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

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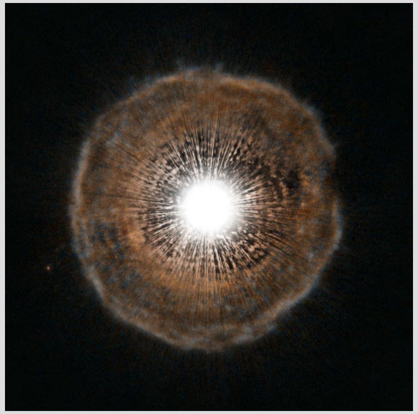
S-PROCESS NEUTRON SOURCES

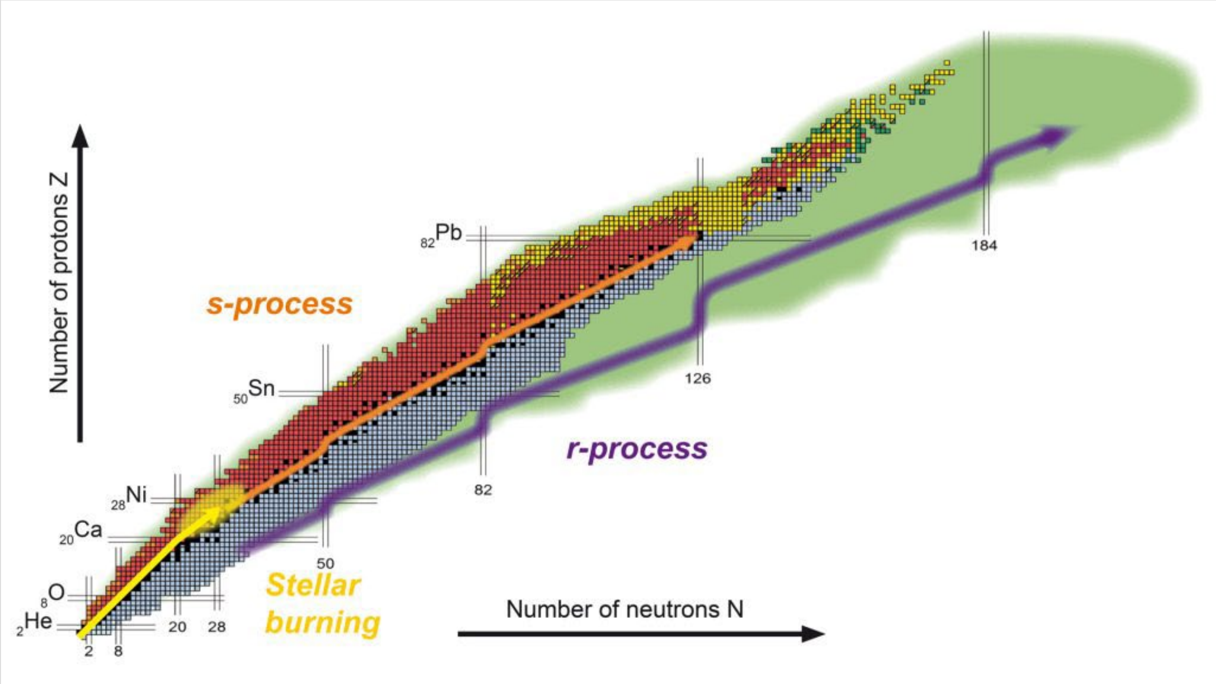
- **$^{13}C(\alpha,n)^{16}O$**
- $^{22}Ne(\alpha,n)^{25}Mg$

- $^{17}O(\alpha,n)^{20}Ne$
- $^{18}O(\alpha,n)^{21}Ne$
- $^{25}Mg(\alpha,n)^{28}Si$
- $^{26}Mg(\alpha,n)^{29}Si$

Helium burning



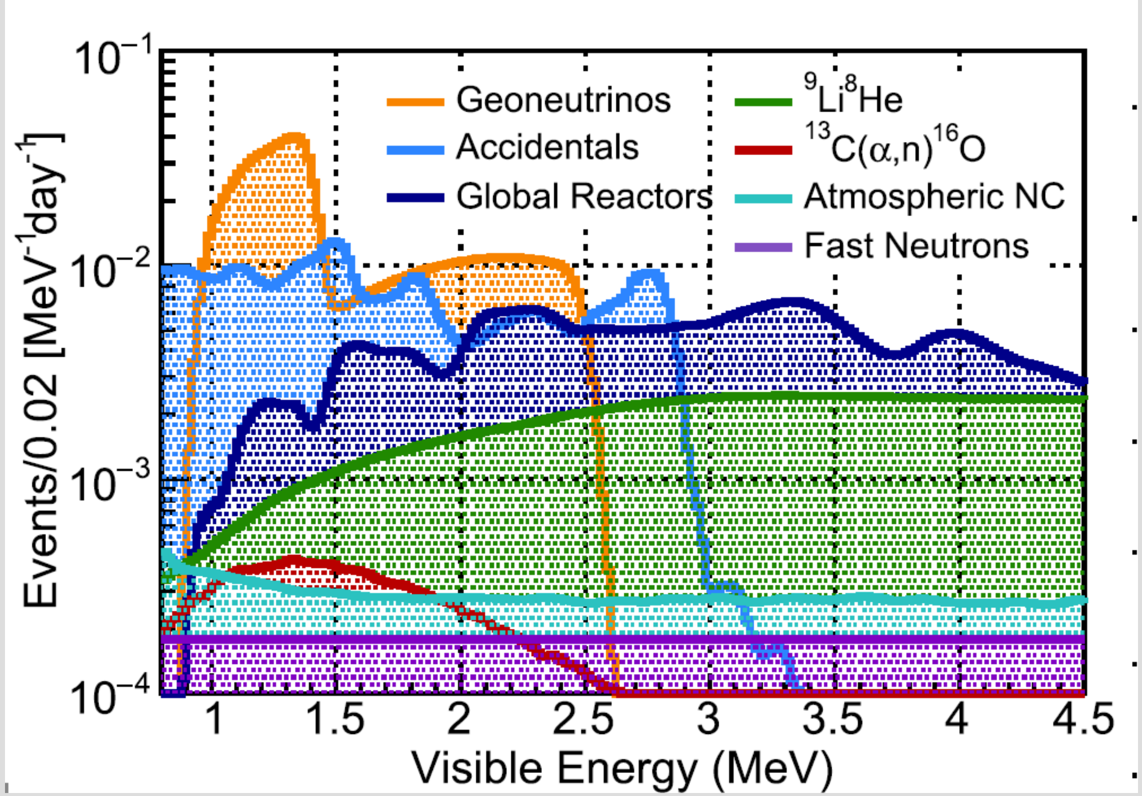
Red Giant Star, ESA/Hubble, NASA H. Olofsson (Onsala Space Obwservatory)



EMMI, GSI/Different Arts

BACKGROUNDS IN TON SCALE EXPERIMENTS

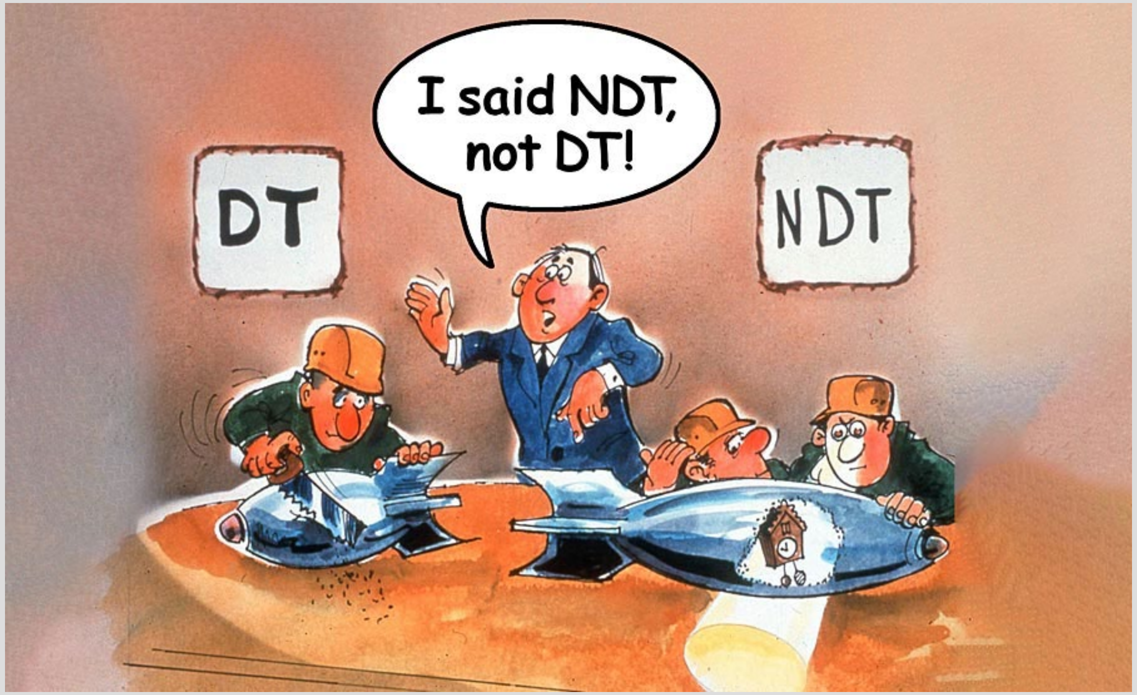
- Trace actinide contamination in all materials, which decay producing α-particles up to 8 MeV
- $^{13}C(\alpha,n)^{16}O$ reaction can occur on carbon present in the detector
- Ex: JUNO, Daya Bay, KamLAND, Borexino, LENA



