NEW $^{13}C(\alpha,n)^{16}O$ MEASUREMENTS AND THE BEGINNINGS OF A NEW EVALUATION OF THE ^{17}O SYSTEM

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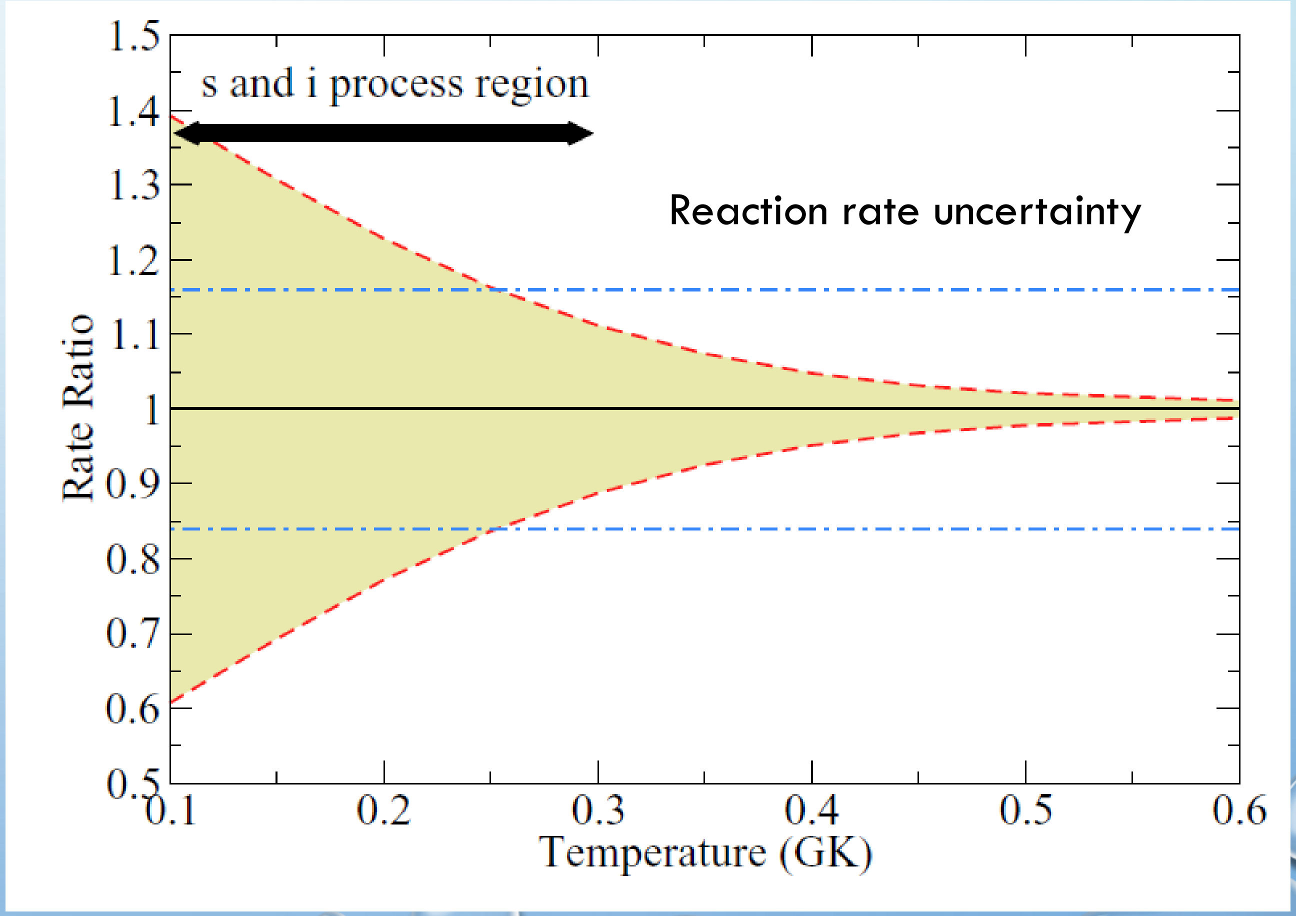
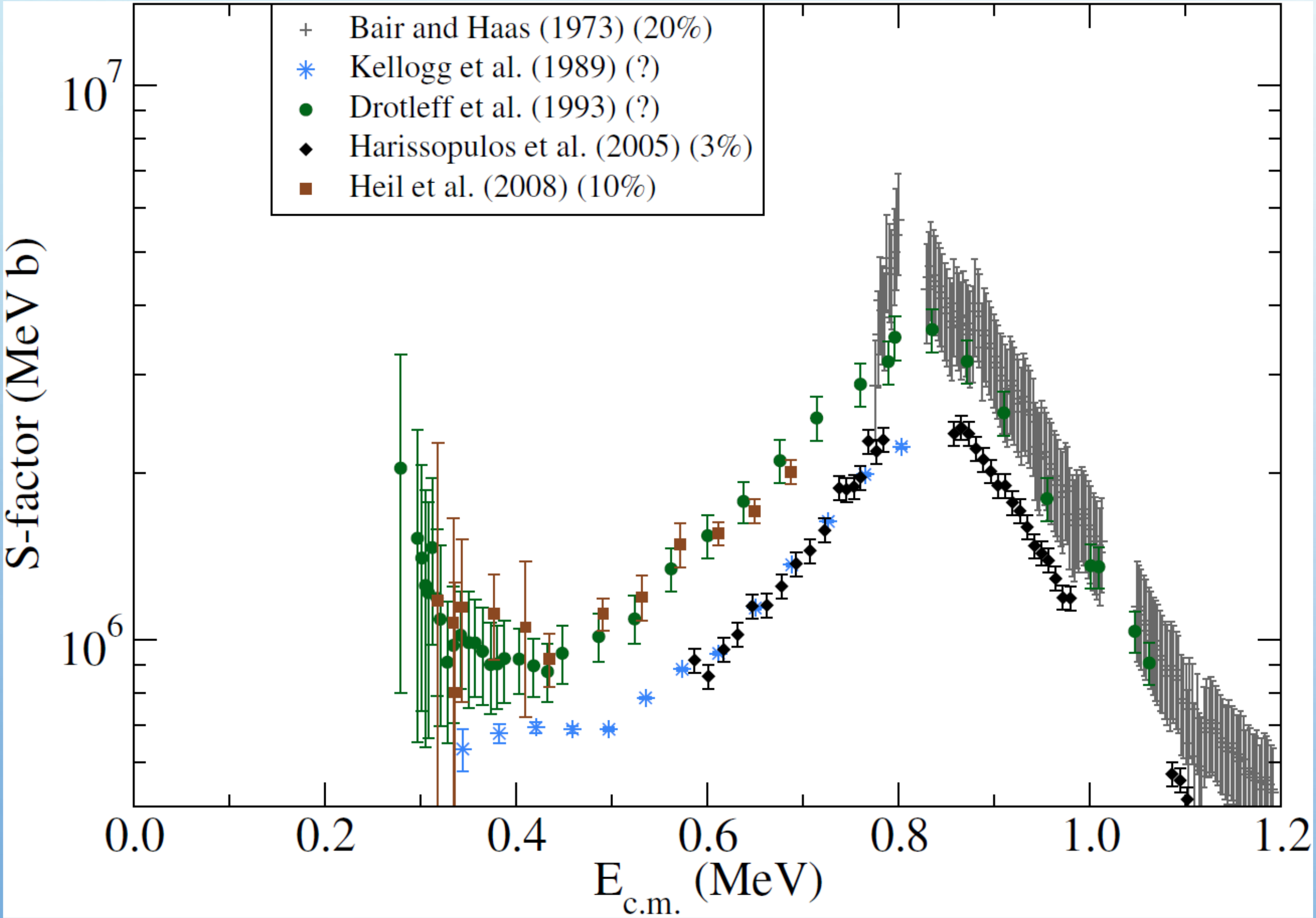
FROM THE NUCLEAR ASTROPHYSICS SIDE

WE WANT TO KNOW THE REACTION RATE OF $^{13}C(\alpha,n)^{16}O$ BETWEEN ABOUT 0.2 AND 0.3 GK FOR s-PROCESS NEUTRON PRODUCTION, WHICH OCCURS DURING HELIUM BURNING IN RED GIANT STARS

