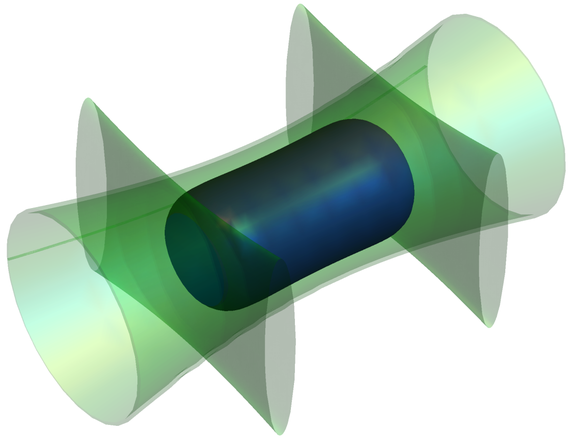
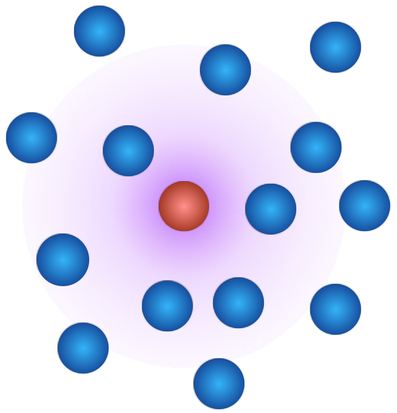
Bose Polarons in a Homogeneous ^{39}K Bose-Einstein Condensate





Christoph Eigen

UNIVERSITY OF CAMBRIDGE

Quantum gases, fundamental interactions and Cosmology,
Pisa, October 28th, 2022

Hadzibabic Group

people

Alec Cao

Jiří Etrych

Gevorg Martirosyan

Lena Dogra

Christopher Ho

Maciej Galka

Nishant Dogra

Zoran Hadzibabic

Martin Gažo

Andrey Karailiev

Paul Wong

Konstantinos Konstantinou

Christoph Eigen

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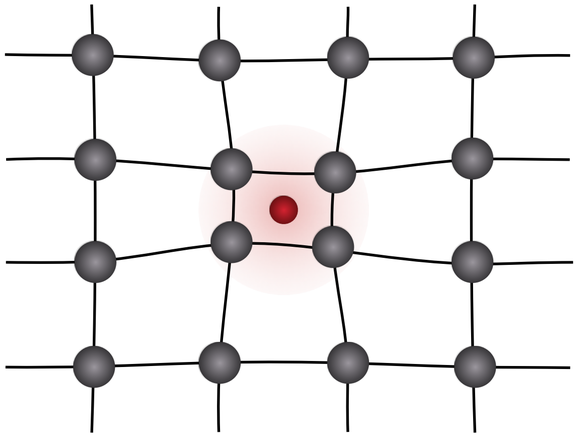
QFC
Pisa, October 28th, 2022

Impurities in a Bose medium

fundamental problem in physics

historically: Landau, Pekar, …



generic!
quantum system + environment

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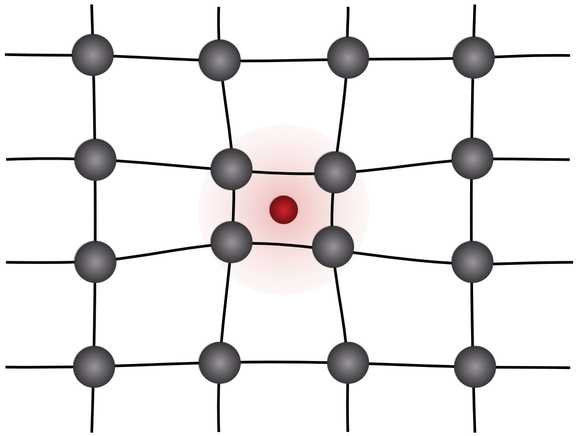
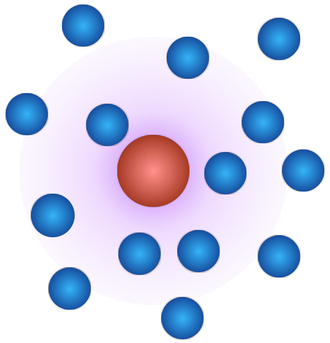


generic!
quantum system + environment

Bose polarons in cold atoms
(in harmonic traps)



JILA, Aarhus, MIT, Paris…

Some highlights:

Hu *et al.*, PRL **117**, 055301 (2016)

Jørgensen *et al.*, PRL **117**, 055302 (2016)

Yan *et al.*, Science **368**, 190 (2020)

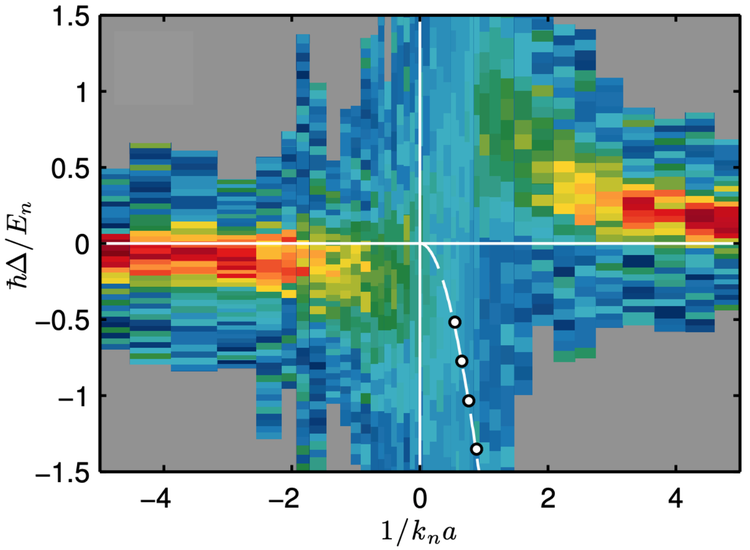
Skou *et al.*, Nat. Phys. **17**, 731 (2021)

Cayla *et al.*, arXiv:2204.10697 (2022)

see also Fermi polarons,
Rydberg impurities, etc.

injection spectrum

from Jørgensen *et al.*, PRL **117**, 055302 (2016)



many rich theories…

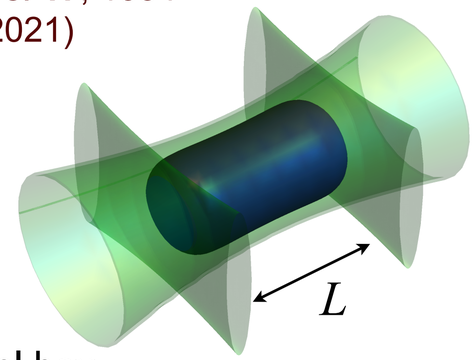
Tempere, Bruun, Massignan, Enss, Schmidt, Demler, Grusdt, Gurarie, Giorgini, Parish, Levinsen, Lewenstein, Devreese, Naidon, Schmelcher, Busch, …

many aspects understood, but
questions remain…

Homogeneous Bose-Einstein condensates

homogeneous density

review: N. Navon *et al*., Nat. Phys. **17**, 1334 (2021)



optical box

A.L. Gaunt *et al*., PRL **110**, 200406 (2013)

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ultracold ^{39}K Bose gas in a box

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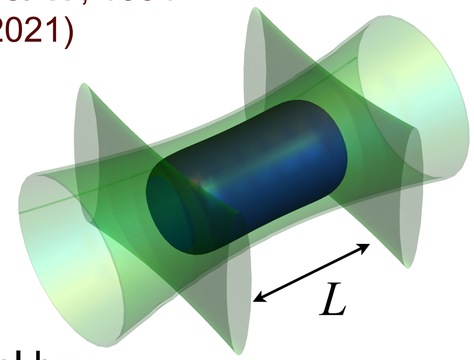

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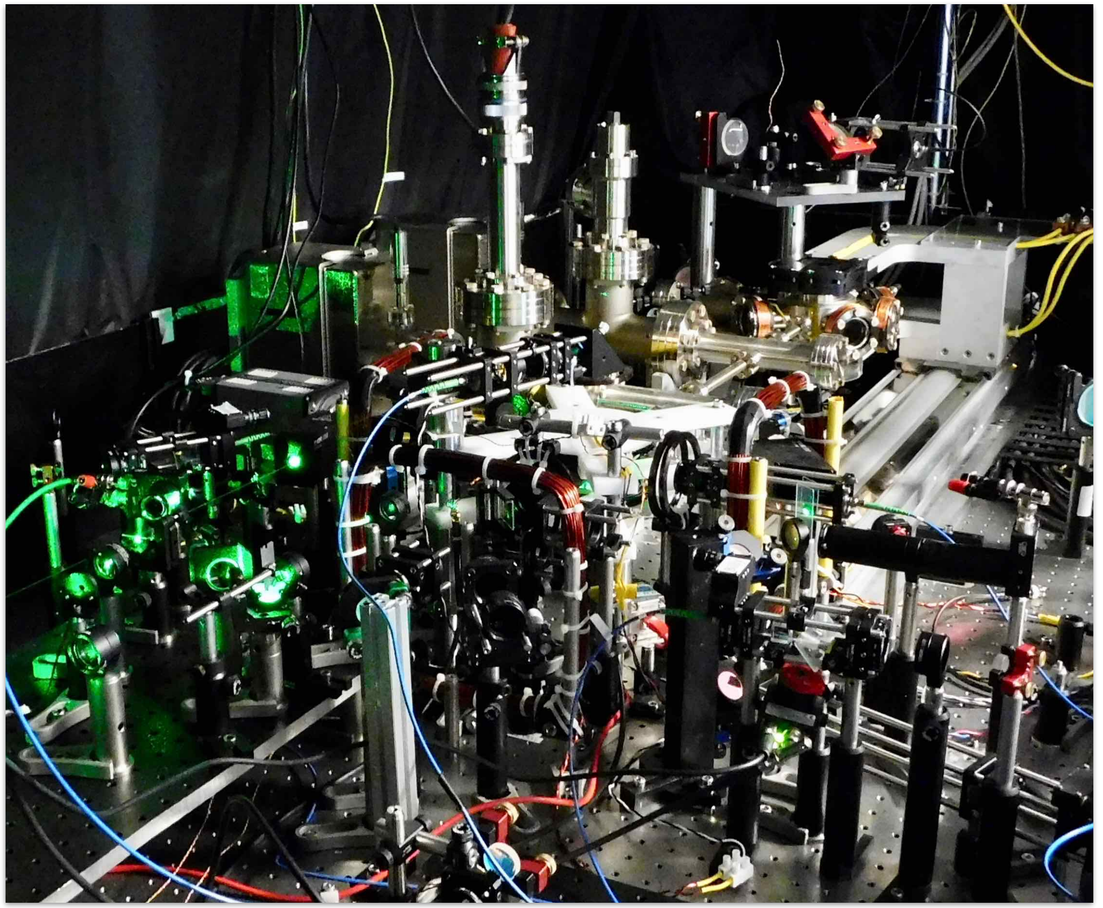

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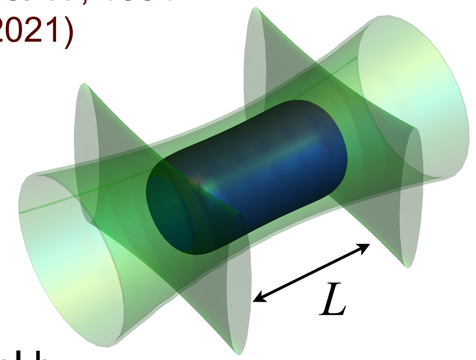

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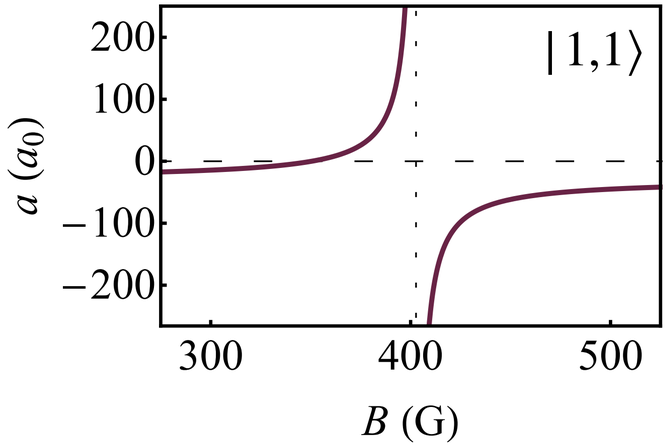


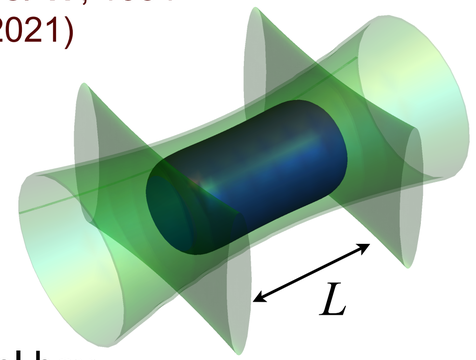
for any single resonance, full control

G. Roati *et al.*, PRL **99**, 010403 (2007)

Homogeneous Bose mixtures?

homogeneous density

review: N. Navon *et al.*, Nat. Phys. **17**, 1334 (2021)



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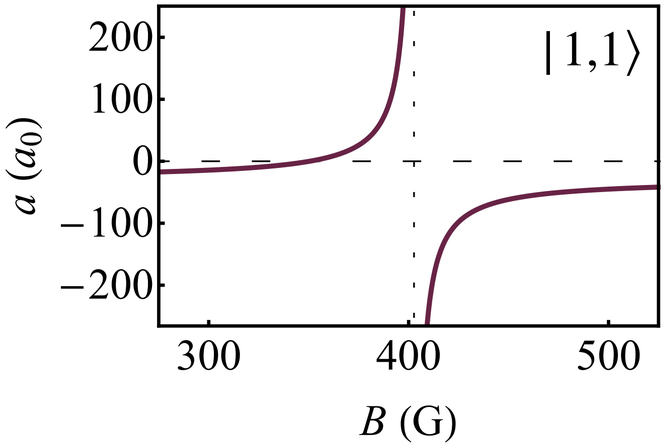

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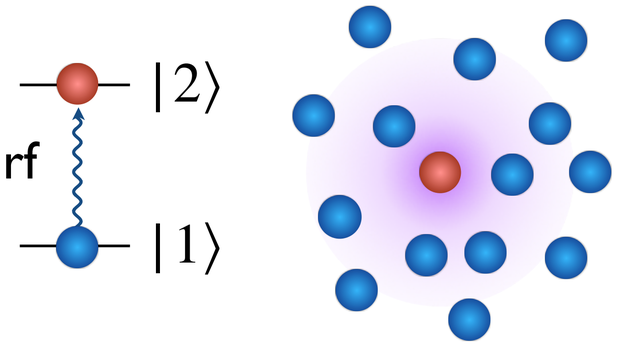
another spin state mobile equal mass impurities/ Bose mixtures



rich Feshbach resonance landscape for tuning intra- and inter-state interactions…

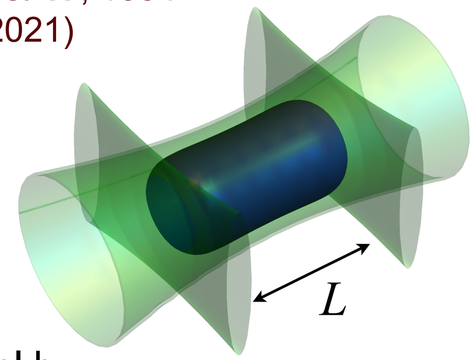
3 interactions strengths

a, a_B, a_I

Homogeneous Bose mixtures?

homogeneous density

review: N. Navon *et al.*, Nat. Phys. **17**, 1334 (2021)



