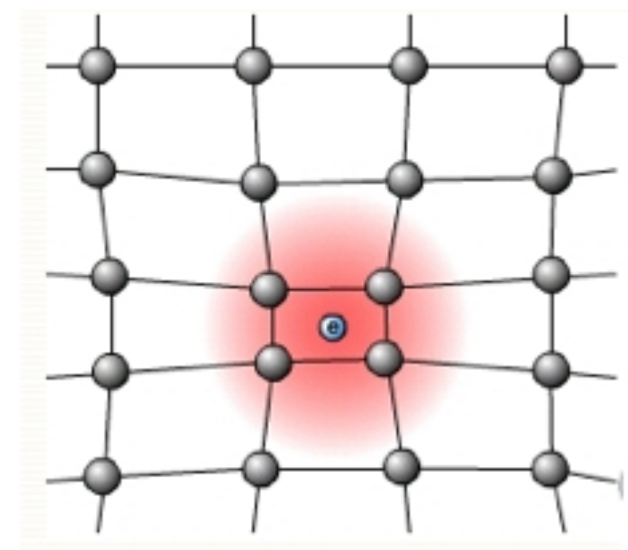
The Bose polaron- theory and experiments

Georg M. Bruun
Aarhus University

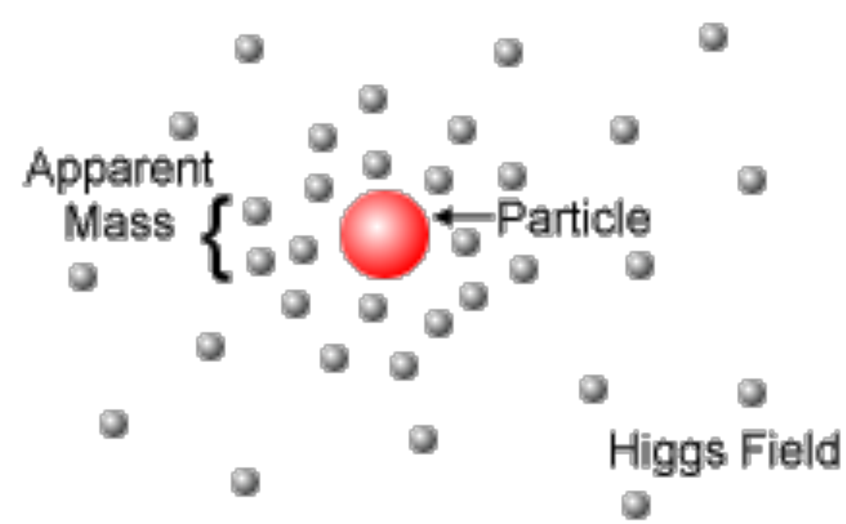
R. S. Christensen, J. Levinsen & GMB, PRL **115**, 160401 (2015)
J. Levinsen, M. M. Parish & GMB, PRL **115**, 125302 (2015)
N. B. Jørgensen et al, arXiv:1604.07883

Bose Polaron

Mobile impurity interacting with *bosonic* reservoir



- Electrons coupled to phonons
- Helium mixtures
- High T_C superconductors
- Elementary particles coupled to the Higgs boson



Nice to have experimental realisation in cold atoms

Fermi polaron gave lots of new insights

1. Schirotzek *et al.*, Phys. Rev. Lett. **102**, 230402 (2009)
2. Kohstall *et al.*, Nature **485**, 615 (2012)
3. Koschourek *et al.*, Nature **485**, 619 (2012)

Very recently *two* independent experimental realisations of the Bose polaron:

❶ N. B. Jørgensen *et al.*, arXiv:1604.07883

❷ Ming-Guang Hu *et al.*, arXiv:1605.00729

This Talk

1. Theory

Good understanding, both at weak and strong coupling

2. Experiment

First observation of long lived Bose polaron using RF spectroscopy

People

Experiment




Jan Arlt

Nils Jørgensen

Lars Wacker

Kristoffer T. Skalmstang

SOLIDUM PETIT IN PROFUNDIS · UNIVERSITAS ARHUSIENSIS ·

Aarhus University

Theory



Rasmus S. Christensen

Jesper Levinsen

Meera Parish

Monash University


Theory

Mean-field:

Astrakharchik & Pitaevskii, Phys. Rev. A **70**, 013608 (2004)
Cucchietti & Timmermans, Phys. Rev. Lett. **96**, 210401 (2006)
Kalas & Blume, Phys. Rev. A **73**, 043608 (2006)
Bruderer, Bao & Jaksch, Eu. Phys. Lett. **82**, 30004 (2008)

Fröhlich:

Huang & Wan, Chin. Phys. Lett. **26**, 080302 (2009)
Tempere *et al.*, Phys. Rev. B **80**, 184504 (2009)
Castels & Wouters, Phys. Rev. A **90**, 043602 (2014)
Grust *et al.*, Sci. Rep. **5**, 12124 (2015)
Vlietinck *et al.*, New J. Phys. **17**, 033023 (2015)

Field theory: Rath & Schmidt, Phys. Rev. A **88**, 053632 (2013)

Variational:

Li & Das Sarma, Phys. Rev. A **90**, 013618 (2014)
Schhaddilova, Schmidt, Grusdt & Demler, arXiv:1604.06469

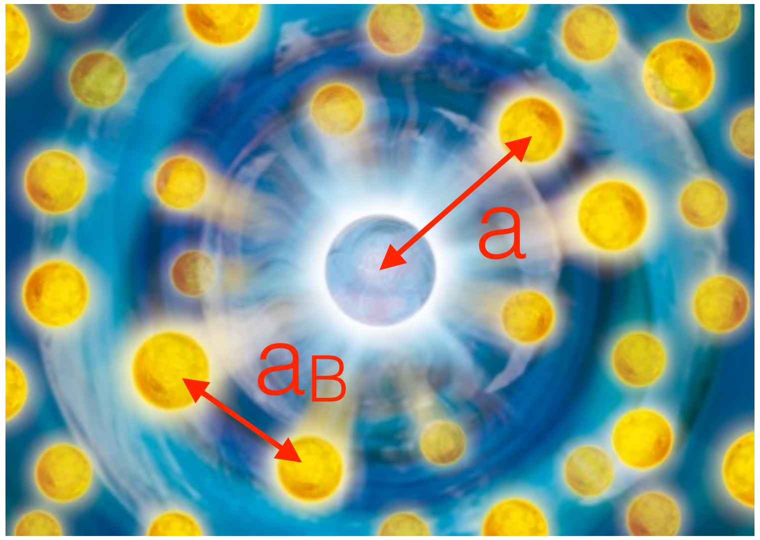
Perturbation theory

$$H = \sum_{\mathbf{k}} \epsilon_k^B a_{\mathbf{k}}^\dagger a_{\mathbf{k}} + \frac{1}{2\mathcal{V}} \sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} V_B(q) a_{\mathbf{k}+\mathbf{q}}^\dagger a_{\mathbf{k}'-\mathbf{q}}^\dagger a_{\mathbf{k}'} a_{\mathbf{k}}$$

BEC

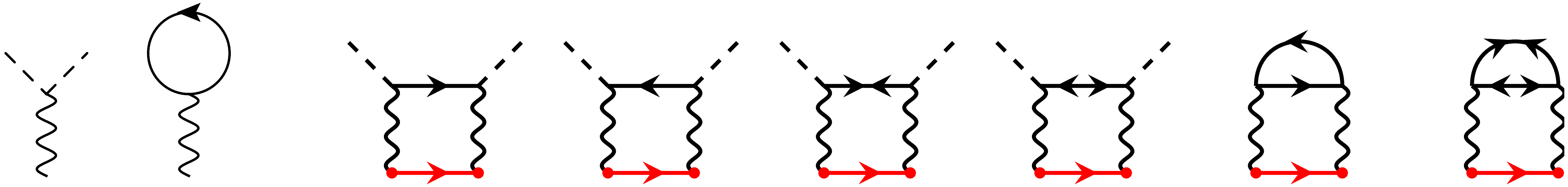
$$+ \sum_{\mathbf{k}} \epsilon_k c_{\mathbf{k}}^\dagger c_{\mathbf{k}} + \frac{1}{\mathcal{V}} \sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} V(q) c_{\mathbf{k}+\mathbf{q}}^\dagger c_{\mathbf{k}'-\mathbf{q}}^\dagger a_{\mathbf{k}'} c_{\mathbf{k}}$$

Impurity — Impurity-BEC interaction



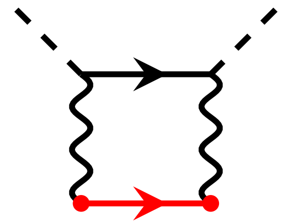
BEC weakly interacting $na_B^3 \ll 1 \Rightarrow$ Bogoliubov theory

Perturbation theory V(q):