Abusleme et al. (2022), JUNO 20 kT neutrino detector

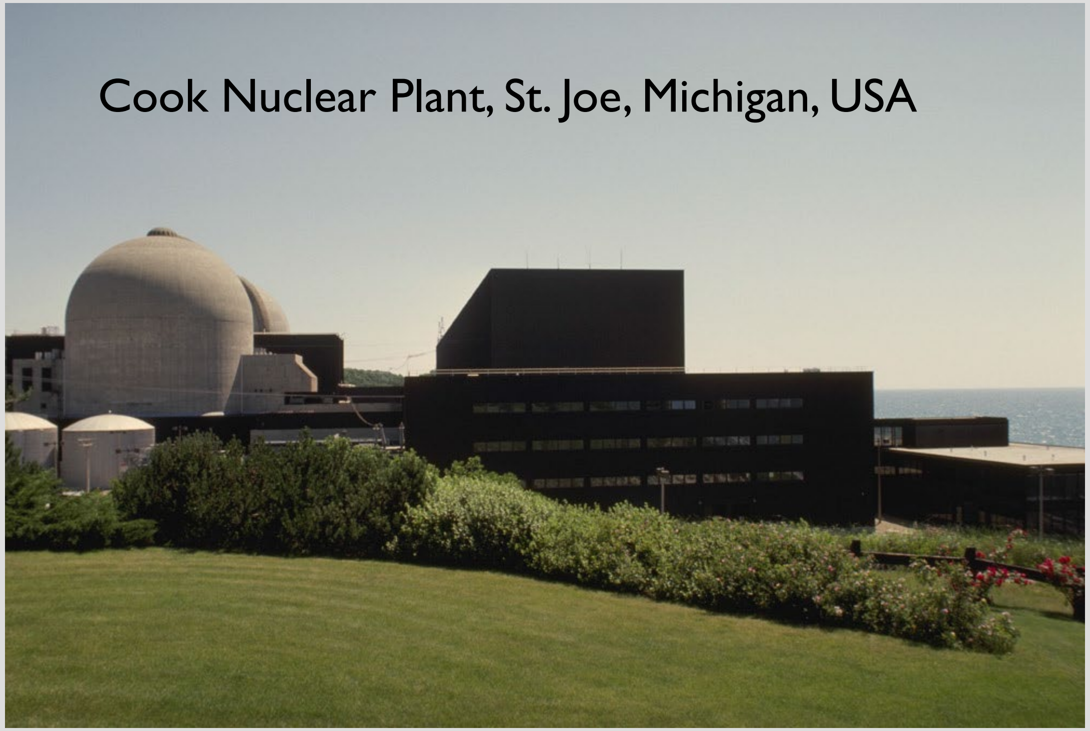
NUCLEAR NONPROLIFERATION

- Nondestructive assay (NDA)
- Can be done through neutron detection from fissile material (like UF_6)
- Unaccounted for (α,n) reactions on light nuclei can skew the results
- DOE scoping study (ORNL/TM-2020/1789) puts the following reactions at top priority: $^{19}F(\alpha,n)^{22}Na$, $^{13}C(\alpha,n)^{16}O$, $^{10}B(\alpha,n)^{13}N$, $^{11}B(\alpha,n)^{14}N$, $^{7}Li(\alpha,n)^{10}B$, $^{6}Li(\alpha,n)^{9}B$



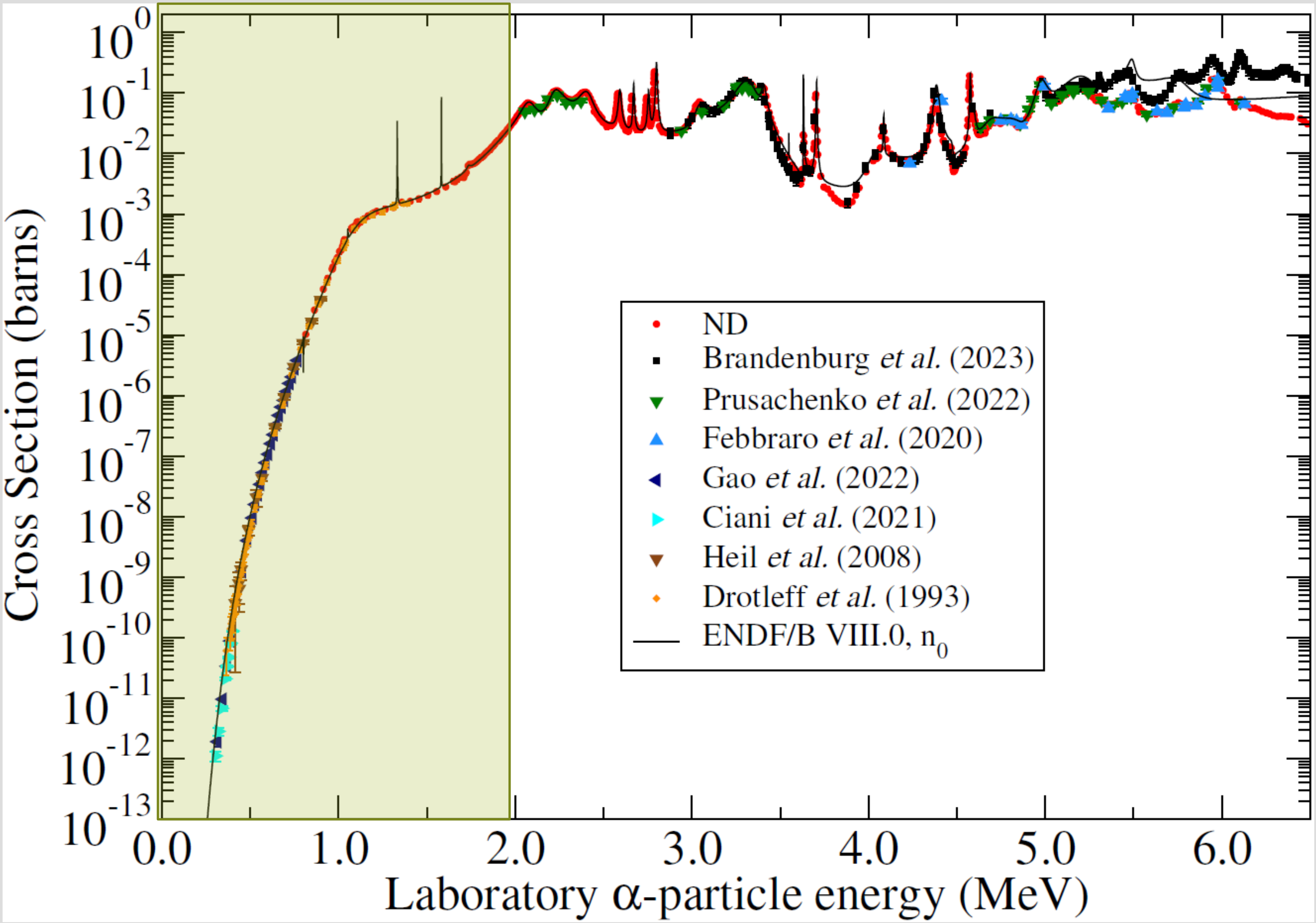
NUCLEAR ENERGY

- Helium generation and release in oxide fuel
- Embrittlement of structural material
- $^{16}O(n,\alpha)^{13}C$