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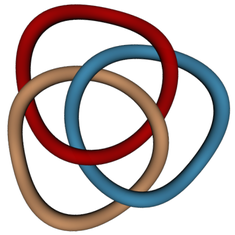
ultracold ^{39}K Bose gas in a box

rich interaction landscapes in ^{39}K

few-body

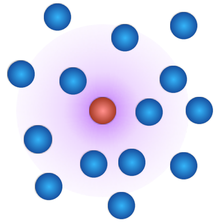
- ✦ testbed for few-body physics



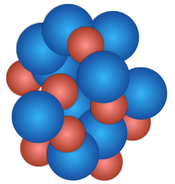
Efimov trimers quantum mechanical analogue of Borromean rings

many-body

- ✦ interaction control (also switches)
- ✦ quantum mixtures



polarons



droplets

solitons, and more…

Homogeneous Bose mixtures?

homogeneous density

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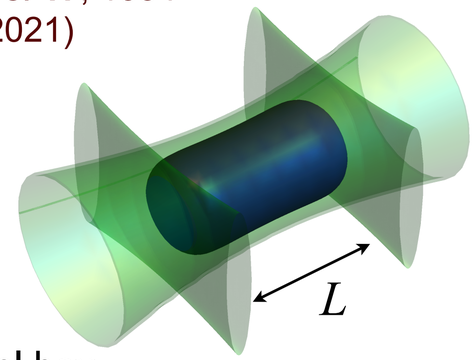

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rich interaction landscapes in ^{39}K

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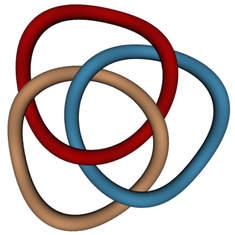
- testbed for few-body physics



Etrych *et al.*, arXiv:2208.13766 (2022)

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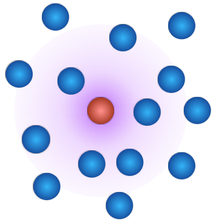

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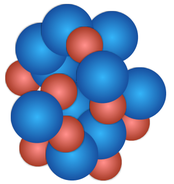

droplets

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suitable states? pinpointing Feshbach resonances in 39K

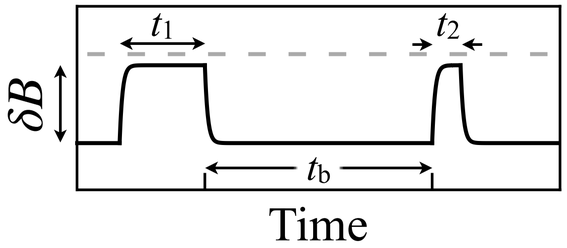
Pinpointing Feshbach resonances in ^{39}K

bound-state spectroscopy

Etrych *et al.*, arXiv:2208.13766 (2022)

e.g. atom-molecule coherence

following E. A. Donley *et al.*, Nature **417**, 529 (2002)



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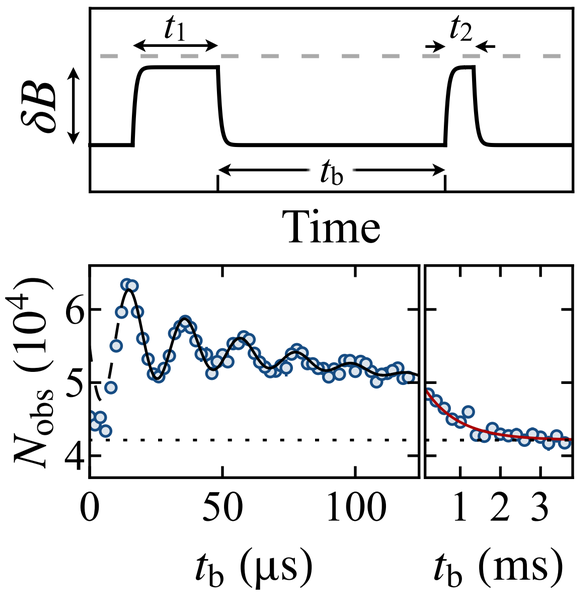

measure dimer binding energy
$E_b = \hbar\omega_b$ down to a few kHz!

$$a \approx \sqrt{\hbar/(m\omega_b)} + \bar{a}$$

$$\bar{a} = 0.956 a_{vdW}$$

$a_{vdW} = 64.6 a_0$ for ^{39}K

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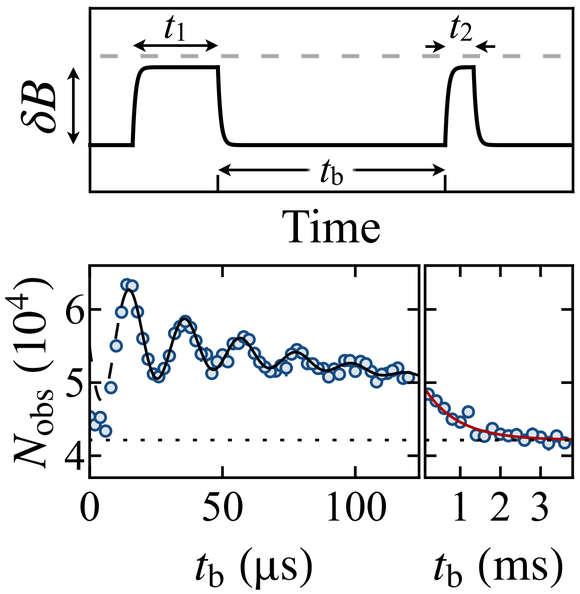

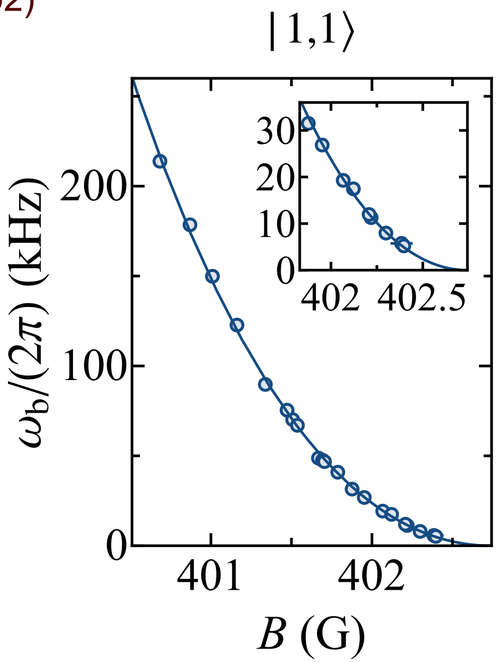

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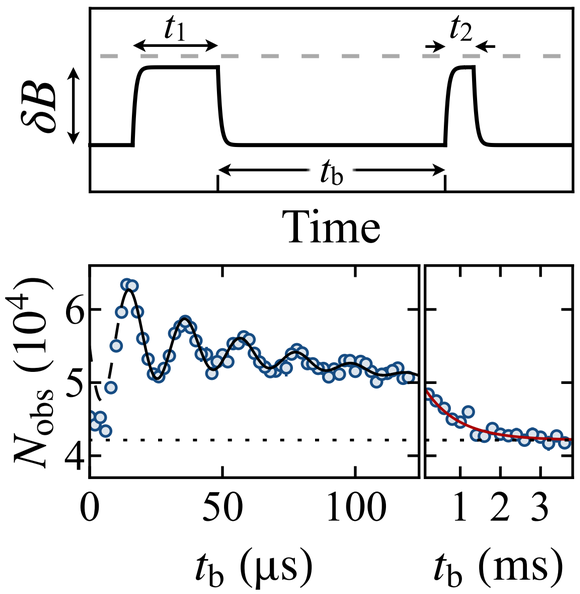

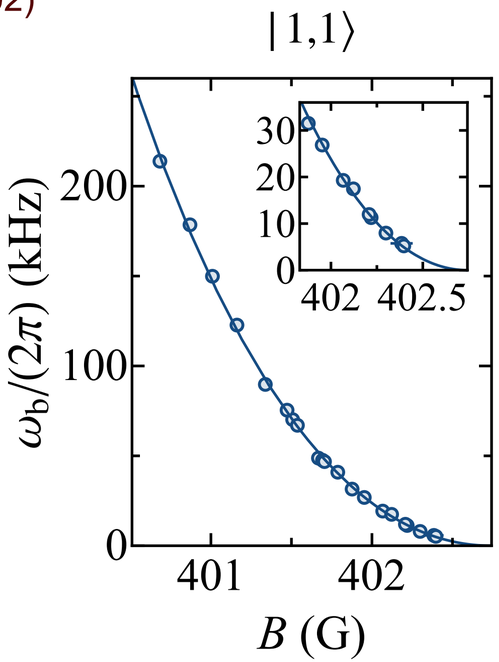

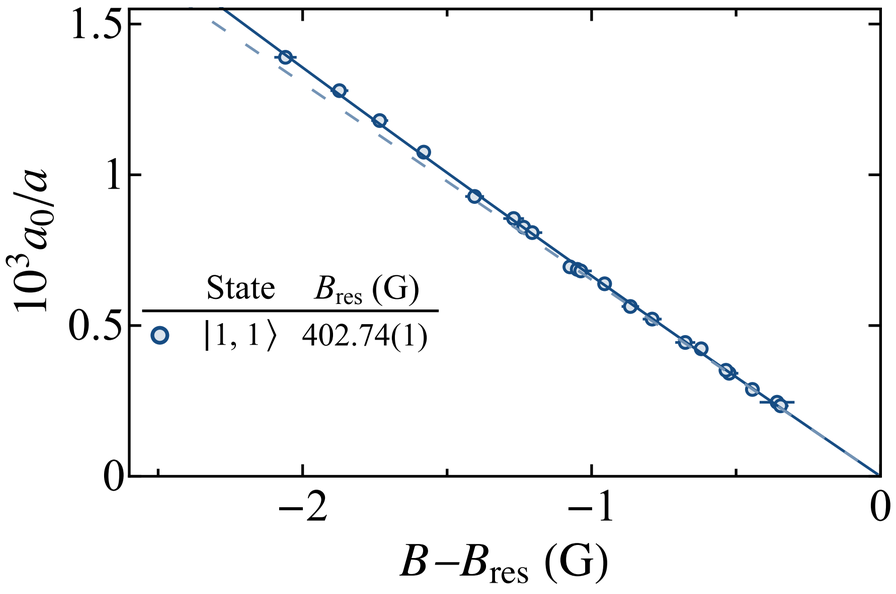

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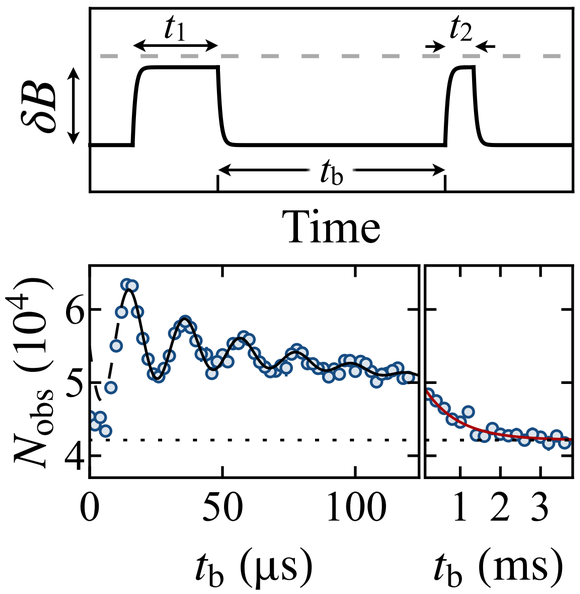

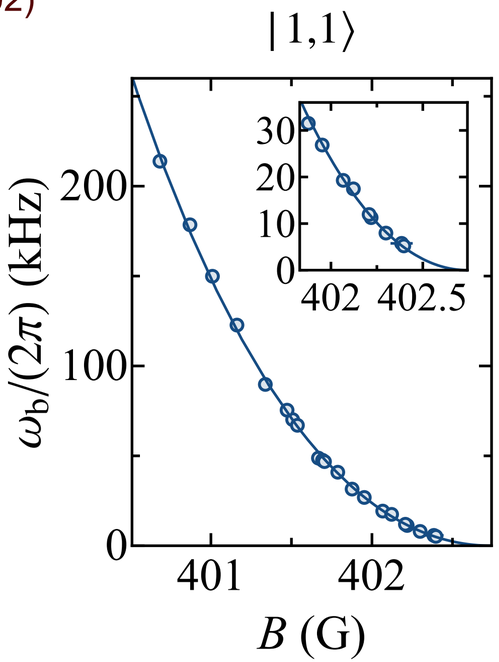

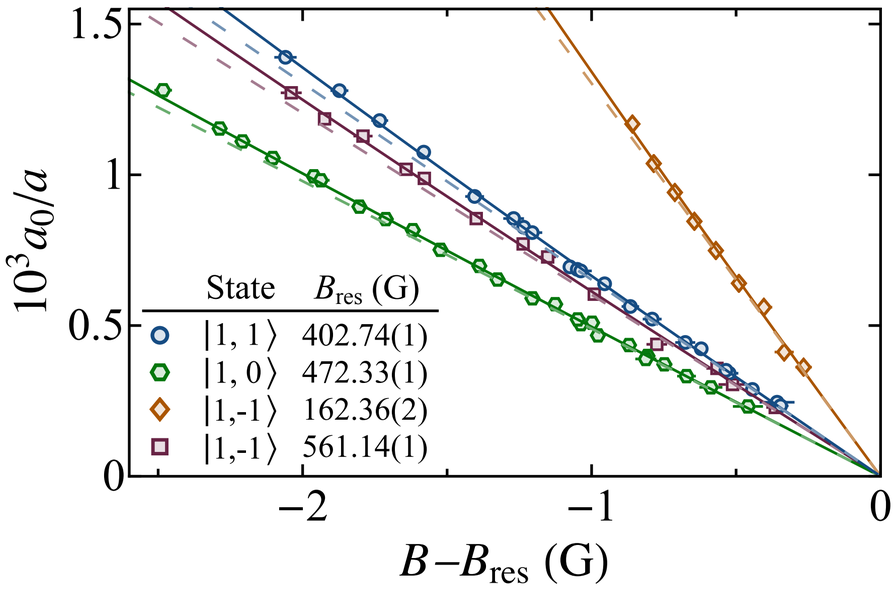

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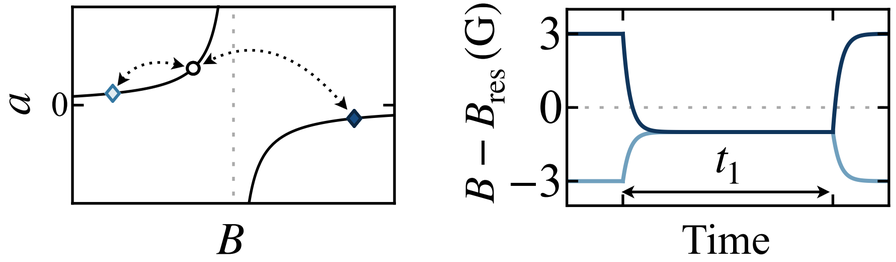
Pinpointing Feshbach resonances in ^{39}K

benchmarking quench-based loss spectroscopy

Etrych *et al.*, arXiv:2208.13766 (2022)

