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

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Nuclei in the Cosmos XVII,
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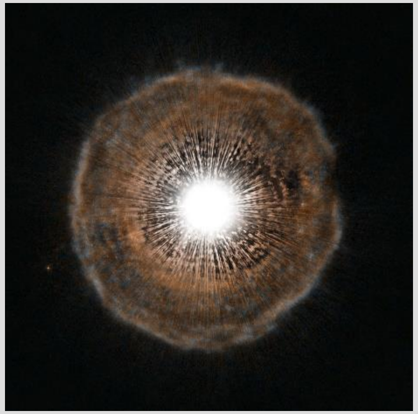
S-PROCESS NEUTRON SOURCES

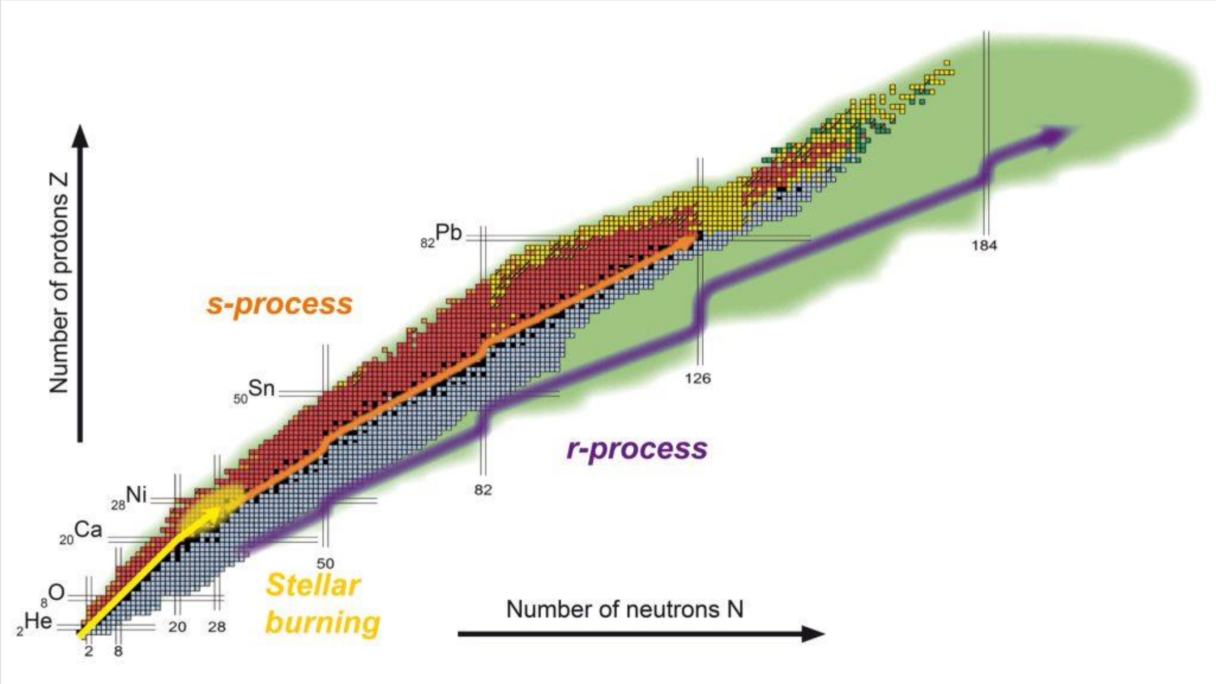
- **$^{13}C(\alpha,n)^{16}O$**
- $^{22}Ne(\alpha,n)^{25}Mg$

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

Helium burning



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



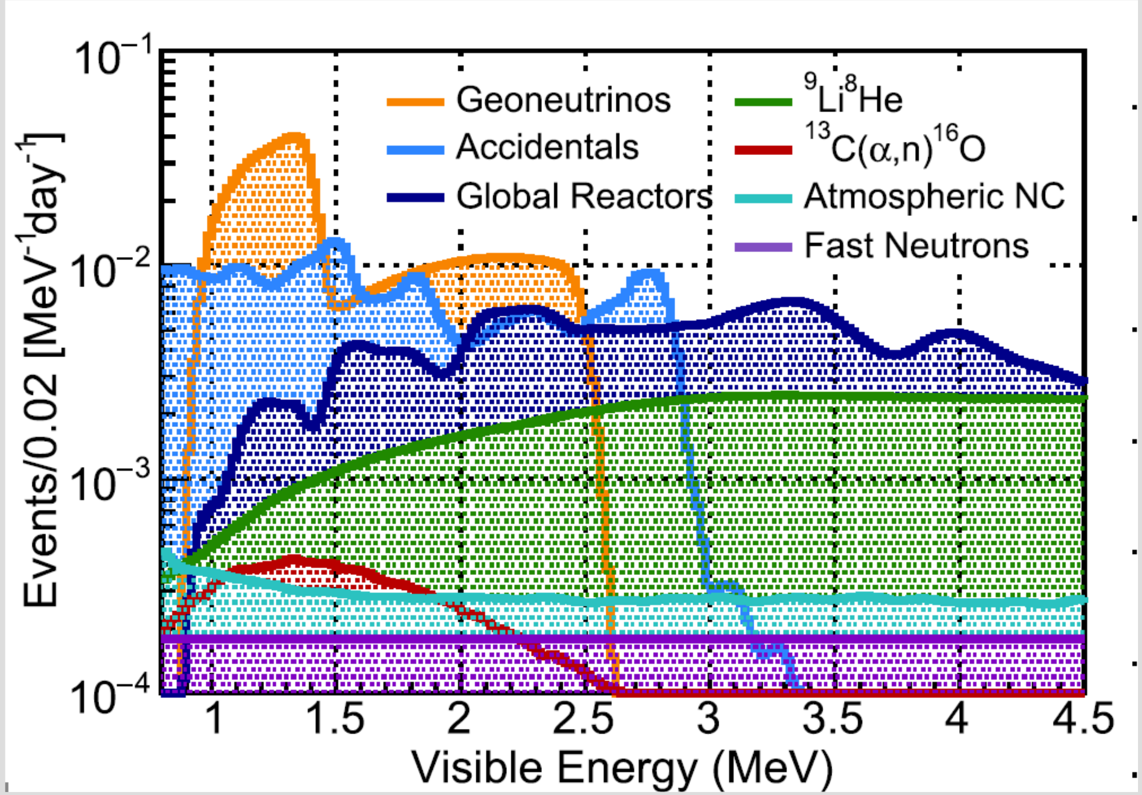
EMMI, GSI/Different Arts

An uncertainty of 10 to 20% is desired

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
- Higher energies are very important but I won't discuss this in this talk

A few % to 20% uncertainty, but more important at high energies, 5 to 8 MeV



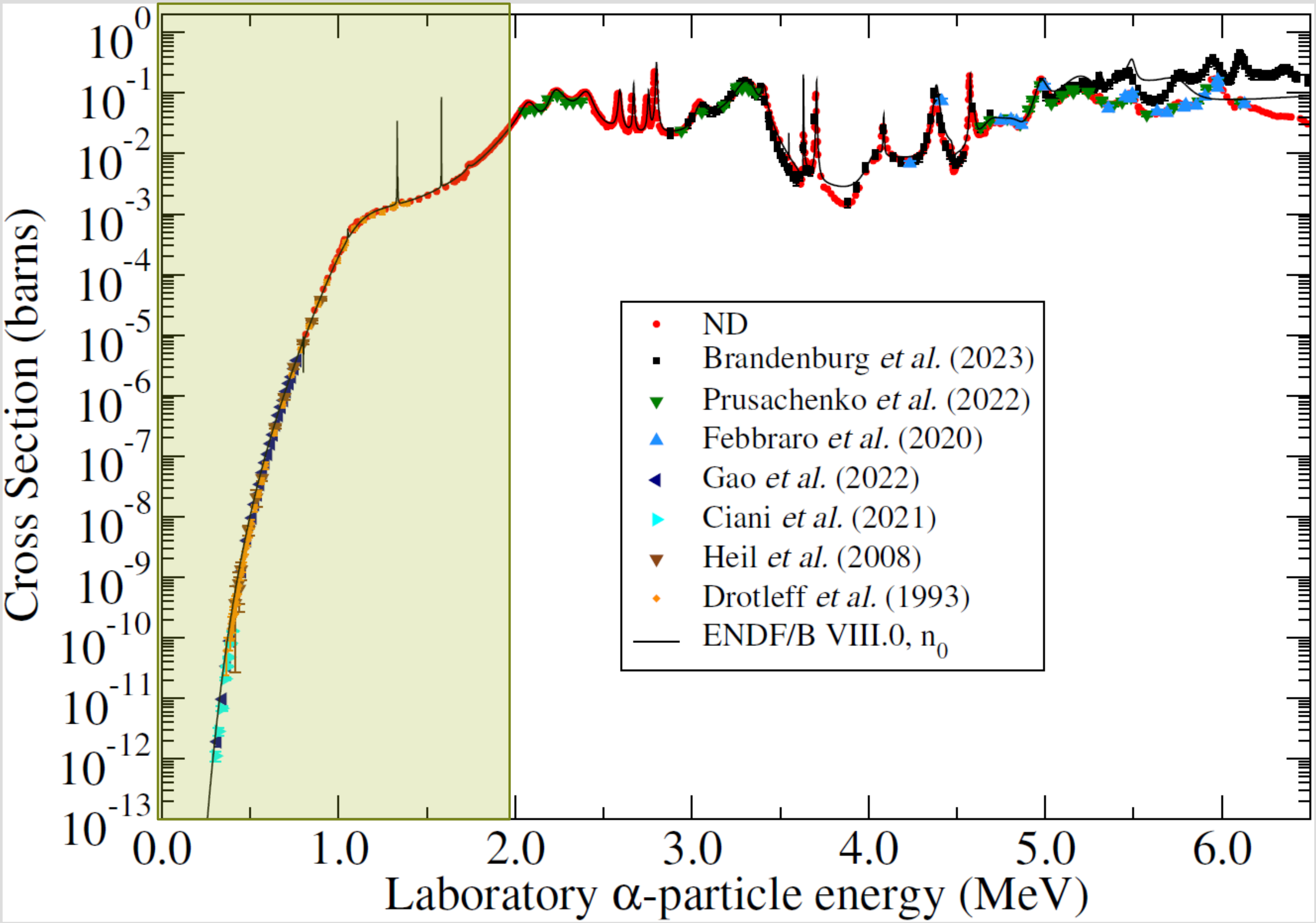
Abusleme et al. (2022), JUNO 20 kT neutrino detector