1. order — 2. order

Replace $V(q) \to \mathcal{T}_v = 2\pi a/m_r$ in a consistent way

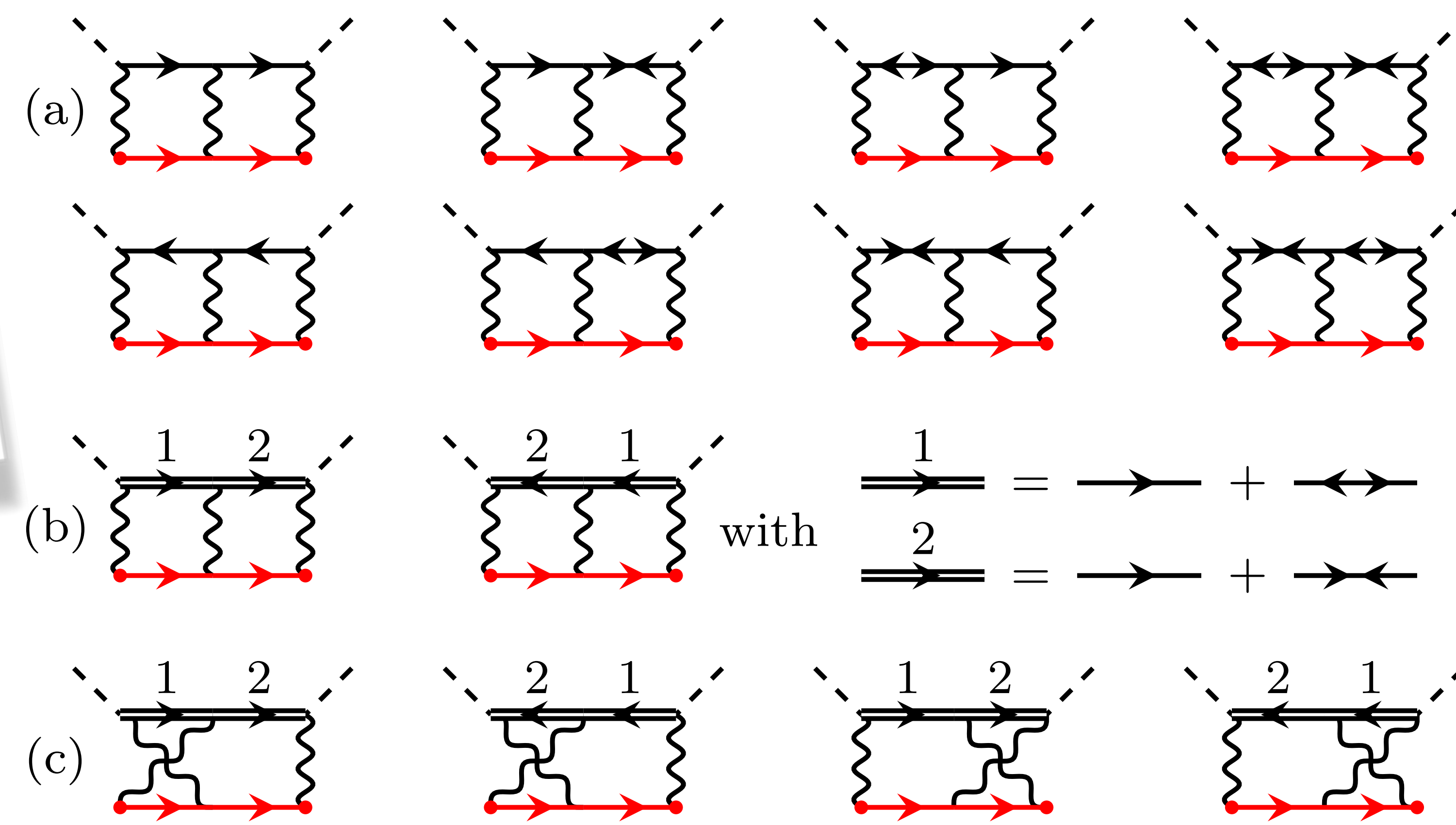
Diagrams like  comes from expanding

$$\mathcal{T}(p) = \frac{\mathcal{T}_v}{1 - \mathcal{T}_v \Pi_{11}(p)} = \mathcal{T}_v + \mathcal{T}_v^2 \Pi_{11}(p) + \ldots$$

Self-energy in powers of a:

$$\Sigma(p,\omega) = \Sigma_1(p,\omega) + \Sigma_2(p,\omega) + \Sigma_3(p,\omega) + \ldots$$

28 third order diagrams



Energy

$E(0)$ …

Same structure as
Lee-Huang-Yang +
Wu-Hugenholz-Pines-Sawada

$A(1)$ … $\Omega = 2\pi n\xi/m_r$

$\alpha = n$ … $= \max(a, a_B)$

a=a$_B$:

$$\frac{E}{N} = \frac{4\pi n a}{m}\left[1 + \frac{32}{3\sqrt{\pi}}(na^3)^{1/2} + 4(\frac{2}{3}\pi - \sqrt{3})na^3\ln(na^3)\right]$$

Weakly interacting BEC

$$\frac{E}{N} = \frac{2\pi n a}{m}\left[1 + \frac{128}{15\sqrt{\pi}}(na^3)^{1/2} + 8(\frac{4}{3}\pi - \sqrt{3})na^3\ln(na^3)\right]$$

Residue & Effective Mass

$$Z^{-1} = 1 + C(\alpha)\frac{a^2}{a_B\xi} + D(\alpha)\frac{a^3}{a_B\xi^2}$$

$$\frac{m^*}{m} = 1 + F(\alpha)\frac{a^2}{a_B\xi} + G(\alpha)\frac{a^3}{a_B\xi^2}$$

$C(1) = 2\sqrt{2}/3\pi$ $D(1) \approx 0.64$ $F(1) = 16\sqrt{2}/45\pi$ $G(1) \simeq 0.37$

Condition for Z≃1: $\frac{a^2}{a_B\xi} \ll 1$

Breaks down for ideal BEC

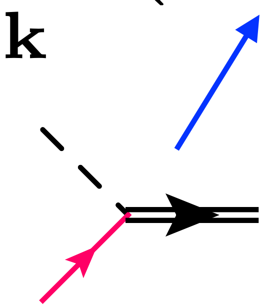
Variational Theory

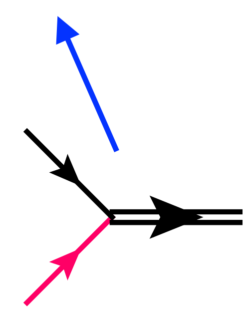
Multichannel model

$$\hat{H} = \sum_{\mathbf{k}} \left[E_{\mathbf{k}} \beta^{\dagger}_{\mathbf{k}} \beta_{\mathbf{k}} + \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}} c_{\mathbf{k}} + \left(\epsilon^{\mathrm{d}}_{\mathbf{k}} + \nu_0 \right) d^{\dagger}_{\mathbf{k}} d_{\mathbf{k}} \right]$$

Bog. modes Impurity Molecule

$$+ g\sqrt{n_0} \sum_{\mathbf{k}} \left(d^{\dagger}_{\mathbf{k}} c_{\mathbf{k}} + h.c. \right) + g \sum_{\mathbf{k},\mathbf{q}} \left(d^{\dagger}_{\mathbf{q}} c_{\mathbf{q}-\mathbf{k}} b_{\mathbf{k}} + h.c. \right)$$



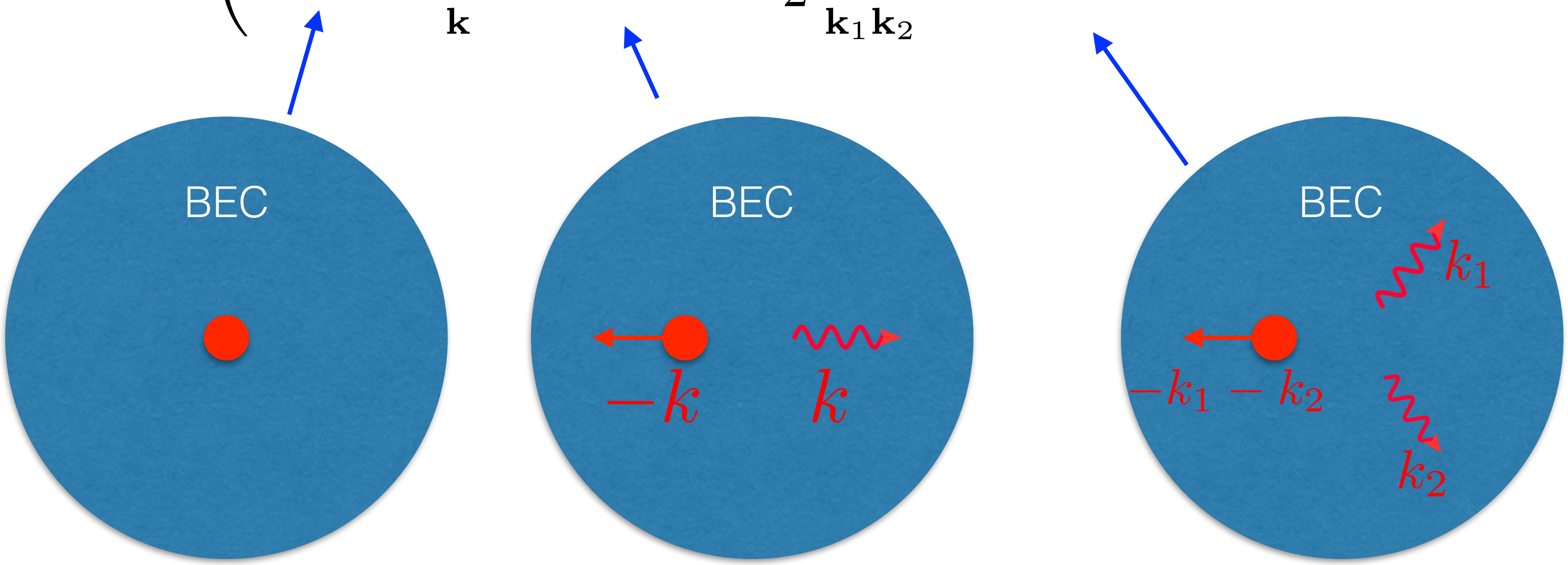


Introduces effective range r_0

Regularises 3-body problem

Variational wave function

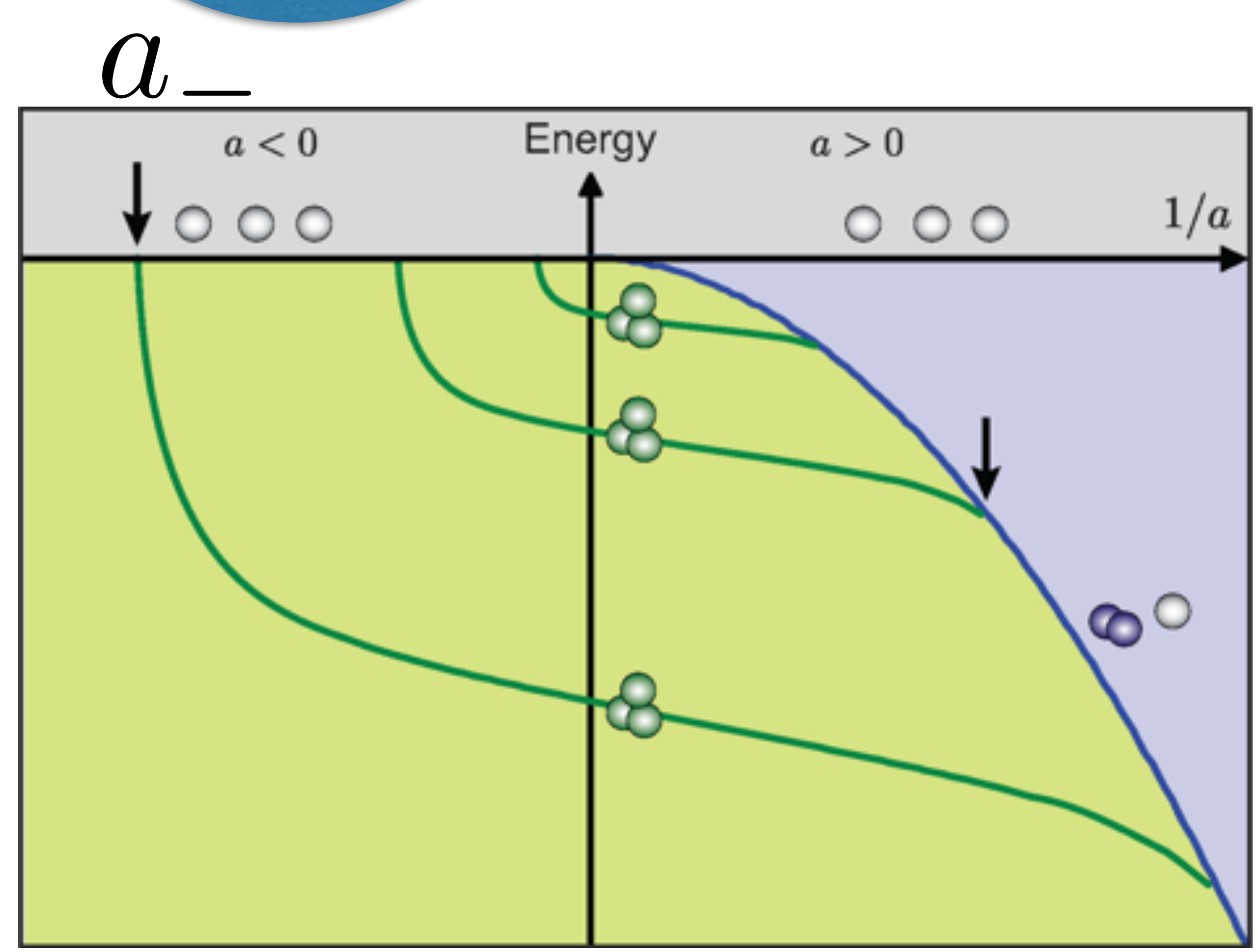
$$|\psi\rangle = \left(\alpha_0 c_0^\dagger + \sum_{\mathbf{k}} \alpha_{\mathbf{k}} c^\dagger_{-\mathbf{k}} \beta^\dagger_{\mathbf{k}} + \frac{1}{2}\sum_{\mathbf{k}_1\mathbf{k}_2} \alpha_{\mathbf{k}_1\mathbf{k}_2} c^\dagger_{-\mathbf{k}_1-\mathbf{k}_2} \beta^\dagger_{\mathbf{k}_1} \beta^\dagger_{\mathbf{k}_2} + \gamma_0 d_0^\dagger + \sum_{\mathbf{k}} \gamma_{\mathbf{k}} d^\dagger_{-\mathbf{k}} \beta^\dagger_{\mathbf{k}}\right)|\mathrm{BEC}\rangle$$

