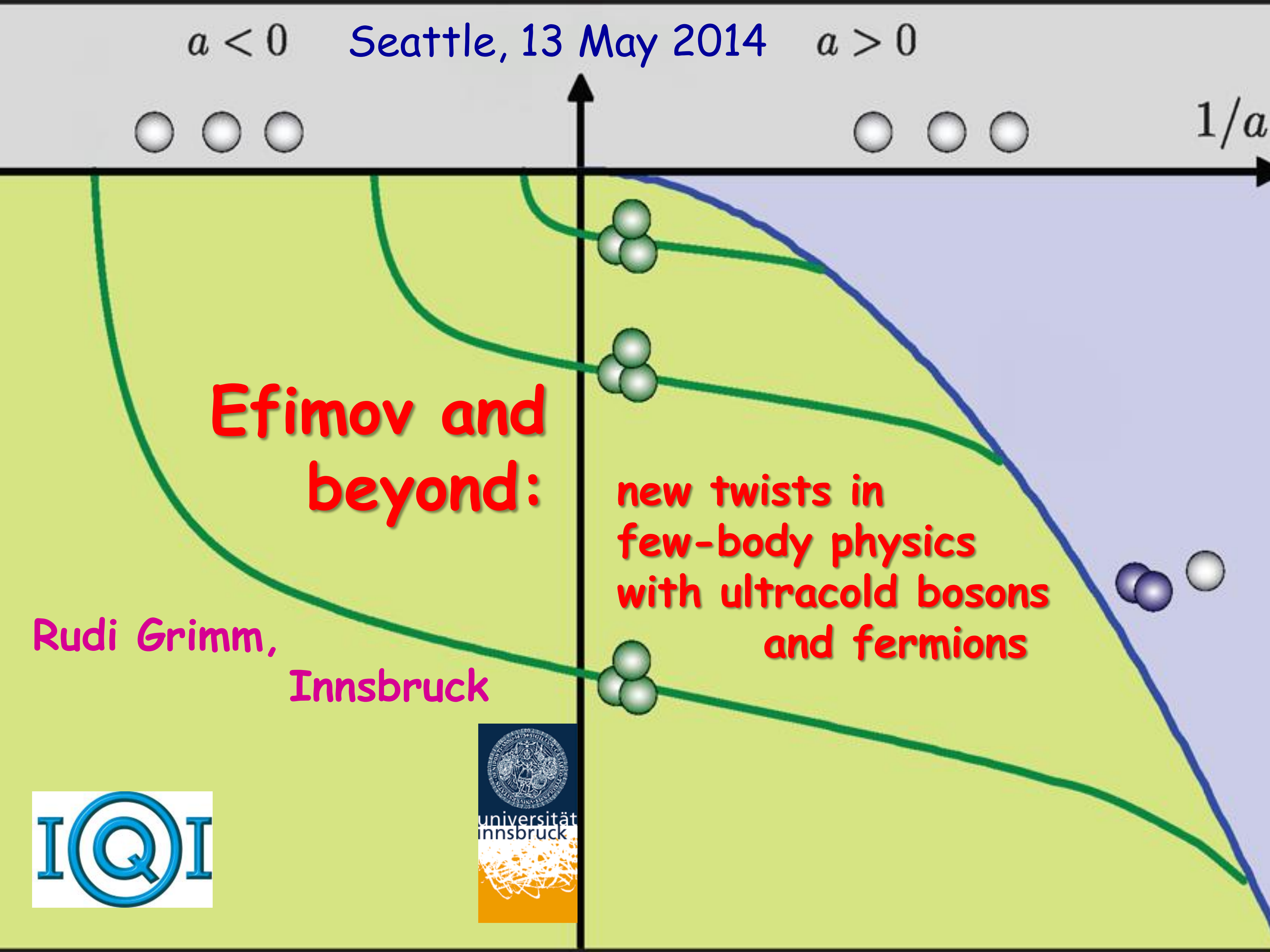
Seattle, 13 May 2014

Efimov and beyond:

new twists in few-body physics with ultracold bosons and fermions

Rudi Grimm,
Innsbruck



Efimov's scenario (1970)

ultracold.atoms

V. Efimov, Yad. Fiz. **12**, 1080 (1970)

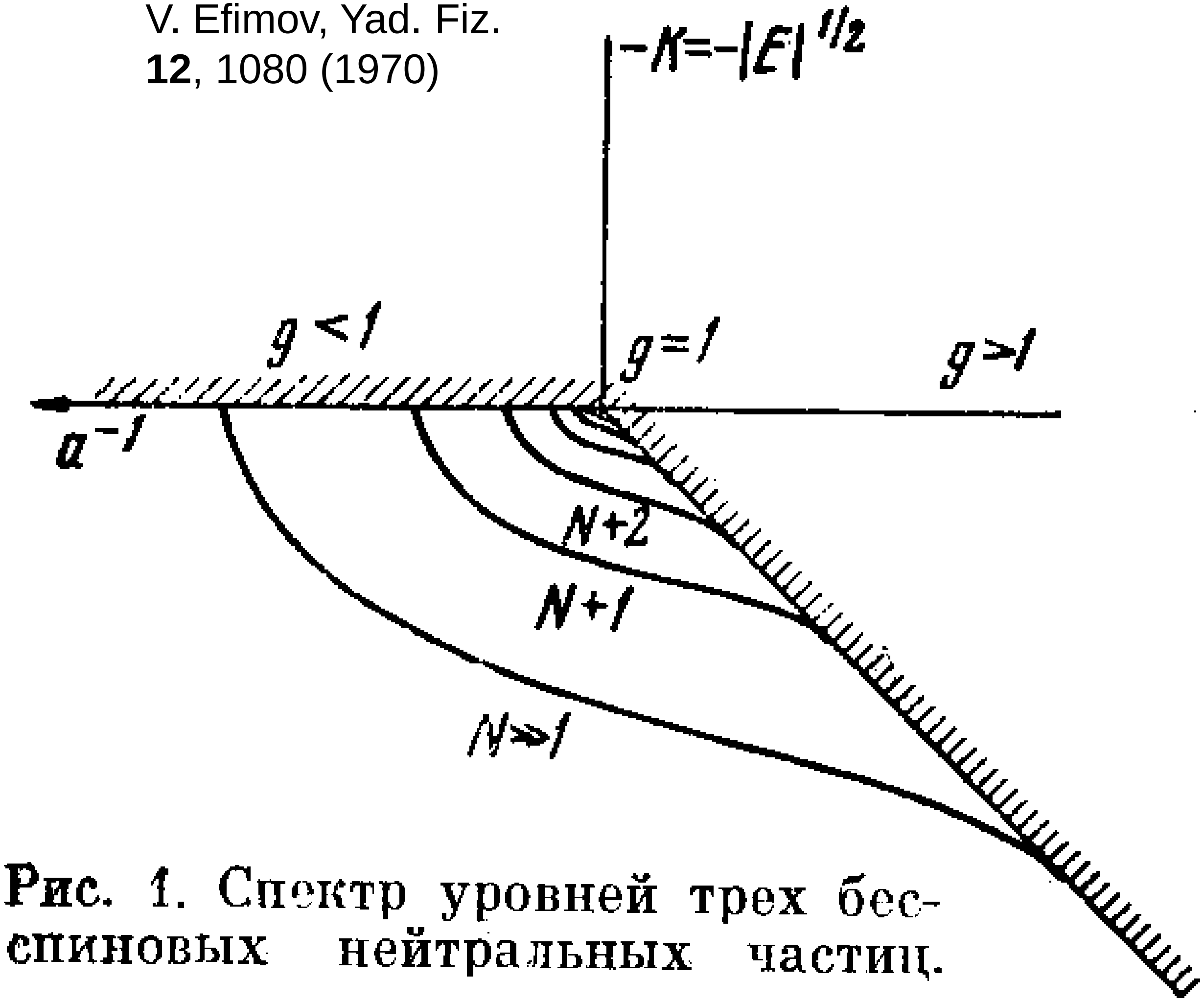


Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц.

Efimov resonances

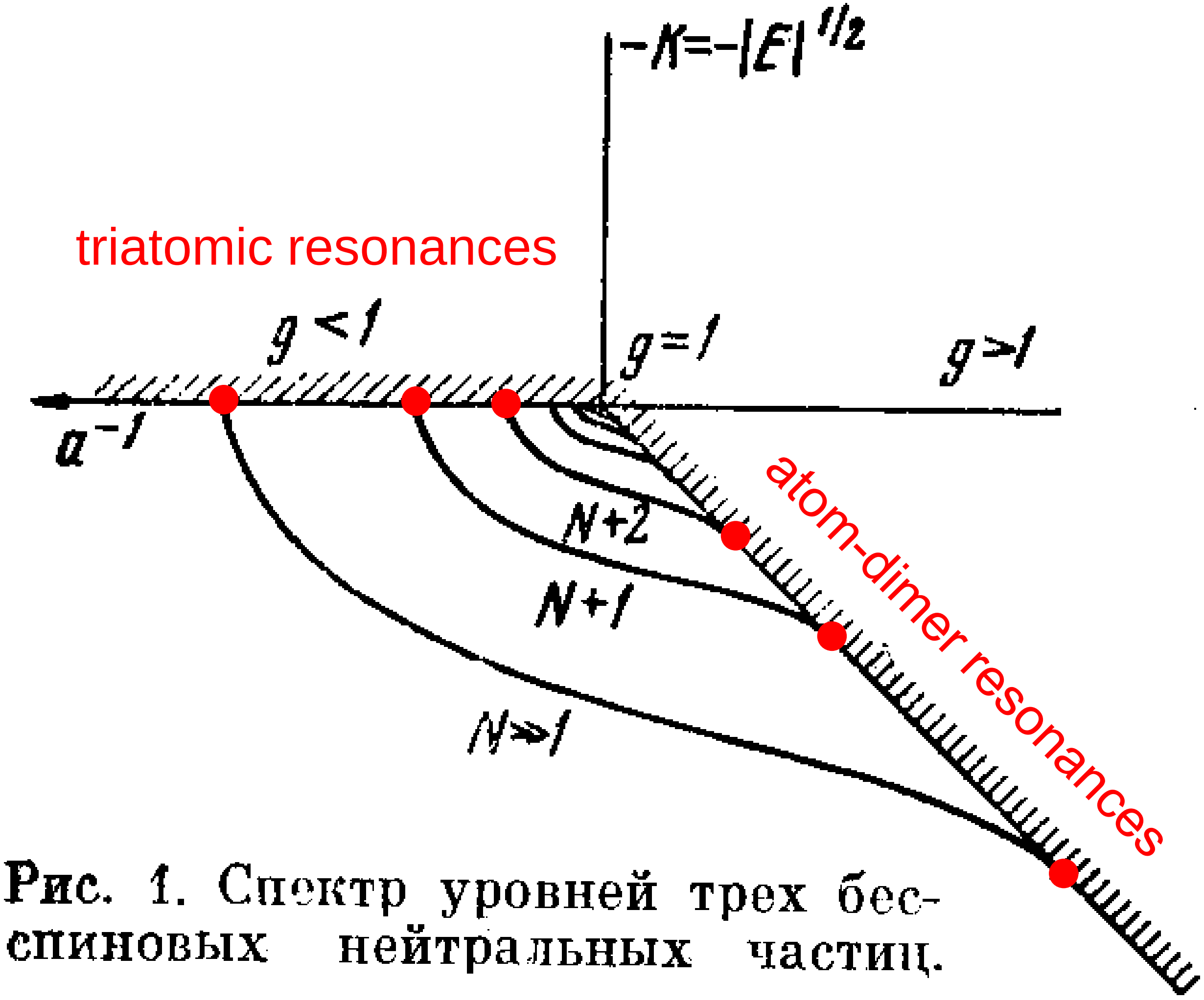


Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц.

universal relations

$a_-^{(n+1)} / a_-^{(n)} = \mathbf{22.7}$

$a_*^{(n+1)} / a_-^{(n)} = 1.06$

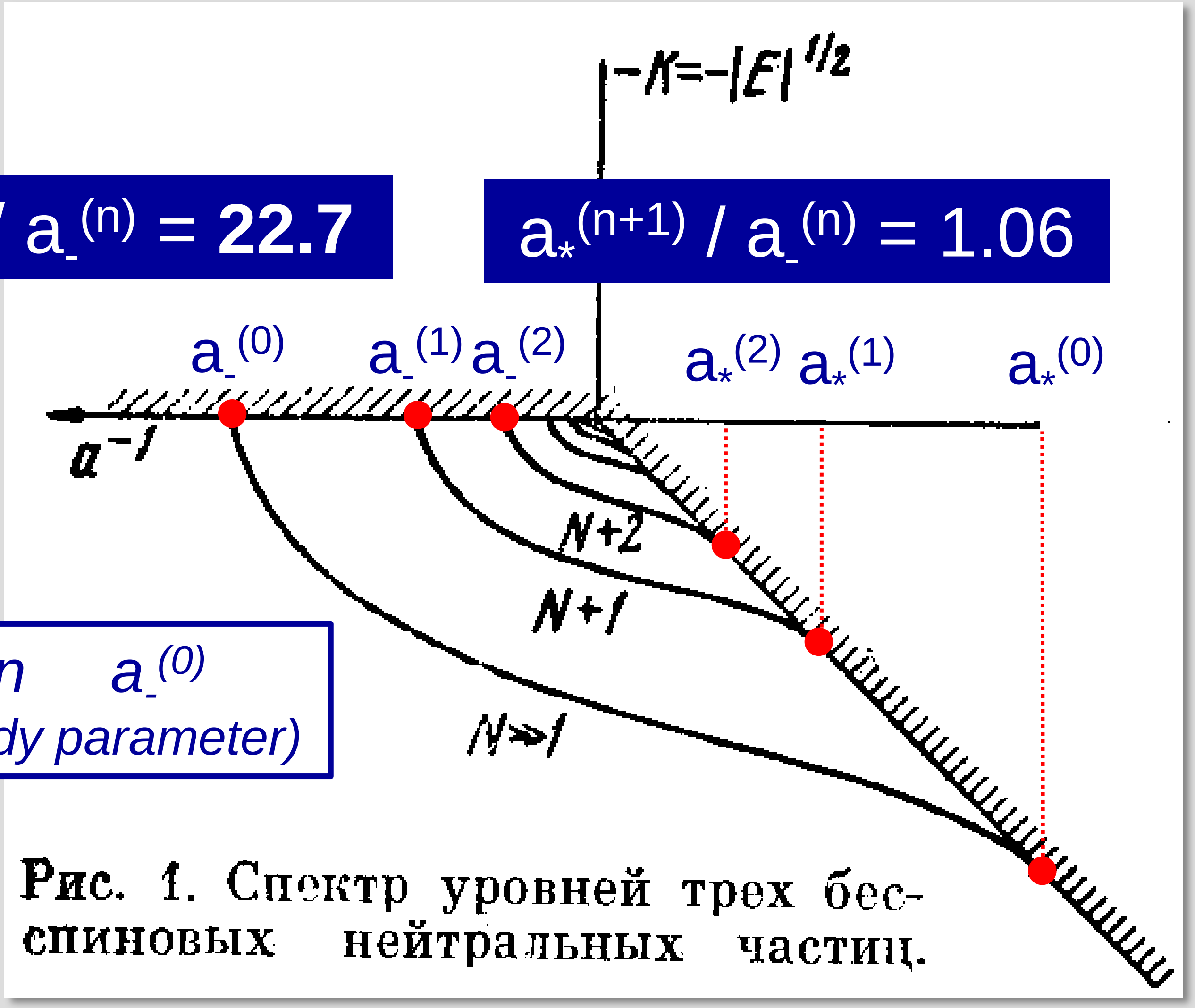
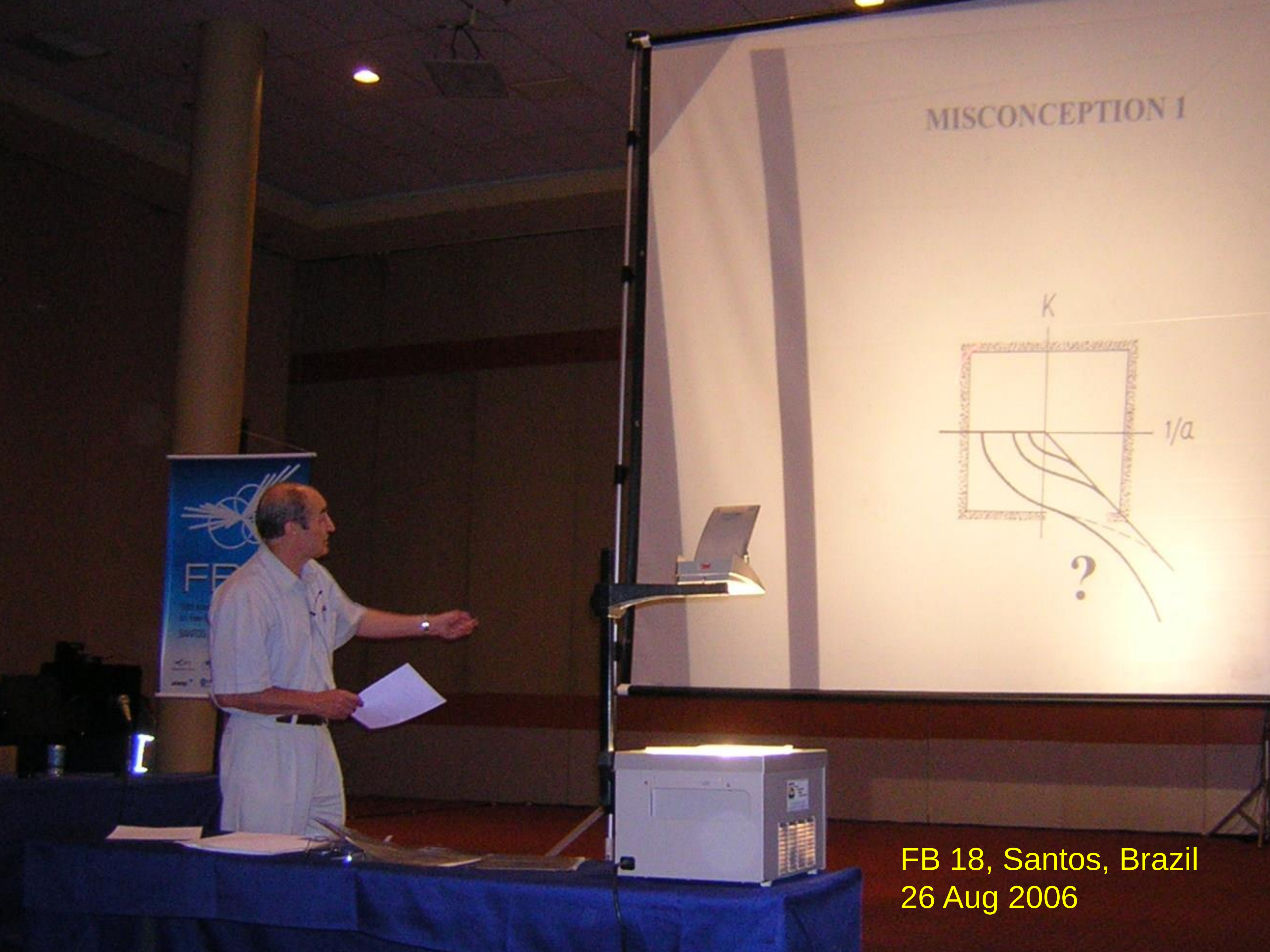


Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц.

unknown $a_-^{(0)}$
(three-body parameter)