CROSS SECTION AND S-FACTOR

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

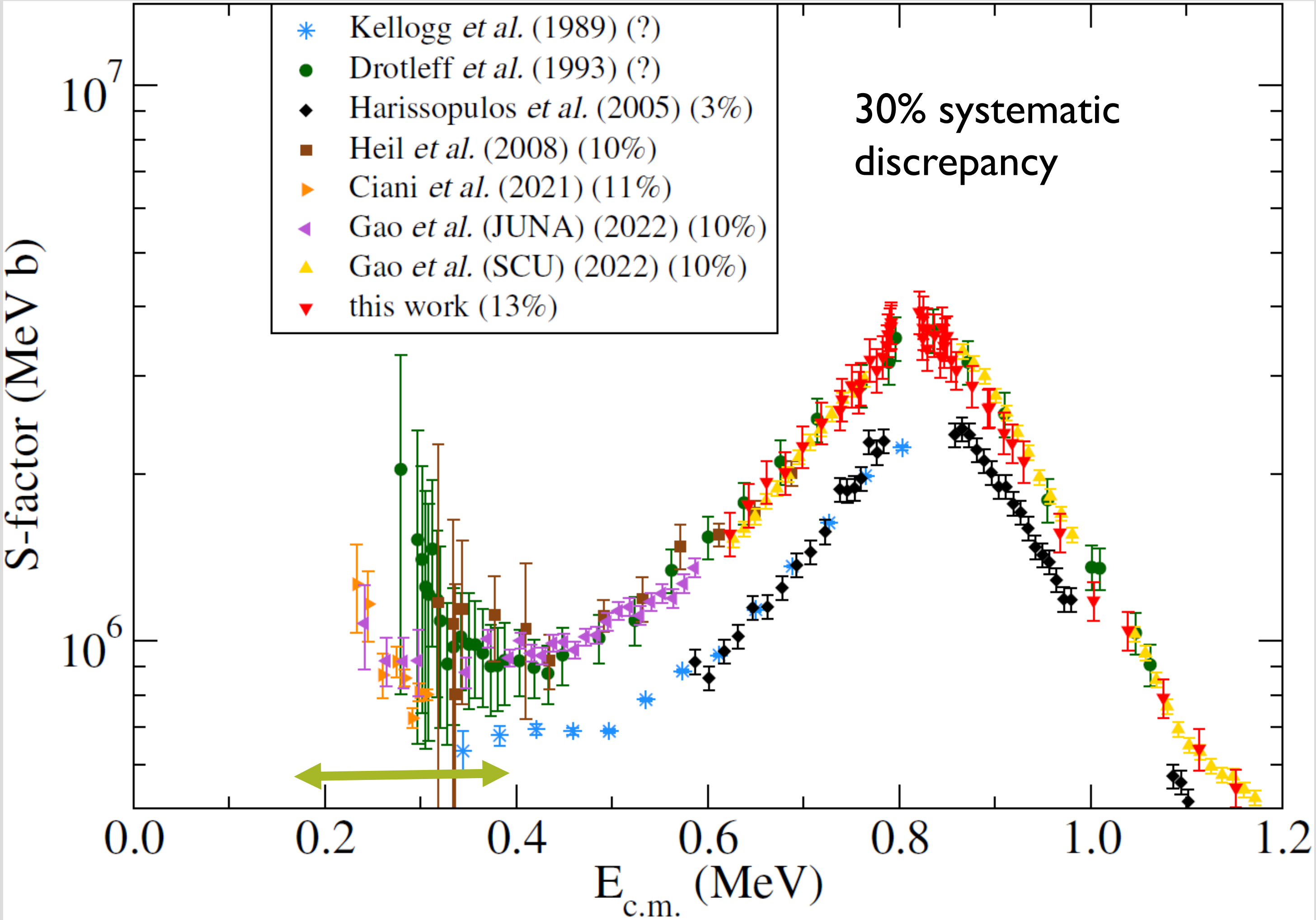
$$S(E) = \sigma(E) E \underbrace{\exp(2\pi\eta)}_{l\,=\,0,\ \text{Coulomb}}$$

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

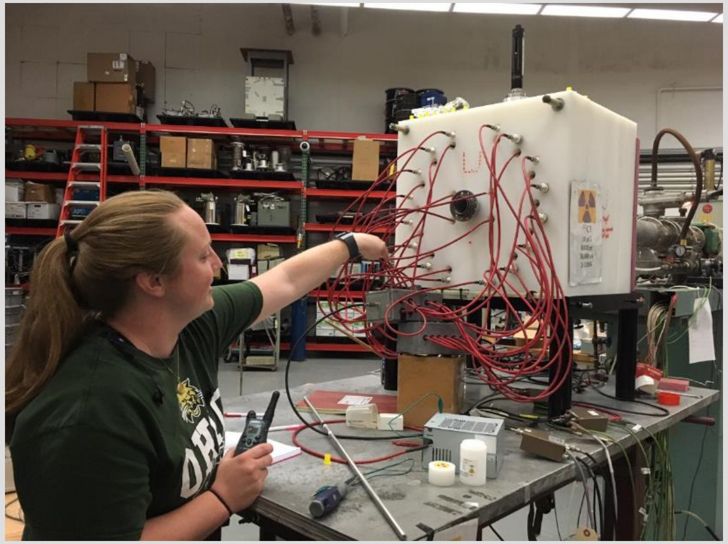


S-FACTOR DATA AT LOW ENERGY

- Almost all angle integrated data measured using 4π neutron moderator counters
- High efficiency for low count rate experiments
- Yields are still sensitive to the underlying neutron angular distributions, which are usually unknown!
- Angular distribution data, even at higher energies, can complement the angle integrated data.
- See Weiping Liu's talk later today for more on the JUNA facility and Bingshui Gao's for the $^{13}C(\alpha,n)^{16}O$ measurements



