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

RICHARD DEBOER

ANTONIOS KONTOS, ETHAN UBERSEDER

GRAN SASSO, OCTOBER 2013

OUTLINE

Why is $^{3}He(\alpha,\gamma)^{7}Be$ such an important reaction?

A brief history of the reaction studies

Different models (Antonino Di Leva)

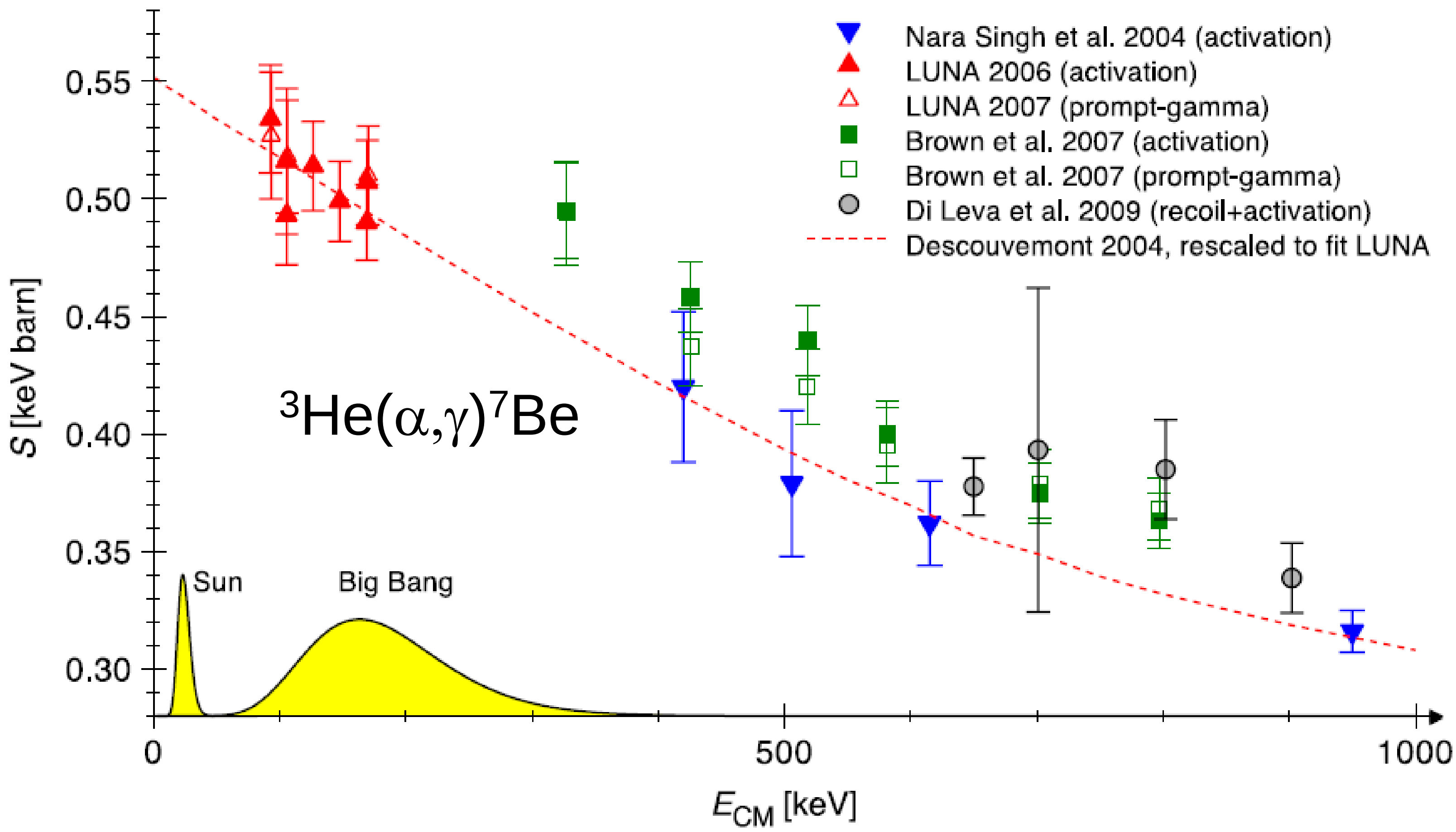
Notre Dame Experiment (Antonios Kontos)

***R*-matrix analysis (Ethan Uberseder)**

Monte Carlo Uncertainty Estimates

ENERGY REGIONS OF INTEREST

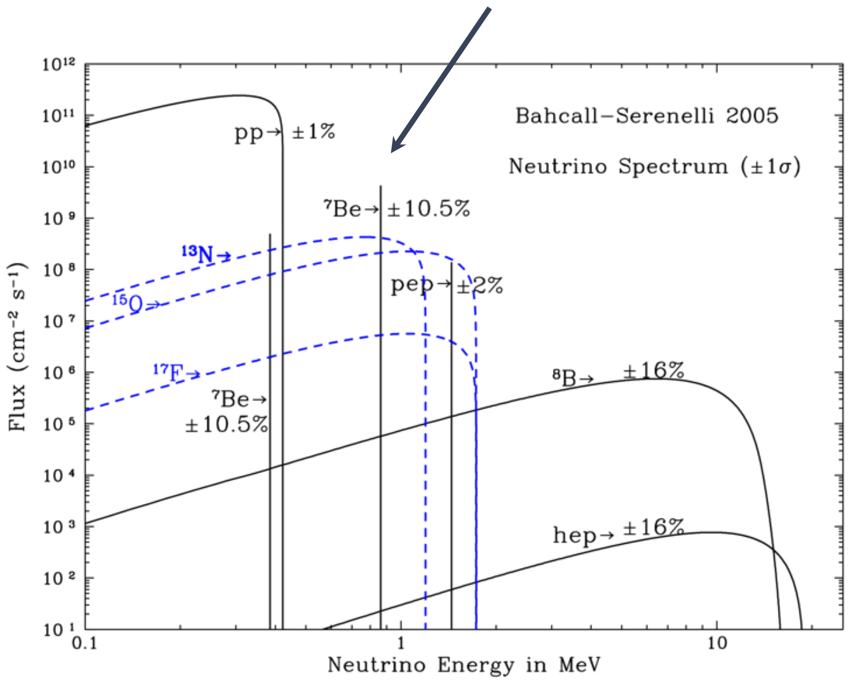
C. Broggini / Progress in Particle and Nuclear Physics 66 (2011) 293–297

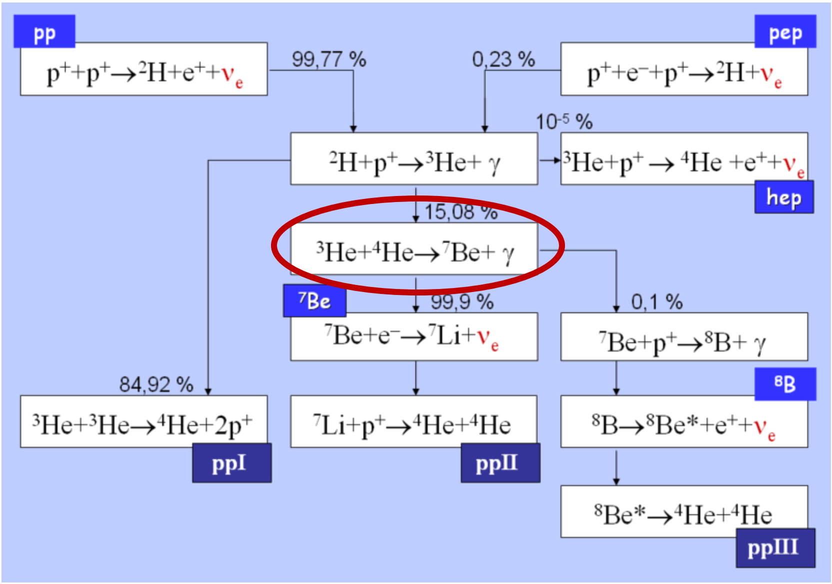


SOLAR NEUTRINOS

Measured to < 5%!

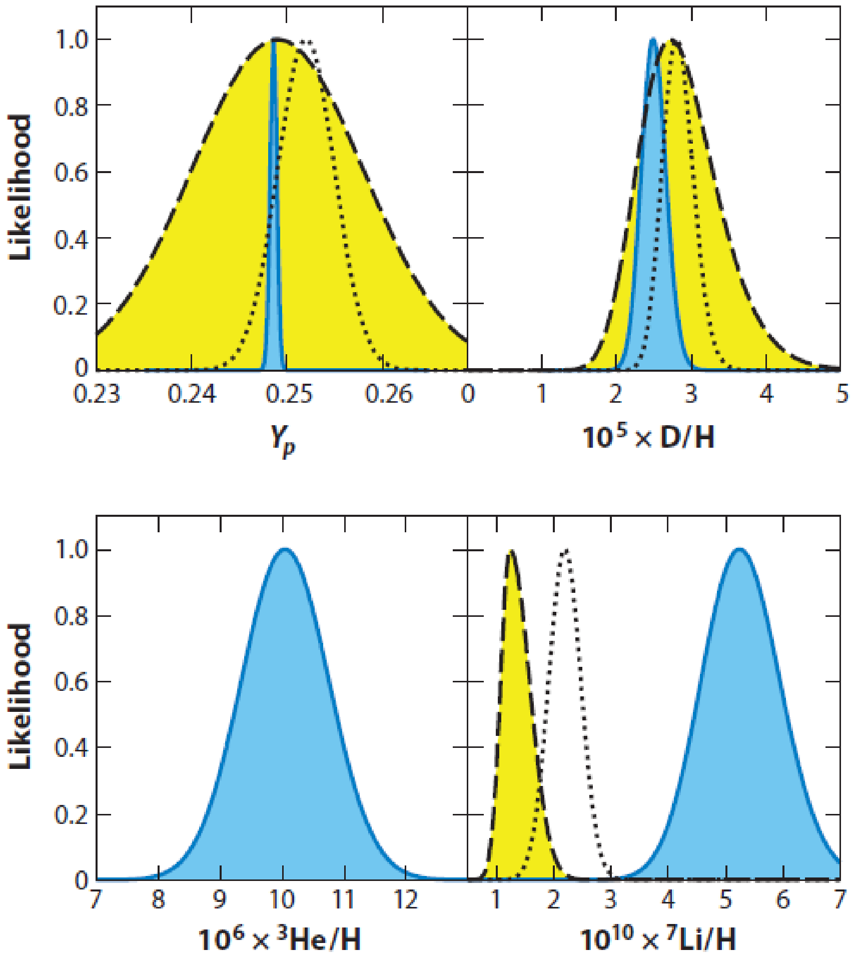
G. Bellini et al., PRL 107, 141302 (2011)





Slide from Antonios Kontos

THE PRIMORDIAL LITHIUM PROBLEM



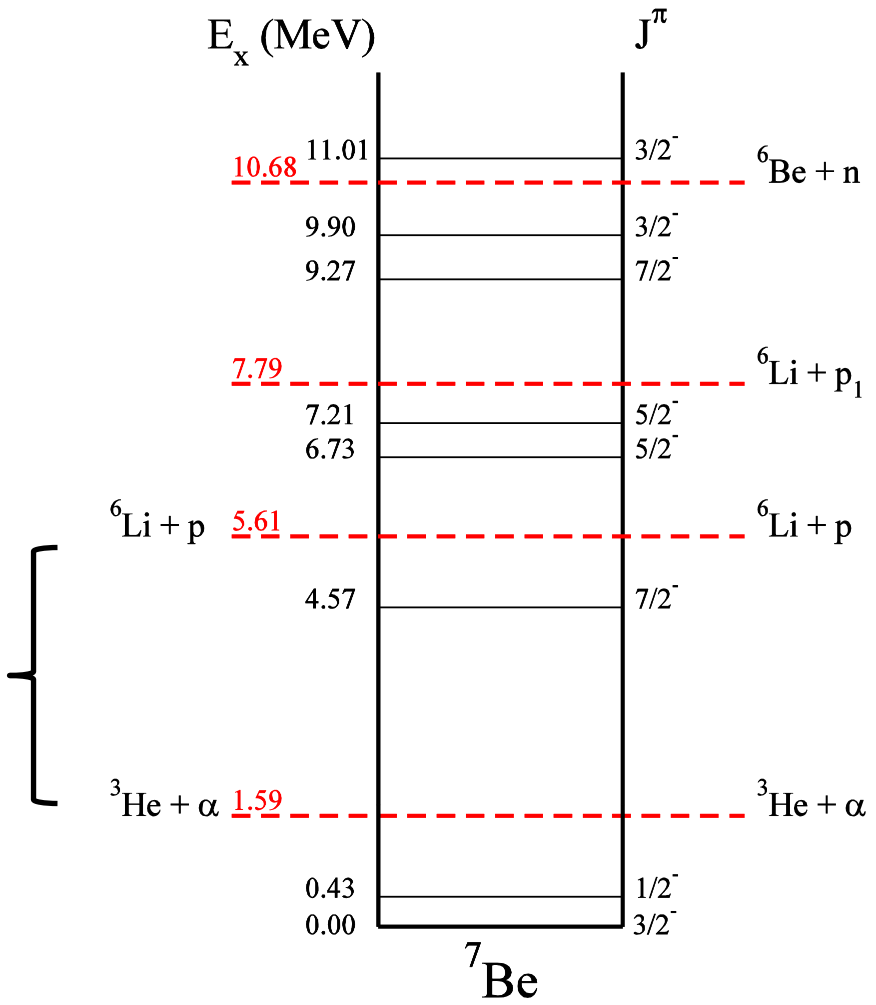
WMAP + BBN

Spectral absorption lines

Brian Fields (2011)

