New experimental results on n+^{14}N

James deBoer

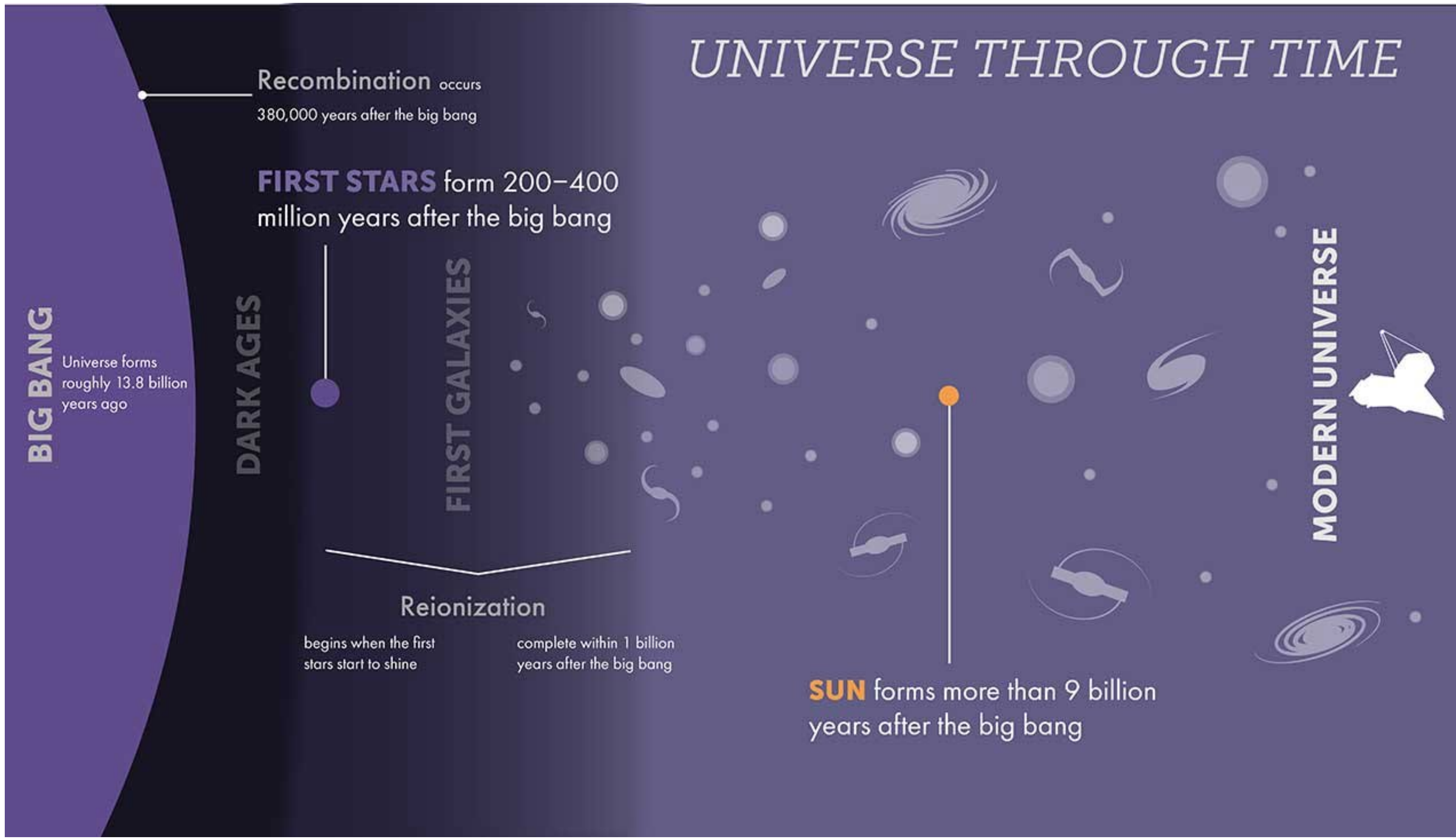
University of Notre Dame

Some motivations: Nuclear Astrophysics

First star nucleosynthesis

The James Webb telescope is searching for Population III stars, the first stars formed in the universe from the primordial elements of the big bang

Without heavier seed nuclei like carbon, nitrogen, and oxygen, how do massive stars that are usually powered by the CNO cycles during hydrogen burning produce energy and convert hydrogen into helium



James Webb telescope website (Credit: STScl)

$^{4}He(d,\gamma)^{6}Li(\alpha,\gamma)^{10}B(\alpha,d)^{12}C$

$^{10}B(\alpha,p)^{13}C$

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

In many well known nuclear burning stages of POP III stars, we know that many of the reactions that happen are very important for nucleosynthesis, but don't really matter for energy production.

Could some different types of reaction sequences happen in POP I stars?

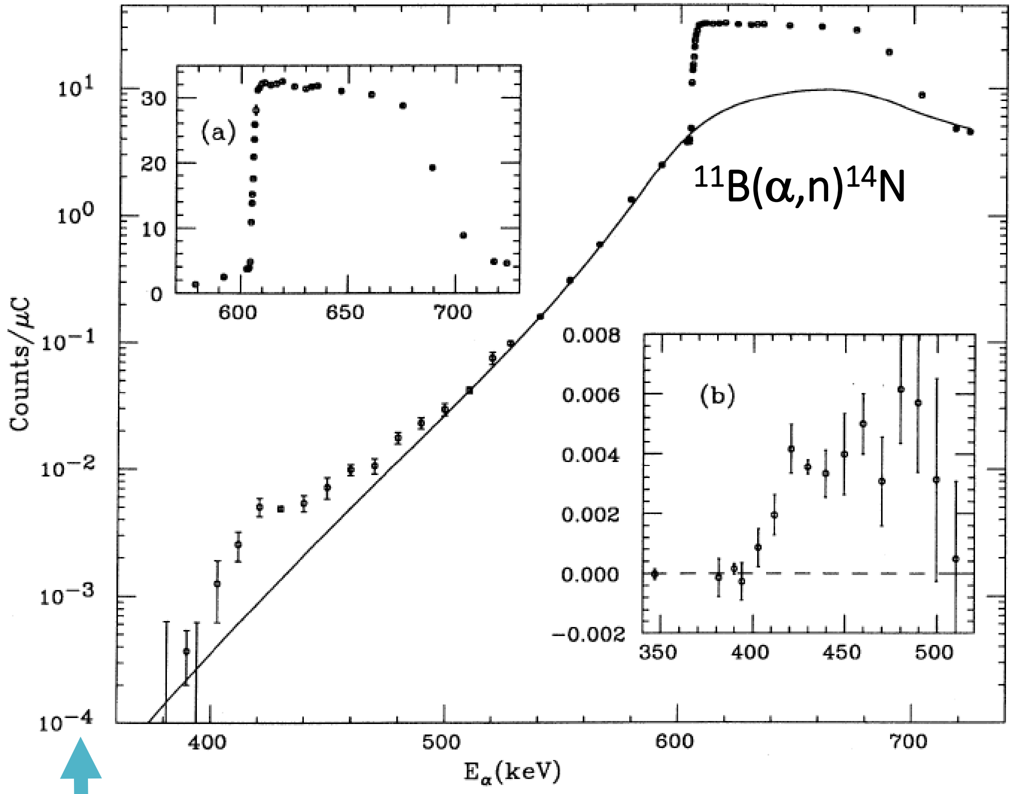
Interesting candidates are reactions on Li and B isotopes, whose low energy cross sections have very large uncertainties.

$^{3}He(\alpha,\gamma)^{7}Be(e^{-}\nu)^{7}Li(\alpha,\gamma)^{11}B(\alpha,n)^{14}N$

James Webb telescope website, artist's conception of early star formation (Credit: Adolf Schaller)

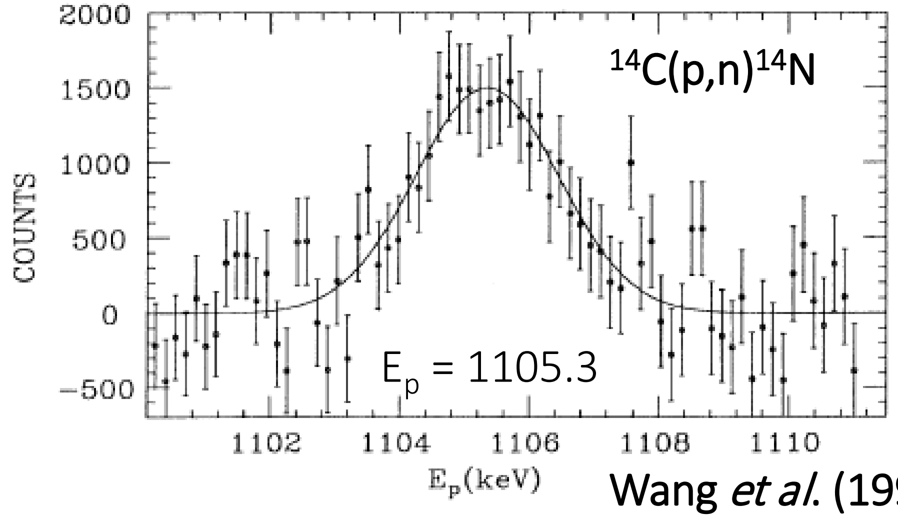
Can there be other interesting "background reactions" that happen?

Previous measurements (E_x = 11238.5)

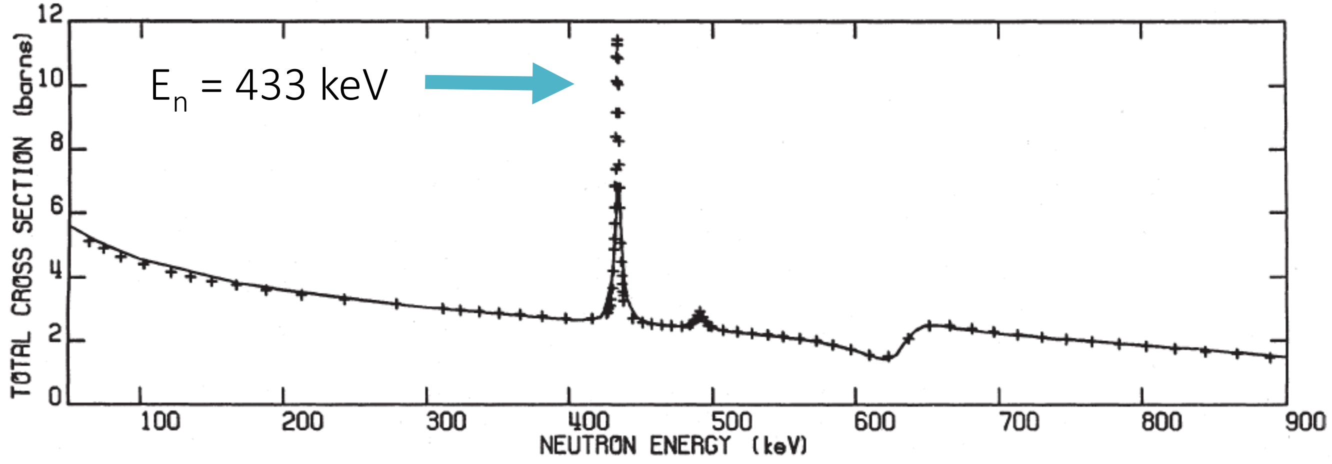


Wang *et al.* (1991)

E_α = 336 keV
was not observed



Wang *et al.* (1991)



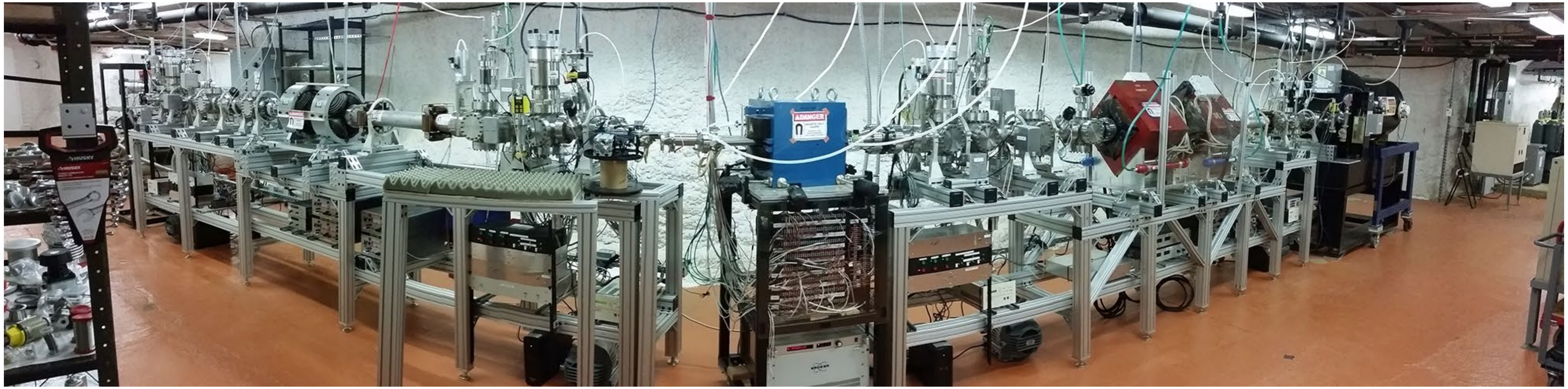
Harvey *et al.* (1992)

$^{11}B(\alpha,n)^{14}N$ at CASPAR (caspar.nd.edu)

Compact Accelerator System for Performing Astrophysical Research

- Michael Wiescher (ND)
- Dan Robertson (ND)
- Frank Strieder (SDSM)
- Tyler Borgwardt (SDSM, now at LANL)

4850 ft level of the Homestake mine in South Dakota



Detector setup

^{3}He tube counters embedded in polyethylene moderator

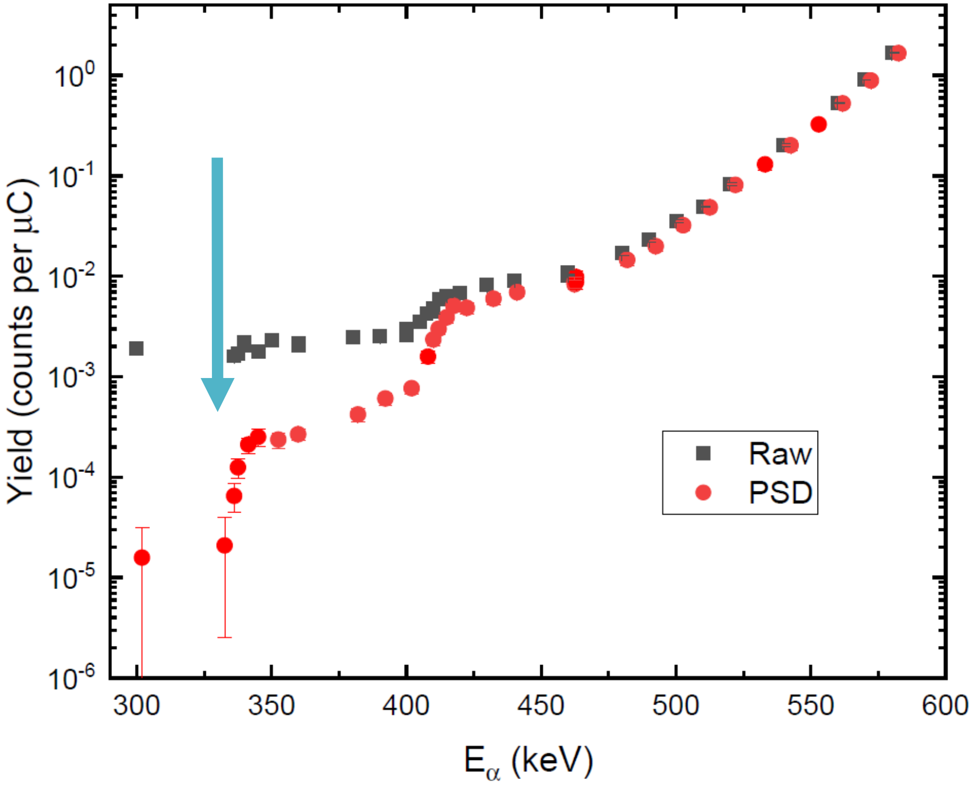
"4π" detector

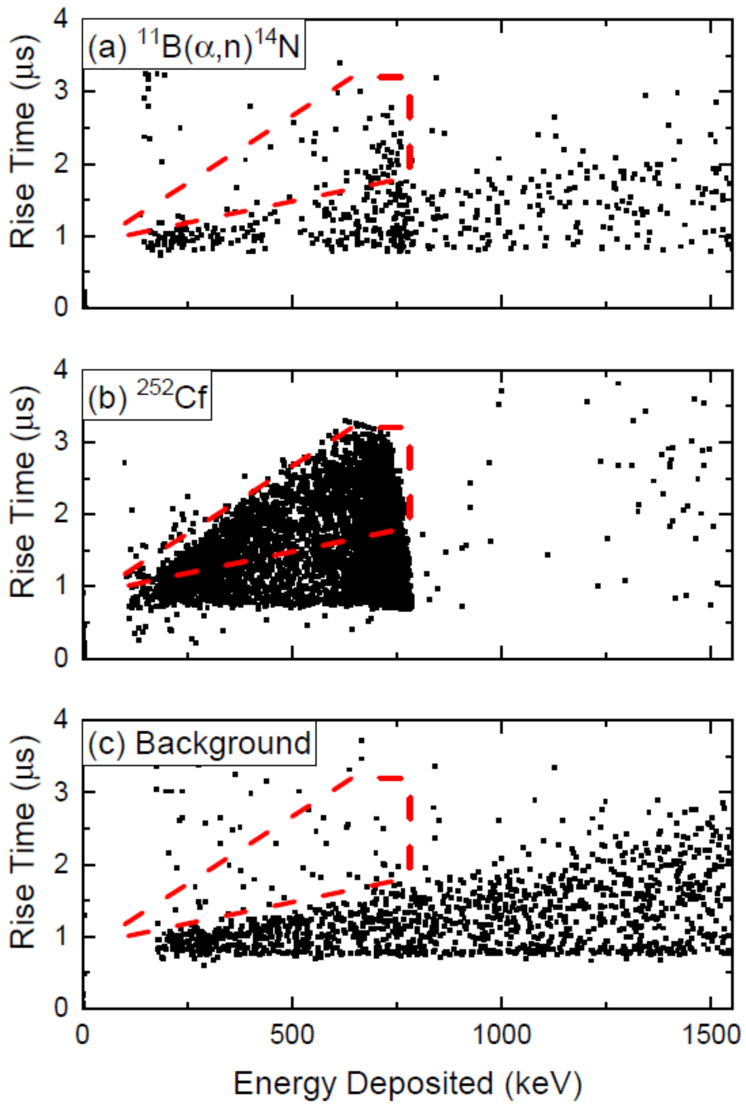
No spectroscopic information, but very high efficiency