PROBLEM: 4π DOESN'T REALLY MEAN 4π



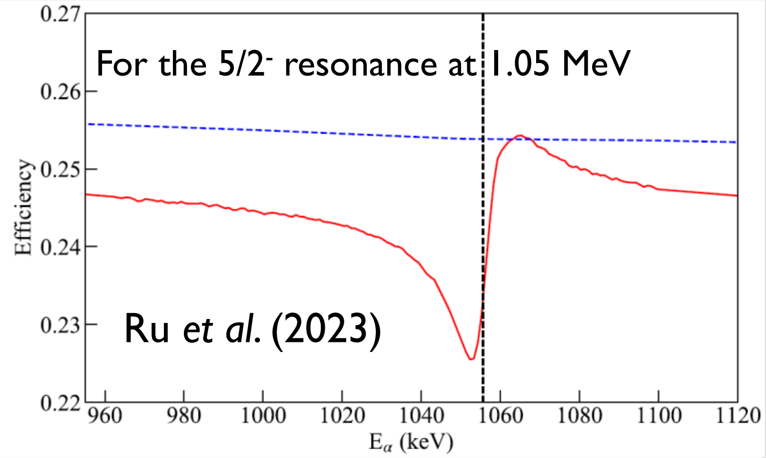
at Ohio University

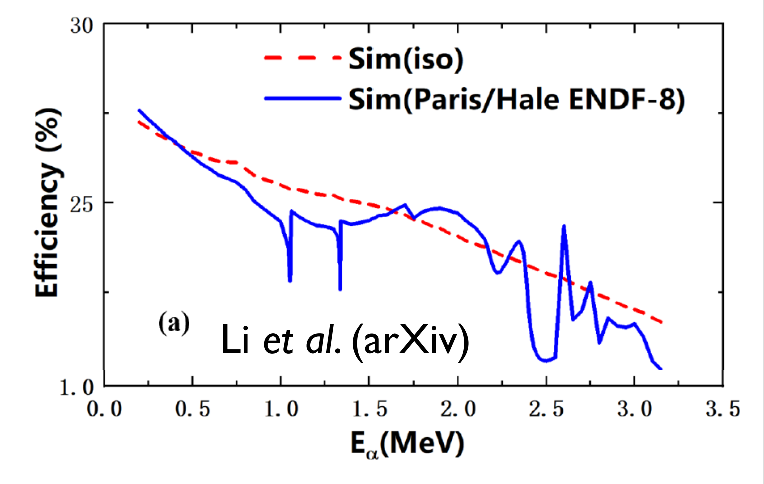
Simulation

4π
measurements

Angular
distribution
measurements

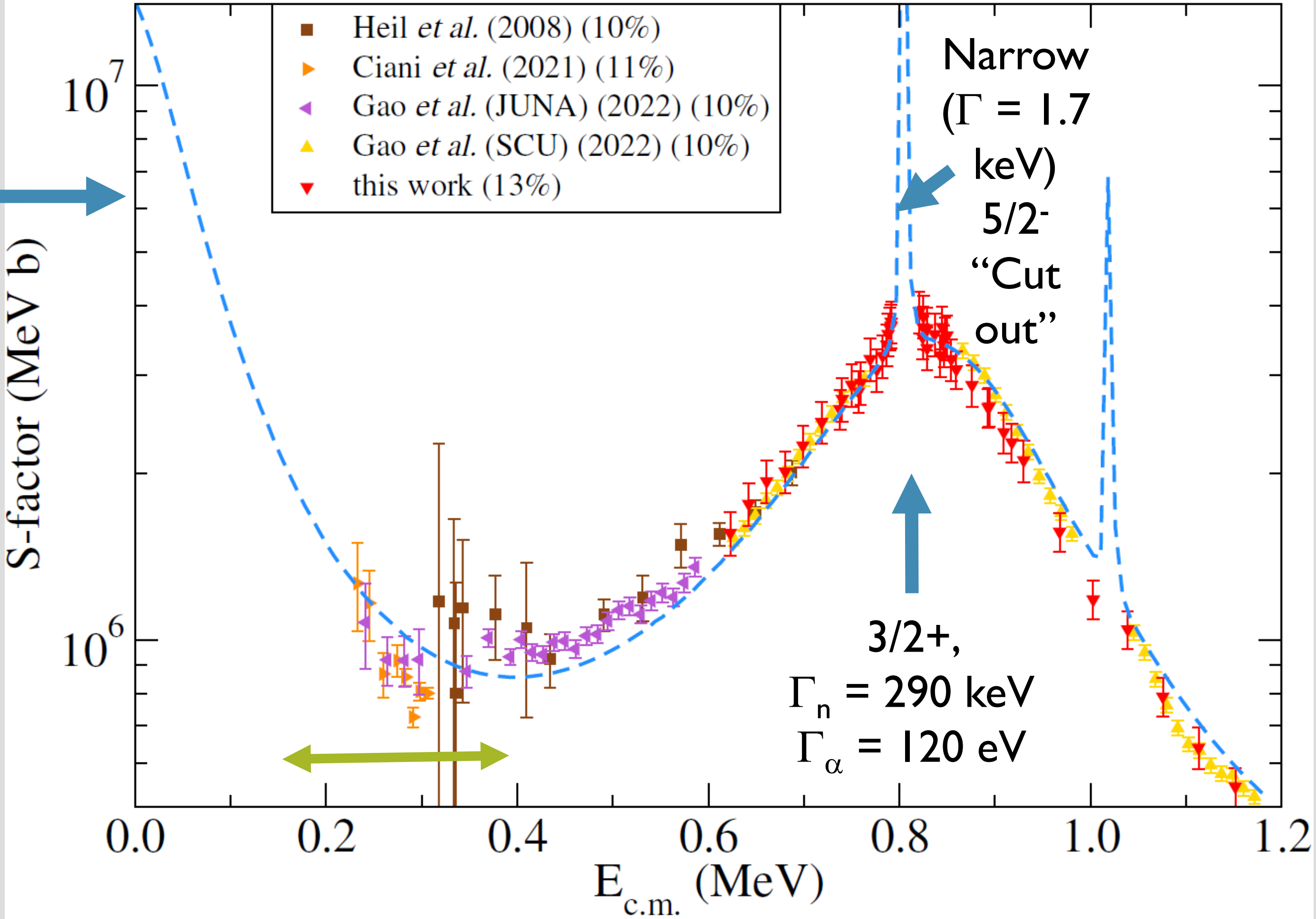
10's of % deviations between isotropic and true angular distributions





PHENOMENOLOGICAL R-MATRIX FIT

Near threshold 1/2+ state ANC from transfer studies

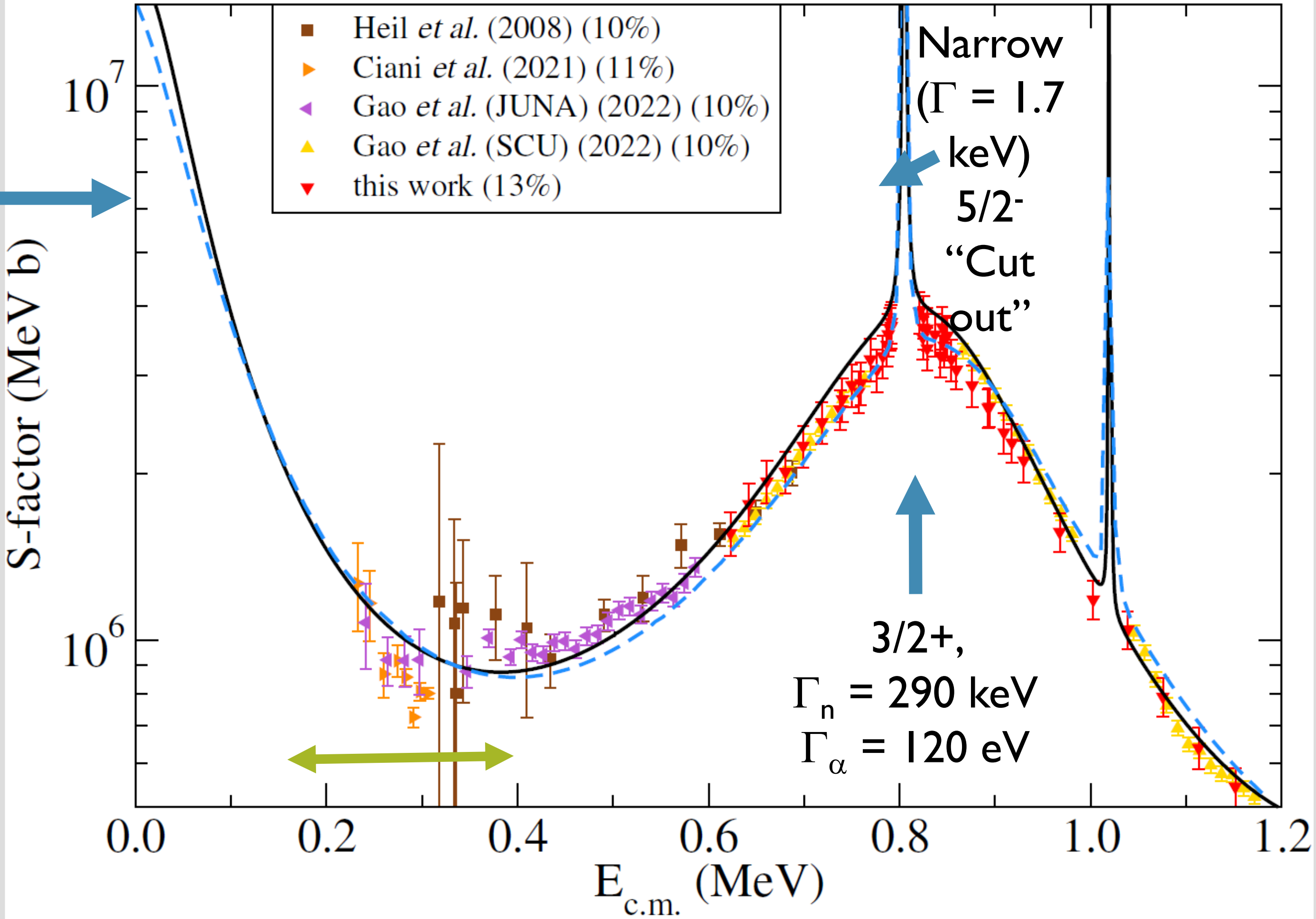


Independent norms

A large threshold resonance enhancement

AN ALTERNATIVE INTERFERENCE PATTERN

Near threshold 1/2+ state ANC from transfer studies

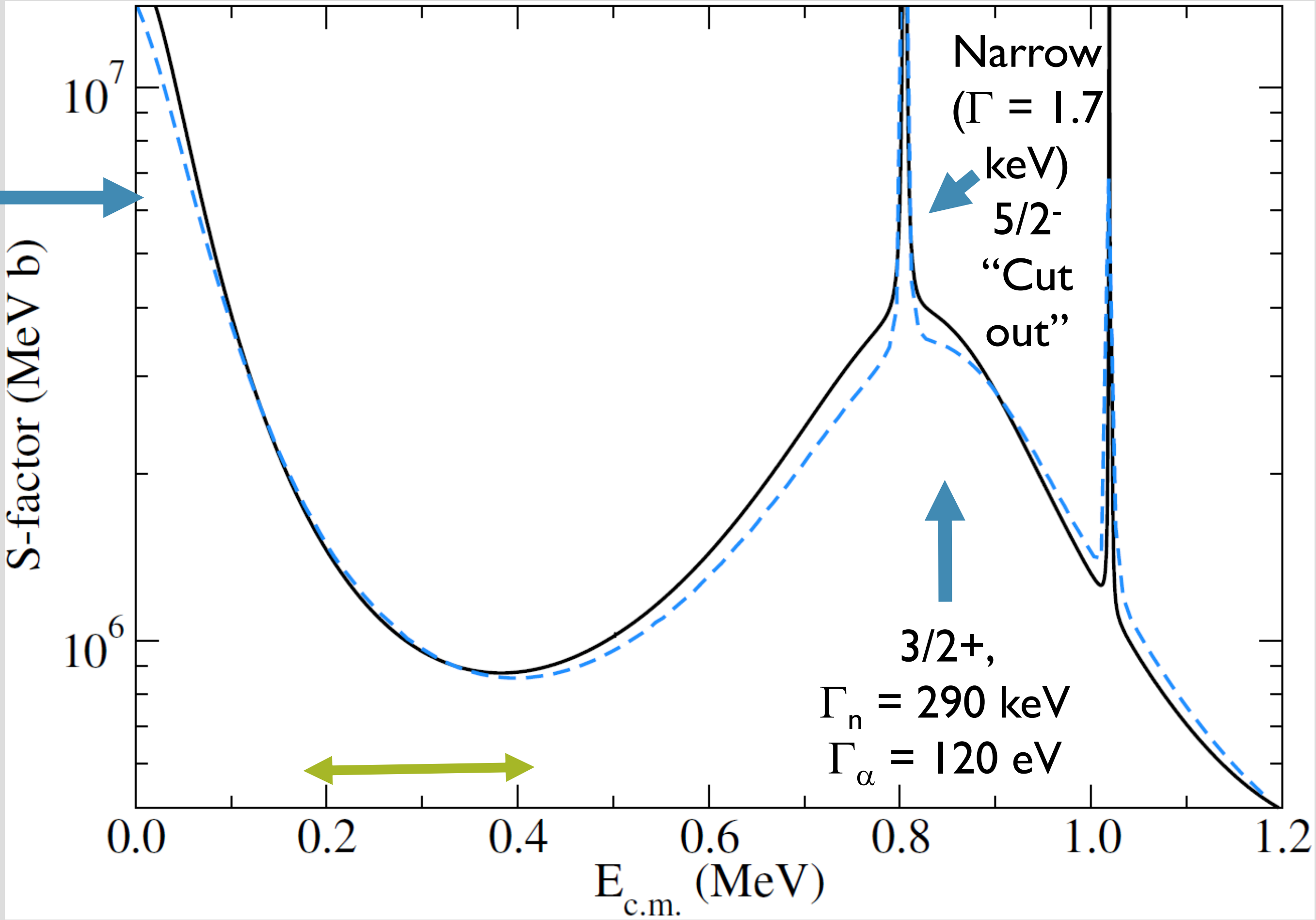


χ^2 is very similar and is actually a bit lower for this alternative interference solution…

