JOŽEF STEFAN days, Ljubljana, 19 March 2012

ULTRAHLADNI ATOMI: MODELSKI SISTEMI ZA KVANTNE SNOVI

Ultracold atoms: Model kits for quantum matter

Rudolf Grimm

"Center for Quantum Physics" in Innsbruck

University of Innsbruck

Austrian Academy of Sciences

outline

**ultracold quantum gases:
introduction into the general ideas**

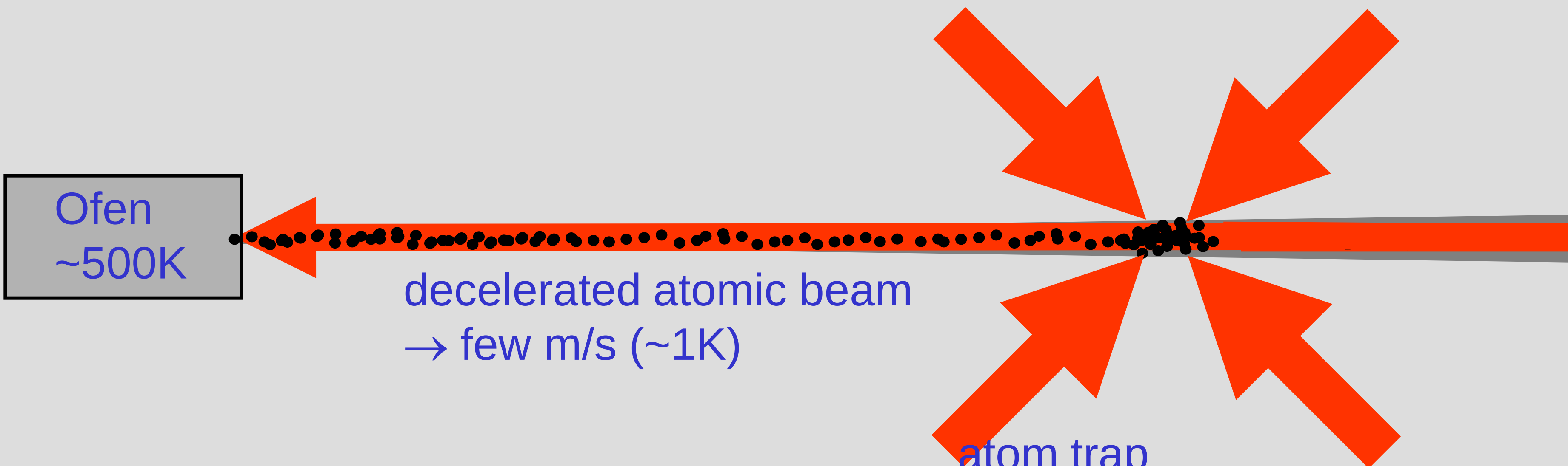
example #1: Efimov‘s mysterious quantum states

example #2: strongly interacting Fermi gases

ultracold quantum gases: the general ideas

laser cooling

important developments: mid 80‘s – early 90‘s



atom trap
accumulation and
further trapping

a billion atoms
at a millionth degree Kelvin

conservative atom traps

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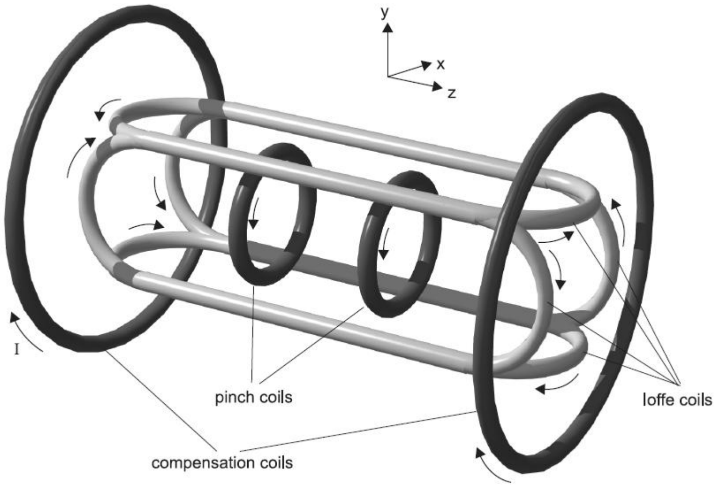
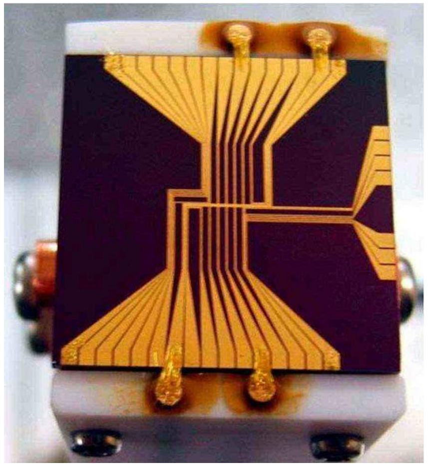
magnetic traps



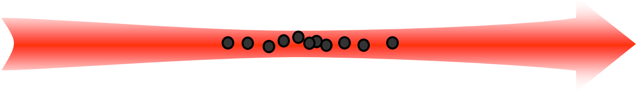
K. Dieckmann, PhD thesis, U Amsterdam, 2001

"atom chip"

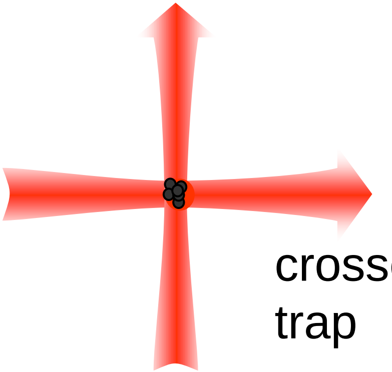
TU Vienna



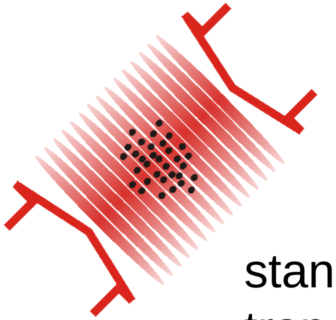
optical dipole traps



focused beam trap

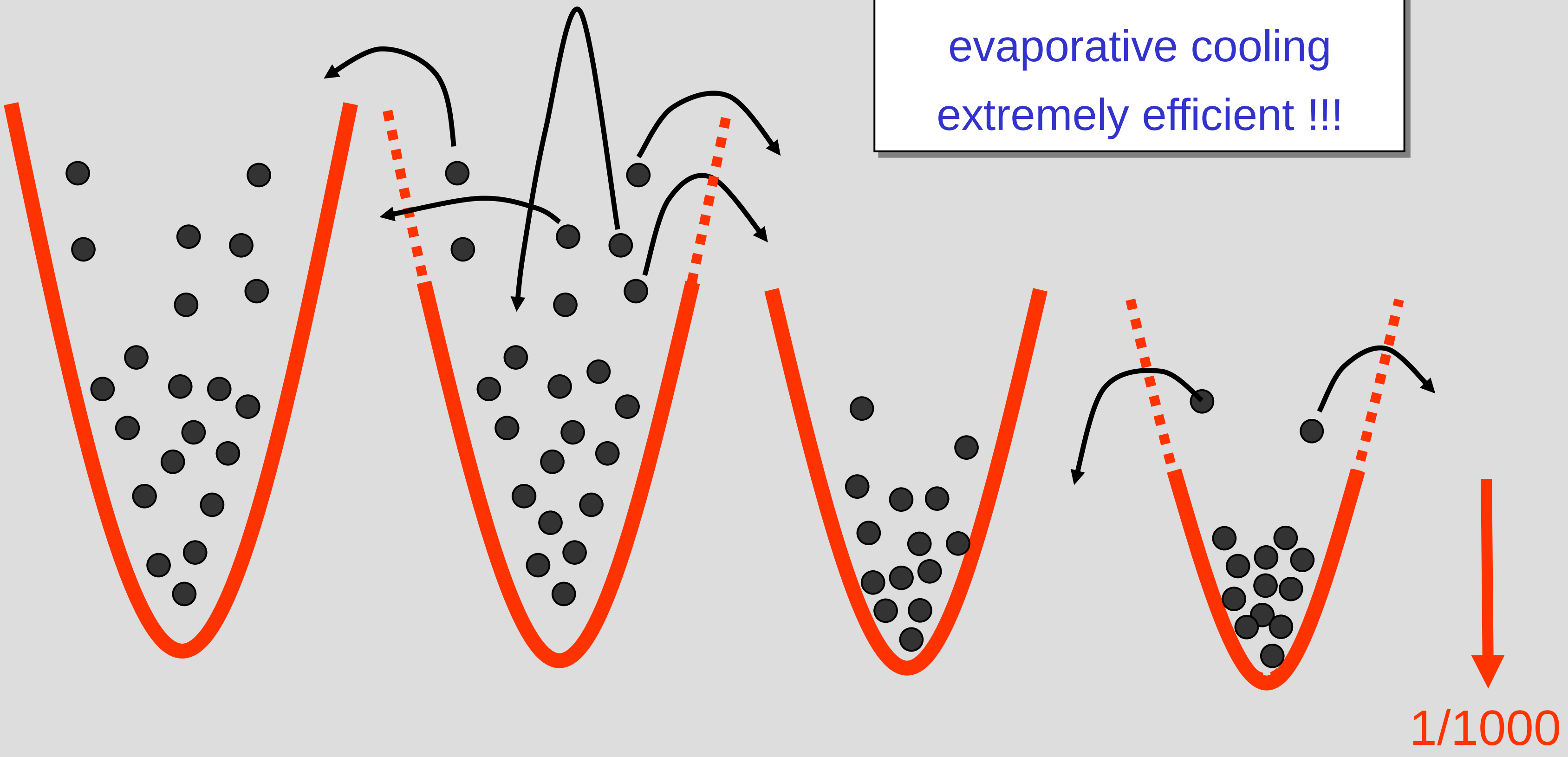


crossed-beam trap



standing-wave trap (1D lattice)

evaporative cooling: basic idea

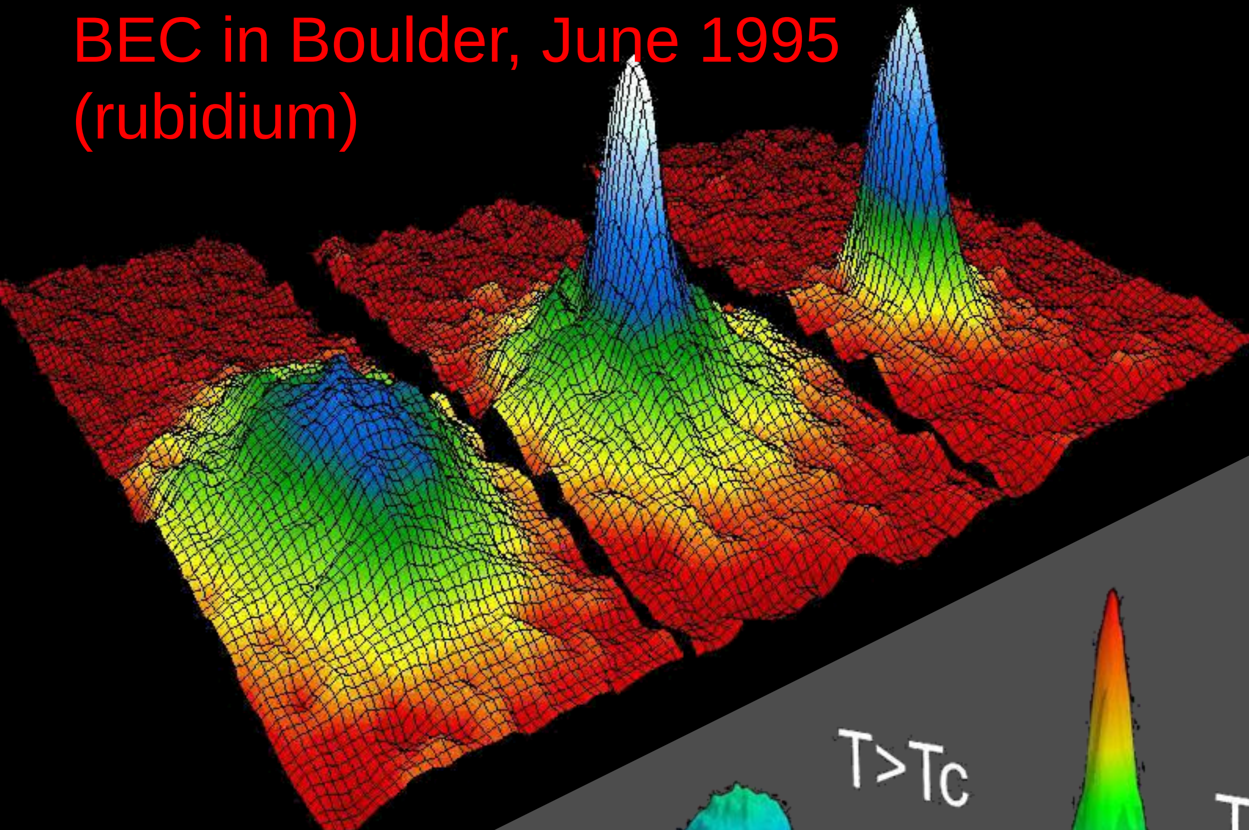


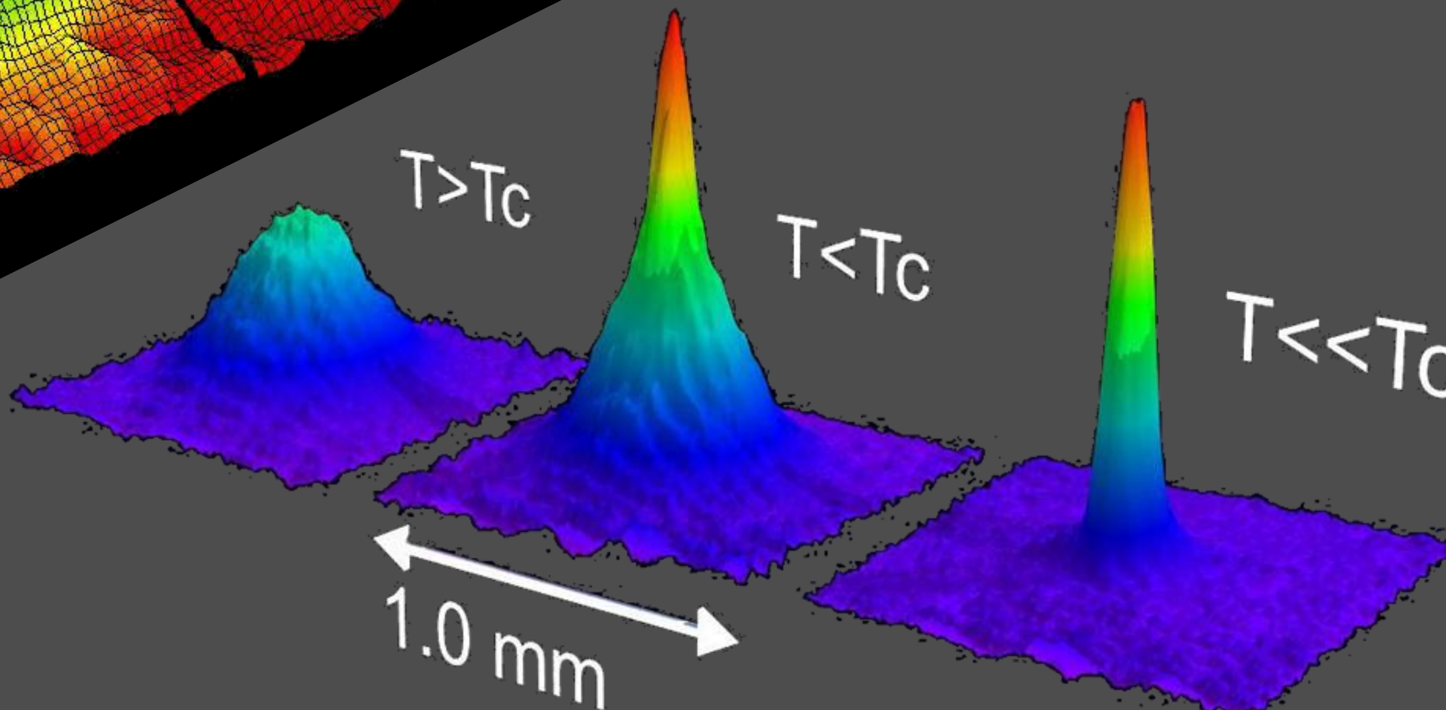
colder
and
denser

evaporative cooling
extremely efficient !!!

reduction of the potential barrier

BEC in Boulder, June 1995
(rubidium)





BEC at MIT, Nov. 1995 (sodium)

