Prospects and experiments with ErLi large mass-imbalance mixtures

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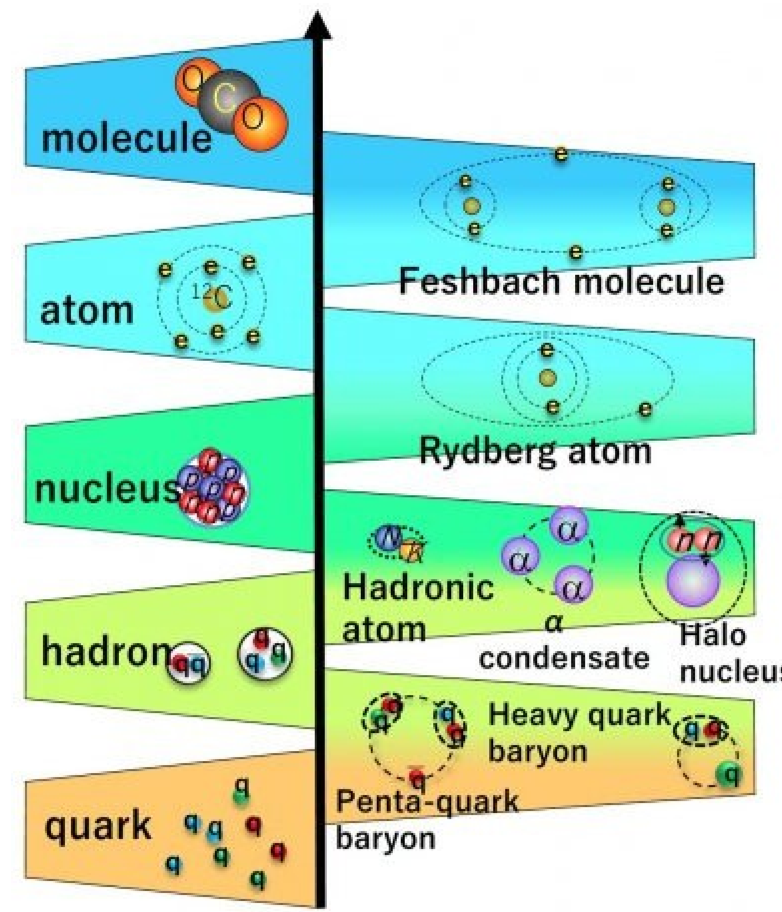
第 8 回クラスター階層領域研究会 , Osaka – 2023/02/09-11

