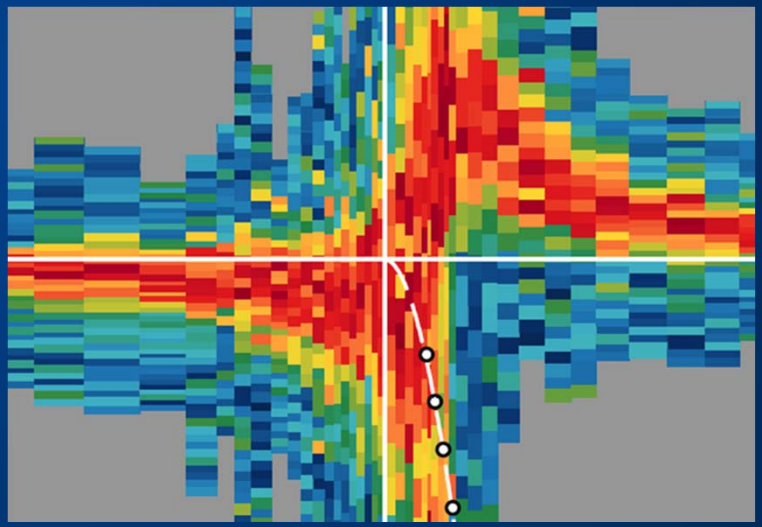
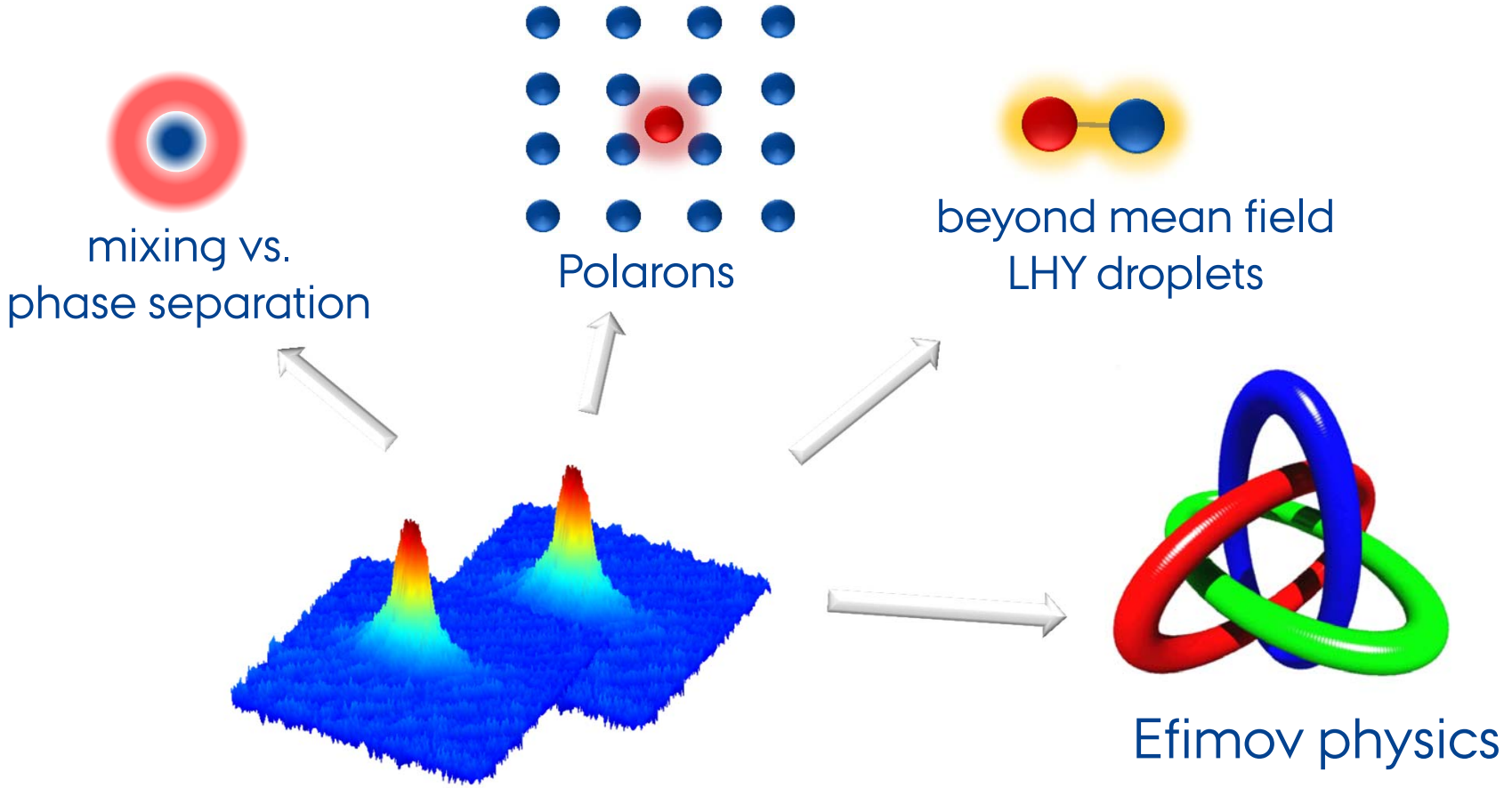
Few-Body physics with ultracold K and Rb: Efimov physics and the Bose polaron



AARHUS
UNIVERSITY
DEPARTMENT OF PHYSICS AND ASTRONOMY

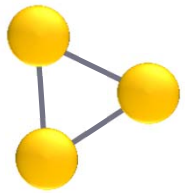
JAN ARLT

Dual species quantum gases with tunable interactions

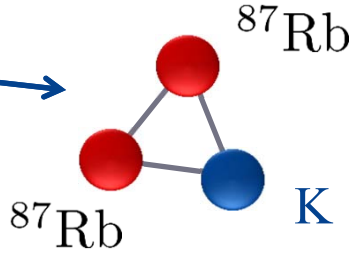


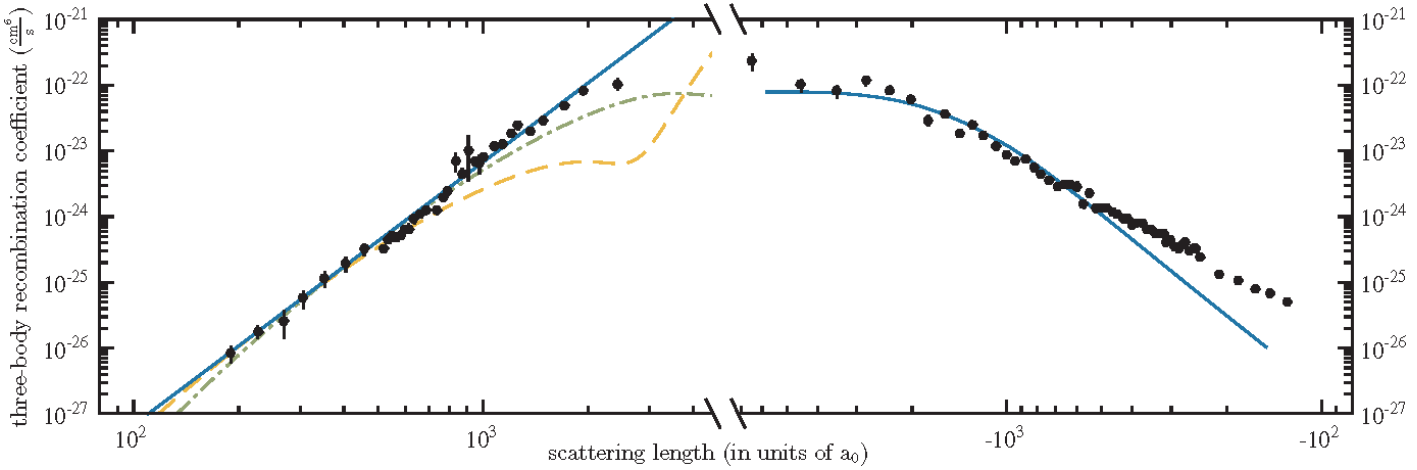
HETERONUCLEAR EFIMOV PHYSICS

Three identical bosons



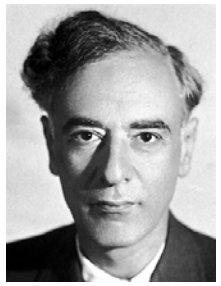
Three non-identical bosons





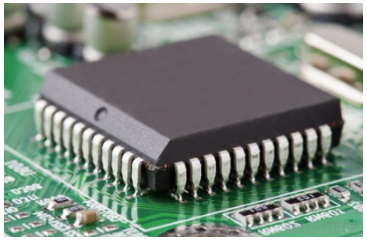
^{39}K + ^{87}Rb

Polaron physics



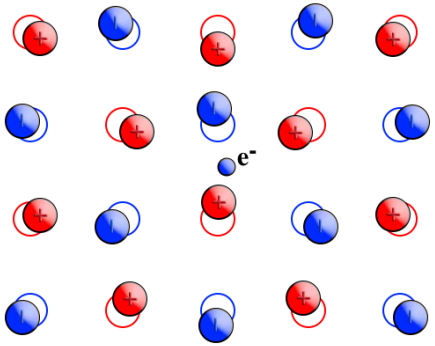
L. D. Landau

S. I. Pekar



Technologically important semiconductors

Superconductors



Electrons in solids

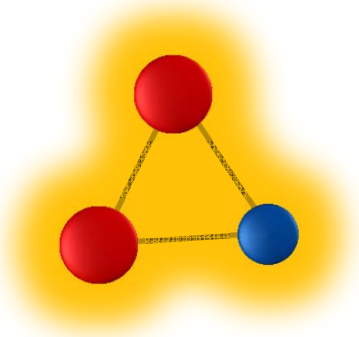
Electron

Coupling

Lattice phonons

Formation of quasiparticle: **Polaron**

OUTLINE



- Motivation
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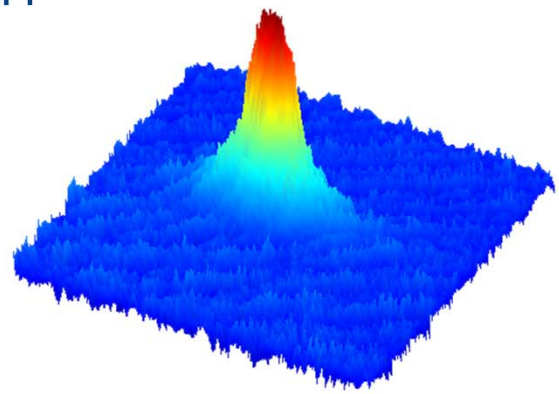
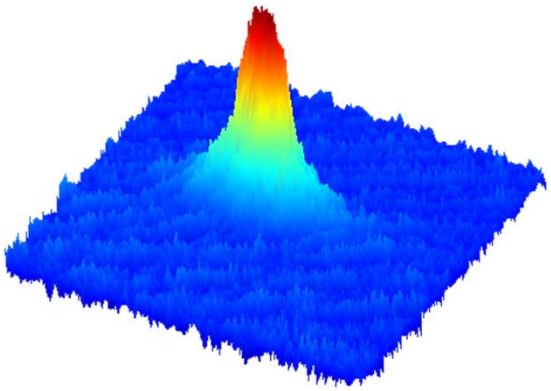
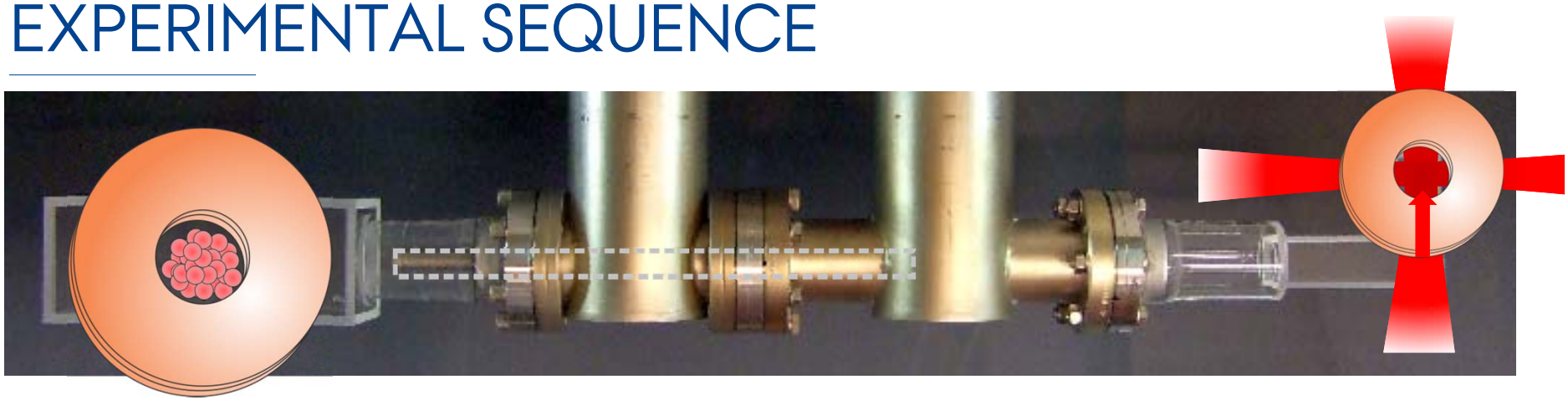
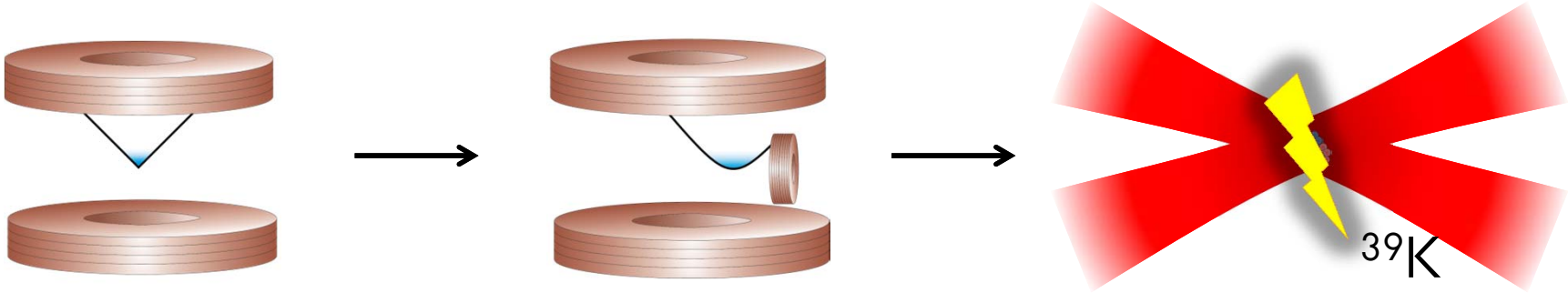




EXPERIMENTAL SEQUENCE



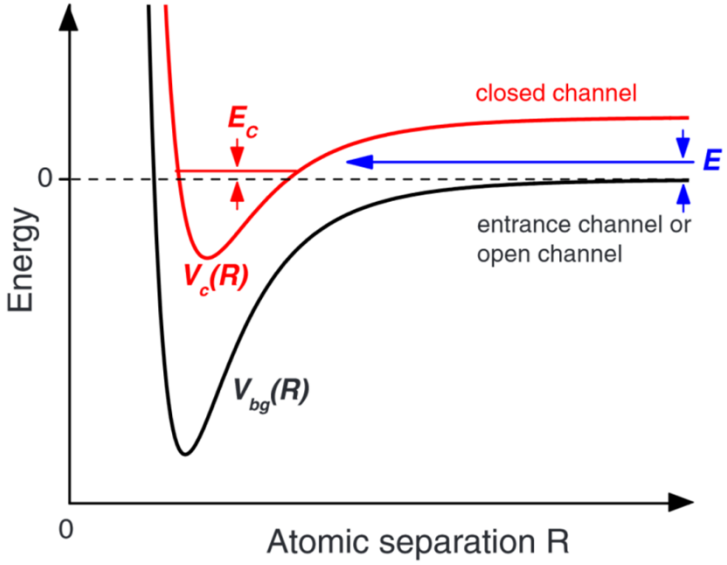
Selective cooling of Rb ⟶ Sympathetic cooling of K

