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Evidence for Efimov Quantum states
in Experiments with Ultracold Cesium Atoms

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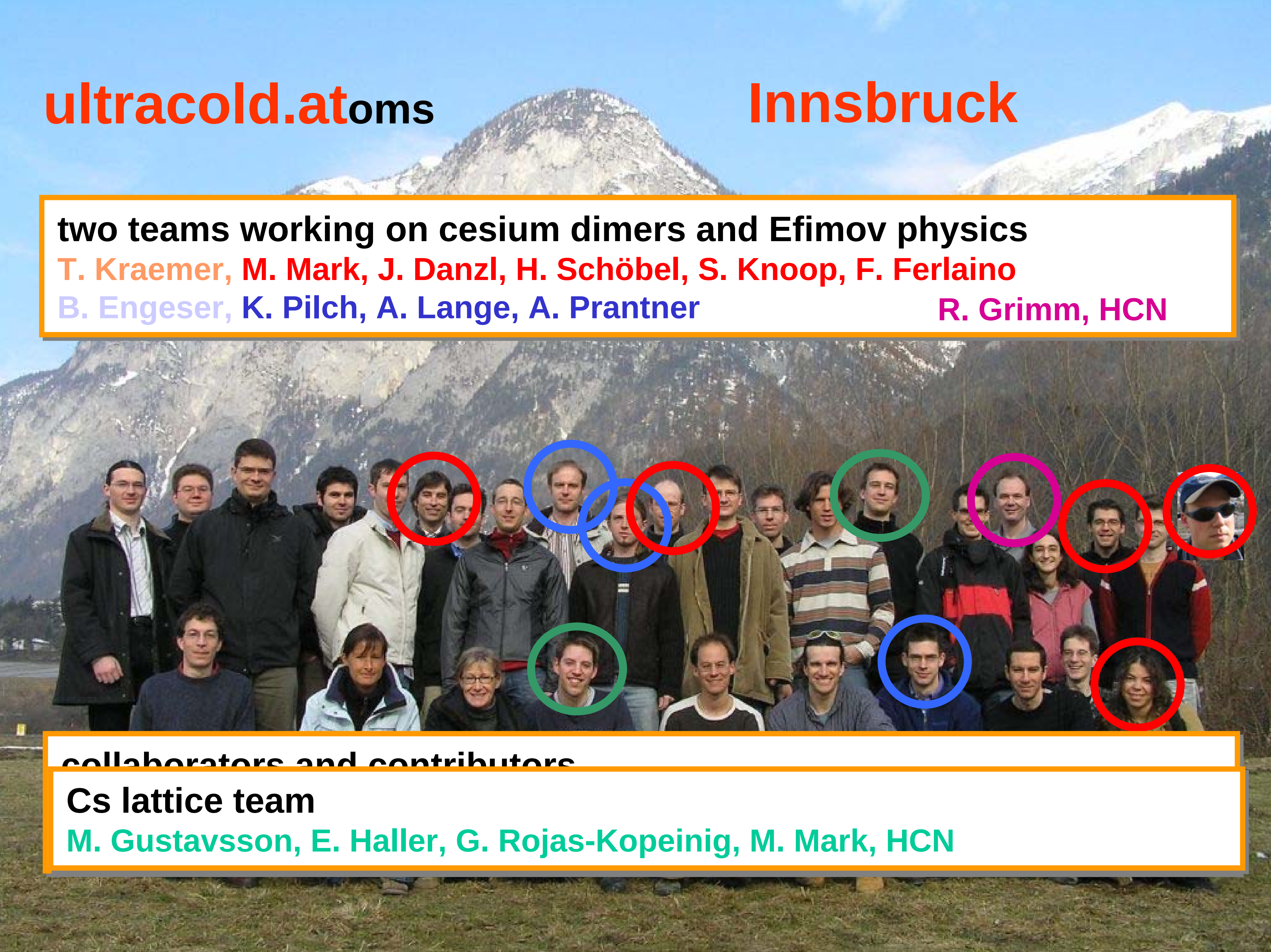
FWF Der Wissenschaftsfonds.

TMR network
Cold Molecules

FASTnet
Field Atom Surface Training Network

ultracold.atoms Innsbruck



two teams working on cesium dimers and Efimov physics

T. Kraemer, M. Mark, J. Danzl, H. Schöbel, S. Knoop, F. Ferlaino

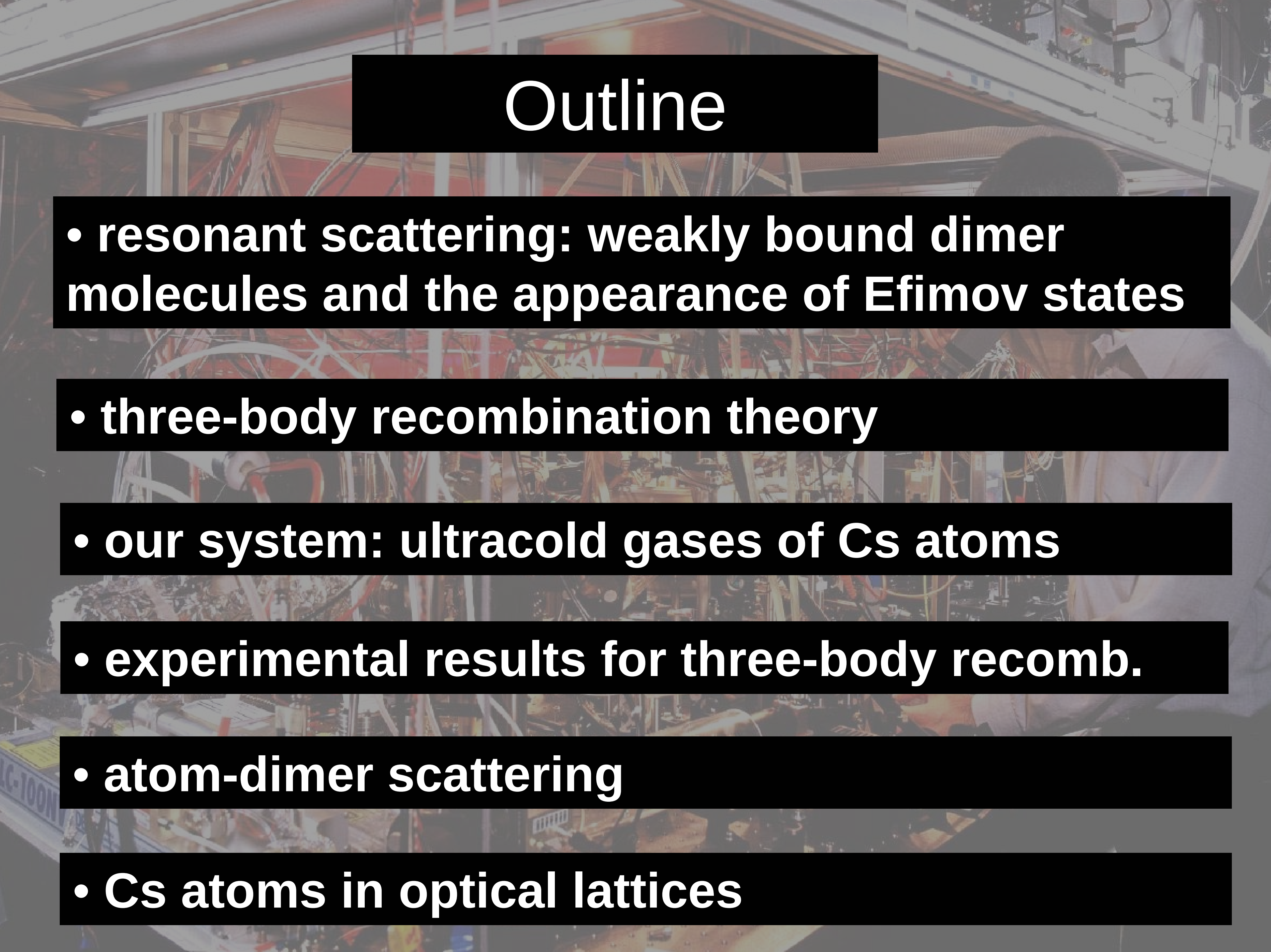
B. Engeser, K. Pilch, A. Lange, A. Prantner

R. Grimm, HCN

collaborators and contributors

Cs lattice team

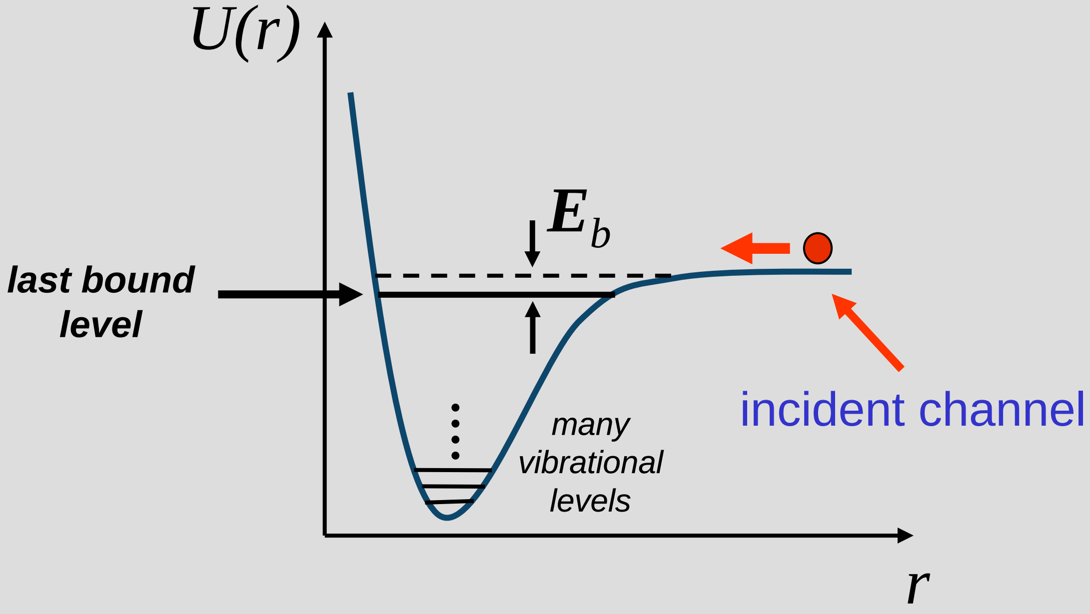
M. Gustavsson, E. Haller, G. Rojas-Kopeinig, M. Mark, HCN



Outline

- **resonant scattering: weakly bound dimer molecules and the appearance of Efimov states**
- **three-body recombination theory**
- **our system: ultracold gases of Cs atoms**
- **experimental results for three-body recomb.**
- **atom-dimer scattering**
- **Cs atoms in optical lattices**

molecular structure: resonant scattering



the s-wave scattering length a, i.e. the scattering radius, is determined by the binding energy E_b of the last bound level:

binding energy $E_b \approx \frac{-\hbar^2}{ma^2}$

elastic cross section $\sigma = 8\pi a^2$

relevance of resonant scattering to BEC

Gross-Pitaevskii equation

$$i\hbar\frac{d\psi}{dt} = -\frac{\hbar^2}{2m}\nabla^2\psi + V(r)\psi + \underset{\uparrow}{g}\,|\psi|^2\,\psi$$

with $g \propto a$ scattering length

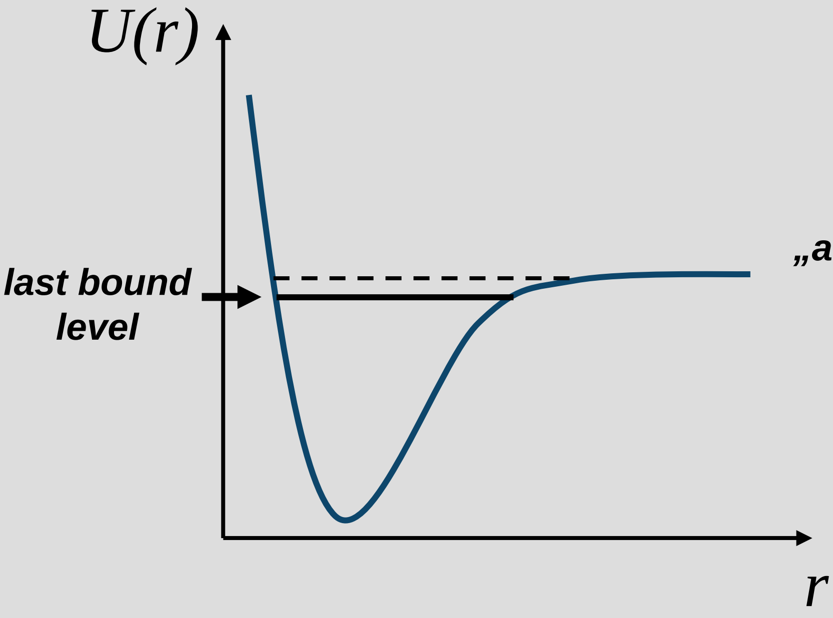
Bose-Hubbard Hamiltonian

$$H = \underbrace{-J\sum_{<j,i>} a_i^\dagger a_j}_{\text{site hopping}} + \underbrace{\overset{\downarrow}{\frac{1}{2}\sum_i U\, n_i(n_i-1)}}_{\text{on-site interaction}} + \underbrace{\sum_i \epsilon_i n_i}_{\text{external confinement}}$$

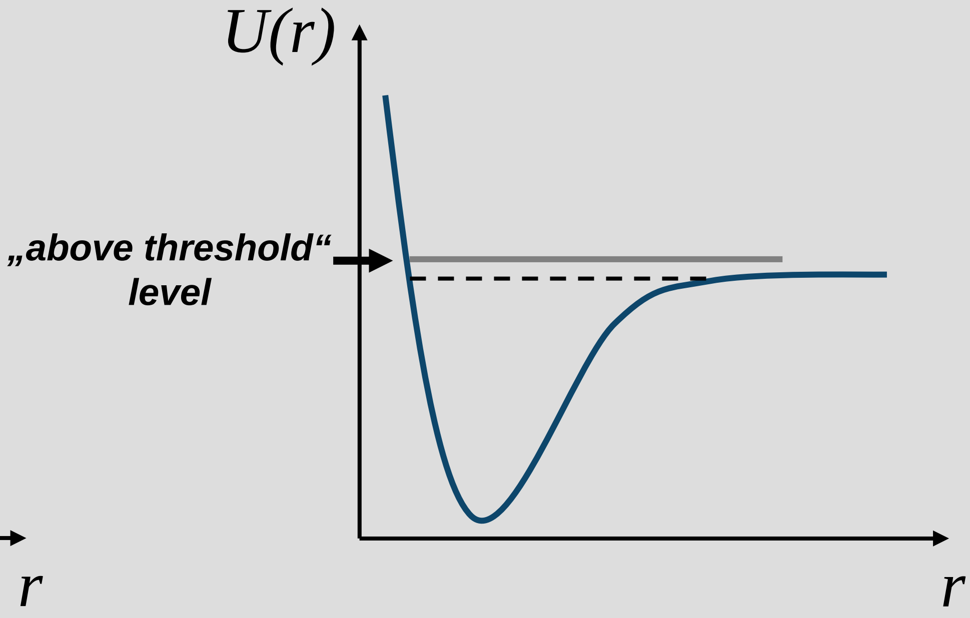
site hopping **on-site interaction** **external confinement**

with $U \propto a$ scattering length

molecular structure: resonant scattering



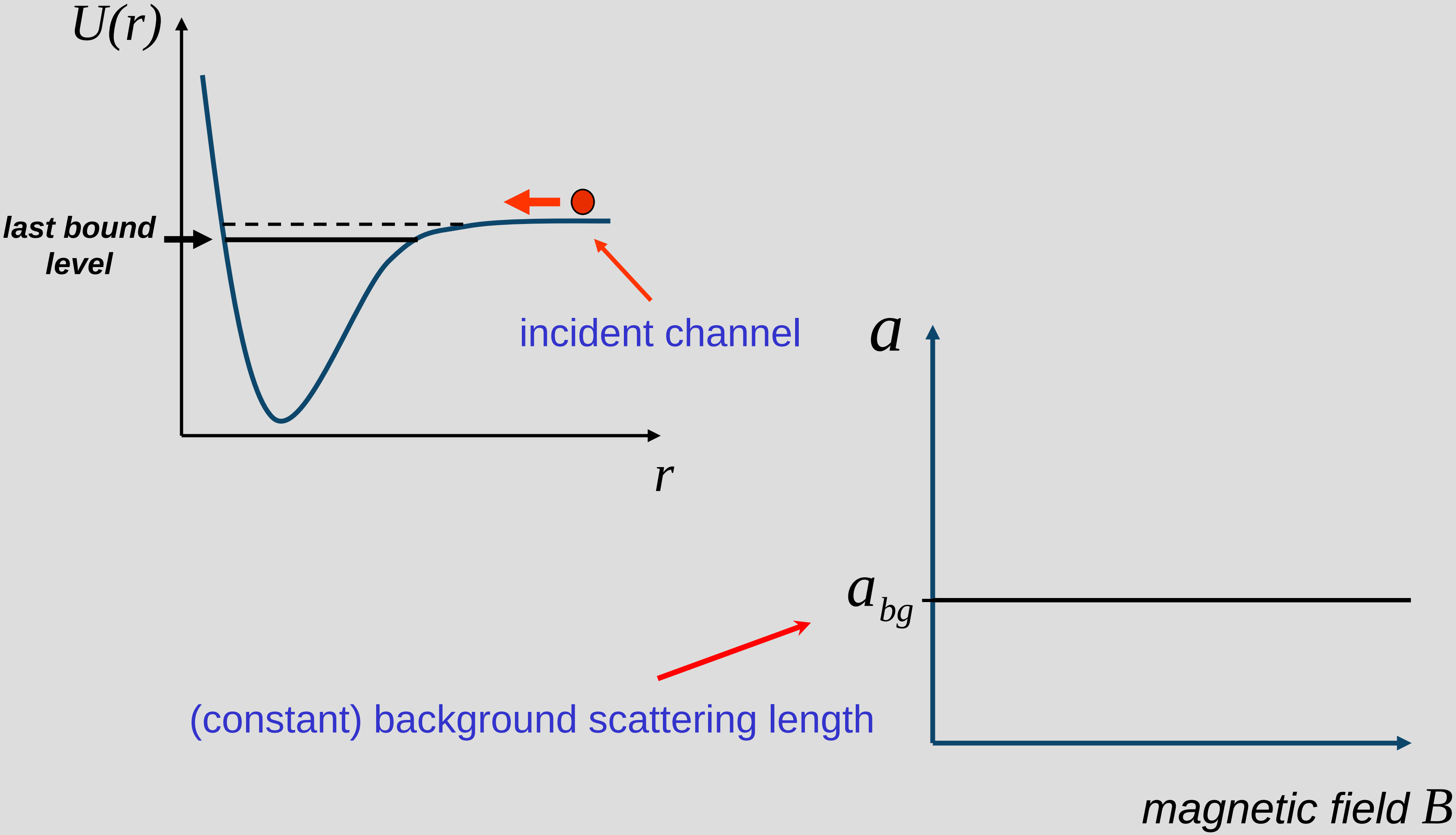
$a > 0$: stable BEC



$a < 0$: unstable BEC

Is there a way to tune a through resonance?