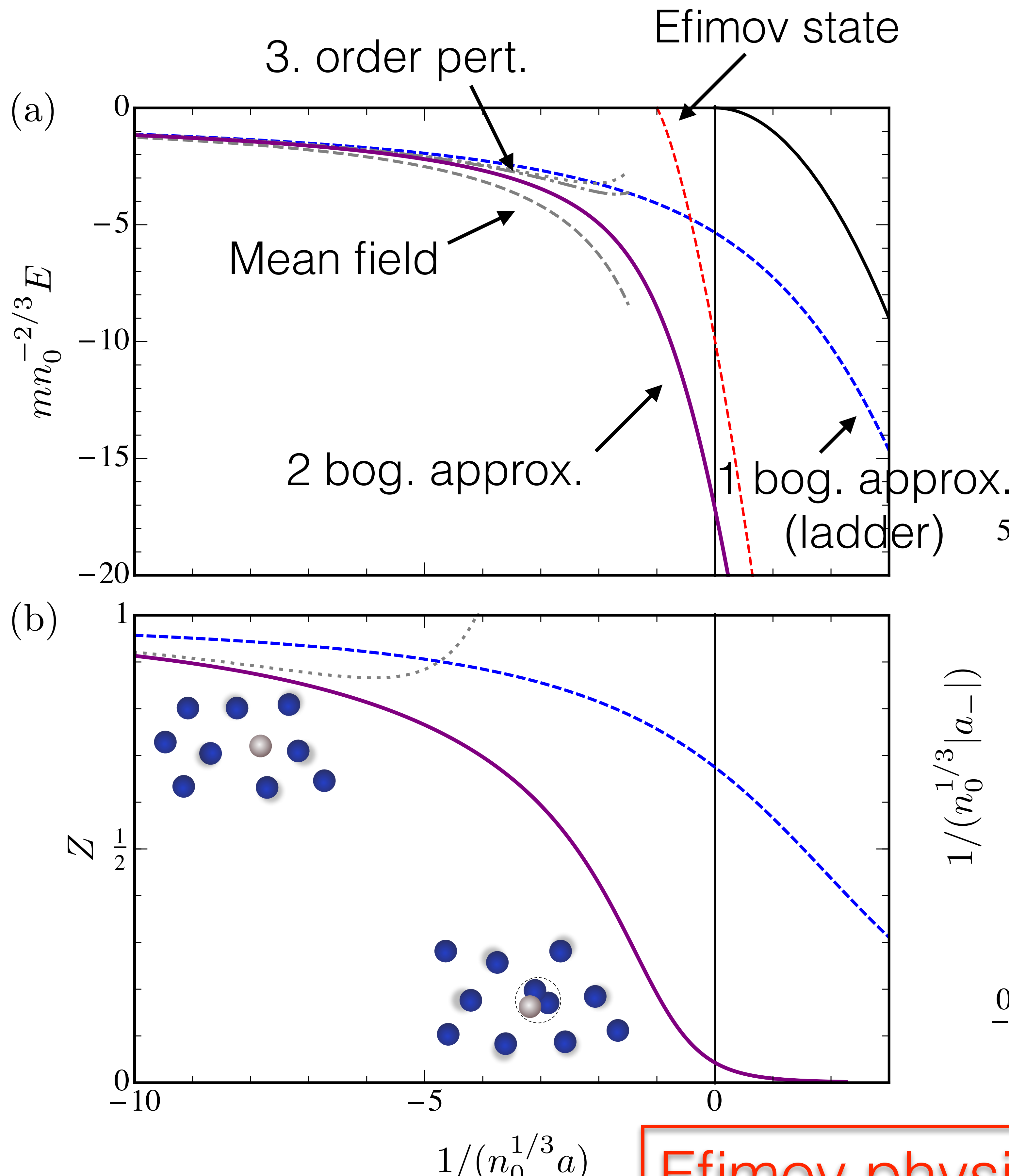


Recovers Efimov spectrum for 1+2 bosons for $n_0 \to 0$

$$a_- \simeq 9000 r_0$$

Can always keep $|a/r_0| \gg 1$ Even when a_- large

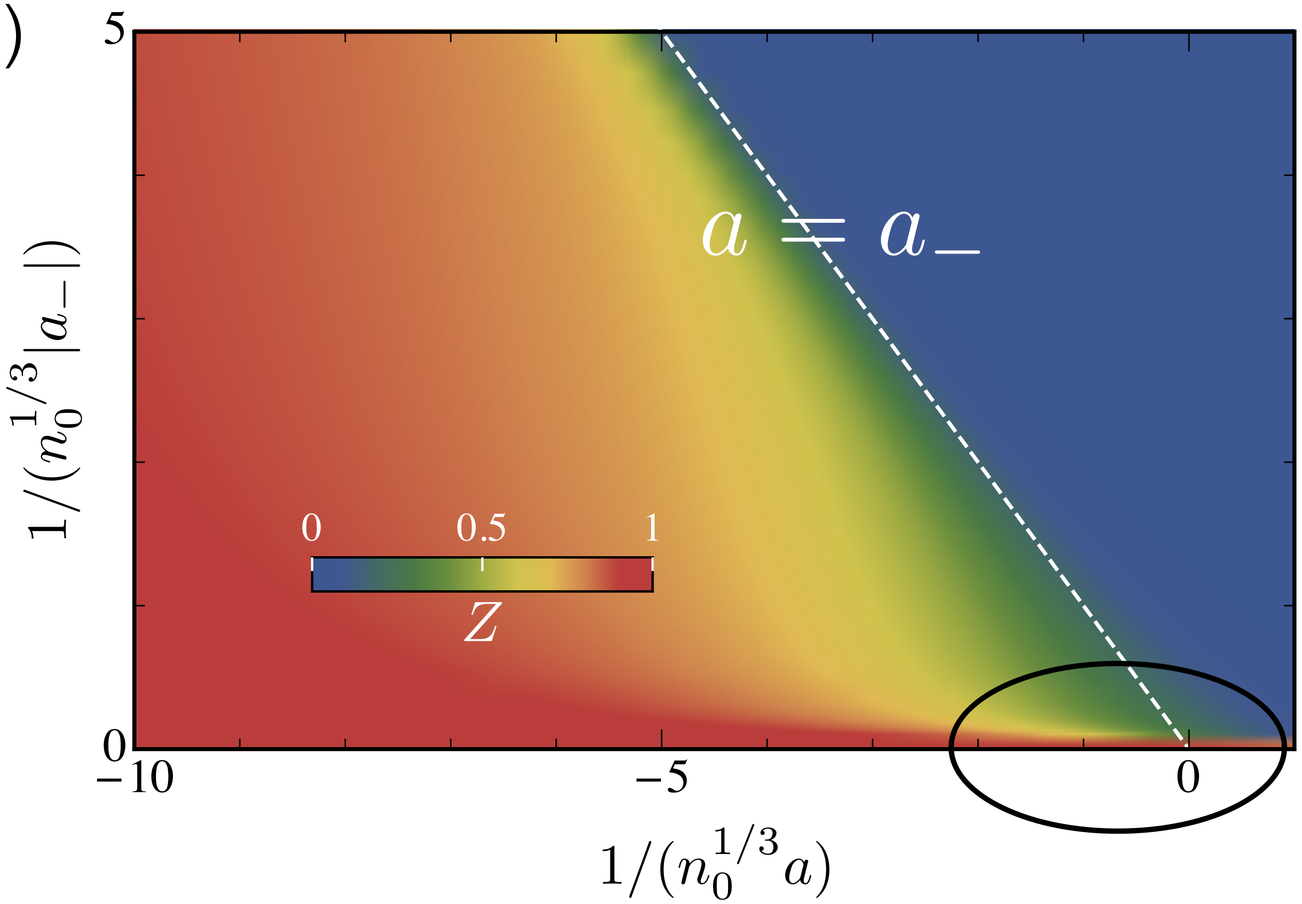




$n_0^{1/3}a_- = -1$

Avoided crossing with Efimov state.

