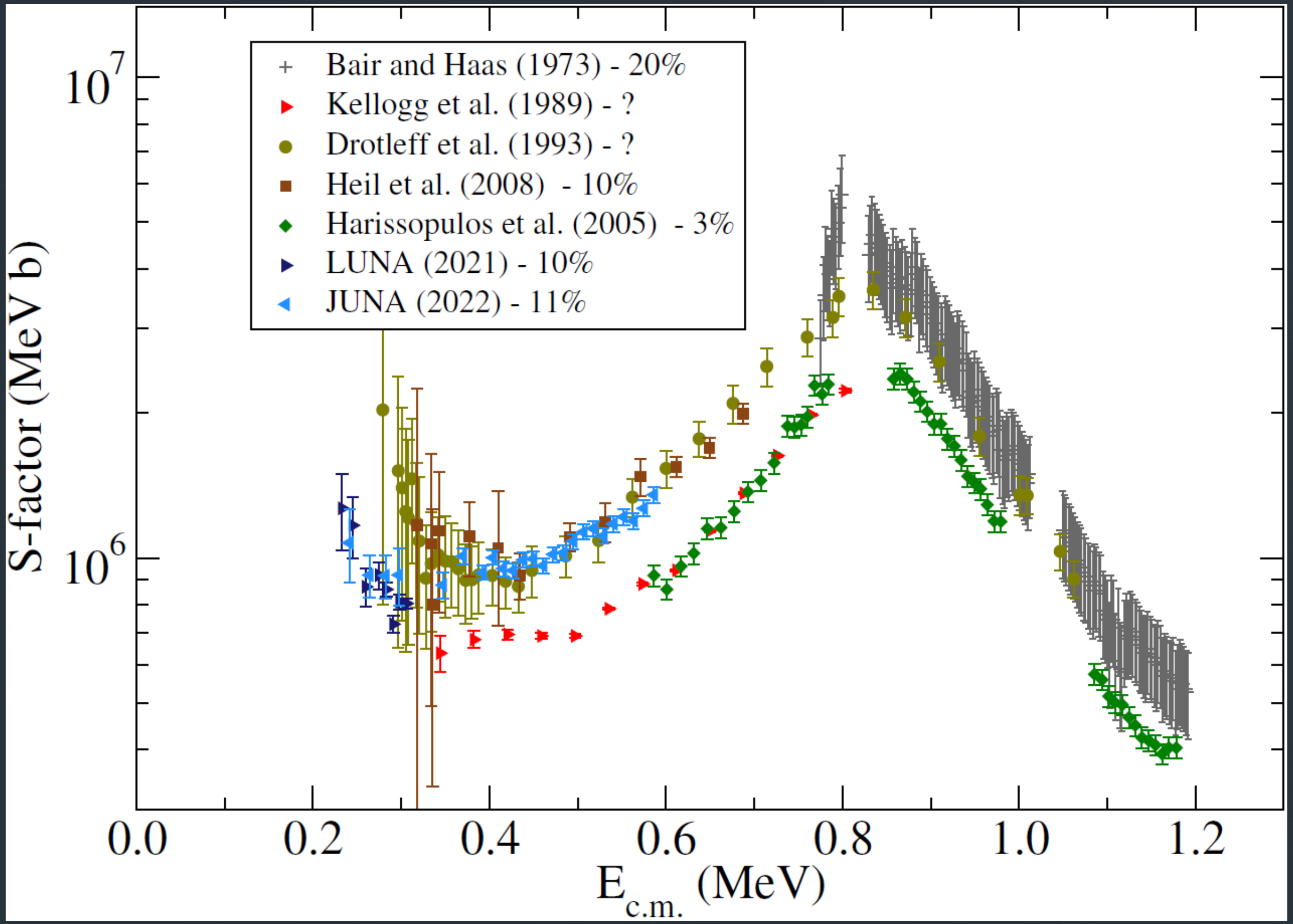
- Biggest issue is with normalization of the data
- Want to extend the R-matrix evaluation E_n = 6.5 MeV
- To do so requires partial cross sections



ENDF/B VIII.0, 2018

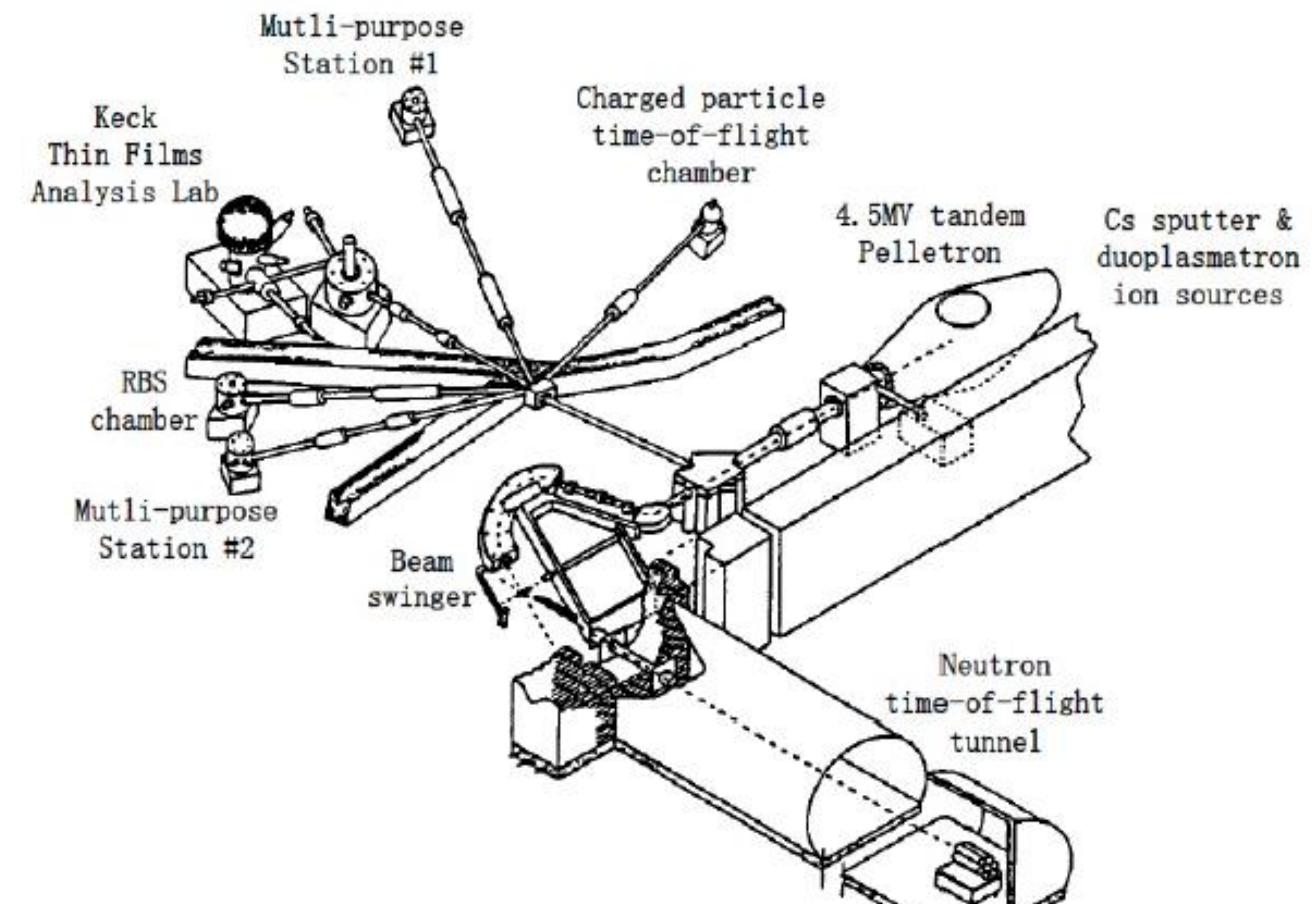
This normalization problem affects all energies