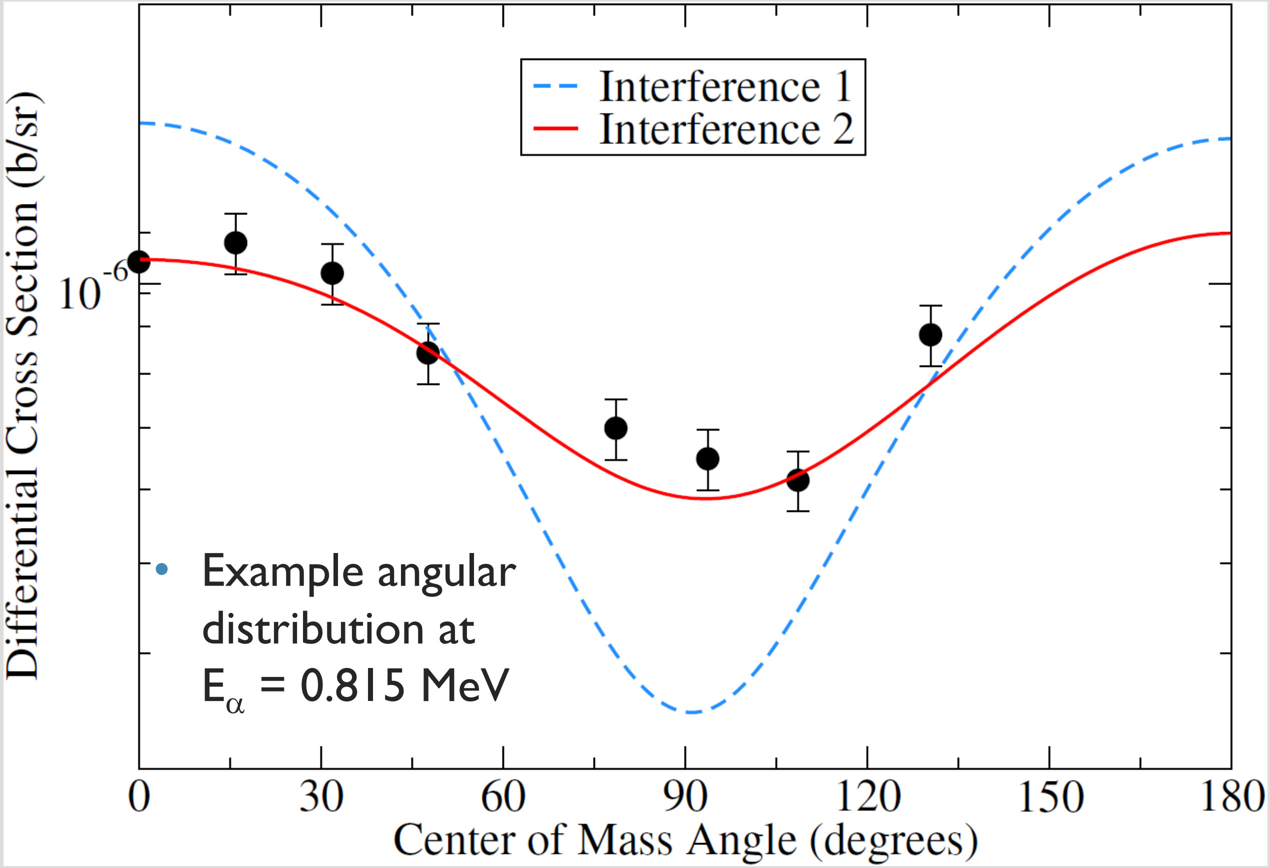
Rather unique to this case, the cross section is still very similar over the range of astrophysical interest

JUST THE R-MATRIX FITS

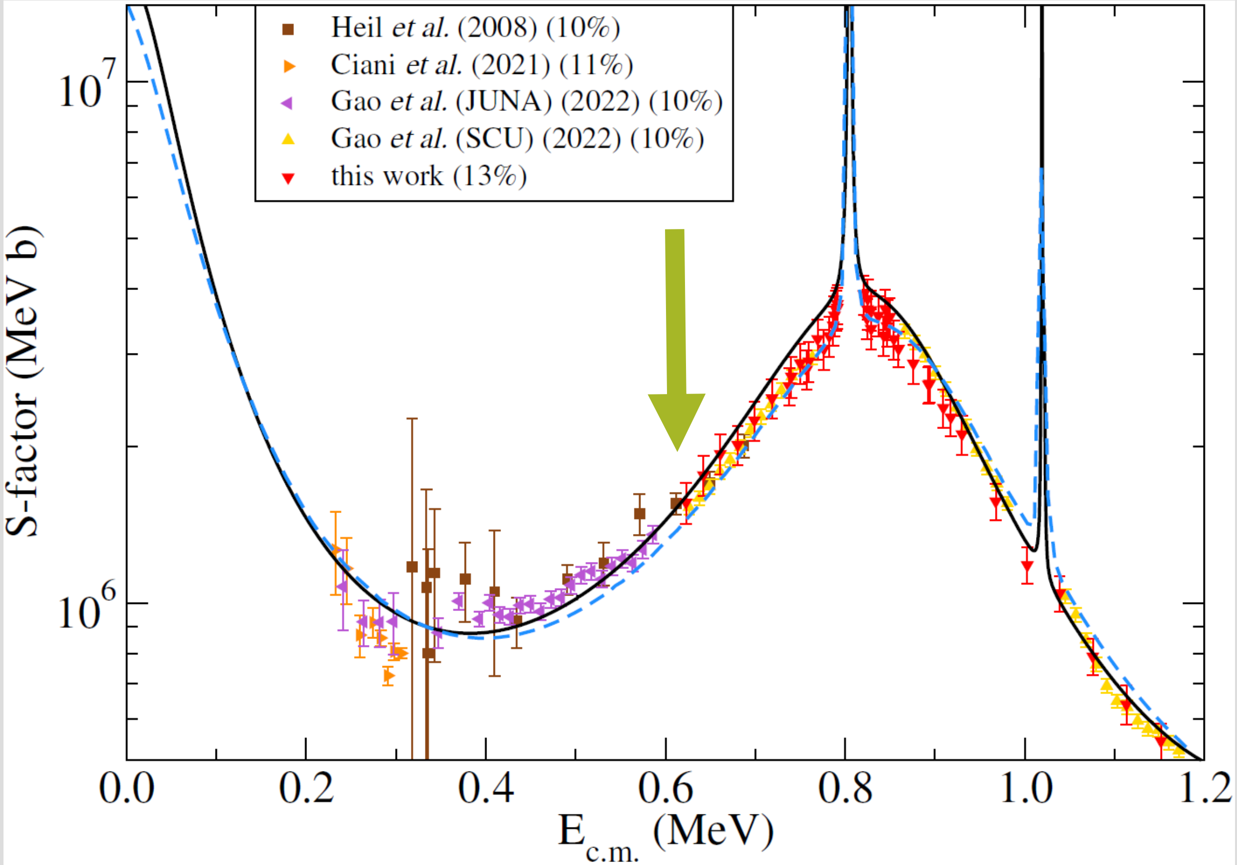
Near threshold 1/2+ state ANC from transfer studies