THIS TEMPERATURE RANGE CORRESPONDS TO A CENTER OF MASS ENERGY RANGE OF 170 TO 530 KeV

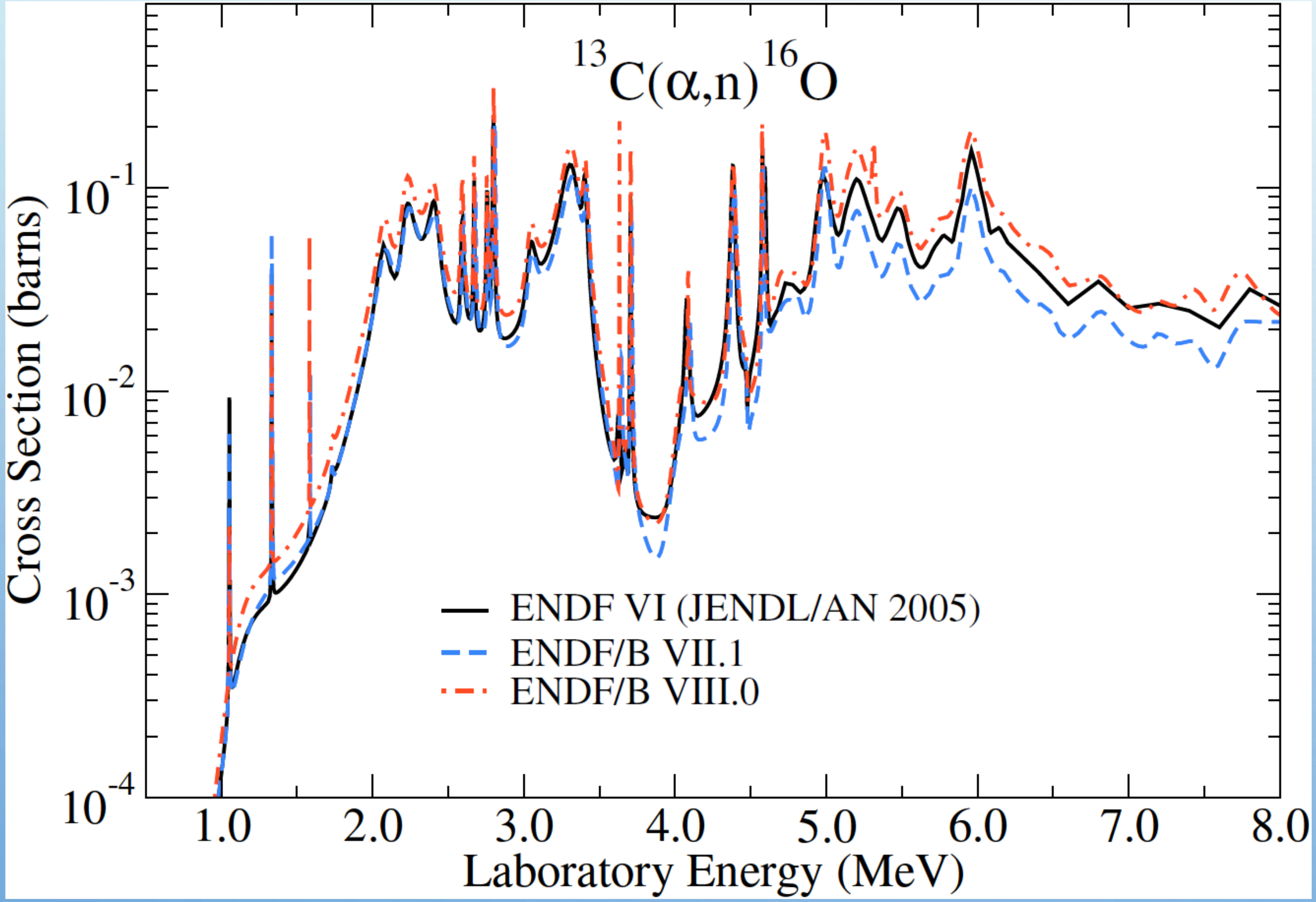


$^{13}C(\alpha,n)^{16}O$ DATA 2 YEARS AGO



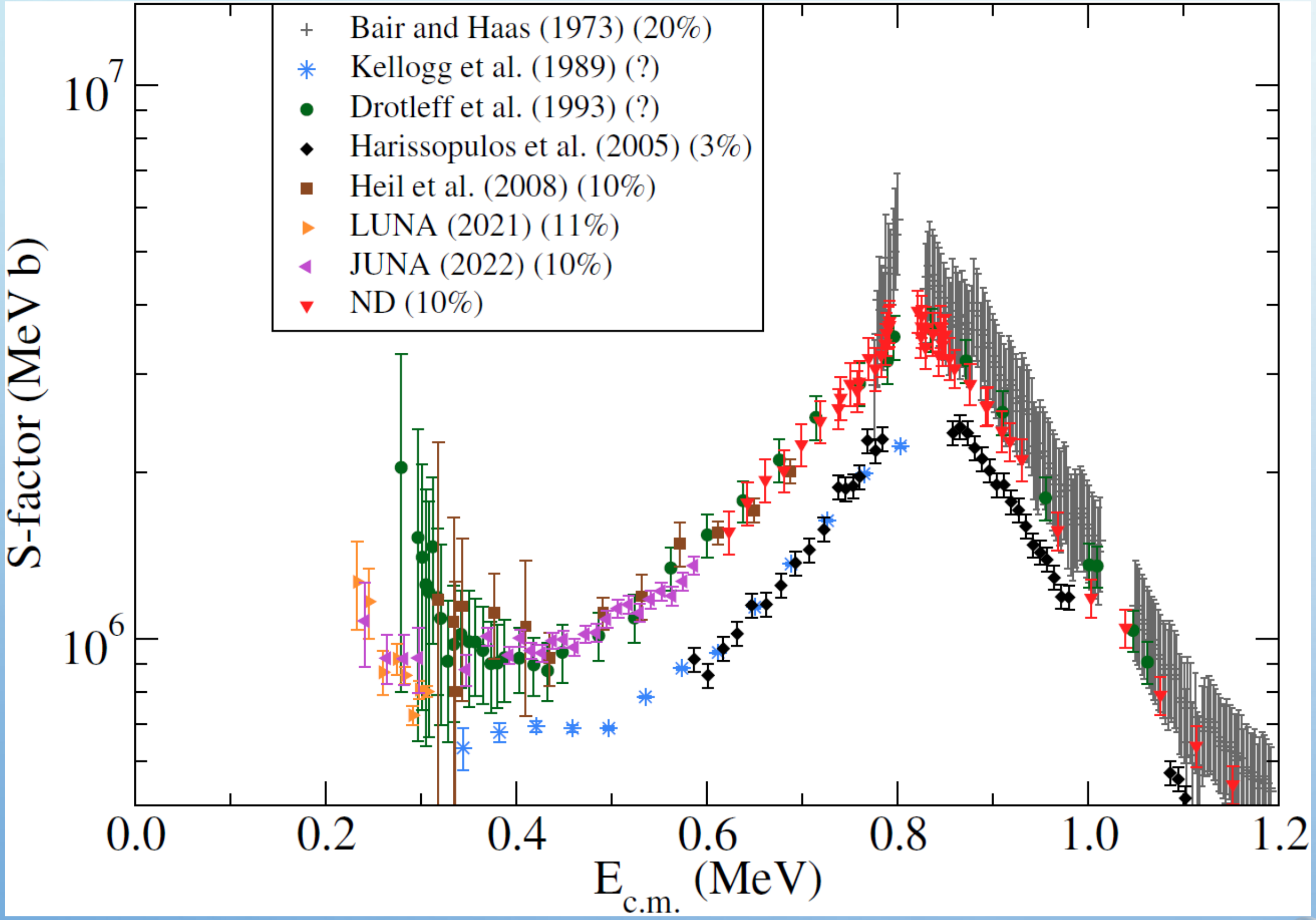
30-40% inconsistency

THESE NORMALIZATION ISSUES SPAN THE FULL ENERGY RANGE



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

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



LUNA

-233 to 306 keV

JUNA

-240 to 780 keV (1.2+ MeV above ground)

ND

-815 to 6500 keV

Two conclusions

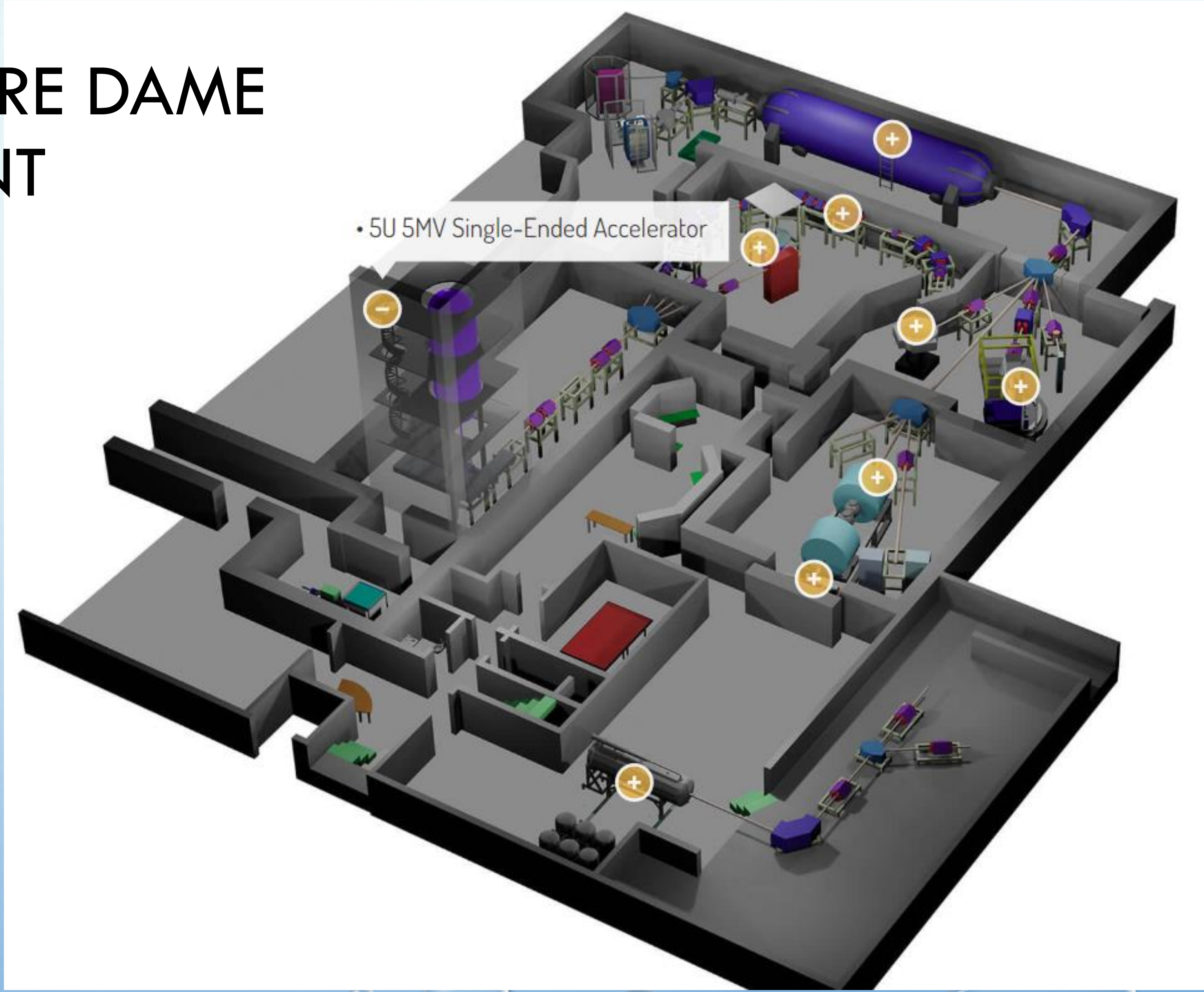
1) Kellogg and Harissopulos measurements are systematically low
2) Lowest energy data of Drotleff and Heil are systematically high

WHAT'S GOING ON WITH THESE LARGE DIFFERENCES IN THE ABSOLUTE CROSS SECTION?

- IT SEEMS LIKE ITS ALL ABOUT DETECTION EFFICIENCY
  - CALIBRATING A NEUTRON DETECTOR'S EFFICIENCY IS MUCH MORE DIFFICULT THAN OTHER DETECTORS
- IT ALSO SEEMS LIKELY THAT THE RESONANCE STRENGTH FOR THE 1.05 MEV RESONANCE GIVEN IN THE TUNL NUCLEAR DATA PROJECT IS ALSO LOW

UNIVERSITY OF NOTRE DAME MEASUREMENT

- NUCLEAR SCIENCE LABORATORY
- 5 MV STABLE ION ACCELERATOR FOR NUCLEAR ASTROPHYSICS (STA. ANA)
- ALPHA PARTICLE BEAMS UP TO ABOUT 9 MEV IN PRACTICE
- BEAM INTENSITIES UP TO ABOUT 100 UA, BUT FOR THIS EXPERIMENT THE TYPICAL INTENSITY WAS 5 UA.



DEUTERATED LIQUID SCINTILLATORS: INTRINSIC EFFICIENCY

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

Q = +2.2 MeV

Ohio University Measurement

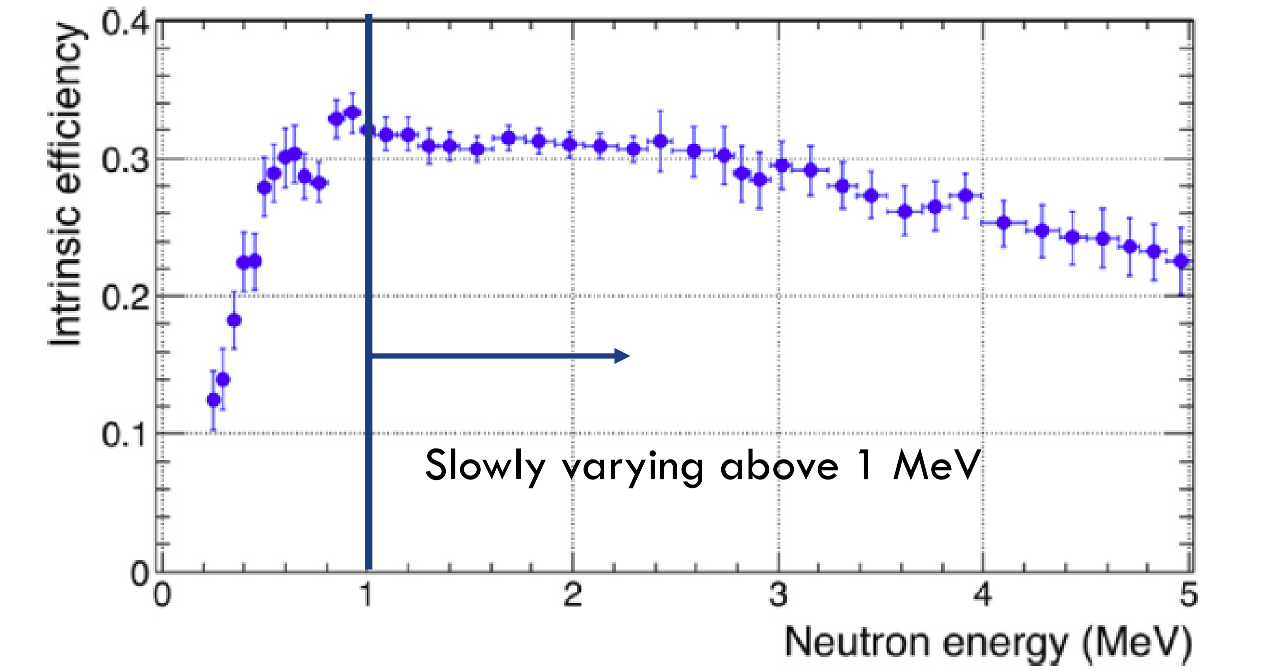


Fig. 8. Intrinsic neutron detection efficiency measured using the $^{9}Be(d,n)$ reaction at E_d = 7.00 MeV for one detector. The low energy threshold is defined by the PSD bands shown in Fig. 4 with fit parameters listed in Table 1.