Pulse shape discrimination

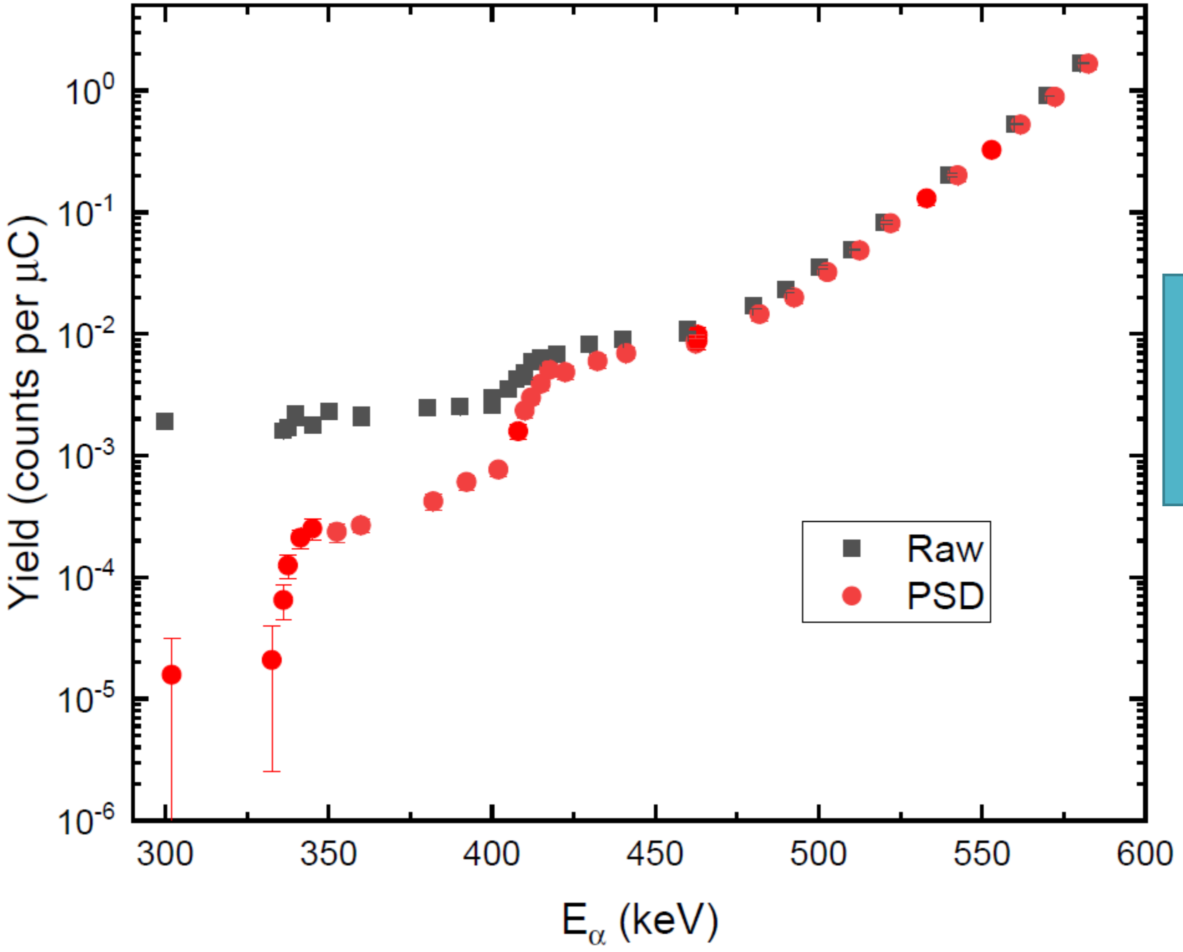
With very low count rates in an underground environment, the count rate of α-particles from actinide decays in the detector material can be very significant.

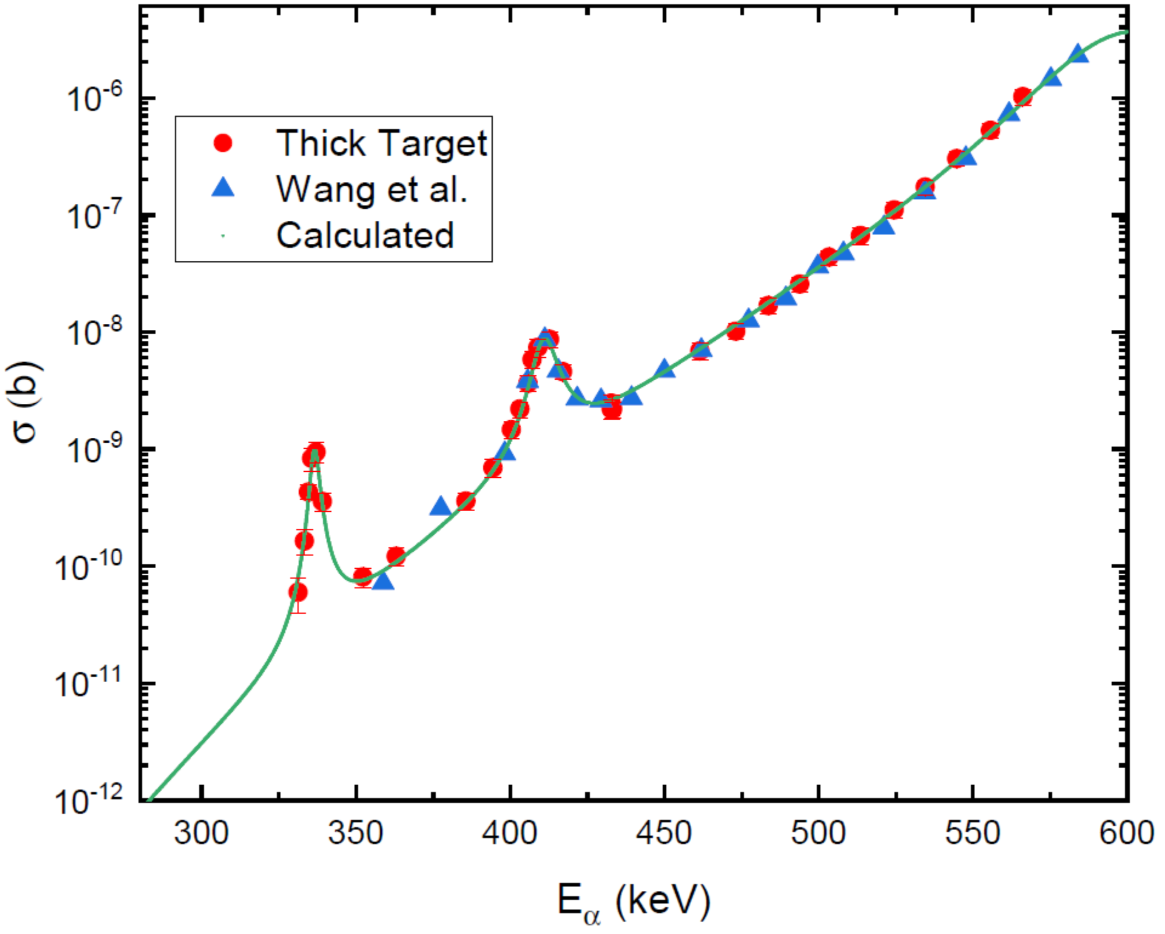
Luckily, the electronic signals have different shapes, so the α-particle signals can be discriminated against with high probability





Thick-target yields





Deconvolution...

Have to assume an underlying shape for the cross section

Would not reproduce the interference regions

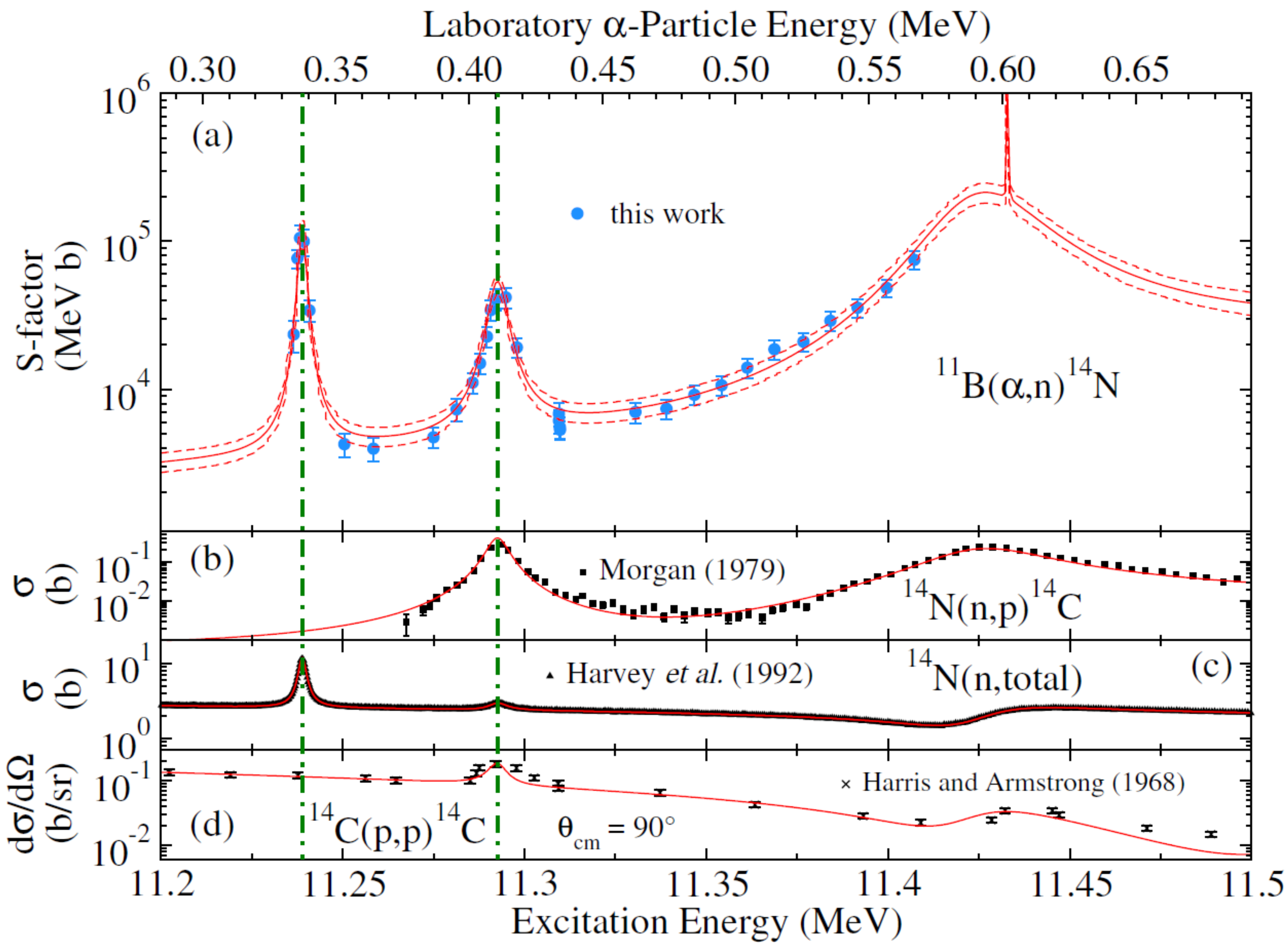
In this case, because the resonances have different J^π, there seems to be little interference

Anyway, I included the data both as the thick-target yields + convolution and the deconvoluted cross sections and did get consistent fits at least with the J^π values as they are presently assumed

Multichannel fit, over a limited energy range

Accepted in PRC

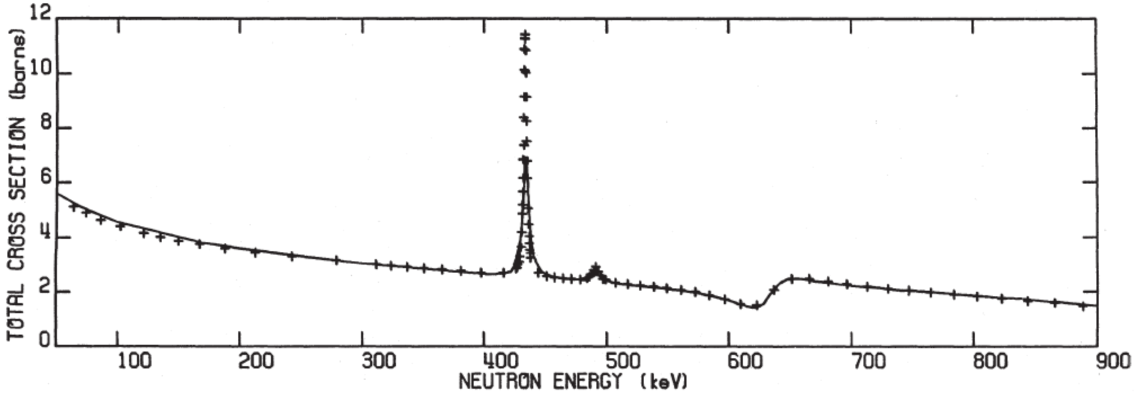
Last corrections were applied and (hopefully) final submission was made last week

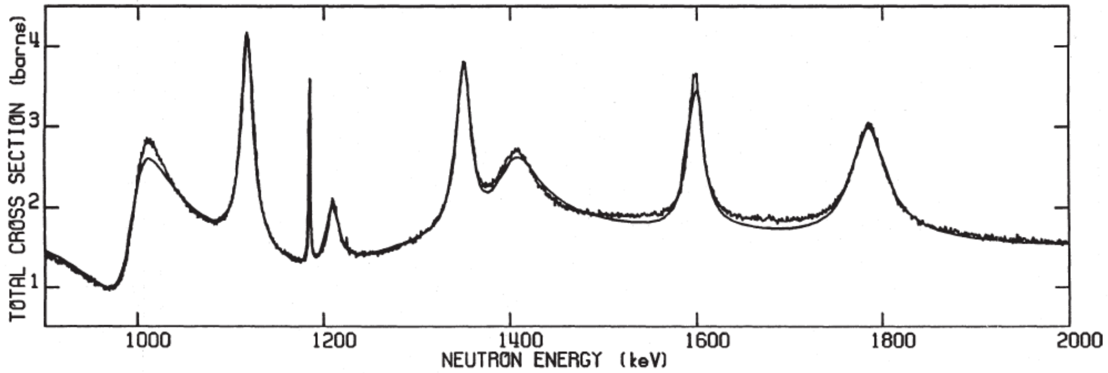


Finally to what this talk is supposed to be about…

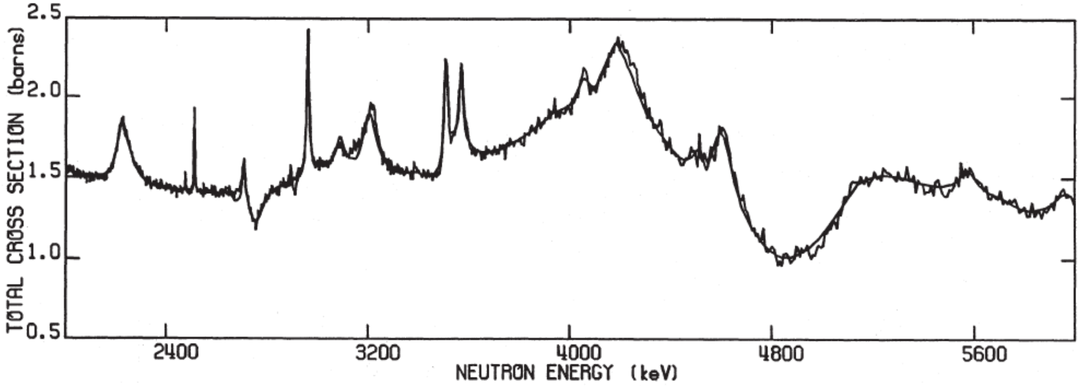
MEASUREMENT OF THE NITROGEN TOTAL CROSS SECTION
FROM 0.5 eV to 50 MeV, AND ANALYSIS OF THE 433-keV RESONANCE