attainment of BEC <2000

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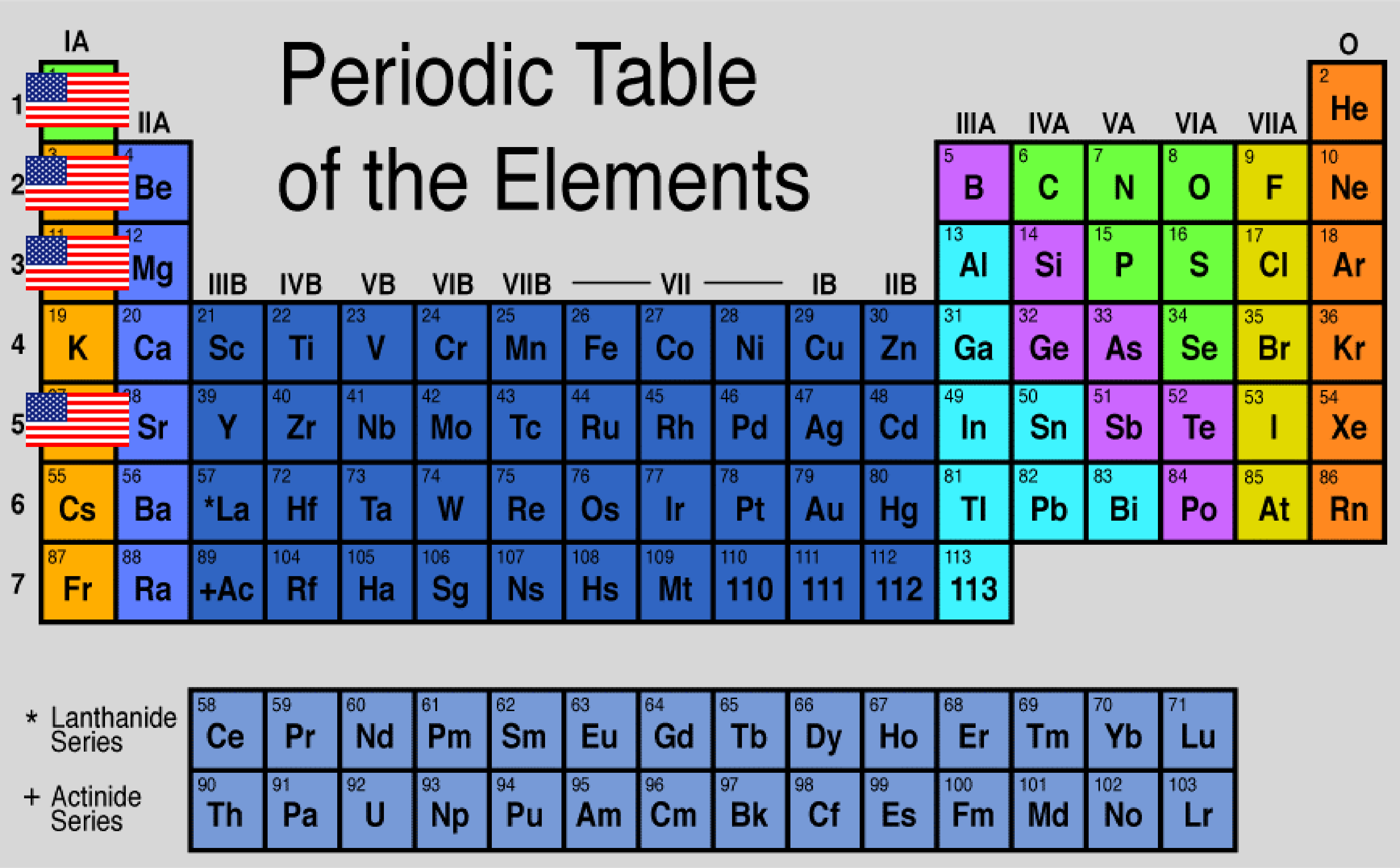
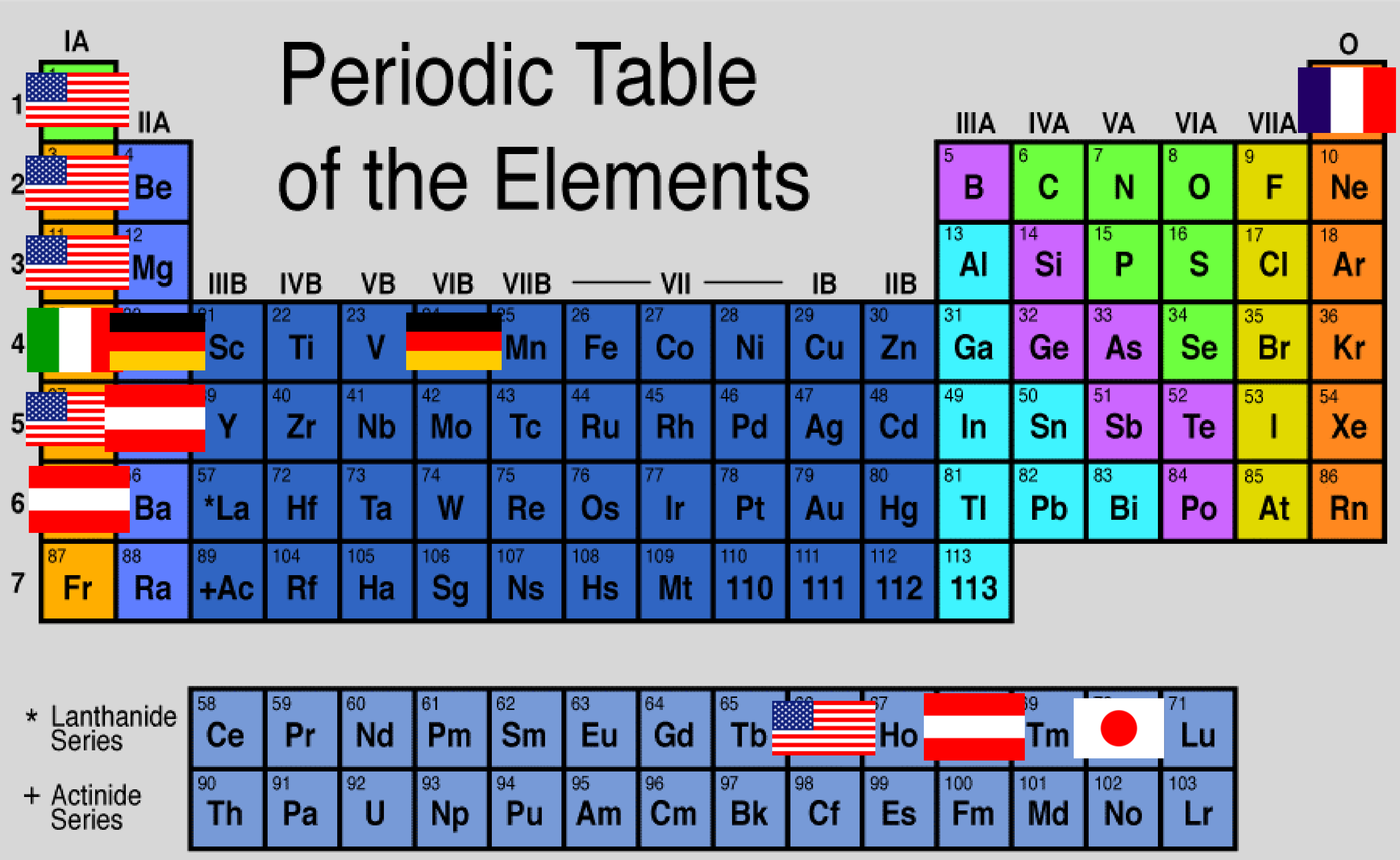
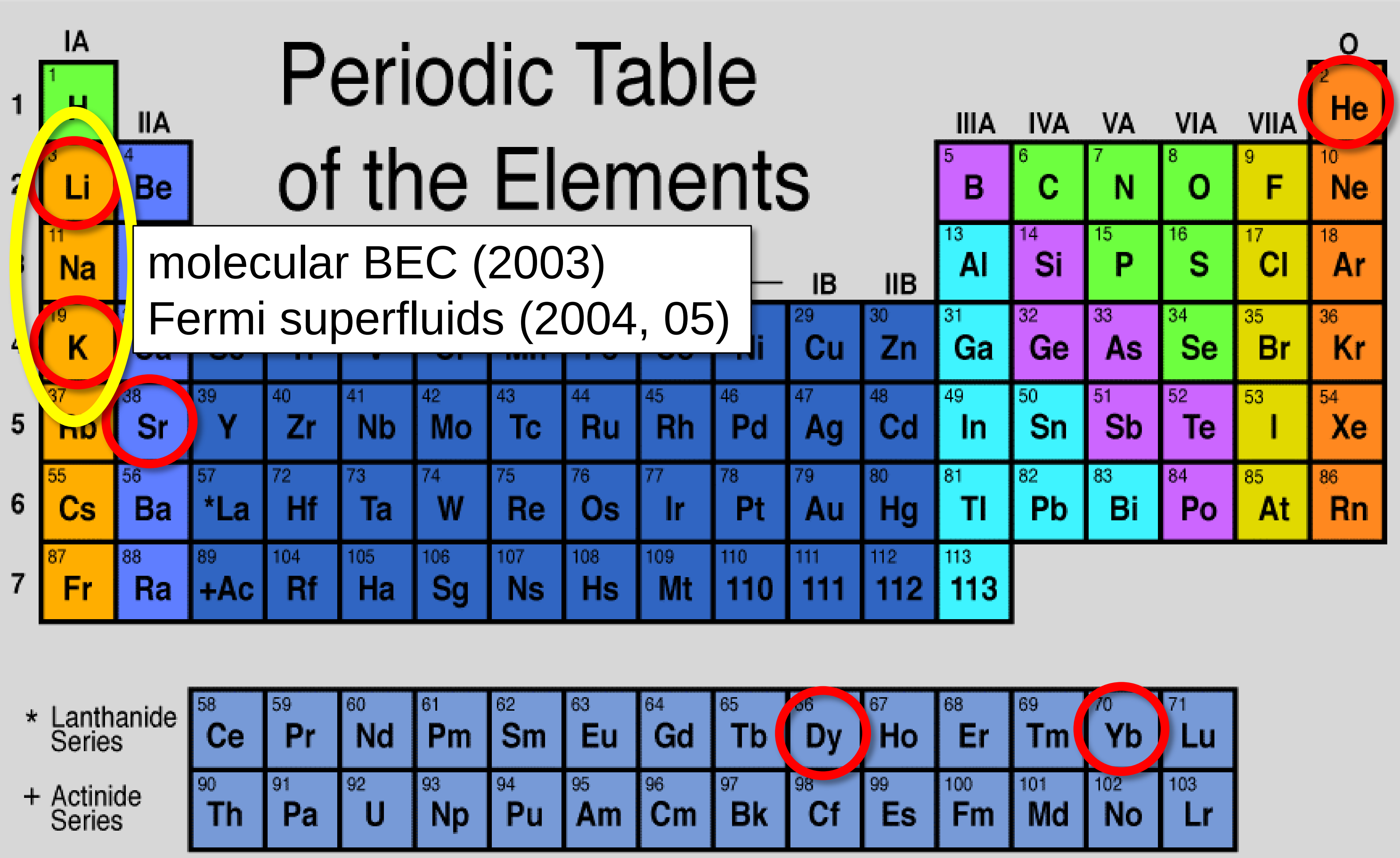


attainment of BEC

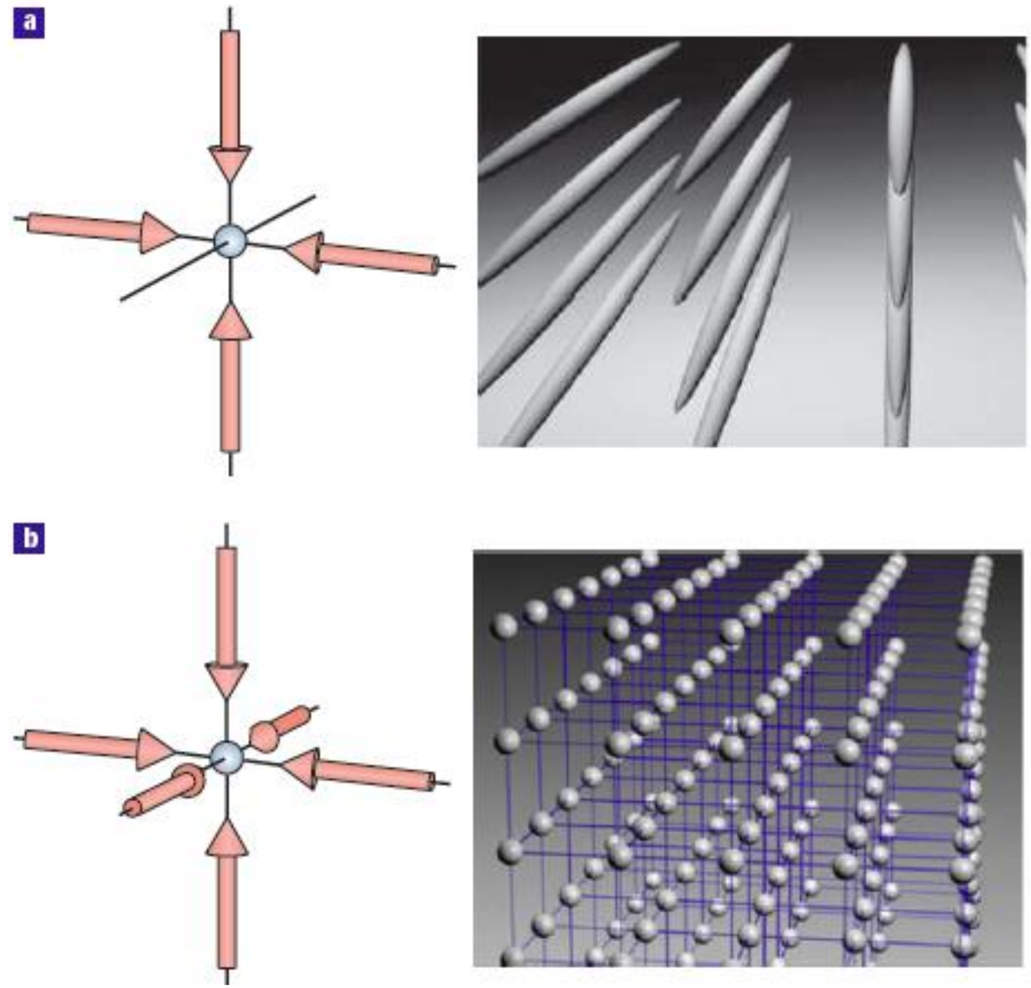


degenerate Fermi gases



molecular BEC (2003)
Fermi superfluids (2004, 05)

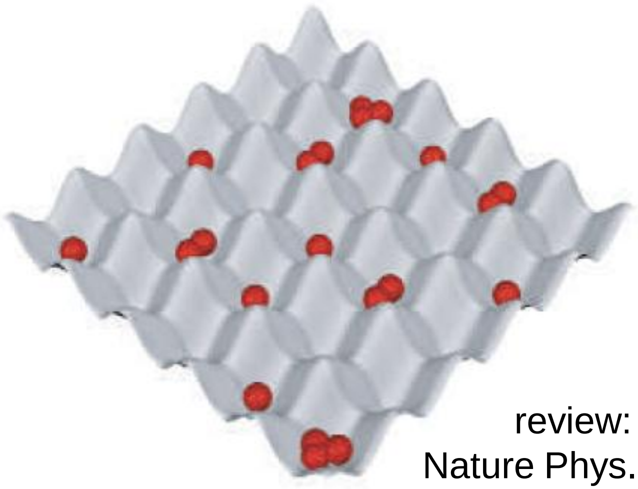
optical lattices

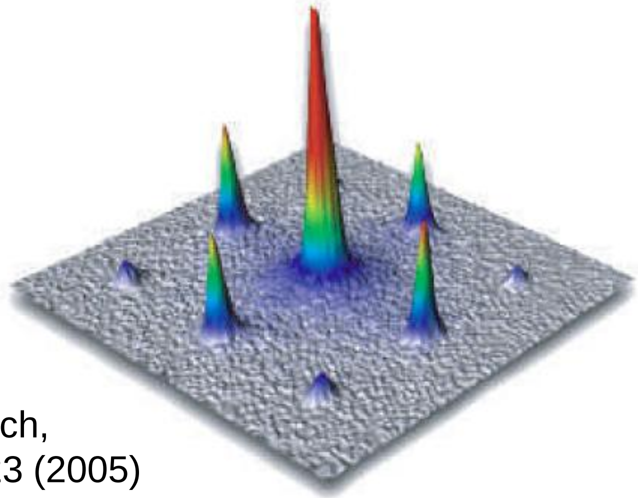


review: I. Bloch, Nature Phys. 01, 23 (2005)

Figure 1 Optical lattice potentials formed by superimposing two or three orthogonal standing waves. **a**, For a 2D optical lattice, the atoms are confined to an array of tightly confining 1D potential tubes. **b**, In the 3D case, the optical lattice can be approximated by a 3D simple cubic array of tightly confining harmonic oscillator potentials at each lattice site.

Mott insulator phase transition

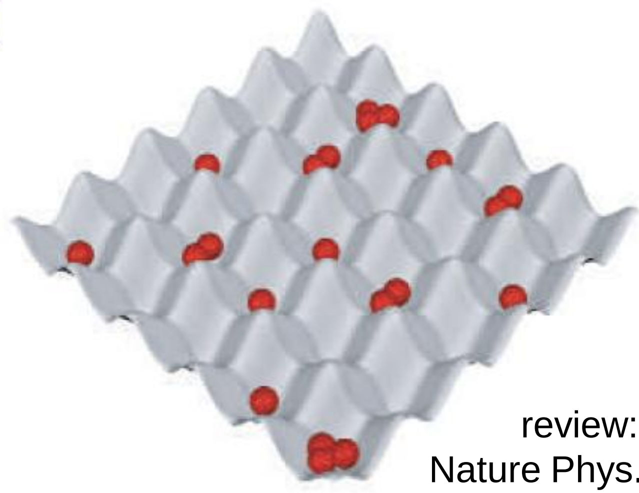


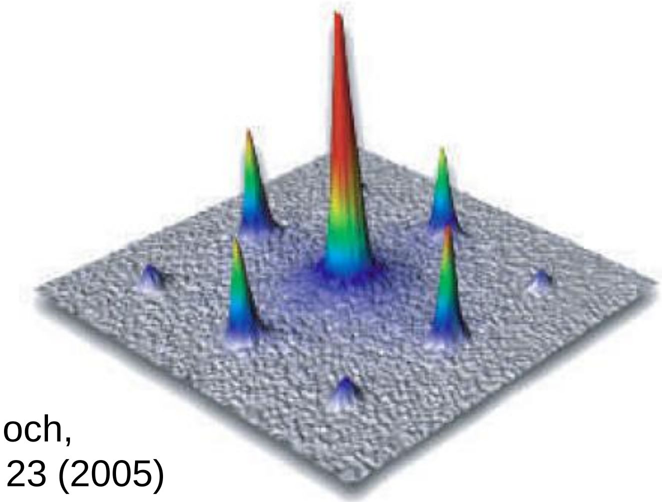


review: I. Bloch,
Nature Phys. 01, 23 (2005)

superfluid: diffraction pattern shows coherence

Mott insulator phase transition

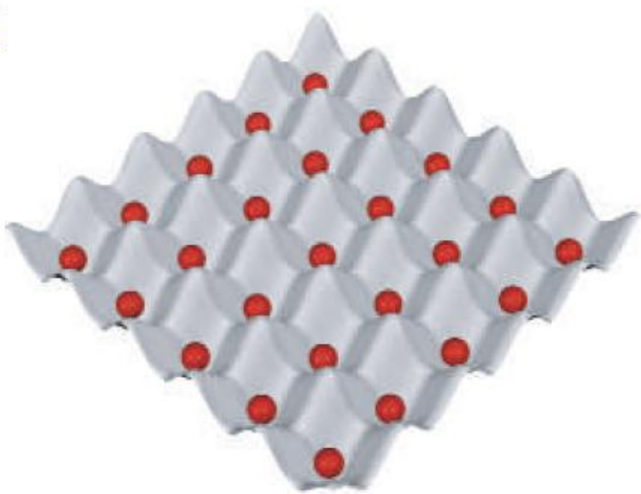


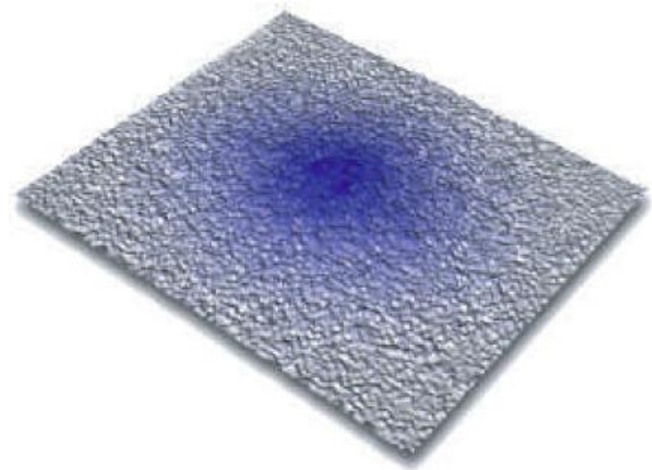


review: I. Bloch,
Nature Phys. 01, 23 (2005)

superfluid: diffraction pattern shows coherence

Mott insulator: disappearance of diffraction pattern





^{84}Sr Mott insulator in Innsbruck

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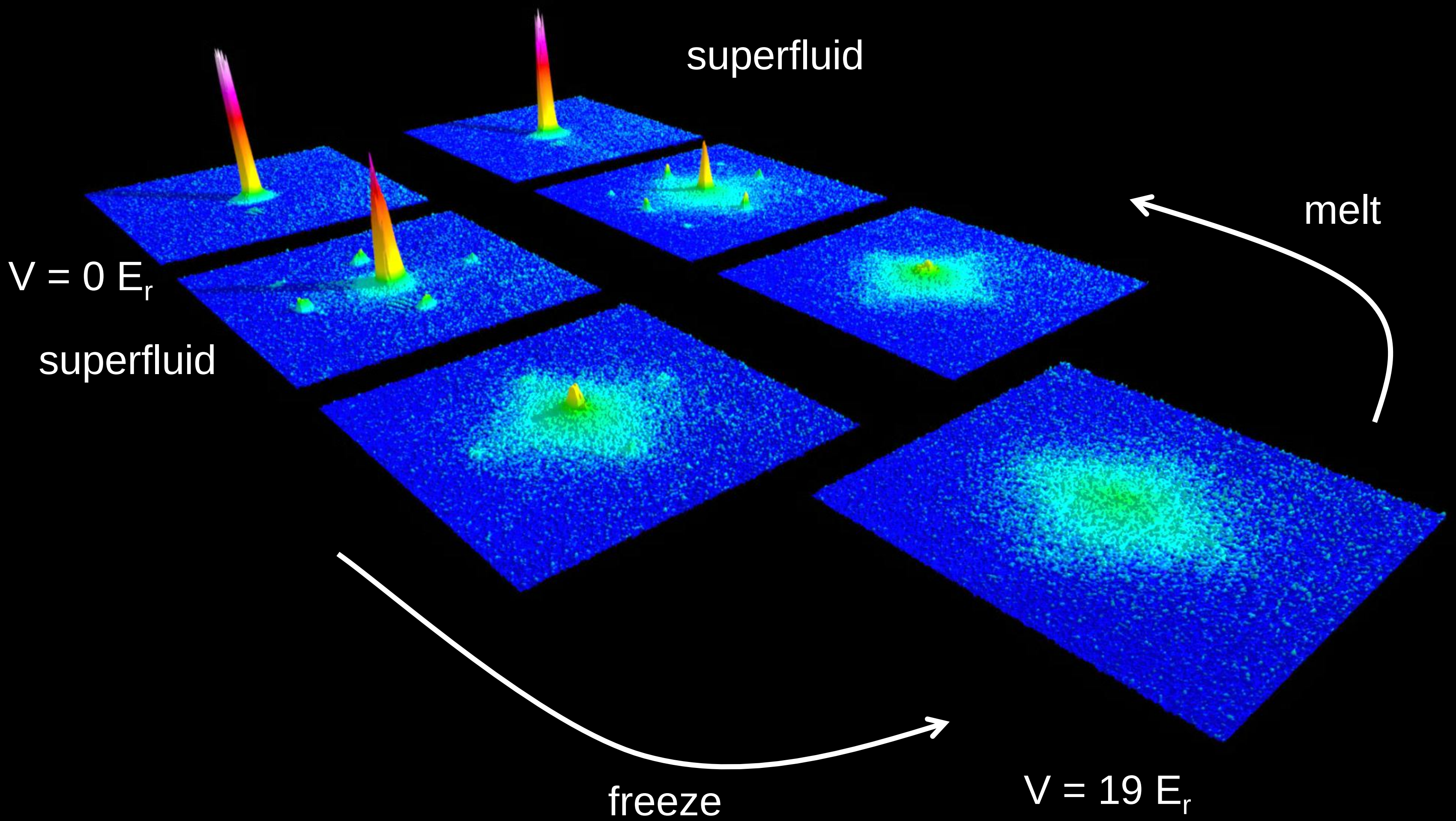
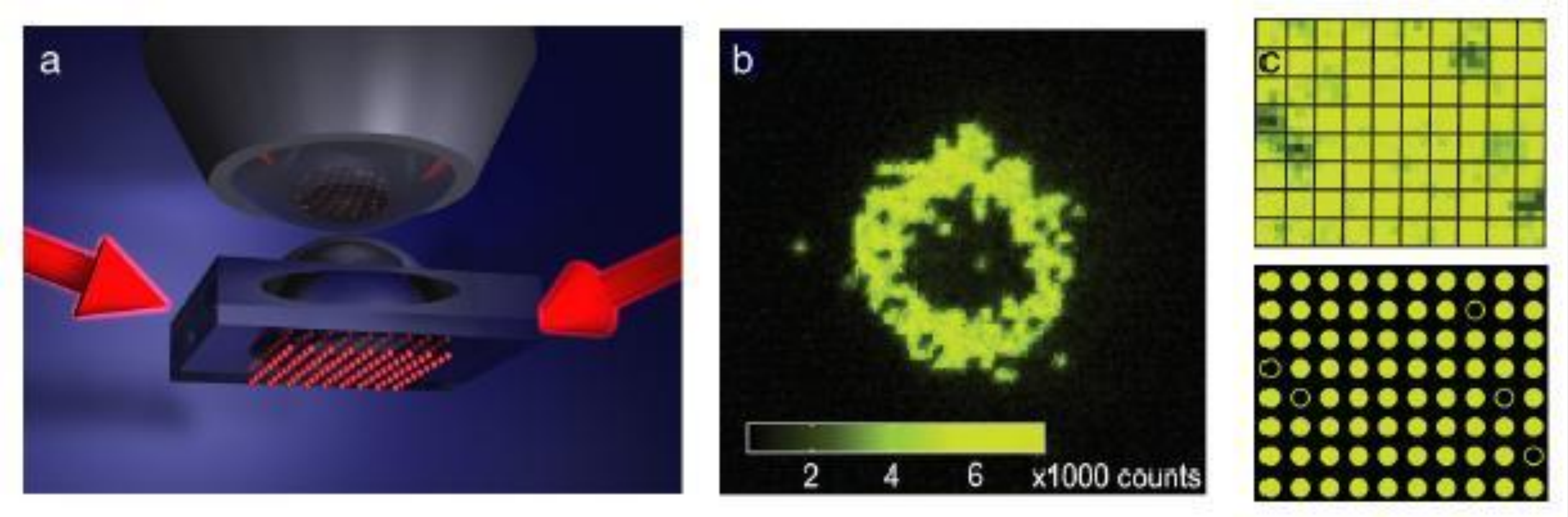