LEVEL STRUCTURE

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



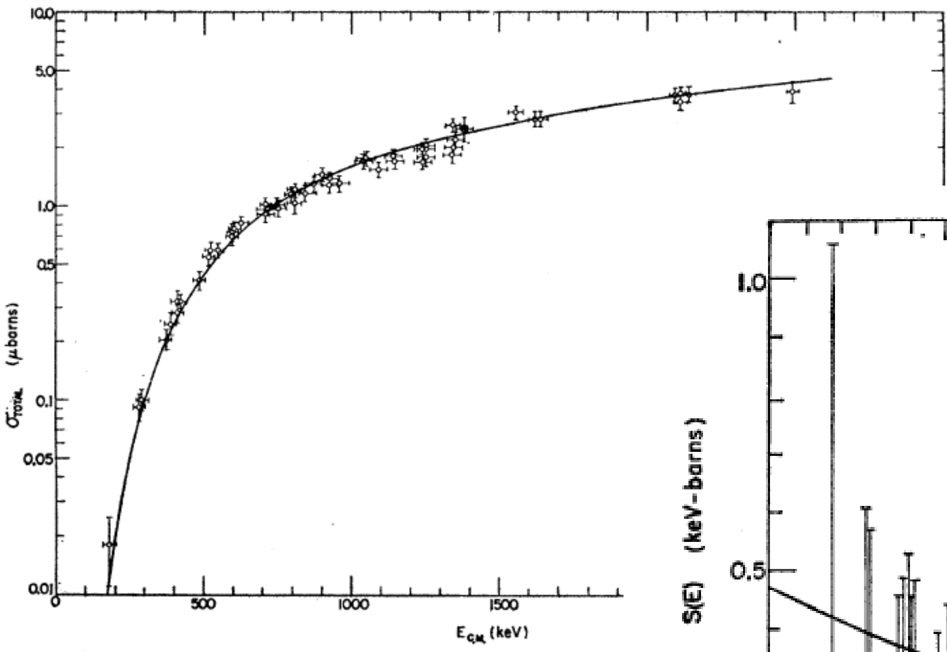
No E1 resonance transitions.

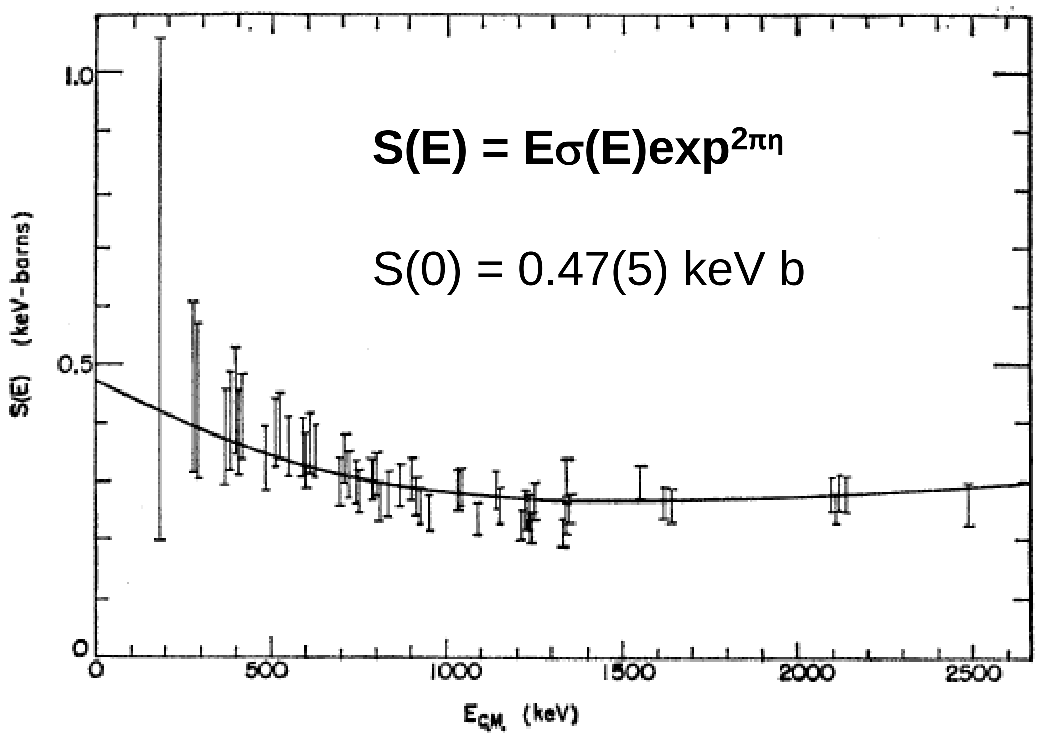
Yet the cross section is all E1!!!

Radiative Capture

PARKER AND KAVANAGH (1963) ✓

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





$S(E) = E\sigma(E)\exp^{2\pi\eta}$

$S(0) = 0.47(5)$ keV b

BARNARD *ET AL.* (1964) ✓

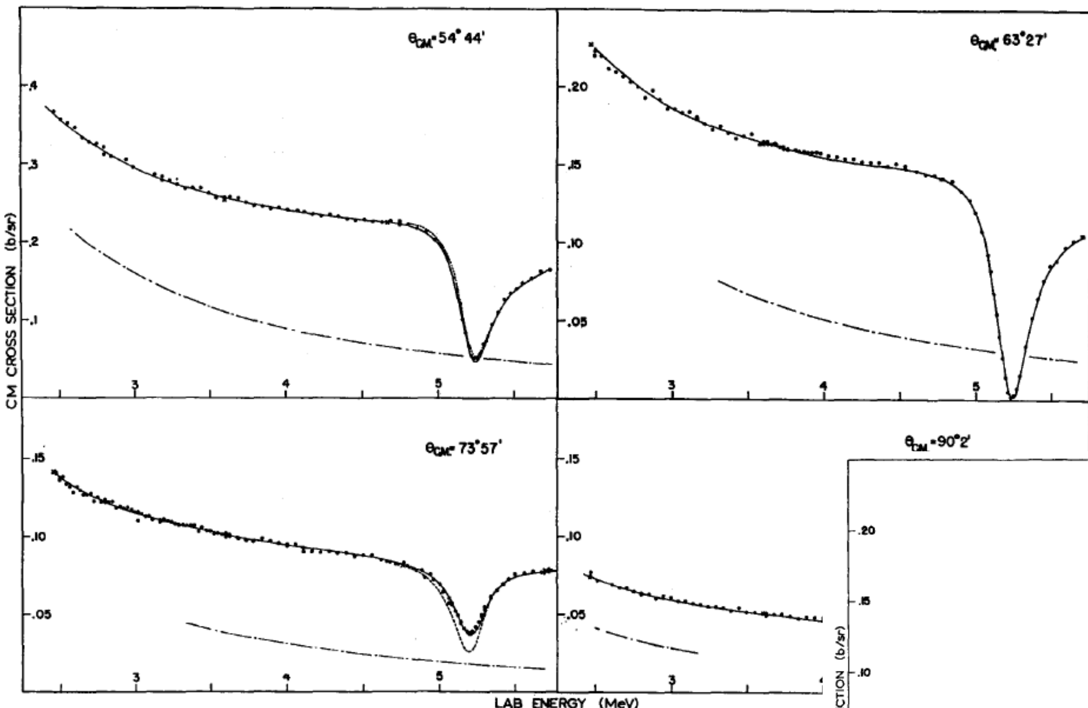
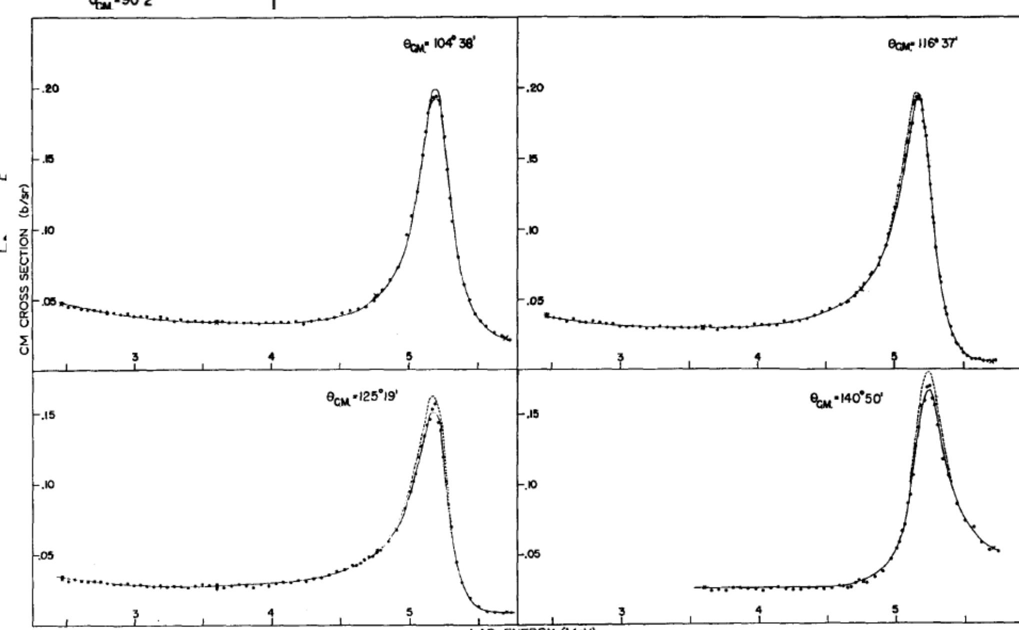


Fig. 2(a).



$^{3}He(\alpha,\alpha)^{3}He$

Other measurements by
Spiger and Tombrello (1967) ✘
Tombrello and Parker (1963) ✘
not so great…

THE SOLAR NEUTRINO PROBLEM --- $^3He(\alpha,\gamma)^7Be$

$$^1H(p, e^+ \nu_e)^2H(p, \gamma)^3He$$

$$^3He(^3He, 2p)^4He$$

$$^3He(\alpha, \gamma)^7Be(p, \gamma)^8B(e^+ \nu_e)^8Be^* \rightarrow 2\alpha$$

$$^7Be(e^-, \nu_e)^7Li(p, \alpha)^4He.$$

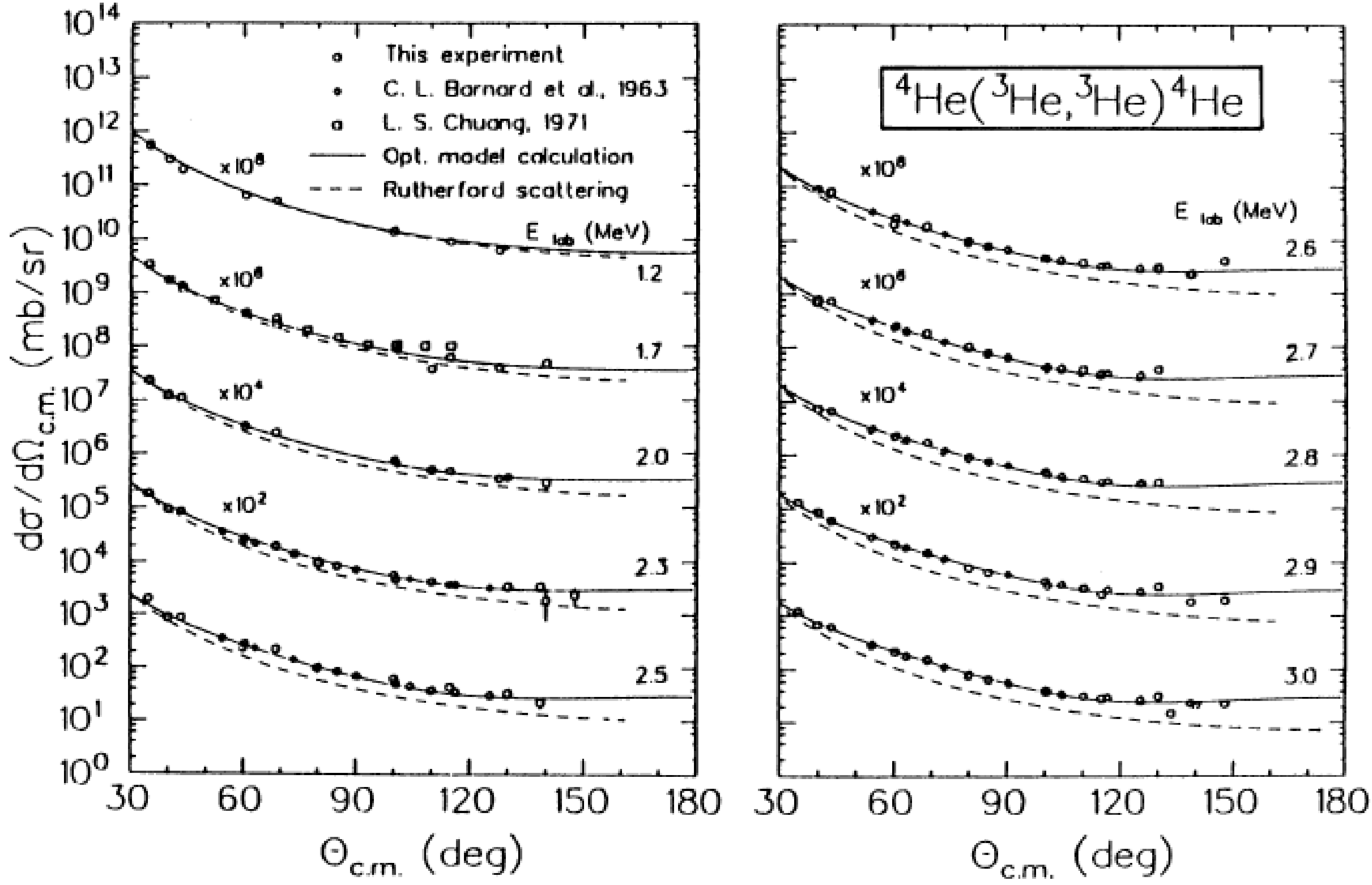
Osborn *et al.* (1983)

TABLE VI. $S(0)$ values from our work and from published data.