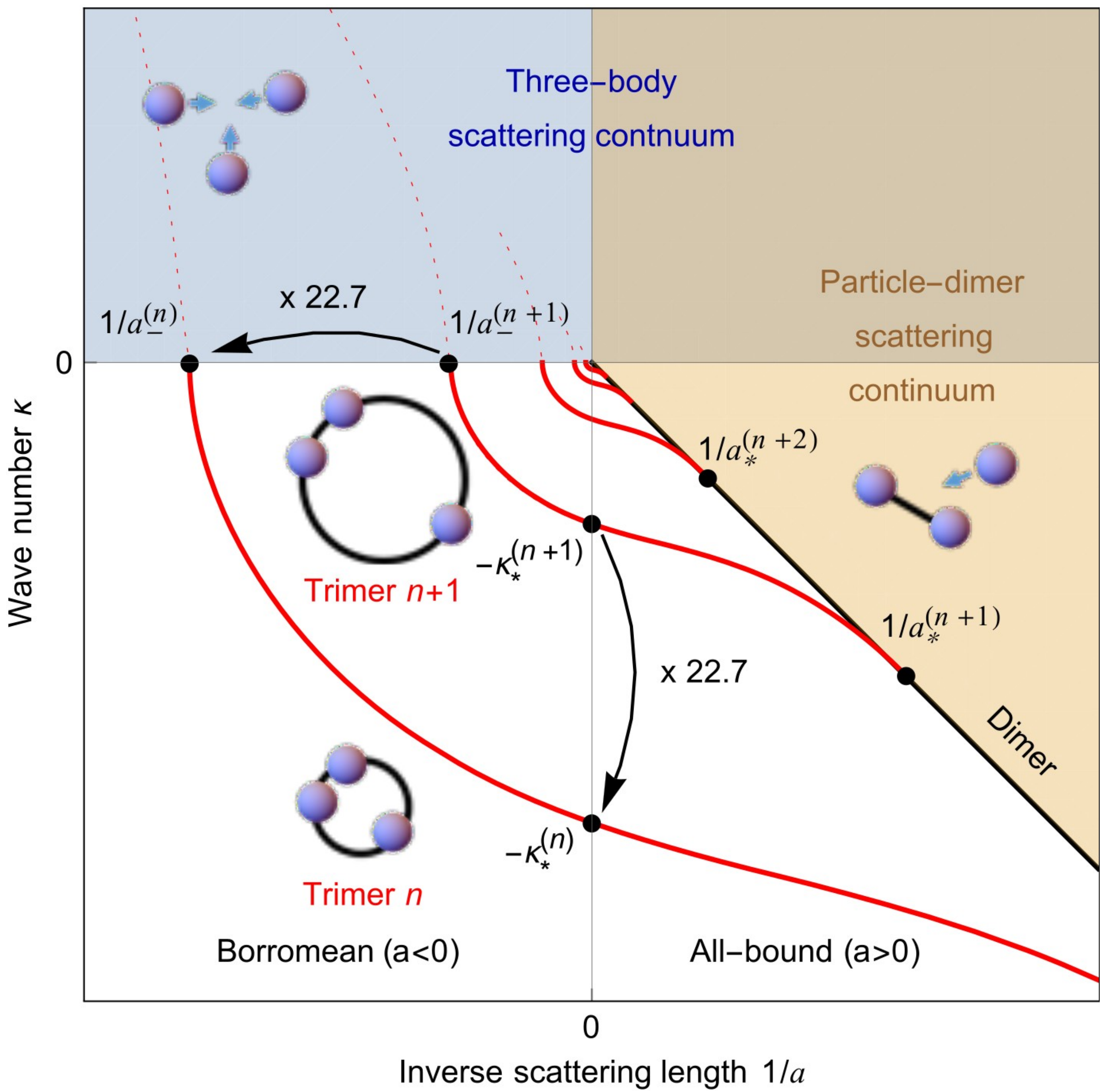
Outline

- 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

Clusters & Hierarchies



Efimov cluster states – scaling

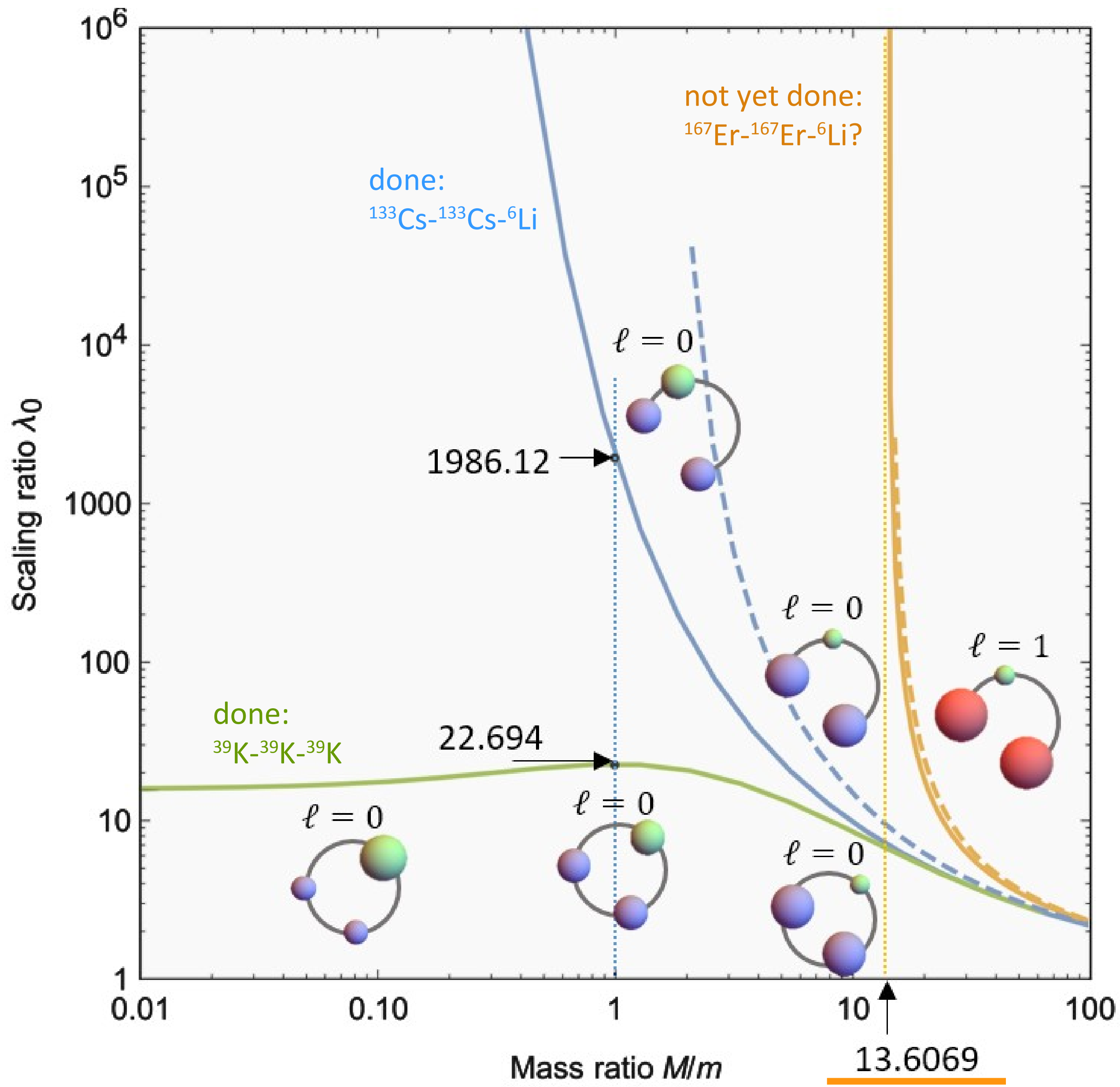


- Infinite number of three-body bound states
- Scaling factor $\lambda_0 \approx 22.694$
- Energy scaling $E/(\lambda_0)^{2n}$
- Deviation of ground-state and first excited-state trimer from universal spectrum

► 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



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

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)

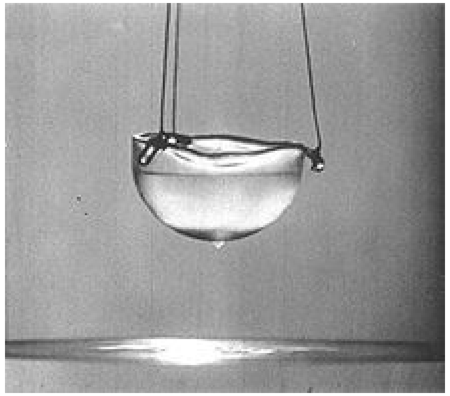
Two identical **fermions** resonant with one particle ($l = 1$)

► Large variety of particle combinations and scaling ratios possible

p-wave superfluidity in mixed dimensional systems

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

► Superfluidity caused by p-wave Cooper pairs

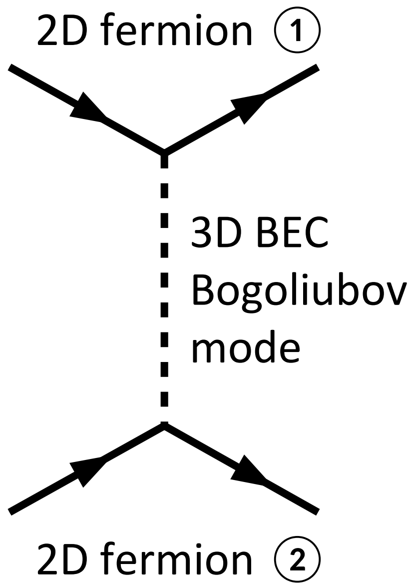


wikipedia.org

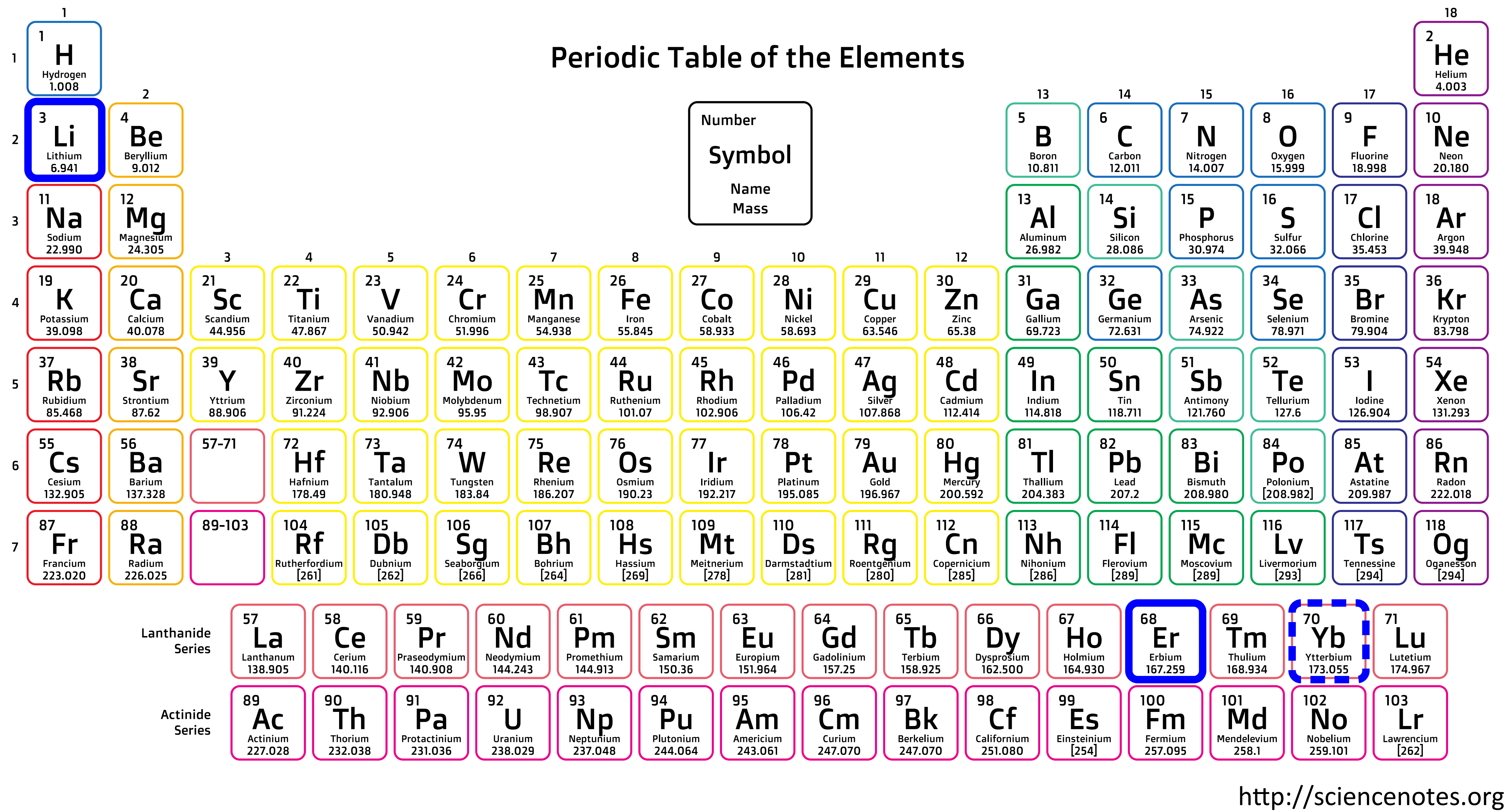
It is hard to find a well controllable system to study p-wave superfluidity.

P-wave superfluidity with ultracold atoms in mixed dimensions

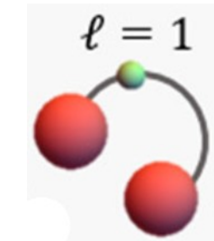
- 2009 – Nishida: 2D Fermi gas within 3D other species Fermi gas
- 2016 – Wu, Bruun: 2D Fermi gas embedded in 3D BEC
- 2017, 2018: Further refinements and detailed calculations for ^{7}Li-^{173}Yb
- Mechanism: Increased critical temperature due to Fermion pairing via Bogoliubov phonon mediated interactions