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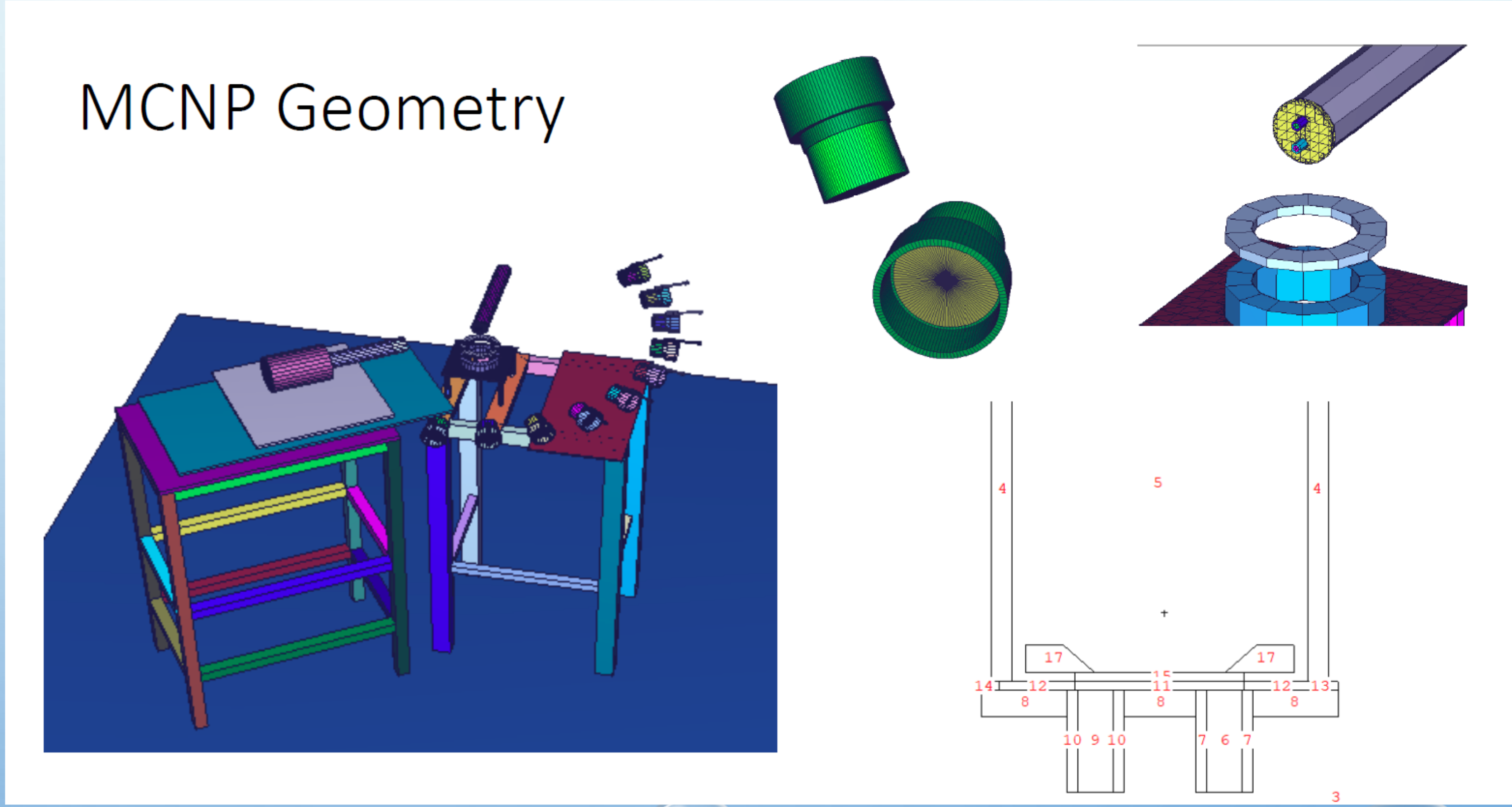
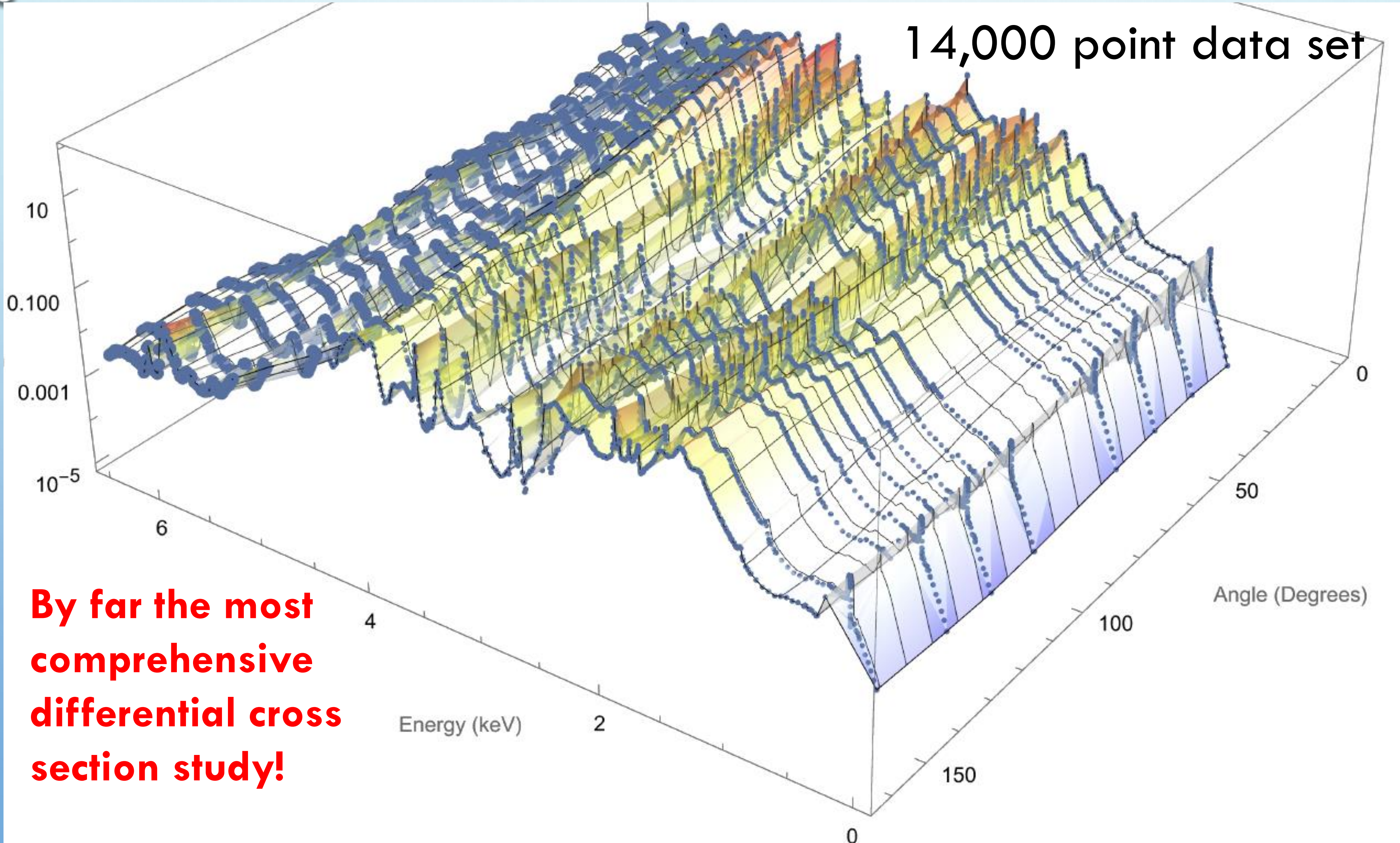
DEUTERATED LIQUID SCINTILLATORS: GEOMETRIC/SCATTERING EFFICIENCY

- LARGEST SOURCE OF UNCERTAINTY
- FUTURE IMPROVEMENTS CAN BE MADE TO TARGET HOLDER / CHAMBER TO FURTHER MINIMIZE THESE EFFECTS