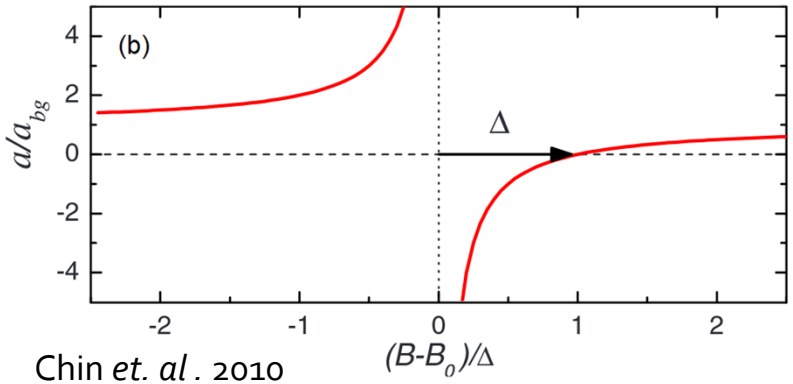


Quadropole trap → QUIC trap → Optical dipole trap

Wacker *et. al* . Phys. Rev. A **92,** 053602 (2015)

FESHBACH RESONANCES IN ULTRACOLD GASES





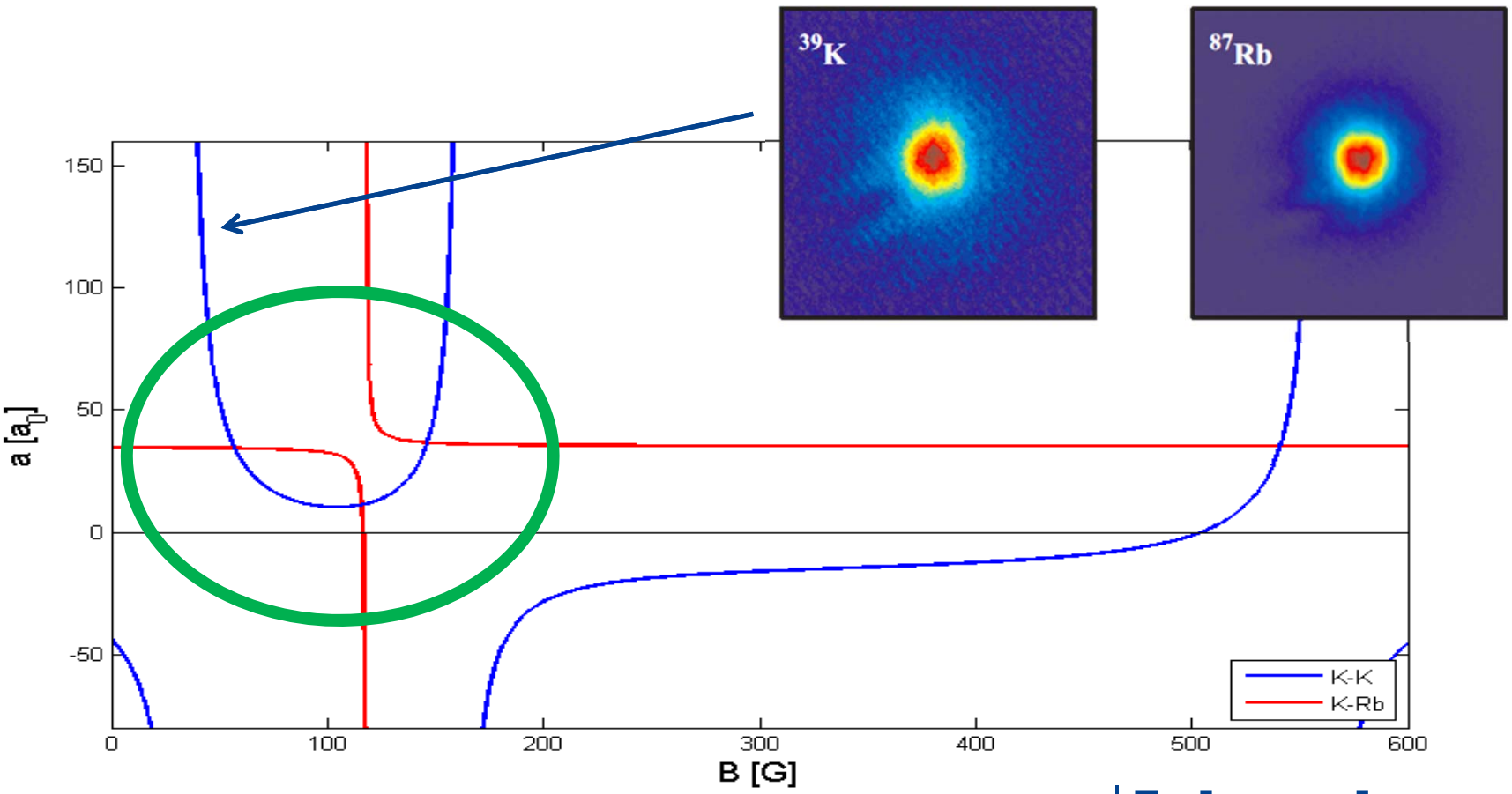
Chin *et. al* . 2010

$$a(B) = a_{\mathrm{bg}}\left(1 - \frac{\Delta}{B - B_0}\right)$$

Applications:

- BEC formation
- control mean field interaction
- associate molecules
- Efimov physics

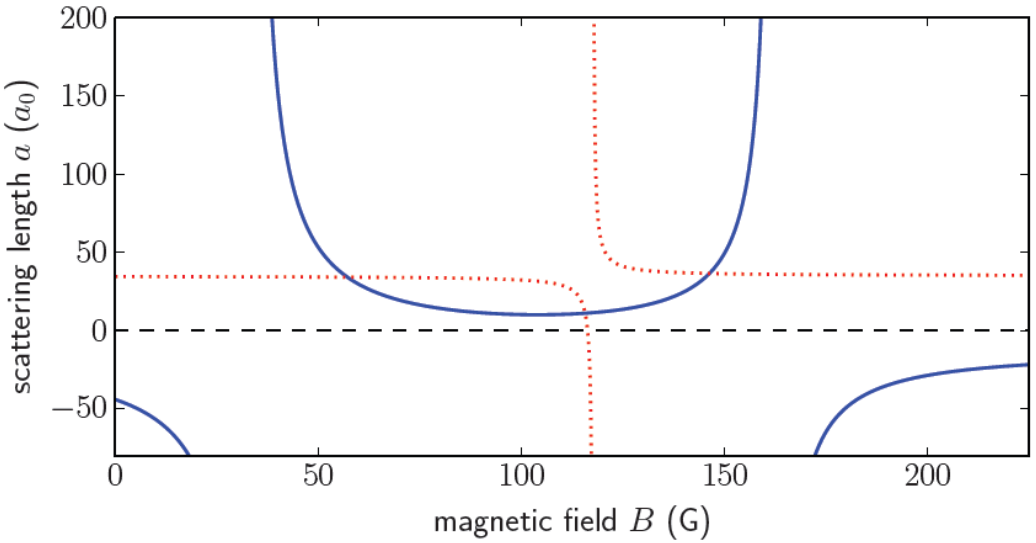
BOSE-EINSTEIN CONDENSATION



$|F=1,m_f=-1\rangle$

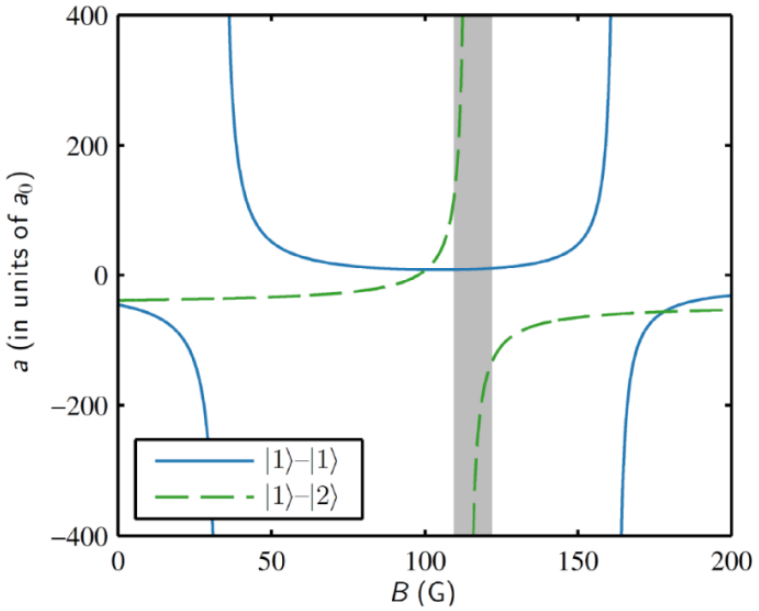
FESHBACH RESONANCES

K-Rb inter species resonance



$|F=1,m_f=-1\rangle$

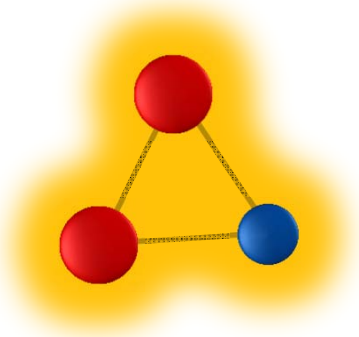
K-K inter state resonance



$|F=1,m_f=-1\rangle+|F=1,m_f=0\rangle$

Lysebo, M., and L. Veseth. Phys. Rev. A **81**. 032702 (2010).

OUTLINE



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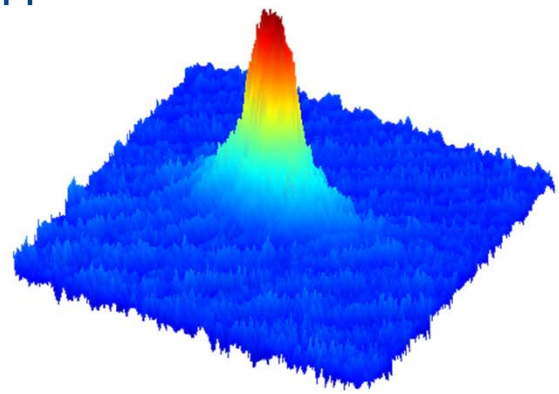
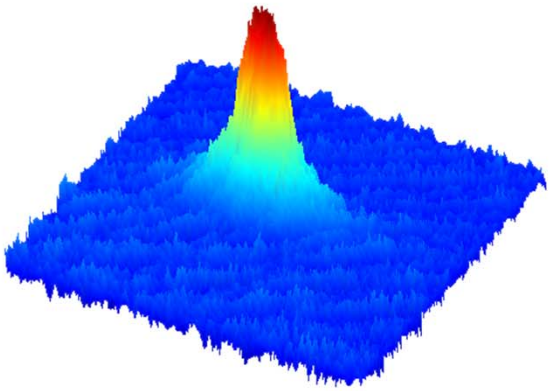
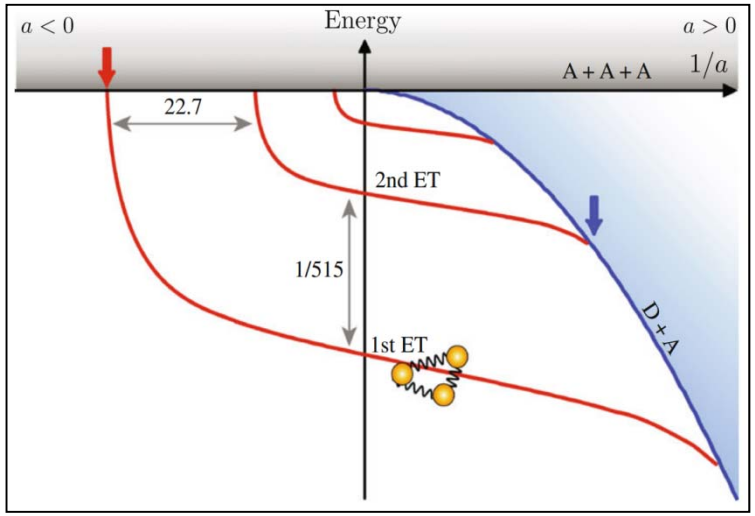
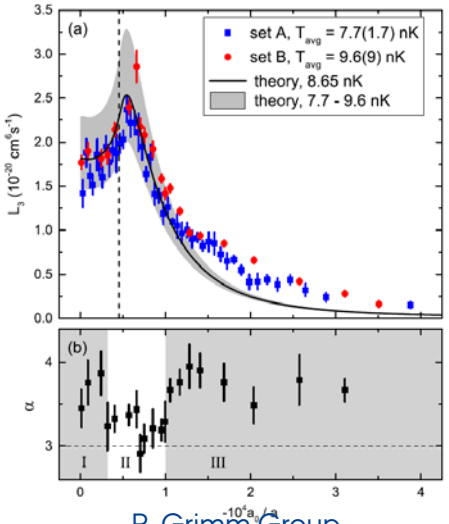