Elements for a large mass-imbalance ultracold mixture

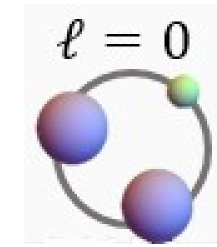


Properties of a large mass-imbalance Er-Li mixture

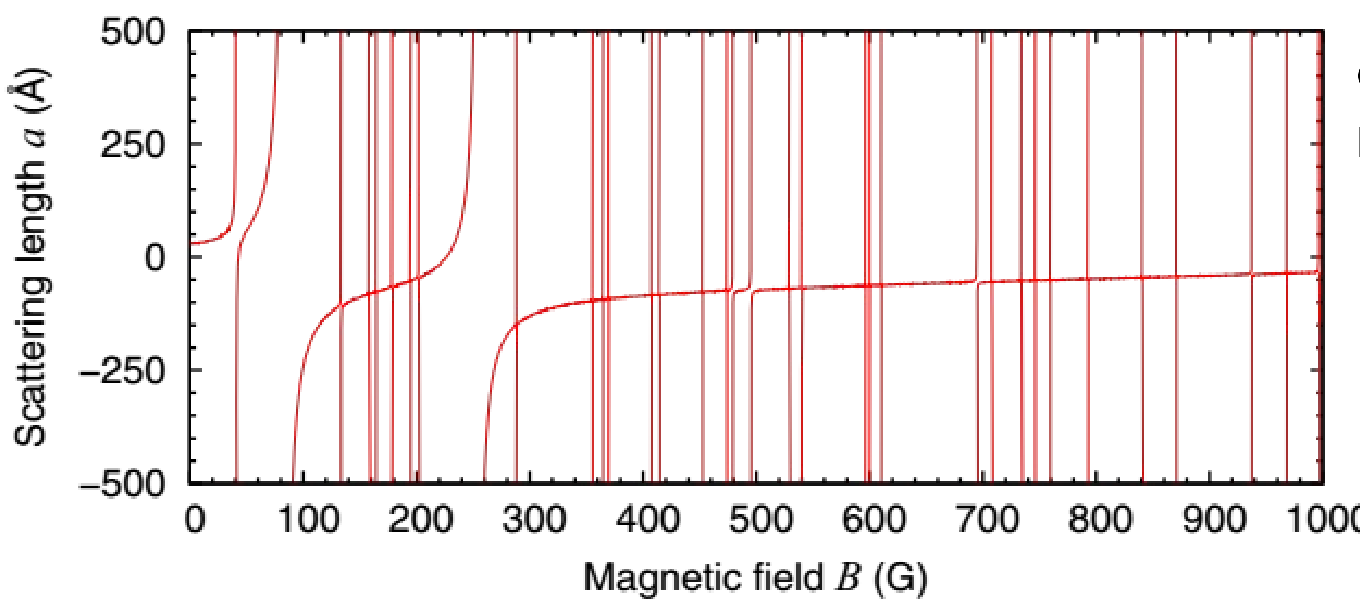


Mass ratio ^{167}Er (fermion) : ^{6}Li (boson) $= 27.8 \gg 13.6$

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



Expect good control of Er-Li interspecies scattering lengths

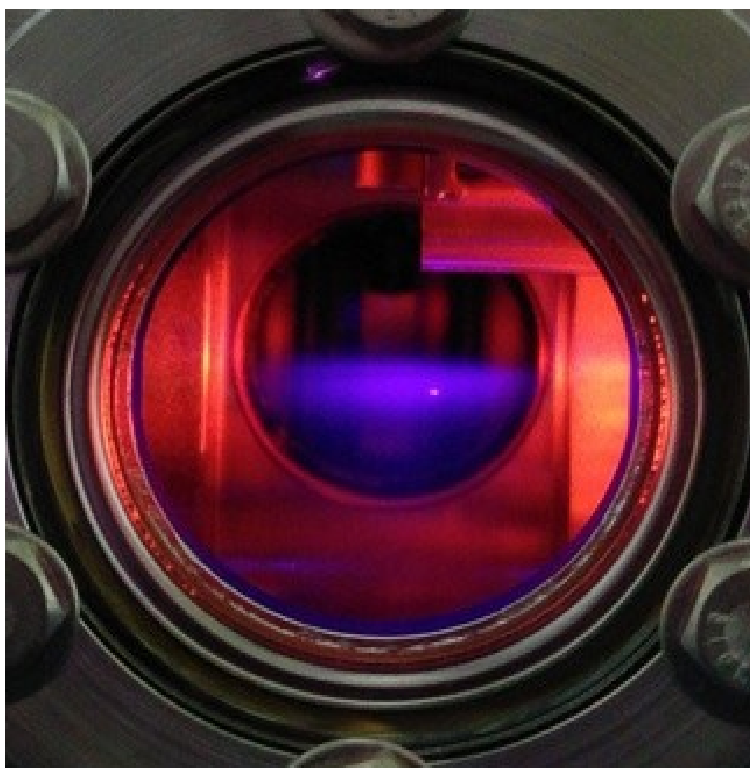


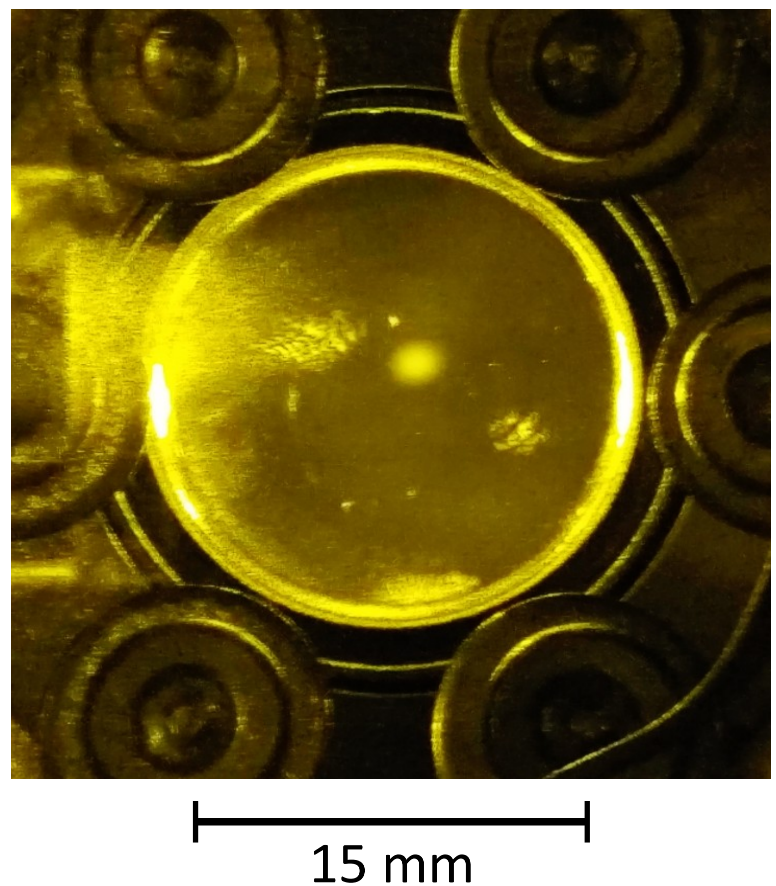
González-Martínez and Żuchowski
PRA 92, 022708 (2015)

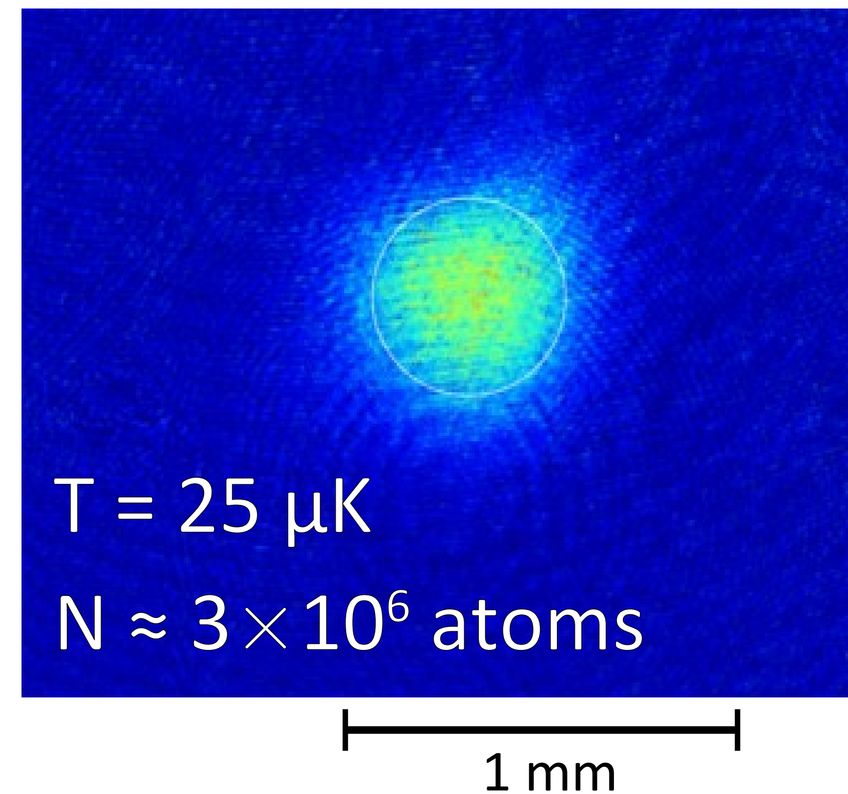
^{6}Li-^{166}Er
(Fermi-Bose)

