Multichannel nature of the lithium few-body puzzle

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Outline

Introduction Li few-body puzzle

Three-body elastic and inelastic scattering for strong and weak interactions

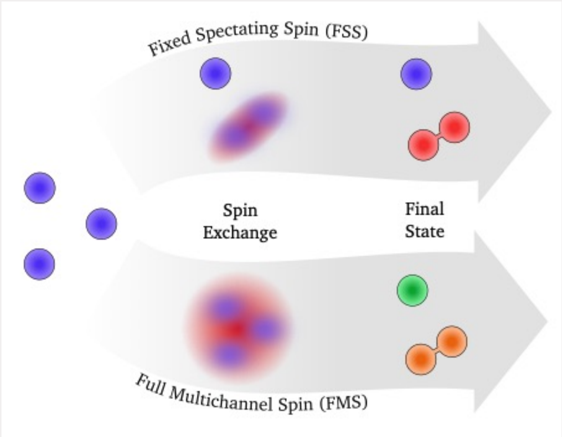
Momentum-space method

Use realistic two-body interaction potentials

Multi-channel three-body scattering

K-39 with Fixed Spectating Spin

Li-7 with Full Multichannel Spin exchange



Conclusions

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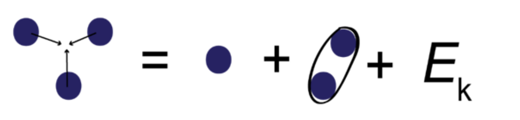
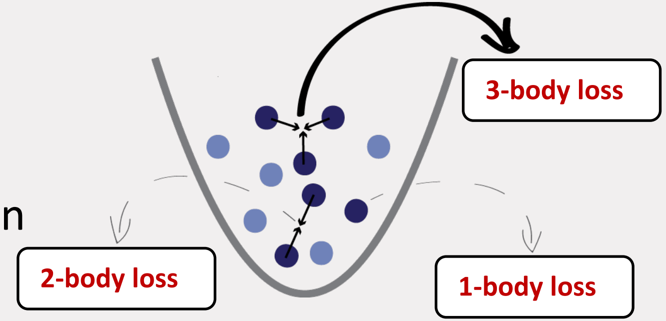
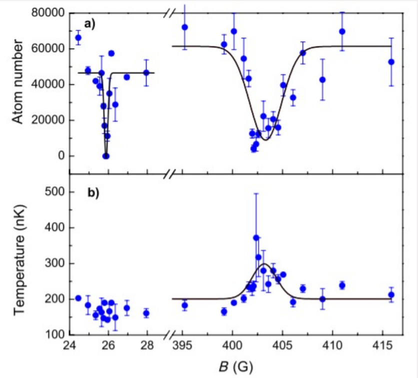
Three-body collisions

Three-body inelastic collisions

Lifetime of gases
Probe methods
Fundamental chemical reaction



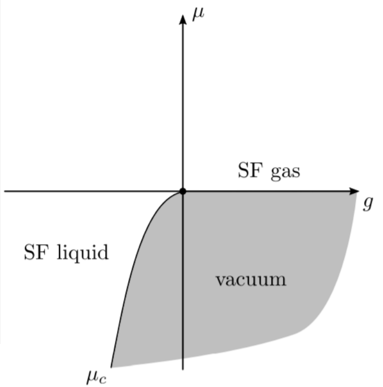




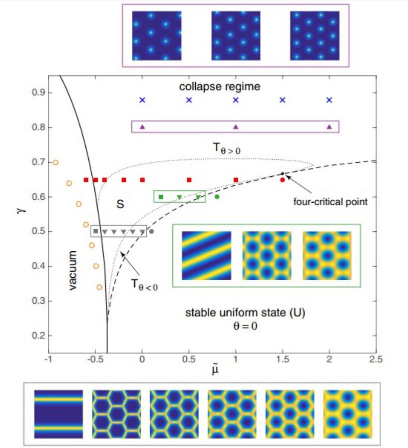
D'Errico *et al*. New J. Phys. **9** 223, 2007

Three-body elastic collisions

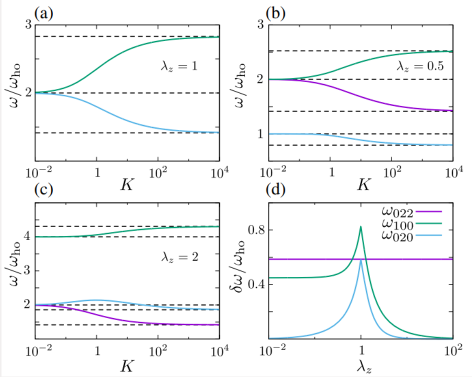
Phase diagram
Exotic MB states
Collective modes



Zwerger, J. Stat. Mech. (2019) 103104



Lu *et al*. Phys. Rev. Lett. 115,075303(2015)



Mestrom *et al*. Phys. Rev. Lett. 124,143401(2020)

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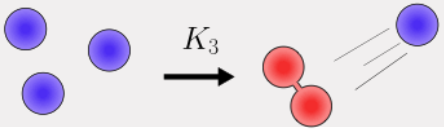
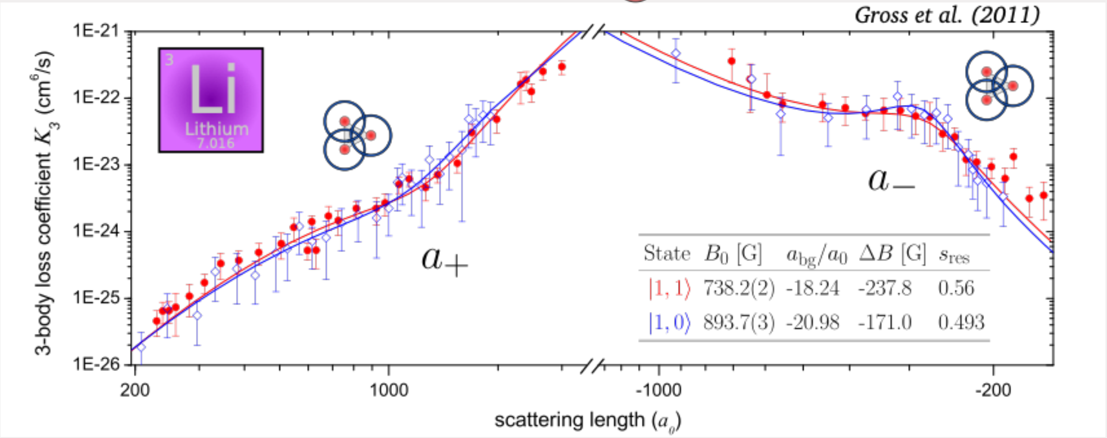
The “lithium few-body puzzle”

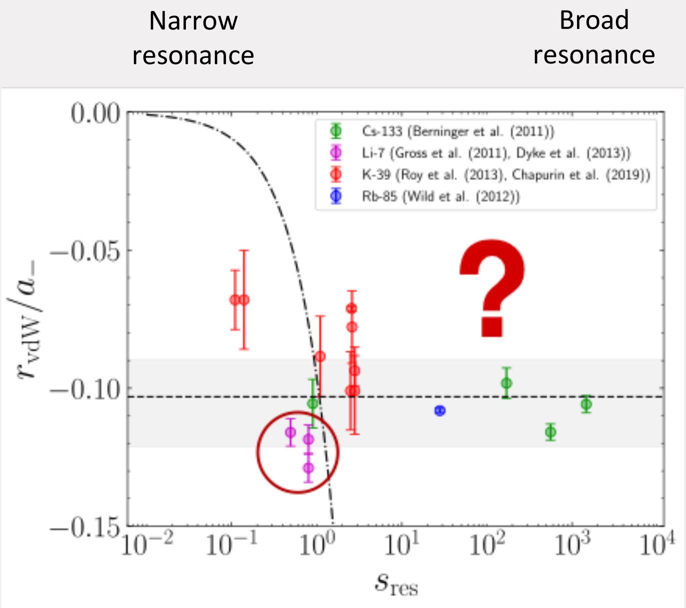
Three-body recombination

- Three identical bosons, Feshbach resonance





N. Gross, et al., C. R. Phys. 12, 4 (2011)



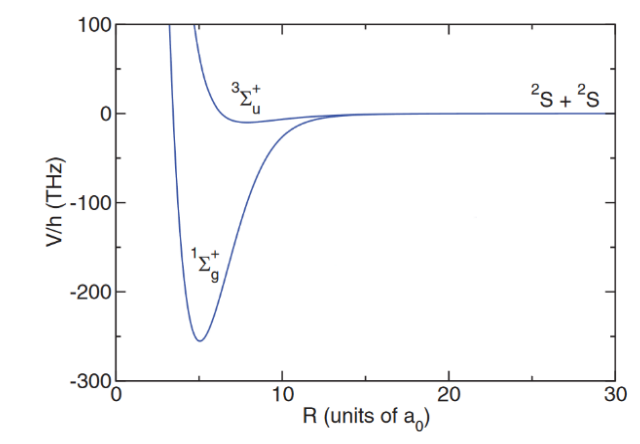
N. Gross, et. al., Phys. Rev. Lett. ***103****, 163202 (2009).*