ANGULAR DISTRIBUTIONS



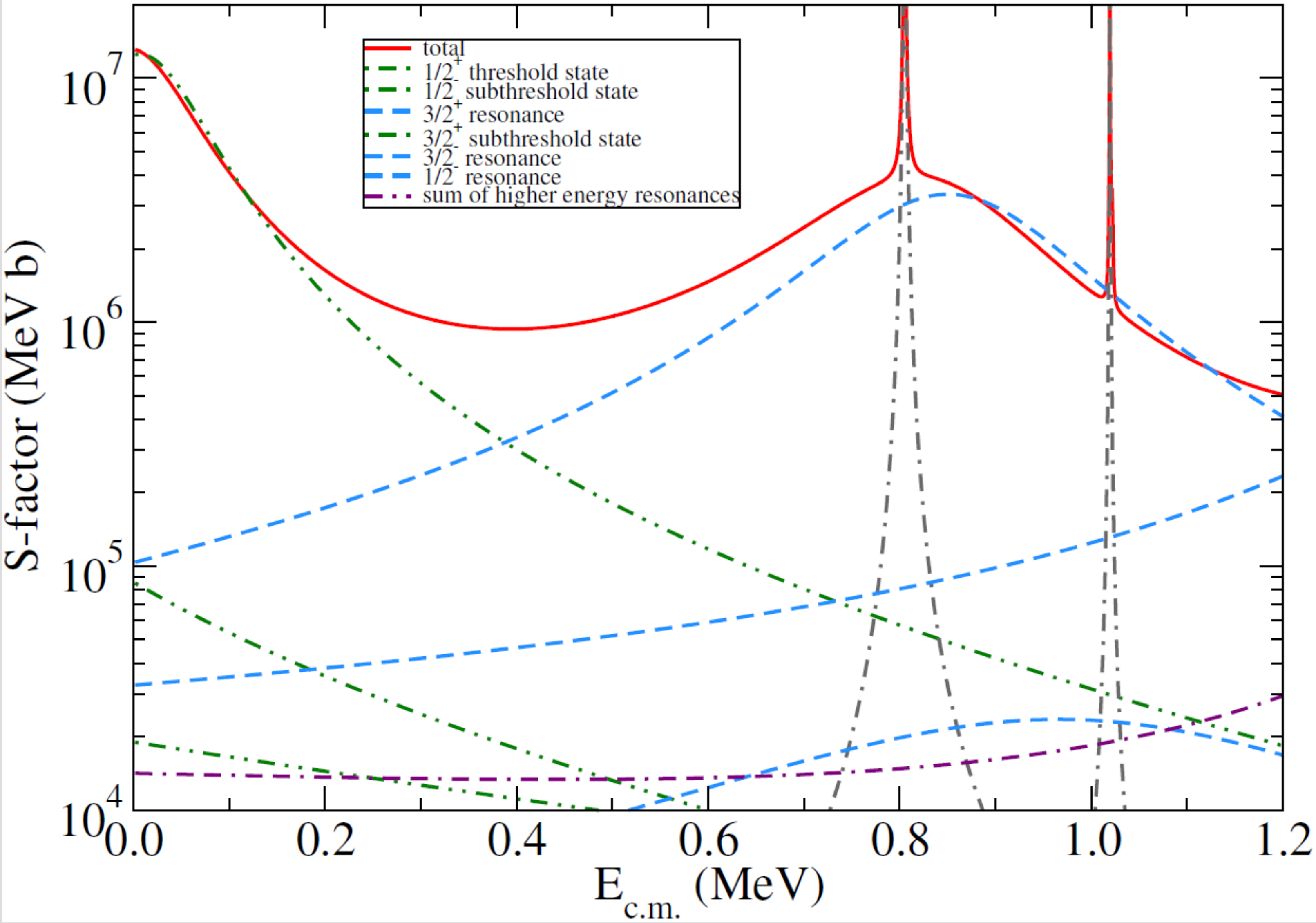
- Example angular distribution at E_α = 0.815 MeV



THE FIT IS DECEPTIVELY COMPLICATED

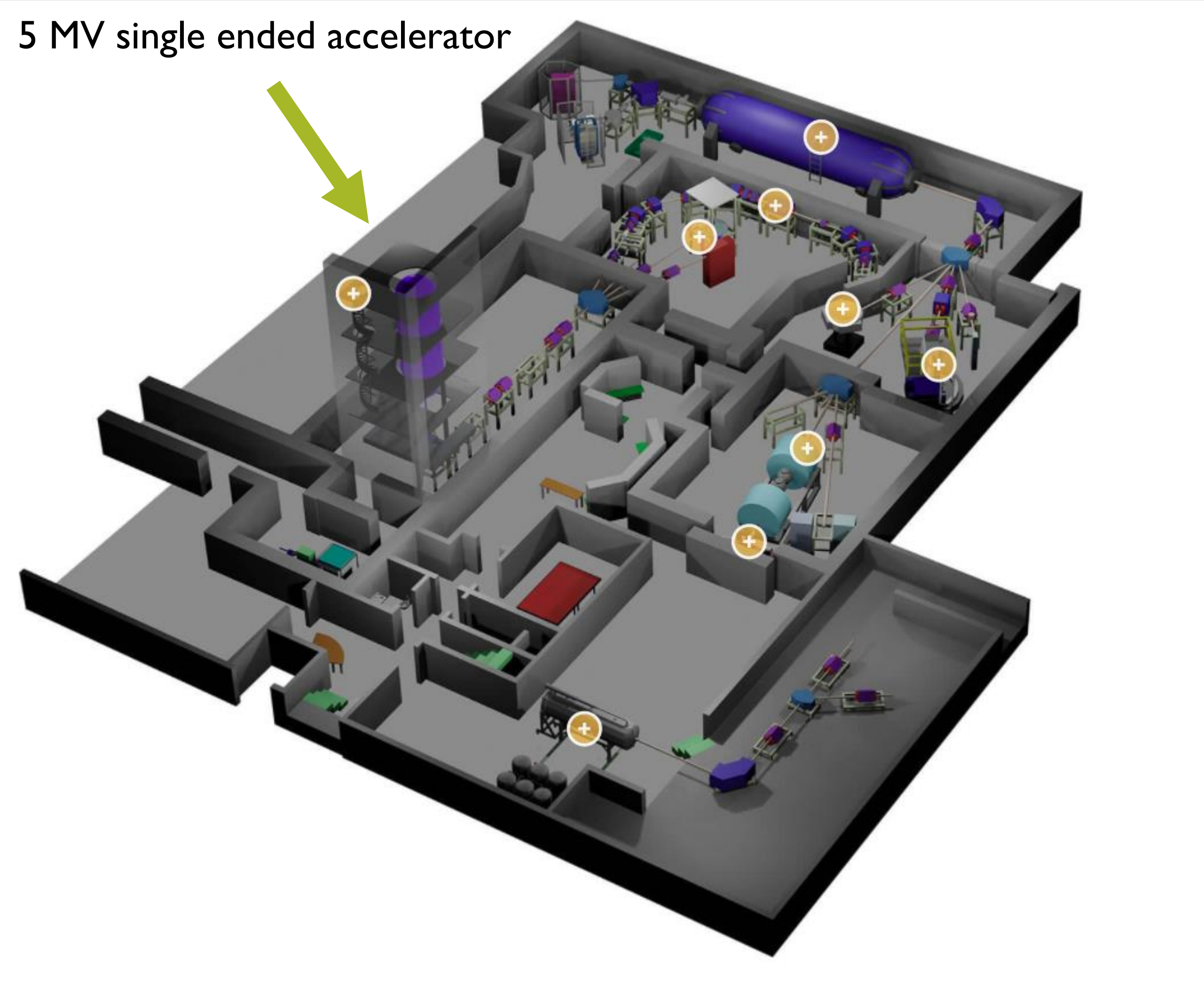
- There are actually multiple subthreshold levels, although one clearly dominates
- There are many background levels as well
- To **EXTRAPOLATE**, we need to constrain the **MODEL**
- Angle integrated cross section
- Differential cross section
- Polarization data

Greater model constraint

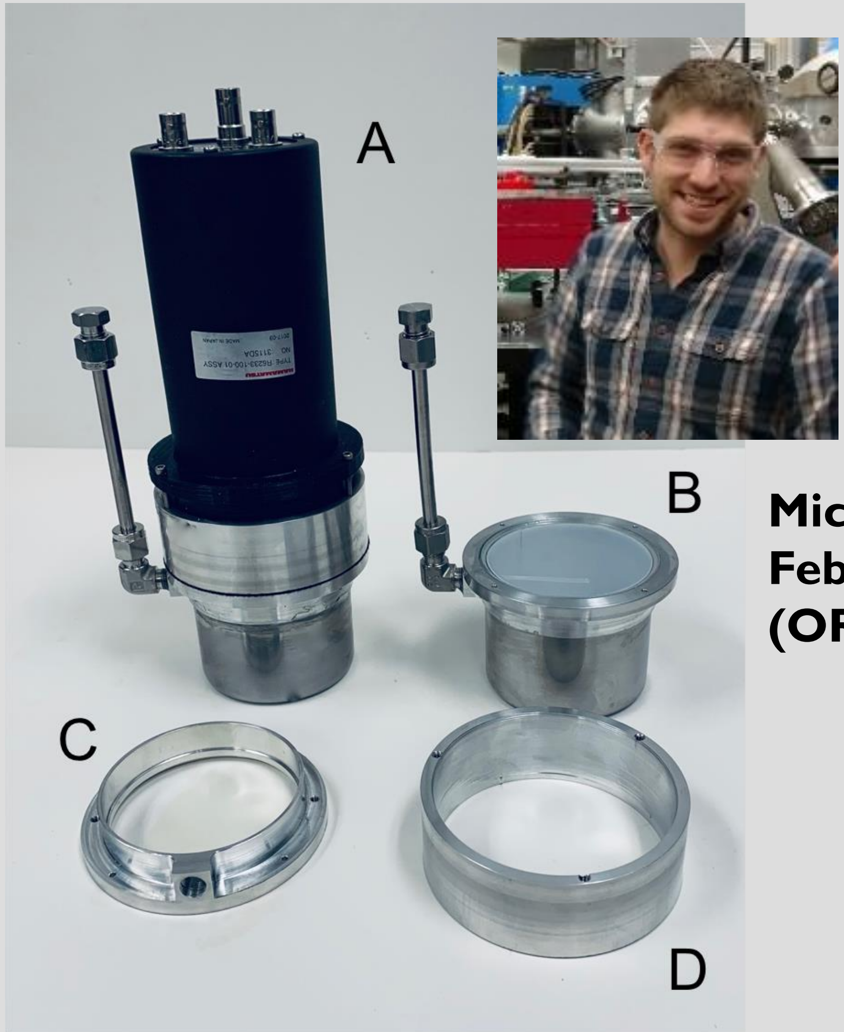


UNIVERSITY OF NOTRE DAME NUCLEAR SCIENCE LABORATORY

- Institute for Structure and Nuclear Astrophysics (isnap.nd.edu)
- Three research accelerators
  - **5 MV single ended**
  - High beam intensities of protons and alpha particles
- Dan Bardayan's talk on Wednesday