The triple-species mixture machine

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



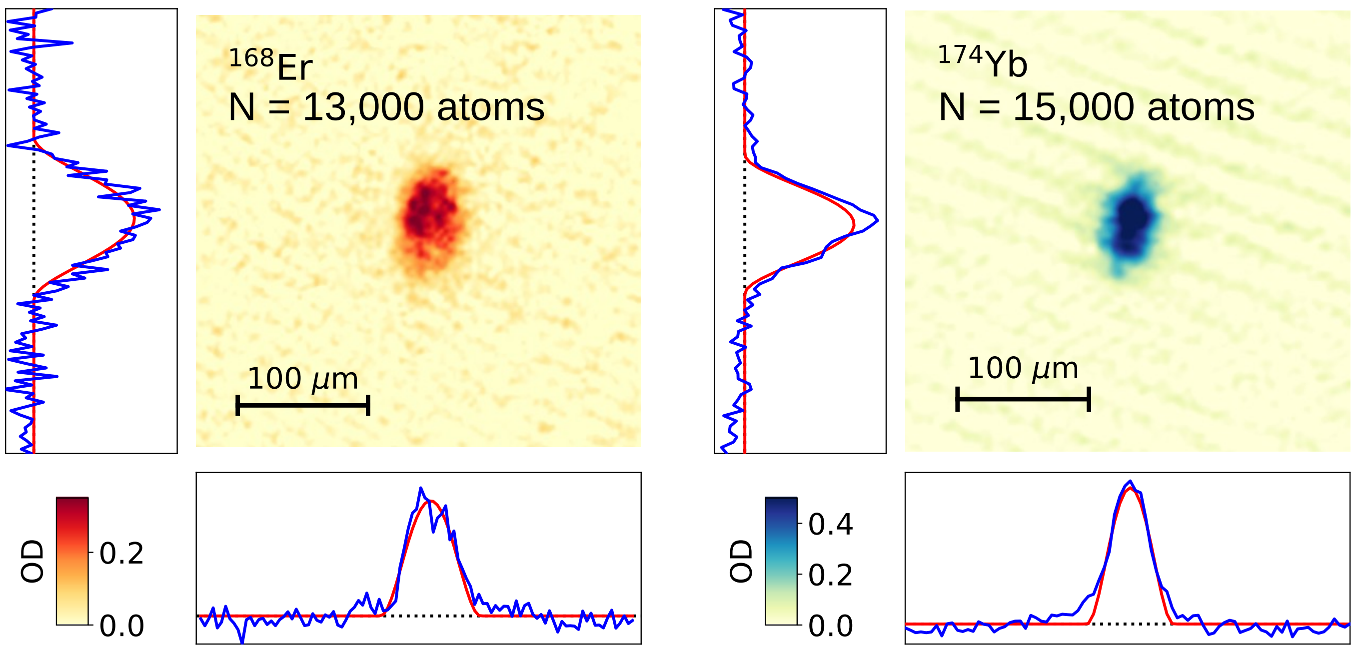


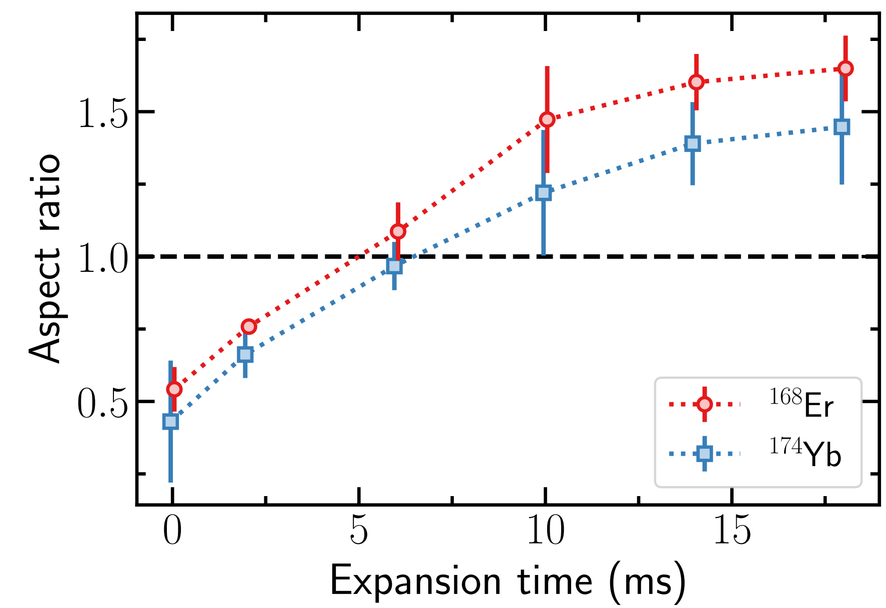


Realization of double quantum degenerate Er-Yb mixture

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

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



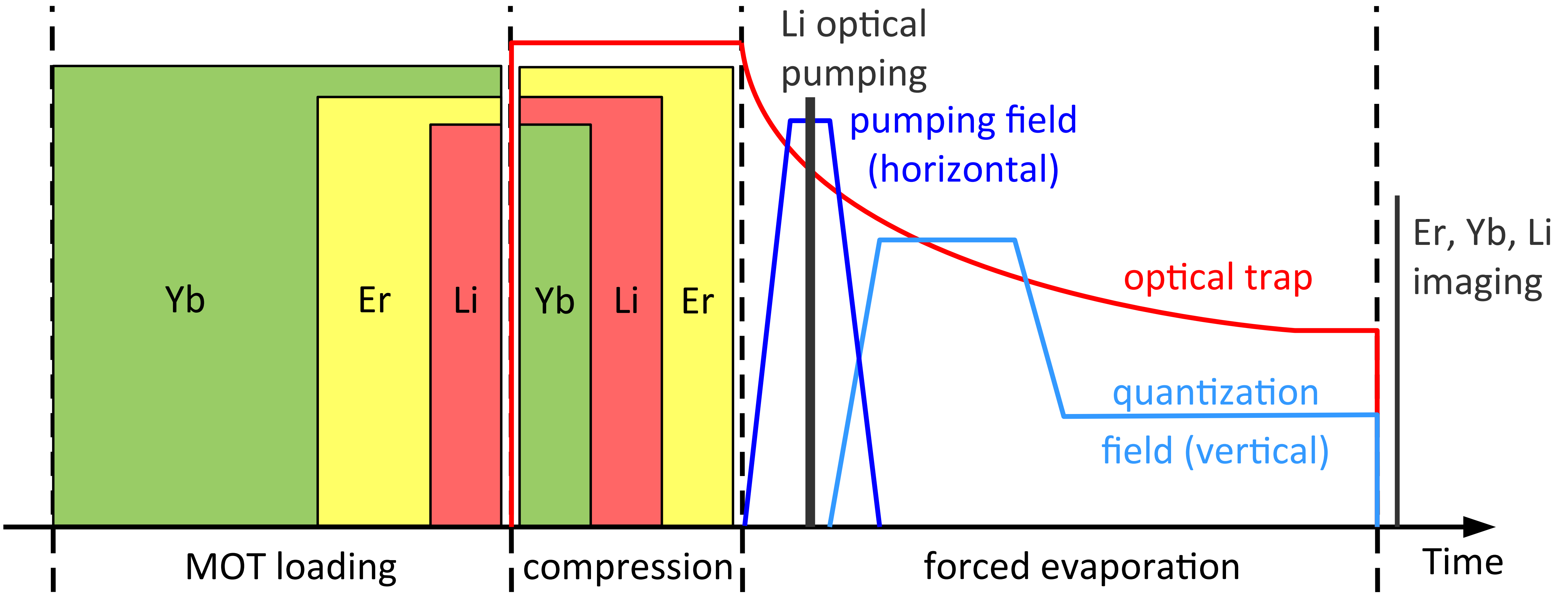


Possible appliations

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

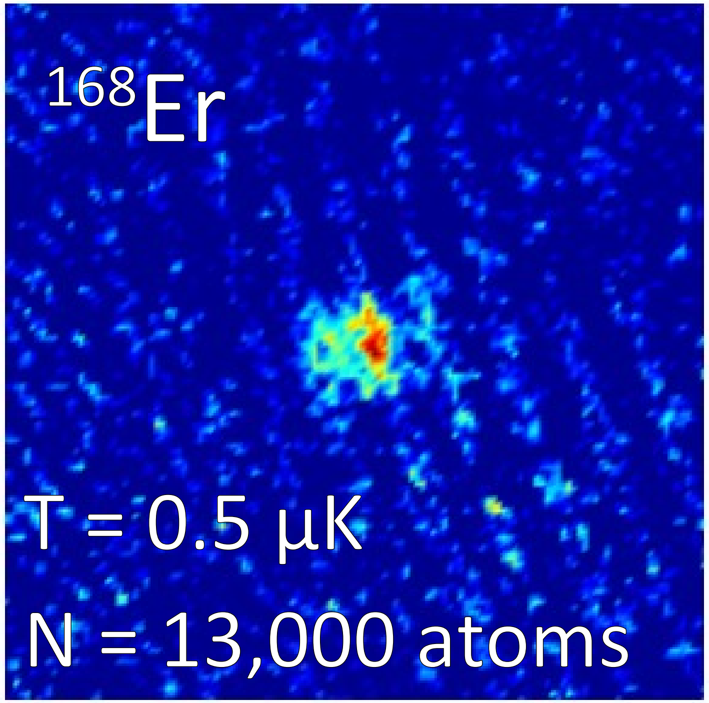
M. Kosicki *et al.*, NJP 22, 023024 (2020)