Residue small close to unitarity

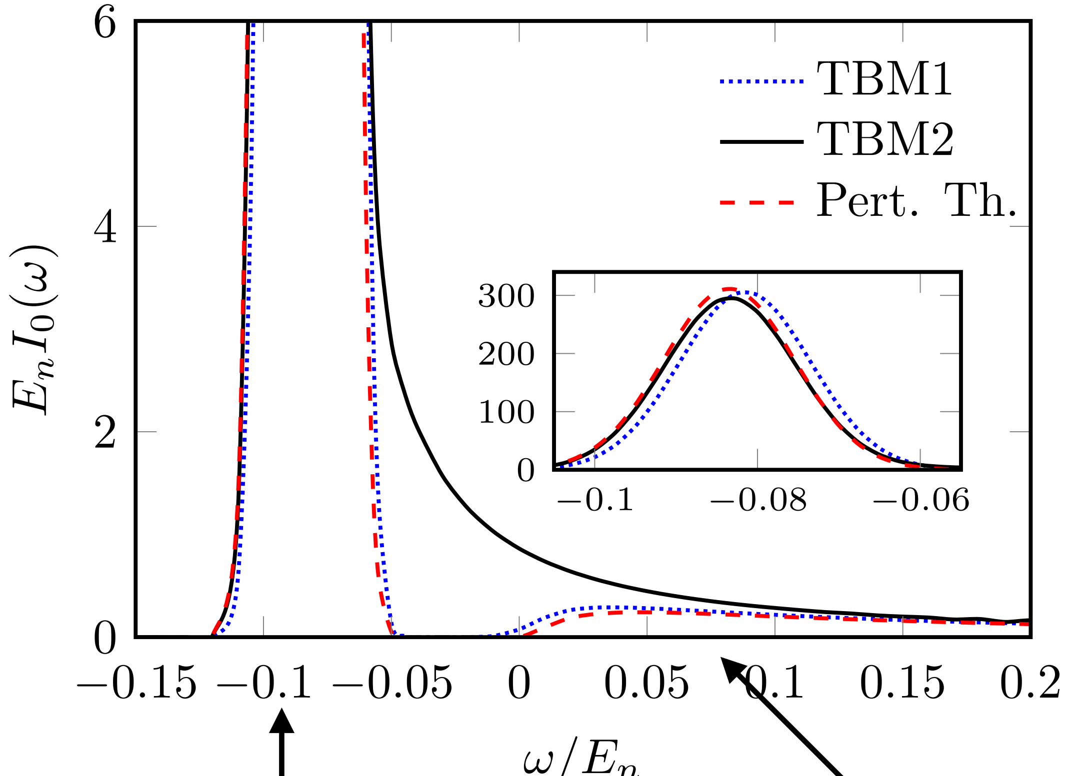


Efimov physics suppressed for $a_- \gg n_0^{-1/3}$

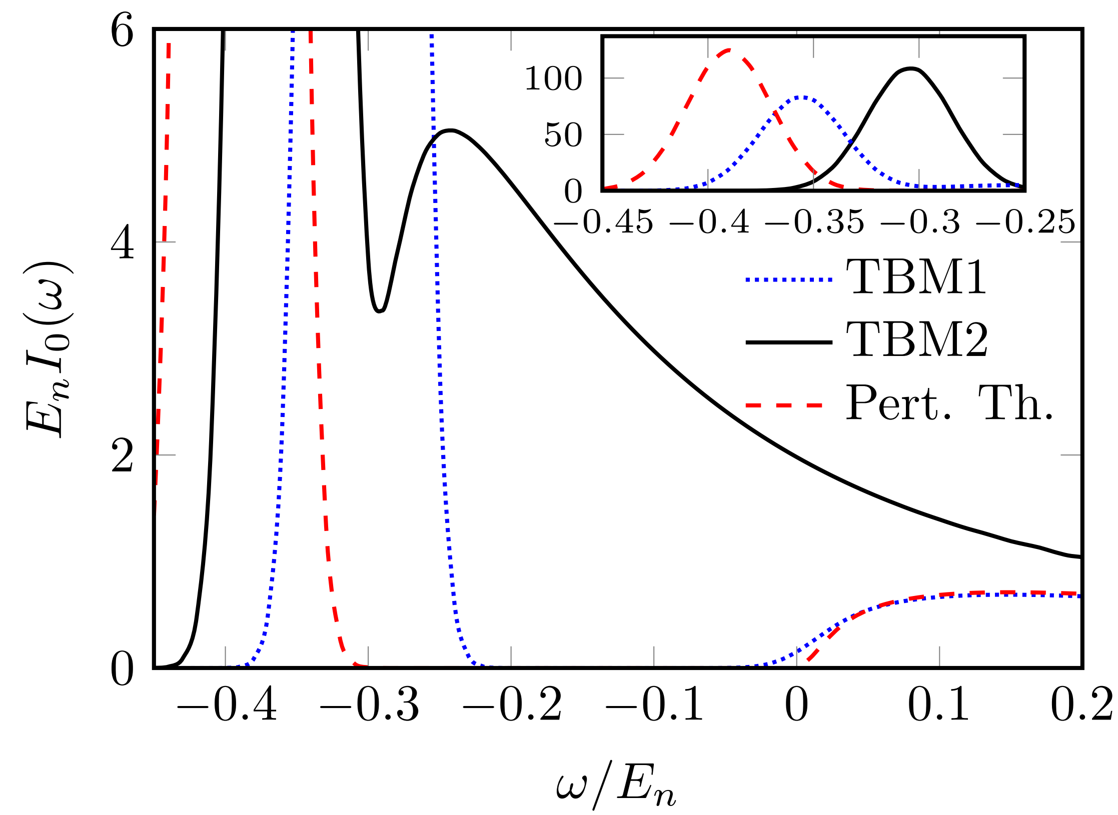
Efimov state “too large”

Spectral functions

$1/k_n a = -5$

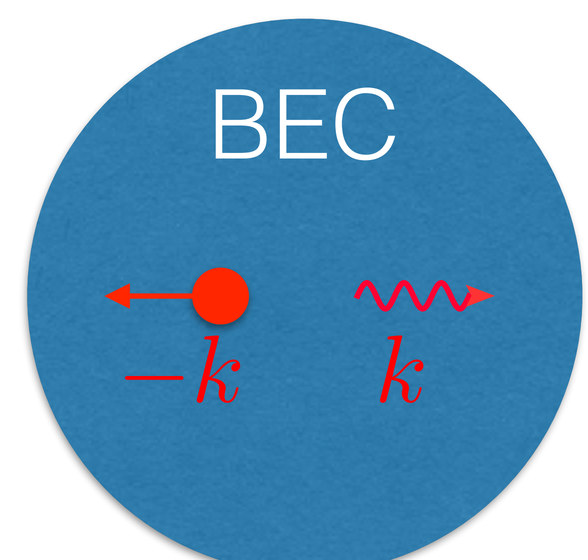


$1/k_n a = -1$



Polaron peak

Many-body continuum



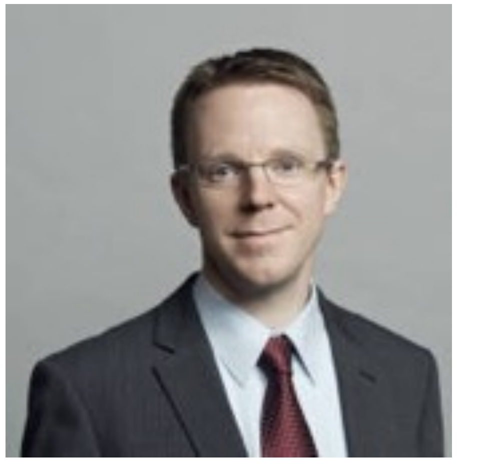
Weak coupling: Variational theory agrees with pert. theory

Strong coupling: Pert. theory breaks down. Many-body continuum significant

Theory - bottom lines

- Analytical perturbation theory to 3.order in a/ξ
- Polaron well-defined for weak coupling
- Strong coupling: Variational ansatz including 3-body Efimov correlations
- Significant many-body continuum for strong coupling
- Impurity atoms in BEC <u>not</u> the Fröhlich model

Experiment bottom lines



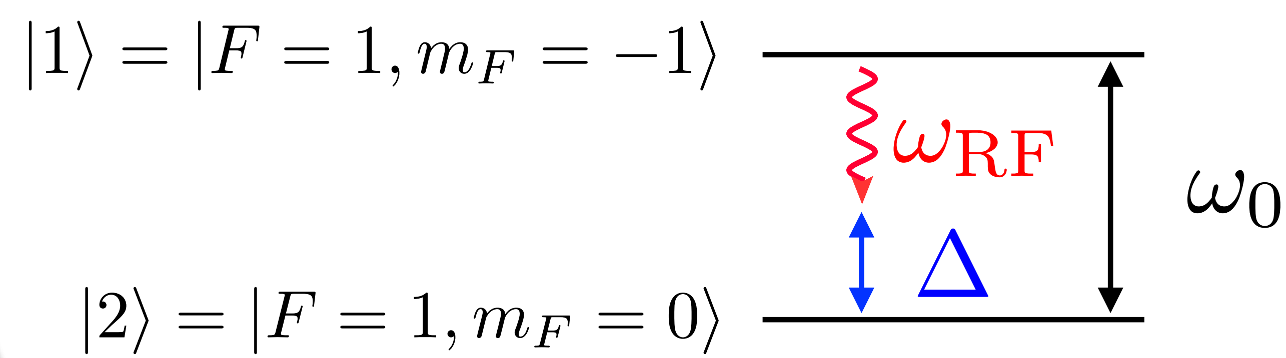
Jan Arlt

- First realisation of the Bose polaron (See also JILA group)
- Well-defined polaron both for repulsive and attractive interaction
- Many-body continuum dominates at strong coupling
- Excellent agreement with theory
- 3-body decay has no significant effects

Earlier experiments

Impurity in thermal bose gas:	Spethman *et al.* Phys. Rev. Lett. **109**, 235301 (2012)
Charged or fixed impurities in BEC:	Zipkes *et al*., Nature **464**, 388 (2010) Schmid *et al*., Phys. Rev. Lett. **105**, 133202 (2010) Balewski *et al*., Nature **502**, 664 (2013) Scelle *et al*., Phys. Rev. Lett. **111**, 070401 (2013)
Impurities in lattice:	Ospelkaus *et al*., Phys. Rev. Lett. **96**, 180403 (2006)
Magnons:	Marti *et al*., Phys. Rev. Lett. **113**, 155302 (2014)