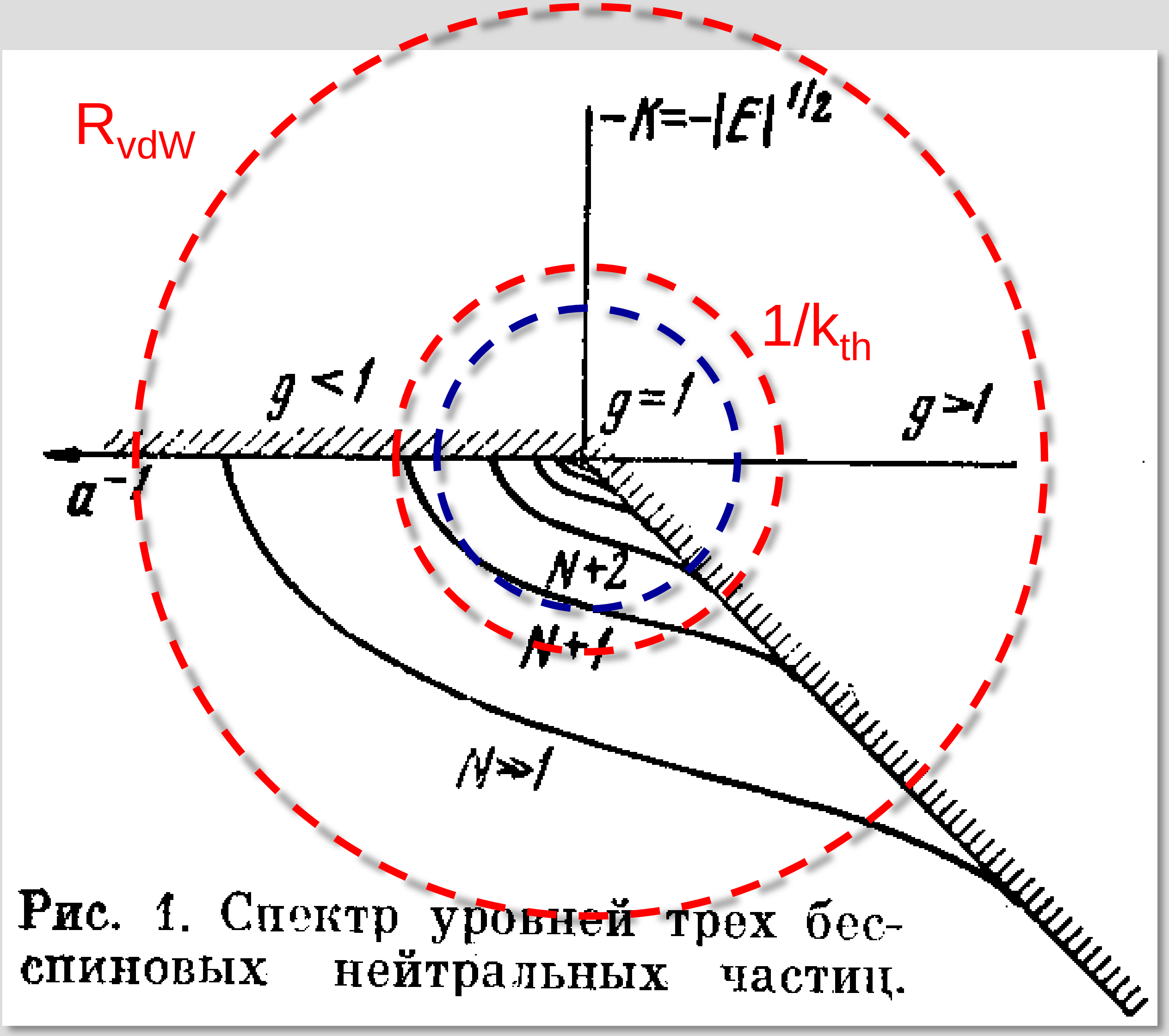
FB 18, Santos, Brazil
26 Aug 2006



FB 18, Santos, Brazil
26 Aug 2006

real experiments: additional length scales

van der Waals length



thermal de Broglie wavelength

mean interparticle distance $n^{-1/3}$

$\approx 1/k_{th}$
near-deg. gas

real experiments: Donut of universality

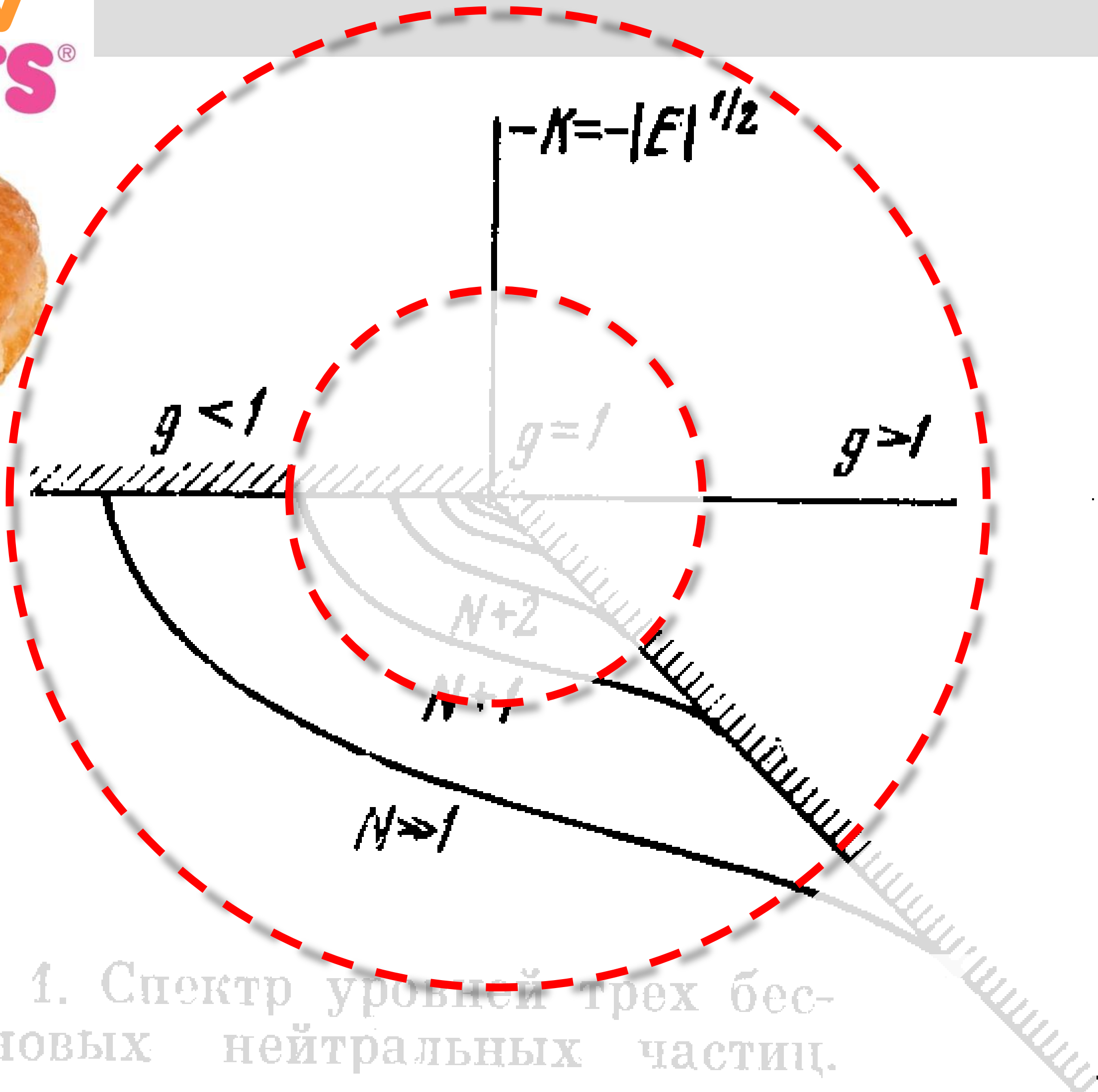
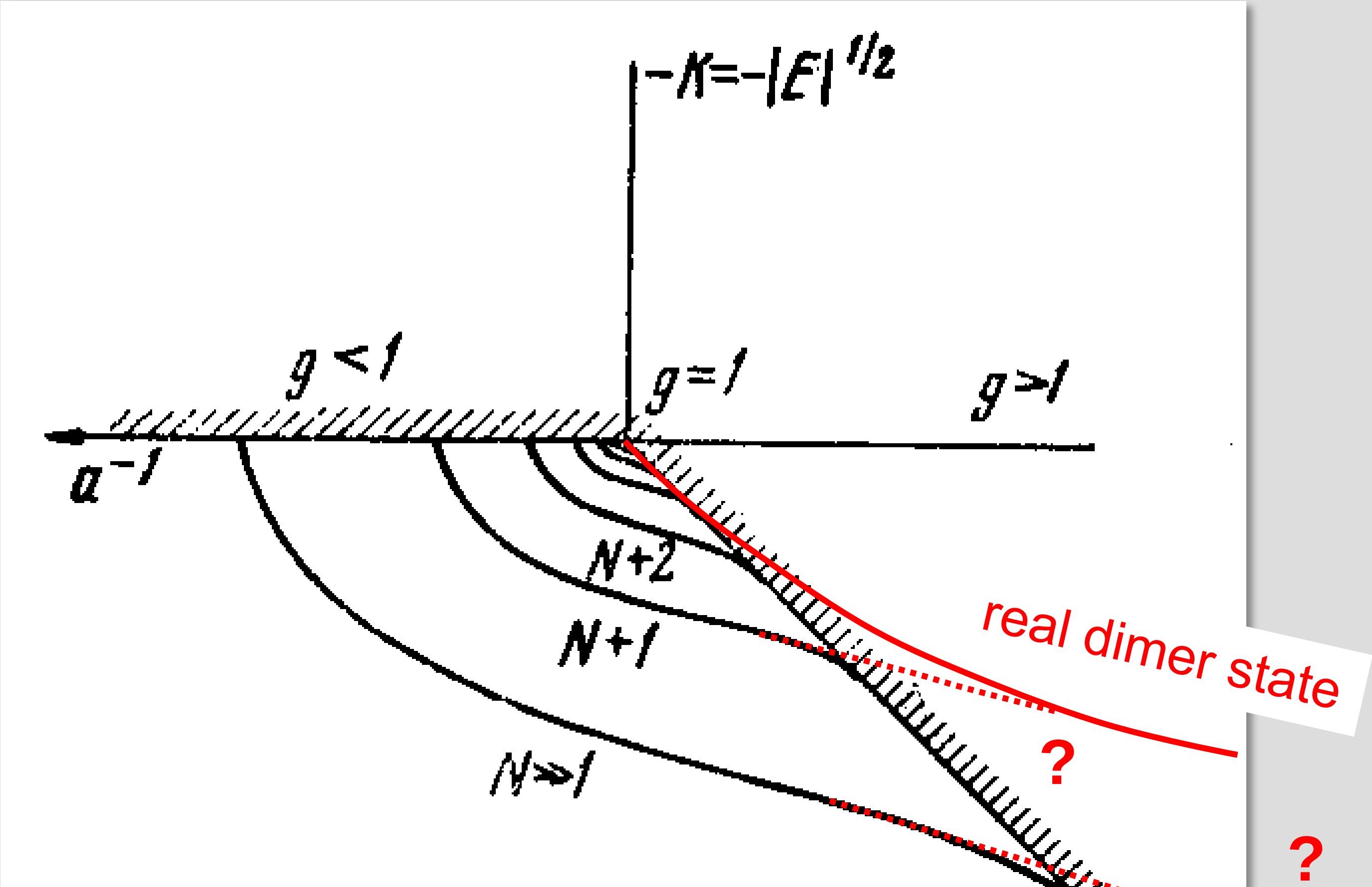


Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц.

real experiments: physics of Feshbach resonance

ultracold.atoms



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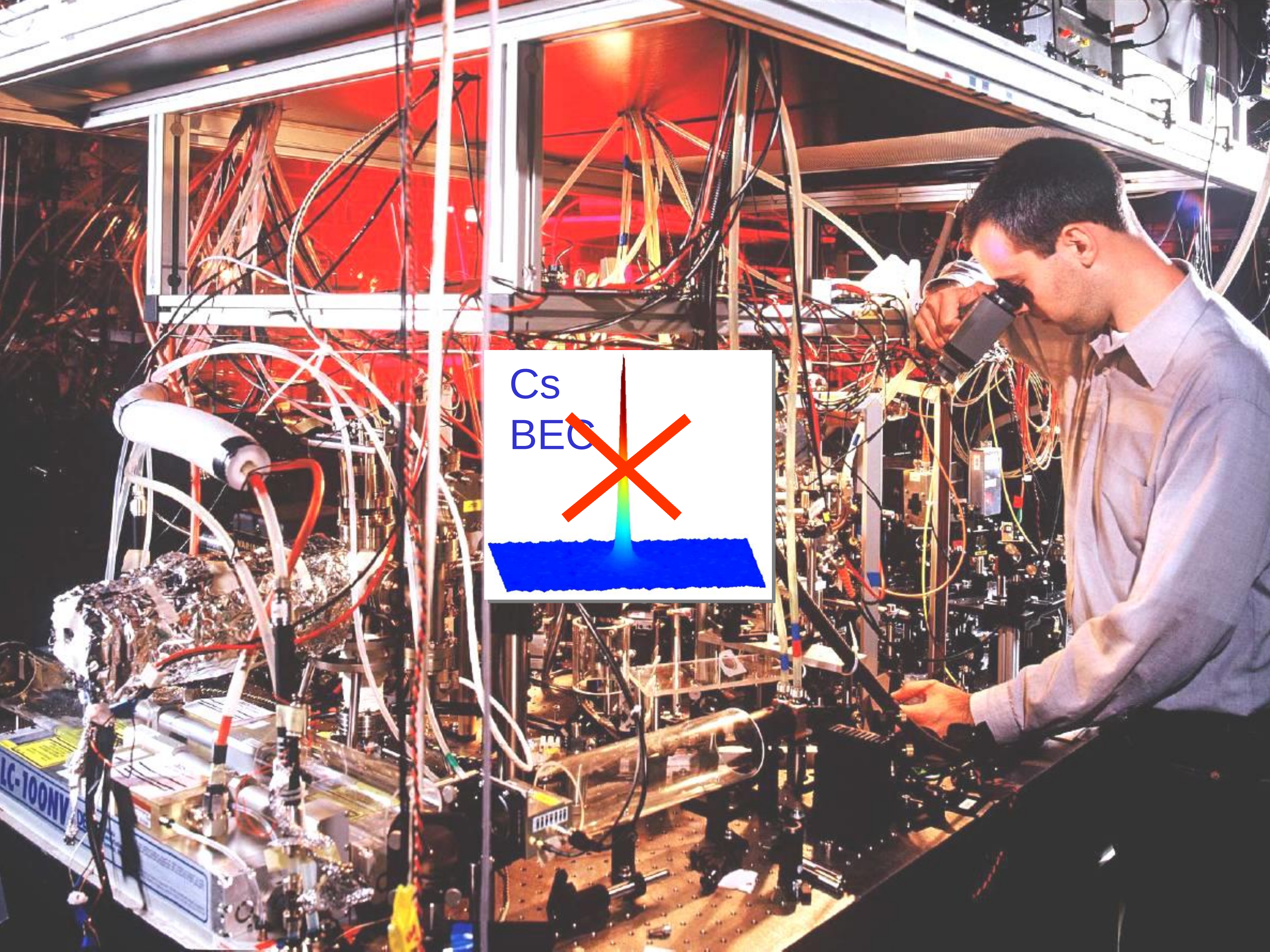
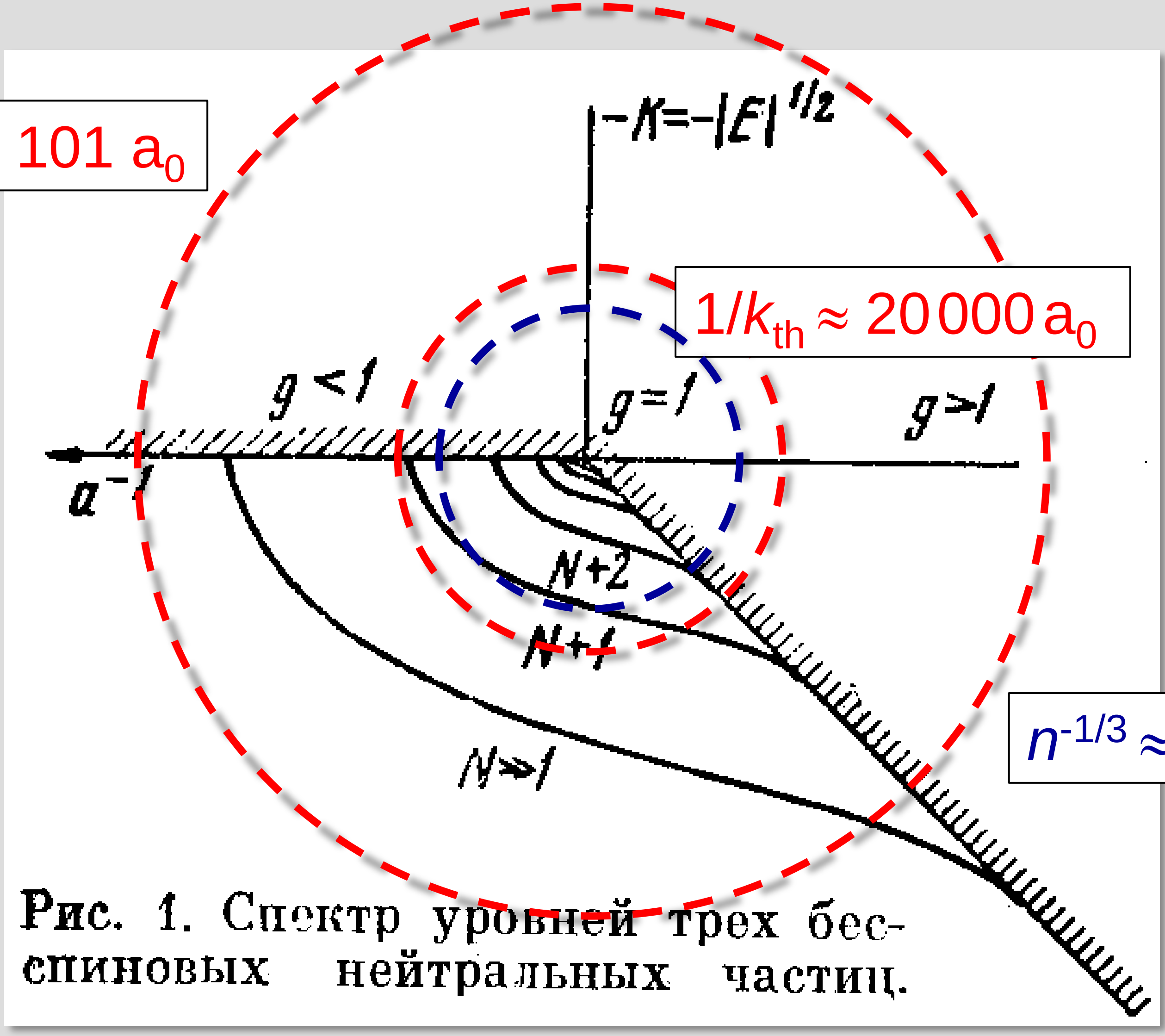

Cs
BEC
LC-100NV

real experiments: length scales for cesium

$R_{vdW} = 101\ a_0$



$1/k_{th} \approx 20\,000\ a_0$

T = 8nK

$n^{-1/3} \approx 70\,000 a_0$

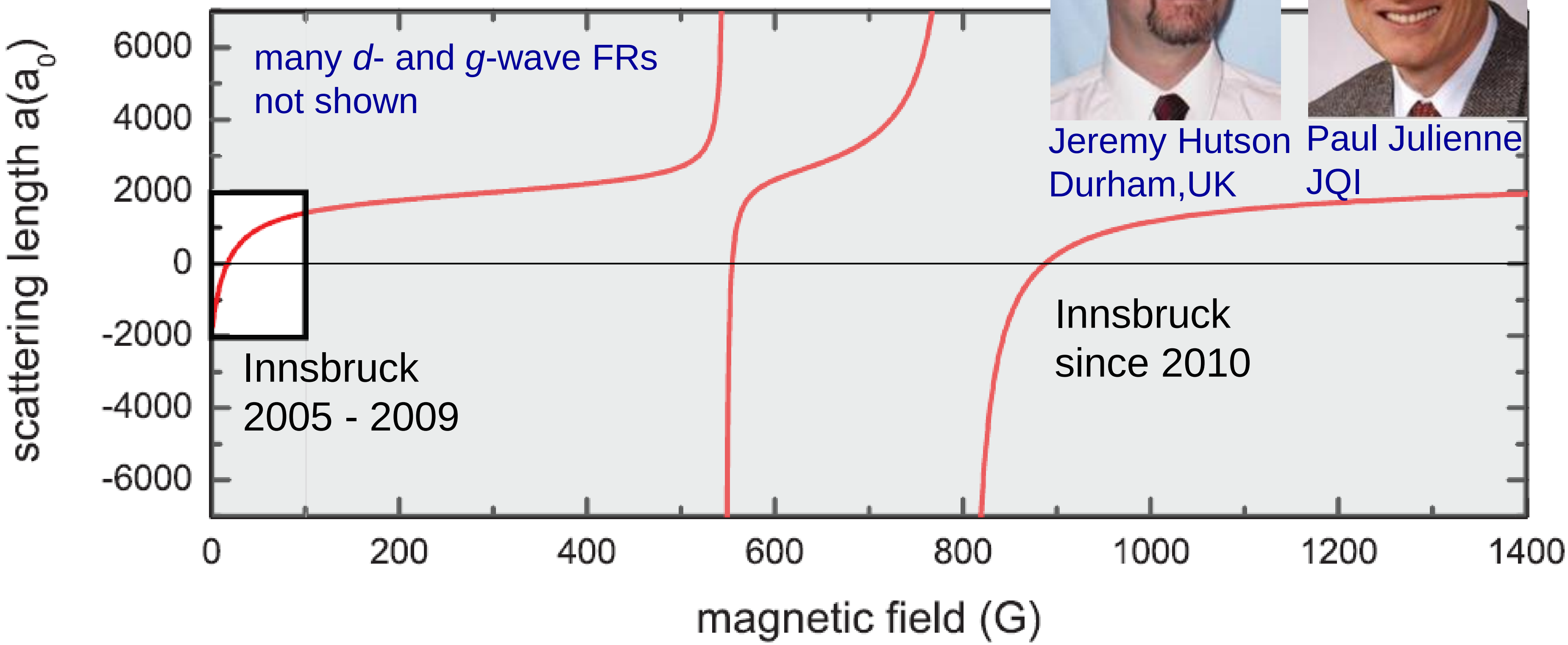
$n = 2 \times 10^{10} cm^{-3}$

magnetic tunability of Cs

many more details and most accurate a(B) mapping
Berninger et al., PRA 87, 032517 (2013)

Jeremy Hutson
Durham,UK

Paul Julienne
JQI

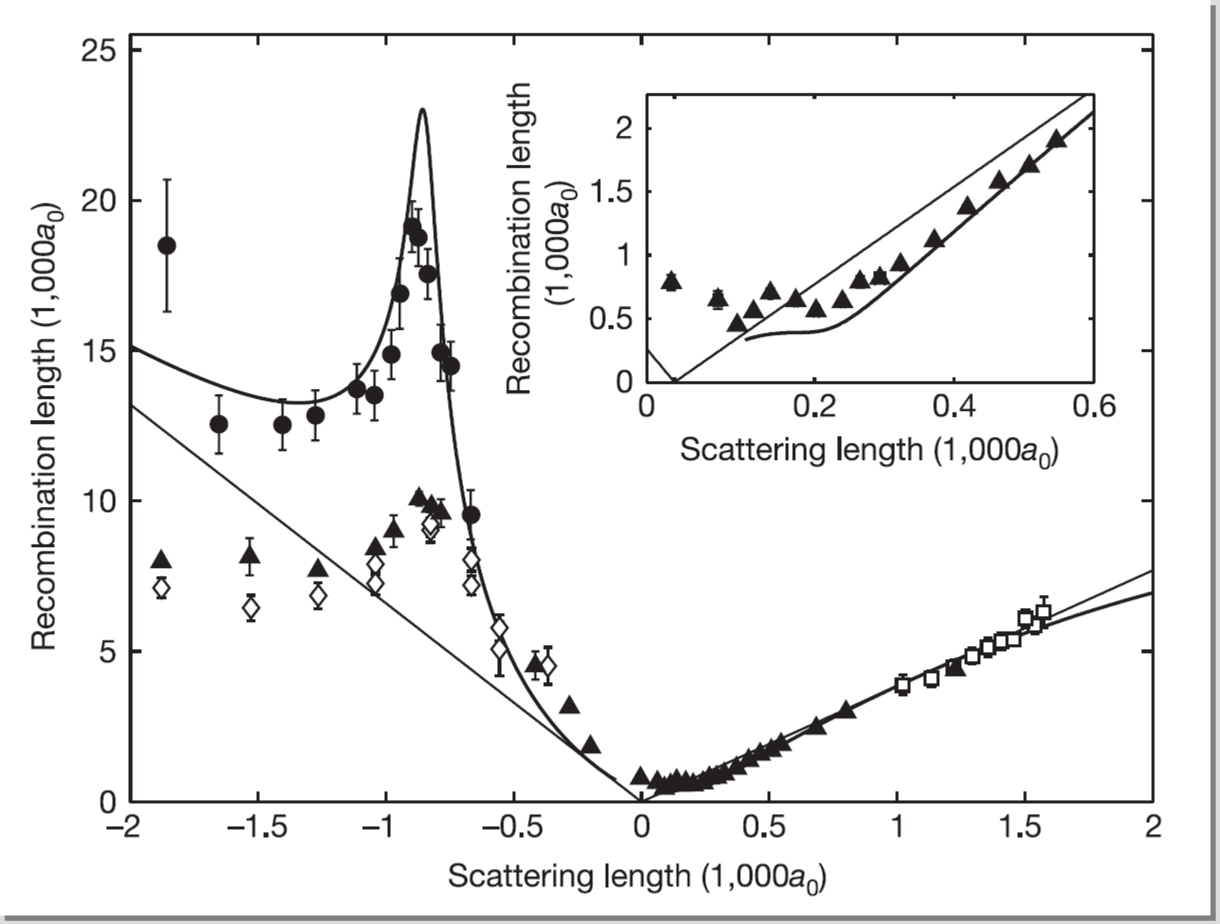


first observations in Cs (2006)

cesium (*F*=3, m_F=3, region of low B-fields)

T=10nK

250nK



original results: Kraemer et al. Nature **440**, 315 (2006)
updated analysis: Berninger et al., PRL **107**, 120401 (2011)