R. Chapurin, et. al., Phys. Rev. Lett. ***123****, 233402 (2019).*

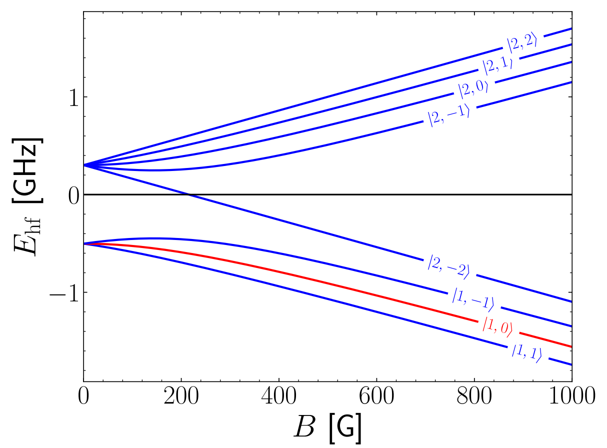
Multichannel three-body simulation

What is missing from our current theoretical and numerical approaches?

Realistic finite range molecular interactions with many vibrational states



Atoms have also spin: $\mathbf{f} = \mathbf{i} + \mathbf{s}$



T. Secker, et. al., Phys. Rev. A **103**, 022825 (2021)
T. Secker, et. al., Phys. Rev. A **103**, 032817 (2021)

Alt-Grassberger-Sandhas (AGS) equations

Two-body transition operator T ➡ a

Three-body transition operators U_{fi} ➡ D

$$\begin{cases} U_{00}(z) = \sum_{\alpha=1}^{3} T_\alpha(z) G_0(z) U_{\alpha 0}(z) \\ U_{\alpha 0}(z) = G_0^{-1}(z) + \sum_{\substack{\beta=1 \\ \beta\neq\alpha}}^{3} T_\beta(z) G_0(z) U_{\beta 0}(z) \\ \quad \text{for } \alpha = 1,2,3, \end{cases}$$

α	**configuration**
0	A + B + C
1	A + BC
2	B + CA
3	C + AB

- $G_0(E) = (E - H_0)^{-1}$ where H_0 is the three-body kinetic energy operator
- T_α is the transition operator of a two-particle subsystem

  E.g. $T_1(E) = V_{23} + V_{23} G_0(E) T_1(E)$

[E. Alt, P. Grassberger, and W. Sandhas, Nucl. Phys. B **2**, 167 (1967)]

Multichannel spin models

AGS equation : $U = Pt(1+P) + PtG_0U$

$$t = V + VG_0t$$
$$V = V_SP_S + V_TP_T$$
$$G_0 = (E - T - H_c)^{-1}$$

V: pairwise interaction
$V_{S/T}$: singlet/triplet interaction potential
H_c: multichannel spin Hamiltonian

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Multichannel spin models

f = i + s $M_{tot} = m_{f1} + m_{f2} + m_{f3}$ **Constant**

^{39}K in the $|f=1, m_f=-1\rangle$ state, for instance

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$$G_0 = (E - T - H_c)^{-1}$$

V: pairwise interaction

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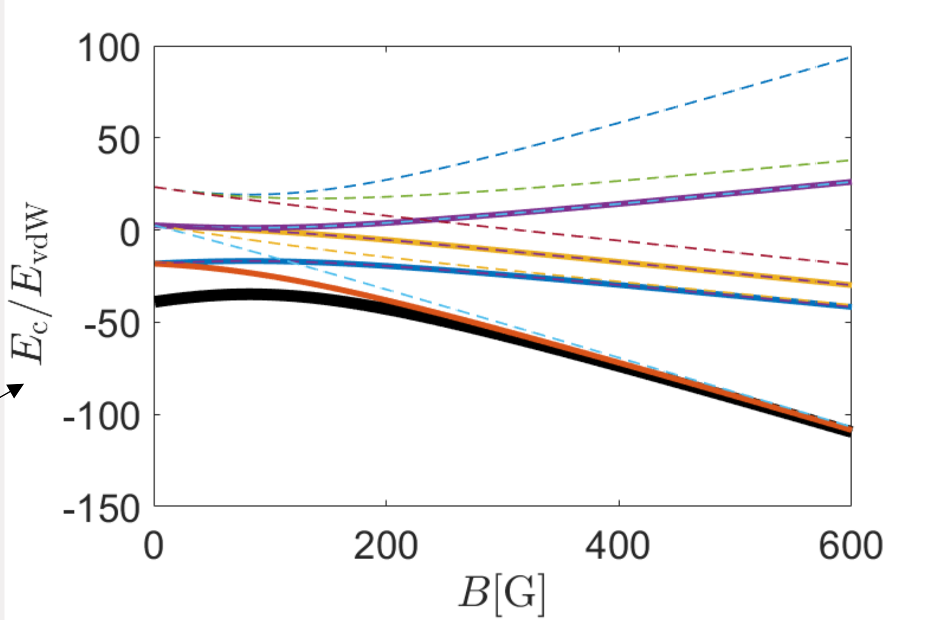
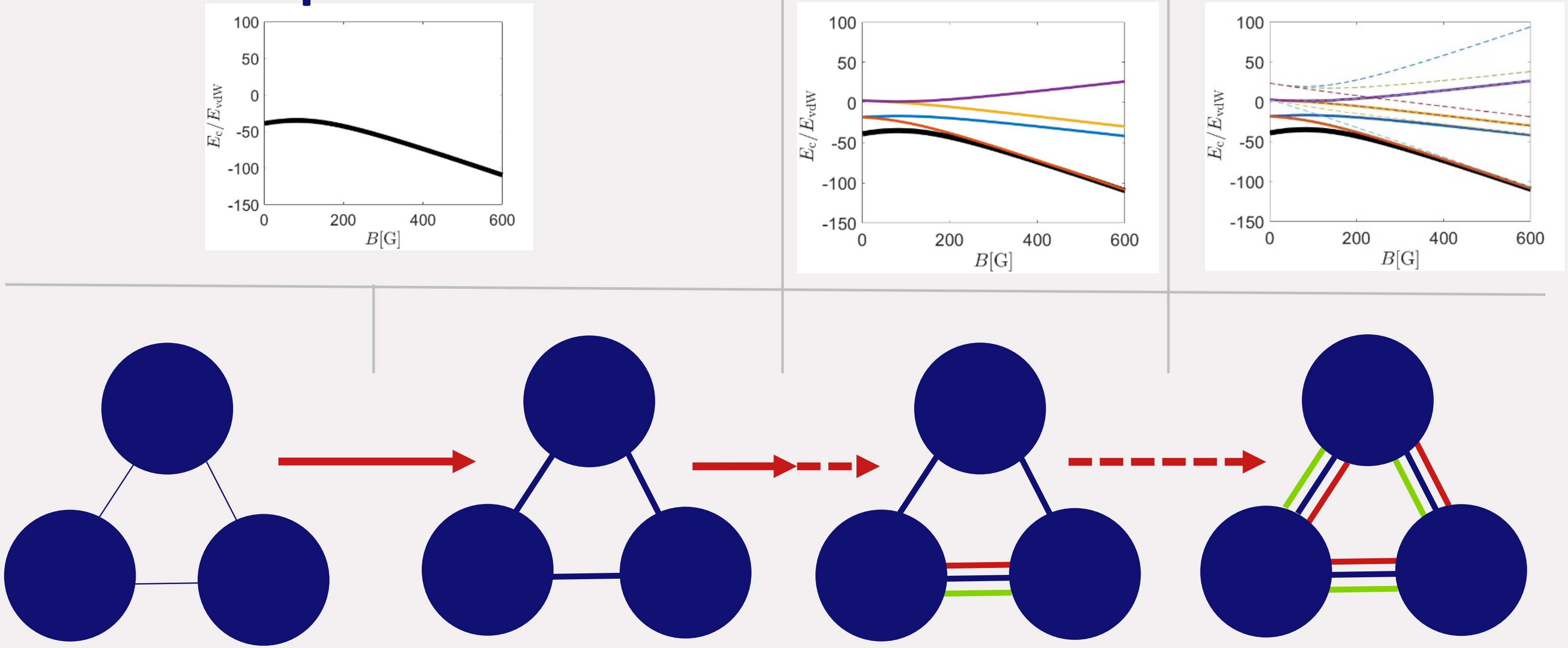
***H_c*: multichannel spin Hamiltonian**