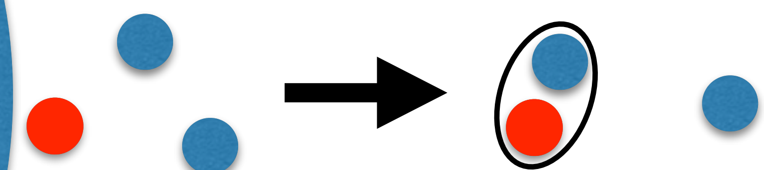
Experimental procedure



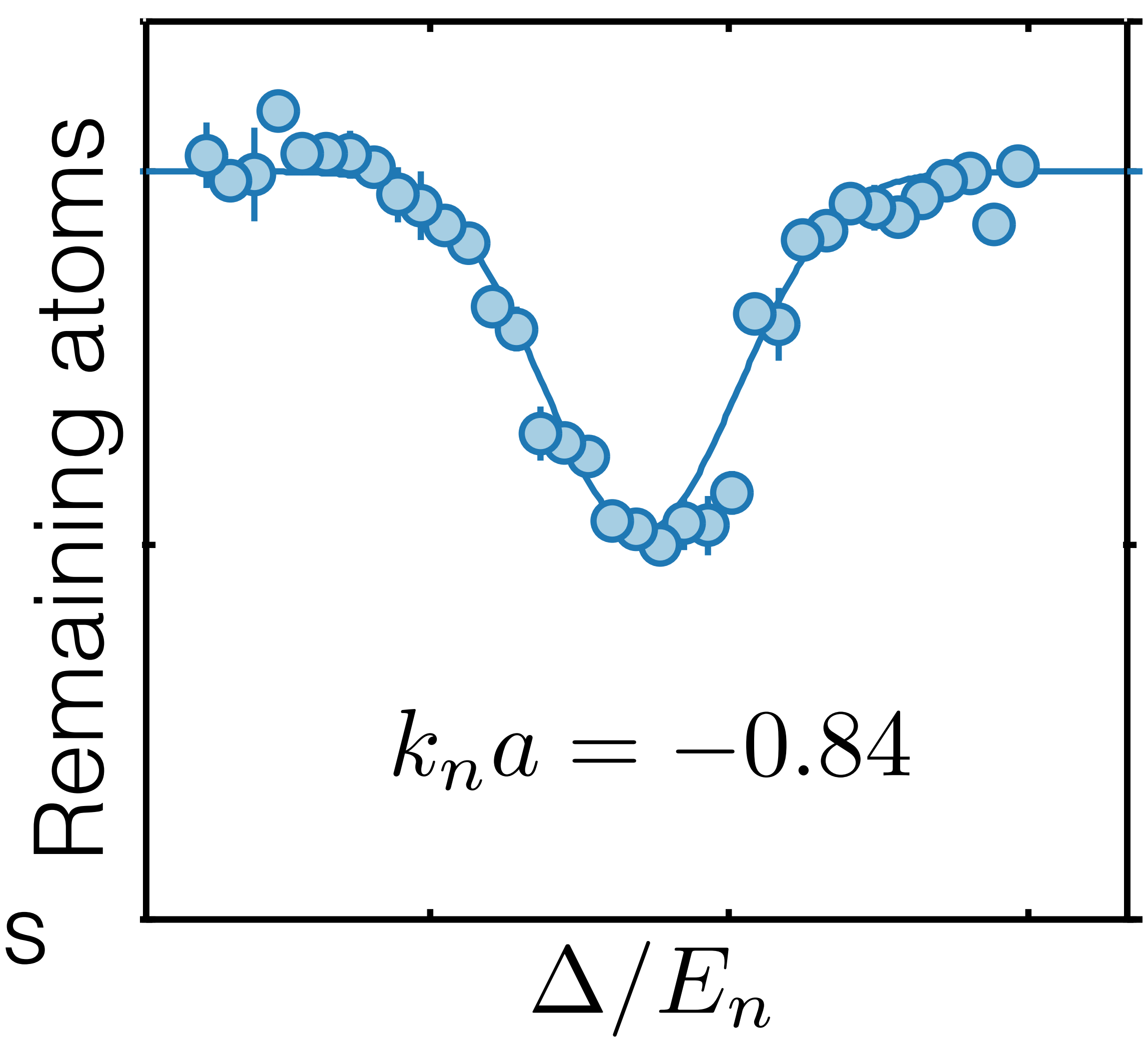
BEC of ^{39}K in $|1\rangle$

RF flip ≤10% to $|2\rangle$

Wait for a while
TOF
} 3-body loss



Count # $|1\rangle$ remaining as fn of detuning $\Delta=\omega_0-\omega_{RF}$



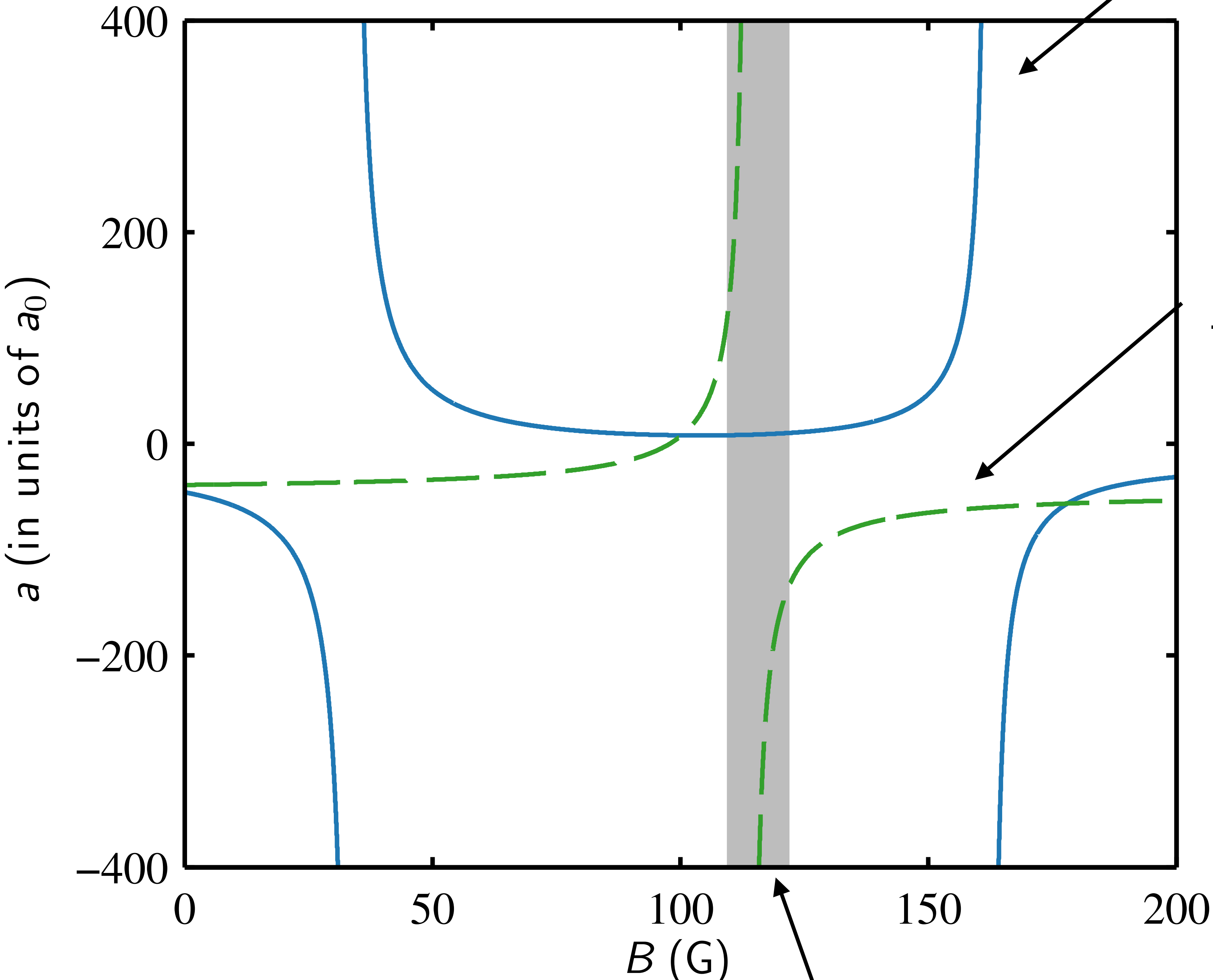
Independent of wait time ⇒

loose 100% of $|2\rangle$ atoms ⇒

lost $|1\rangle$ atoms = 3×created $|2\rangle$ atoms

Scattering lengths

|1⟩ - |1⟩: a_B



|1⟩ - |2⟩ resonance

$$B_0 = 113.83\text{G}$$

$$\Delta B = -15.93\text{G}$$

$$a_{\text{bg}} = -45.24 a_0$$

$$R^* \simeq 60 a_0$$

Lysebo and Veseth, PRA **81**, 032702 (2010)

Experiment takes place here. $a_B \simeq 9 a_0$

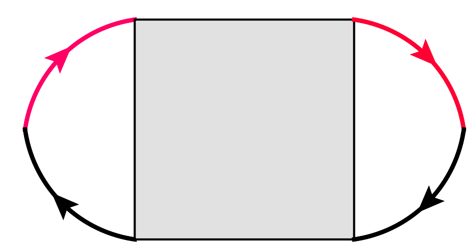
Advantages of RF flipping out of BEC

❶ Perfect spatial overlap between impurities and BEC

❷ Selectively probe only k=0 polarons

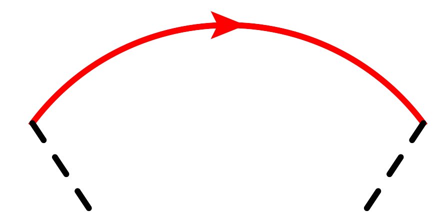
❸ Simple theoretical interpretation

$$\dot{N}_2 = -2\Omega^2 \mathrm{Im} D(\omega)$$



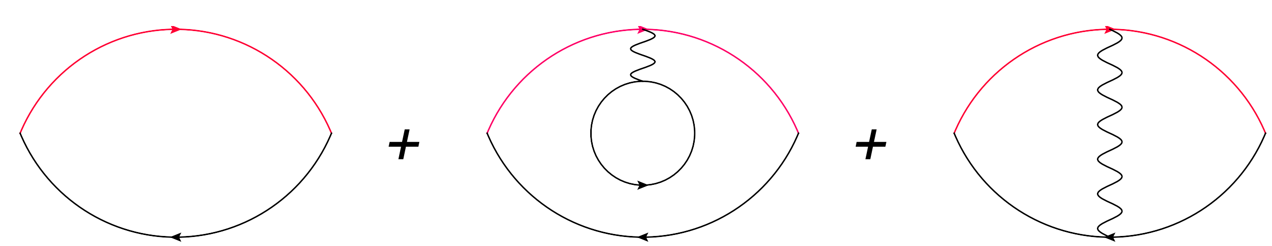
$$D(t-t') = -i\theta(t-t')\langle[\sum_{\mathbf{k}} a^\dagger_{\mathbf{k}1}(t)a_{\mathbf{k}2}(t), \sum_{\mathbf{k}'} a^\dagger_{\mathbf{k}'2}(t')a_{\mathbf{k}'1}(t')]\rangle$$