	$S(0)^a$ (keV b)	Reference		
Activity	0.577 ± 0.035	Osborne *et al.*	[7]	**1983**
	0.660 ± 0.040	Robertson *et al.*	[10]	**1983**
	0.560 ± 0.030[a]	Volk *et al.*	[11]	**1983**
	0.546[c] ± 0.020	Nara Singh *et al.*	[13]	2004
	0.545 ± 0.017	Bemmerer *et al.*	[14]	2006
	0.595 ± 0.018	Present work		2007
Prompt	0.481 ± 0.053	Parker and Kavanagh	[4]	1963
	0.579 ± 0.07[d]	Nagatani *et al.*	[5]	1969
	0.449 ± 0.06[e]	Kräwinkel *et al.*	[6]	**1982**
	0.522 ± 0.03	Osborne *et al.*	[7]	**1983**
	0.478 ± 0.04	Alexander *et al.*	[8]	**1984**
	0.542 ± 0.03	Hilgemeier *et al.*	[9]	**1988**
	0.560 ± 0.021	Confortola *et al.*	[15]	2007
	0.596 ± 0.021	Present work		
Total[f]	0.560 ± 0.017[b]	Confortola *et al.*	[15]	
	0.595 ± 0.018	Present work		

Brown *et al.* (2007)

MOHR *ET AL.* (1993) ✓



"MODERN MEASUREMENTS"

TABLE I: Data sets considered in the the present analysis. The quoted systematic uncertainty is also given. The normalization is the result of the R-matrix fit using a χ^2 measure of the goodness of fit. For comparison with the Monte Carlo analysis, the weighted average of the normalization and the internal and external uncertainty are calculated.

Data Set	Transition	Systematic Uncertainty	Normalization
Barnard *et al.* (Elastic) [13]		5%	1.033
Mohr *et al.* (Elastic) [14]		$5\%^a$	1.020
Singh *et al.* (2004) (Activation) [15]	Total	3.7%	1.063
Gyürky *et al.* and Confortola *et al.* (2007) (Activation) [4, 5]	Total	3.2%	1.013
Confortola *et al.* (2007) (Prompt) [5]	G.S. & 1^{st} E.S.	3.8%	1.002
Brown *et al.* (2007) (Activation) [6]	Total	3.0%	0.980
Brown *et al.* (2007) (Prompt) [6]	G.S. & 1^{st} E.S.	3.5%	0.975
Di Leva *et al.* (2009) (Activation) [7]	Total	5.0%	0.973
Di Leva *et al.* (2009) (Prompt) [7]	G.S. & 1^{st} E.S.	7.0%	0.986
Di Leva *et al.* (2009) (Recoils) [7]	Total	5.0%	0.982
Carmona-Gallardo *et al.* (2012) (Activation) [8]	Total	3.0%	0.976
Kontos *et al.* (2013) (Prompt) [3]	Total	8.0%	0.970
Weighted Average	Total	int: 1.2%, ext: 1.0%	0.995

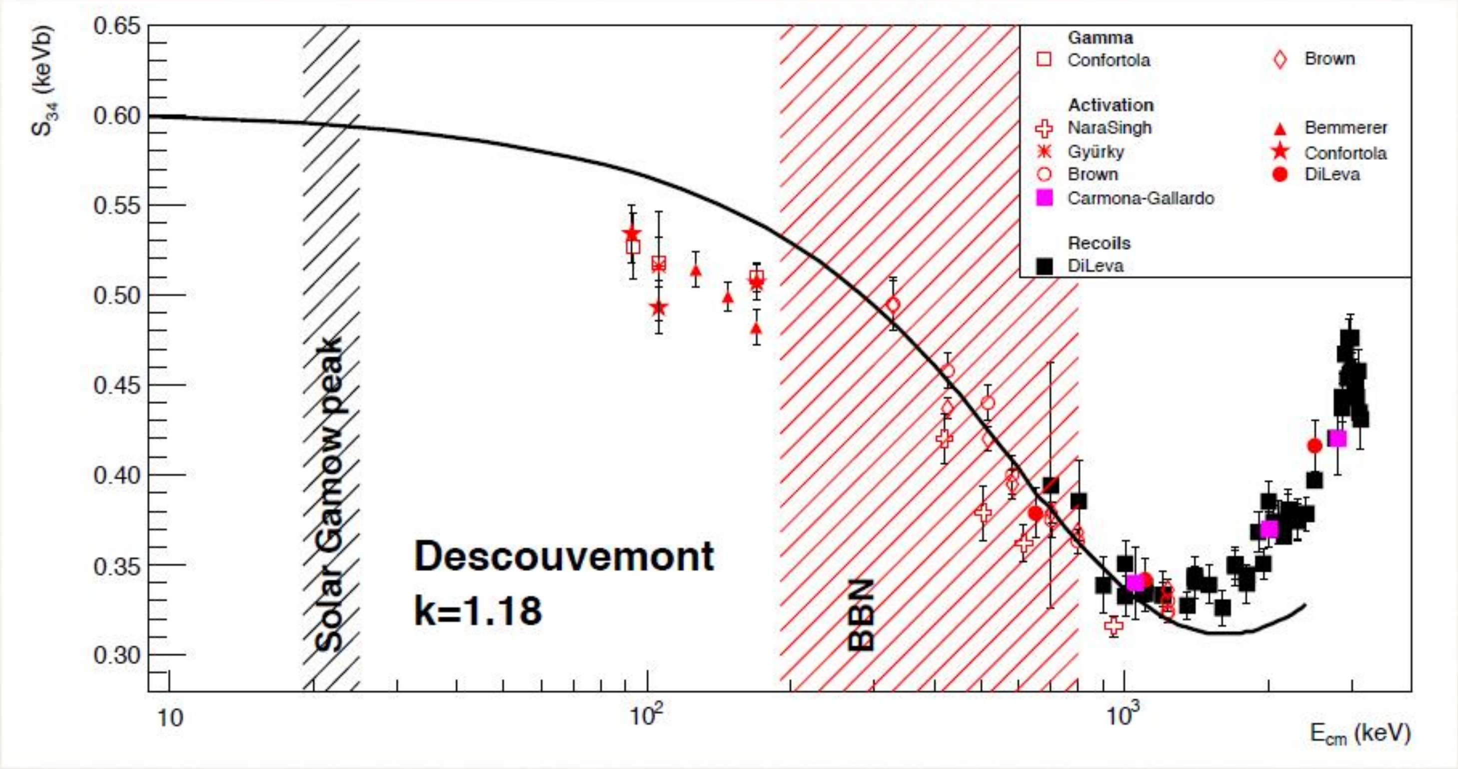
Model fit to the data

Slide from Antonino Di Leva

Potential models (global scaling parameter): Tombrello & Parker, Descouvemont (R-matrix based), Mohr

Microscopic models (no global scaling parameter): Csótó & Langanke, Kajino et al., Nollett, etc...

Usually claimed to be valid up to E_{cm}~2.0MeV



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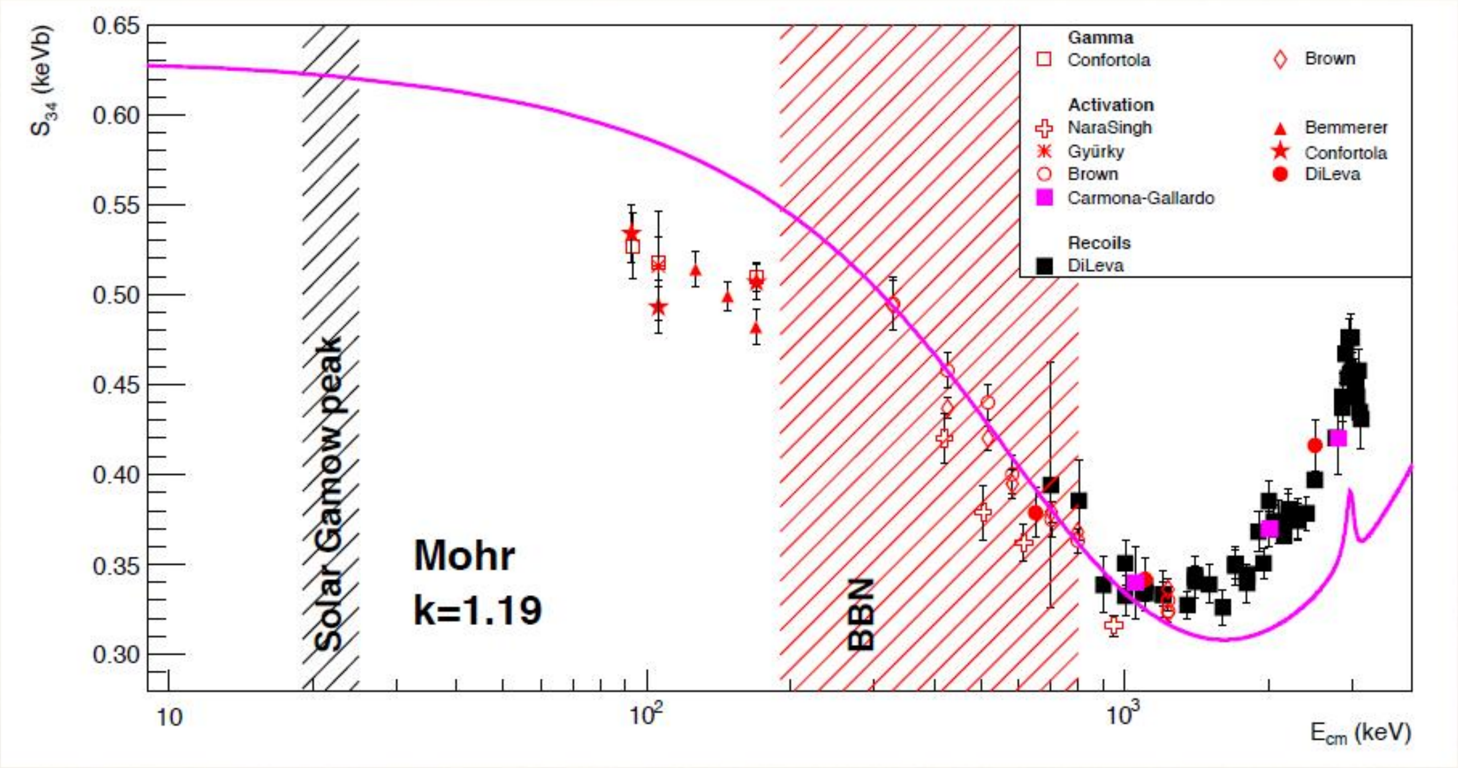