$|1,1\rangle$ - know that $B_{\mathrm{res}} = 402.74(1)\,\mathrm{G}$



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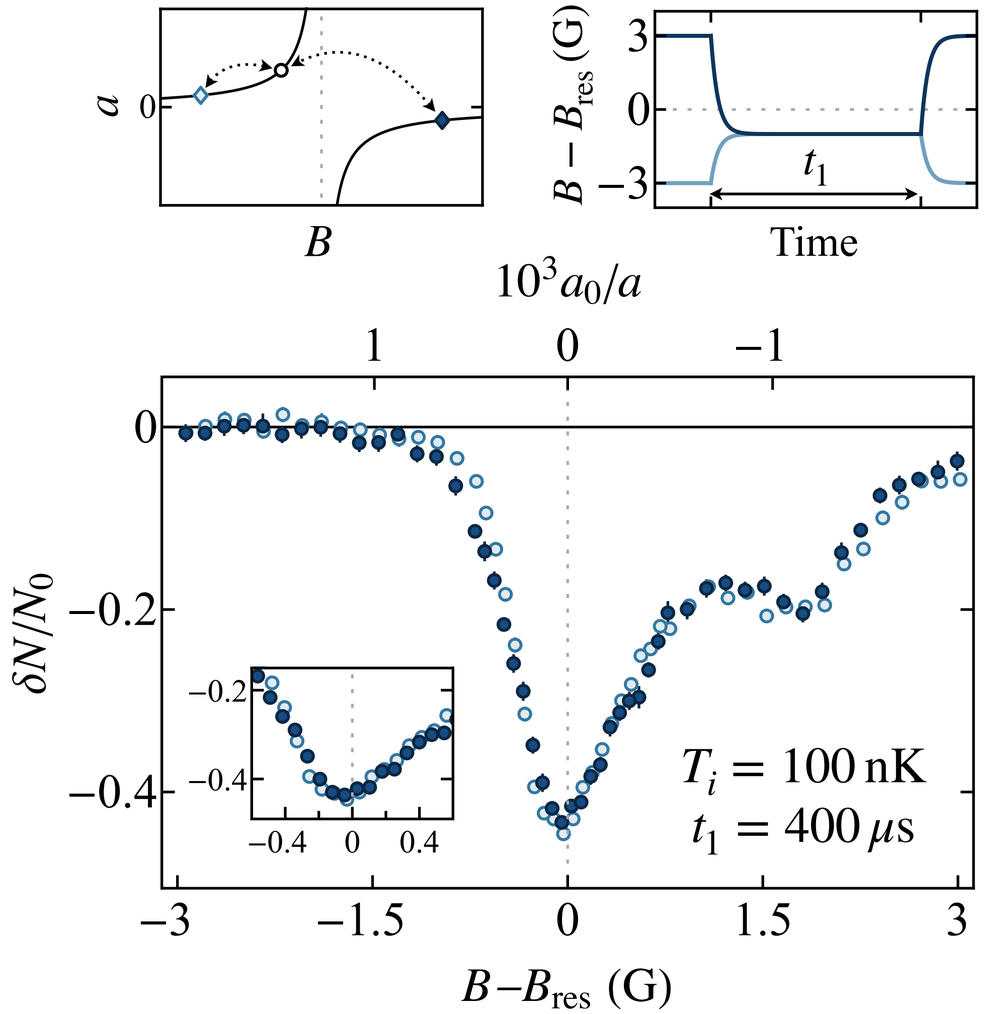

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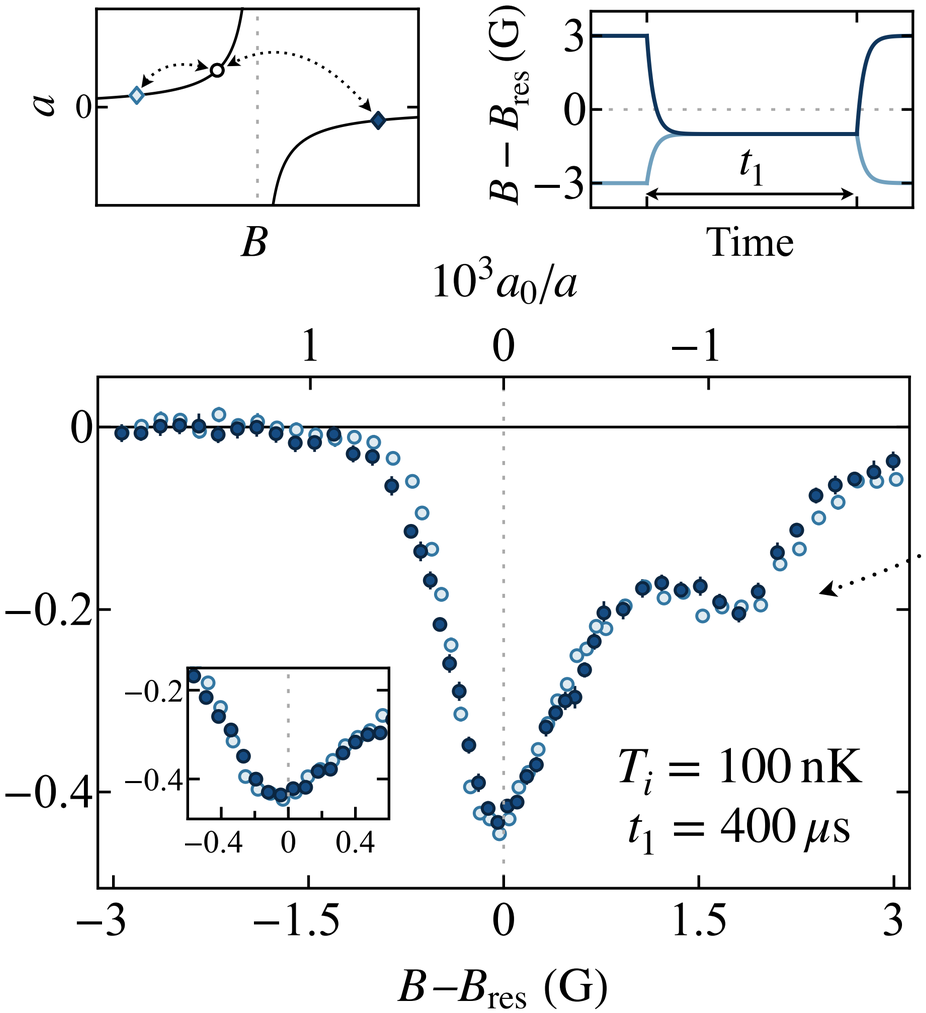

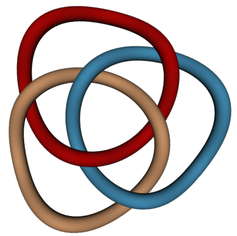

Efimov trimers quantum mechanical analogue of Borromean rings

Test Efimov universalities across the Feshbach resonance

Systematic breakdown of Efimov-van-der-Waals universality

$a_{-} = -13(1)\,a_{\mathrm{vdW}}$

Etrych *et al.*, arXiv:2208.13766 (2022)

see also:
Chapurin *et al.*, PRL **123**, 233402 (2019)
Xie *et al.* PRL **125**, 243401 (2021)

Pinpointing Feshbach resonances in ^{39}K

benchmarking quench-based loss spectroscopy

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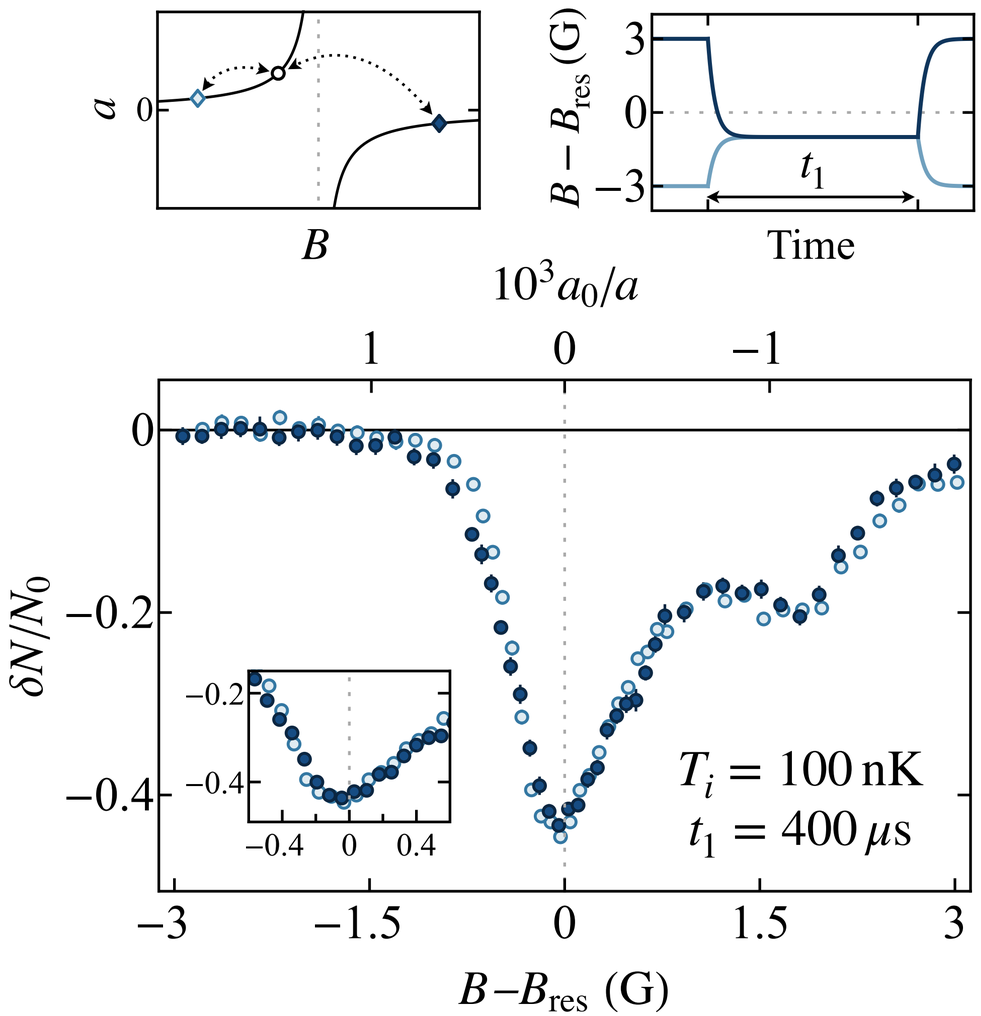

characterized 8 intrastate resonances!

$\lvert F, m_F\rangle$	B_{res} (G)	$a_{\mathrm{bg}}\Delta$ (a_0 G)	B_{zero} (G)	$\mu(\mu_{\mathrm{B}})$
$\lvert 1,1\rangle$	25.91(6)	-	-	−0.605
$\lvert 1,1\rangle$	402.74(1)	1530(20)	350.4(1)[a]	−0.961
$\lvert 1,1\rangle$	752.3(1)[b]	-	-	−0.987
$\lvert 1,0\rangle$	58.97(12)	-	-	−0.337
$\lvert 1,0\rangle$	65.57(23)	-	-	−0.370
$\lvert 1,0\rangle$	472.33(1)	2040(20)	393.2(2)	−0.945
$\lvert 1,0\rangle$	491.17(7)	140(30)	490.1(2)	−0.949
$\lvert 1,-1\rangle$	33.5820(14)[c]	−1073	/	0.324
$\lvert 1,-1\rangle$	162.36(2)	760(20)	/	−0.489
$\lvert 1,-1\rangle$	561.14(2)	1660(20)	504.9(2)	−0.959

a) Fattori *et al.*, PRL **101**, 190405 (2008) b) D'Errico *et al.*, NJP **9**, 223 (2007)
c) Chapurin *et al.*, PRL **123**, 233402 (2019)

Pinpointing Feshbach resonances in ^{39}K

six previously predicted but experimentally elusive interstate resonances

Etrych *et al.*, arXiv:2208.13766 (2022)

Intrastate

$\|F, m_F\rangle$	B_{res} (G)	$a_{\mathrm{bg}}\Delta$ (a_0 G)	B_{zero} (G)	$\mu(\mu_B)$
$\|1,1\rangle$	25.91(6)	-	-	−0.605
$\|1,1\rangle$	402.74(1)	1530(20)	350.4(1)[a]	−0.961
$\|1,1\rangle$	752.3(1)[b]	-	-	−0.987
$\|1,0\rangle$	58.97(12)	-	-	−0.337
$\|1,0\rangle$	65.57(23)	-	-	−0.370
$\|1,0\rangle$	472.33(1)	2040(20)	393.2(2)	−0.945
$\|1,0\rangle$	491.17(7)	140(30)	490.1(2)	−0.949
$\|1,-1\rangle$	33.5820(14)[c]	−1073[c]	/	0.324
$\|1,-1\rangle$	162.36(2)	760(20)	/	−0.489
$\|1,-1\rangle$	561.14(2)	1660(20)	504.9(2)	−0.959

Interstate

$\|F, m_F\rangle_1 + \|F, m_F\rangle_2$	B_{res} (G)	$a_{\mathrm{bg}}\Delta$ (a_0 G)	$\mu_1(\mu_B)$	$\mu_2(\mu_B)$
$\|1,1\rangle + \|1,0\rangle$	25.81(6)	-	−0.605	−0.155
$\|1,1\rangle + \|1,0\rangle$	39.81(6)	-	−0.651	−0.235
$\|1,1\rangle + \|1,0\rangle$	445.42(3)	1110(40)	−0.967	−0.939
$\|1,1\rangle + \|1,-1\rangle$	77.6(4)	-	−0.747	0.034
$\|1,1\rangle + \|1,-1\rangle$	501.6(3)	-	−0.973	−0.948
$\|1,0\rangle + \|1,-1\rangle$	113.76(1)[d]	715(7)[d]	−0.569	−0.215
$\|1,0\rangle + \|1,-1\rangle$	526.21(5)	970(50)	−0.956	−0.953

d) Tanzi *et al.*, PRA **98**, 062712 (2018) - used for previous ^{39}K polarons

a) Fattori *et al.*, PRL **101**, 190405 (2008) b) D'Errico *et al.*, NJP **9**, 223 (2007)
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Collaboration with Jeremy Hutson;
two-body coupled-channel calculations

Pinpointing Feshbach resonances in ^{39}K

six previously predicted but experimentally elusive interstate resonances

Etrych *et al.*, arXiv:2208.13766 (2022)

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Collaboration with Jeremy Hutson;
two-body coupled-channel calculations

445.42(3)G

$a_B \approx 50a_0$
$a_I \approx -65a_0$

526.21(5)G

$a_B \approx 18a_0$
$a_I \approx -64a_0$

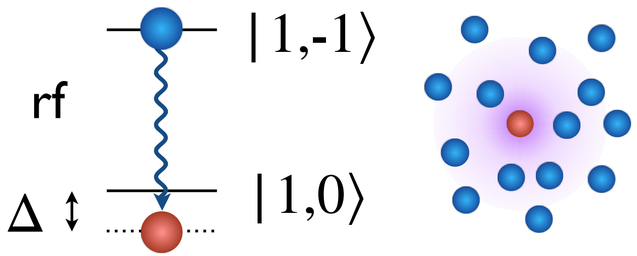
tuneable interstate interactions a

Weakly interacting Bose polarons

benchmarking our system

protocol

- prepare a BEC in $|1,-1\rangle$ near interstate resonance (526G)
- rf injection to $|1,0\rangle$ to measure excitation spectrum
- atom loss as the observable (after long times)



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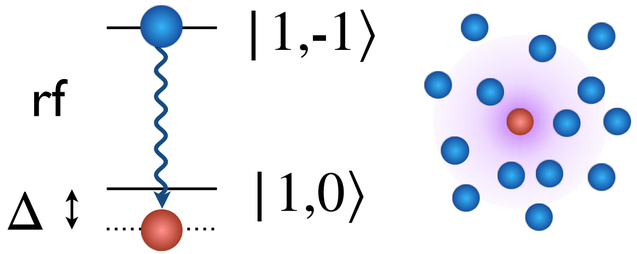

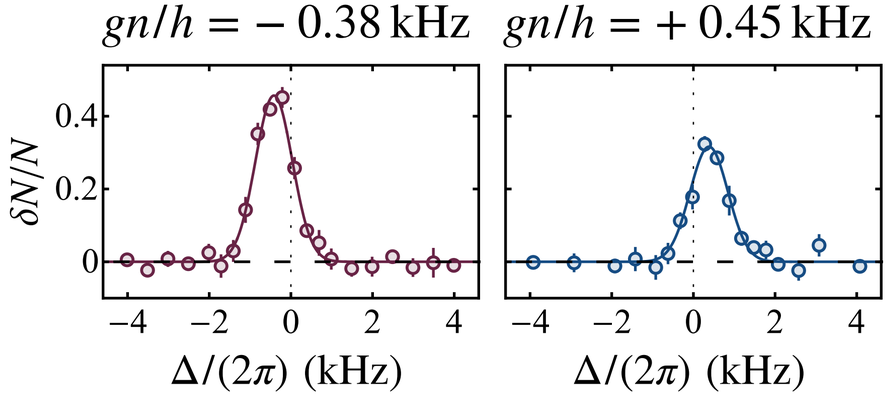

narrow!
little technical broadening
(800 μs pulse,
$\lesssim$ 15 % transfer)