- The normalization issues is also the main uncertainty in the low energy region for astrophysics calculations



Ohio University's Edwards Accelerator Laboratory

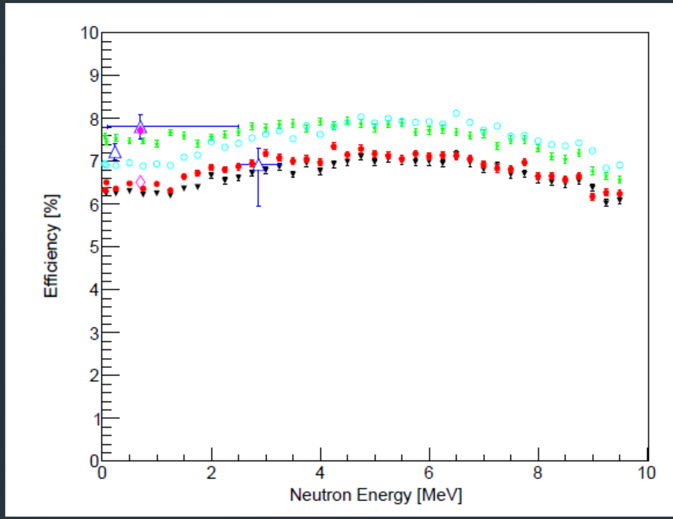
- 4.5 MV tandem provides alpha particle beams
- Energy calibration of a few keV and resolution better than 1 keV
- 10's of nano amps on target with an Alphatross

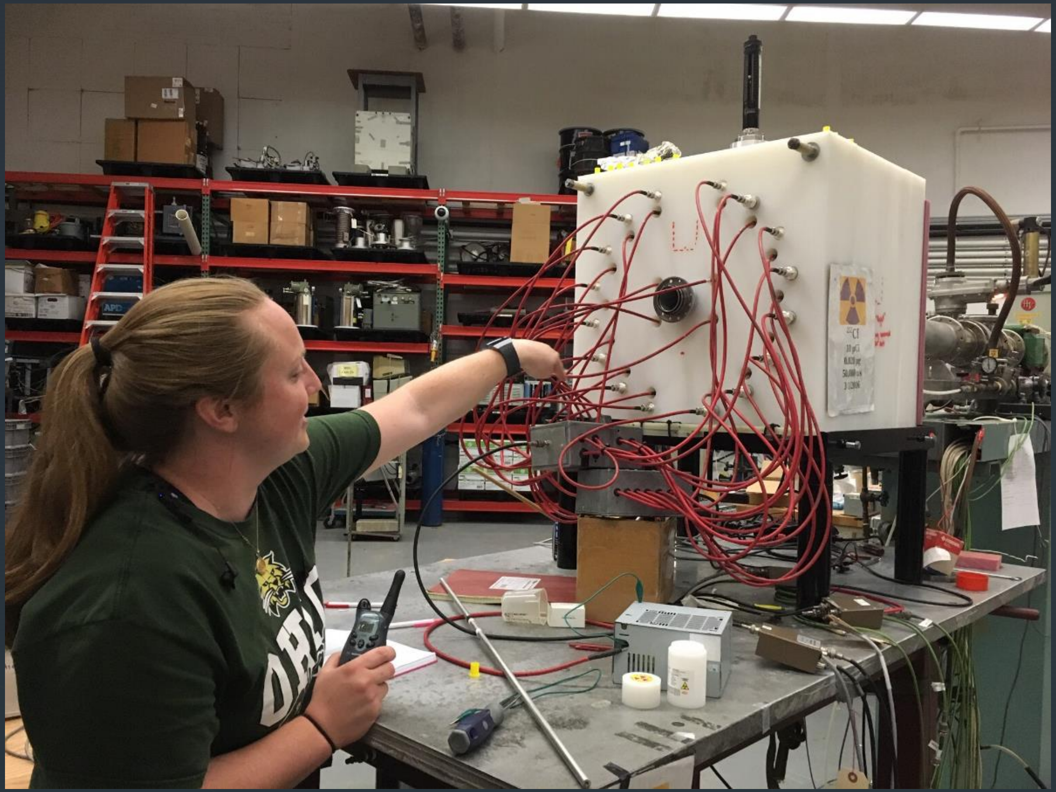


Howard *et al*. (1981)

