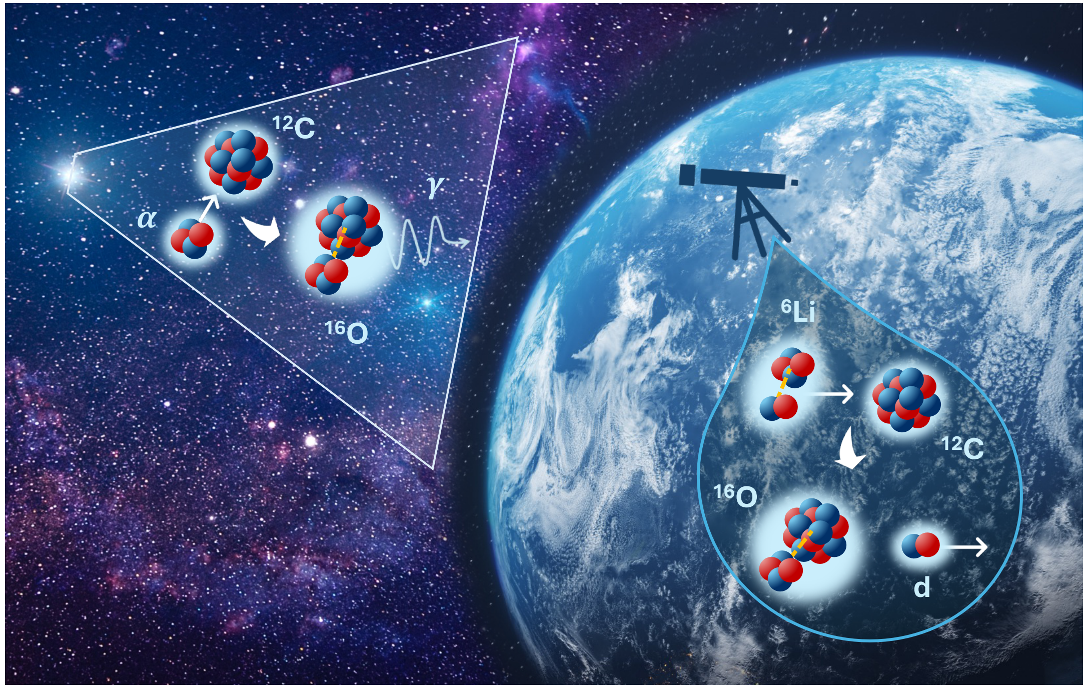
Constraining accurately astrophysical rates using indirect reactions

INT Workshop “Quantum Physics of Stars” 2026

Chloe Hebborn

Analysis of indirect reaction require accurate description of the reaction



Need to have accurate reaction description and reliable quantification of uncertainties

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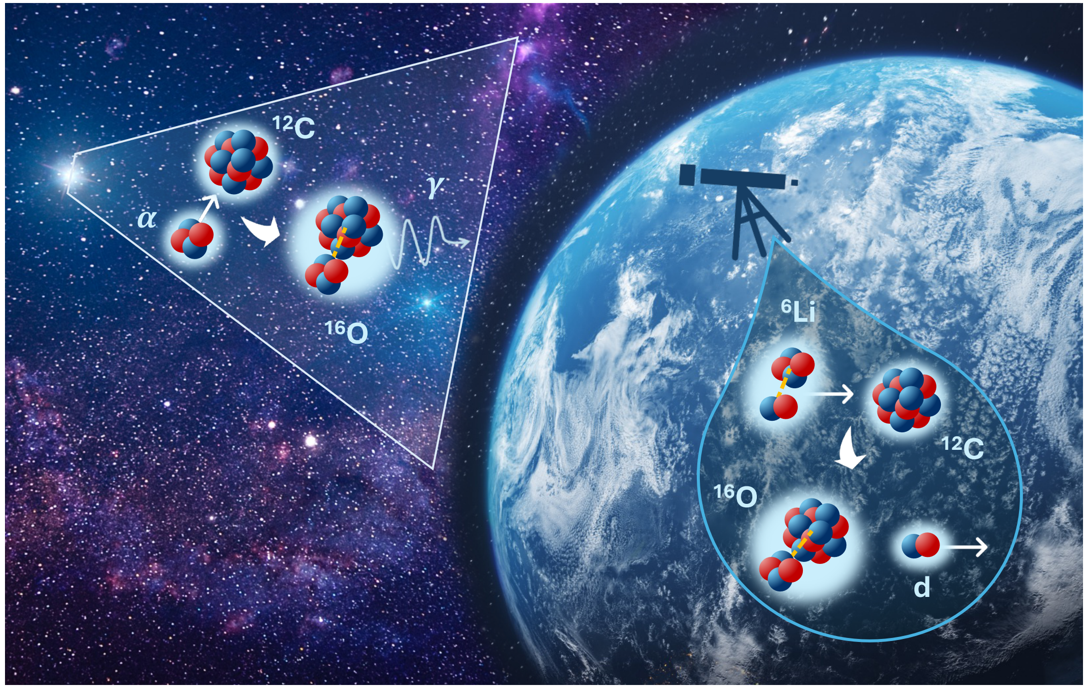


Need to have accurate reaction description and reliable quantification of uncertainties

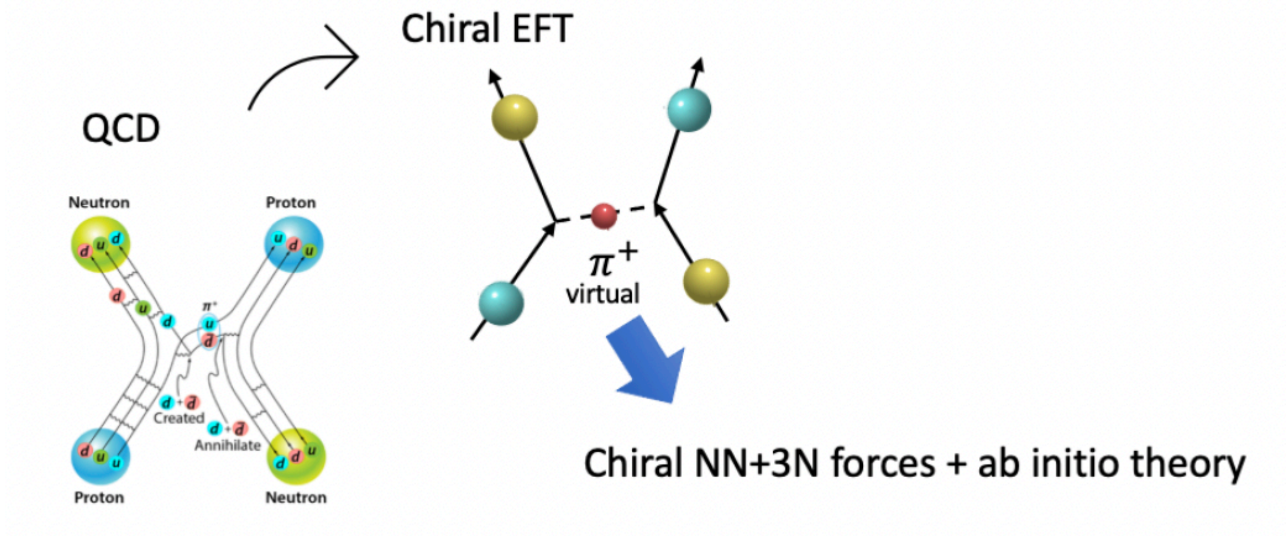
Three main ingredients in any models:

1) Interactions grounded in the underlying theory

2) Use an accurate model

3) Quantify uncertainties

Ideally, we want to describe all reactions from nucleon's degrees of freedom, with interactions derived from QCD



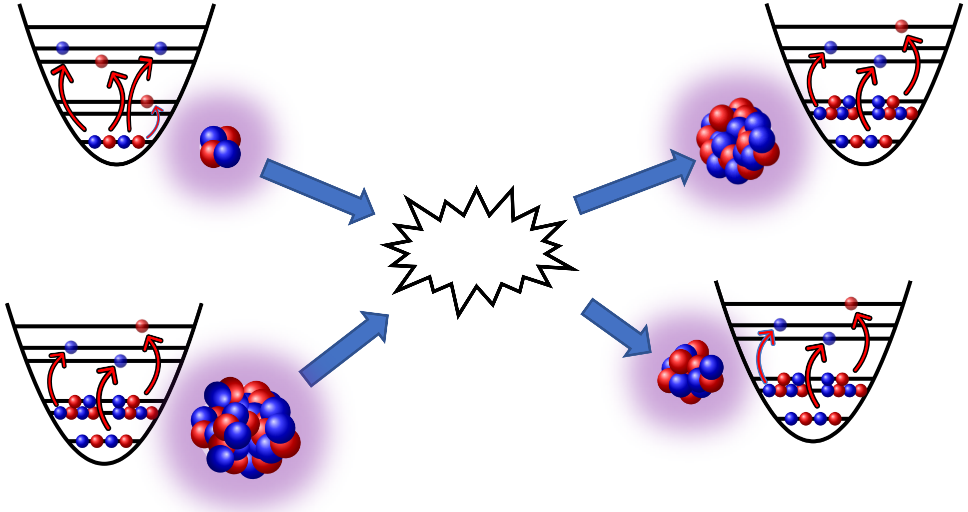
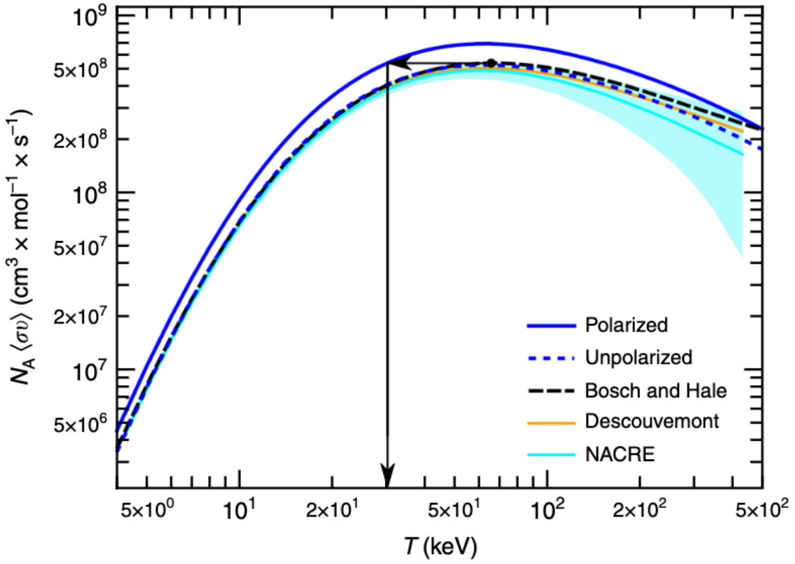
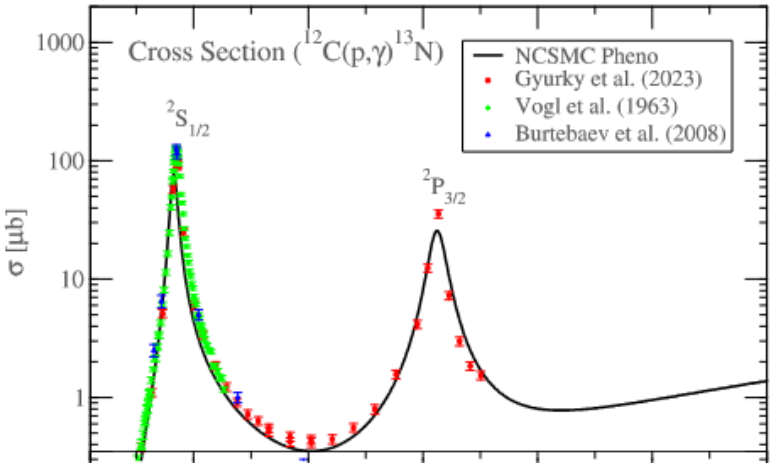
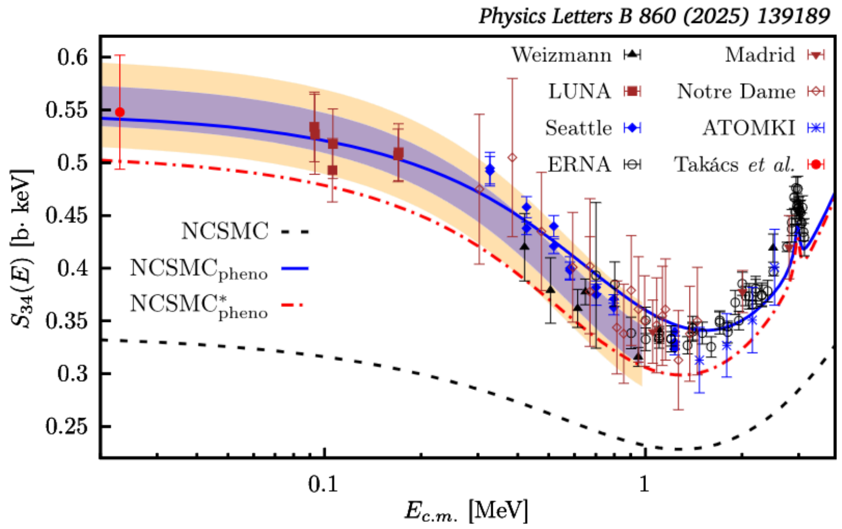


Figure courtesy of S. Quaglioni

Ab initio predictions have provided accurate evaluation of reaction rates



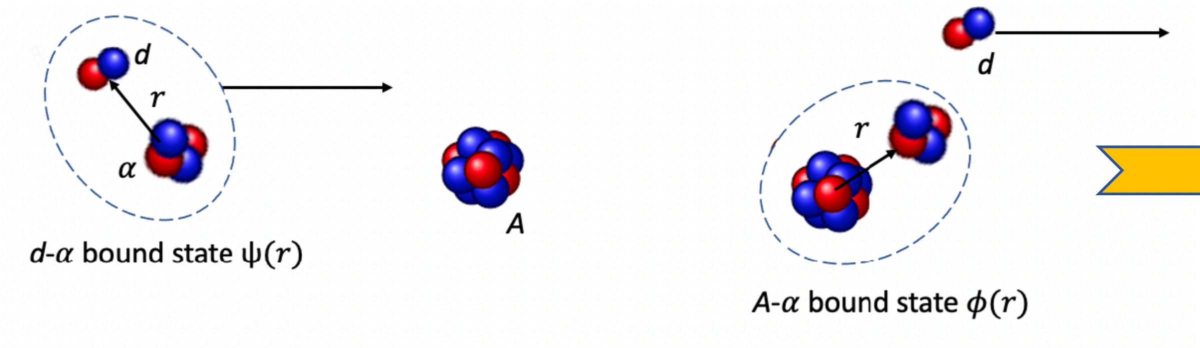


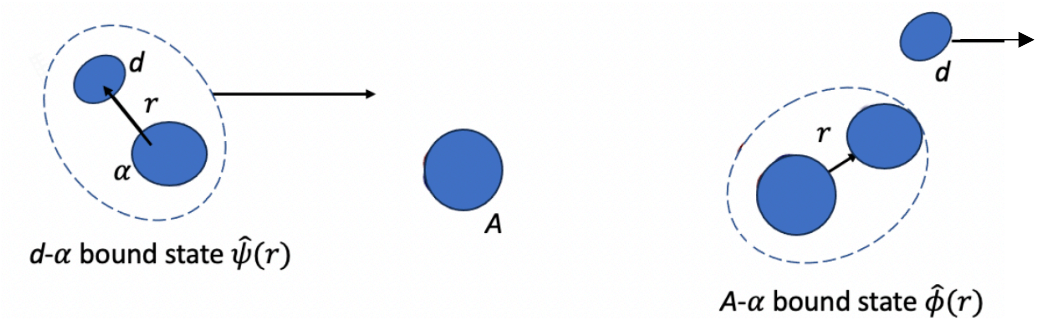


But they are (for the moment) stuck to light systems and low energies*..