$$H_c = \sum_{i=1}^{3} H_i^{hf} + H_i^{zm}$$

Multichannel spin models

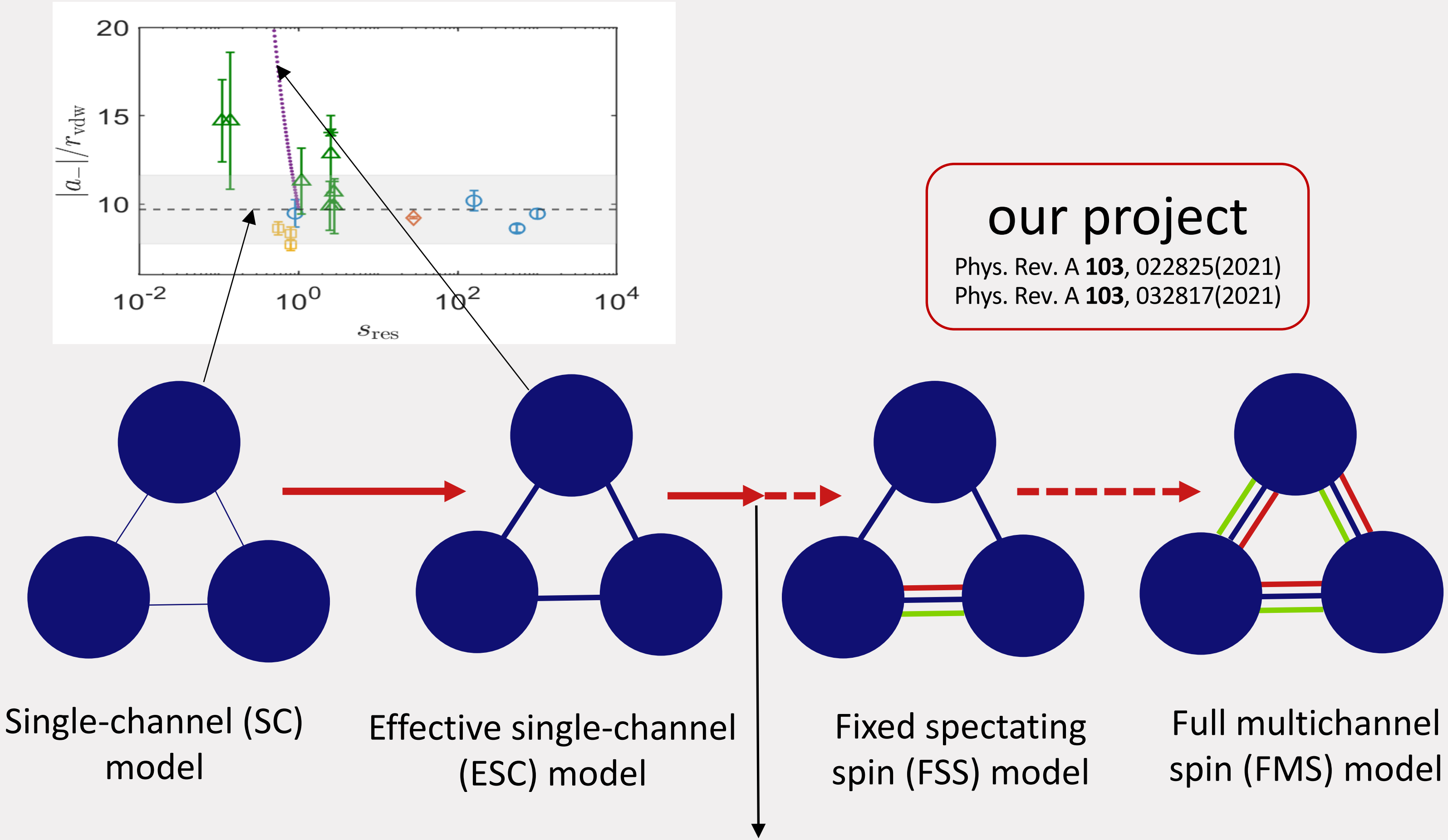


Single-channel (SC) model

Effective single-channel (ESC) model

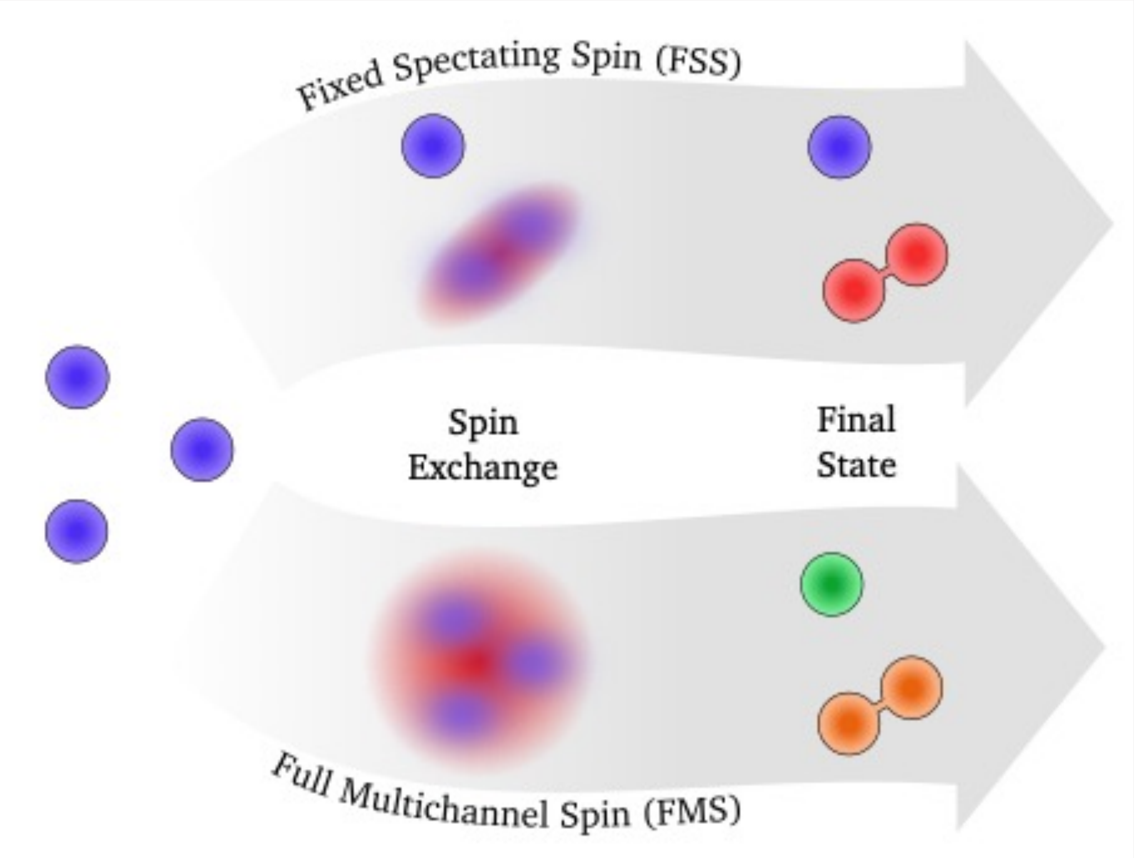
Fixed spectating spin (FSS) model

Full multichannel spin (FMS) model



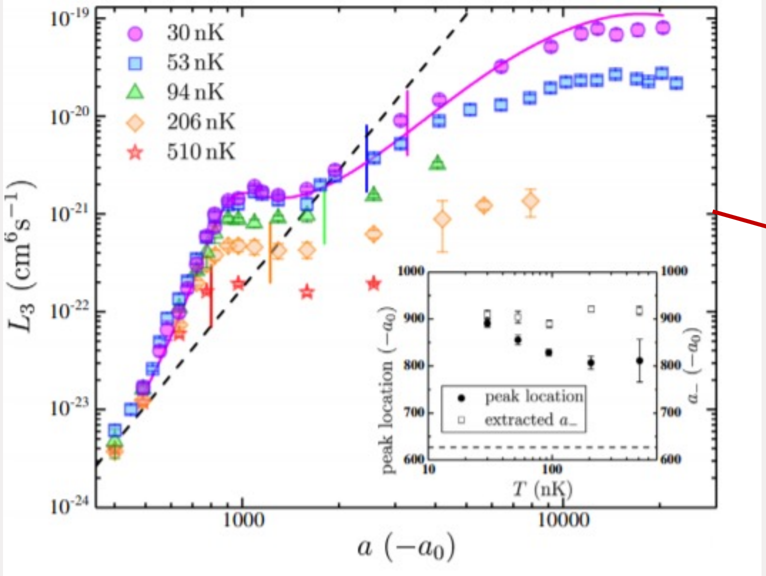
[R. Chapurin et al., Phys. Rev. Lett. 123, 233402 (2019)]