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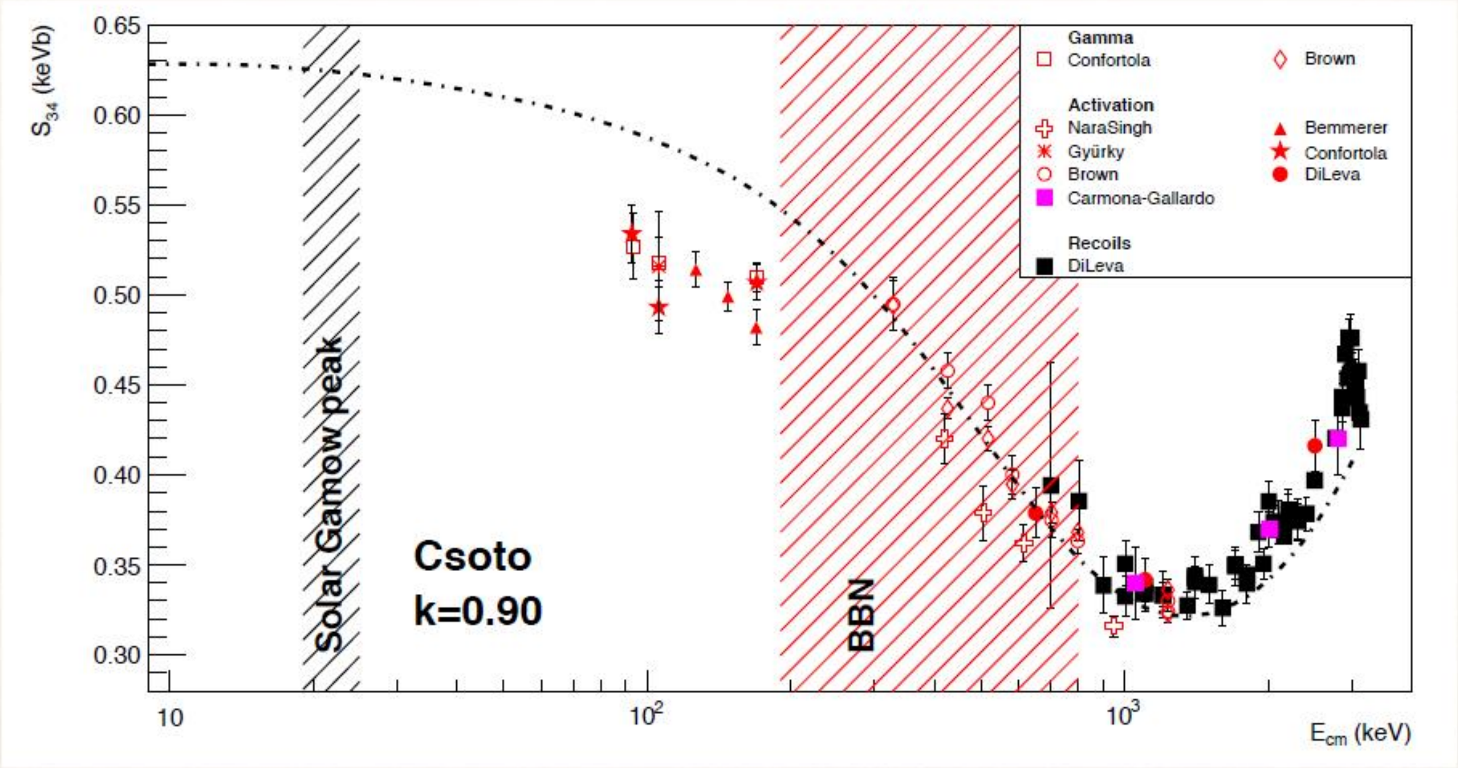

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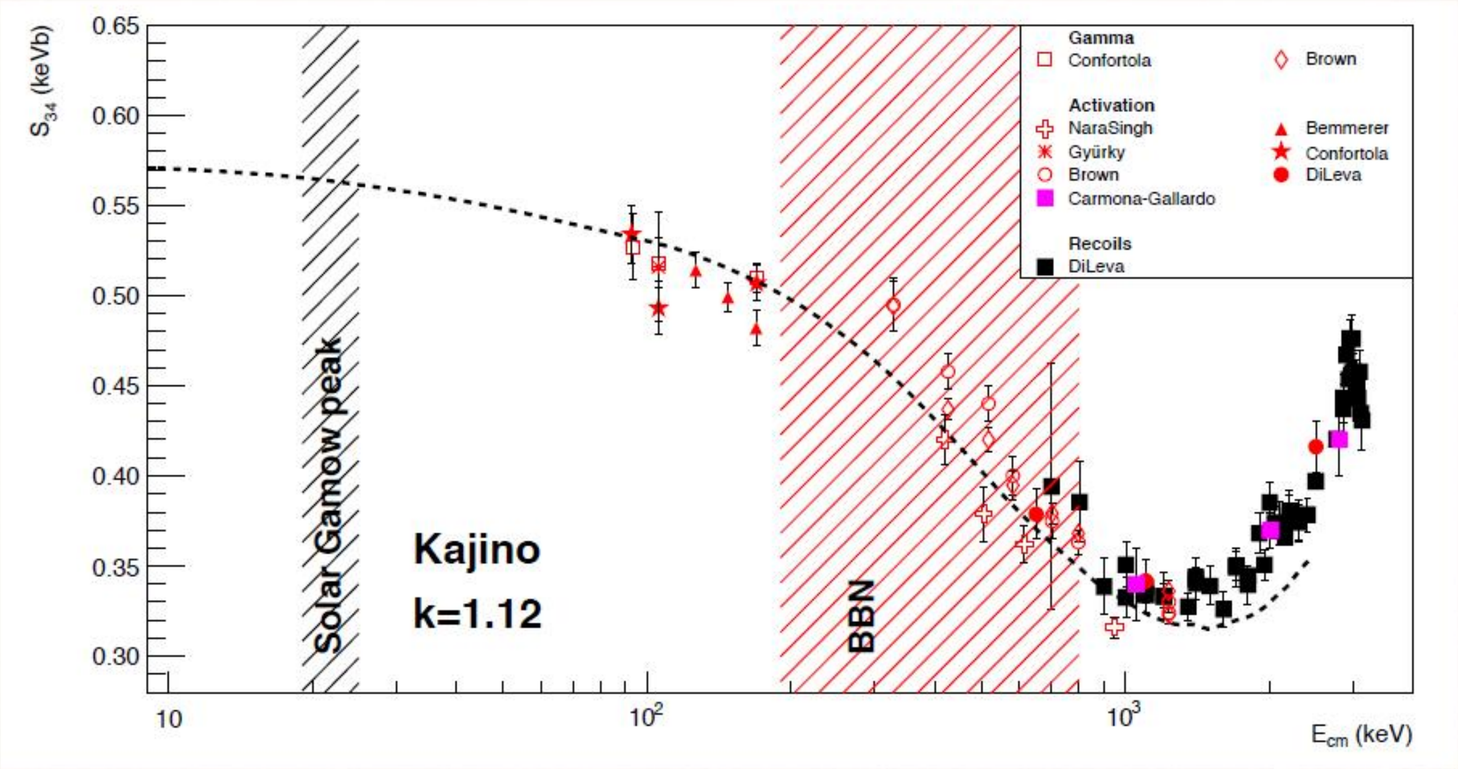

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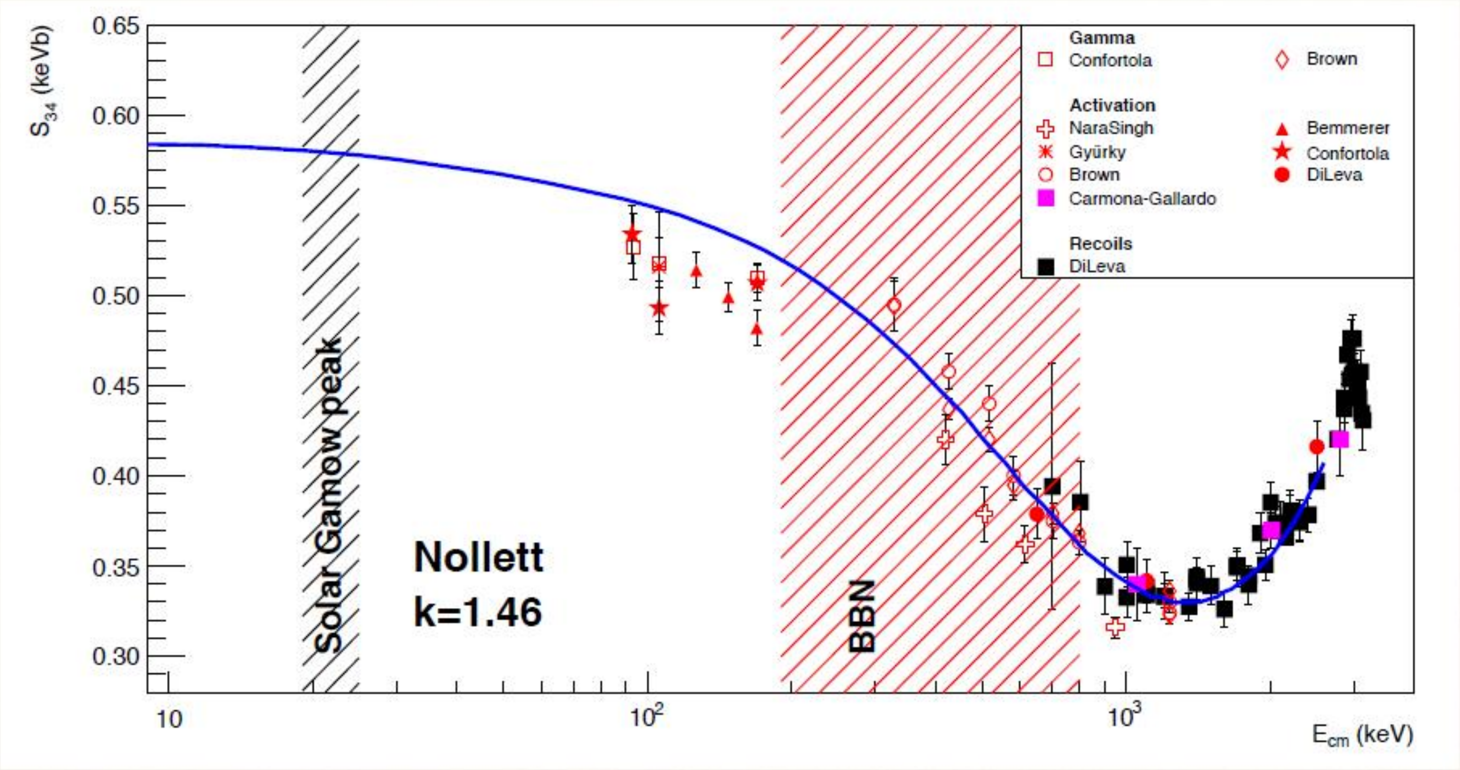

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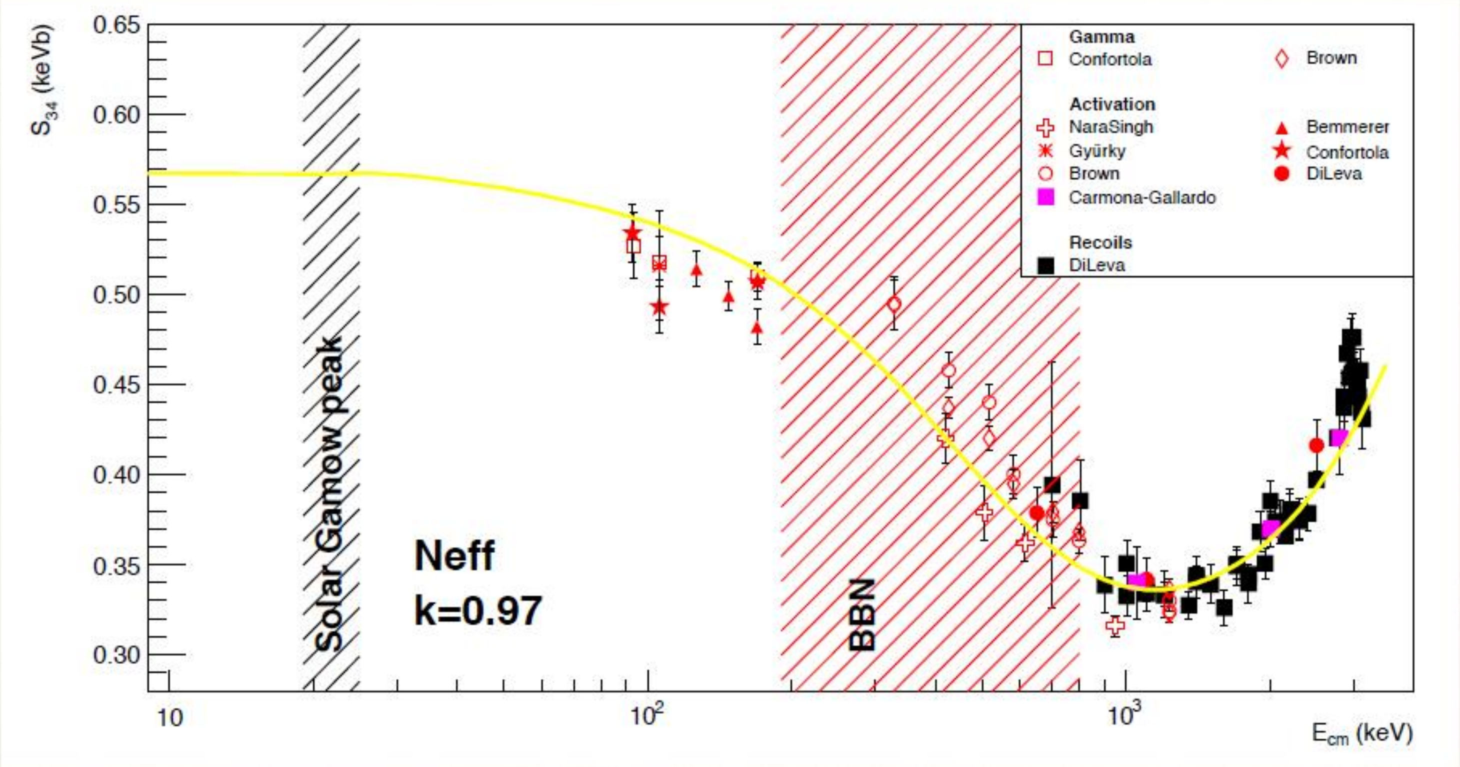

