



# Prospects and experiments with ErLi large mass-imbalance mixtures

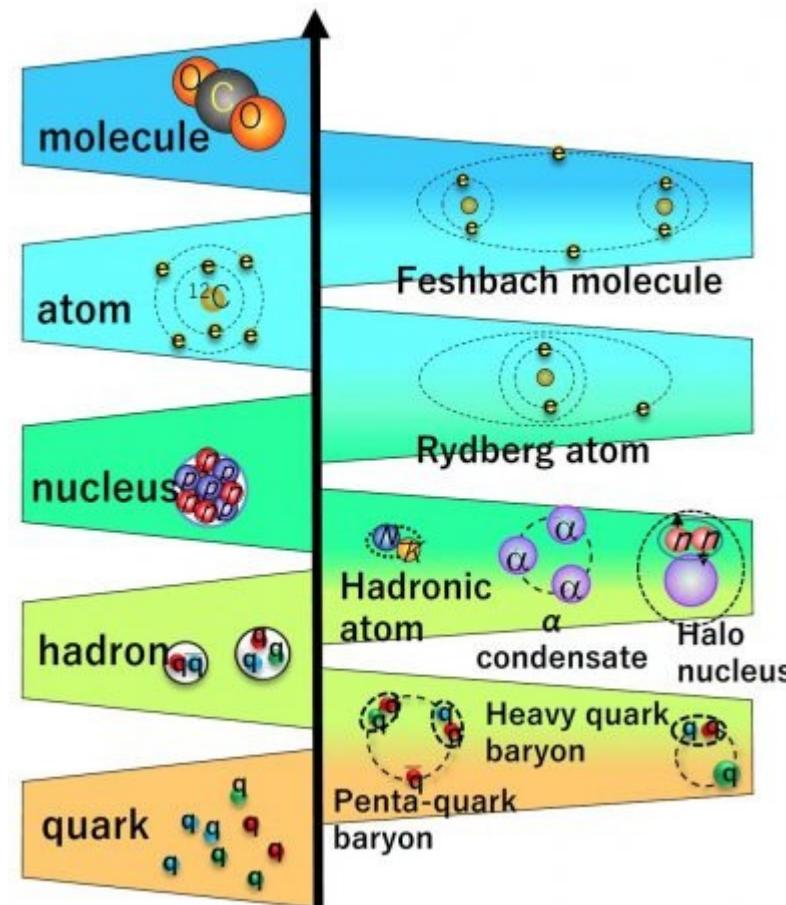
Kyoto University

F. Schäfer, Y. Haruna, and Y. Takahashi

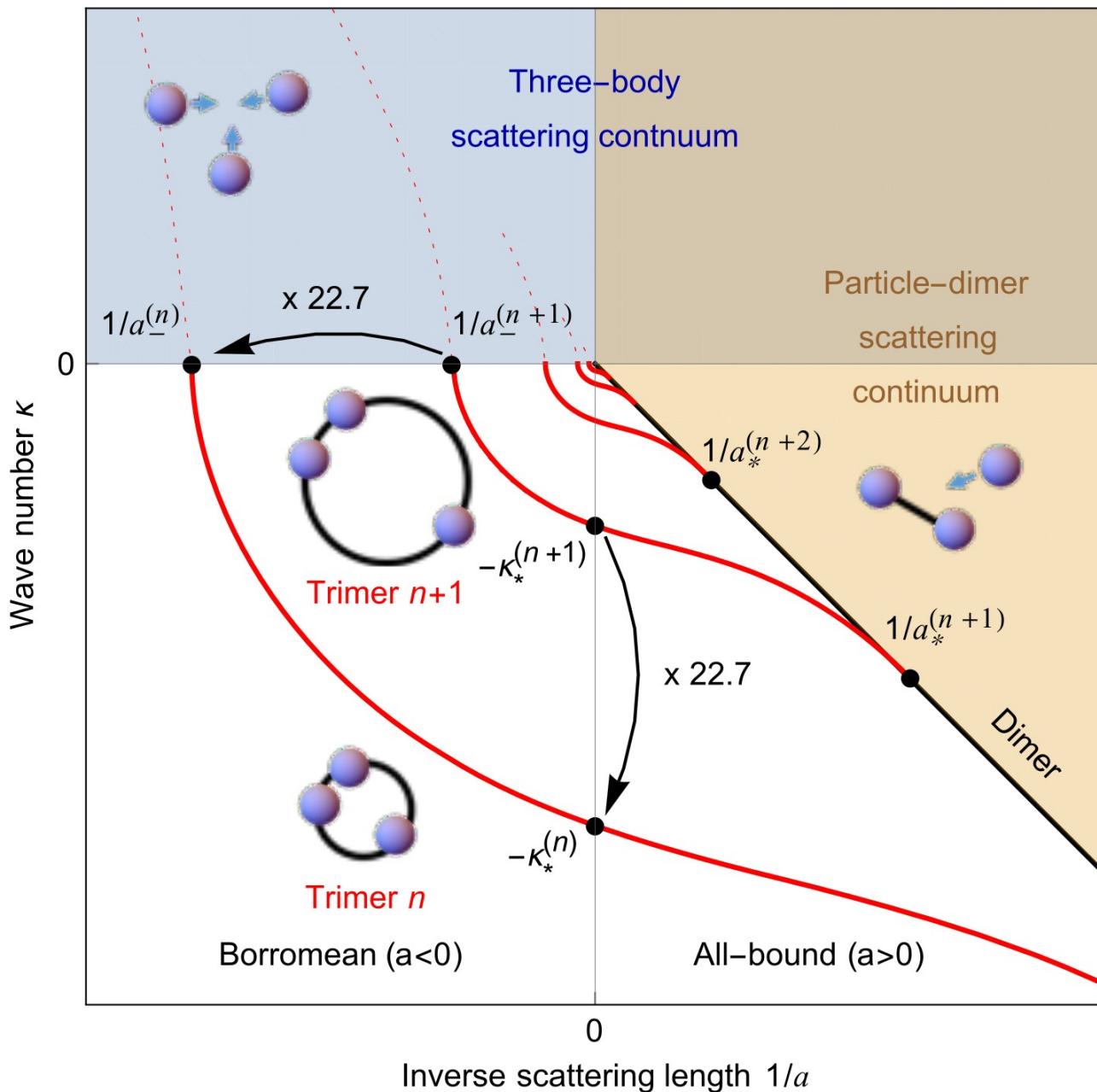
第8回クラスター階層領域研究会, Osaka – 2023/02/09-11

# Outline

- Why? - Introduction
  - Efimov cluster states in quantum mixtures
  - p-wave superfluidity in mixed dimensions
- How? - Prospects of large mass-imbalanced Er-Li mixtures
  - Properties of Er-Li quantum degenerate mixtures
  - Possibilities of interspecies interaction control
- What? - Feshbach resonances in Er-Li mixtures
  - Formation triple-species mixtures of Er, Li and Yb
  - Observation of Er-Li Feshbach resonances
  - Towards the realization of new Efimov states
- Summary