Three-body multi-channel physics

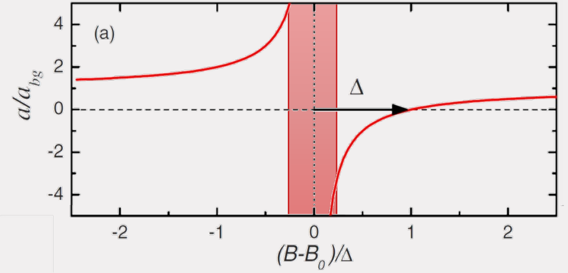


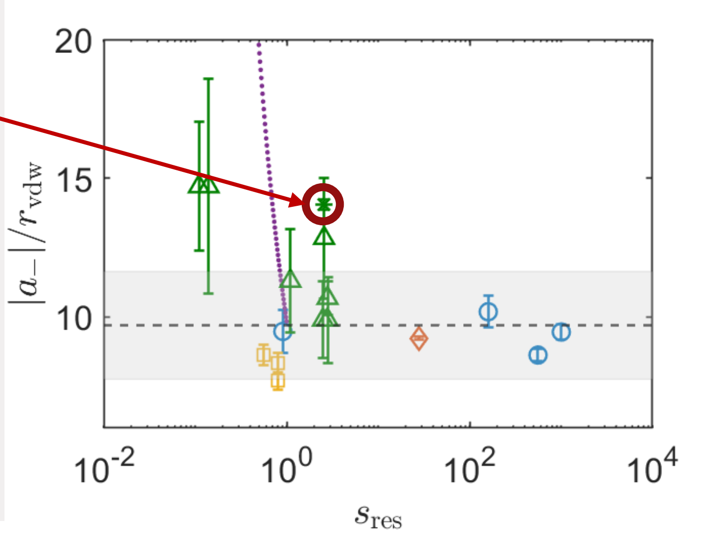
Strongly interacting regime

^{39}**K** in the|1,-1> state



R. Chapurin et al., Phys. Rev. Lett. ***123****, 233402 (2019).*

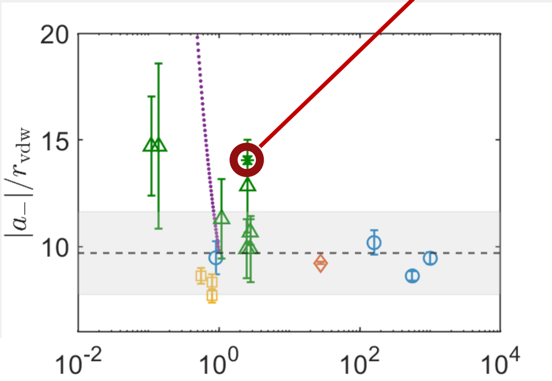




Strongly interacting regime

FSS result

	$a_-[r_{\mathrm{vdW}}]$ this work	$a_-[r_{\mathrm{vdW}}]$ Ref. [18]
N=2, LJ	−13.51	−7.61
N=3, LJ	−14.33	−11.20
N=4, LJ	−14.16	−12.27
N=5, LJ	−14.60	−12.69
full	−14.12	–
full40	−14.03	–
measurement	-14.05 (17)	

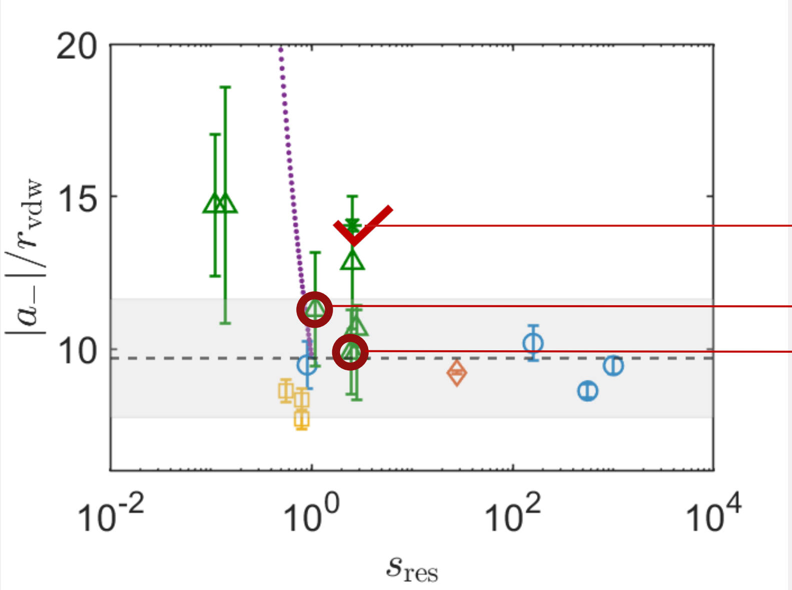


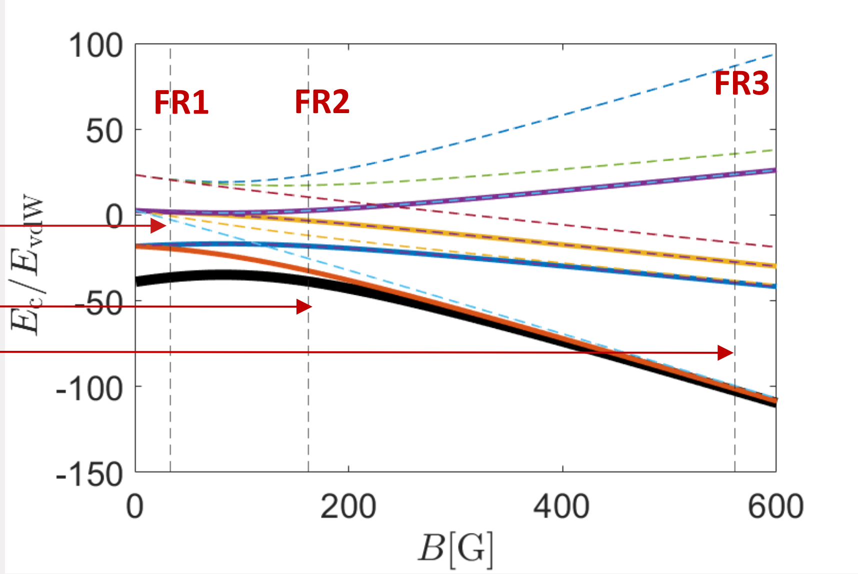
$V_{S/T}$ is modeled by a Lennard-Jones (LJ) potential with N s-wave bound states or taken as full molecular potential (**full**) from *Phys. Rev. A 78 012503(2008)*

[18] *R. Chapurin et al., Phys. Rev. Lett.* ***123****, 233402 (2019).*

[T. Secker et al., Phys. Rev. A **103**, 022825(2021)]

Strongly interacting regime





	FSS(full)	Expt.
FR2	-29.76	-11.30
FR3	-16.33	-9.90

small energy separation leads to strong multichannel coupling

[T. Secker D. J. M. Ahmed-Braun, P. M. A. Mestrom, S. J. J. M. F. Kokkelmans, Phys. Rev. A **103**, 022825(2021)]