The $^{3}HeBF_{3}$ Giant Barrel (HeBGB) neutron counter

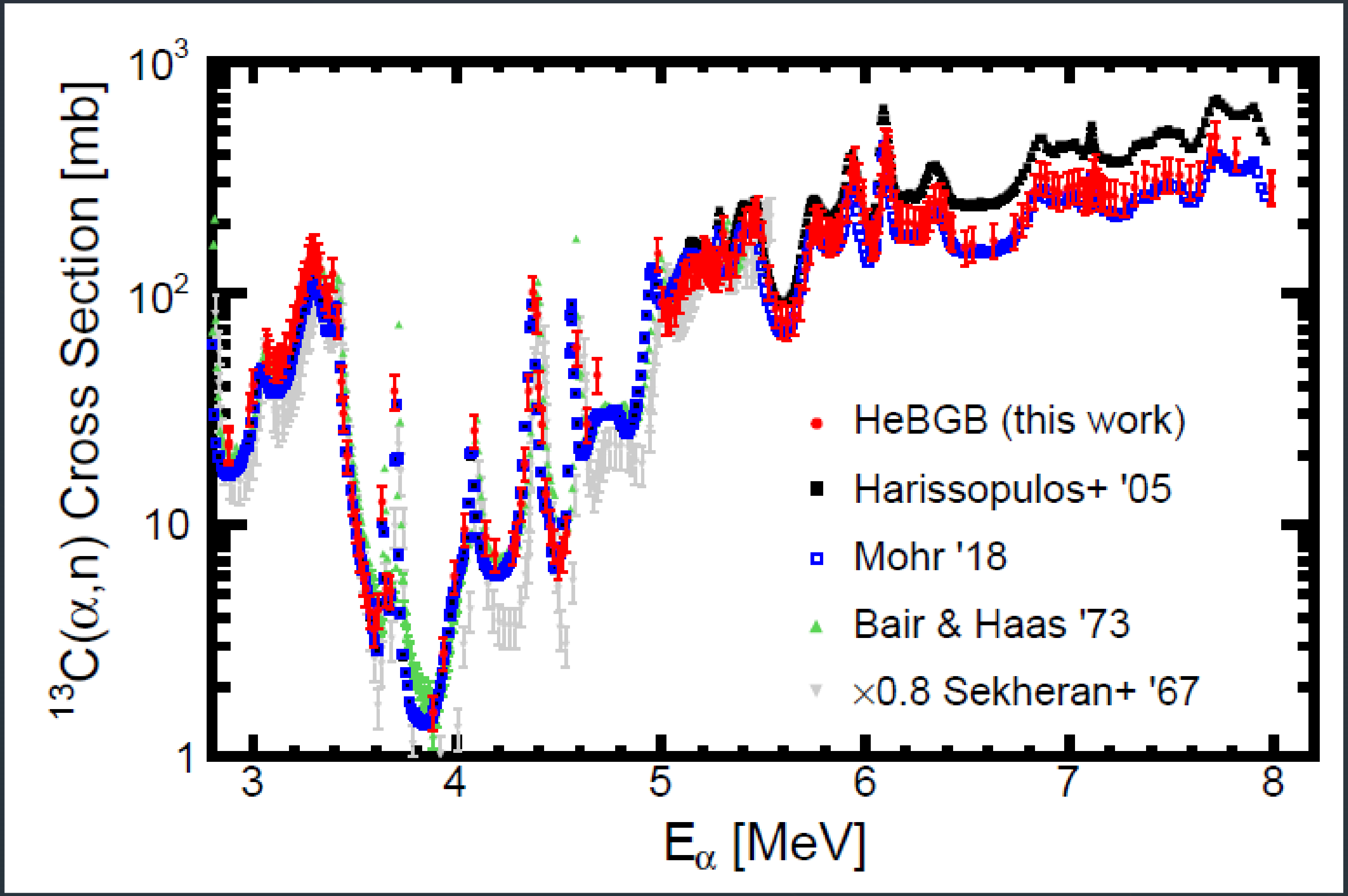
- “4π” neutron counter
- Sacrifices low neutron energy efficiency for a much more constant efficiency over a wider neutron energy range
- This largely mitigates the problem of unknown efficiency when more than one final state can be populated





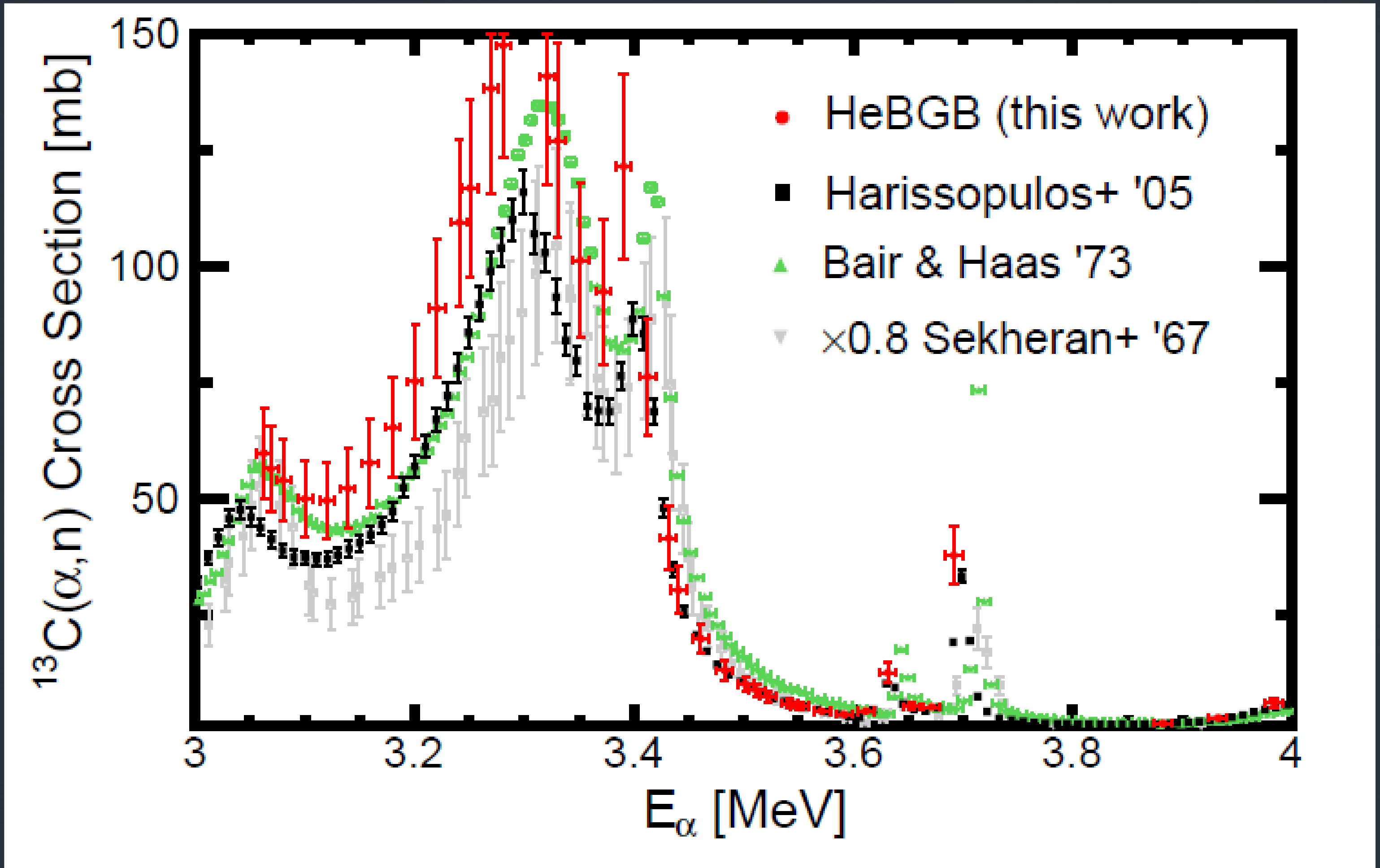
Total reaction cross section measurement

- Measurements spans from 2.9 to 8.0 MeV
- Yields have been corrected for angular distribution effects using MCNP6