In weakly interacting limit (clock shifts):

$$\hbar\bar{\Delta} = 4\pi\hbar^2 an/m = gn$$

Weakly interacting Bose polarons

benchmarking our system

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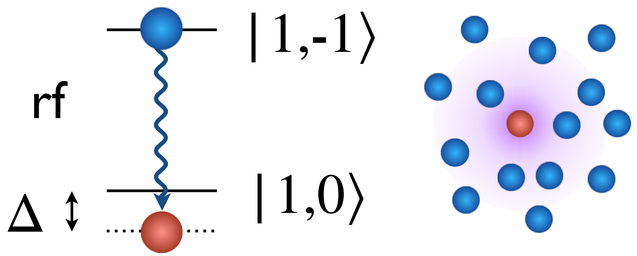

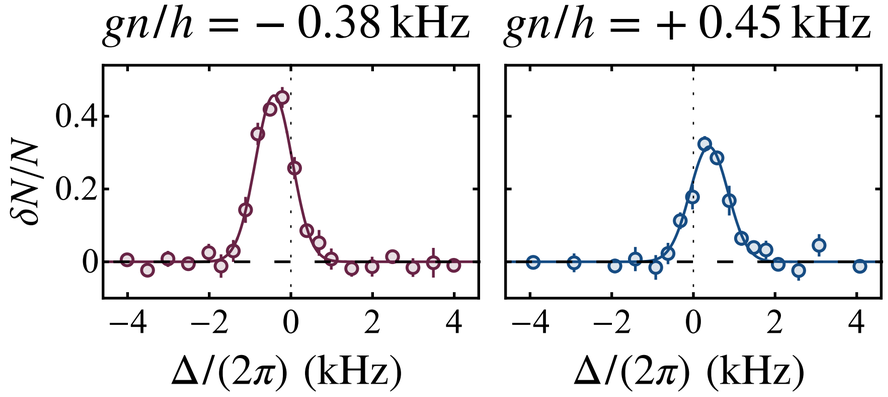

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In weakly interacting limit (clock shifts):

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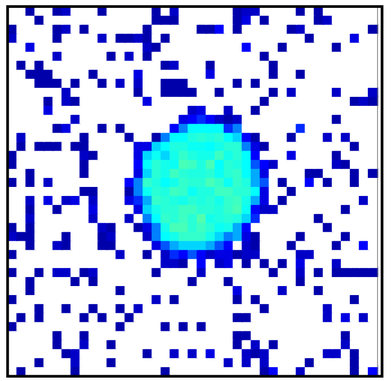
in situ image of impurities after injection



Weakly interacting Bose polarons

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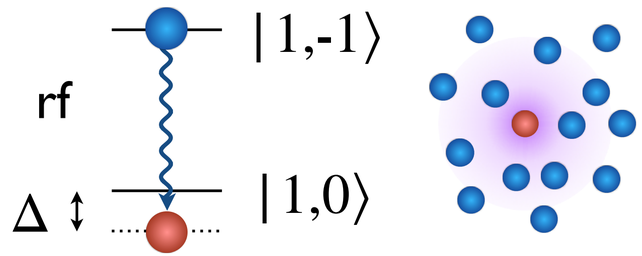

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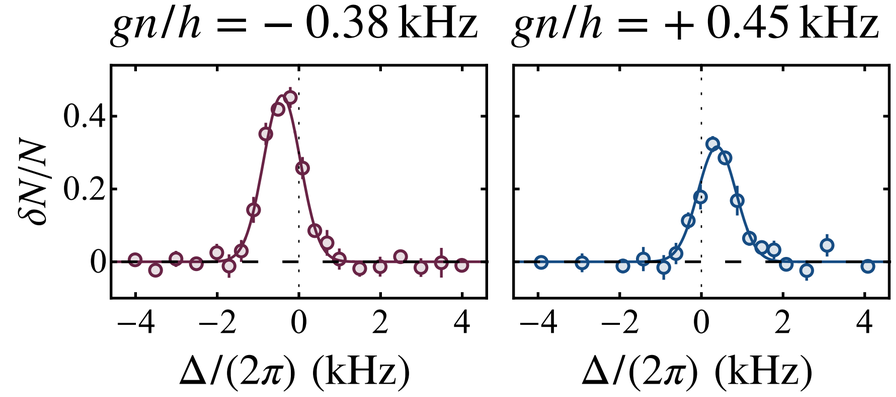
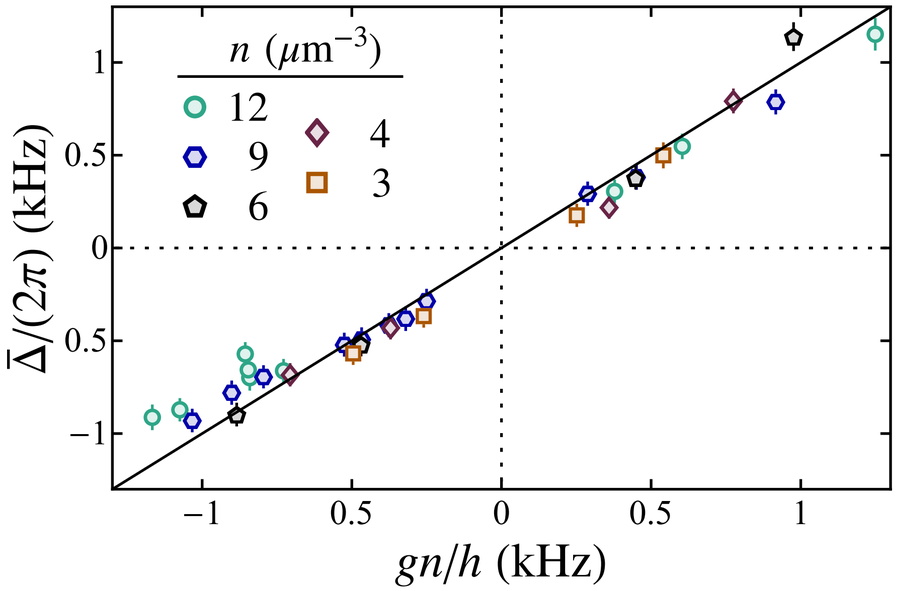




narrow!
little technical broadening
(800 μs pulse, $\lesssim$ 15 % transfer)

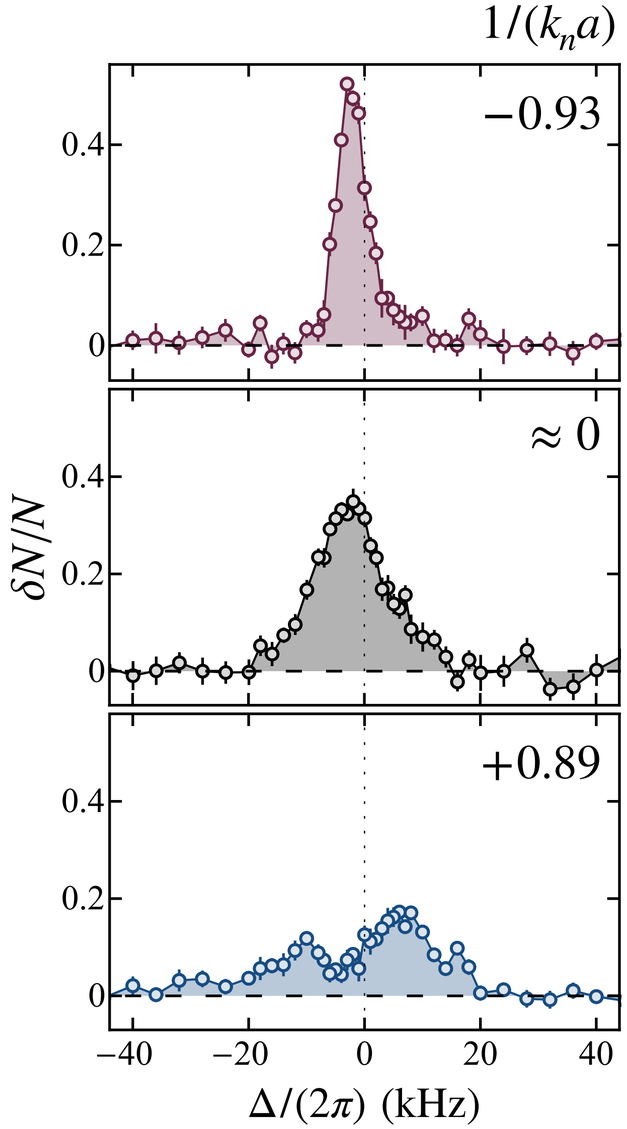
benchmark ✓

next:
larger $|a|$?

Strongly interacting Bose polarons

preliminary!

exploring the polaron spectrum



$|1,-1\rangle$

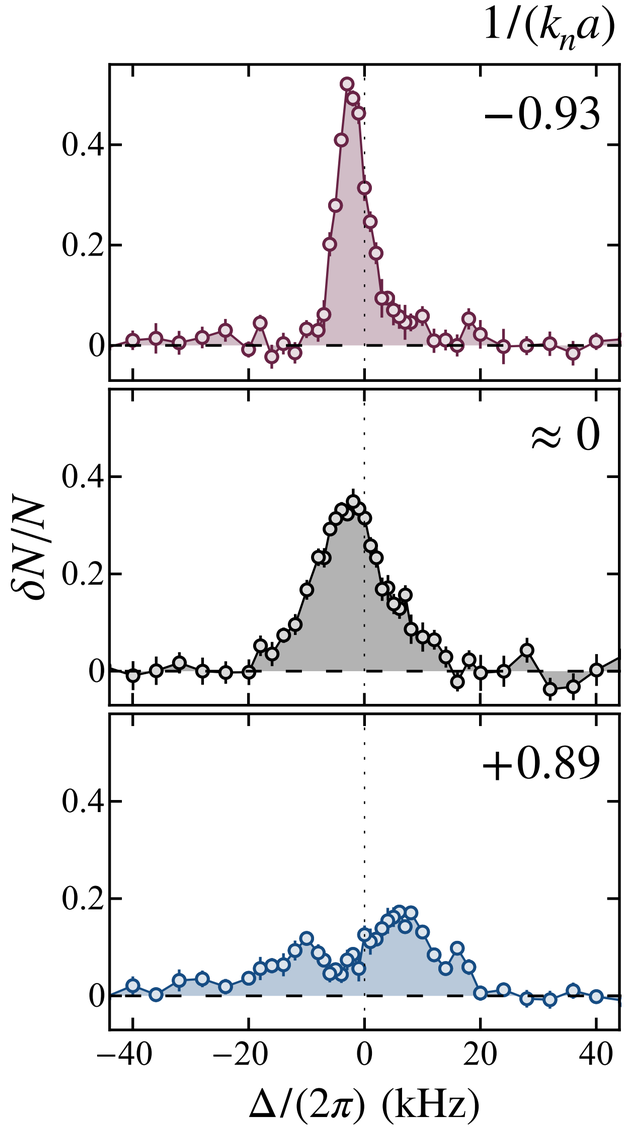
natural units?

$k_n = (6\pi^2 n)^{1/3}$ $\quad$ $E_n = \hbar^2 k_n^2/(2m)$

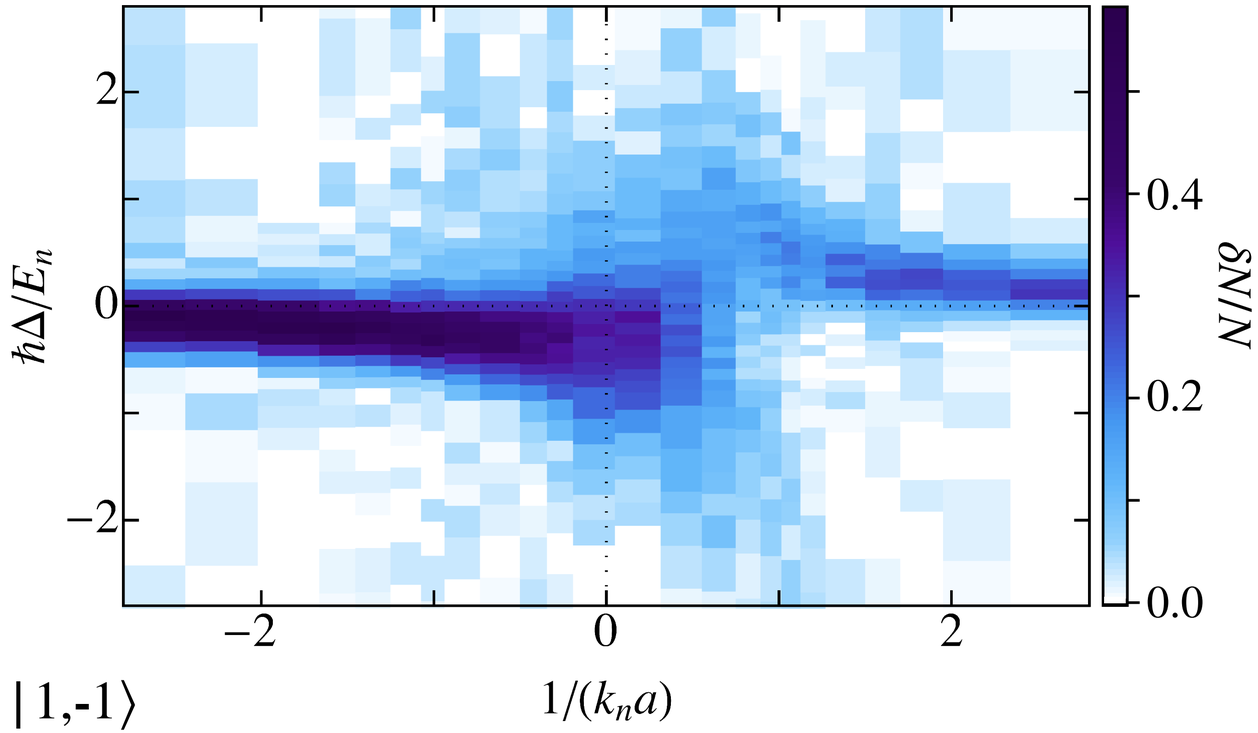
Strongly interacting Bose polarons

preliminary!

exploring the polaron spectrum



fix $k_n = 8.7\mu\text{m}^{-1}$, vary a



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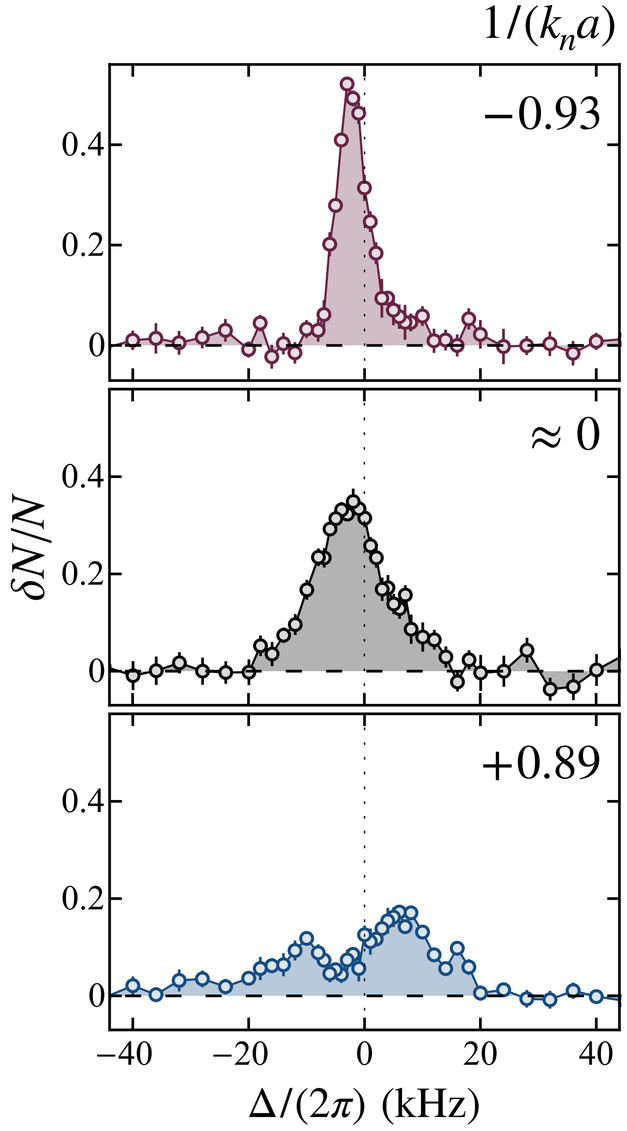