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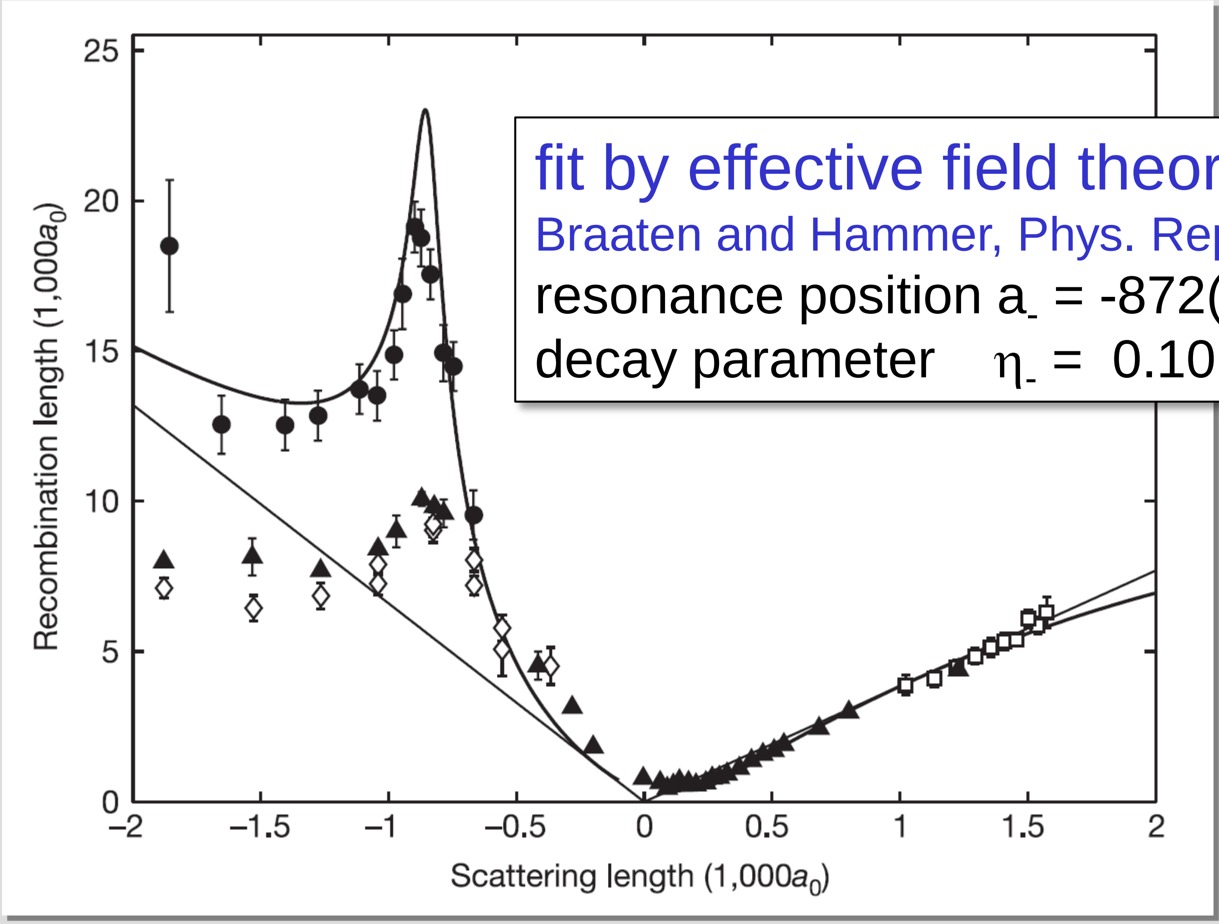


fit by effective field theory

Braaten and Hammer, Phys. Rep. (2006)

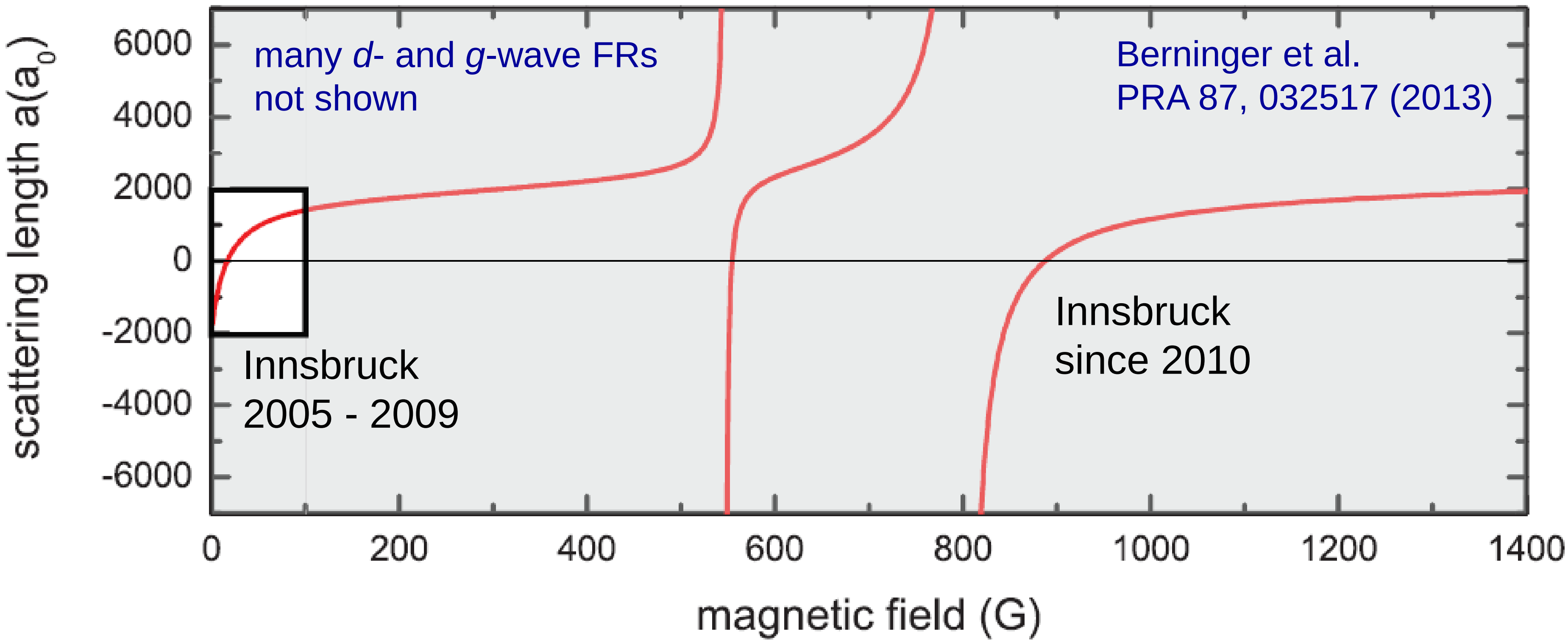
resonance position $a_- = -872(22)\ a_0$

decay parameter $\eta_- = 0.10(3)$

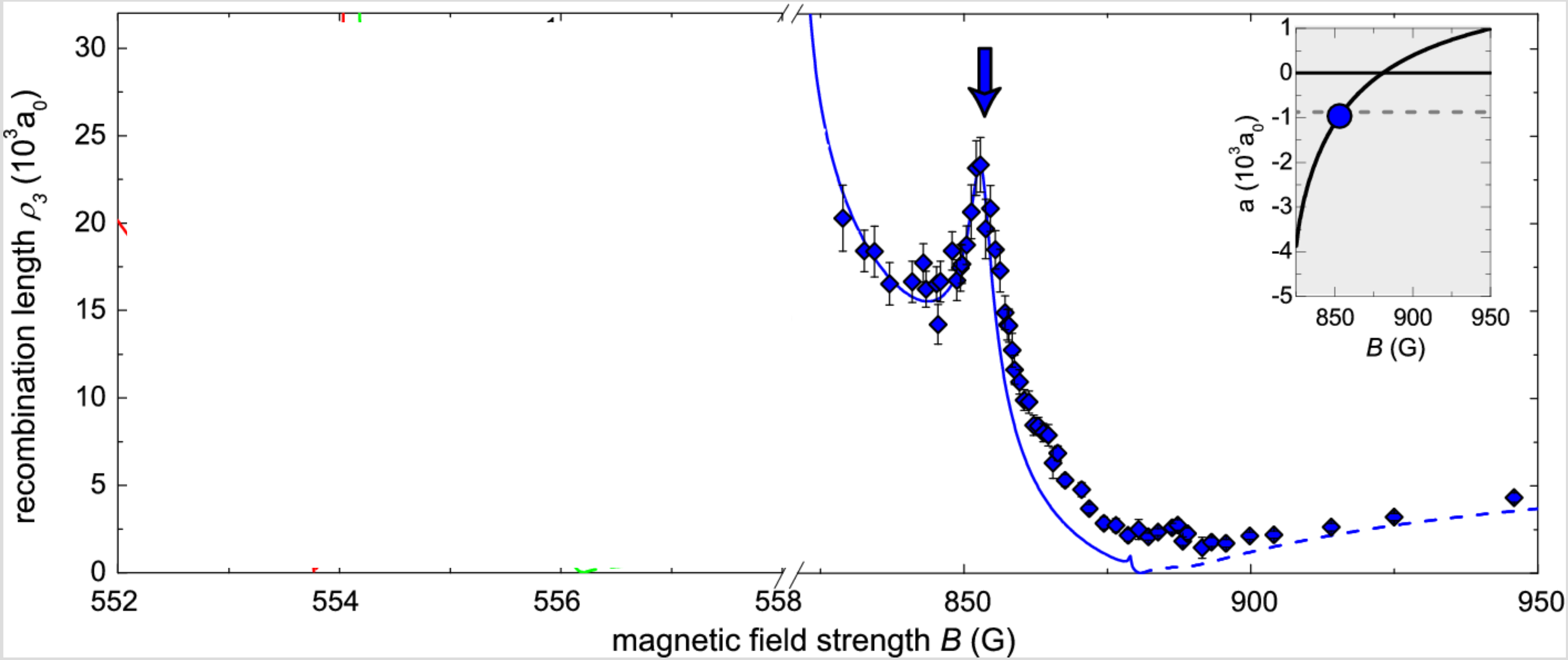
original results: Kraemer et al. Nature **440**, 315 (2006)

updated analysis: Berninger et al., PRL **107**, 120401 (2011)

magnetic tunability of Cs

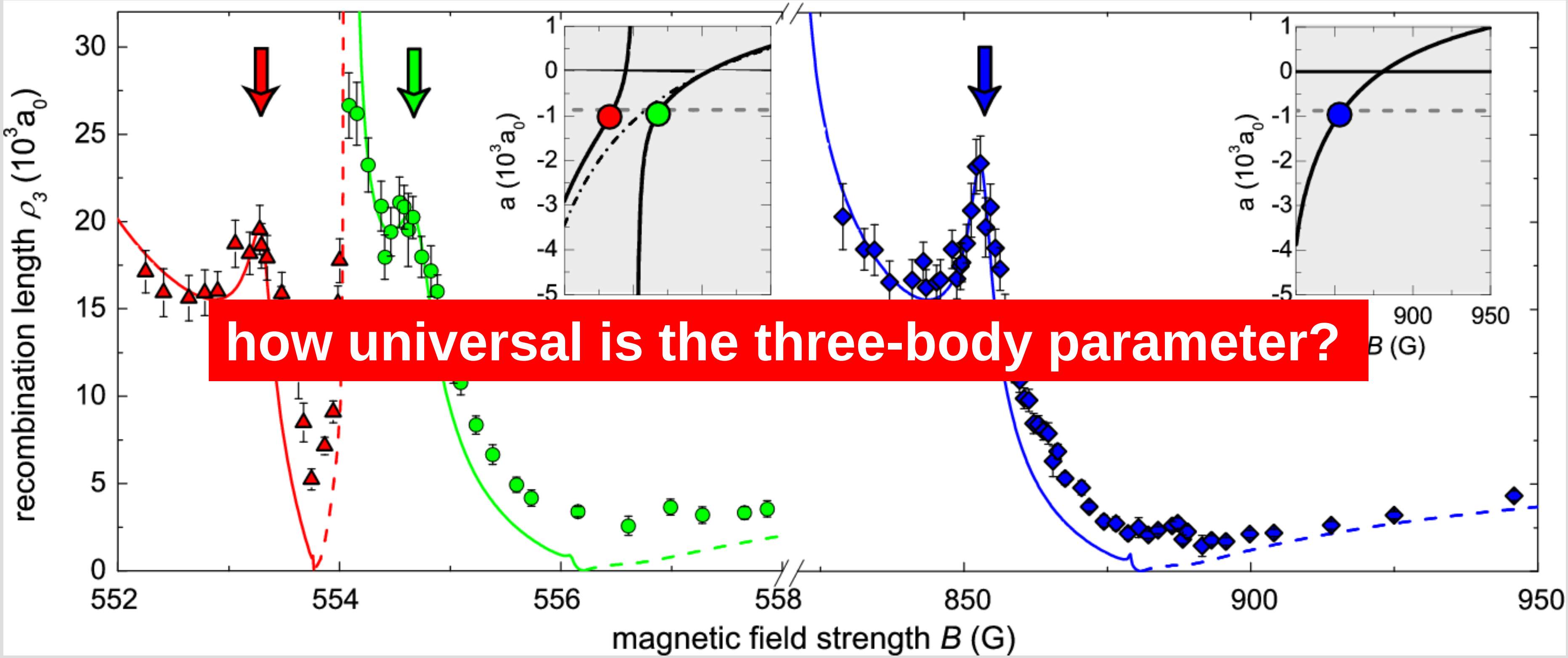


observation of new Efimov resonances in Cs



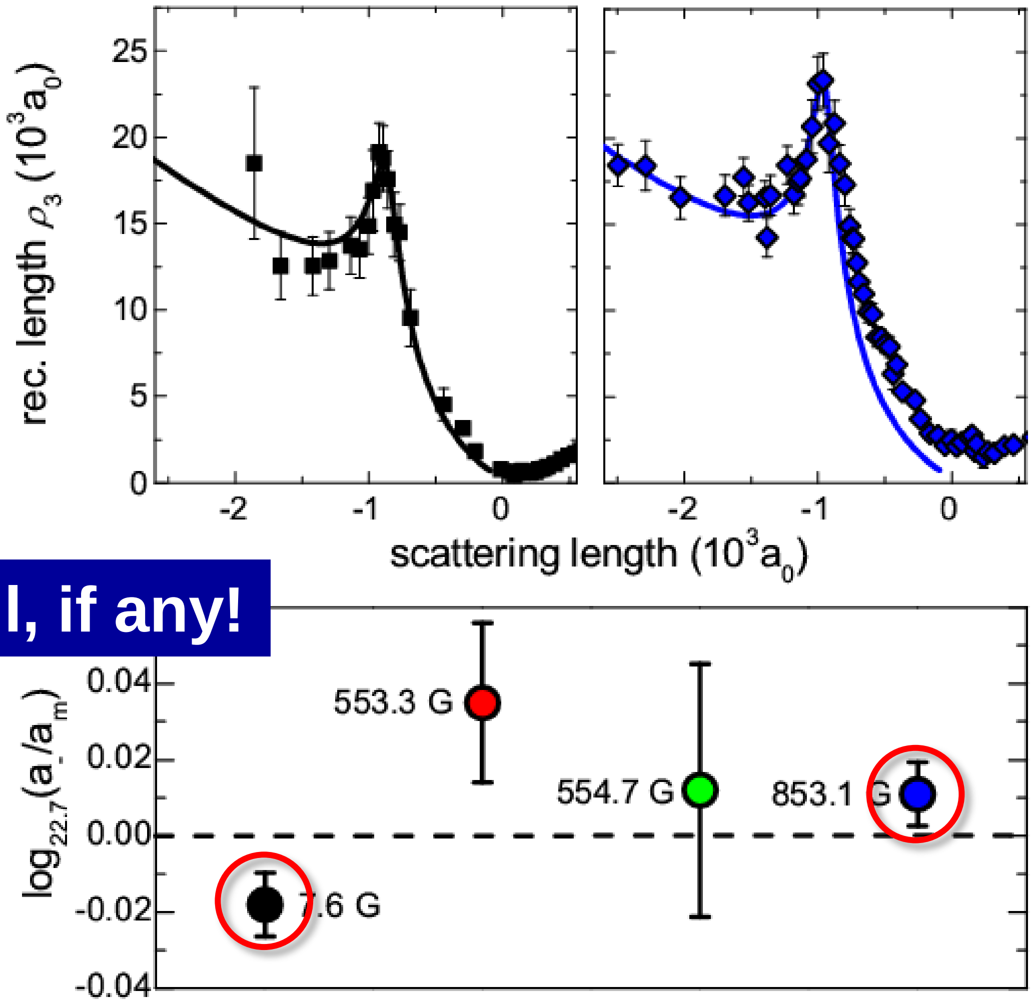
observation of new Efimov resonances in Cs

ultracold.atoms



how universal is the three-body parameter?

variations of the three-body parameter?



very small, if any!

one tenth of Efimov period

strongly entrance-channel dominated FRs

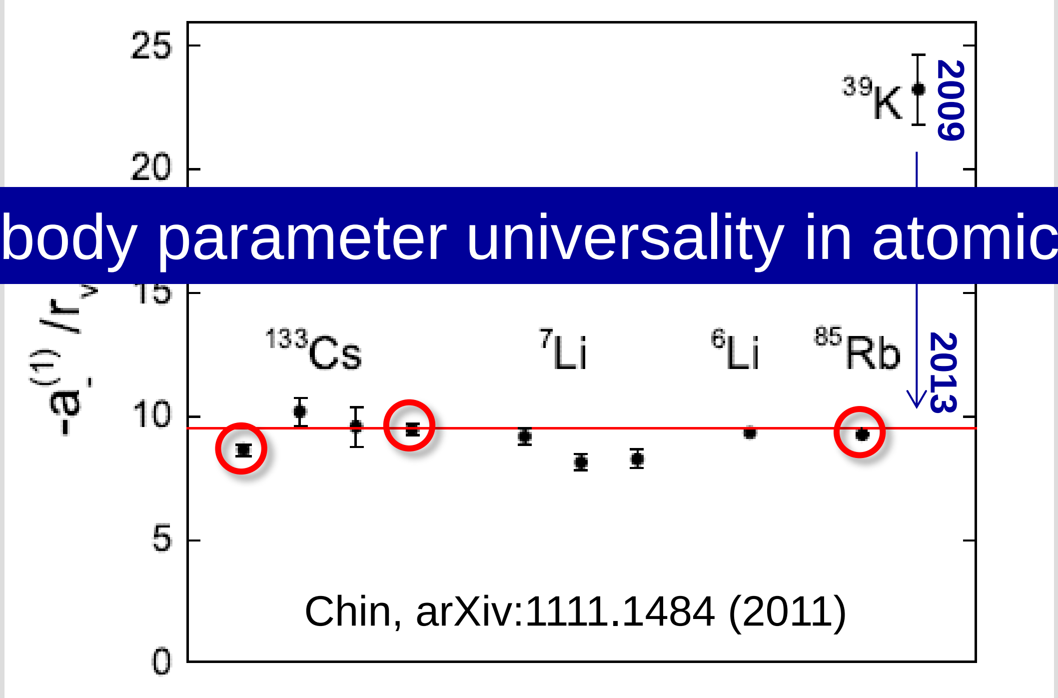
same message from other species

experiments on **^{6}Li, ^{7}Li, ^{39}K, ^{85}Rb, ^{133}Cs** show

$$a_- \approx -9.5\, R_{vdW}$$

$$R_{vdW} = \frac{1}{2}\left(\frac{2\mu C_6}{\hbar^2}\right)^{1/4}$$

van der Waals length



three-body parameter universality in atomic systems

Wang et al., PRL **106**, 263001 (2012)

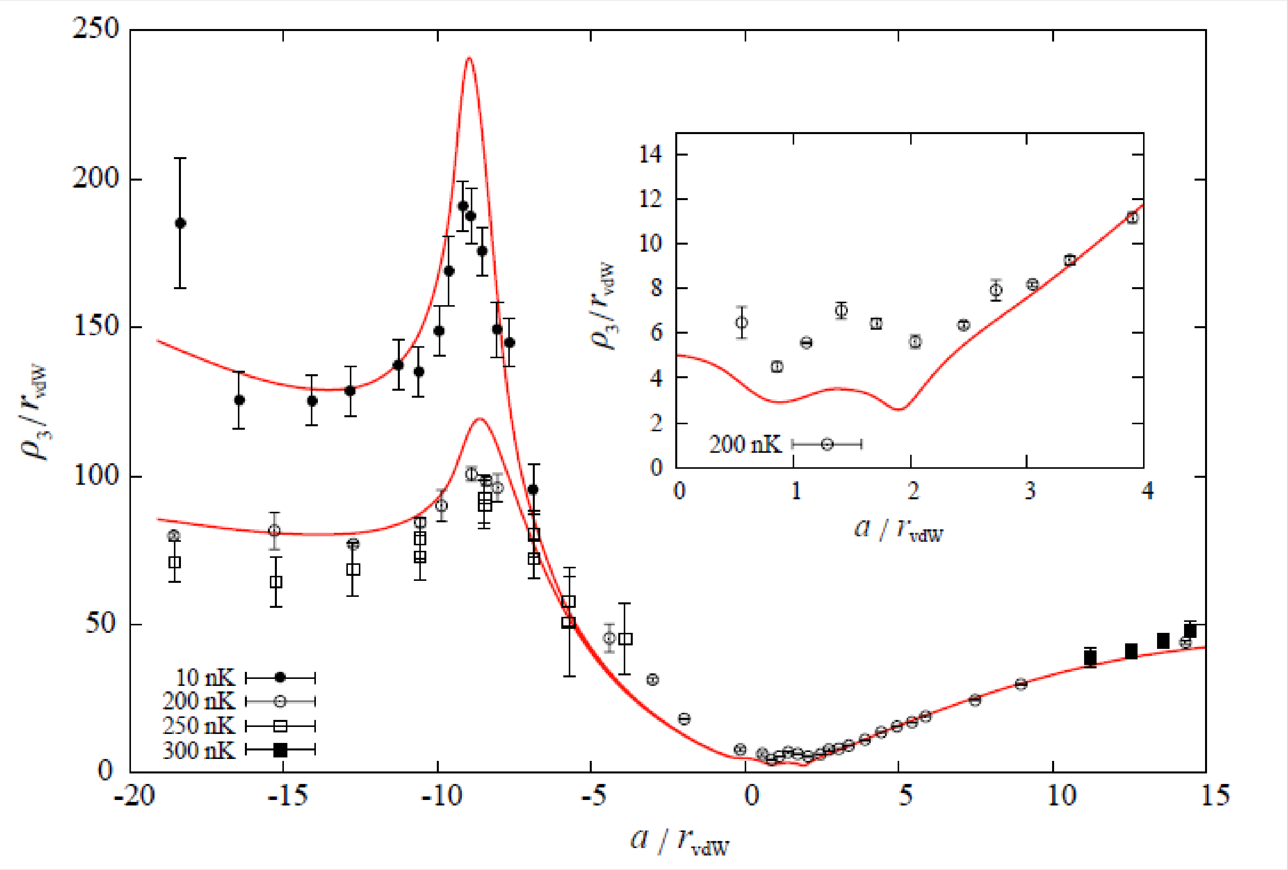
Schmidt et al., EPJB **85**, 386 (2012)

Naidon et al., PRL **112**, 105301 (2014)

van der Waals universality

Y. Wang and P. Julienne
arXiv:1404.0483

two dimensionless parameters to describe particular Feshbach resonance: s_{res} and r_{bg}



universal relations

can we test these relations?