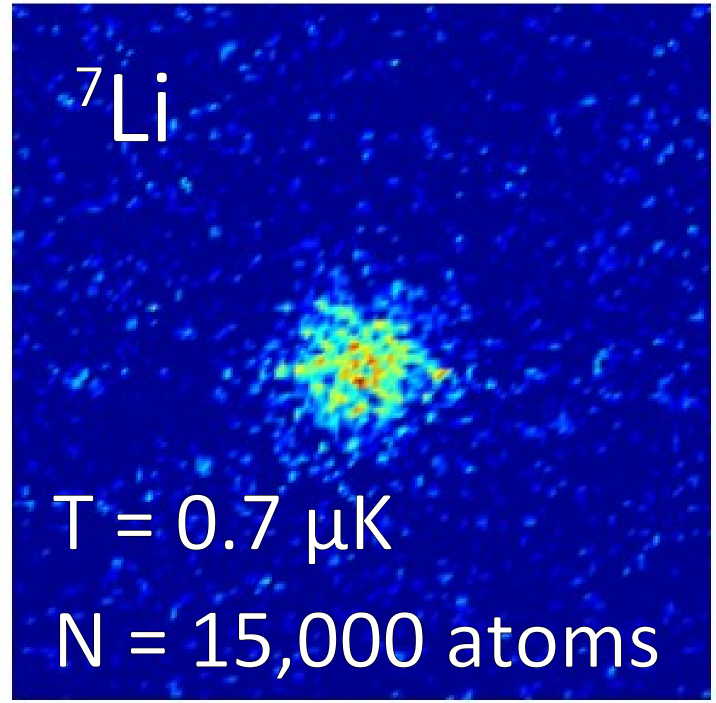
Creation and probing of an ultracold Er-Yb-Li mixture

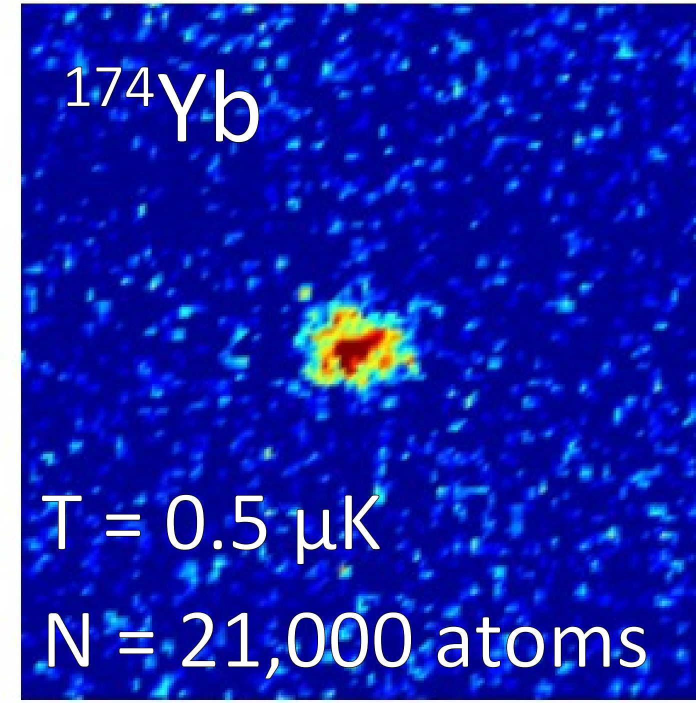


- Optimization of sequence parameters heavily supported by machine learning
- Magnetic field control to maintain polarization of Er in lowest-energy magnetic substate
- Control of Li spin state by optical pumping to a stretched-state configuration

Realization of ultracold triple-species mixtures

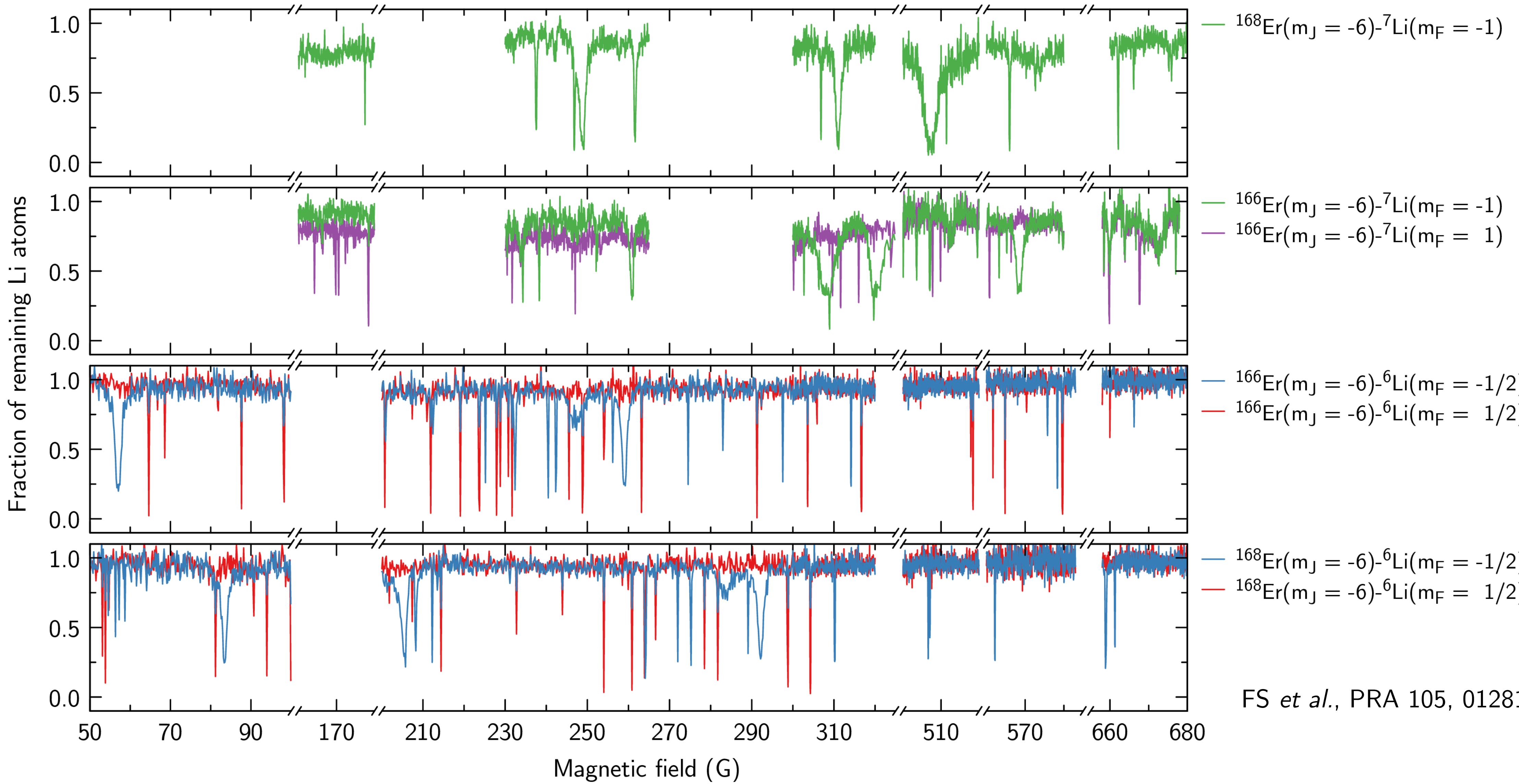






- Efficient cooling of Er and Li by sympathetic cooling with ^{174}Yb
- Also realized: triple-species mixture with fermionic ^{167}Er and/or ^{6}Li
- Removal of “unwanted” species from trap after evaporation by blast light possible
- First task: Control of Er-Li interspecies interaction (via magnetic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