J. A. Harvey, N. W. Hill, N. M. Larson and D. C. Larson
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6356 USA





Looks like a very good measurement, but the publication is pretty light on the details



New measurement at the ELBE facility at HZDR

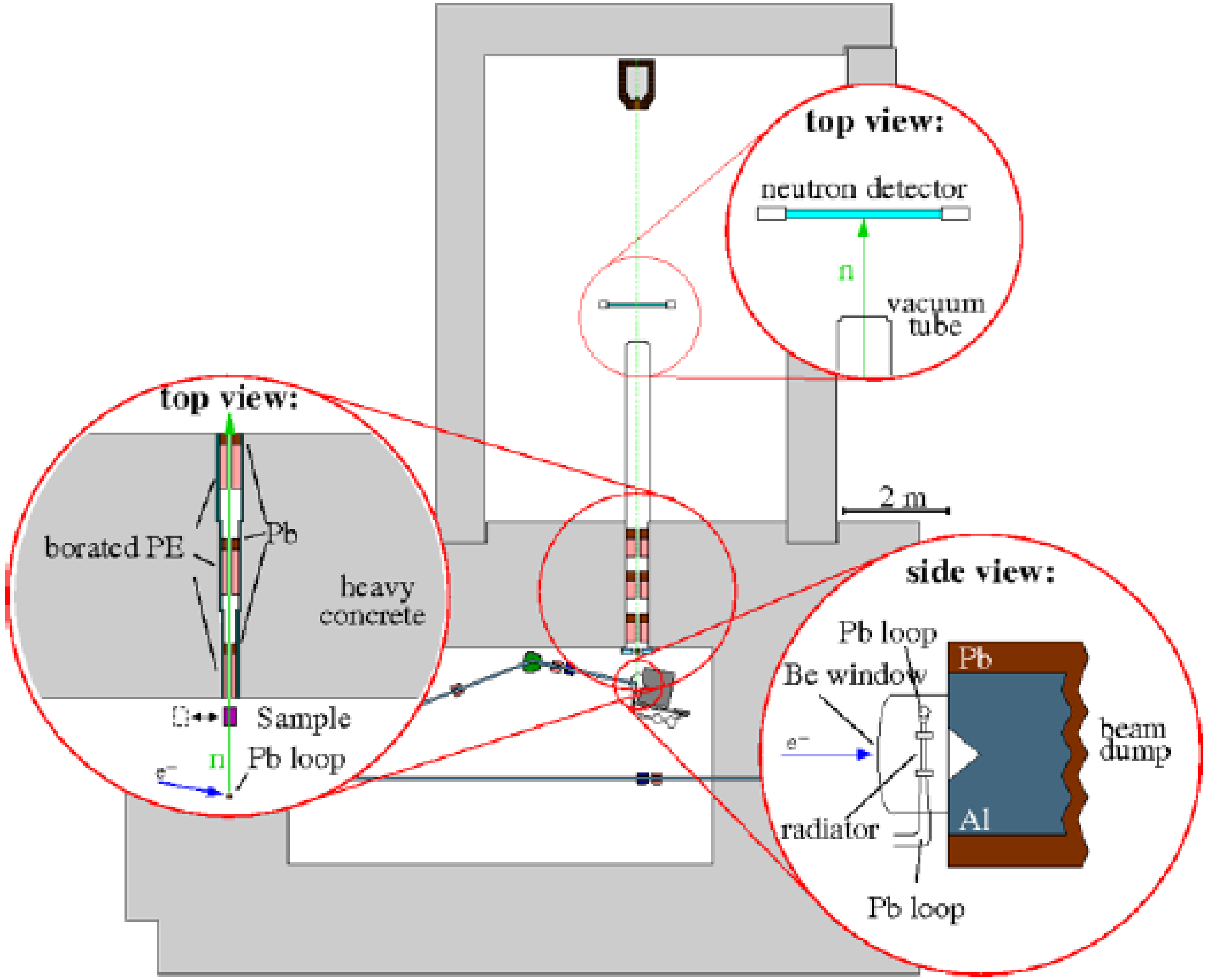
Arnd Junghans and Roland Beyer et al. (2020)

Pulsed electron beam for time of flight

Impinged on a thick liquid lead production target where they produce bremsstrahlung radiation

Neutrons produced by Pb(γ,n), creating a "white" neutron source

Built for fast neutron induced measurements in the keV to MeV range

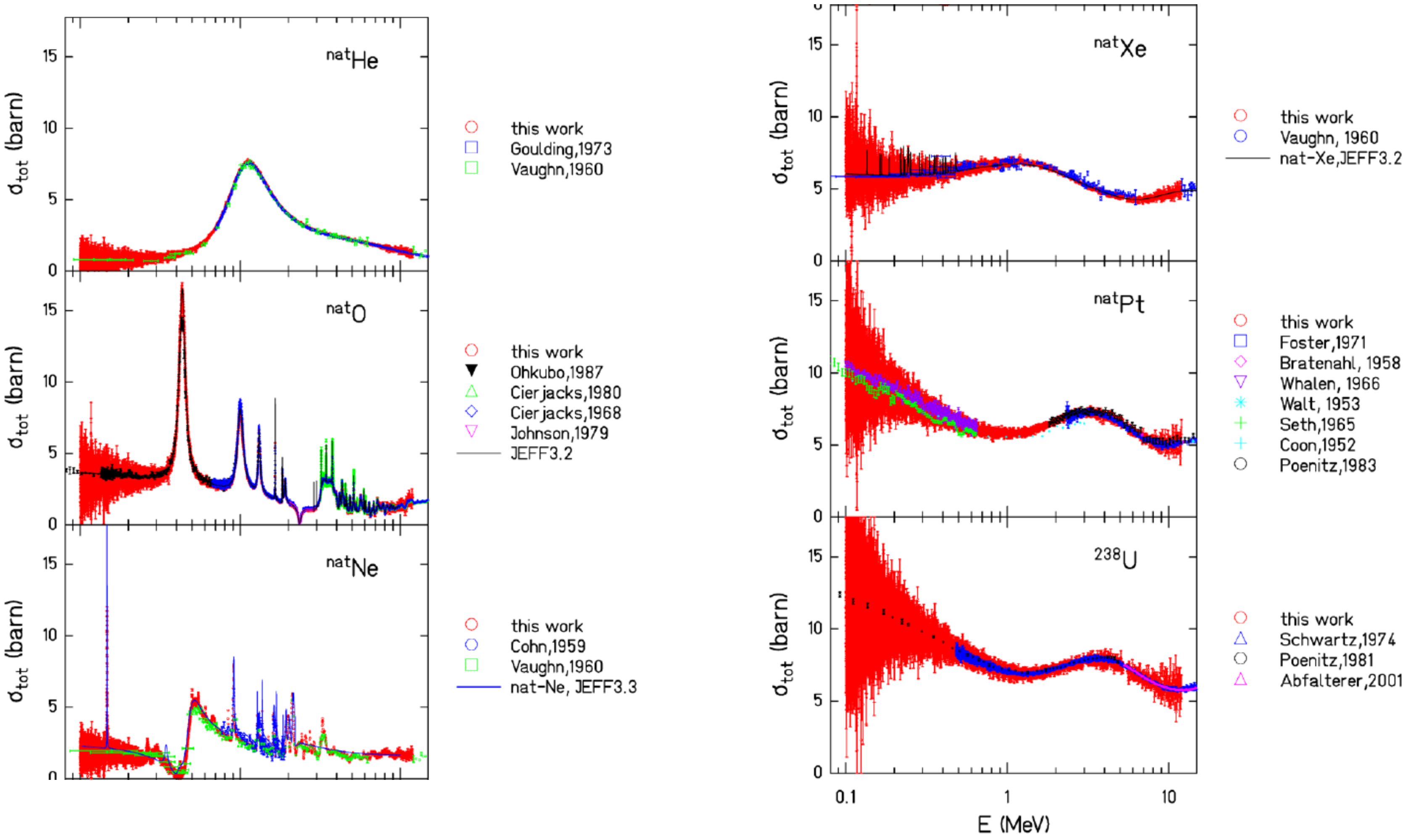


A lot of recent measurements at the ELBE facility

Arnd Junghans and Roland Beyer *et al*. (2020)

For us, the n+16O data is interesting

Also n+Ne for the $^{17}O(\alpha,n)^{20}Ne$ reaction

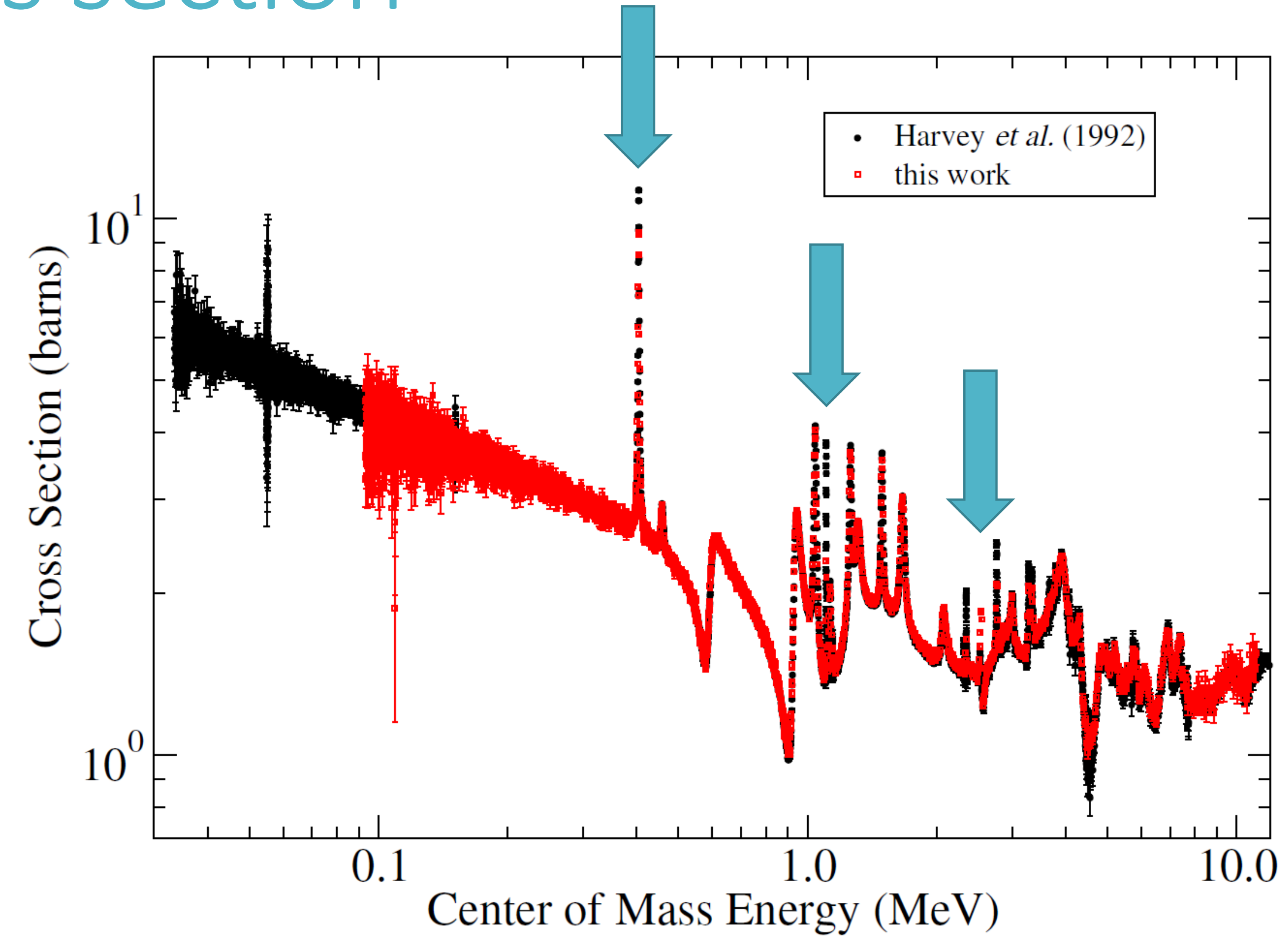


Total n+^{14}N cross section

ELBE measurement is from 0.1 to 12 MeV

Generally good agreement

Our data still have some issues to be sorted out (which I just realized when preparing this talk)



With the very small uncertainties, there are some differences

433 keV resonance (the lowest energy resonance in n+^{14}N)

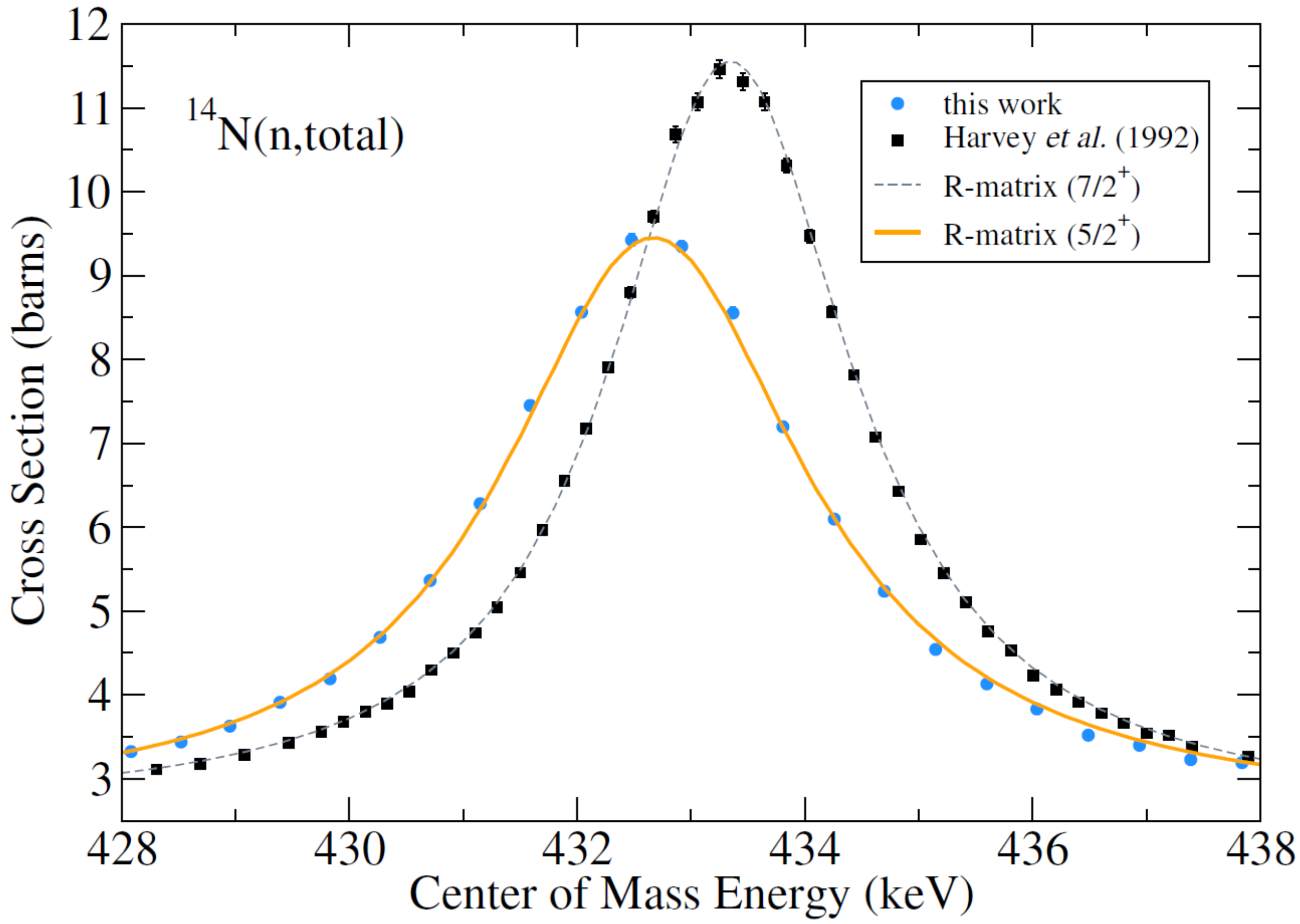
This was also one of the only things Harvey et al. (1992) discuss. They give a J^{π} assignment of $7/2^{+}$, which I confirm based on their data.