molecular structure: resonant scattering

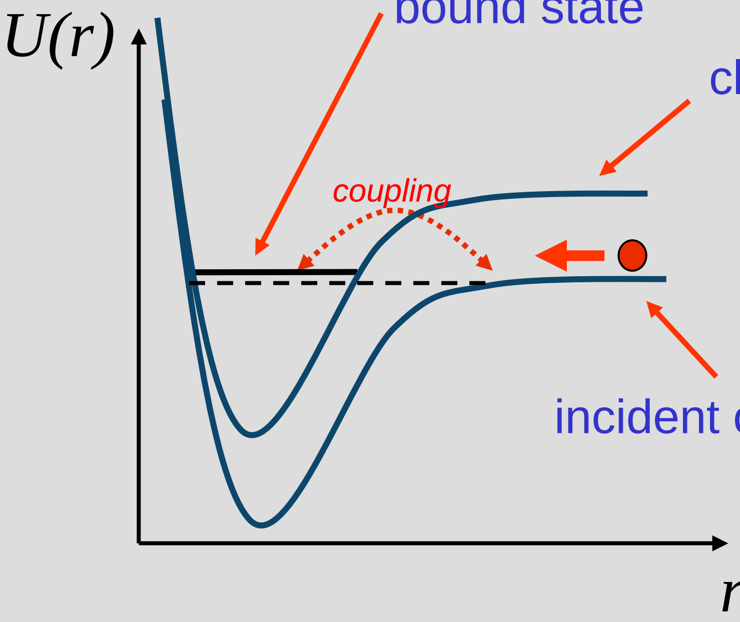


incident channel

(constant) background scattering length

molecular structure: resonant scattering

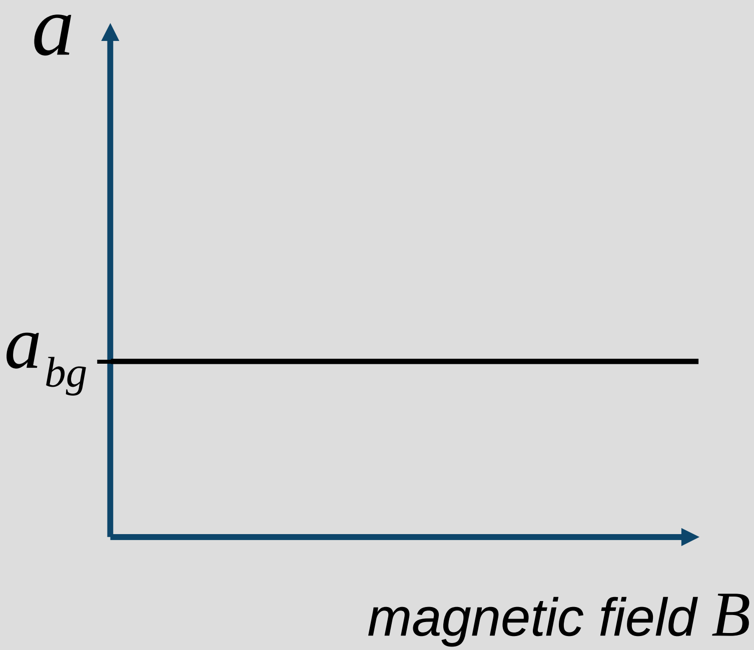
now add a second channel



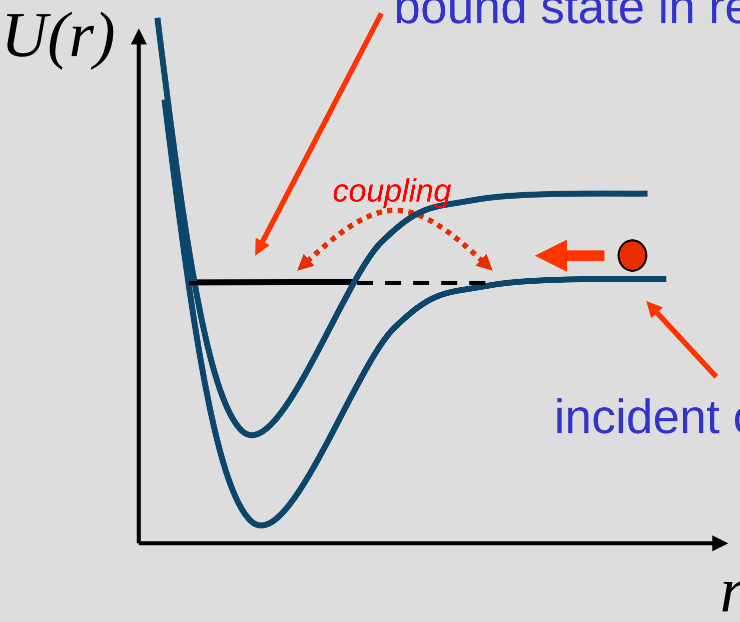
bound state

closed channel

incident channel



Fano-Feshbach resonance



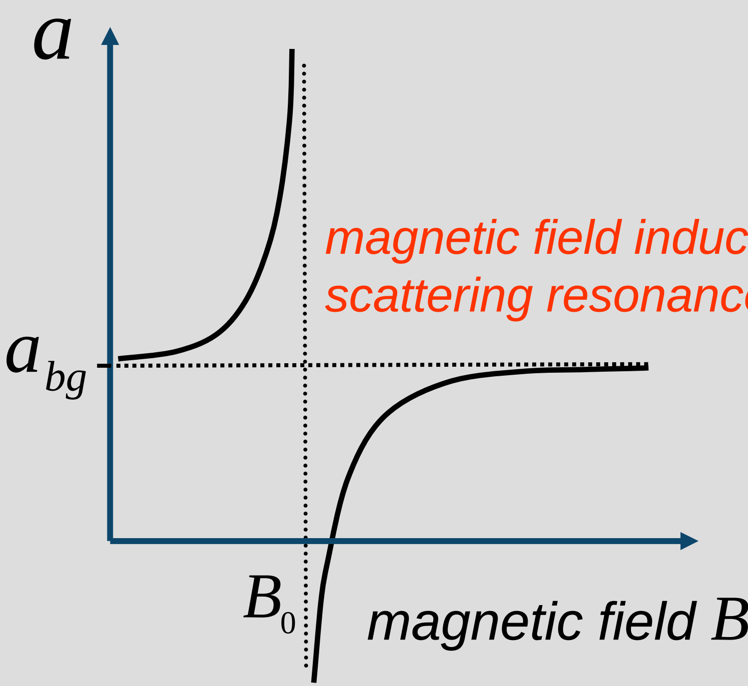
bound state in resonance

incident channel

s-wave scattering length a

as a function of magnetic field B

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



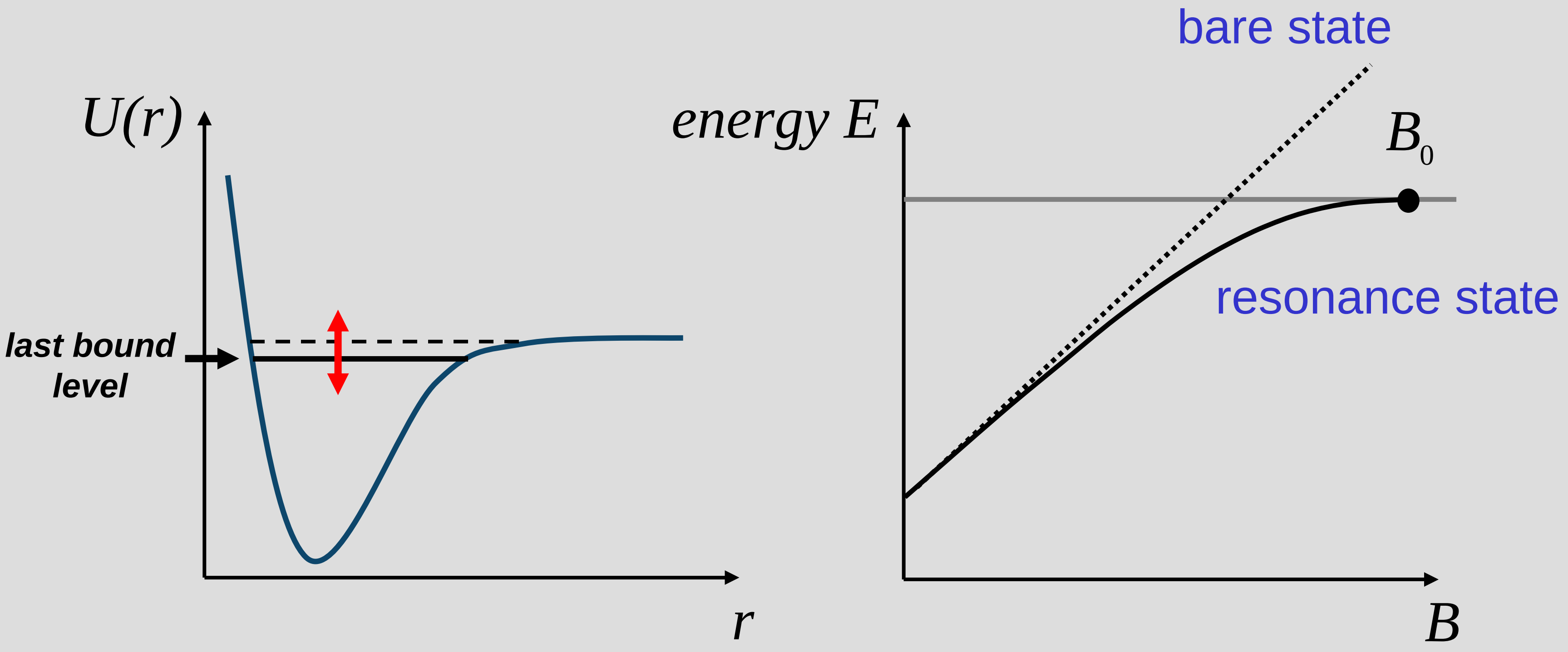
magnetic field induced scattering resonance

magnetic moment of bound state differs from the magnetic moment of the incident channel

$\Delta \propto$ *coupling*

molecular structure: single channel description

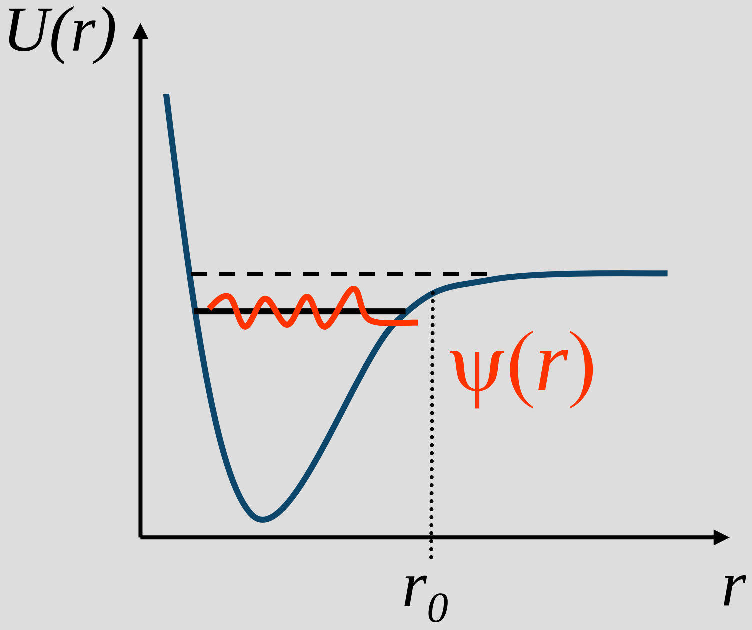
for sufficiently strong coupling: single channel approach possible



$$E_b \propto -\frac{1}{a^2} \propto -(B-B_0)^2$$

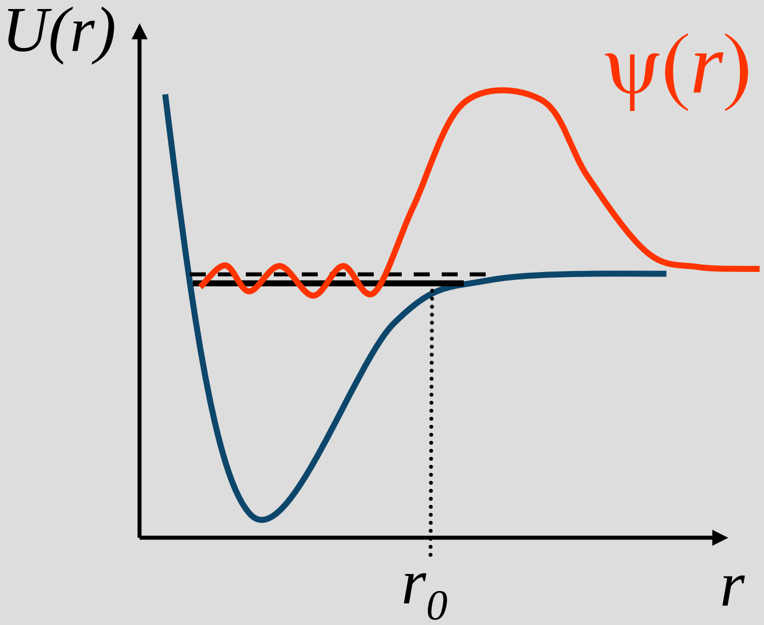
T. Koehler, K. Goral, P. S. Julienne, Rev. Mod. Phys. **78**, 1311 (2006).

molecular structure: wavefunction



r_0 = *range of potential*

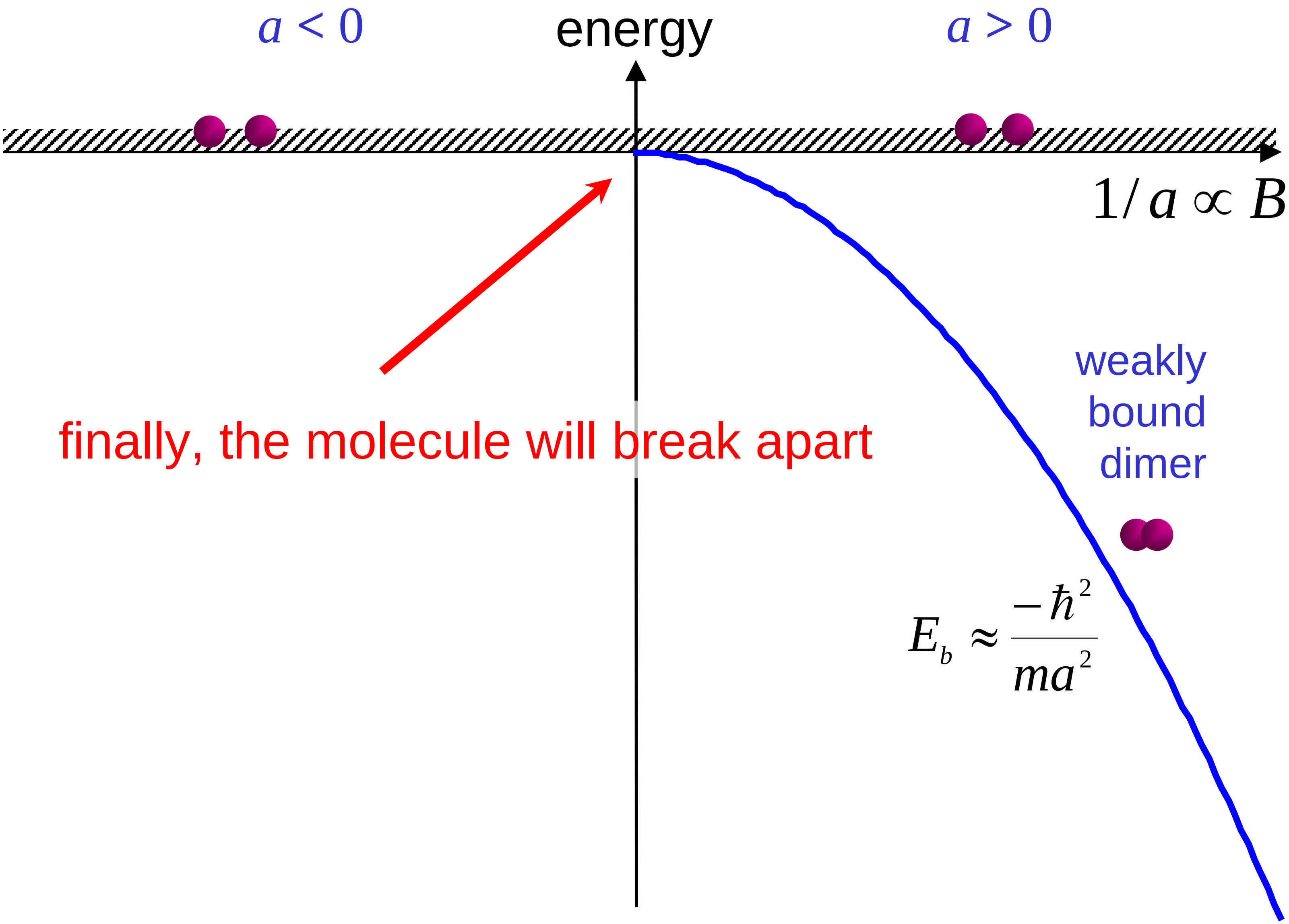
„quantum halo states“:
deuteron, He_2,
Feshbach molecules !!!



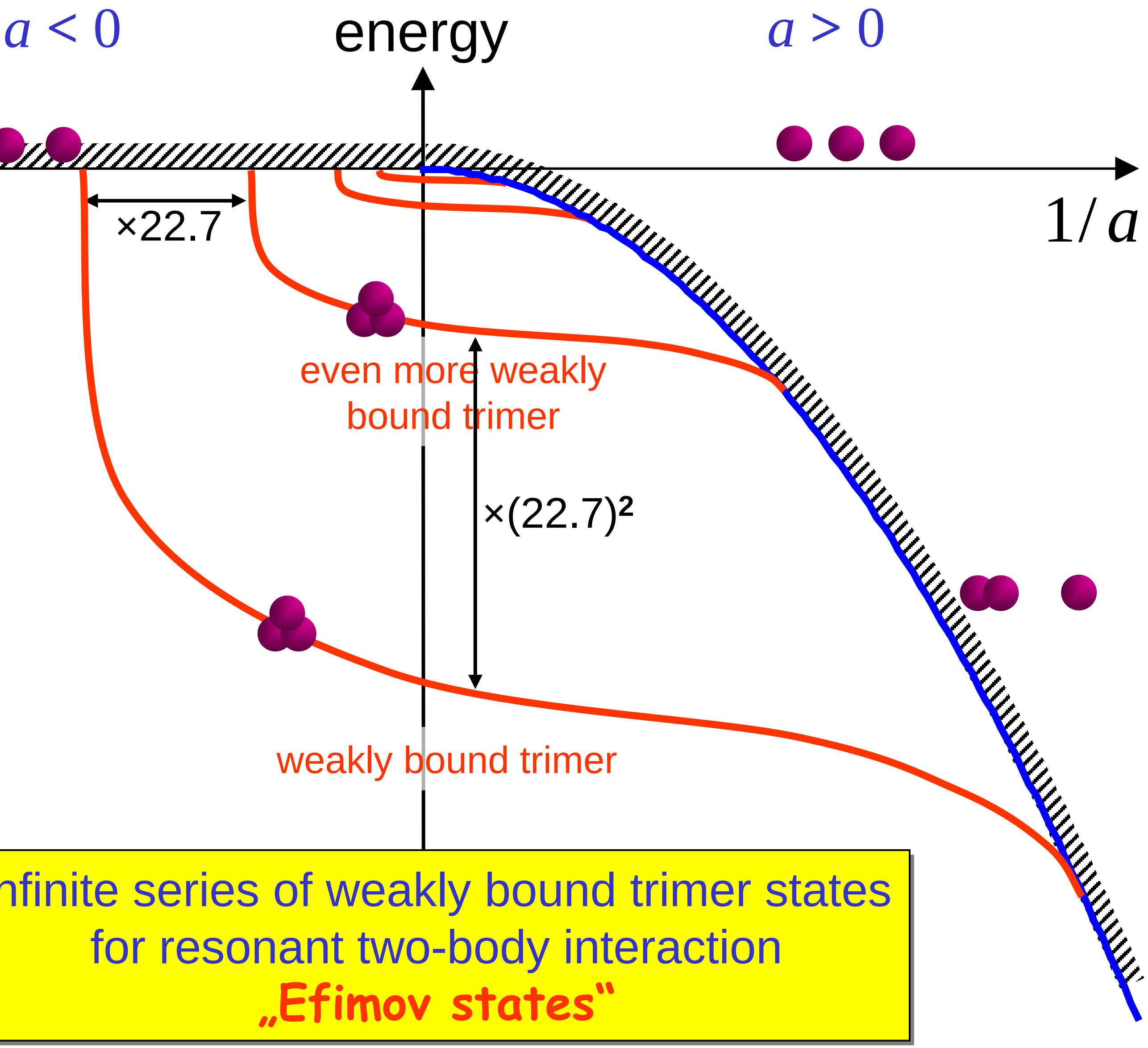
states with universal properties for $\boldsymbol{r \gg r_0}$

$$E_b = \frac{-\hbar^2}{ma^2} \text{ with bond length } \langle r \rangle = a/2$$

The generic two-body resonance



Quantum states near a two-body resonance



Efimov 1971

infinite series of weakly bound trimer states
for resonant two-body interaction
„Efimov states"

Effective $1/R^2$-potential for the 3-body problem

$$\frac{\hbar^2}{2m}\left[-\frac{\partial^2}{\partial R^2}-\frac{s_0^2+1/4}{R^2}\right]f_0(R)=E\,f_0(R)$$

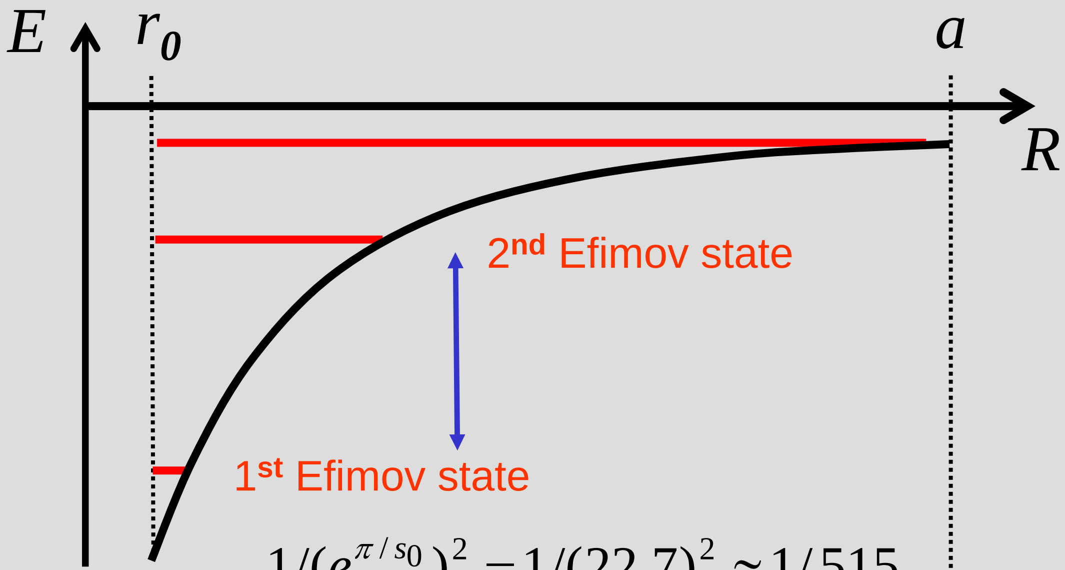
$s_0 = 1.00624$

effective radial Schrödinger equation for $r_0 << R << a$

$f_0(R)$ hyperspherical wave function as a function of

$$R^2 = \frac{1}{3}\left(r_{12}^2+r_{23}^2+r_{31}^2\right)$$

hyperradius



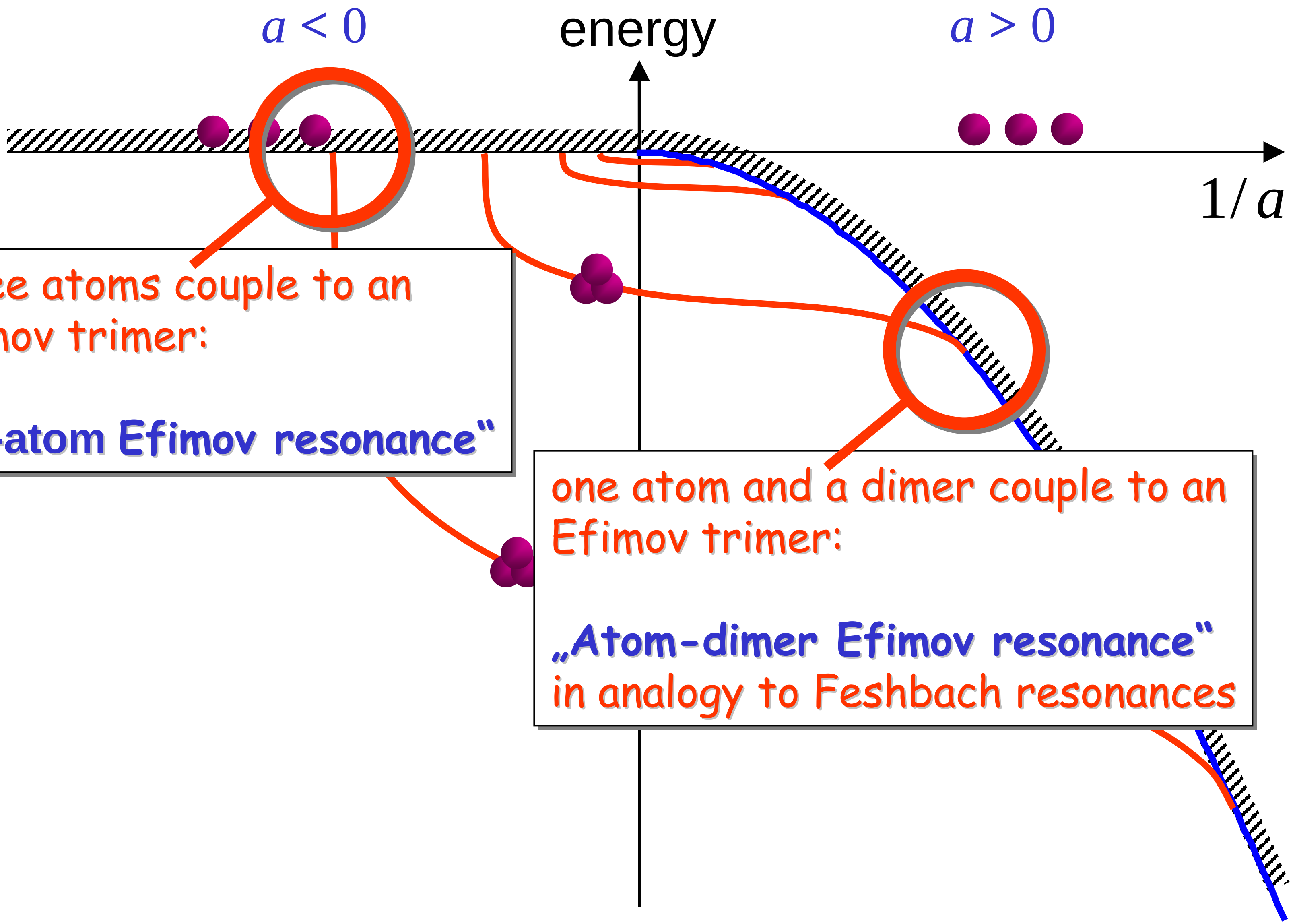
$$1/(e^{\pi/s_0})^2 = 1/(22.7)^2 \approx 1/515$$

number of Efimov states

$$N_E \approx \frac{1}{\pi}\ln(|a|/r_0)$$

review: E. Braaten and H. Hammer Physics Reports **428**, 259 (2006)