Li-7 – Three-body recombination

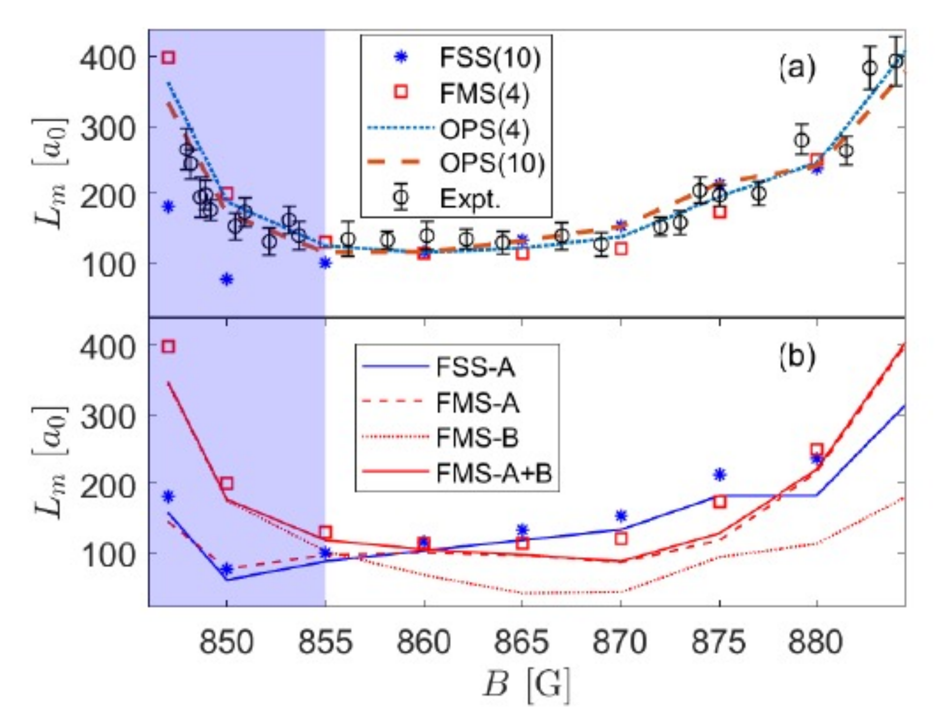
^{7}Li in the |1,0> state around B=850 G

Weakly interacting regime

$K_3 \propto L_m^4$

$M_{2b} = m_{f1} + m_{f2}$

	f_3	m_{f3}	M_{2b}
A	1	0	0
B	1	1	-1

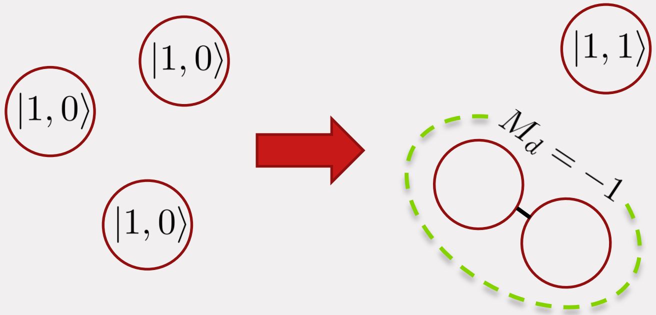


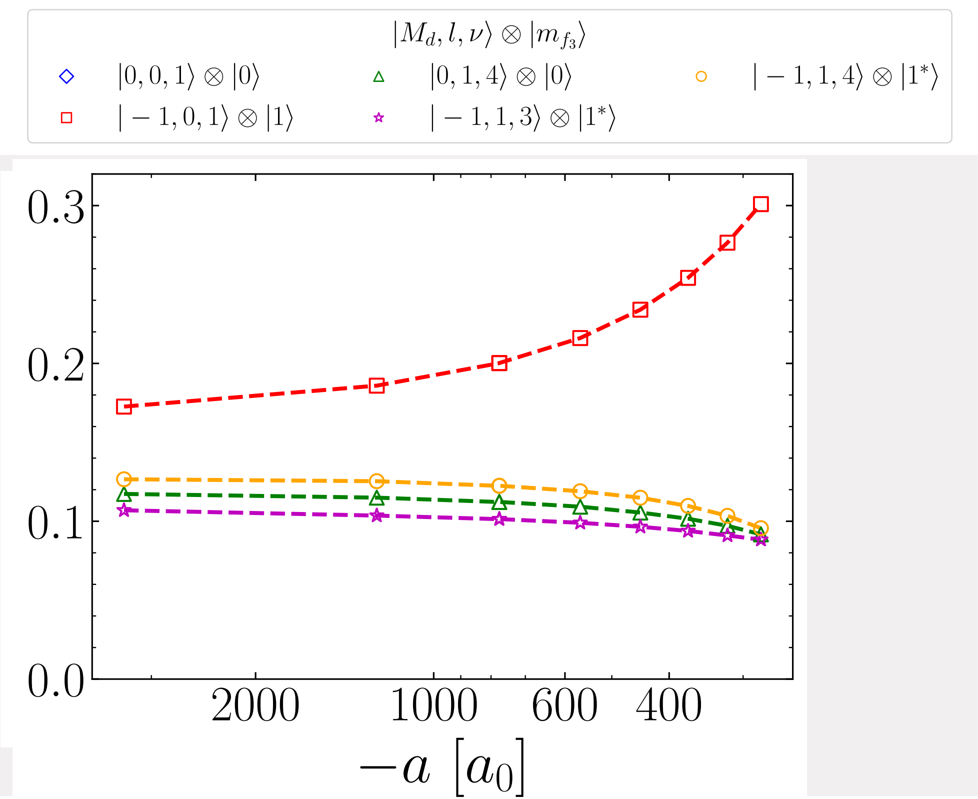
→**B:** Spin-exchange process, cannot be described by the FSS model

[J.-L. Li, T. Secker, P. M. A. Mestrom, S. J. J. M. F. Kokkelmans, Phys. Rev. Research. **4**, 023103 (2022)]

[Z. Shotan, O. Machtey, S. Kokkelmans, and L. Khaykovich, Phys. Rev. Lett. **113**, 053202 (2014)]

Li-7 – Three-body recombination





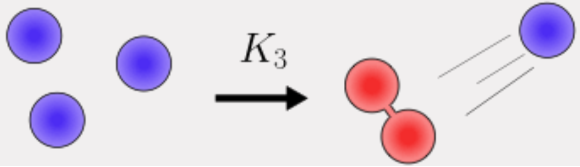
Importance of specific FMS channel, also seen in earlier studies!

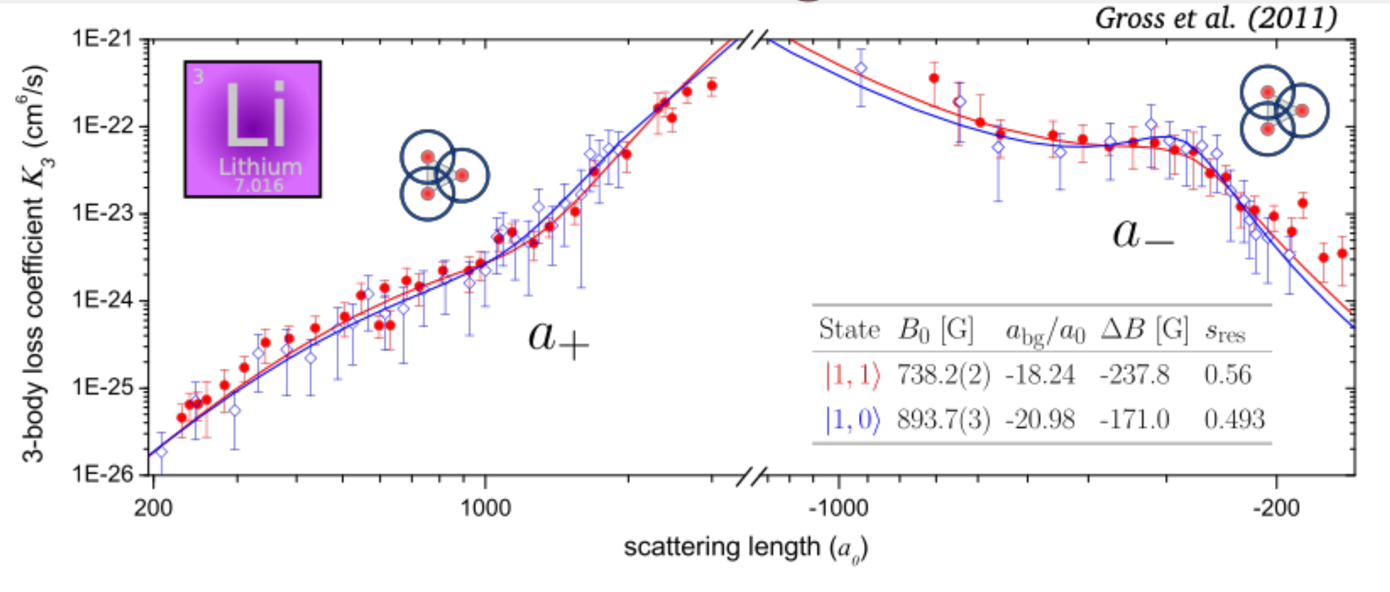
J.-L. Li, et al., Phys. Rev. Research. **4**, 023103 (2022).
T. Secker, et. al., Phys. Rev. A **103**, 052805 (2021).