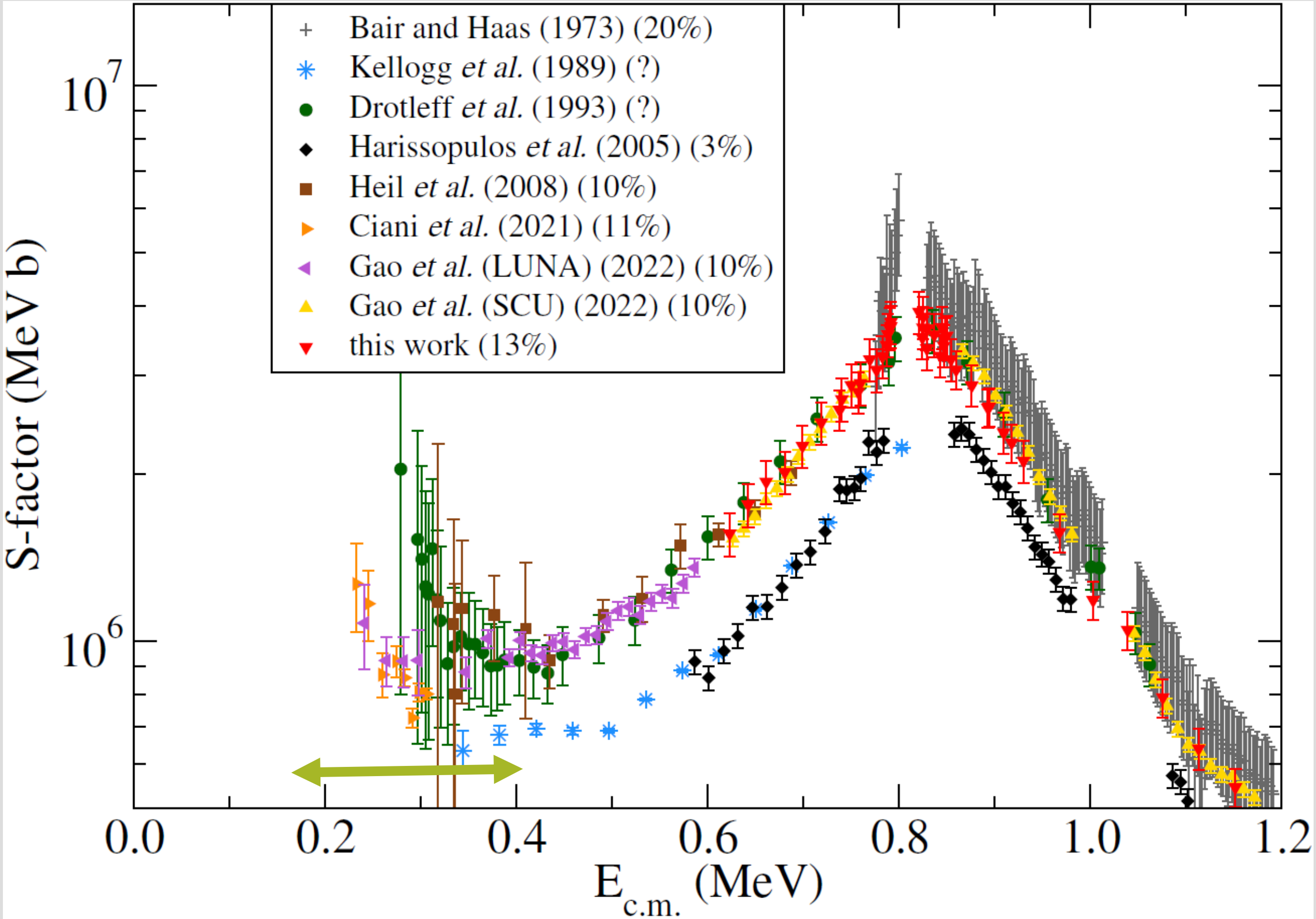
CROSS SECTION AND S-FACTOR

- The low energy cross section for charged particle reactions is dominated by the Coulomb penetrability
- Let's divide that out (approximately) so we can highlight the nuclear component of the reaction



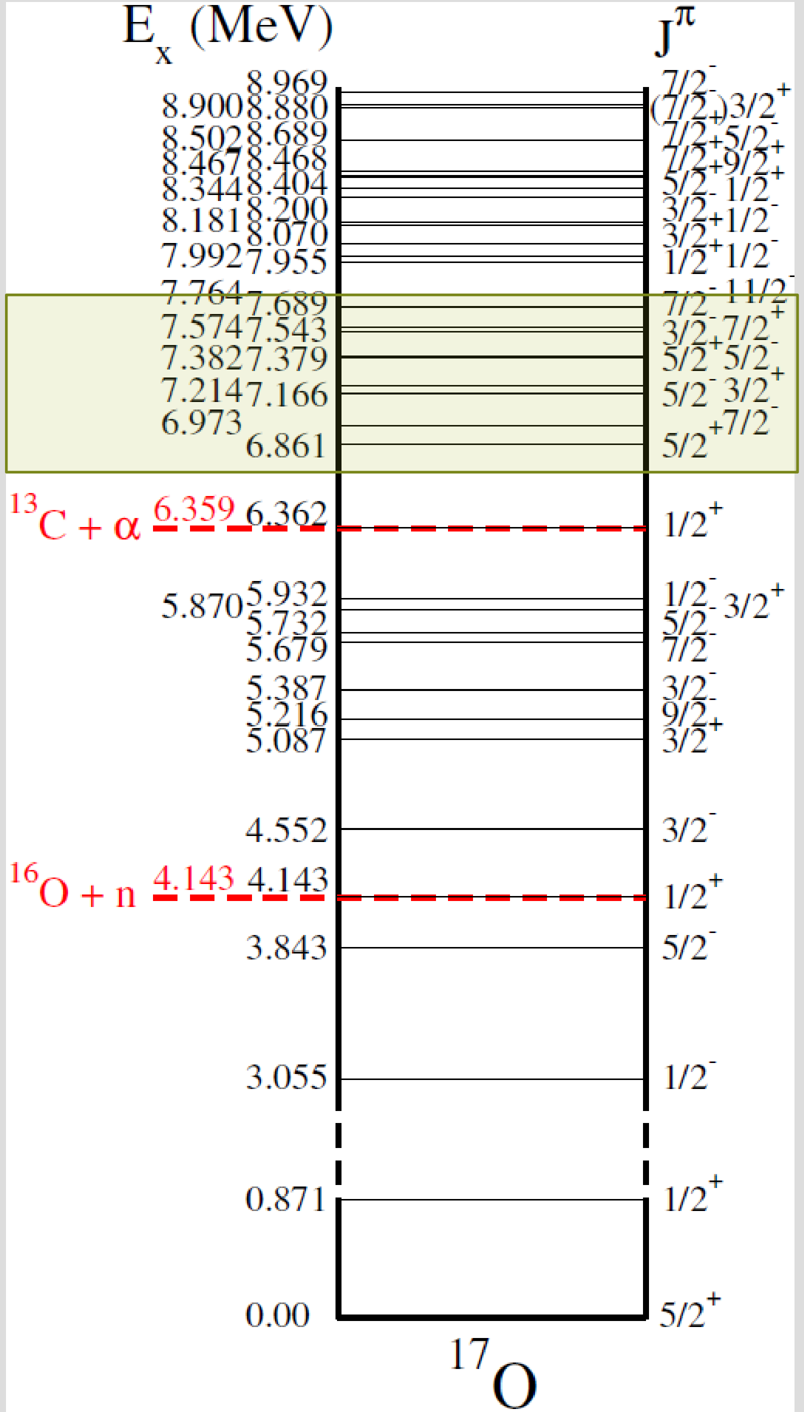
S-FACTOR DATA AT LOW ENERGY

- Almost all angle integrated data measured using 4π neutron moderator counters
- High efficiency for low count rate experiments
- Lack of neutron spectroscopy can make background subtraction more difficult
- Two groups of data
  - Kellogg and Harissopulos are low
  - Probably the result of an issue with the strength of 1.05 MeV resonance
- LUNA and JUNA data push down into the Gamow energy range!