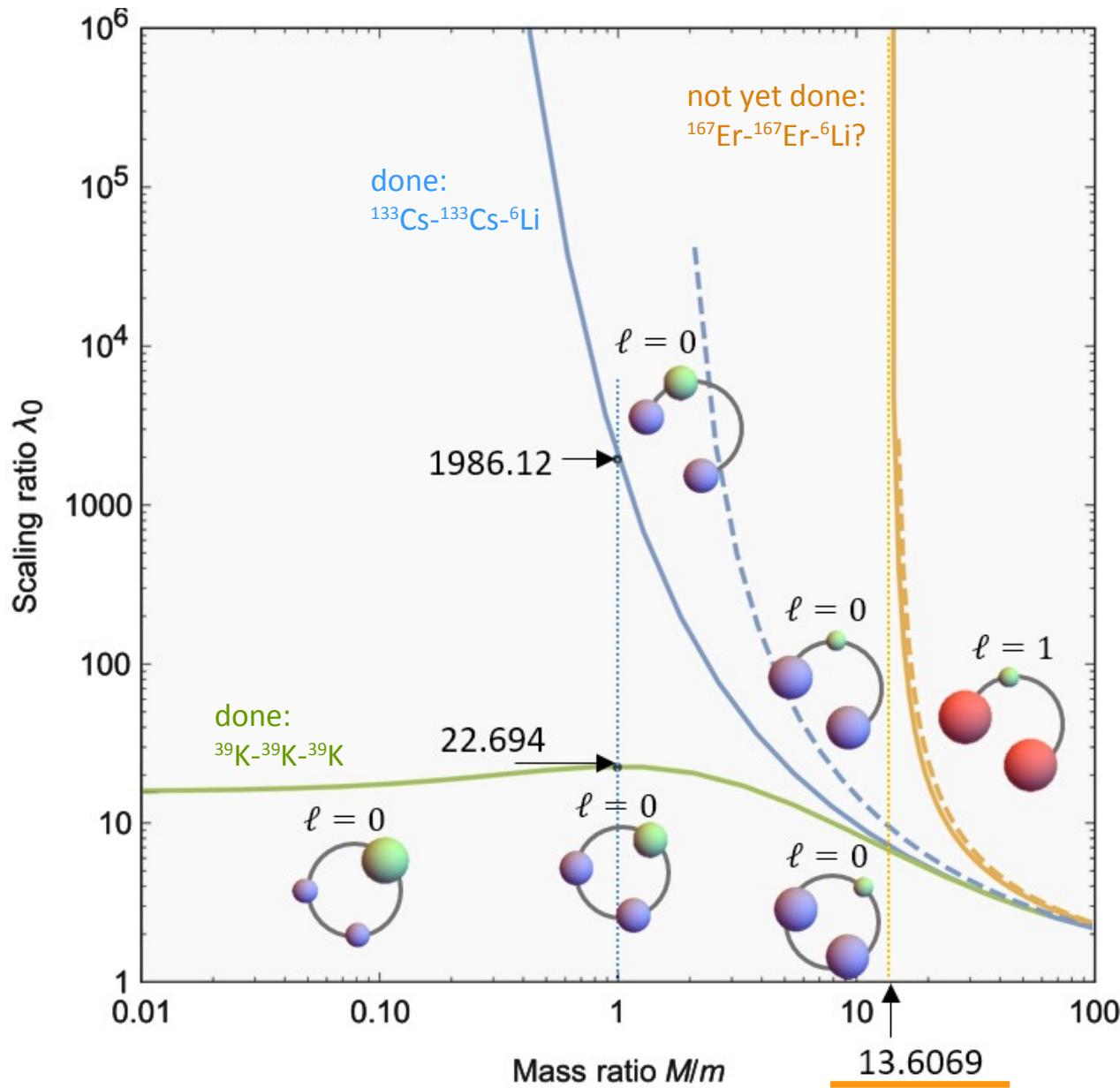
# Efimov cluster states – scaling



- Infinite number of three-body bound states
  - Scaling factor  $\lambda_0 \approx 22.694$
  - Energy scaling  $E/(\lambda_0)^{2n}$
  - Deviation of ground-state and first excited-state trimer from universal spectrum
- Difficulty to observe series of Efimov trimers due to large scaling factor

P. Naidon and S. Endo, Rep. Prog. Phys. 80, 056001 (2017)

# Efimov physics beyond three identical bosons



Two identical bosons  
and one particle  
(all resonant)

M. Zaccanti *et al.*, Nat. Phys. 5, 586 (2009)

Two identical **bosons**  
resonant with  
one particle

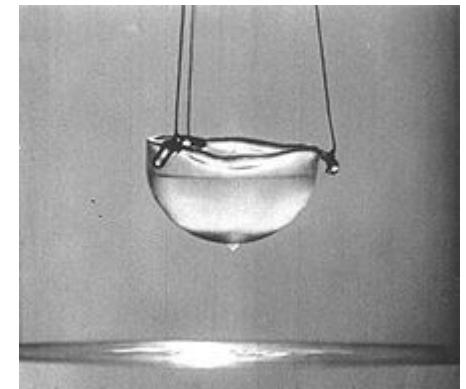
R. Pires *et al.*, Phys. Rev. Lett. 112, 250404 (2014)  
S.-K. Tung *et al.*, Phys. Rev. Lett. 113, 240402 (2014)

Two identical **fermions**  
resonant with  
one particle ( $l = 1$ )

- Large variety of particle combinations and scaling ratios possible

# p-wave superfluidity in mixed dimensional systems

- 1972: Discovery of superfluidity in  $^3\text{He}$  by Lee, Osheroff and Richardson (Nobel Prize 1996)
- $^3\text{He}$  is a fermion → no s-wave coupling possible
  - Superfluidity caused by p-wave Cooper pairs

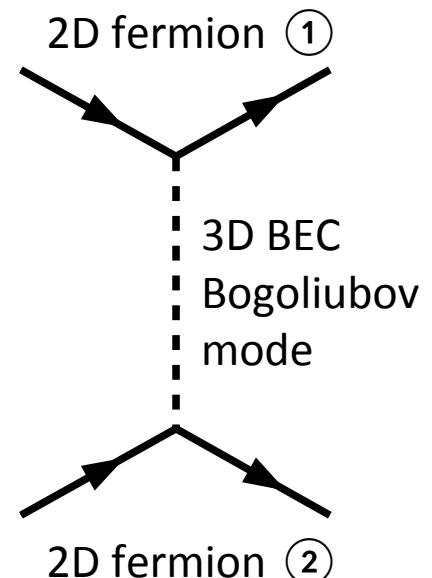


wikipedia.org

It is hard to find a well **controllable** system to study p-wave superfluidity.

## P-wave superfluidity with ultracold atoms in mixed dimensions

- 2009 – Nishida: 2D Fermi gas within 3D other species Fermi gas
- 2016 – Wu, Bruun: 2D Fermi gas embedded in 3D BEC
- 2017, 2018: Further refinements and detailed calculations for  $^7\text{Li}-^{173}\text{Yb}$
- Mechanism: Increased critical temperature due to Fermion pairing via **Bogoliubov phonon mediated interactions**



# Elements for a large mass-imbalance ultracold mixture

Periodic Table of the Elements

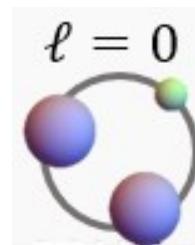
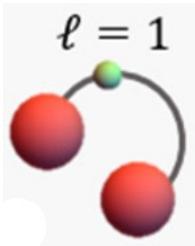
	Number	Symbol	Name	Mass
1	1	H	Hydrogen	1.008
2	2	He	Helium	4.003
3	3	Li	Lithium	6.941
4	4	Be	Beryllium	9.012
5	11	Na	Sodium	22.990
6	12	Mg	Magnesium	24.305
7	19	K	Potassium	39.098
8	20	Ca	Calcium	40.078
9	21	Sc	Scandium	44.956
10	22	Ti	Titanium	47.867
11	23	V	Vanadium	50.942
12	24	Cr	Chromium	51.996
13	25	Mn	Manganese	54.938
14	26	Fe	Iron	55.845
15	27	Co	Cobalt	58.933
16	28	Ni	Nickel	58.693
17	29	Cu	Copper	63.546
18	30	Zn	Zinc	65.38
19	31	Ga	Gallium	69.723
20	32	Ge	Germanium	72.631
21	33	As	Arsenic	74.922
22	34	Se	Selenium	78.971
23	35	Br	Bromine	79.904
24	36	Kr	Krypton	83.798
25	37	Rb	Rubidium	85.468
26	38	Sr	Strontium	87.62
27	39	Y	Yttrium	88.906
28	40	Zr	Zirconium	91.224
29	41	Nb	Niobium	92.906
30	42	Mo	Molybdenum	95.95
31	43	Tc	Technetium	98.907
32	44	Ru	Ruthenium	101.07
33	45	Rh	Rhodium	102.906
34	46	Pd	Palladium	106.42
35	47	Ag	Silver	107.868
36	48	Cd	Cadmium	112.414
37	49	In	Indium	118.818
38	50	Sn	Tin	118.711
39	51	Sb	Antimony	121.760
40	52	Te	Tellurium	127.6
41	53	I	Iodine	126.904
42	54	Xe	Xenon	131.293
43	55	Cs	Cesium	132.905
44	56	Ba	Barium	137.328
45	57-71			
46	72	Hf	Hafnium	178.49
47	73	Ta	Tantalum	180.948
48	74	W	Tungsten	183.84
49	75	Re	Rhenium	186.207
50	76	Os	Osmium	190.23
51	77	Ir	Iridium	192.217
52	78	Pt	Platinum	195.085
53	79	Au	Gold	196.967
54	80	Hg	Mercury	200.592
55	81	Tl	Thallium	204.383
56	82	Pb	Lead	207.2
57	83	Bi	Bismuth	208.980
58	84	Po	Polonium	[208.982]
59	85	At	Astatine	209.987
60	86	Rn	Radon	222.018
61	87	Fr	Francium	223.020
62	88	Ra	Radium	226.025
63	89-103			
64	104	Rf	Rutherfordium	[261]
65	105	Db	Dubnium	[262]
66	106	Sg	Seaborgium	[266]
67	107	Bh	Bohrium	[264]
68	108	Hs	Hassium	[269]
69	109	Mt	Meitnerium	[278]
70	110	Ds	Darmstadtium	[281]
71	111	Rg	Roentgenium	[280]
72	112	Cn	Copernicium	[285]
73	113	Nh	Nihonium	[286]
74	114	Fl	Flerovium	[289]
75	115	Mc	Moscovium	[289]
76	116	Lv	Livermorium	[293]
77	117	Ts	Tennessee	[294]
78	118	Og	Oganesson	[294]
Lanthanide Series				
57	La	Lanthanum	138.905	
58	Ce	Cerium	140.116	
59	Pr	Praseodymium	140.908	
60	Nd	Neodymium	144.243	
61	Pm	Promethium	144.913	
62	Sm	Samarium	150.36	
63	Eu	Europium	151.964	
64	Gd	Gadolinium	157.25	
65	Tb	Terbium	158.925	
66	Dy	Dysprosium	162.500	
67	Ho	Holmium	164.930	
68	Er	Erbium	167.259	
69	Tm	Thulium	168.934	
70	Yb	Ytterbium	173.055	
71	Lu	Lutetium	174.967	
Actinide Series				
89	Ac	Actinium	227.028	
90	Th	Thorium	232.038	
91	Pa	Protactinium	231.036	
92	U	Uranium	238.029	
93	Np	Neptunium	237.048	
94	Pu	Plutonium	244.064	
95	Am	Americium	243.061	
96	Cm	Curium	247.070	
97	Bk	Berkelium	247.070	
98	Cf	Californium	251.080	
99	Es	Einsteinium	[254]	
100	Fm	Fermium	257.095	
101	Md	Mendelevium	258.1	
102	No	Nobelium	259.101	
103	Lr	Lawrencium	[262]	