Bogoliubov theory: $D(\omega) = n_0 G_2(\mathbf{k}=\mathbf{0}, \omega)$



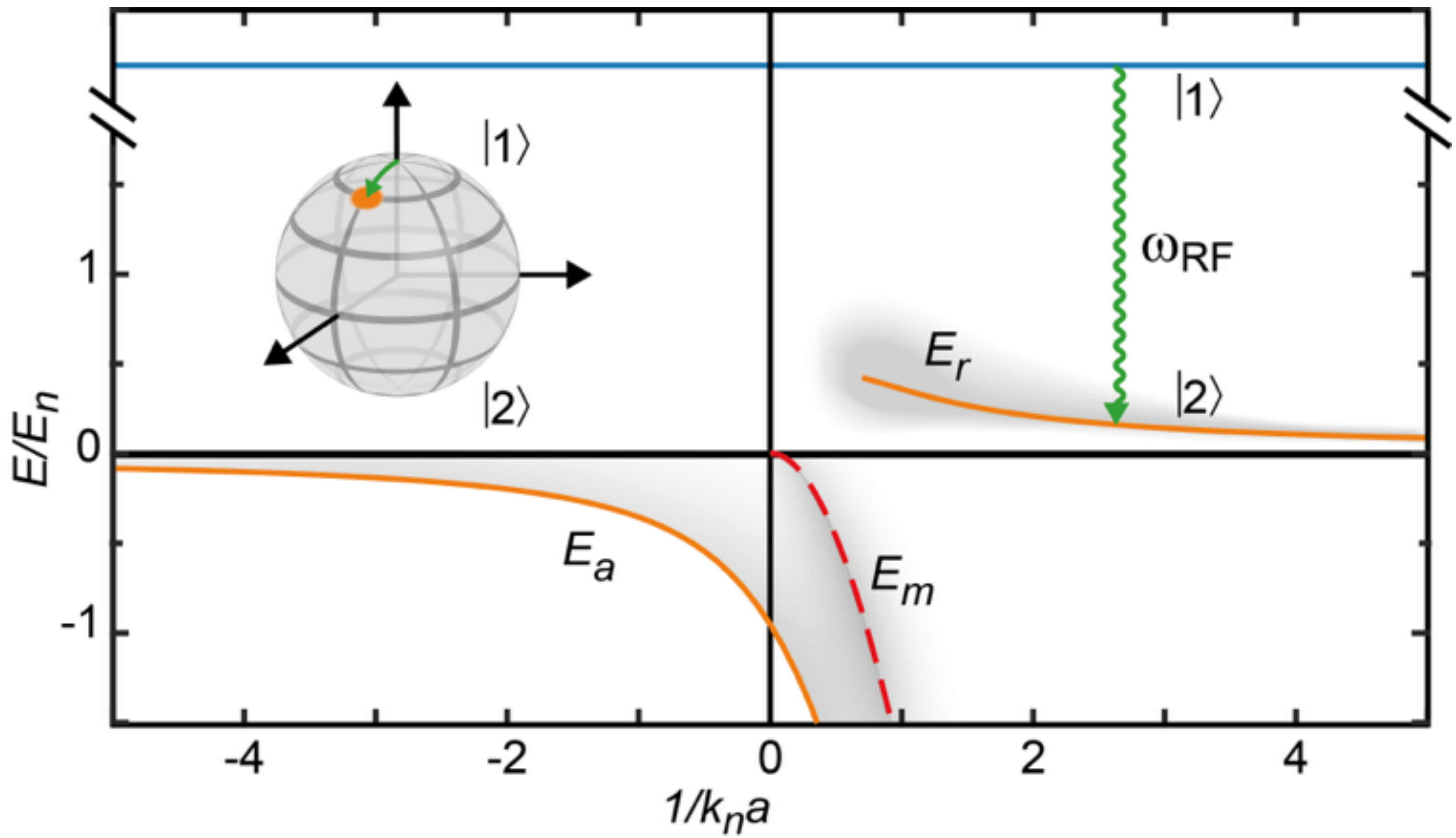
RF probes k=0 impurity spectral function: $\dot{N}_2 \propto A(\mathbf{k}=\mathbf{0},\omega) = -2\mathrm{Im}G_2(\mathbf{k}=\mathbf{0},\omega)$

Contrast with Fermi gas or thermal Bose gas



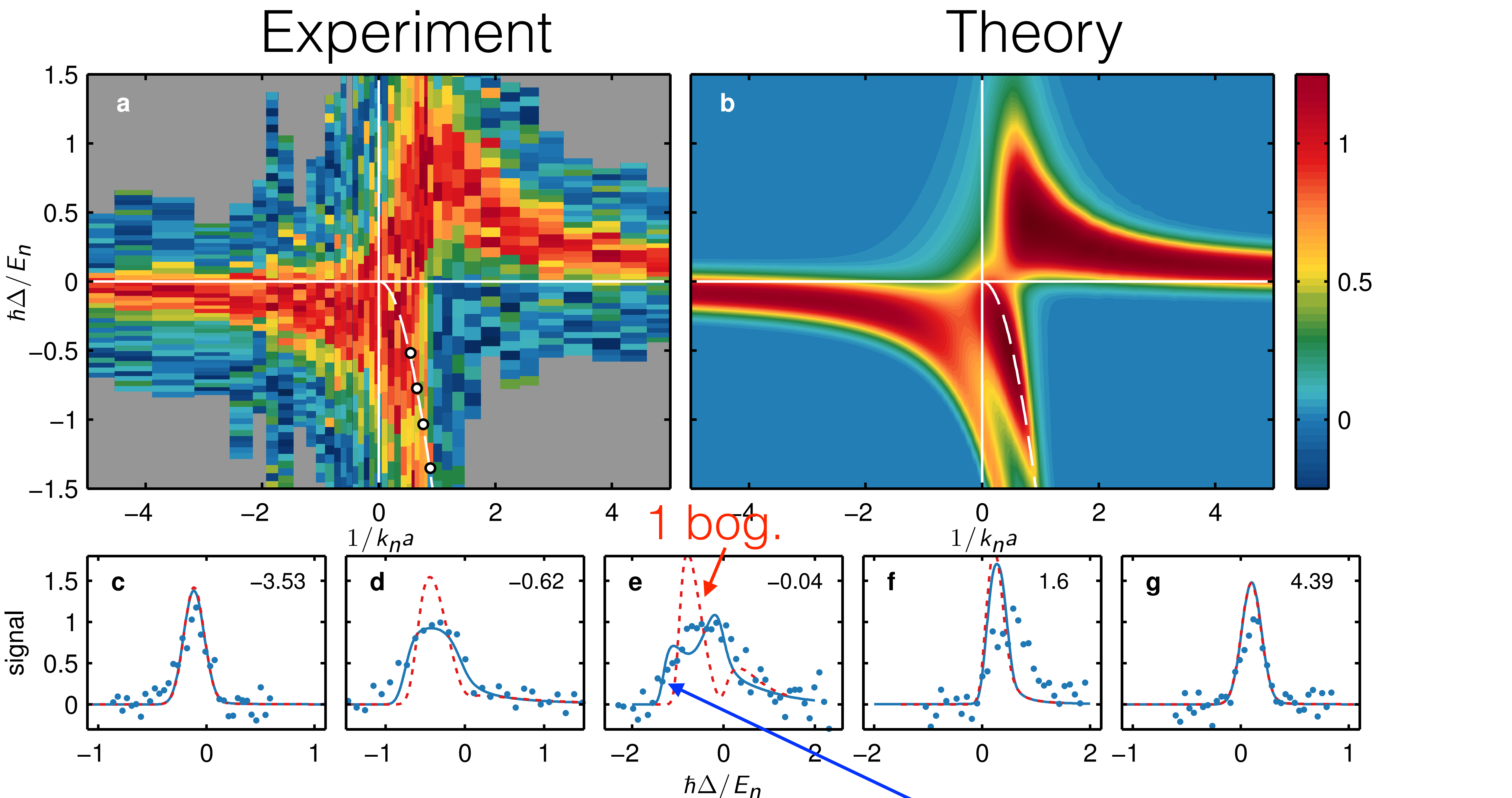
vertex corrections

Generic Physics



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

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



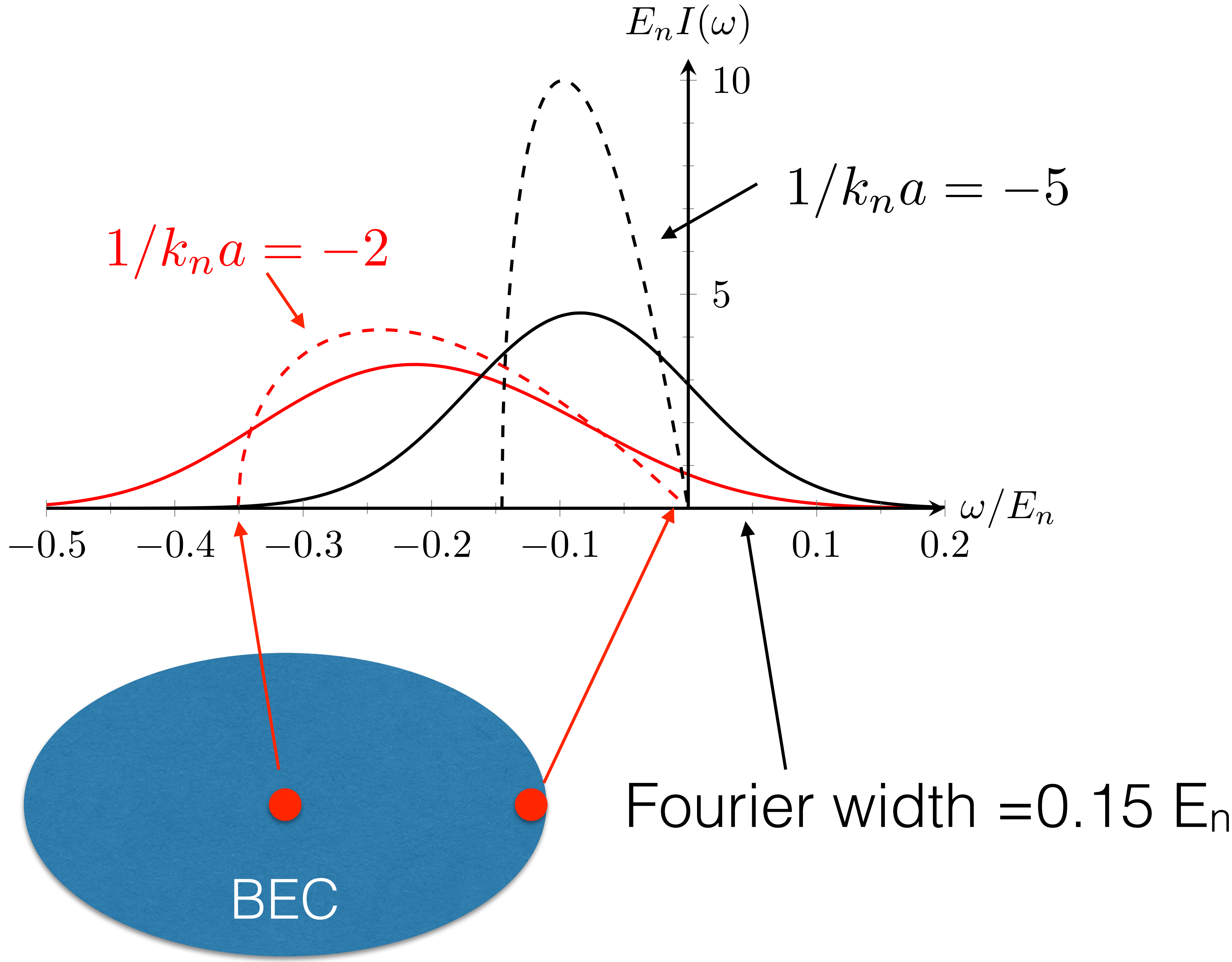
☆Clear shift away from ω_0

☆Excellent agreement between experiment and 2 bog. theory
(trap averaging important!)