*new methods being developed (Bonaiti, Johnson, Kimura)

Often we are using few-body models to describe these reactions





Microscopic Hamiltonian

Effective Hamiltonian

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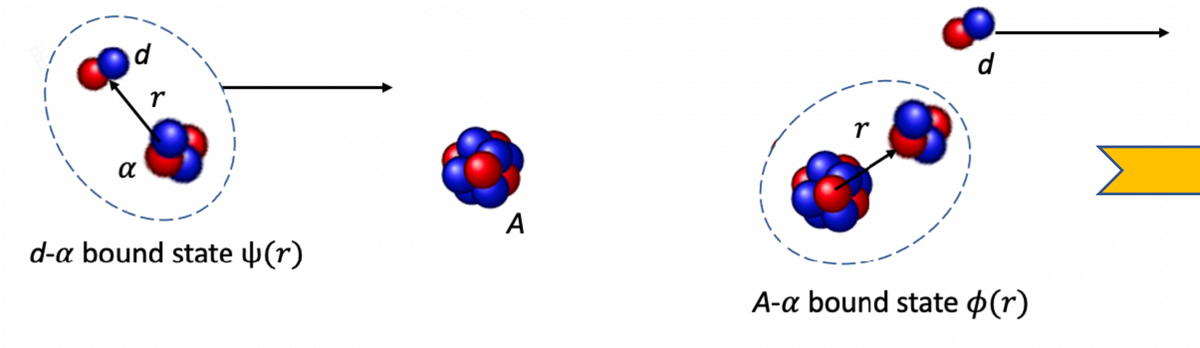

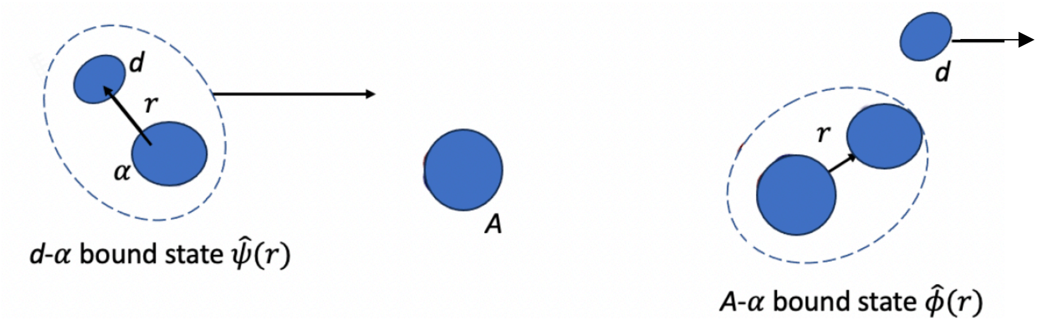

Microscopic Hamiltonian → Effective Hamiltonian

Solve the 3-body problem with 3-b Hamiltonian (prior vs post form):

$$H^{3b} \approx T_{6Li-A} + V_{opt}^{\alpha A} + V_{opt}^{dA} + h_{\alpha d} \approx T_d + V_{opt}^{\alpha d} + V_{opt}^{dA} + h_{\alpha A}$$

(+3-b force almost always neglected)

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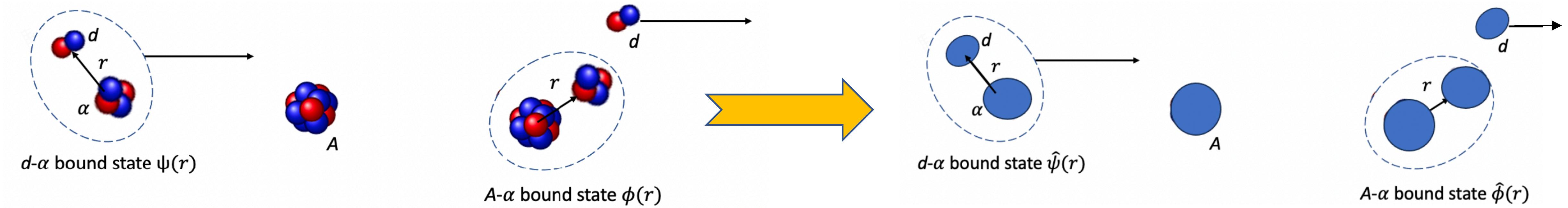


Microscopic Hamiltonian → Effective Hamiltonian

Solve the 3-body problem with 3-b Hamiltonian (prior vs post form):

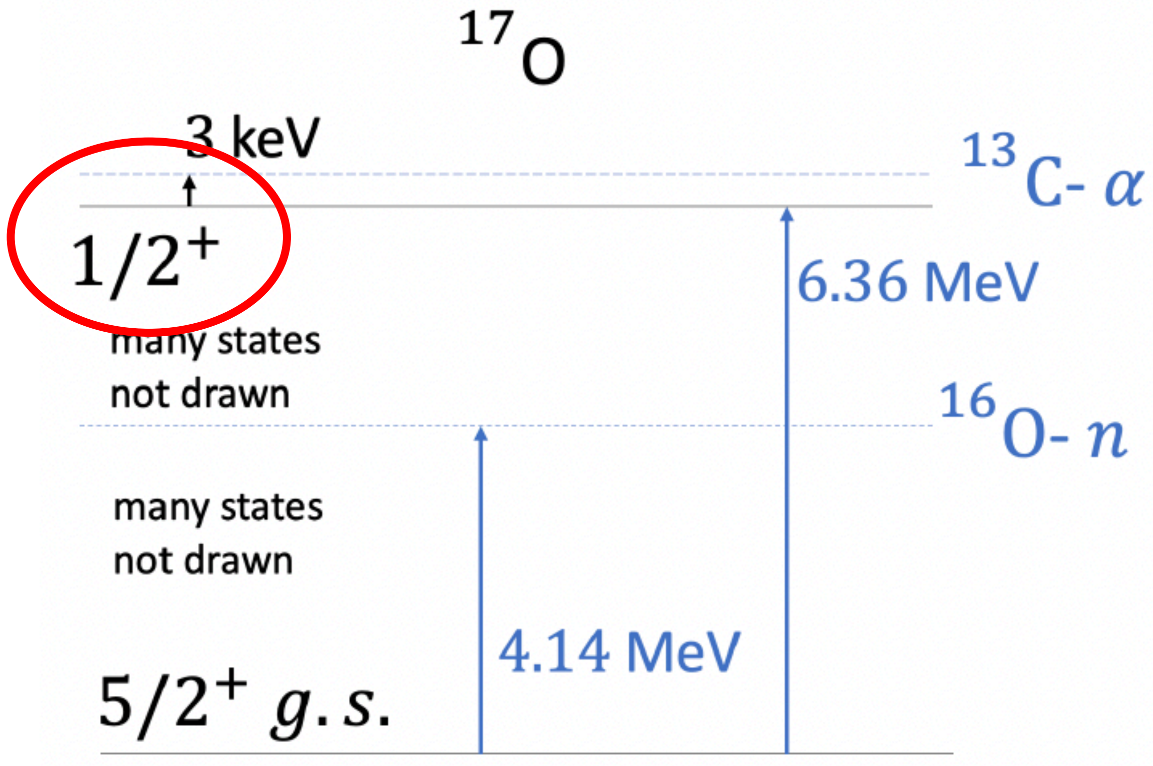
What we want to learn from data

$$H^{3b} \approx T_{6Li-A} + V_{opt}^{\alpha A} + V_{opt}^{dA} + h_{\alpha d} \approx T_d + V_{opt}^{\alpha d} + V_{opt}^{dA} + h_{\alpha A}$$

(+3-b force almost always neglected)

Compute observables, compare with data and deduce information about $h_{\alpha A}$

For example, ANCs of ^{17}O were extracted from ^{13}C(α,n)^{16}O data



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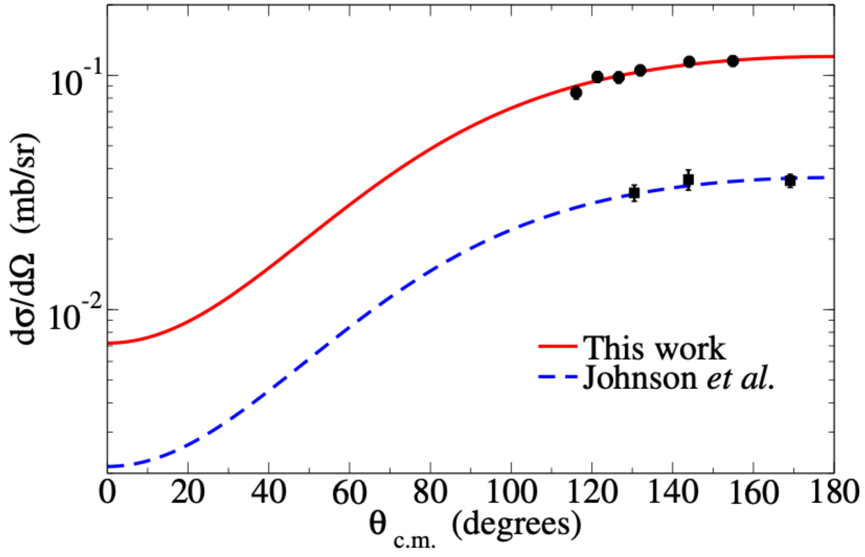
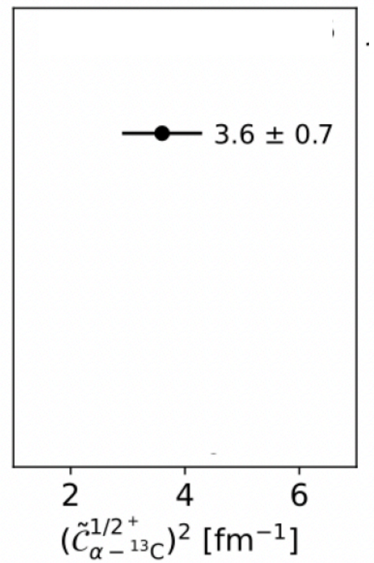
Transfer data
+ reaction theory

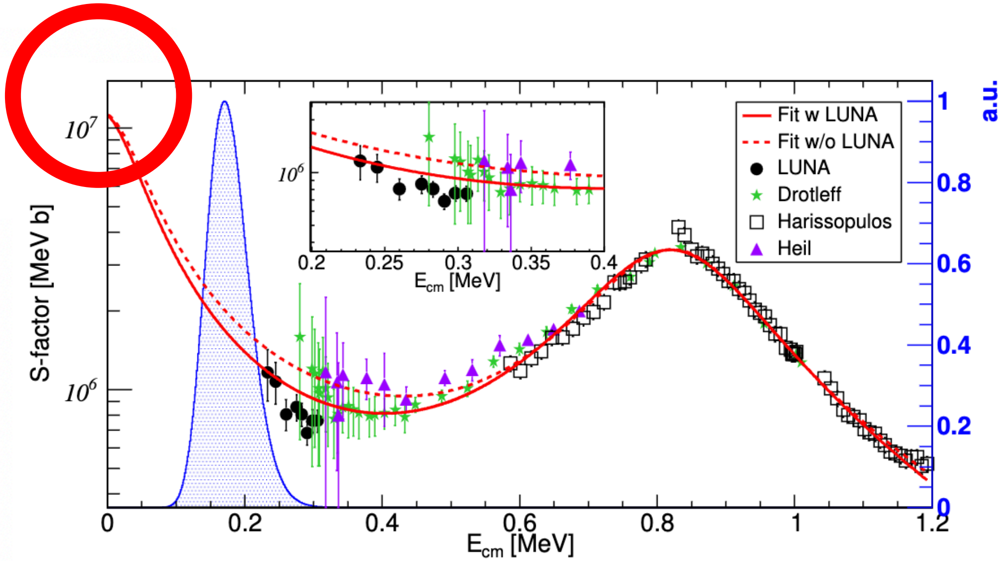
^{17}O ANCs

R-matrix evaluation



Avila et al. PRC 91 048801 (2015)





Ciani et al. PRL 127 152701 (2021)

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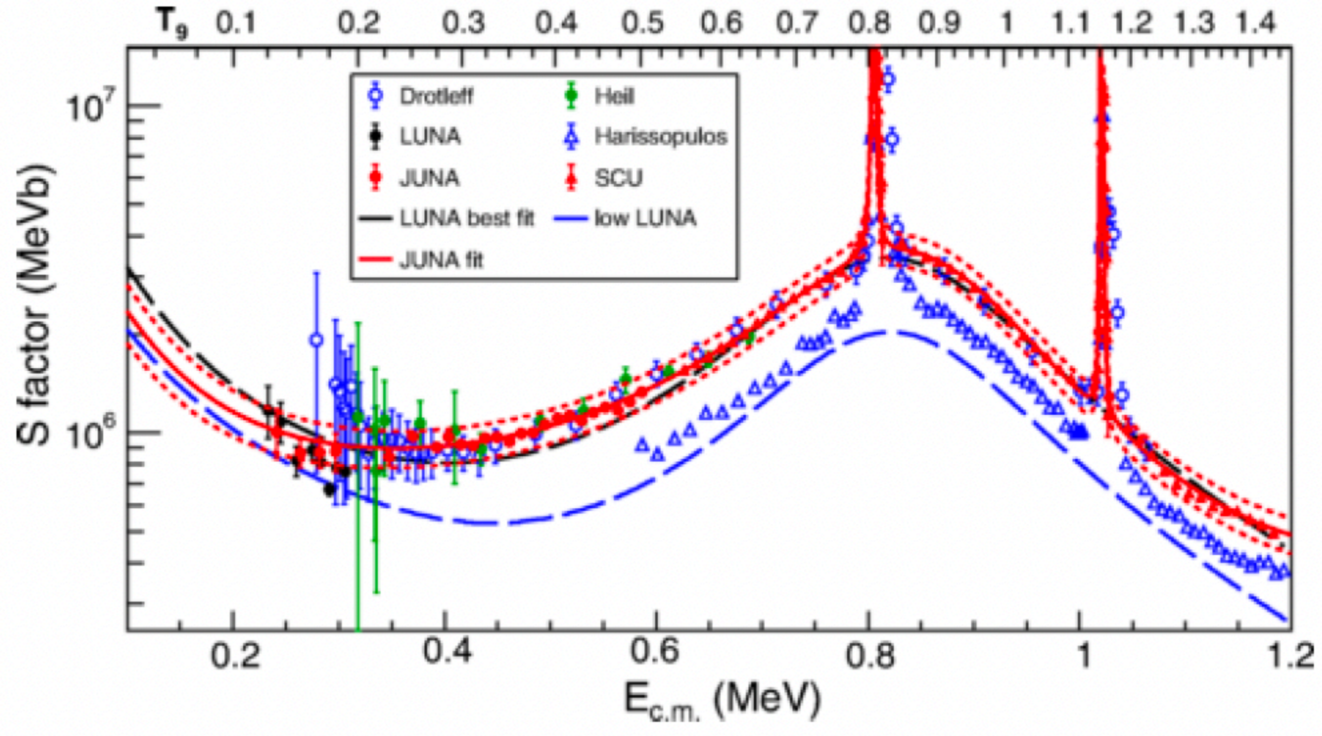
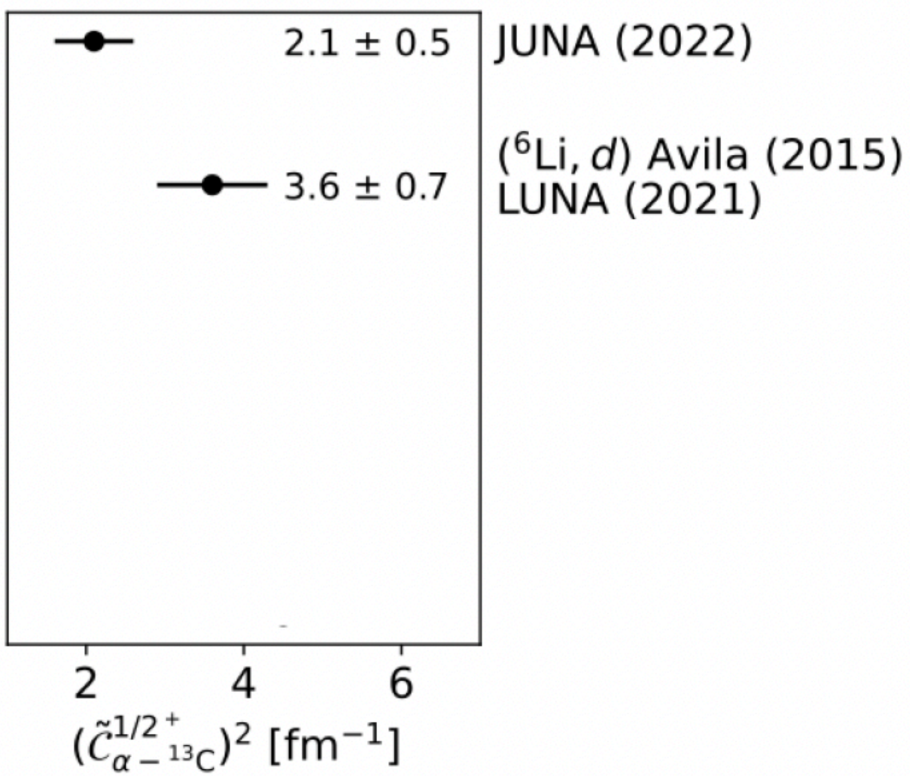
But different ANCs obtained from JUNA… Leads to different evaluation



[Gao *et al.* PRL **129**, 132701 (2022)]



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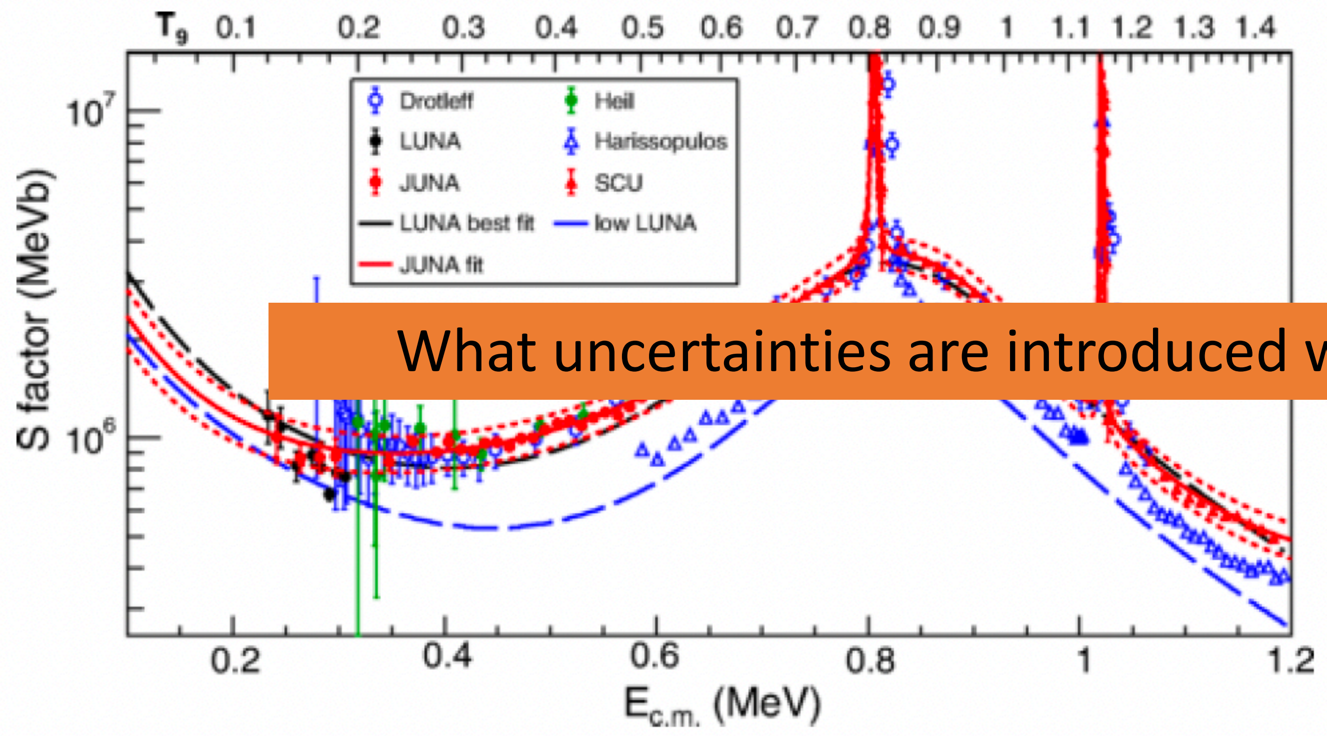