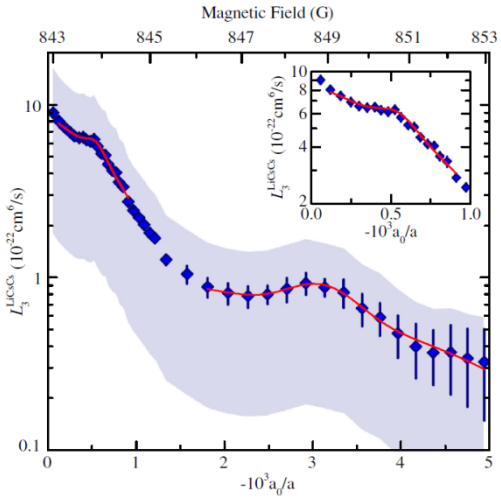


EFIMOV PHYSICS – EXAMPLES OF UNIVERSALITY

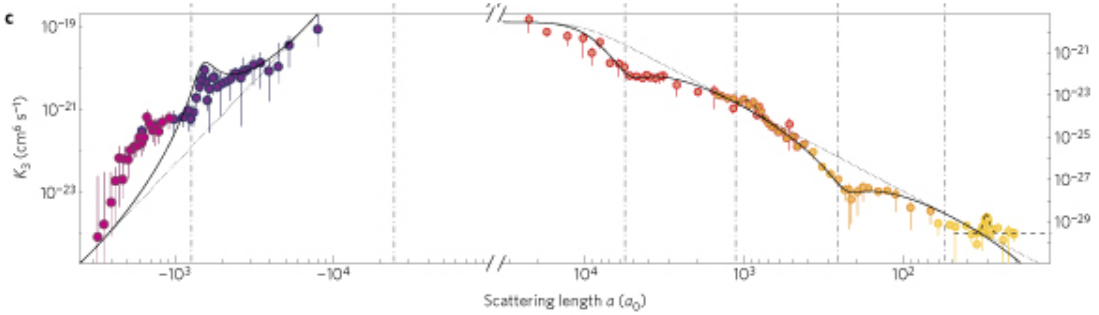




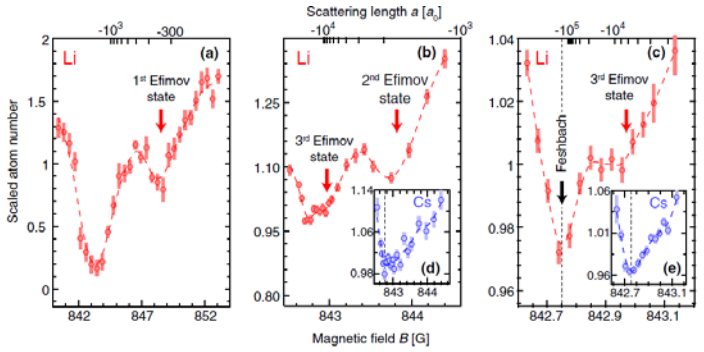
R. Grimm Group



M. Weidemüller Group



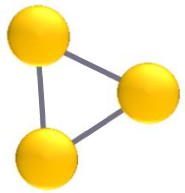
M. Inguscio Group



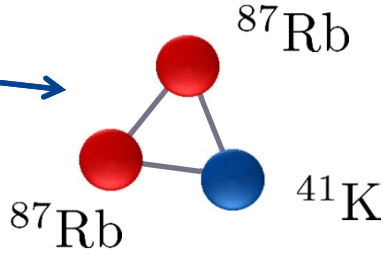
C. Chin Group

HETERONUCLEAR EFIMOV PHYSICS

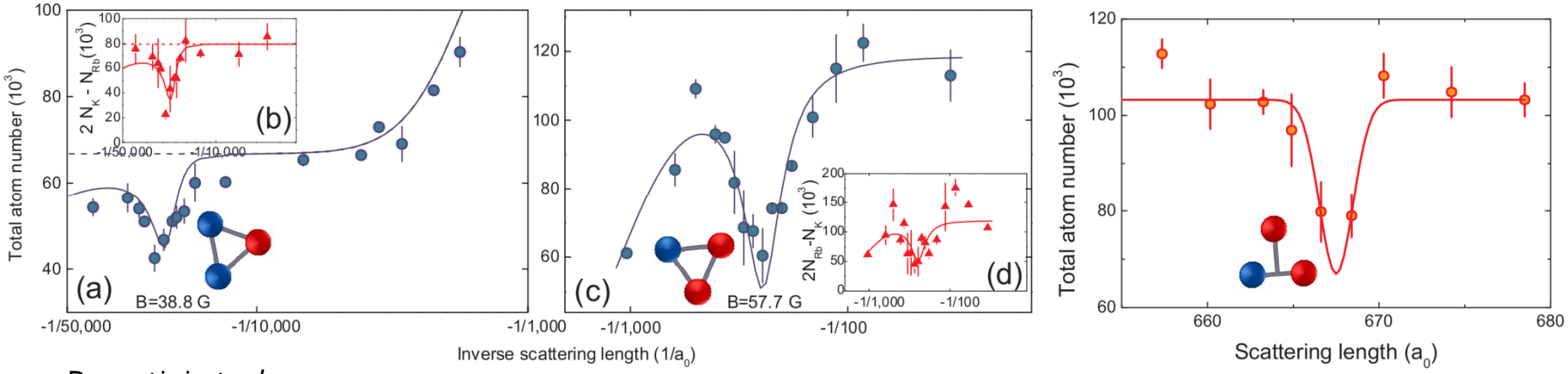
Three identical bosons



Three non-identical bosons

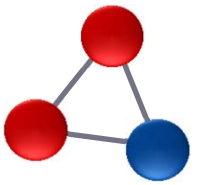


$$^{41}\mathrm{K} + {}^{87}\mathrm{Rb}$$



Barontini *et. al* . 2009

HETERONUCLEAR EFIMOV PHYSICS



$^{41}\mathrm{K} + {}^{87}\mathrm{Rb}$

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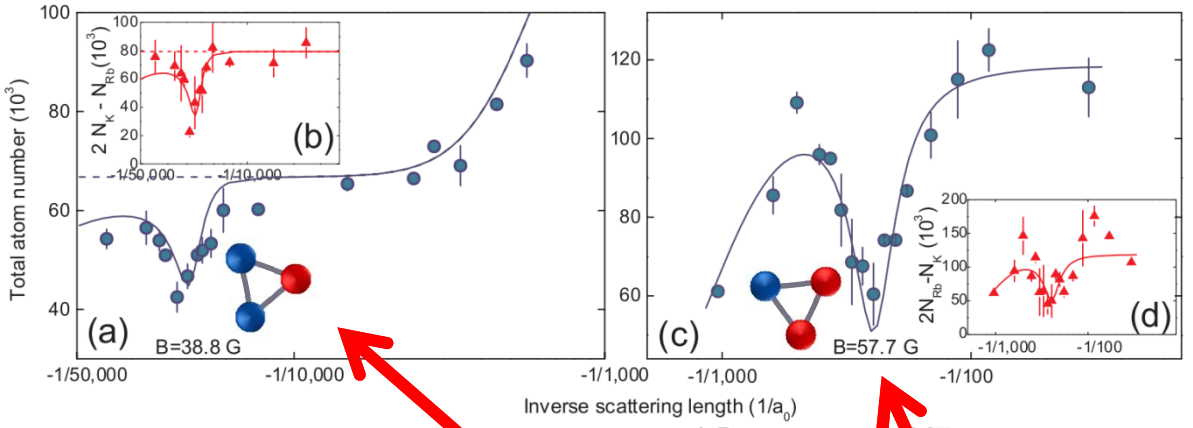
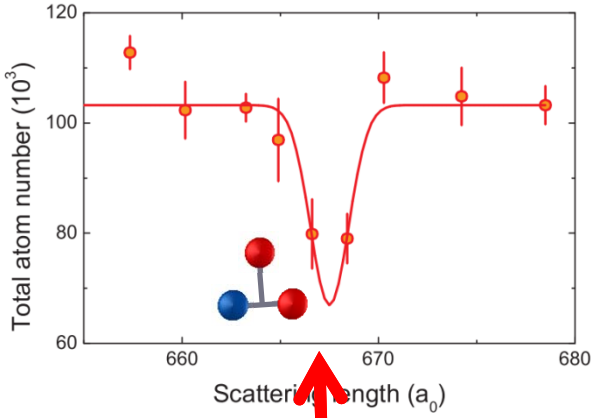
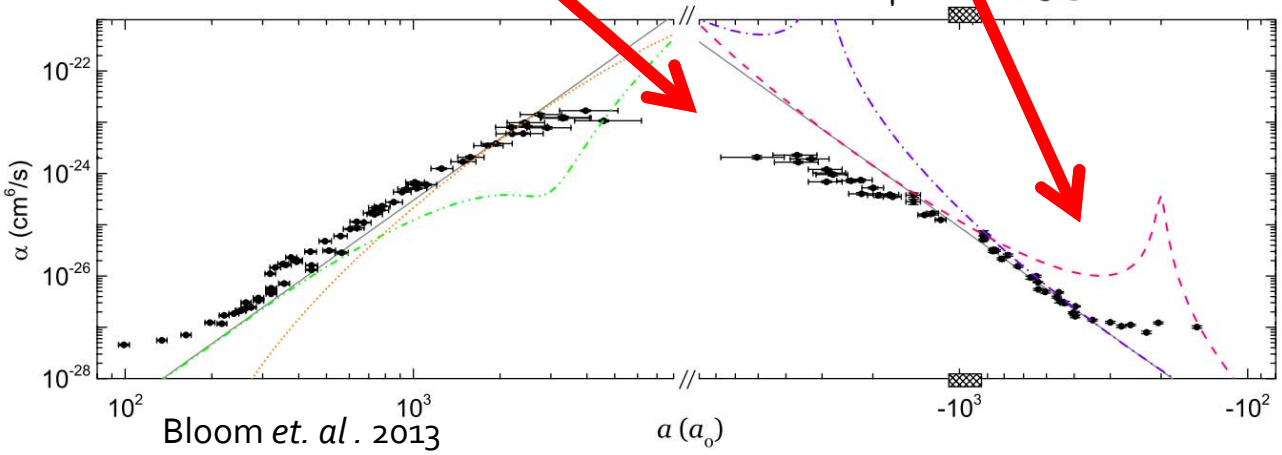


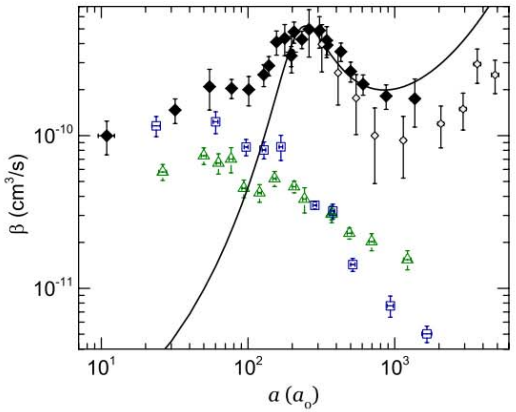


Barontini *et. al* . 2009

$^{40}\mathrm{K} + {}^{87}\mathrm{Rb}$



Bloom *et. al* . 2013



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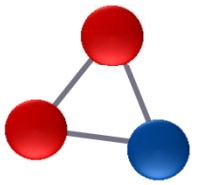

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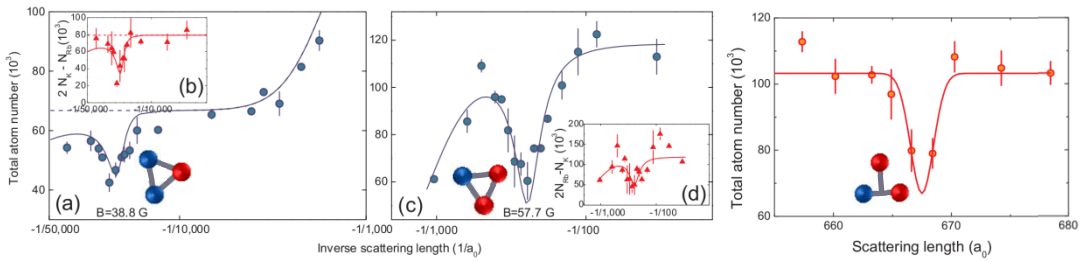
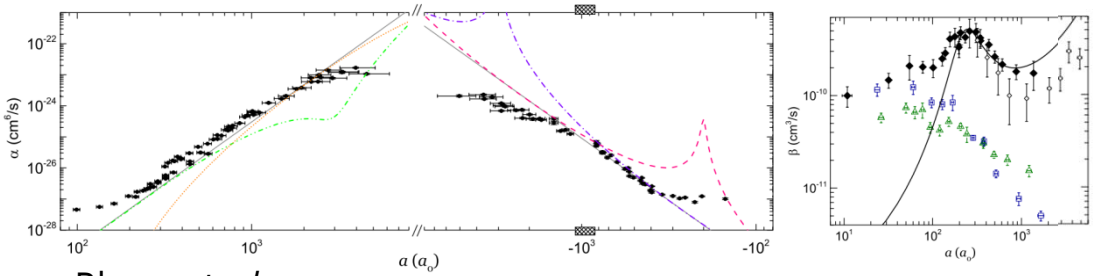


Barontini *et. al* . 2009

$^{41}\mathrm{K} + {}^{87}\mathrm{Rb}$

???



Bloom *et. al* . 2013

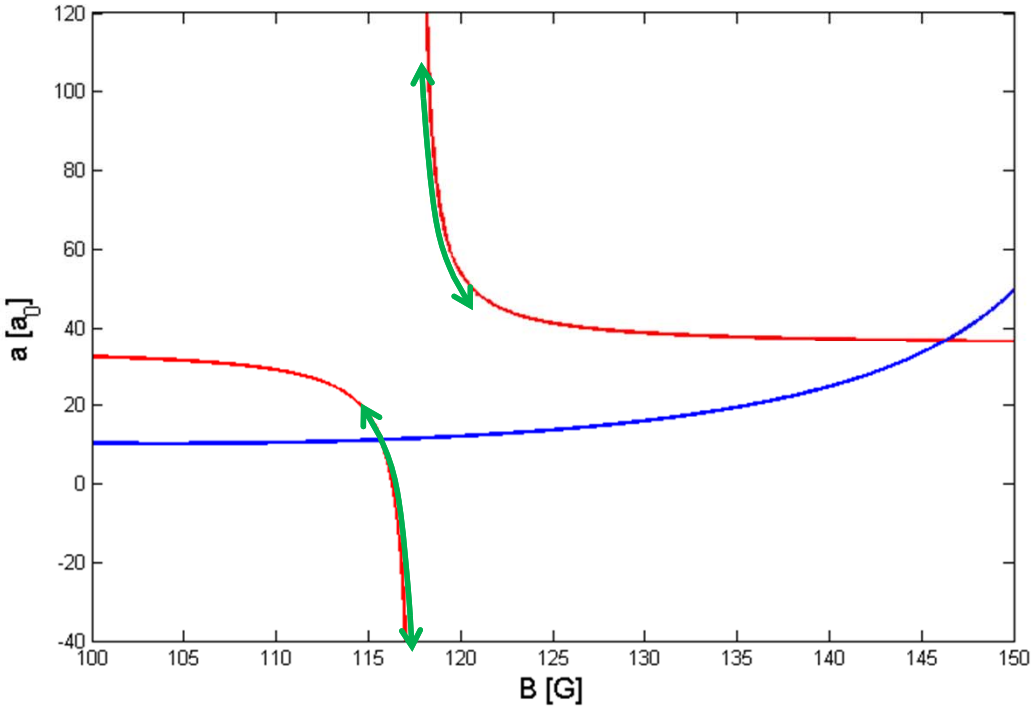
$^{40}\mathrm{K} + {}^{87}\mathrm{Rb}$

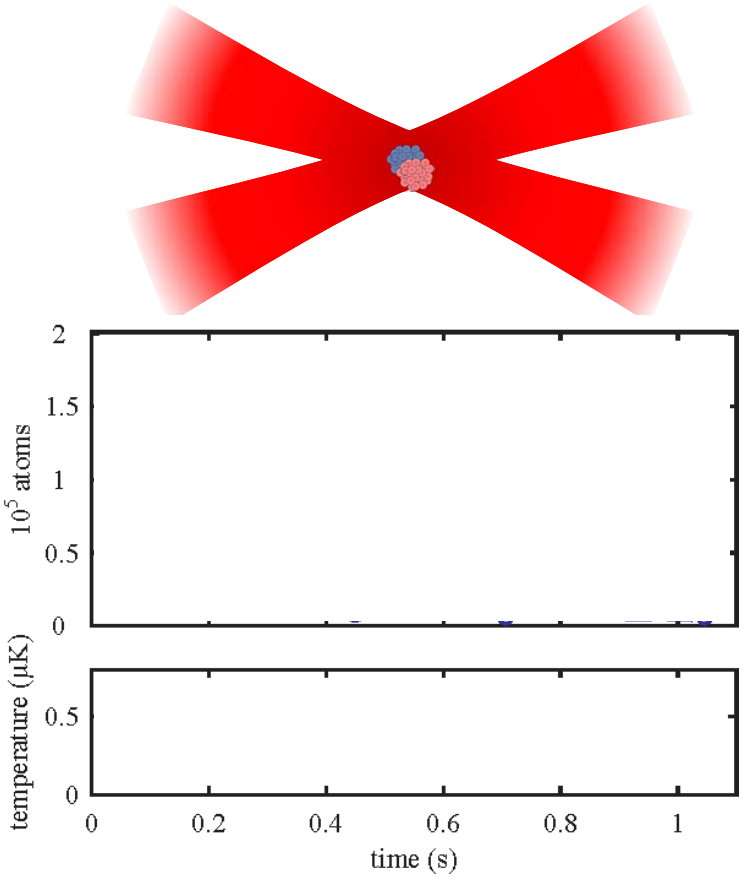
^{39}K + ^{87}Rb system

One more isotope to study!