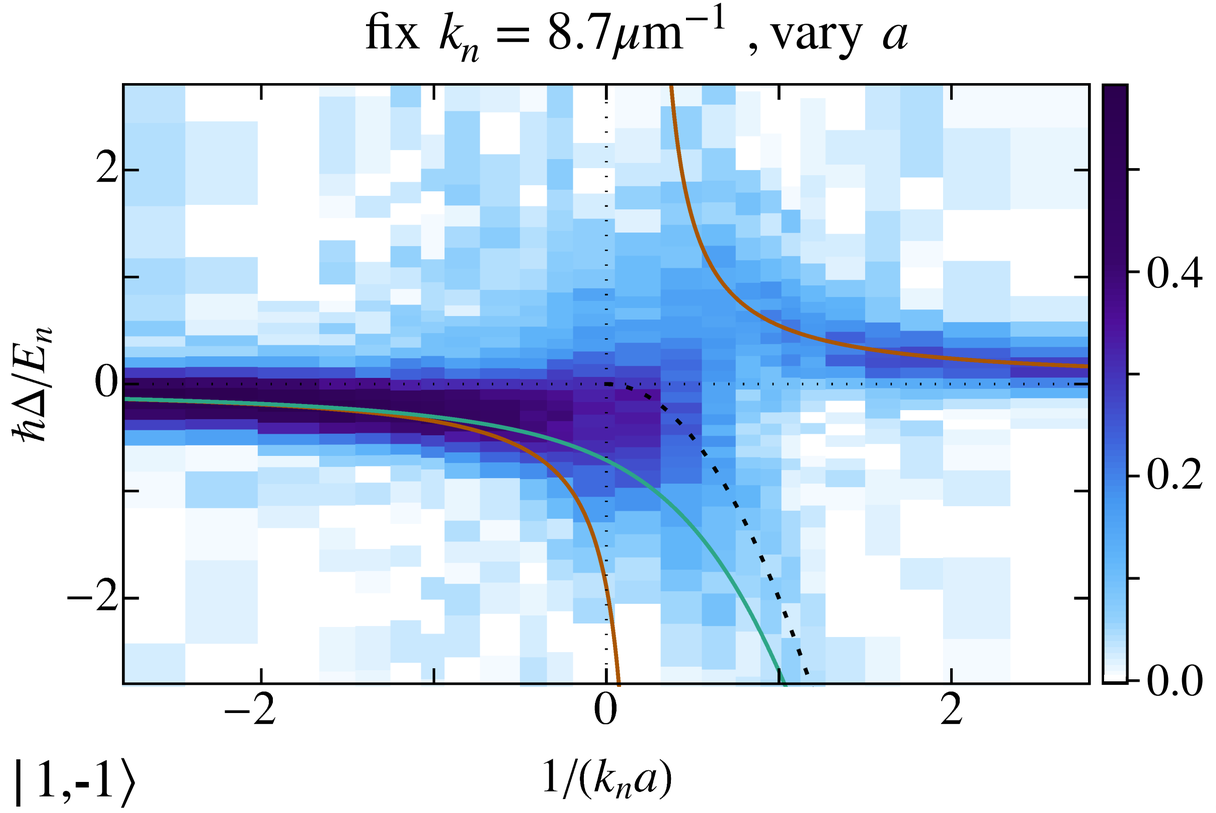

simple theories
(no free parameters!)

--- dimer

shifted mean-field

variational ansatz

natural units?

$k_n = (6\pi^2 n)^{1/3}$ $\quad E_n = \hbar^2 k_n^2/(2m)$

theory:
Tempere, Bruun, Massignan, Enss, Schmidt, Demler, Grusdt, Gurarie, Giorgini, Parish, Levinsen, Lewenstein, Devreese, Naidon, Schmelcher, Busch, …

Strongly repulsive Bose polarons

preliminary!

exploring the polaron spectrum

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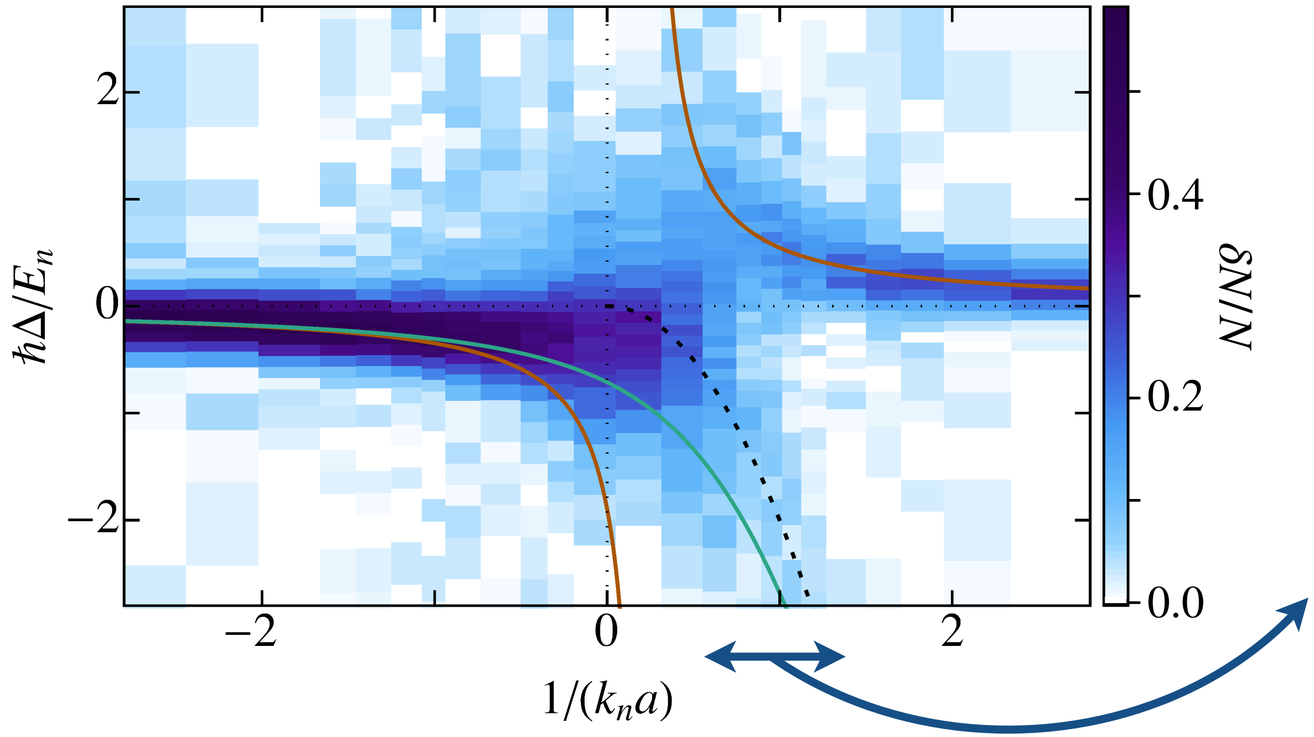
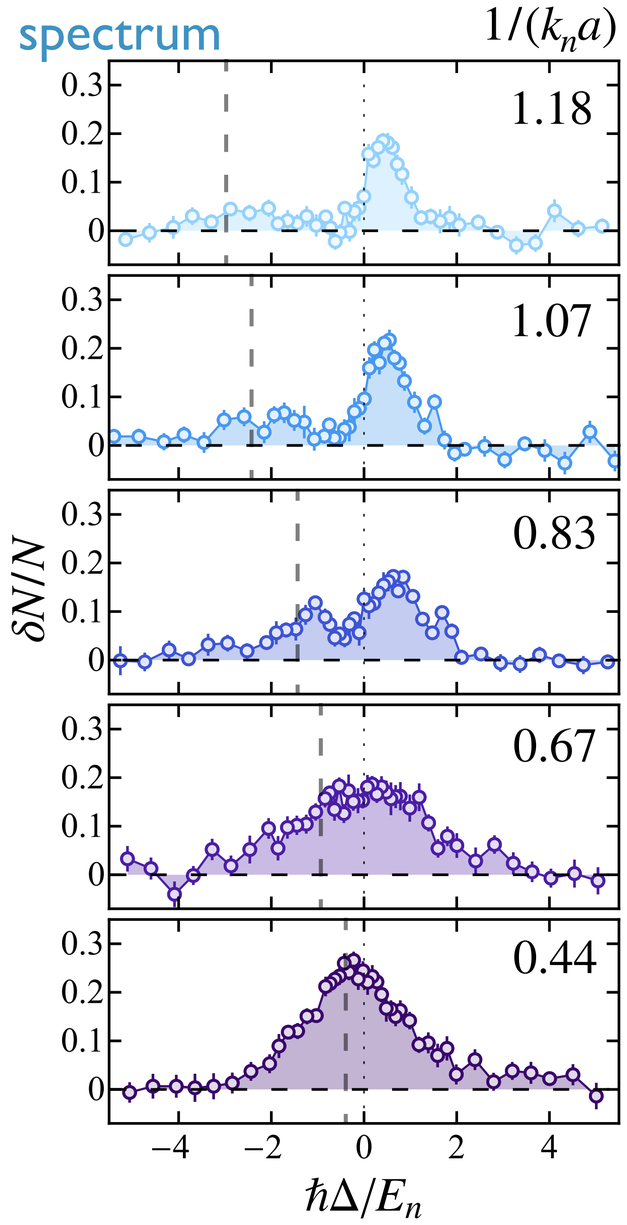
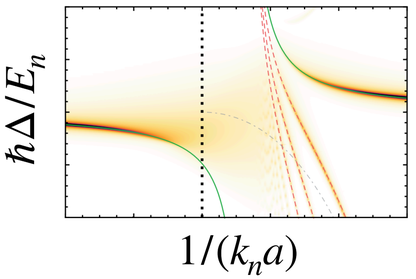




novel many-body state?



Y. E. Shchadilova *et al.*, PRL **117**, 113002 (2016)

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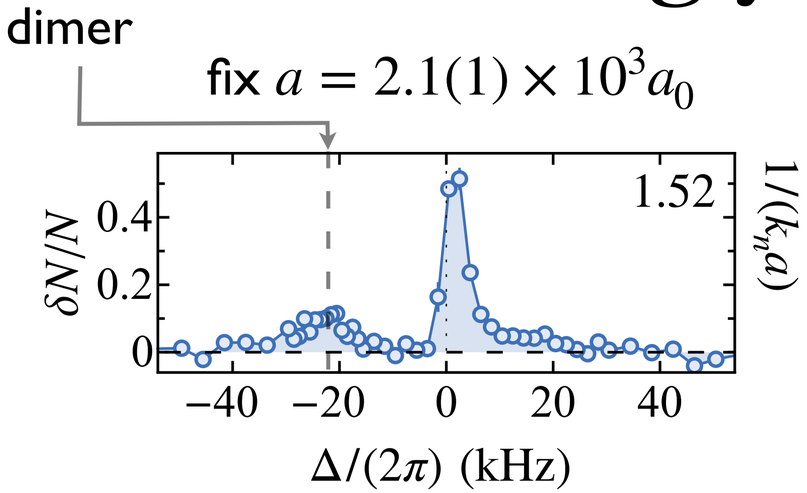
Strongly repulsive Bose polarons

preliminary!



nature of dimer-like peak?

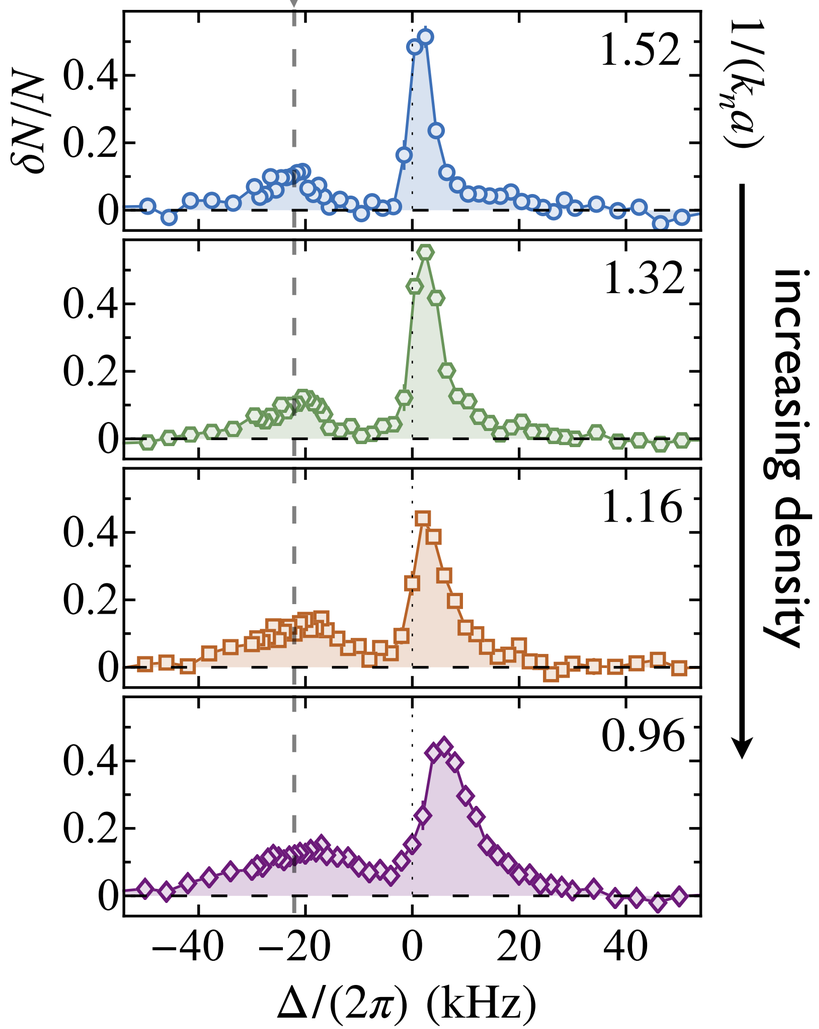
vary density

Strongly repulsive Bose polarons

preliminary!

dimer

fix $a = 2.1(1) \times 10^3 a_0$



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both peaks shift and broaden!

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$|1,0\rangle$

Strongly repulsive Bose polarons

preliminary!