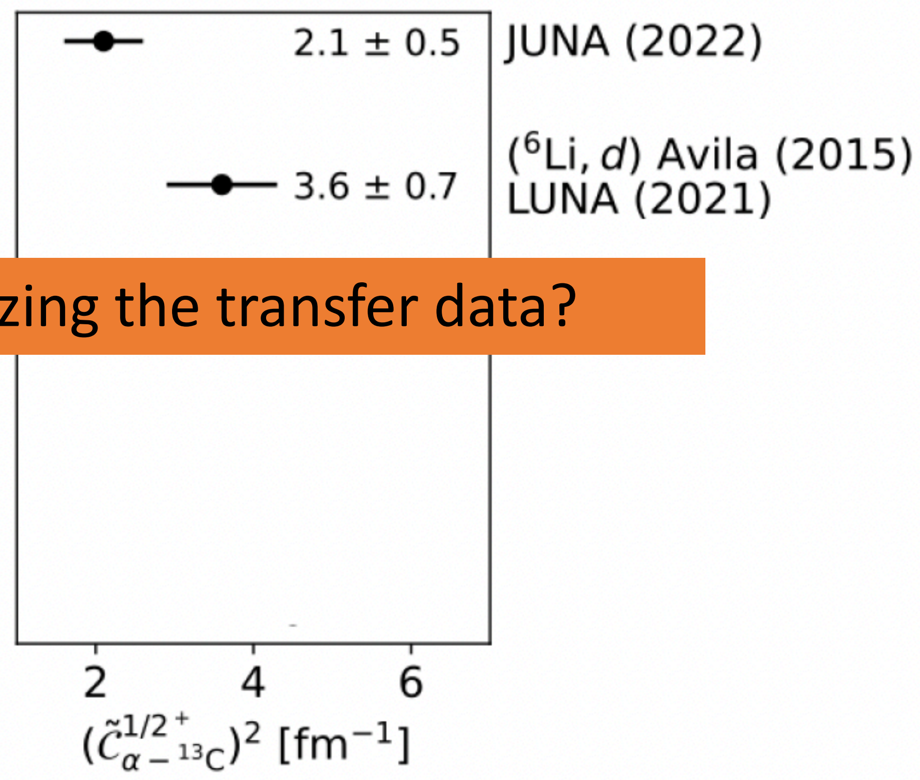

What uncertainties are introduced when analyzing the transfer data?

[Gao *et al.* PRL **129**, 132701 (2022)]

First we do not know the Hamiltonian accurately…

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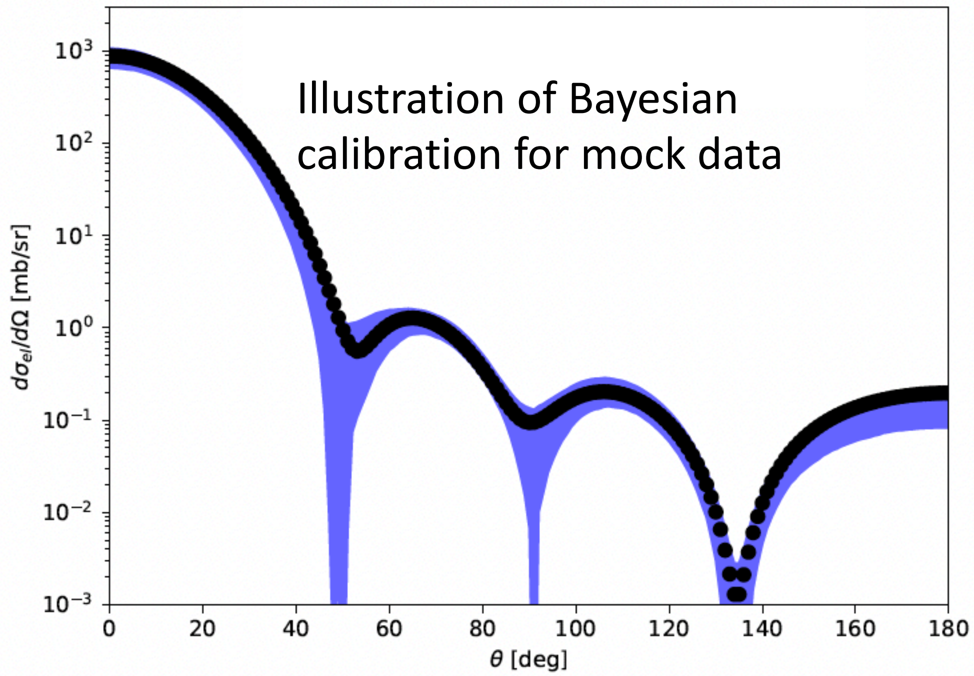
Potentials (Woods-Saxon) fitted to scattering data

Often 6-12 parameters…

→ Parametric uncertainties (often not quantified)

→ Model uncertainties (often not quantified)

Sometimes there are not even data to fit to…
rely on global parametrization



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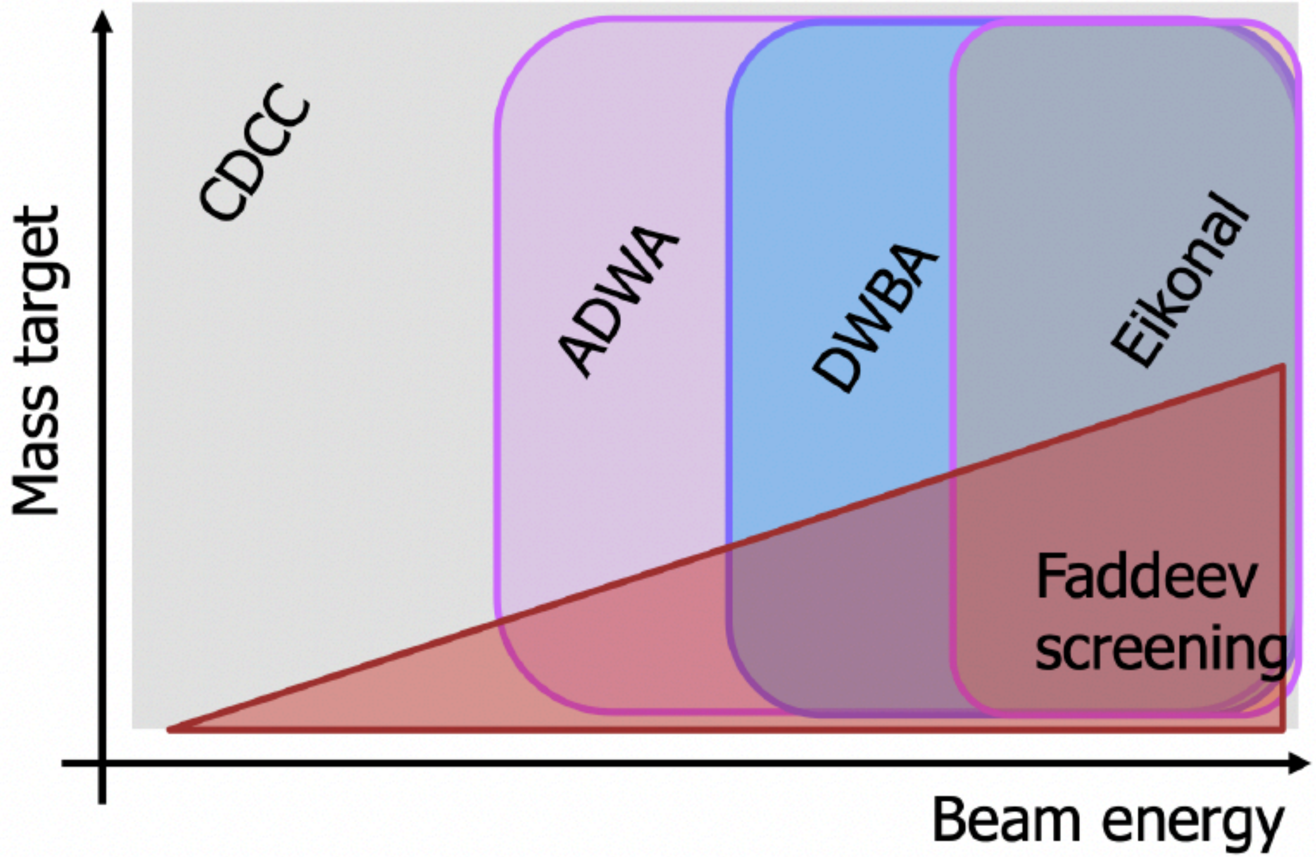
Effective interaction for α-d

Anything you can find to constrain it…

Phase shift analysis

Structure prediction for spectroscopic amplitudes…

Second, we do not know the exact solution to the few-body problem.. Many (imperfect) models exist



[Figure courtesy of F. Nunes]

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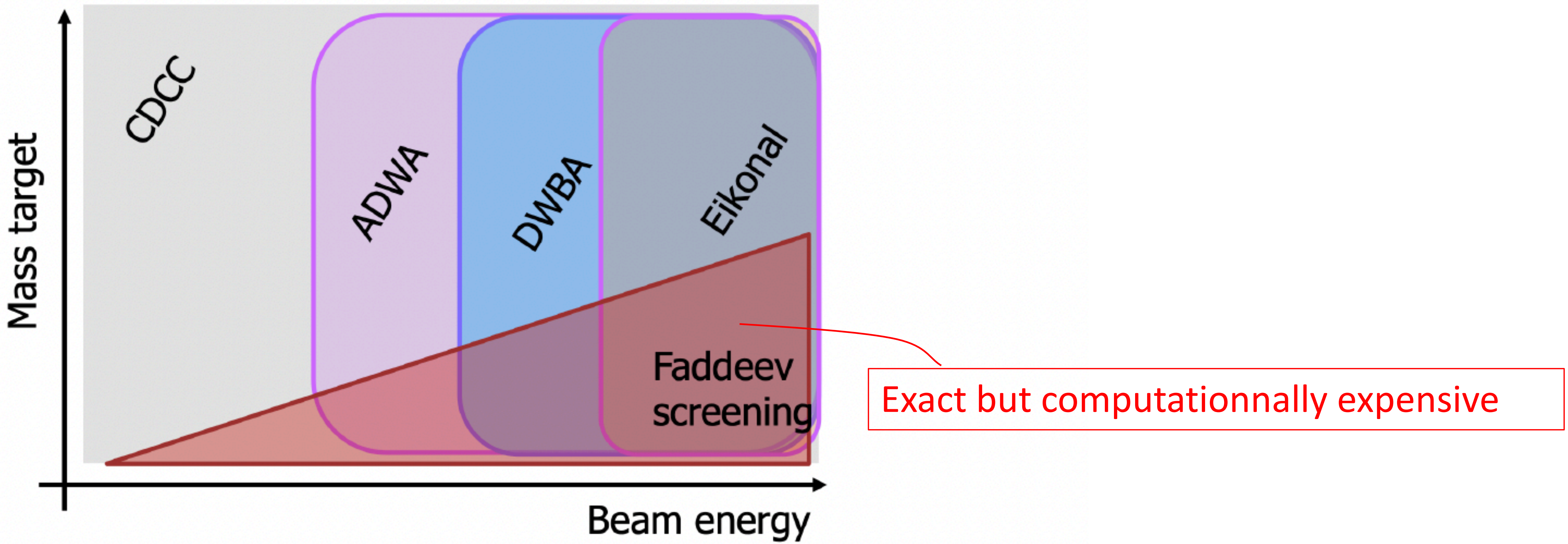

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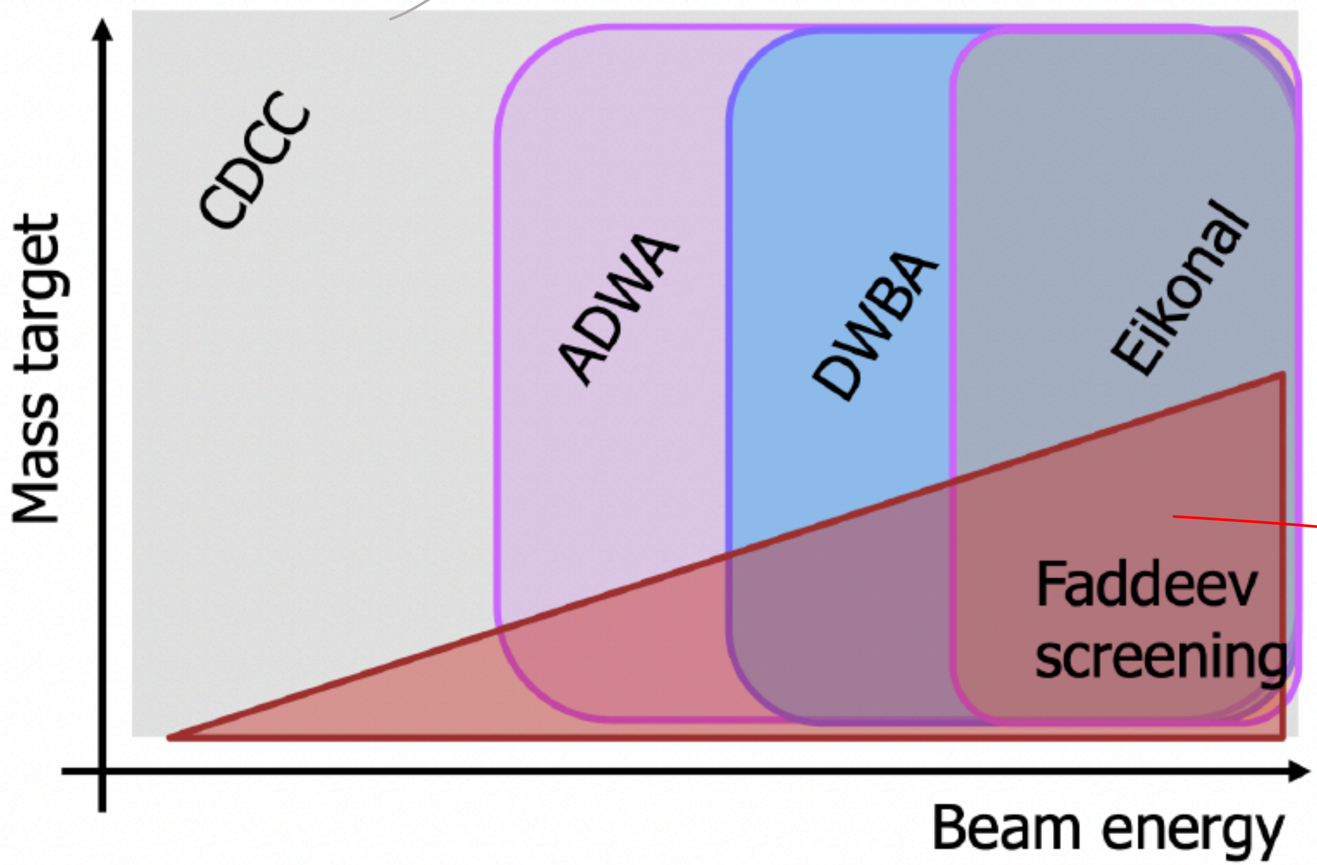
Accurate but can be difficult to converge and computationally expensive



Exact but computationnally expensive

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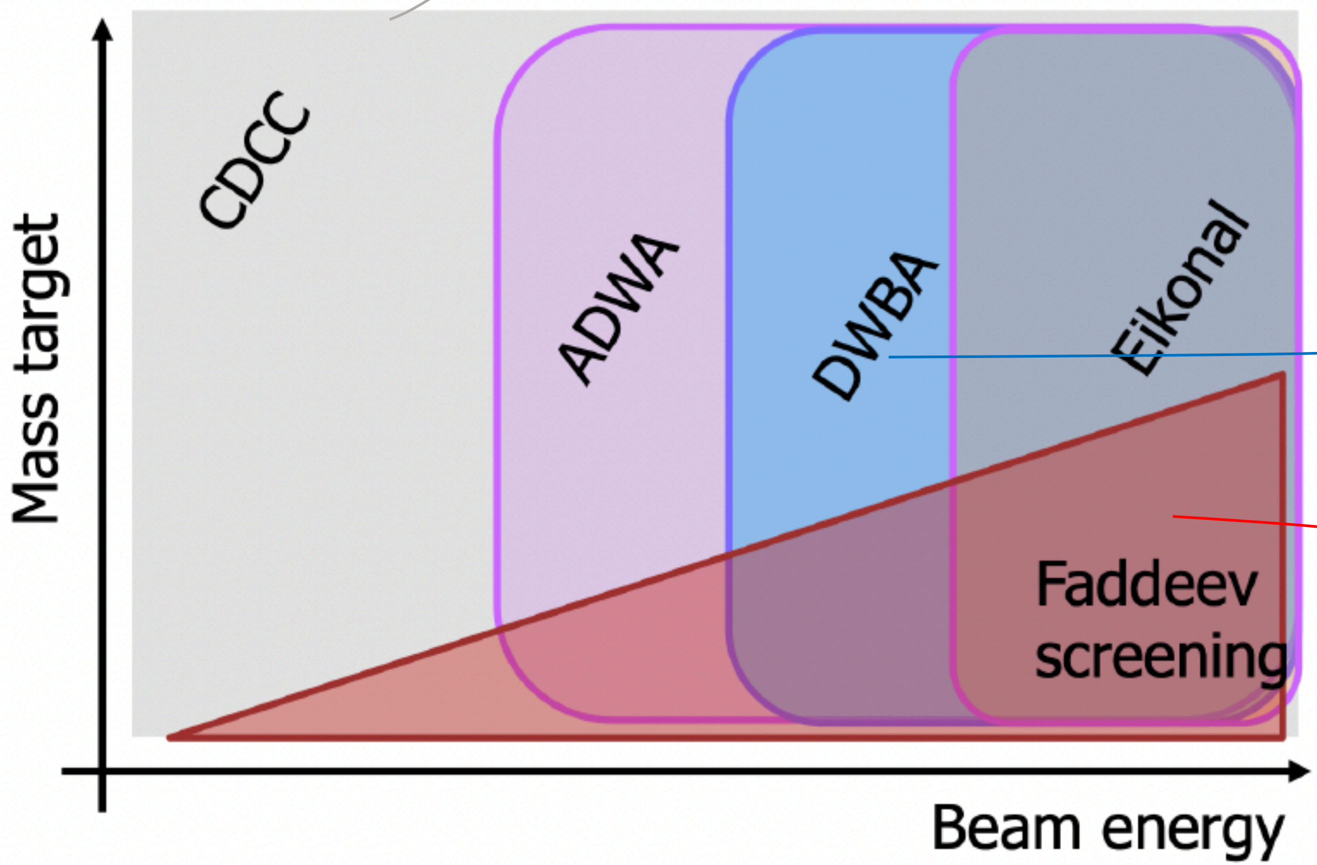