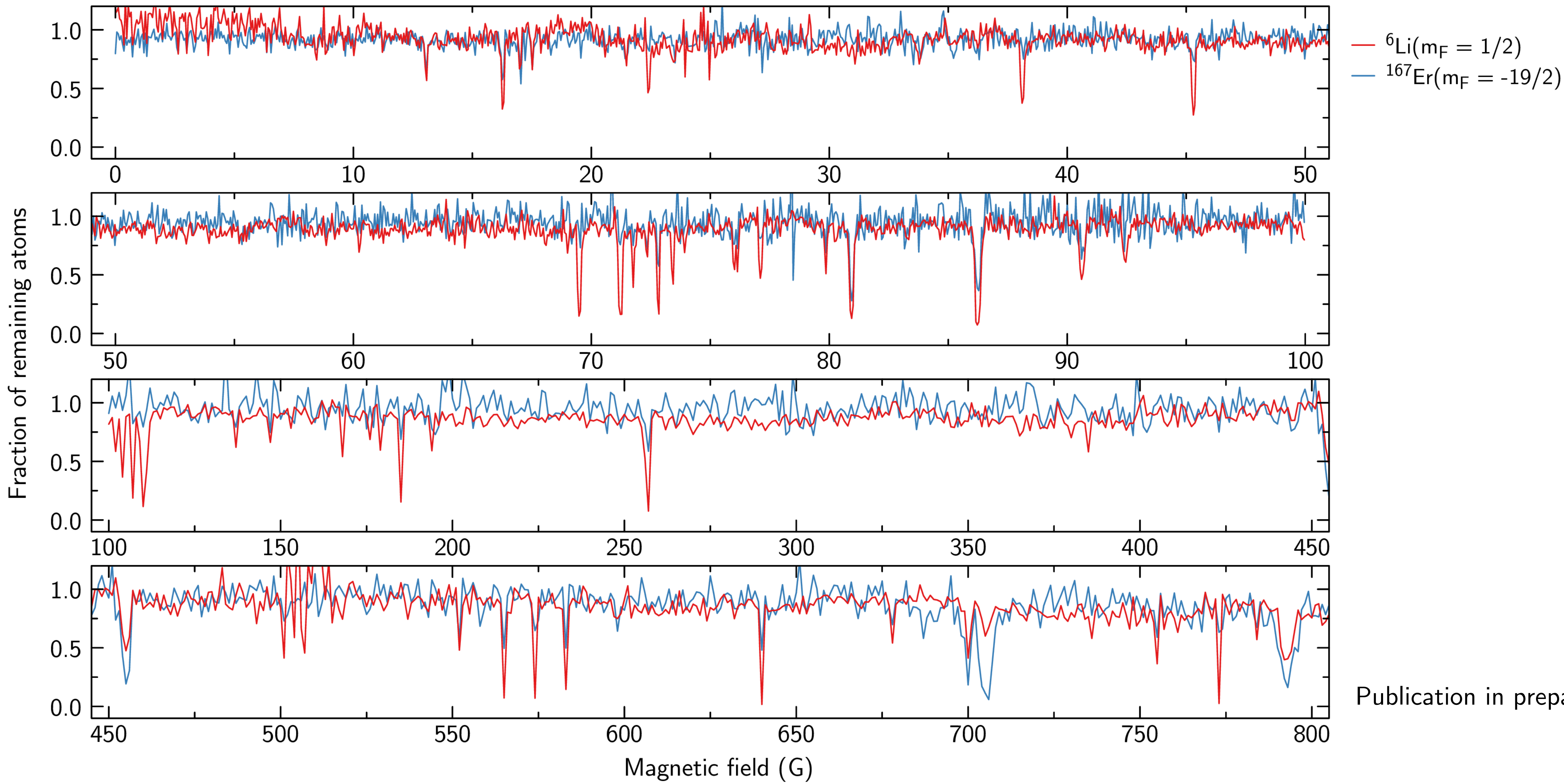
Previously: Feshbach resonances in Er-Li mixture with bosonic Er



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

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

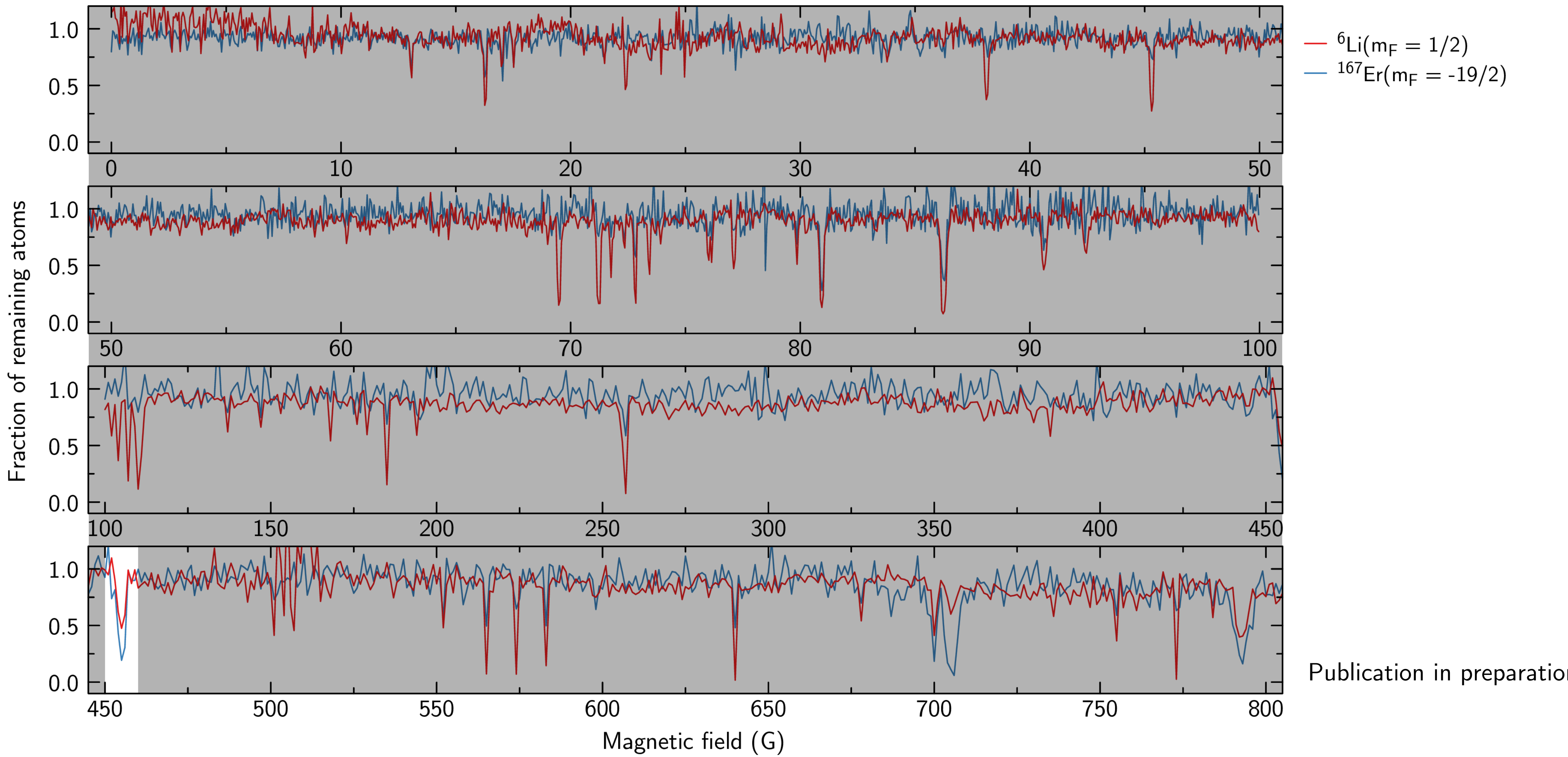
Recently: Feshbach resonances in ^{167}Er-^{6}Li Fermi-Fermi mixture



Publication in preparation

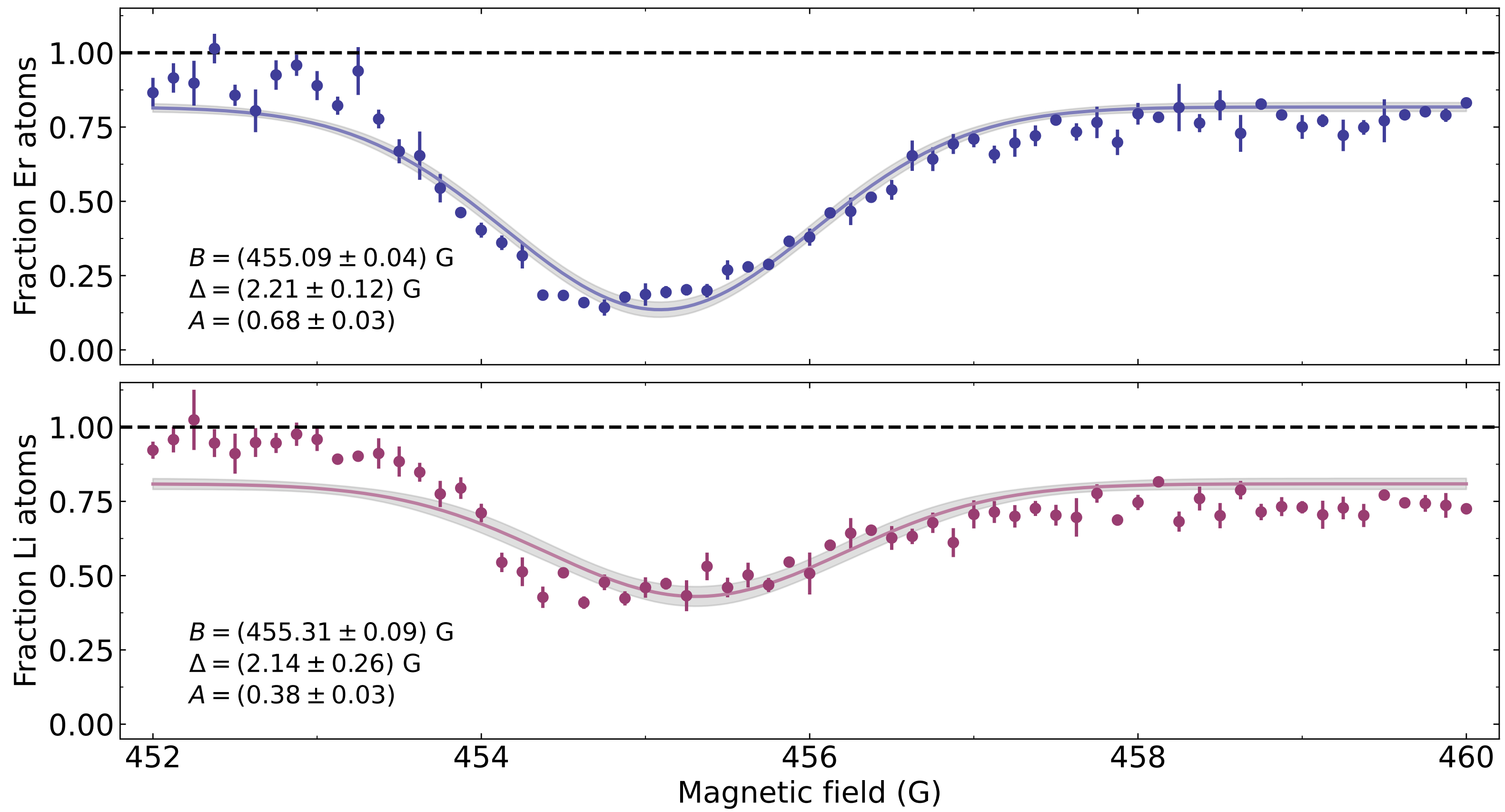
► Rich spectrum of Er-Li Feshbach resonances, with some rather broad ones (> 1 G)