<http://scienzenotes.org>

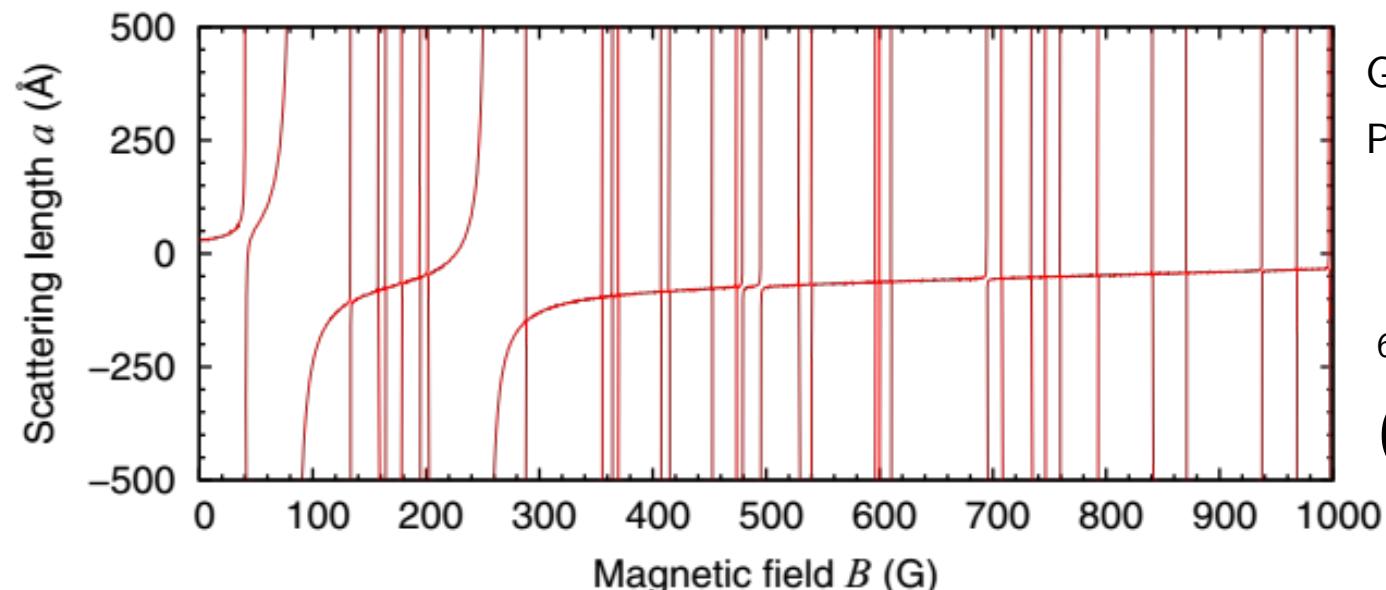
# Properties of a large mass-imbalance Er-Li mixture

Mass ratio  $^{167}\text{Er}$  (fermion) :  $^6\text{Li}$  (boson) = 27.8  $\gg$  13.6

- Mass ratio  $> 13.6 \rightarrow$  Possibility of Efimov states involving fermions
- Expected scaling ratio for Fermi-Fermi  $^{167}\text{Er}$ - $^{167}\text{Er}$ - $^6\text{Li}$  trimer:  $\lambda_0 \approx 8$
- Also possible: all bosonic case,  $^{168}\text{Er}$ - $^{168}\text{Er}$ - $^7\text{Li} \rightarrow \lambda_0 \approx 4.5$



Expect good control of Er-Li interspecies scattering lengths

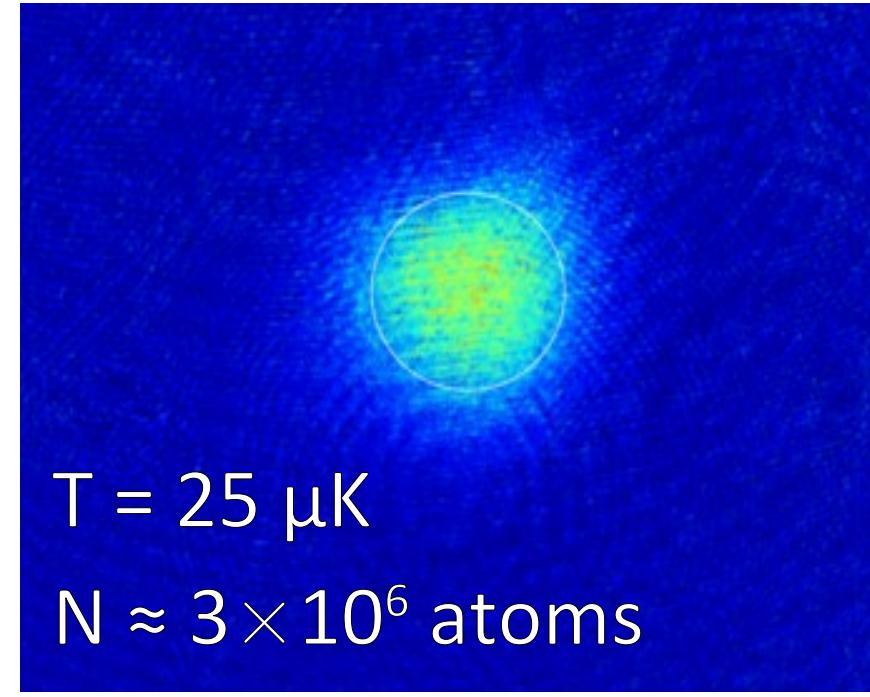
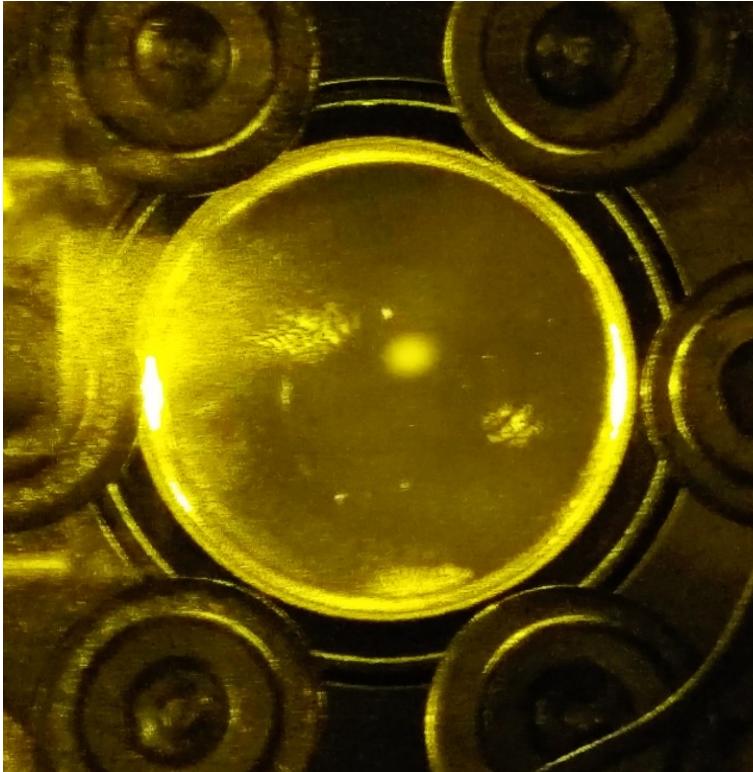
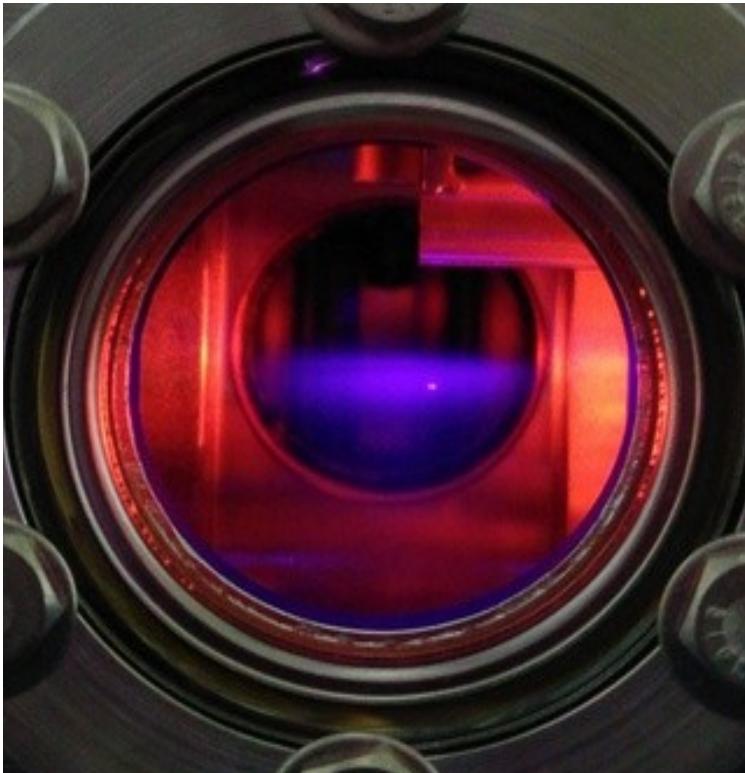


González-Martínez and Żuchowski  
PRA 92, 022708 (2015)

$^6\text{Li}$ - $^{166}\text{Er}$   
(Fermi-Bose)

# The triple-species mixture machine

- Upgrade of existing Yb-Li experiment to **additionally** include Er
- Successful slowing, trapping and cooling of  $^{166}\text{Er}$ ,  $^{167}\text{Er}$ ,  $^{168}\text{Er}$  to microkelvin temperatures
- Simultaneous trapping of Er-Li, Er-Yb, Yb-Li and Er-Yb-Li demonstrated