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One-step description of the reaction → cheaper computationally

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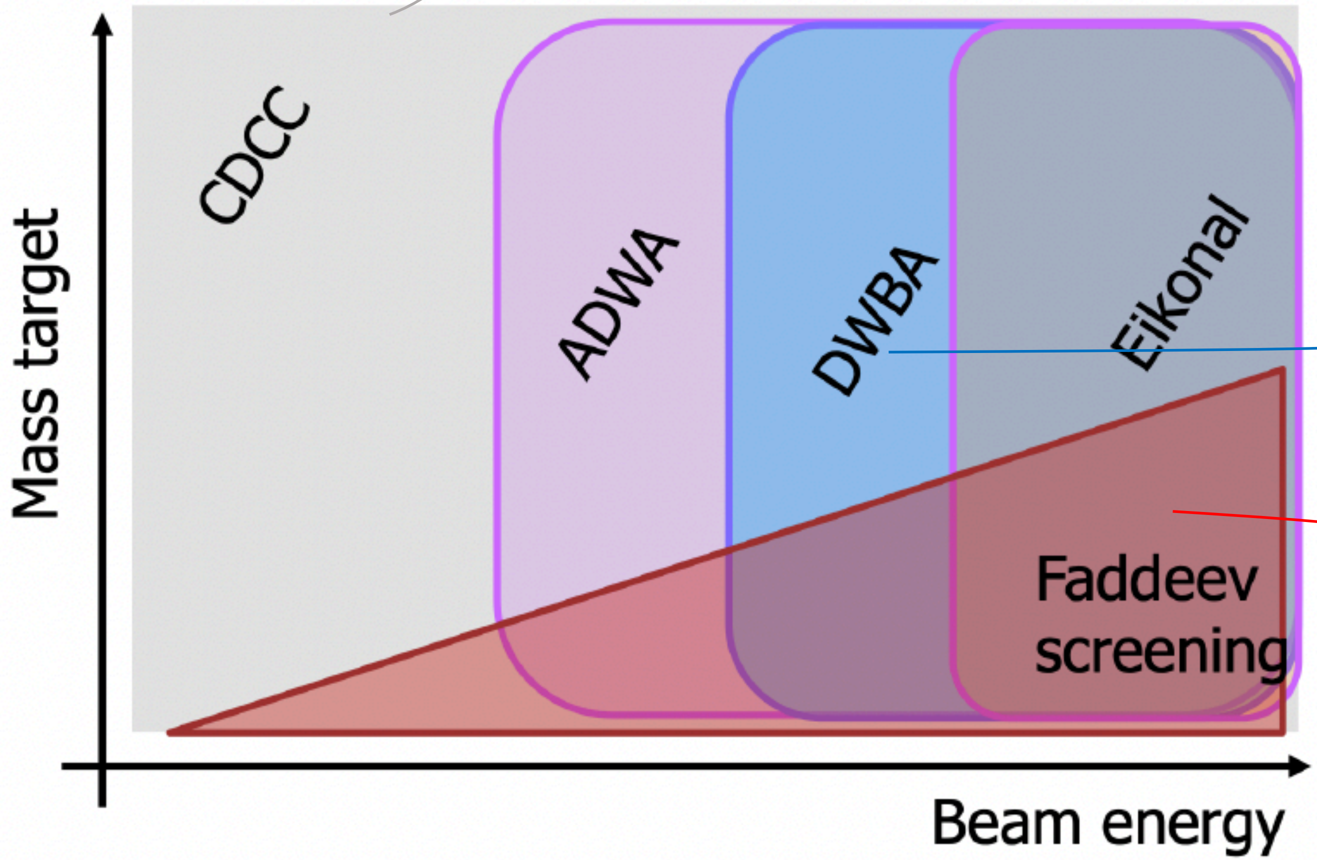

[Figure courtesy of F. Nunes]

Accurate but can be difficult to converge and computationally expensive

One-step description of the reaction
→ cheaper computationally

Exact but computationnally expensive

→ Many models which are accurate for different energy regimes and targets….

Choose wisely… And be critical ☺

What can we do to improve reaction analysis?

1) Use state-of-the art predictions to ground our interactions

2) Use improved reaction models

3) Quantify uncertainties

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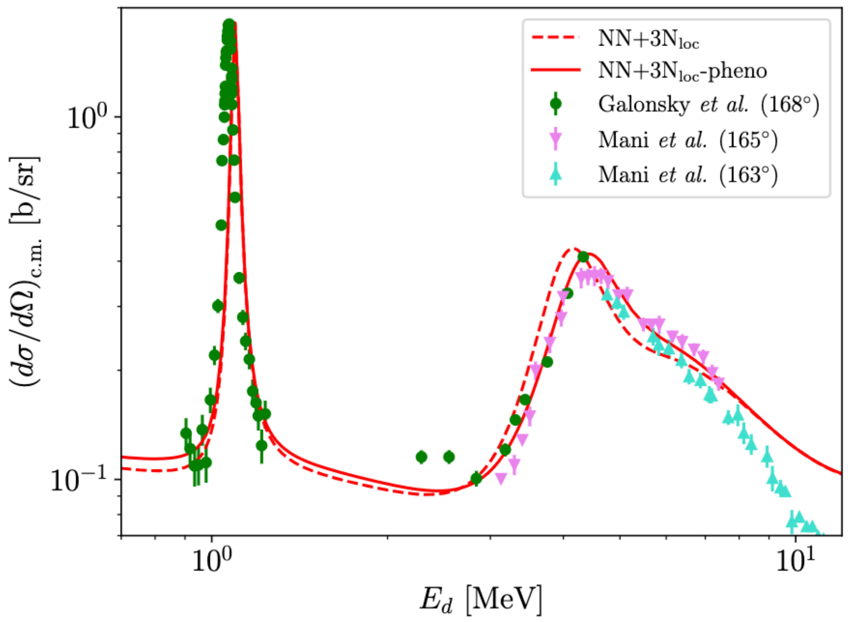
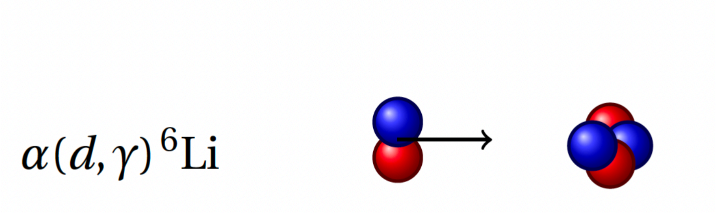
Recent ab initio prediction for ^{6}Li reproduce both scattering and S-factor with reduced uncertainties

Prediction with NCSMC with NN and 3N chiral forces





Hebborn et al. PRL 129 042503 (2022)

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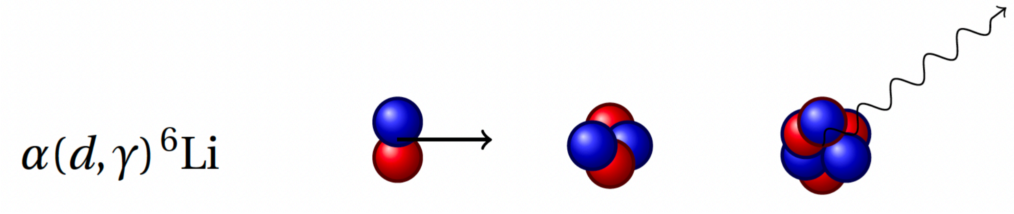

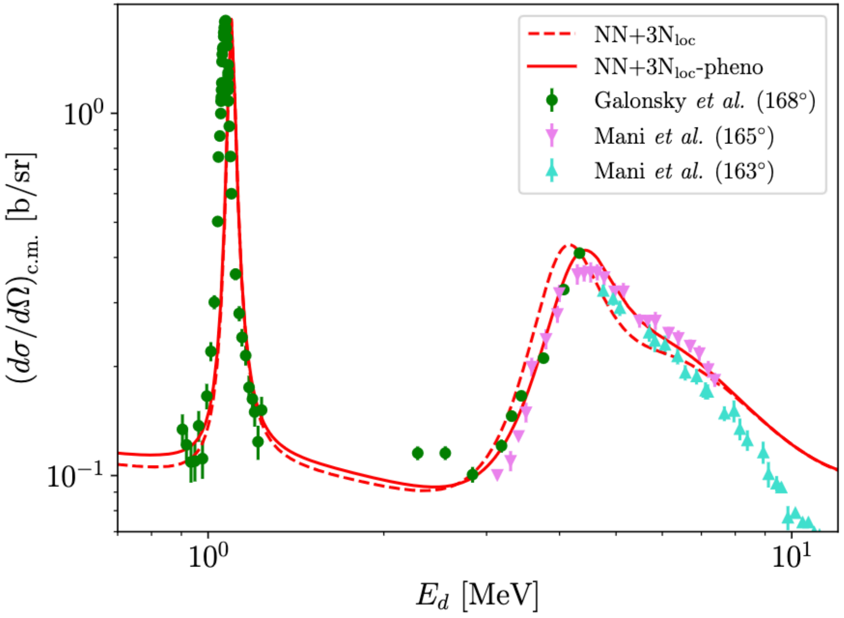

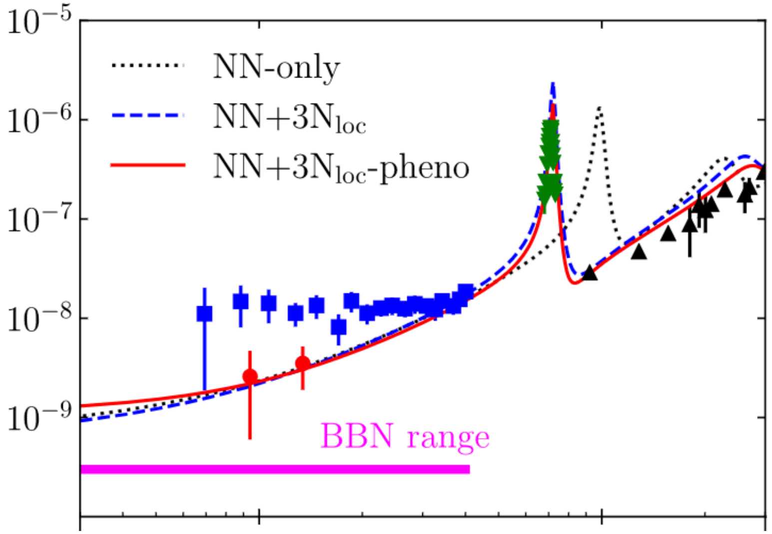

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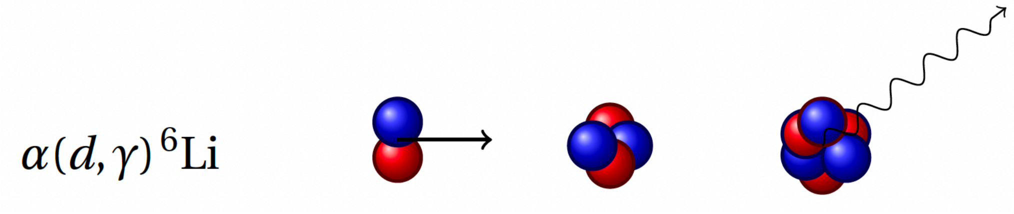
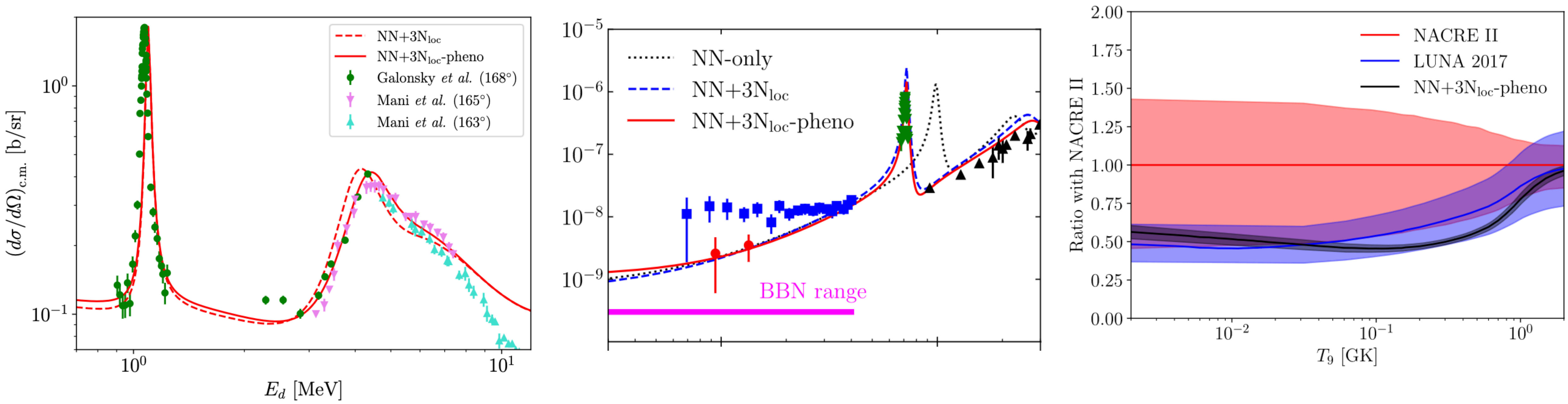
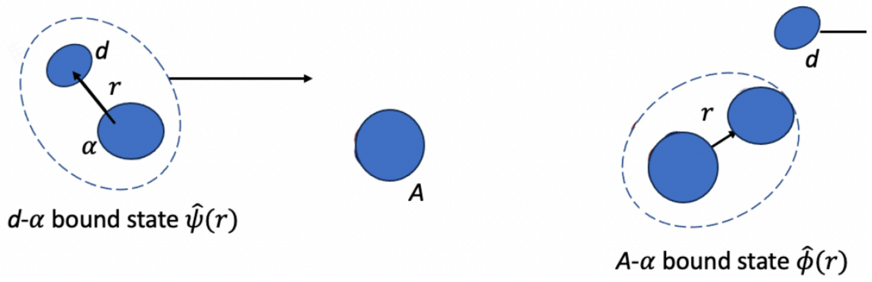
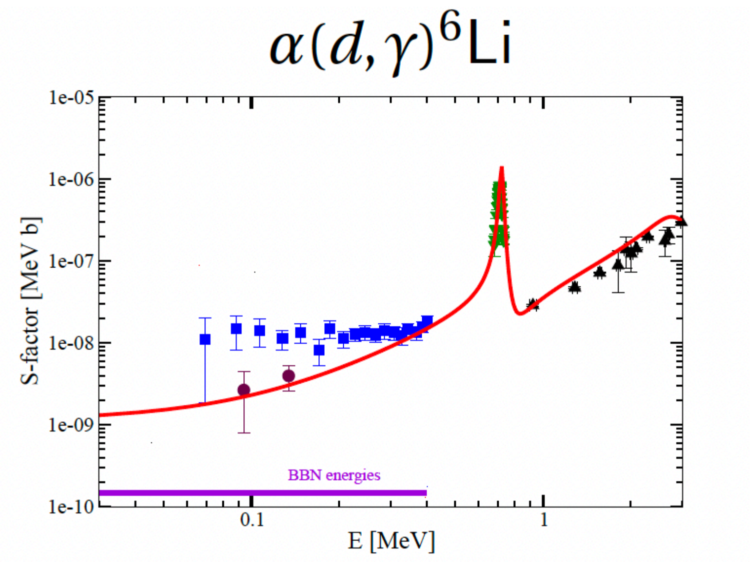




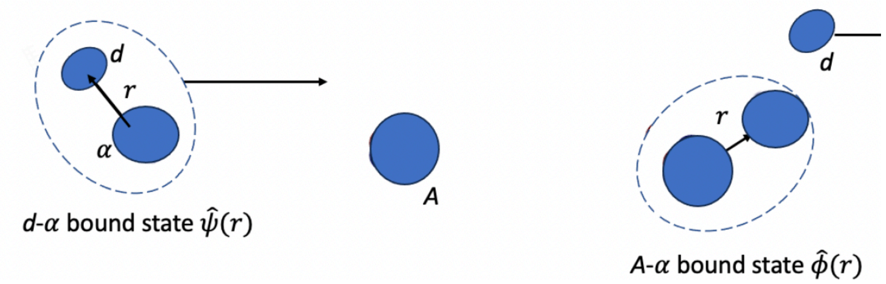
Hebborn et al. PRL 129 042503 (2022)