Previous measurements (Johnson *et al*. (1951) and Hinchey *et al*. (1952)) lacked the resolution to give any restriction except J>1/2.

However, our new data give a smaller maximum cross section inconsistent with $7/2^{+}$, but consistent with $5/2^{+}$.

Our experimental resolution over this resonance is about 0.1 keV, which gives only a very small distortion to the observed shape.

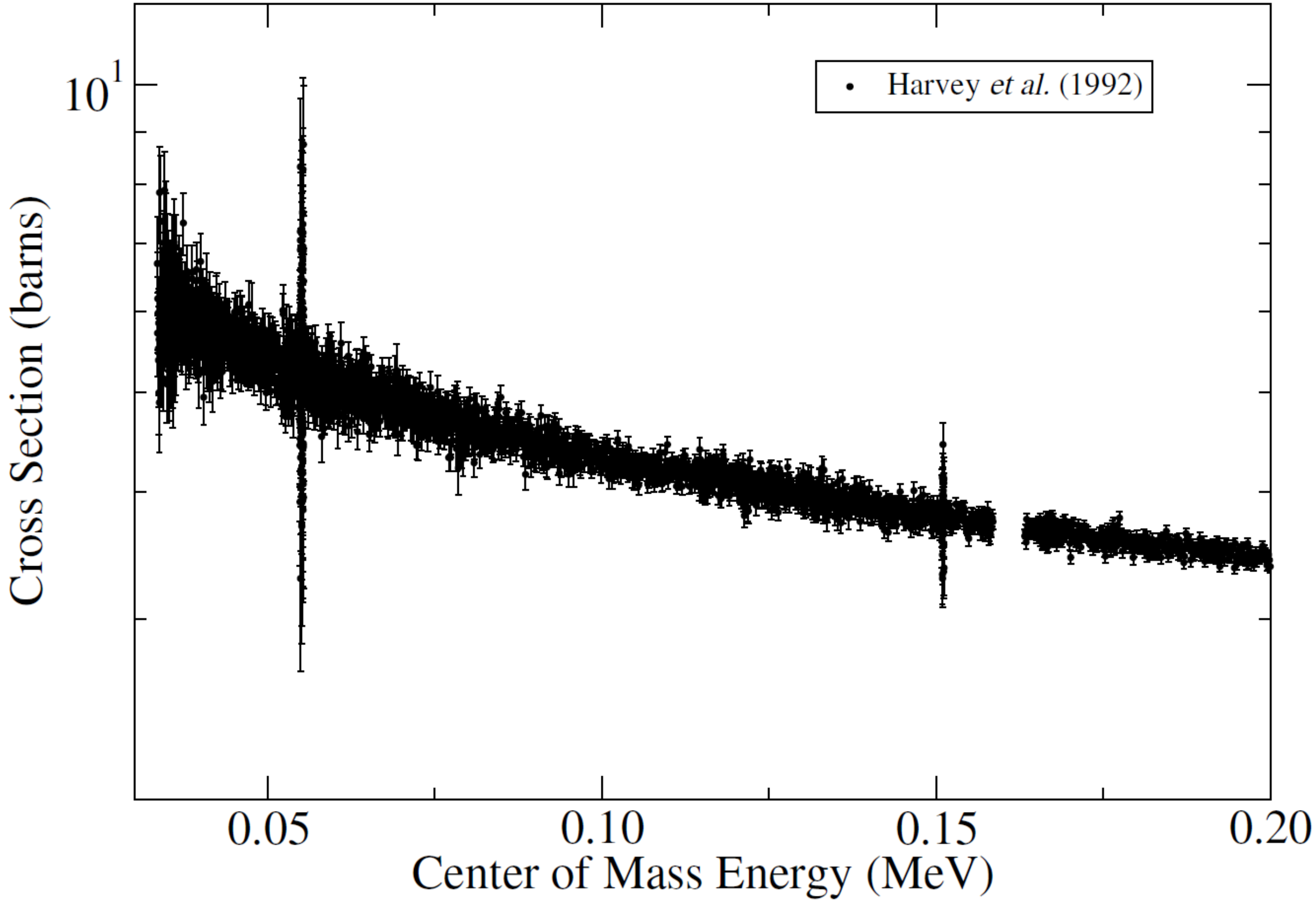
Energy shift: 433.35(3) → 432.67 keV (preliminary)



Low energy Harvey data

Two “spikes”, what are those?

(“hole” is where I cut out some data because of AZURE2 numerical problems near the proton threshold)

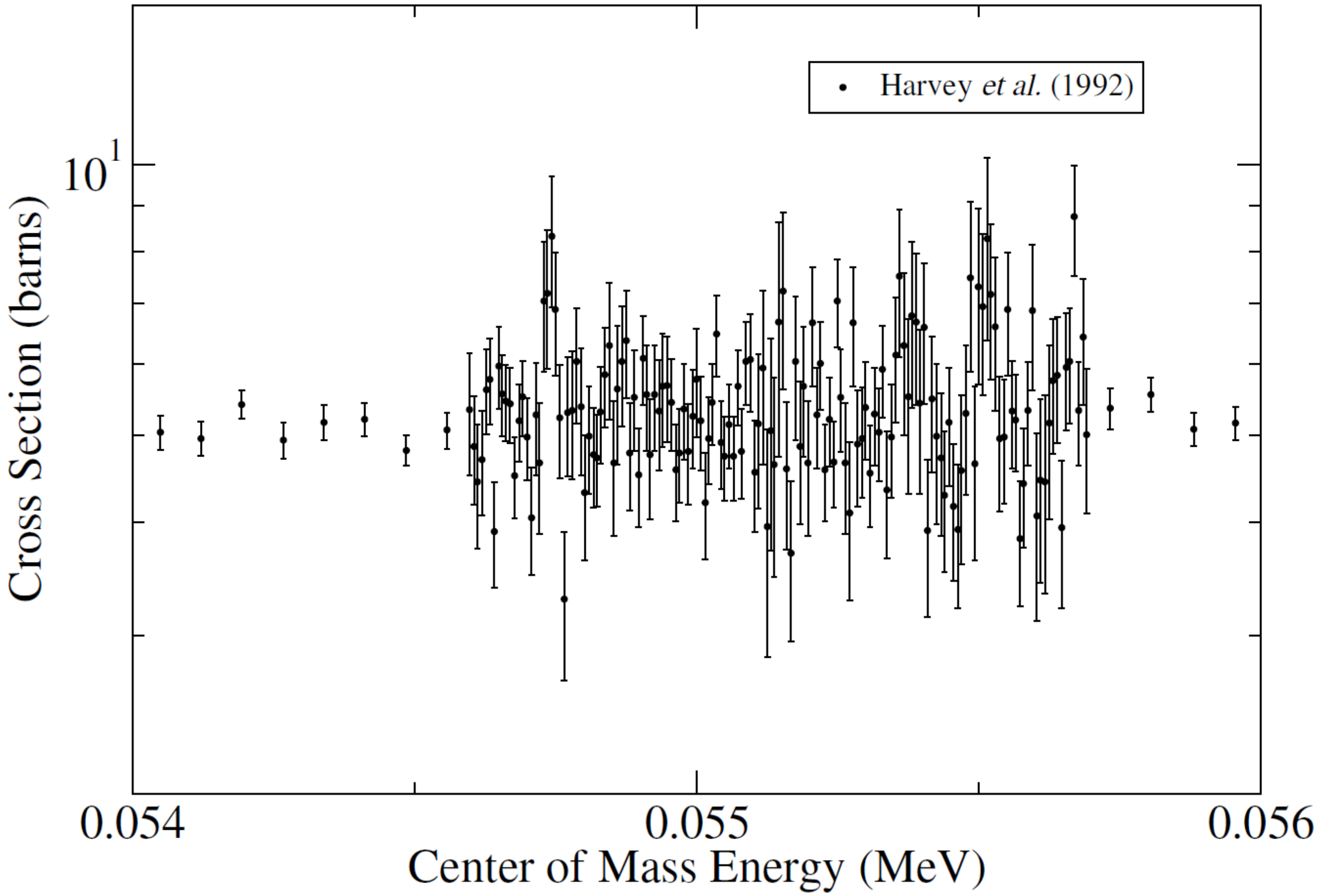


Really zoom in

This just seems to be a place where they forgot to “rebin”.

Looks like no statistically significant structure

This energy range would be about E_x = 10835 keV. No known level reported here.



A review of experimental capture data for the ^{7}Be evaluation

James deBoer

University of Notre Dame

Quick history of past problems and solutions

$^3He(\alpha,\gamma)^7Be$

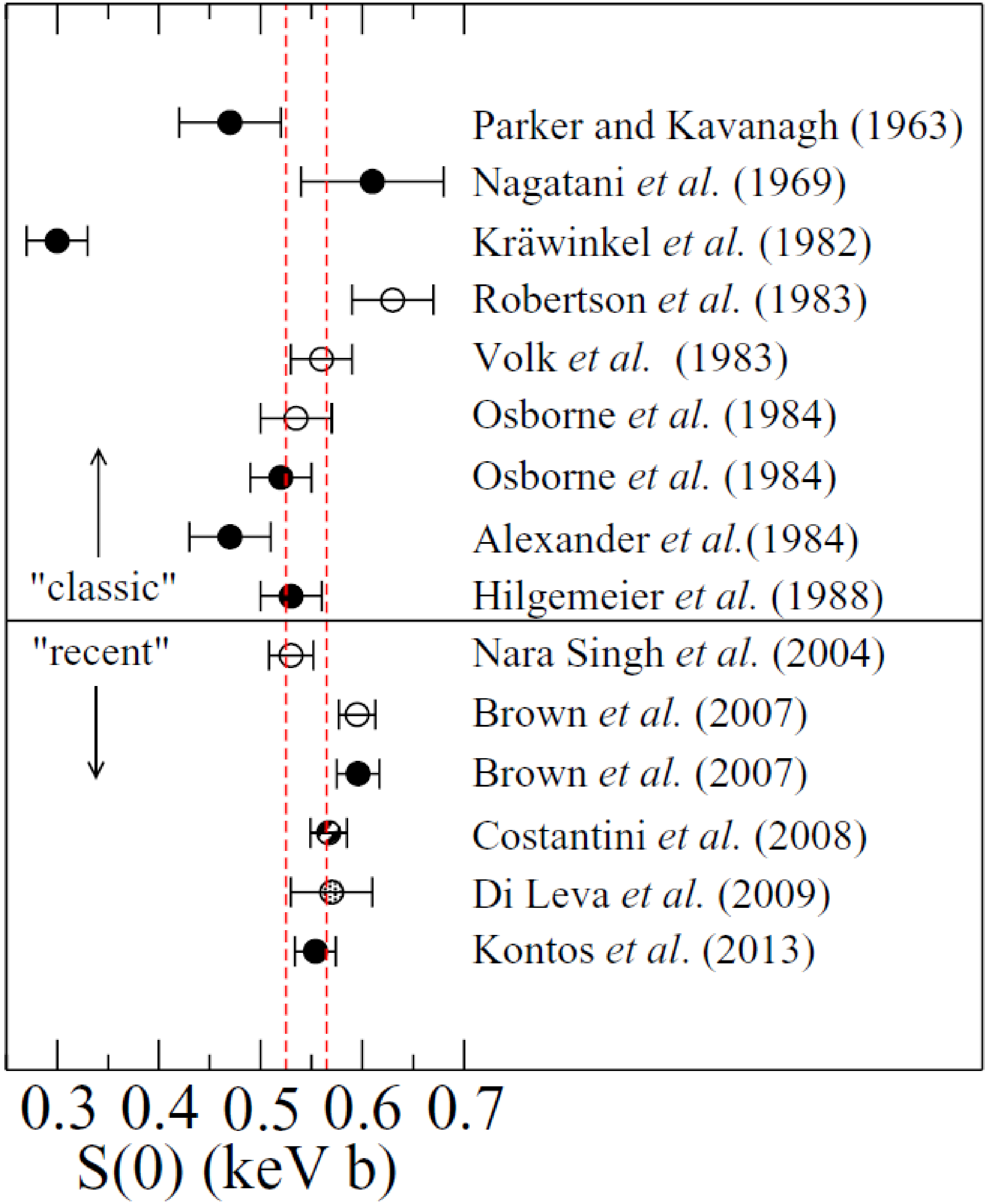
- 1961 – Christy and Duck model the reaction using external direct capture
- 1963 - Parker and Kavanagh make the first really detailed measurements
- 1982 – Rolfs famously erroneously reports a measurement of the reaction a factor of 2 smaller than those previously claiming to solve the solar neutrino problem.
- 1998 – SFI Highlights the tension at 2.5σ level between prompt and activation measurements
- 2009 – Di Leva et al. make a very comprehensive recoil measurement for the first time and measure to higher energies than Parker and Kavanagh
- 2011 – SFII finds that consistency has now been obtained for measurements post 2000. Several more measurements have been made that all are consistent. All later evaluations only use data post 2000 for this reason and because of incomplete uncertainty quantification.
- 2014 – deBoer *et al*. (really Uberseder) finds that a combination of external and internal capture is needed to fit the higher energy ERNA data
- 2019 – 2023 Measurements at ATOMKI explore the cross section at higher energies
- 2020 – Kiss et al. report first measurement of ANCs, but they are substantially larger than those found from *R*-matrix and EFT fits
- 2022 – Odell *et al*. solve issue with inconsistent simultaneous fit with scattering data
- Future – Hopefully someone remeasures the ANCs soon

$^6Li(p,\gamma)^7Be$

- 1979 – Switkowski makes the first comprehensive measurements from 200 to 1200 keV. The branching ratio between ground state and first excited state is assumed to be constant in energy over this range
- 1980 – Barker uses fits to $^6Li(n,\gamma)$ to calculate $^6Li(p,\gamma)$
- 2004 – Prior *et al*. measure ground state to first excited state branching ratio and compare with previous determinations
- 2013 – He *et al*. (aka Rolfs again) reports a new measurement where the cross section is found to unexpectedly decrease rapidly at low energy (James tells them this is impossible but they publish anyway)
- 2013 to present – several theory and indirect measurements made that don't support this decreasing cross section.
- 2020 – Piatti *et al*. (LUNA) measure the reaction over the same energy range and find no down turn. In fact, their data show an anomalous increase in cross section at low energy (which they don't highlight)
- 2021 – Kiss *et al*. report first measurement of ANCs
- Future – Possible remeasurement at LUNA

S-factor

Post 2000 measurements give S(0) extrapolations with about 4% uncertainty



The angular distribution of the $^{3}He(\alpha,\gamma)^{7}Be$ reaction

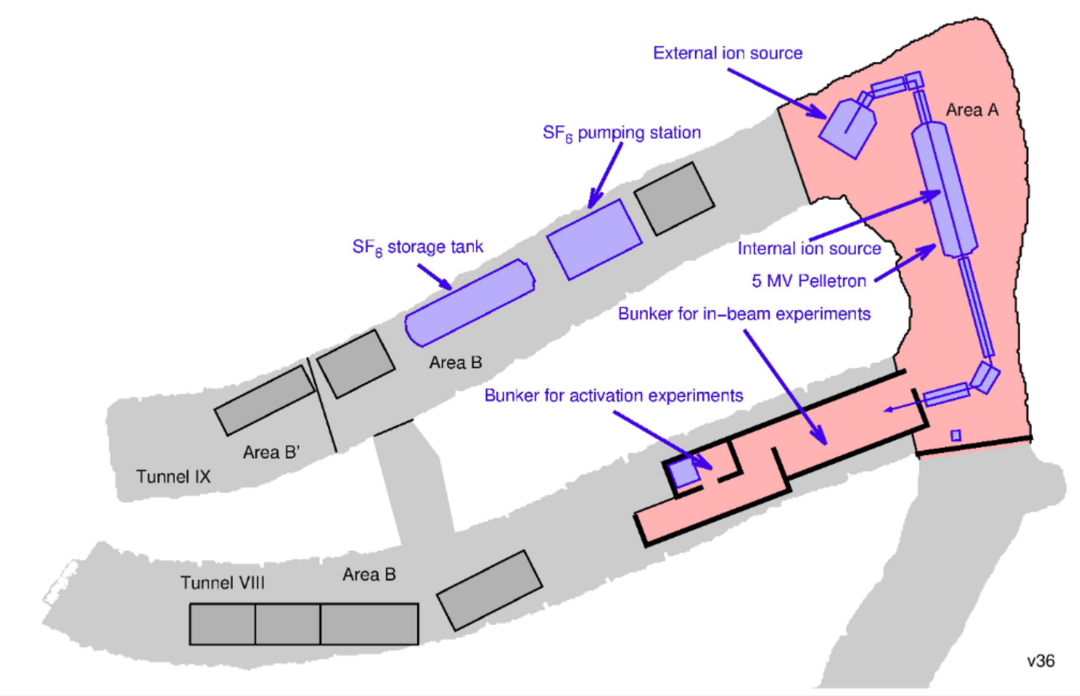
Not measured!