HETERONUCLEAR EFIMOV PHYSICS

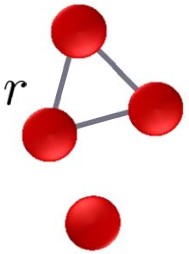
Efimov physics are explored by studying decay rates at various interactions



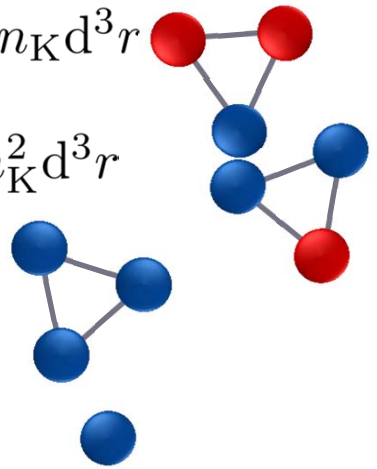


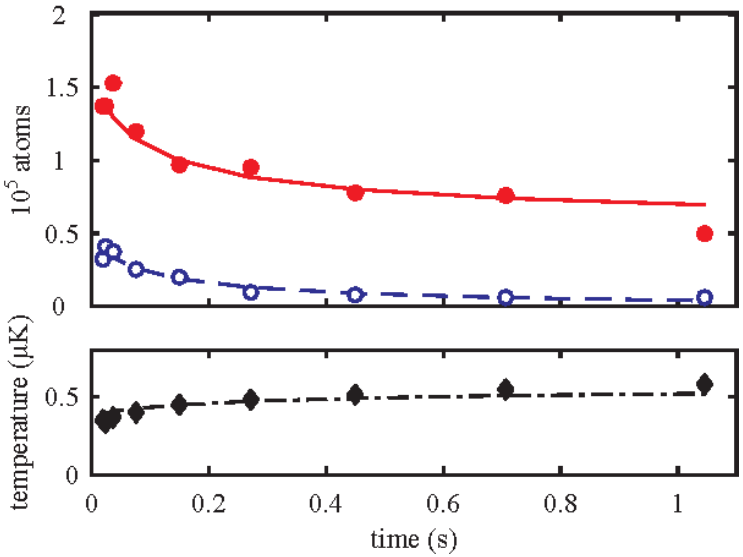
LOSSES IN MIXTURES

$$\frac{\mathrm{d}N_{\mathrm{Rb}}}{\mathrm{d}t} = -\frac{2}{3}\alpha_{\mathrm{RbRbK}}\int n_{\mathrm{Rb}}^2 n_{\mathrm{K}}\mathrm{d}^3r - \frac{1}{3}\alpha_{\mathrm{RbKK}}\int n_{\mathrm{Rb}} n_{\mathrm{K}}^2\mathrm{d}^3r - \alpha_{\mathrm{RbRbRb}}\int n_{\mathrm{Rb}}^3\mathrm{d}^3r - \frac{1}{\tau_{\mathrm{Rb}}}\int n_{\mathrm{Rb}}\mathrm{d}^3r$$



$$\frac{\mathrm{d}N_{\mathrm{K}}}{\mathrm{d}t} = -\frac{1}{3}\alpha_{\mathrm{RbRbK}}\int n_{\mathrm{Rb}}^2 n_{\mathrm{K}}\mathrm{d}^3r - \frac{2}{3}\alpha_{\mathrm{RbKK}}\int n_{\mathrm{Rb}} n_{\mathrm{K}}^2\mathrm{d}^3r - \alpha_{\mathrm{KKK}}\int n_{\mathrm{K}}^3\mathrm{d}^3r - \frac{1}{\tau_{\mathrm{K}}}\int n_{\mathrm{K}}\mathrm{d}^3r$$





Heating: $\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\alpha T}{3N}\int n^3\mathrm{d}^3r$ (single species)

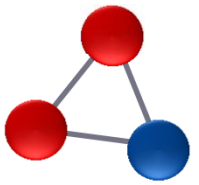
Well known: $\alpha_{\mathrm{RbRbRb}}, \alpha_{\mathrm{KKK}}$

Use: $\alpha_{\mathrm{RbRbK}} \gg \alpha_{\mathrm{RbKK}}$

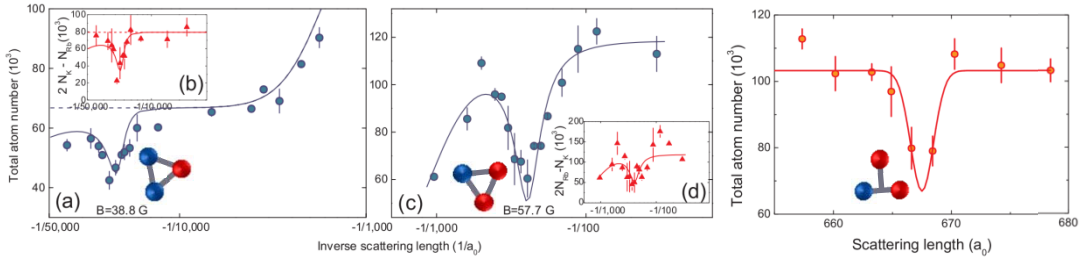
Solve and fit differential equations:

Extract: α_{RbRbK}

HETERONUCLEAR EFIMOV PHYSICS



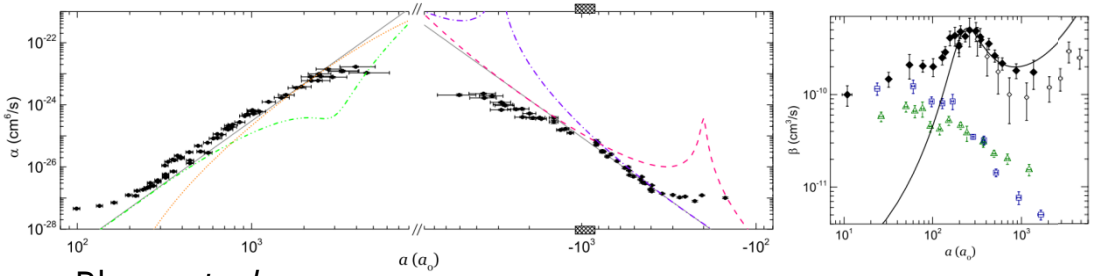
Three non-identical bosons



Barontini *et. al* . 2009

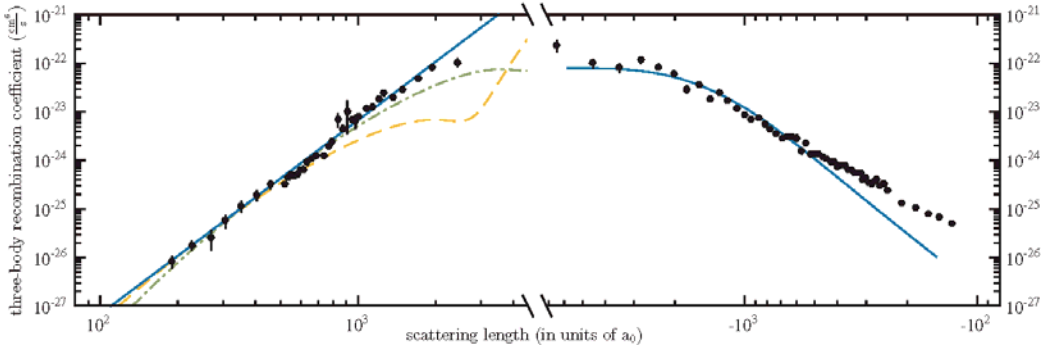
$^{41}\mathrm{K} + {}^{87}\mathrm{Rb}$

???



Bloom *et. al* . 2013

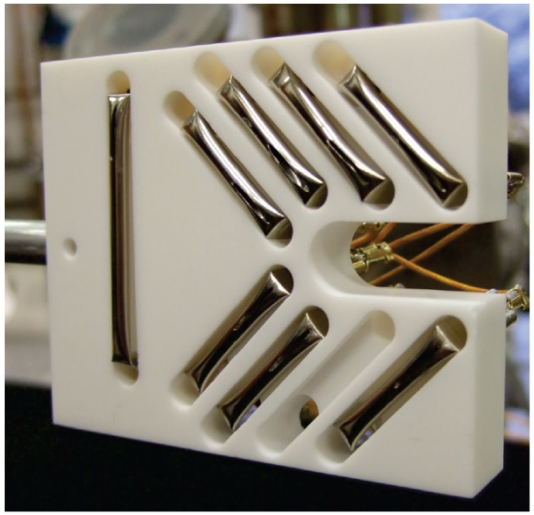
$^{40}\mathrm{K} + {}^{87}\mathrm{Rb}$



$^{39}\mathrm{K} + {}^{87}\mathrm{Rb}$

HETERONUCLEAR EFIMOV PHYSICS

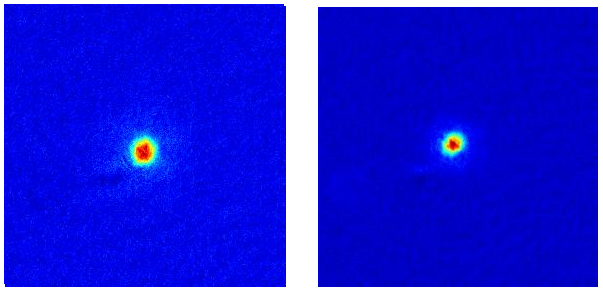
Dispensers providing atomic vapor of K and Rb



Potassium dispenser

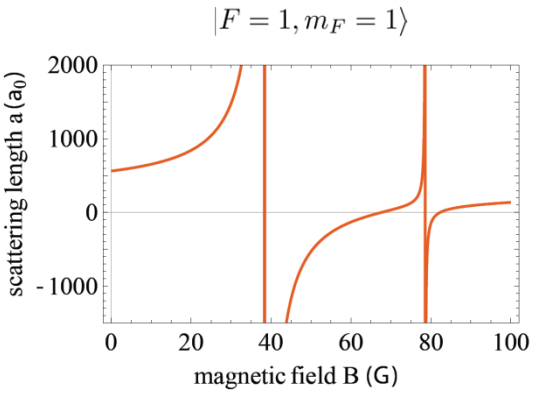
iso	NA	half-life	DM	DE (MeV)	DP
^{39}K	93.26%	^{39}K is stable with 20 neutrons			
^{40}K	0.012%	$1.248(3)\times10^{9}$ y	β^-	1.311	^{40}Ca
			ε	1.505	^{40}Ar
			β^+	1.505	^{40}Ar
^{41}K	6.73%	^{41}K is stable with 22 neutrons			

Wikipedia

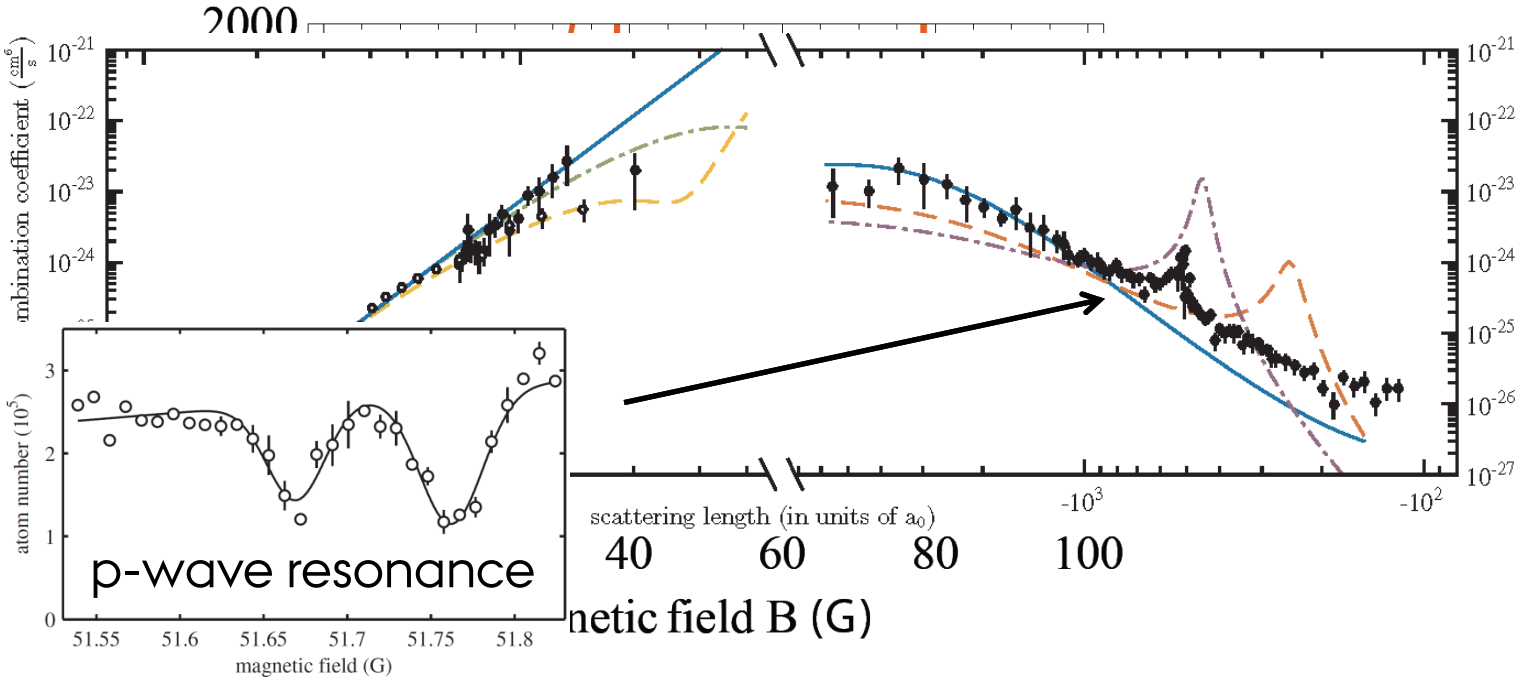


^{41}K ^{87}Rb

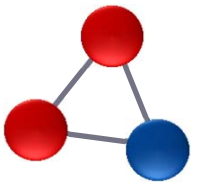
HETERONUCLEAR EFIMOV PHYSICS



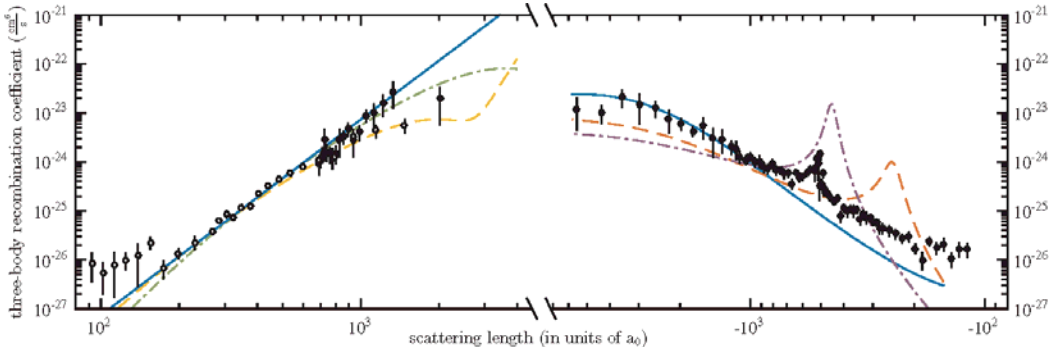
Target state: $|F = 1, m_F = 1\rangle$



HETERONUCLEAR EFIMOV PHYSICS

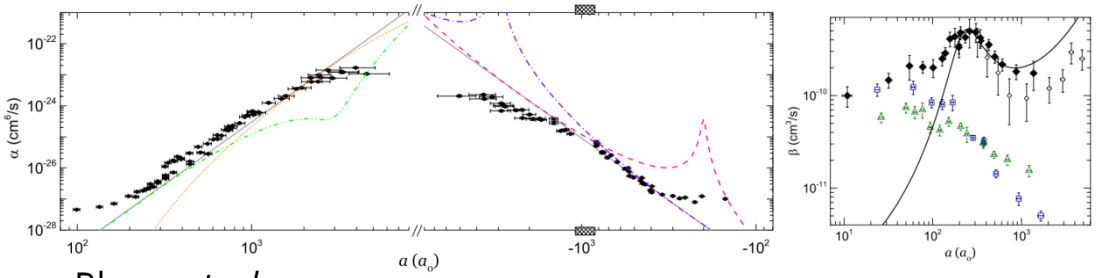


No observable Efimov resonances!