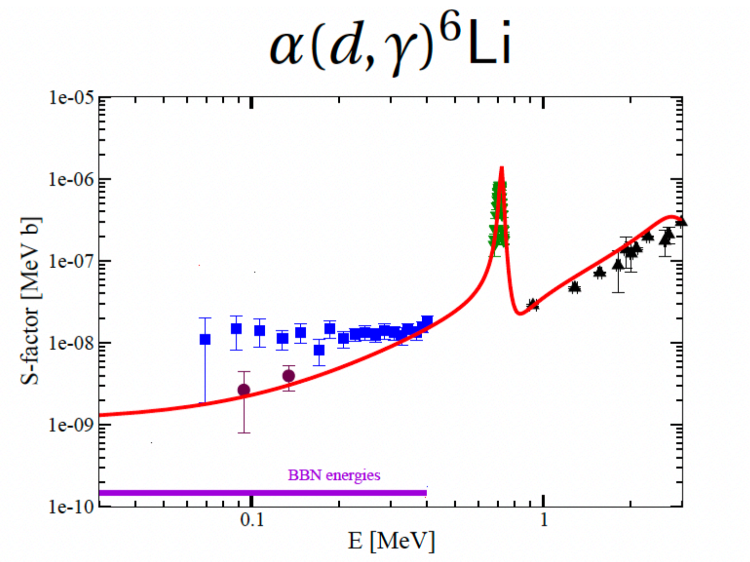
Reanalysis of transfer data using ^{6}Li description informed by ab initio prediction



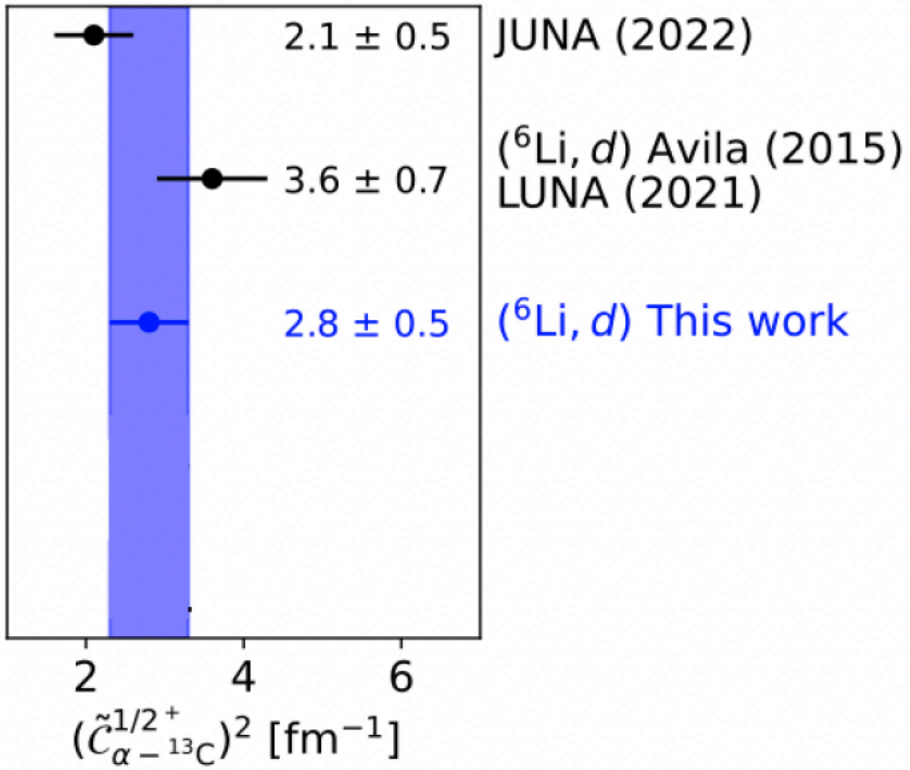


Reanalysis of transfer data using ^{6}Li description informed by ab initio prediction explains the discrepancy





Transfer data analysis



Hebborn et al. PRC 109 L061601 (2024)

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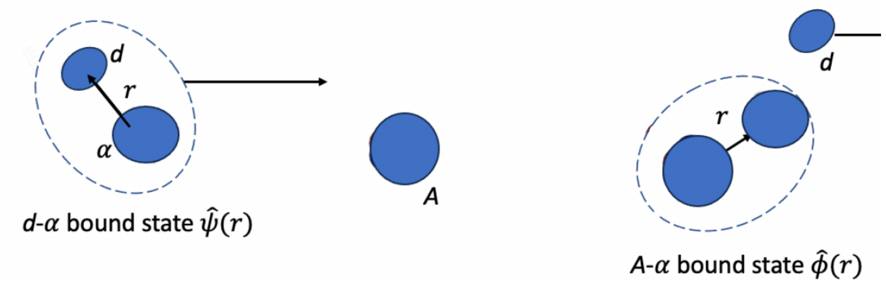

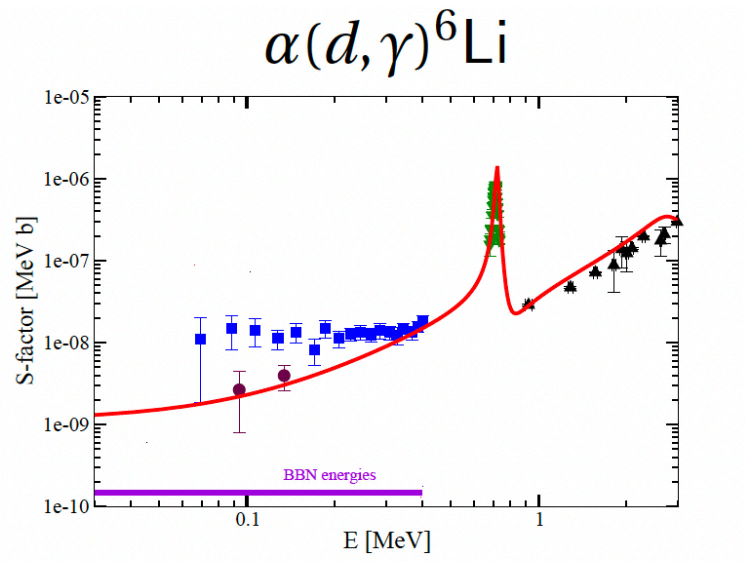

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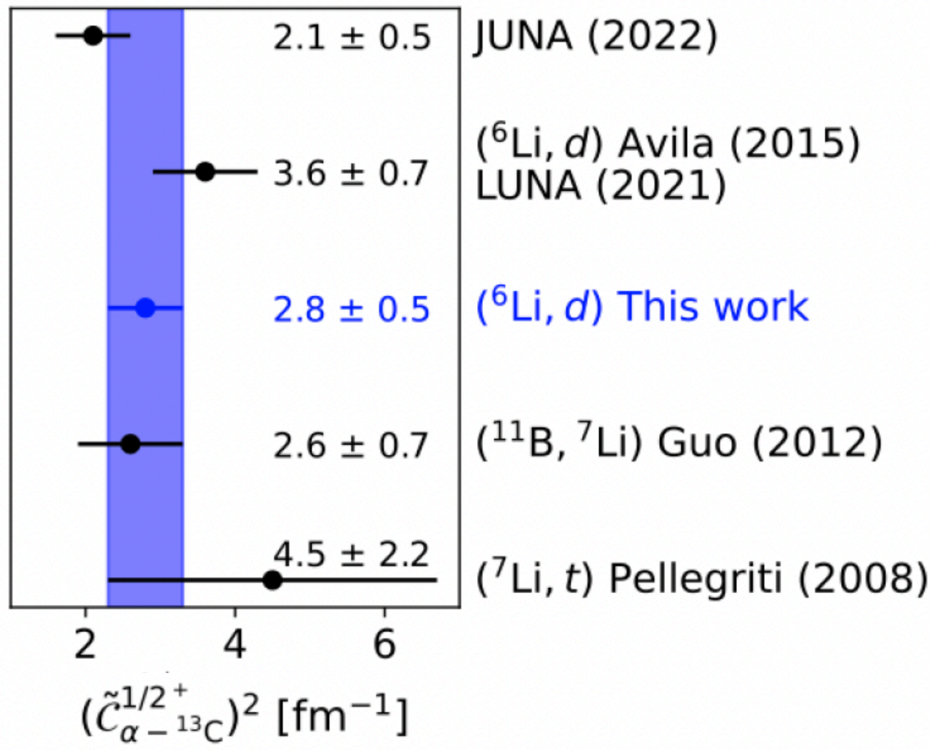
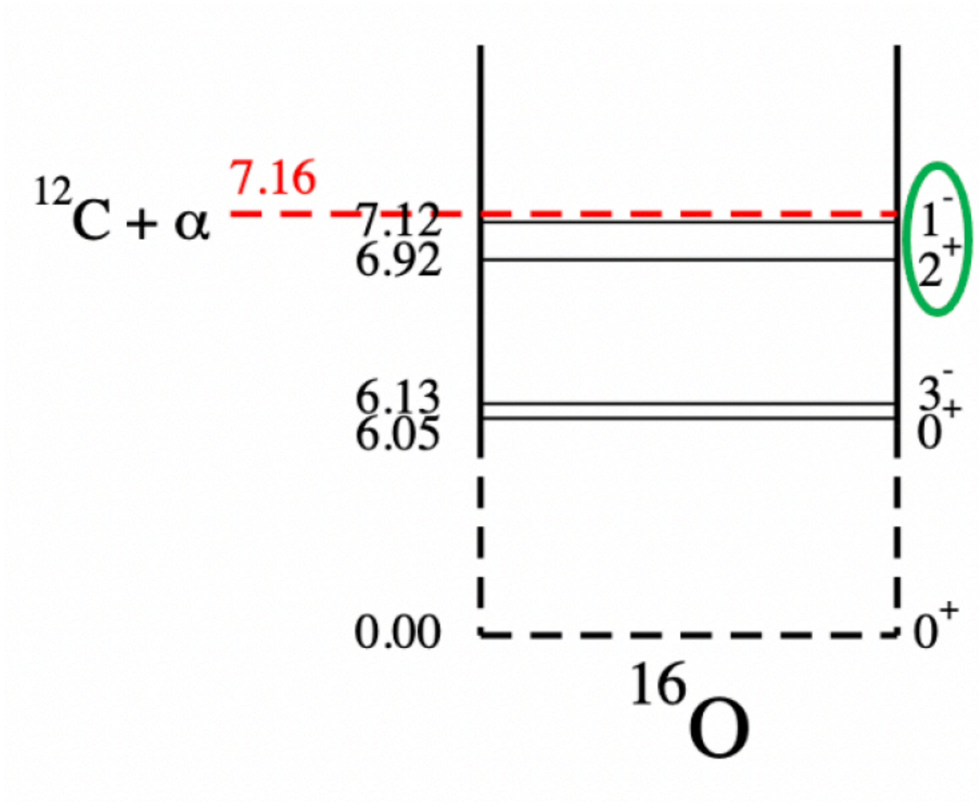
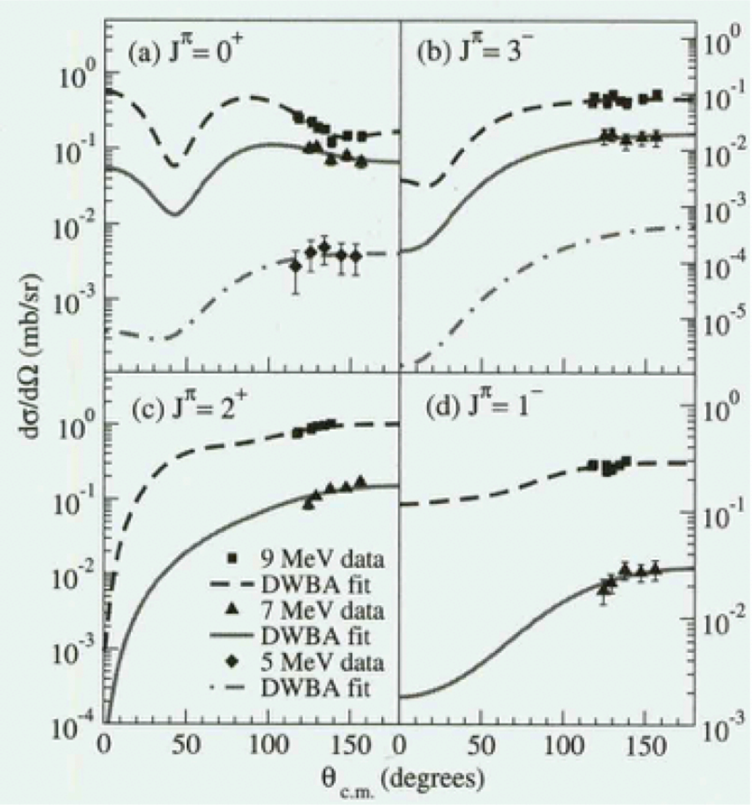


Hebborn et al. PRC 109 L061601 (2024)

(^{6}Li,d) transfer data were also used to constrain ANCs relevant for astrophysics…





[Avila *et al.* PRL **114**, 071101 (2015)]
[Brune *et al.* PRL **83**, 4025 (1999)]

These ANCs were determined from different model

TABLE XIII Summary of α particle asymptotic normalization coefficients of the two subthreshold states at $E_x = 6.92$ and 7.12 MeV. Because the CN reaction data does not place strong constraints on the ANCs (and are sometimes inconsistent), the values obtained from transfer studies are adopted as the best estimates for this analysis. For comparison, theoretical values, and those deduced from R-matrix analysis are also shown.

Ref.	$\mathrm{ANC}_\alpha(\mathrm{fm}^{-1/2})$ 6.92 MeV, 2^+	$\mathrm{ANC}_\alpha(\mathrm{fm}^{-1/2})$ 7.12 MeV, 1^-
Theory		
Descouvemont (1987)	[a] 1.34×10^5	
Sparenberg (2004)	$1.445(85)\times10^5$	
Dufour and Descouvemont (2008)	$1.26(5)\times10^5$	
***R*-matrix**		
Barker and Kajino (1991)	[b] 3.19×10^5	
Azuma *et al.* (1994)		1.90×10^{14}
Angulo and Descouvemont (2000)	[a] 4.02×10^5	
Buchmann (2001)	[a] $2.28^{+33}_{-37}\times10^5$	
Matei *et al.* (2008)	$2.3(4)\times10^5$	
Tischhauser *et al.* (2009)	[a] $1.54(18)\times10^5$	
Tang *et al.* (2010)	1.67×10^5	1.96×10^{14}
Schürmann *et al.* (2012)	1.5×10^5	1.94×10^{14}
Sayre *et al.* (2012)	1.59×10^5	
Transfer		
Brune *et al.* (1999)	$1.14(10)\times10^5$	$2.08(20)\times10^{14}$
Belhout *et al.* (2007)	[c] $1.40(50)\times10^5$	$1.87(54)\times10^{14}$
Oulebsir *et al.* (2012)	$1.44(28)\times10^5$	$2.00(35)\times10^{14}$
Avila *et al.* (2015)	$1.22(7)\times10^5$	$2.09(14)\times10^{14}$

[a] γ_α transformed to ANC_α by Sparenberg (2004).
[b] γ_α transformed to ANC_α by Dufour and Descouvemont (2008).
[c] Renormalized by Oulebsir *et al.* (2012).

Not always uncertainties

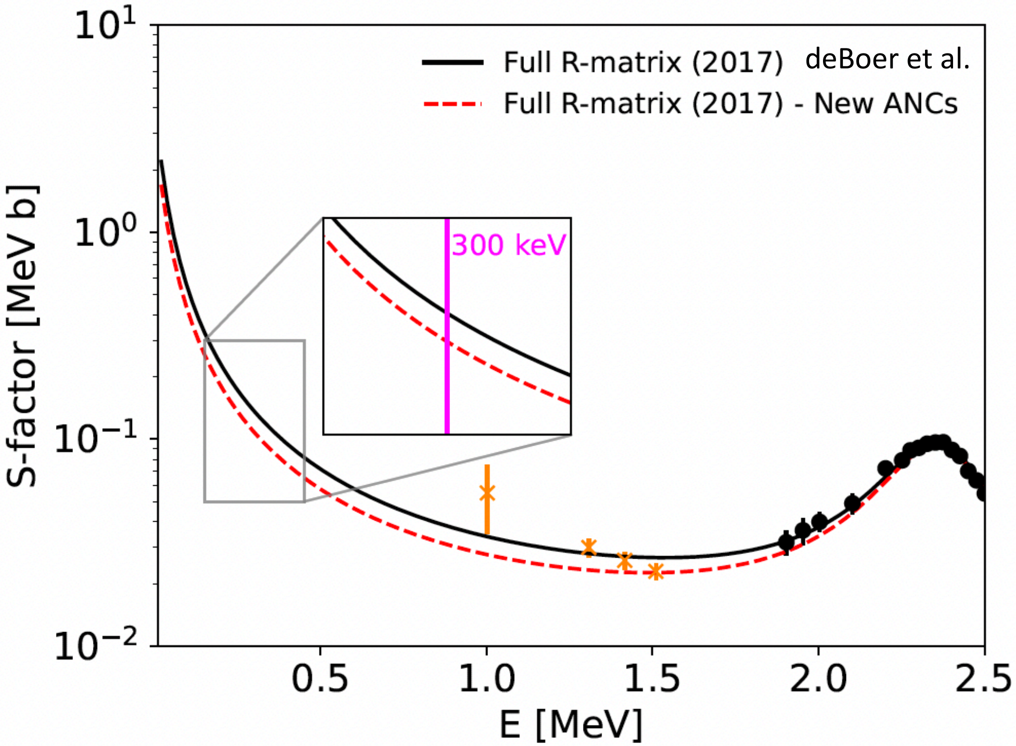
These ANCs were determined from different model and taken in the R-matrix evaluation of $^{12}C(\alpha,\gamma)^{16}O$