Efimov states: properties



three atoms couple to an Efimov trimer:

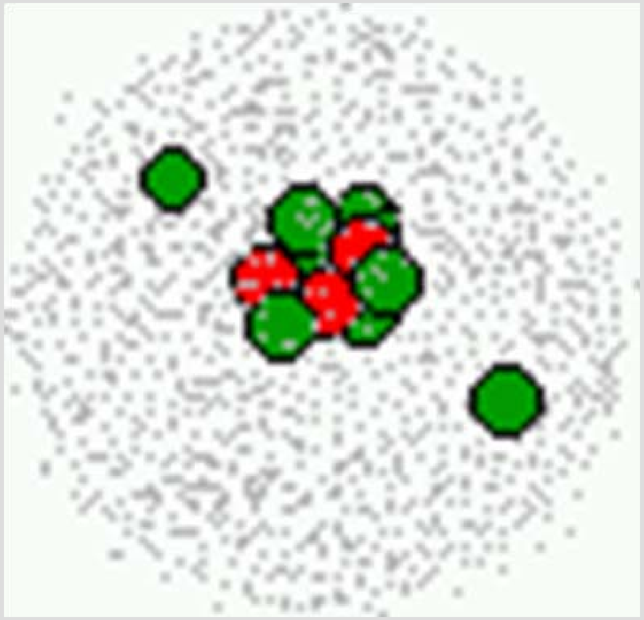
„Tri-atom Efimov resonance“

one atom and a dimer couple to an Efimov trimer:

„Atom-dimer Efimov resonance“
in analogy to Feshbach resonances

Candidate systems for Efimov states

nuclear physics

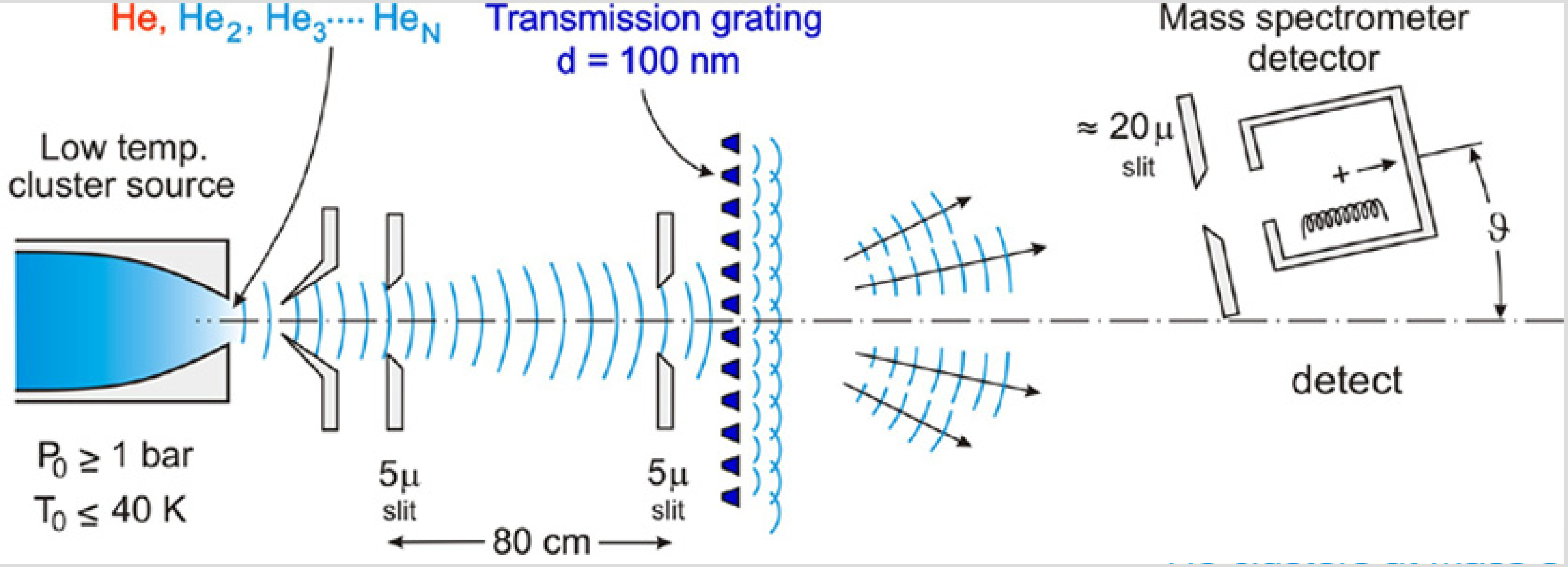


halo nuclei with many neutrons:
e.g. ^{14}Be, ^{18}C, ^{20}C
best candidates: core + n + n
simplest case: triton

Review: A. S. Jensen et al., RMP 76, 215 (2004)

Candidate systems for Efimov states

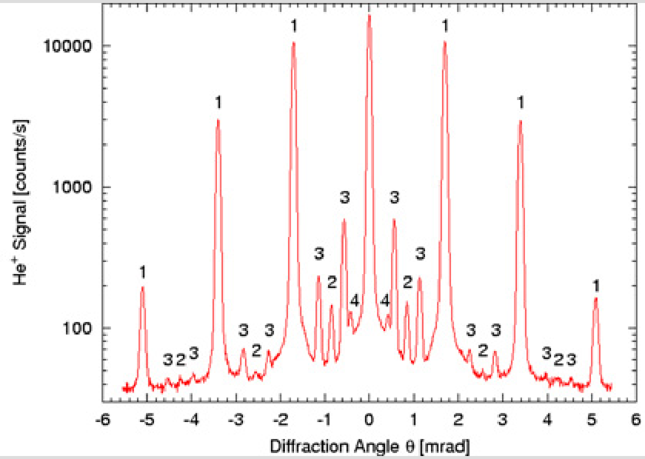
atomic physics: $^4He_3$



Beams with He, He_2, He_3,...

He_2: binding energy 1.1 mK, <r> = 5.2 nm
He_3: binding energy 126 mK, <r> = 0.96 nm

Efimov-He_3: binding energy 2.3 mK, <r> = 7.8 nm



J. P. Toennies et al, PRL 95, 063002 (2005)

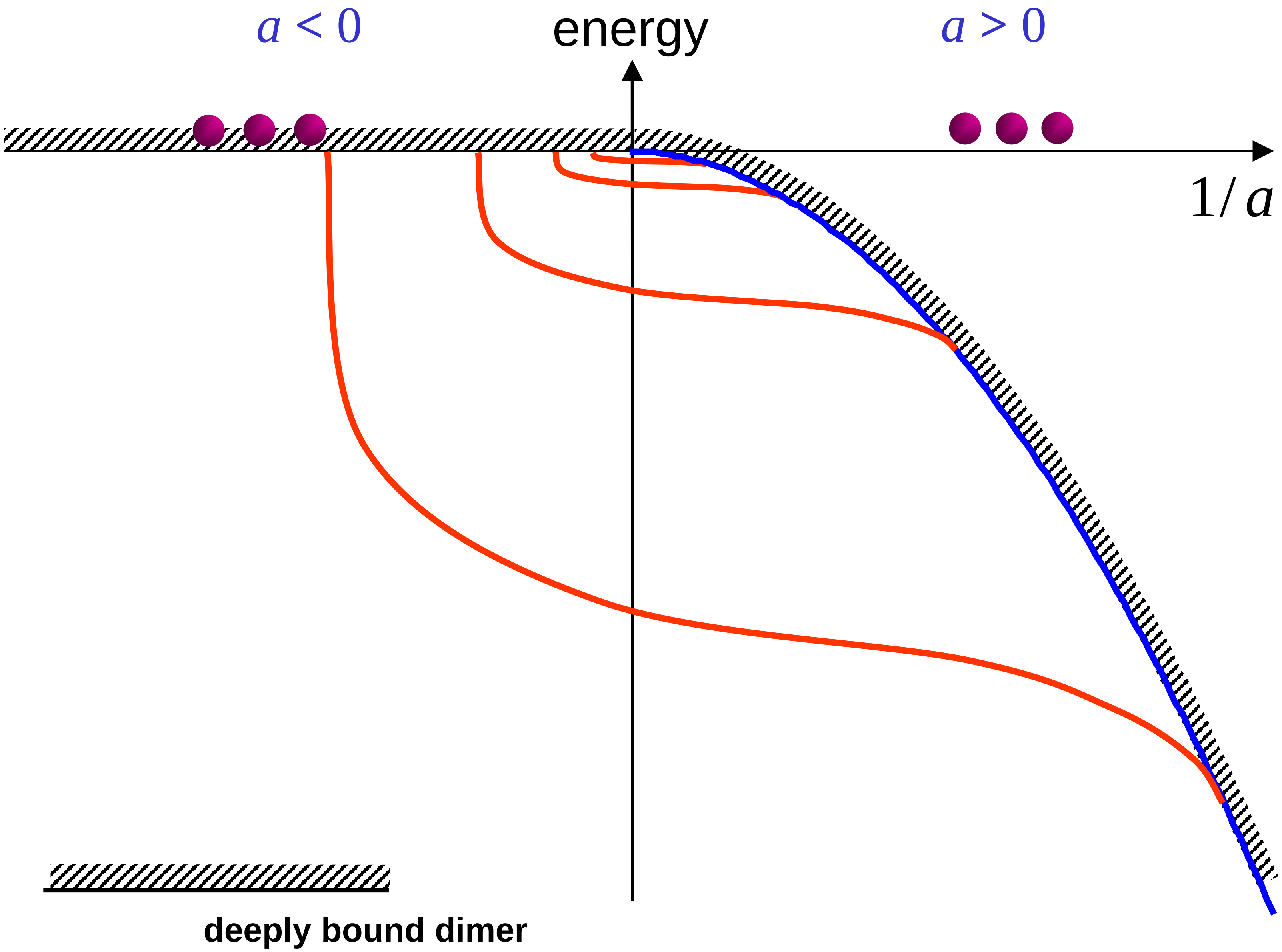
ultracold atomic gases: signature of Efimov states

three-body recombination

for positive scattering lengths: formation of the weakly bound dimer

for negative scattering lengths: population of deeply bound dimers states

Three-body recombination



Three-body recombination: theory basics

$$\dot{n} = -L_3\, n^3$$

L_3: three-body loss coefficient [cm^6/s]

$$L_3 = 3\,C\,\frac{\hbar}{m}a^4$$

Fedichev *et al*., PRL **77**, 2921 (1996)
prediction of a^4 scaling $a >> r_0$, $C \sim 4$

Nielsen & Macek, PRL 83, 1566 (1999)
Esry et al., PRL 83, 1751 (1999)
Bedaque et al., PRL 85, 908 (2000)
Braaten & Hammer, PRL 87, 160407 (2001)

$C = C(a)$

with upper limit ~70 for $a > 0$

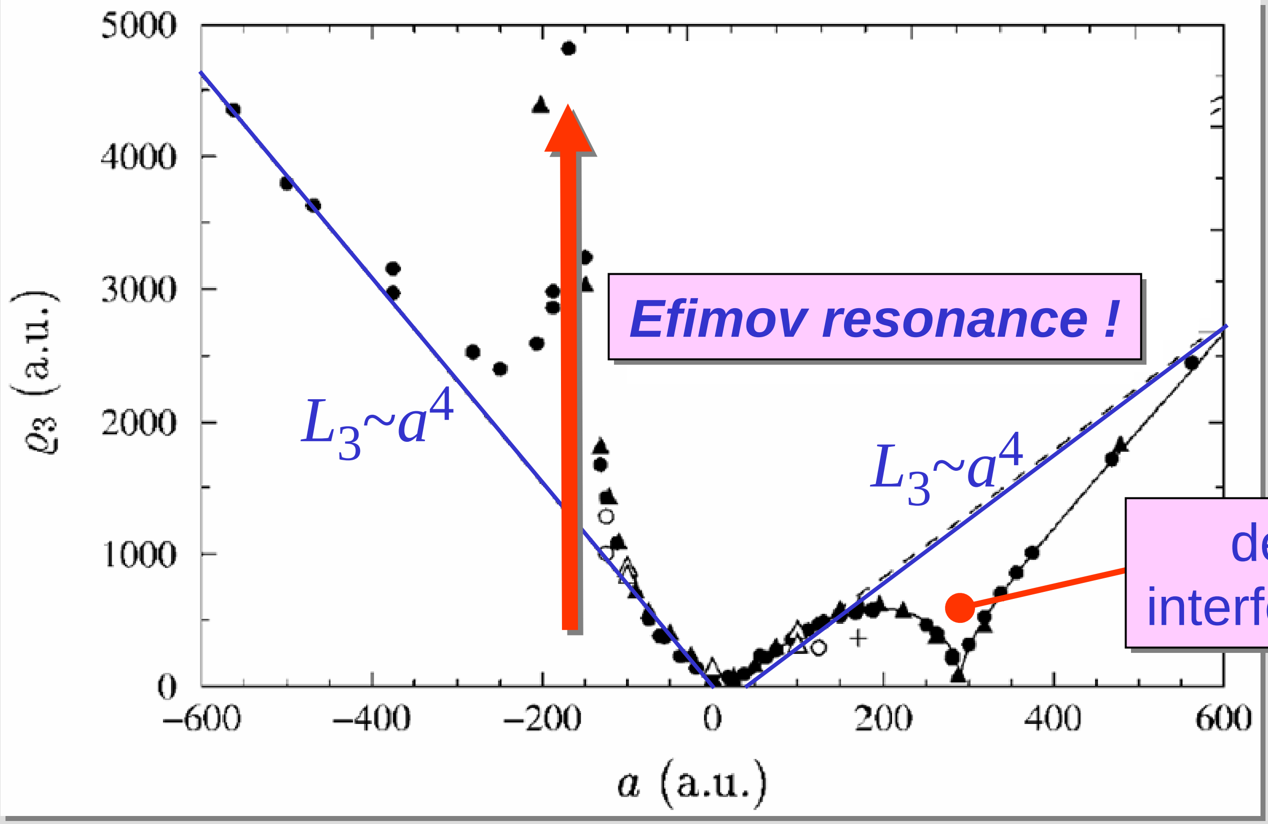
oscillatory behavior
× $e^{\pi} \sim 22.7$

Esry-Greene theory

PRL **83**, 1751 (1999)   numerical calculations for model potentials

definition of
a recombination length

$$\rho_3 = \left(\frac{2}{\sqrt{3}}\frac{m}{\hbar}L_3\right)^{1/4}$$



Efimov resonance !

destructive interference effect

Braaten-Hammer theory

Three-body loss coefficient

$$L_3 = 3\,C\,\frac{\hbar\,a^4}{m} \text{ with } C = C(a)$$

mostly loss into shallow dimer

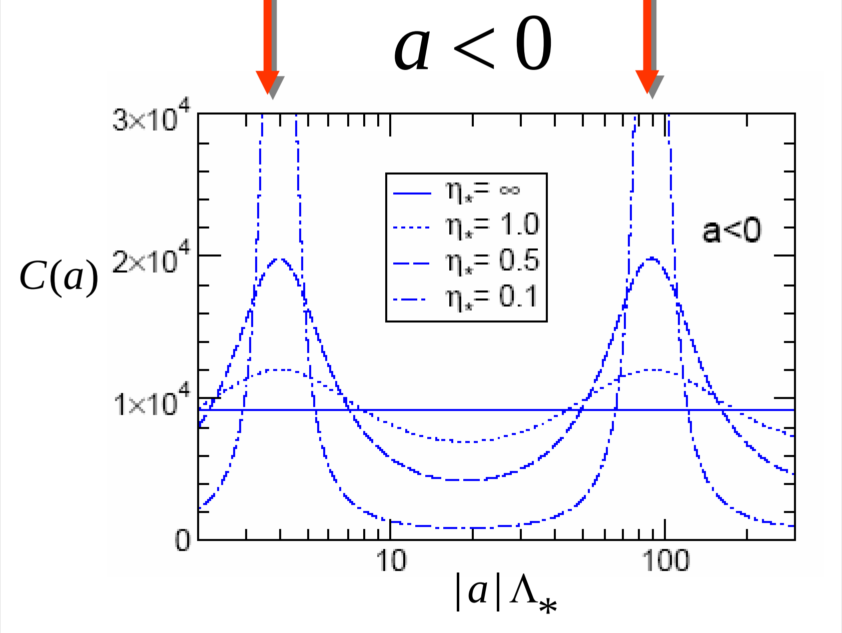
$$C(a) = \frac{4590\,\sinh(2\eta_*)}{\sin^2(s_0\ln(|a|\Lambda_*)+1.72)+\sinh^2\eta_*}$$