Li-7 – Three-body recombination

Three-body recombination

$$K_3(a) = 3C_-(a)\frac{\hbar a^4}{m}$$



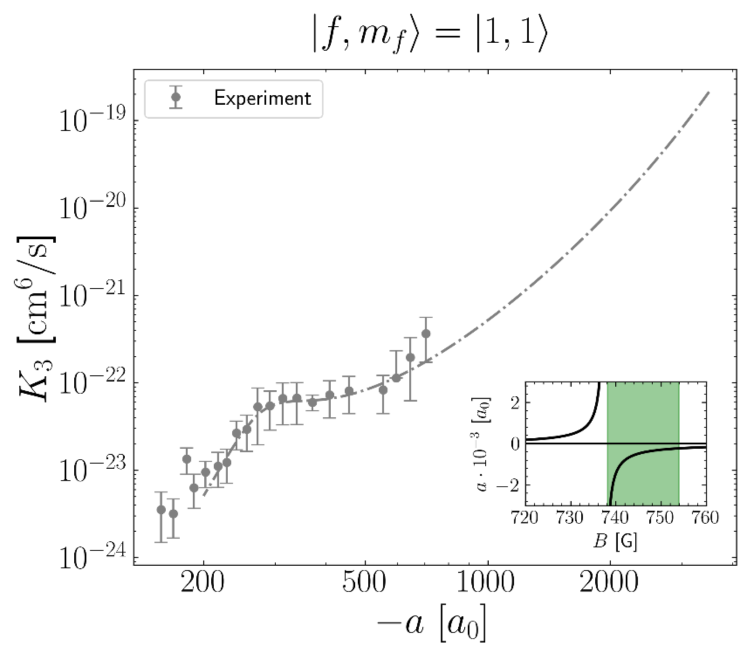


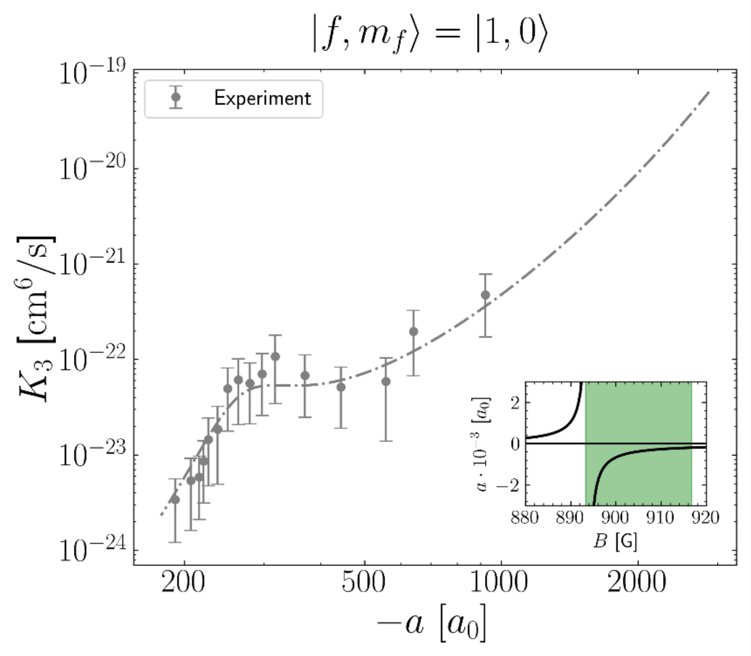
N. Gross, et al., C. R. Phys. 12, 4 (2011)

Three-body recombination

	a_-/r_{vdW} Experiment
$\|1,1\rangle$	-8.43(49)
$\|1,0\rangle$	-8.13(34)

N. Gross, et al., C. R. Phys. 12, 4 (2011)

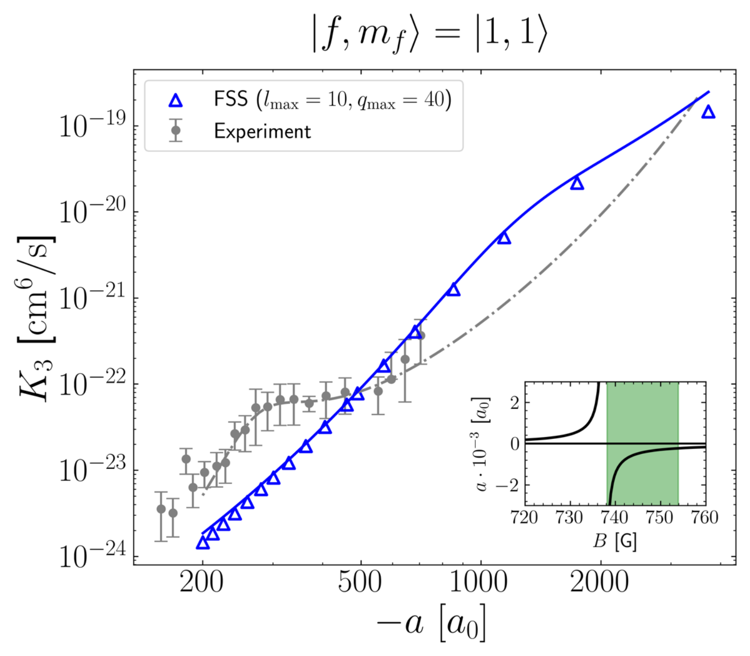


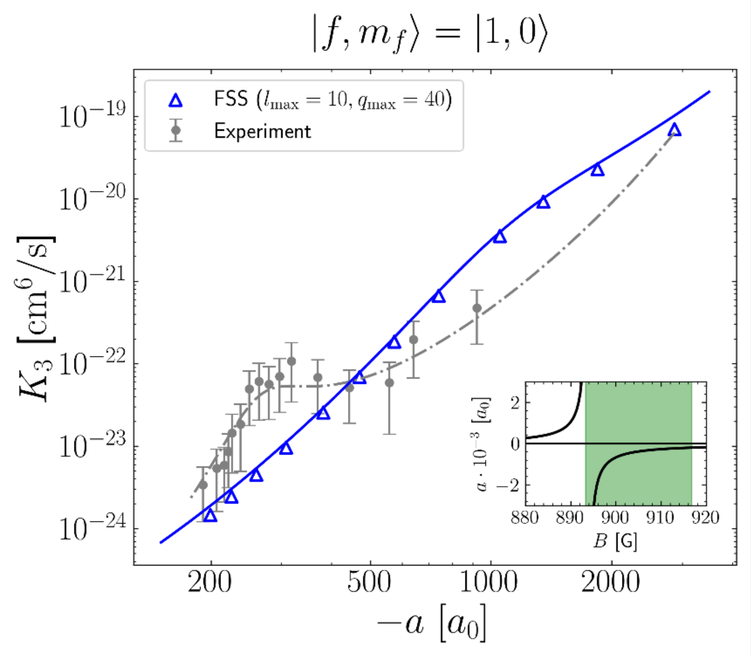


Three-body recombination

	$a_-/r_{\rm vdW}$	
	FSS	Experiment
$\|1,1\rangle$	-39.4	-8.43(49)
$\|1,0\rangle$	-34.4	-8.13(34)