J^π	$\tilde{E}_x$ (MeV)		(keV or fm$^{-1/2}$)					
			$\tilde{\Gamma}_{\alpha 0}$ or ANC$_\alpha$		$\tilde{\Gamma}_{p0}$ or ANC$_p$		$\tilde{\Gamma}_{\alpha 1}$	
	this work	lit.	this work	lit.	this work	lit.	this work	lit.
0^-	$\mathbf{12.7954}^{(4,0)}_{(3,0)}$	12.7937			$\mathbf{40.9}^{(15,1)}_{(15,2)}$	40		
0^+		0.0	58			13.9(19)		
0^+		6.0494(10)		1560(100)				
0^+		12.049(2)		1.5(5)				
0^+	15 (BGP)		$\mathbf{-11.900}^{(220,50)}_{(165,110)}\times\mathbf{10^3}$		$\mathbf{420}^{(37,70)}_{(47,20)}$			
1^-		7.1165(14)		$2.08(20)\times10^{14}$		0.98(12)		
1^-	$\mathbf{9.586}^{(1,0)}_{(1,8)}$	9.585(11)	$\mathbf{382}^{(3,0)}_{(3,4)}$	420(20)				
1^-	$\mathbf{12.4493}^{(8,2)}_{(8,0)}$	12.440(2)	$\mathbf{99.2}^{(11,2)}_{(8,2)}$	91(6)	$\mathbf{1.73}^{(4,2)}_{(4,20)}$	1.1	$\mathbf{-0.031}^{(2,4)}_{(2,2)}$	0.025
1^-	$\mathbf{13.094}^{(1,2)}_{(1,0)}$	13.090(8)	$\mathbf{-29.9}^{(1,0)}_{(1,6)}$	45	$\mathbf{110.4}^{(2,5)}_{(2,0)}$	100	$\mathbf{0.636}^{(27,5)}_{(43,0)}$	1
1^-	17.09 (BGP)		500					
1^-	20 (BGP)		$\mathbf{15.6}^{(7,1)}_{(4,2)}\times\mathbf{10^3}$		$\mathbf{270}^{(61,15)}_{(30,170)}$			
1^+	$\mathbf{13.6646}^{(7,0)}_{(7,2)}$	13.664(3)			$\mathbf{-10.3}^{(2,1)}_{(4,3)}$	8(3)	$\mathbf{61.1}^{(23,4)}_{(17,2)}$	55(3)
2^+		6.9171(6)		$1.14(20)\times10^5$		0.45(13)		
2^+		9.8445(5)		0.62(10)				
2^+	$\mathbf{11.5055}^{(3,0)}_{(5,1)}$	11.520(4)	$\mathbf{83.0}^{(6,1)}_{(3,0)}$	71(3)				
2^+	$\mathbf{12.9656}^{(14,5)}_{(28,2)}$	13.02(1)	$\mathbf{-349}^{(8,2)}_{(3,3)}$	150(10)	$\mathbf{1.82}^{(8,4)}_{(8,18)}$		$\mathbf{-4.0}^{(7,0)}_{(9,0)}$	
2^+	15		$\mathbf{5.5}^{(5,2)}_{(5,2)}\times\mathbf{10^3}$		$\mathbf{-8.1}^{(20,0)}_{(15,5)}$			
3^-		6.12989(4)		139(9)		1.88(23)		
3^-	$\mathbf{11.5058}^{(28,0)}_{(19,7)}$	11.60(2)	$\mathbf{902}^{(5,1)}_{(6,1)}$	800(100)				
3^-	$\mathbf{13.1412}^{(10,3)}_{(13,0)}$	13.129(10)	$\mathbf{72.9}^{(42,9)}_{(24,8)}$	90(14)	$\mathbf{-1.11}^{(2,1)}_{(3,2)}$	1	$\mathbf{20.5}^{(13,0)}_{(16,1)}$	20
3^-	13.2650	13.259(2)	$\mathbf{12.8}^{(6,2)}_{(4,2)}$	9(4)	$\mathbf{3.66}^{(10,1)}_{(8,2)}$	4.1	$\mathbf{11.74}^{(33,1)}_{(54,1)}$	8.2(11)
3^-	20 (BGP)		$\mathbf{-22}^{(1,2)}_{(2,0)}\times\mathbf{10^3}$					
4^+	$\mathbf{10.3581}^{(1,0)}_{(1,1)}$	10.356(3)	$\mathbf{26.13}^{(25,3)}_{(15,3)}$	26(3)				
4^+		11.0967(16)		0.28(5)				
4^+	15 (BGP)		$\mathbf{2.57\times10^3}^{(22,2)}_{(14,4)}$					
5^-	14.66 (BGP)		$\mathbf{1.22\times10^3}^{(10,12)}_{(6,9)}$		8			

Reanalysis using ^{6}Li ab initio prediction leads to a reduction of $^{12}C(\alpha,\gamma)^{16}O$ of 21% at 300 keV!

J^π	E_{ex}	Probe	$(\mathcal{C}^{J^\pi}_{\alpha\text{-}^{12}C})^2$ Past Work		
0^+	6.05	(^{6}Li, d)	2.43(30)	1.88(16)	$\times 10^6$
3^-	6.13	(^{6}Li, d)	1.93(25)	1.49(14)	$\times 10^4$
2^+	6.92	(^{6}Li, d)	1.24(24)	0.96(16)	$\times 10^{10}$
		(^{6}Li, d)	1.48(16)	1.14(7)	
1^-	7.12	(^{6}Li, d)	4.33(84)	3.34(58)	$\times 10^{28}$
		(^{6}Li, d)	4.39(59)	3.39(34)	

[Brune *et al.* PRL **83**, 4025 (1999)]
[Avila *et al.* PRL **114**, 071101 (2015)]



[Schürmann *et al.* EPJA **26**, 301 (2005)]
[Plag *et al.* PRC **86**, 015805 (2012)]

Hebborn et al. PRC 109 L061601 (2024)

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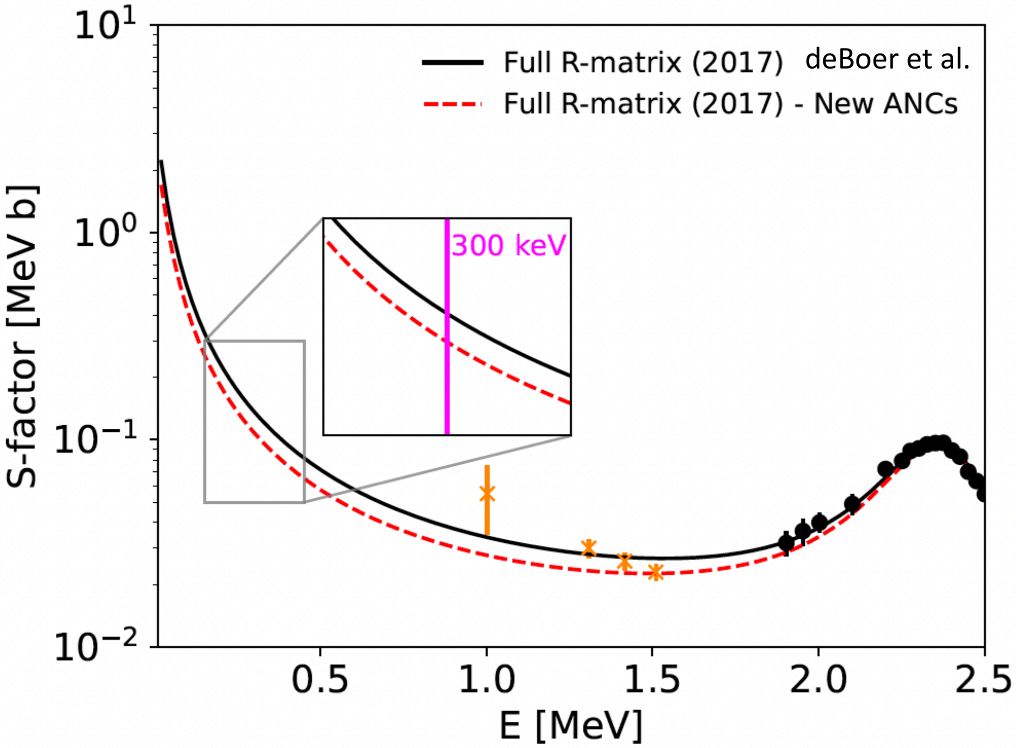
2^+	6.92	$(^6Li, d)$	1.48(16)	1.14(7)	$\times 10^{10}$
		$(^7Li, t)$	1.33(29)		
		$(^7Li, t)$	2.07(80)		
		$(^6Li, d)$	4.33(84)	3.34(58)	
1^-	7.12	$(^6Li, d)$	4.39(59)	3.39(34)	$\times 10^{28}$
		$(^7Li, t)$	4.00(138)		

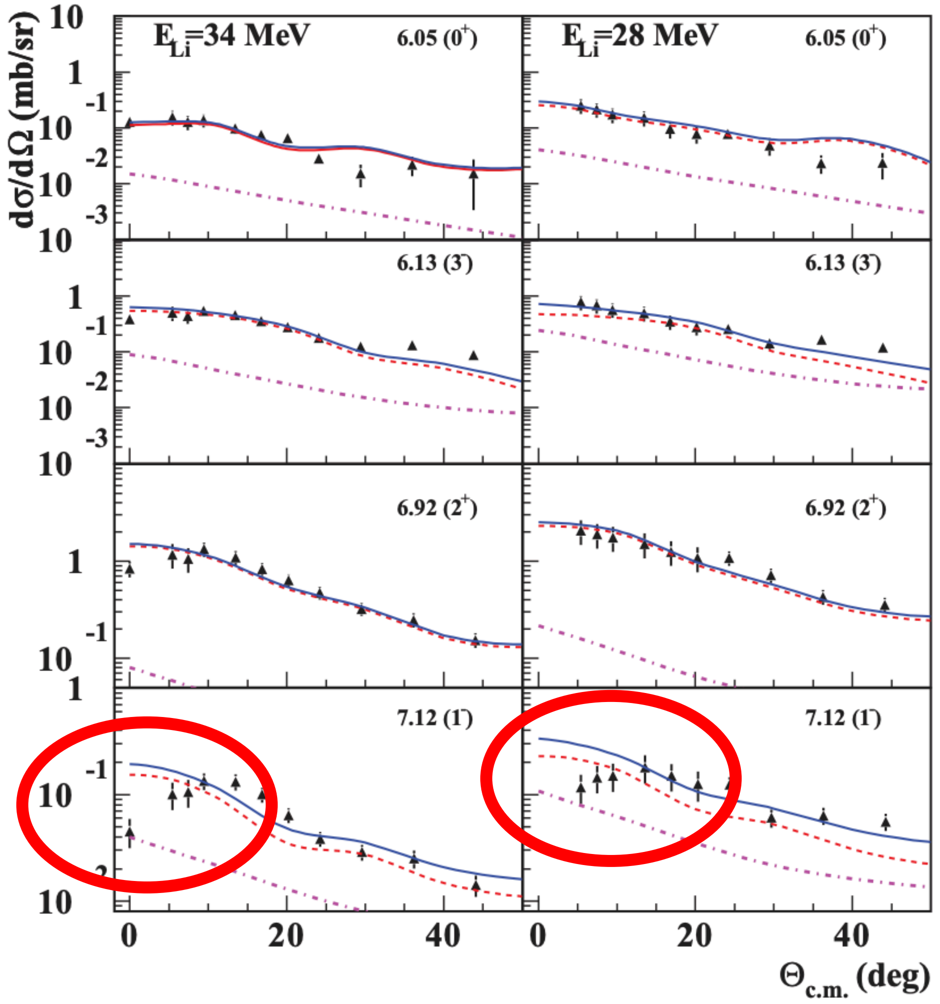
[Brune *et al.* PRL **83**, 4025 (1999)]
[Avila *et al.* PRL **114**, 071101 (2015)]
[Oulebsir *et al.* PRC **85**, 035804 (2012)]



[Schürmann *et al.* EPJA **26**, 301 (2005)]
[Plag *et al.* PRC **86**, 015805 (2012)]

Still some tension with (^{7}Li,t) results…
How accurate was the analysis of transfer data?

Unexplained discrepancies in (^{7}Li,t) data used to constrain ANCs of ^{16}O



^{12}C(^{7}Li,t)^{16}O

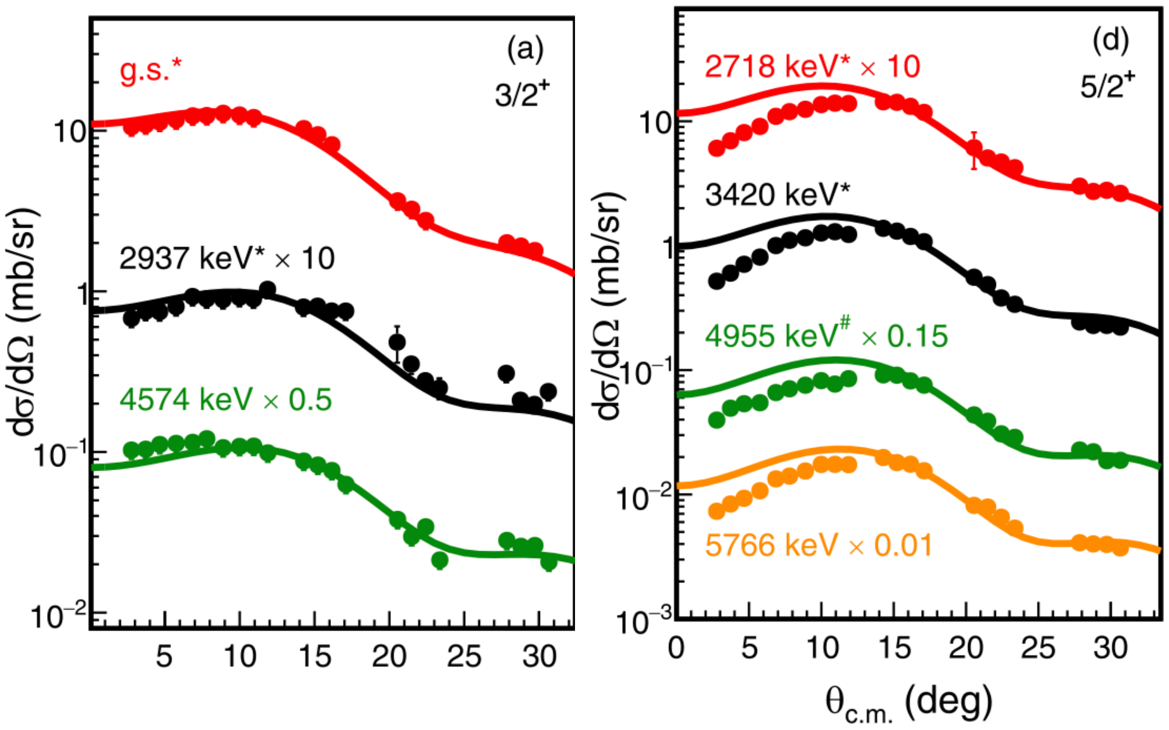
At higher beam energy

& over **larger angular range!**

Oulebsir et al. PRC 85 035804 (2012)

Similar discrepancy in transfer analysis were observed for spin orbit partners…

$^{36}S(p,d)^{35}S$ measured with 98 states identified!

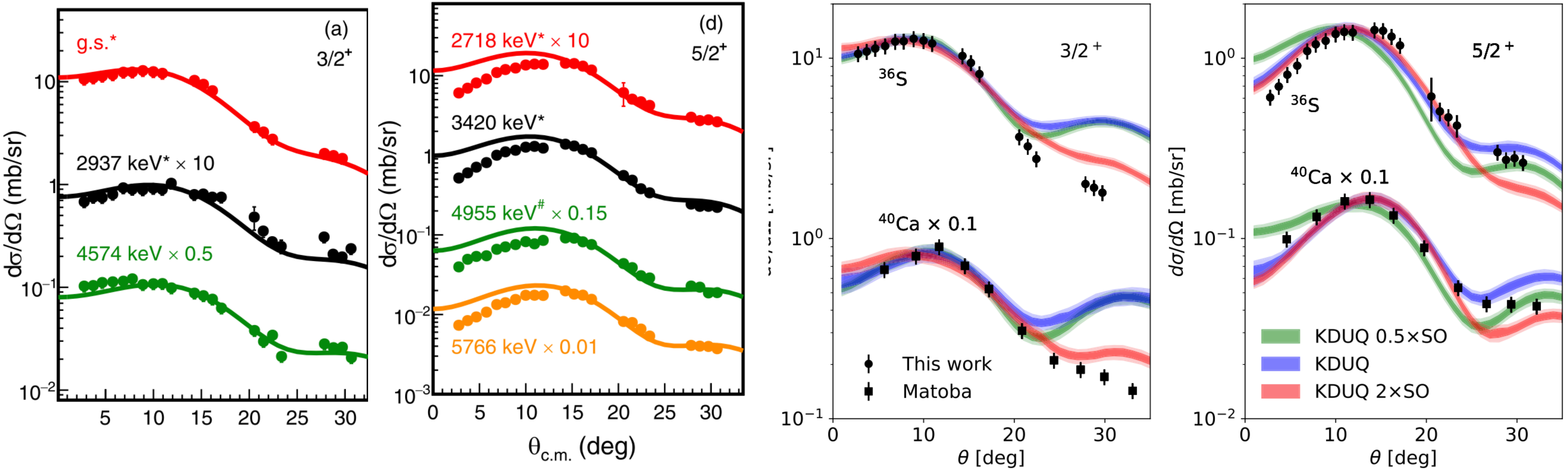


Jongile et al. PRC 113 024323 (2026)

Recent work suggests that it could be due to spin-orbit terms in the optical potentials

$^{36}S(p,d)^{35}S$ measured with 98 states identified!