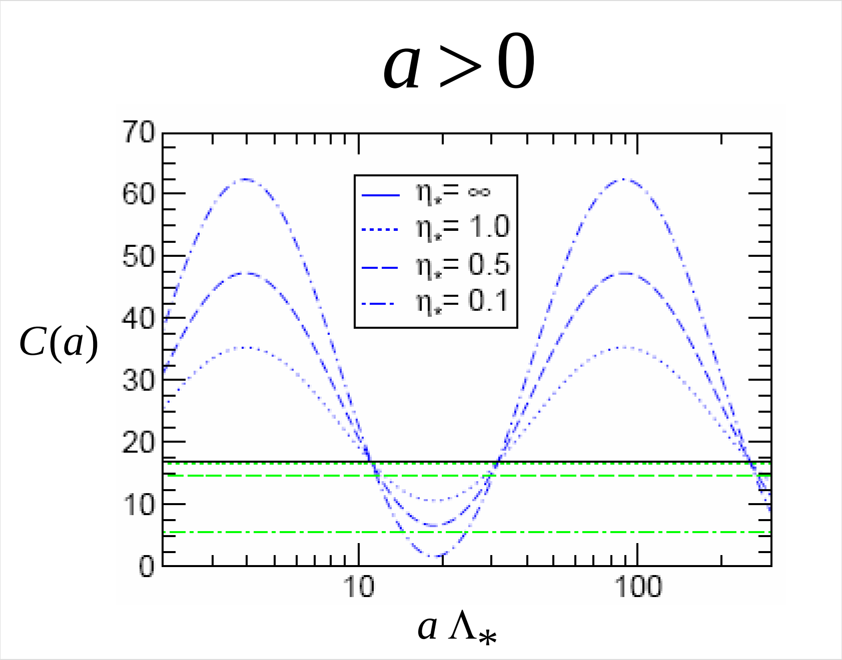
$$C(a) = 67.1\,\mathrm{e}^{-2\eta_*}\left(\cos^2(s_0\ln(a\Lambda_*)+1.76)+\sinh^2\eta_*\right) + 16.8\,(1-e^{-4\eta_*})$$

loss into deeply bound molecules only

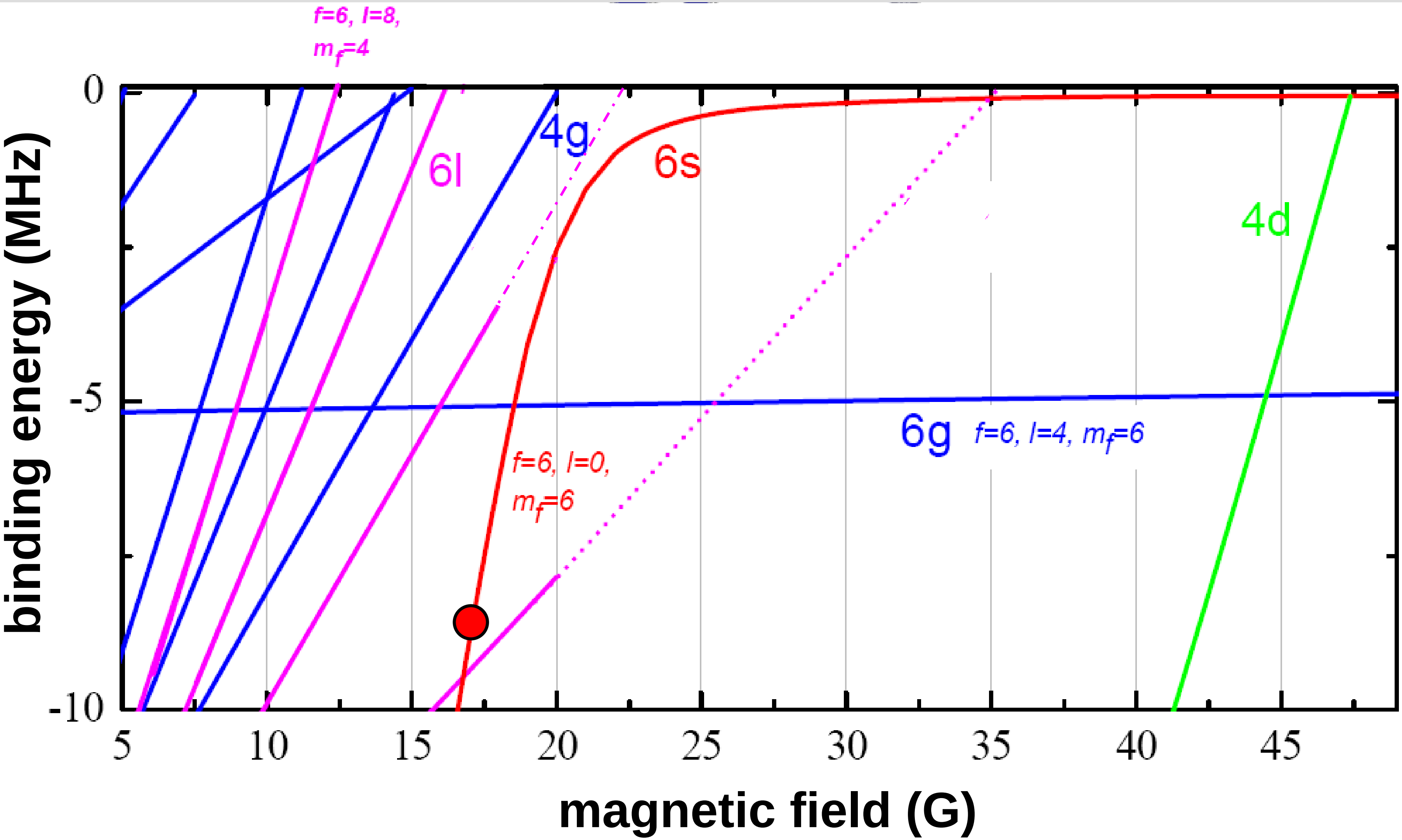
also loss into deeply bound molecules

Efimov resonances



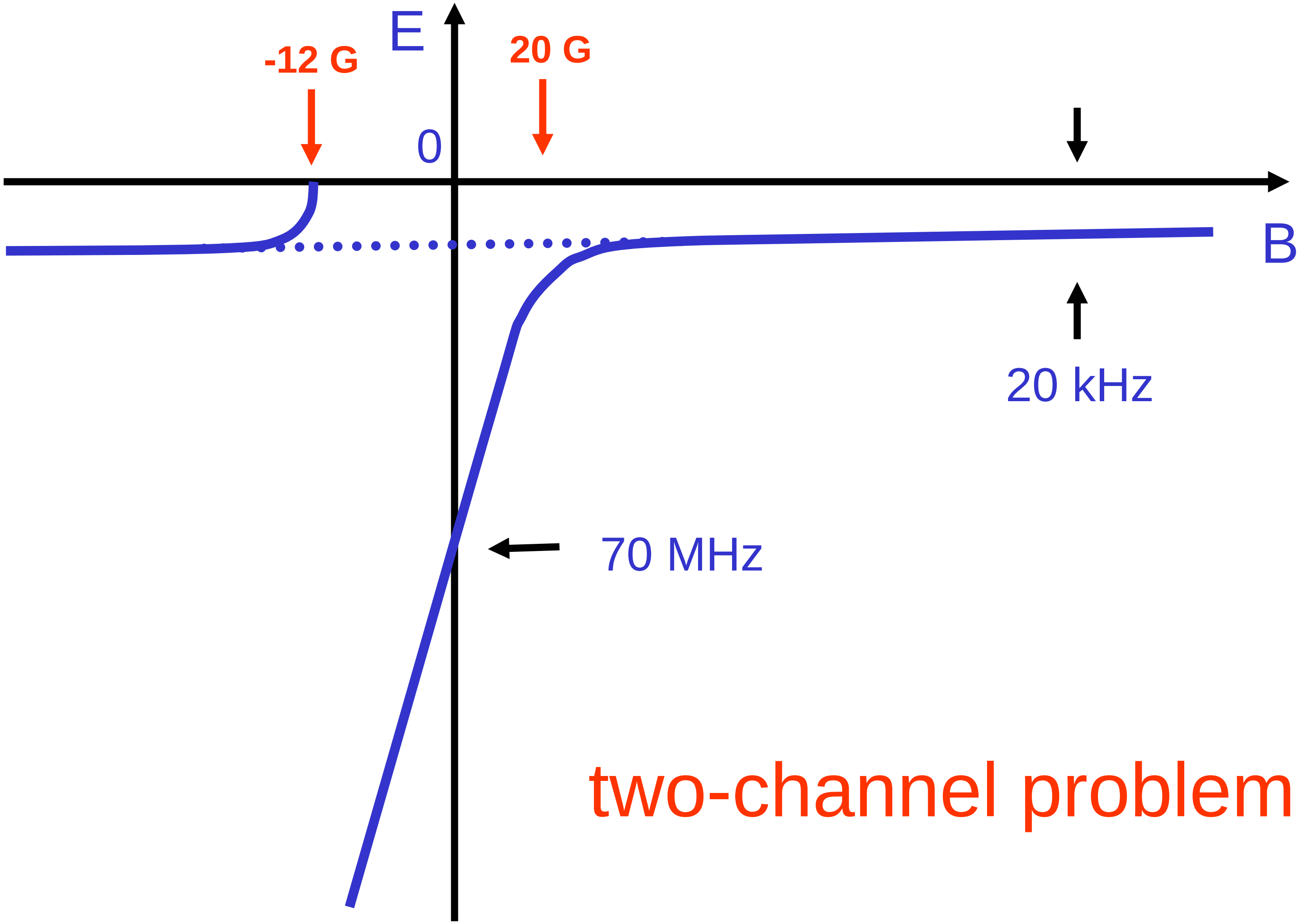


Molecular energy structure for Cs_2: the weakly bound dimer



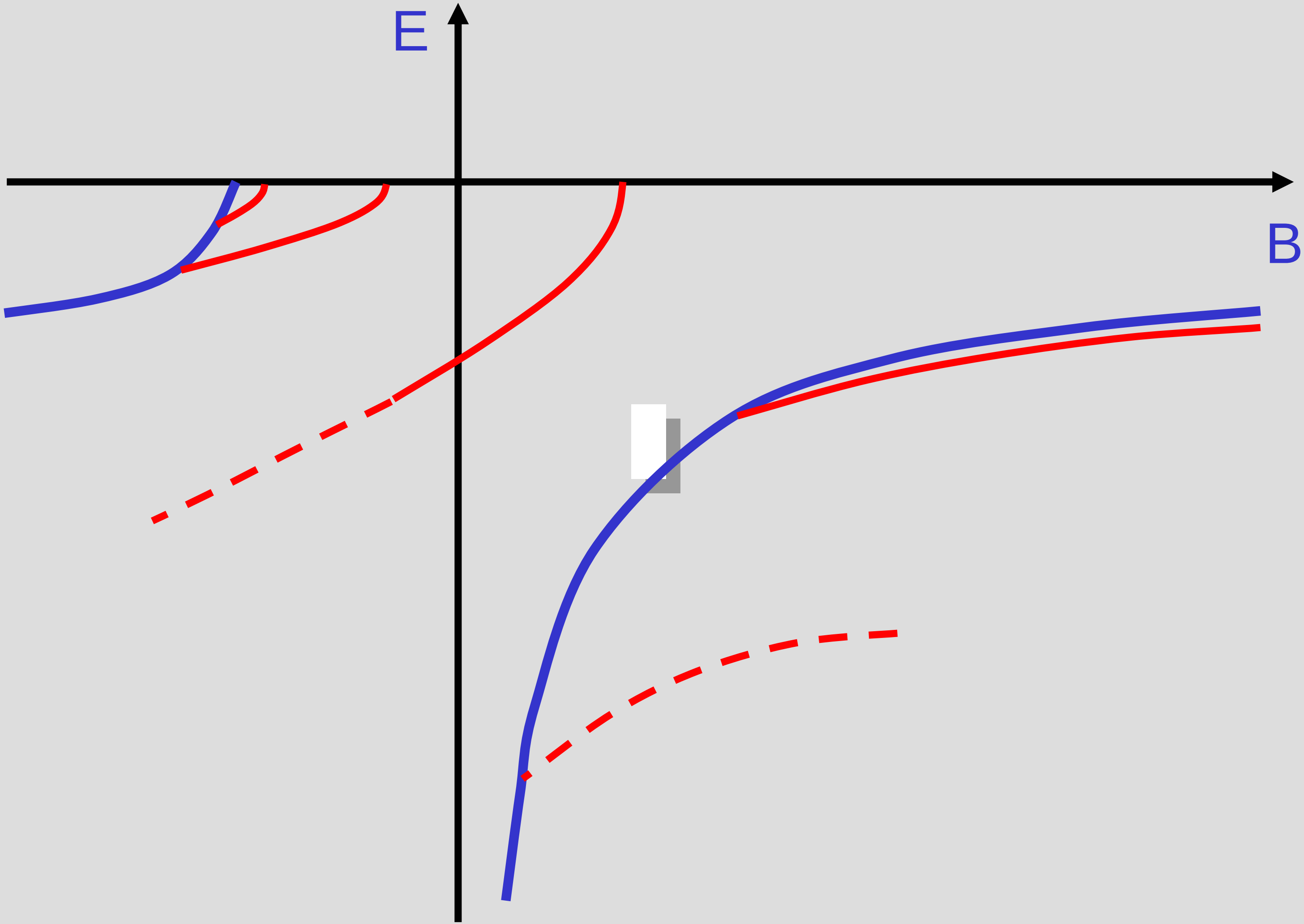
P. Julienne, E. Tiesinga

Cs molecular structure simplified



two-channel problem

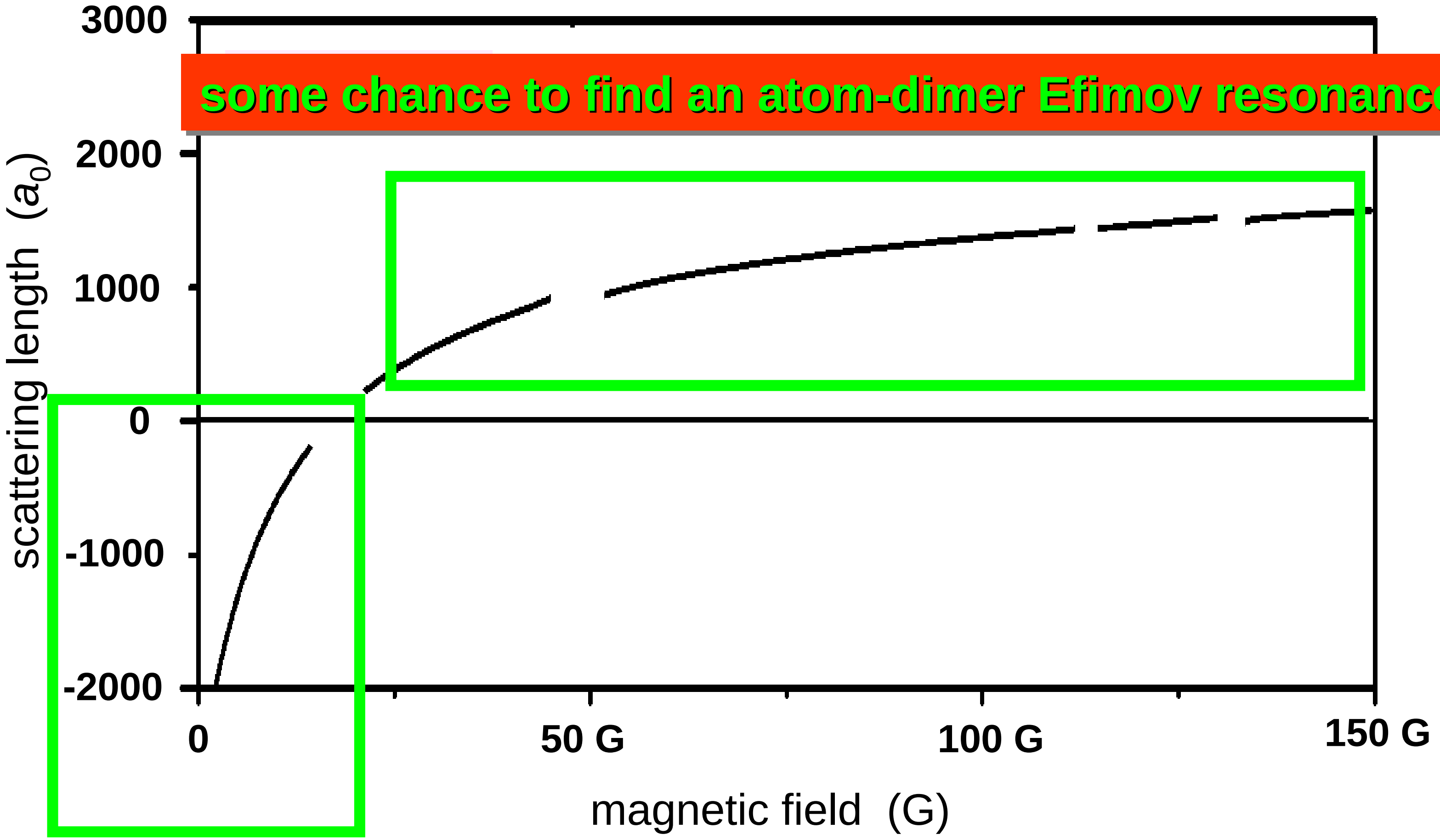
Where do the Efimov states show up?



not to scale

T. Köhler, see next talk

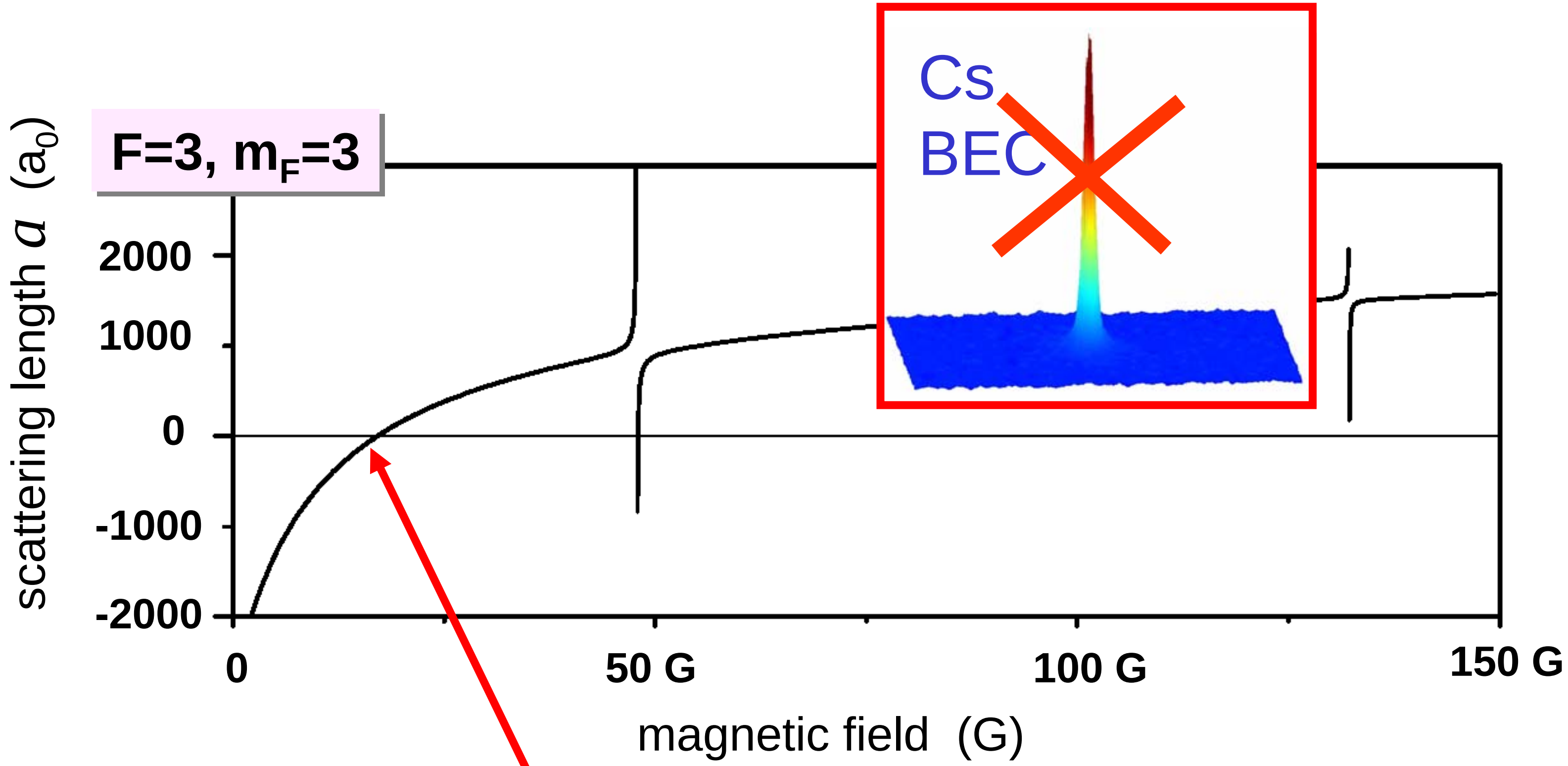
accessible range for the scattering length



some chance to find an atom-dimer Efimov resonance !

good chance to find a tri-atom Efimov resonance !