DIFFERENTIAL CROSS SECTIONS WITH ODeSA



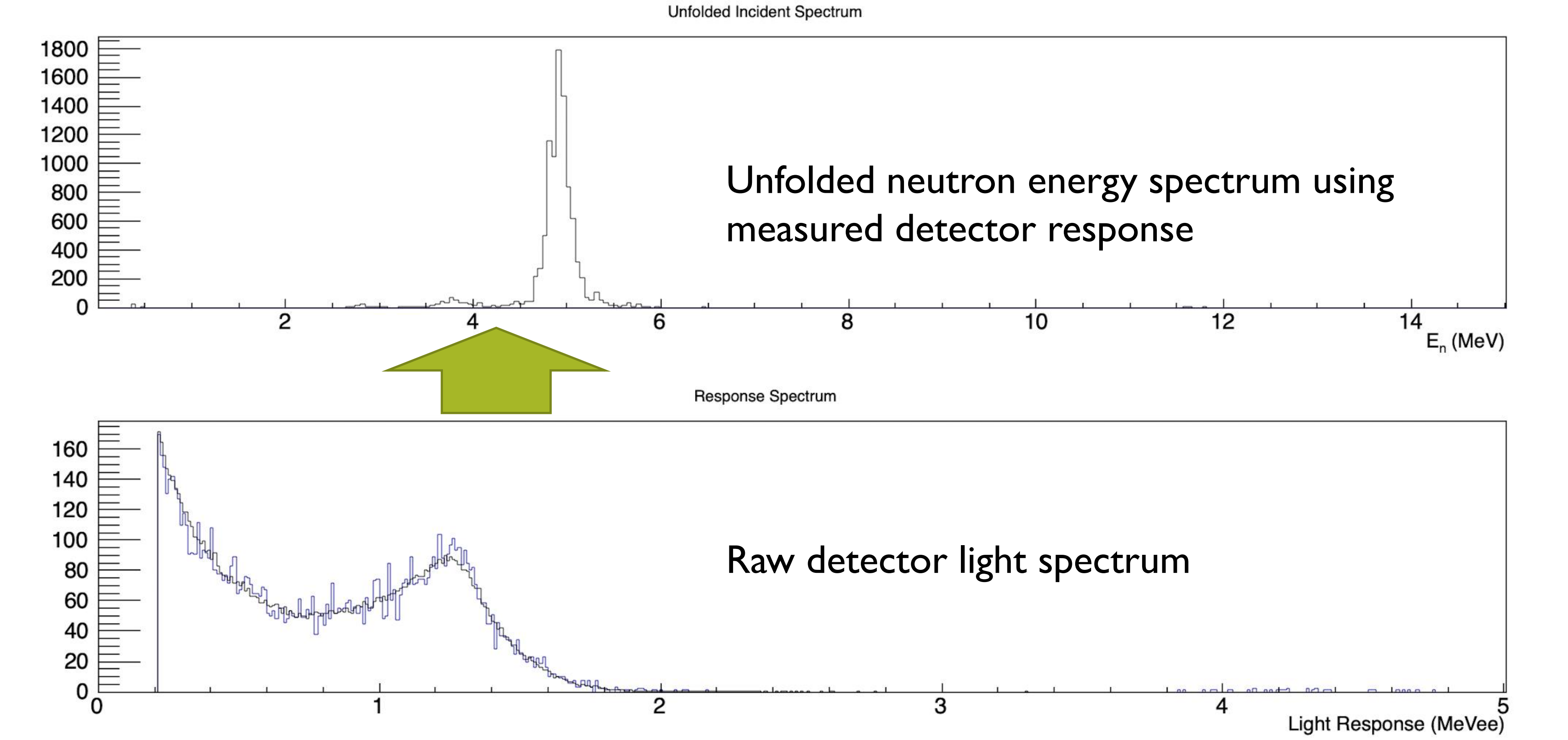
Michael Febbraro (ORNL)

- ORNL deuterated spectroscopic array (ODeSA)
- 9 **deuterated liquid scintillators** (one had issues)
- 1 EJ315
- 10's of microamp beam intensity from ND 5U accelerator

SPECTRUM UNFOLDING

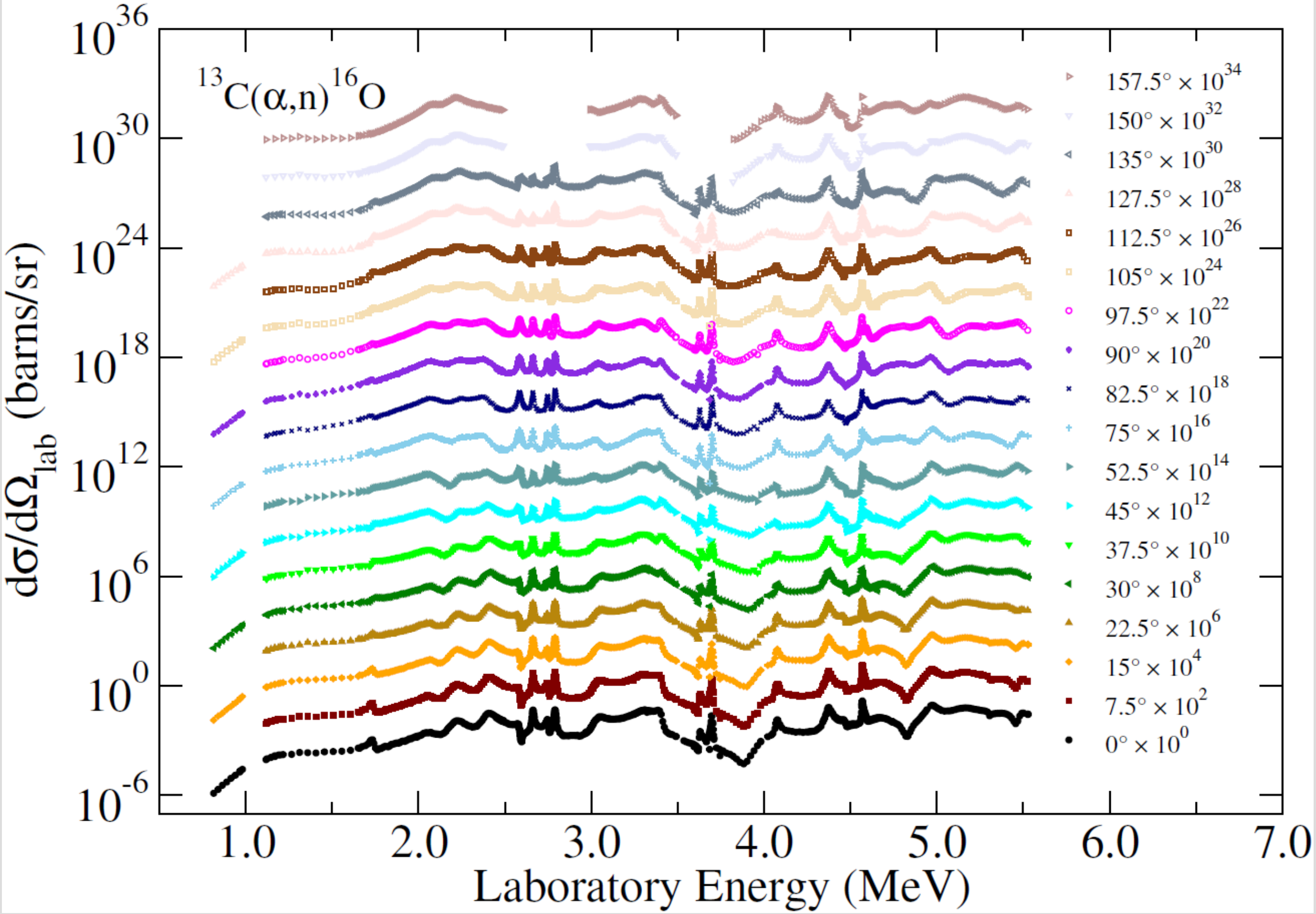
- Experimentally determine detector response in separate calibration runs
- No time of flight information needed!
  - No flight path distance restrictions
- **Very efficient measurements**