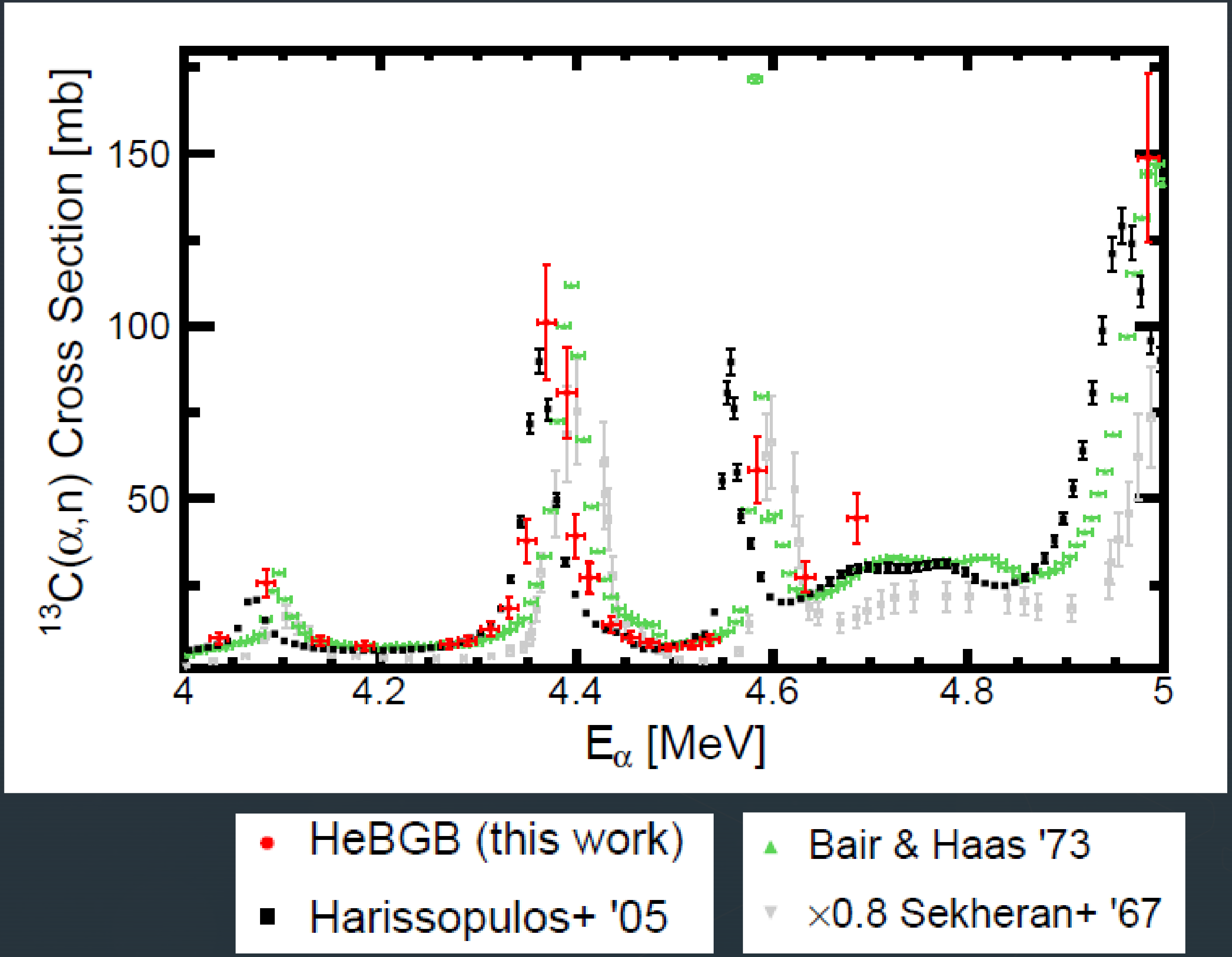
Brandenburg *et al*. (submitted to PRC (letters))