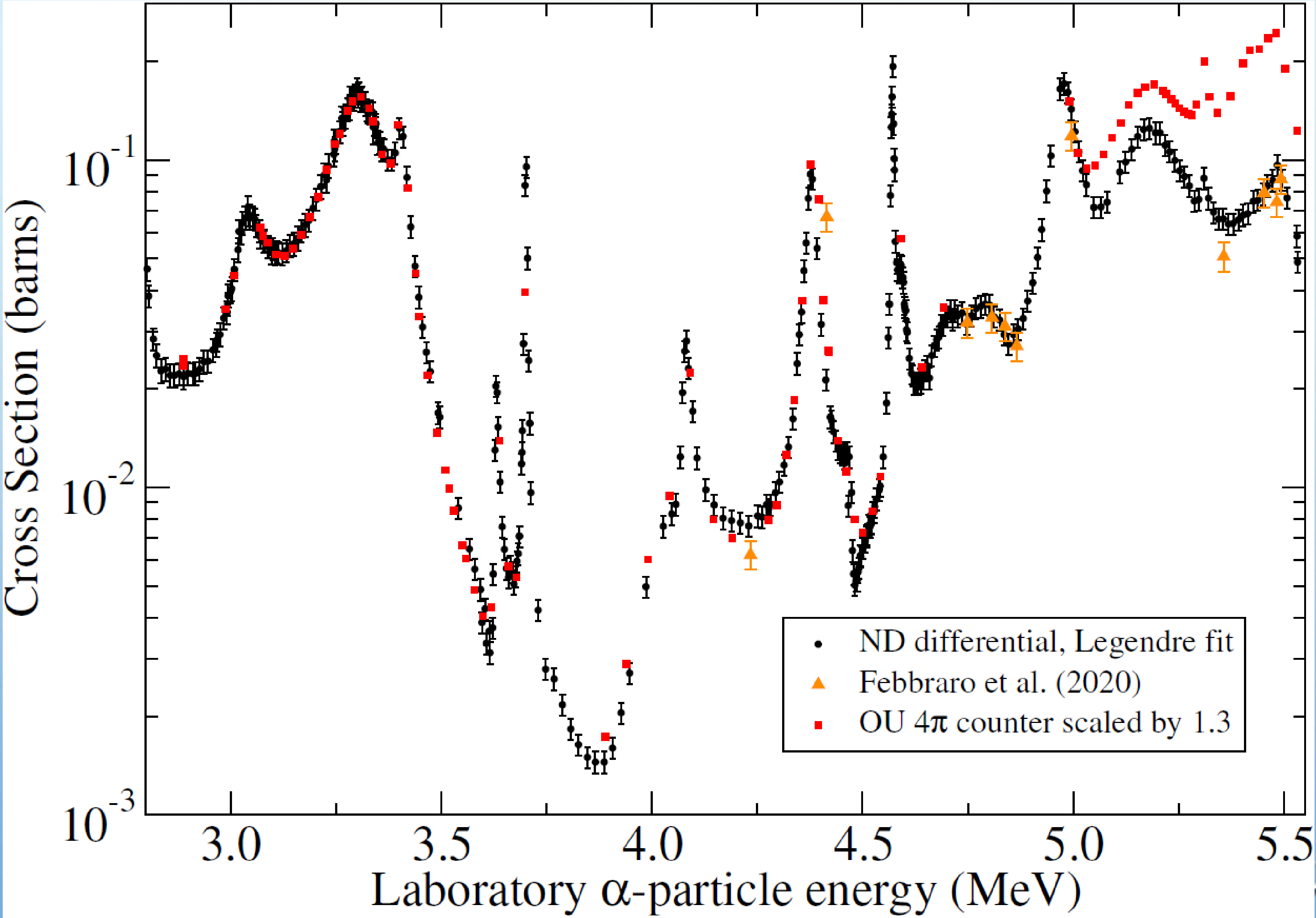


AN IDEA OF THE FULL DATA RANGE

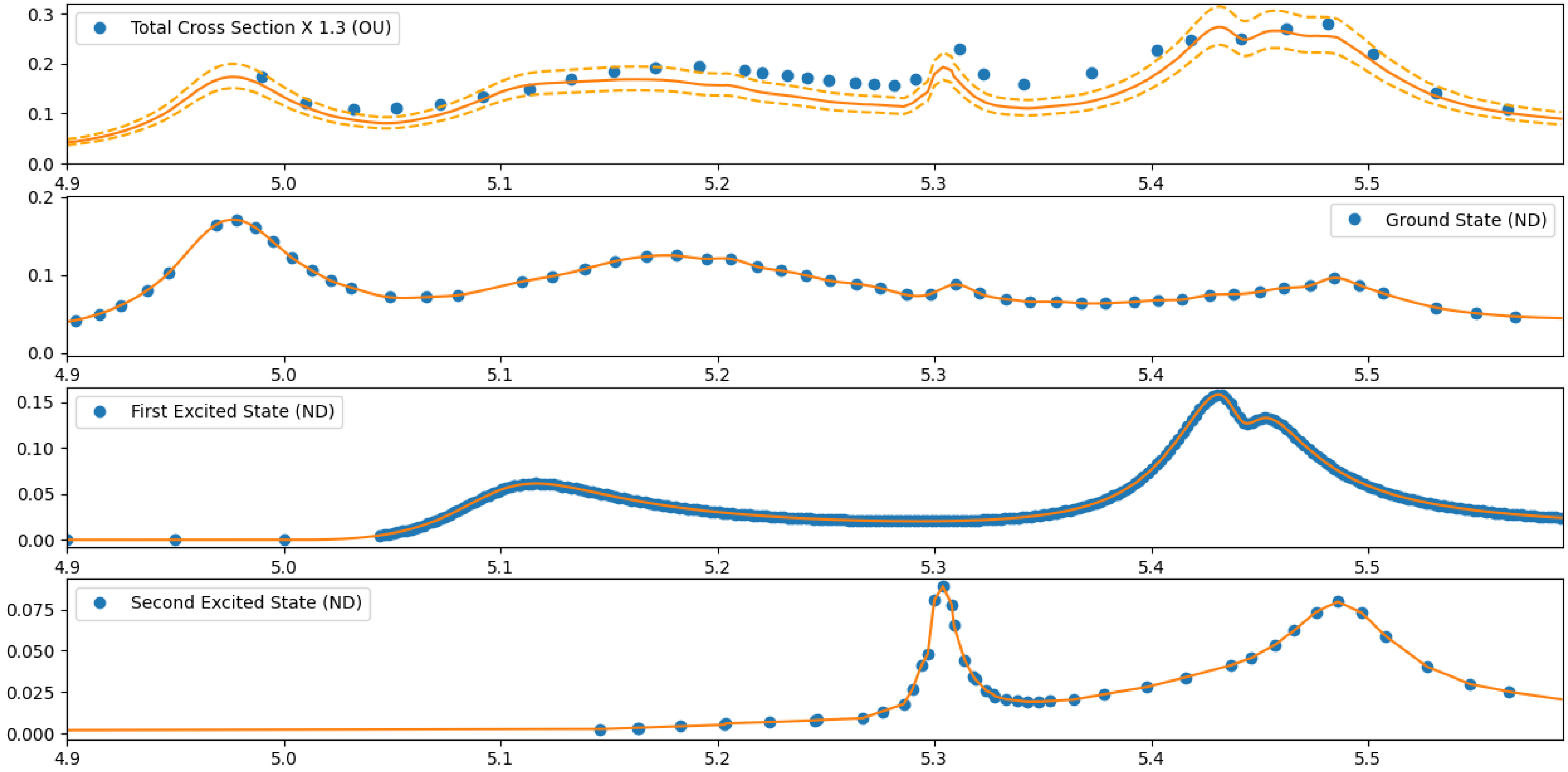


By far the most comprehensive differential cross section study!