E. Tiesinga et al.



BEC-implosion at slightly negative *a* gives a *thermal* ensemble at 10 nK

Three-body loss measurement

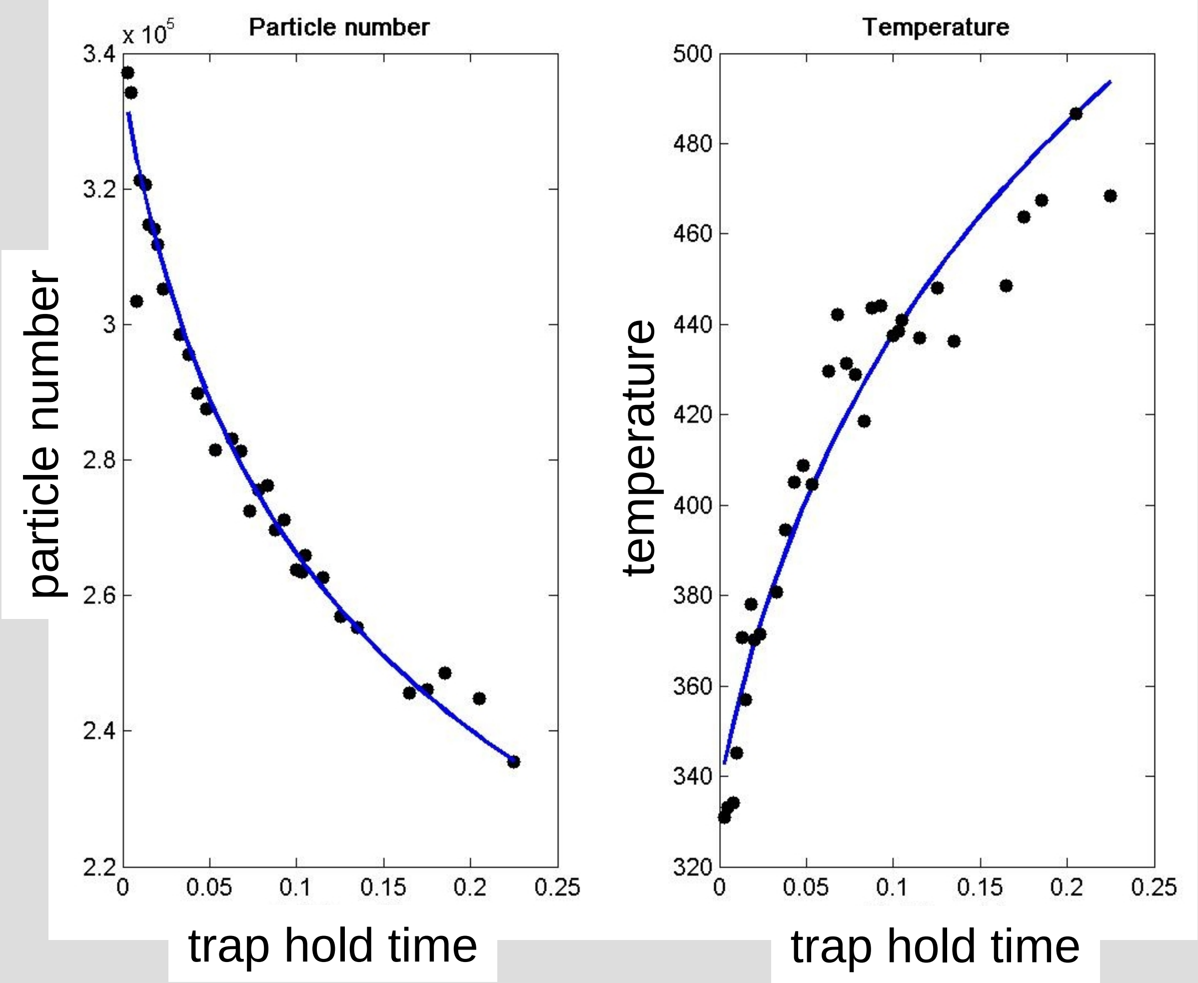
$$\dot{n} = -L_3 n^3$$

$$\frac{dN}{dt} = -\gamma \frac{N^3}{T^3}$$

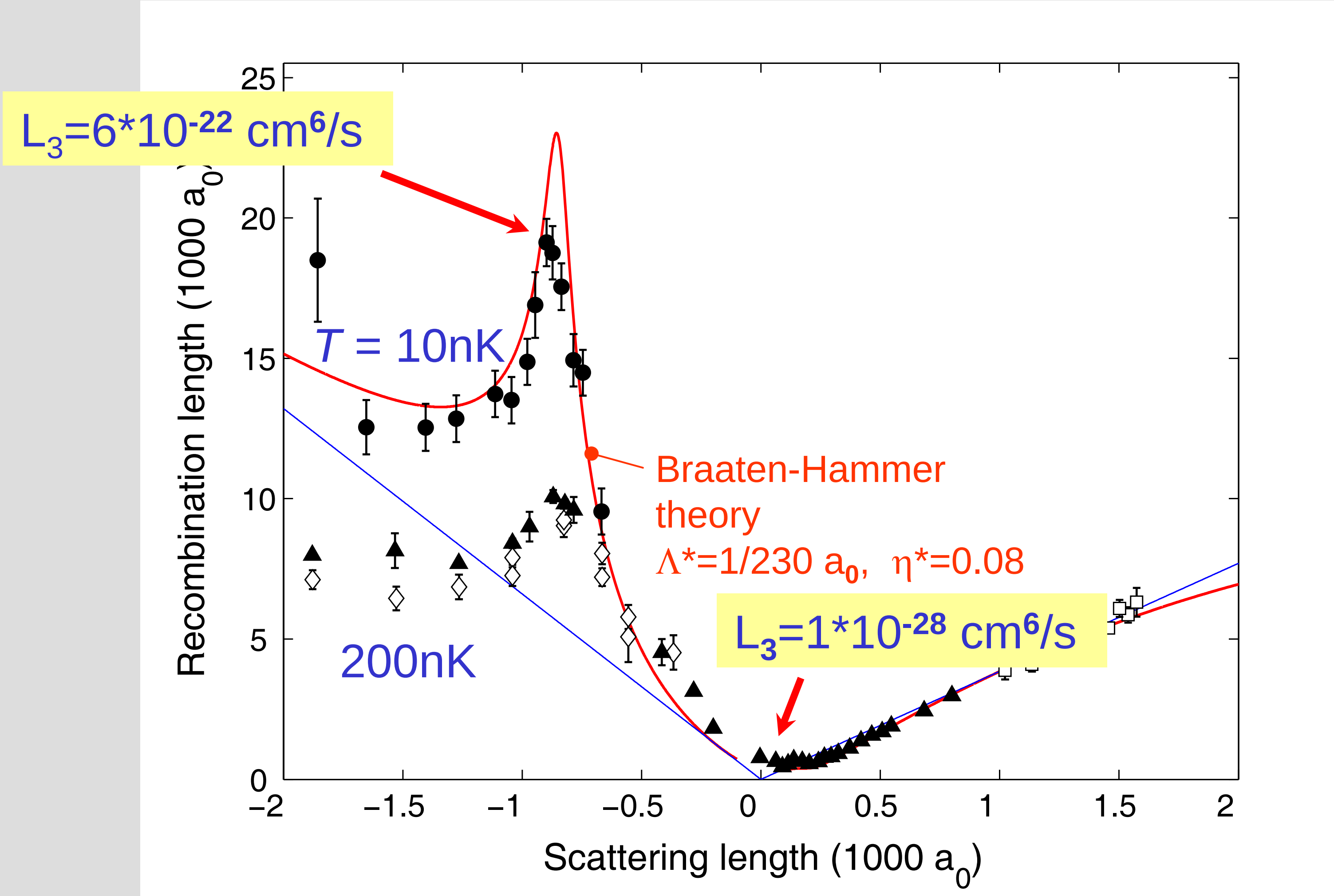
$$\frac{dT}{dt} = \gamma \frac{N^2}{T^3} \frac{T + T_h}{3}$$

Fit $\gamma \sim L_3$

anti-evaporation and
recombination heating



experimental results



$L_3=6*10^{-22}$ cm^6/s

T = 10nK

200nK

Braaten-Hammer theory

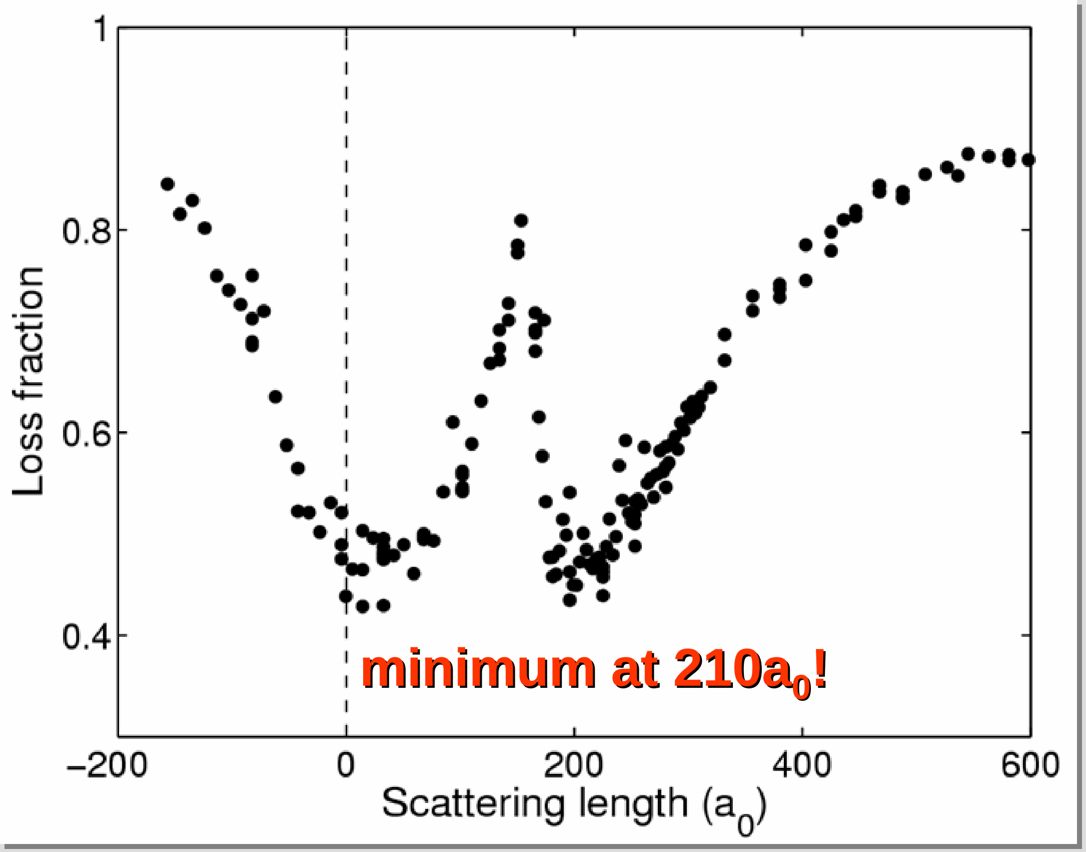
$\Lambda^*=1/230$ a_0, $\eta^*=0.08$

$L_3=1*10^{-28}$ cm^6/s

Nature **440**, 315 (2006)

three-body loss minimum

three-body loss after 200ms storage in recompressed trap

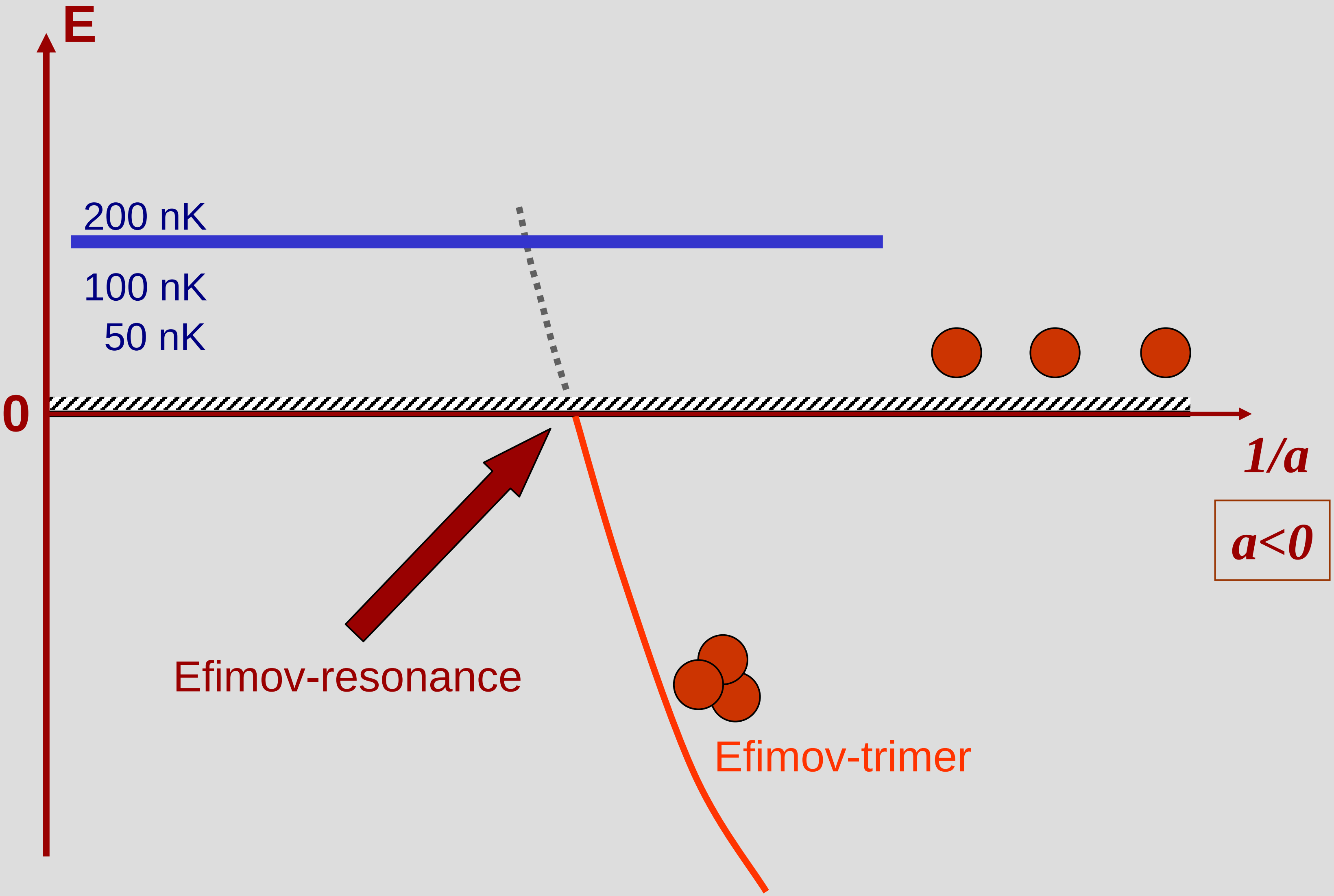


minimum at 210a_0!

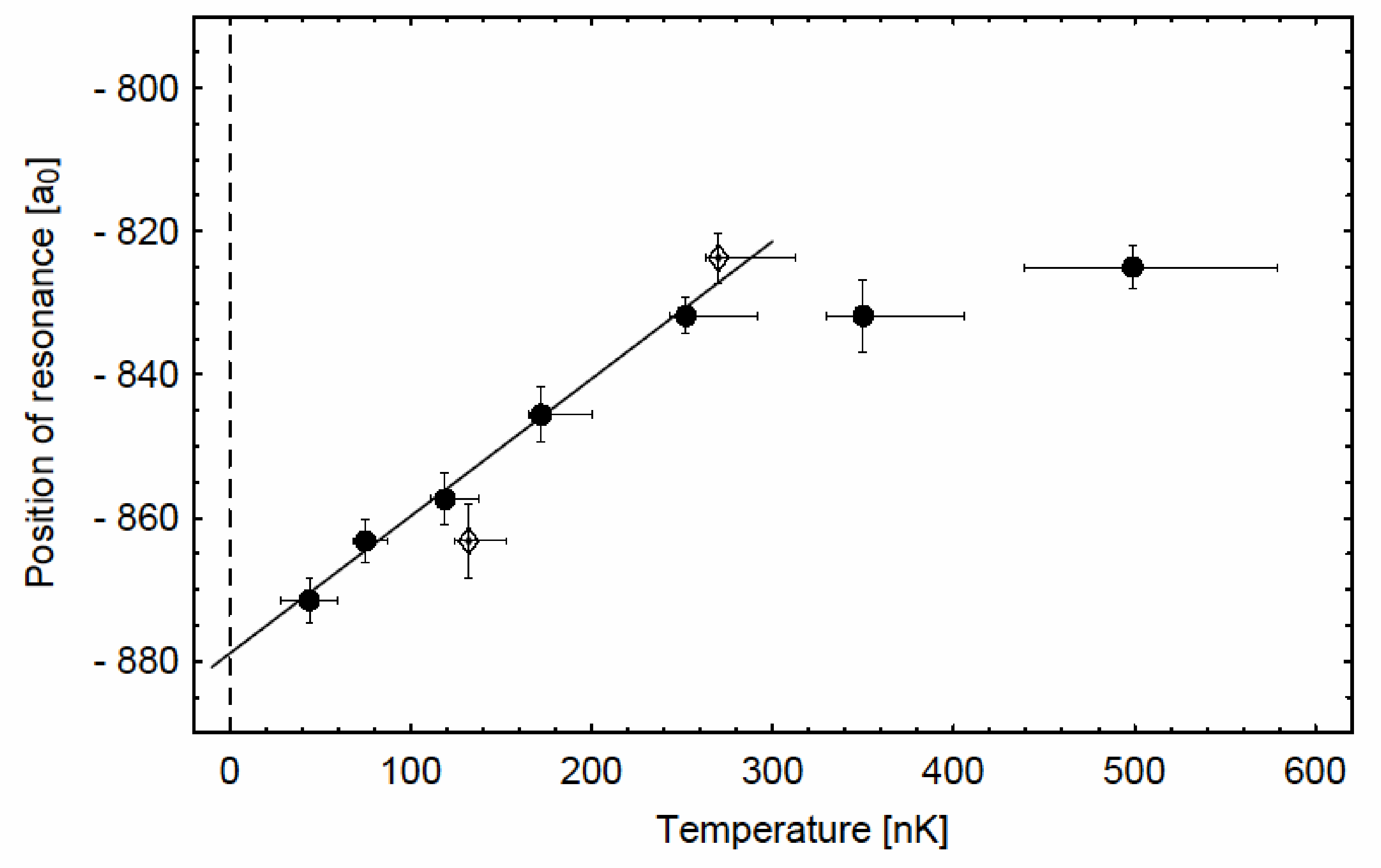
half Efimov period ($22.7^{1/2}$) observed: min.-max. loss !