These angular effects are significant, even for a “4π” detector

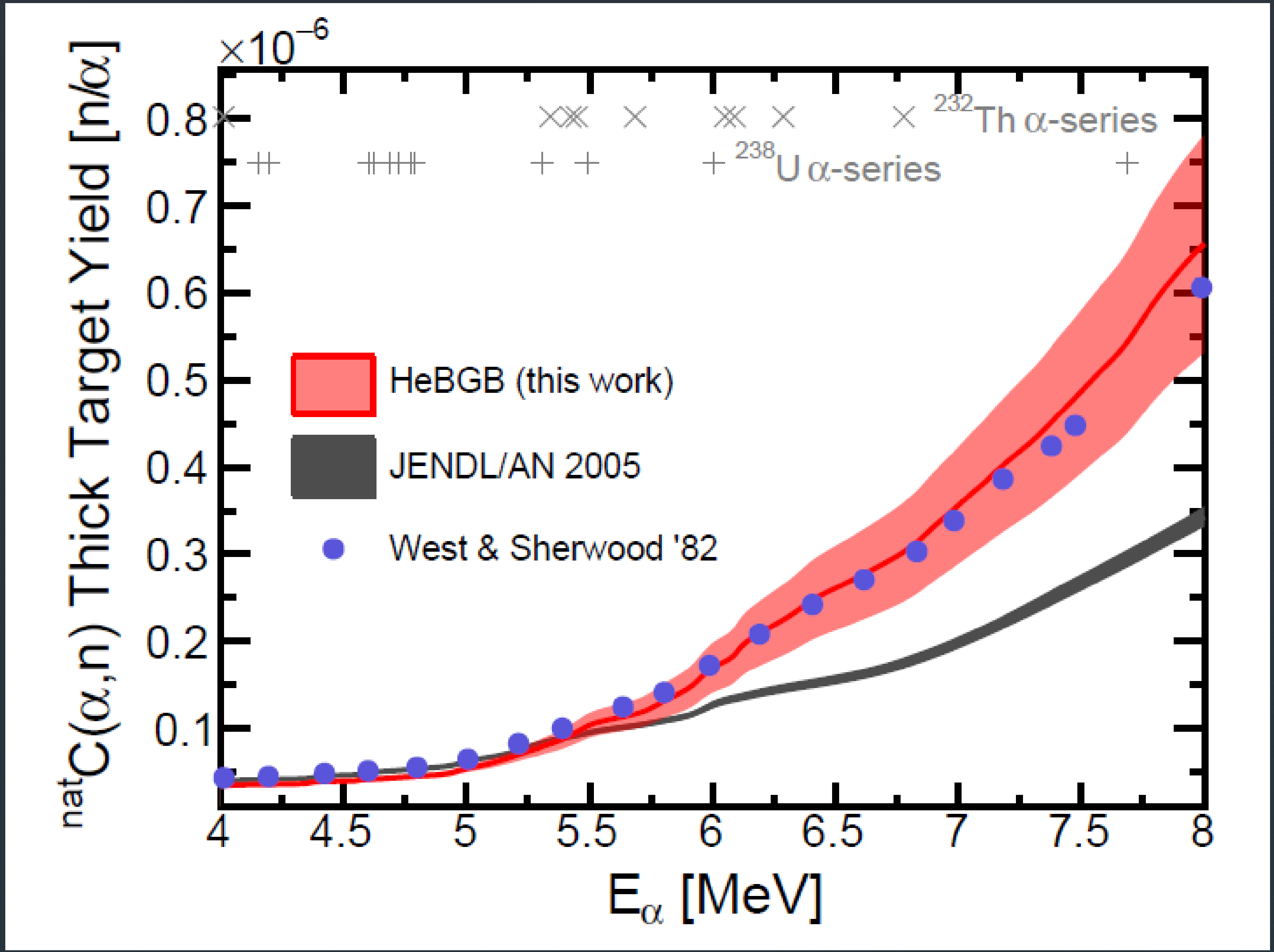


Energy calibration

- At higher energies, some energy calibration issues are also significant

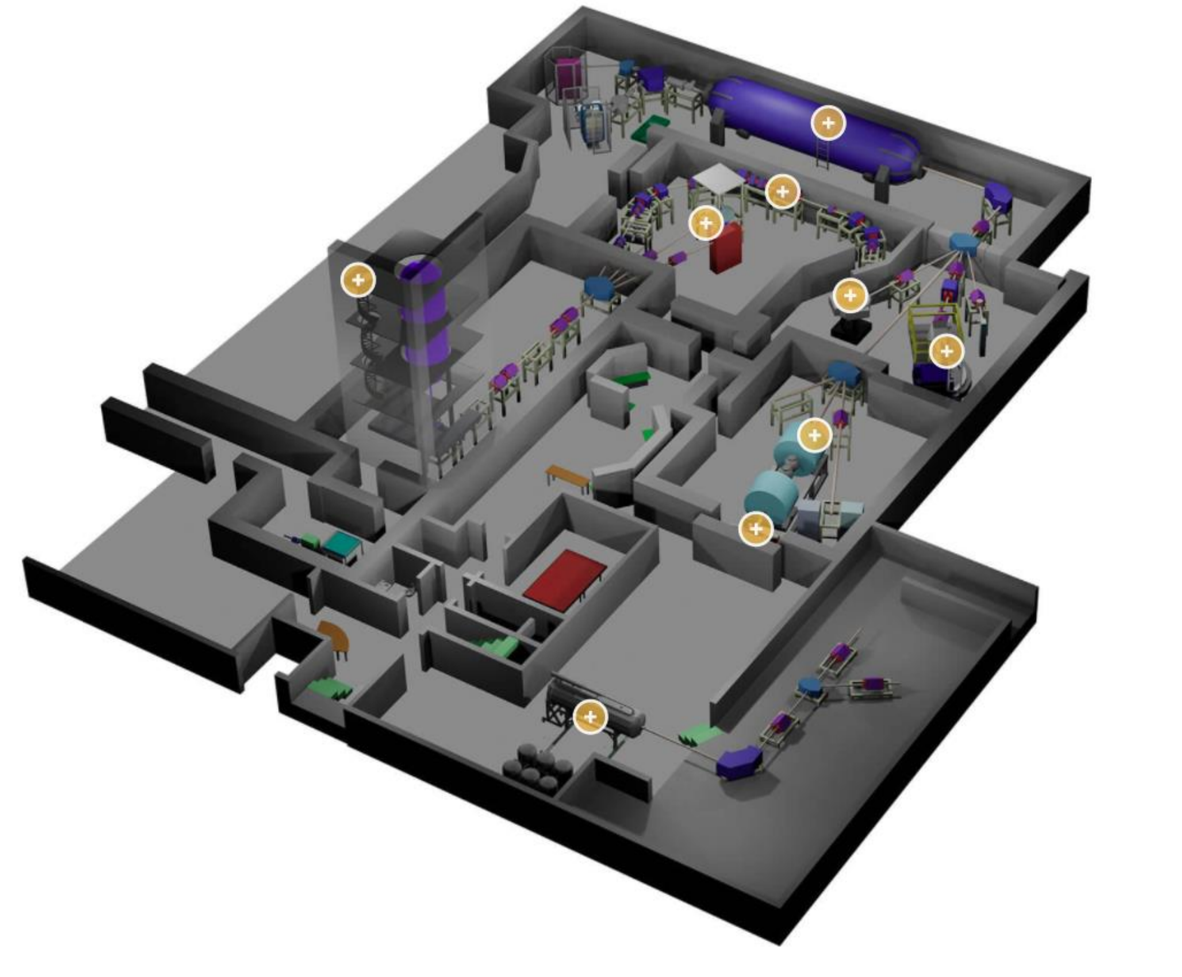


Thick target comparison



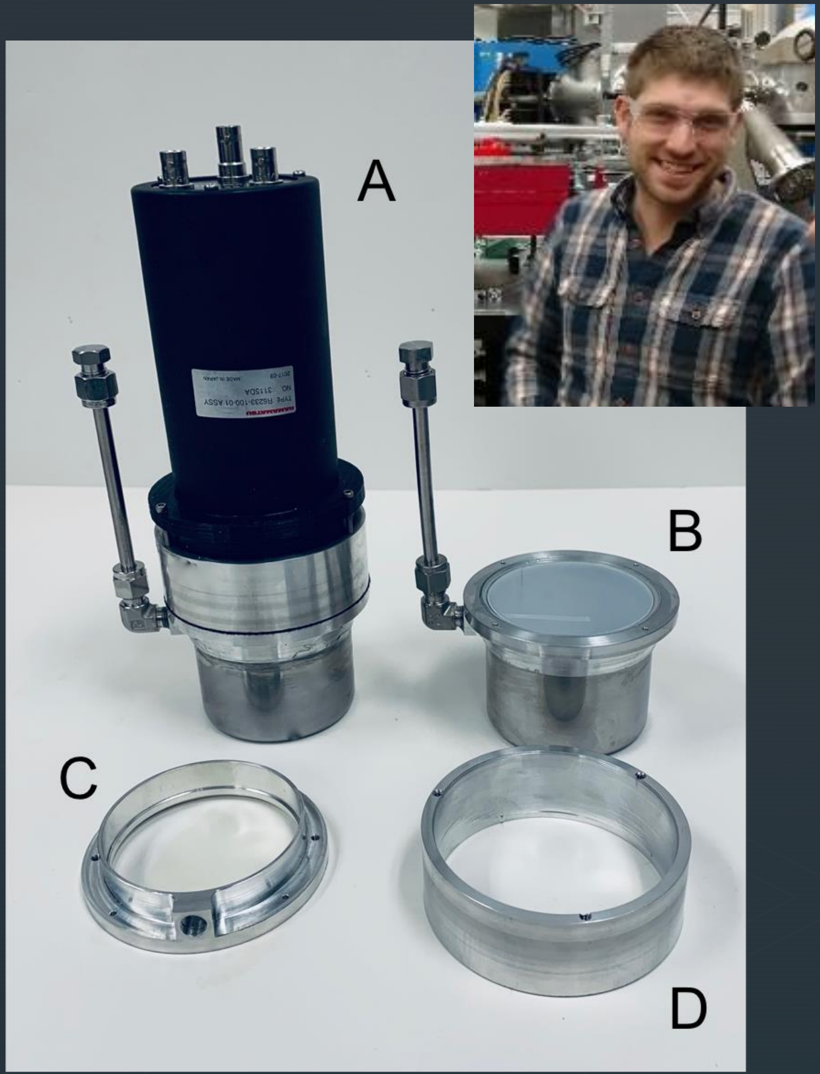
University of Notre Dame's Nuclear Science Laboratory

- 5 MV single ended accelerator
  - 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 of better than 1 keV, energy uncertainty of less than 10 keV
- FN tandem
  - Pulsed alpha beams from 4 to 30 MeV
  - 1 uA (DC), 100 nA (pulsed)