$^{41}\mathrm{K} + {}^{87}\mathrm{Rb}$

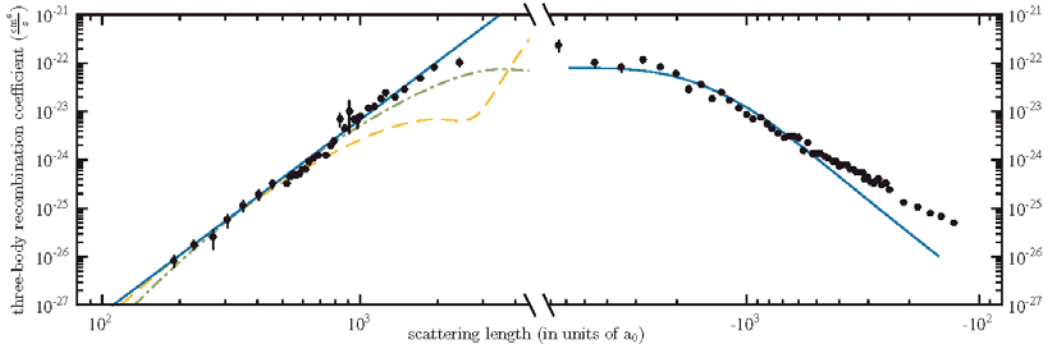
No observable Efimov resonances!



Bloom *et. al* . 2013

$^{40}\mathrm{K} + {}^{87}\mathrm{Rb}$

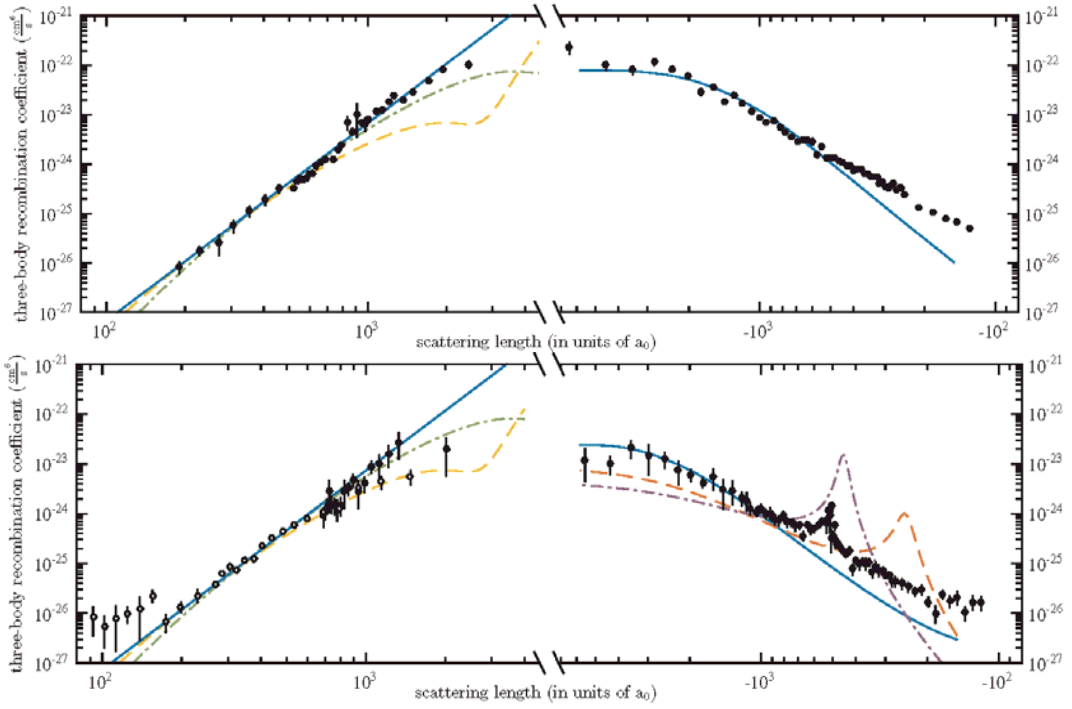
No observable Efimov resonances!



$^{39}\mathrm{K} + {}^{87}\mathrm{Rb}$

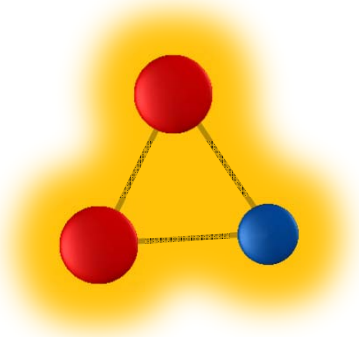
CONCLUSION AND OUTLOOK

- No observable atomic Efimov resonances in KRb below 2000 a_0
- Restores universality
- Find ^{39}K-^{87}Rb dimer resonance

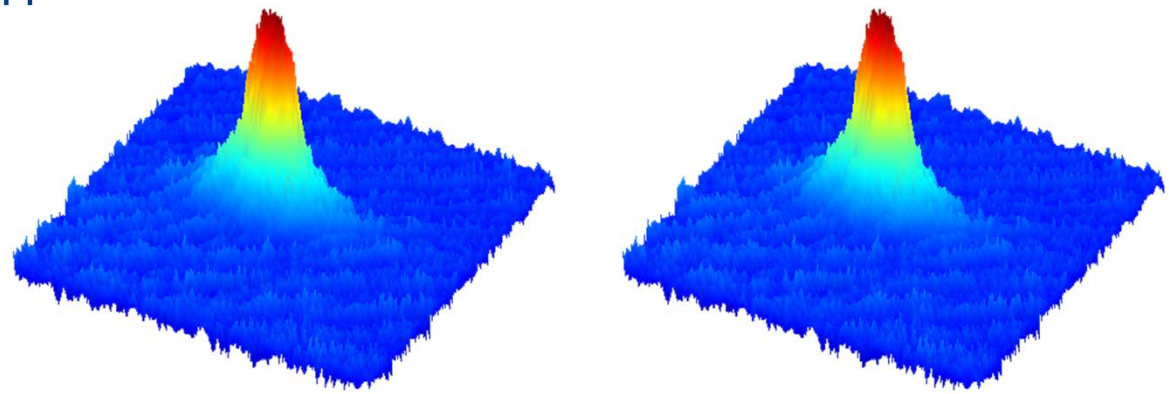


L. J. Wacker, N. B. Jørgensen, D. Birkmose, N. Winter, M. Mikkelsen, J. Sherson, N. Zinner, and J. J. Arlt
Phys. Rev. Lett. **117**, 163201 (2016)

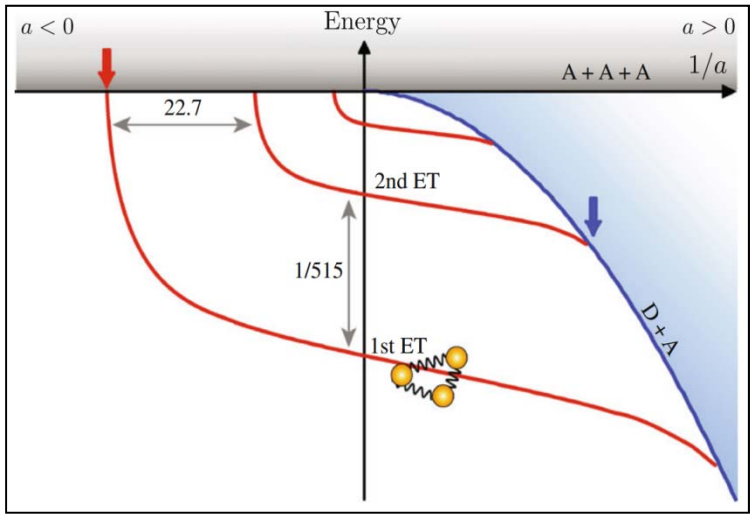
OUTLINE

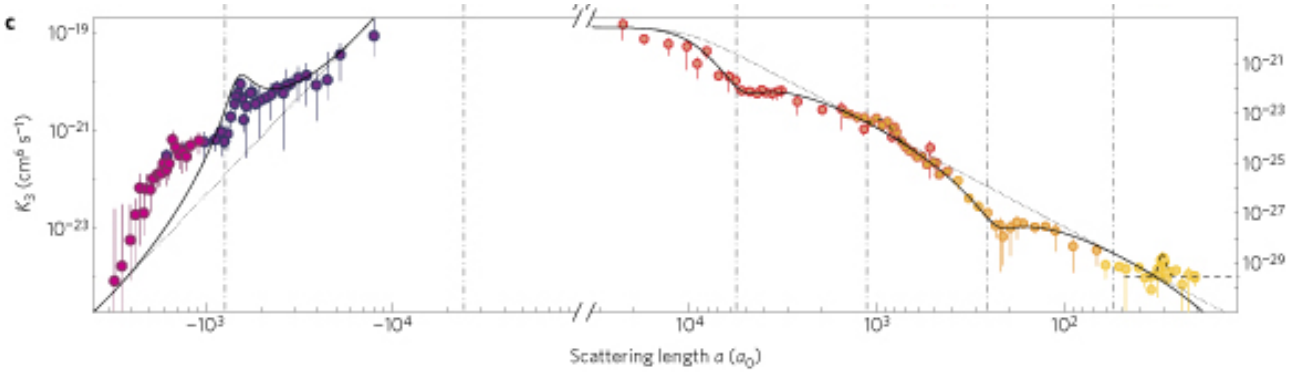


- Motivation
- Quantum gases with tunable interactions
- Efimov physics in K-Rb mixtures
- **Disappearance of Efimov resonances in K**
- The Bose polaron
- Conclusion



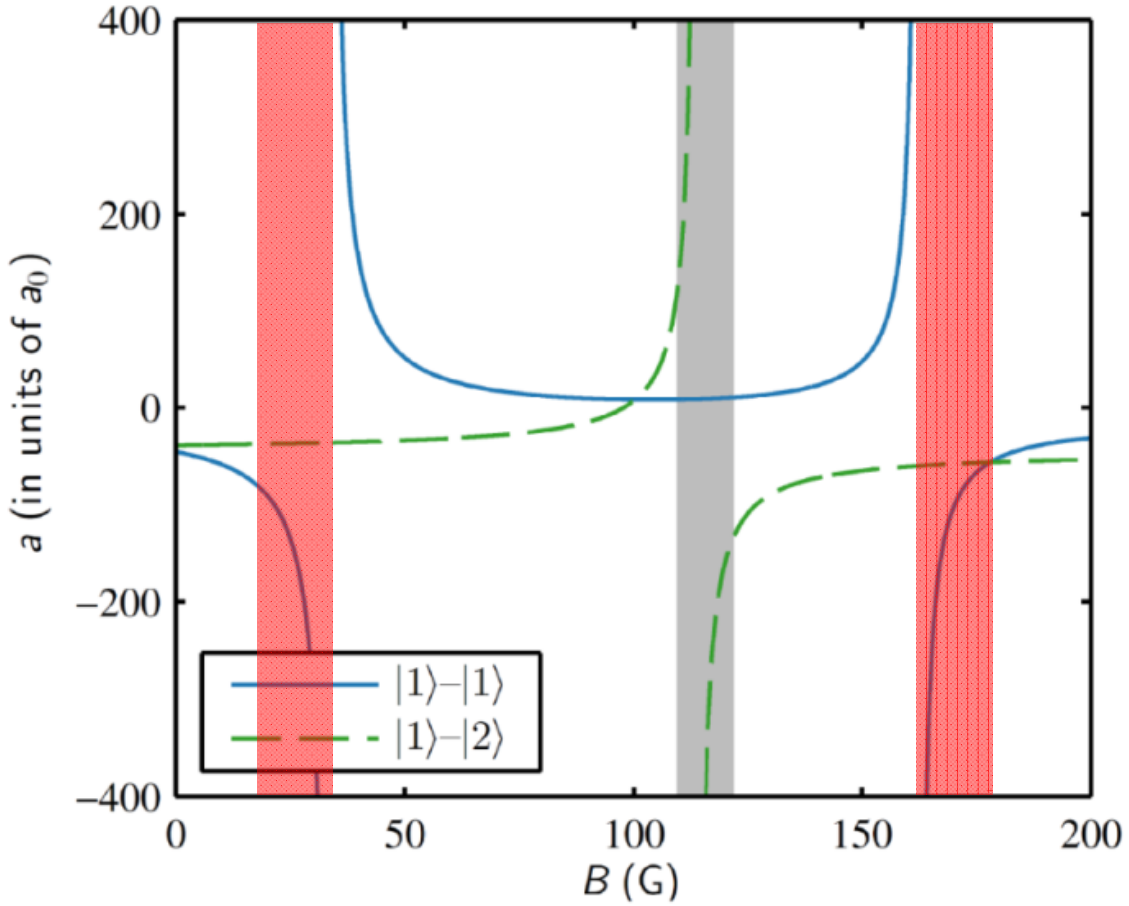
EFIMOV PHYSICS IN ^{39}K



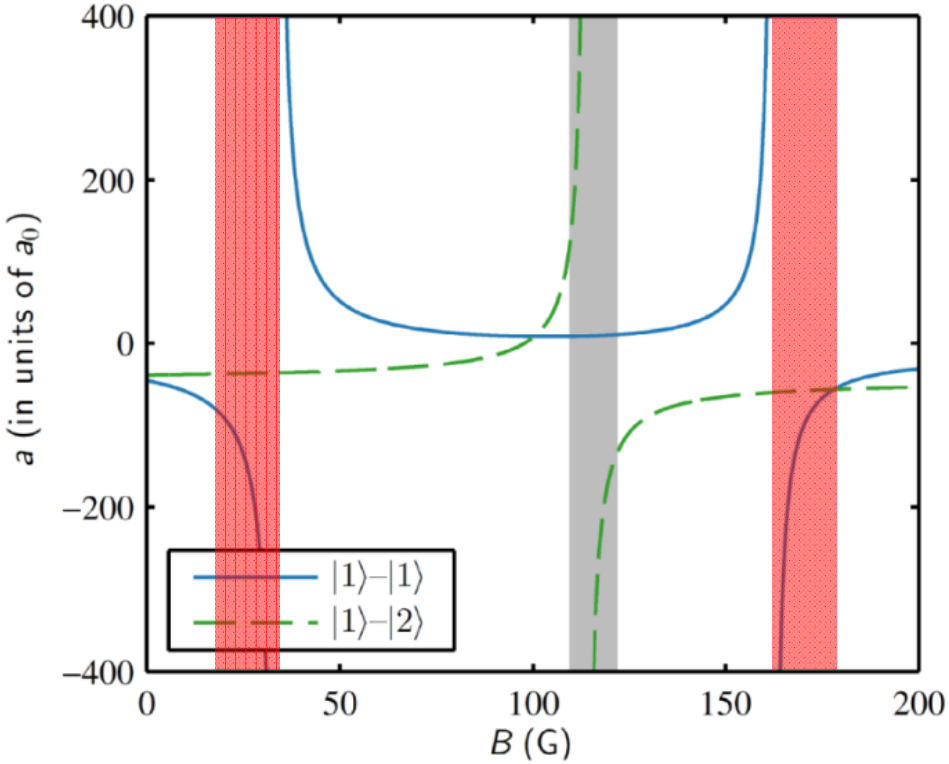


M. Inguscio Group

EFIMOV RESONANCE REGIONS

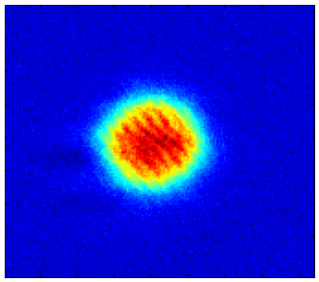


AIMS

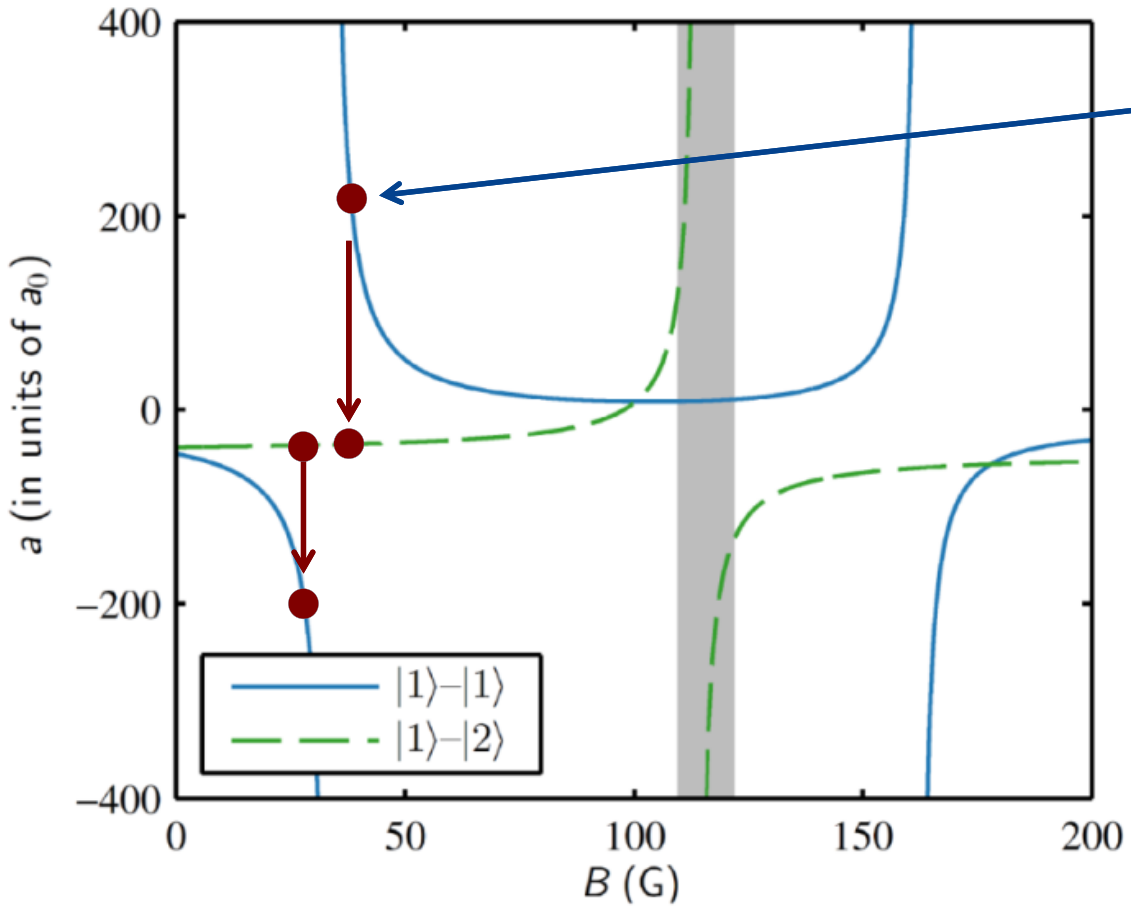


- Observation of second Efimov resonance
- Test of universality at adjacent Feshbach resonances