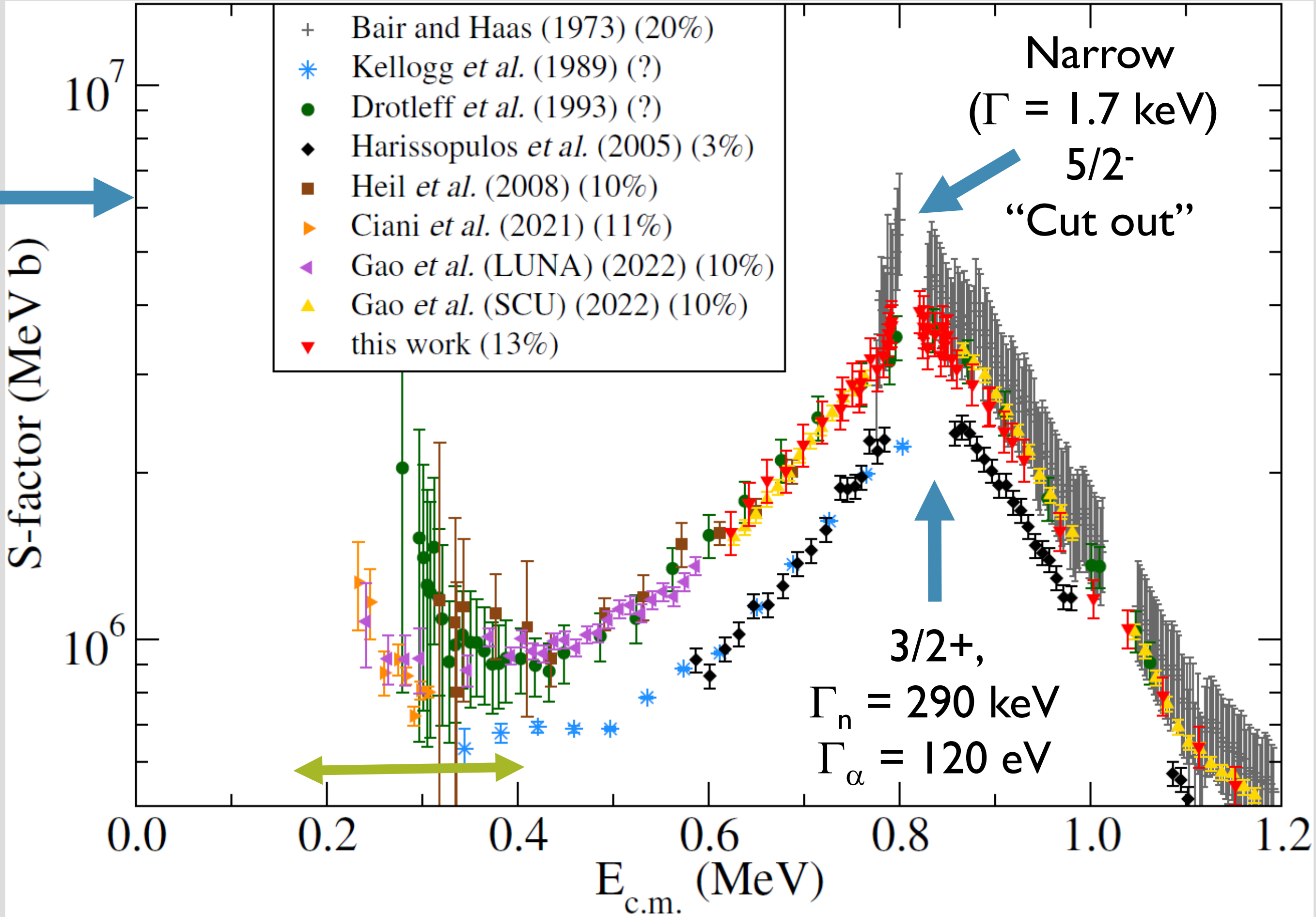
LEVEL DIAGRAM & R-MATRIX ANALYSIS

- Moderate level density
- $1/2^+$ state right at the alpha separation energy that enhances the cross section near threshold
- Broad $3/2^+$ state at higher energy
- A narrow resonance at 1.05 MeV is convenient for checking energy calibration and determining target thickness, but its reported strength has recently been found to be too low
- Near threshold, $\Gamma \approx \Gamma_n$ and $\Gamma_\alpha << \Gamma_n$



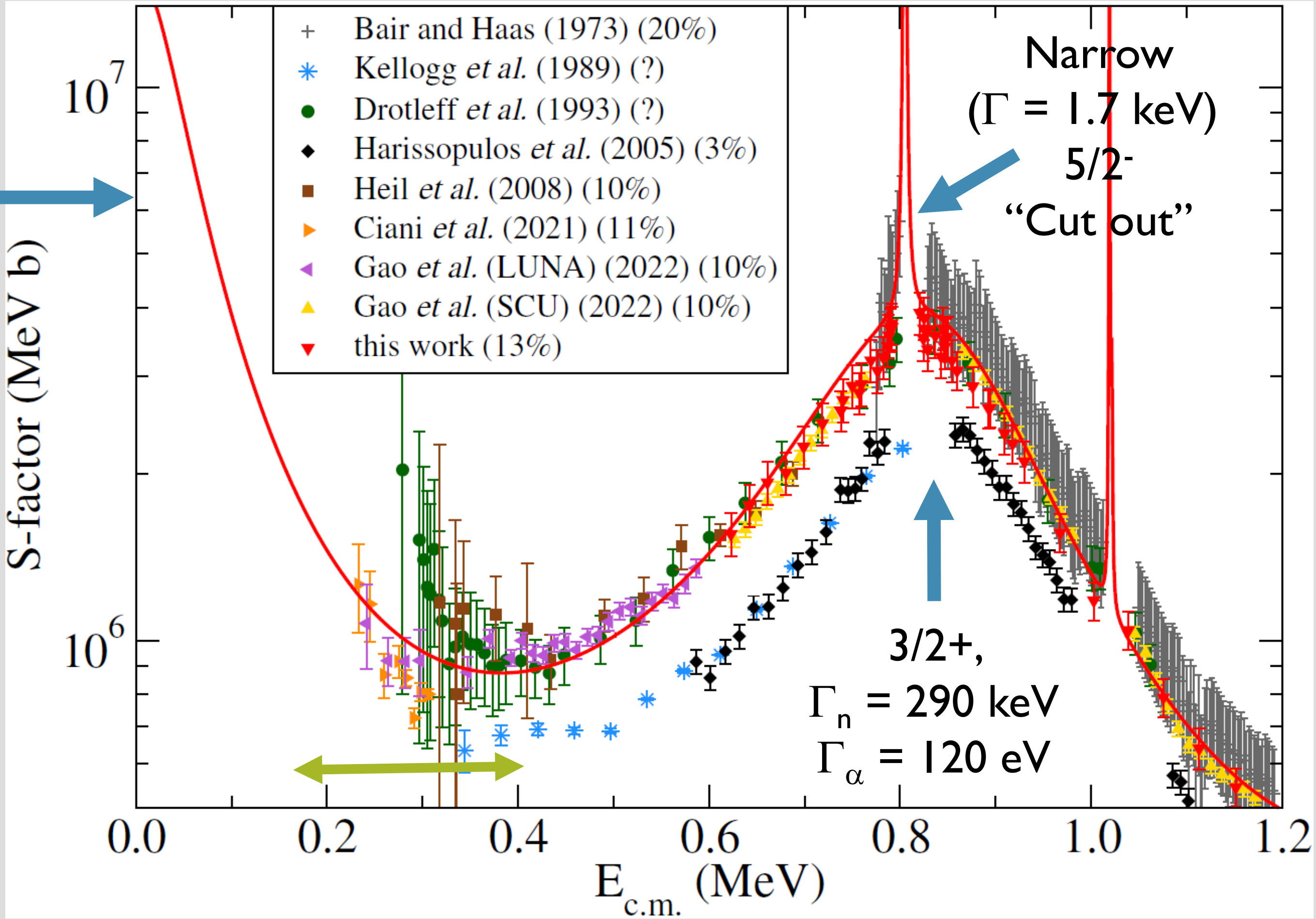
CORRESPONDING RESONANCES

Near threshold
1/2+ state
ANC from
transfer studies



PHENOMENOLOGICAL R-MATRIX FIT

Near threshold 1/2+ state ANC from transfer studies

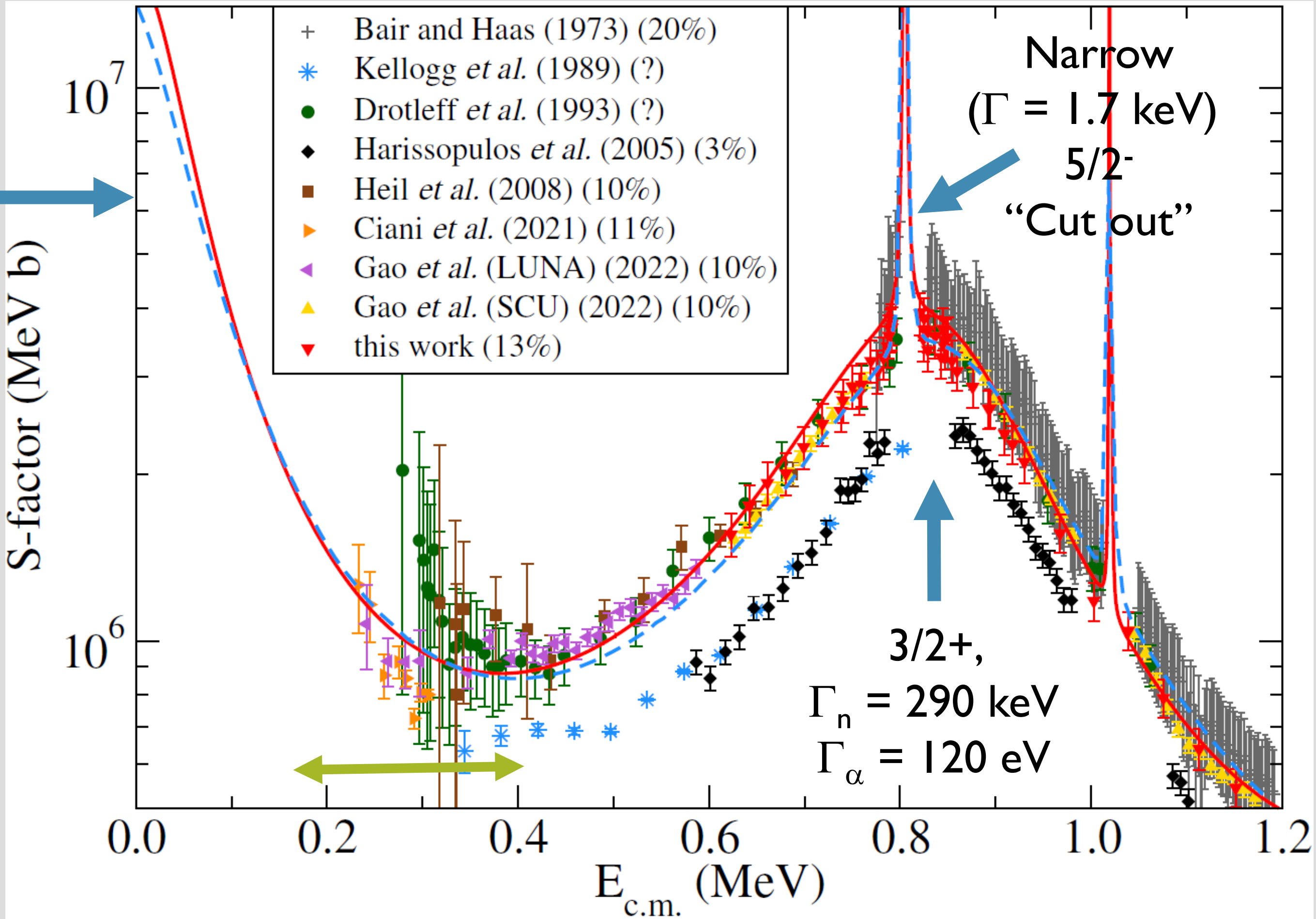


In the fit, each data set is given an independent normalization factor to reflect its systematic uncertainty.