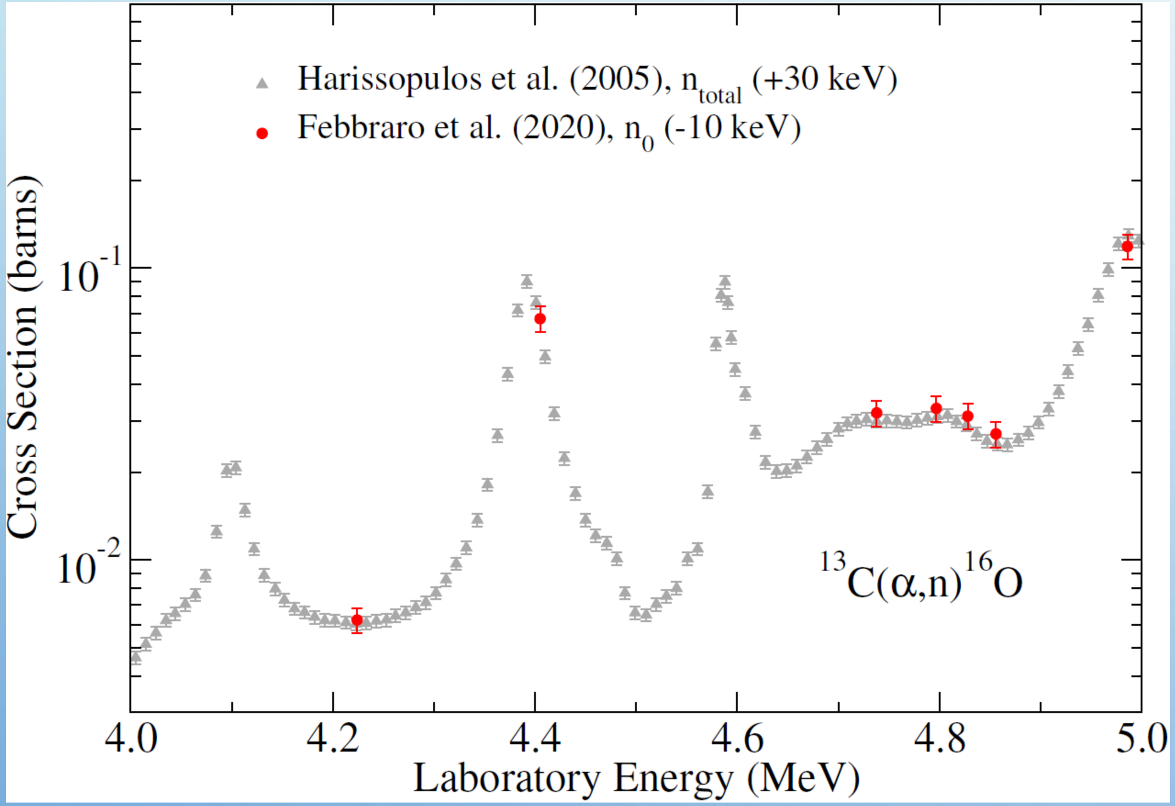
OU/ND DATA COMPARISON

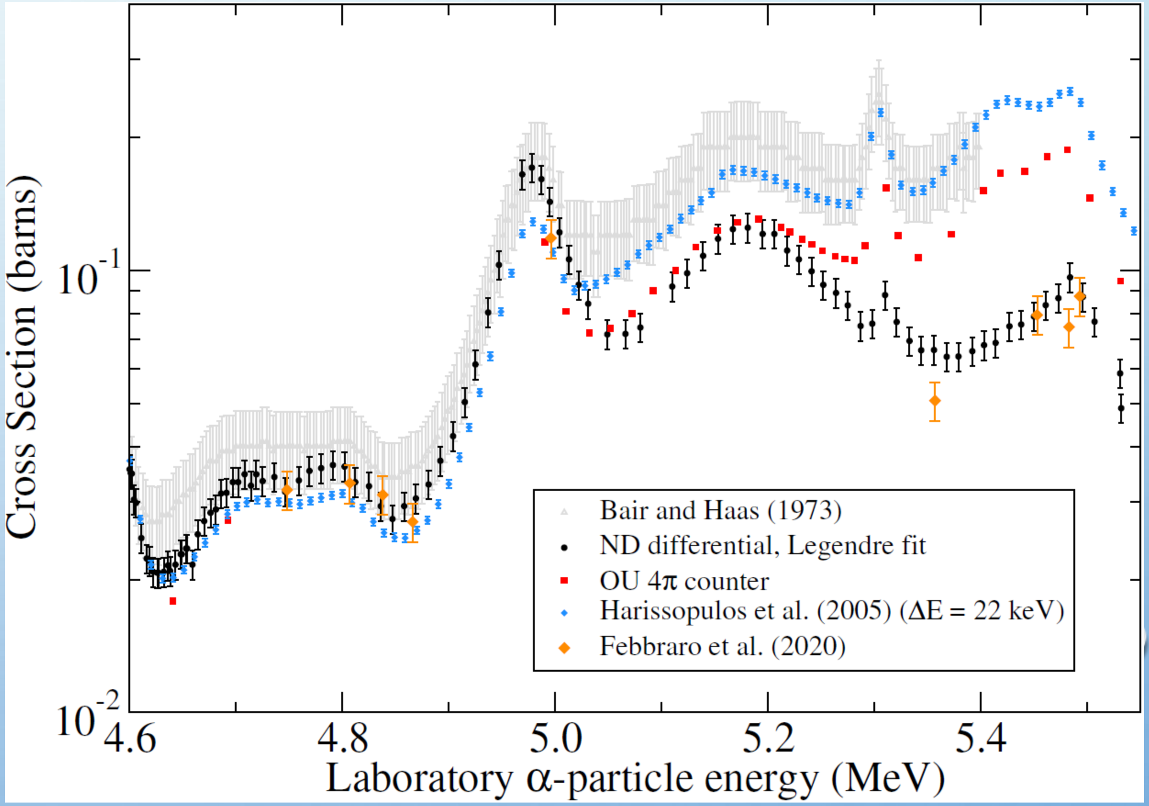


SUMMING PARTIALS TO GET THE TOTAL

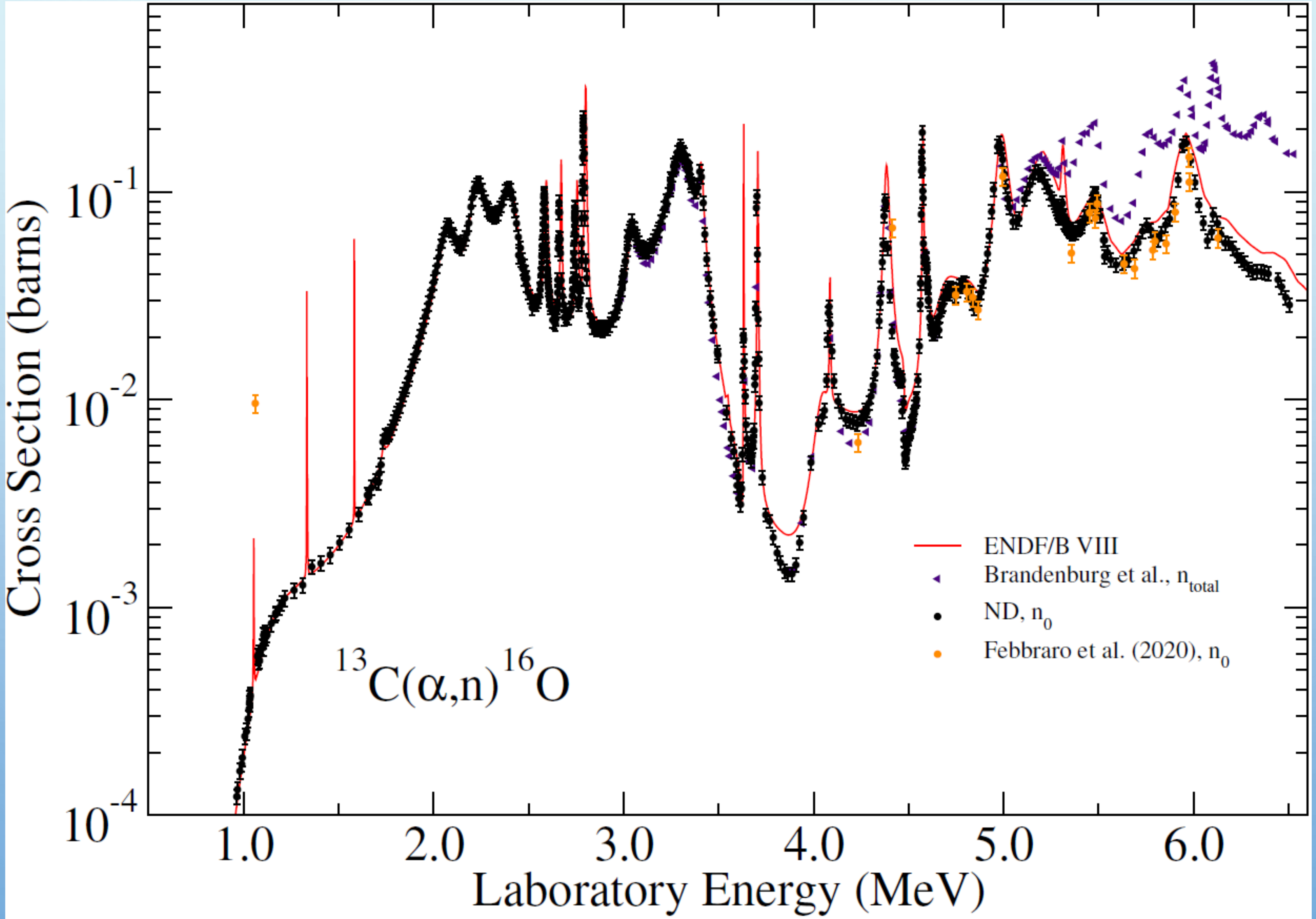


COMPARISON TO 2020 PRL DATA: A BIT TRICKY

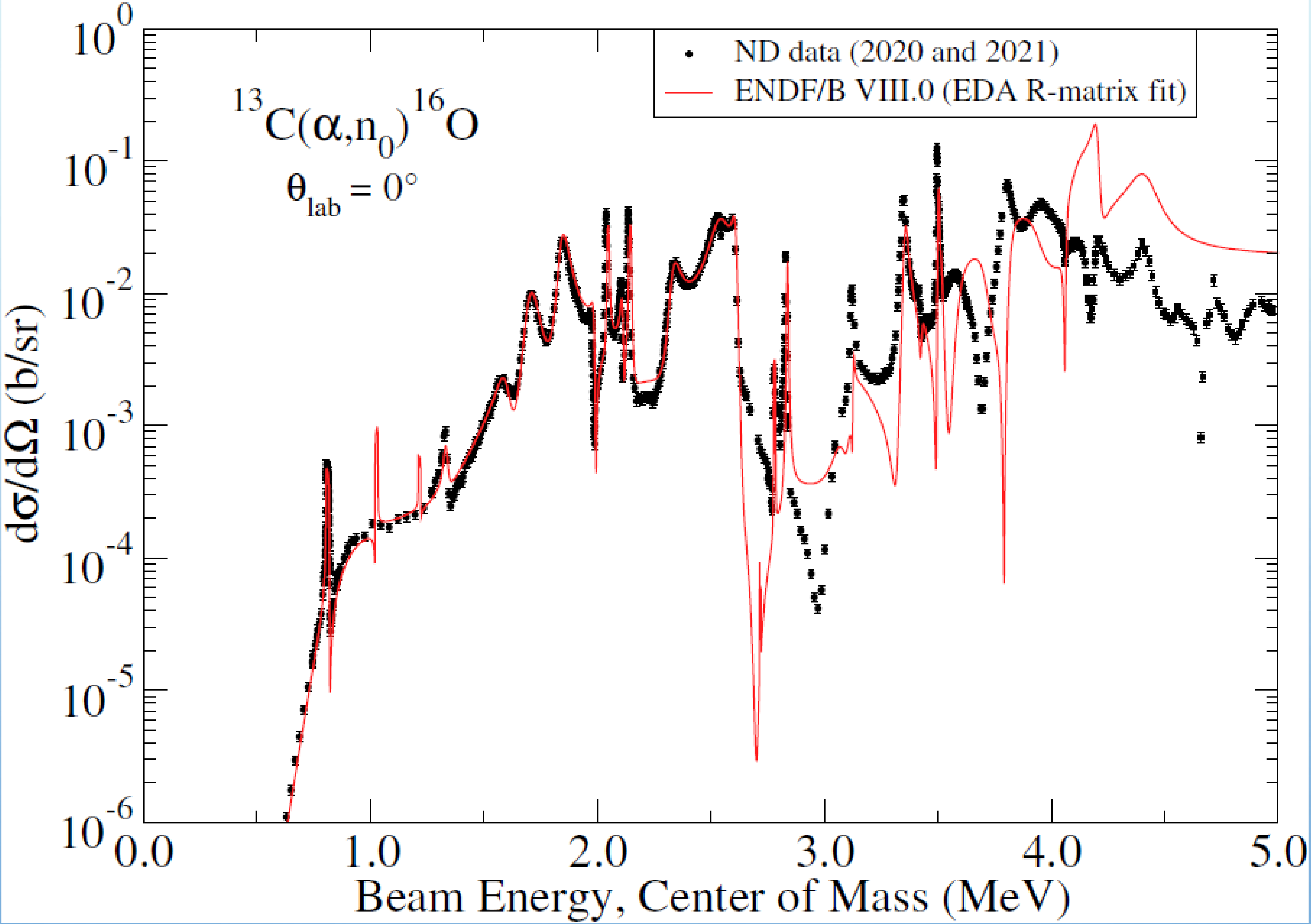




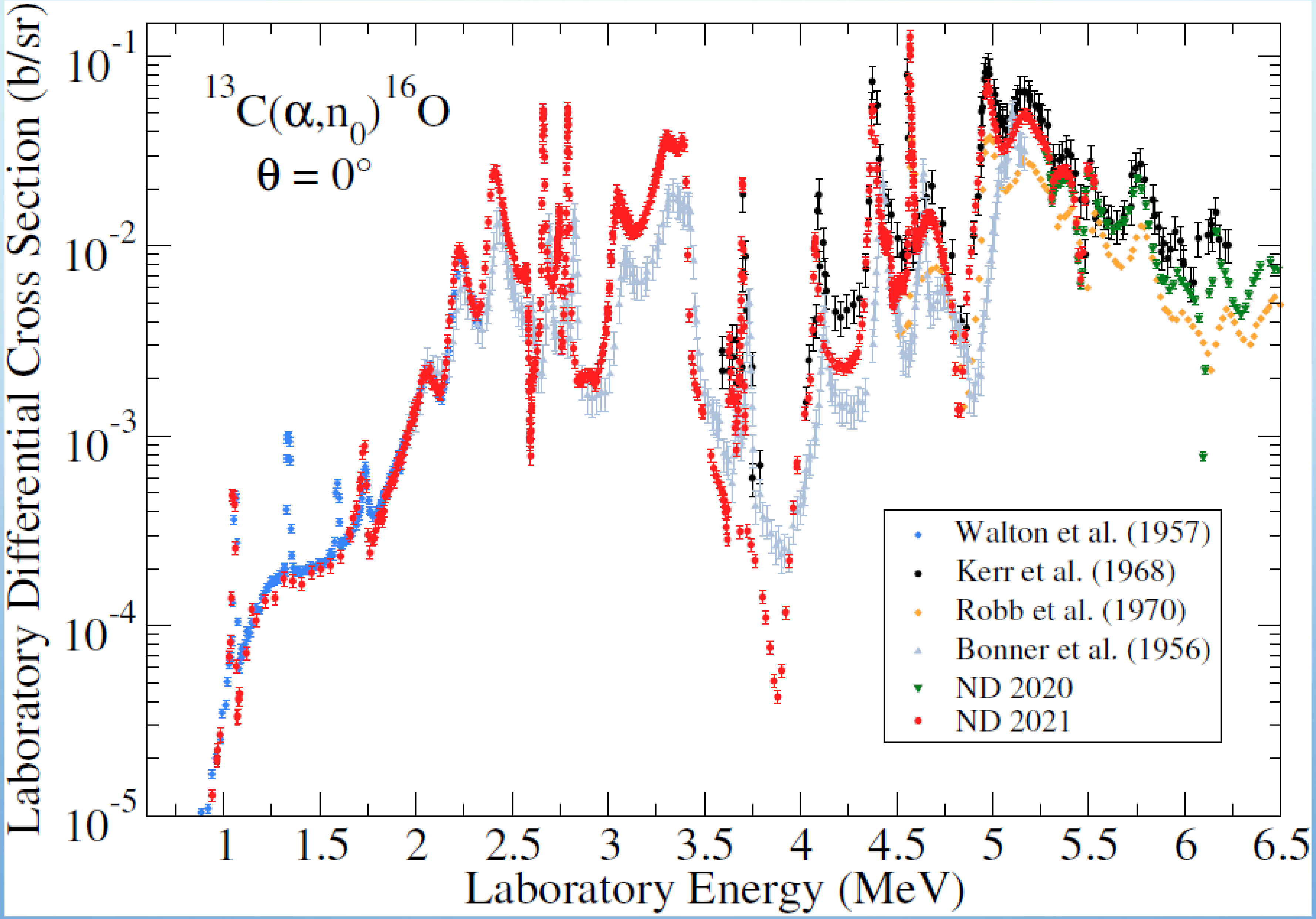
COMPARISON WITH ENDF/B VIII.0



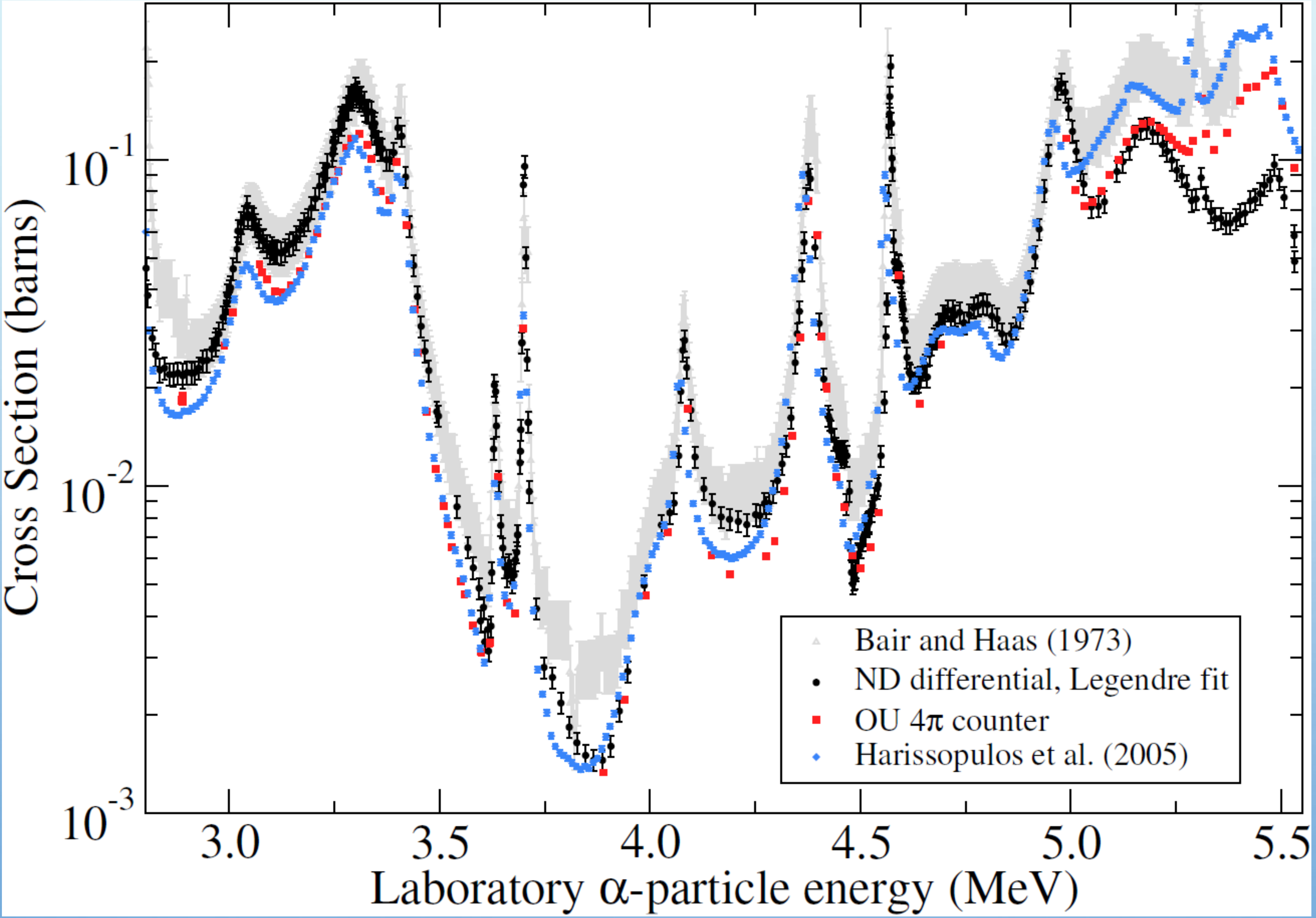
ENDF/B VIII.0 COMPARISON AT ZERO DEGREES



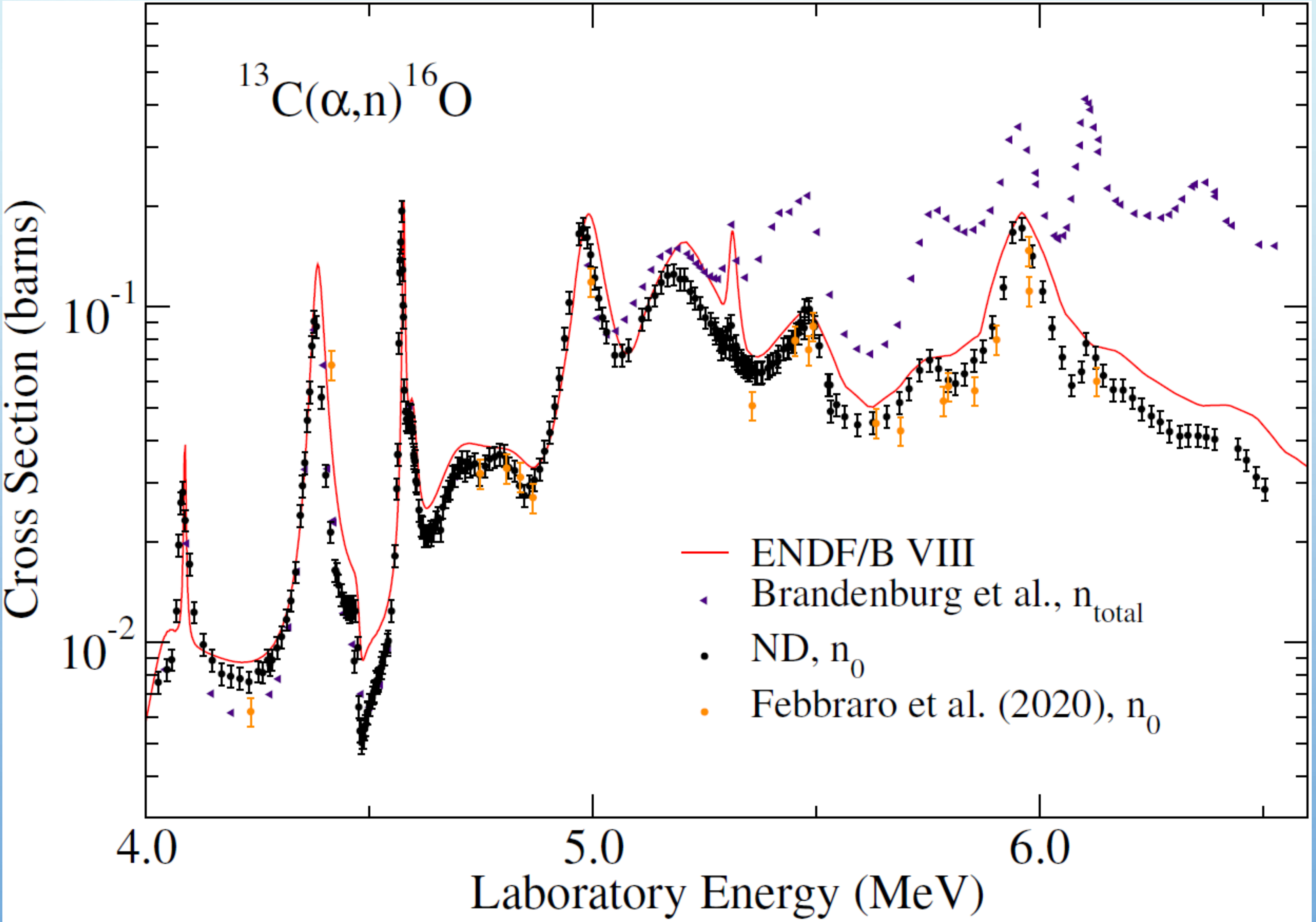
ZERO DEGREE CROSS SECTION, WORLD DATA SET



TOTAL CROSS SECTION COMPARISONS

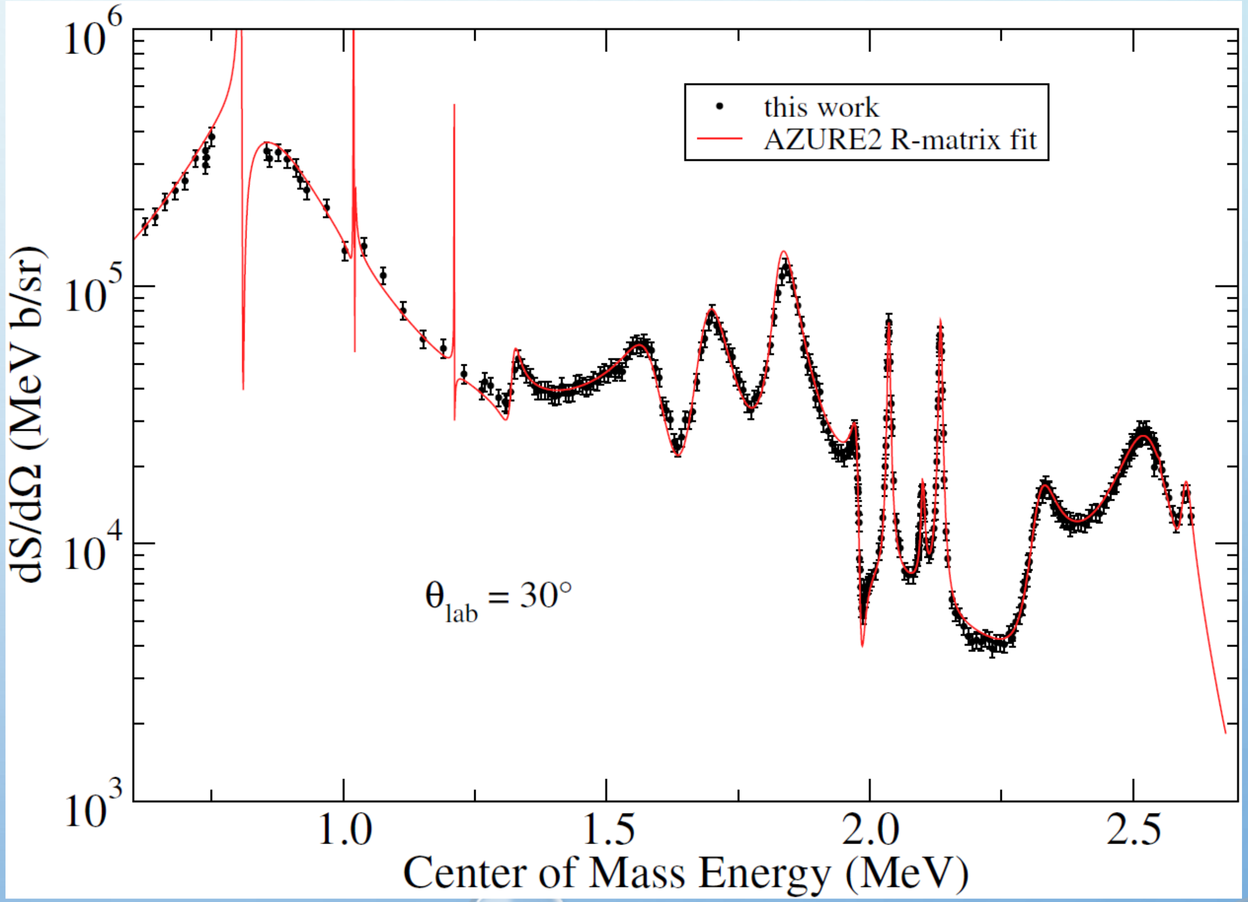


FOCUS IN ON Febbraro 2020 REGION



FITTING PROGRESS WITH AZURE2

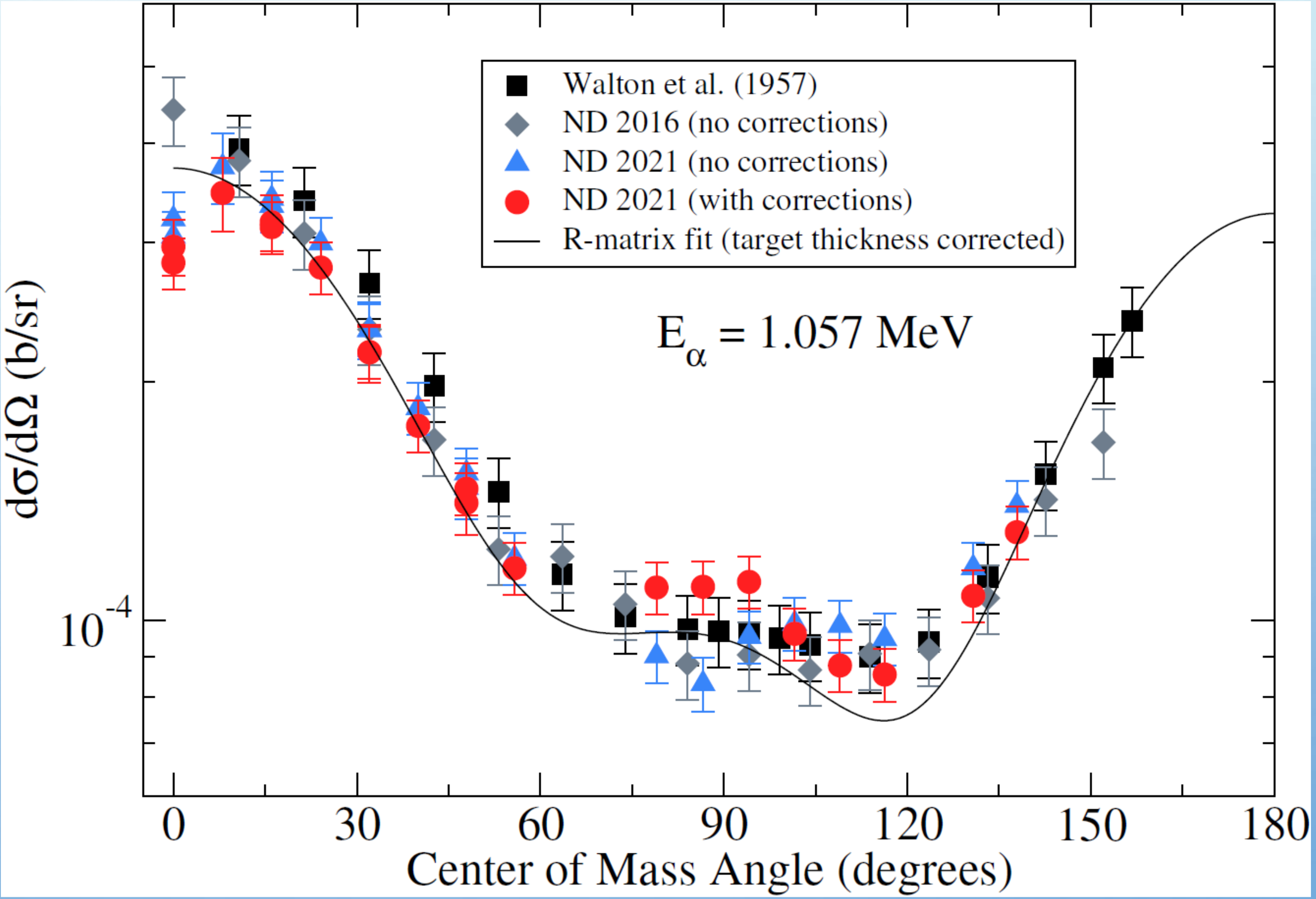