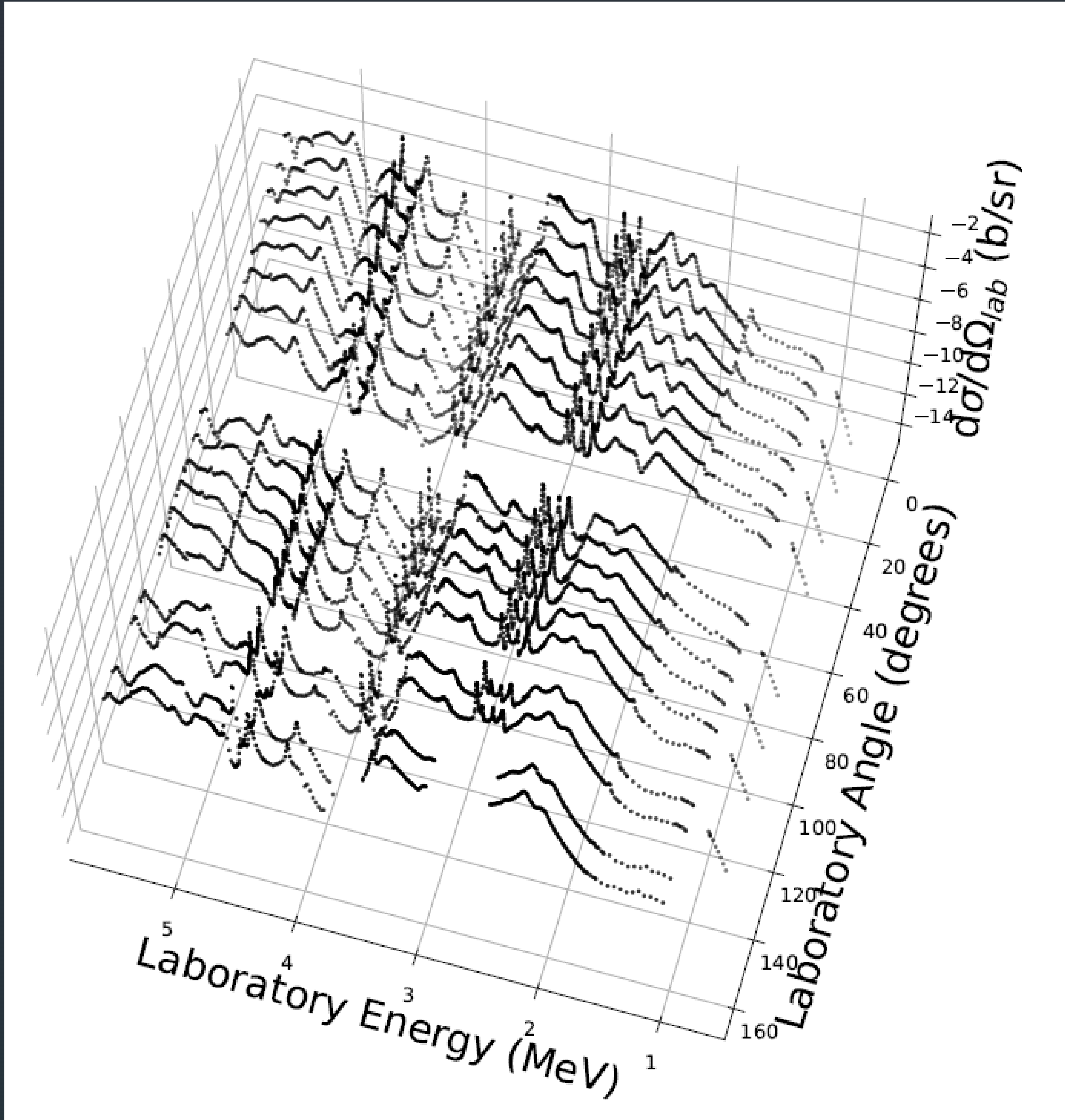
December 2021 setup

Michael Febbraro (ORNL)



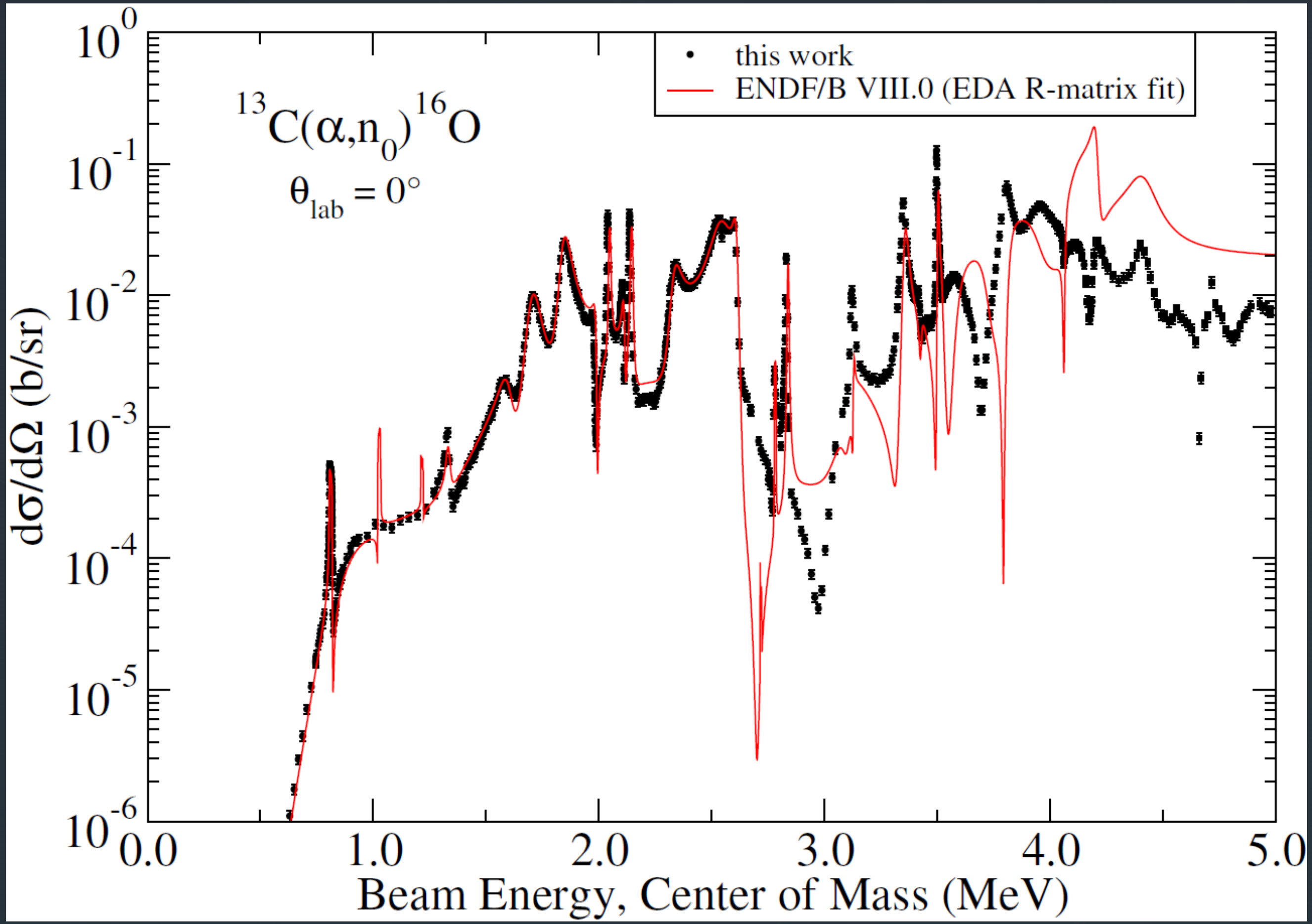
- ORNL deuterated spectroscopic array (ODeSA)
- 9 deuterated liquid scintillators (one had issues)
- 1 EJ315