The near threshold state results in a large enhancement at low energy and this is reflected for the first time in both the recent measurements of Ciani *et al.* and Gao *et al.* (LUNA and JUNA, respectively)

AN ALTERNATIVE INTERFERENCE PATTERN

Near threshold 1/2+ state ANC from transfer studies

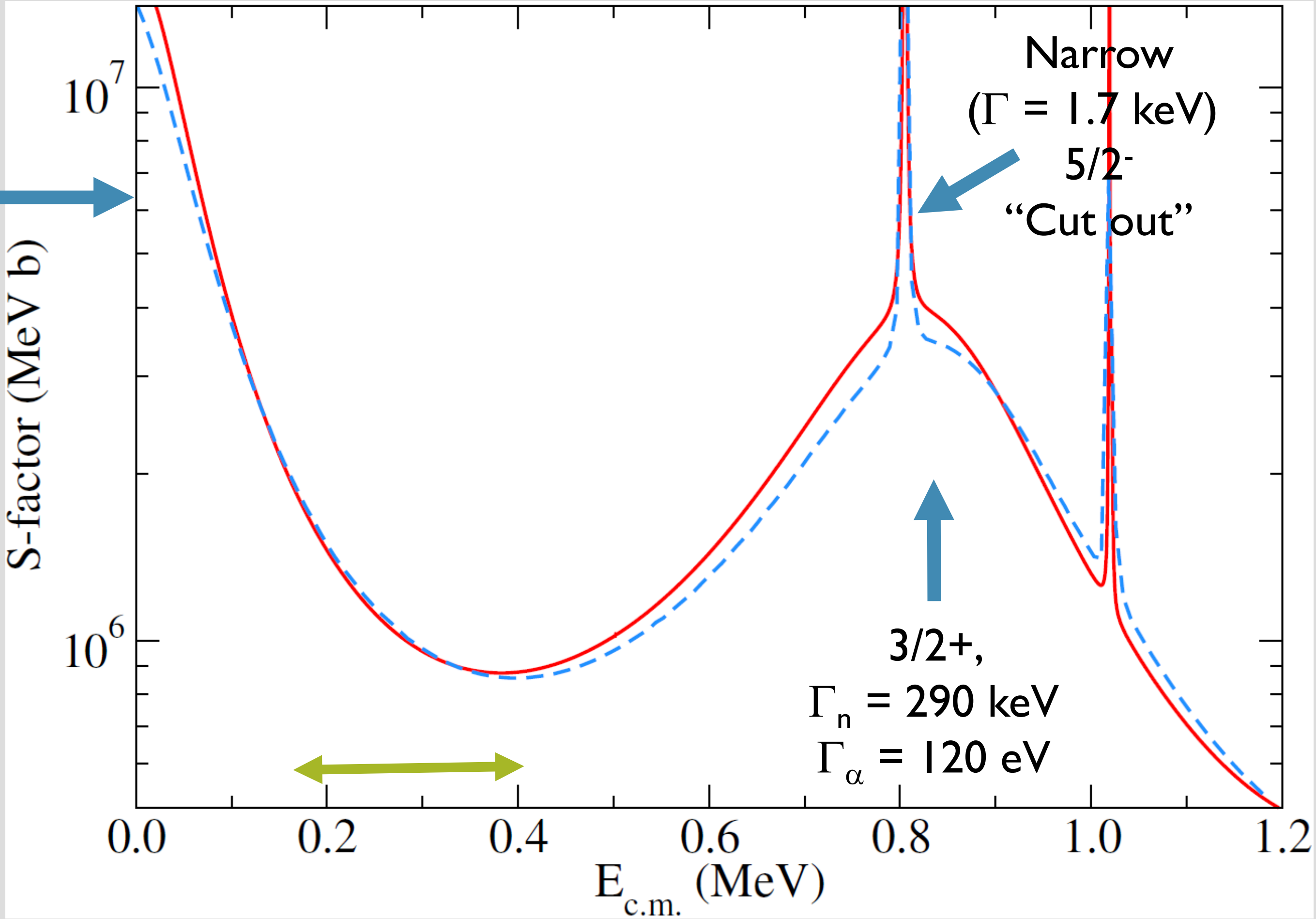


χ^2 is very similar and is actually a bit lower for this alternative interference solution…

Rather unique to this case, the cross section is still very similar over the range of astrophysical interest