- R-MATRIX FITTING GREATLY ACCELERATED WITH THE R-MATRIX PARAMETERS FROM ENDF/B.VIII FROM **MARK PARIS** AND **GERRY HALE**. **CARL BRUNE** TRANSFORMED THEIR PARAMETERS TO AZURE2 PARAMETERS
- RIGHT NOW I'M CONSIDERING
  - LOW ENERGY $^{13}C(\alpha,n)^{16}O$ DATA UP TO 3.42 MeV (LAB)
  - ^{16}O(n,TOTAL) UP TO 5.16 MeV (LAB)



ENERGY ADJUSTMENTS

- ASSUMING THAT THE ND AND OU ENERGY CALIBRATIONS ARE CORRECT, AS THEY ARE CONSISTENT WITH EACH OTHER
- CIERJACKS FOUND TO NEED A CONSTANT **-7 keV ENERGY SHIFT**
  - POSSIBLE REASON: REVISION OF ENDPOINT ENERGY FOR THE ^{27}AL(α,n) CALIBRATION (XIAODONG TANG)
- BAIR AND HAAS REQUIRED A MORE COMPLICATED LINEAR CORRECTION
- INFLATED HARISSOPULOS UNCERTAINTIES TO 10%, NO ENERGY SHIFT NEEDED UP TO 2.6 MeV CM ENERGY