Everyone takes old theory calculations from the 1960's

Ongoing effort at the Felsenkeller underground lab at HZDR, but not yet published

The Felsenkeller underground ion accelerator lab

The Felsenkeller underground ion accelerator lab has been built jointly by HZDR (group of Daniel Bemmerer) and TU Dresden (group of Kai Zuber). Felsenkeller science is based on two major installations: A 5 MV Pelletron ion accelerator (Berufungsmittel Prof. Dr. Thomas E. Cowan) and a 163% high-purity germanium detector (DFG Großgeräteprogramm Prof. Dr. Kai Zuber). The construction of the lab was supported by TU Dresden (Excellence Initiative, "support the best" fund for Prof. Dr. Kai Zuber), and by HZDR.



Felsenkeller, layout of tunnels VIII and IX.

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Measurement summary for $^3He(\alpha,\gamma)^7Be$

Parker and Kavanagh (1963) – 10% (combined)

Nagatani, Dwarakanath, and Ashery (1969) – 5% (combined?)

Krawinkel *et al*. (1982) – 12%R (combined)

Osborne *et al*. (1982, 1984) -- ??

Robertson *et al*. (1983) – 4.2%

Volk *et al*. (1983) – 9% or less (combined, complicated)

Alexander *et al*. (1984) – 6% (these do some to be separated)

Hilgemeier *et al*. (1988) – 3.6%R?? (combined)

(see Adelberger *et al*. (1998, 2011) aka SFI & II for a great review)

Singh et al. (2004) – 3.7%

Brown et al. (2007) – 3.0%a, 3.5%p

The LUNA mess - Bemmerer *et al*. 2006, Confortola *et al*. (2007), Gyurky *et al*. (2007), collected in Costantini *et al*. (2008) – 3.2%a, 3.8%p

Di Leva *et al*. (2009) – 5%a

Carmona-Gallardo *et al*. (2012) – 3%

Bordeanu *et al*. (2013) – 6%

Kontos *et al*. (2013) – 8%

Szucs *et al*. (2019) – 4.6% (see erratum)

Toth et al. (2023) – 4.3%

Measurement summary for $^{6}Li(p,\gamma)^{7}Be$

Bashkin and Carlson (1955) – 50%

Warren *et al*. (1956) – 50%

Switkowski *et al*. (1979) – 13% (separated errors!)

Ostojic *et al*. (1983) – 8% (combined?)

Tingwell *et al*. (1987) -- ?? (combined?, only angular distributions available)

Prior *et al*. (2004) – (BR's and A_y only)

He *et al*. (2019) – 9%R, (measured relative to (p,α) of Cruz)

Piatti *et al*. (2020) – 11% (separated, but underestimated)

I have been fitting to

Switkowski *et al*. (1979)

Tingwell *et al*. (1987) (angular distributions!!!)

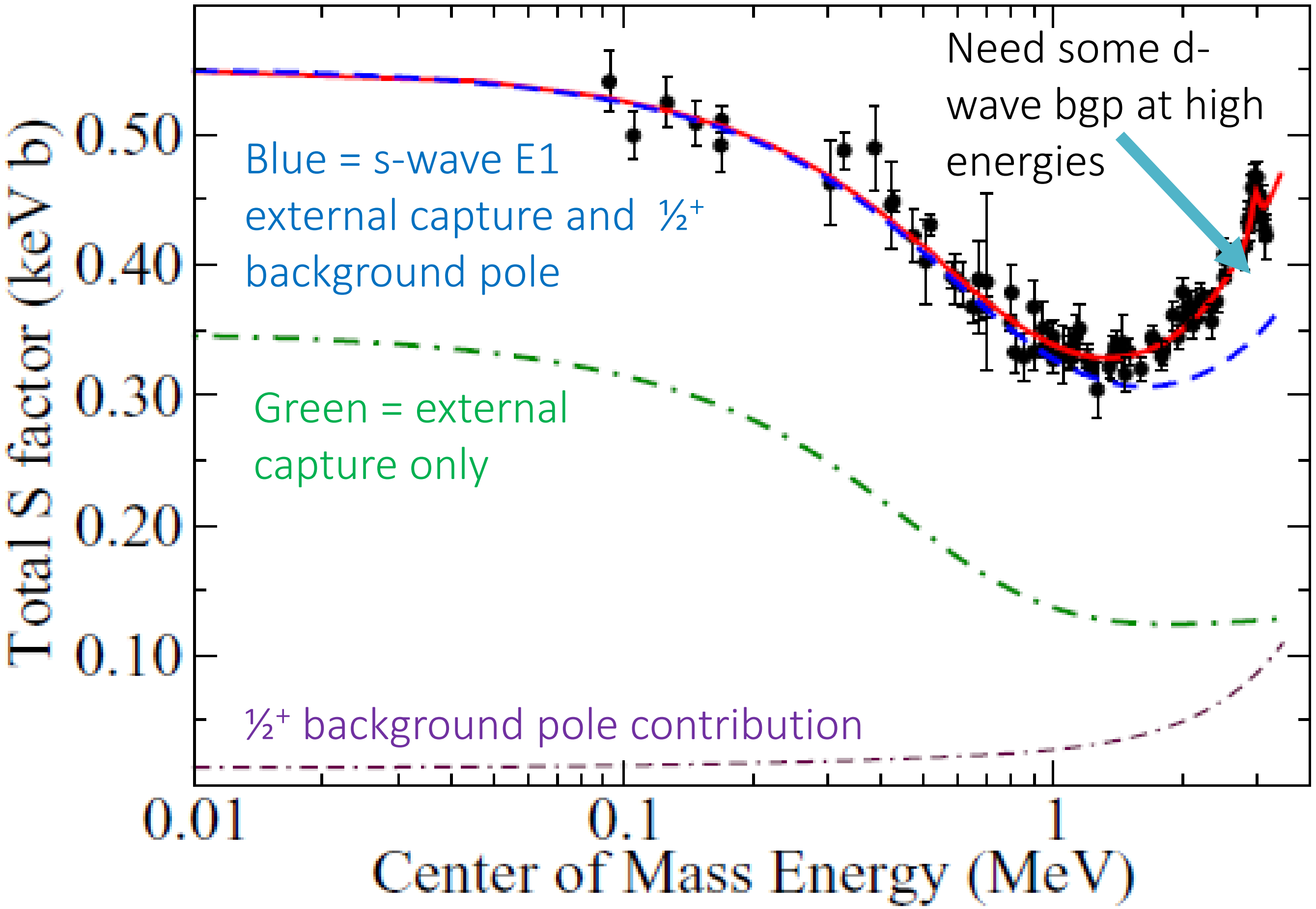
Piatti *et al*. (2020)

Other data are inconsistent or it is unclear how to extract cross sections, but we should have another look

My interpretation of the fit to $^3He(\alpha,\gamma)^7Be$

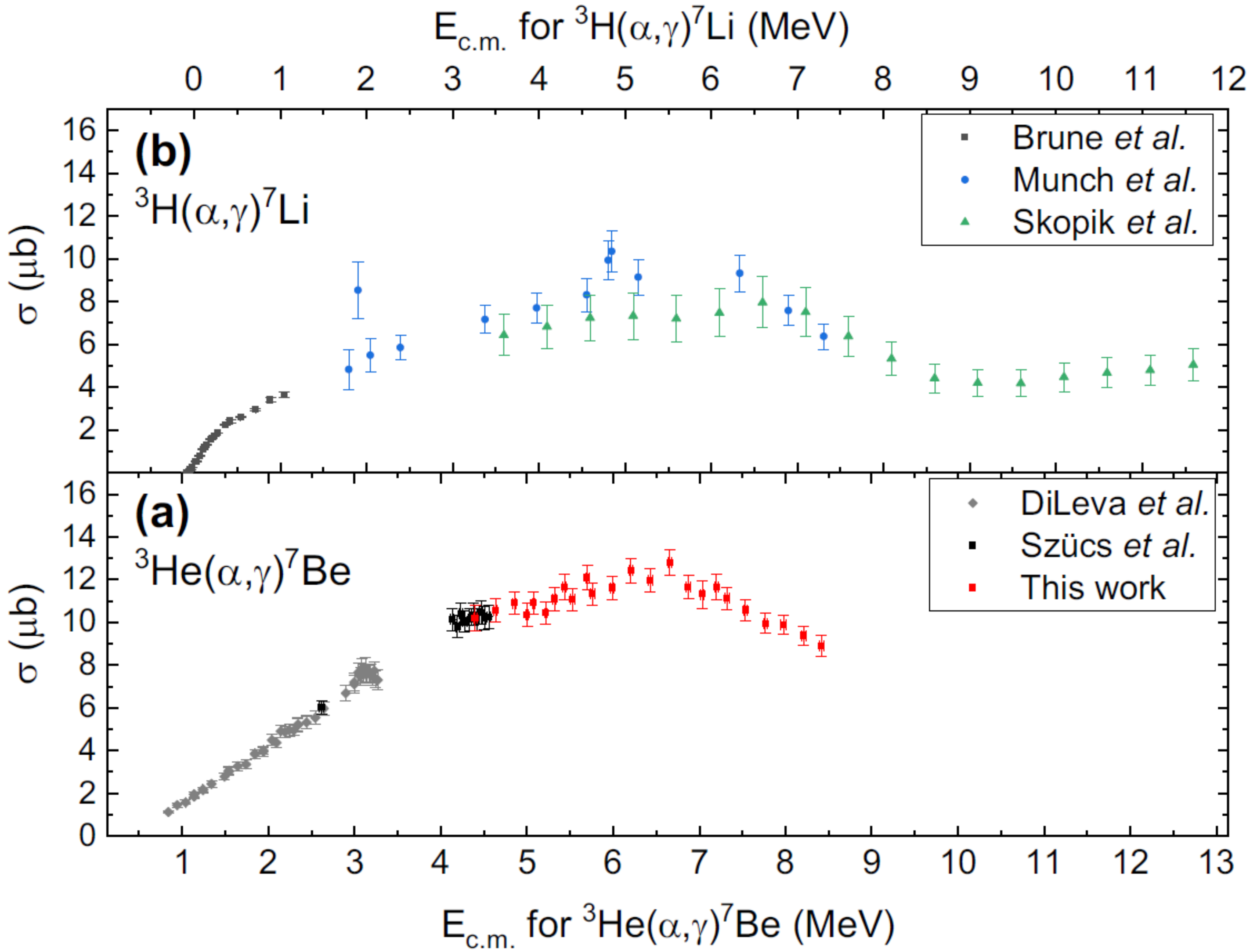
External capture model **plus s-wave background pole**

Interference contribution is proportional to $2\sqrt{\sigma_{BGP}\sigma_{EC}}$



High energy Toth data

Carl Brune recommended a comparing to $^3H(\alpha,\gamma)^7Li$, which has some other high energy measurements



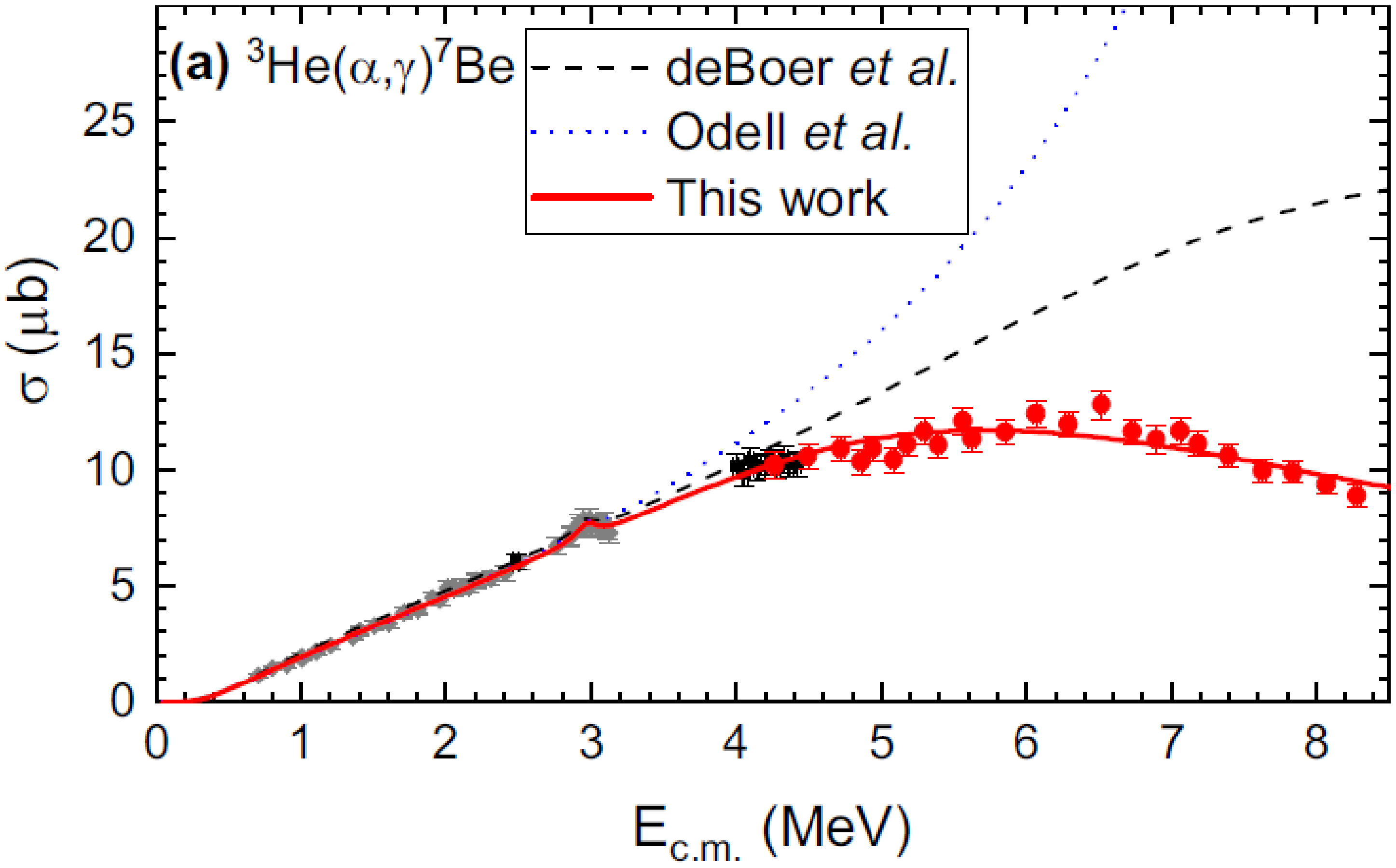
The high energy Toth data

The data seem to indicate a resonance at these higher energies, but none of the known levels in ^{7}Be seem to be able to reproduce the shape

Background levels from R-matrix fits overshoot the data, but maybe not surprising

Toth introduces a very broad ½+ level at E_x= 7.5 MeV with a width of 8 MeV!!!

This looks like an interesting challenge for this group



Experimental results for the $^{13}C(\alpha,n)^{16}O$ reaction and future (α,n) studies at the University of Notre Dame

James deBoer

University of Notre Dame

$^{13}C(\alpha,n_0)^{16}O$ at ND (and OU)

Goal – measure the differential cross section of the ground state reaction from low energy up to 8 MeV

Current status – measurements have been made in two experimental campaigns from 0.8 to 5.5 MeV and from 5 to 8 MeV

- Lower energy measurements are good to go, submitted to PRL
- Higher energy measurements had issues with the zero degree detector above 6.5 MeV, but other data seem to be good. We will, eventually, go back and measure this.