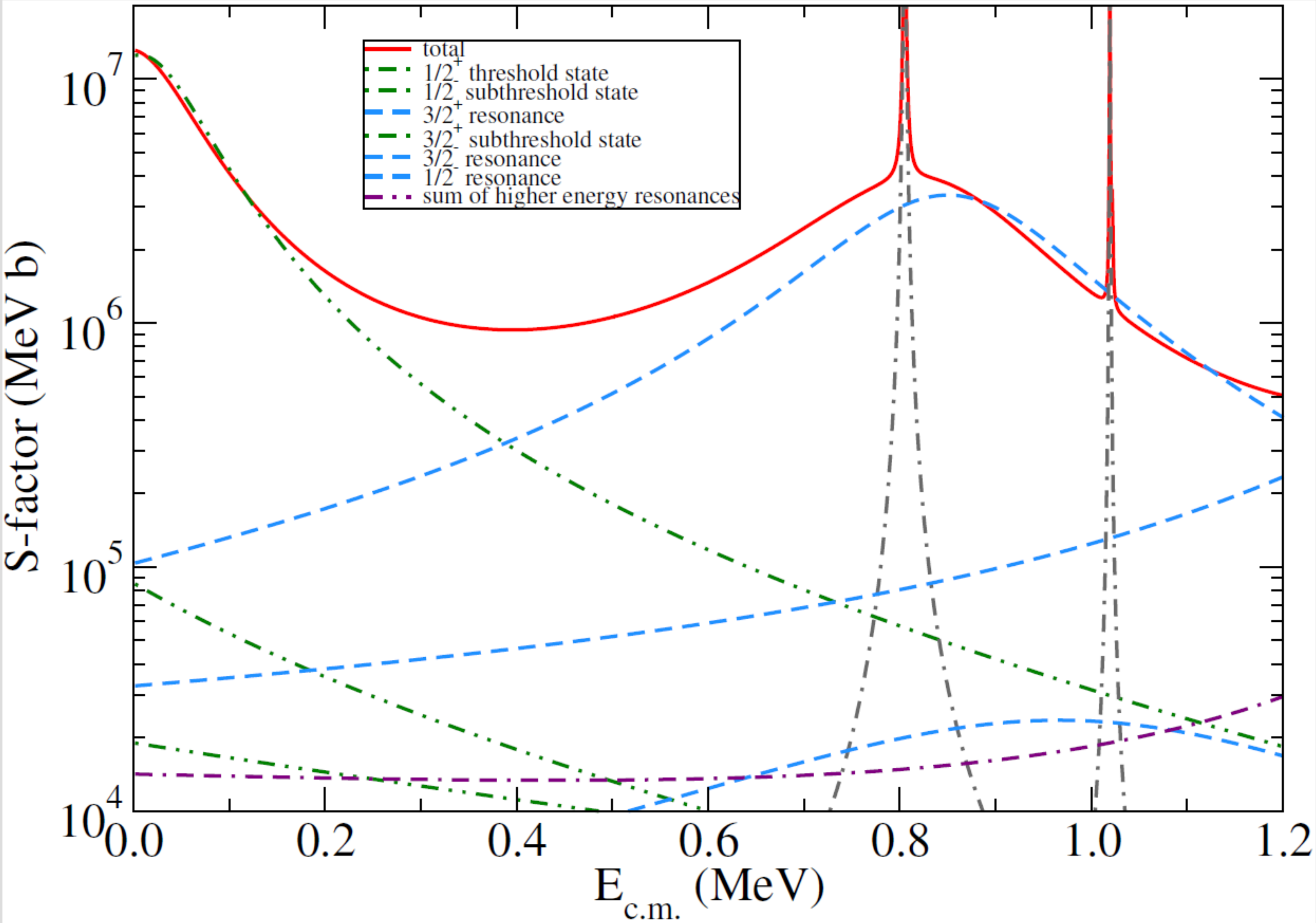
JUST THE R-MATRIX FITS

Near threshold
1/2+ state
ANC from
transfer studies



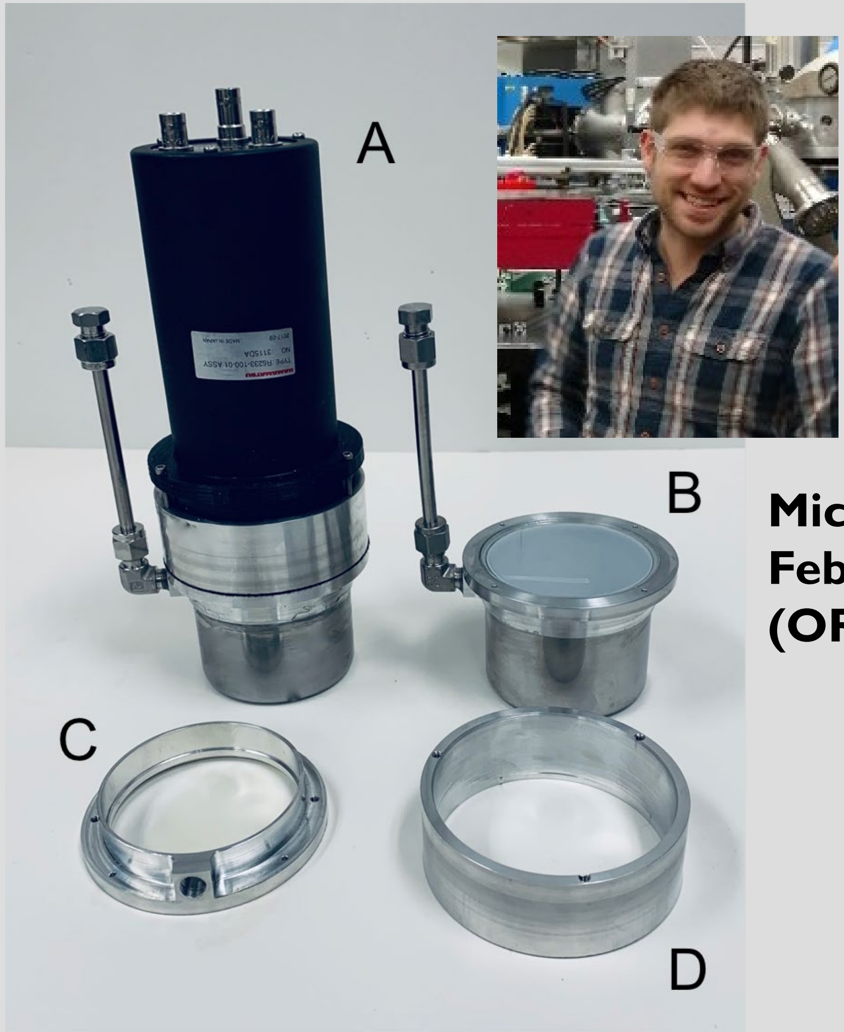
THE FIT IS DECEPTIVELY COMPLICATED

- There are actually multiple subthreshold levels, although one clearly dominates
- There are many background levels as well



DIFFERENTIAL CROSS SECTION MEASUREMENT AT THE UNIVERSITY OF NOTRE DAME NUCLEAR SCIENCE LABORATORY

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

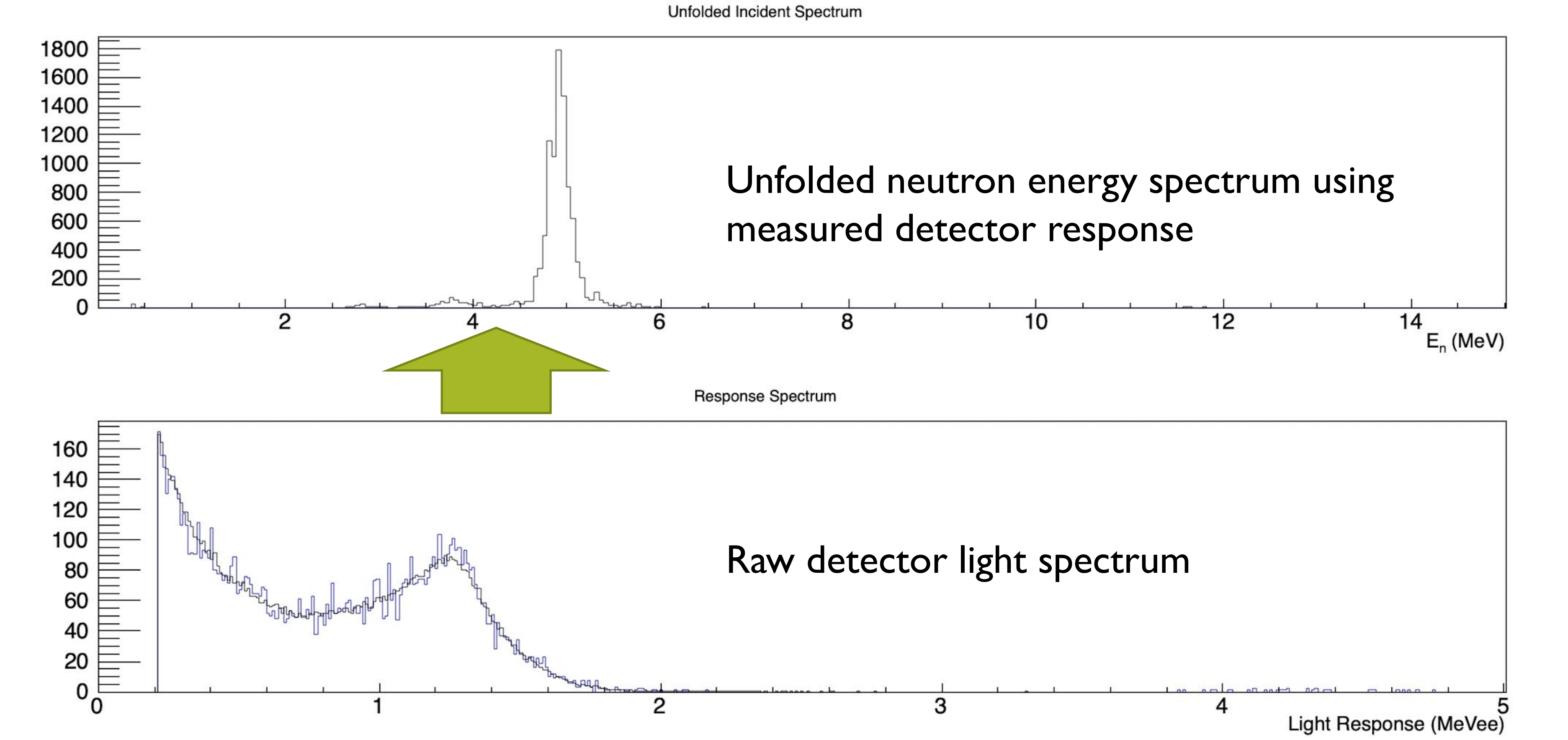


Michael Febbraro (ORNL)

SPECTRUM UNFOLDING

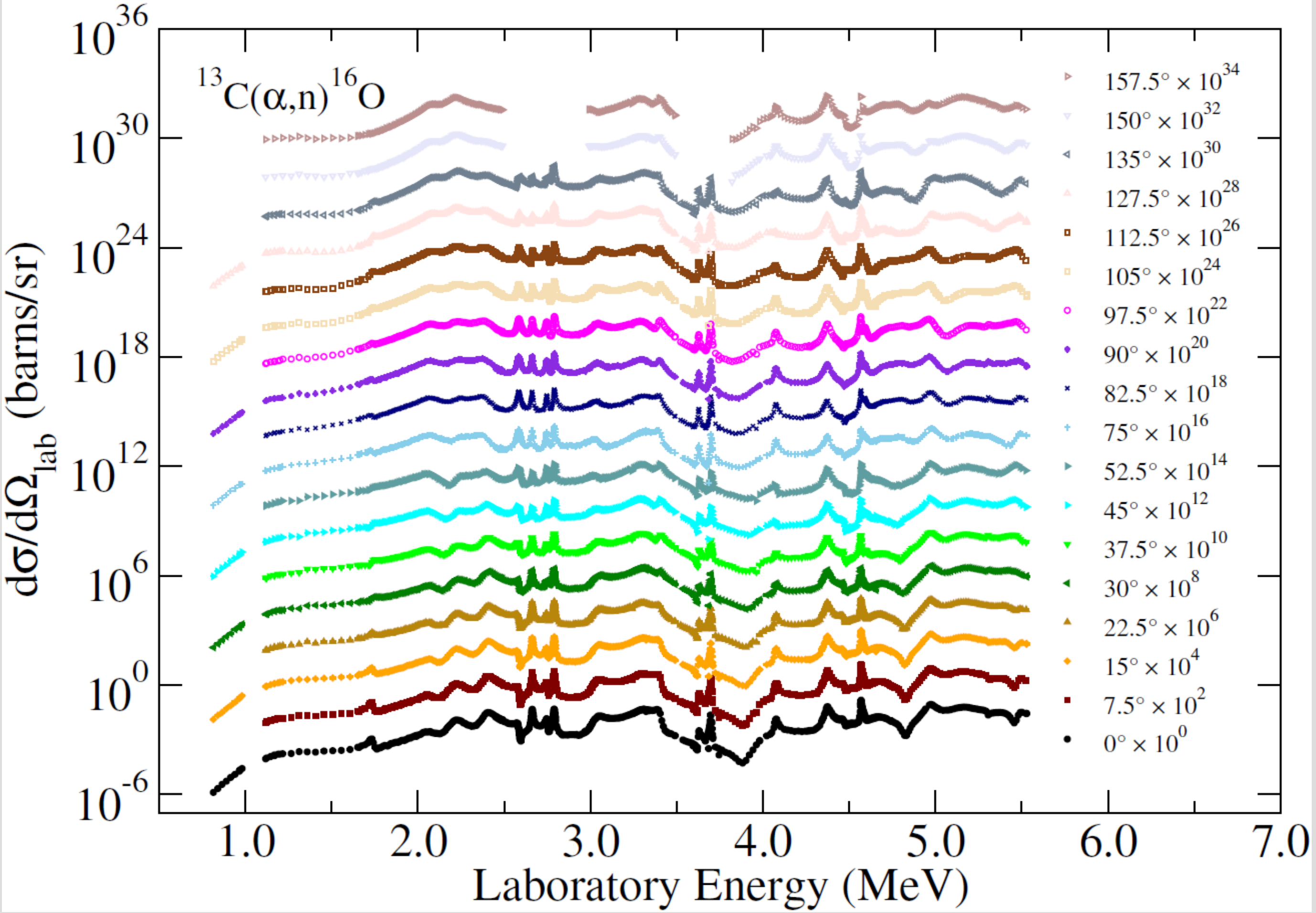
- Experimentally determine detector response in separate calibration runs