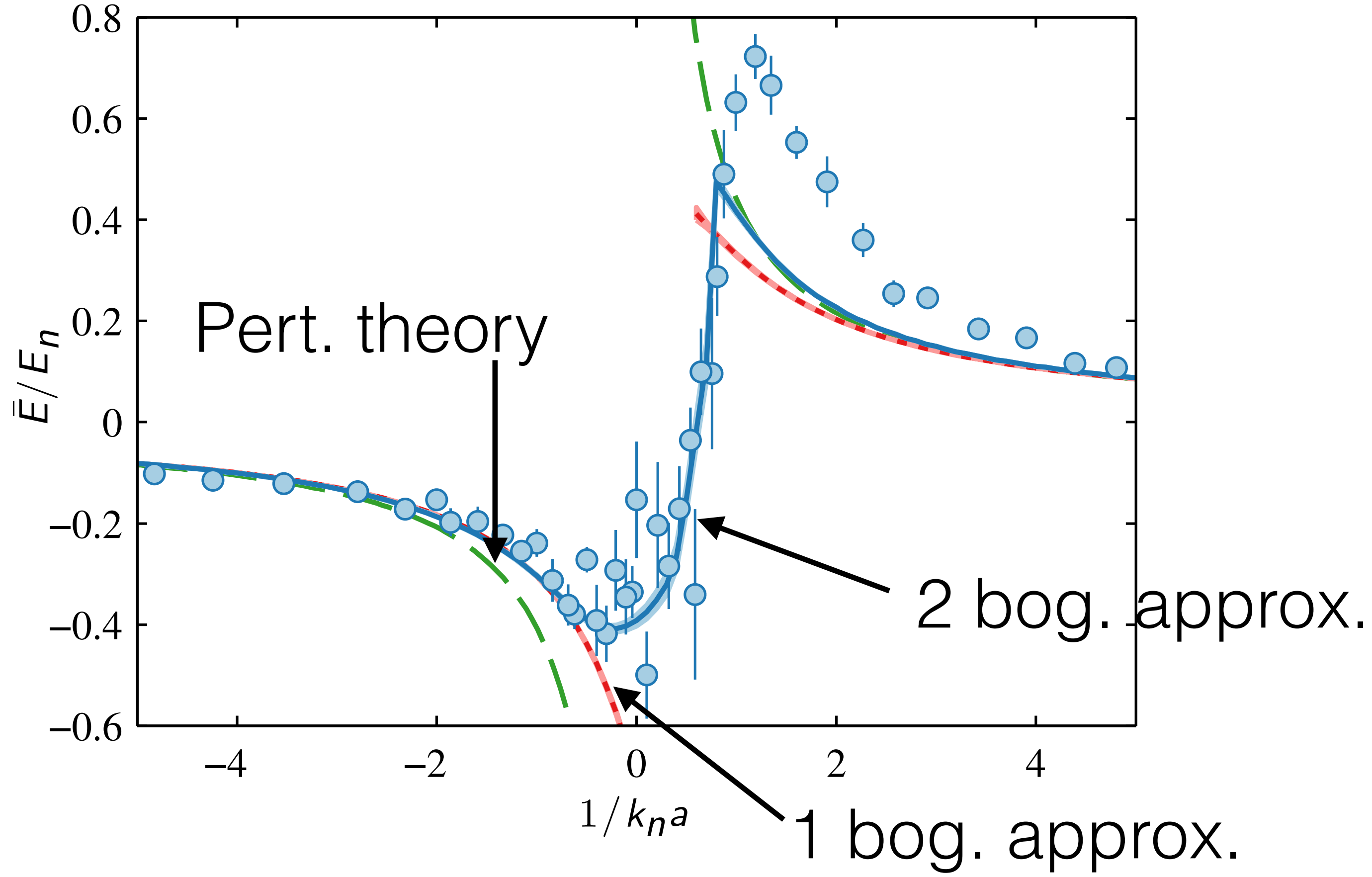
☆Well-defined polaron for weak coupling

☆Many-body continuum dominates for strong coupling

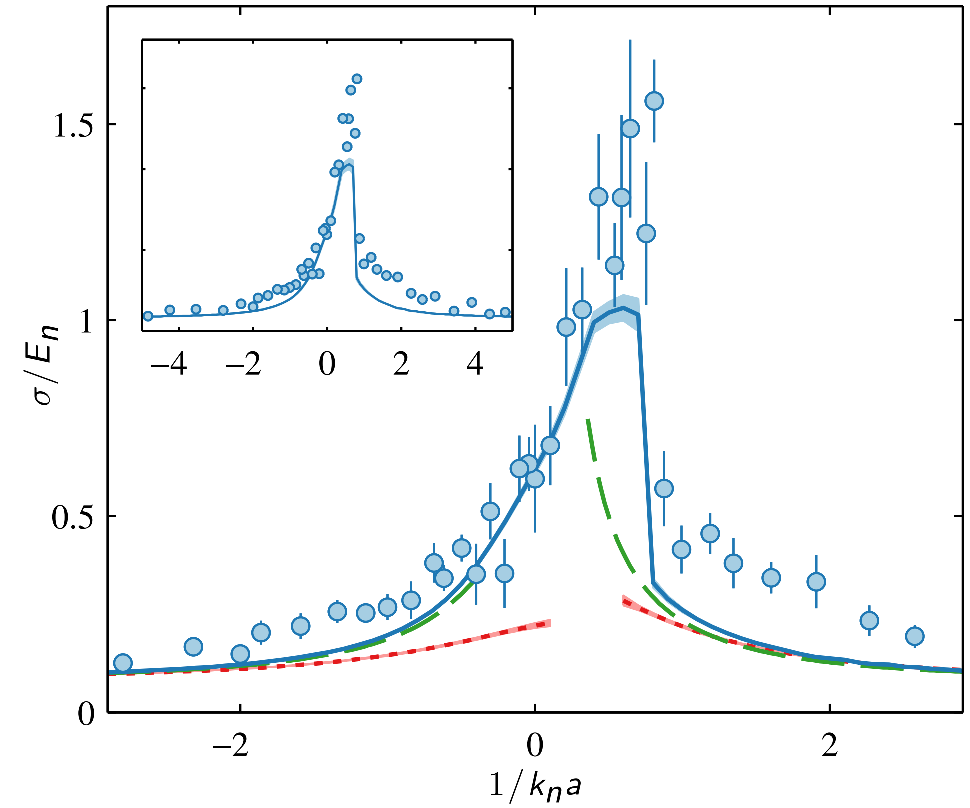
Trap averaging & Fourier broadening



Energy



Width



☆Remarkable agreement between experiment and theory
(some problems at strong repulsion)

☆Pert. theory explains data for weak coupling ⇒ well defined polaron

☆3-body decay <u>not</u> needed to explain width

$\Gamma \propto n_0^2 a^4$ weak coupling

$\Gamma \propto E_n$ unitarity

Makotyn *et al.*, Nat. Phys. **10**, 116 (2014)

Conclusions

❶ Good theoretical understanding of Bose polaron both for weak and for strong coupling

❷ Experimental observation of Bose polaron for the first time

R. S. Christensen, J. Levinsen & GMB, PRL **115**, 160401 (2015)
J. Levinsen, M. M. Parish & GMB, PRL **115**, 125302 (2015)
N. B. Jørgensen et al, arXiv:1604.07883