$a_-^{(n+1)} / a_-^{(n)} = \mathbf{22.7}$

$a_*^{(n+1)} / a_-^{(n)} = 1.06$

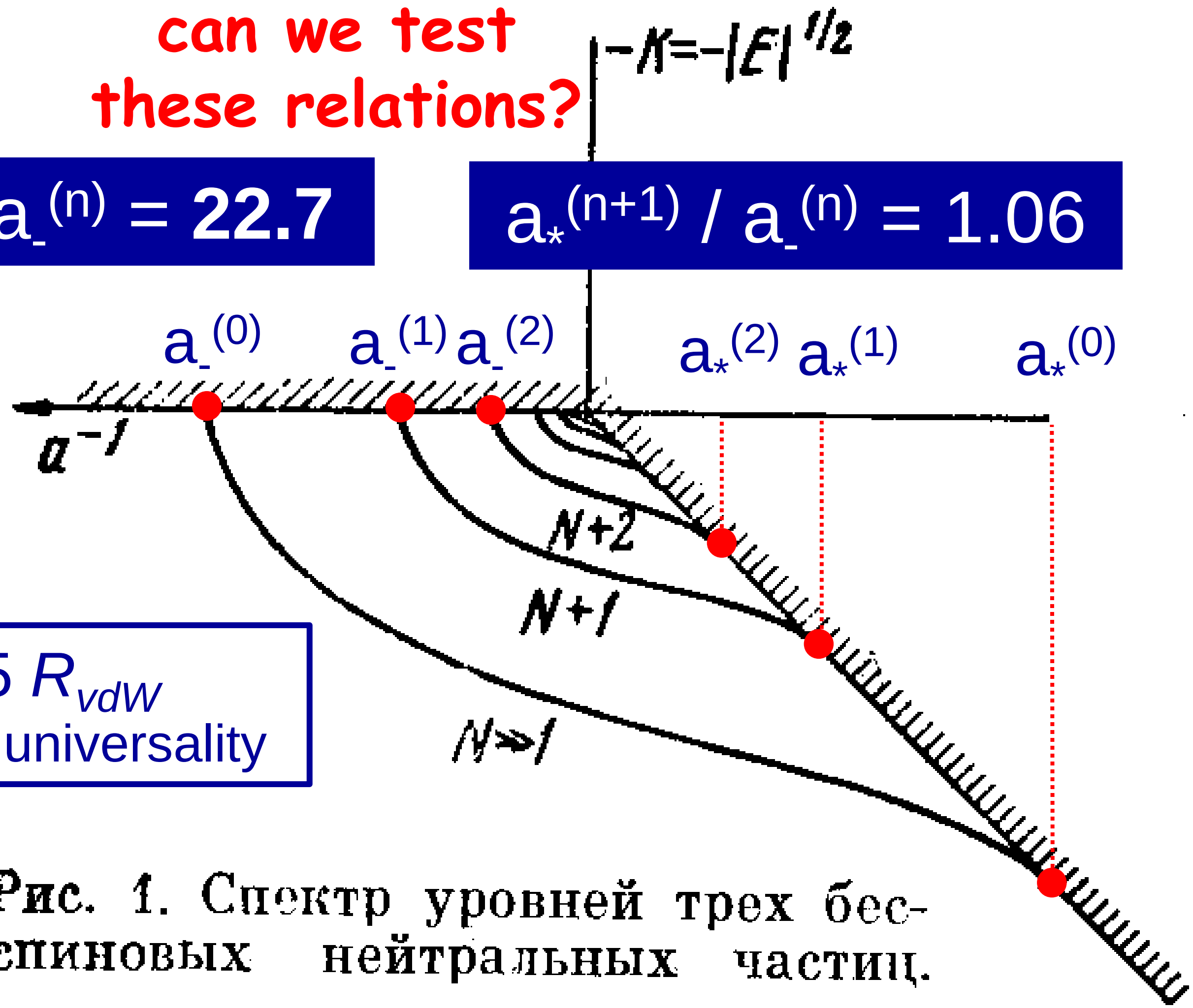
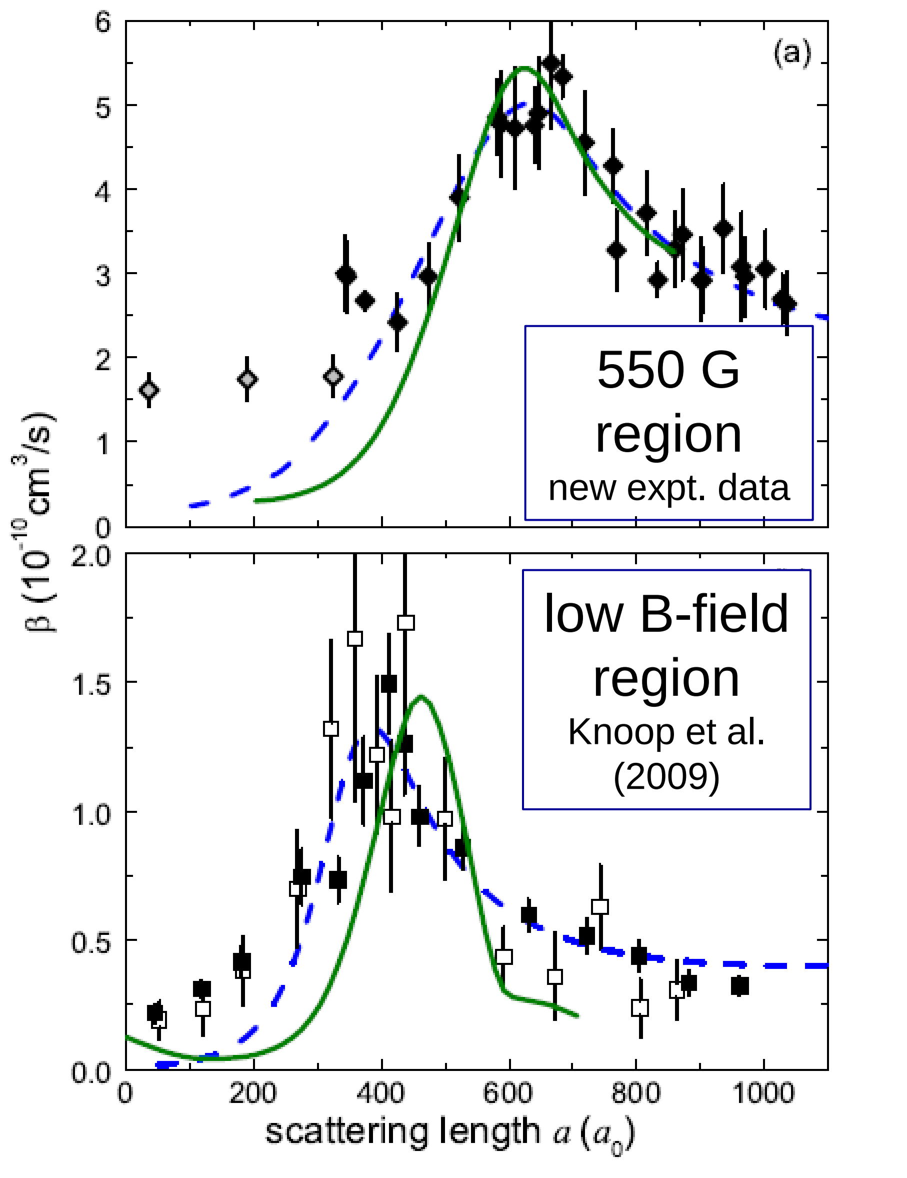


Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц.

$a_-^{(0)} \approx -9.5\ R_{vdW}$
vdW universality

atom-dimer resonances in Cs



Zenesini et al., soon on arXiv

EFT fit →

$a_*^{(1)} / a_-^{(0)} = 0.48(2)$

≠ 1.06

$a_*^{(1)} / a_-^{(0)} = 0.68(6)$

vdW universal model gets positions essentially right !

Y. Wang and P. Julienne

real experiments: physics of Feshbach resonance

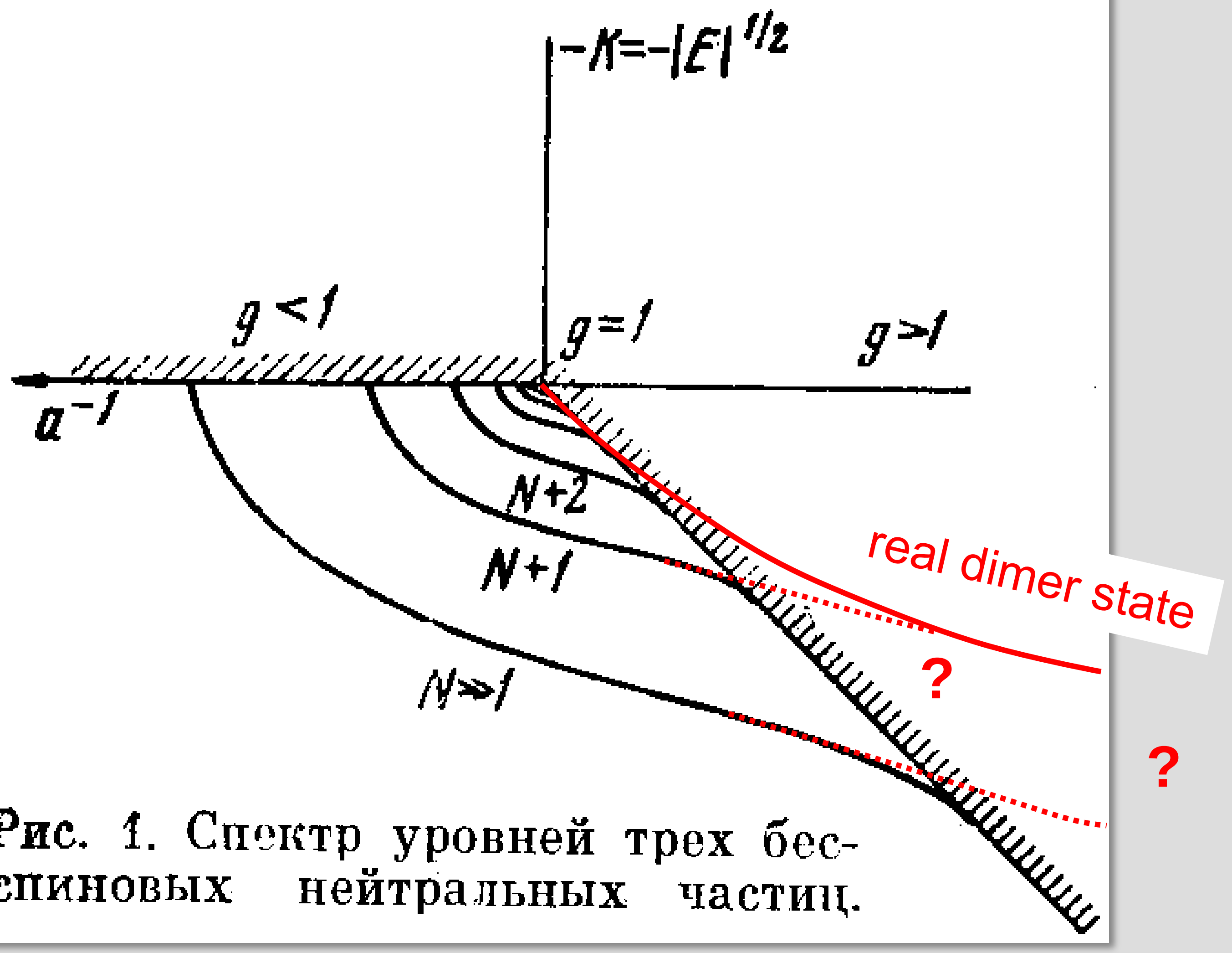


Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц.

test of Efimov period?

$a_-^{(n+1)} / a_-^{(n)} = \mathbf{22.7}$

$a_*^{(n+1)} / a_-^{(n)} = 1.06$

problematic in real atomic systems (but vdW univ. works)

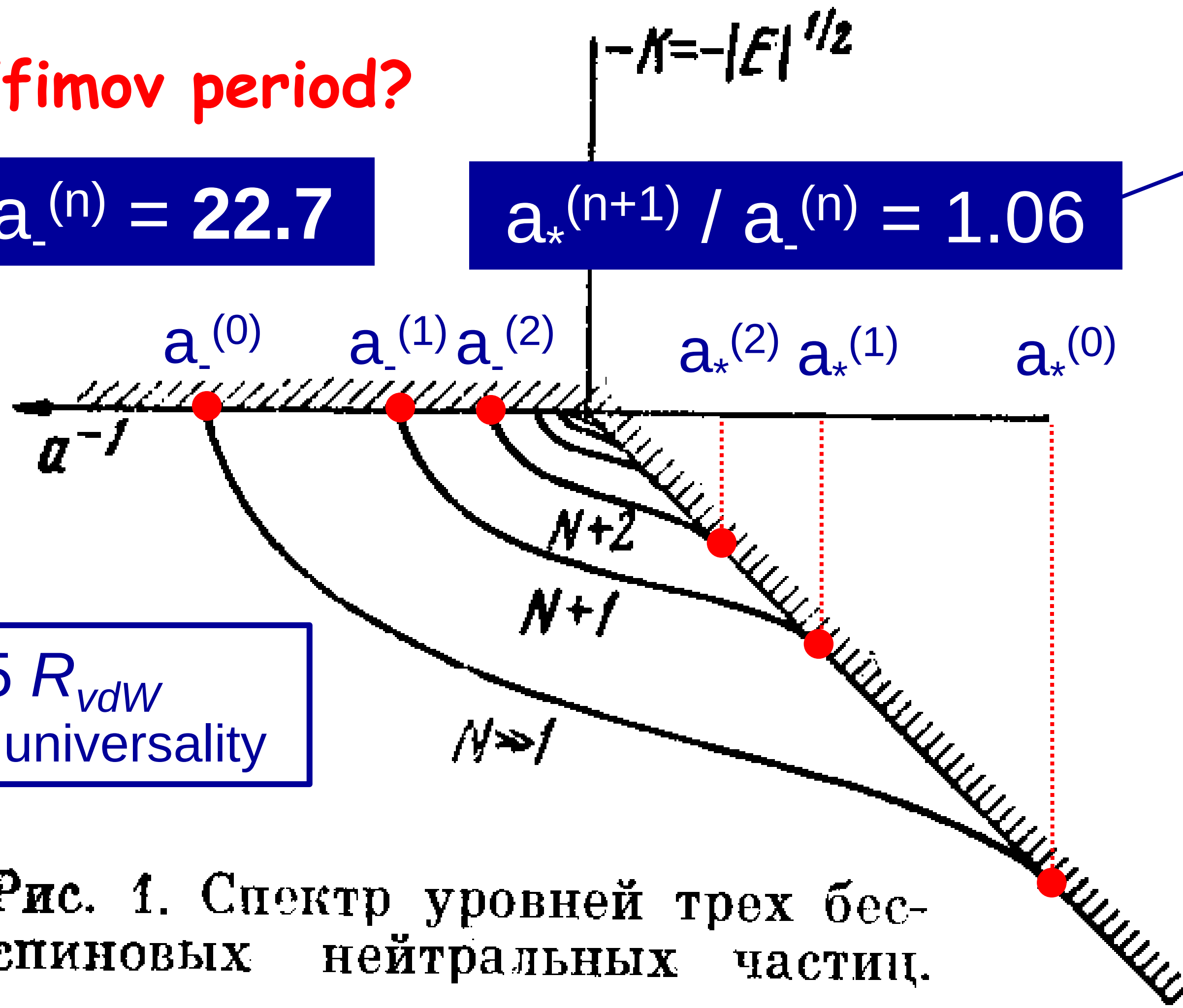


Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц.

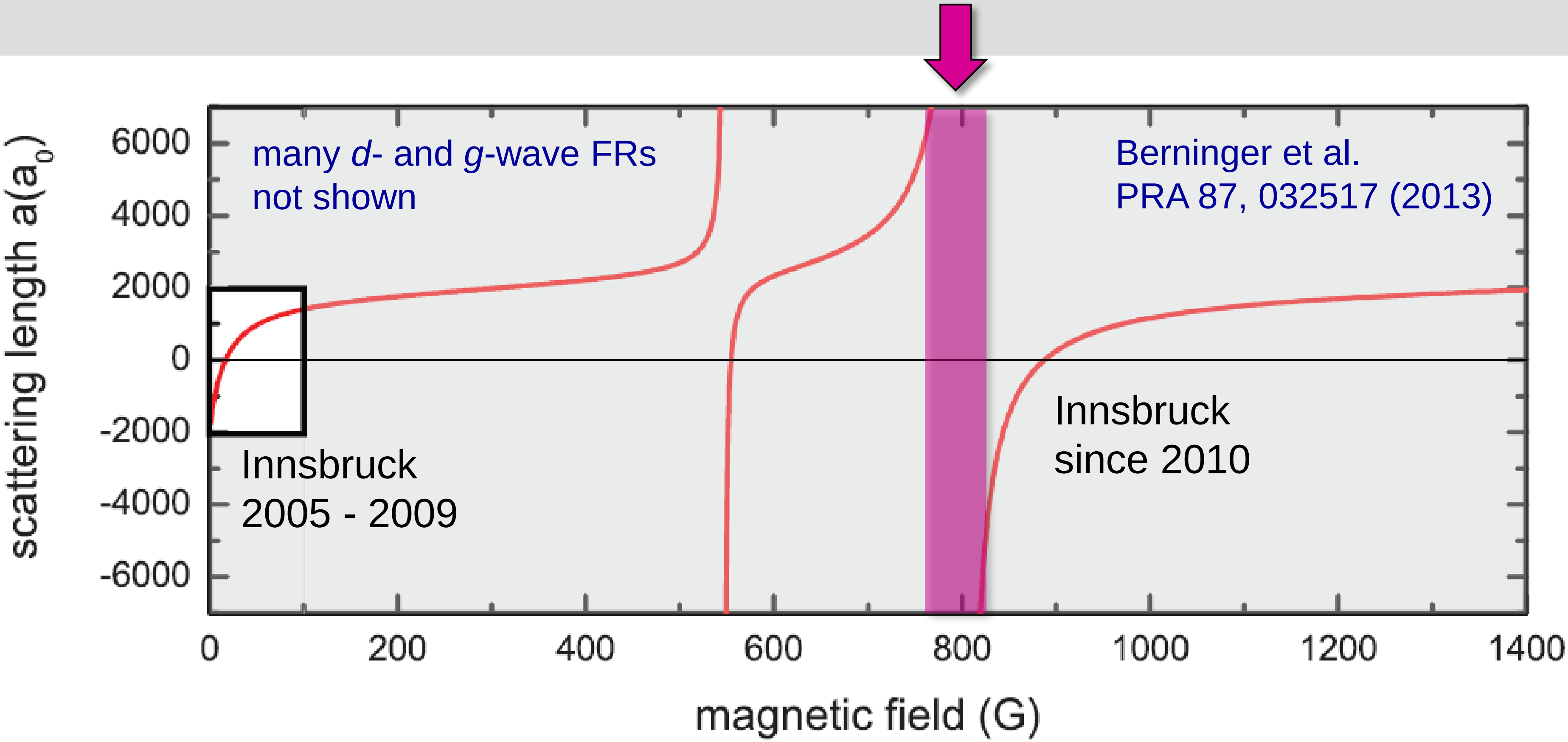
$a_-^{(0)} \approx -9.5\, R_{vdW}$

vdW universality

magnetic tunability of Cs

amazing 800-G Feshbach resonance

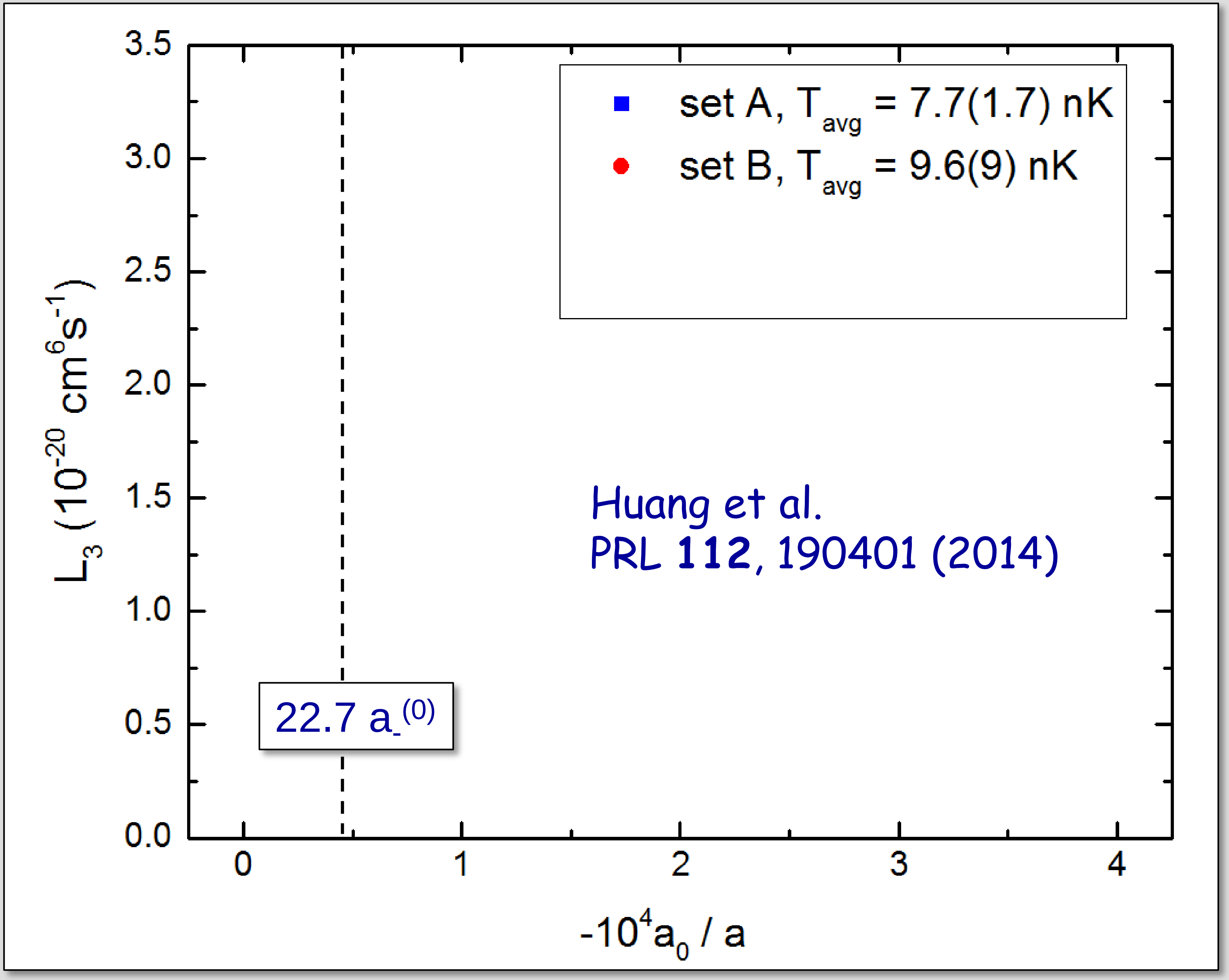
$s_{res} \approx 15,000$



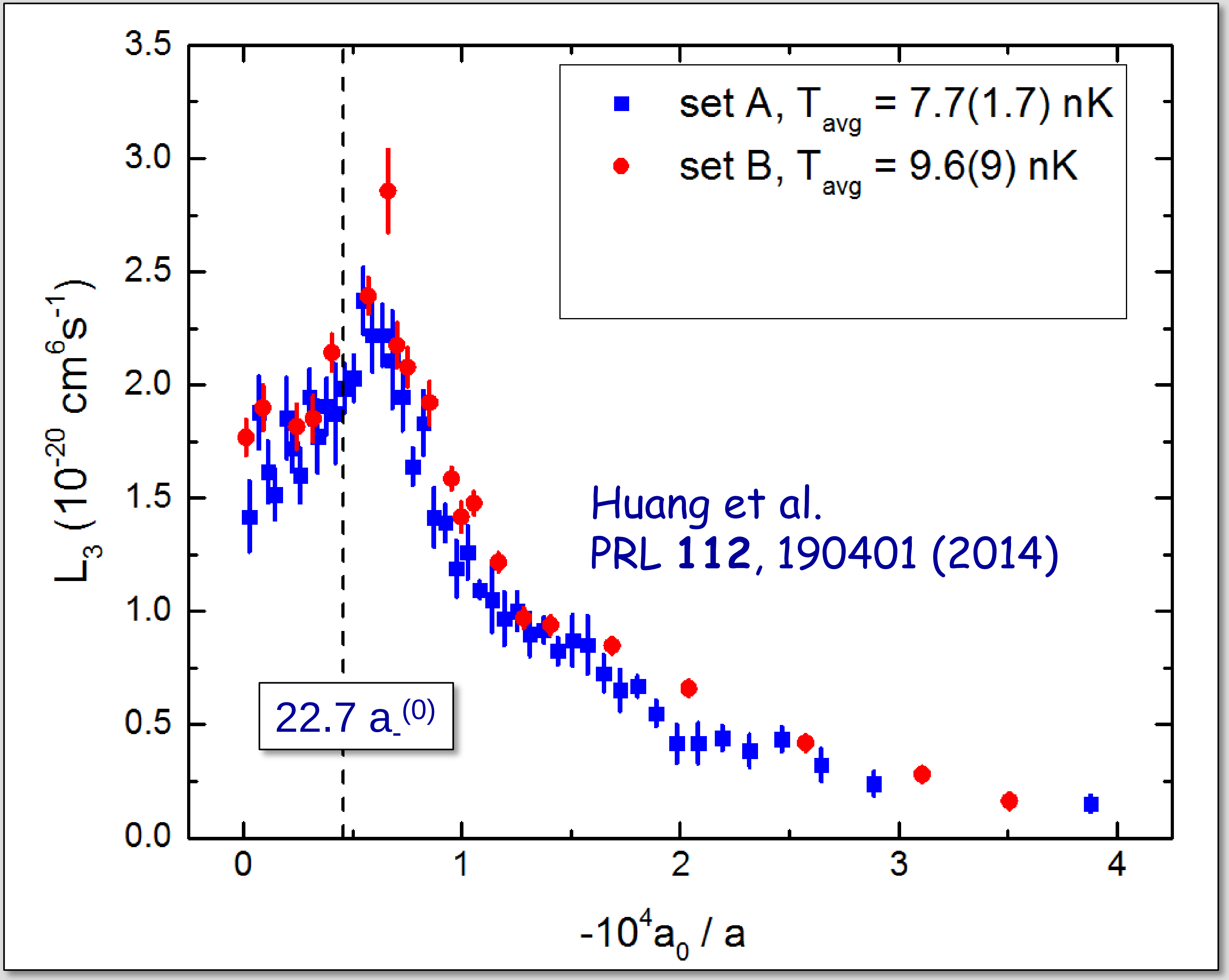
accurate control of *a* on the few *10,000 a_0* level !