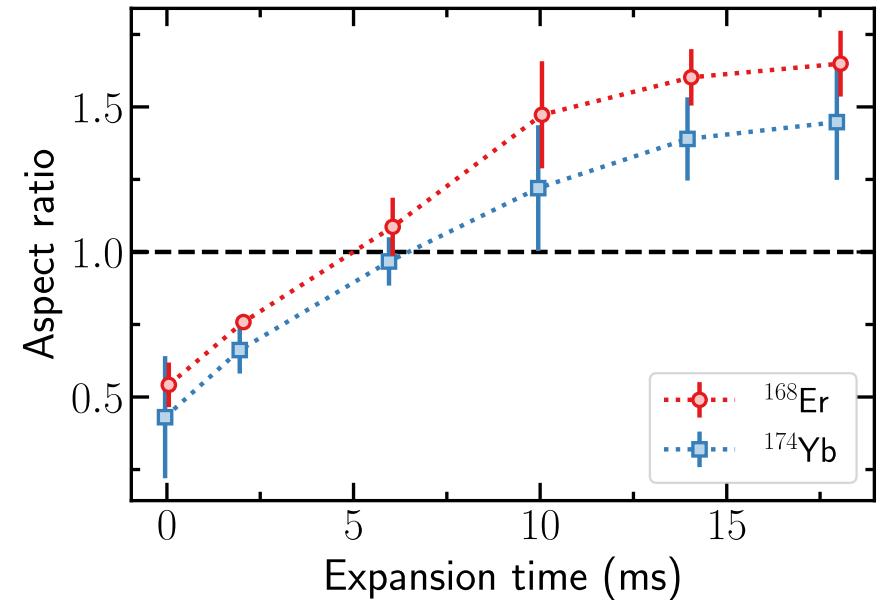
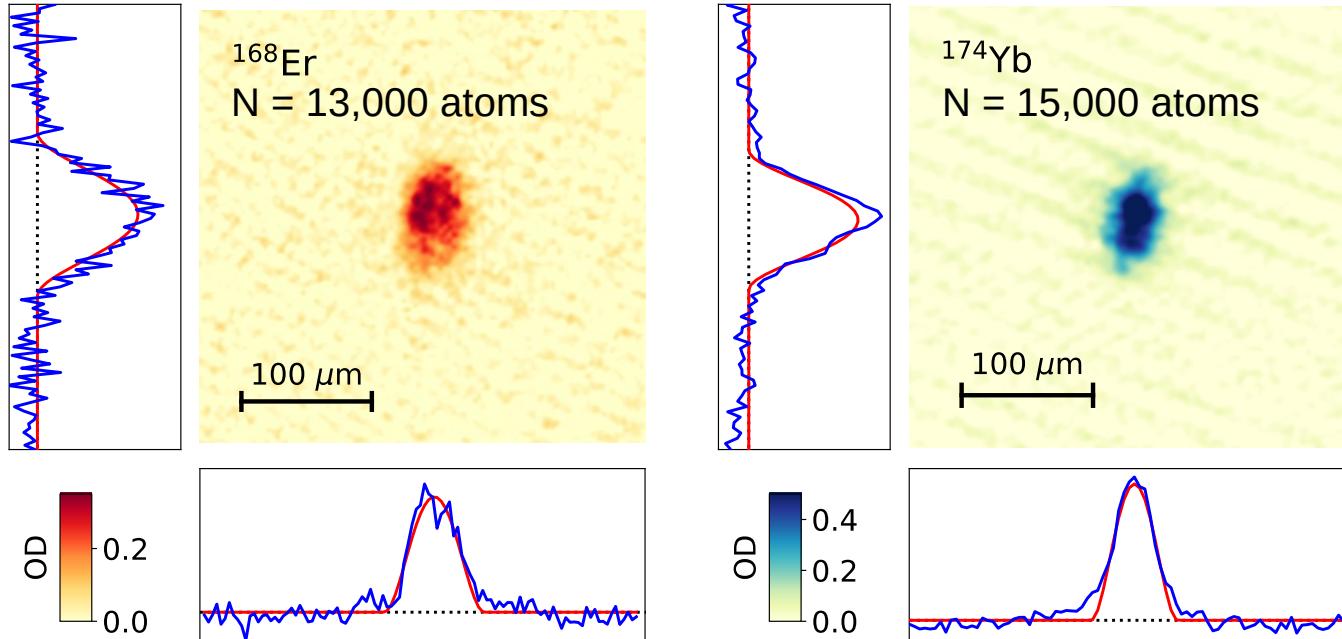


15 mm

# Realization of double quantum degenerate Er-Yb mixture

- Combines **highly-magnetic**  $^{168}\text{Er}$  with **non-magnetic**  $^{174}\text{Yb}$

Submitted for publication in PRA  
FS et al., arXiv:2301.08890 (2023)

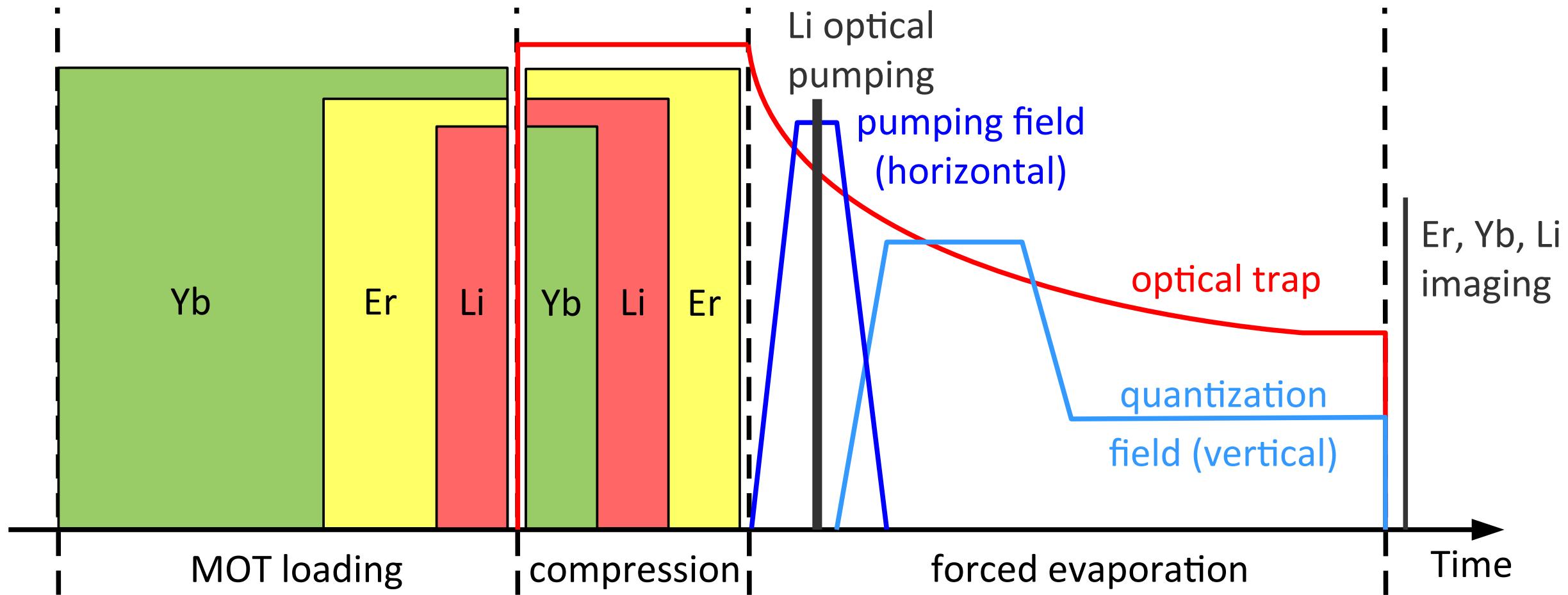


## Possible applications

- Study of magnetic impurity systems
- Observation of quantum chaotic Feshbach spectra while still “*ab initio* capable”
- Search for proton-to-electron mass ratio changes