ANGULAR DISTRIBUTION CORRECTIONS WITH MCNP



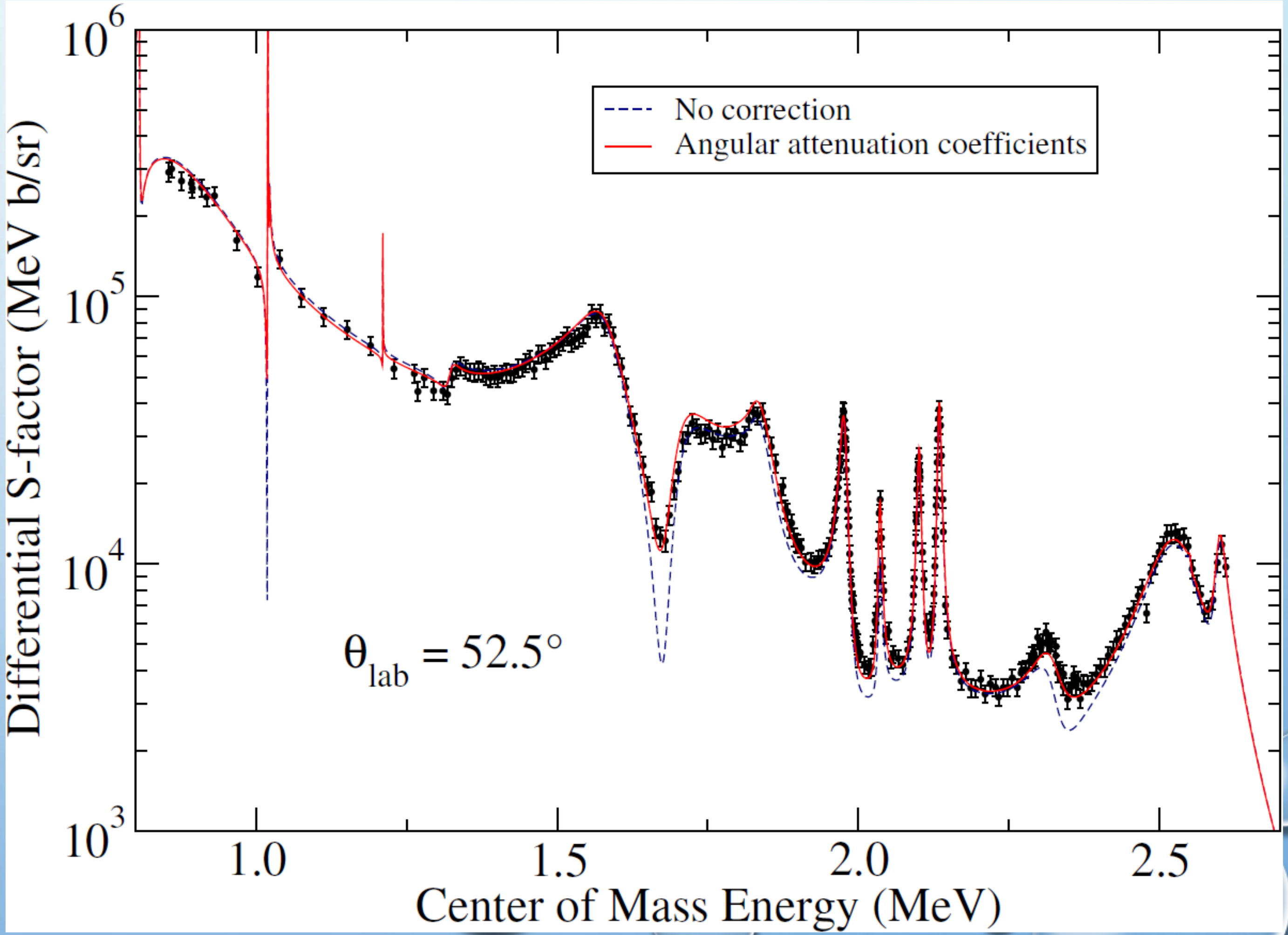
ANGULAR DISTRIBUTION EFFECTS

- EACH DETECTOR COVERS ABOUT 7 DEGREES (3 IN DIAMETER, 2 FEET FROM TARGET)
- THIS SEEMS TO BE QUITE SIGNIFICANT BECAUSE THERE ARE PLACES WHERE THE CROSS SECTION CHANGES VERY RAPIDLY WITH ANGLE

$$W(\theta) = \sum_i a_i Q_i P_i(\cos(\theta))$$

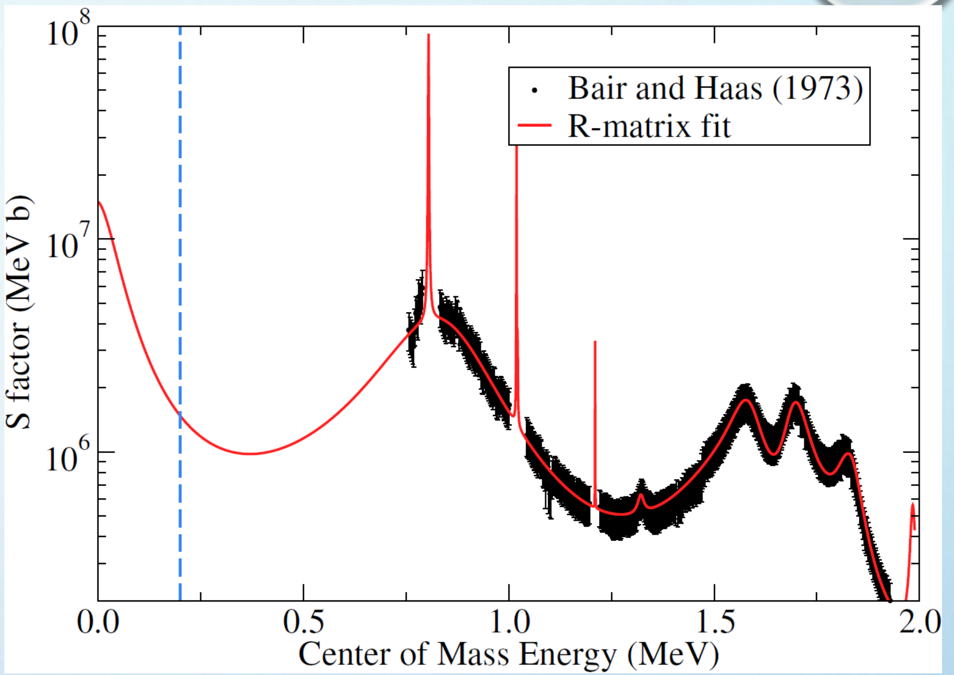
Angular attenuation coefficients

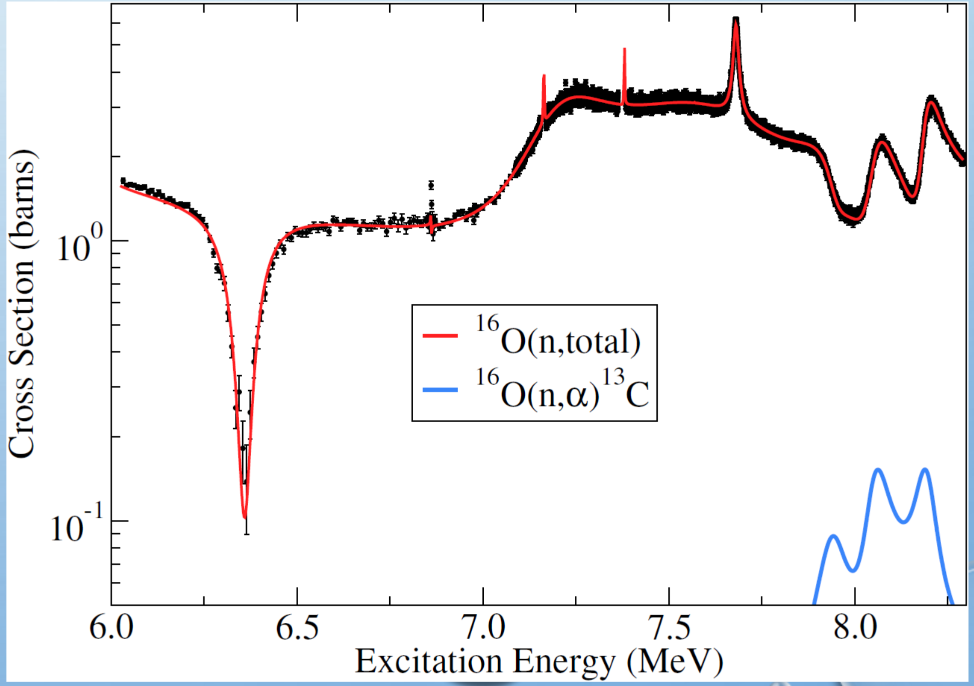
$a_i = 1,\ 0 < a_i < 1,\ a_i > a_{i+1}$



R-MATRIX FIT TO HIGHER ENERGIES

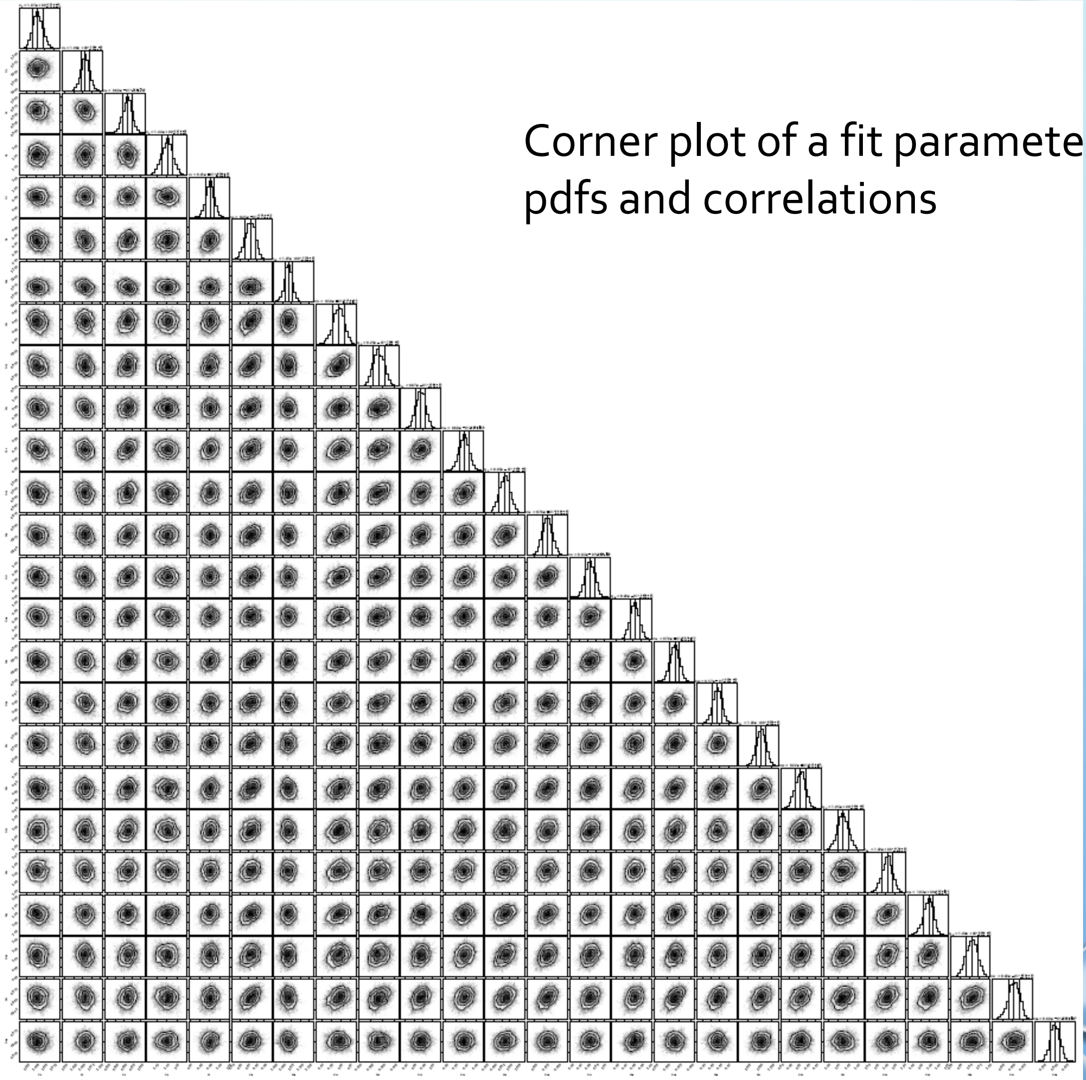
- **$^{16}O(n,n) + ^{16}O(n,\alpha) = ^{16}O(n,total)$**
- $^{16}O(n,total)$ CROSS SECTIONS ARE MEASURED TO HIGH PRECISION!
  - **SYSTEMATIC UNCERTAINTY OF 5%**
  - THIS HAS BEEN WHAT THE ENDF/B EVALUATION HAS BEEN DOING FOR MANY YEARS





IMPROVEMENT IN UNCERTAINTY ANALYSIS, MCMC

- DEVELOPMENT OF THE **BAYESIAN ANALYSIS INFERENCE CODE KIT (BRICK)** FOR THE AZURE2 R-MATRIX CODE (ACCEPTED IN FRONTIERS OF PHYSICS)
- **DANIEL ODELL**, A POSTDOC AT OU, IS THE MAIN DEVELOPER
- THIS WORK IS POSSIBLE THANKS TO **DANIEL PHILLIPS AND CARL BRUNE** AND A GRANT FROM NNSA National Nuclear Security Administration
- PIP INSTALL BRICK-JAMES