uncertainty of pole ±0.3 G correponds to ±500,000 a_0

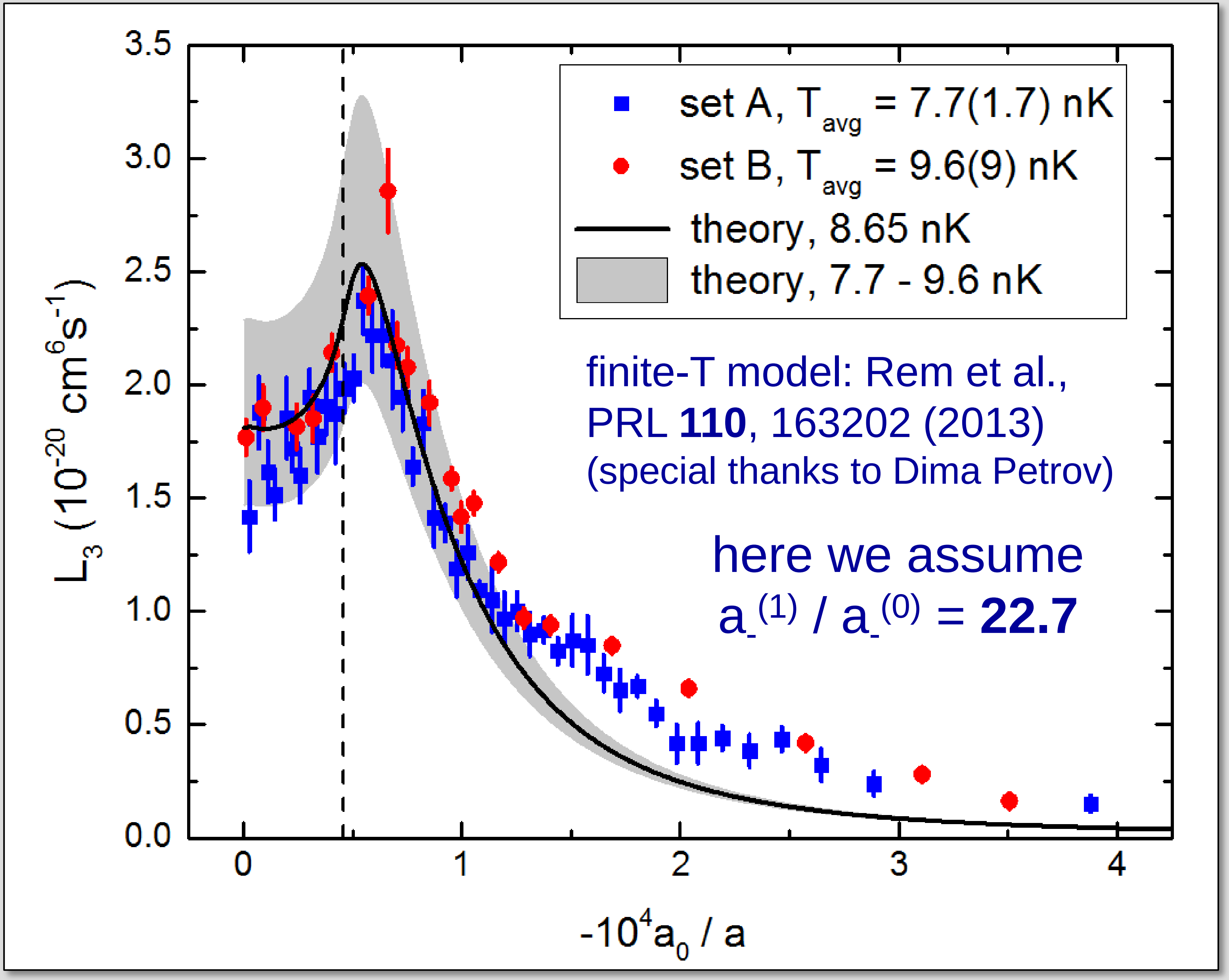
experimental results



experimental results



experimental results & theory



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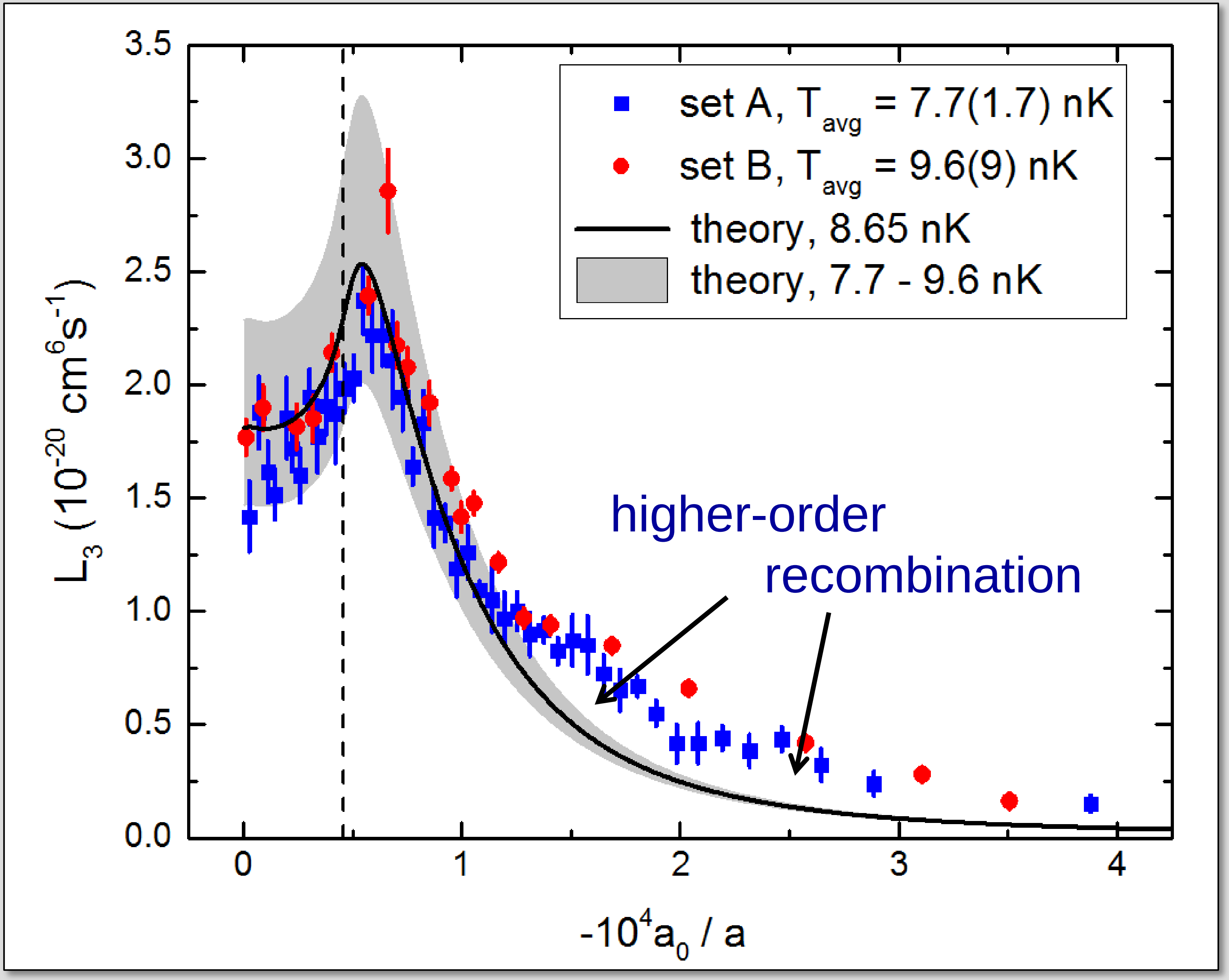
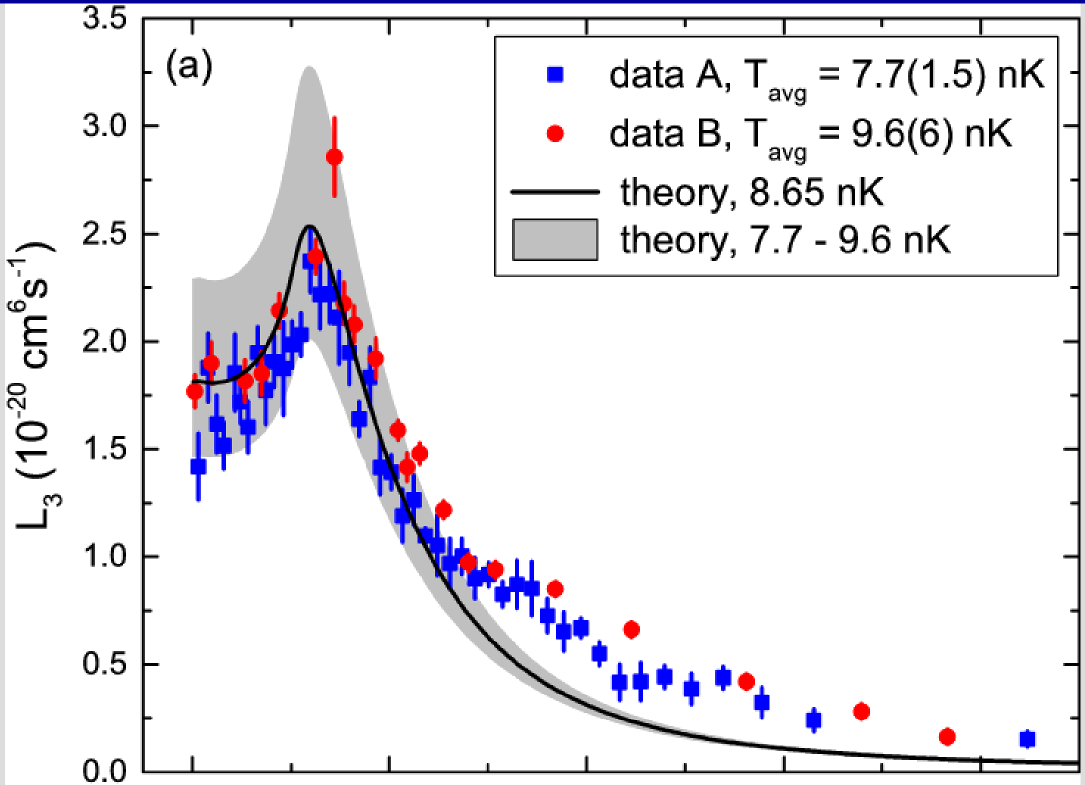


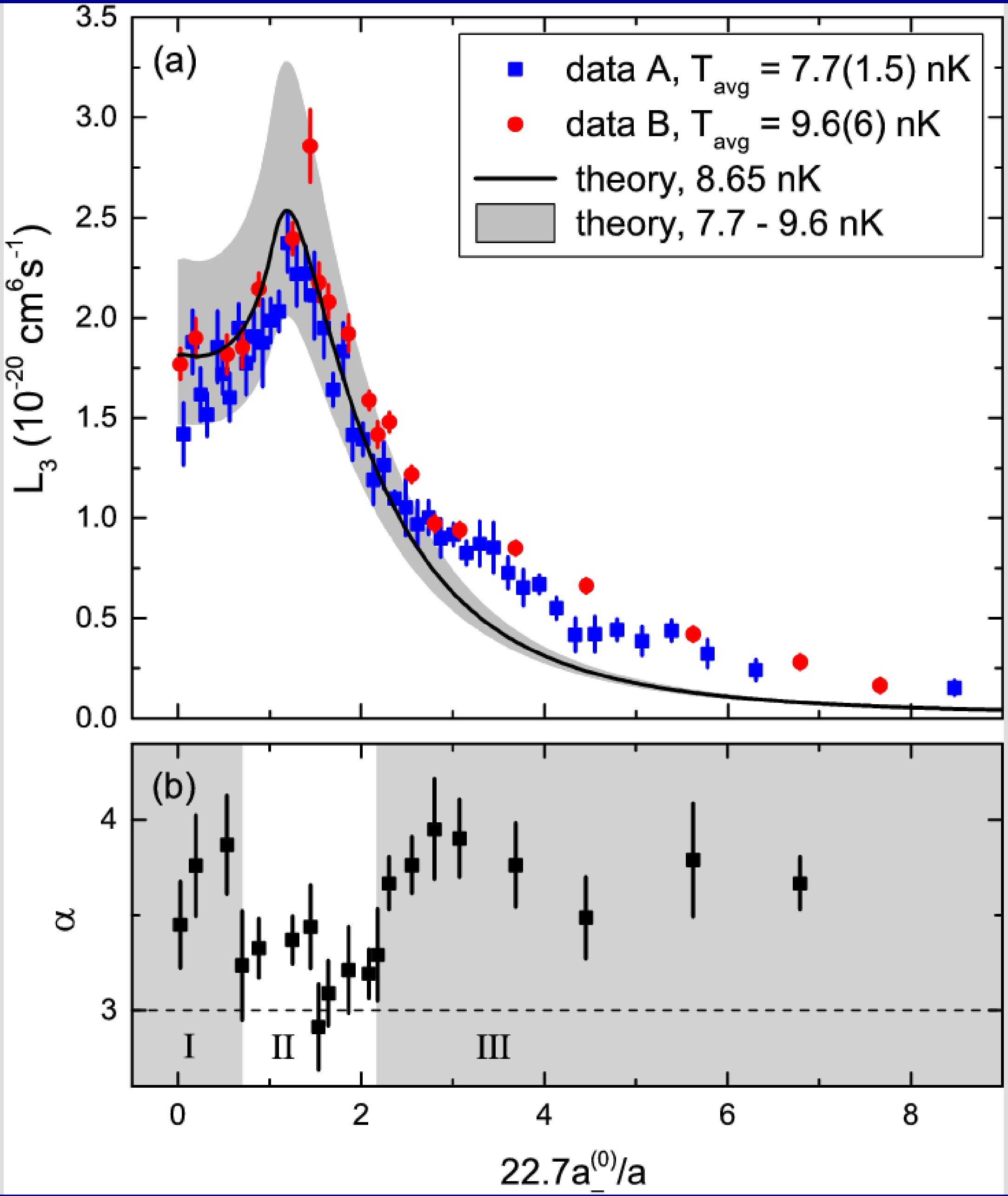
order of recombination loss



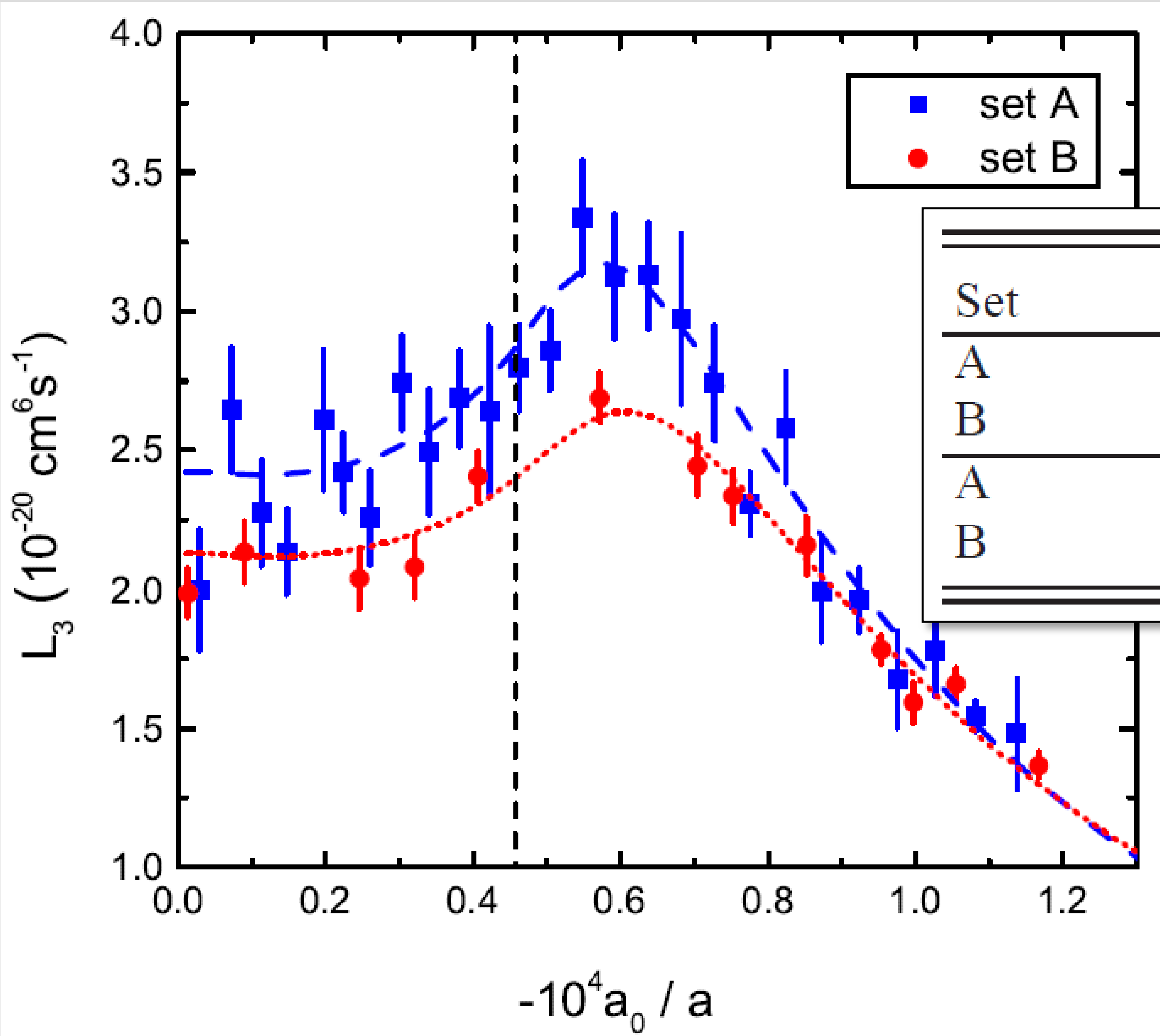
$$\dot{n} = -L_\alpha n^\alpha$$

α-body loss

order of recombination loss



let‘s get more accurate - let‘s fit



Set	T/nK	$a_-^{(1)}/a_0$
A	8.7(2)	-20790(390)
B	10.0(2)	-19740(430)
A	7.7*	-20580(390)
B	9.6*	-19650(430)

Efimov period

2nd Efimov resonance: $a_-^{(1)} = -20190(1200)\ a_0$

1st Efimov resonance: $a_-^{(0)} = -933(16)\ a_0$

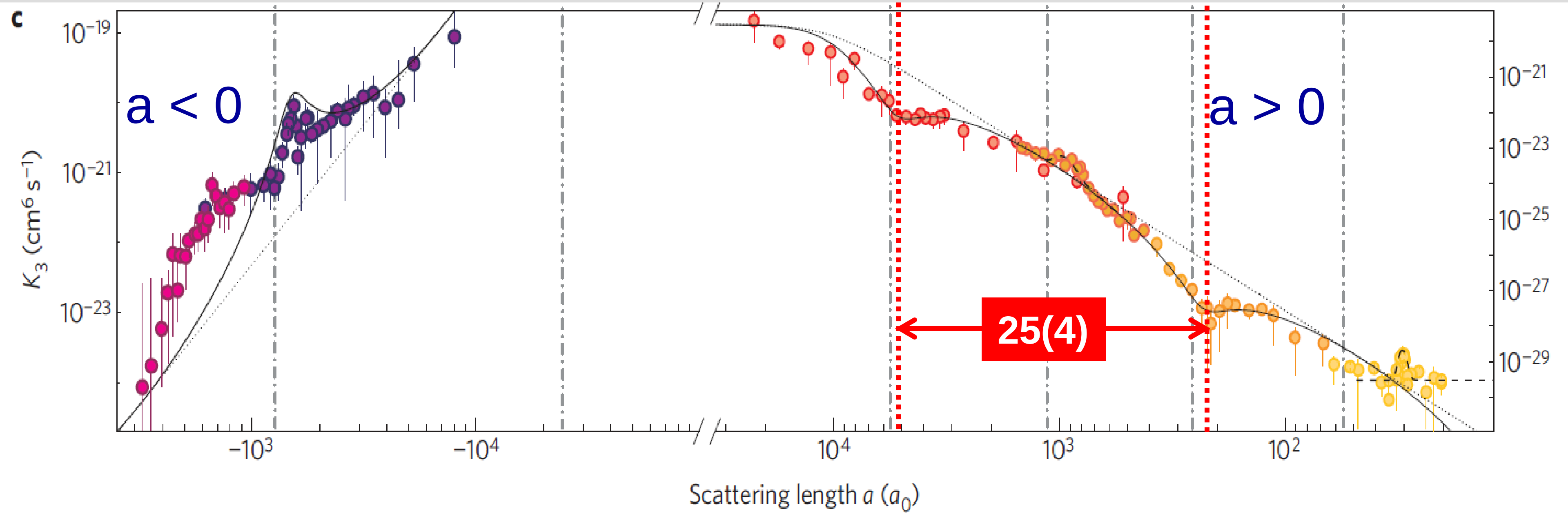
21.0(1.3)