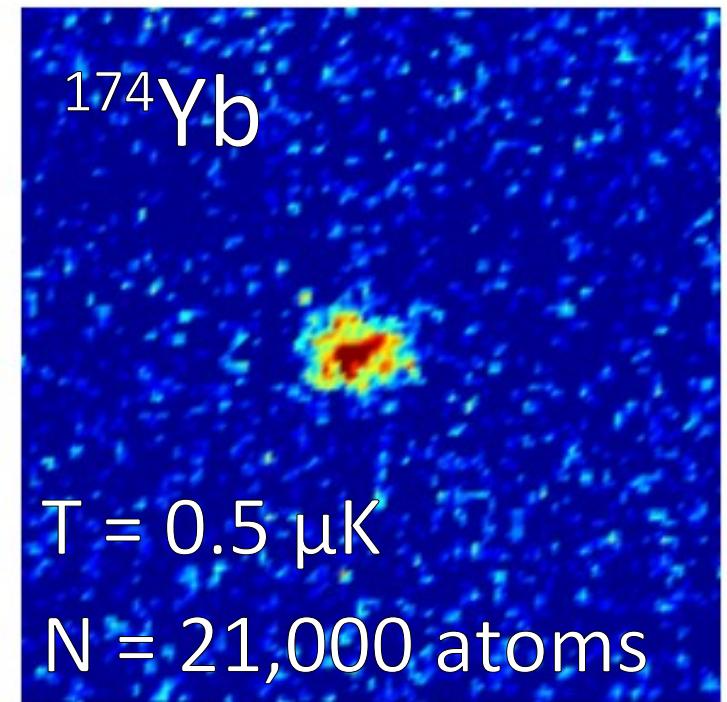
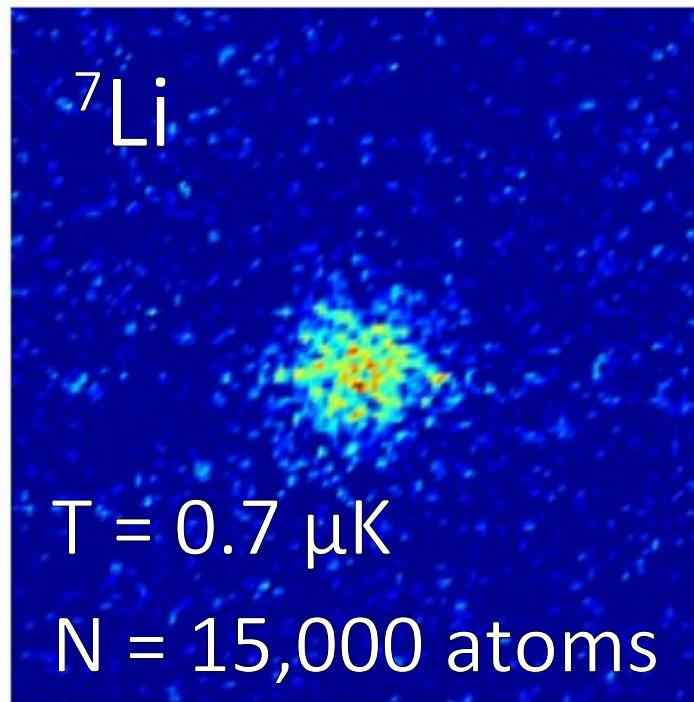
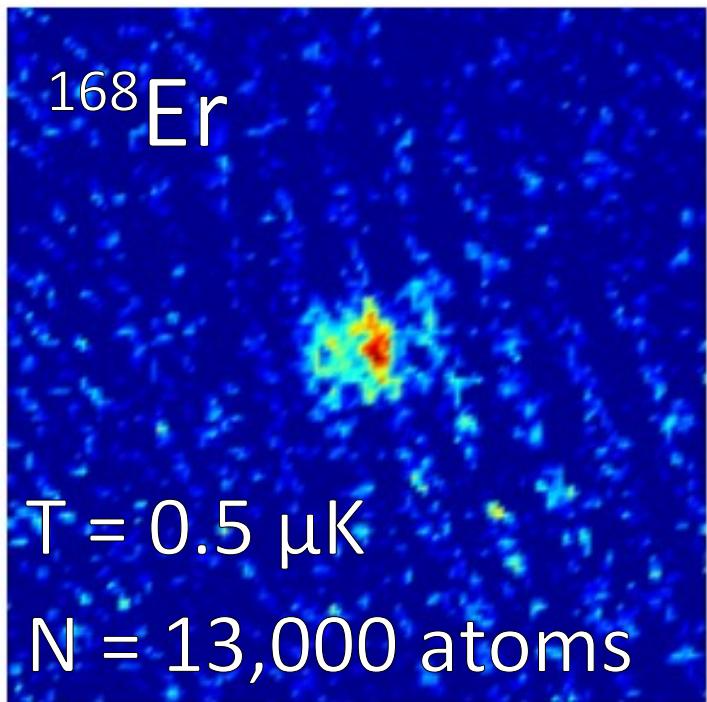
M. Kosicki et al., NJP 22, 023024 (2020)

# Creation and probing of an ultracold Er-Yb-Li mixture



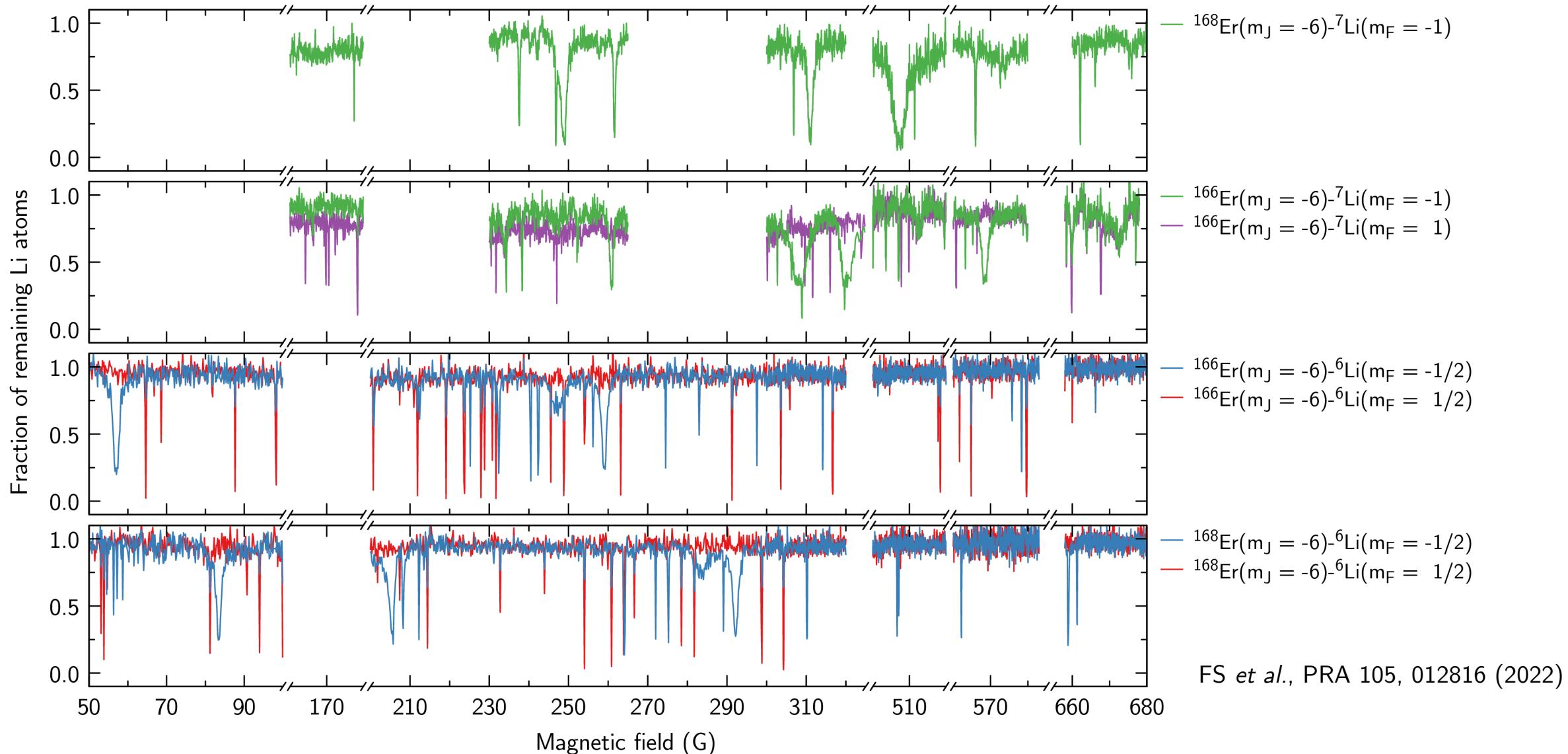
- Optimization of sequence parameters heavily supported by machine learning
- Magnetic field control to maintain polarization of Er in lowest-energy magnetic substate
- Control of Li spin state by optical pumping to a stretched-state configuration

# Realization of ultracold triple-species mixtures



- Efficient cooling of Er and Li by sympathetic cooling with  $^{174}\text{Yb}$
- Also realized: triple-species mixture with fermionic  $^{167}\text{Er}$  and/or  $^6\text{Li}$
- Removal of “unwanted” species from trap after evaporation by blast light possible
- First task: Control of Er-Li interspecies interaction (via magnetic Feshbach resonances)