N. Gross, et al., C. R. Phys. 12, 4 (2011)

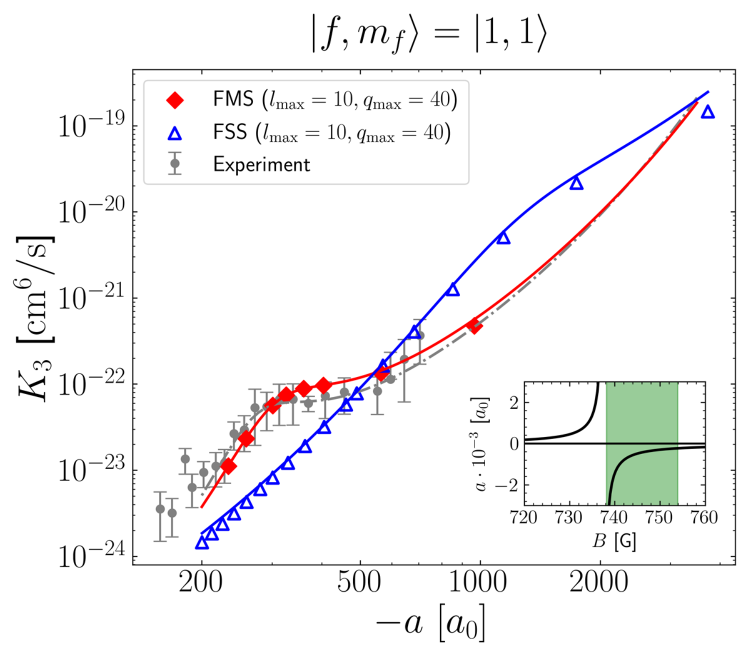


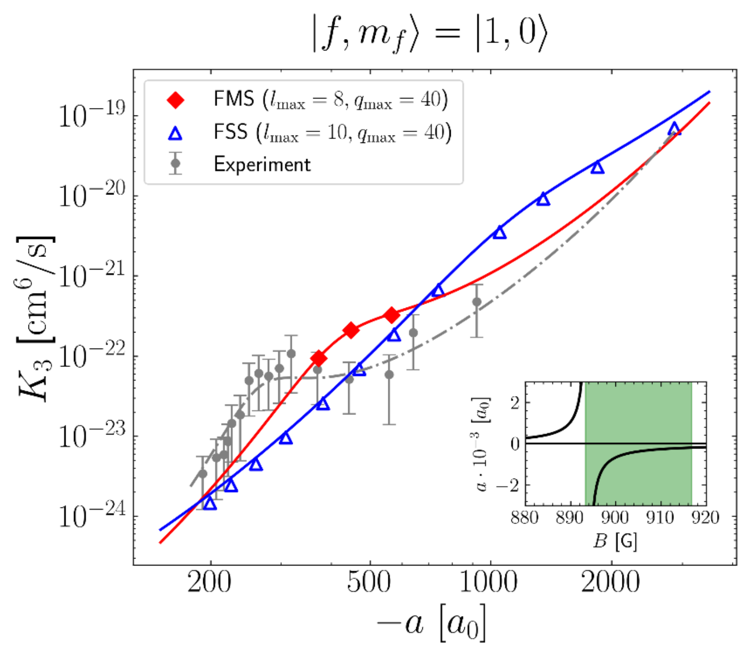


Three-body recombination

	$a_-/r_{\rm vdW}$		
	FSS	FMS	Experiment
$\|1,1\rangle$	-39.4	-9.4	-8.43(49)
$\|1,0\rangle$	-34.4	-12.7	-8.13(34)

N. Gross, et al., C. R. Phys. 12, 4 (2011)





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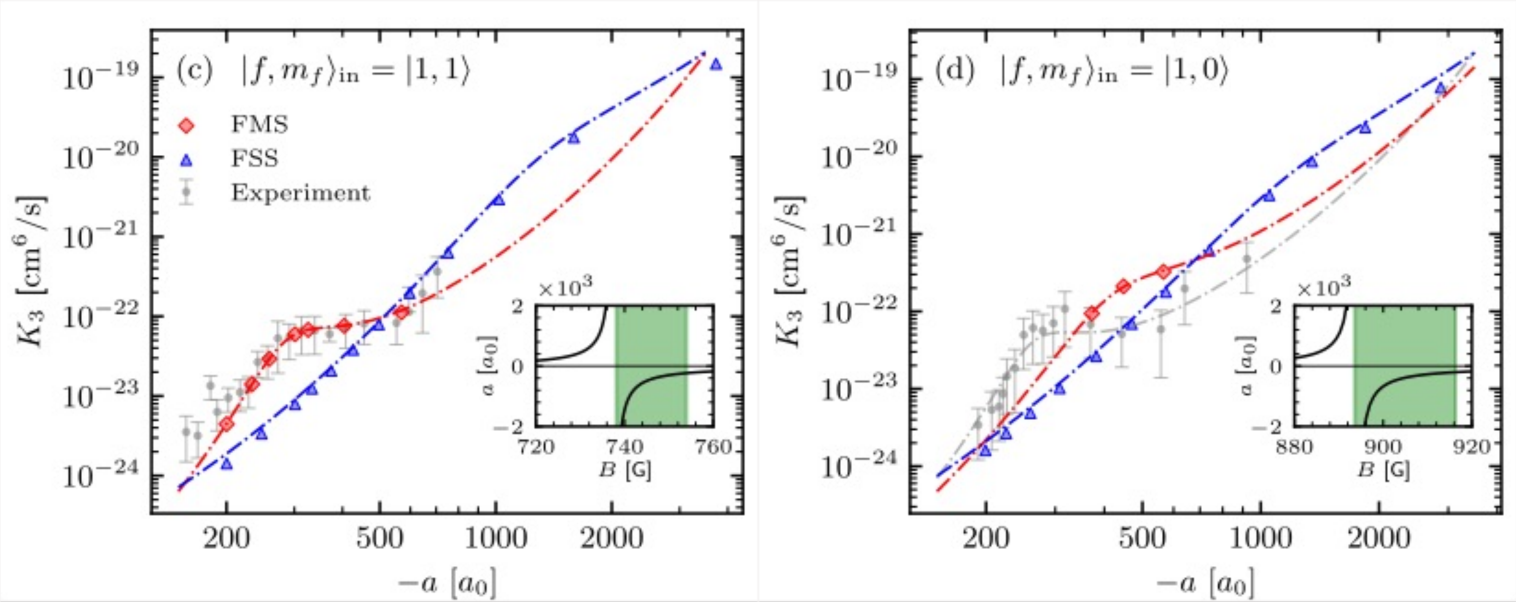
Li-7 Three-body parameter

(a)	$a_-/r_{\rm vdW}$			
	FSS	FMS	Gross et. al. (2011)	Dyke et. al. (2013)
$\|1,1\rangle$	-41.1	-8.79	-8.43(49)	-7.76(31)
$\|1,0\rangle$	-36.3	-12.7	-8.13(34)	-

(b)	η_-			
	FSS	FMS	Gross et. al. (2011)	Dyke et. al. (2013)
$\|1,1\rangle$	0.66	0.27	0.253(62)	0.17
$\|1,0\rangle$	0.78	0.38	0.236(43)	-



[J. van de Kraats, D. J. M. Ahmed-Braun, J. -L. Li, S. J. J. M. F. Kokkelmans, arXiv:2309.13128]

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Li-7 Three-body parameter

Main challenge: non-trivial convergence with maximum partial wave and third-particle momentum:

Significant numerical effort required

|1,1>

	a_-/r_{vdW}		η_-	
l_{max}	FSS	FMS	FSS	FMS
4*	-40.4	-15.6	0.76	0.32
6*	-46.5	-11.1	0.78	0.38
8*	-43.1	-10.1	0.71	0.32
10*	-39.4	-9.39	0.68	0.29
12*	**-41.1**	**-8.79**	**0.66**	**0.27**
10	-33.1	-11.2	0.64	0.36
12	-33.3	-10.8	0.65	0.36

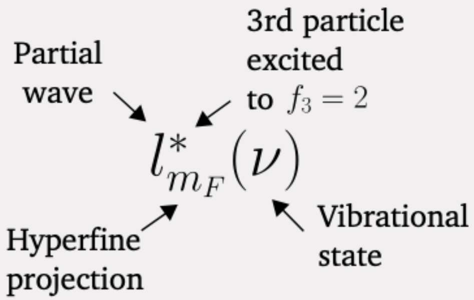
|1,0>

	a_-/r_{vdW}		η_-	
l_{max}	FSS	FMS	FSS	FMS
4	-19.6	-17.6	0.43	0.34
6	-35.6	-15.1	0.48	0.38
8	-30.5	-14.2	0.62	0.38
8*	**-36.3**	**-12.7**	**0.78**	**0.38**
10	-31.3	-13.7	0.57	0.41