EXPERIMENTAL SEQUENCE



^{39}K BEC



T = 42 nK

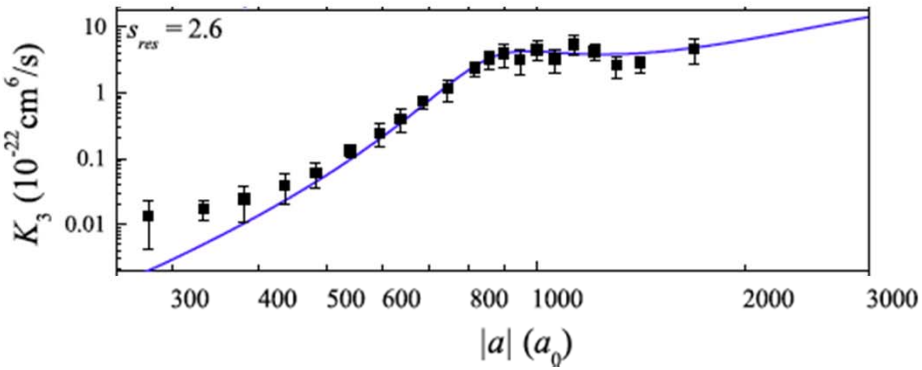
a_{max}= 25782 a_0

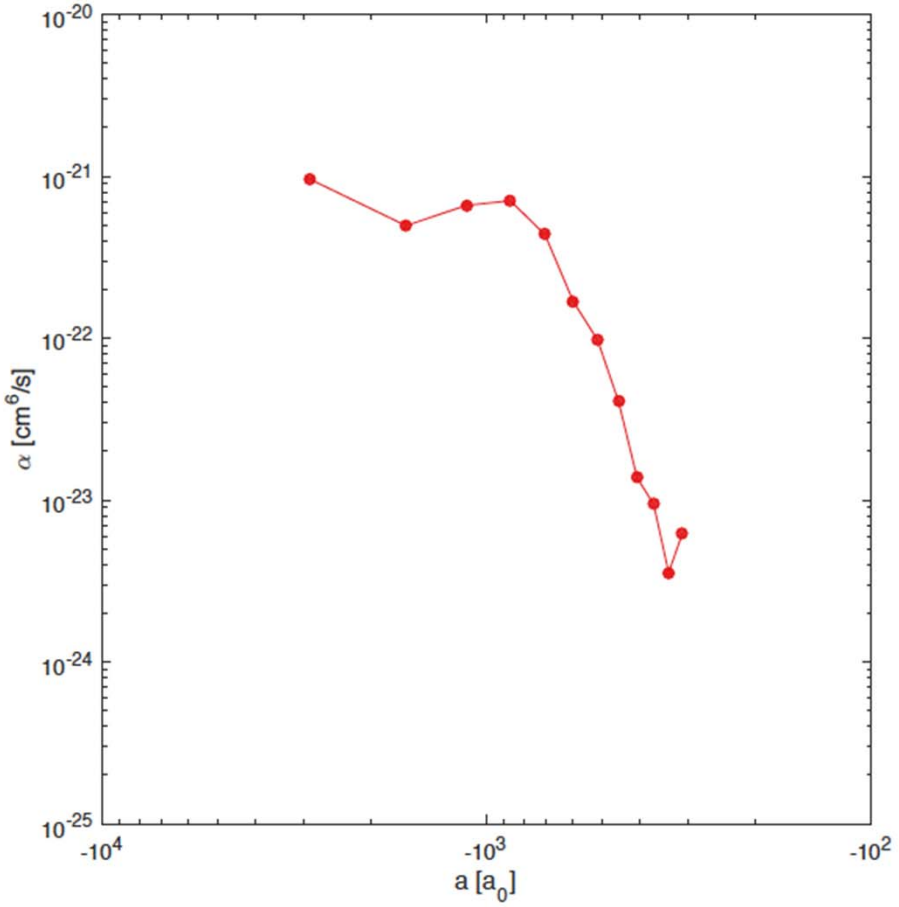
ANALYSIS OF FIRST RESONANCE

$$N(t) = \frac{N_0}{(1 + \frac{3\beta^2}{\sqrt{27}} \frac{N_0^2}{T_0^3} K_3 t)^{1/3}}$$

$$T(t) = T_0 (1 + \frac{3\beta^2}{\sqrt{27}} \frac{N_0^2}{T_0^3} K_3 t)^{1/9}$$

$$\beta = (m\bar{\omega}^2 / 2\pi k_B)^{3/2}$$

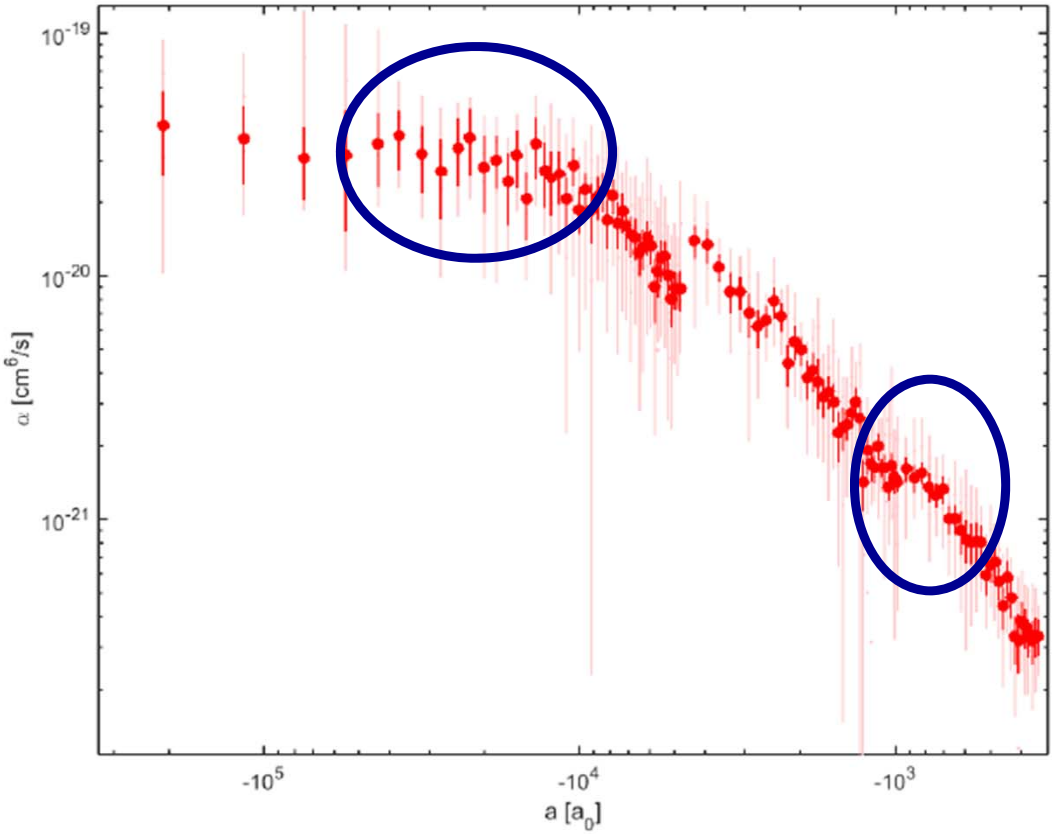




S. Roy et al., Phys. Rev. Lett. **111**, 053202 (2013)

Good agreement of experimental results at T=100nK

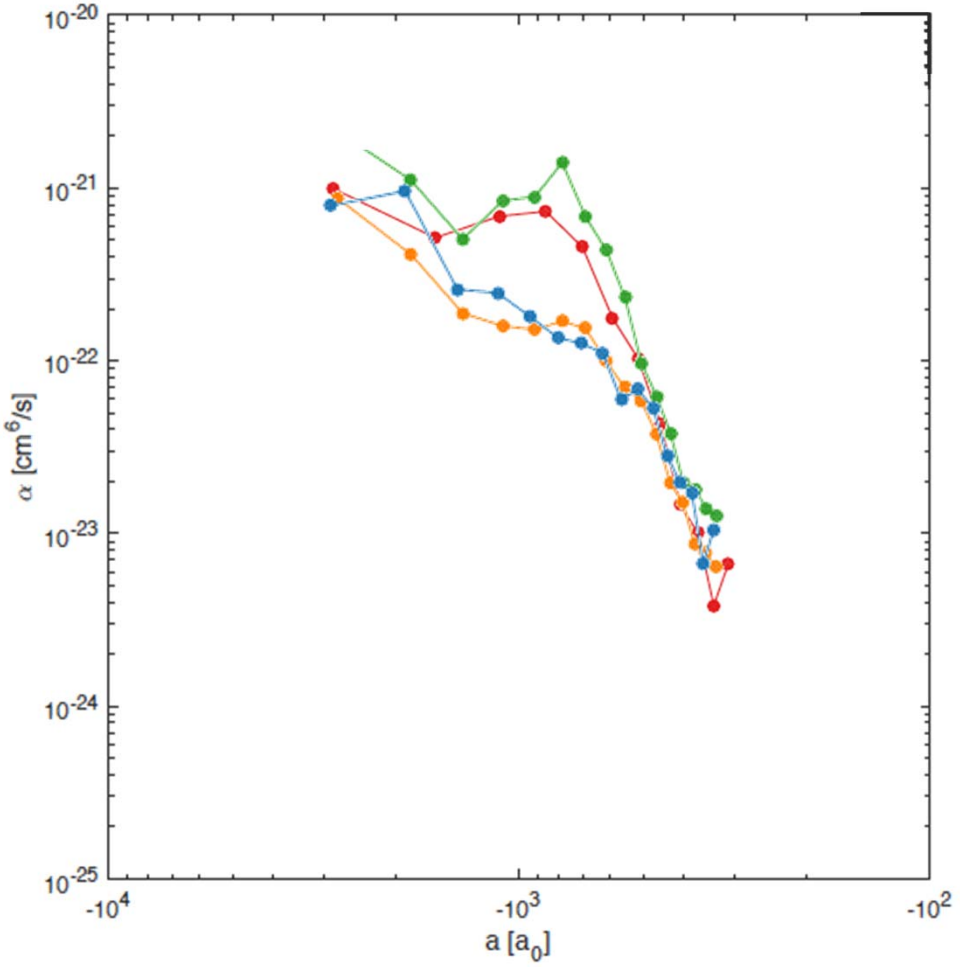
ANALYSIS OF SECOND RESONANCE



Surprises:

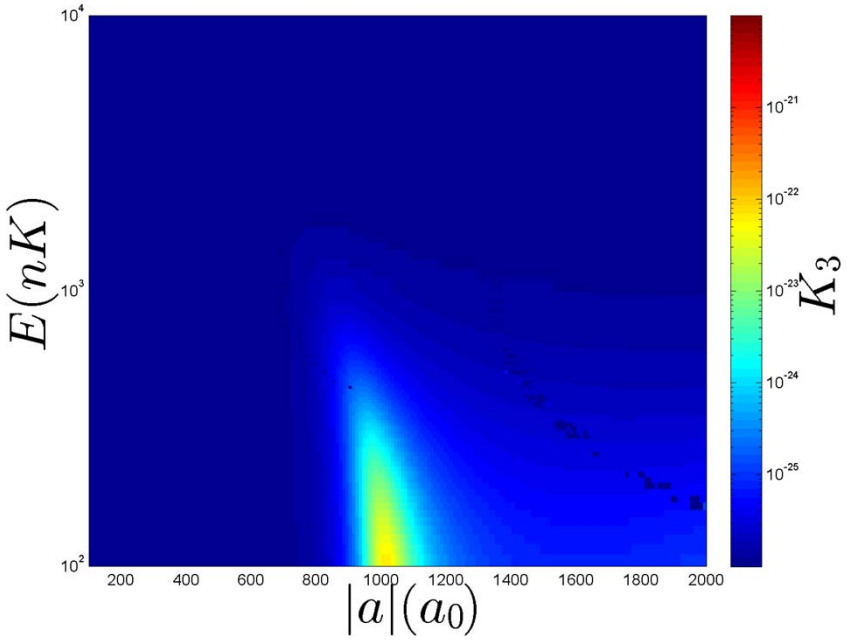
1. No clear second resonance
2. First resonance is extremely weak

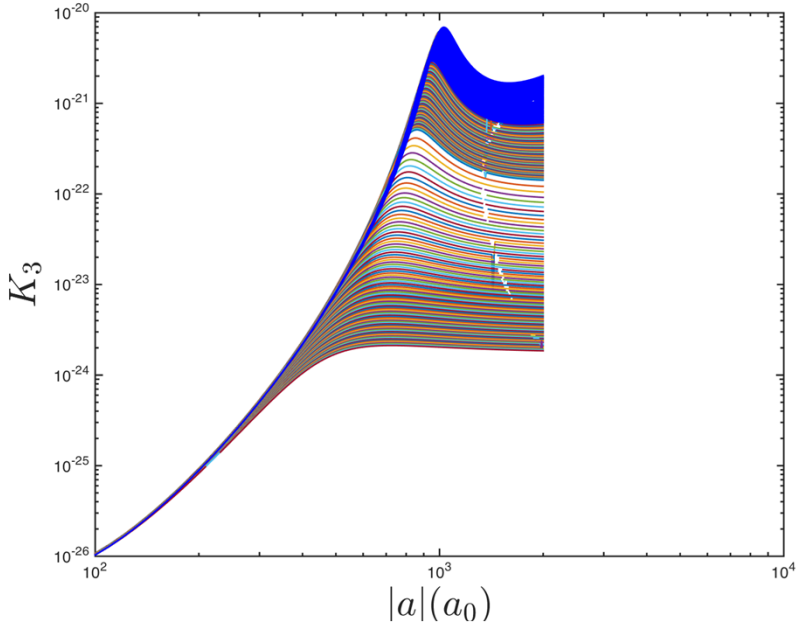
T DEPENDENCE OF FIRST RESONANCE



- 80nK
- 120nK
- 250nK
- 500nK

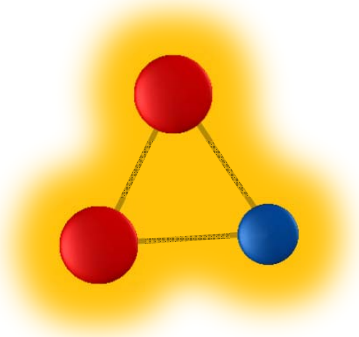
TEMPERATURE DEPENDENCE





- No decrease of recombination rate in theory (N. Zinner)
- Is something missing from theory?
- Is the measurement suitable?