AARHUS UNIVERSITY

εFB23

EFB23

23RD EUROPEAN CONFERENCE ON **FEW-BODY PROBLEMS IN PHYSICS**

DEPARTMENT OF MATHEMATICS, AARHUS UNIVERSITY, DENMARK

8TH-12TH AUGUST 2016

INVITED SPEAKERS

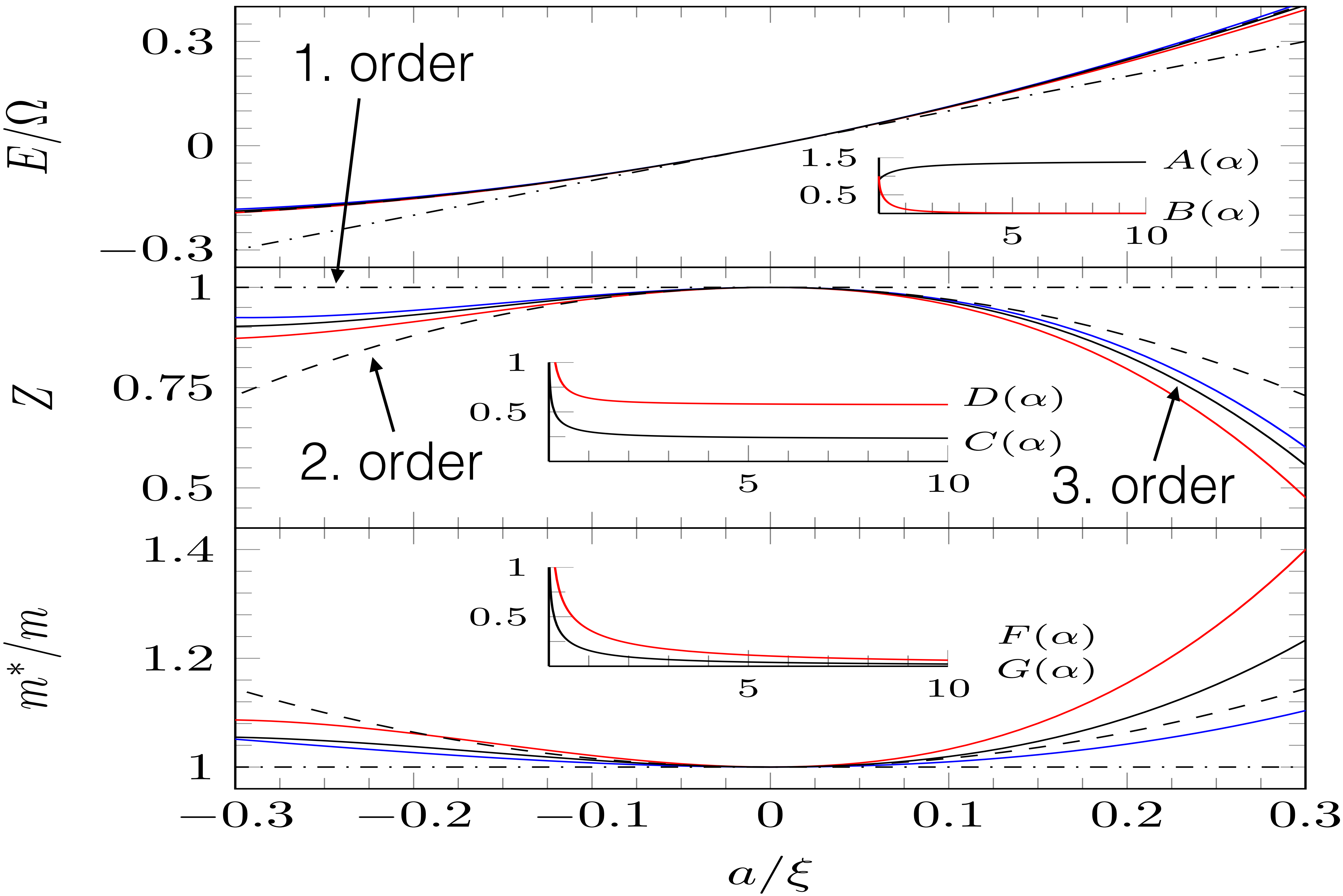
Arnoldas Deltuvas, Vilnius University
Artem Volosniev, TU Darmstadt
Brian Lester, JILA Boulder
Chen Ji, ECT* Trento
Chris Greene, Purdue University
Dorte Blume, Washington State University
Elzbieta Stephan, University of Silesia
Evgeny Epelbaum, Bohum Univesrity
Francesca Sammarruca, University of Idaho
Frank Deuretzbacher, ITP University of Hannover
Laura Marcucci, Pisa University
Lucas Platter, University of Tenessee
Mohammad Ahmed, Duke Iniversity
Nicholas Zachariou, JLAB
Nir Barnea, Racah Institute of Physics HUJI
Or Hen, MIT
Patrick Achenbach, University of Mainz
Selim Jochim, University of Heidelberg
Susumo Shimoura, University of Tokyo
Valery Nesvizhevsky, Institut Laue-Langevin
Yusuke Nishida, Tokyo Institute of Technology

International Advisory Committee: Alejandro Kievsky, Chris Greene, Christian Forssen, Craig Roberts, Doerte Blume, Eduardo Garrido, Francisco Fernandez Gonzalez, Hans-Werner Hammer, Henryk Witala, Jaume Carbonell, Jean-Marc Richard, Johann Haidenbauer, Kalman Varga, Lauro Tomio, Mantile Leslie Lekala, Nasser Kalantar-Nayestanaki, Nina Shevchenko, Nir Barnea, Peter Schmelcher, Peter Zoller, Pierre Descouvemont, Stanisław Kistryn, Teresa Pena, Victor Mandelzweig, Werner Tornow, Willibald Plessas, Xiaoling Cui

Local Organisers: Dmitri Fedorov (Chair), Georg Bruun, Hans Fynbo, Jan Arlt, Michael Drewsen, Nikolaj Thomas Zinner

Conference Secretary: Karin

http://conferences.au.dk/efb23



1. order
2. order
3. order
E/Ω
Z
m*/m
a/ξ
A(α)
B(α)
C(α)
D(α)
F(α)
G(α)
0.3
0
−0.3
1
0.75
0.5
1.4
1.2
1
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
1.5
0.5
5
10

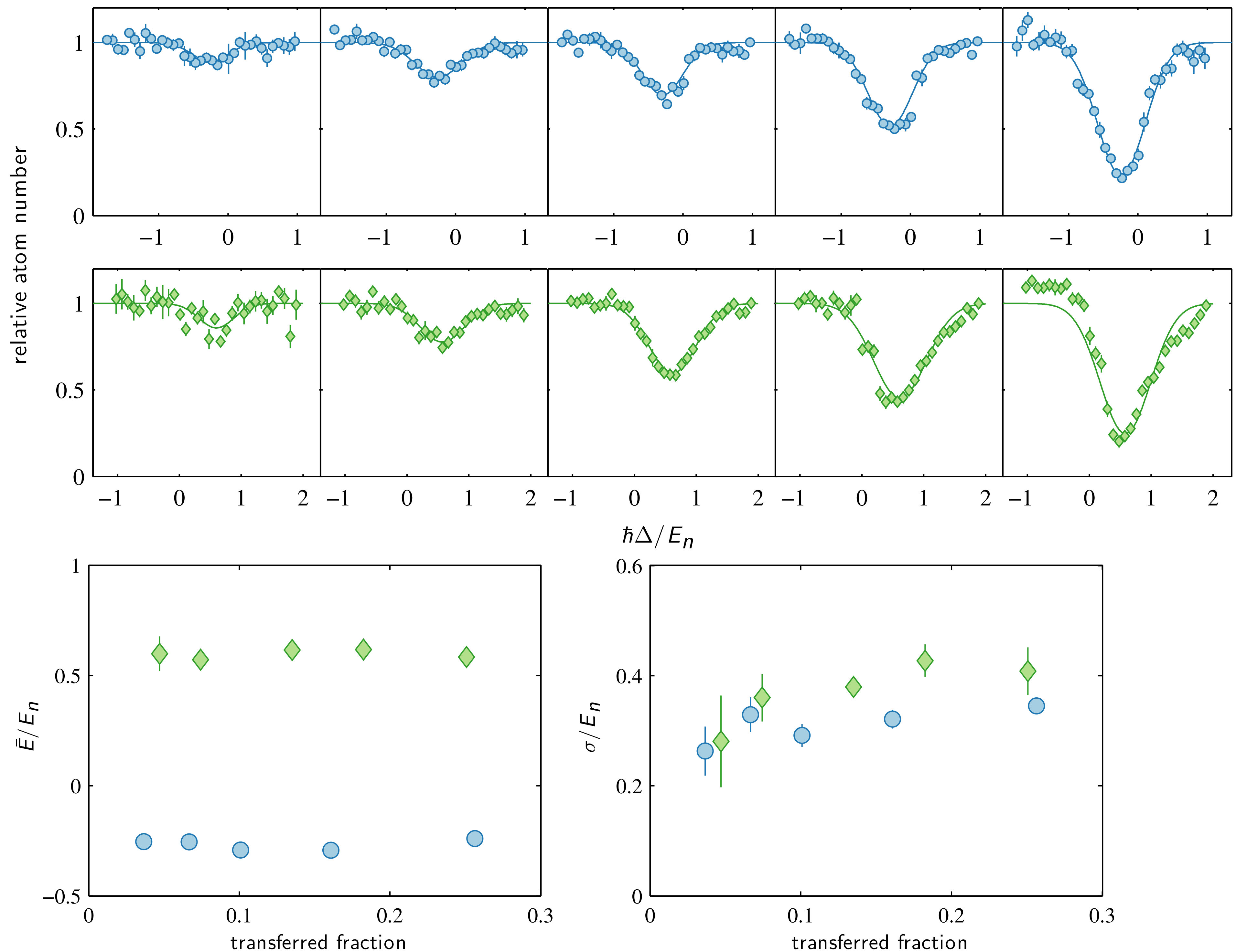
$a_B/\xi = 0.1$

Linear Response regime

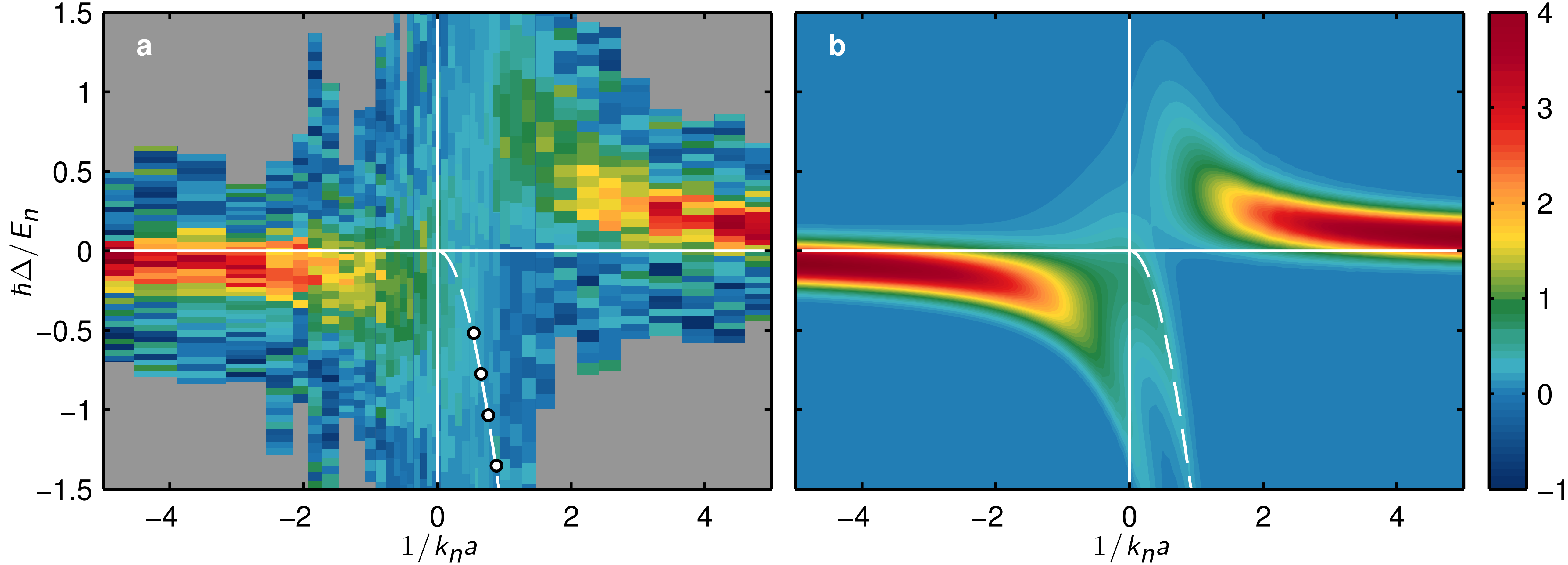
Increasing RF power

$1/k_n a = -0.84$

$1/k_n a = 1.6$



Position and width stable


a
b
1.5
1
0.5
0
−0.5
−1
−1.5
−4
−2
0
2
4
$\hbar\Delta/E_n$
$1/k_n a$
4
3
2
1
0
−1