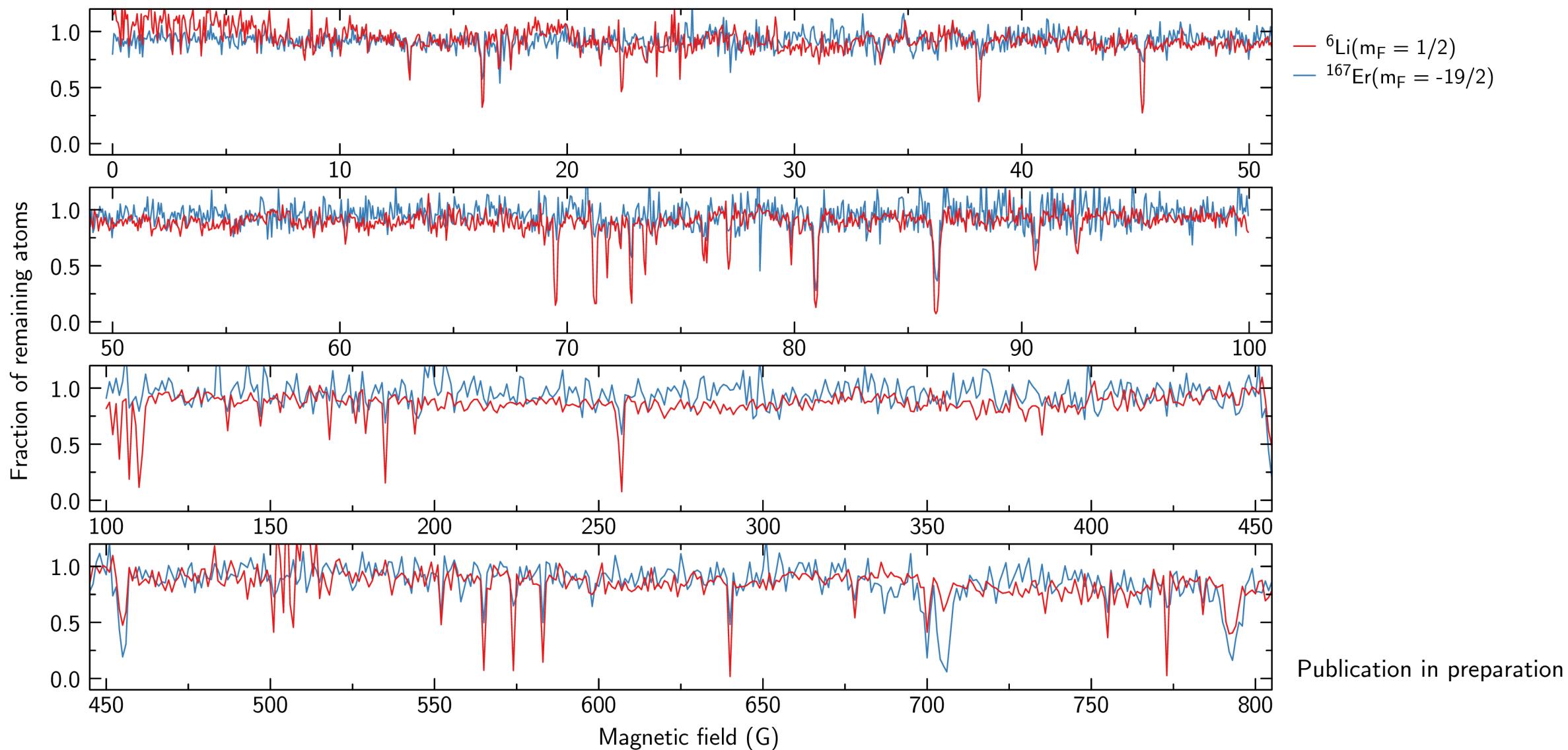
## Previously: Feshbach resonances in Er-Li mixture with bosonic Er



FS et al., PRA 105, 012816 (2022)

► Rich spectrum of Er-Li Feshbach resonances for many isotope & spin combinations

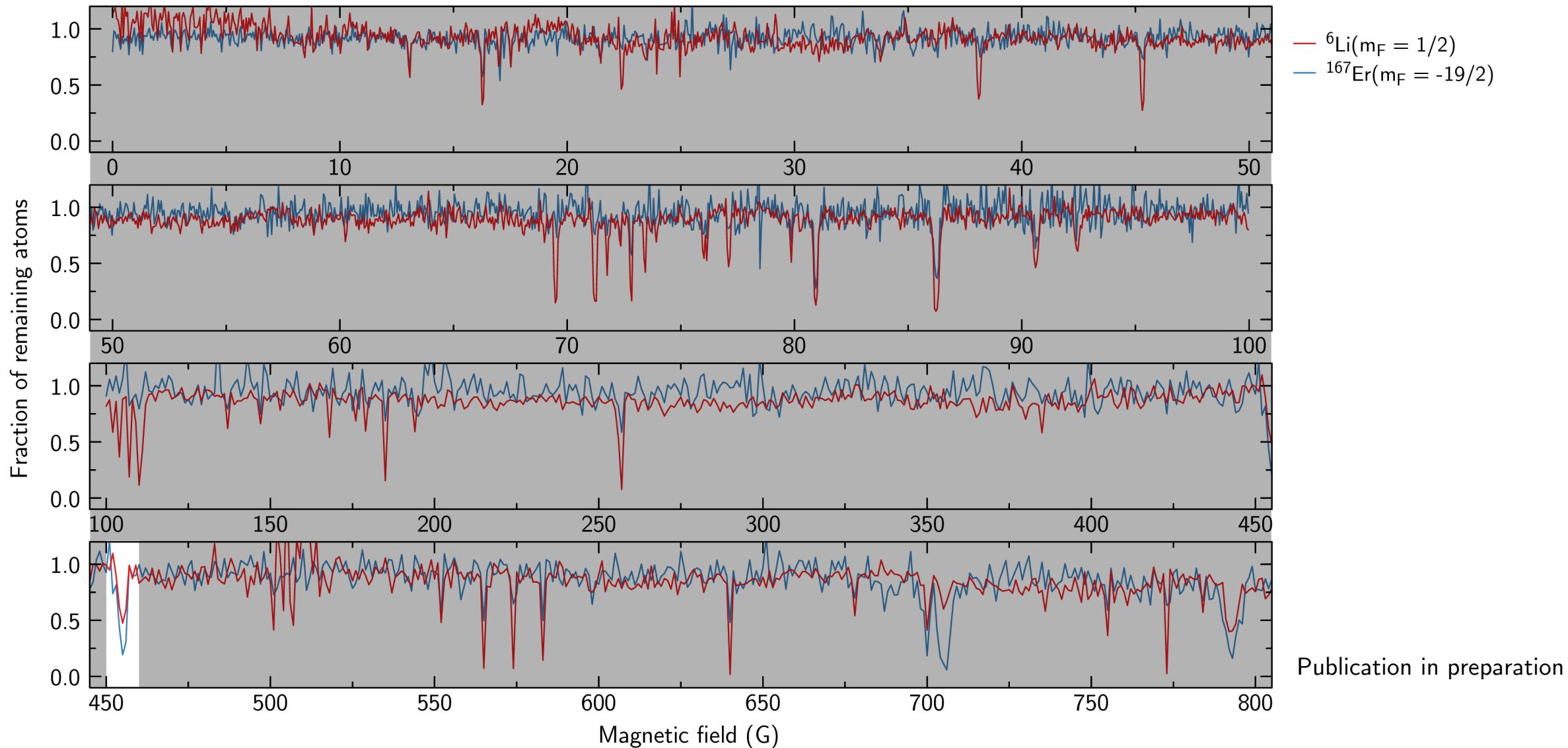
# Recently: Feshbach resonances in $^{167}\text{Er}$ - $^6\text{Li}$ Fermi-Fermi mixture



Publication in preparation

- Rich spectrum of Er-Li Feshbach resonances, with some rather broad ones ( $> 1 \text{ G}$ )

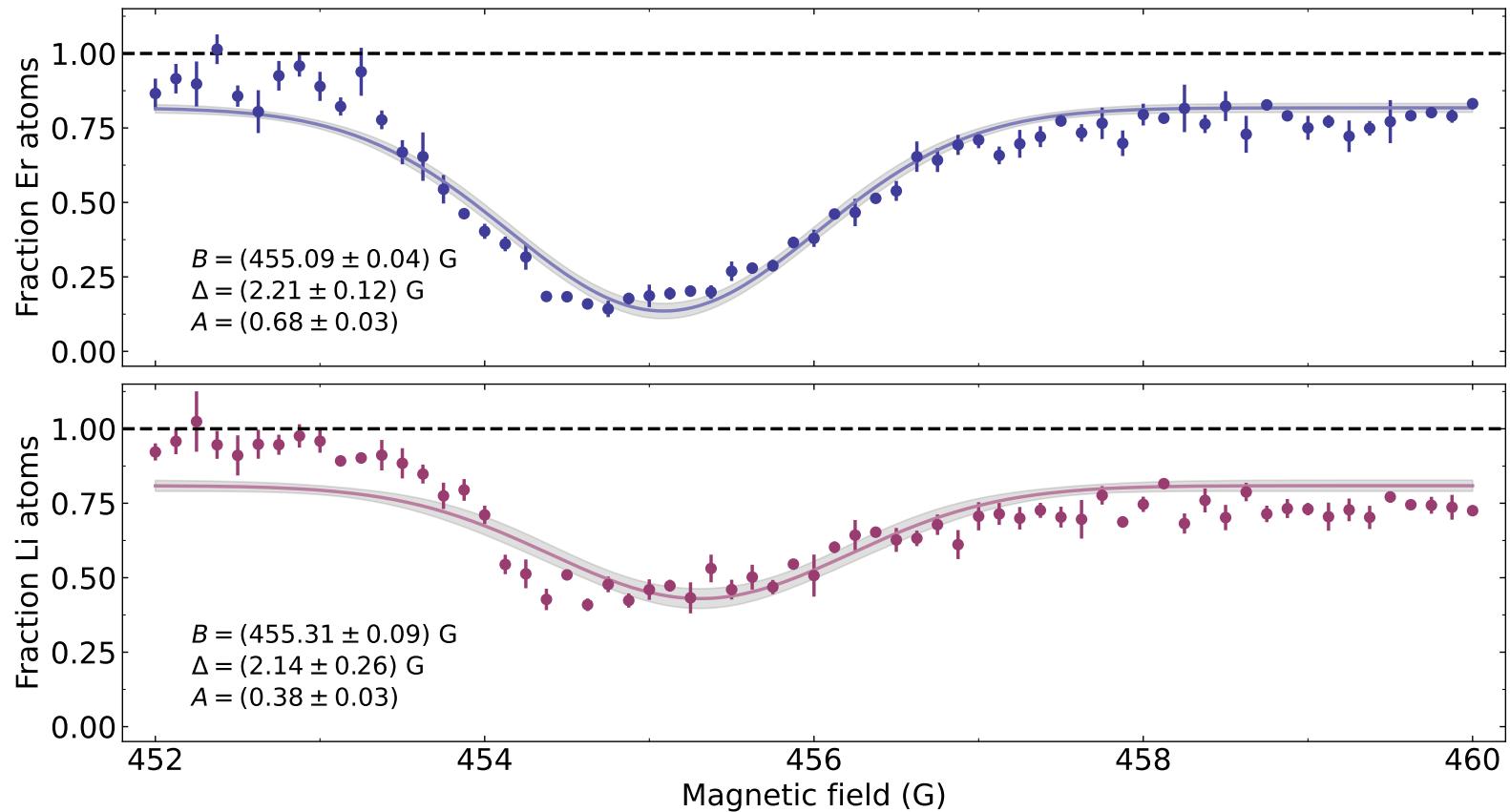
# Recently: Feshbach resonances in $^{167}\text{Er}$ - $^6\text{Li}$ Fermi-Fermi mixture