OUTLINE



- Motivation
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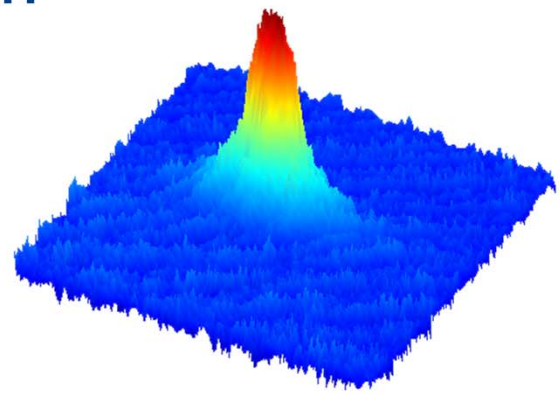
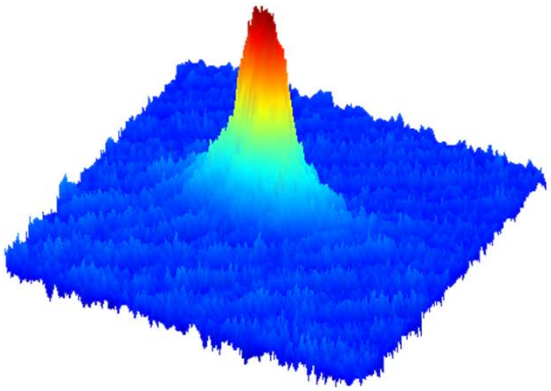
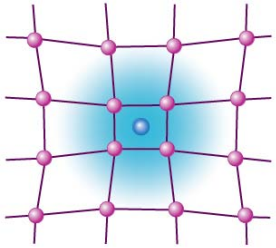
- Conclusion





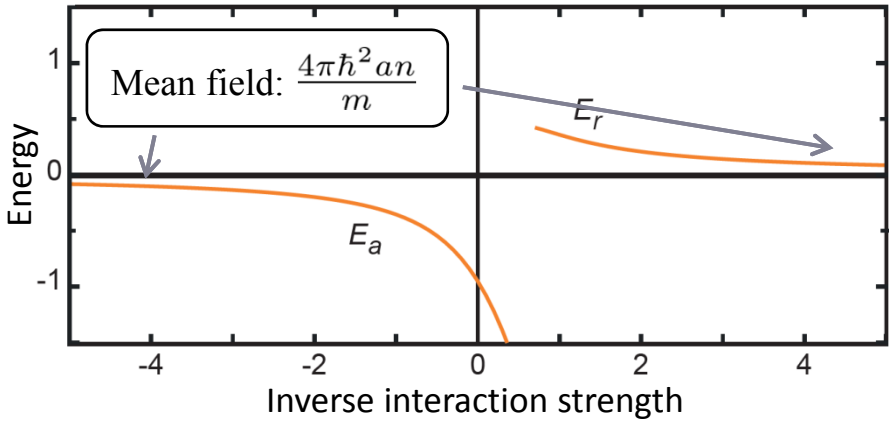
Polarons in ultracold gases

Polaron
in a solid



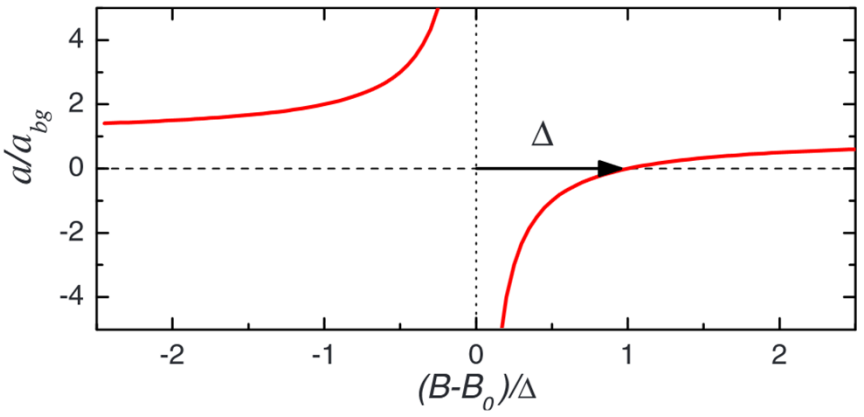
Ultracold gases → High purity
Ultracold gases → High flexibility
Ultracold gases → Tunable interactions

Energy of the polaron

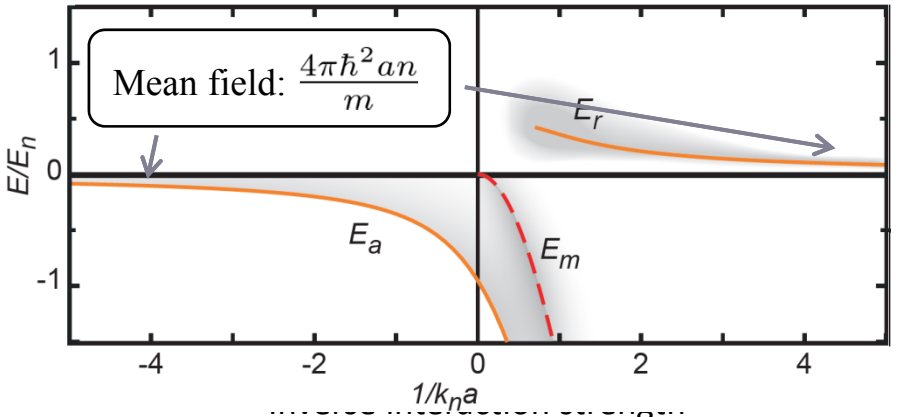


Polarons in ultracold gases

Feshbach resonances provide tunable interactions



Energy of the polaron

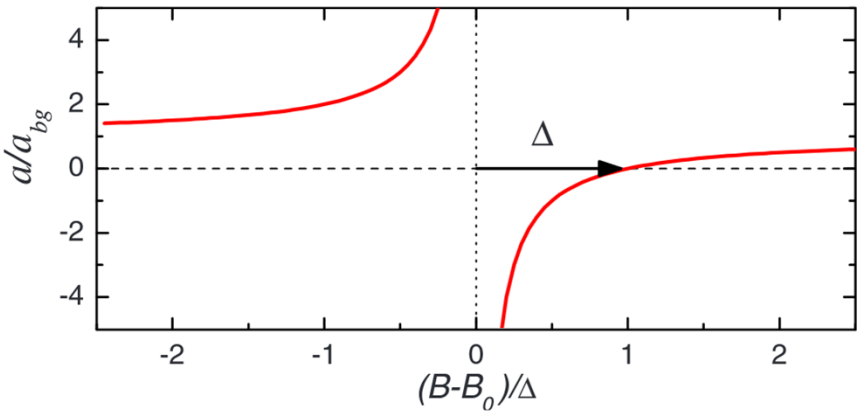


$k_n = (6\pi^2 n_0)^{1/3}$

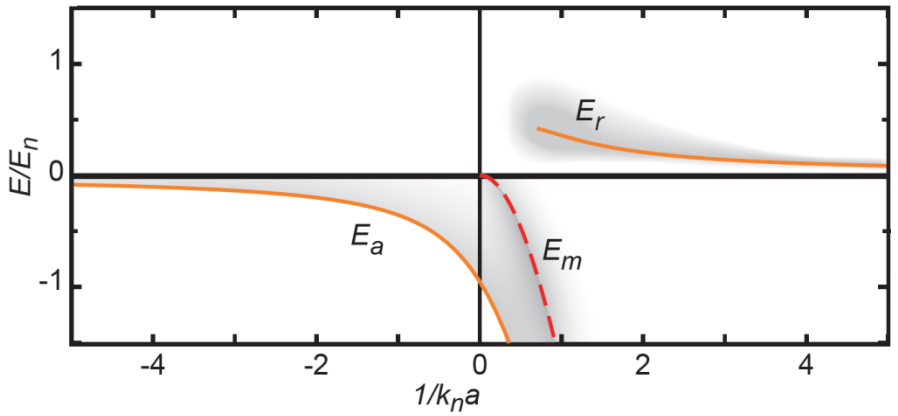
$E_n = \frac{\hbar^2 k_n^2}{2m}$

Polarons in ultracold gases

Feshbach resonances provide tunable interactions



Energy of the polaron



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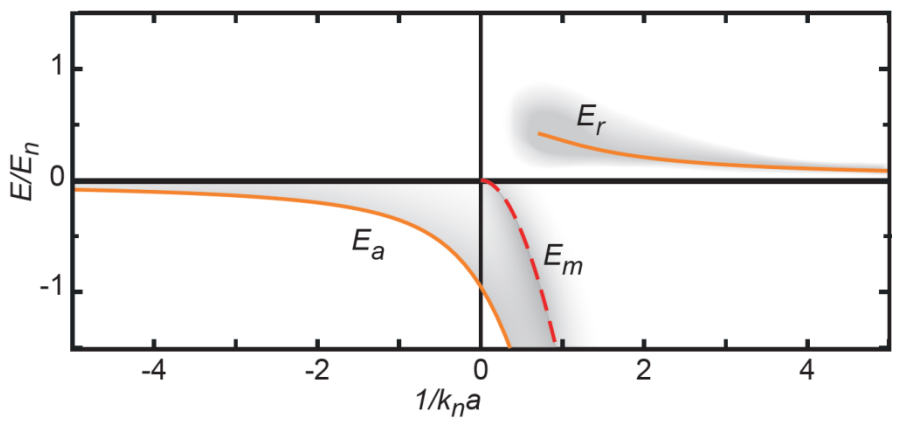
Polarons in ultracold gases

Energy of the polaron



$$k_n = (6\pi^2 n_0)^{1/3}$$

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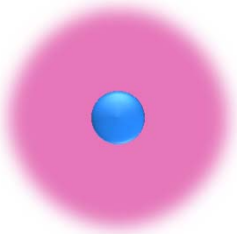
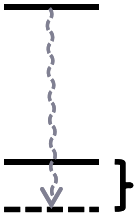
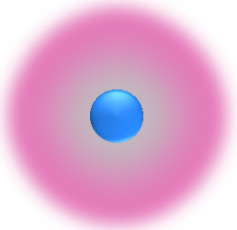
General experimental procedure

Prepare impurity in non-interacting state





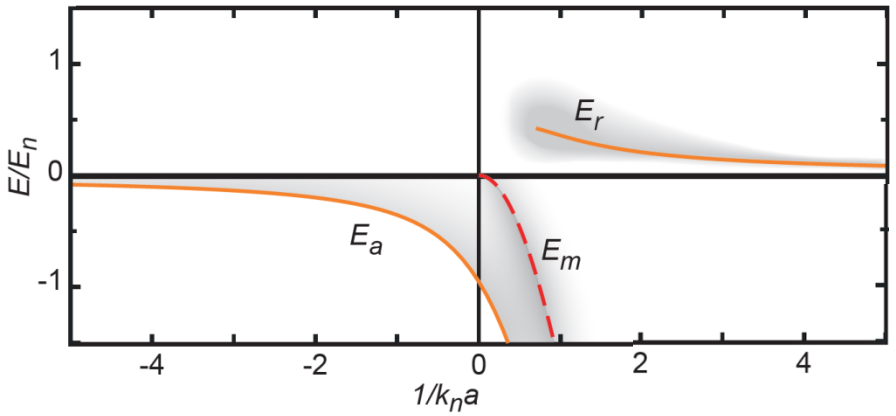
Perform spectroscopy into interacting state



Obtain energy shift and repeat for different interactions!

Polarons in ultracold gases

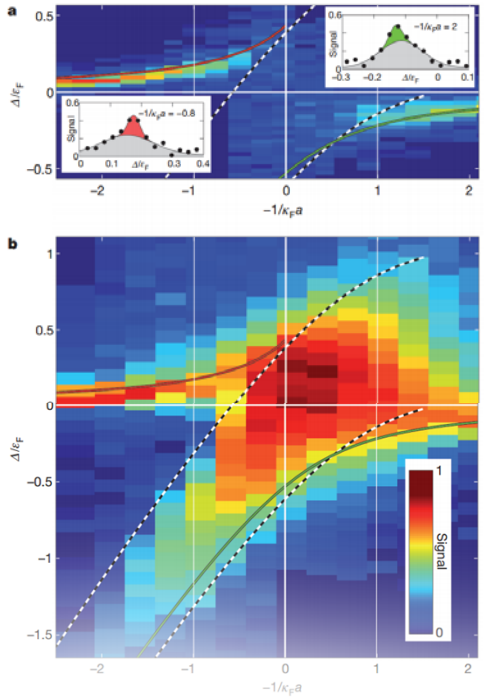
Energy of the polaron



$$k_n = (6\pi^2 n_0)^{1/3}$$

$$E_n = \frac{\hbar^2 k_n^2}{2m}$$

Results from ultracold Fermi gases



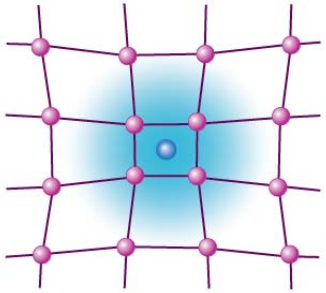
(Axis reversed)

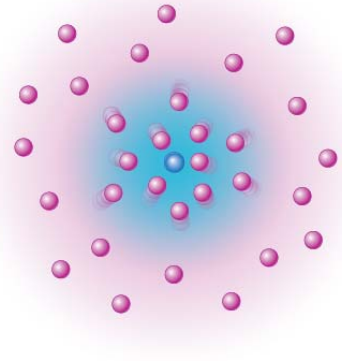
- Kohstall, C. *et al.*, *Nature* **485**, 615 (2012).
- Koschorreck, M. *et al.*, *Nature* **485**, 619 (2012).
- Schirotzek, A. *et al.*, Phys. Rev. Lett. **102**, 230402 (2009).

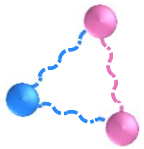
What about bosons?

The Bose polaron

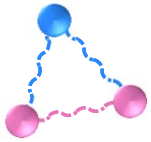
Stronger parallel to solid state physics
(phonons are bosons)

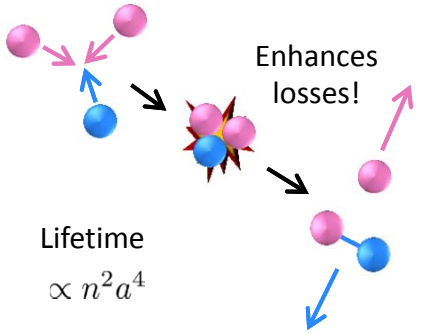






Three-body physics enter!





Enhances
losses!