E_α = 2454 keV



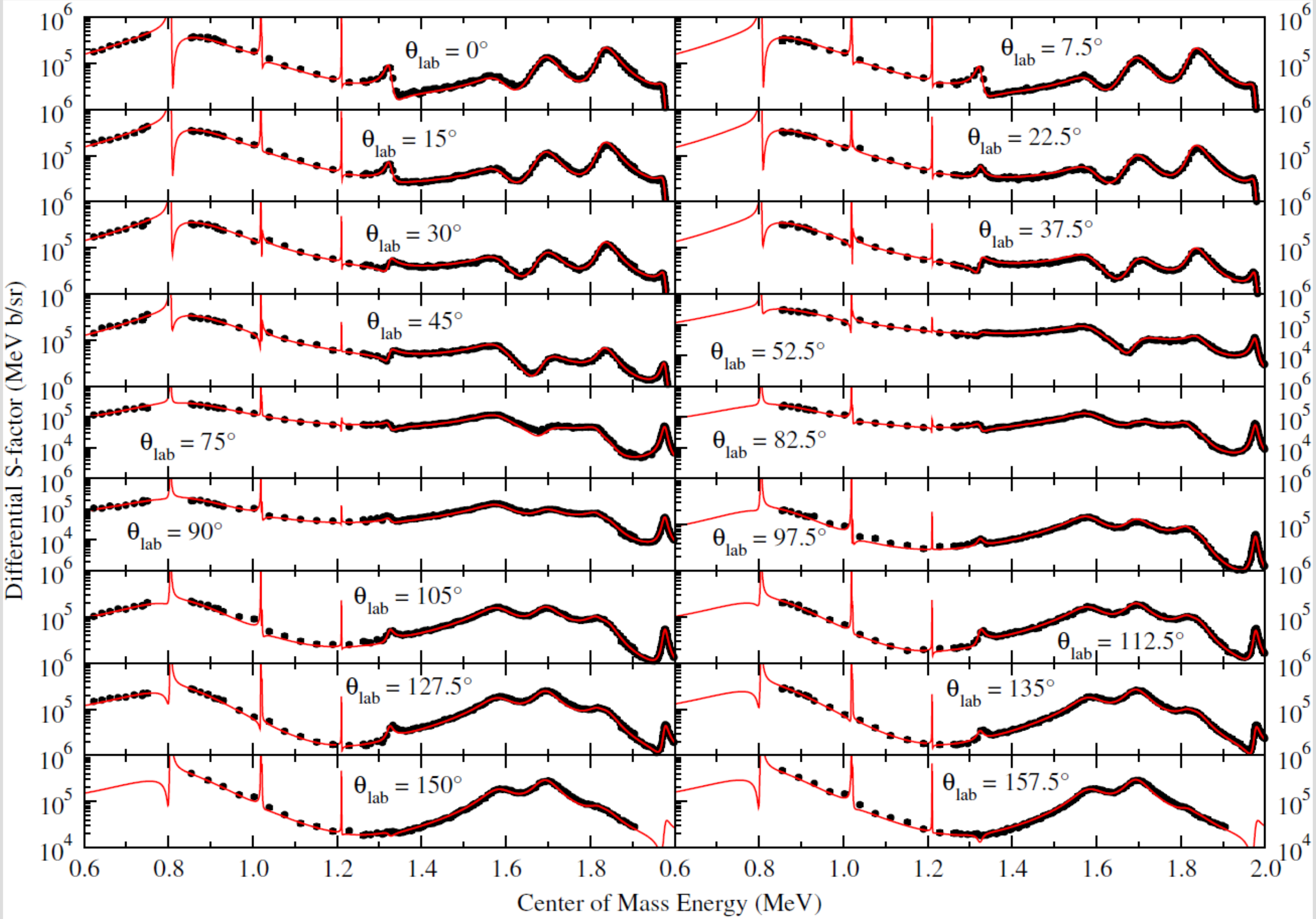
ND DIFFERENTIAL CROSS SECTIONS

- 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

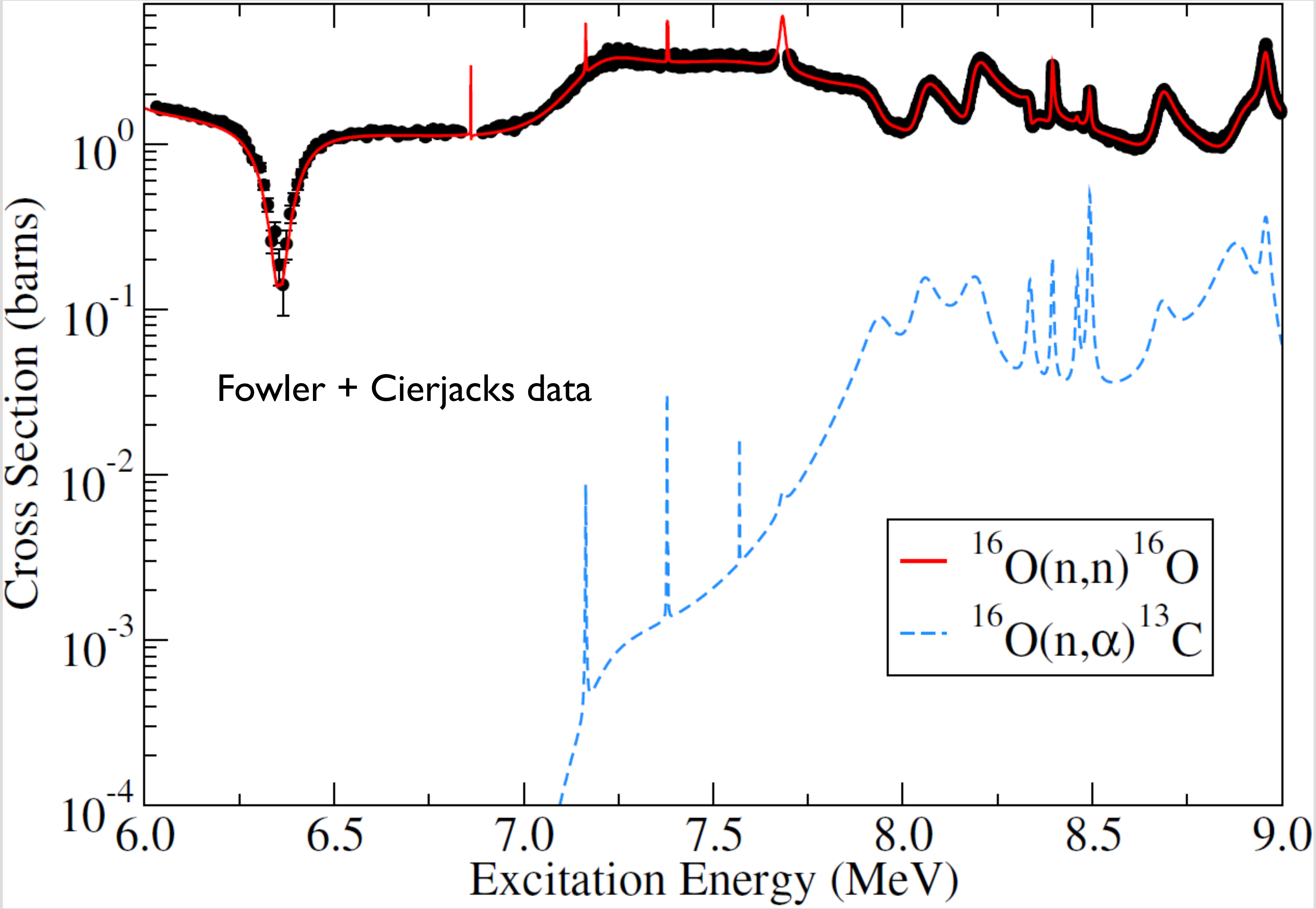
- Fit was expanded from 1.2 up to 2 MeV CM frame and the differential data from this work was added
- A lot more levels here, built off of the ENDF/B fit from LANL (Gerry Hale and Mark Paris)
- A good fit was achieved ($\chi^2/N = 1.6$)



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

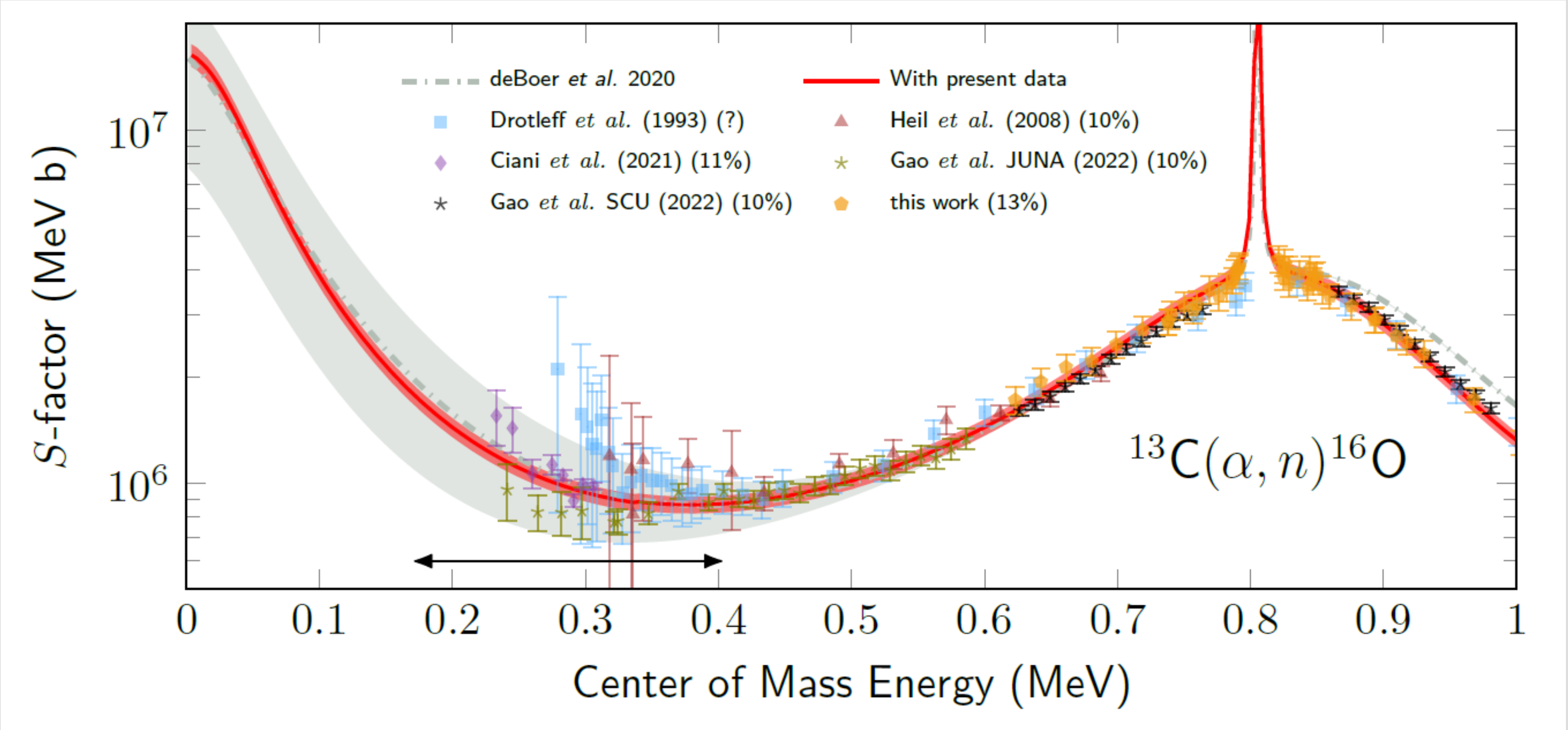
- Total cross section n+^{16}O

- Puts strong constraints on the ^{13}C(α,n)^{16}O cross section at higher energy