It’s an easy measurement in many respects

Carbon targets are fairly stable

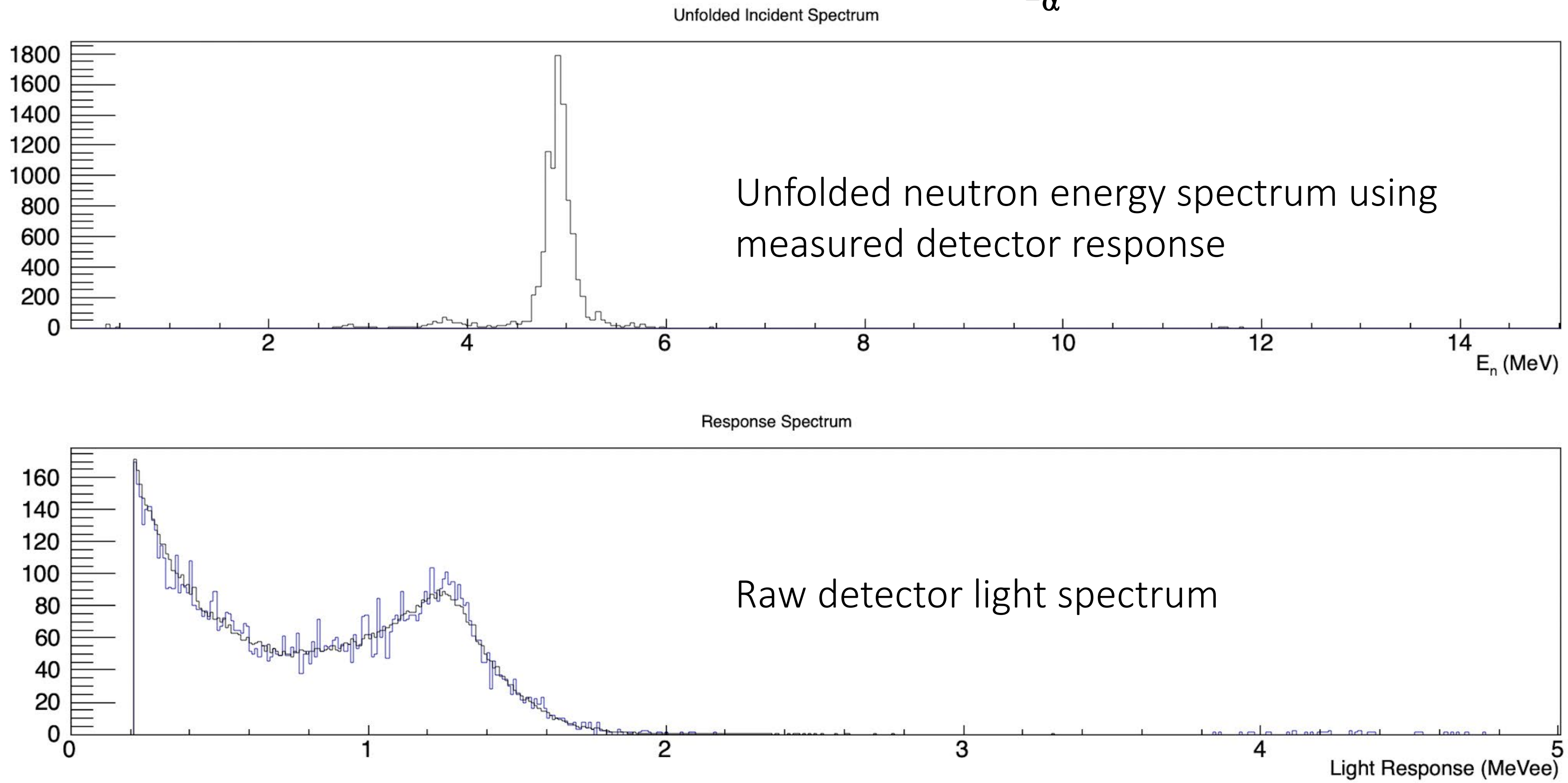
There’s almost no background below 3 MeV!

Walton *et al*. (1957)

Detector is the hard part

1.05 MeV resonance strength has been in error since Bair and Haas?! (more later)

E_α = 2454 keV

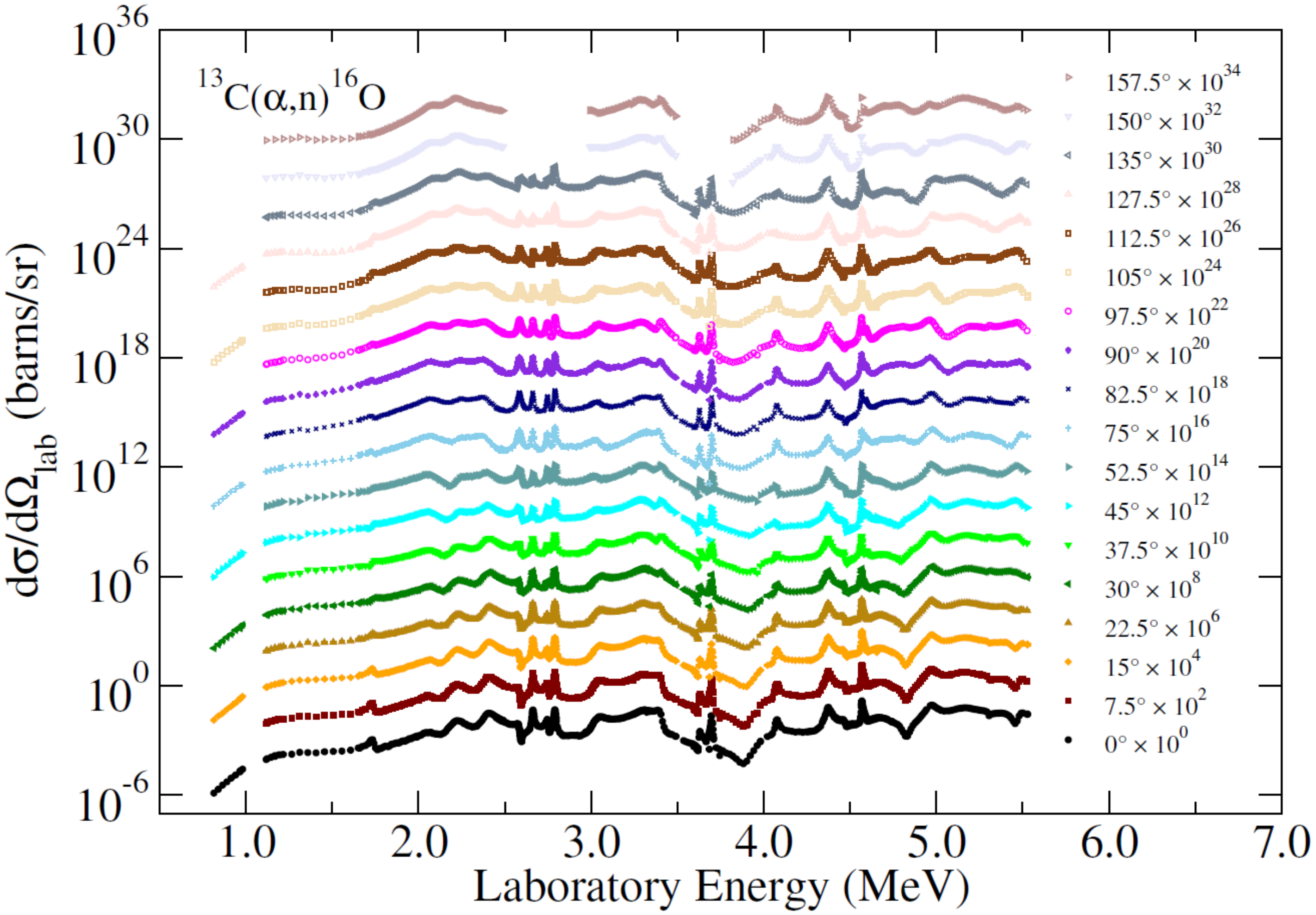


“Low energy” data set

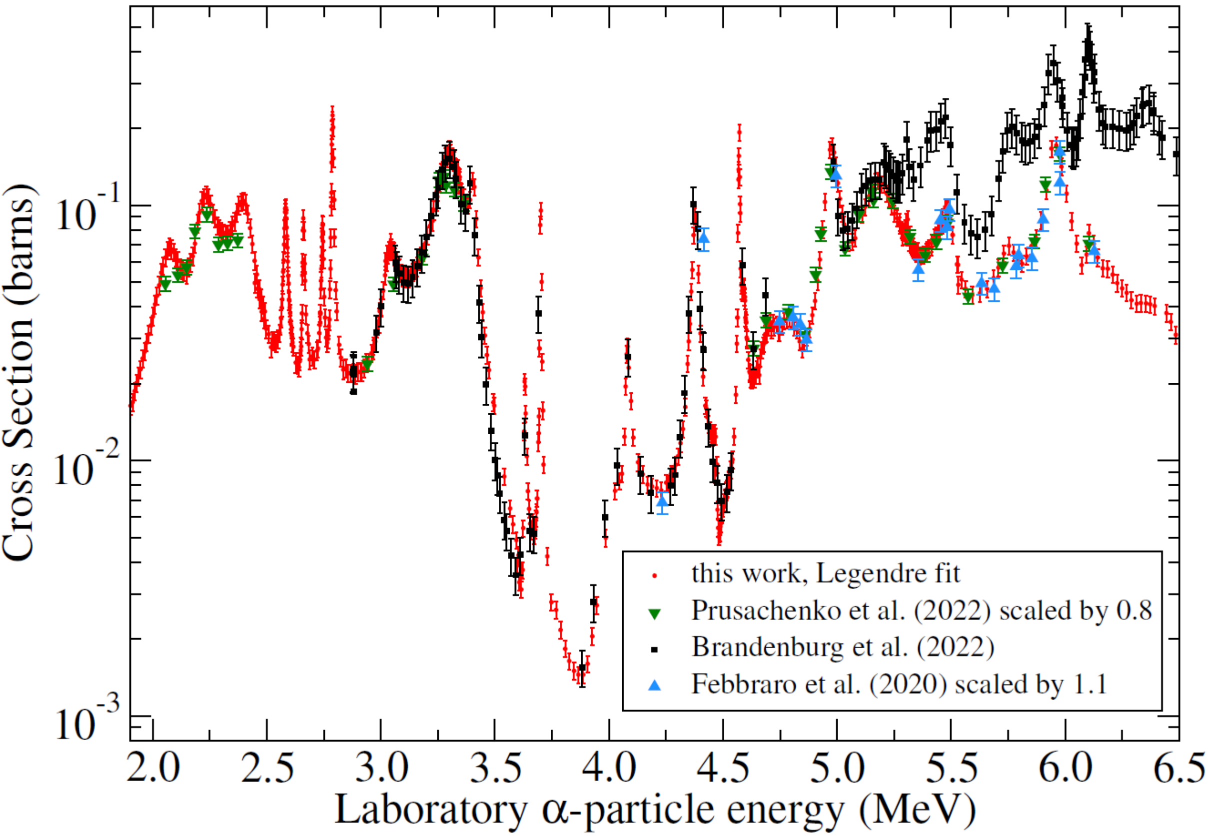
634 energies

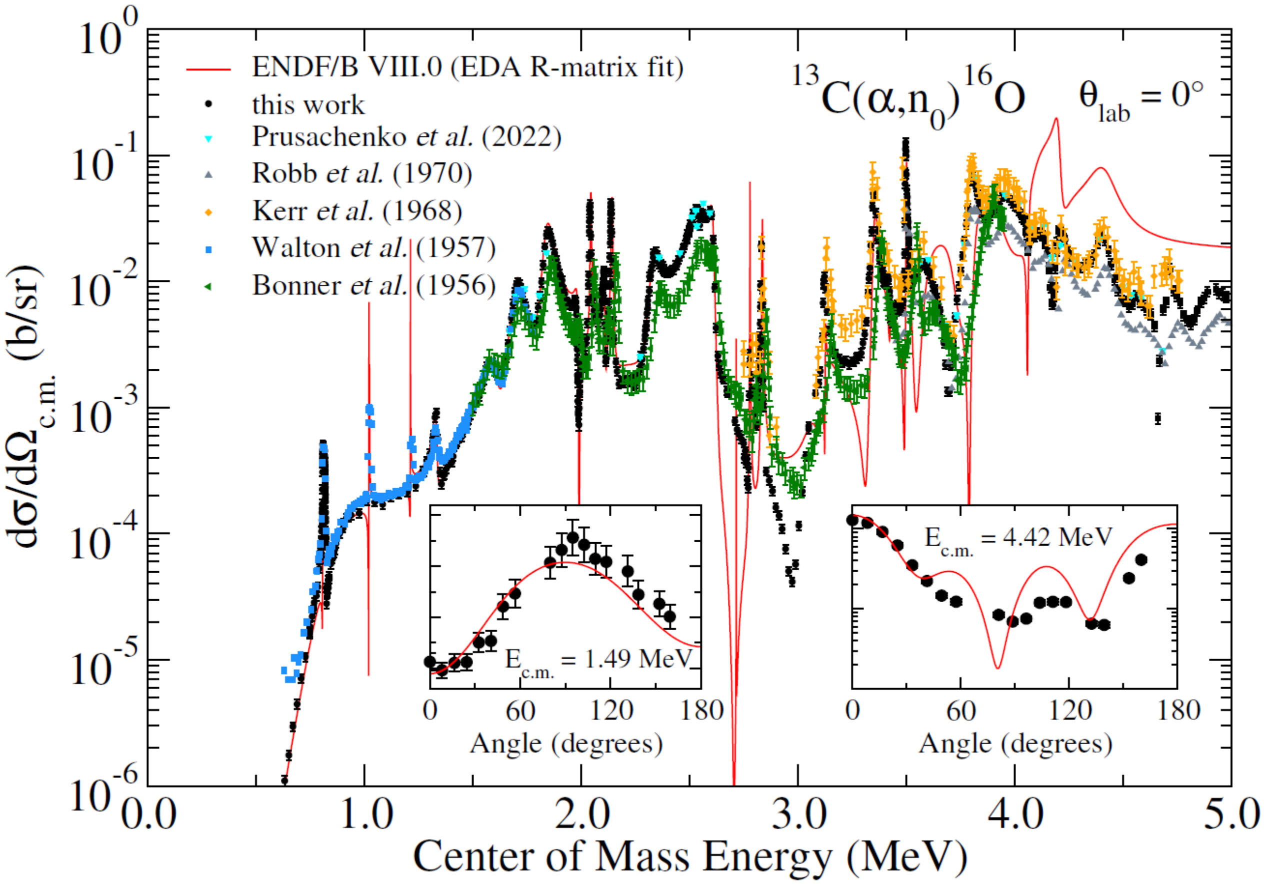
18 point angular distributions for most of the data, 9 point for low energies below 1 MeV

Some issues with most back angle detector where only about ¾ of the data were recorded ☹



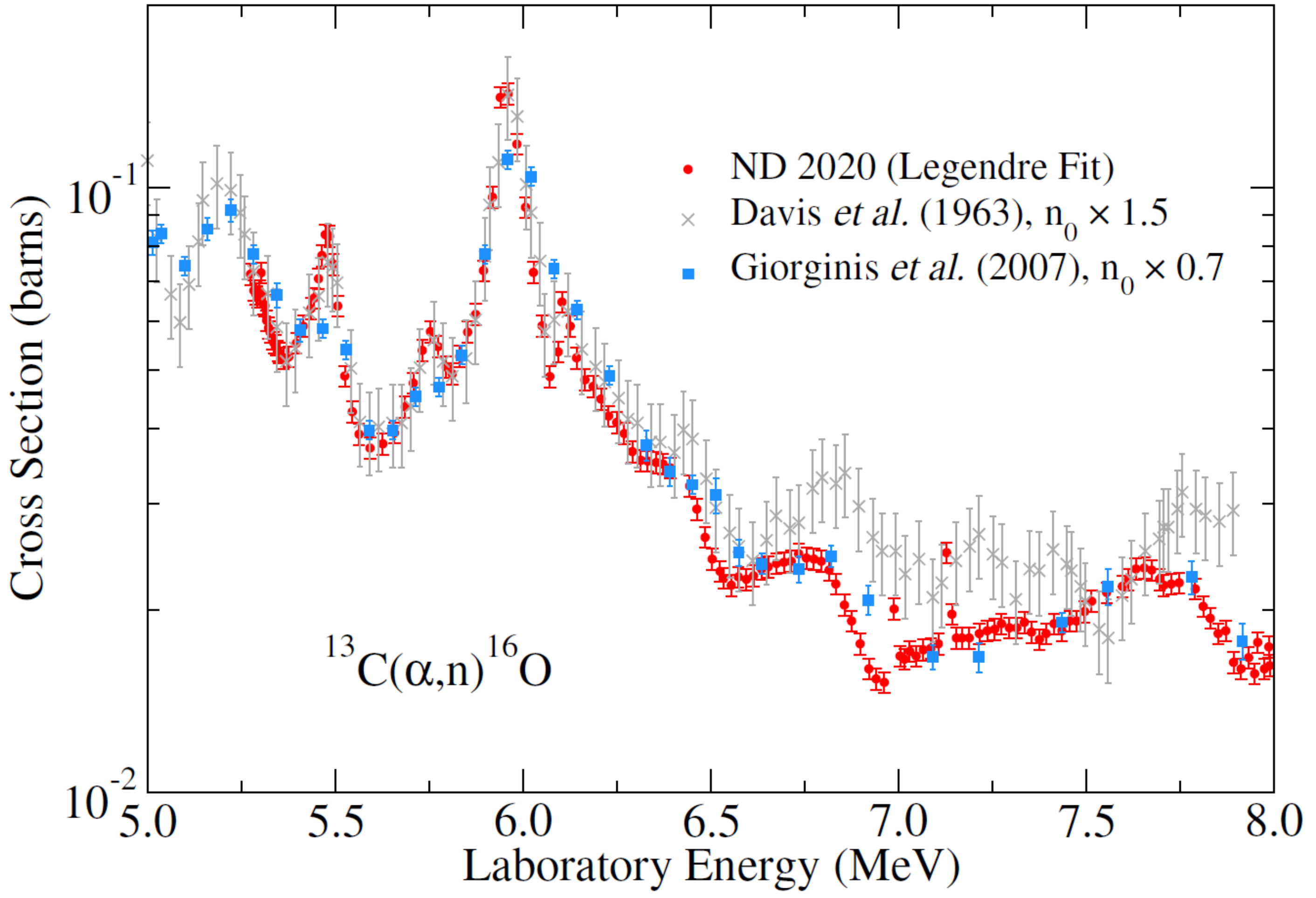
Some cross section comparisons





This higher energy data remains unpublished

I will release this higher energy data to this group now that I am more confident in it