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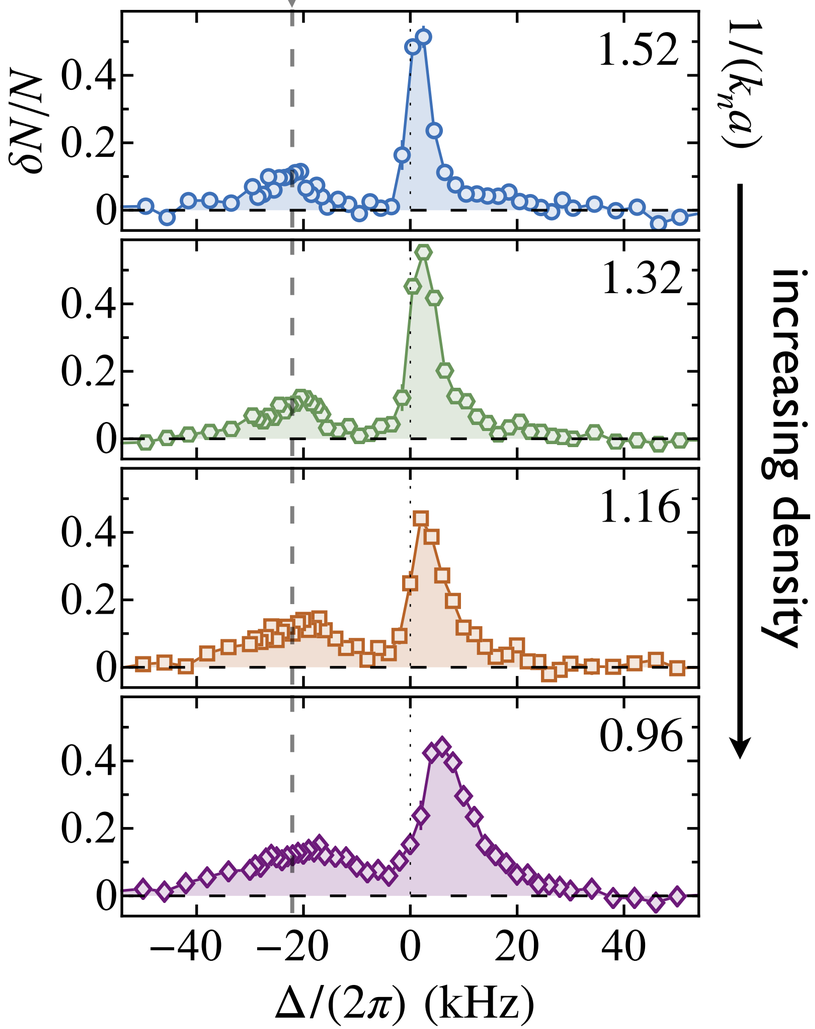

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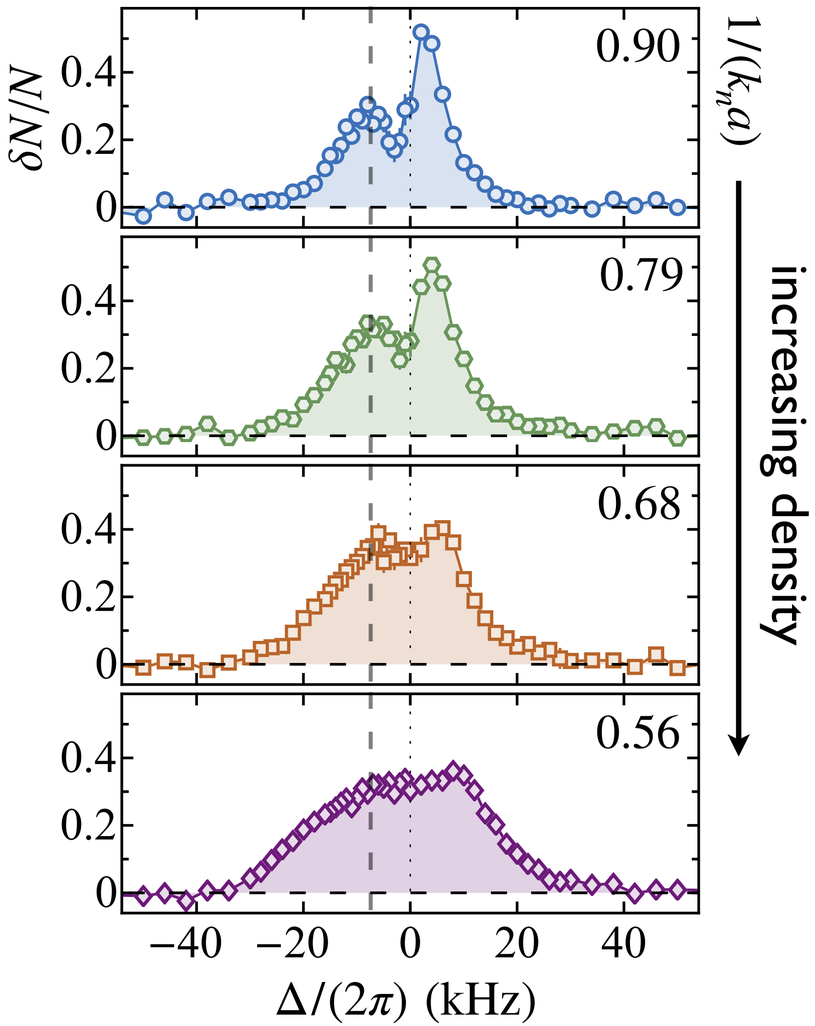


Strongly repulsive Bose polarons

preliminary!

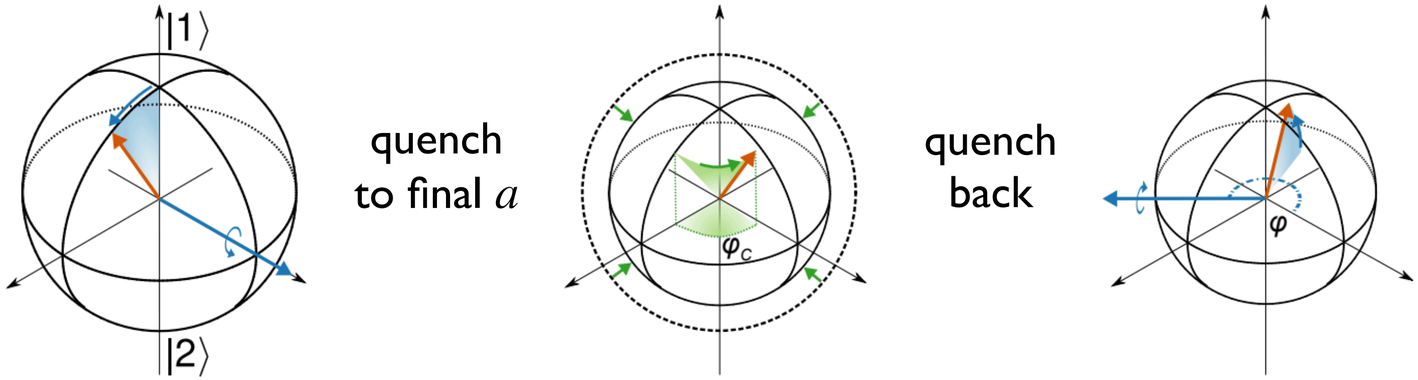
many-body interferometry

$|1,-1\rangle$

inject impurity at low $|a|$

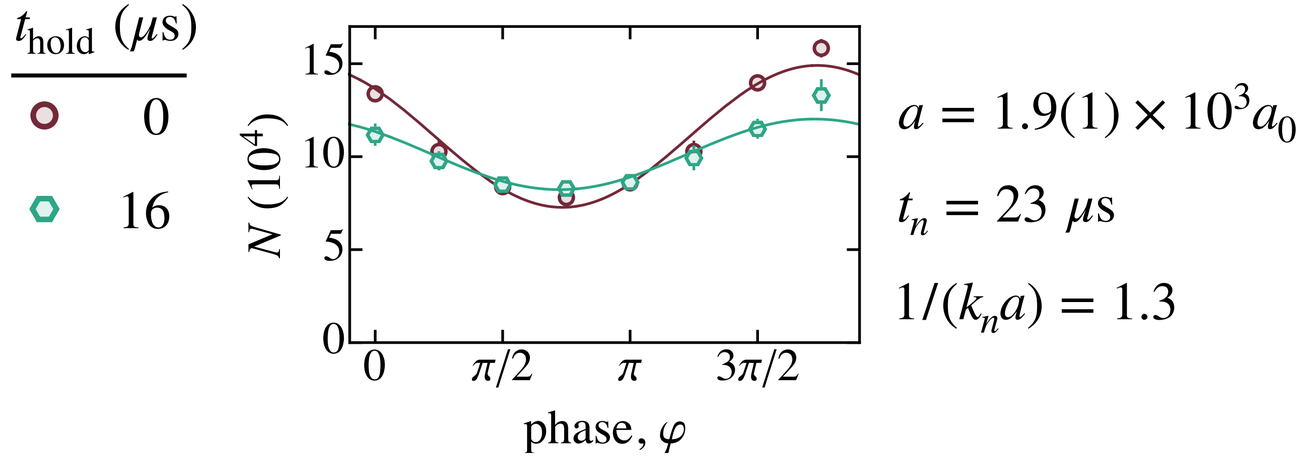
wait time, t_{hold}

interfere, vary phase φ



following (and adapted from)
Cetina et al. Science **354**, 96 (2016) and Skou et al. Nat. Phys. **17**, 731 (2021)

$$N(\phi) = N_0 - A\cos(\varphi - \varphi_c)$$



$a = 1.9(1) \times 10^3 a_0$

$t_n = 23\ \mu\mathrm{s}$

$1/(k_n a) = 1.3$

Strongly repulsive Bose polarons

preliminary!

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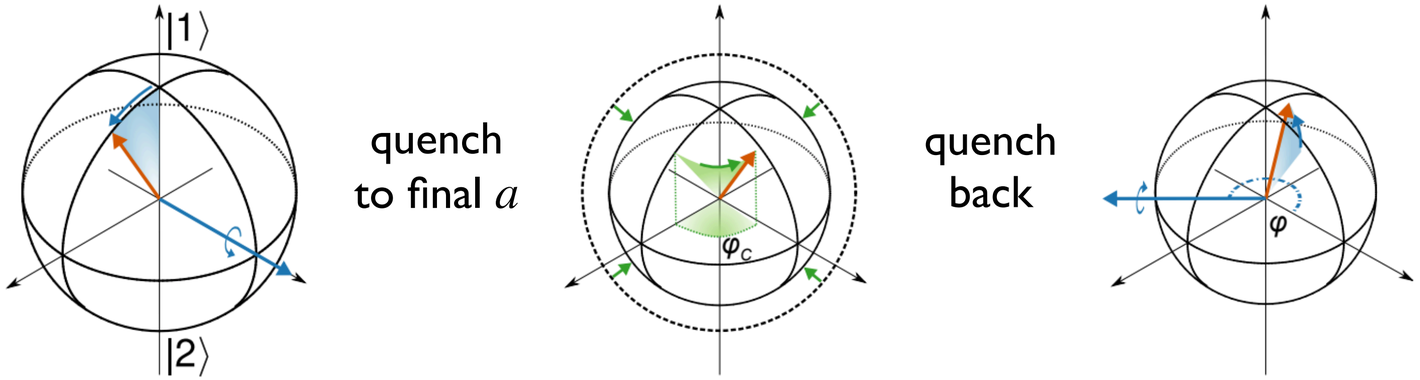

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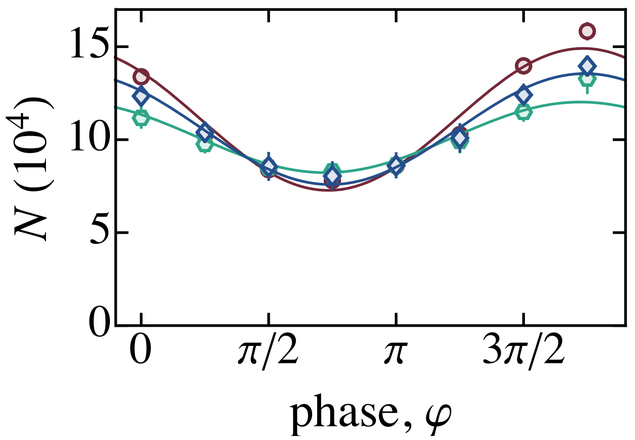

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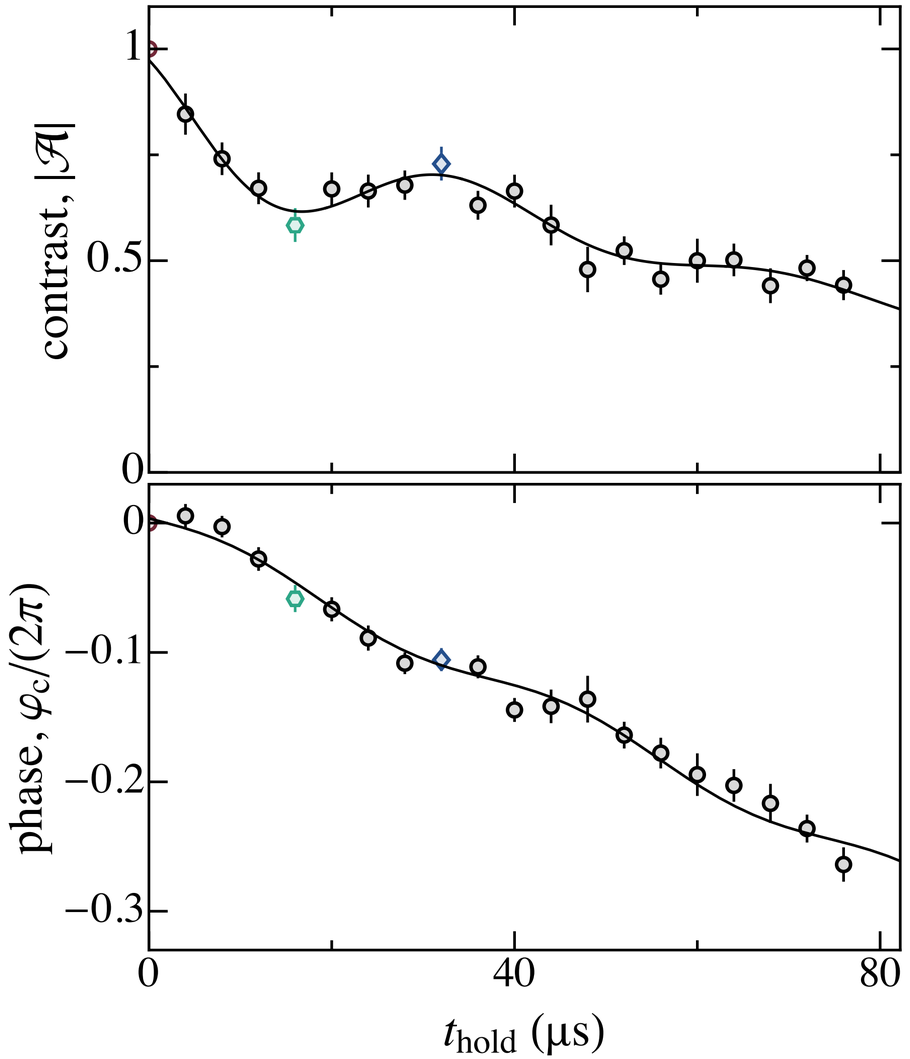
$|1,-1\rangle$



Strongly repulsive Bose polarons

preliminary!