1.2σ away from 22.7

universal vdW theory (Wang, Julienne) predicts
20.5 ... 21.5 for our particular case

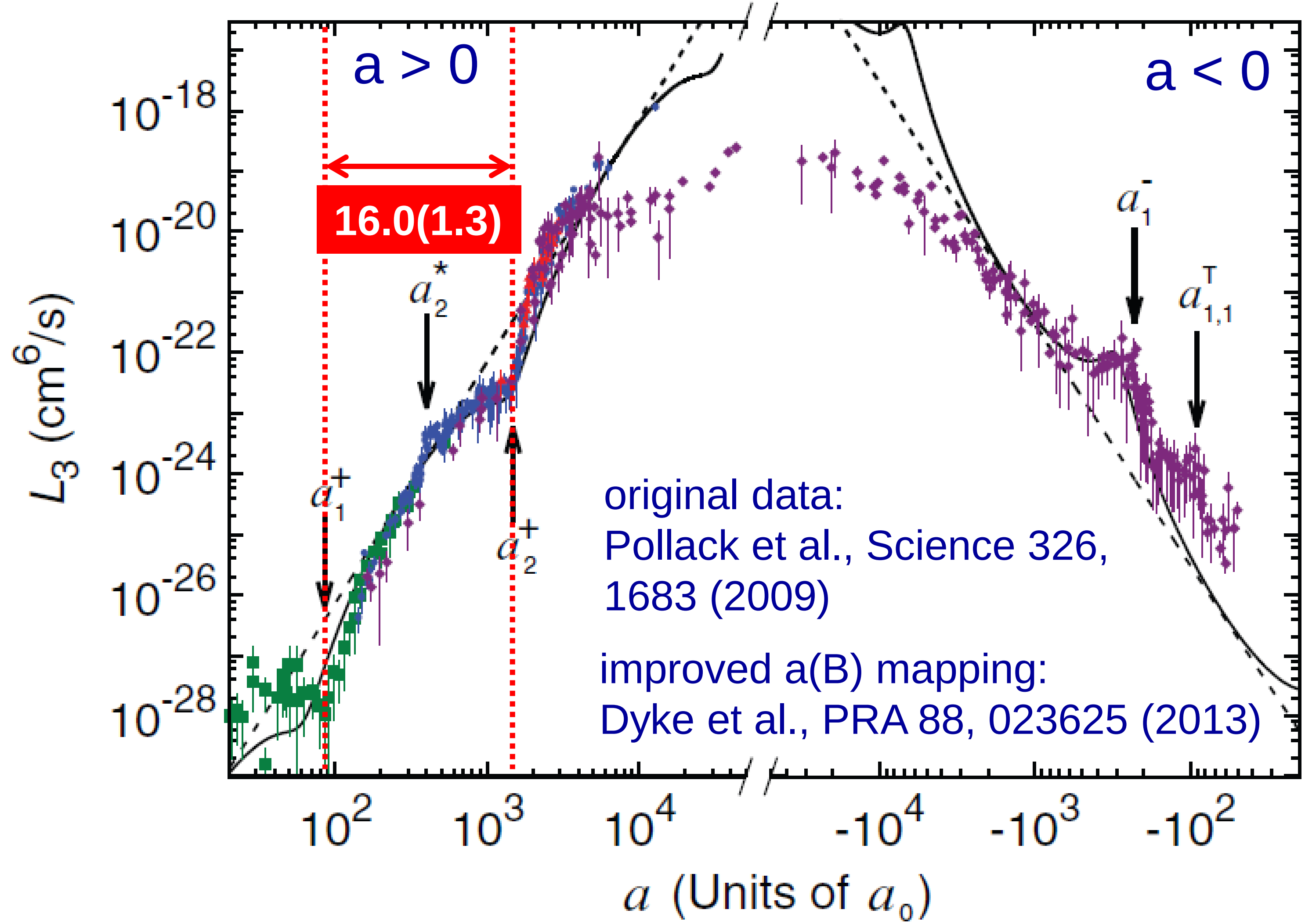
observations in ^{39}K (Florence, 2009)

observables:
recombination minima



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

observations in ^{7}Li (Rice, 2009/2013)



original data:
Pollack et al., Science 326, 1683 (2009)

improved a(B) mapping:
Dyke et al., PRA 88, 023625 (2013)

a few remarks

experiments on ^{39}K, ^{7}Li

lowest reference points (minima) at ~ 3 R_{vdW}

phenomena at a>0 generally sensitive to non-universal corrections (weakly bound mol. state)

Feshbach resonances of intermediate character

^{133}Cs

1st triatomic resonance at -9.5 R_{vdW}

a < 0: situation quite robust

extremely broad Feshbach resonances available

much closer to ideal conditions

the team (Feb. 2014)

ultracold.atoms

the team & our collaborators

photo: M. Knabl / IQOQI

Few-body physics with ultracold atoms

is this (only) the physics of losses?

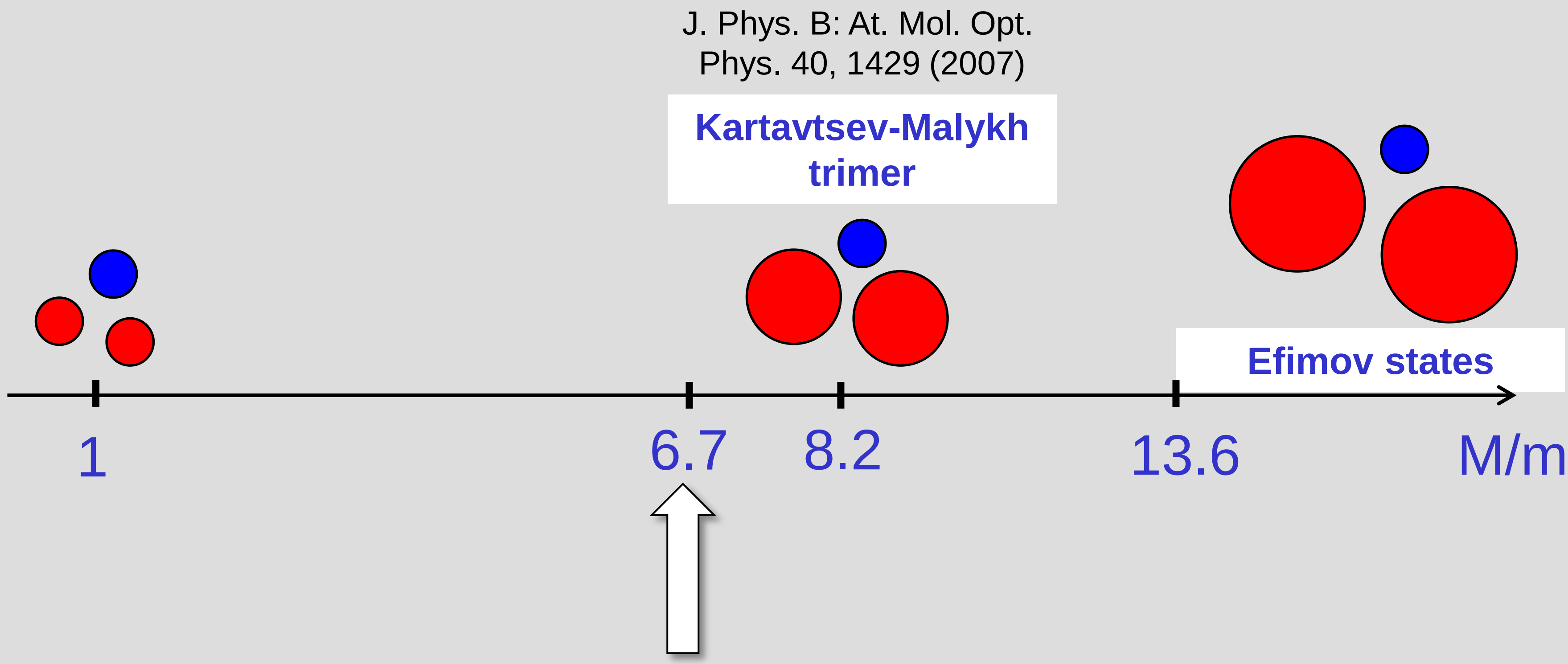
Few-body physics with ultracold atoms

is this (only) the physics of losses?

no !

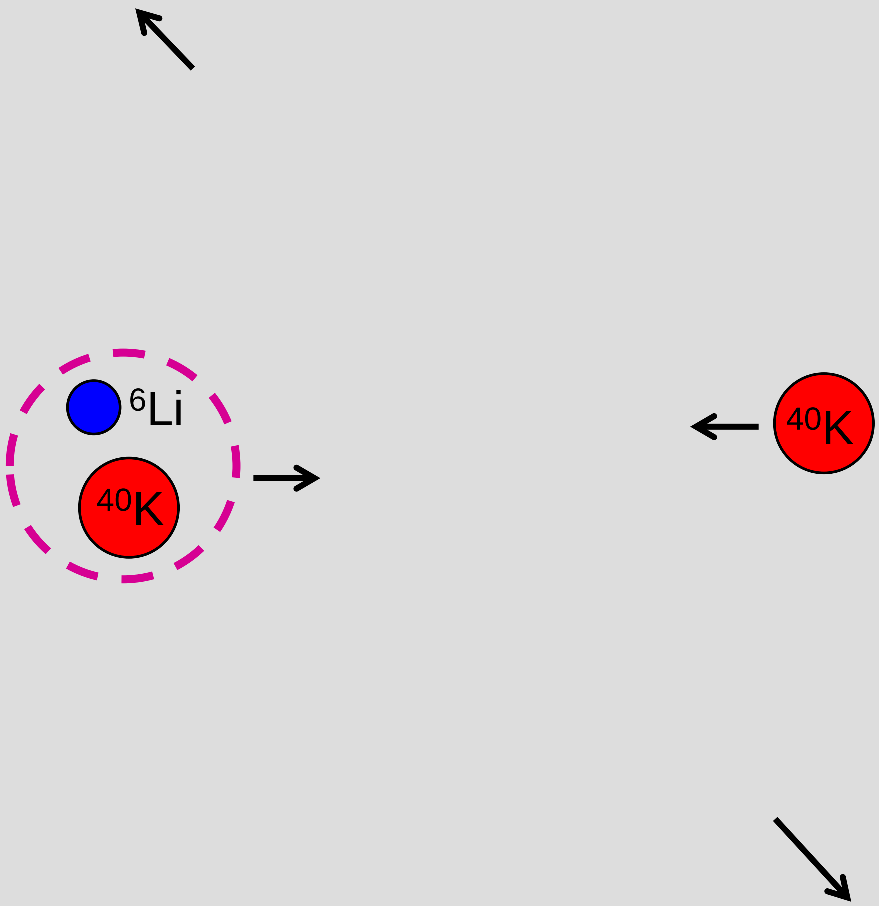
Jag et al., PRL **112**, 075302 (2014)

three-body physics of fermion systems



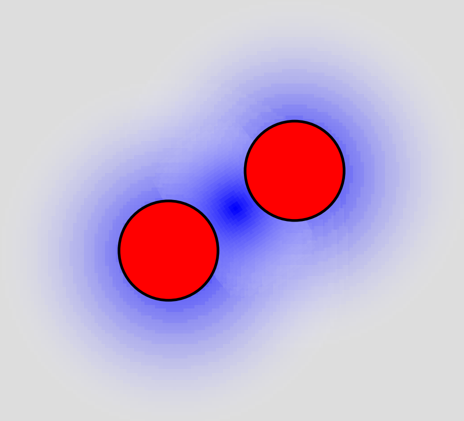
we are here !
^{40}K - ^{6}Li

atom-dimer scattering



atom-dimer scattering

three-body process

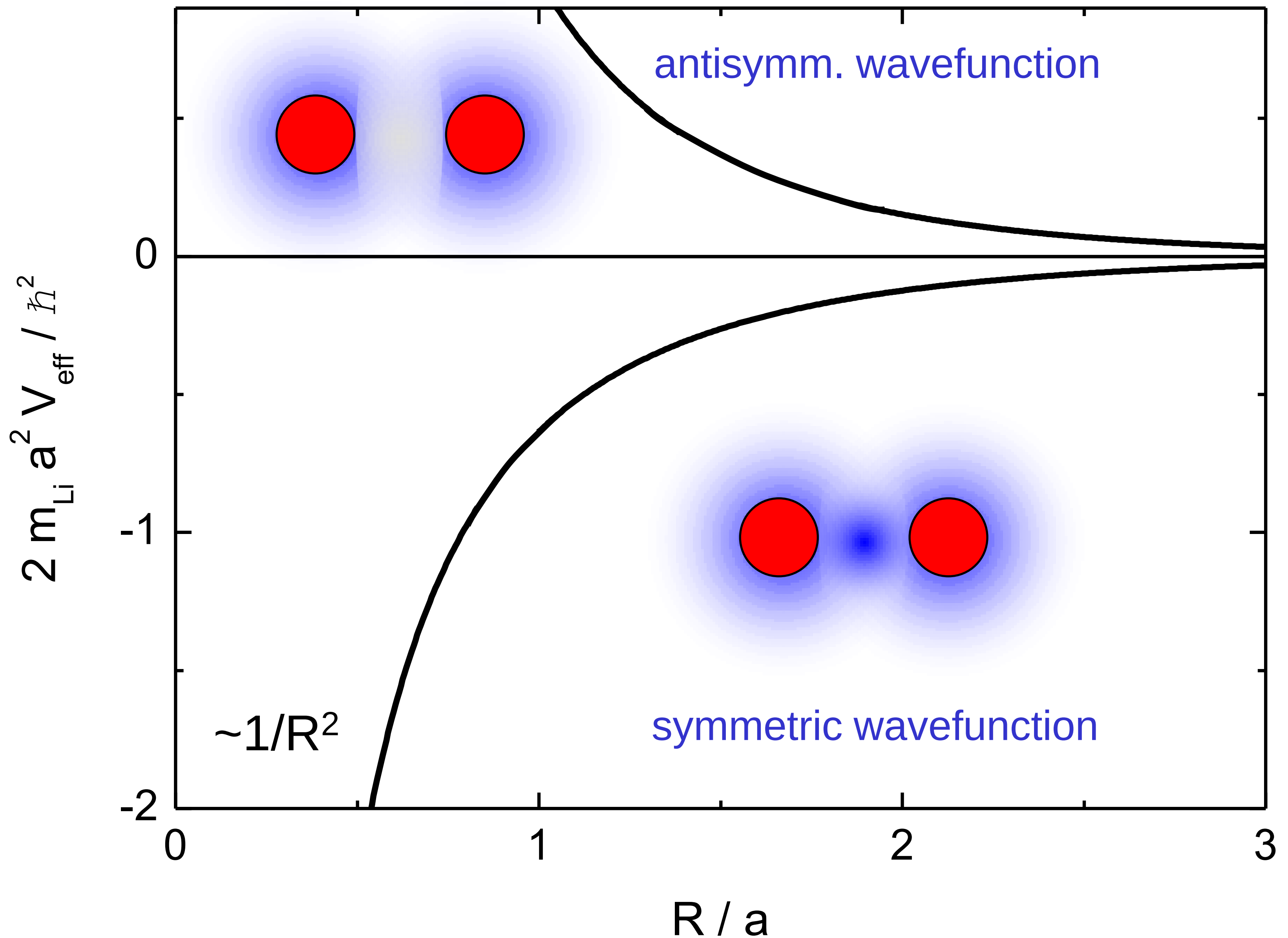


Levinsen, Tiecke, Walraven, Petrov, PRL **103**, 153202 (2009)

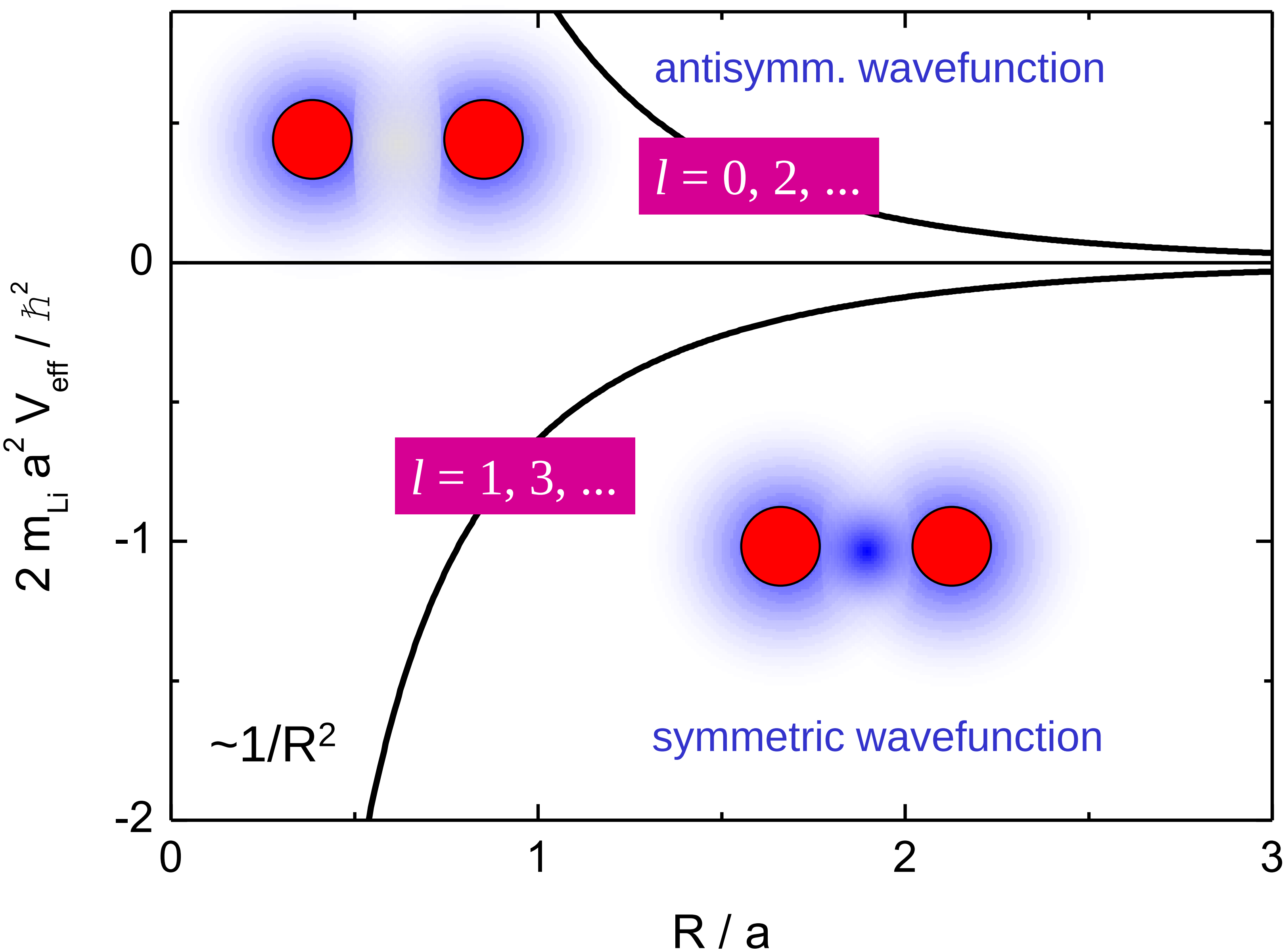
Levinsen, Petrov, EPJD **65**, 67 (2011)

see also Alzetta, Combescot, Leyronas, PRA **86**, 062708 (2012)

Born-Oppenheimer 3-body potentials

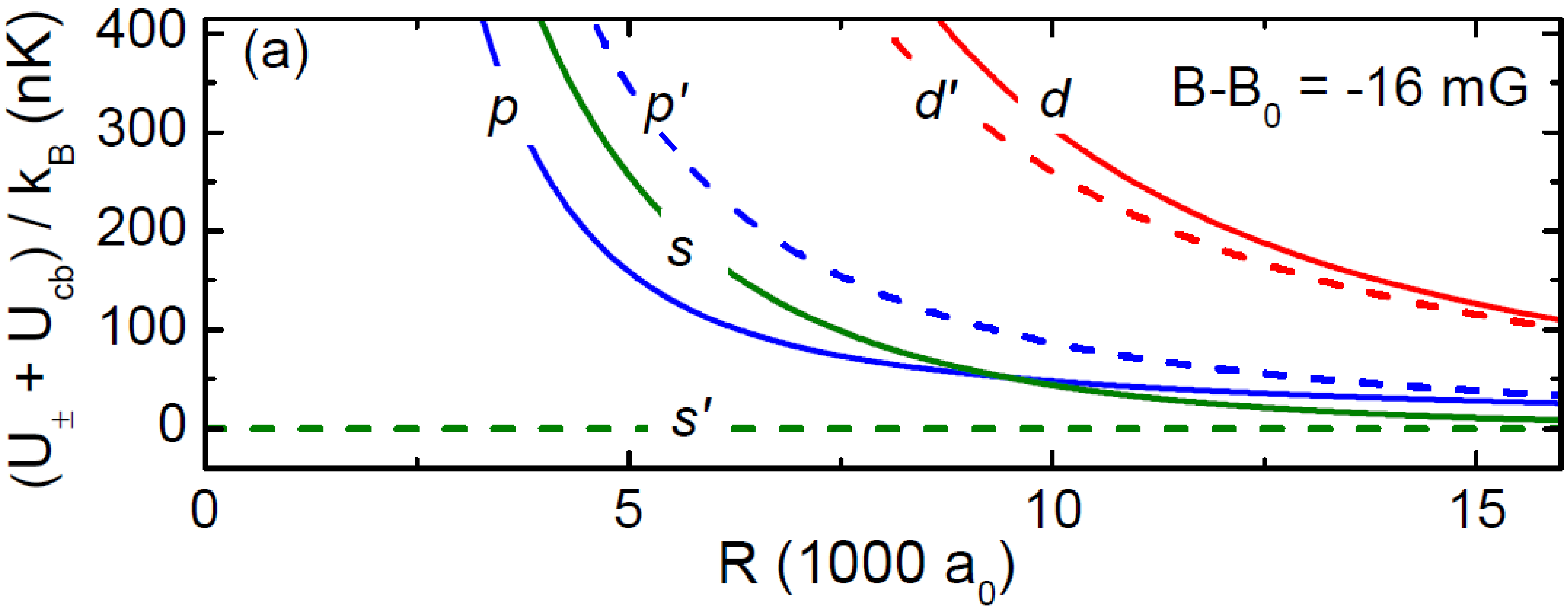


symmetry of AD wavefunction



effective potentials in partial-wave channels

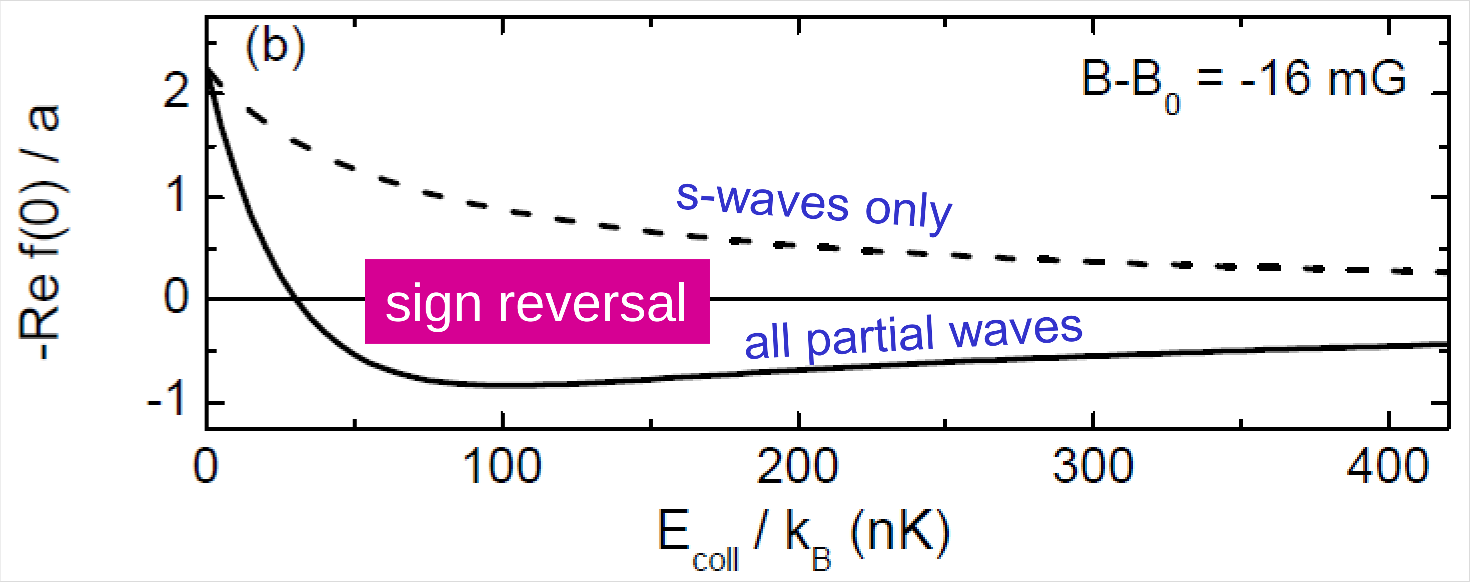
for 155G Li-K Feshbach resonance (880mG wide)