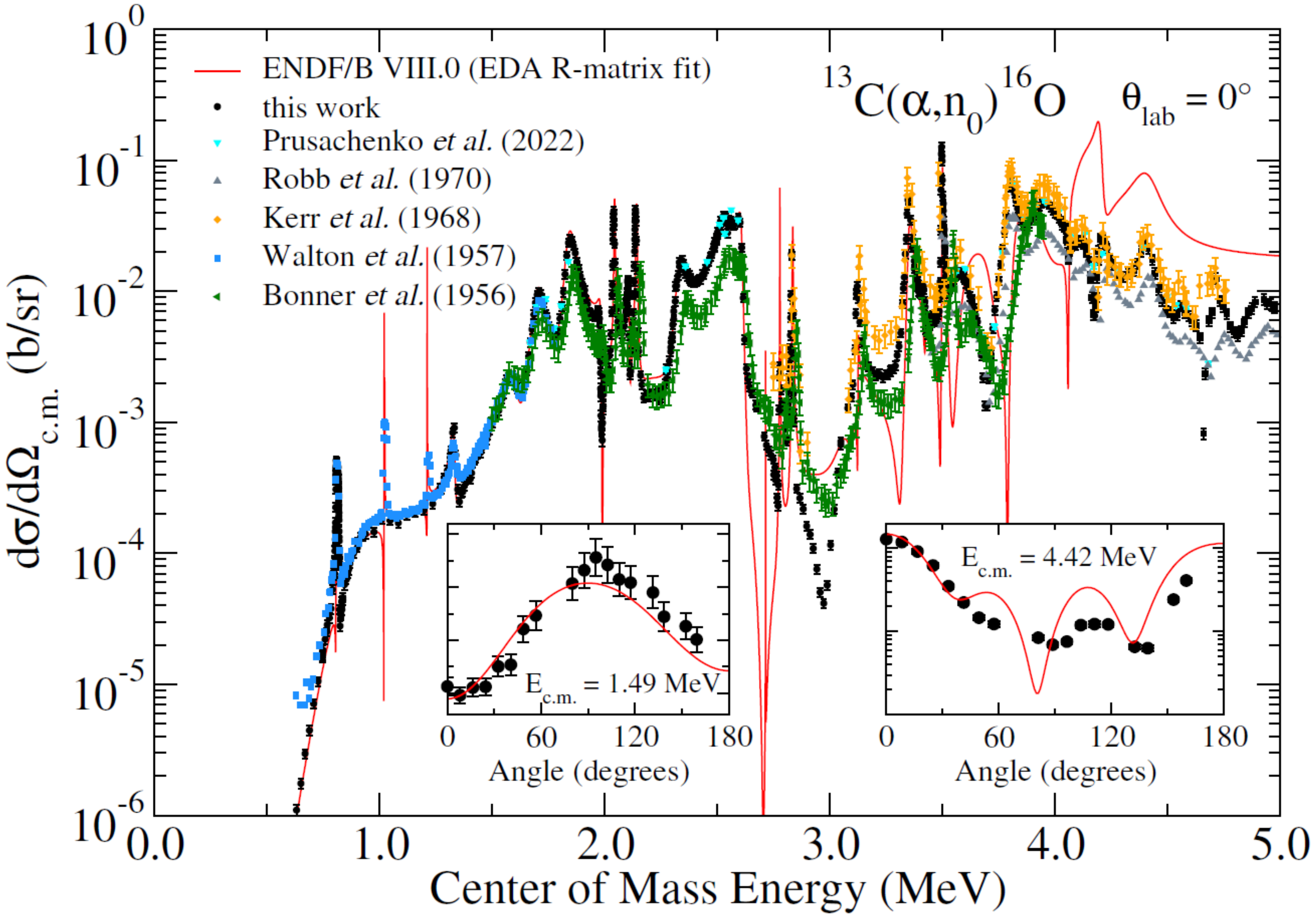


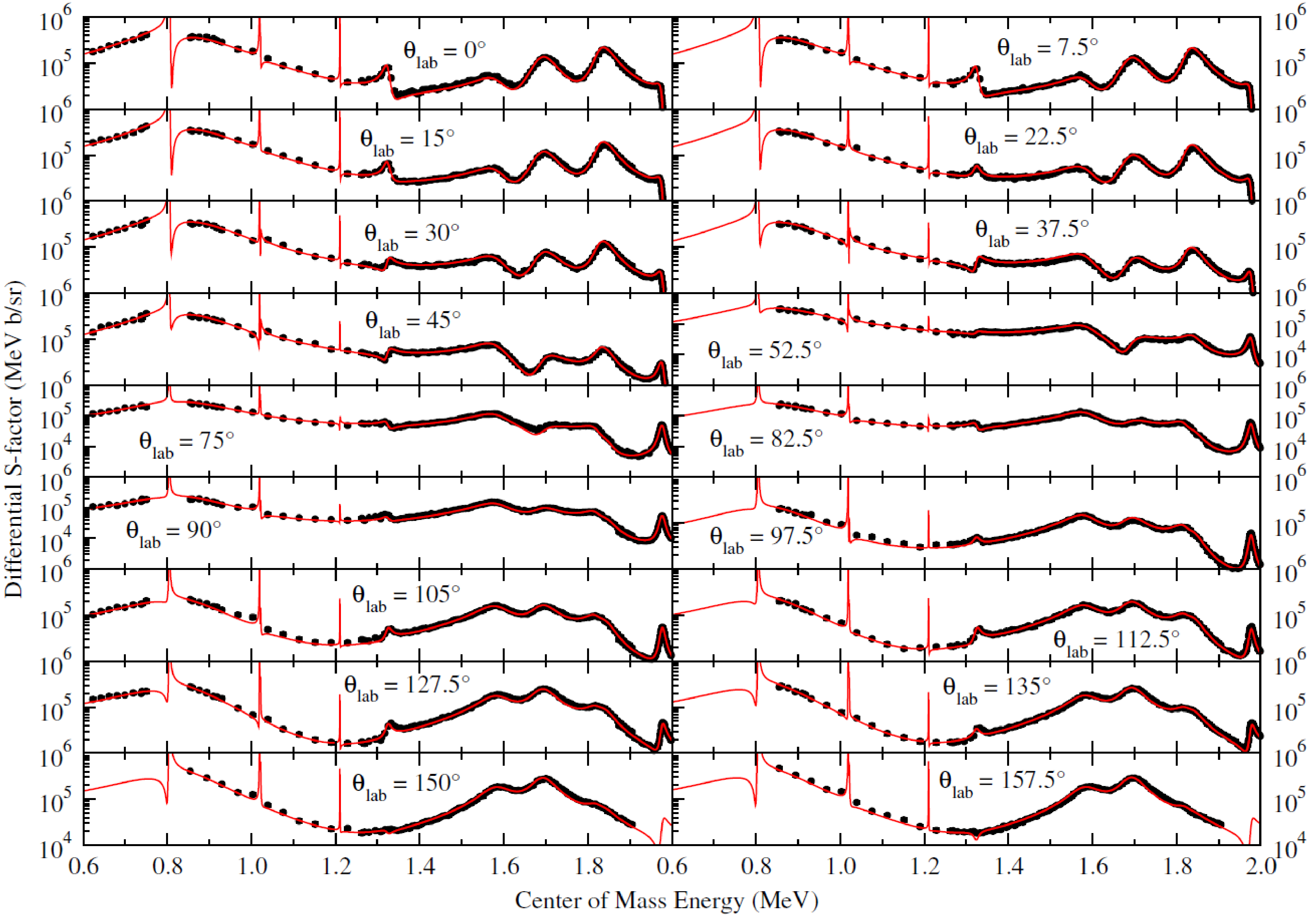
Fit

Uses the ENDF/B VIII.0 parameters from Mark and Gerry as starting parameters (transformed by Carl)

Fit only extends up to 2 MeV center of mass energy so far

Focus is on very low energy extrapolation for nuc astro





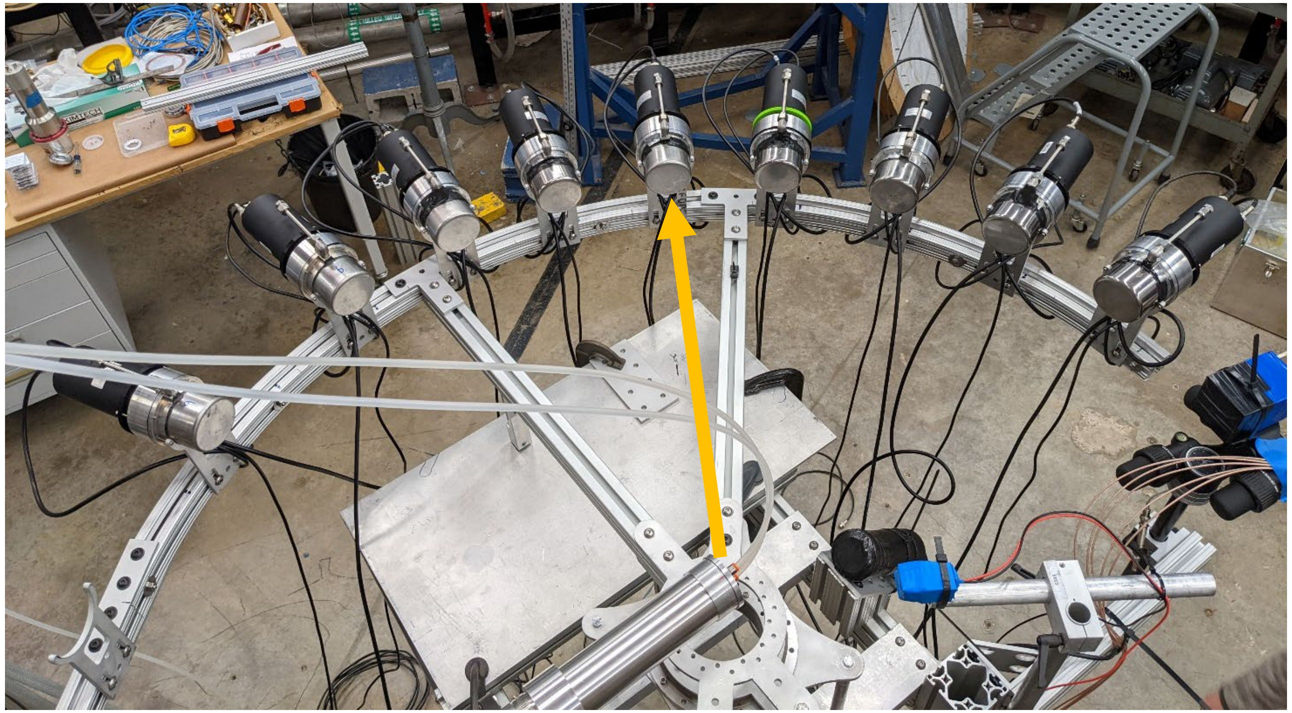
θlab = 0°
θlab = 7.5°
θlab = 15°
θlab = 22.5°
θlab = 30°
θlab = 37.5°
θlab = 45°
θlab = 52.5°
θlab = 75°
θlab = 82.5°
θlab = 90°
θlab = 97.5°
θlab = 105°
θlab = 112.5°
θlab = 127.5°
θlab = 135°
θlab = 150°
θlab = 157.5°
Differential S-factor (MeV b/sr)
Center of Mass Energy (MeV)
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
10^4
10^5
10^6

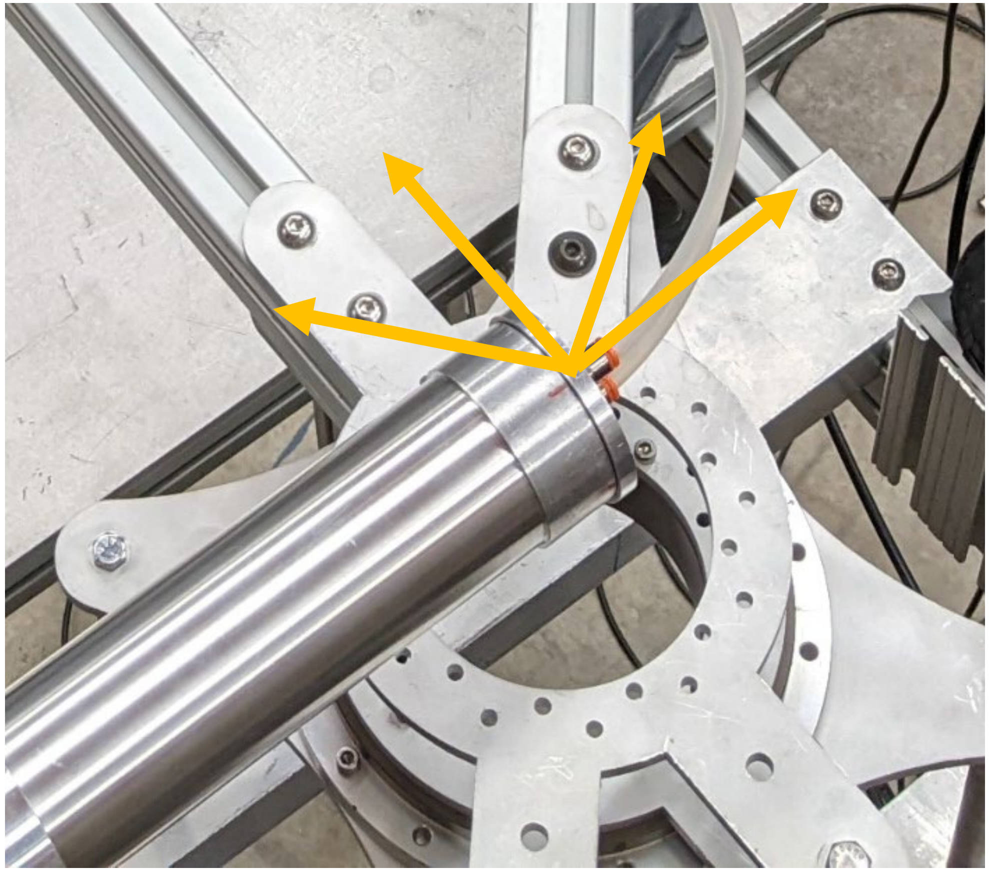
Fairly large uncertainties still from target holder attenuation

TABLE II. Priors, number of data points (N), χ^2 over number of data points, and normalization factors (Norm) obtained from the Bayesian analysis using BRICK [8] for the differential cross section data from this work. A common Gaussian prior was taken for the entire data set of 0.13.