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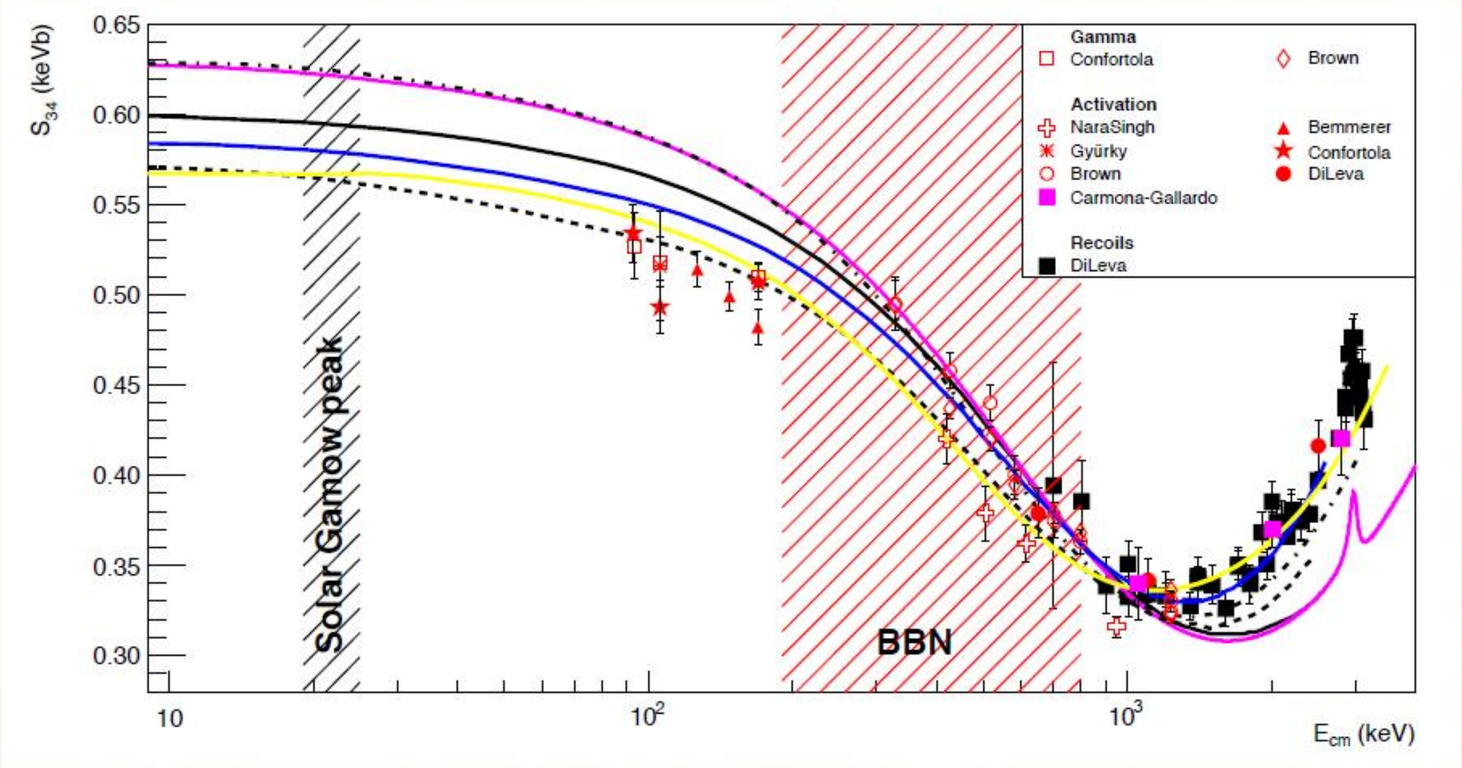
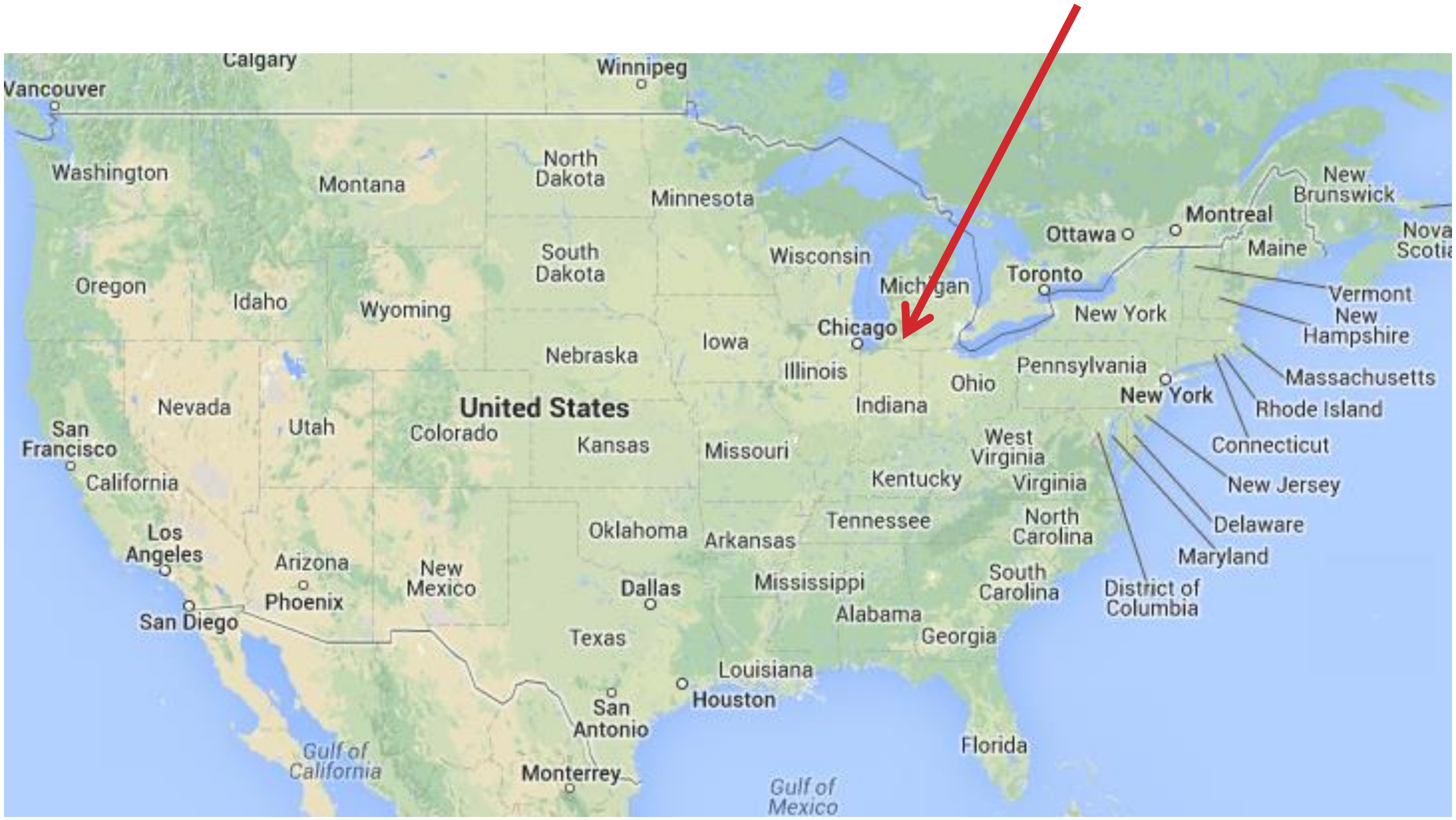
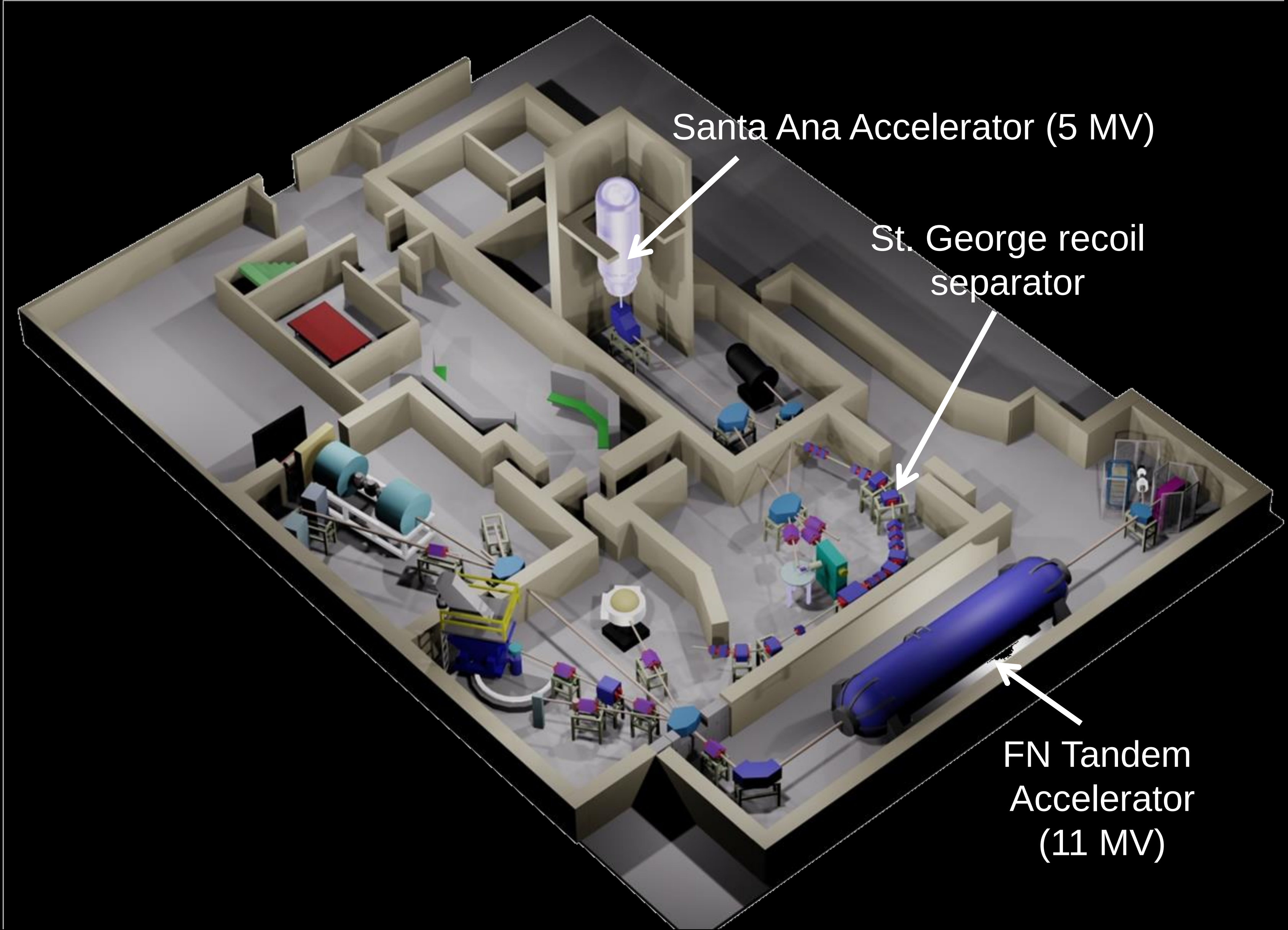