Publication in preparation

- Rich spectrum of Er-Li Feshbach resonances, with some rather broad ones ( $> 1 \text{ G}$ )

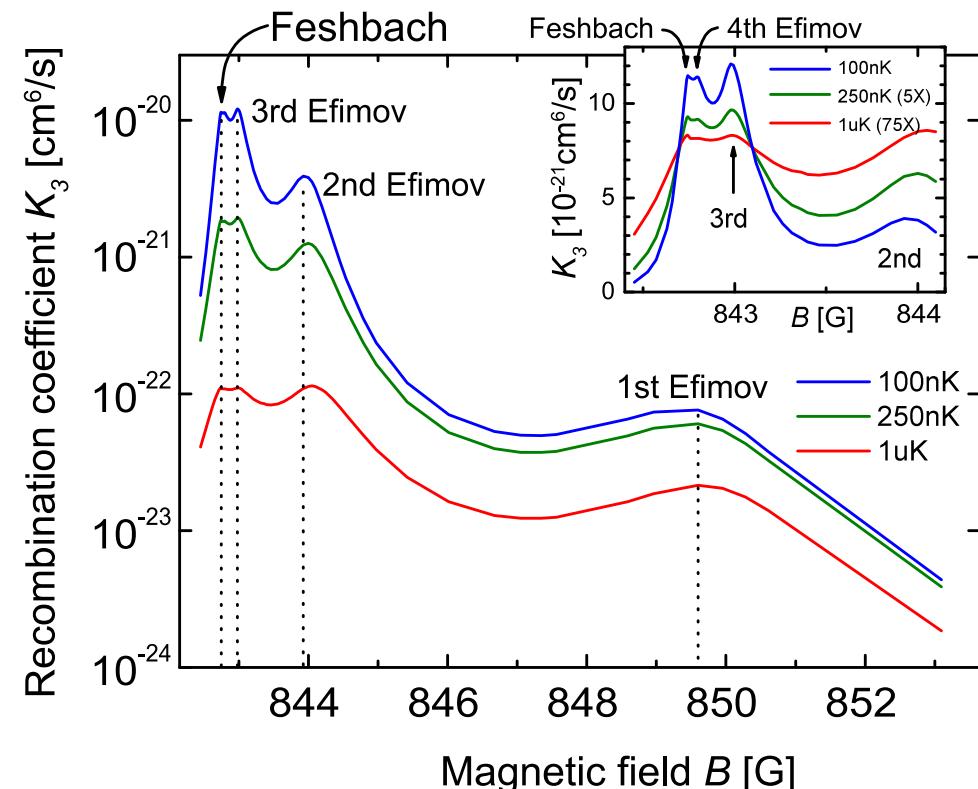
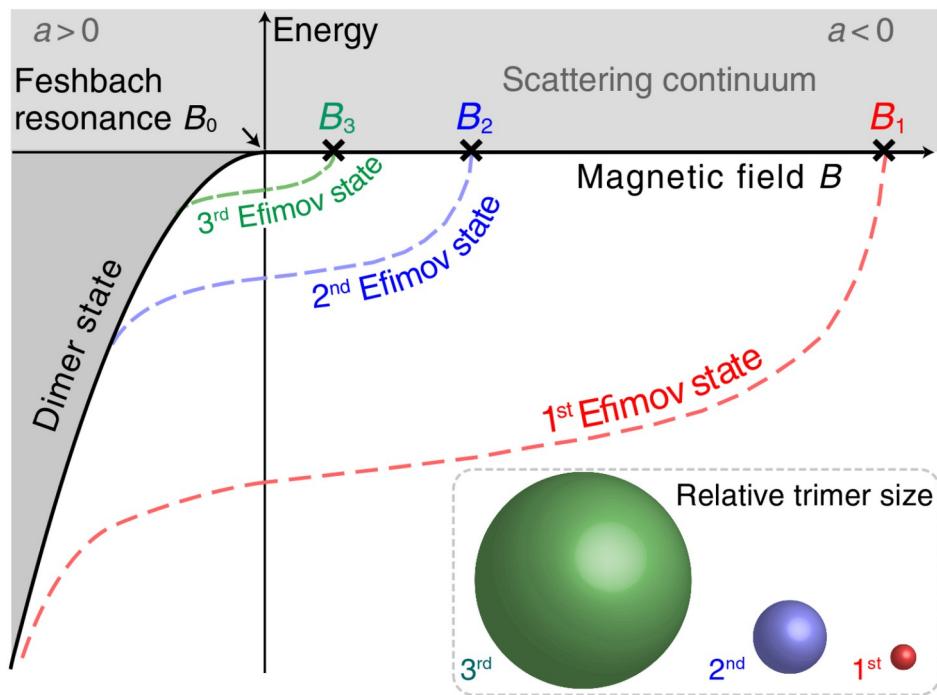
# A closer look at a broad $^{167}\text{Er}$ - $^6\text{Li}$ Feshbach resonance



- Width  $> 2 \text{ G} \rightarrow$  good candidate for precise interspecies interaction control
- Losses for Er about twice as strong as for Li  $\rightarrow$  suggests Er-Er-Li interaction
- Asymmetric lineshape  $\rightarrow$  Indicator of complex structure  $\rightarrow$  Efimov physics?

# Relationship to Efimov resonances and their experimental signature

S.-K. Tung et al., PRL 113, 240204 (2014)

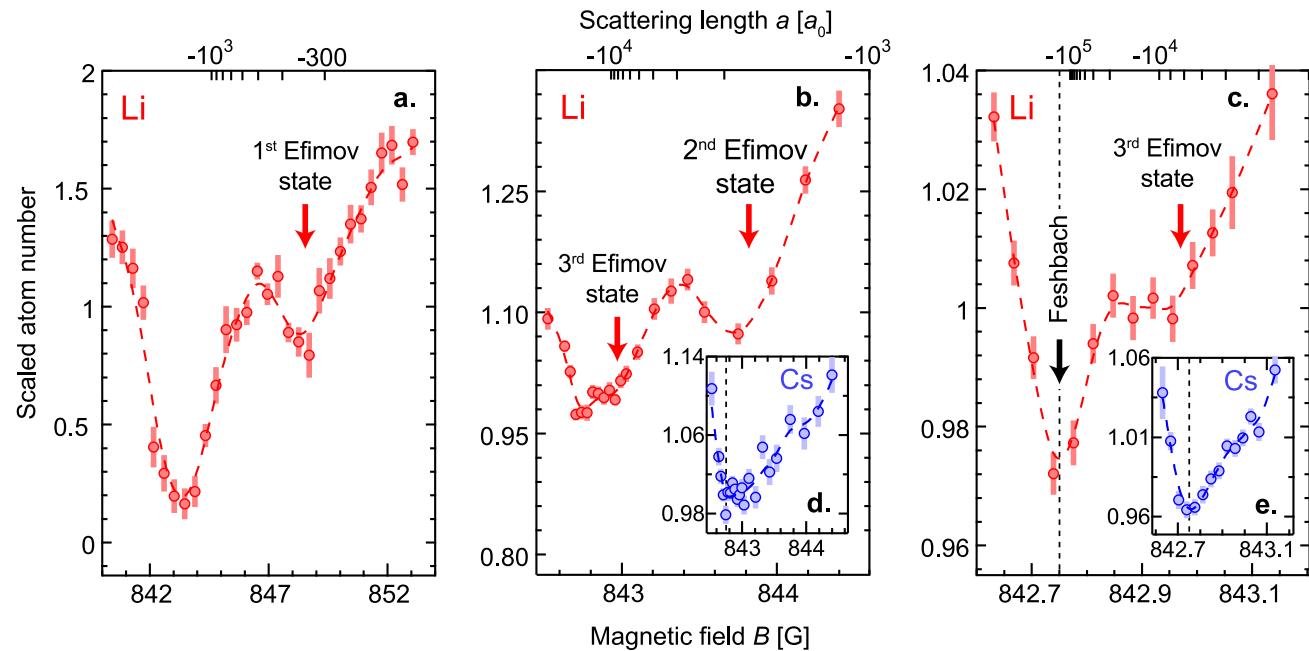


- Expect series of Efimov resonances on “attractive side” ( $a < 0$ ) of Feshbach resonance
- Discrete scaling symmetry in trimer size, binding energy and scattering length
- Enhanced recombination coefficient  $K_3$  leads to increased atom loss from the trap