our detectors: imaging of atom clouds

the high end: quantum gas microscopy



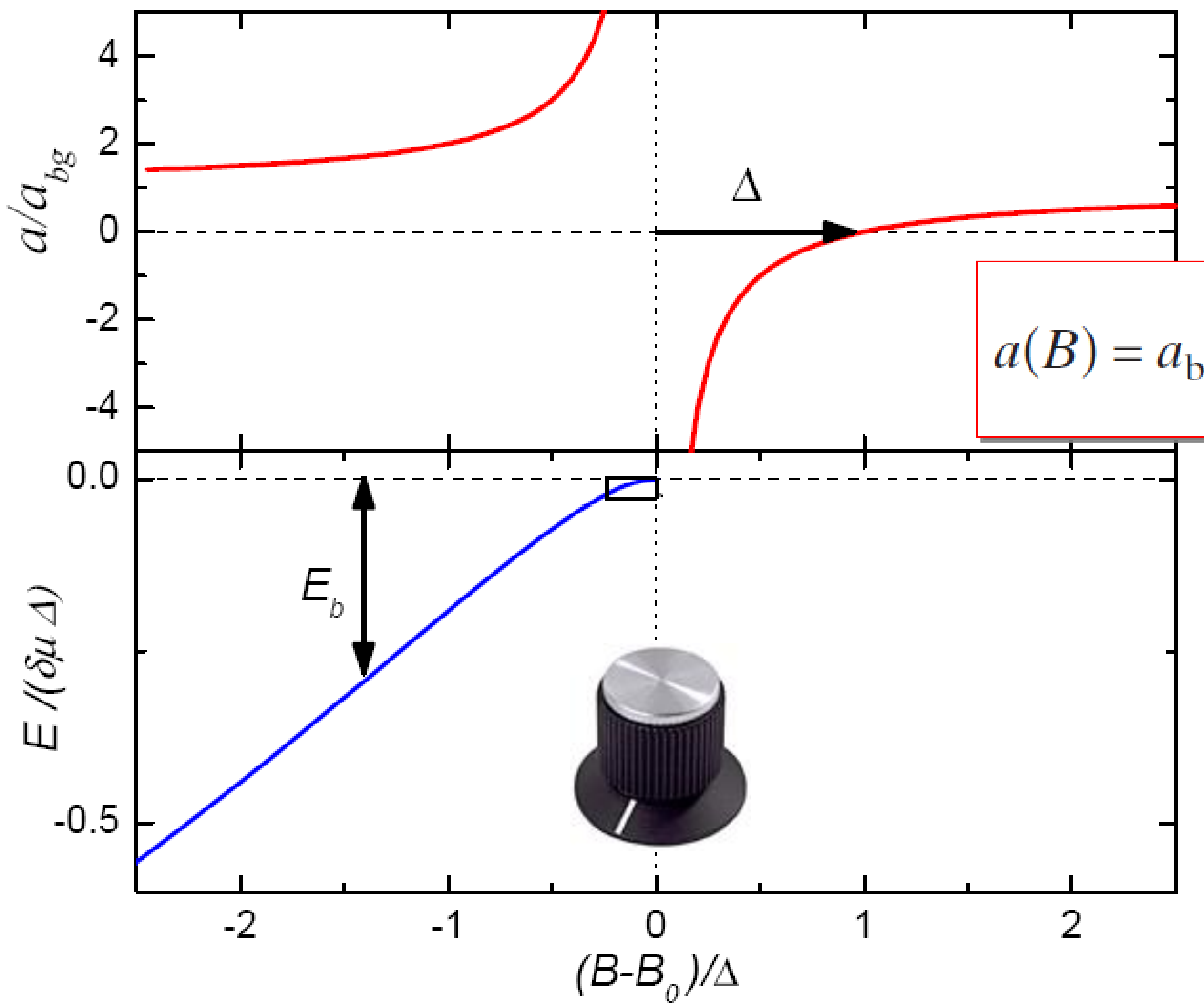
Greiner group @ Harvard

single parameter characterizes everything

***s*-wave scattering length a**

but can we control it?

Feshbach resonance



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

review: Chin, Grimm, Julienne, Tiesinga, RMP 74, 1205 (2010)

table-top set up

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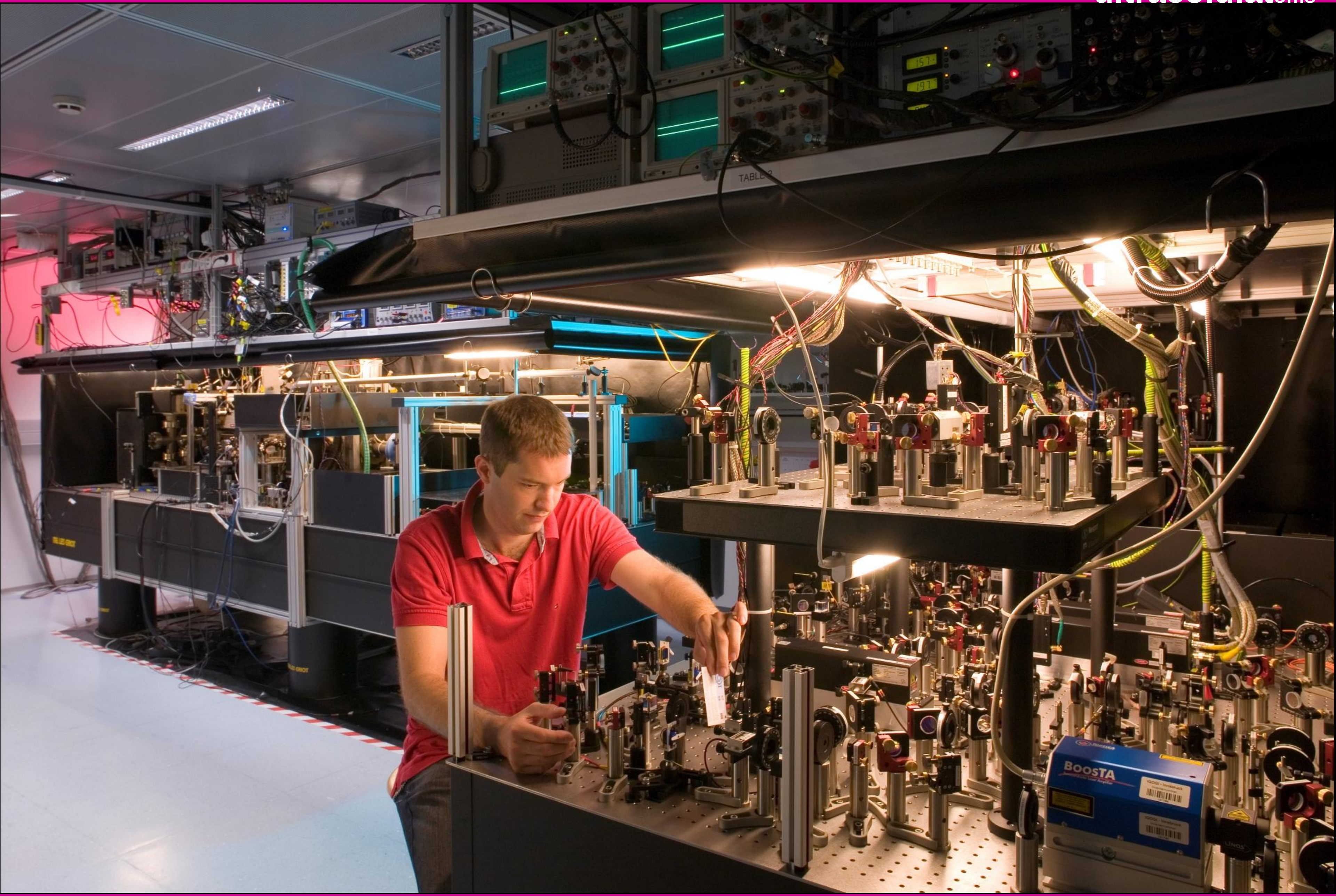

magneto-optically trapped Sr atoms (461nm)

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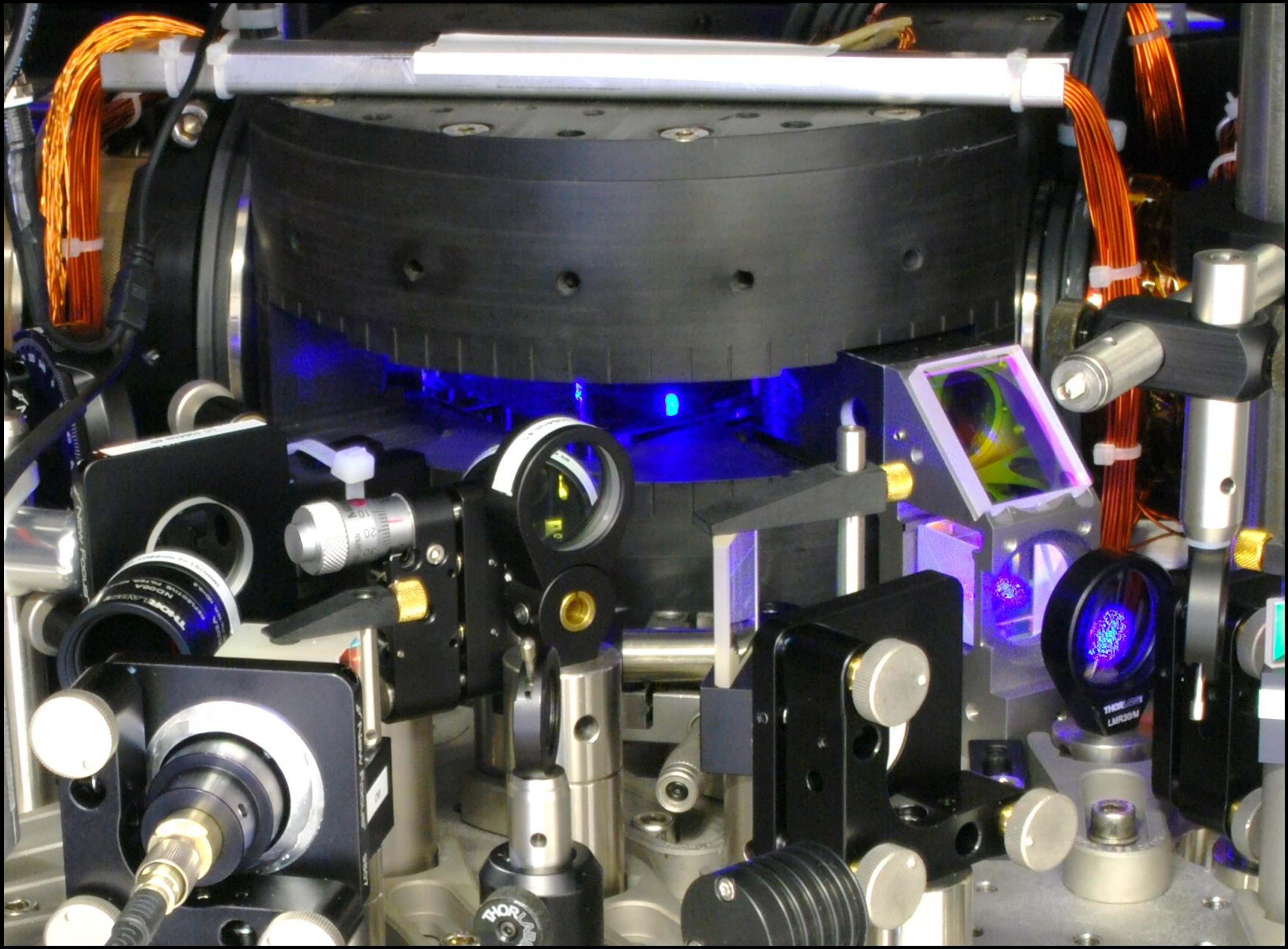

Sr and Li: two-species MOT (461nm and 671nm)

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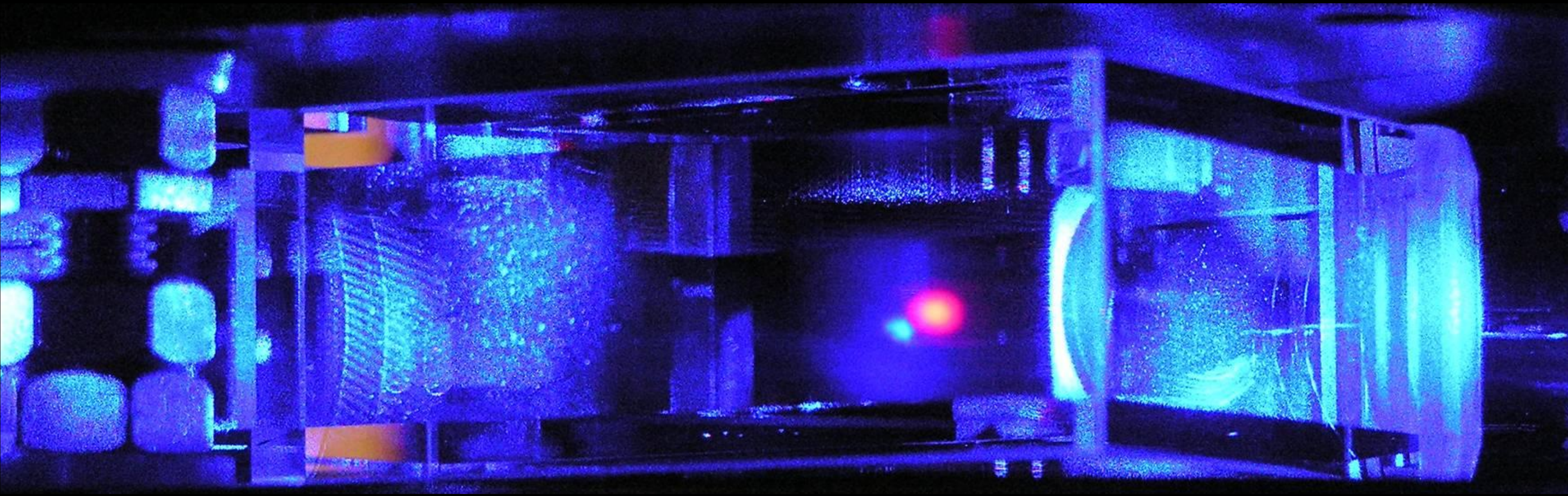
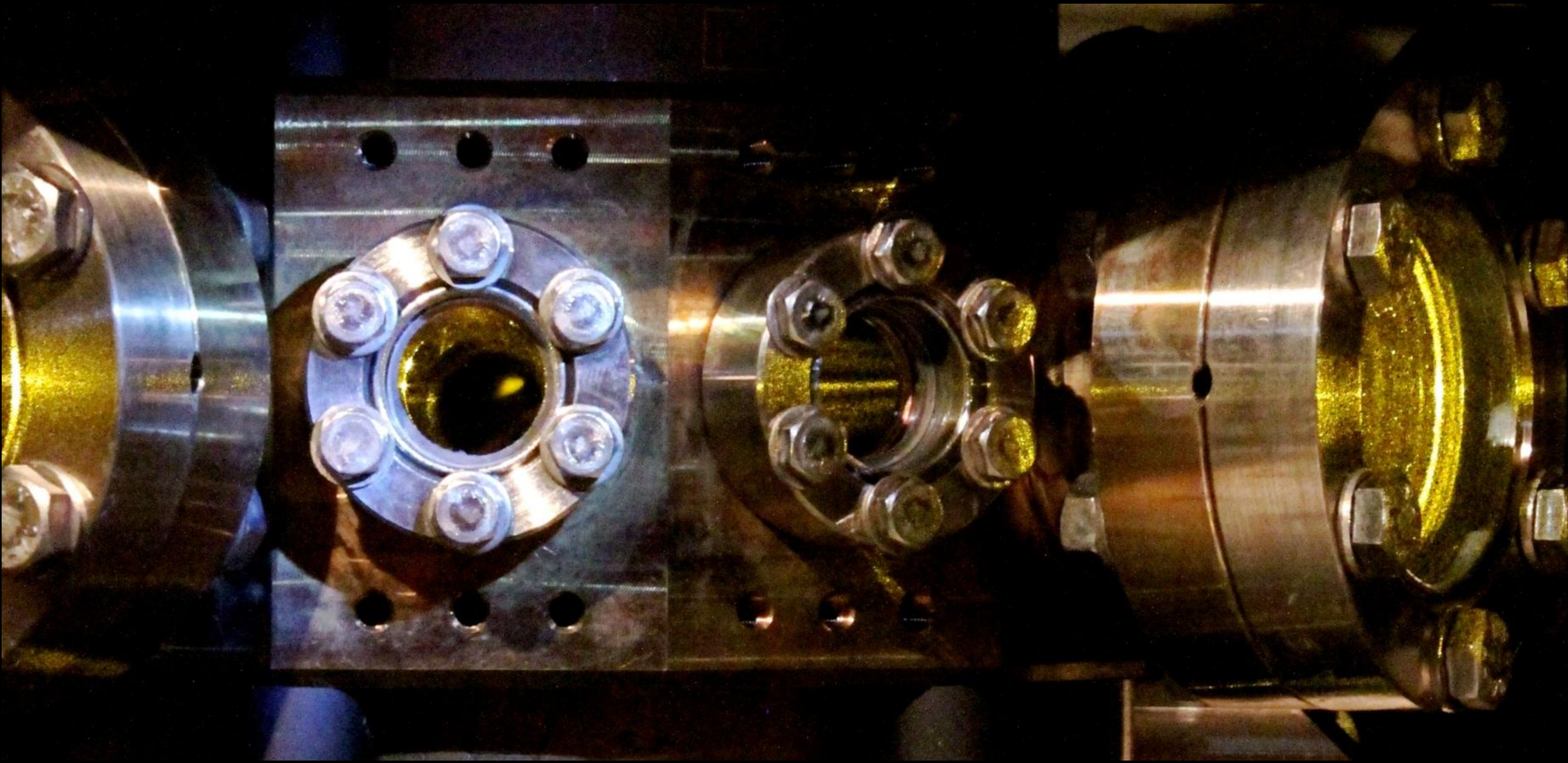


magneto-opically trapped erbium (583nm)

ultracold.atoms



ultracold group in Innsbruck (April 2011)

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ultracold PIs

ultracold.atoms

4 PIs

Cs - ground-state molecules
1D quantum gases
RbCs - heteronuc. molecules

Hanns-Christoph Nägerl

Florian Schreck

Sr - quantum simulations
RbSr - ground state molecules

Francesca Ferlaino

Er - new, strongly dipolar quantum gas

RG

Cs - few-body physics
LiK - Fermi-Fermi mixtures

Li - fermionic spin mixtures

mysterious Efimov quantum states

43 years ago ...

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СЛАБОСВЯЗАННЫЕ СОСТОЯНИЯ ТРЕХ РЕЗОНАНСНО ВЗАИМОДЕЙСТВУЮЩИХ ЧАСТИЦ

В. И. ЕФИМОВ

ФИЗИКО-ТЕХНИЧЕСКИЙ ИНСТИТУТ им. А. Ф. ИОФФЕ АКАДЕМИИ НАУК СССР

(Поступила в редакцию 16 февраля 1970 г.)

Показано, что при достаточной резонансности парных сил у трех тождественных частиц возникает семейство связанных состояний малой энергии. Квантовые числа всех состояний одинаковы: для бесспиновых бозонов 0^+, для нуклонов $1/2^+$, $T = 1/2$. Размер состояний больше радиуса парных сил. Наиболее благоприятные условия ... уровней имеют место для трех бесспиновых нейтральных бозо-... тные — для заряженных частиц и частиц со спином и изоспи-... можность существования таких уровней в системе трех α-час-... х нуклонов (H^3).