E$_\alpha$ **=** 2454 keV



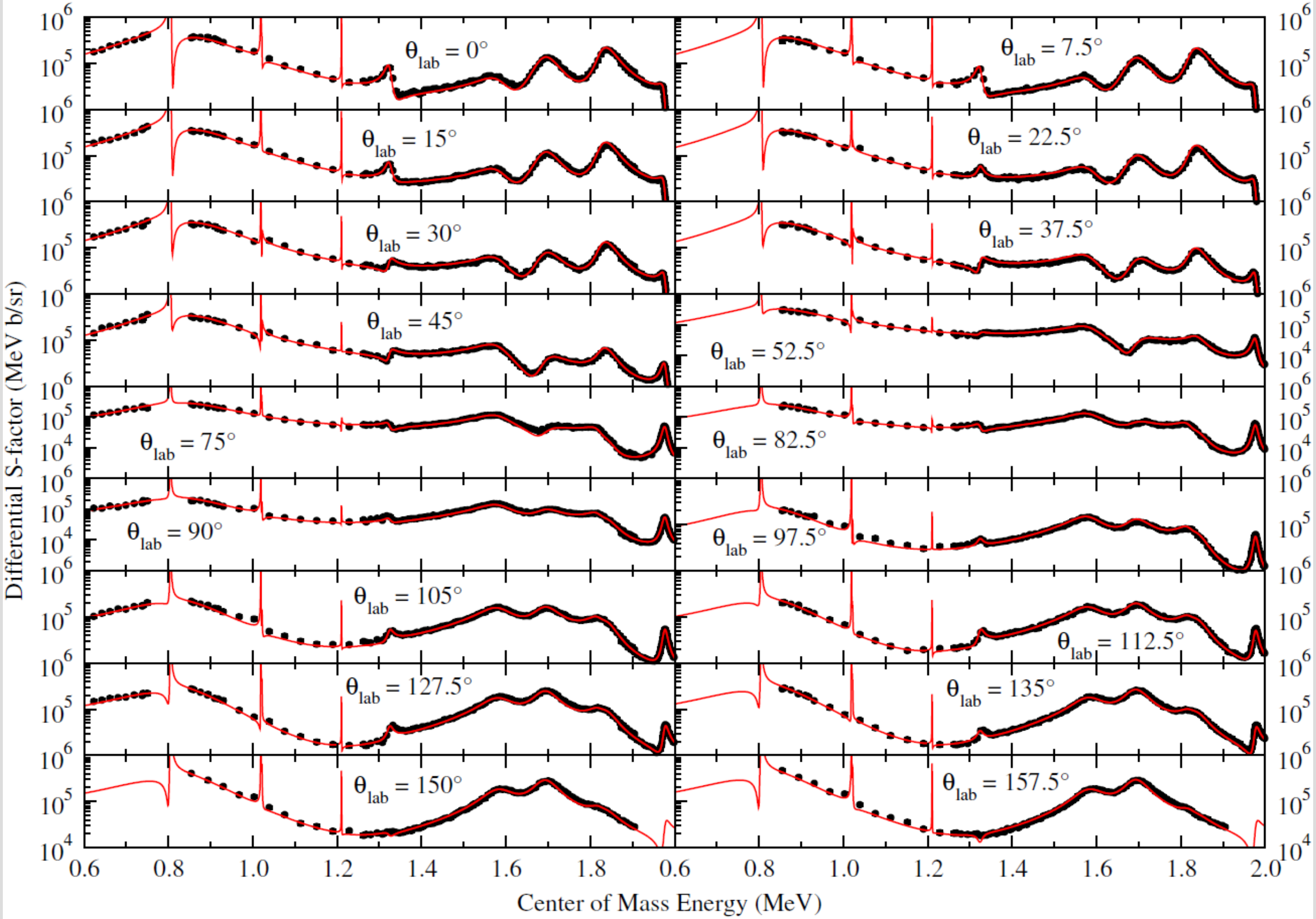
ND DIFFERENTIAL CROSS SECTIONS

- Only one low energy differential cross section measurement
  - Walton *et al.* (1957) – 47 angular distributions from1.0 to 3.5 MeV
  - Here we expanded over this region with 342 additional angular distributions and also going down to 0.8 MeV
  - An additional 366 at higher energies up to 6.5 MeV



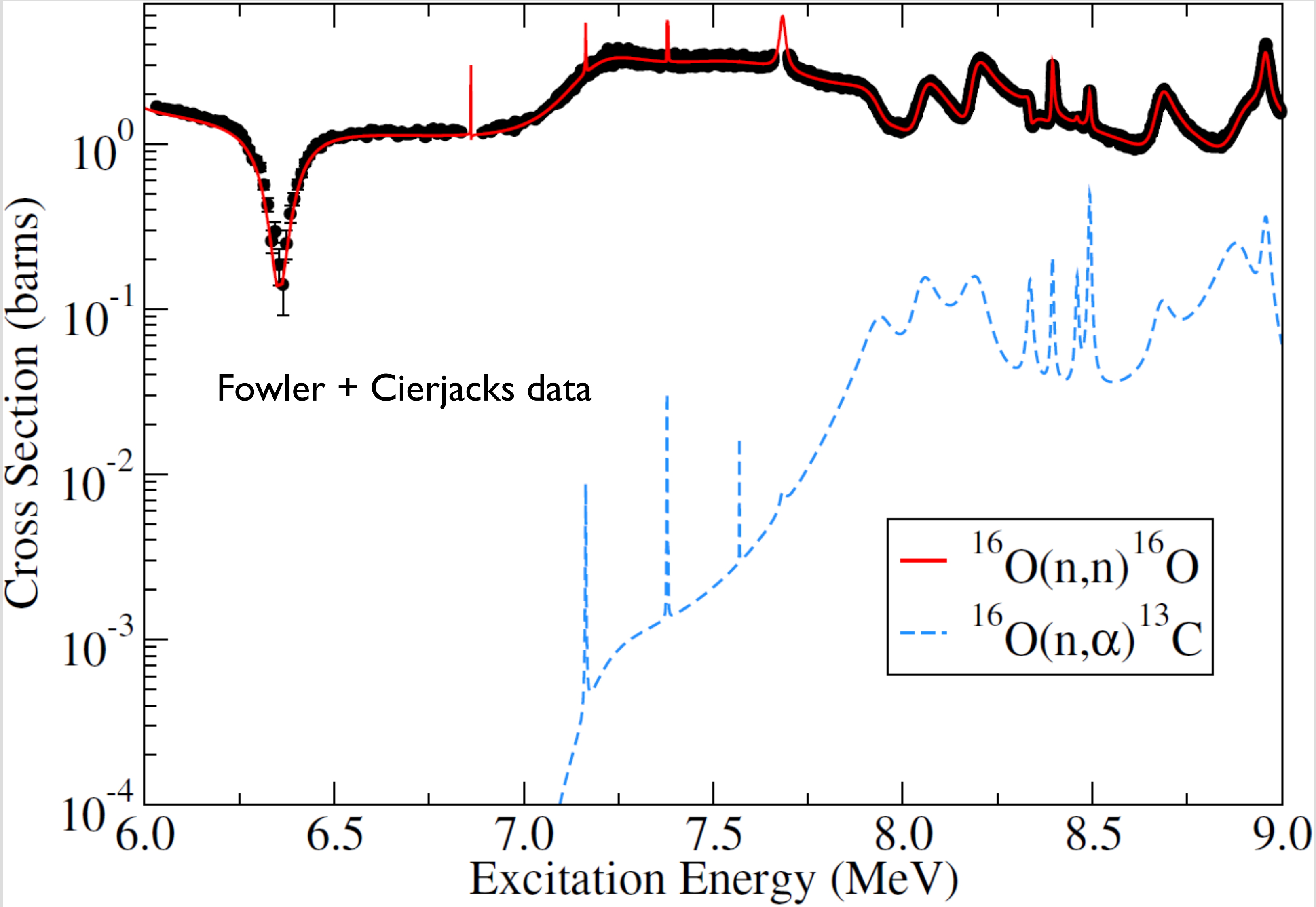
R-MATRIX FIT EXPANDED TO NEW DATA

- Fit was expanded from 1.2 up to 2 MeV CM frame and the differential data from this work was added
- A lot more levels here, built off of the ENDF/B fit from LANL (Gerry Hale and Mark Paris)
- A good fit was achieved