Angle	Prior	N	χ^2/N	Norm
0°	Uniform	323	2.495	0.908
7.5°	Uniform	284	2.231	0.881
15°	Uniform	323	1.065	0.948
22.5°	Uniform	284	1.968	0.944
30°	Uniform	323	1.105	0.979
37.5°	Uniform	284	2.231	0.967
45°	Uniform	323	1.184	0.988
52.5°	Uniform	284	1.755	0.984
75°	Uniform	323	1.315	0.972
82.5°	Uniform	284	2.023	0.954
90°	Uniform	323	1.458	1.018
97.5°	Uniform	284	1.525	0.921
105°	Uniform	323	0.989	1.052
112.5°	Uniform	284	1.702	1.023
127.5°	Uniform	323	1.283	1.027
135°	Uniform	284	1.855	0.992
150°	Uniform	148	0.941	0.979
157.5°	Uniform	138	1.598	0.975

Corrections for interactions with target holder





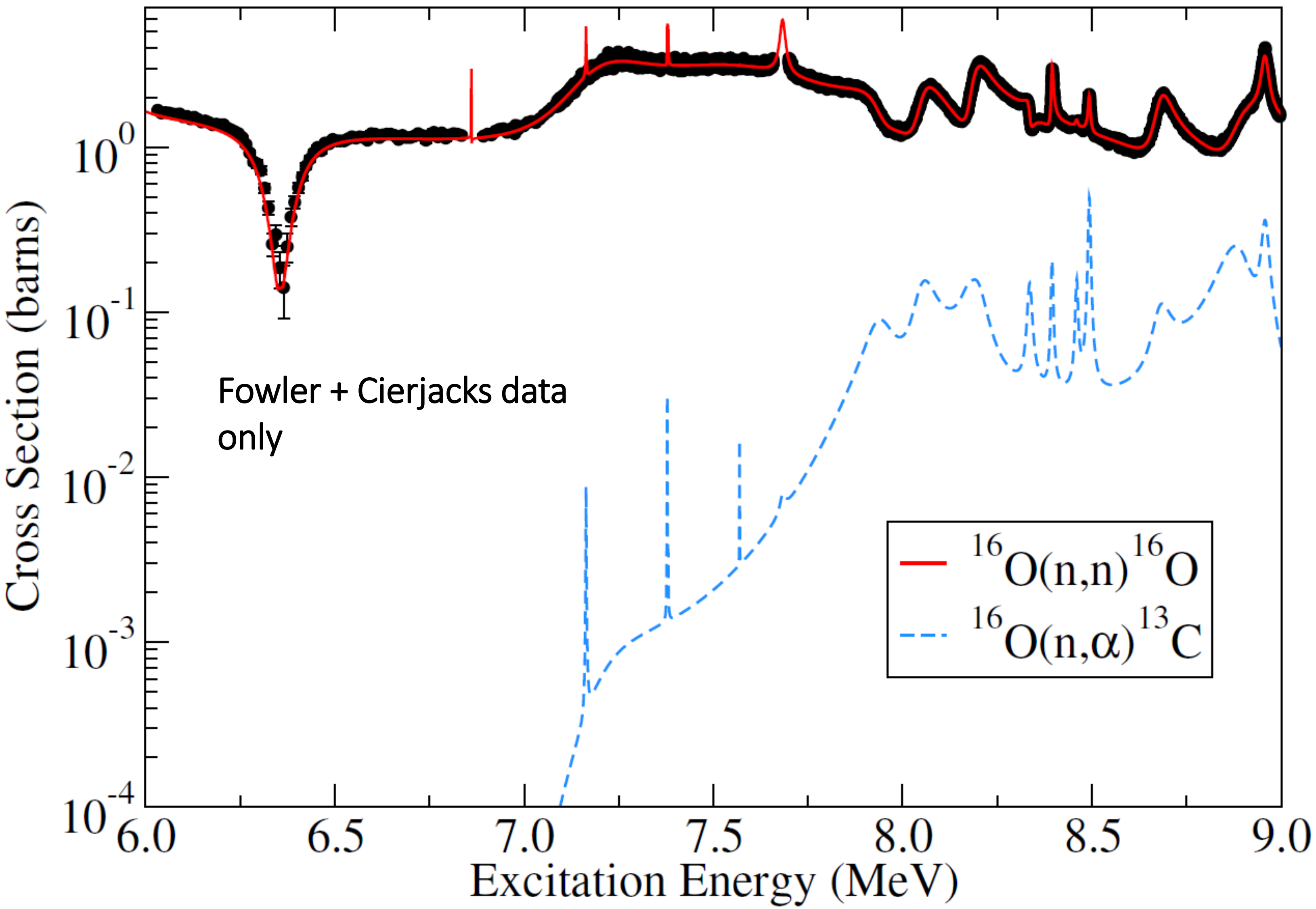
Has to be corrected using MCNP simulations, can't measure it easily

big difference between neutron and γ-ray producing experiments

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



Low energy fit using Bayesian uncertainty estimation (MCMC)

Fit is done with the same assumptions as other previous work

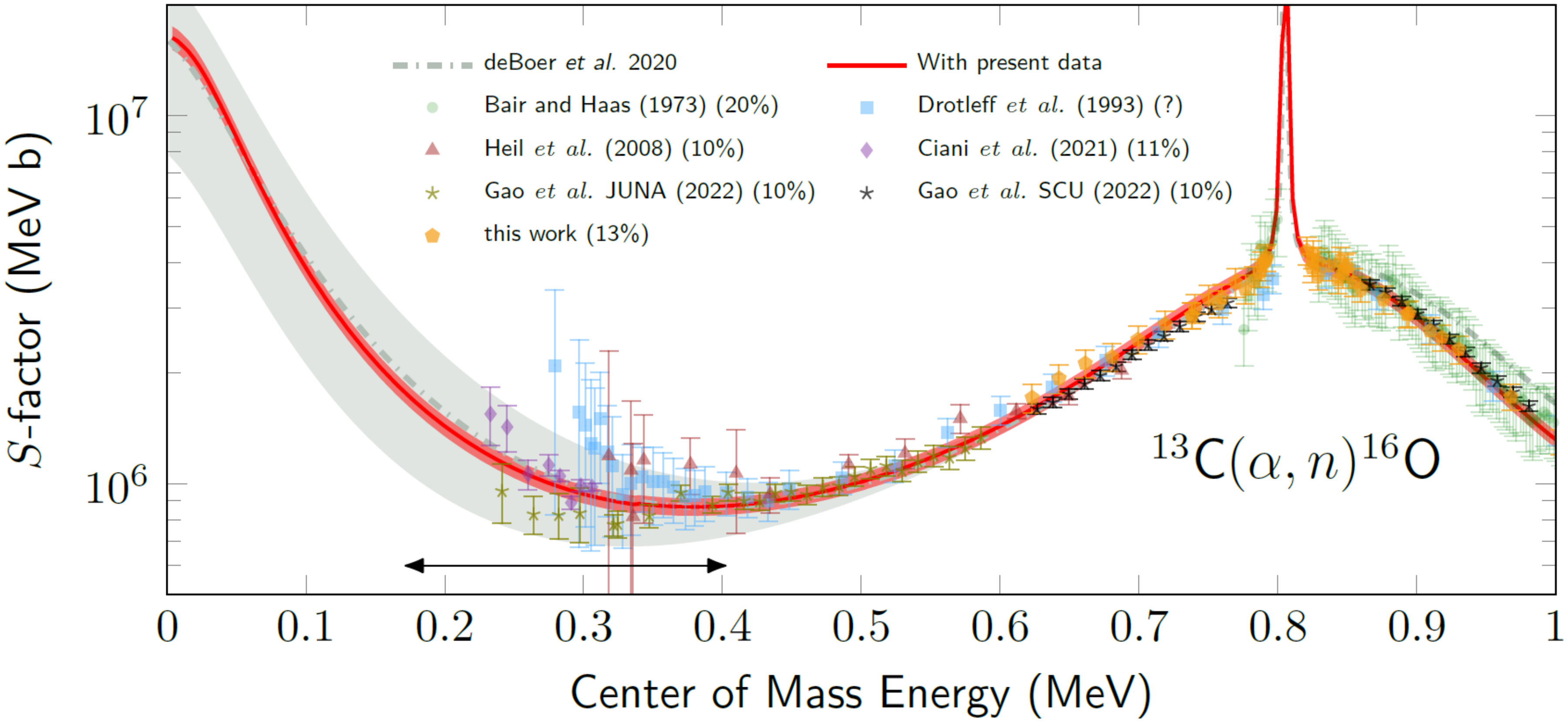
BRICK

Uncertainty is small, gets reduced from 10% to 5% (essentially what you get if you combine all the systematic uncertainties)

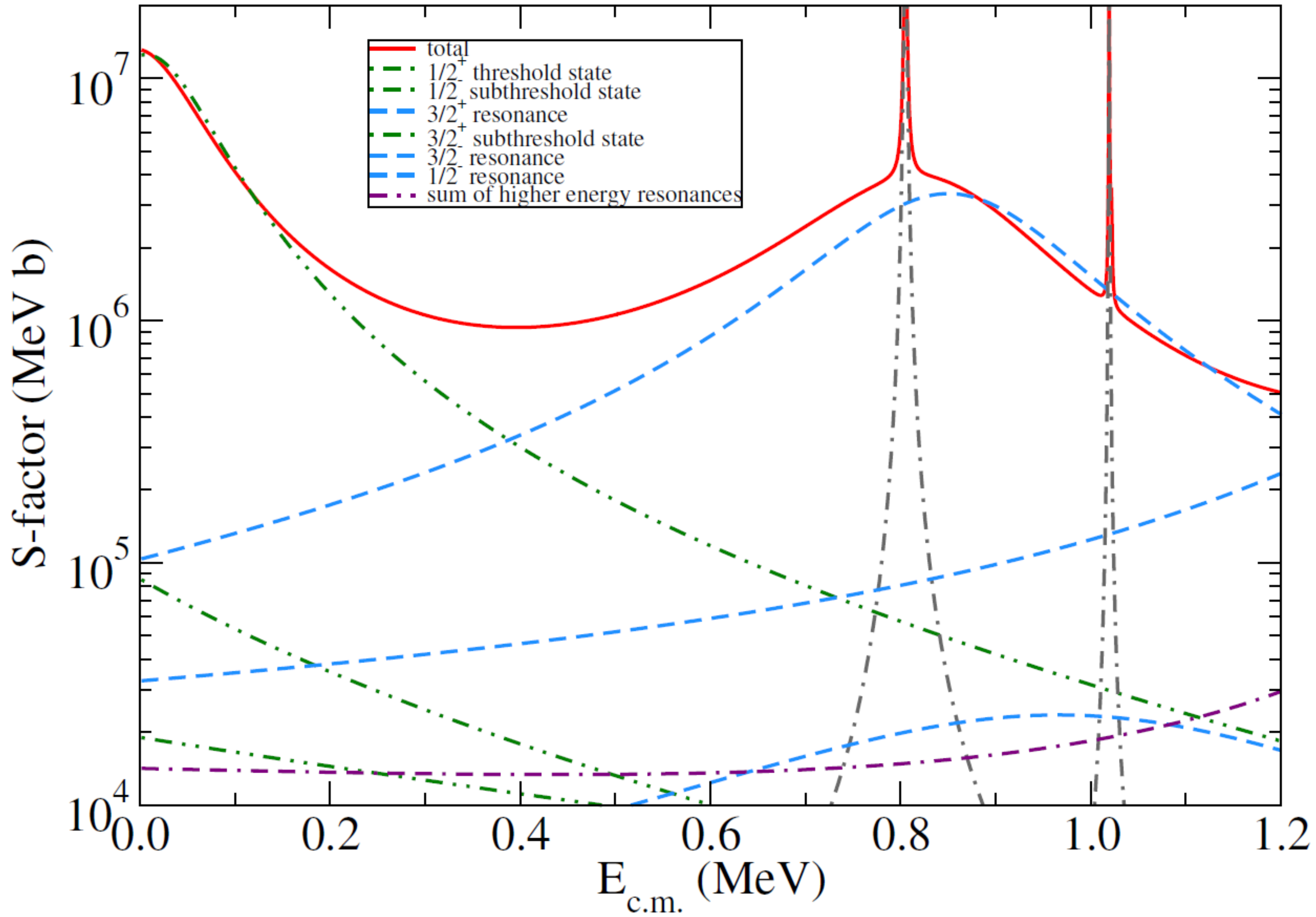
Assumes all measurements are independent

Doesn't include model uncertainties

A more complete uncertainty analysis is planned for an upcoming review



Deceptively complicated

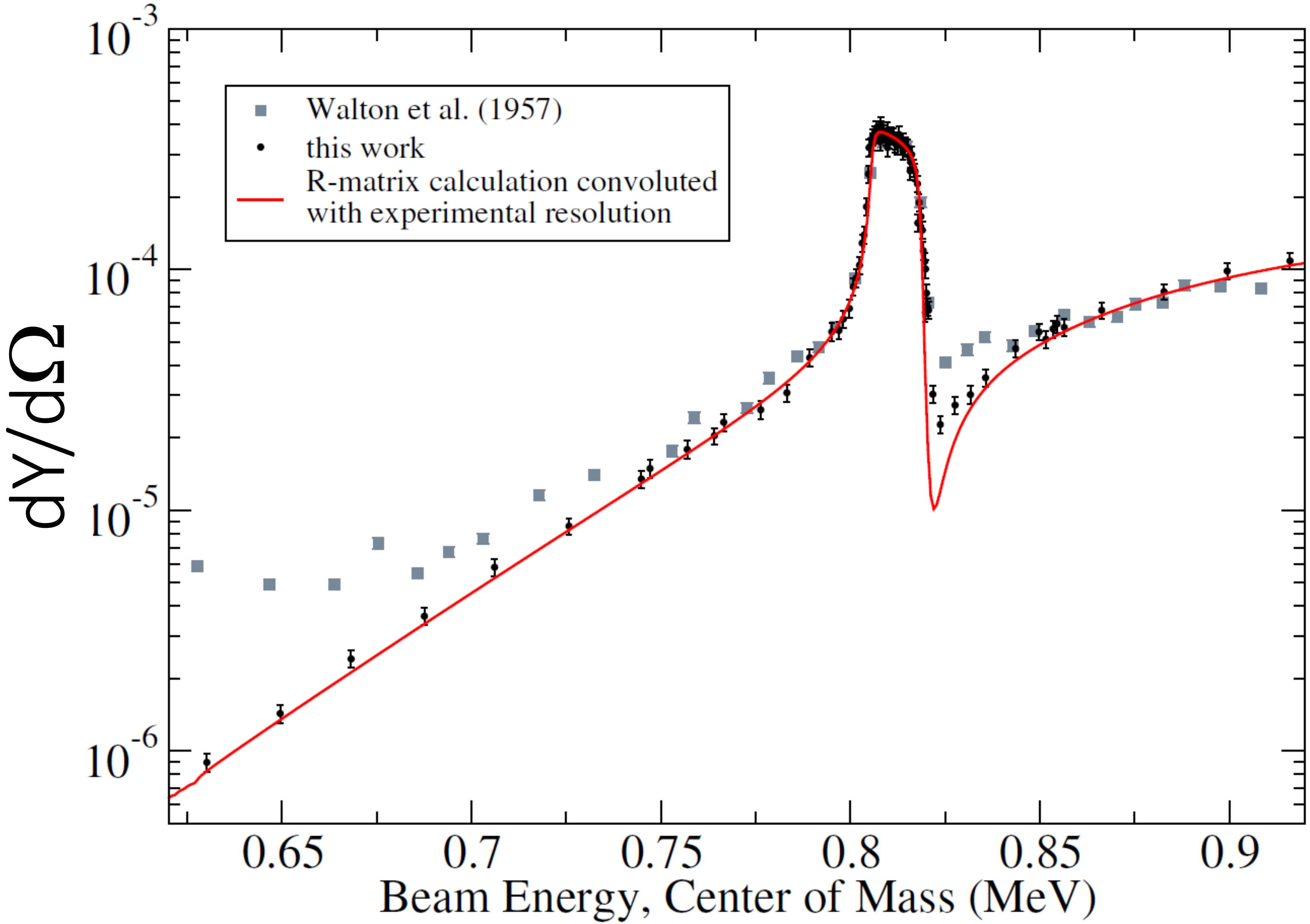


Priors and posteriors from the fit for the low energy data

TABLE I. Priors, number of data points (N), χ^2 over number of data points, and normalization factors (Norm) obtained from the Bayesian analysis using `BRICK` [8] for experimental data from previous works.

Data Set	Prior	N	χ^2/N	Norm
Fowler *et al.* [1], Cierjacks *et al.* [2]	Gaussian, 0.05	6565	1.394	1.061
Drotleff *et al.* [3]	Uniform	31	0.853	1.030
Heil *et al.* [4]	Gaussian, 0.1	13	1.243	1.016
Gao *et al.* [5], (JUNA)	Gaussian, 0.11	26	1.253	0.924
Gao *et al.* [5], (SCU)	Uniform	36	2.967	1.047
Bair and Haas [6]	Gaussian, 0.2	735	0.409	0.914
Ciani *et al.* [7]	Gaussian, 0.10	8	3.020	1.255

The narrow resonance at 1.05 MeV



Thick-target yield of the 1.05 MeV resonance

In principle the $^{13}C(\alpha,n)^{16}O$ reaction should be a standard!

- Cross section is large
- Targets are readily available

However, past measurements seem to have major problems

OU group used 14.8(7) eV (not sure where this came from

I get 6320 n/uC for our ND measurements

Working with Andreas Best at LUNA to do a joint paper of our own

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	

[a]Calculated for a pure ^{13}C target.
[b]Systematic uncertainty (10%) is not included.
[c]Systematic uncertainty (8.6%) is not included.
[d]Derived using $S(E) = 39.2/(10^{15}\ \text{atoms/cm}^2)$ [7].
[e]Derived using $S(E) = 36.9/(10^{15}\ \text{atoms/cm}^2)$ [16].

Ru *et al.* (2023), JUNA