- Unprecedented energy and granularity
  - Resolution better than 10 keV (target energy loss)
  - 10 keV or smaller energy steps
- and angular coverage
  - 0 to 157.5 degrees
  - 18 point angular distributions



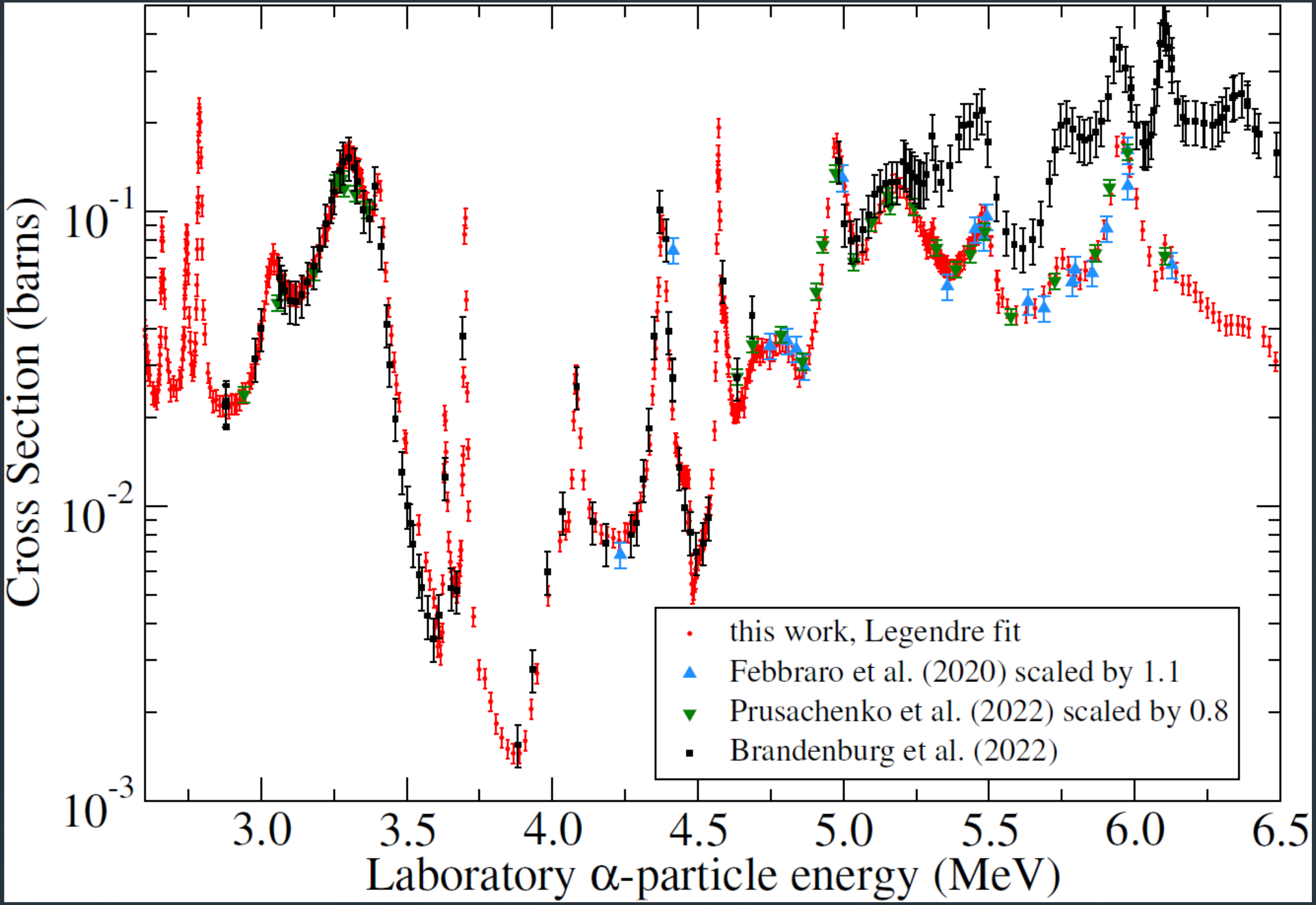
Zero degree excitation function

- Low energies
  - Good agreement with ENDF/B VIII.0
  - Walton et al. (1957) data constrains the fit
- Higher energies, very little angular distribution data to constrain the fit previously