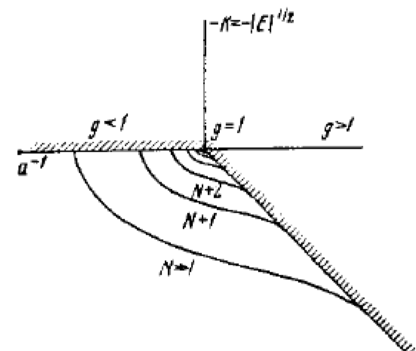

Рис. 1. Спектр уровней трех бесспиновых нейтральных частиц. Штриховкой показана граница непрерывного спектра трех частиц. Соседние траектории уровней отличаются только преобразованием масштаба приблизительно в 22 раза. В целях наглядности это соотношение на рисунке не выдержано

42 years ago ...

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SOVIET JOURNAL OF NUCLEAR PHYSICS VOLUME 12, NUMBER 5 MAY, 1971

WEAKLY-BOUND STATES OF THREE RESONANTLY-INTERACTING PARTICLES

V. N. EFIMOV

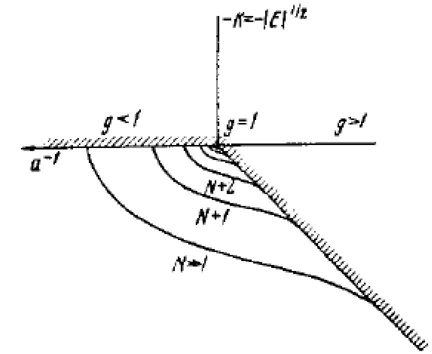
A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

Submitted February 16, 1970

Yad. Fiz. 12, 1080–1091 (November, 1970)

It is shown that if the pair forces of three identical particles are sufficiently resonant, a family of bound states of low energy is produced. The quantum numbers of all the states are the same: for ...leons $\frac{1}{2}^{+}$, T = $\frac{1}{2}$. The dimension of the states is larger than the ... most favorable conditions for the appearance of a family of levels ...al bosons: the conditions are less favorable for charged particles ...spin. The possibility of existence of such levels in a system of three ...and of three nucleons (H^3) is considered.

FIG. 1. Level spectrum of three spinless neutral particles. The cross hatching denotes the boundary of the continuous spectrum of the three particles. Neighboring level trajectories differ only in a scale transformation by an approximate factor of 22. For clarity, this ratio is not maintained in the figure.



Efimov observations in three-body systems

three identical bosons

^{133}Cs (Innsbruck)

Kraemer et al., Nature **440**, 315 (2006)
Knoop et al., Nature Phys. **5**, 227 (2009)

^{39}K (Florence)

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

^{7}Li (Ramat Gan, Rice)

Gross et al., PRL **103**, 163202 (2009)
Pollack et al., Science **326**, 1683 (2009)

^{85}Rb (Boulder)

Wild et al., arXiv:1112.0362

three-component spin mixture of fermions

^{6}Li (Heidelberg, Penn State Univ., U Tokyo)

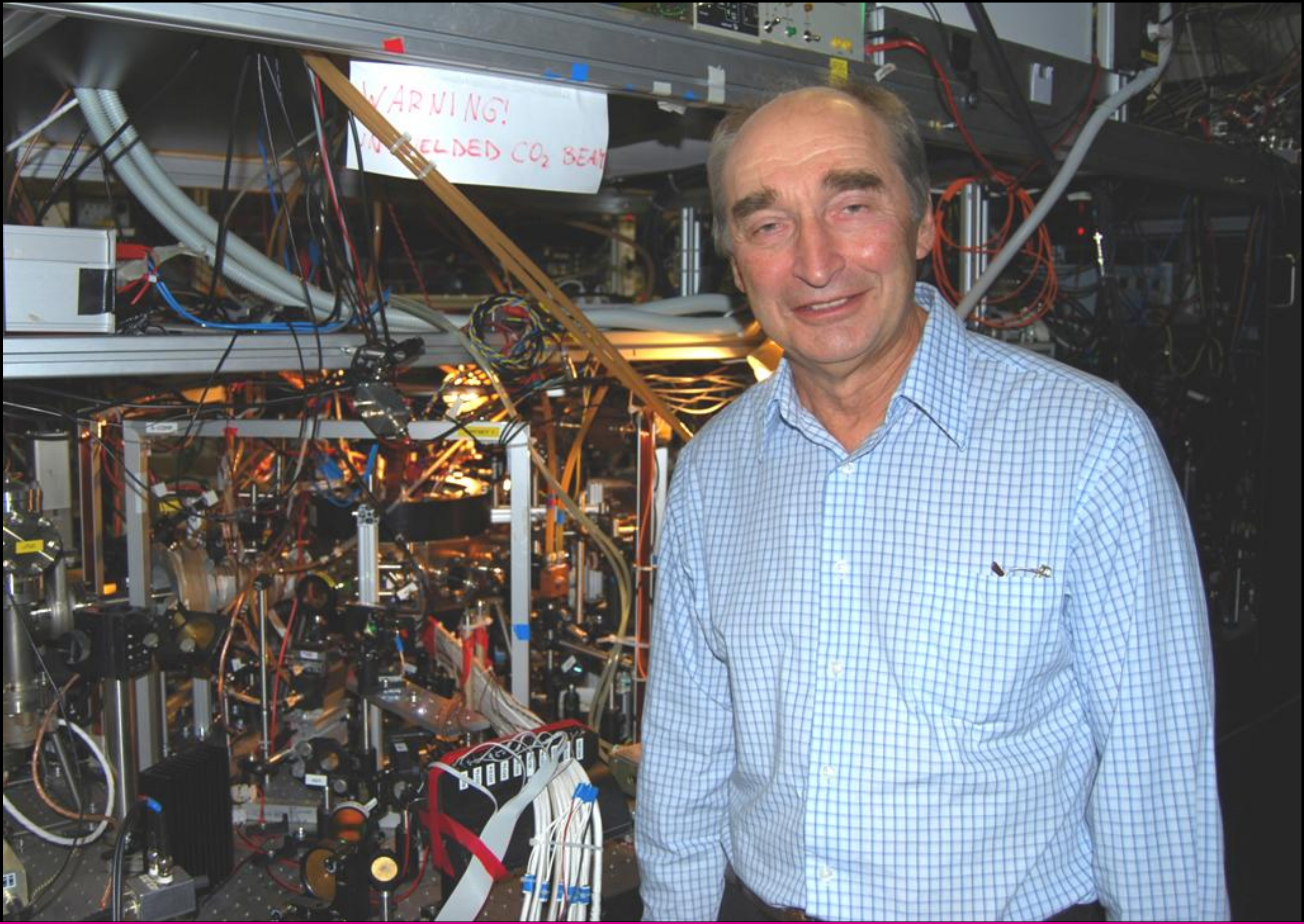
Ottenstein et al., PRL **101,** 203202 (2008)
Huckans et al., PRL **102**, 165302 (2009)
Williams et al., PRL **103,** 130404 (2009)
Lompe et al., Science **330**, 940 (2010)
Nakajima et al., PRL **106**, 143201 (2011)

Bose-Bose mixture

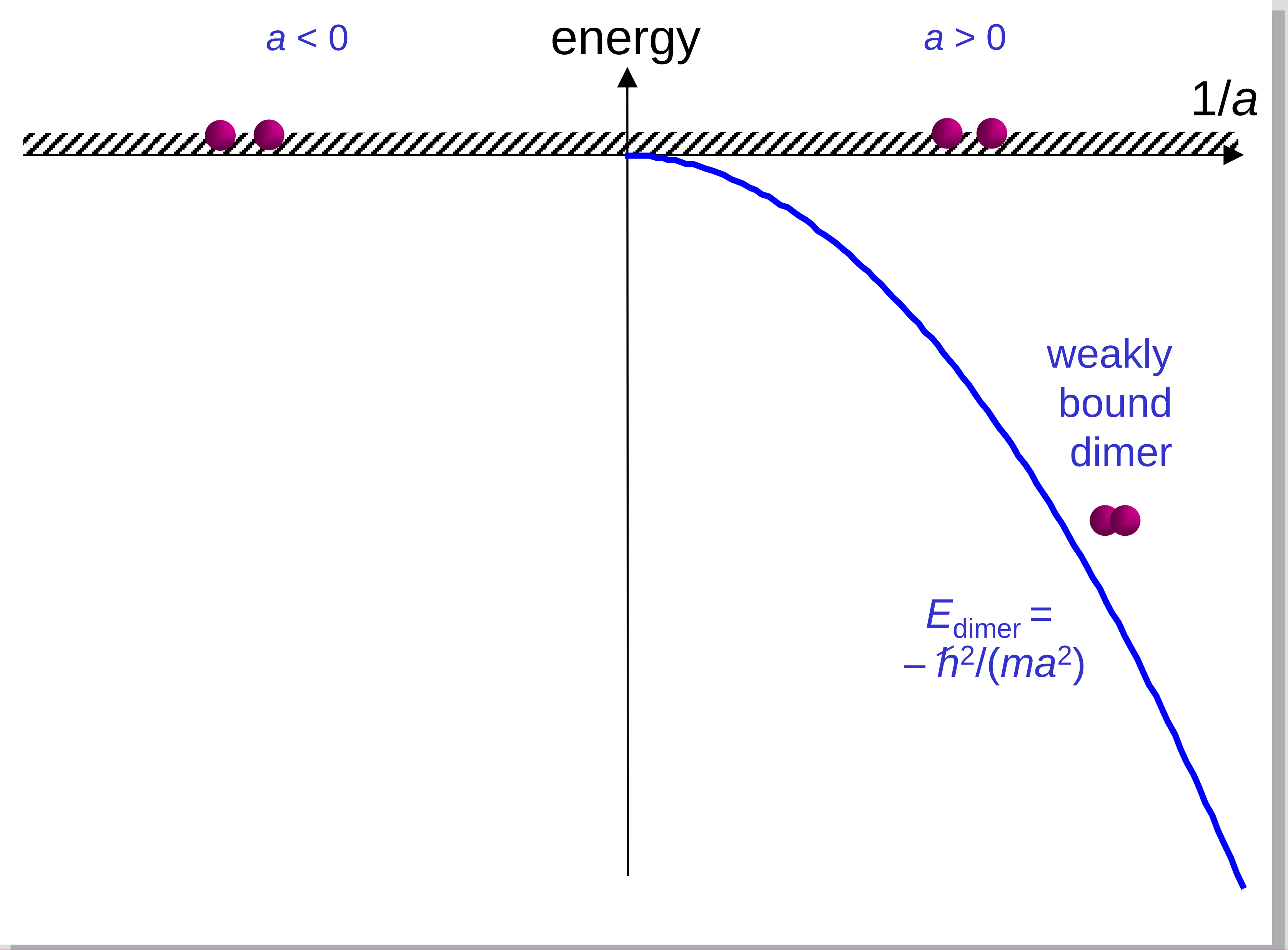
^{41}K – ^{87}Rb (Florence)

Barontini et al., **PRL** 043201 (2009)

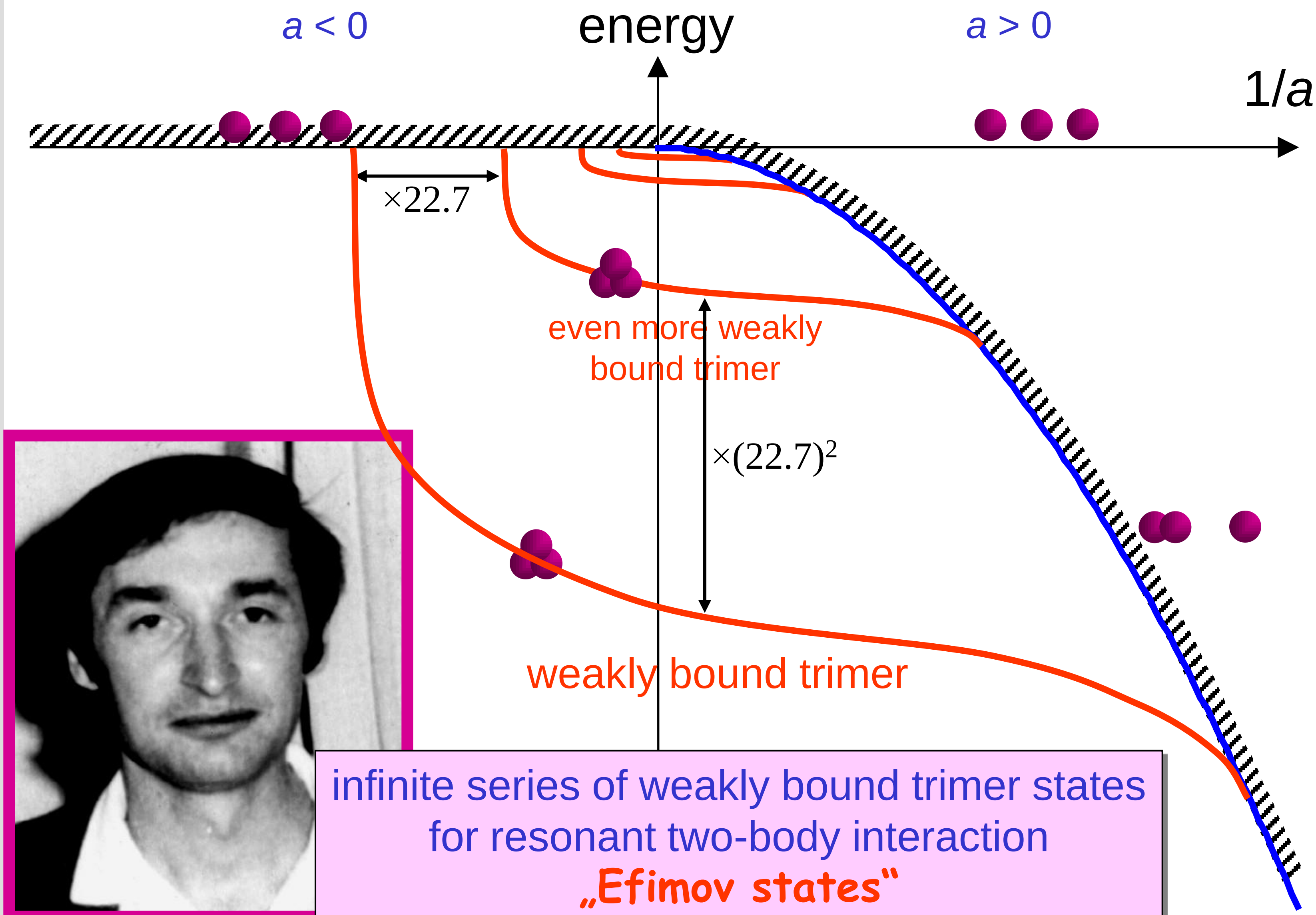
Vitaly Efimov visiting Innsbruck, 23 Oct 2009



quantum states near two-body resonance

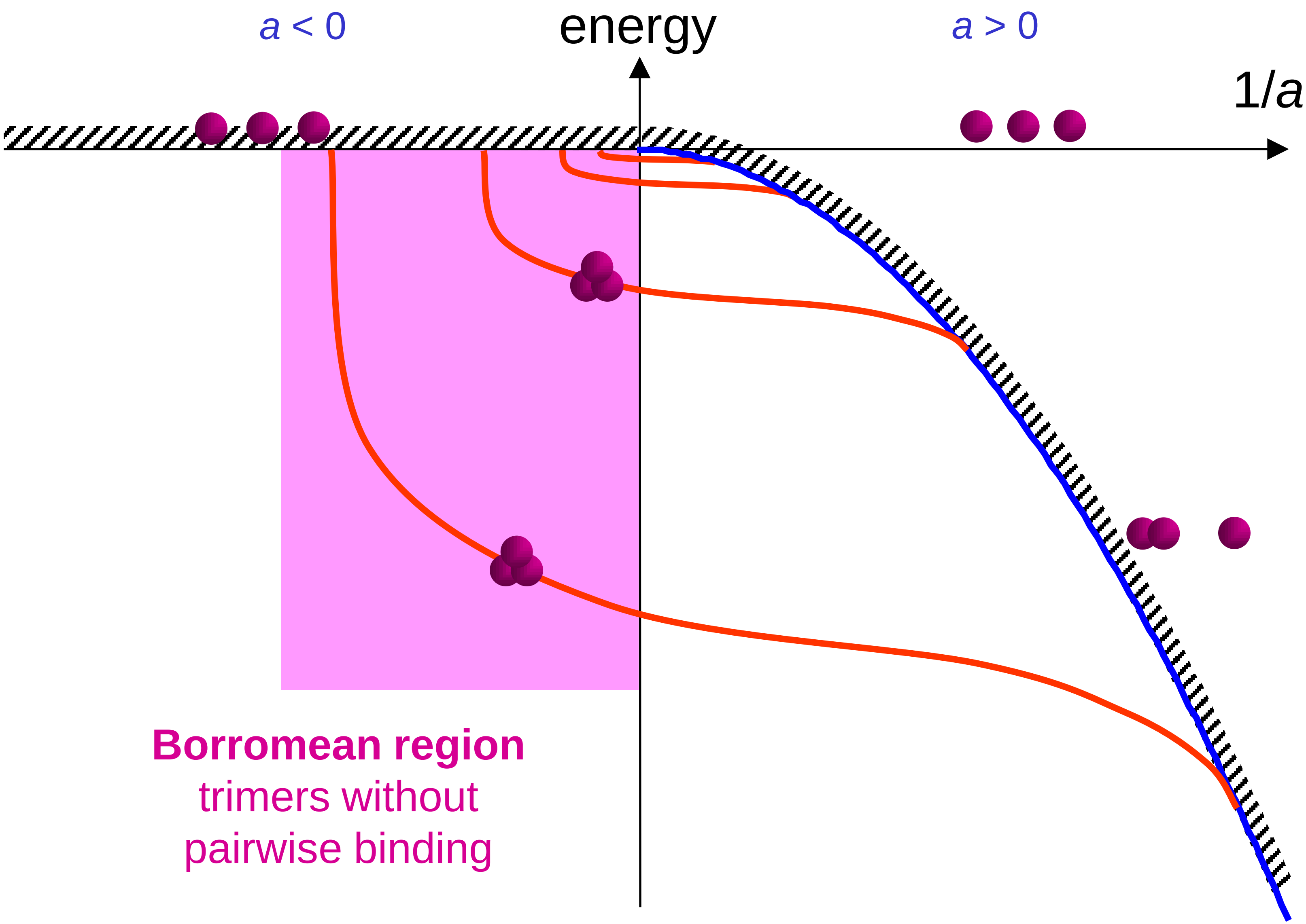


quantum states near two-body resonance



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

Efimov states: Borromean region

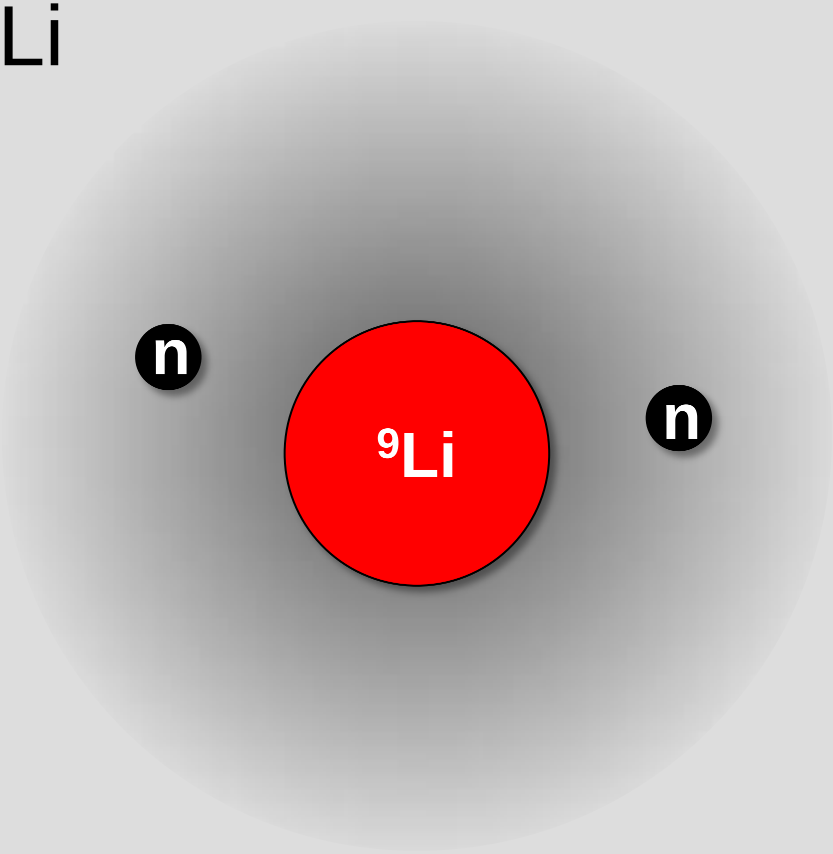


Borromean region

trimers without pairwise binding

Borromean states in nuclear physics

^{11}Li



review on halo states in nuclear physics:

Jensen, Riisager, Fedorov, Rev. Mod. Phys. 76, 215 (2004)

search for Efimov states in He (1994-2005)