optimization of evaporative cooling towards BEC -> 200...250a_0

Continuum resonance

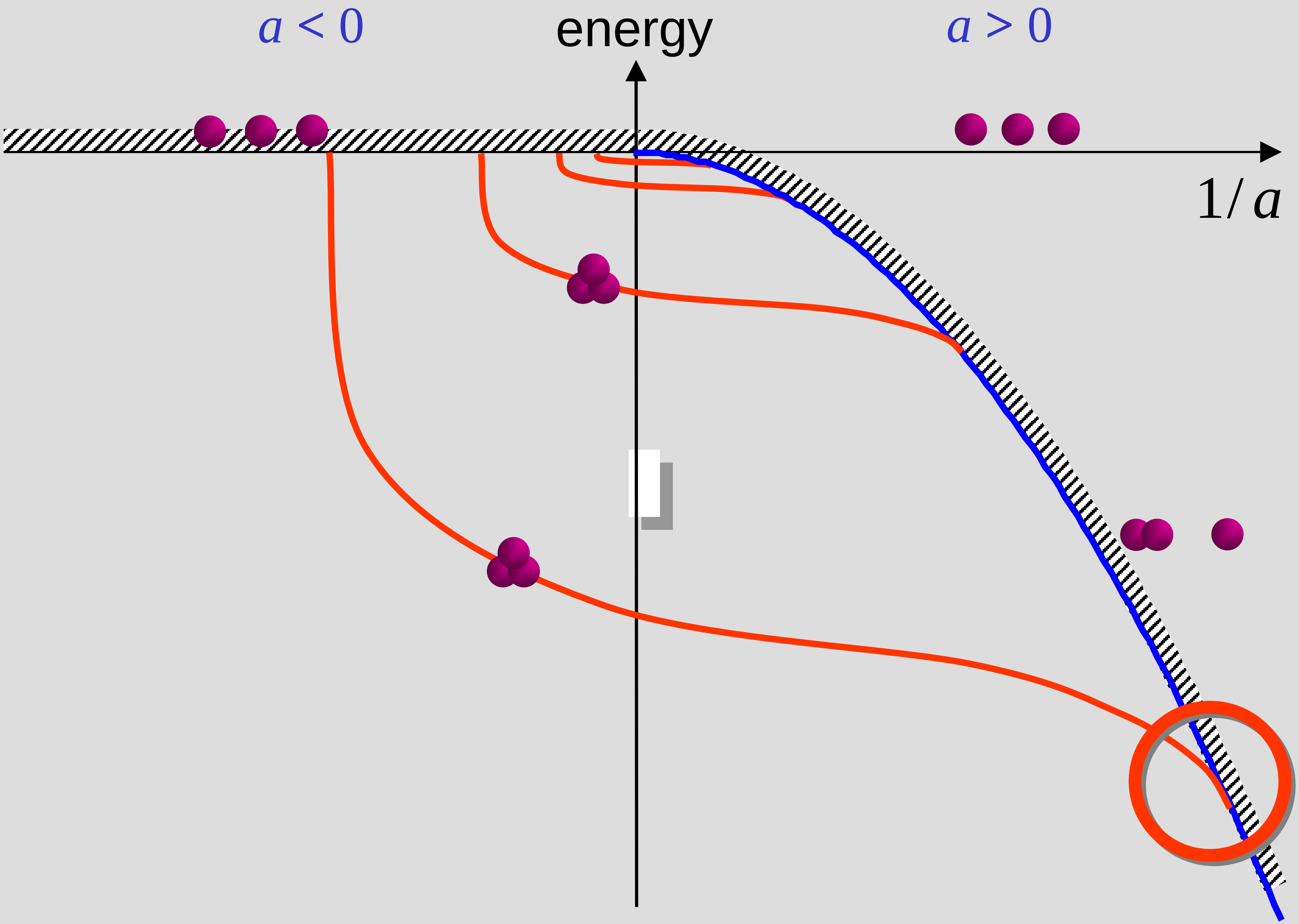


Resonance shift

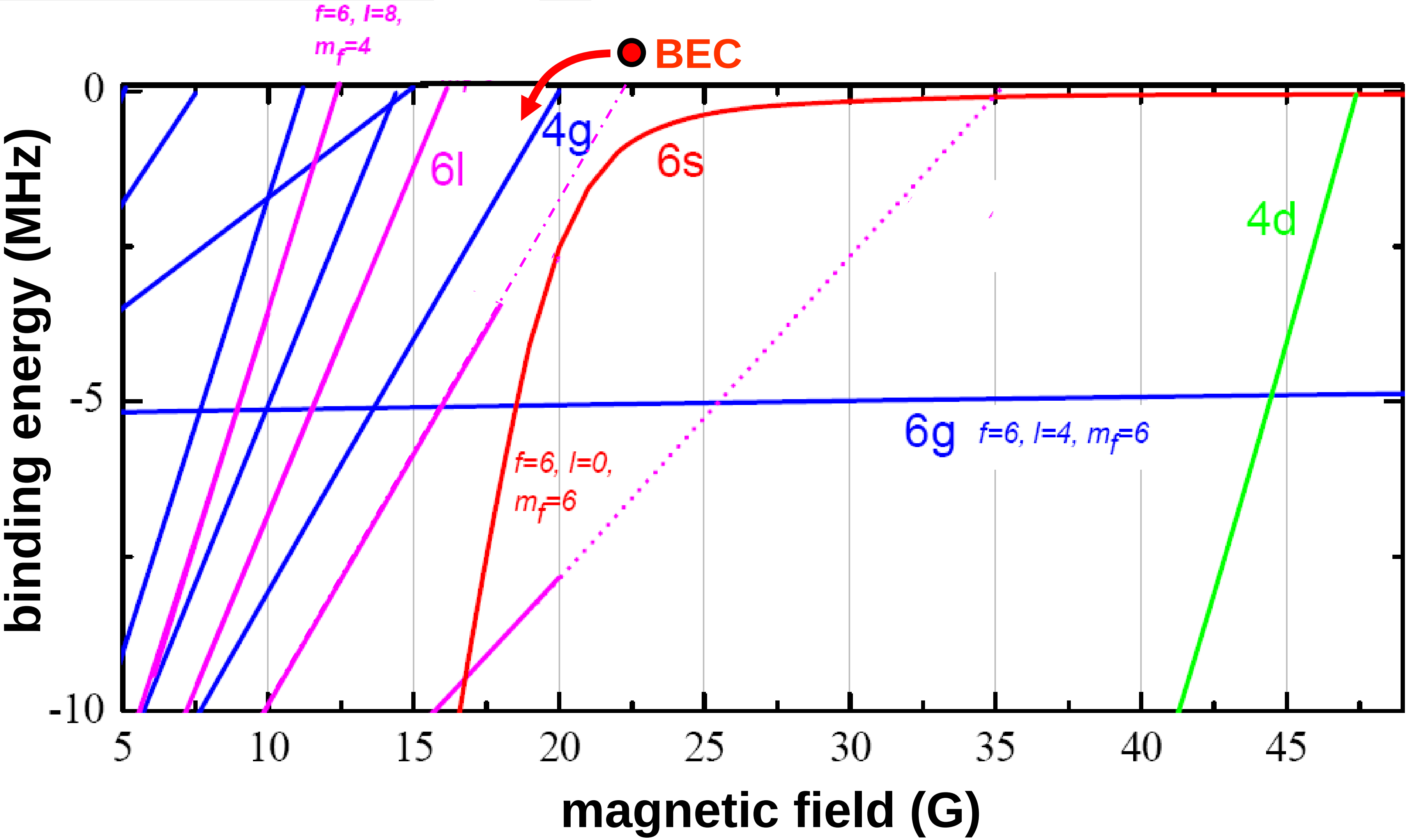


$a/a_0 = -879\ (15) + 0.19\ (5)\ T/\mathrm{nK}$

Efimov states: connection to atom-dimer scattering

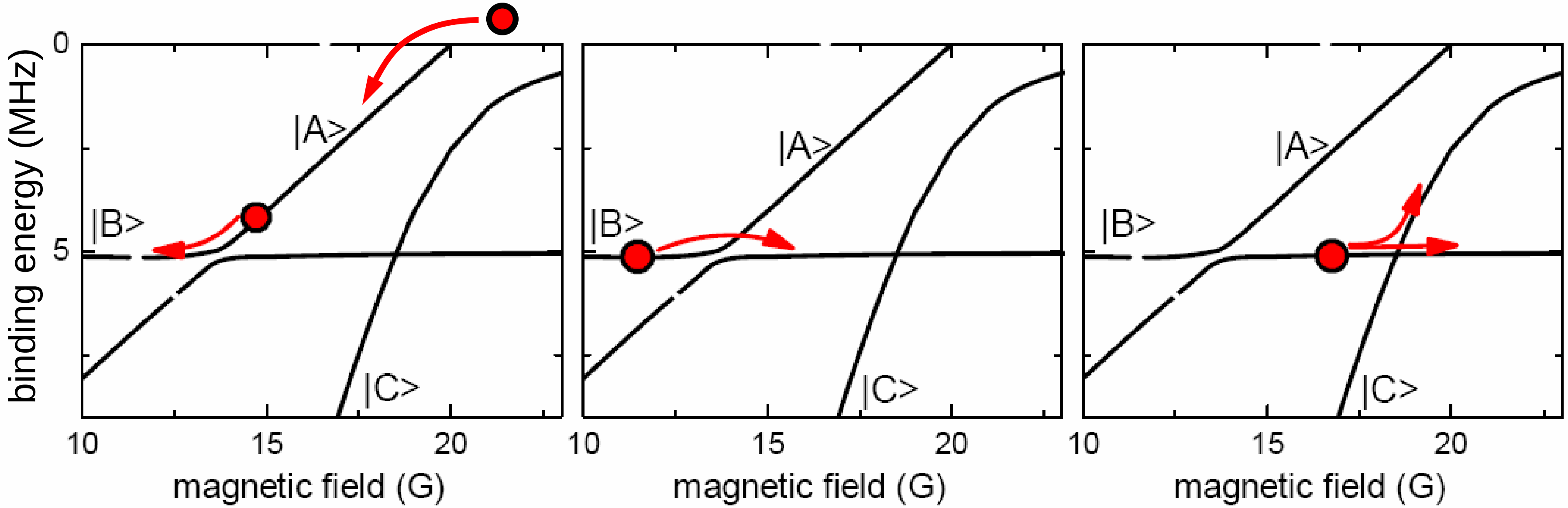


State preparation for Cs_2



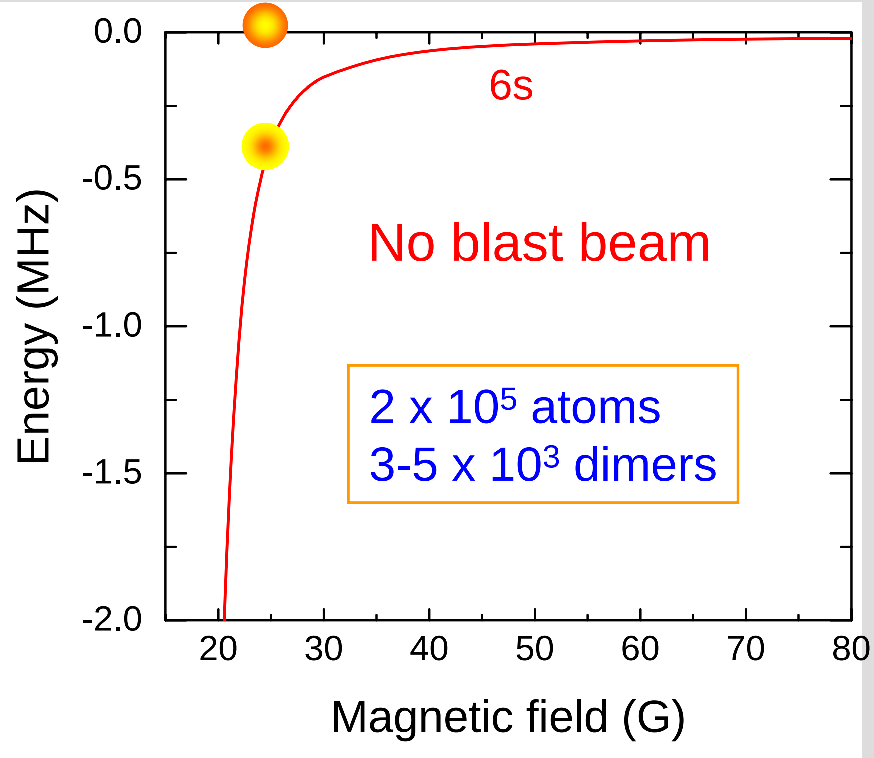
P. Julienne, E. Tiesinga

State preparation for Cs_2

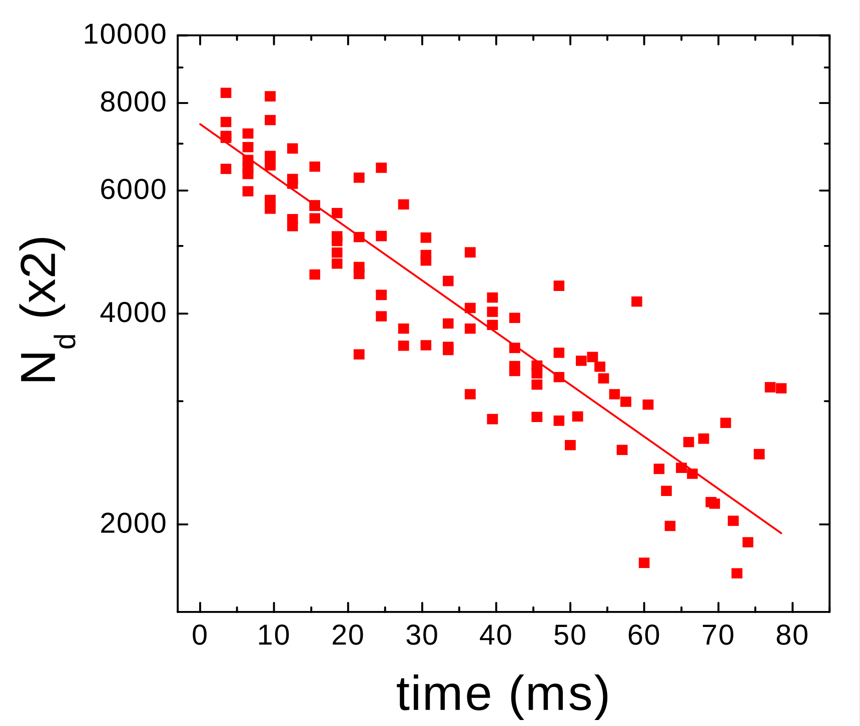


10% efficiency for molecule production,
nearly 100% efficiency for molecule transfer

Atom-dimer mixture



2 x 10^5 atoms
3-5 x 10^3 dimers

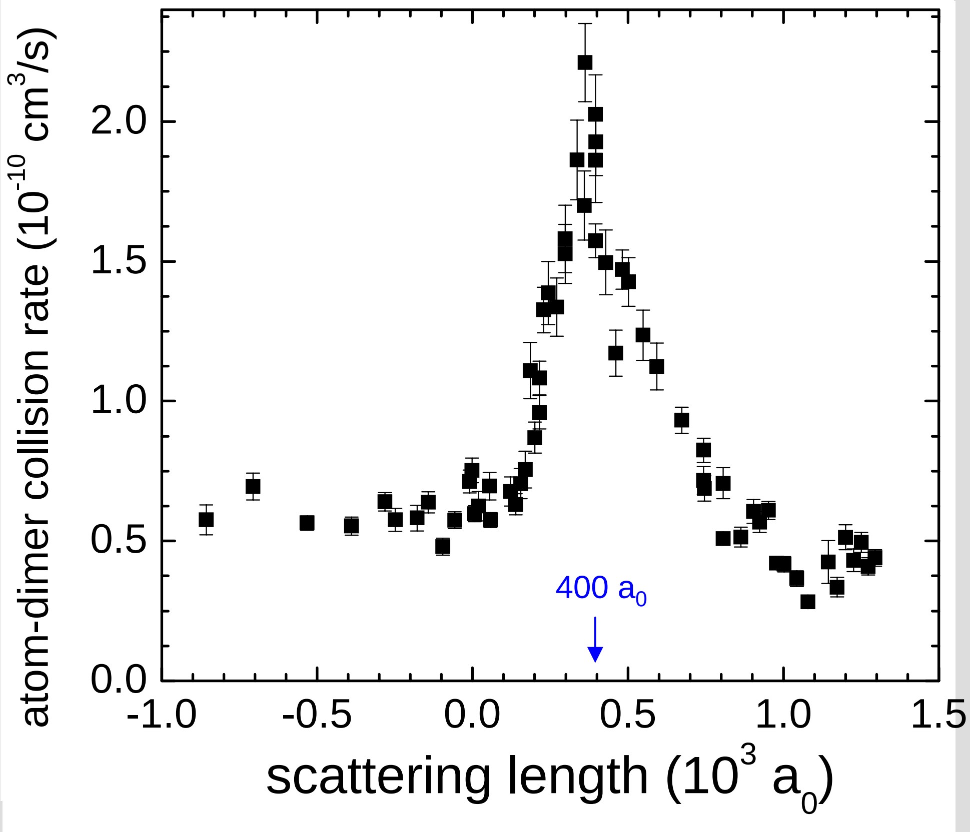


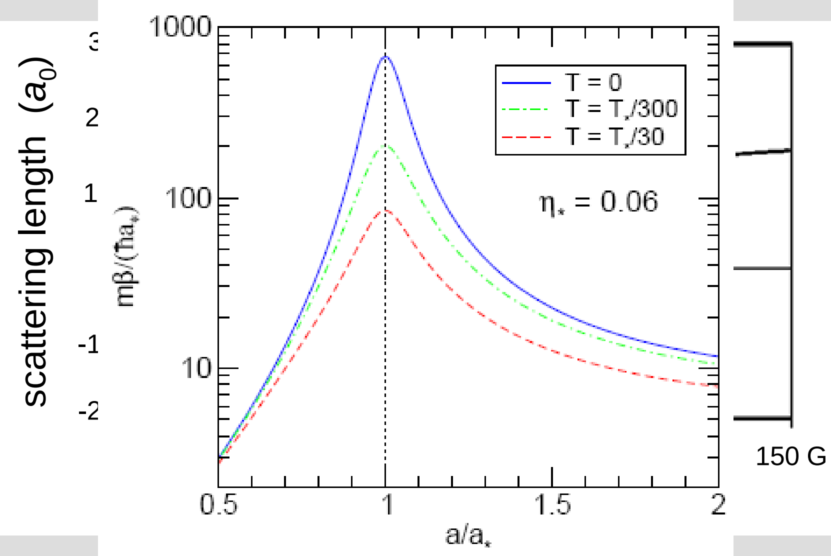
$$\boxed{\dot{n}_D = -R n_A n_D}$$

$n_{A(D)}$: atom(dimer) density
R: atom-dimer collisional loss rate ⟶ Dependence on scattering length ?

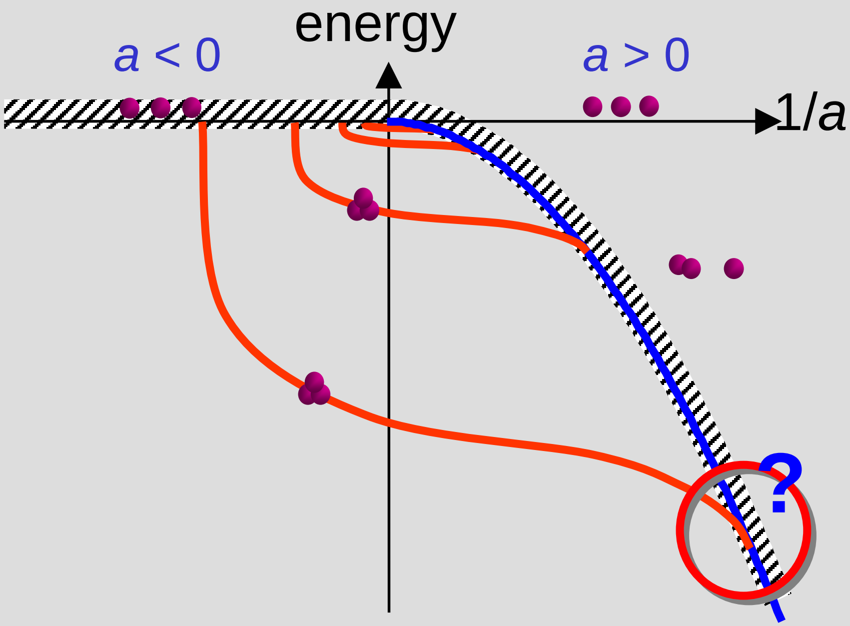
Na-Na$_2$: Mukaiyama et. al., PRL 2004, ^{87}Rb-^{87}Rb$_2$: Syassen et. al., PRA 2006

Atom-dimer inelastic collision rate





Braaten & Hammer, cond-mat/0610116



- Resonant enhancement !!!
- Coupling to a trimer state ?
- Efimov physics ?
- Universal regime ?
  - $a \gg r_0$
  - Cs: r_0 ~100 a_0
- Temperature dependence

Optical lattices

VOLUME 81, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1998

Cold Bosonic Atoms in Optical Lattices

D. Jaksch,[1,2] C. Bruder,[1,3] J. I. Cirac,[1,2] C. W. Gardiner,[1,4] and P. Zoller[1,2]
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[2]*Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
[3]*Institut für Theoretische Festkörperphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[4]*School of Chemical and Physical Sciences, Victoria University, Wellington, New Zealand*
(Received 26 May 1998)

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

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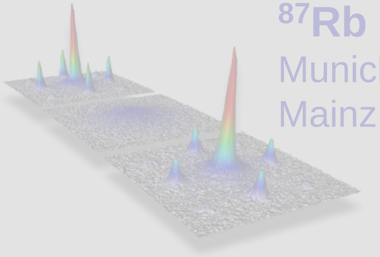
† *Quantenelektronik, ETH Zürich, 8093 Zurich, Switzerland*

Nature. **415** 39 (2002)



^{87}**Rb**
Munich
Mainz

^{23}**Na** (MIT)

PHYSICAL REVIEW A **72**, 043604 (2005)

Sodium Bose-Einstein condensates in an optical lattice

K. Xu,* Y. Liu, J. R. Abo-Shaeer, T. Mukaiyama, J. K. Chin, D. E. Miller, and W. Ketterle†
Department of Physics, MIT–Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, MIT, Cambridge, Massachu… USA

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Department of Physics, Williams Colle… ab Campus Dr… stown, Massachusetts 01267, USA

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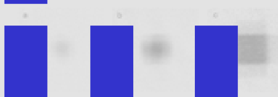
Atomic Physics Division, National Institute of Stand… Technology, 100 Bureau Drive, …24, Gait… Mar… 0899, USA

^{40}**Ka**
(ETH)

FERMIONIC ATOMS WITH TUNABLE INTERACTIONS IN A 3D OPTICAL LATTICE



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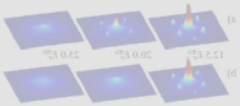
Cesium

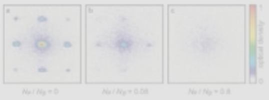
Mixture ^{87}**Rb** / ^{40}**Ka** (Hamburg, ETH, Mainz)

Localization of bosonic atoms by fermionic impurities in a 3d optical lattice

S. Ospelkaus, C. Ospelkaus, O. Wille, M. Succo, P. Ernst, K. Sengstock and K. Bongs
Institut für Laserphysik, Luruper Chaussee 149, 22761 Hamburg / Germany

Phys. Rev. Lett. **96,** 180403 (2006)





Bose-Fermi Mixtures in a Three-dimensional Optical Lattice

Kenneth Günter, Thilo Stöferle, Henning Moritz, Michael Köhl*, Tilman Esslinger
Institute of Quantum Electronics, ETH Zürich, CH–8093 Zürich, Switzerland
(Dated: May 17, 2006)

Phys. Rev. Lett. **96,** 180402 (2006)

Molecules ^{87}**Rb** (Munich, Innsbruck)

Repulsively bound atom pairs in an optical lattice

K. Winkler, G. Thalhammer, F. Lang, R. Grimm[1], and J. Hecker Denschlag
Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria and
[1] *Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria*

A. J. Daley, A. Kantian, H. P. Büchler, and P. Zoller
Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria and
Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria
(Dated: 8 May 2006)

Nature 441, **854** (2006)

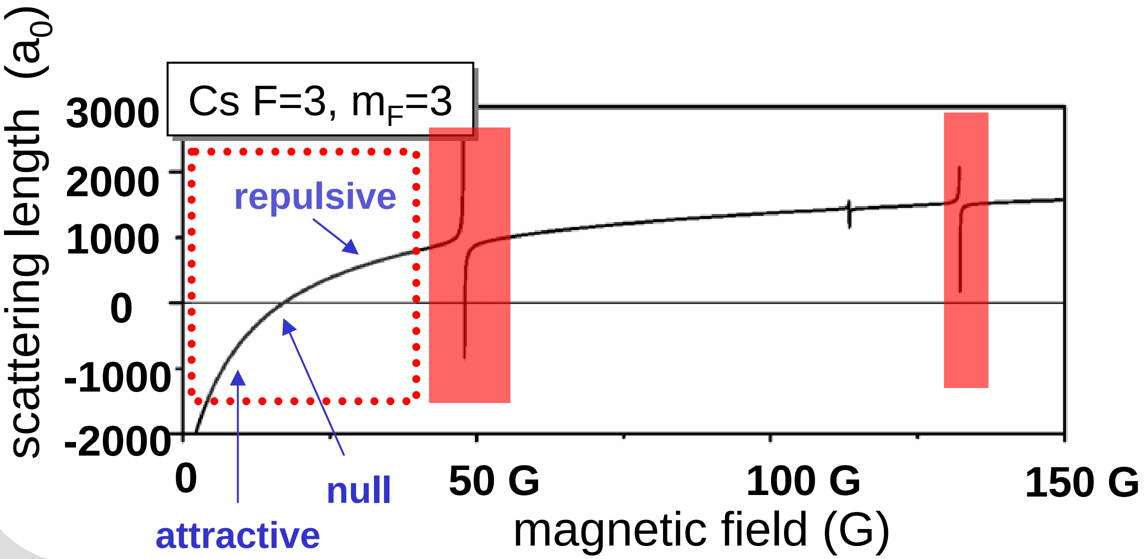
A Mott state of molecules

T. Volz, N. Syassen, D. M. Bauer, E. Hansis, S. Dürr, and G. Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

cond-mat/0612148

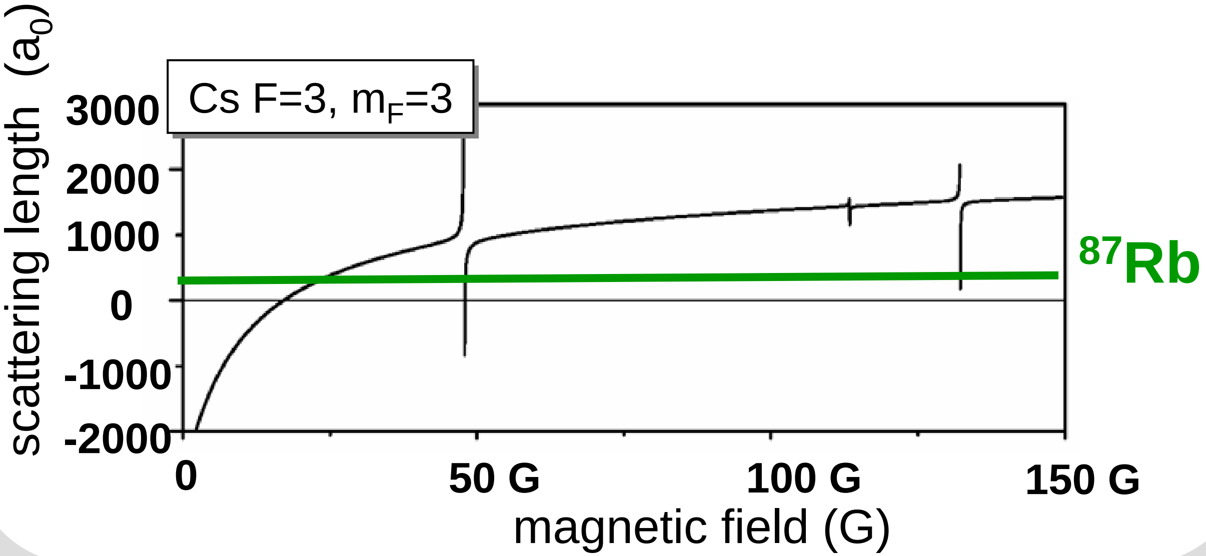
Tunability

Feshbach resonances:



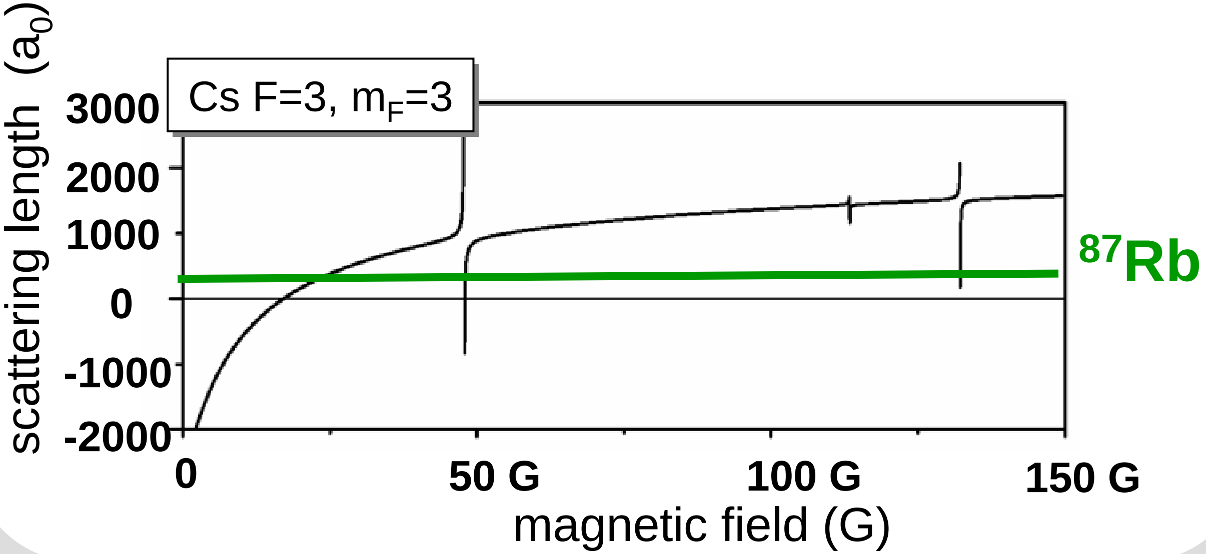
Tunability

Feshbach resonances:

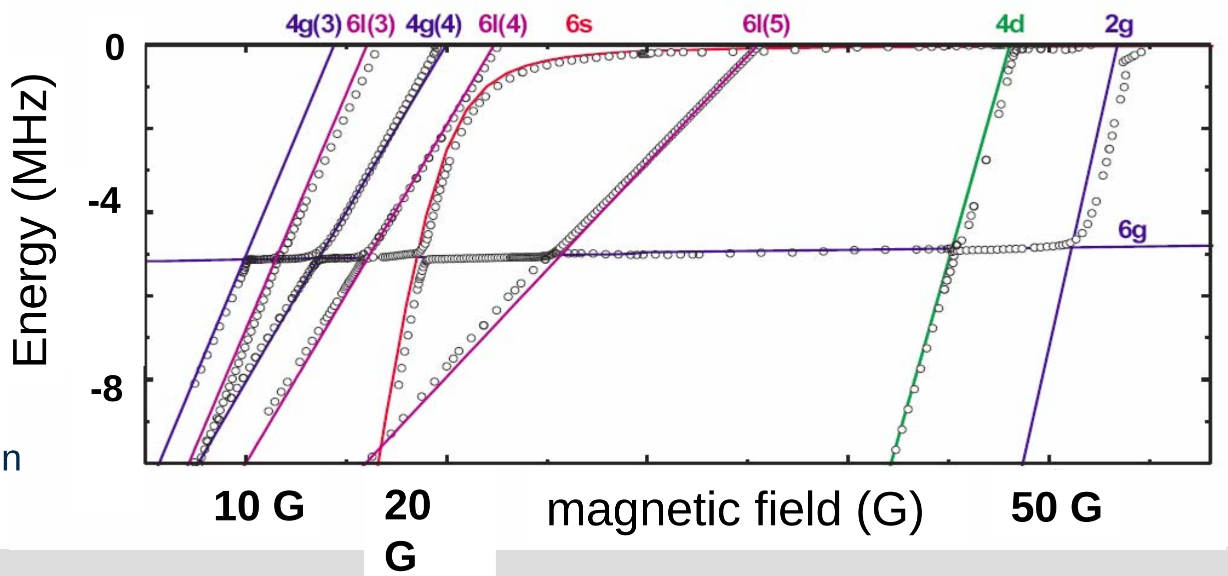


Tunability and abundance of molecular states

Feshbach resonances:

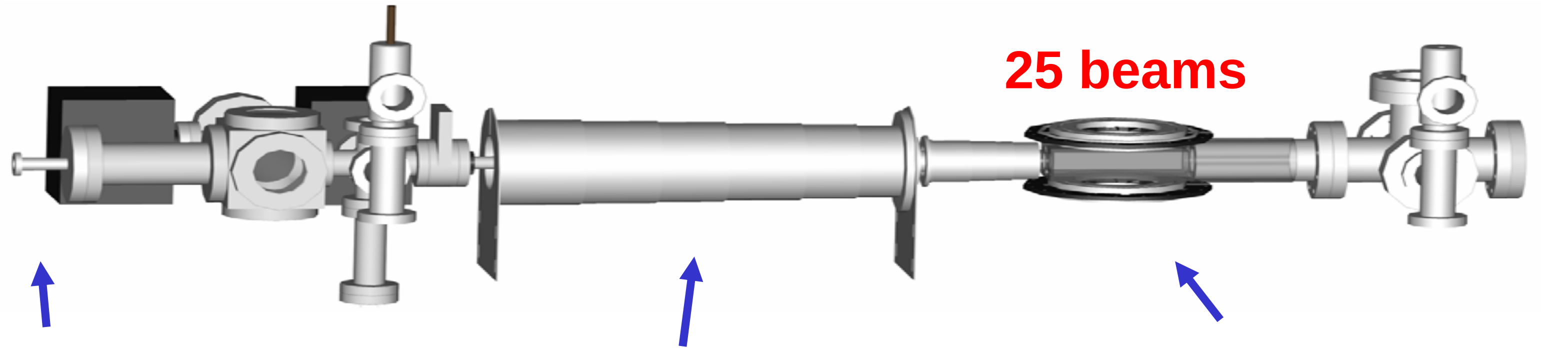


Feshbach molecules:



M. Mark et al., in preparation

Experimental setup



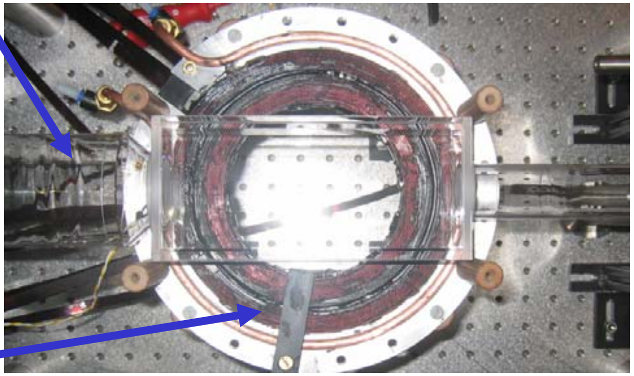
25 beams

oven section

Zeeman slower

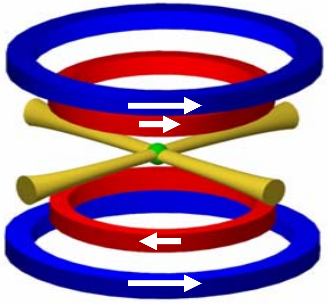
glass cell & coils

glass cell



gradient+offset

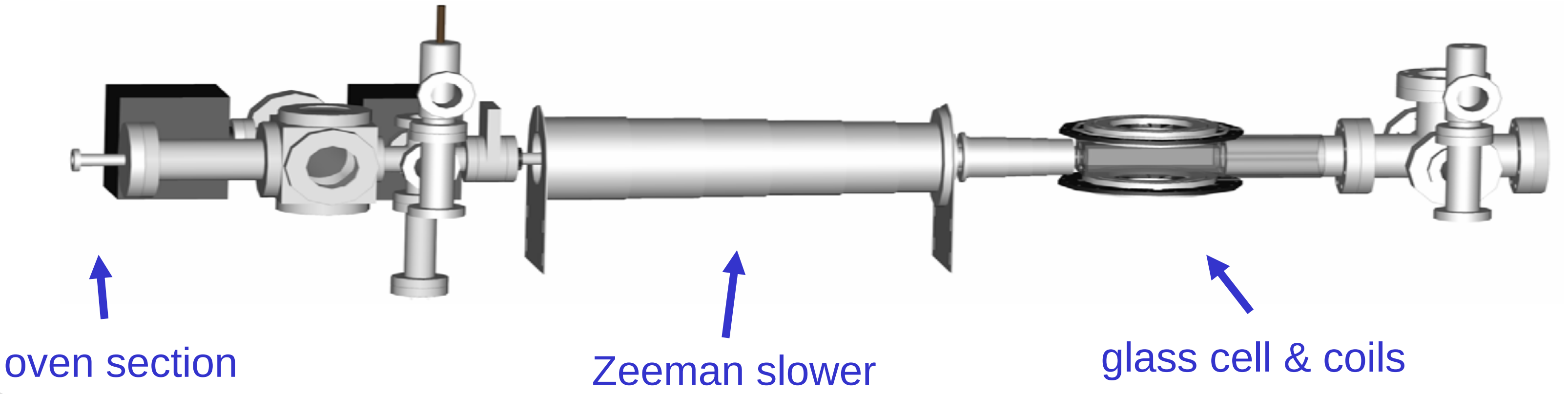
coils



offset field **gradient field**

dipole trap **atoms**

Experimental setup

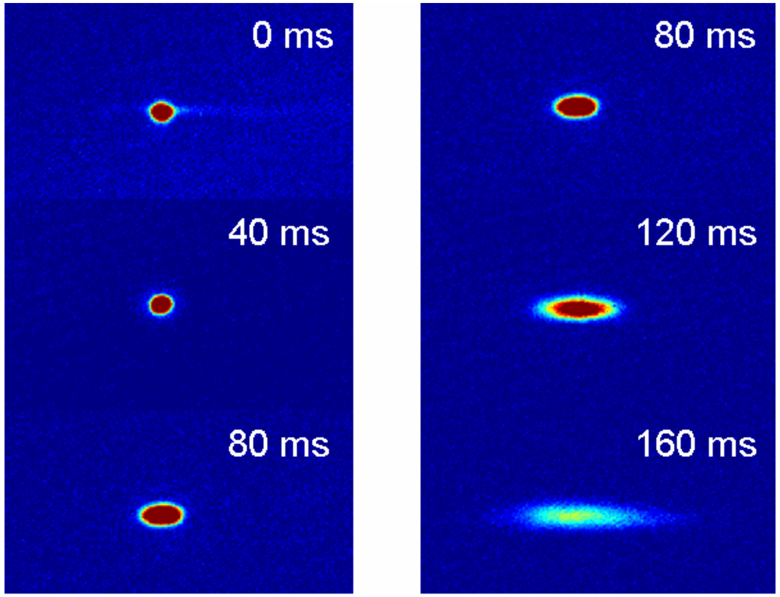


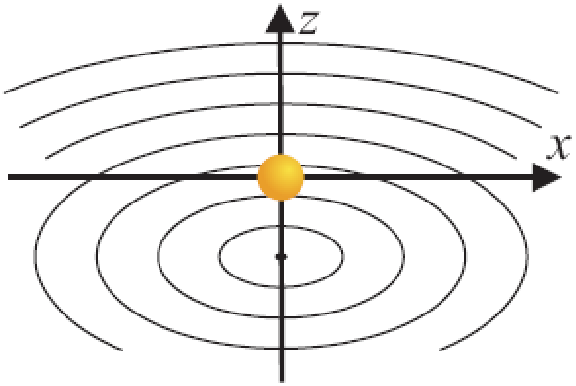
BEC:

levitated

expansion

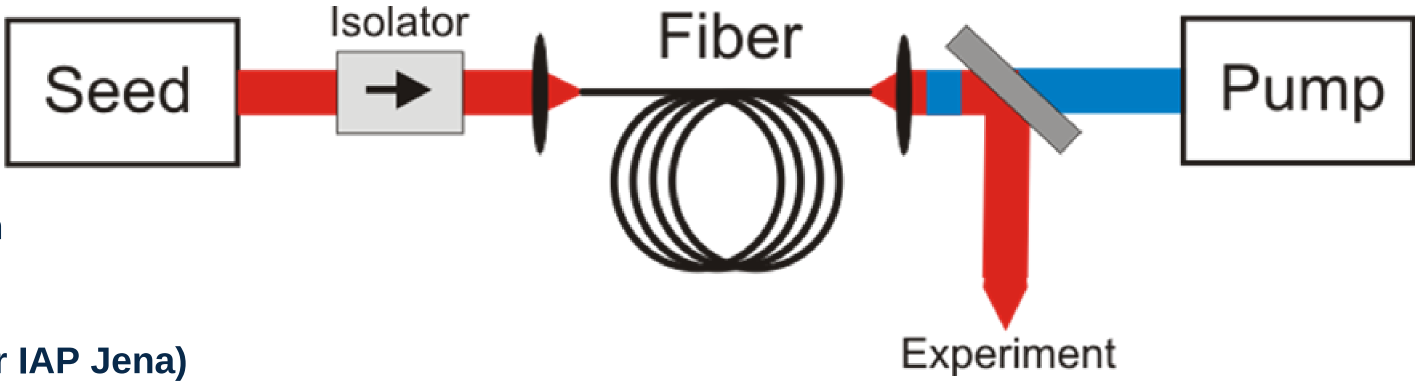
at 10 a_0





Optical lattice

fiber amplifier

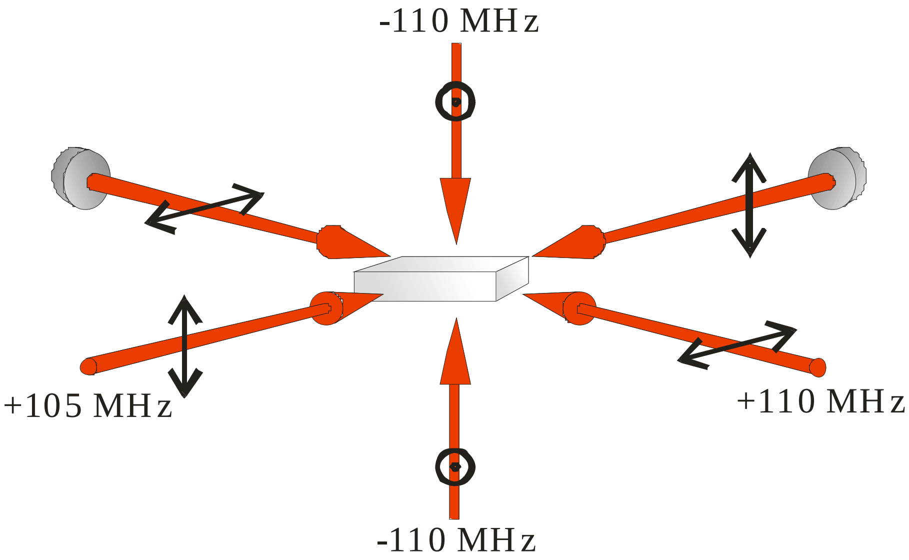


P<20W @ 1064nm

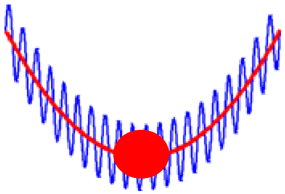
1 kHz linewidth

(design H.Zellmer IAP Jena)