UNIVERSITY OF NOTRE DAME

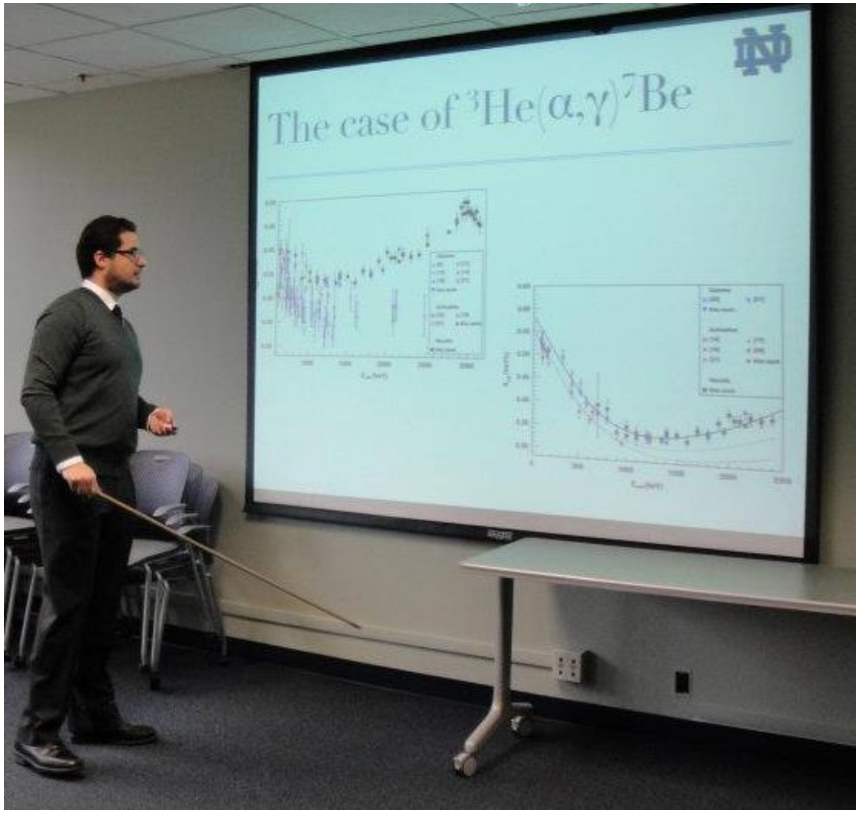


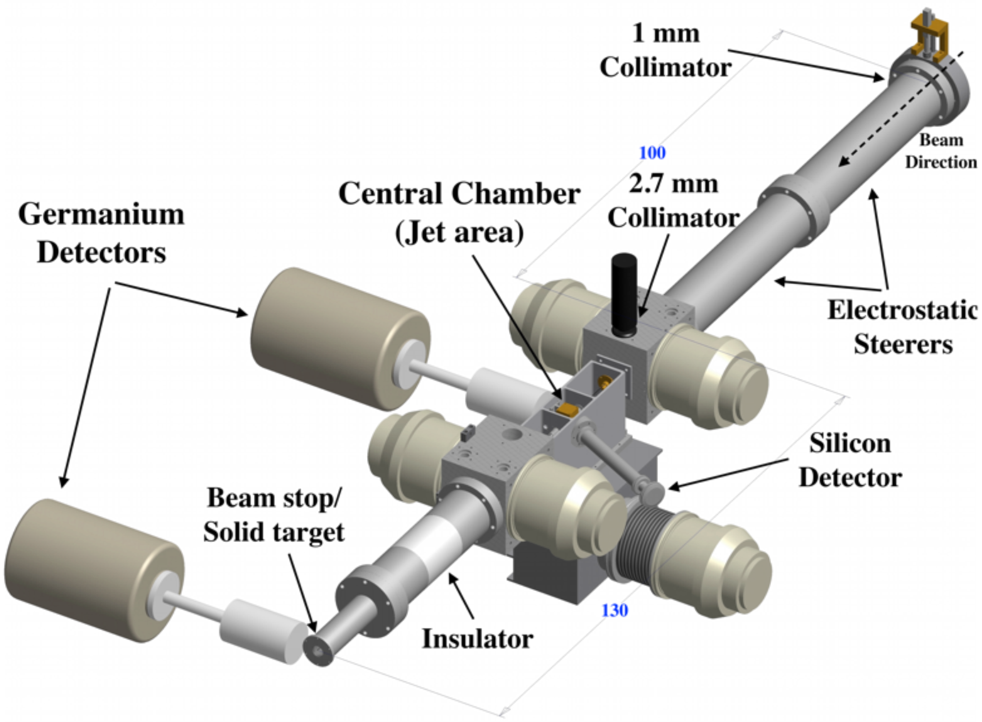


NUCLEAR SCIENCE LABORATORY (NSL) AT NOTRE DAME

NOTRE DAME EXPERIMENT: GAS JET CHARACTERIZATION

Antonios Kontos





Kontos *et al.* (2013)

REAL LIFE

***R*-matrix theory: reaction framework for low energy nuclear reactions**

Based on the algorithms developed for AZURE FORTRAN

by R.E. Azuma →

Written in C++, Graphical Interface created with Qt

Utilizes currently maintained pubic libraries

- MINUIT2
- GNU Scientific Library

Open Source soon

Multiple entrance/exit channels

- Particle, particle
- Particle, gamma
- Beta delayed particle emission

Full external capture calculation with E1, E2, and M1 as well as channel capture

AZURE2

SYSTEMATIC UNCERTAINTY

$$\chi^2 = \sum_i \left(\sum_j \frac{(c_i \cdot f(x_{i,j}) - y_{i,j})^2}{\sigma_{i,j}^2} + \boxed{\frac{(c_i - 1)^2}{\sigma_{c_{\exp,i}}^2}} \right)$$

G. D'Agostini, Nucl. Instrum. Methods A 346 (1994) 306.

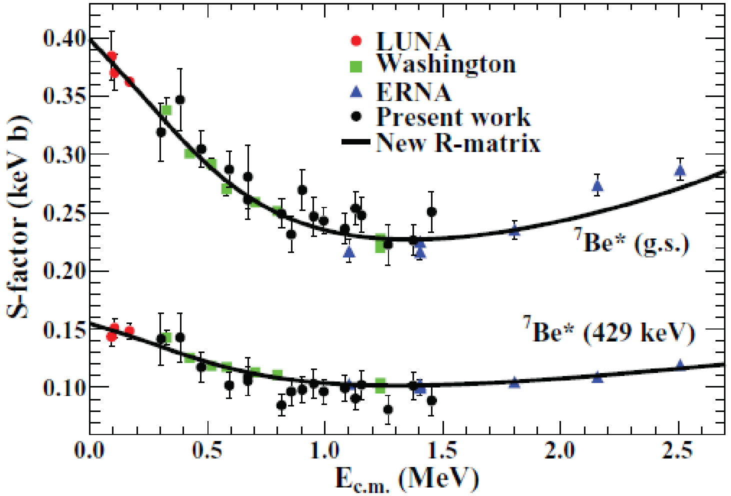
Schürmann *et al.* (2012)

$$\chi^2_{\text{norm}}(n1, n2) = \frac{\left[\delta_{n2}^2(\alpha_{n1} - 1)^2 - 2\delta_c^2(\alpha_{n1} - 1)(\alpha_{n2} - 1) + \delta_{n1}^2(\alpha_{n2} - 1)^2\right]}{\left[\delta_{n1}^2\delta_{n2}^2 - \delta_c^4\right]}$$

Common Uncertainties

Cybert and Davids (2008)

R-MATRIX FITS



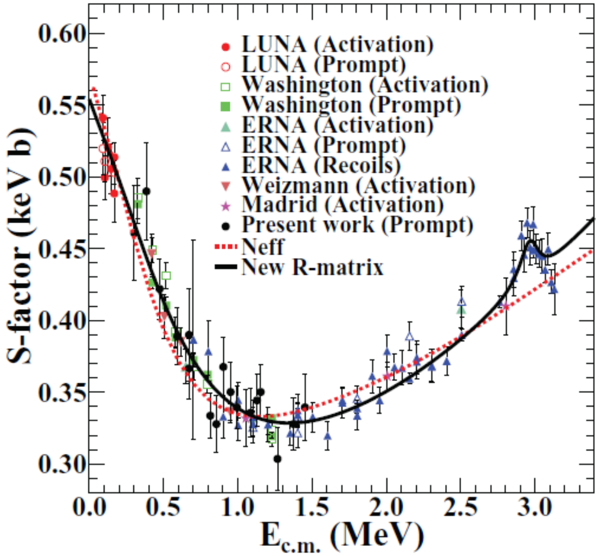


TABLE II. Data set normalization factors.

Data set	Quoted sys. uncertainty	Normalization
Barnard *et al.* (Elastic) [20]	5%	1.033
Mohr *et al.* (Elastic) [19]	5%[a]	1.020
LUNA (Activation) [4,5]	3.2%	1.013
LUNA (Prompt) [5]	3.8%	1.002
Washington (Activation) [6]	3.0%	0.980
Washington (Prompt) [6]	3.5%	0.975
ERNA (Activation) [8]	5.0%	0.973
ERNA (Prompt) [8]	7.0%	0.986
ERNA (Recoils) [8]	5.0%	0.982
Weizmann (Activation) [3]	3.7%	1.063
Madrid (Aactivation) [9]	3.0%	0.976
Notre Dame (Prompt)	8.0%	0.970
Capture average		0.993

$\chi^2/\nu = 1.4$

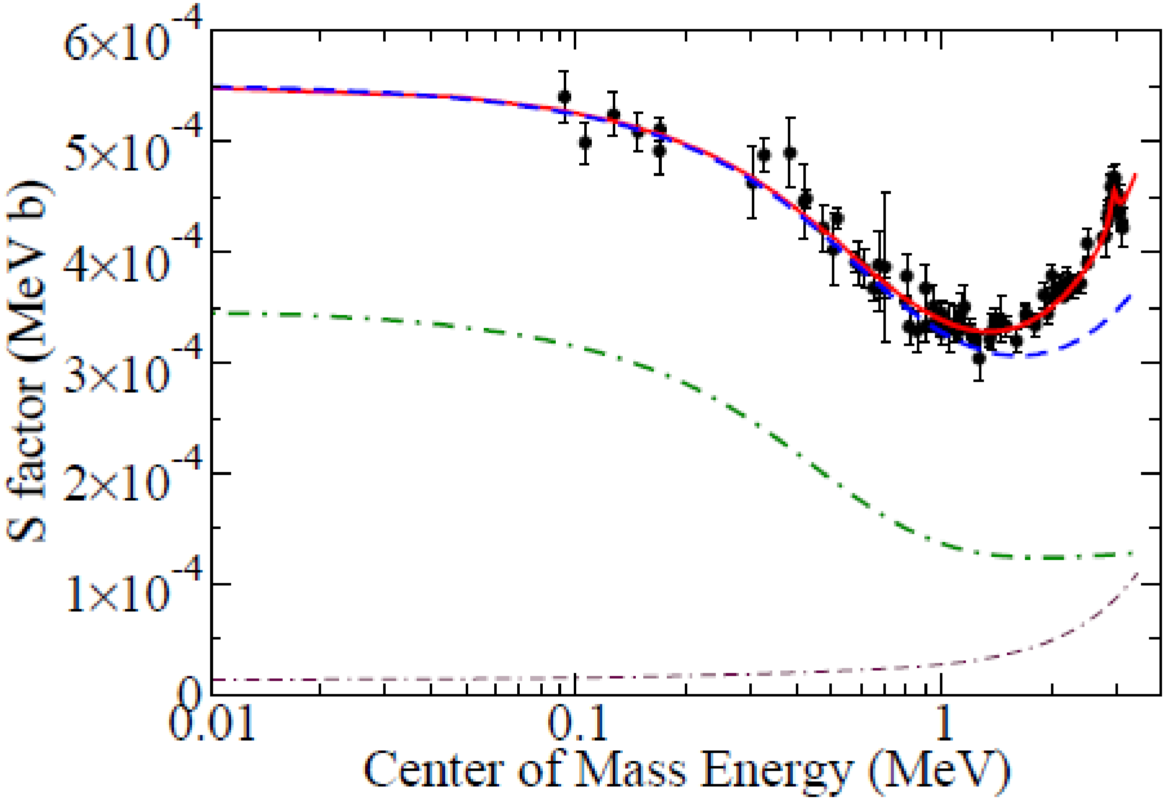
WHY DO WE LIKE THE *R*-MATRIX FIT?

1) **It can fit all of the data simultaneously**
    1) Capture and
    2) Elastic scattering
2) **It is phenomenological but it is a direct fit to the experimental data**
3) **What are the issues with the models?**
    1) Ab initio is good but only gets close, is not tuned to the data
    2) Previous *R*-matrix analysis were incomplete, external contributions (channel capture) ignored in background pole

WHAT ARE THE DETAILS?