(band associated with UQ on optical potentials)



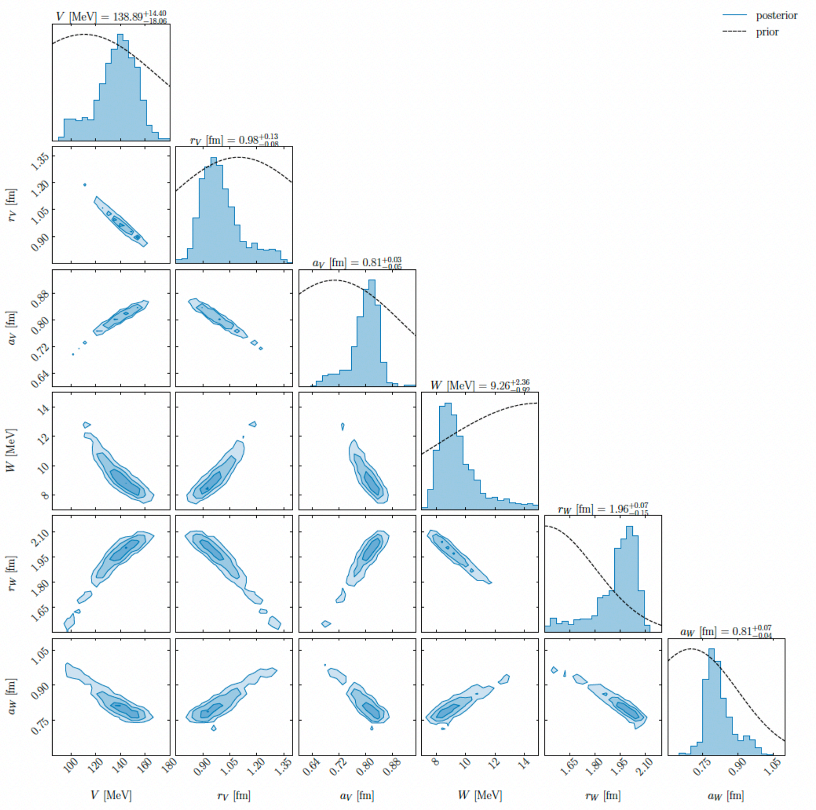
Jongile et al. PRC 113 024323 (2026)

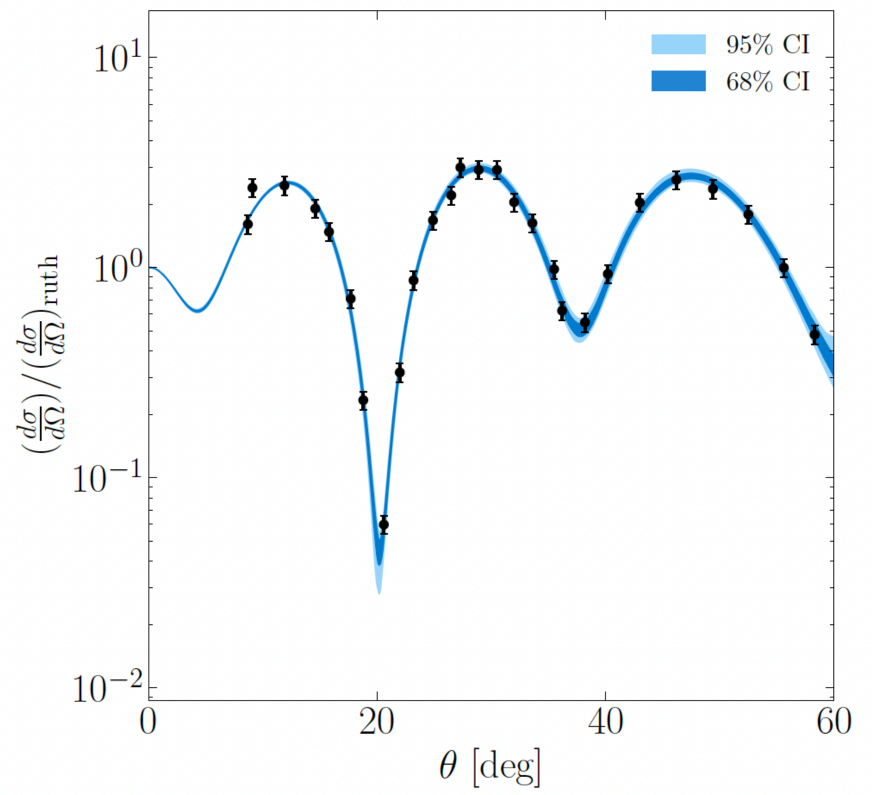
Reanalysis of these data quantifying all interaction uncertainties

Elouan Boucheron

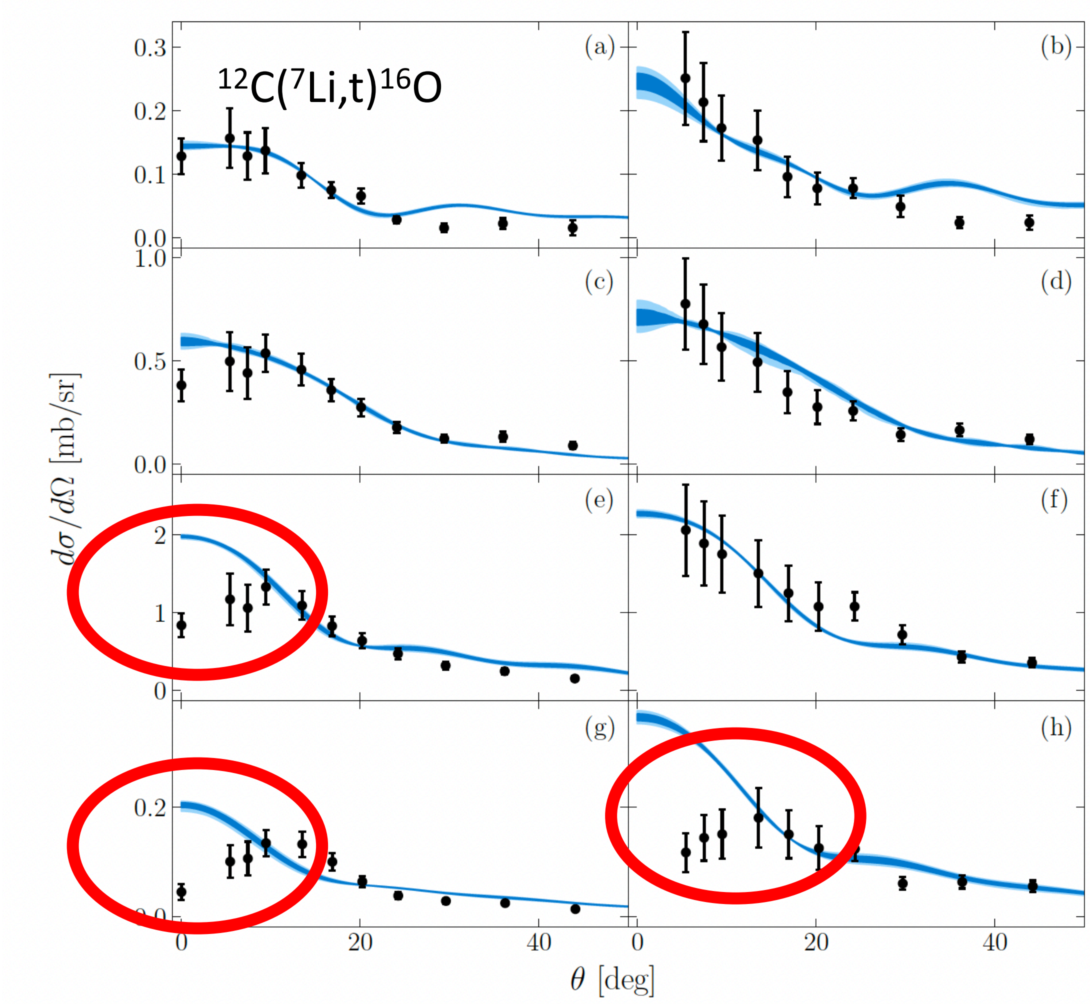
Bayesian analysis for UQ associated to optical potentials in $^{12}C(^{7}Li,t)^{16}O$

(First time for heavy ion transfer)





The optical potentials uncertainties do not seem to explain the discrepancy…



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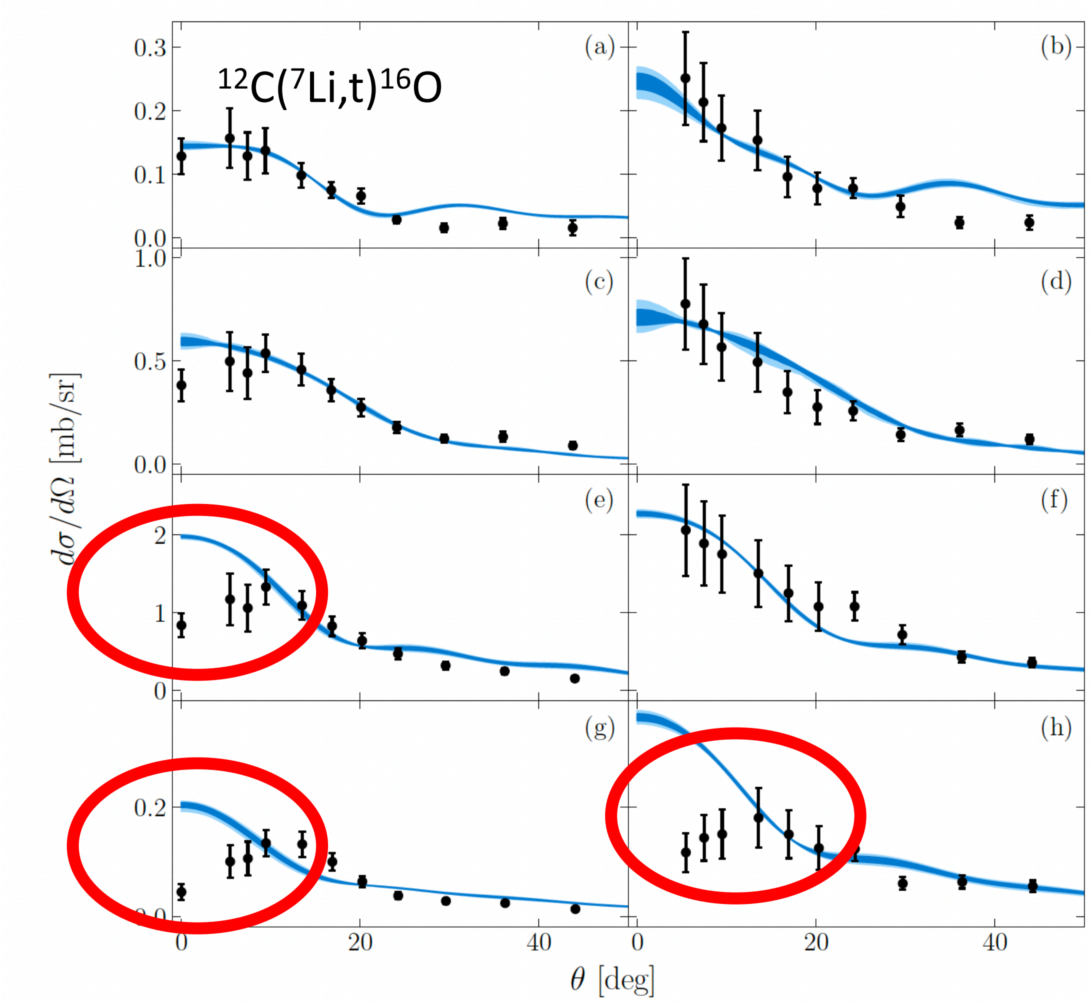


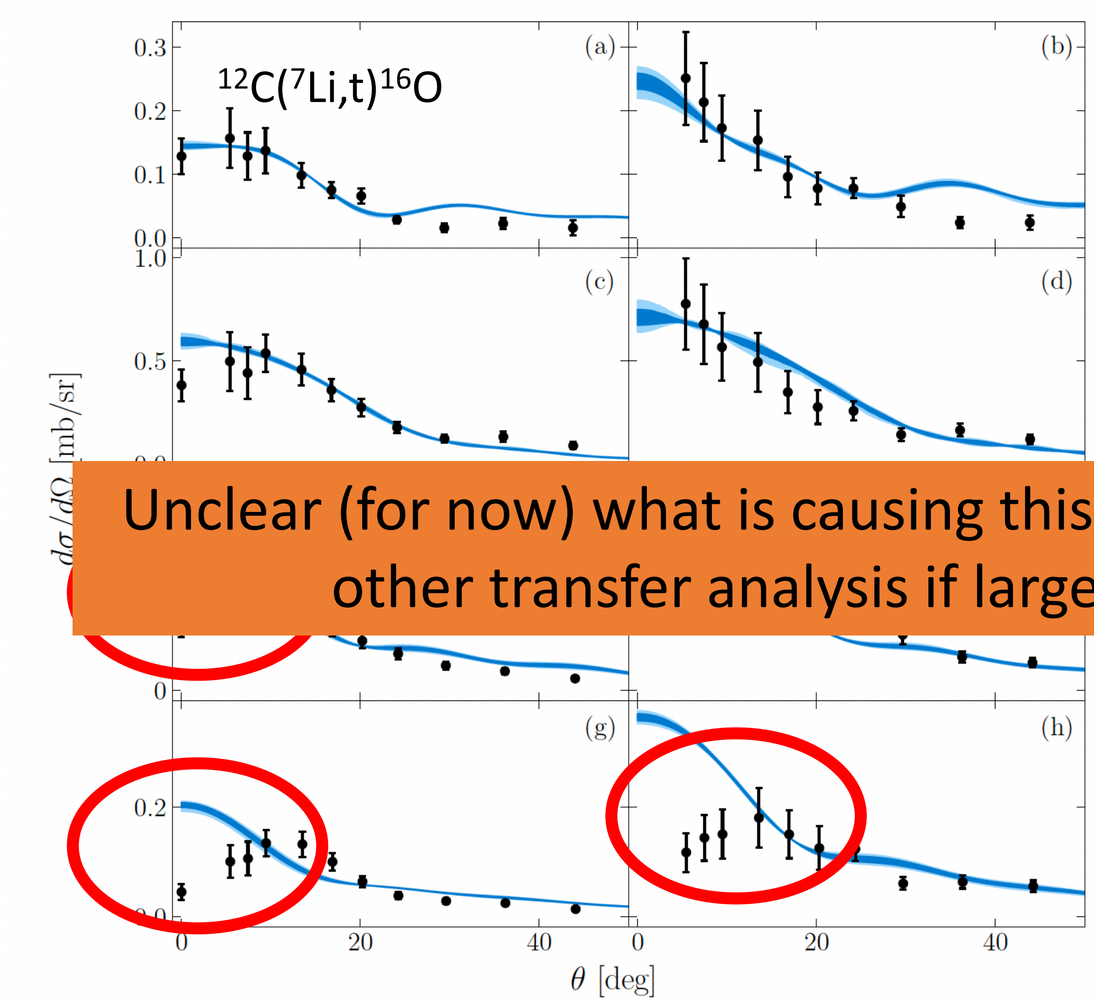
Other attempts to quantify model uncertainties also do not explain the discrepancy.. (preliminary)

- Two step mechanism

- Adding excited states of ^{12}C

The optical potentials uncertainties do not seem to explain the discrepancy…

Elouan Boucheron



Other attempts to quantify model uncertainties also do not explain the discrepancy.. (preliminary)

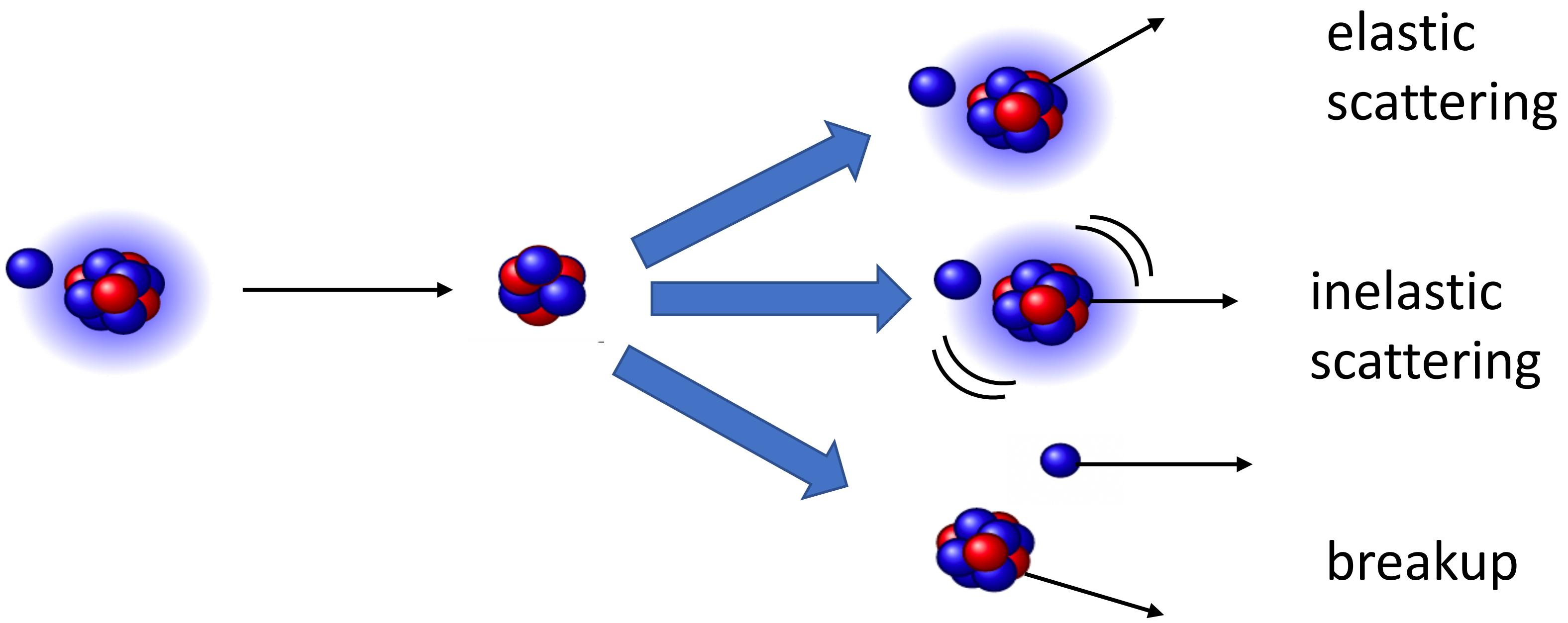
- Two step mechanism

Unclear (for now) what is causing this discrepancy and if it would be visible in other transfer analysis if larger angular range were measured

What can we do to decrease the uncertainties in direct reactions and validate reaction analysis?

Measure various channels and identify ratio of observables that cancel uncertainties

(both exp & theory!)