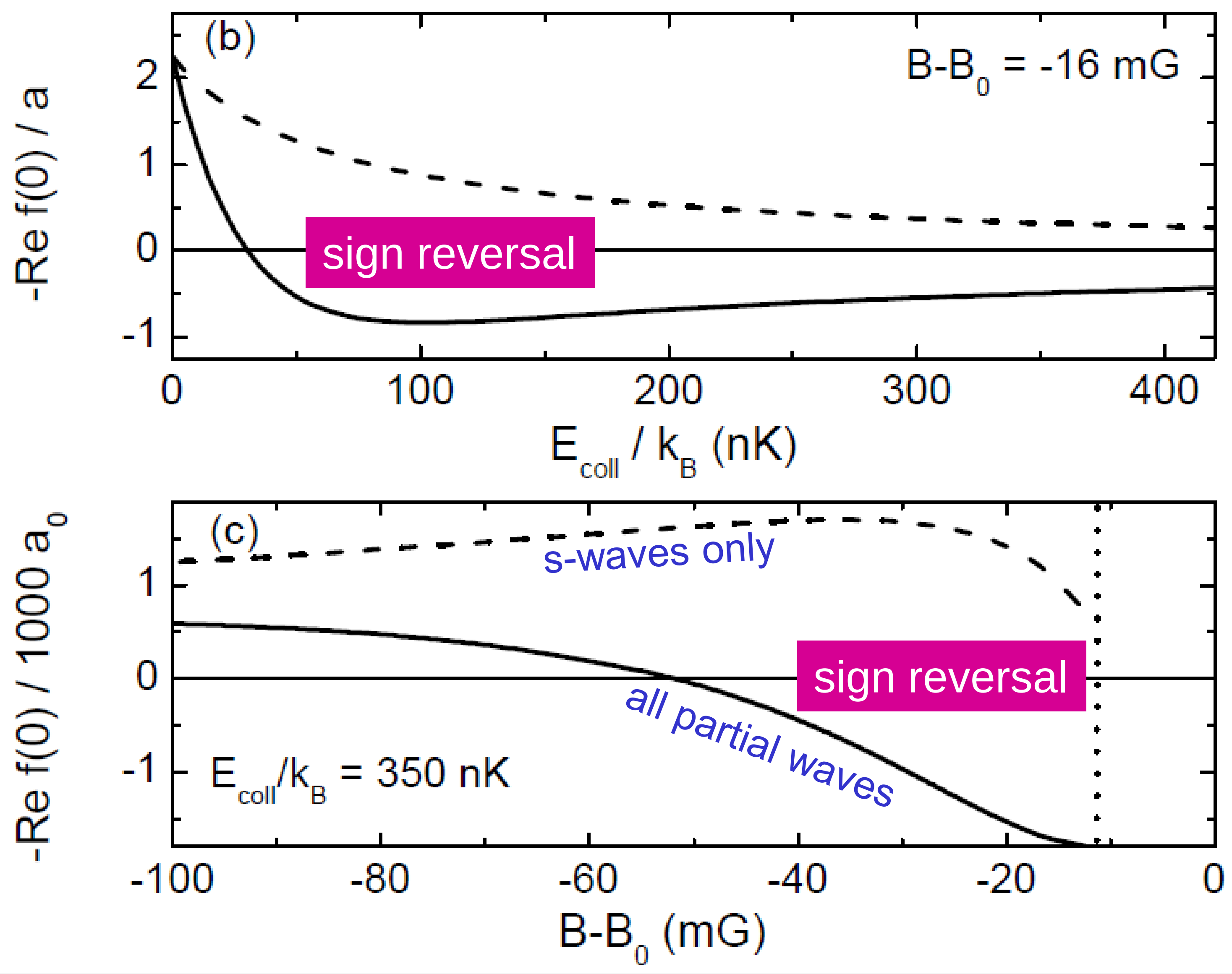
strong effect on *p*-wave barrier

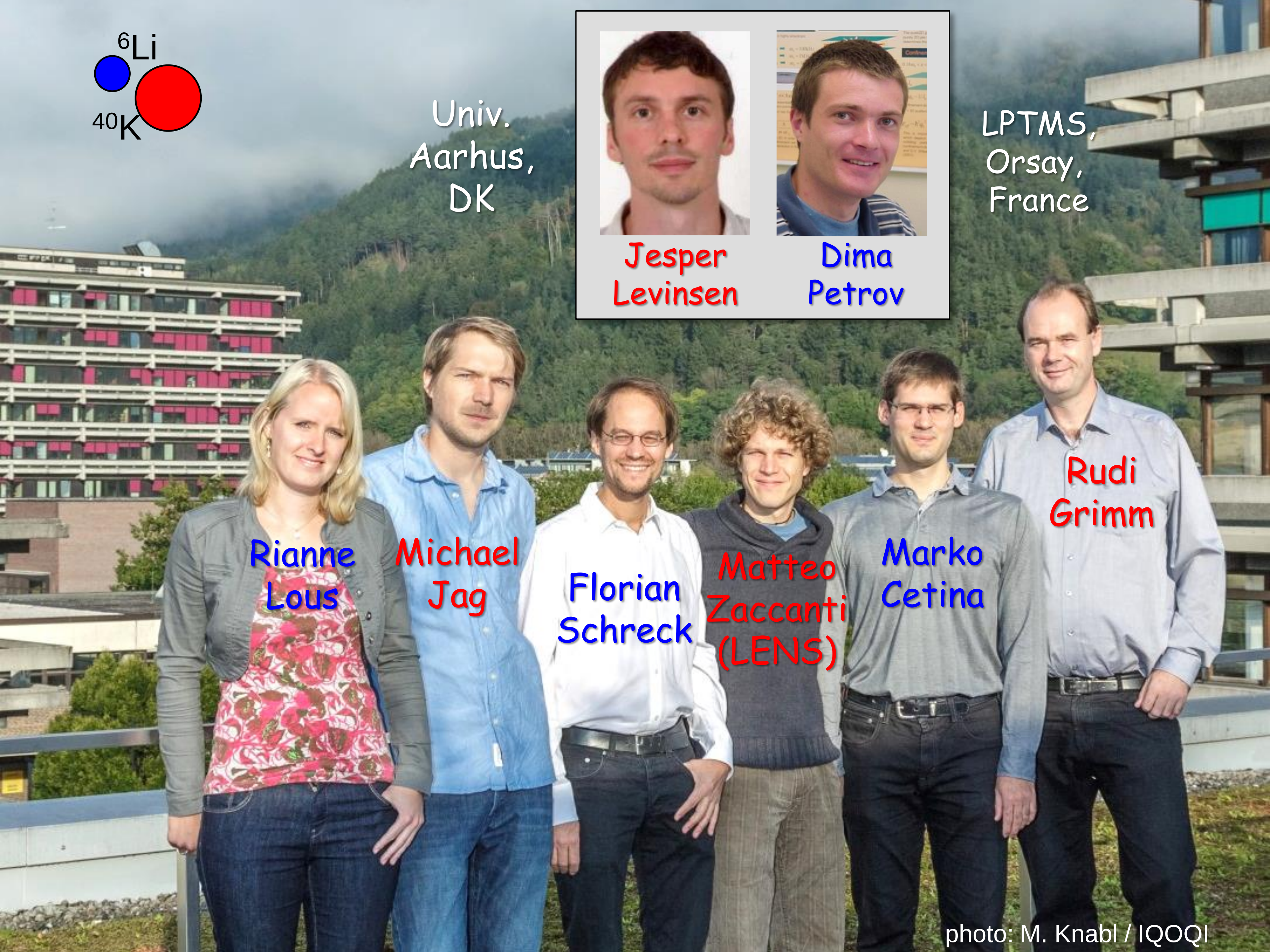
strong atom-dimer attraction!

scattering amplitude



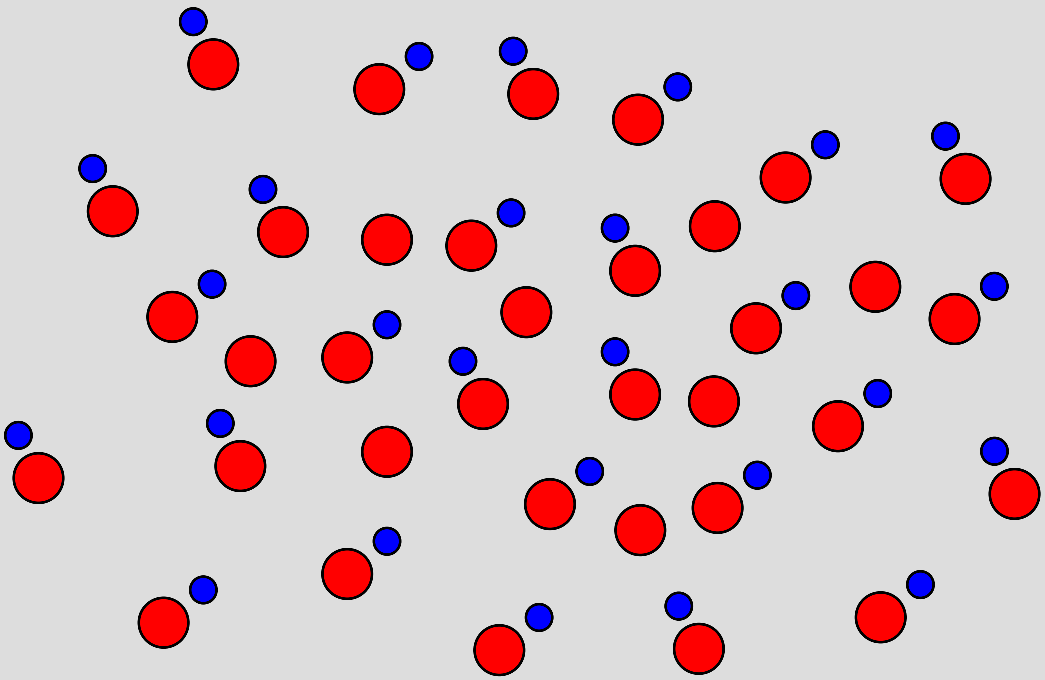
scattering amplitude





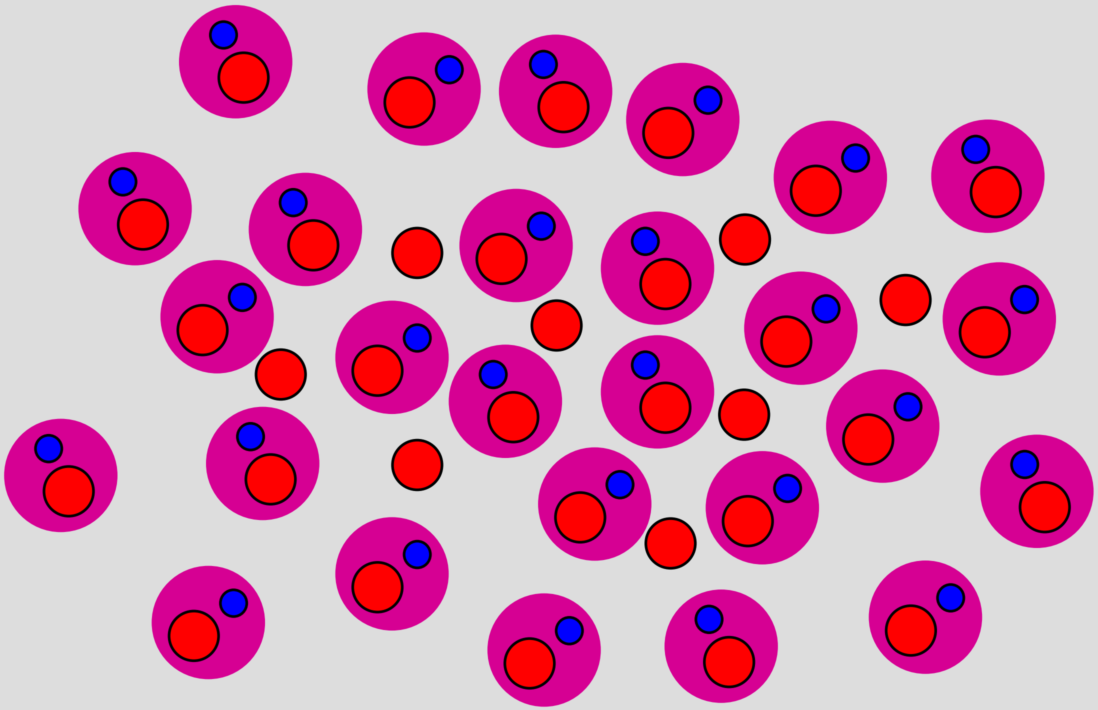
^{6}Li
^{40}K
Univ. Aarhus, DK
Jesper Levinsen
Dima Petrov
LPTMS, Orsay, France
Rianne Lous
Michael Jag
Florian Schreck
Matteo Zaccanti (LENS)
Marko Cetina
Rudi Grimm
photo: M. Knabl / IQOQI

mixture of heavy and light fermions: ^{40}K-^{6}Li



making weakly bound dimers (a>0)

ultracold.atoms

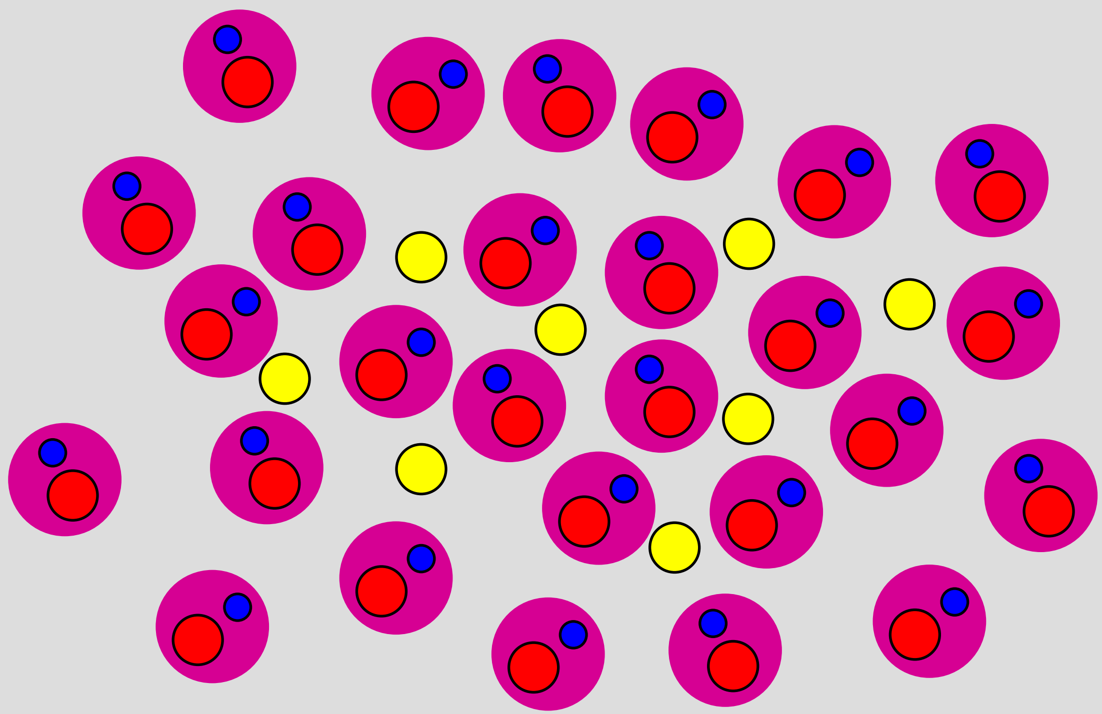


flipping the spin state of the free atoms

^{40}K

- interacting spin state
- non-interacting spin state

} *rf* coupling



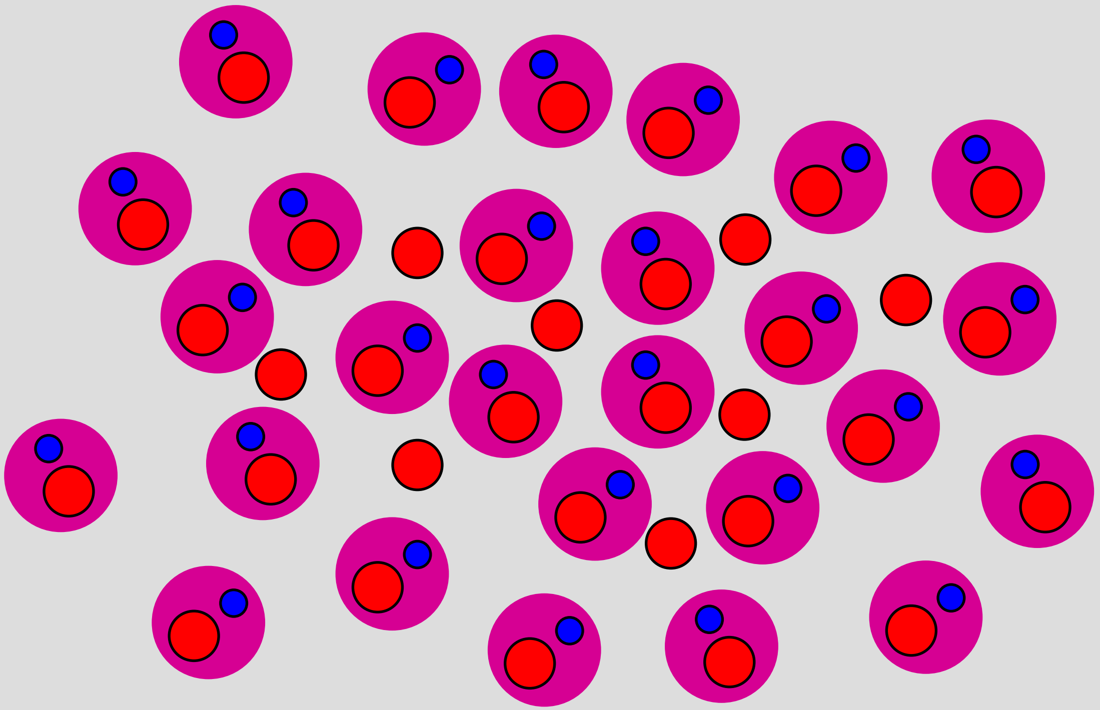
flipping the spin state of the free atoms