U = U(int. res) + U(ch. res.) + U(hard sphere)

Lane and Lynn (1960)



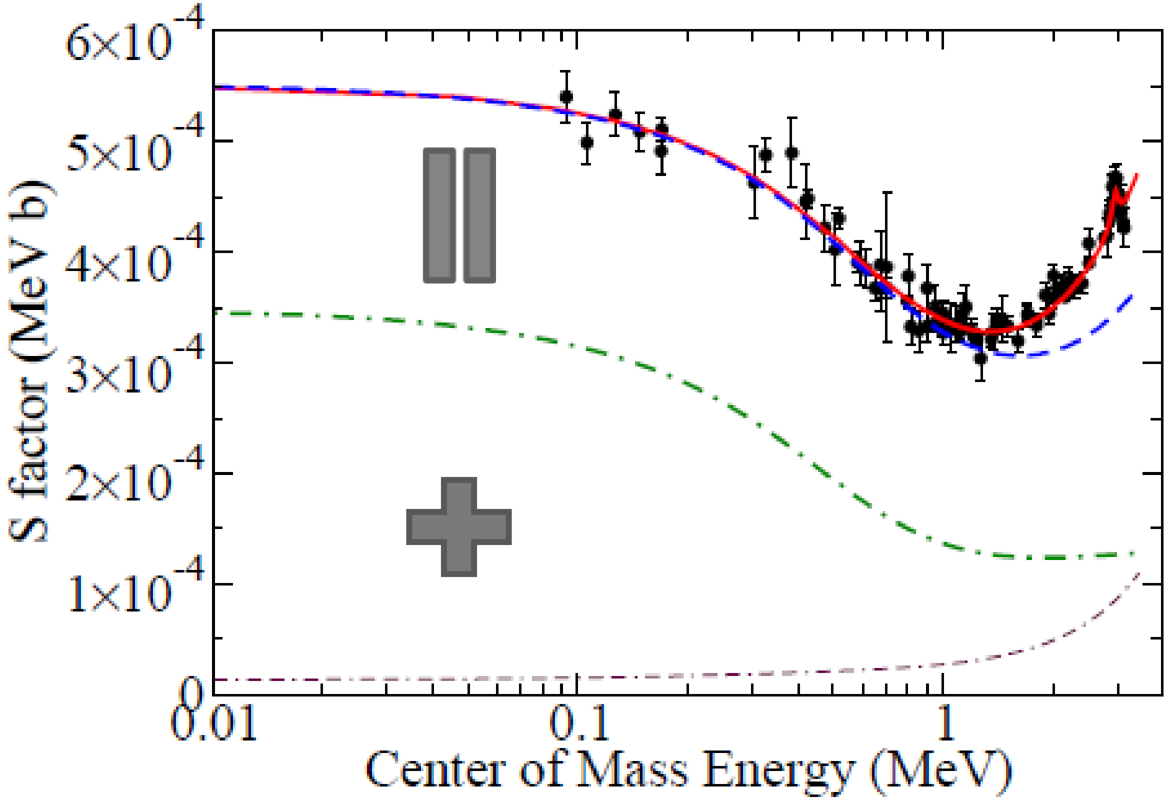
Total

s-wave EC + BGP

s-wave External Capture

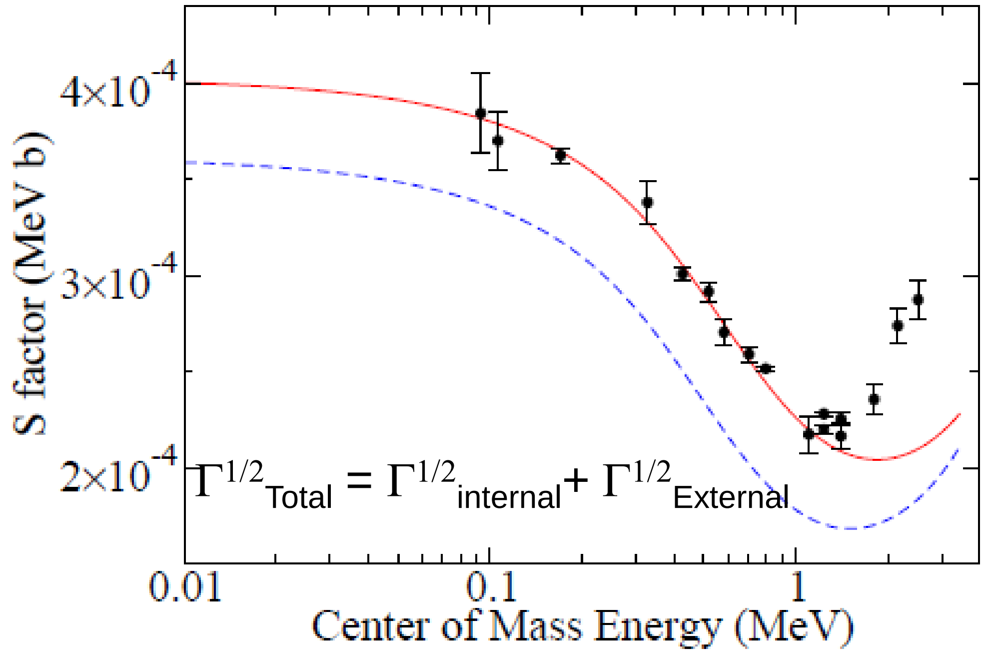
s-wave Background Pole (with channel capture)

INTERFERENCE IS IMPORTANT



$$\sigma_{int} \propto \sqrt{2\sigma_1\sigma_2}$$

EXTERNAL CAPTURE MODIFIES BACKGROUND POLE CONTRIBUTION: "CHANNEL CAPTURE"



Ethan Uberseder

Only S and D wave **external** capture is important

-Tombrello and Parker (1963)

Internal contribution is also important

-Neff (2011)

RECENT ESTIMATES OF THE UNCERTAINTY

Descouvemont *et al.* (2004)

5 data sets (classic data)

external capture *R*-matrix, $\Delta\chi^2$ method

S(0) = 0.51 ± 0.04 (7.8%) keV b

Cybert and Davids (2008)

4 data sets (modern data)

MCMC using a physically motivated polynomial expansion

S(0) = 0.580 ± 0.043 (7.4%) keV b

Adelberger *et al.* (2011)

4 data sets (modern)

Potential Models (scaled), different models

S(0) = 0.56 ± 0.02(exp) ± 0.02(theory) (5%)

Kontos *et al.* (2013)

6 data sets (modern)

external and internal capture *R*-matrix, $\Delta\chi^2$ method

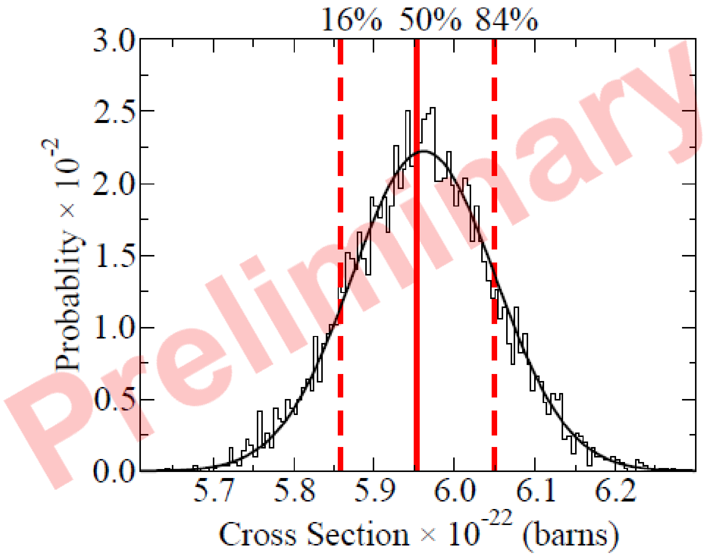
S(0) = 0.554 ± .020 (3.6%)

UNCERTAINTY: MONTE CARLO

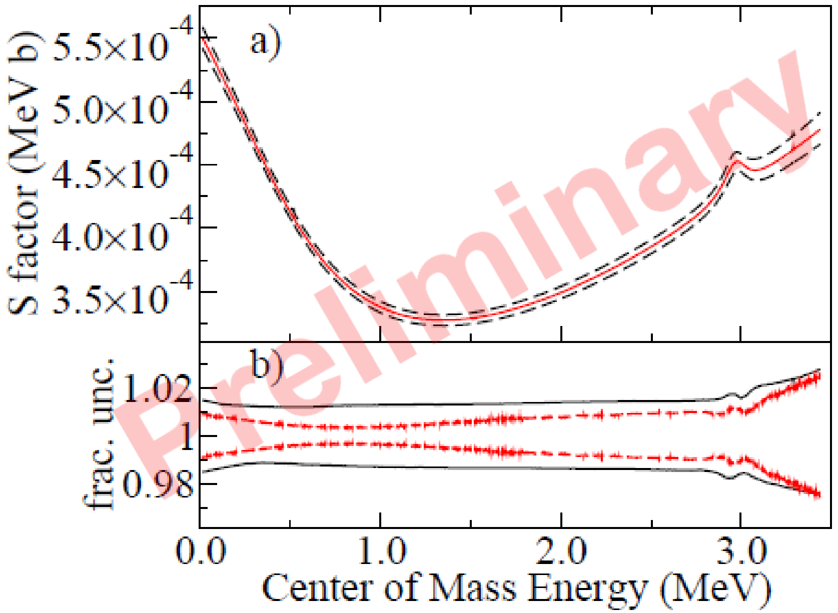
6 data sets (modern)

1) **For the data, sample over a Gaussian distribution (statistical uncertainty)**
2) **Throw normalization over a Gaussian or Uniform distribution (systematic uncertainty)**
3) **Redo *R*-matrix fit**
4) **Repeat 1-3 several thousand times**

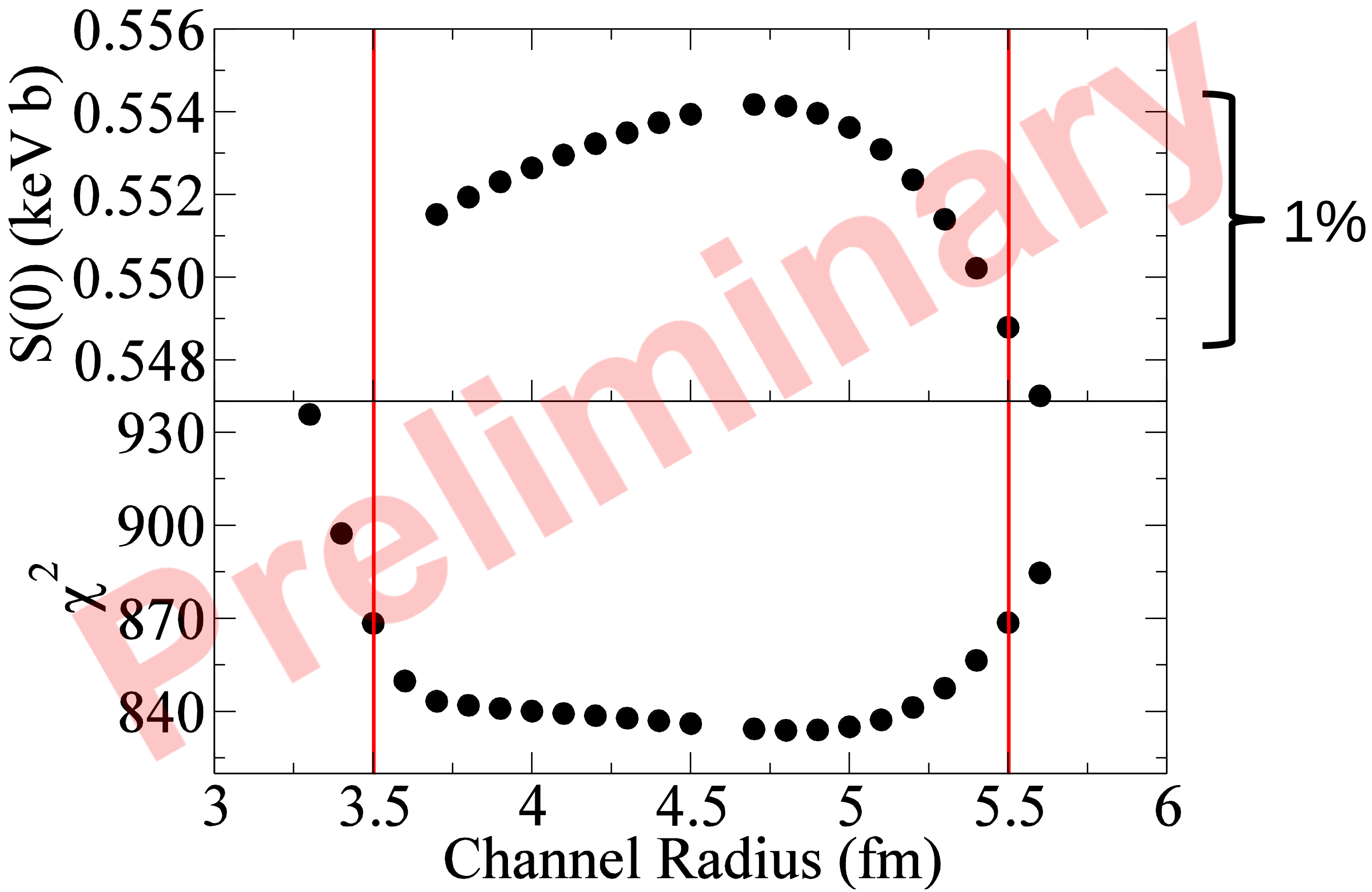
Gialanella et al. (2001)
Schürman et al. (2012)