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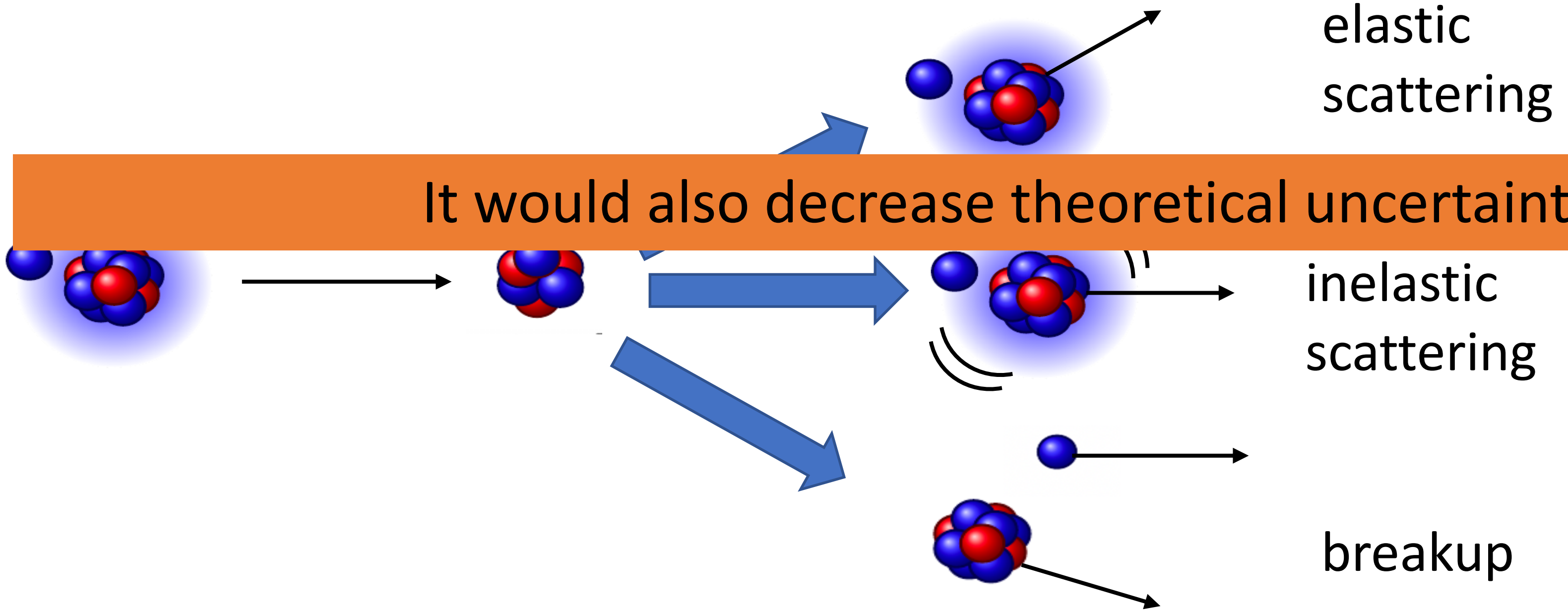
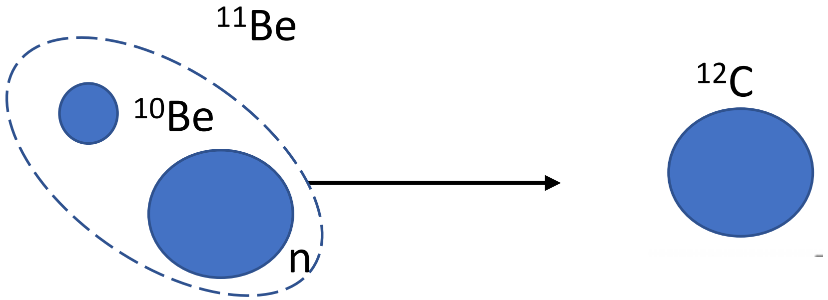
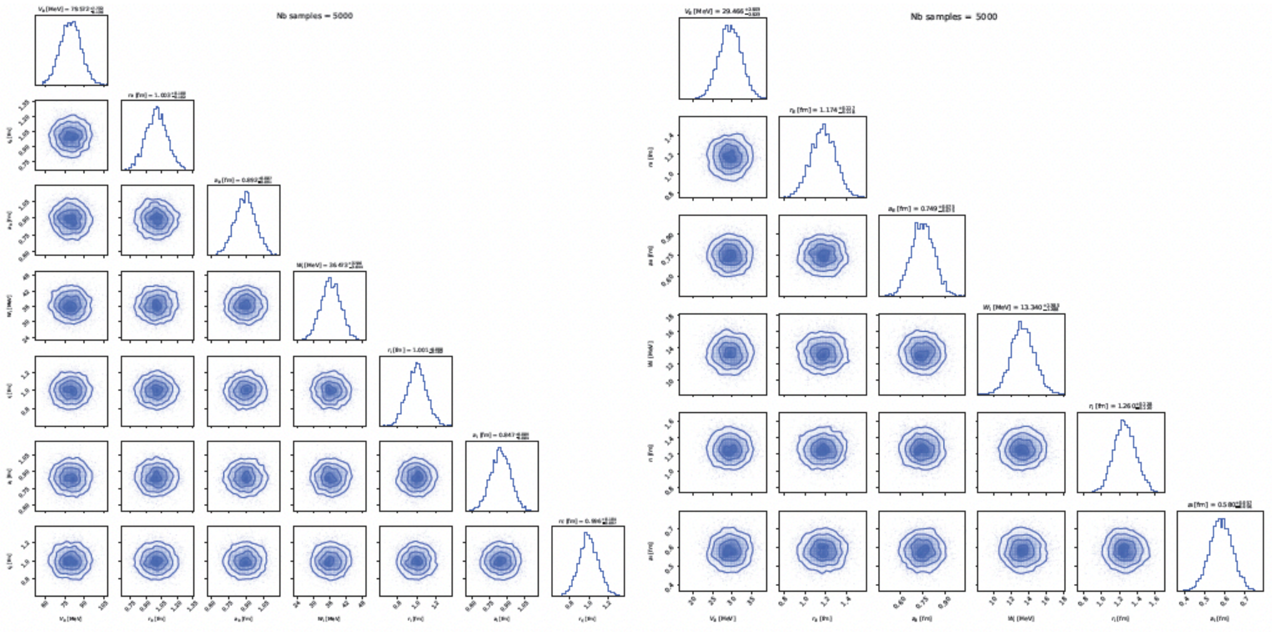


It would also decrease theoretical uncertainties…

^{11}Be on ^{12}C @ 67AMeV as case study



- Start from realistic potentials
- Consider random variations of all potentials parameters around their realistic values



(a) U_{cT} (b) U_{nT}

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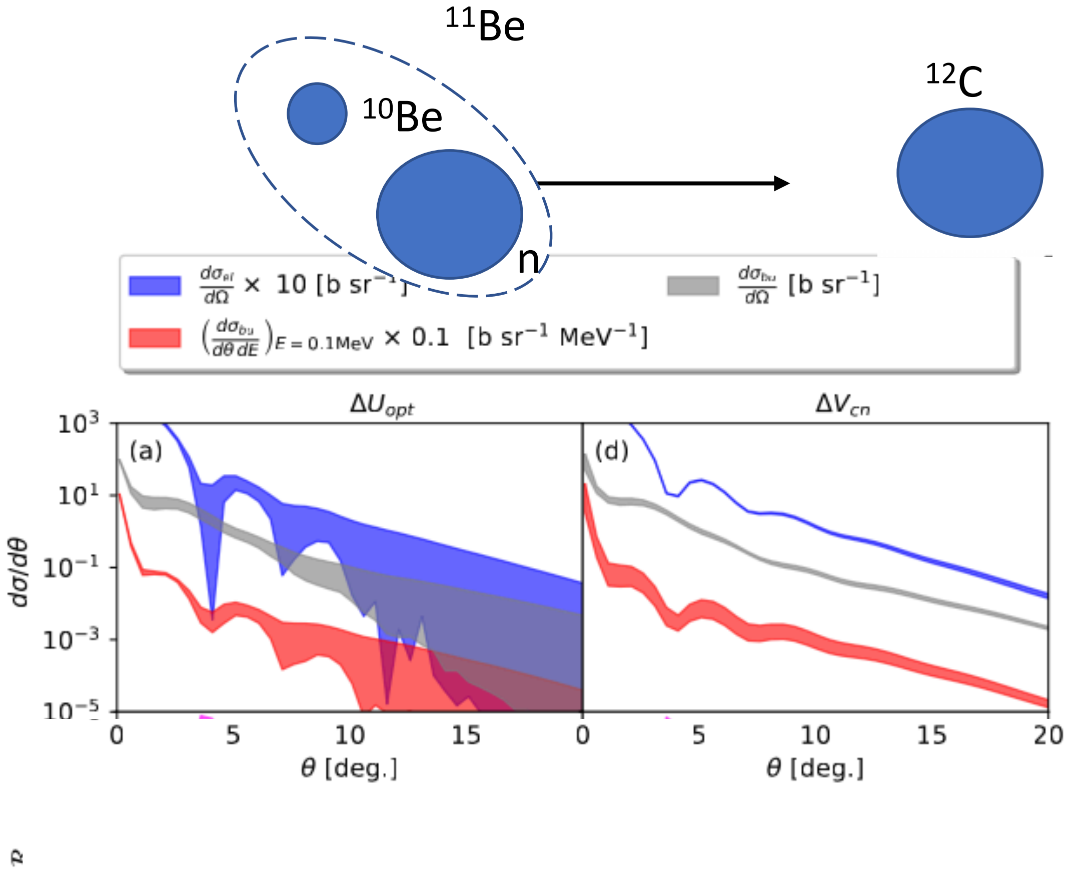

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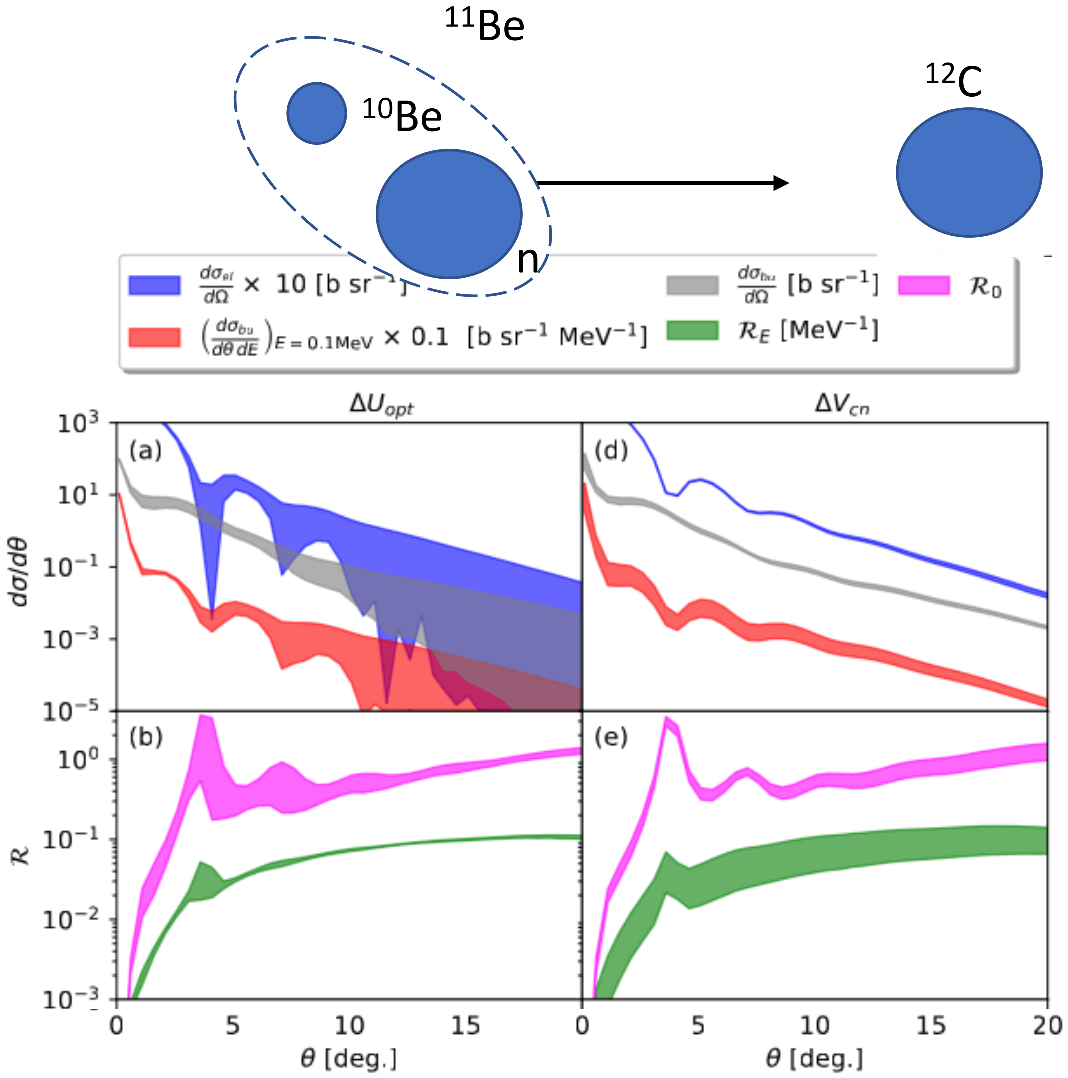
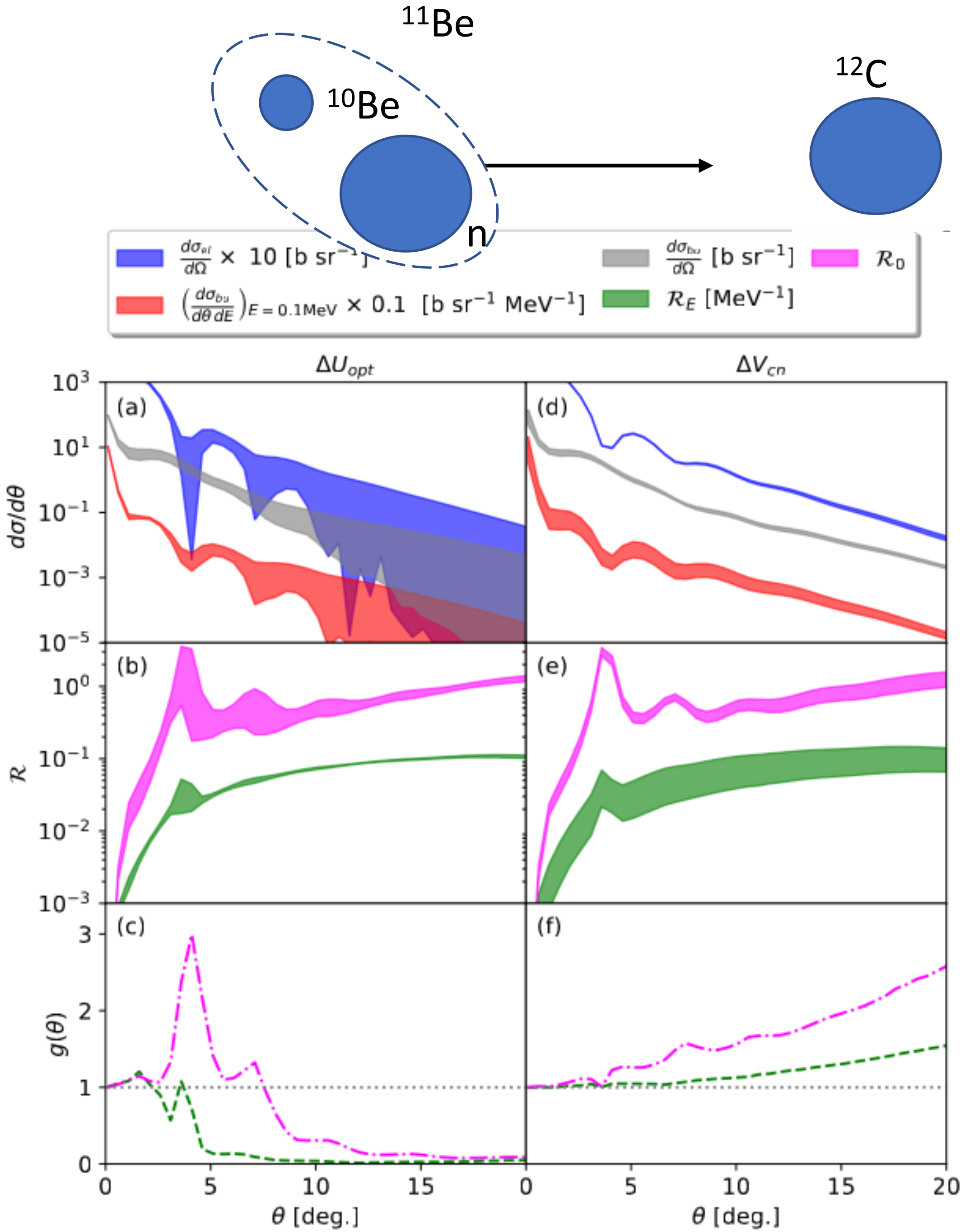


^{11}Be on ^{12}C @ 67AMeV as case study

- Start from realistic potentials
- Consider random variations of all potentials parameters around their realistic values
- Compute the cross sections
- Compute the ratios
- Compute the sensitivity factor

$$g_E(E,\theta) = \frac{\Delta\mathcal{R}_E(E,\theta)}{\Delta d\sigma_{bu}/dEd\Omega},$$
$$g_0(\theta) = \frac{\Delta\mathcal{R}_0(\theta)}{\Delta d\sigma_{bu}/d\Omega},$$



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Need for **unified description of indirect reactions** and more systematic use of robust UQ

Still discrep … ar range

→Optical p … (yet)

Need for new measurements involving multiple channels (when possible)…

→ Possibility to decrease theoretical uncertainties by taking ratios

Thank you for your attention, my collaborators,...

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JG|U


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Argonne NATIONAL LABORATORY


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IJCLab Irène Joliot-Curie


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Thank you for your attention, my collaborators, and the few-body reaction group at MSU