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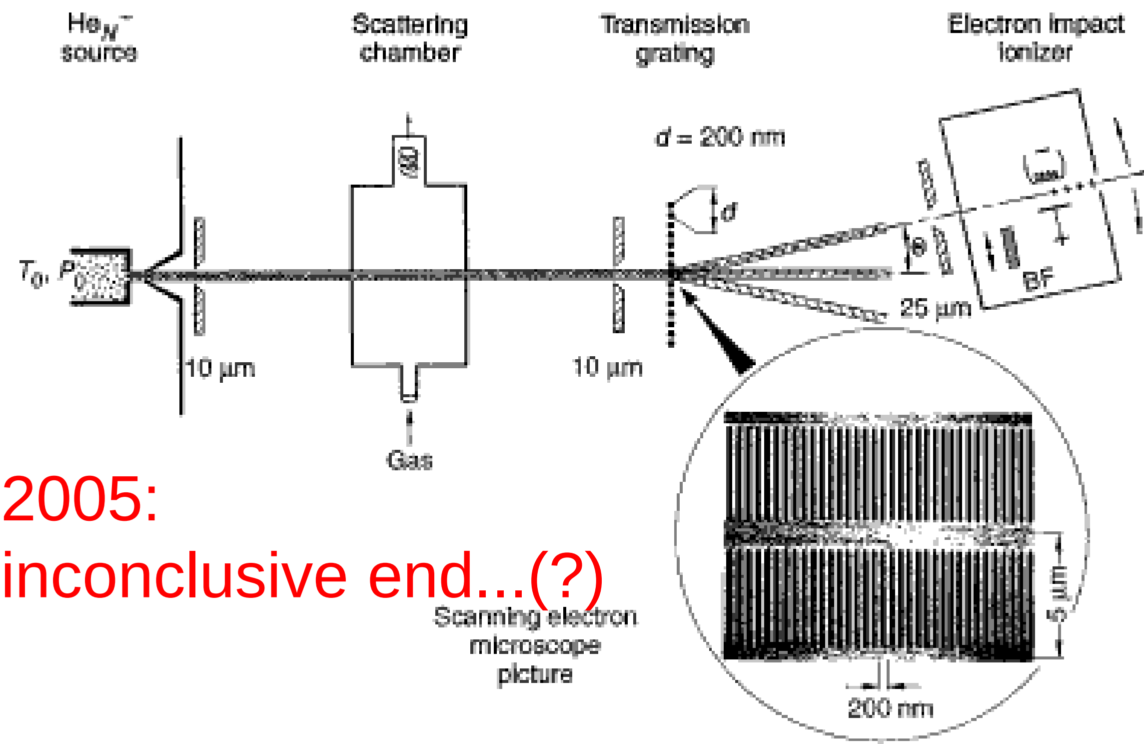
Nondestructive Mass Selection of Small van der Waals Clusters

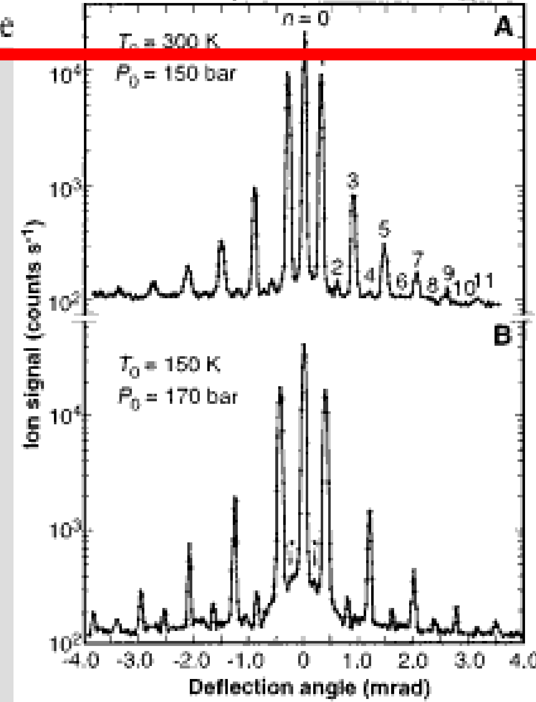
Wieland Schöllkopf and J. Peter Toennies

ters. This large enhancement is of considerable interest in connection with the question of the existence of Efimov states. In 1970, Efimov (19) first predicted that three bosons will have an infinite number of special long-range bound states, which are now called Efimov states, in the limit that the two-body interaction approaches zero binding energy. So far, Efimov states have not been found in nuclear systems, but there is now some evidence that they may exist for He_3 because of the very weak binding energy of He



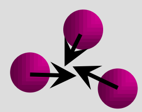
2005:
inconclusive end...(?)

Fig. 1. Schematic diagram of the apparatus used for diffraction of the different components in a He cluster beam. Only the vacuum system containing the ionizer is indicated. BF designates the beam flag that intercepts the incident beam in the stagnation mode measurements. The inset (bottom right) shows a scanning electron microscope picture of the grating used (10, 11).

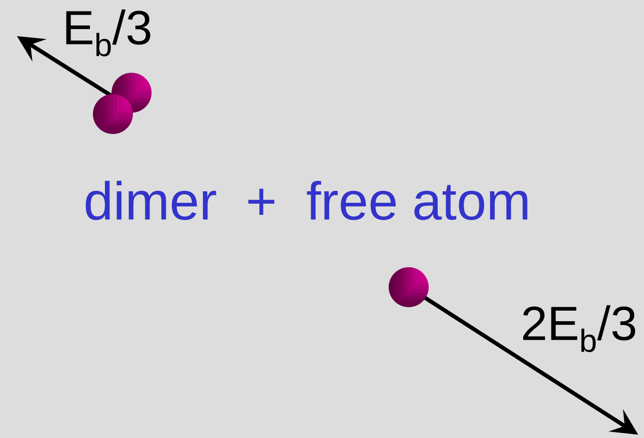


three-body recombination

elementary process



three atoms



dimer + free atom

causes trap loss → our observable

three-body recomb. theory basics

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

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

dimensional analysis

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

dimensionless

a^4 - scaling !
very strong dependence on scattering length

valid if a exceeds all other length scales
(vdW length of molecular potential, typ. 30 – 100a_0)
good near a Feshbach resonance

early theory paper:
Fedichev *et al*., PRL **77**, 2921 (1996), a^4 scaling with $C = 3.9$

discrete scale invariance in 3-body decay

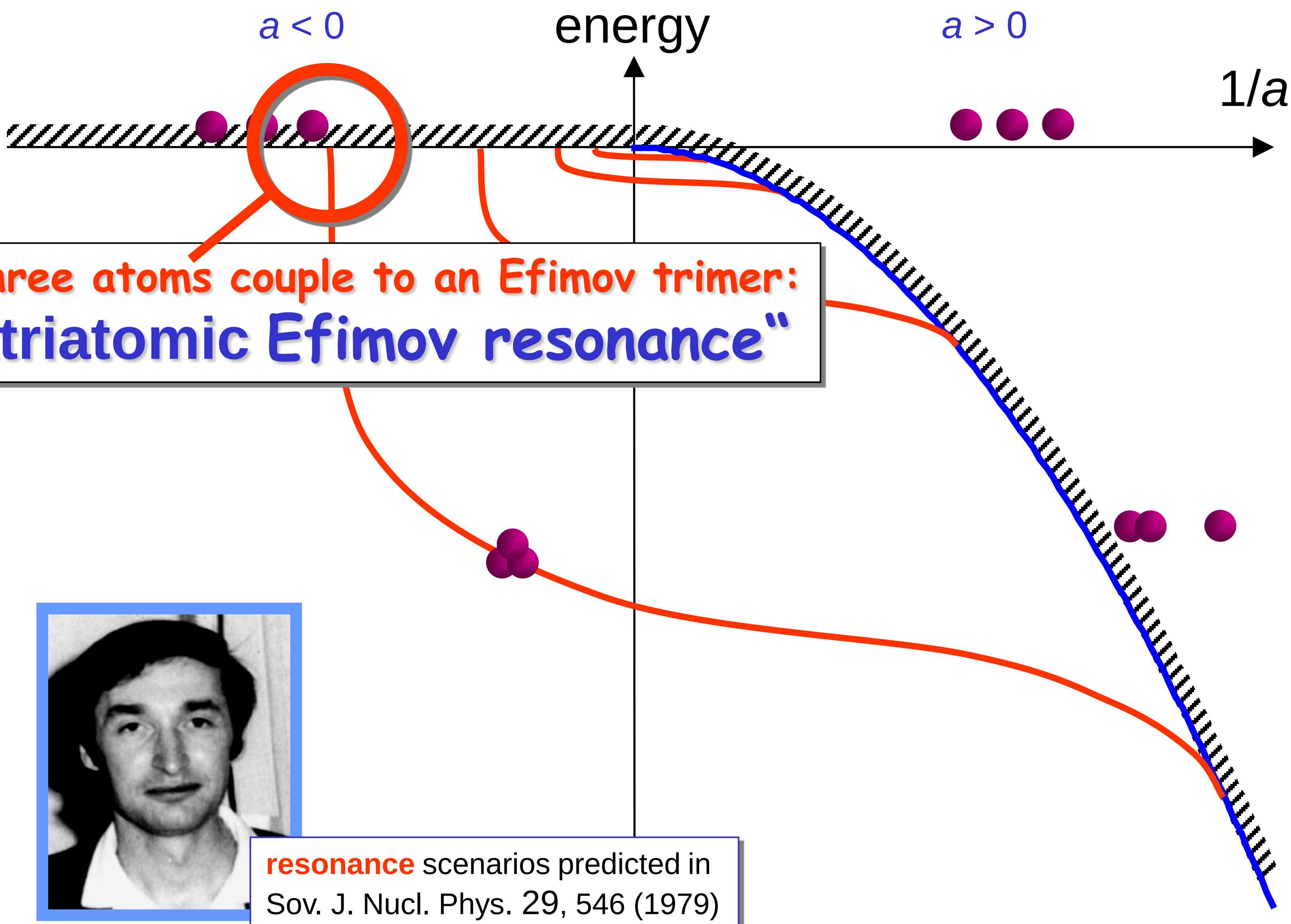
review: Braaten and Hammer, Phys. Rep. (2006)

$$\boxed{C(a) = C(22.7a)}$$

analytic expression available, based on effective-field theory

need two parameters:
three-body parameter (universal)
decay parameter (non-universal)

Efimov resonances



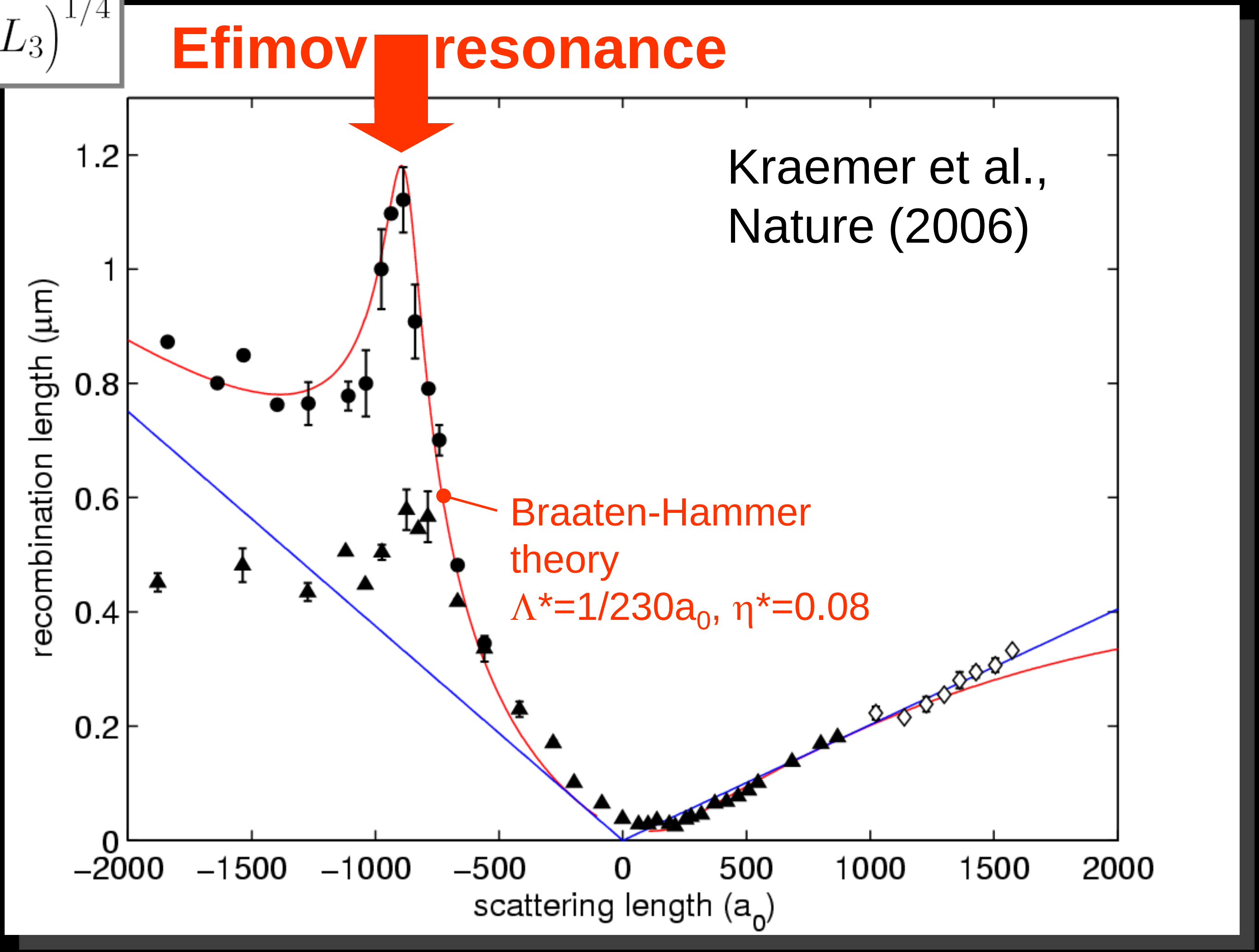
three atoms couple to an Efimov trimer:

„triatomic Efimov resonance“

resonance scenarios predicted in
Sov. J. Nucl. Phys. 29, 546 (1979)

exp. results (2005) !

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



magnetic tunability of Cs

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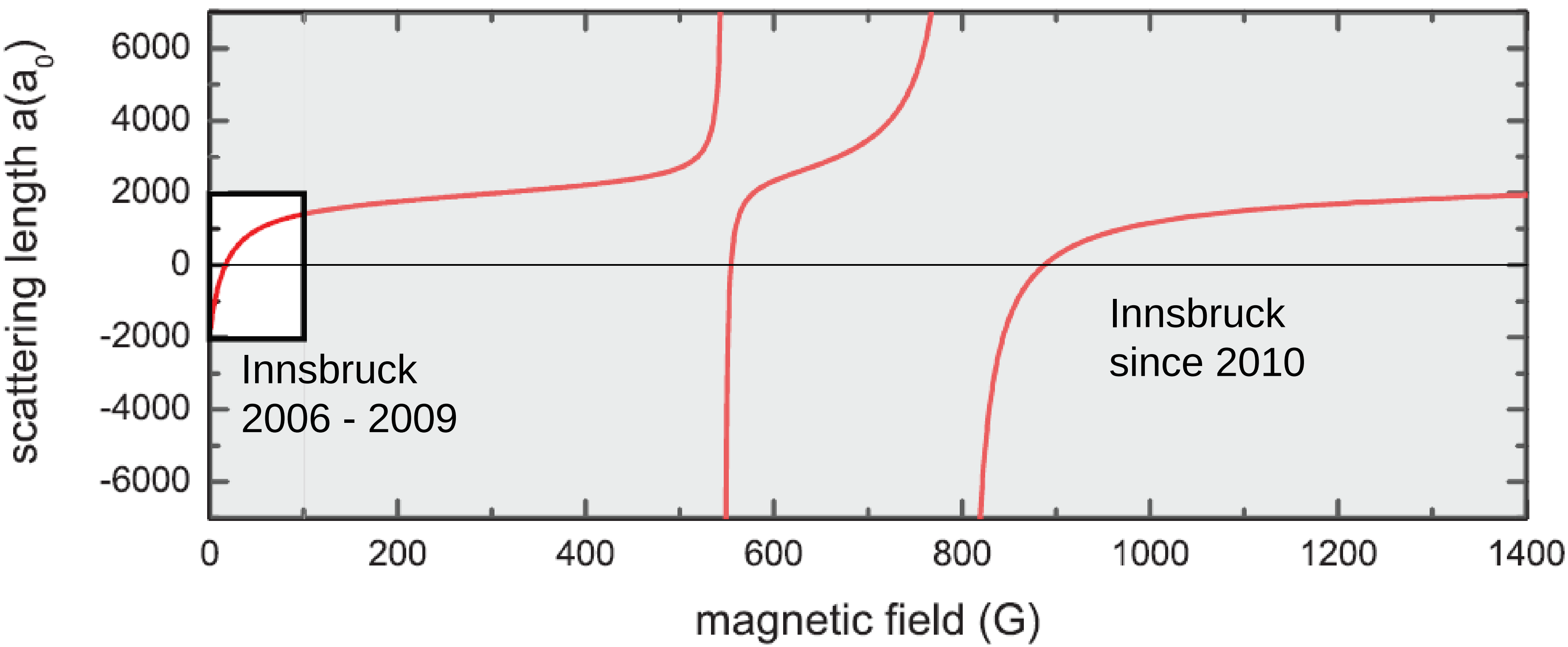
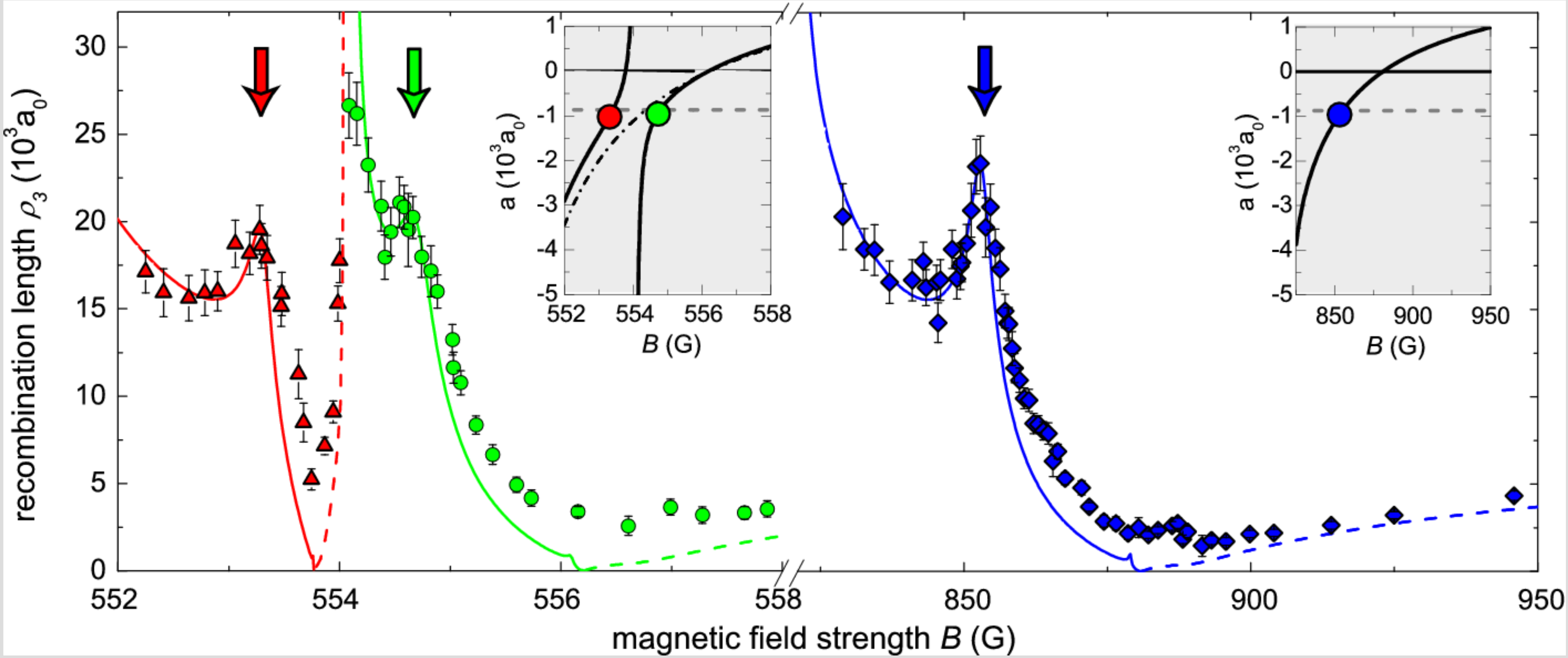
<u>three</u> broad *s*-wave FRs



plus many d- and g-wave FRs (not shown)

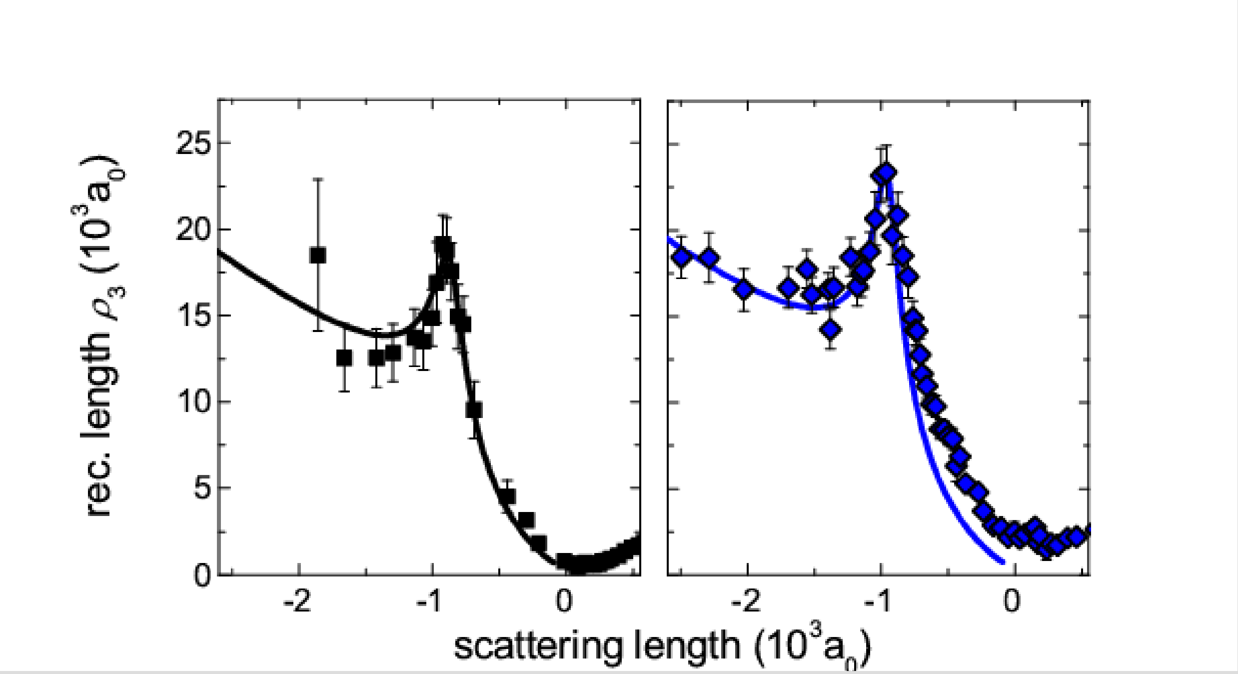
observation of three new Efimov resonances