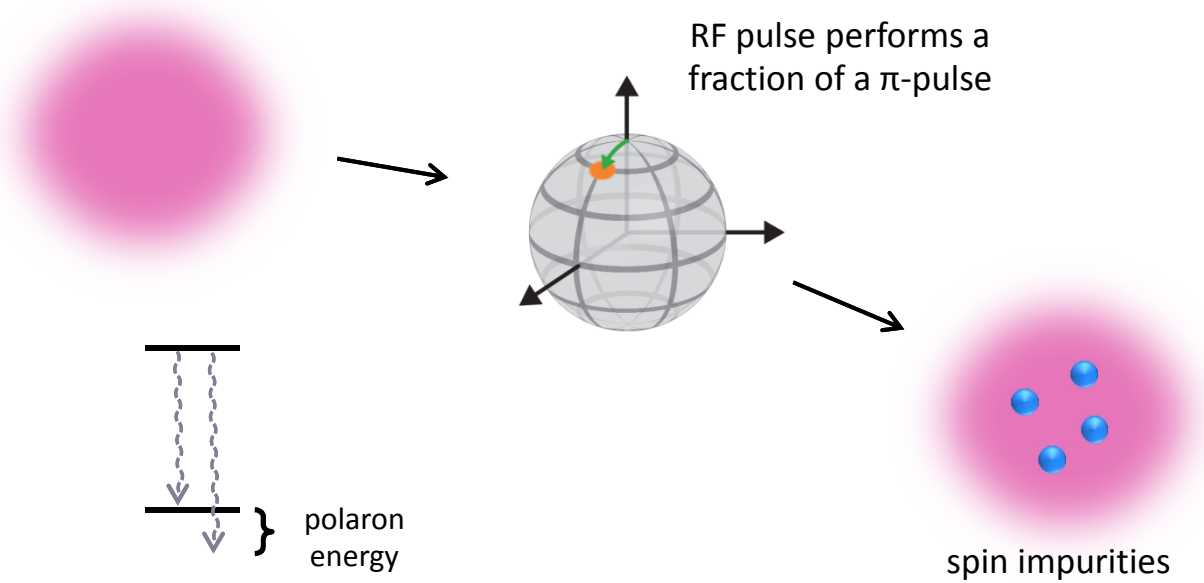
Lifetime
$\propto n^2 a^4$

Is the polaron even well defined?

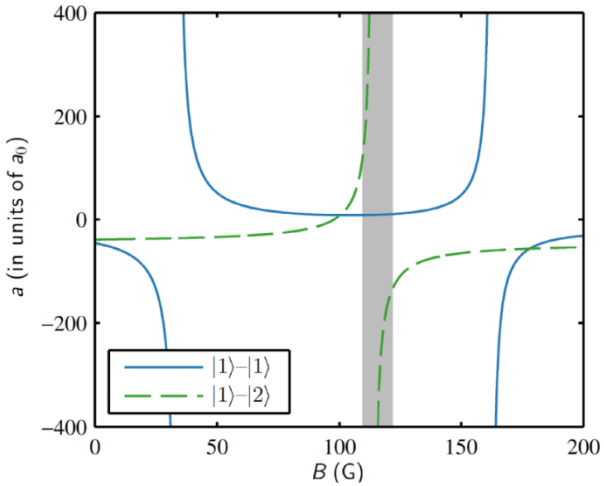
Polaron
energy

The Bose polaron – Our approach

Single component ^{39}K BEC in state

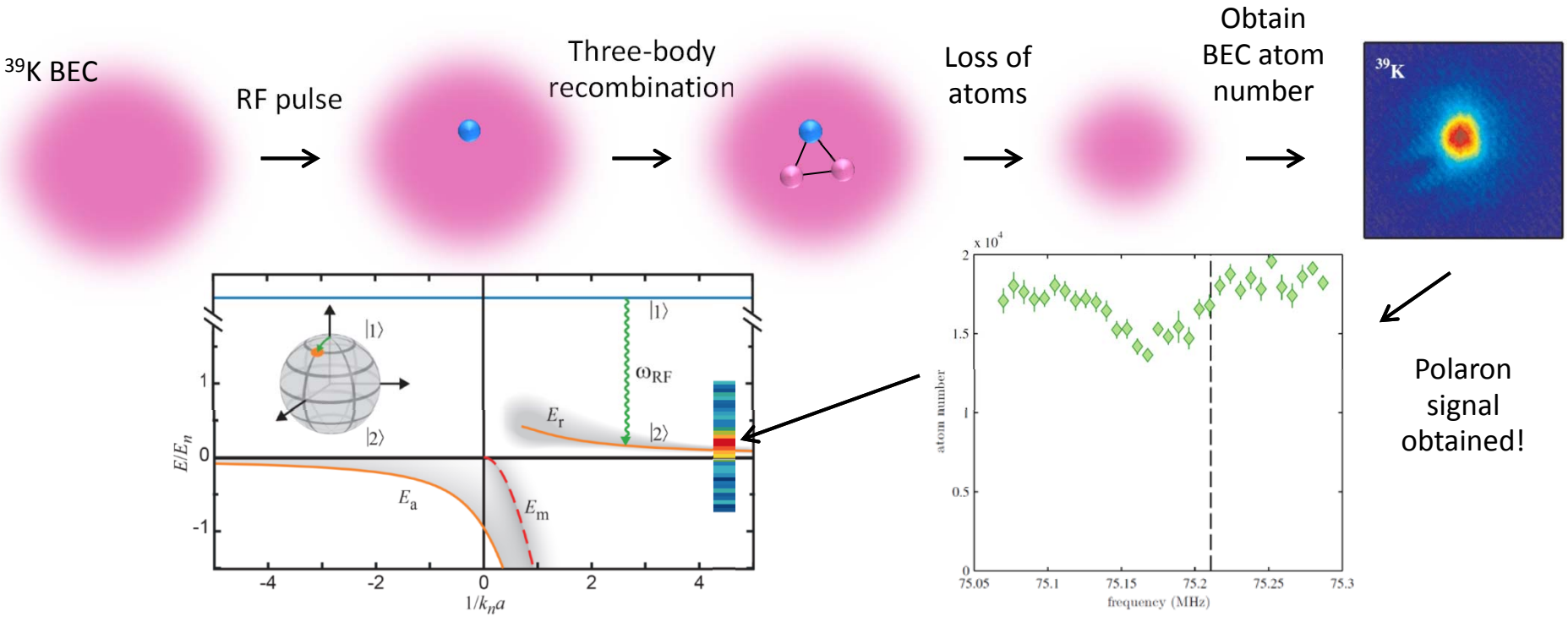


Requires Feshbach resonance
between two hyperfine states

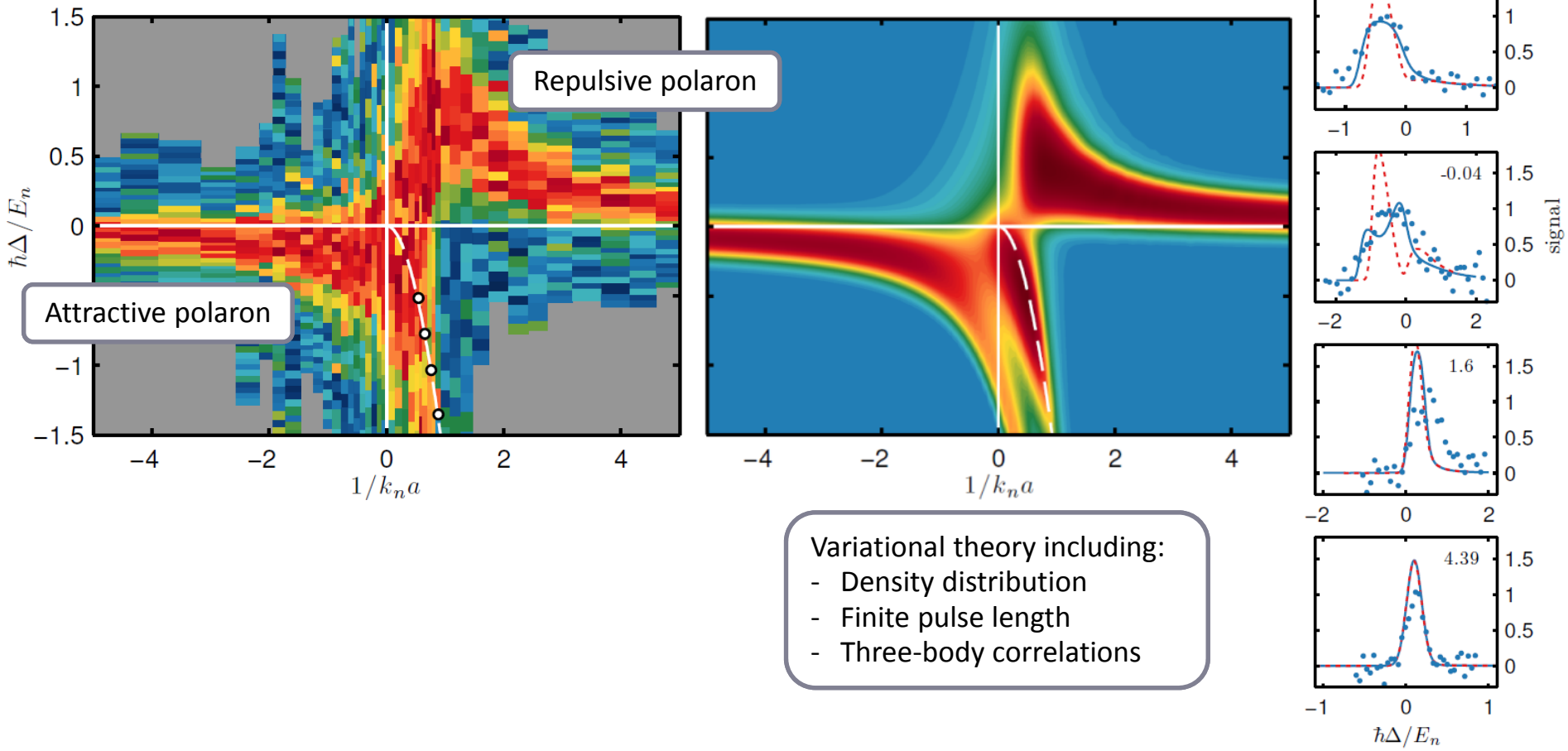


Lysebo, M., and L. Veseth. Phys. Rev. A **81**. 032702 (2010).

Experimental procedure



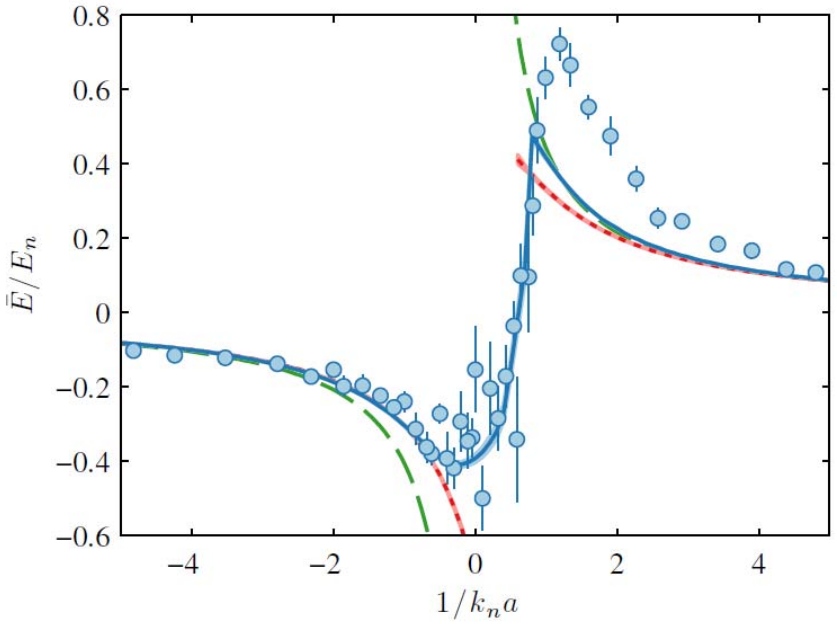
Polaron spectrum



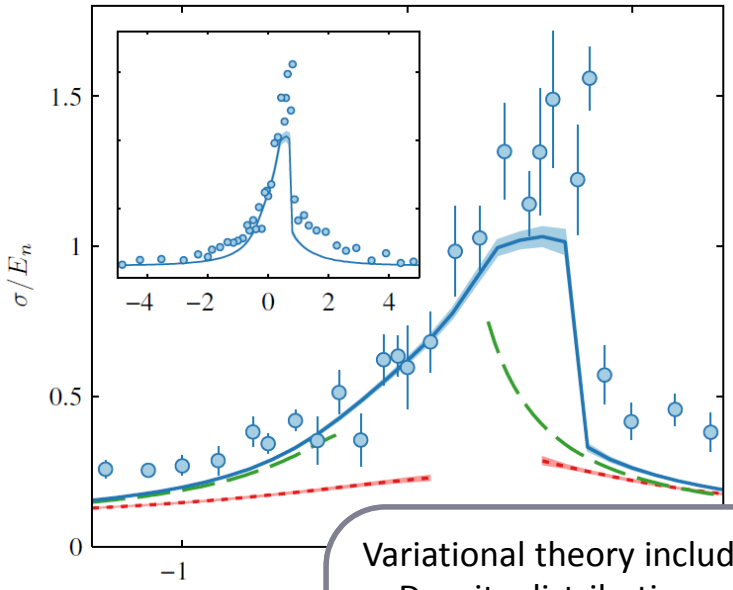
Variational theory including:
- Density distribution
- Finite pulse length
- Three-body correlations

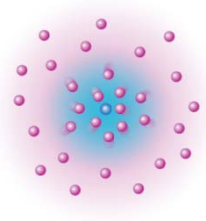
Quantitative analysis

Average energy



Signal width





→ Polaron well-defined and long lived!

Variational theory including:
- Density distribution
- Finite pulse length
- Three-body correlations

- Does **not** include three-body recombination

Conclusion and Outlook

- First observation of the repulsive and attractive polaron in a BEC
- Excellent agreement with theory
- The polaron is long-lived
- Quantum impurities can now be studied in a bosonic environment systematically!

- How does temperature affect the polaron?
- What is the quasiparticle residue of the polaron?
- Dynamical behaviour of the polaron?
- Which role does Efimov physics play?

N. B. Jørgensen *et al.*, Phys. Rev. Lett. **117**, 055302 (2016)

published back-to-back with

M. Hu *et al.*, Phys. Rev. Lett. **117**, 055301 (2016)

EFIMOV PHYSICS IN K-Rb AND K-K

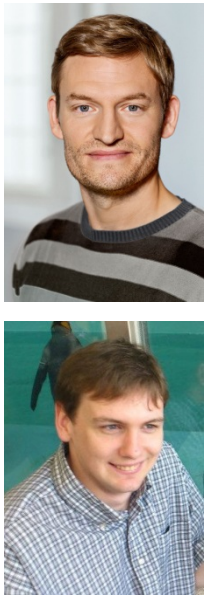
Experimental work:

Nils B. Jørgensen

Lars Wacker

Jacob Sherson

Jan J. Arlt



Theoretical work:

Nikolaj Zinner

Mathias Mikkelsen

L. J. Wacker, N. B. Jørgensen, D. Birkmose, N. Winter, M. Mikkelsen, J. Sherson, N. Zinner, and J. J. Arlt
Phys. Rev. Lett. **117**, 163201 (2016)

POLARONS IN A BOSE-EINSTEIN CONDENSATE

Experimental work:

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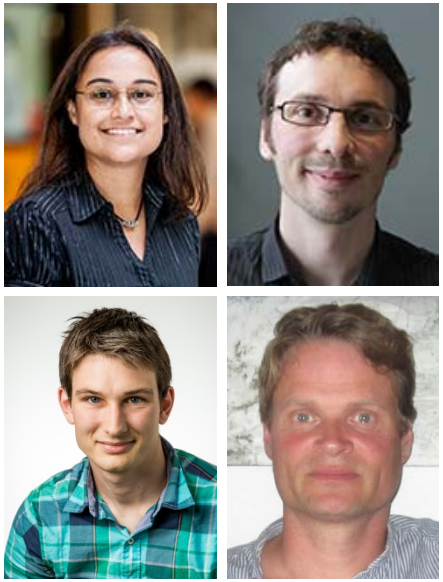
Kristoffer T. Skalmstang

Jan J. Arlt



Theoretical work:

Meera M. Parish

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N. B. Jørgensen, L. Wacker, K. T. Skalmstang, M. M. Parish, J. Levinsen, R. S. Christensen, G. M. Bruun, and J. J. Arlt
Phys. Rev. Lett. **117**, 055302 (2016)

Thank you for your attention!