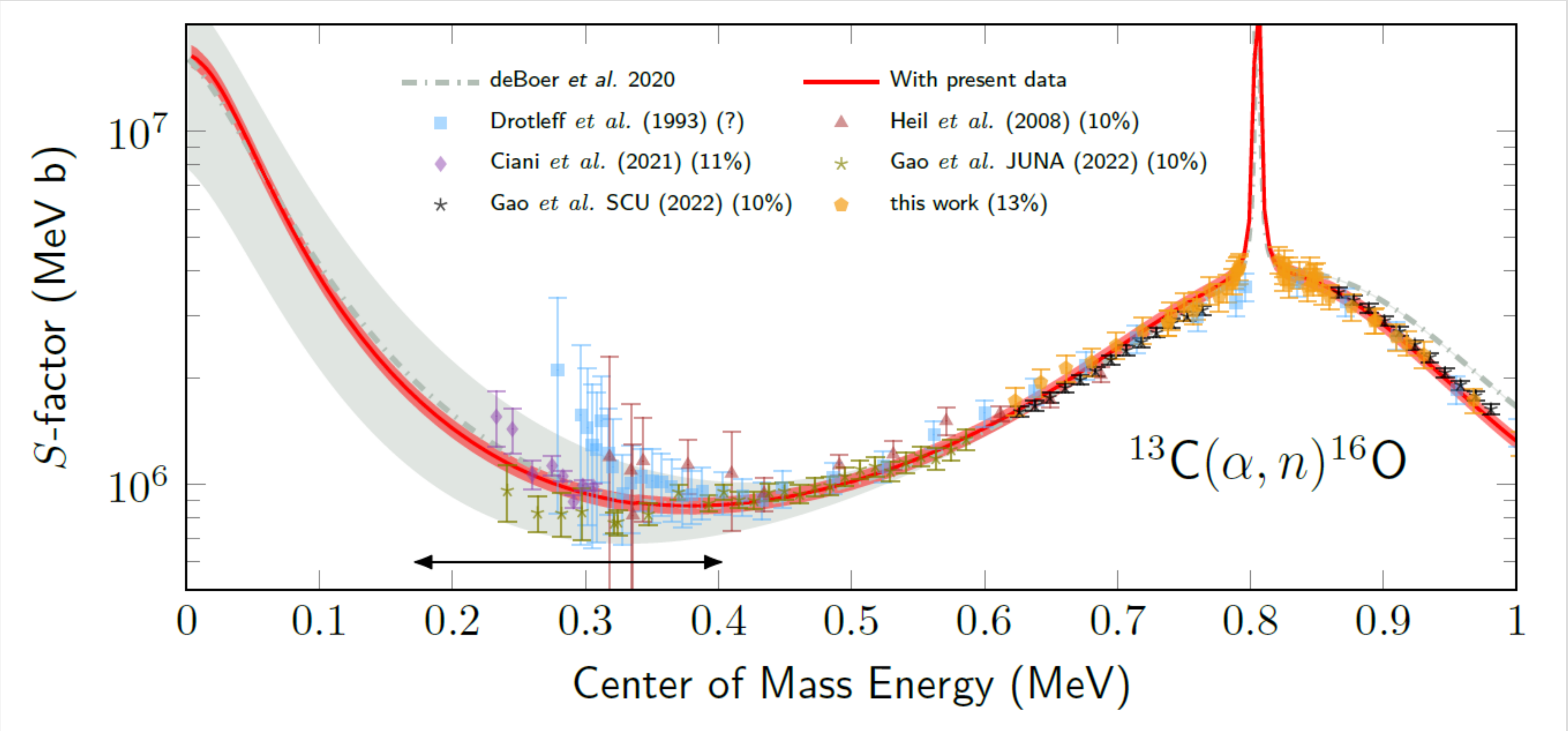
TOTAL ^{16}O+n CROSS SECTION DATA IS ALSO INCLUDED

- Total cross section n+^{16}O
- Puts strong constraints on the $^{13}C(\alpha,n)^{16}O$ cross section at higher energy



THE PUNCH LINE

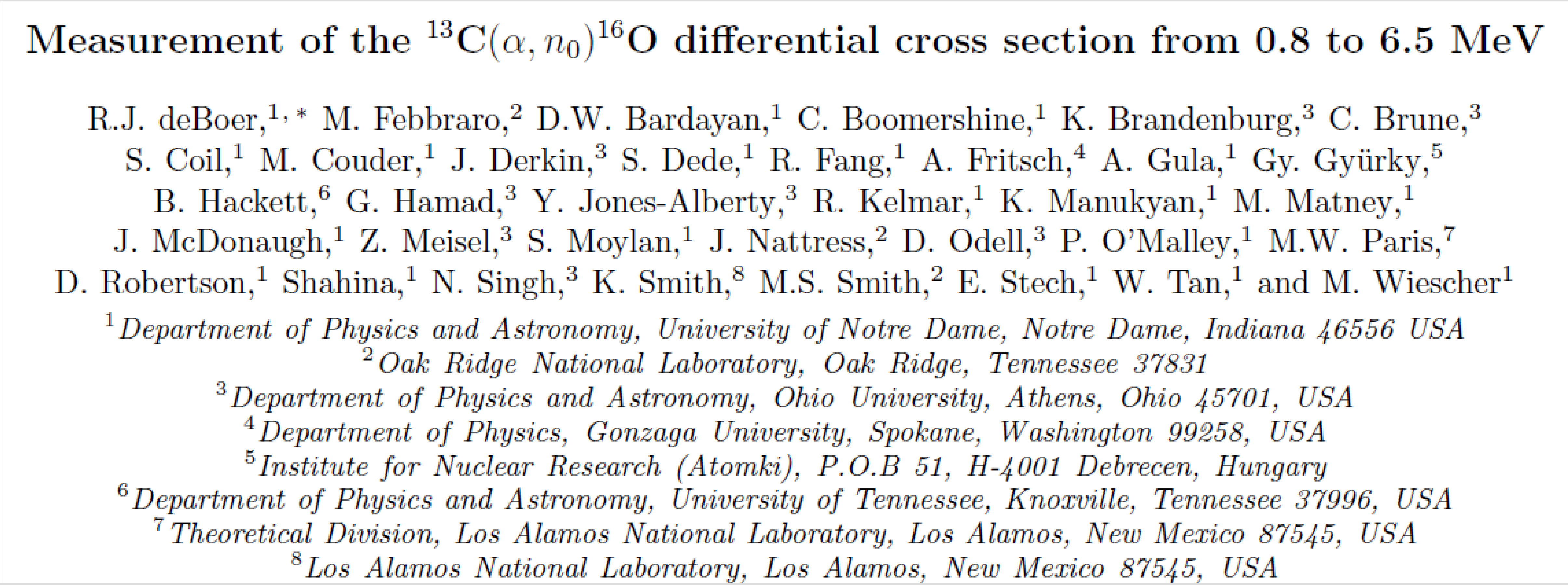
- Differential data provides additional constraint to the R-matrix fit, reducing the uncertainty from 10 to 5%.
- Some additional tension with low energy data and ANC (fit overshoots)
- Previous interference pattern that was allowed without the differential data is now forbidden



CONCLUSIONS

- It looks like recent measurements are coming into agreement!
- Long standing normalization problems between different data sets have been largely resolved
- Differential cross section measurements provide additional constraints that reduced the uncertainty from about 10% to 5%, at least when treated on the same basis as previous uncertainty estimations.
- To move forward to sub 5% uncertainty, we will probably have to do a careful re-evaluation of the uncertainty contributions that are significant.
- Further measurements and reaction analyses can still be improved and we can probably push into a really unprecedented level of precision for this reaction.

COLLABORATORS


Measurement of the $^{13}C(\alpha, n_0)^{16}O$ differential cross section from 0.8 to 6.5 MeV

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- Submitted to PRL

EDINBURGH AZURE2 *R*-MATRIX WORKSHOP

- A workshop dedicated to learning how to use the AZURE2 *R*-matrix code
- Local organizer: Marialiusa Aliotta
- Some introductory theory
- I will go through a series of hands on examples
- June 2024, University of Edinburgh
- Scotch

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