^{40}K

interacting spin state

non-interacting spin state

rf coupling



flipping the spin state of the free atoms

^{40}K

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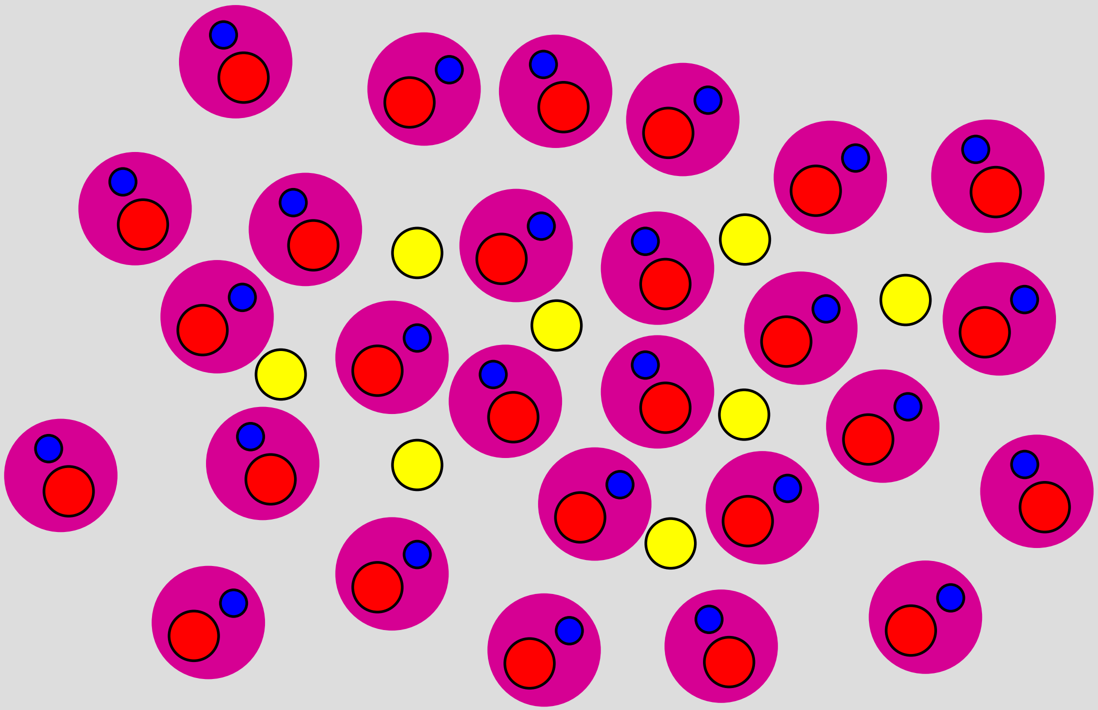
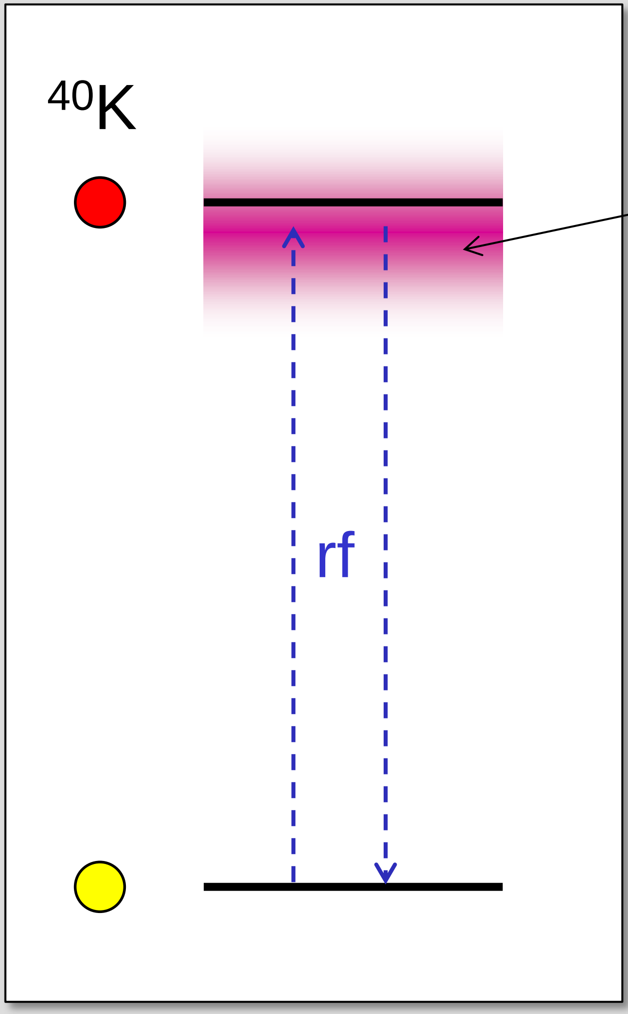


radio-frequency spectroscopy

interacting
spin state

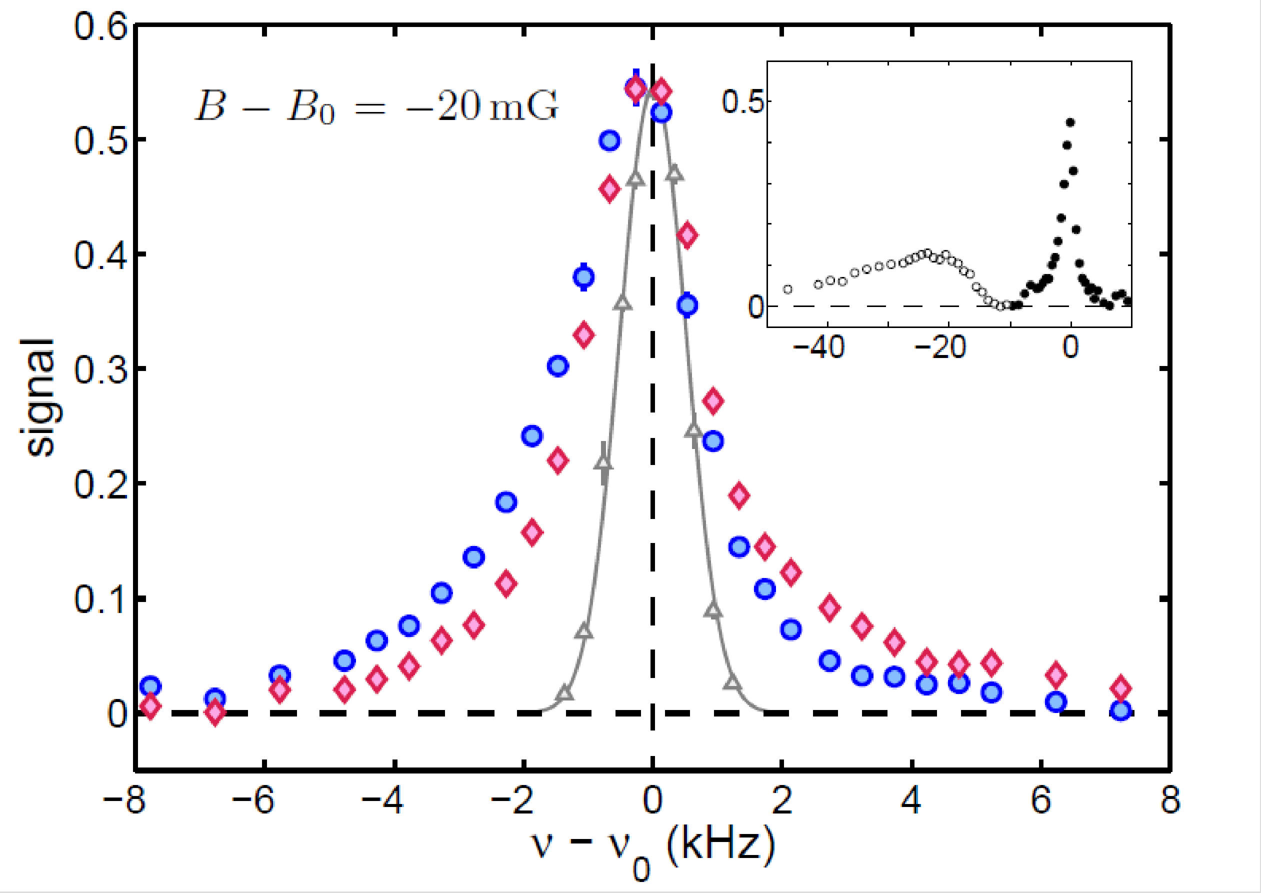
non-interacting
spin state



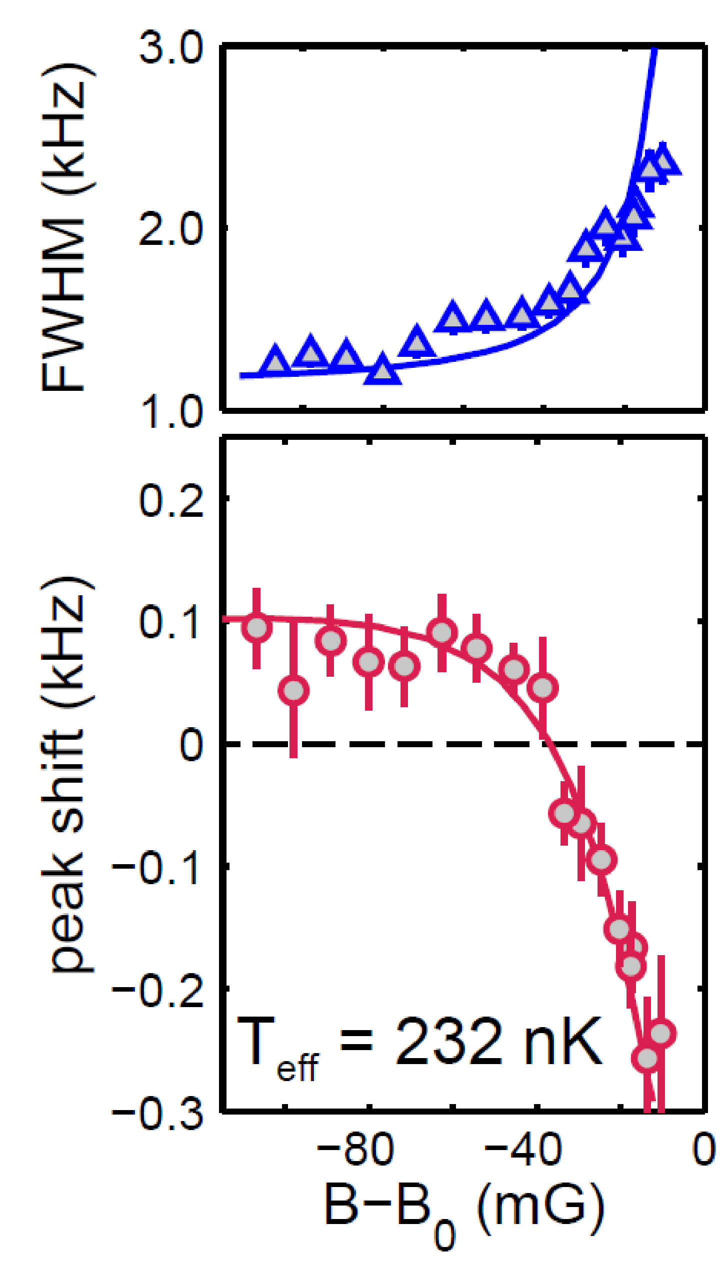
interaction with
^{6}Li^{40}K dimers

excellent tool to probe interaction shifts !!!

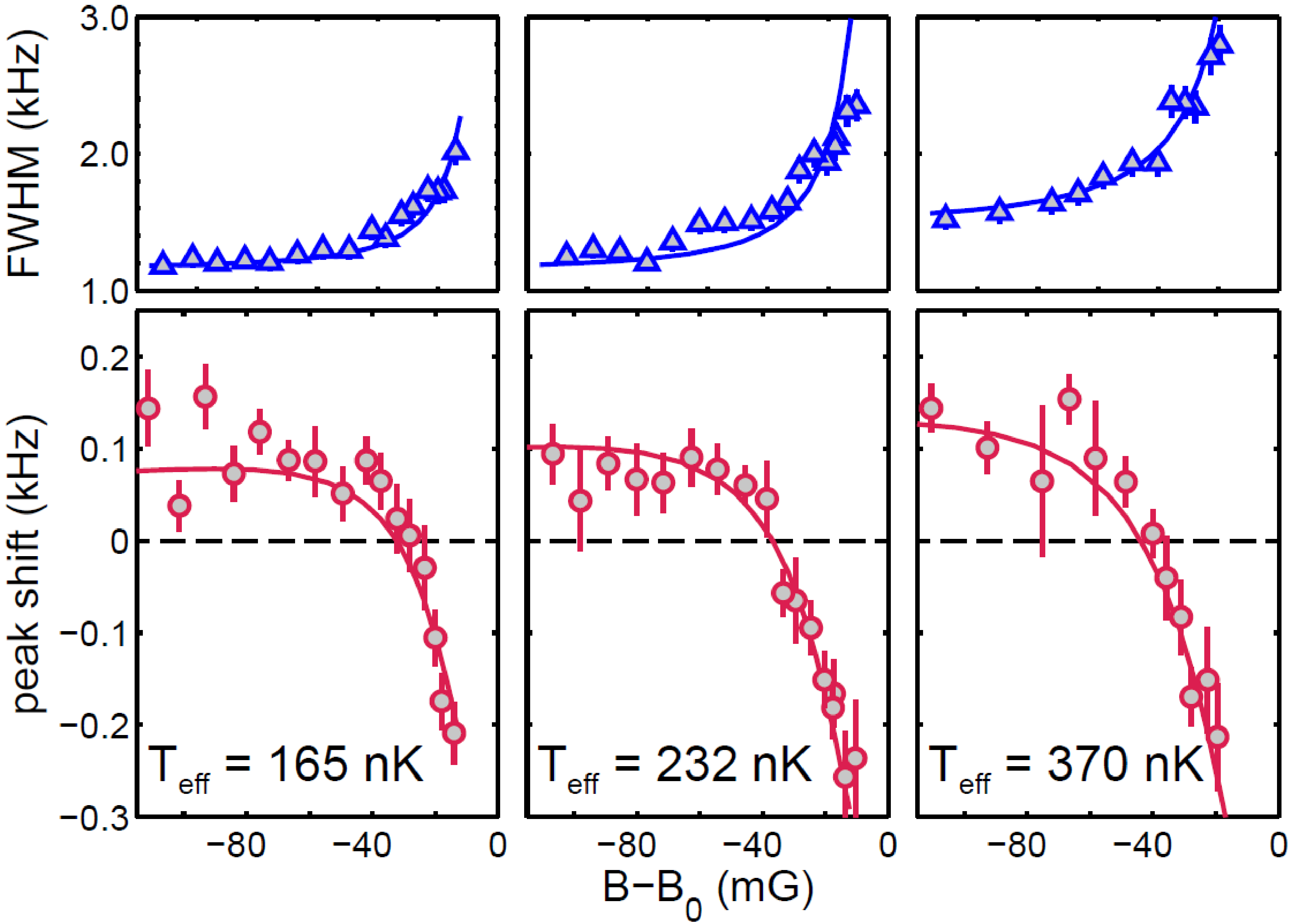
sample rf spectra



broadening and shift

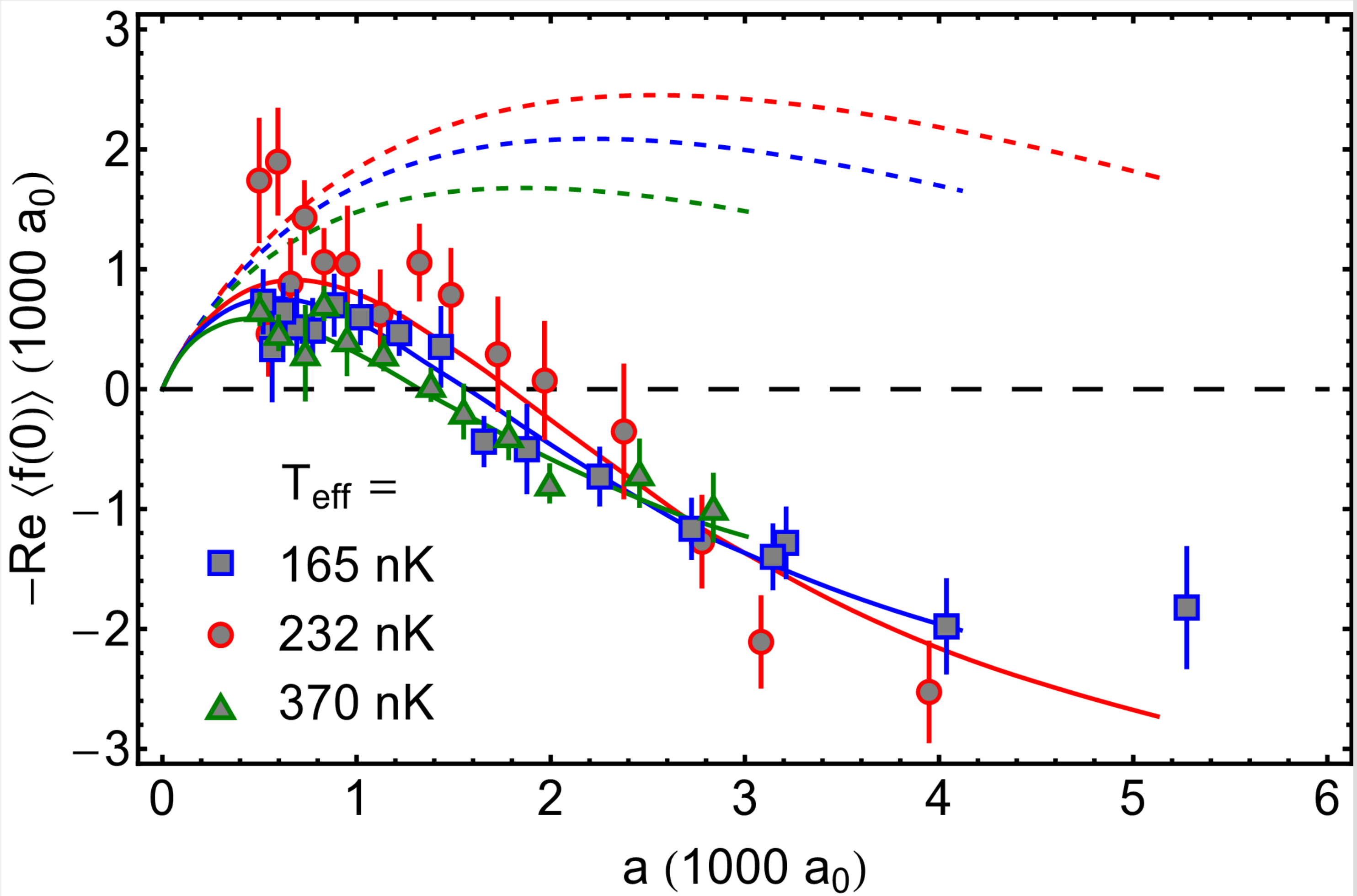


broadening and shift

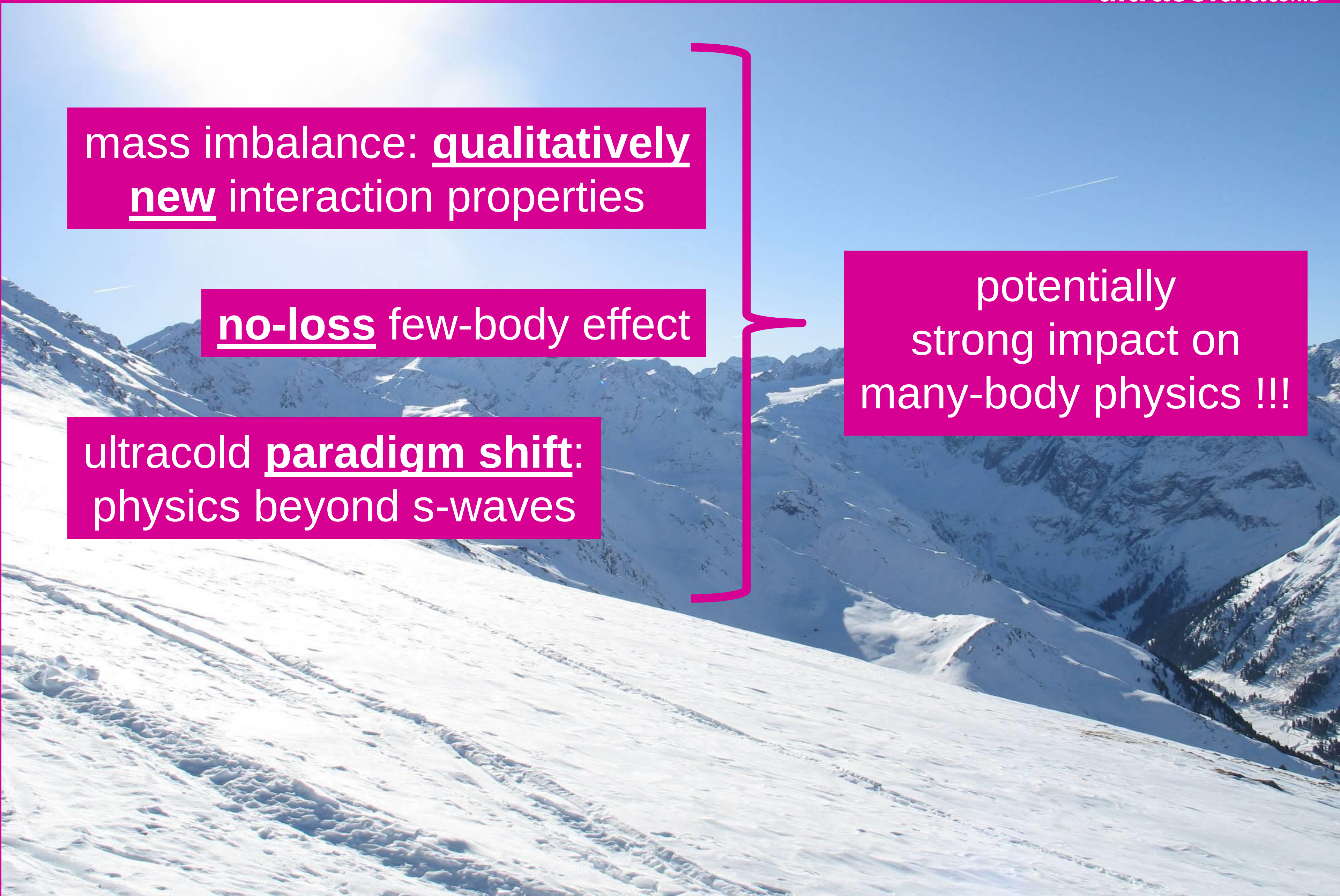


sign reversal

$\delta\nu = \hbar \bar{n}_{\mathrm{D}} a_{\mathrm{eff}} / \mu_3$ shift in terms of eff. sc. length



why we are so excited!



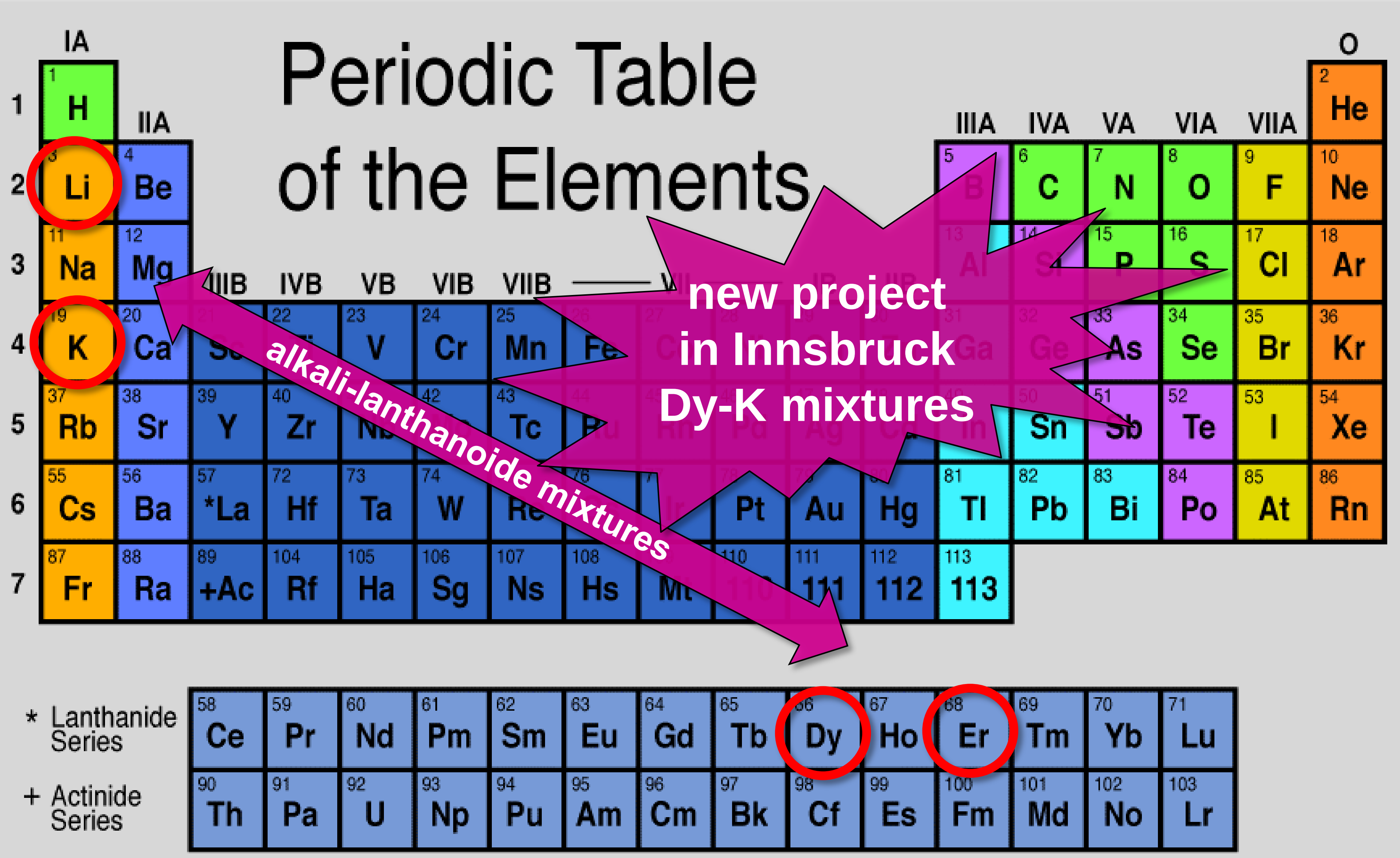
mass imbalance: **qualitatively new** interaction properties

no-loss few-body effect

ultracold **paradigm shift**: physics beyond s-waves

potentially strong impact on many-body physics !!!

strongly interacting, mass-imbalanced mixtures

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thank you for your attention
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Foundations and Applications of Quantum Science