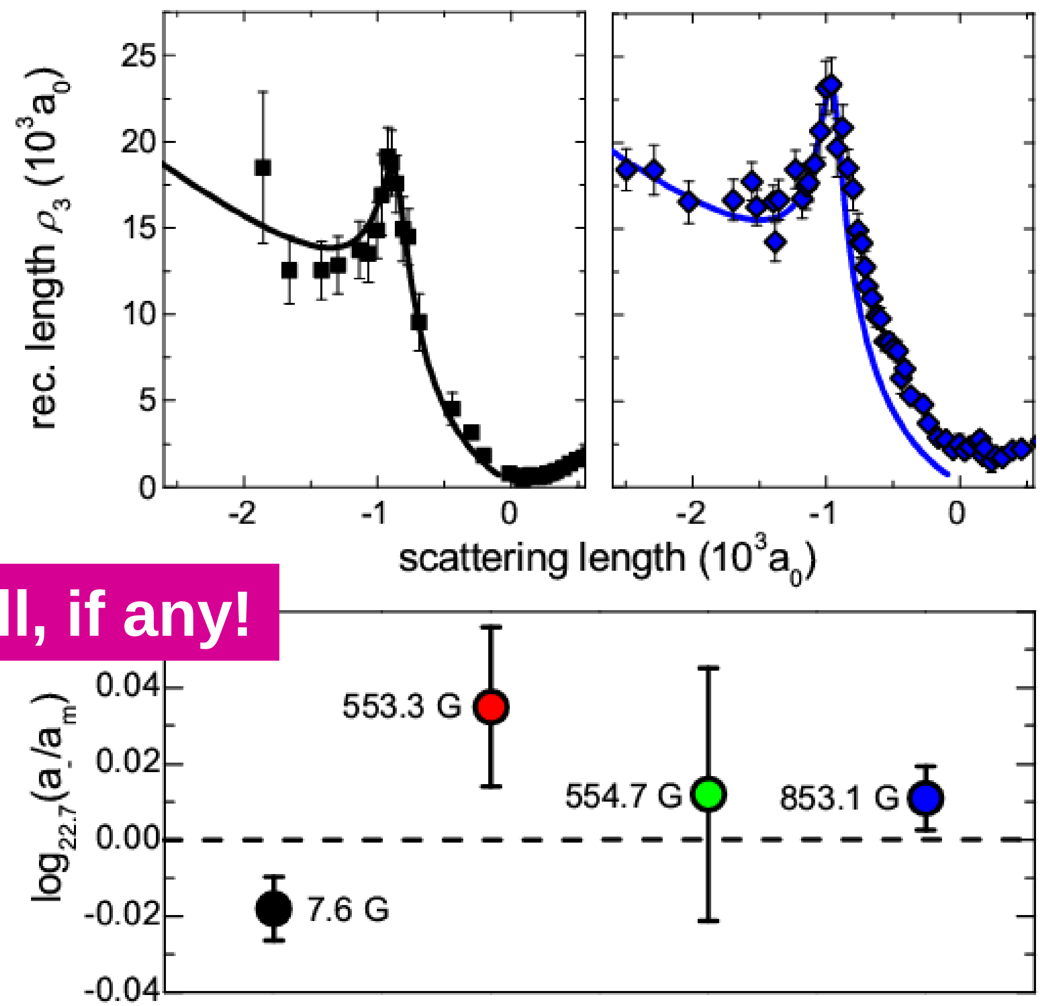
how universal is the three-body parameter?

M. Berninger et al., PRL **107**, 120401 (2011)

variations of the three-body parameter?



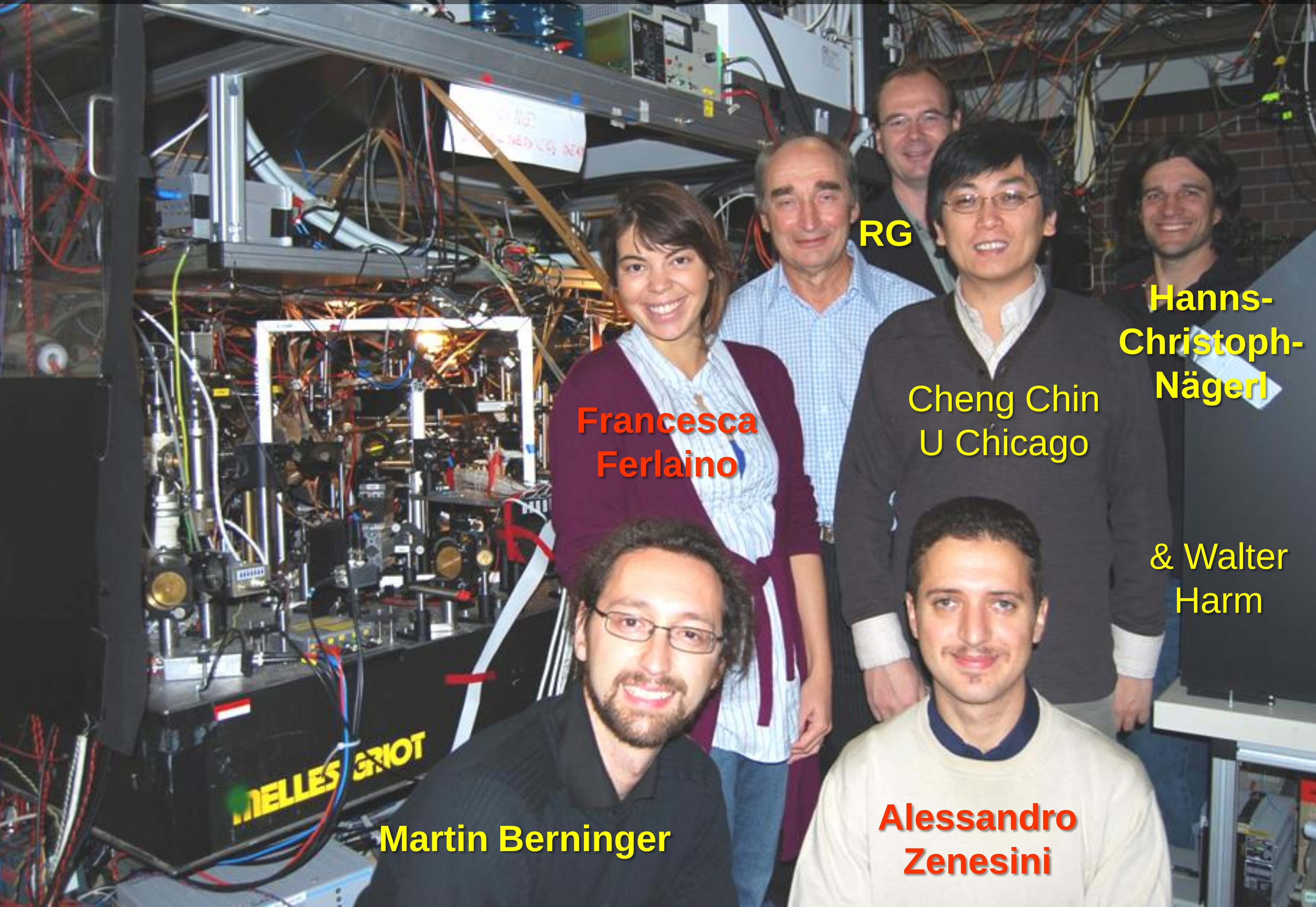
variations of the three-body parameter?



very small, if any!

one tenth of Efimov period

Vitaly Efimov & the Innsbruck Cs team



2, 3, 4,…. many

Weakly bound cluster states of Efimov character

Javier von Stecher

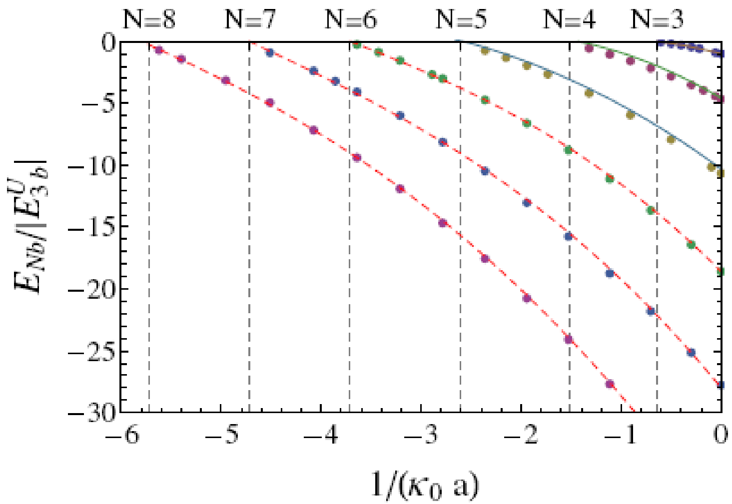


Figure 2. Bos
region. Symbo
The numbers a
dashed lines c
curves corresp
$N = 5$, the solid curve corresponds to CG predictions using our model Hamiltonian. Dashed curves are fits to an analytic simple form (see the text).

Atomic Color Superfluid via Three-Body Loss

A. Kantian,[1] M. Dalmonte,[1,2] S. Diehl,[1] W. Hofstetter,[3] P. Zoller,[1] and A. J. Daley[1]

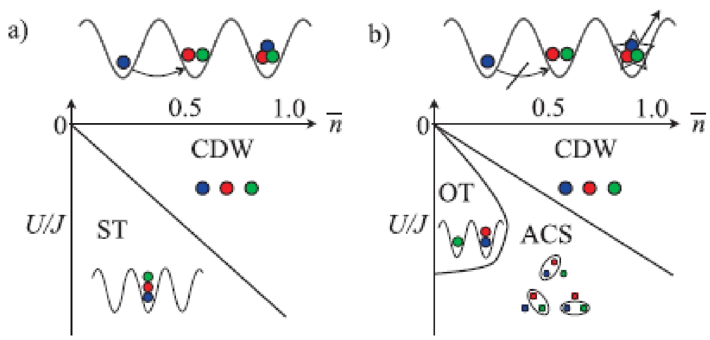


FIG. 1 (color online). Qualitative phase diagram for attractive interactions $U < 0$ and equal populations $\bar{n}/3$ of each component in a three-component 1D Fermi gas. These are shown in the SU(3) symmetric case (where all pairwise interactions between … thout and … om three- … competi- … a charge- density wave (CDW). The hard-core constraint suppresses trion formation, stabilizing BCS pairing in an atomic color superfluid (ACS), which competes with a CDW and off-site trions (OT).

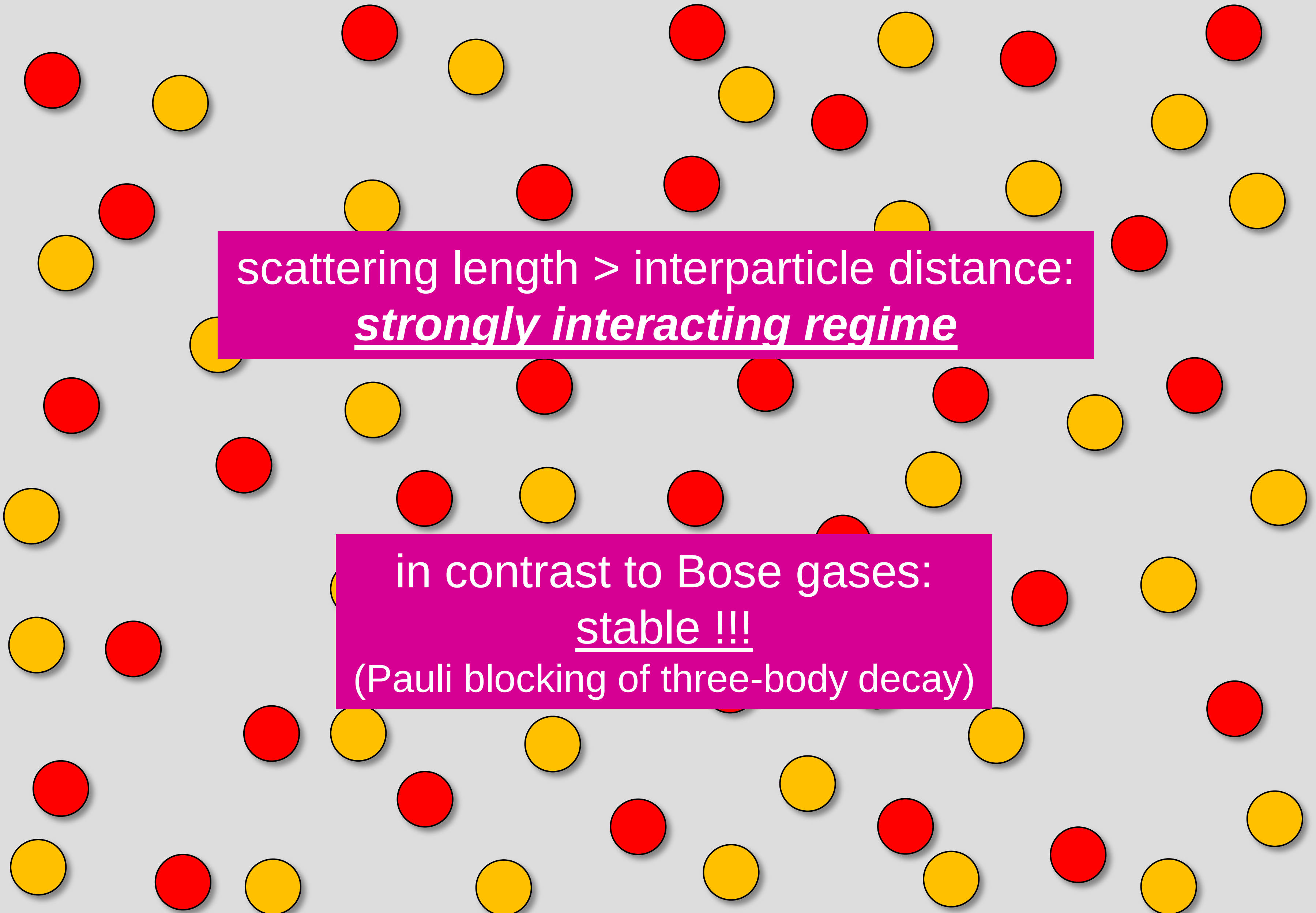
few-body interactions important
to understand and control many-body physics

J. Phys. B **43**, 101002 (2010)

PRL **103**, 240401 (2010)

Strongly interacting Fermi gases

two-component Fermi gas



scattering length > interparticle distance:

strongly interacting regime

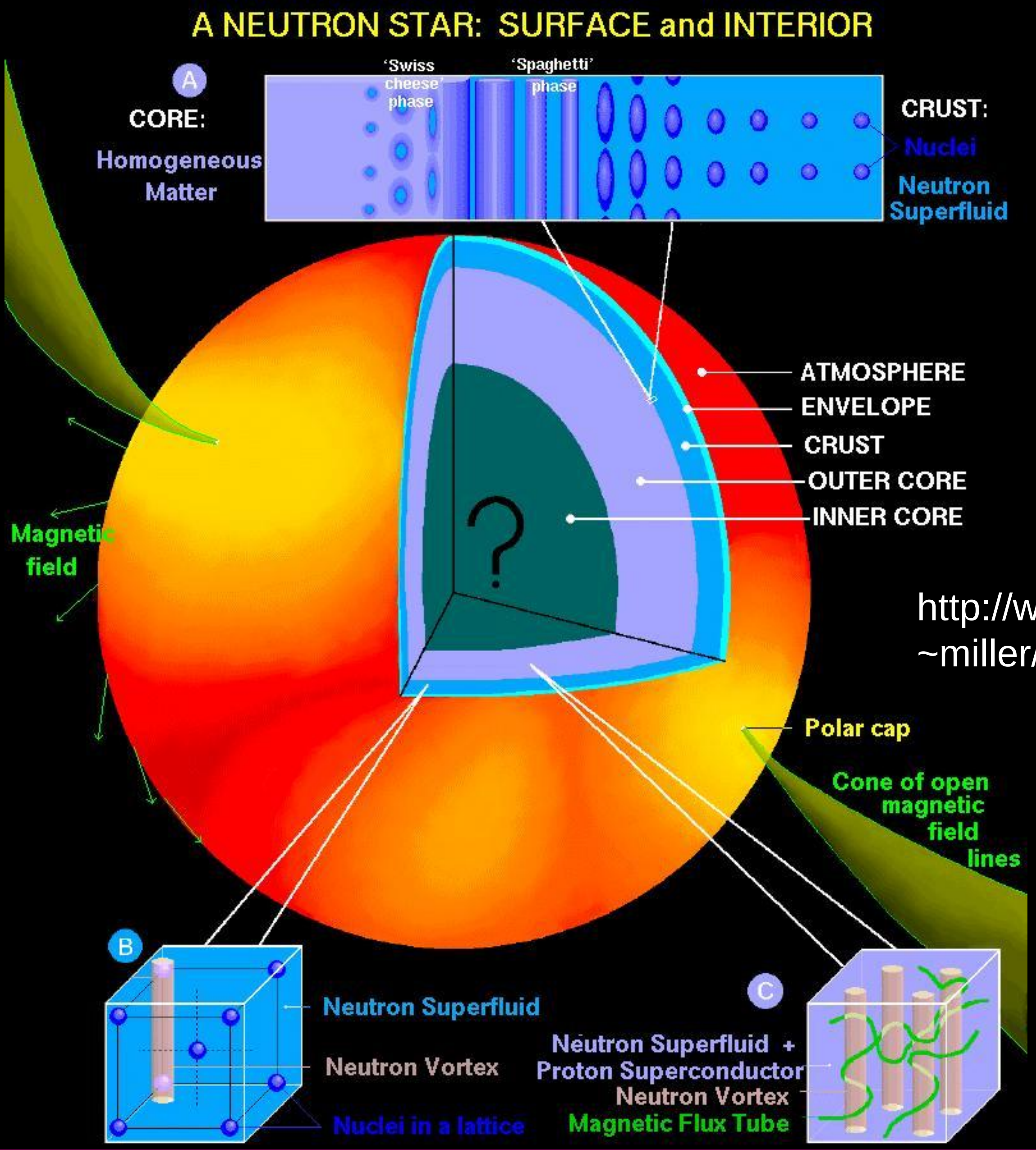
in contrast to Bose gases:

stable !!!

(Pauli blocking of three-body decay)

neutron star

ultracold.atoms



http://www.astro.umd.edu/~miller/nstar.html

interesting question

what happens if $a \rightarrow \infty$?