Recently: Feshbach resonances in ^{167}Er-^{6}Li Fermi-Fermi mixture



► Rich spectrum of Er-Li Feshbach resonances, with some rather broad ones (> 1 G)

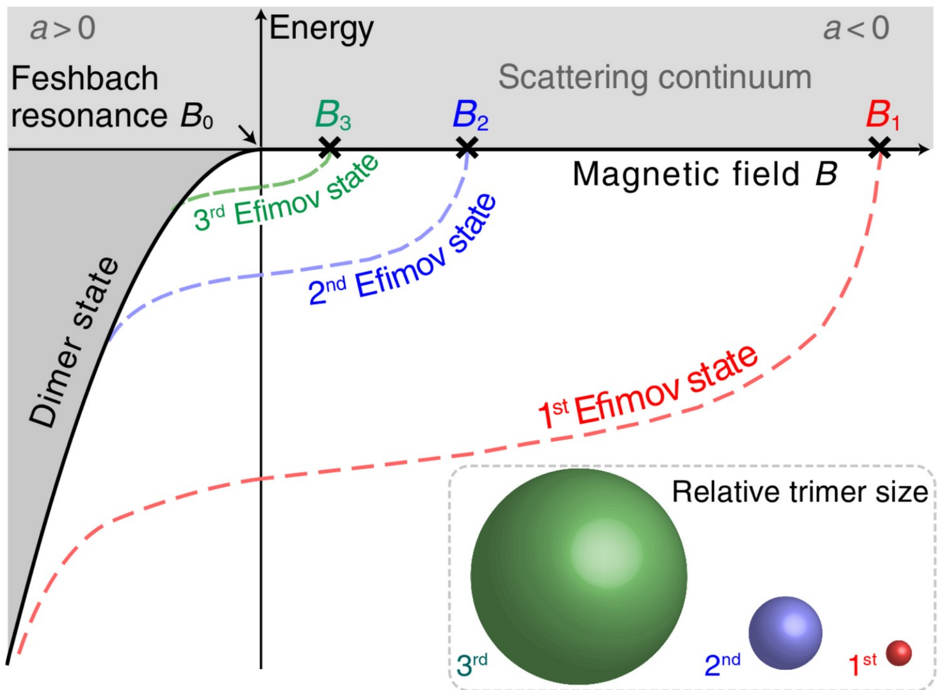
A closer look at a broad ^{167}Er-^{6}Li Feshbach resonance

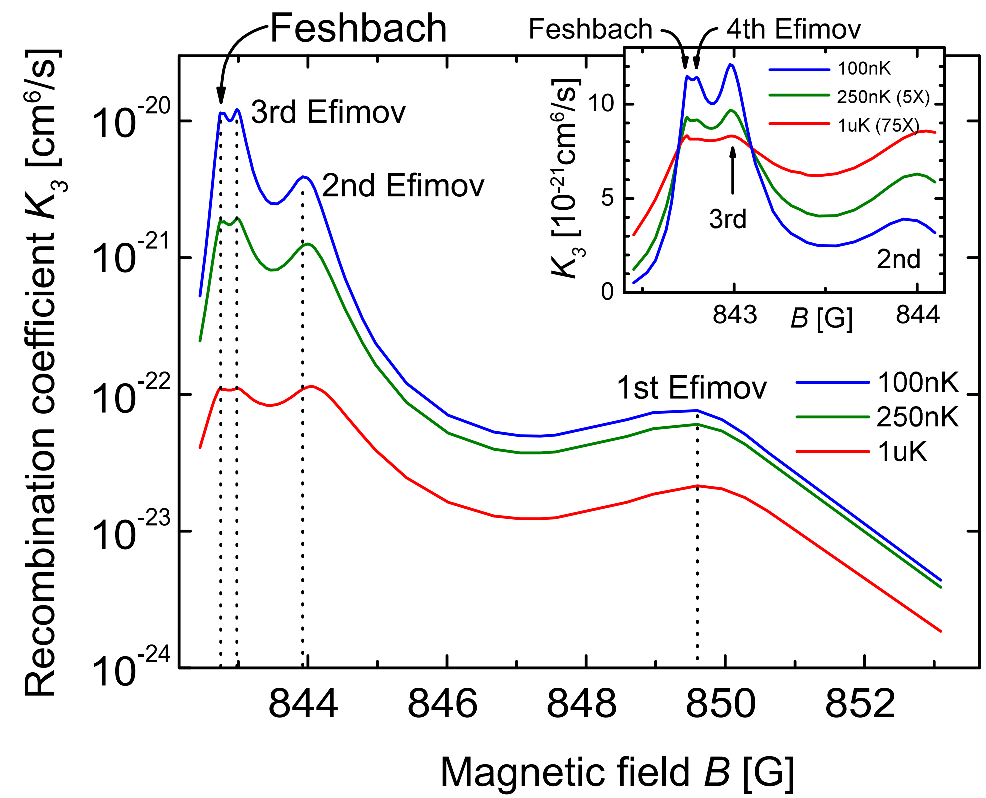


- Width > 2 G $\rightarrow$ good candidate for precise interspecies interaction control
- Losses for Er about twice as strong as for Li $\rightarrow$ suggests Er-Er-Li interaction
- Asymmetric lineshape $\rightarrow$ Indicator of complex structure $\rightarrow$ Efimov physics?

Relationship to Efimov resonances and their experimental signature

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



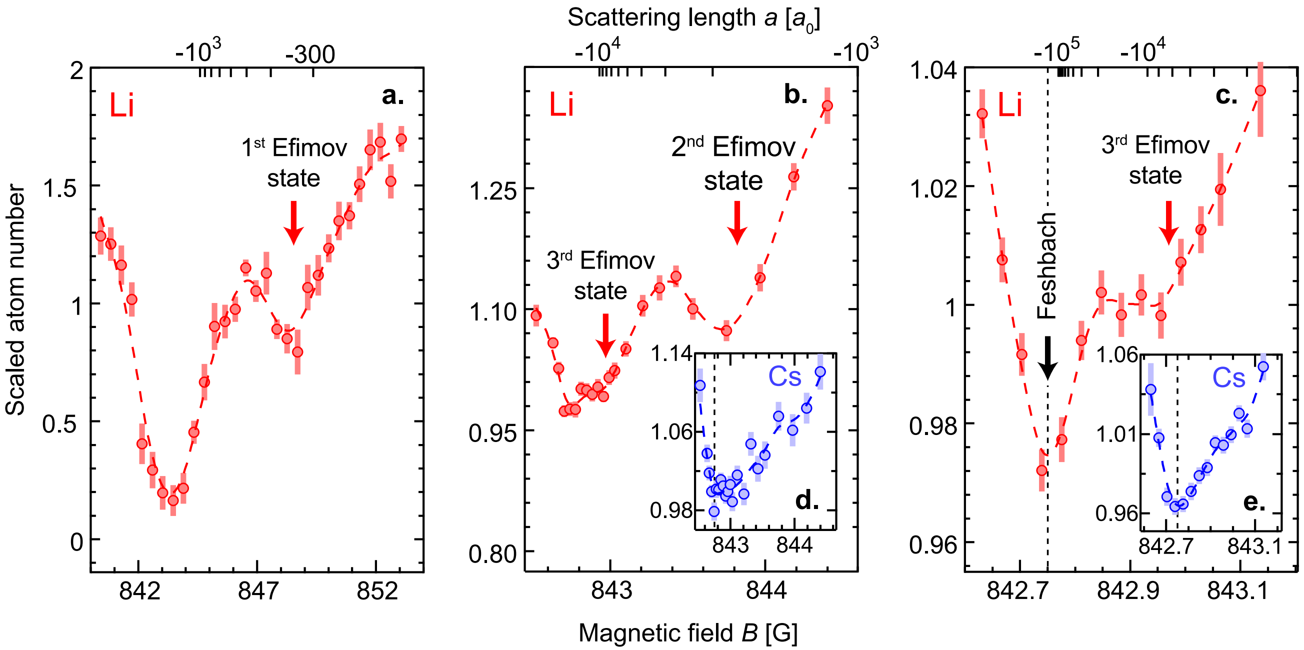


- Expect series of Efimov resonances on "attractive side" ($a < 0$) of Feshbach resonance
- Discrete scaling symmetry in trimer size, binding energy and scattering length
- Enhanced recombination coefficient K_3 leads to increased atom loss from the trap