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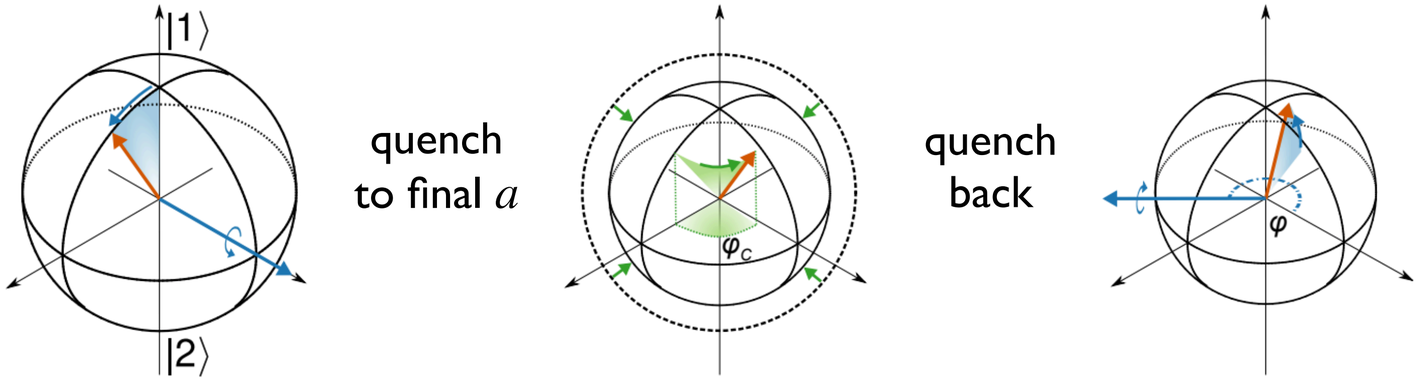

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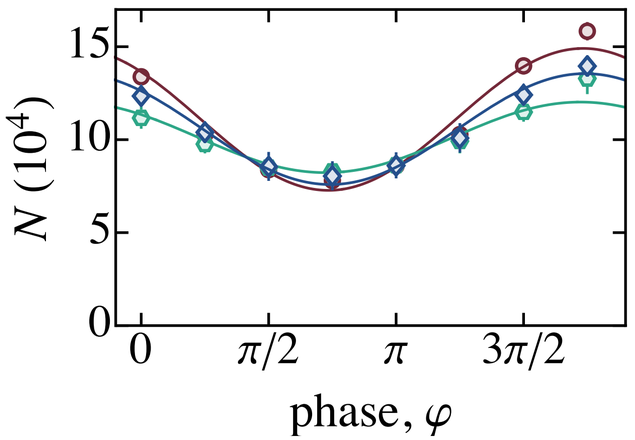

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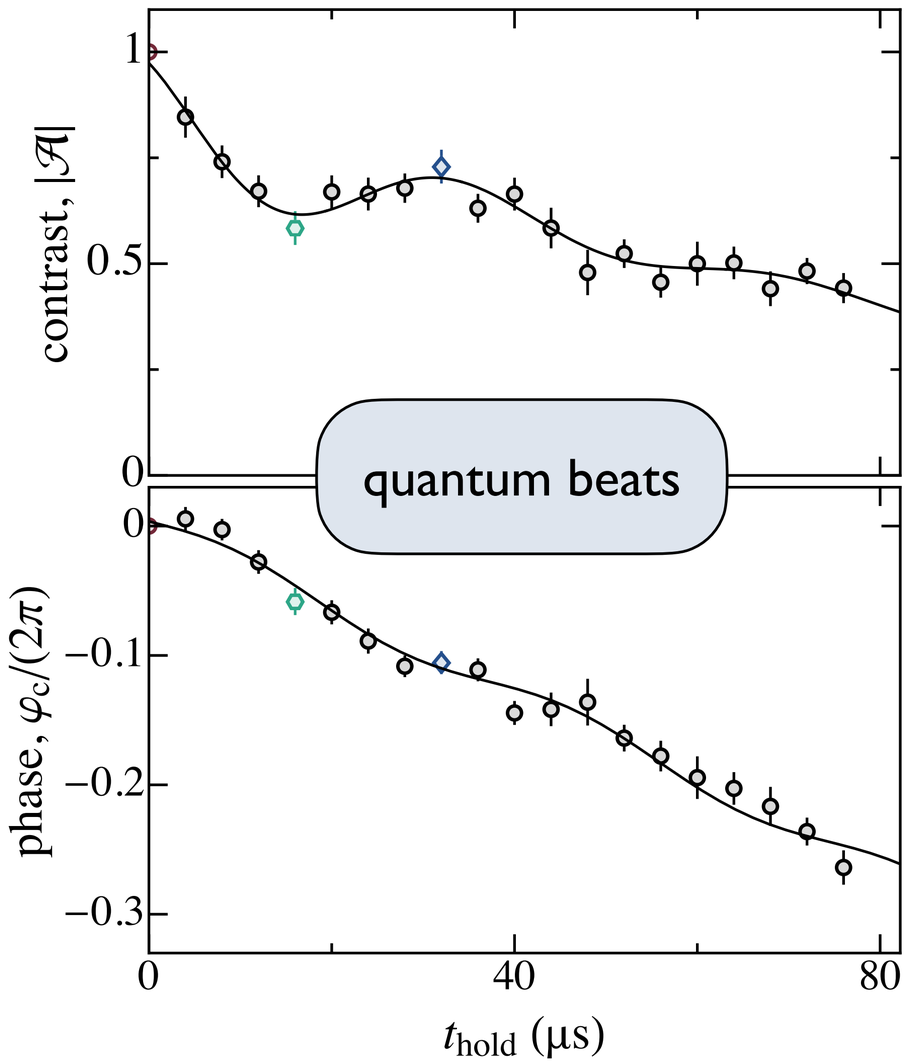
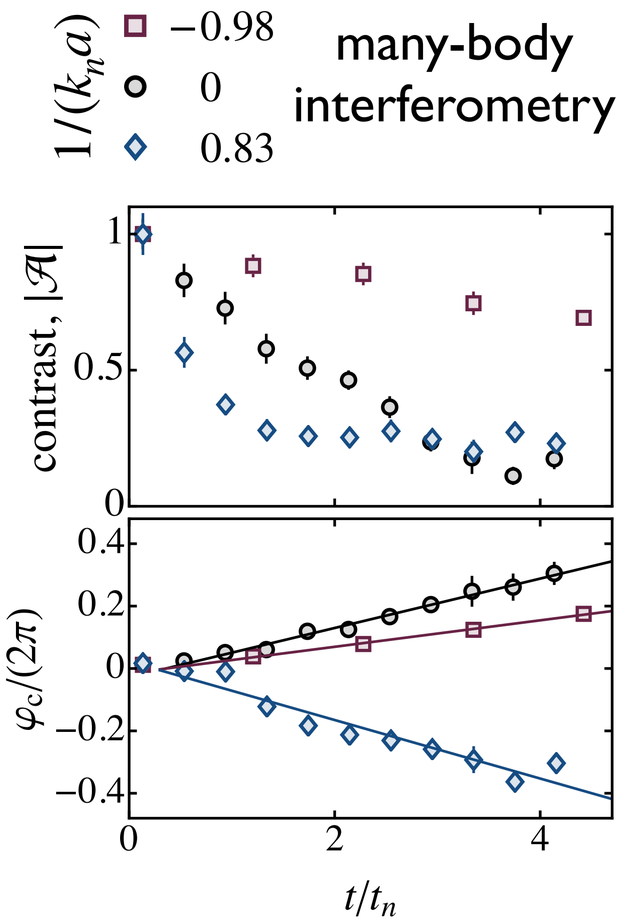


Strongly interacting Bose polarons

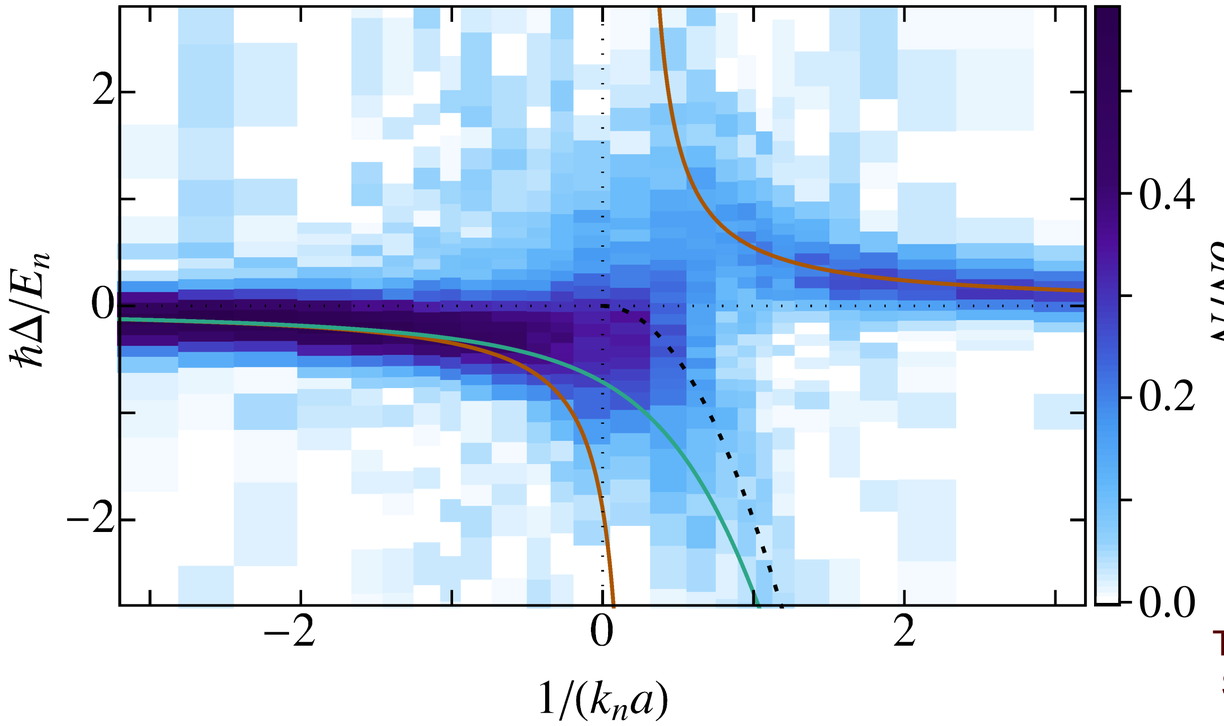
preliminary!

many-body interferometry



$$E = -\hbar \mathrm{d}\varphi_c/\mathrm{d}t$$

fix $k_n \approx 9\mu\mathrm{m}^{-1}$, vary a



simple theories
(no free parameters!)

- dimer
- shifted mean-field
- variational ansatz

theory:
Tempere, Bruun, Massignan, Enss, Schmidt, Demler, Grusdt, Gurarie, Giorgini, Parish, Levinsen, Lewenstein, Devreese, Naidon, Schmelcher, Busch, …

Strongly interacting Bose polarons

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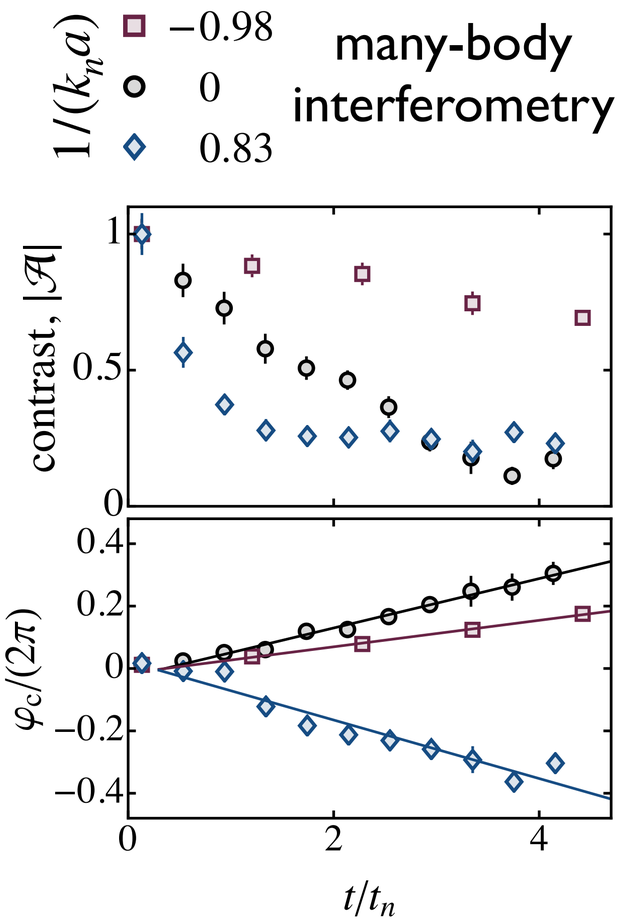
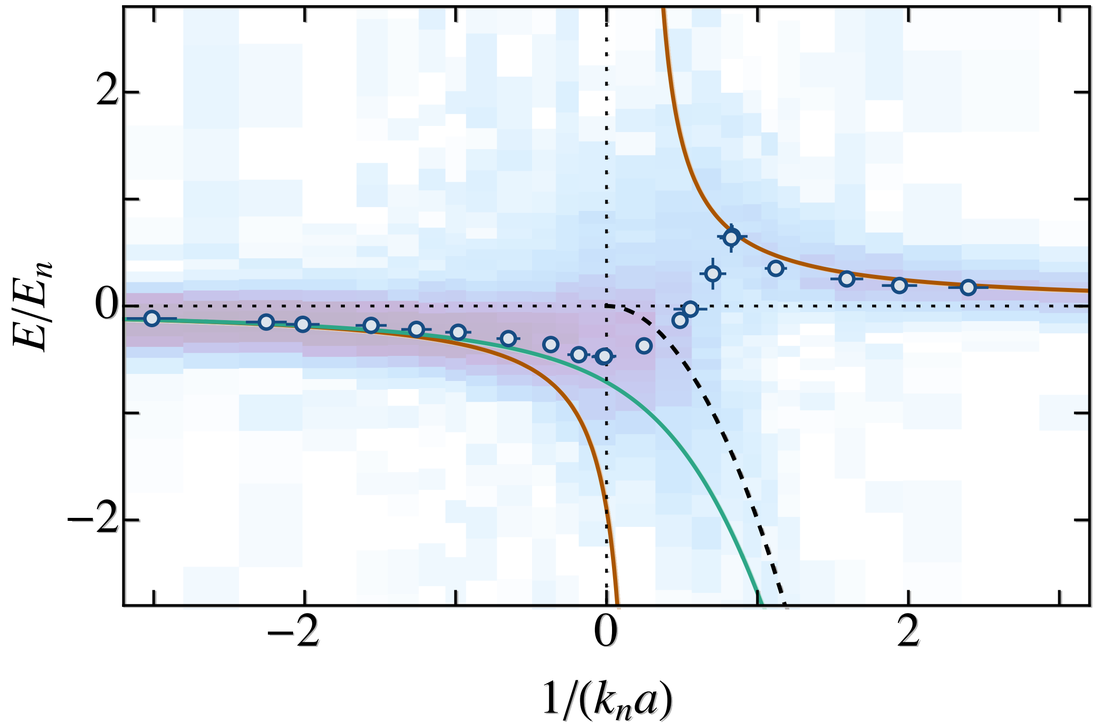


many-body interferometry

$$E = -\hbar \mathrm{d}\varphi_c/\mathrm{d}t$$

fix $k_n \approx 9\mu\mathrm{m}^{-1}$, vary a



simple theories
(no free parameters!)

--- dimer

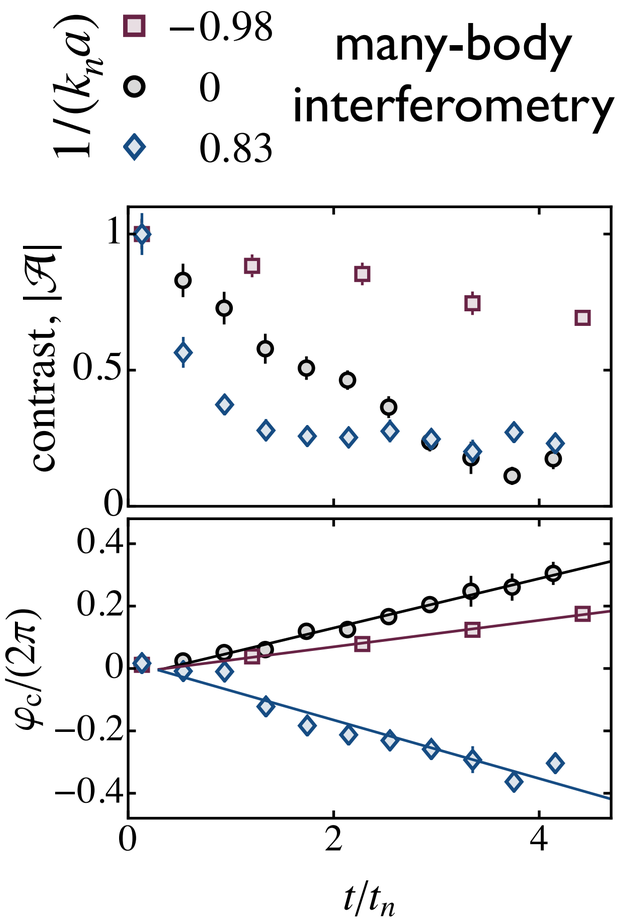
shifted mean-field

variational ansatz

theory:
Tempere, Bruun, Massignan, Enss, Schmidt, Demler, Grusdt, Gurarie, Giorgini, Parish, Levinsen, Lewenstein, Devreese, Naidon, Schmelcher, Busch, …

Strongly interacting Bose polarons

preliminary!