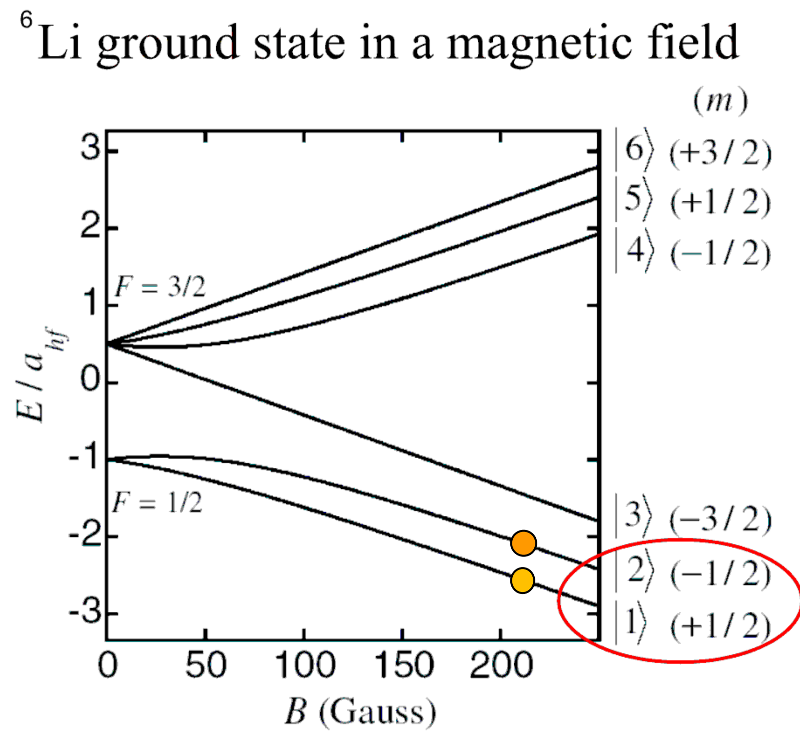
(so-called Bertsch problem)

answer is simple:

renormalized chem. potential $\mu \rightarrow \xi\mu$

with $\xi \approx 0.37$

^{6}Li spin mixture



spin mixture of
two lowest states
stable against
two-body decay

Feshbach resonance

prediction: Houbiers et al., PRA 57, R1497 (1998)
precise characterization:
Bartenstein et al., PRL 94, 103201 (2005)

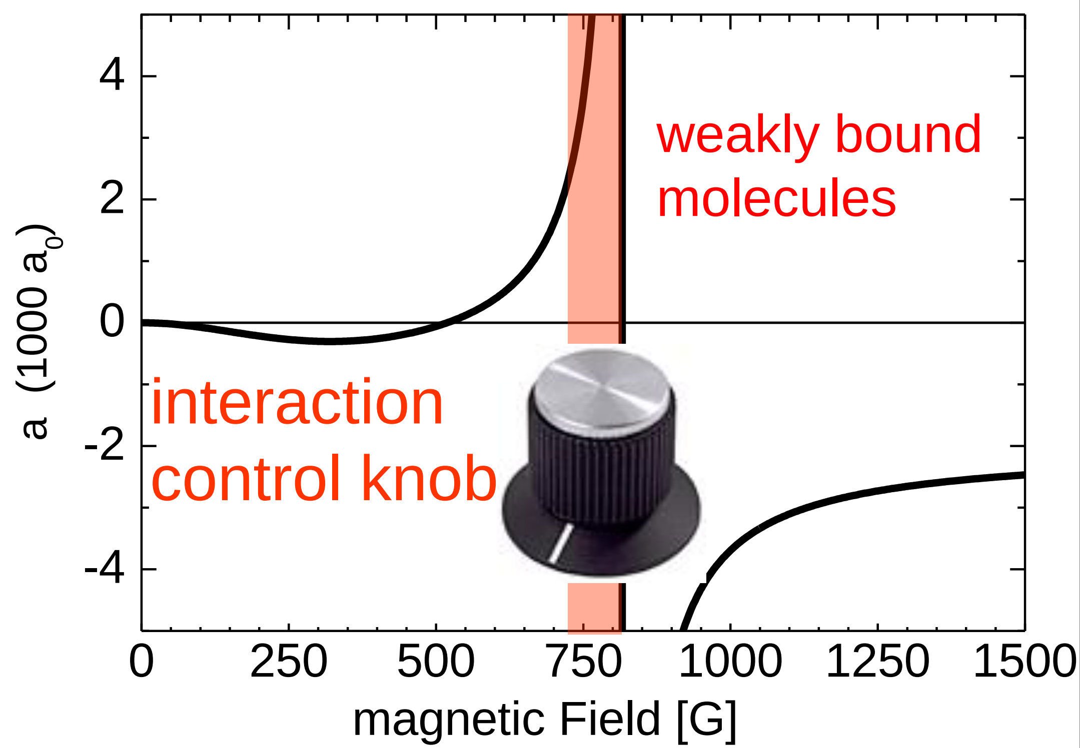
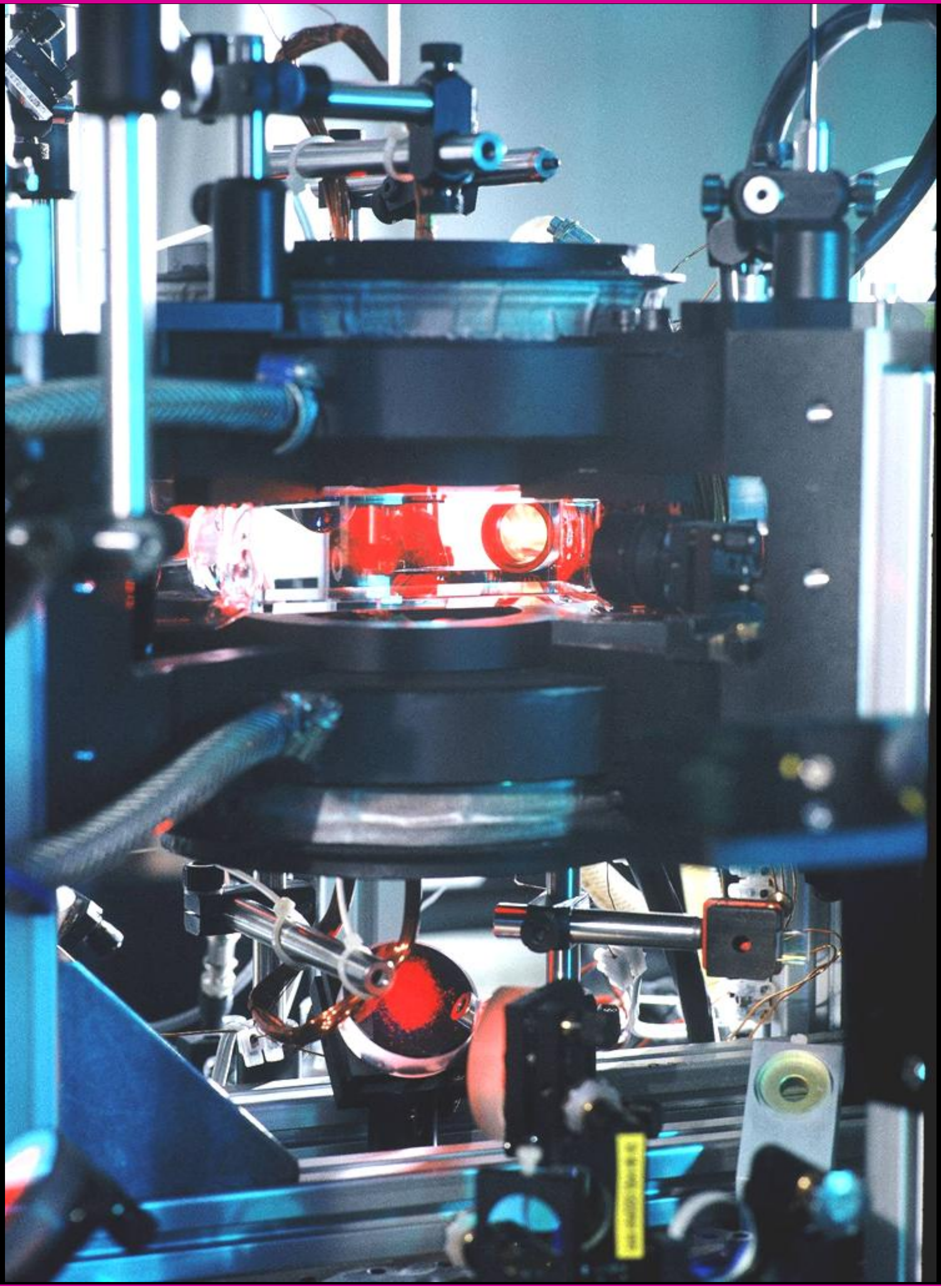
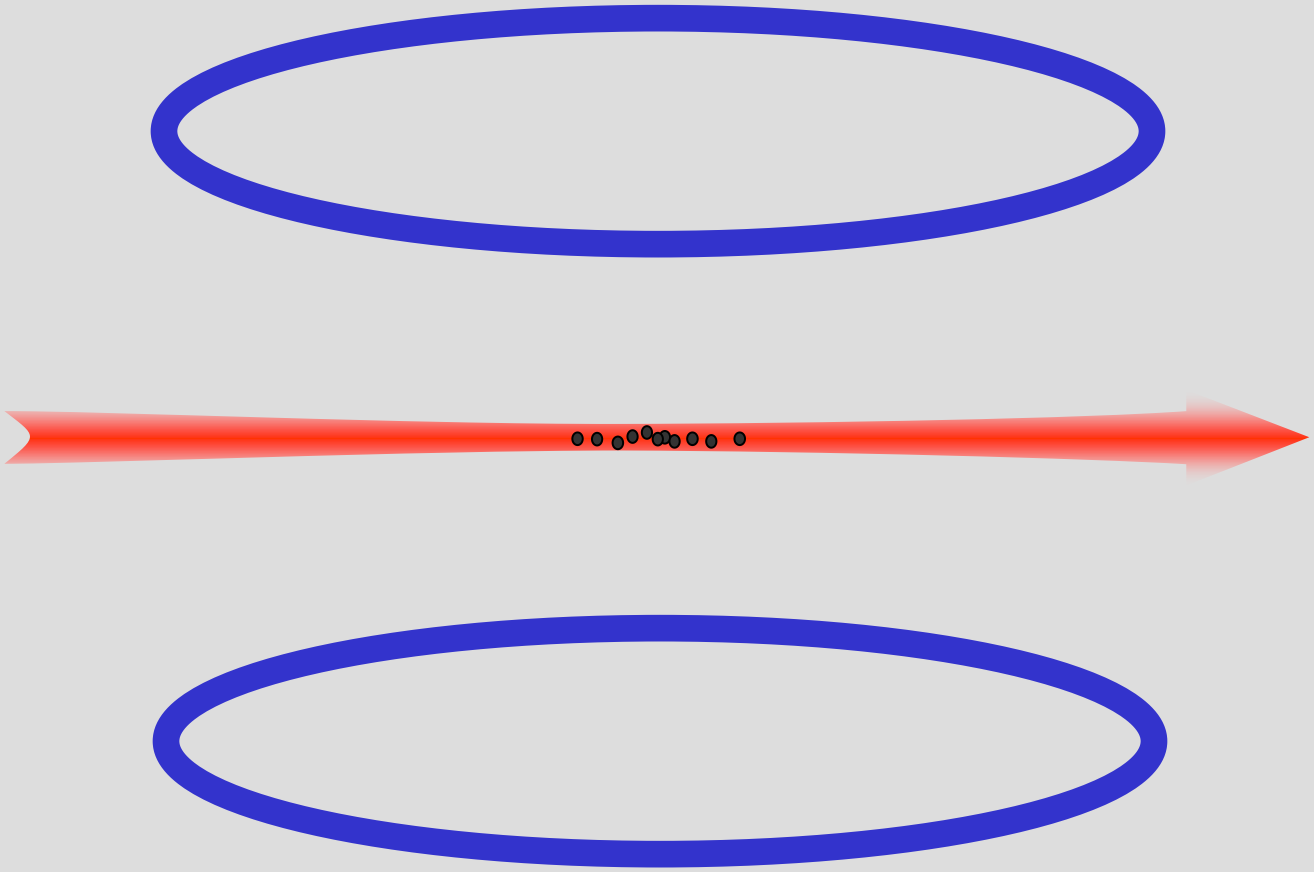


table-top trapping apparatus

ultracold.atoms

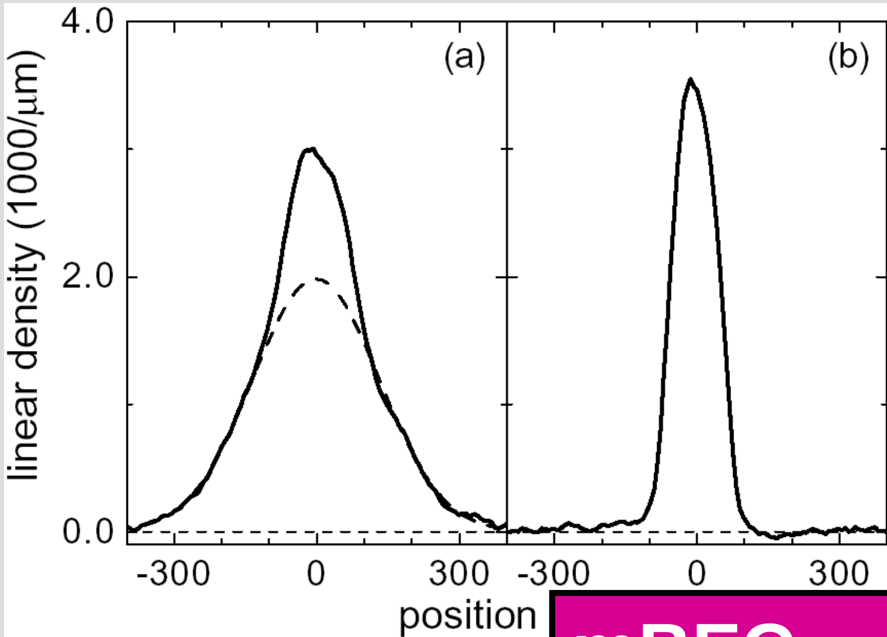


optical trap for evaporative cooling



BEC of molecules

partially condensed **almost pure**



final trap power	28mW
number of molecules	400.000
temperature	430nK
condensate fraction	~20%

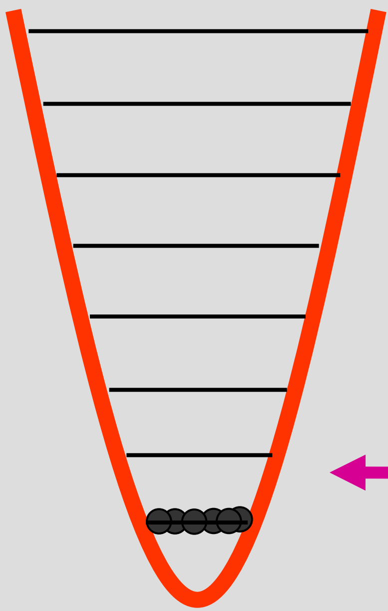
mBEC:
excellent starting point for studies on BEC-BCS crossover

two classes

ultracold.atoms

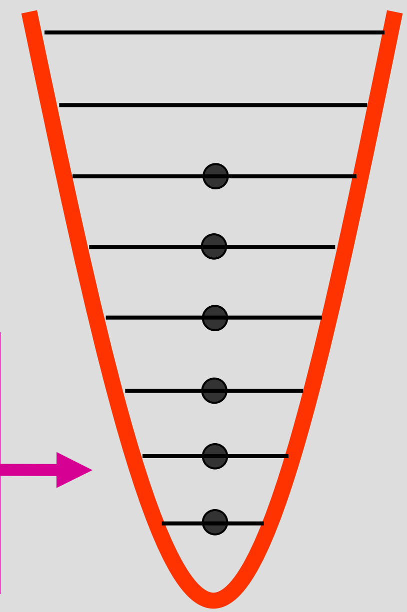
Bosons

integer spin



Fermions

half-integer spin



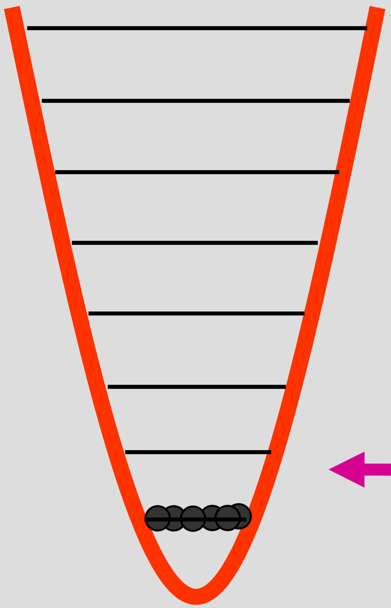
trapped atoms
at *T*=0

these two worlds are connected !

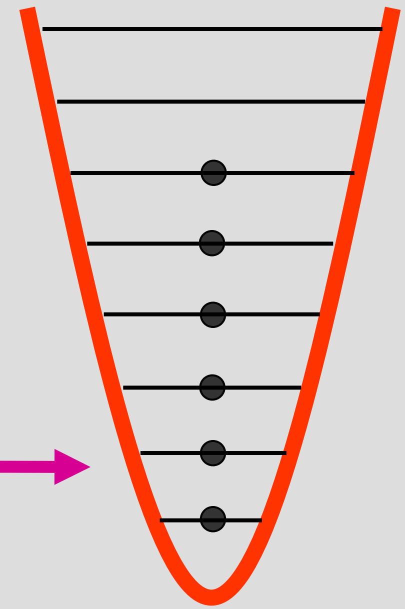
all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas

Bosons
integer spin



Fermions
half-integer spin



trapped atoms at *T*=0

„pairing“ is the key

all in ground state: Bose-Einstein condensate

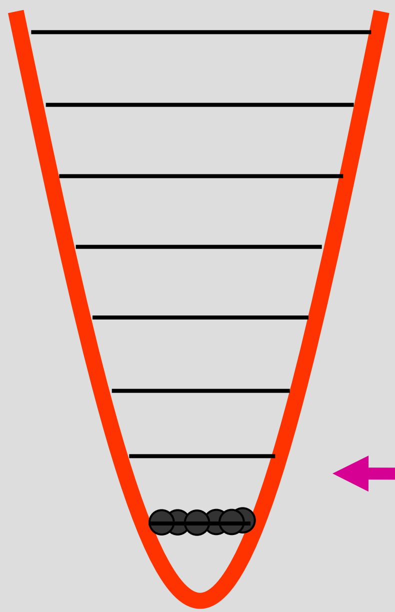
only one particle per state: degenerate Fermi gas

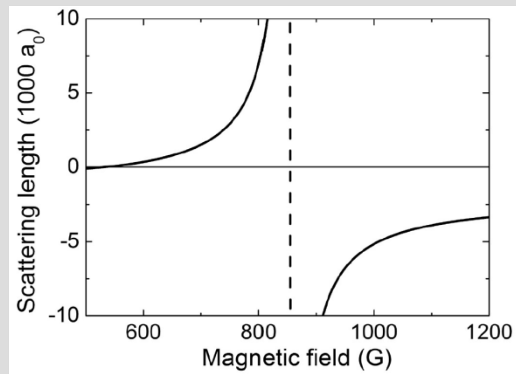
two classes

Bosons
integer spin

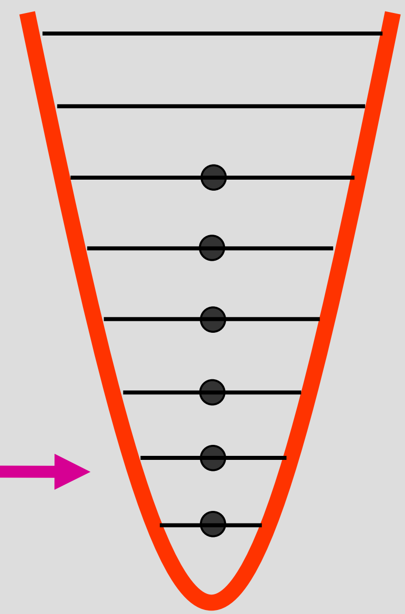
Feshbach resonance

Fermions
half-integer spin





interaction control !!!



all in ground state:
Bose-Einstein condensate

only one particle per state:
degenerate Fermi gas

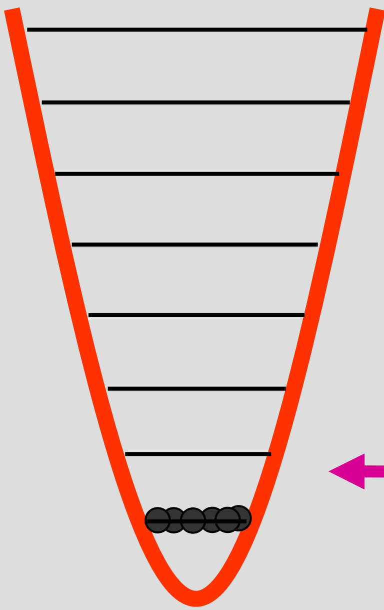
Bosons

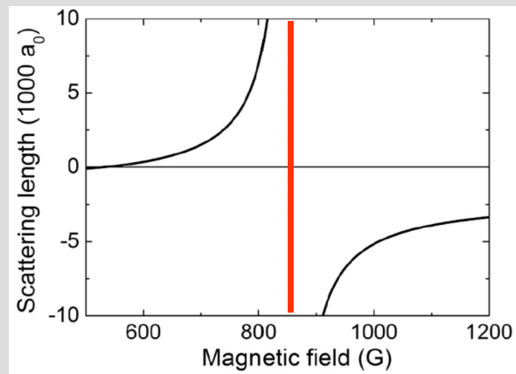
integer spin

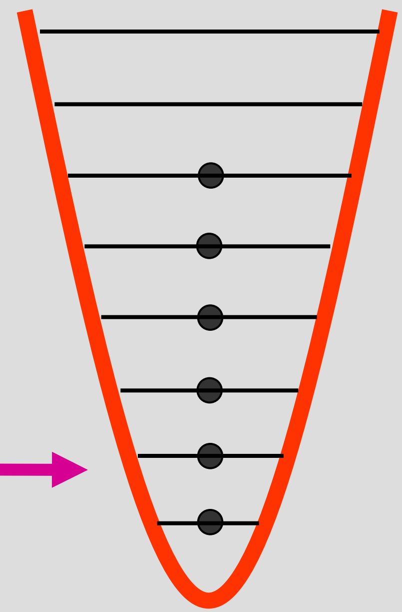
Fermions

half-integer spin

universal !!!







interaction control !!!