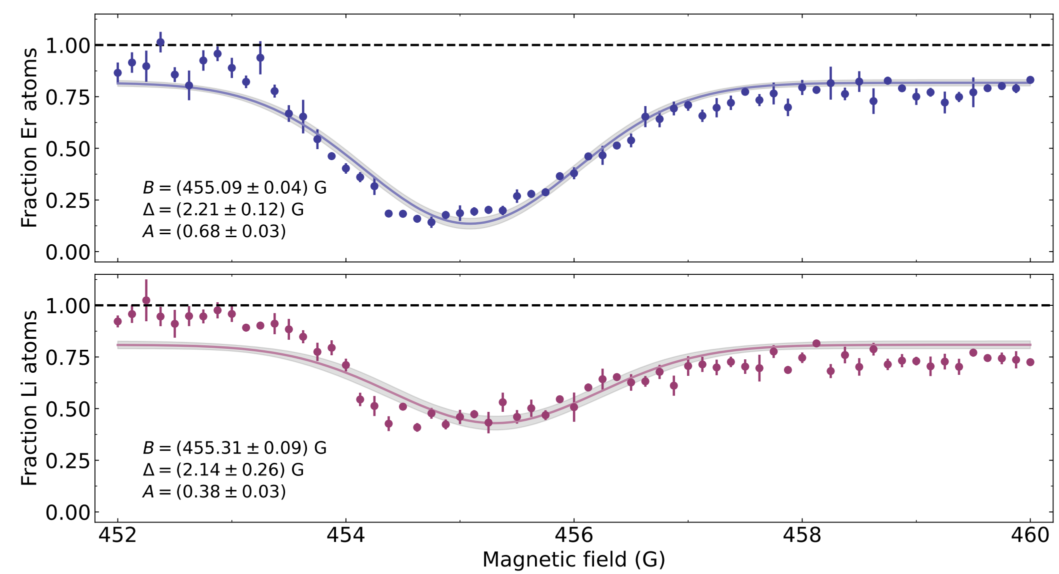
Comparsion to previously observed Efimov resonances

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

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



Our work: ^{167}Er-^{167}Er-^{6}Li



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

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- Some "fine-structure" visible
- Additional data for analysis needed

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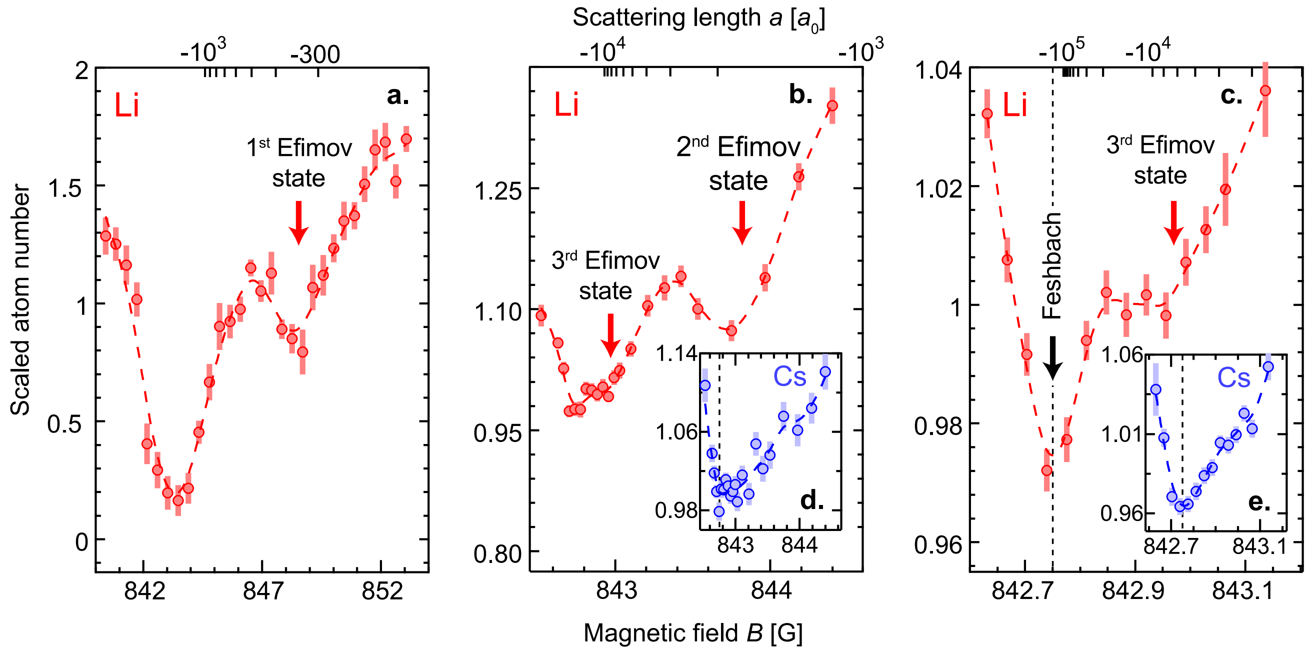

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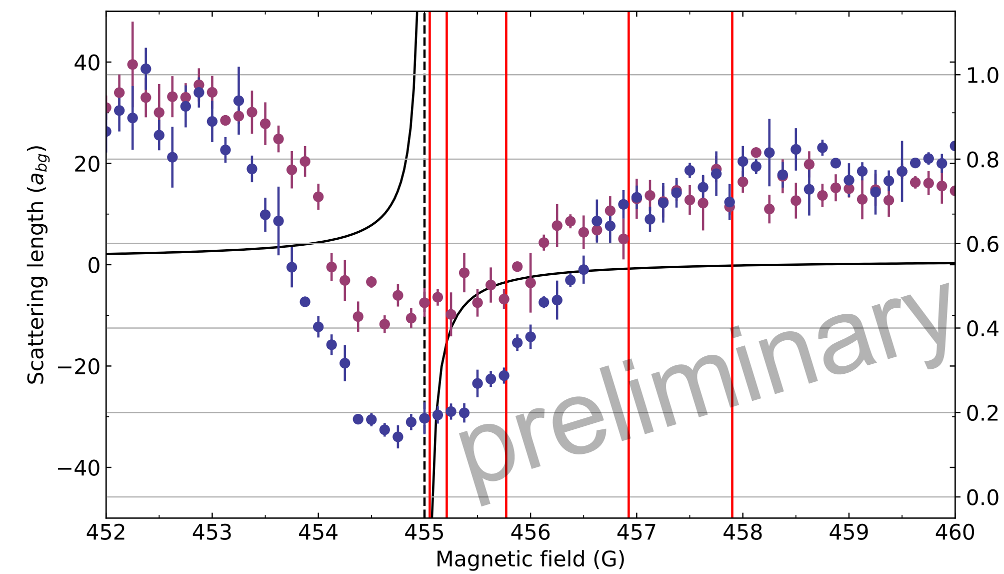

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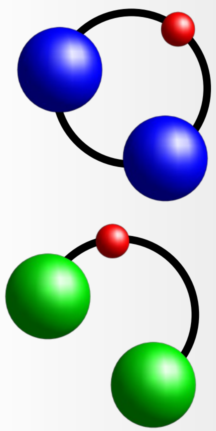
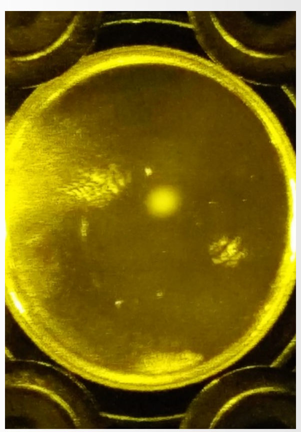
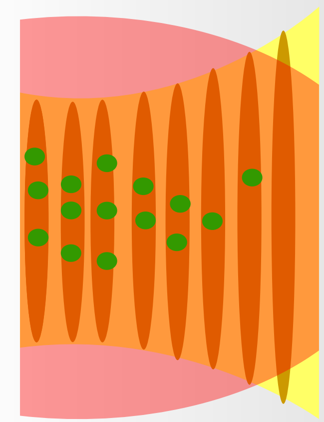
Summary



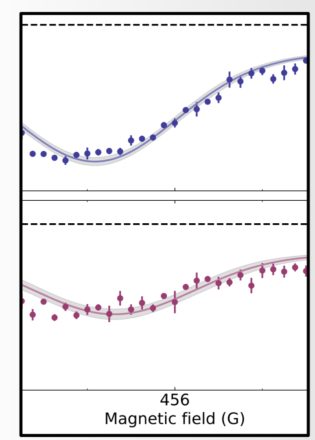
Large mass-imbalance ultracold atom systems as gateway to new Efimov trimer states



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}Er-^{6}Li Feshbach resonance candidates for future experimental work