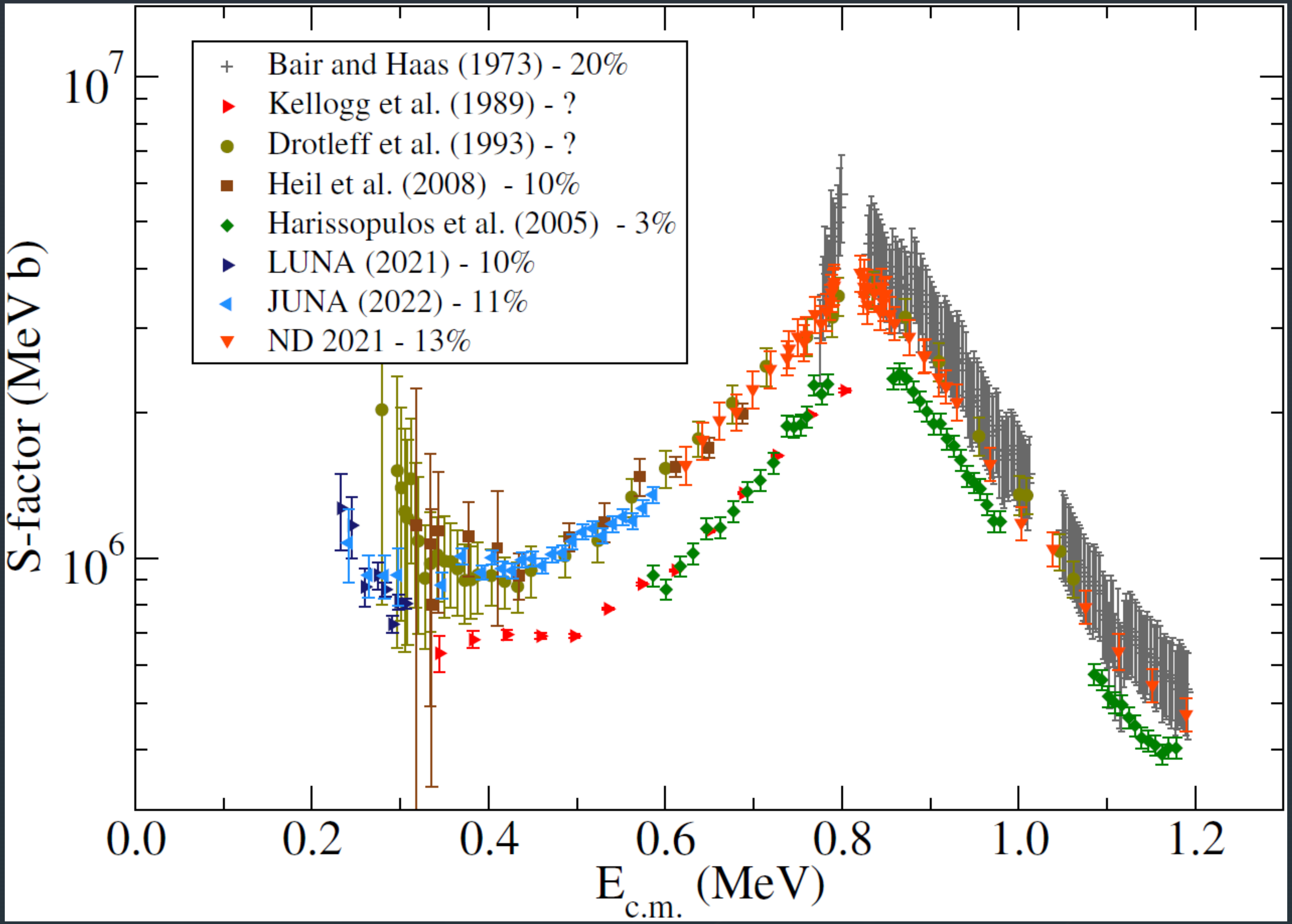


Legendre fit, compare with 4π data

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

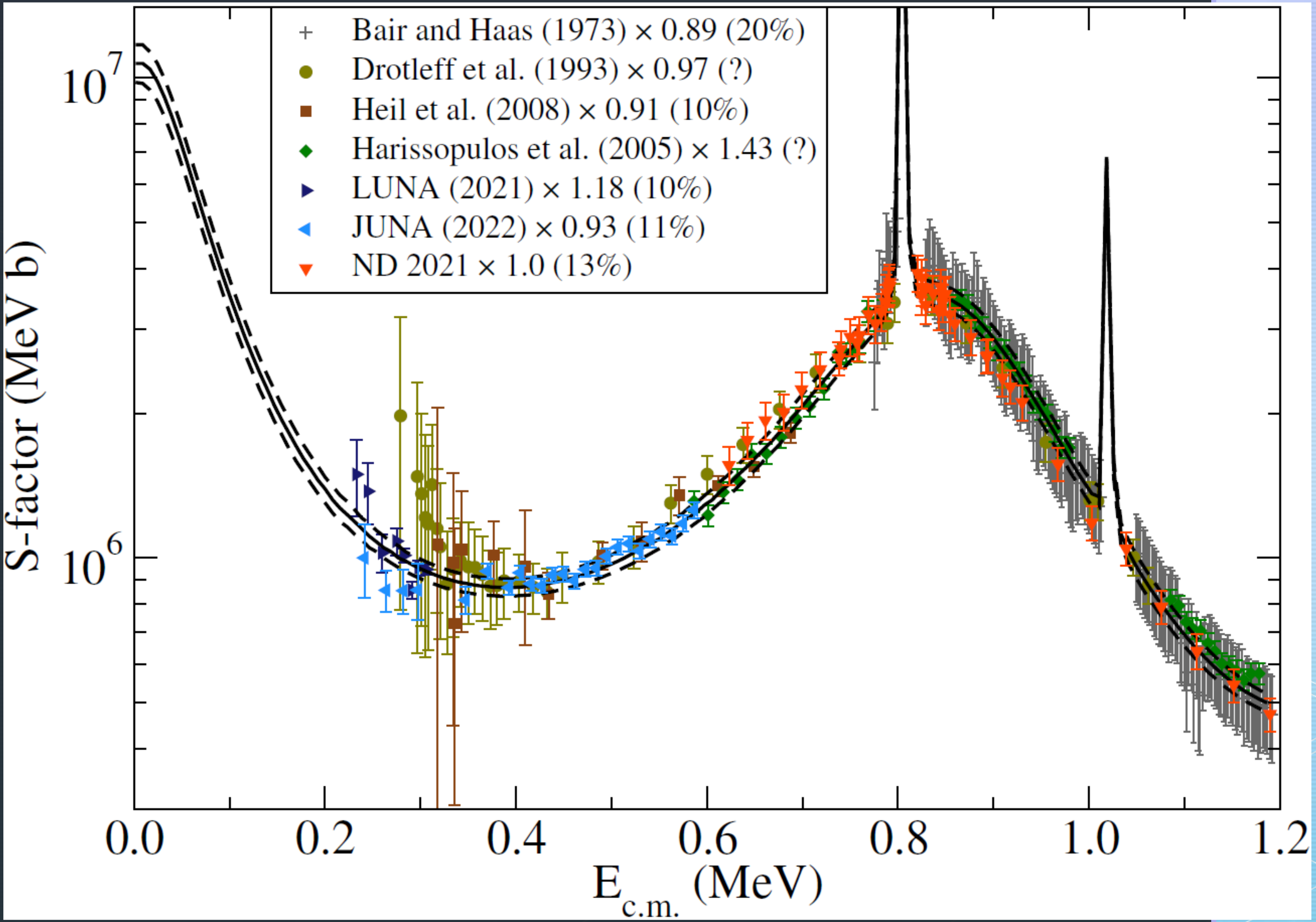


Two more measurements in favor of larger normalization factor



Normalization consistency is getting better!

- Will dramatically decrease the uncertainty in the low energy extrapolation of the $^{13}C(\alpha,n)^{16}O$ reaction
- Bayesian MCMC analysis is ongoing, using the ND R-matrix code AZURE2 and the Bayesian framework BRICK, developed by **Daniel Odell** at OU



Conclusion

- New OU comprehensive measurement of the total reaction cross section of $^{13}C(\alpha,n)^{16}O$ is more accurate thanks to flat neutron efficiency of detector and corrections for angular distributions (2.9 to 8 MeV)
- New unprecedented differential cross section measurement of the $^{13}C(a,n_0)^{16}O$ ground state reaction has been done at ND (0.7 to 6.5 MeV).
- The two measurements are consistent in both energy calibration and overall normalization despite being under very different experimental conditions
- These cross sections will have a dramatic impact on both the ^{16}O+n evaluation and on the low energy extrapolation of the $^{13}C(a,n)^{16}O$ reaction for astrophysics application

Collaborators

- Mike Febbraro (ORNL)
- August Gula (ND)
- Shahina (ND)
- Beka Kelmar (ND)
- Dan Bardayan (ND)
- Carl Brune (OU)
- Zach Meisel (OU)
- Jason Nattress (ORNL)
- Fry Fang (ND)
- Karl Smith (LANL)
- Ed Stech (ND)
- Dan Robertson (ND)
- György Gyürky (ATOMKI)
- Don Carter (OU)
- B. Kenady (OU)
- M. Saxena (OU)
- Alexander V. Voinov (OU)
- J. Warren (OU)

- Miriam Matney (ND)
- 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)
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- D.C. Ingram (OU)
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Announcement: The 2023 *R*-matrix Workshop on Methods and Applications

- **Athens, Ohio USA**
- Ohio University, **June 19 to 23, 2023**
- Introductory lectures and travel support **for students**
- Any type of R-matrix related project of any technical level