beams



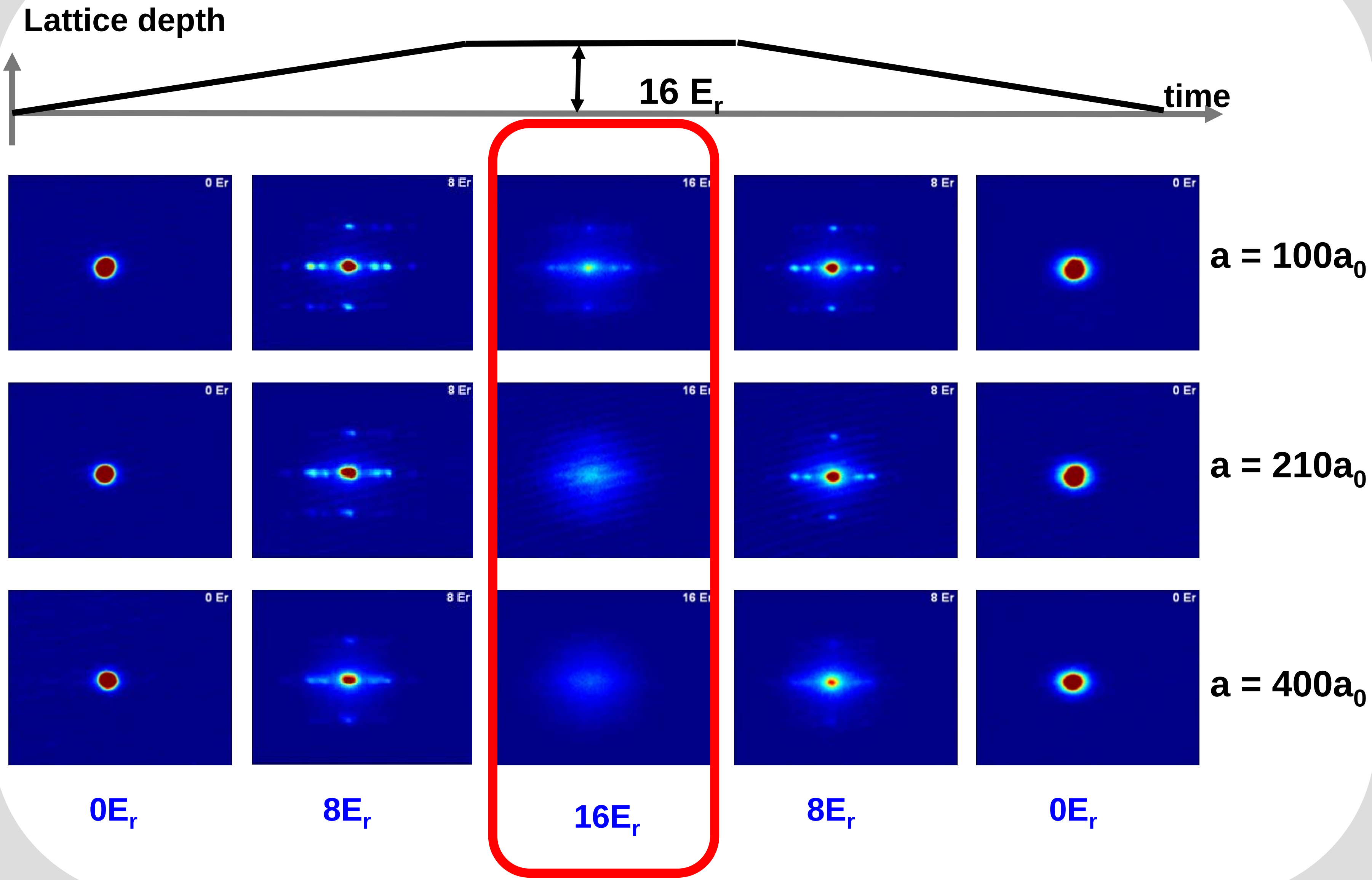
waist 500µm



external confining potential

not modified due to lattice

Mott-insulator transition: ramping the lattice depth



Lattice depth

$16\ E_r$

time

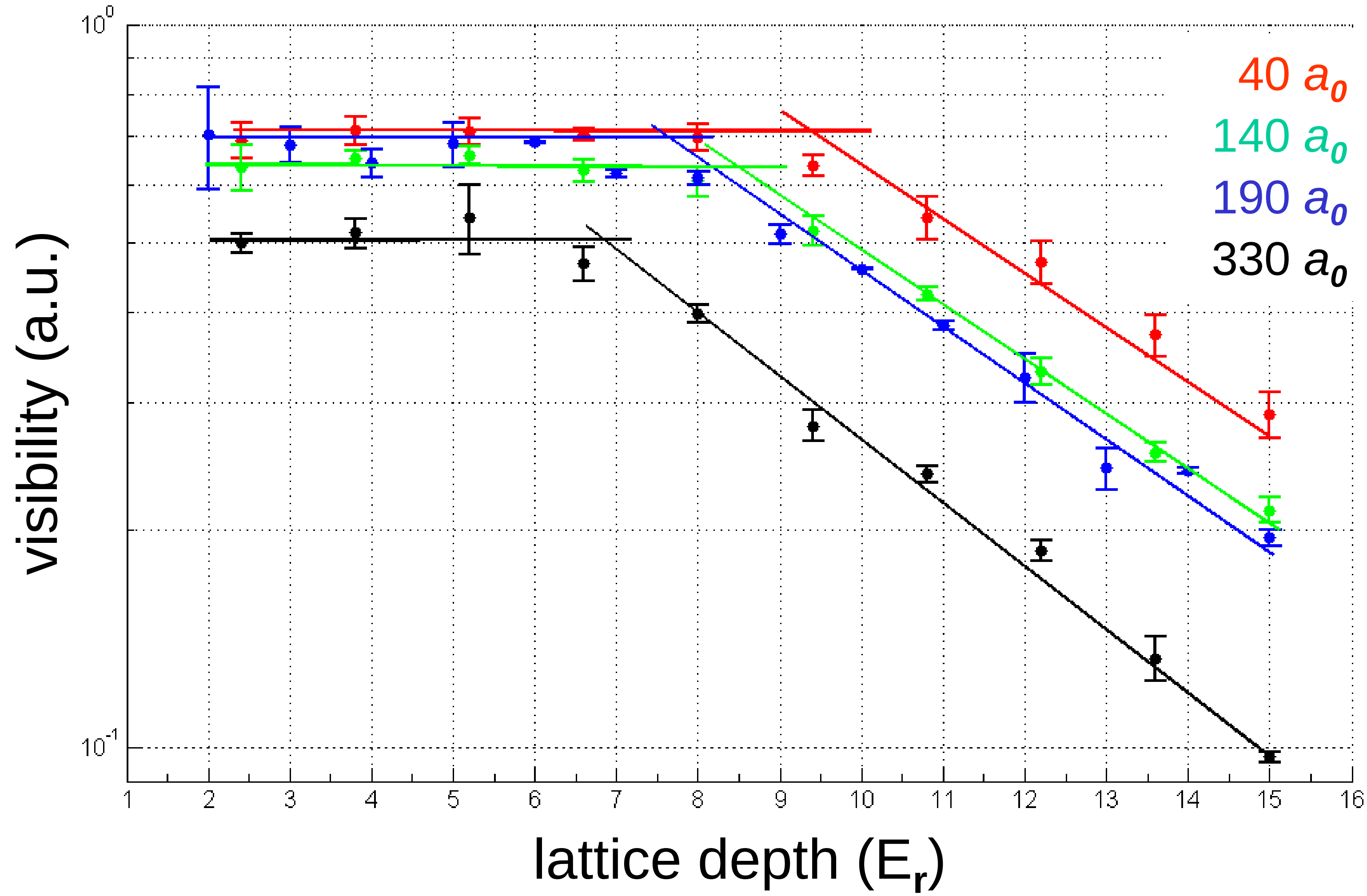
$a = 100a_0$

$a = 210a_0$

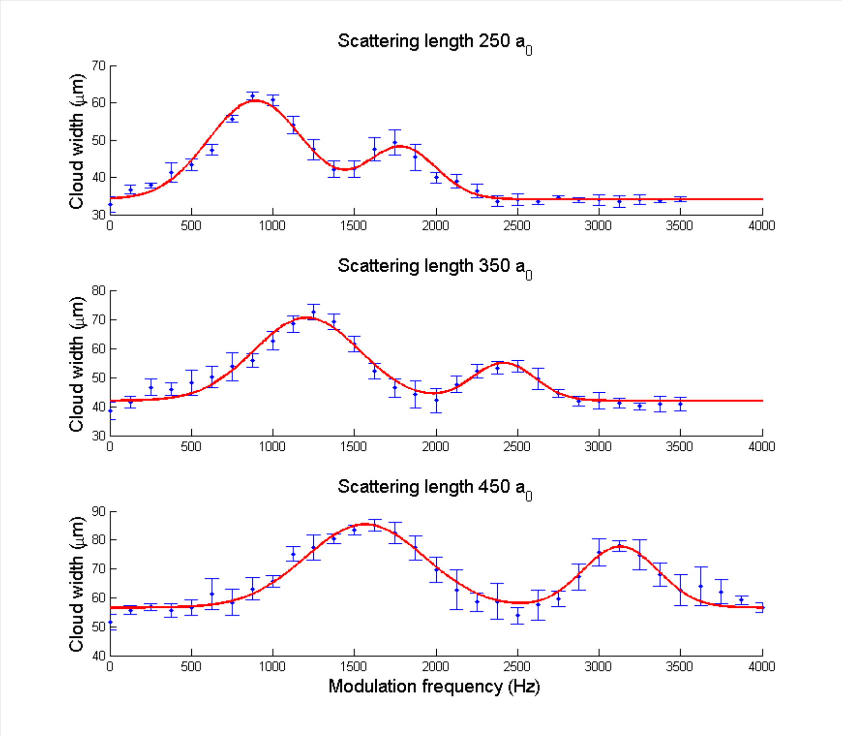
$a = 400a_0$

$0E_r$ $8E_r$ $16E_r$ $8E_r$ $0E_r$

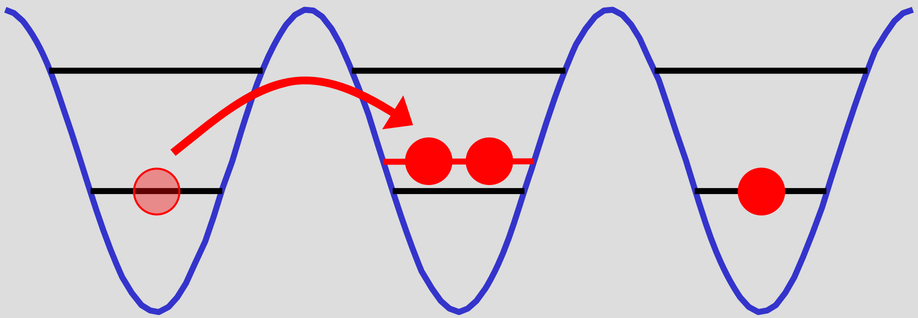
Mott-insulator transition: ramping the lattice depth



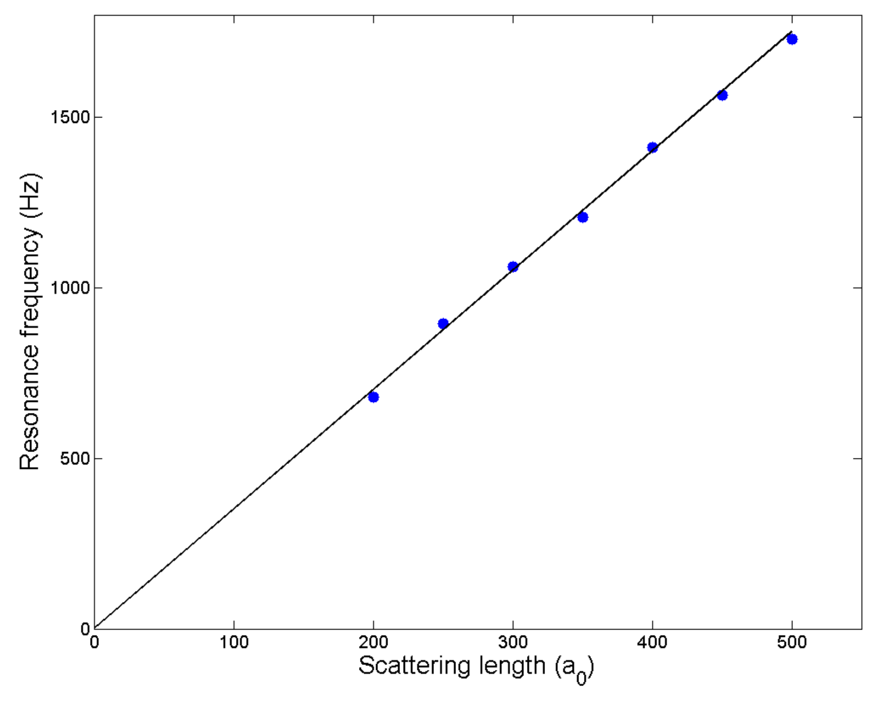
Excitation spectrum



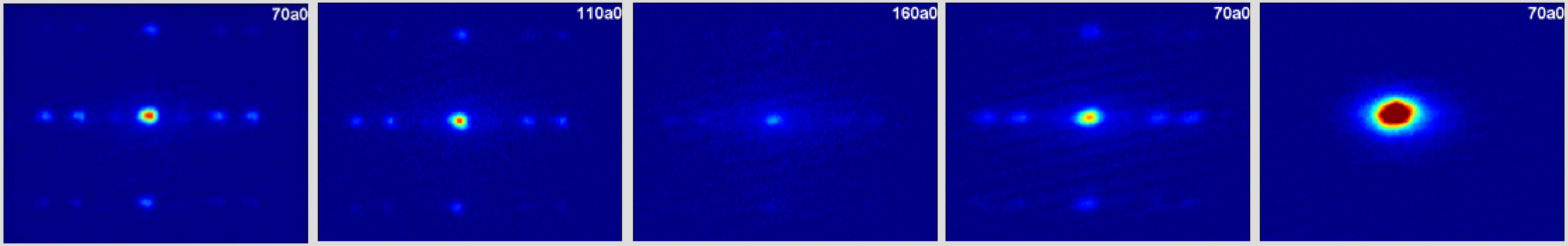
lattice depth 13 E_r



lattice depth modulation

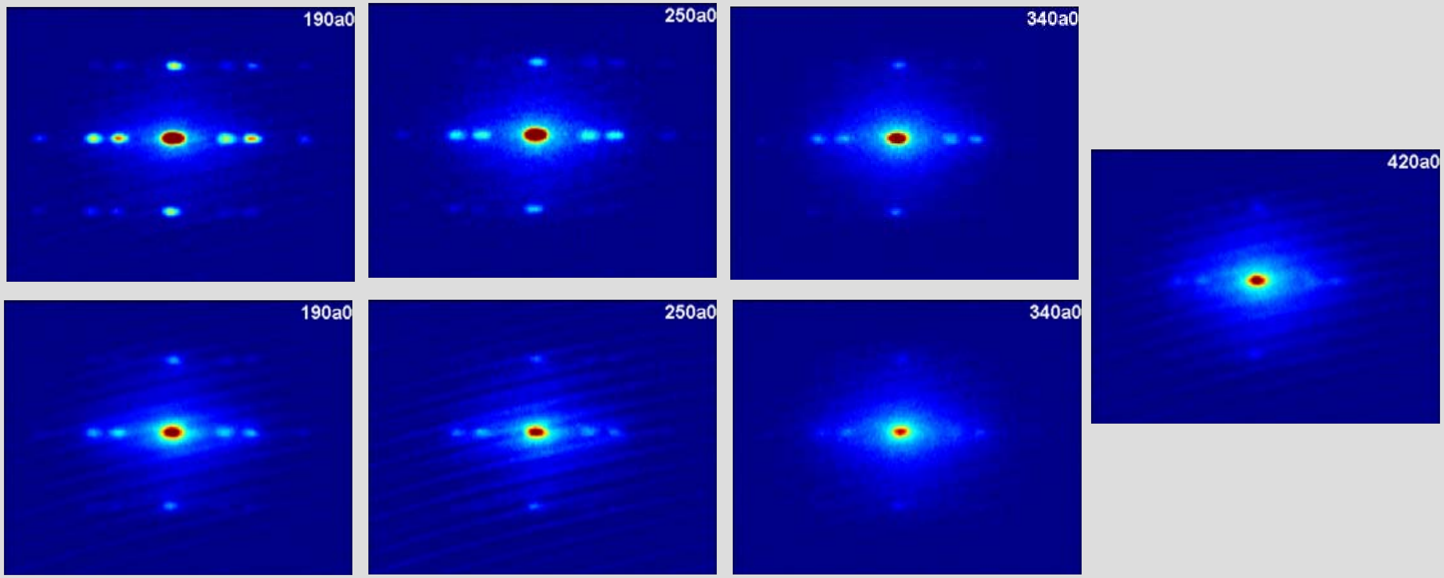


Mott-insulator transition: ramping the interactions



70 a_0 110 a_0 160 a_0 70 a_0 no lattice70 a_0

larger scattering lengths: requires jump across a narrow Feshbach resonance



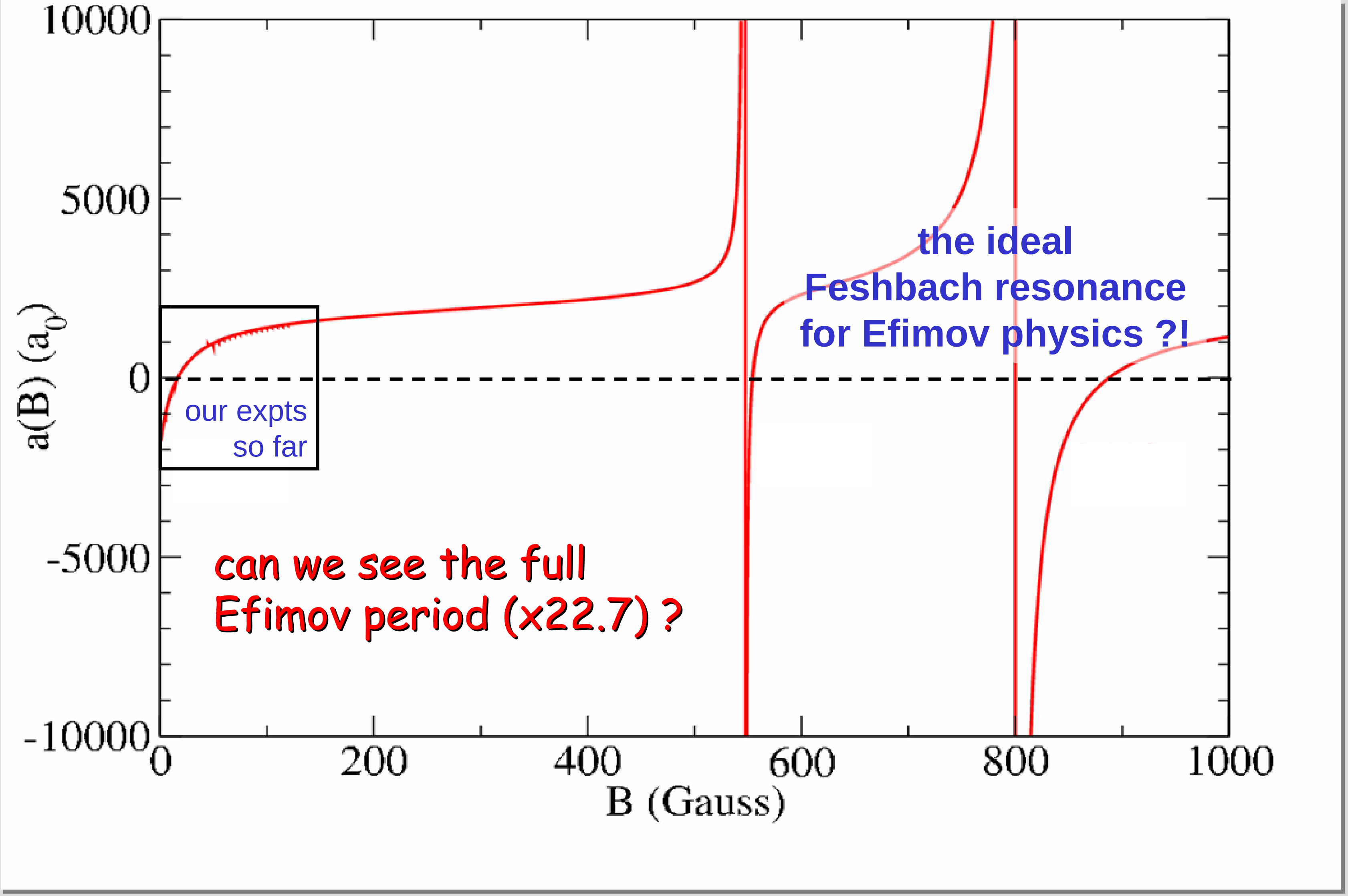
190 a_0 250 a_0 340 a_0 420 a_0

for larger scattering lengths: we do not recover interference. Heating?

outlook

Outlook 1

taking full advantage of Cs tunability



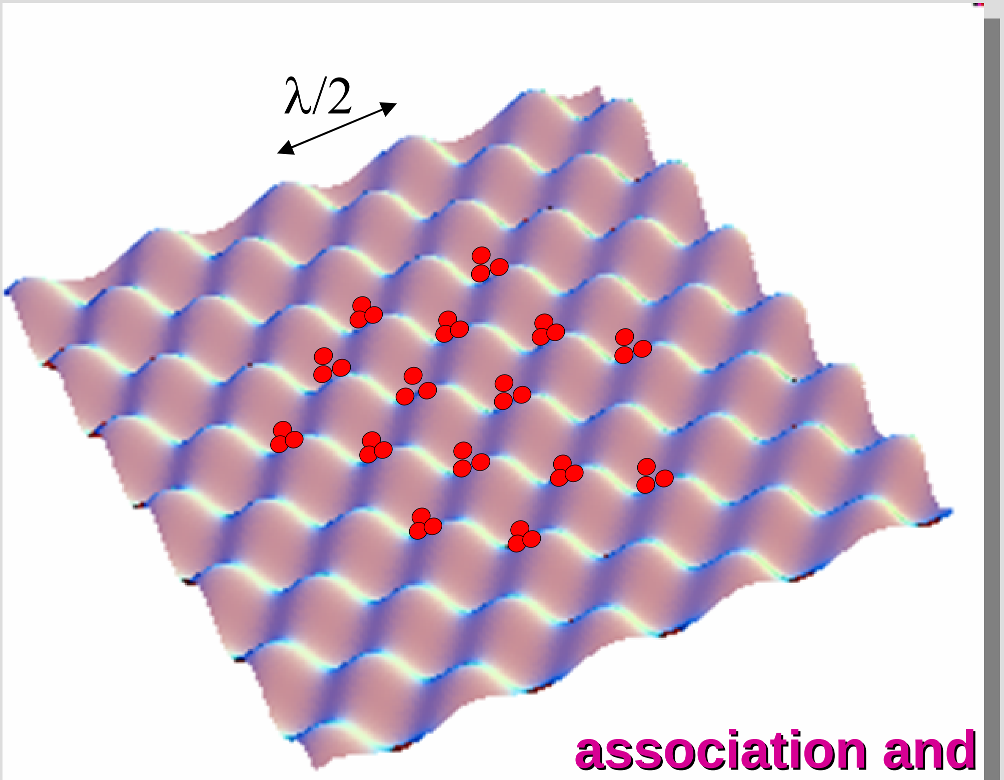
our expts
so far

the ideal
Feshbach resonance
for Efimov physics ?!

can we see the full
Efimov period (x22.7) ?

Outlook 2

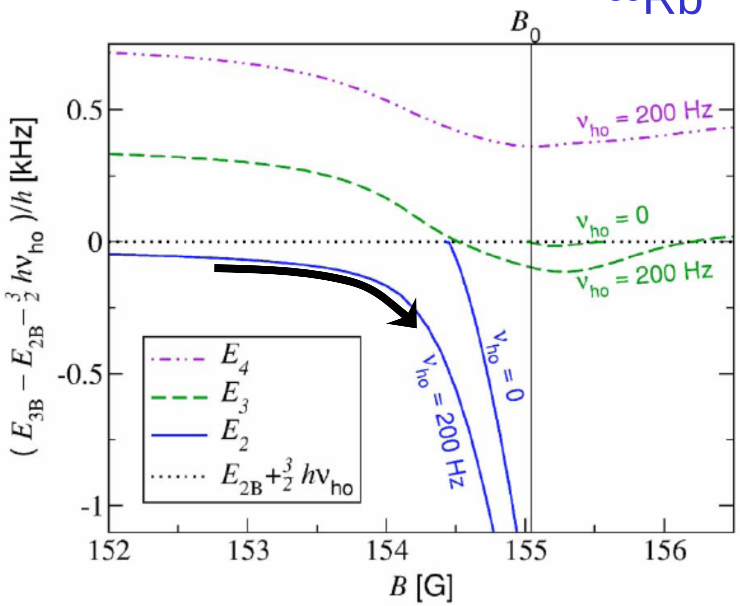
Few-body physics & Efimov states in an optical lattice



association and detection of Efimov trimers

making Efimov trimers in an optical lattice

^{85}Rb



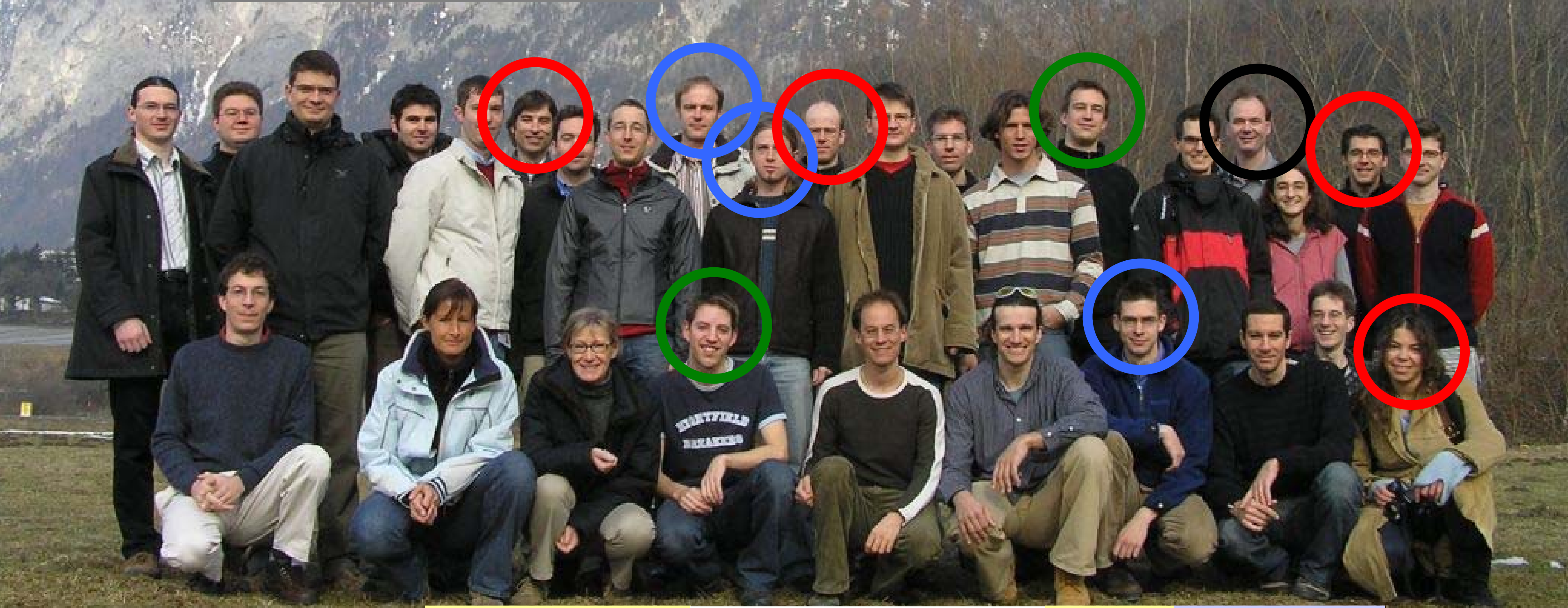
Stoll & Köhler, PRA **71**, 022714 (2005)

ultracold.atoms Innsbruck

3 Cs teams

- Cs BEC & ultracold molecules: T. Kraemer, M. Mark, J. Danzl, H. Schöbel, S. Knoop, F. Ferlaino, HCN, R. Grimm
- Rb-Cs mixtures: B. Engeser, K. Pilch, A. Lange, A. Prantner, HCN, R. Grimm
- Cs in optical lattices: M. Gustavsson, E. Haller, G. Rojas-Kopeinig, M. Mark, HCN

the Cs coolers



funded by FWF Der Wissenschaftsfonds. and bm:bwk