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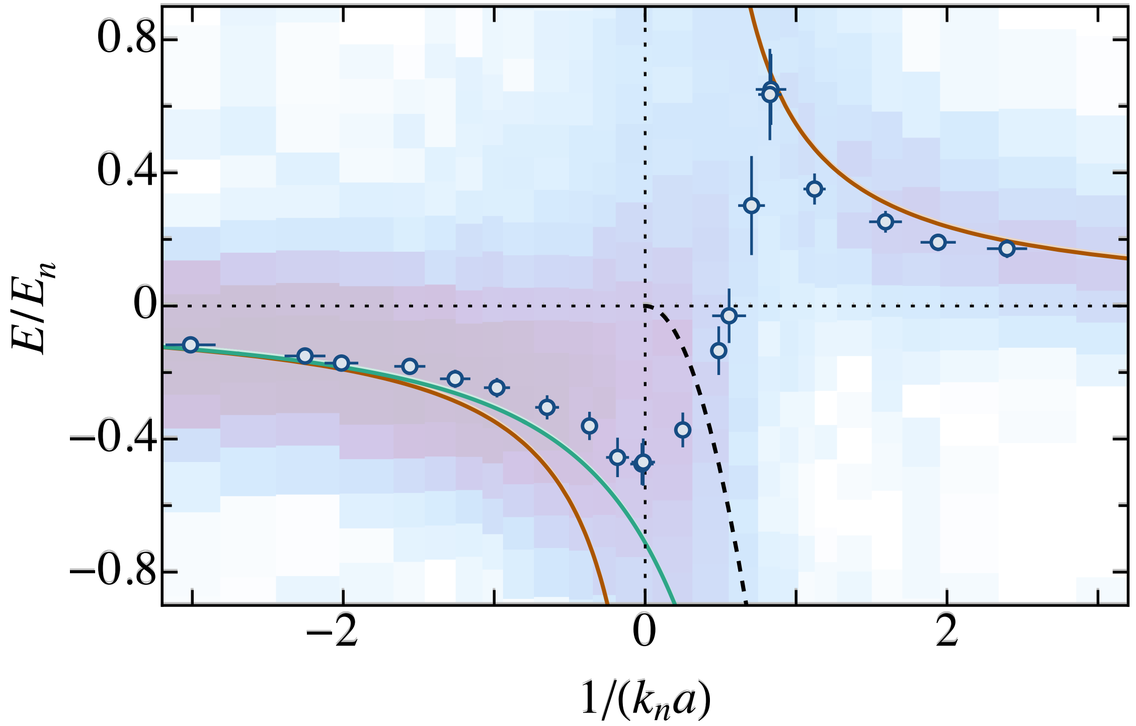

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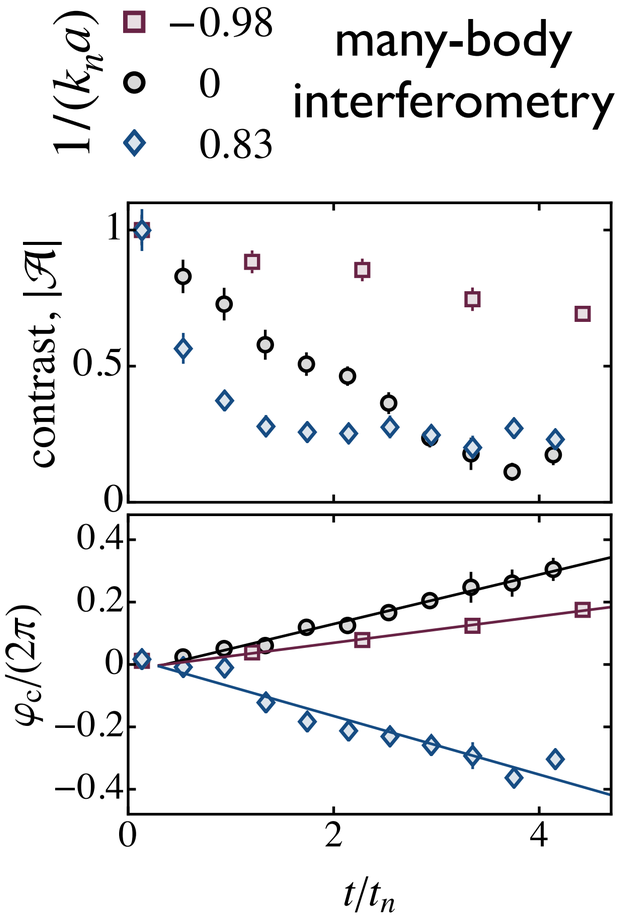

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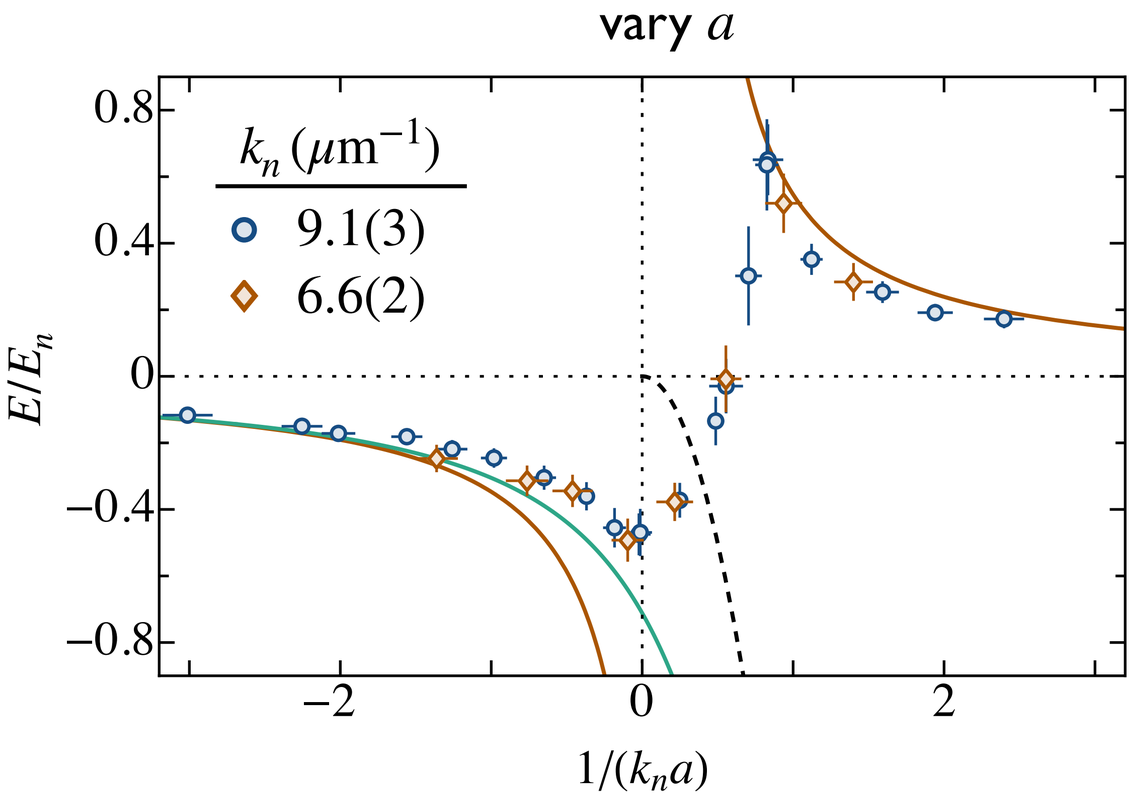
vary a



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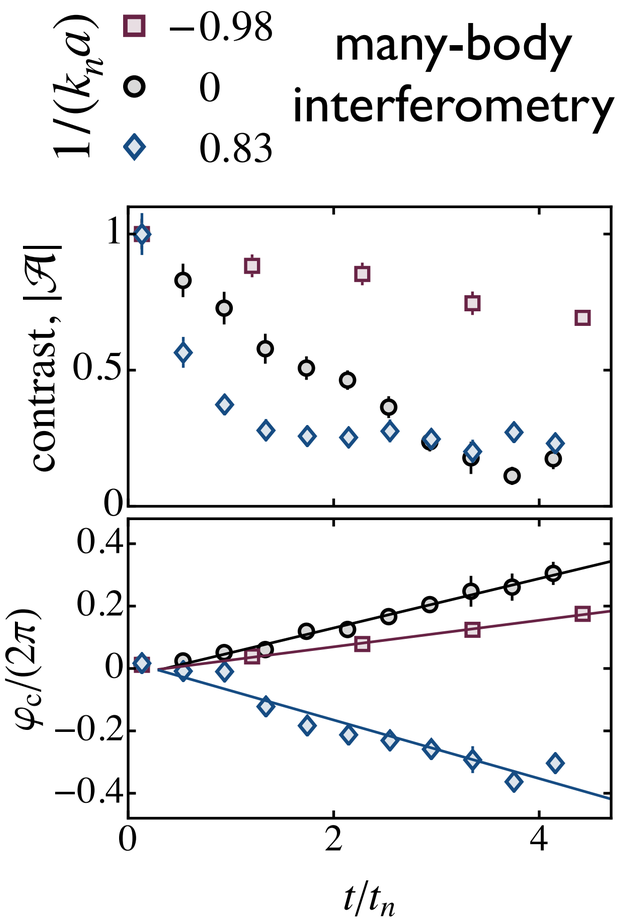
Strongly interacting Bose polarons

preliminary!

deviations expected due to Efimov physics ?

Yoshida *et al.*, PRX **8** 011024 (2018)

many-body interferometry



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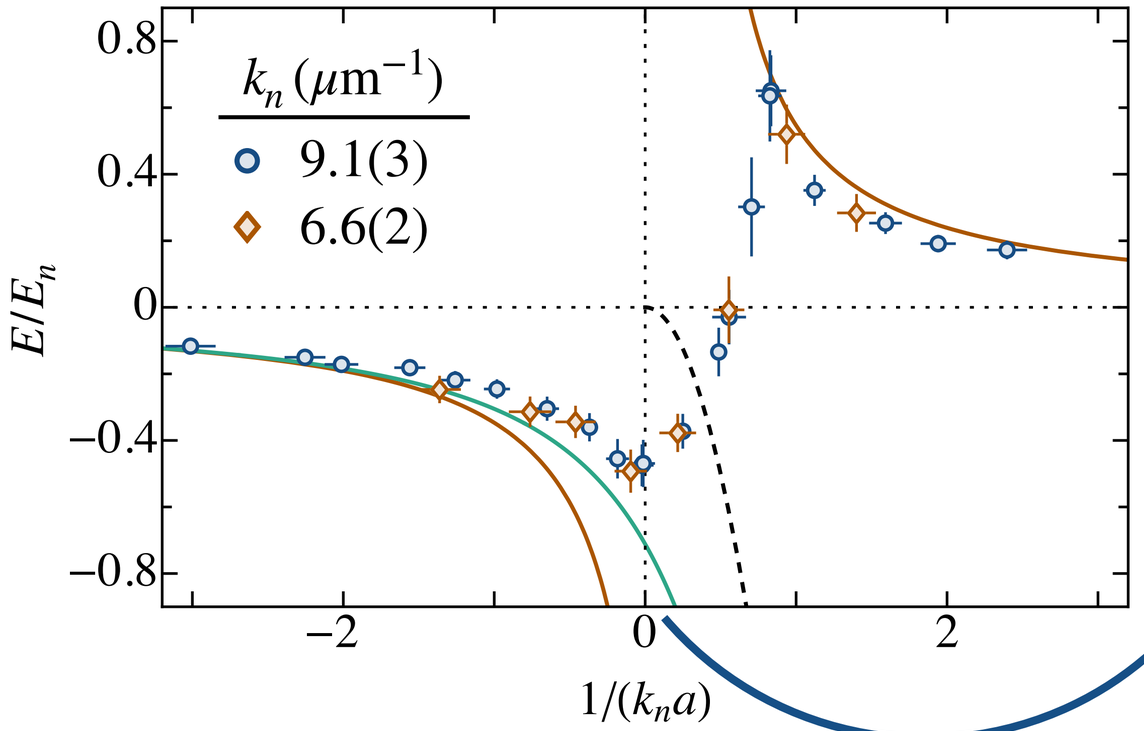
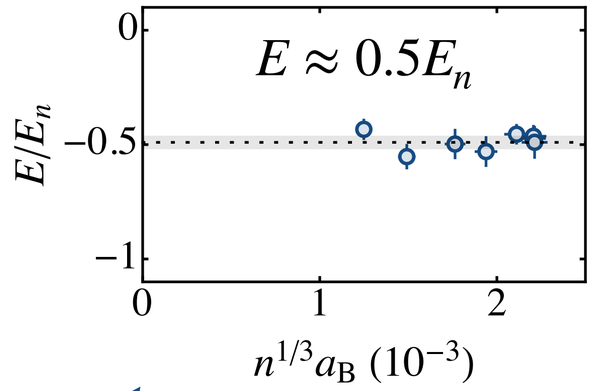
vary a



vary n at $1/a = 0$



universal?!

theory:
Tempere, Bruun, Massignan, Enss, Schmidt, Demler, Grusdt, Gurarie, Giorgini, Parish, Levinsen, Lewenstein, Devreese, Naidon, Schmelcher, Busch, …

Outlook

next steps on Bose polarons

- ✦ quantitatively compare spectra and interferometry measurements to state-of-the-art theory
- ✦ access to quasi-particle residues?
- ✦ effective mass?
- ✦ finite temperature

✦ further explore strongly interacting Bose polarons:

i. formation dynamics

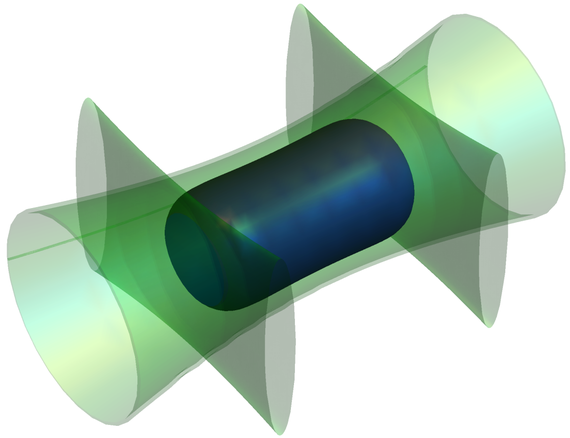
ii. vary bath properties - universal ($E_n, k_n, \ldots$)?

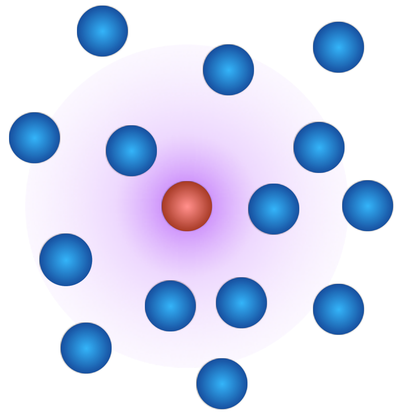
$|1,0\rangle$ vs. $|1,-1\rangle$ bath - a_B ratio is 2.8!

iii. bipolarons?

Camacho-Guardian et al. PRL **121**, 013401 (2018)

Thank you!





Christoph Eigen

UNIVERSITY OF CAMBRIDGE

Quantum gases, fundamental interactions and Cosmology,
Pisa, October 28th, 2022