THE PUNCH LINE

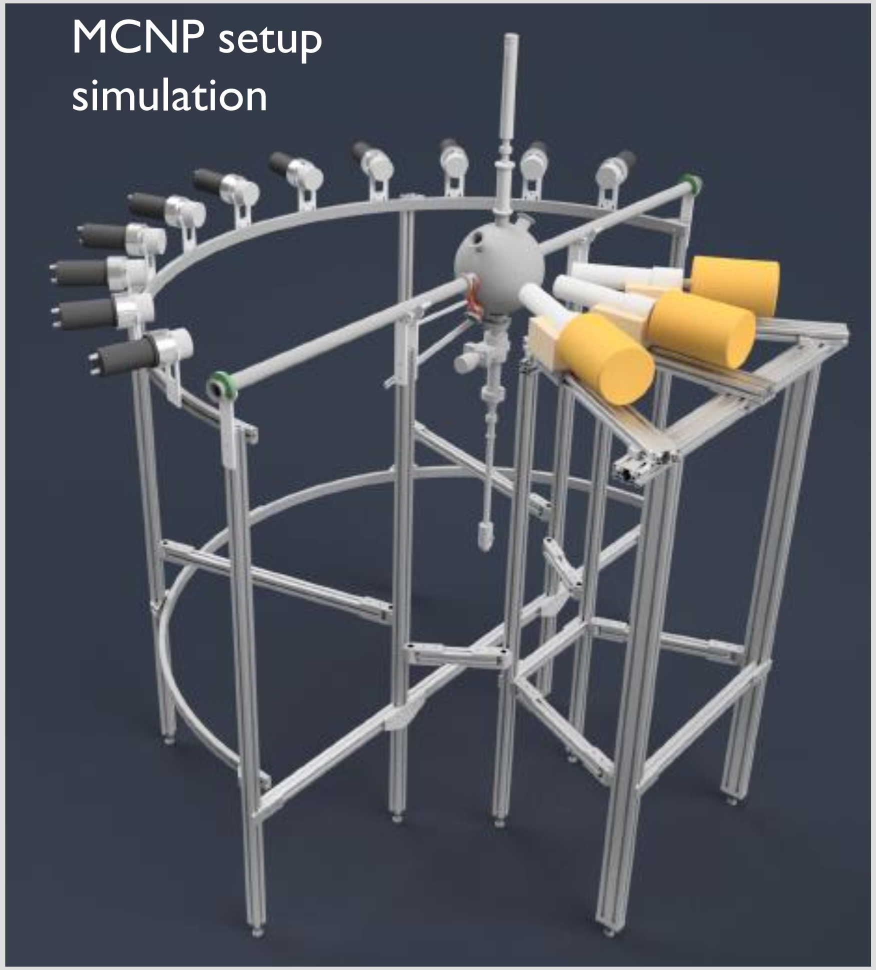
- Differential data provides additional constraint to the *R*-matrix fit, reducing the uncertainty from **10 to 5%**.
- Some additional tension with low energy data and ANC (fit overshoots)
- Previous interference pattern that was allowed without the differential data is now forbidden



CONCLUSIONS

- We have rapidly pushed into a new uncertainty range 30% → 5% over the last few years
- Differential cross section measurements provide
  - **additional constraints on the R-matrix model**
  - **are needed to correct the yields from 4π detector measurements**

  that reduced the uncertainty from about **10% → 5%**
- Further improvement even seems on the horizon
  - Reaching the goal of astrophysics uncertainty?
  - Can be used as a new calibration standard!
- Look for more (α,n) from ND in the near future!



COLLABORATORS AND ACKNOWLEDGEMENTS

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

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IReNA

International Research Network for Nuclear Astrophysics

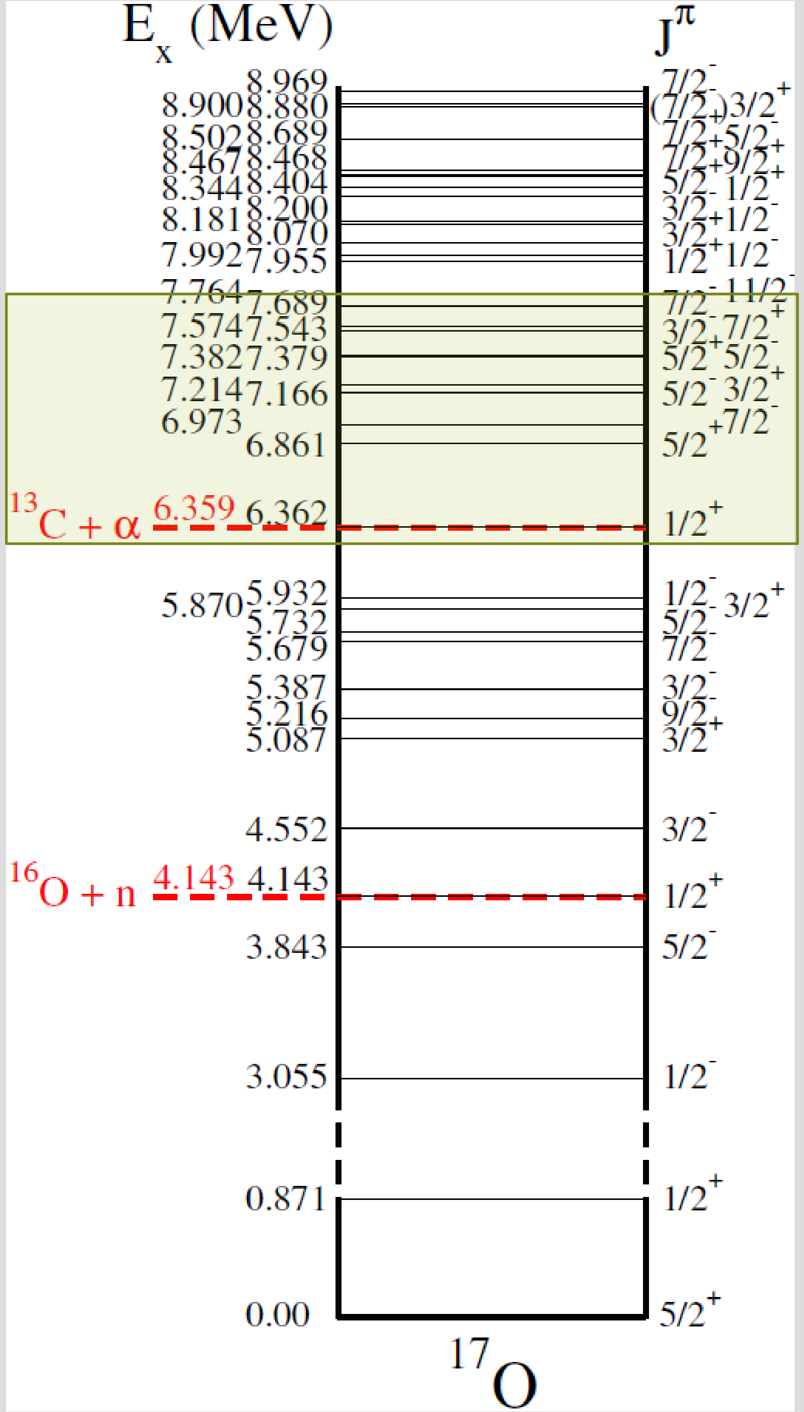
EDINBURGH AZURE2 *R*-MATRIX WORKSHOP

- A workshop dedicated to learning how to use the AZURE2 *R*-matrix code
- Local organizer: Marialiusa Aliotta
- Introductory theory
- A series of hands on examples
- June 22 to 28, 2024, University of Edinburgh
- Scotch

azure.nd.edu

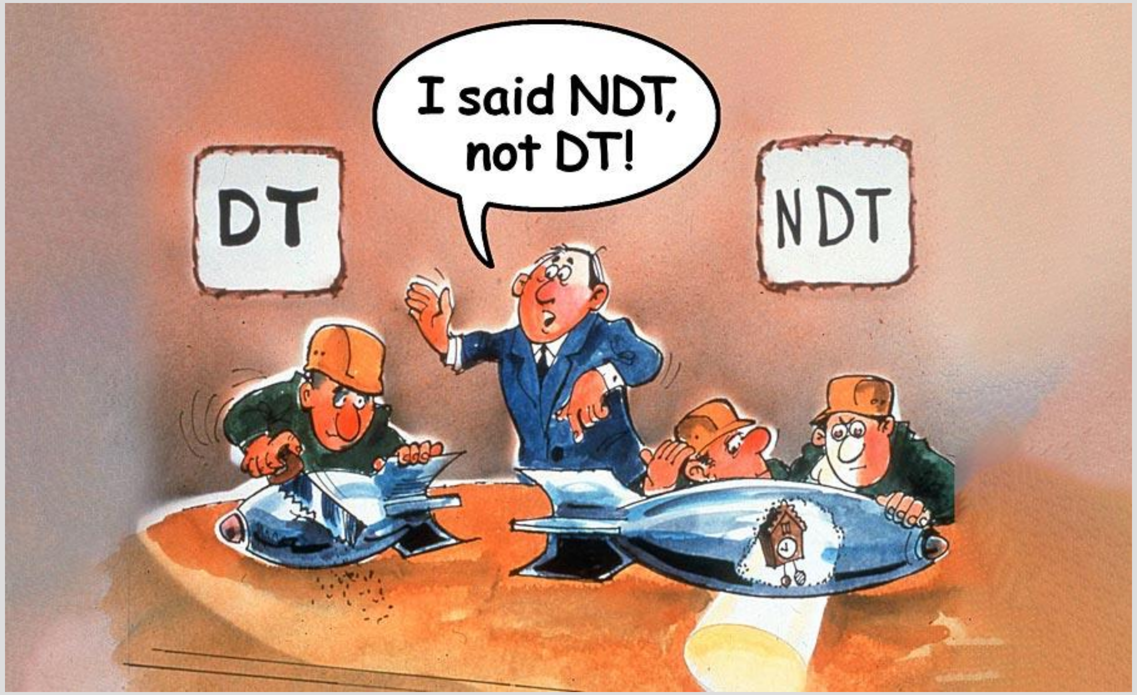
LEVEL DIAGRAM & R-MATRIX ANALYSIS

- 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



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