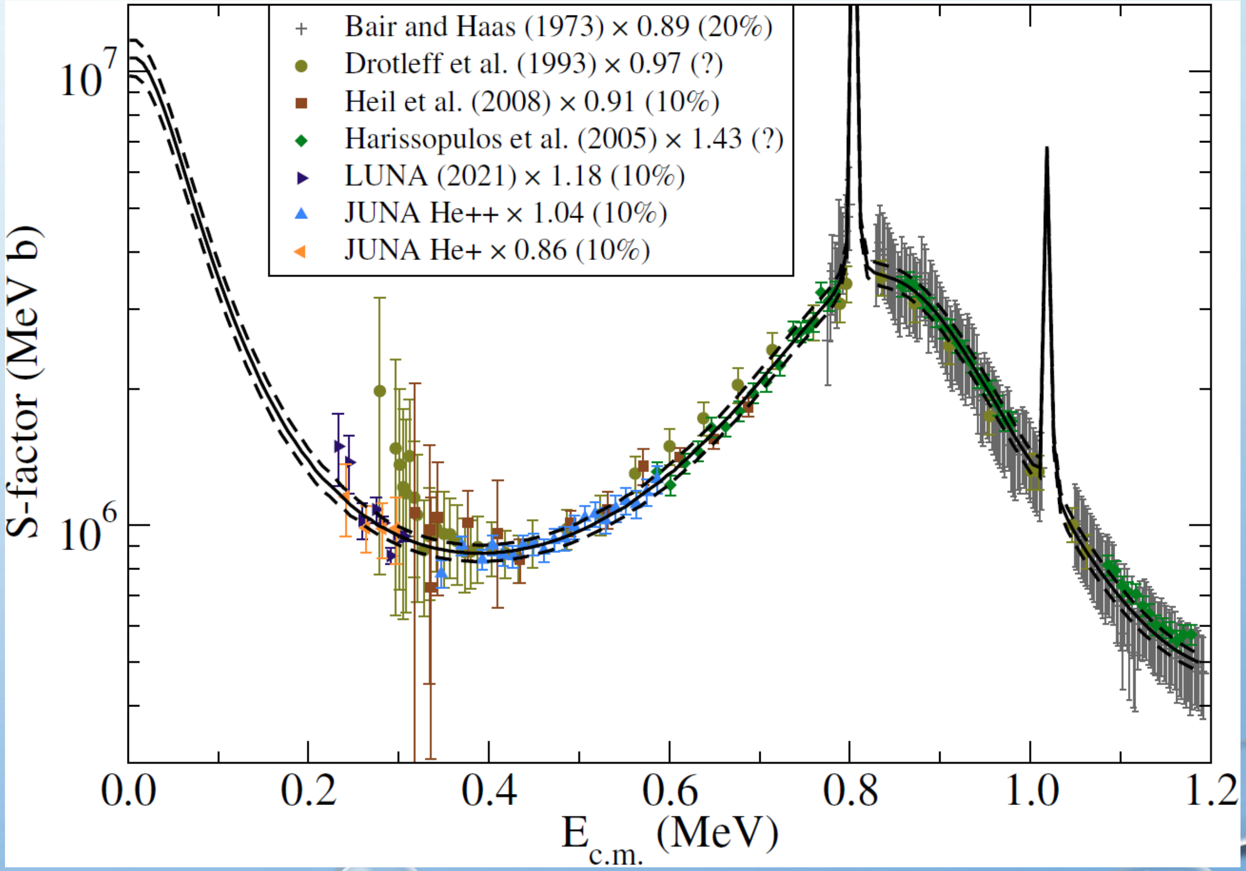
Corner plot of a fit parameter pdfs and correlations

CURRENT NORMALIZATIONS (APPLIED TO DATA)

	χ^2/N
FOWLER + CIERJACKS $^{16}O(n,total)$ --- 5%, 1.06	1.55
DROTLEFF --- ?, 1.03	0.93
HEIL --- 10%, 1.02	1.29
HERISSOPULOS --- ? (~~4%~~), 1.45	0.62 (10% PTP UNCERTAINTY)
JUNA --- 11%, 0.94	1.66
BAIR AND HAAS --- 20%, 0.91	0.10
LUNA --- 10%, 1.09	0.68
ND --- 12% (OVERALL), 0.89 TO 1.04	1.07 TO 3.08

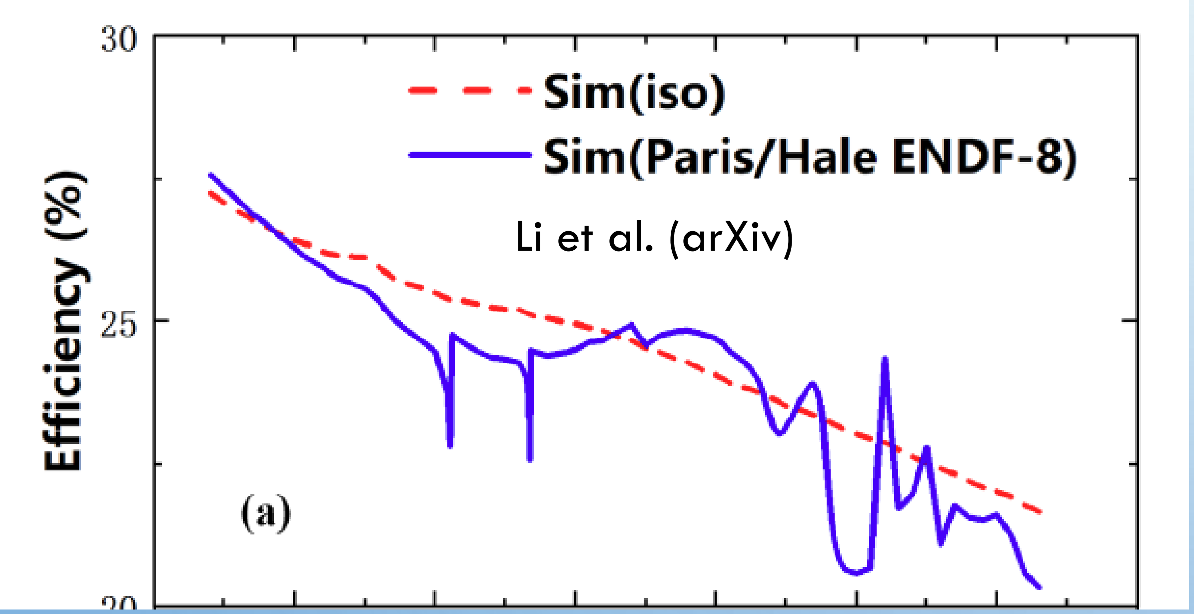
SUMMARY AND OUTLOOK

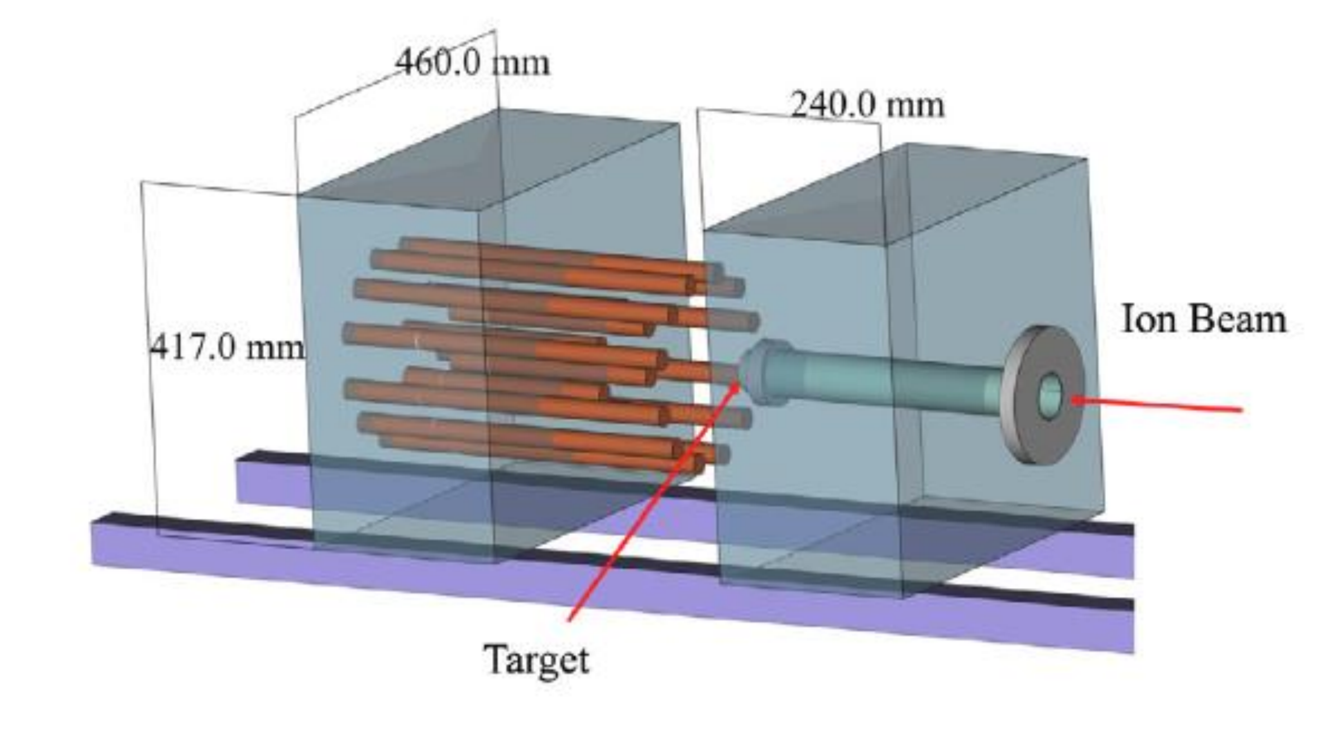
- NEW DATA SETS HAVE ACHIEVED A NEW LEVEL OF **CONSISTENCY** BETWEEN $^{13}C+\alpha$, $^{16}O+n$, AND TRANSFER MEASUREMENTS
- THIS MAY ALLOW US TO PUSH THE UNCERTAINTY FROM 30% DOWN TO 10% OR PERHAPS EVEN LESS
- SOME MEASUREMENTS I WOULD LIKE TO SEE
    - **ALPHA AND NEUTRON ANC MEASUREMENTS OF OTHER BOUND STATES IN ^{17}O**
    - IT SHOULD NOW BE POSSIBLE TO DECREASE THE UNCERTAINTIES OF FUTURE 4π COUNTER MEASUREMENTS WITH SIMULATIONS AND MEASURED ANGULAR DISTRIBUTIONS



CAN WE IMPROVE PREVIOUS (α,n) DATA?

Csedreki et al. (2022)





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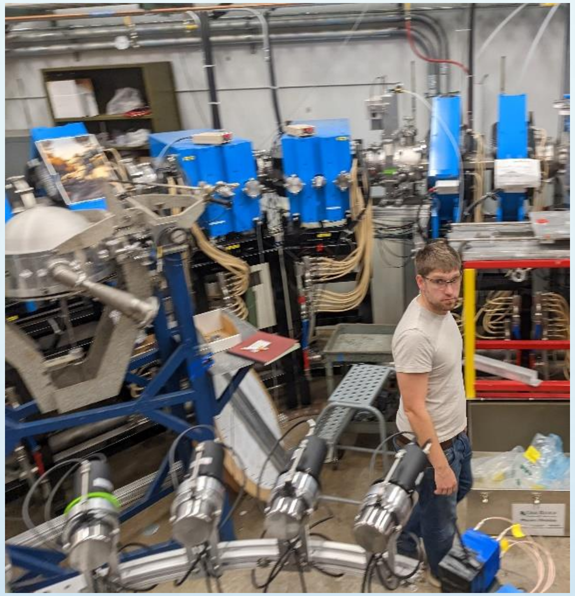

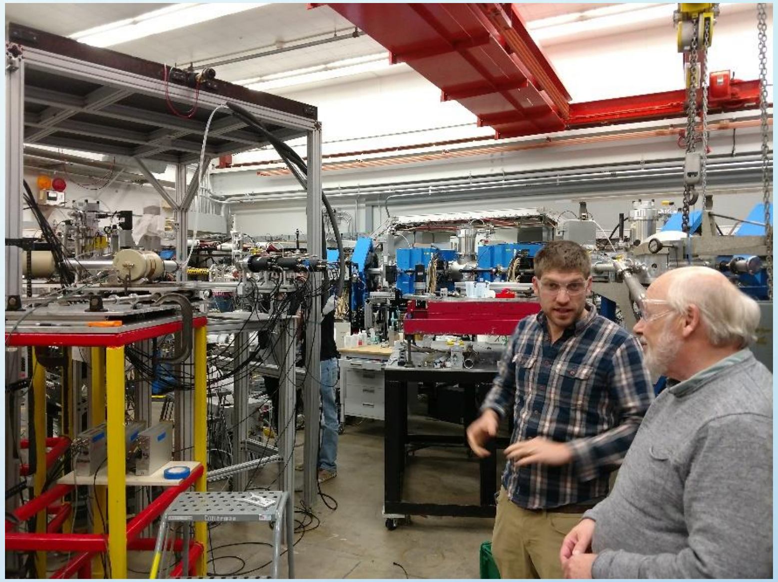


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