Results with * have $q_{max} r_{vdW} = 40$, otherwise $q_{max} r_{vdW} = 20$

Results show importance of multichannel physics in the lithium few-body puzzle

Analysis partial recombination rates

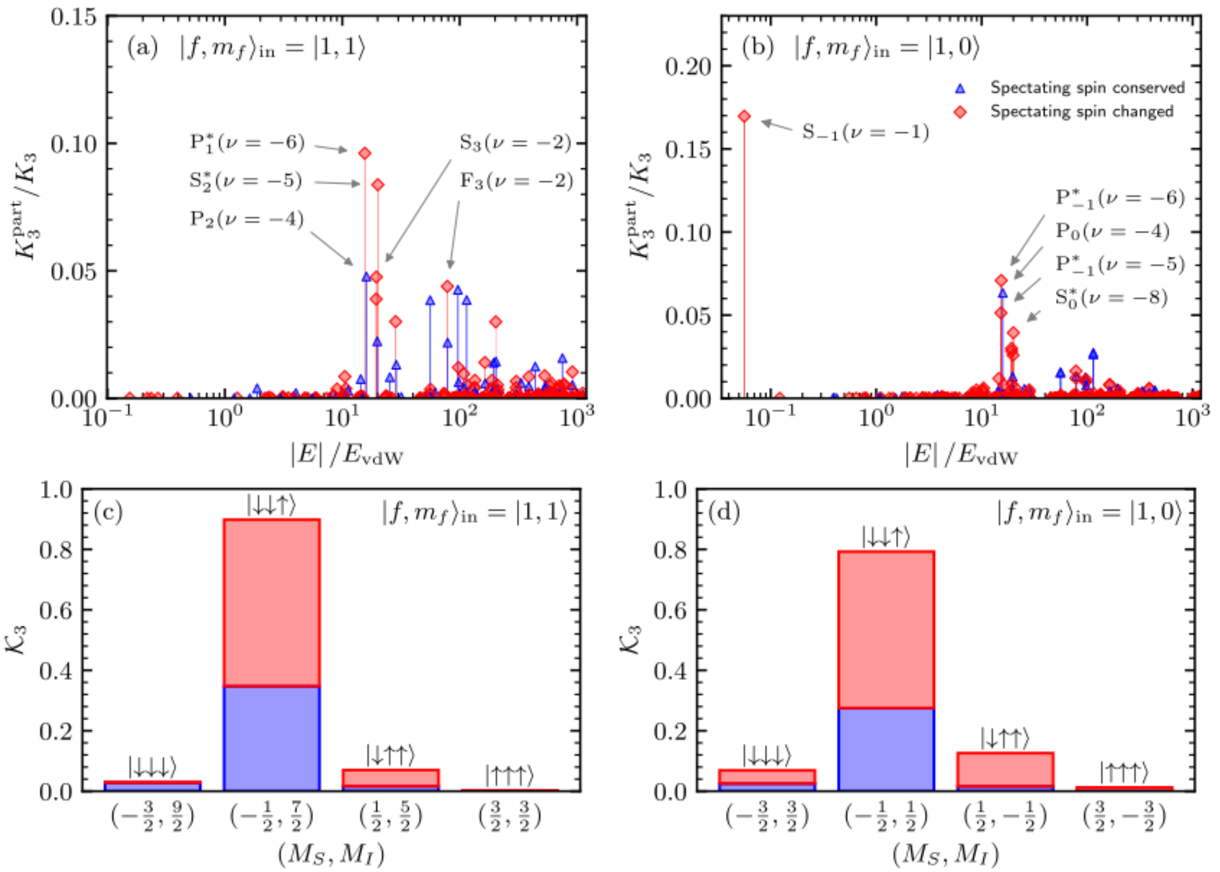


$m_F = m_{f1} + m_{f2}$

FMS channels dominate

The final state distribution

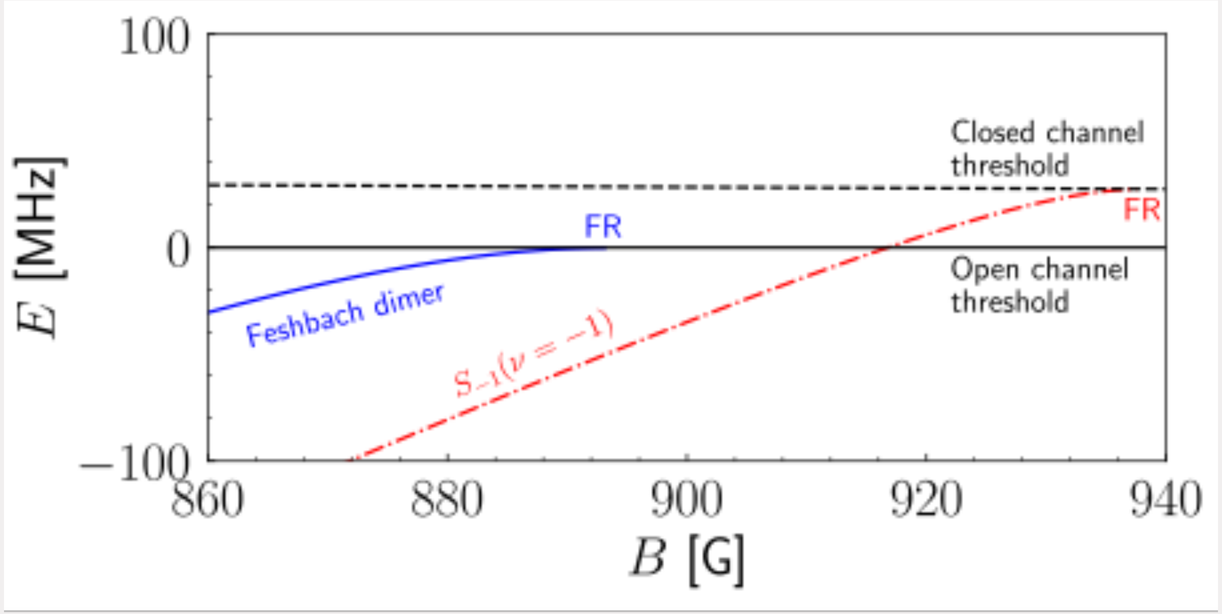
[J. van de Kraats, D. J. M. Ahmed-Braun, J. -L. Li, S. J. J. M. F. Kokkelmans, arXiv:2309.13128]



Analysis partial recombination rates

In the |1,0> state we find a single dominant FMS channel

- Originates from closed-channel Feshbach resonance

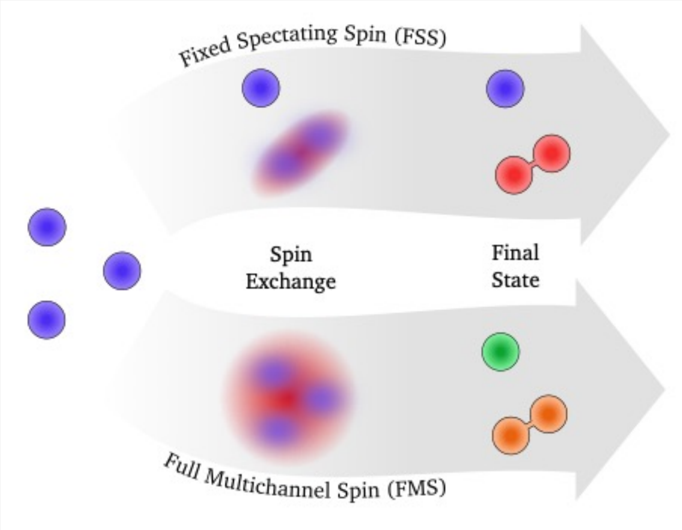


Conclusions/outlook

Three-body recombination Li-7

Three-body physics in Lithium-7 is strongly influenced by multichannel effects

Strong coupling to specific three-body hyperfine channels, which have often been neglected in earlier studies



[J. van de Kraats, D. J. M. Ahmed-Braun, J. -L. Li, S. J. J. M. F. Kokkelmans, Emergent inflation of the Efimov spectrum under three-body spin-exchange interactions, arXiv:2309.13128]

Go back to simplified models, investigate approximations based on physical effects

The team!

Paul Mestrom

Thomas Secker

Silvia Musolino

Denise Ahmed-Braun

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Jinglun Li

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NWO Netherlands Organisation for Scientific Research

MOQS Molecular Quantum Simulations

Quantum Delta the Netherlands

EuRyQa