^{3}He(α,γ)^{7}Be Monte Carlo Uncertainty



MODEL UNCERTAINTY: RADIUS PARAMETER

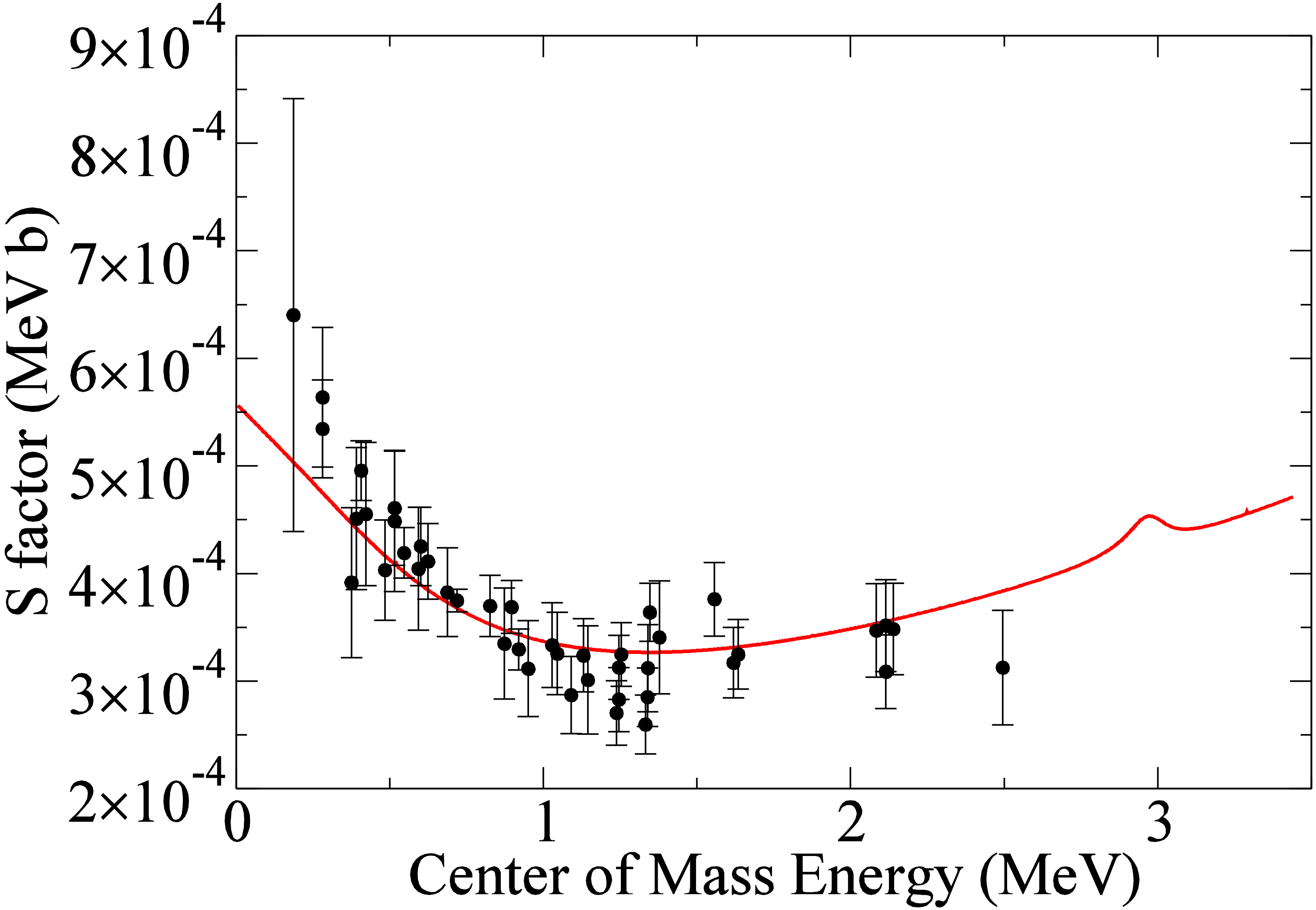


NEW UNCERTAINTY ESTIMATE

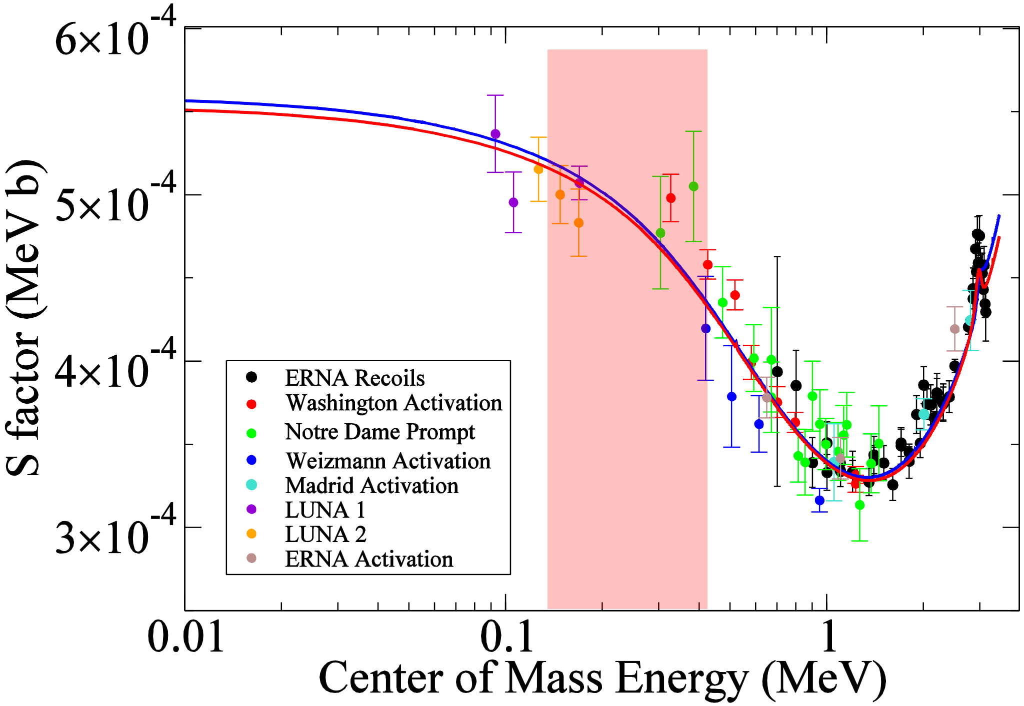
0.554 ± 1.9% (syst and stat) ± 1.5% (model) keV b

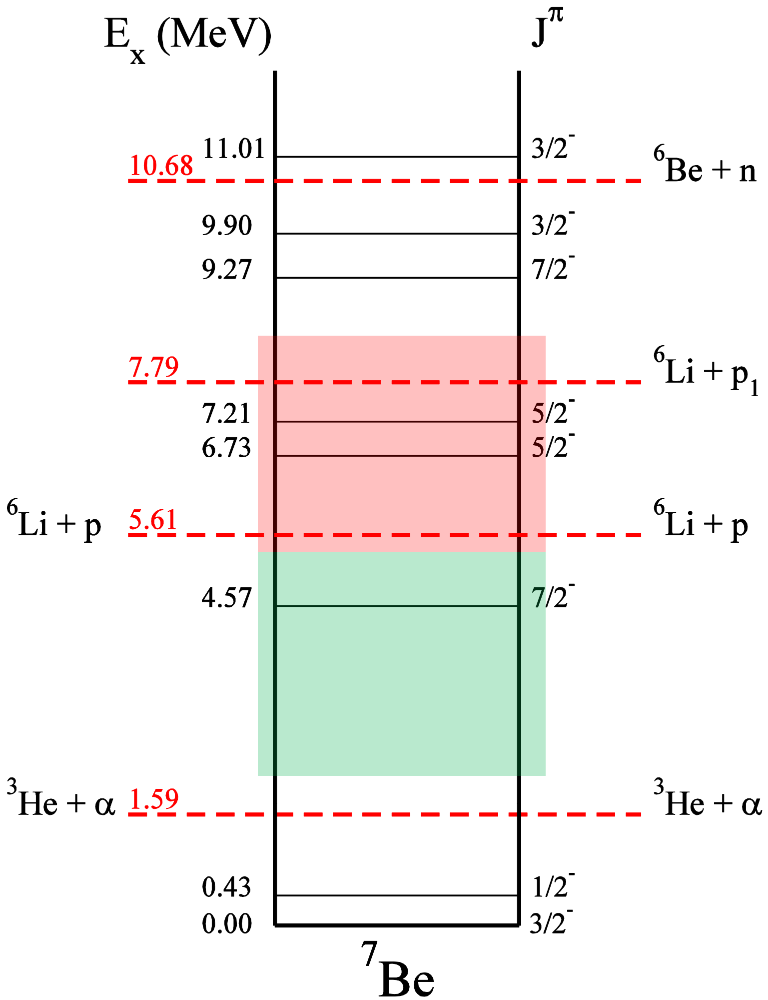
2.4% total (ideal estimate)

LOOKING BACK: PARKER AND KAVANAGH (1963)



LOOKING FORWARD





CONCLUSIONS

1) R-matrix fit can reproduce all of the “modern” data sets if systematic uncertainties are considered.

2) Channel Capture, which is often ignored, is very important for this calculation

3) The reaction rate may be known to as well as 2.4%!

4) Connect LUNA data with higher energy measurements

5) Measure to higher energies to test the R-matrix model

COLLABORATORS

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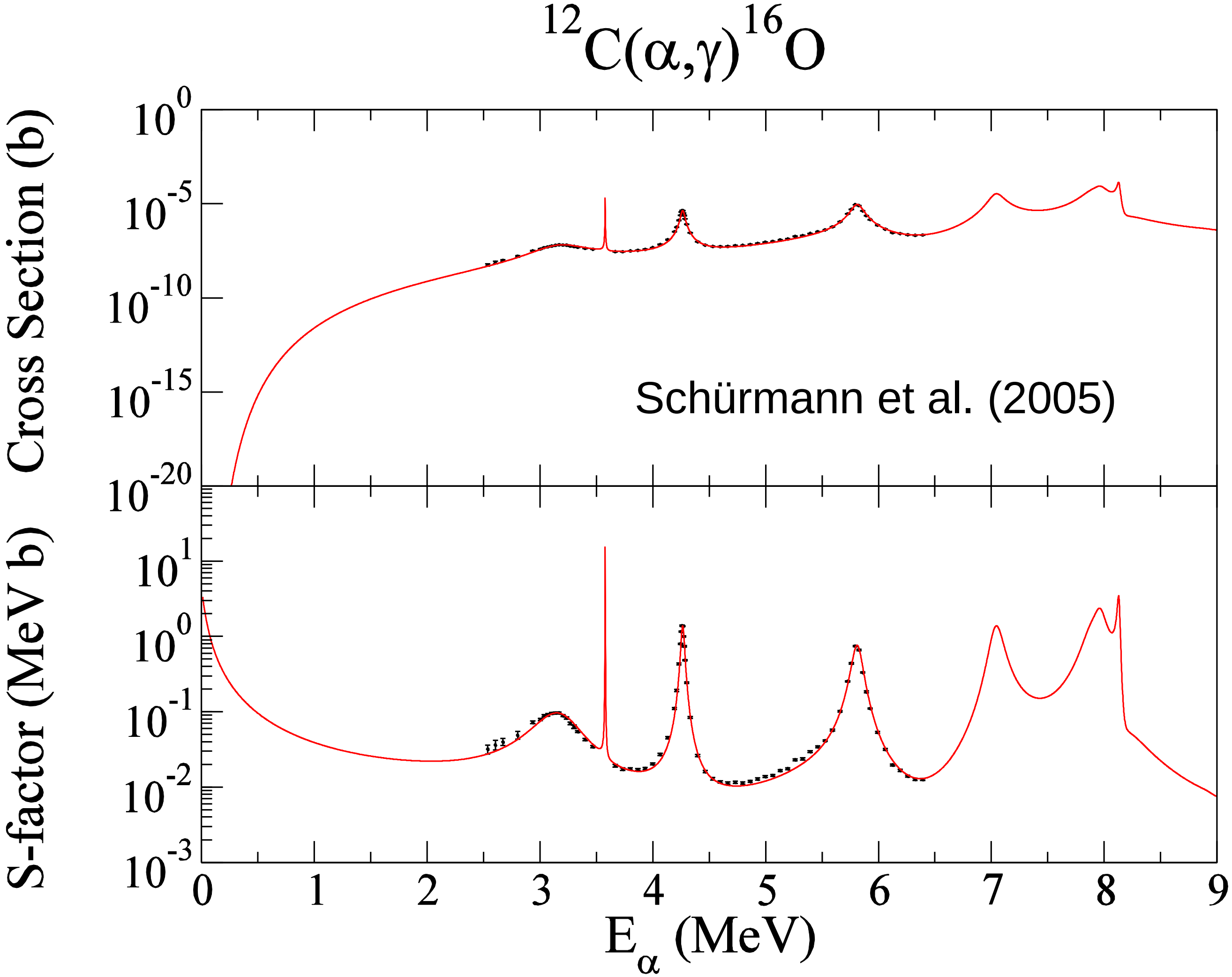
Gianluca Imbriani

Frank Strieder

Antonino Di Leva

EXAMPLE REACTION: $^{12}C(\alpha,\gamma)$



EXAMPLE REACTION: $^{22}Ne(\alpha,n)$