# Comparision to previously observed Efimov resonances

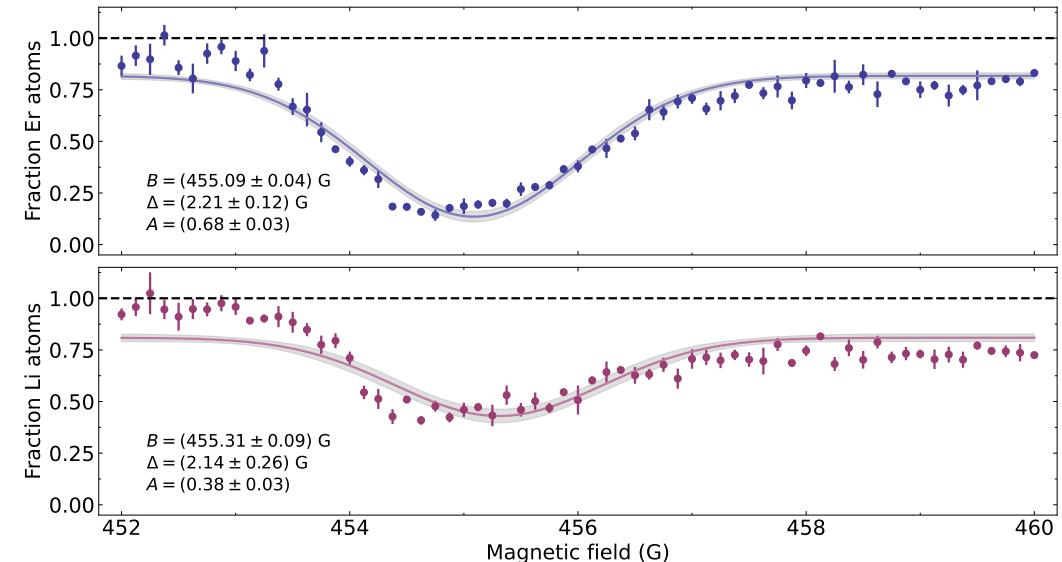
Cheng Chin's group work:  $^{133}\text{Cs}$ - $^{133}\text{Cs}$ - $^6\text{Li}$

S.-K. Tung *et al.*, Phys. Rev. Lett. 113, 240402 (2014)



- Asymmetric lineshape of resonant losses
- Three Efimov resonances observed
- Geometric series 1,  $\lambda$ ,  $\lambda^2$  with  $\lambda_{\text{expt}} = 4.9(4)$

Our work:  $^{167}\text{Er}$ - $^{167}\text{Er}$ - $^6\text{Li}$

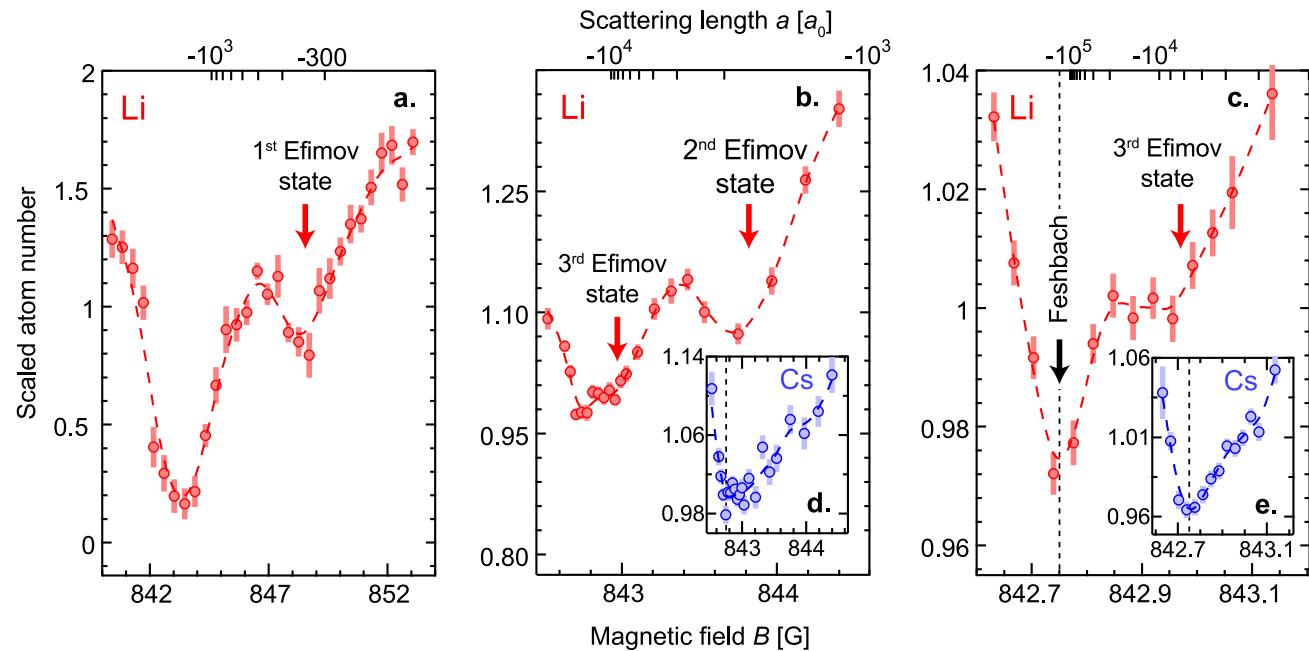


- Asymmetric lineshape observed
- Some “fine-structure” visible
- Additional data for analysis needed

# Comparision to previously observed Efimov resonances

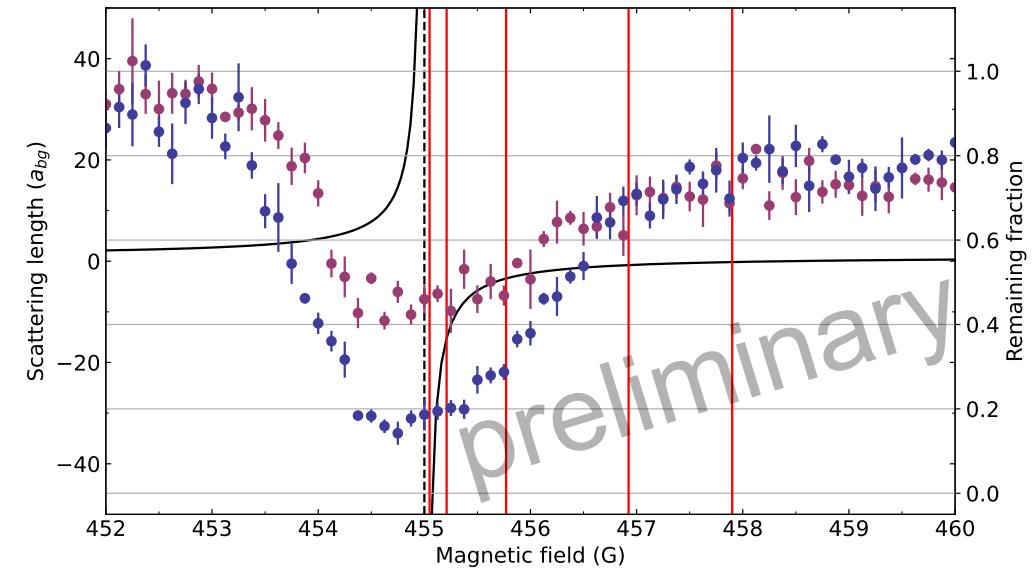
Cheng Chin's group work:  $^{133}\text{Cs}$ - $^{133}\text{Cs}$ - $^6\text{Li}$

S.-K. Tung *et al.*, Phys. Rev. Lett. 113, 240402 (2014)



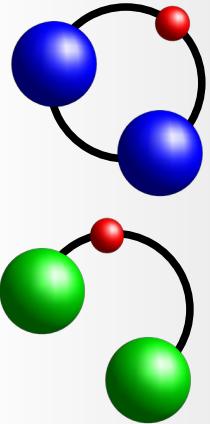
- Asymmetric lineshape of resonant losses
- Three Efimov resonances observed
- Geometric series 1,  $\lambda$ ,  $\lambda^2$  with  $\lambda_{\text{expt}} = 4.9(4)$

Our work:  $^{167}\text{Er}$ - $^{167}\text{Er}$ - $^6\text{Li}$

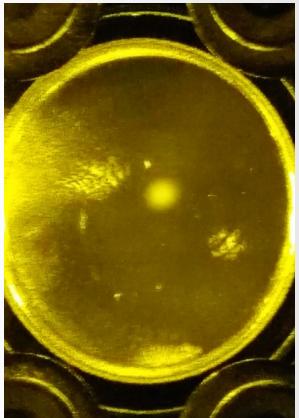


- Asymmetric lineshape observed
- Some “fine-structure” visible
- Additional data for analysis needed

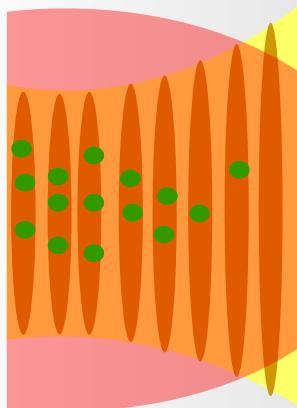
# Summary



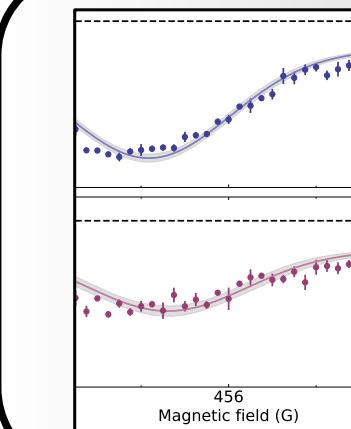
Large mass-imbalance ultracold atom systems as gateway to new **Efimov** trimer states



First experimental realization of cold **Er-Li** large mass-imbalance and **Er-Yb** mixtures



Bose-Fermi mixtures in mixed-dimensions for **non-s-wave superfluid** states of matter



Identified  **$^{176}\text{Er}-^6\text{Li}$**  **Feshbach resonance** candidates for future experimental work