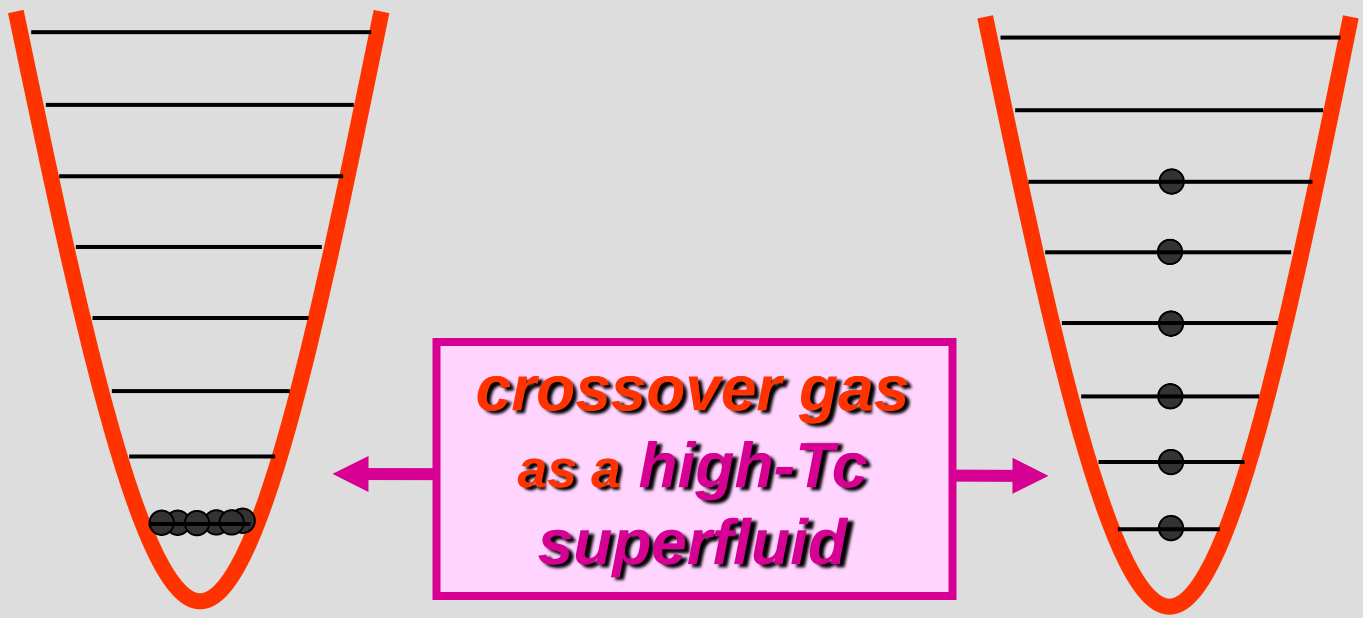
all in ground state: Bose-Einstein condensate

only one particle per state: degenerate Fermi gas

two classes

Bosons
integer spin

Fermions
half-integer spin

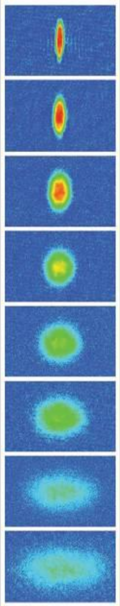


all in ground state:
Bose-Einstein condensate

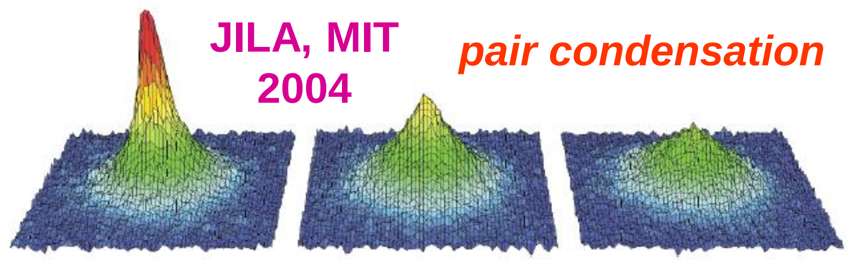
only one particle per state:
degenerate Fermi gas

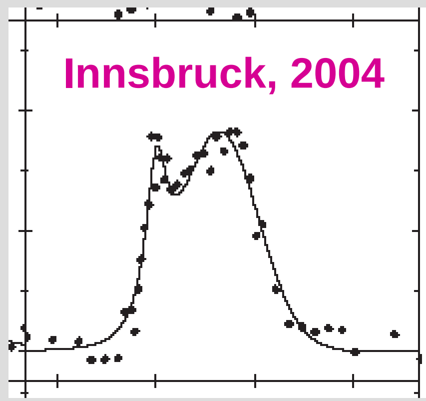
establishing superfluidity

Duke, 2002



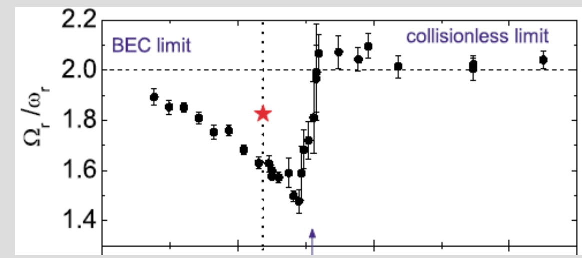
hydrodynamic expansion



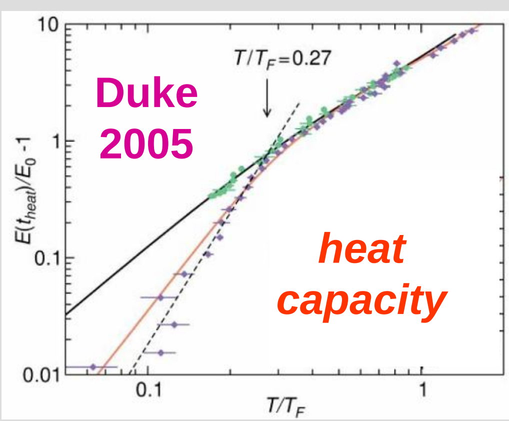


pairing gap

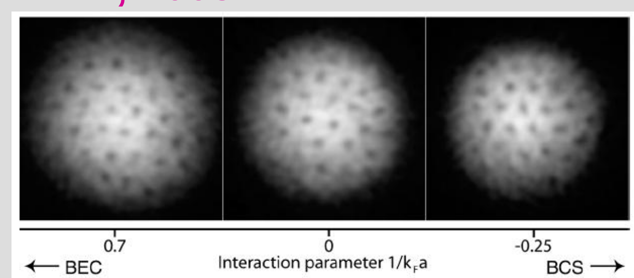
Duke, Innsbruck, 2004



collective modes



MIT, 2005 *vortices*



BEC-BCS crossover well understood,
remarkable benchmark for many-body theories

"high-Tc" superfluidity established

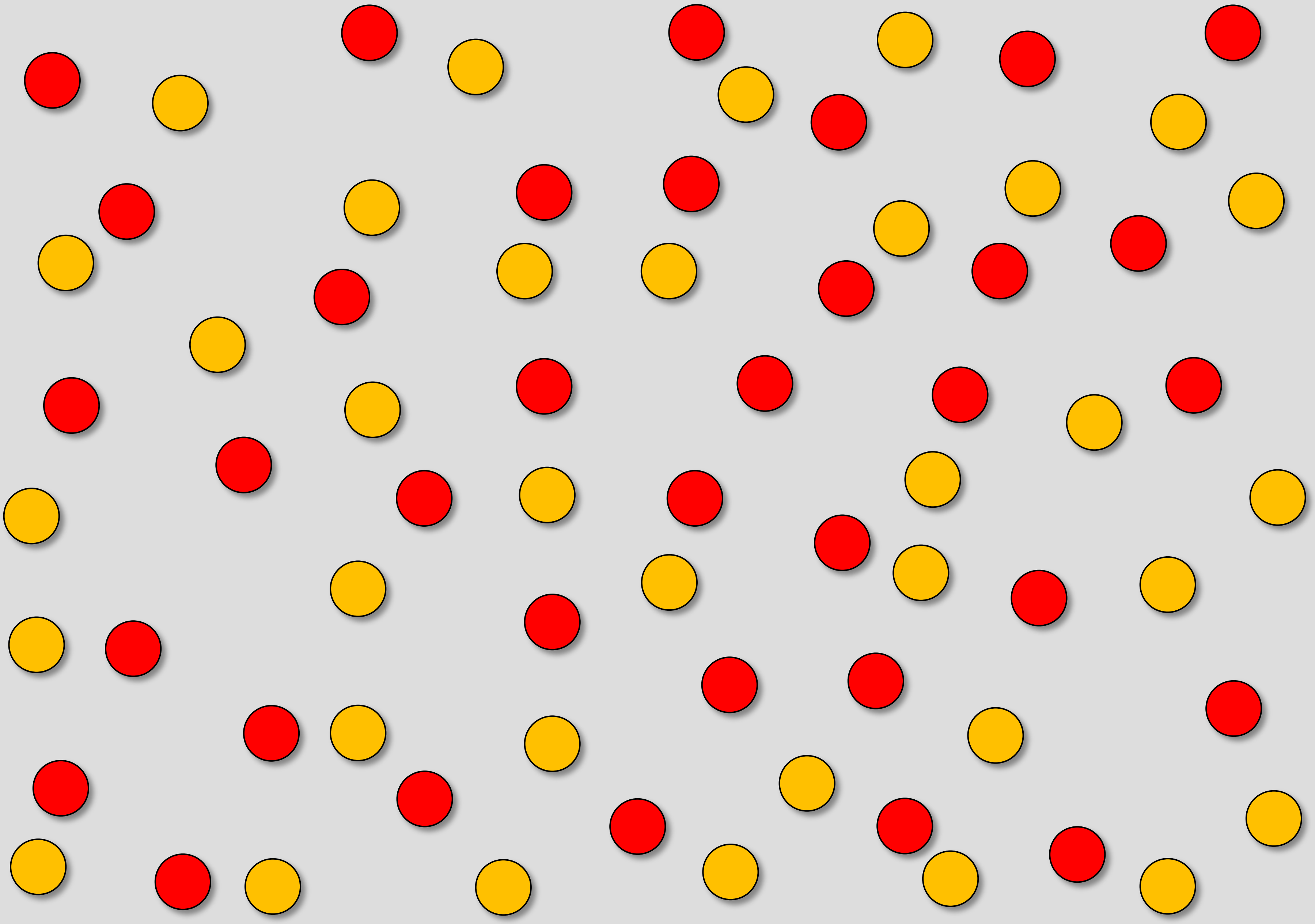
some open issues:
low-D Fermi gases, second sound...

new frontier:
strongly interacting Fermi-Fermi mixtures

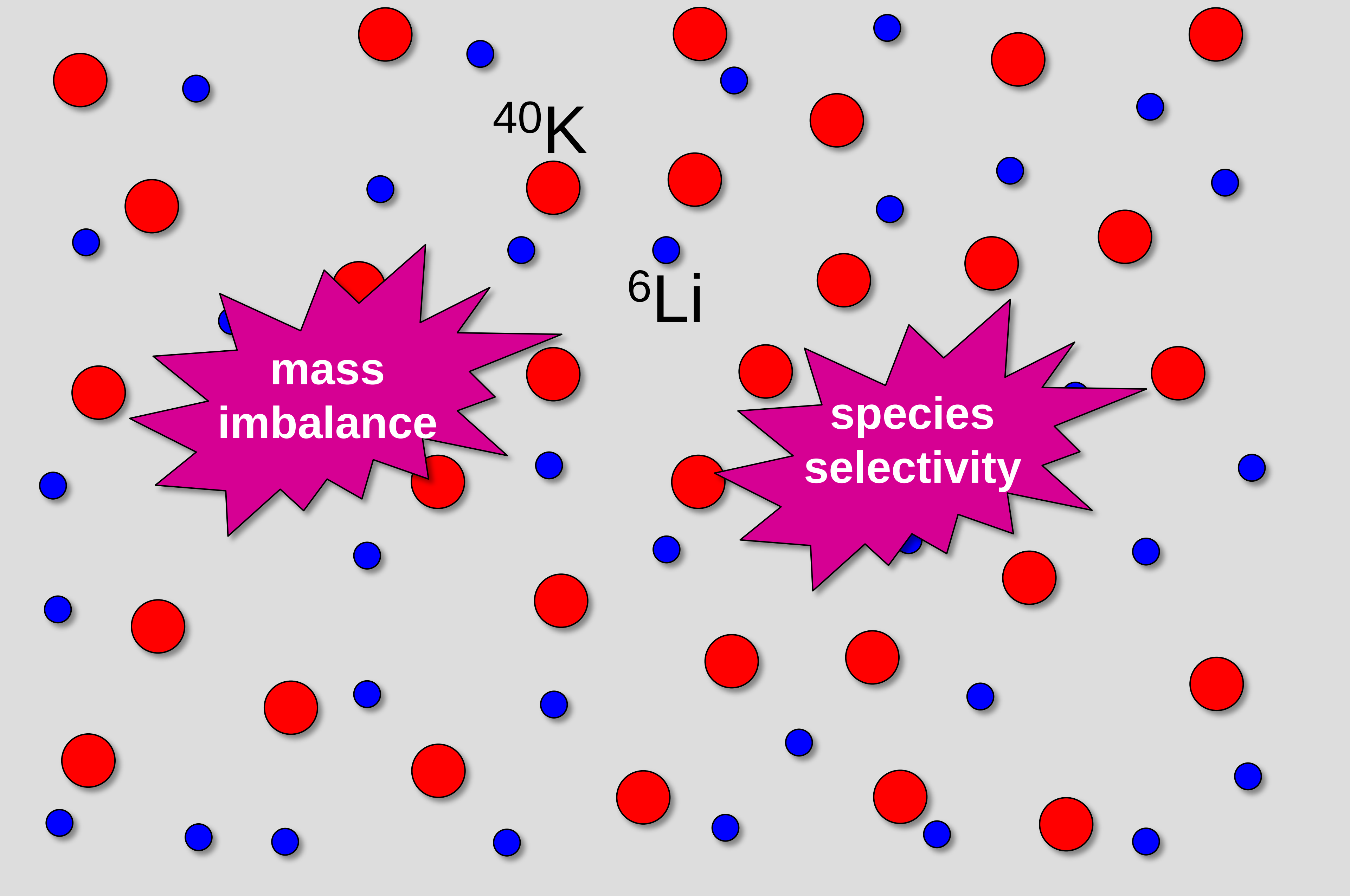
experiments:
Innsbruck, Munich/Singapore, Amsterdam,
MIT, ENS Paris

two-component Fermi system (spin mixture)

ultracold.atoms

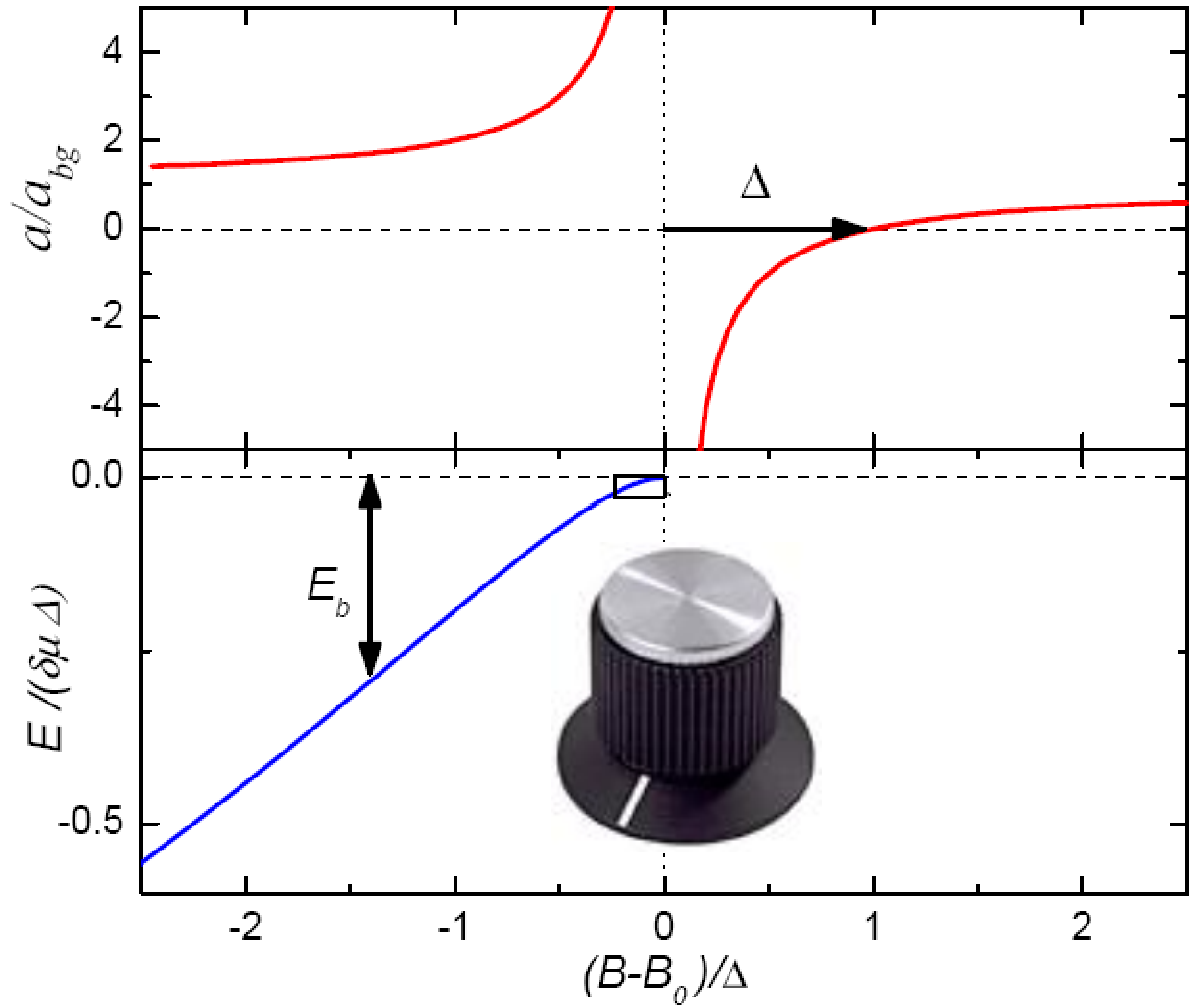


two-species: Fermi-Fermi mixture



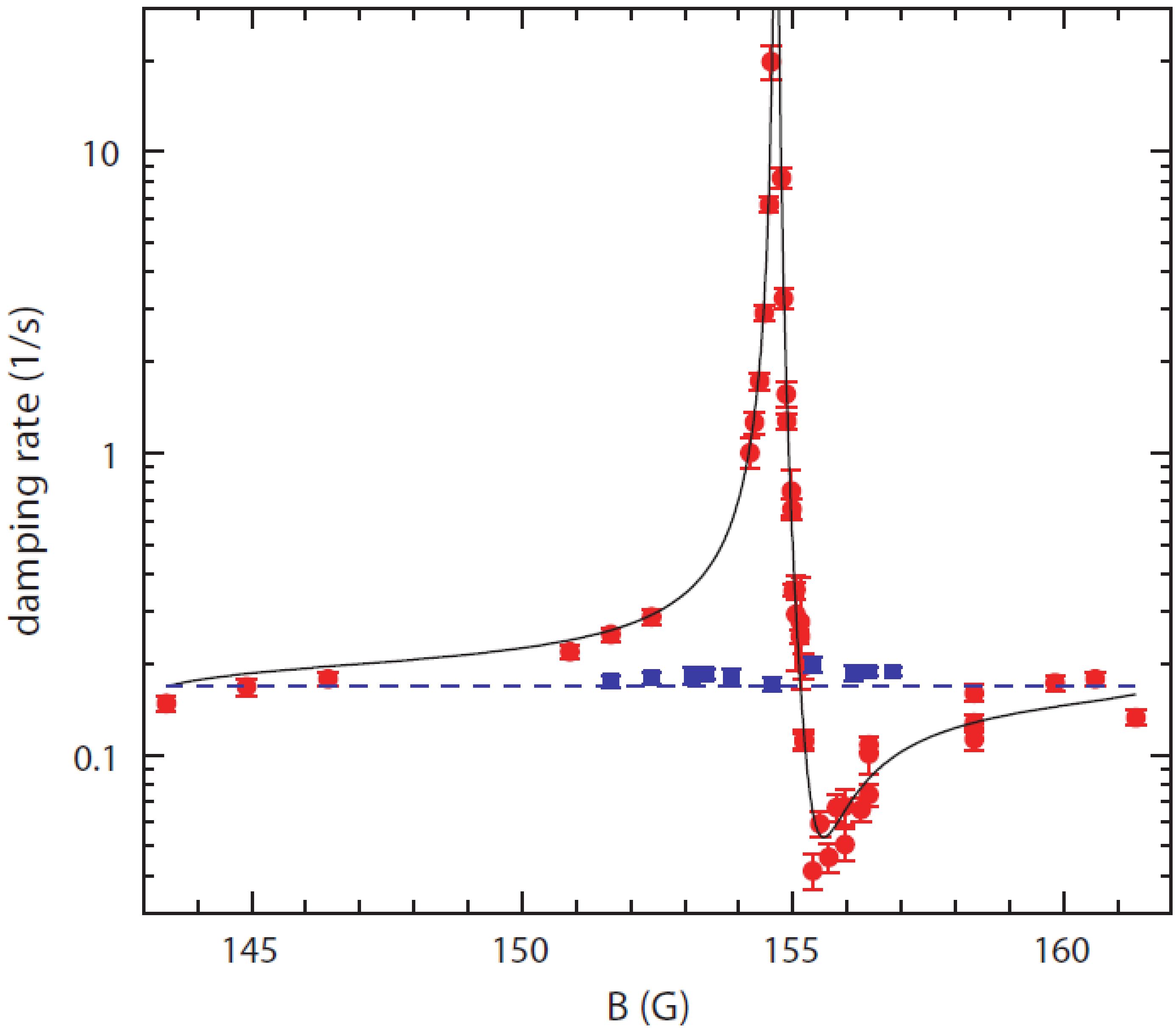
how about tunability?

Feshbach resonance



review: Chin, Grimm, Julienne, Tiesinga, RMP 74, 1205 (2009)

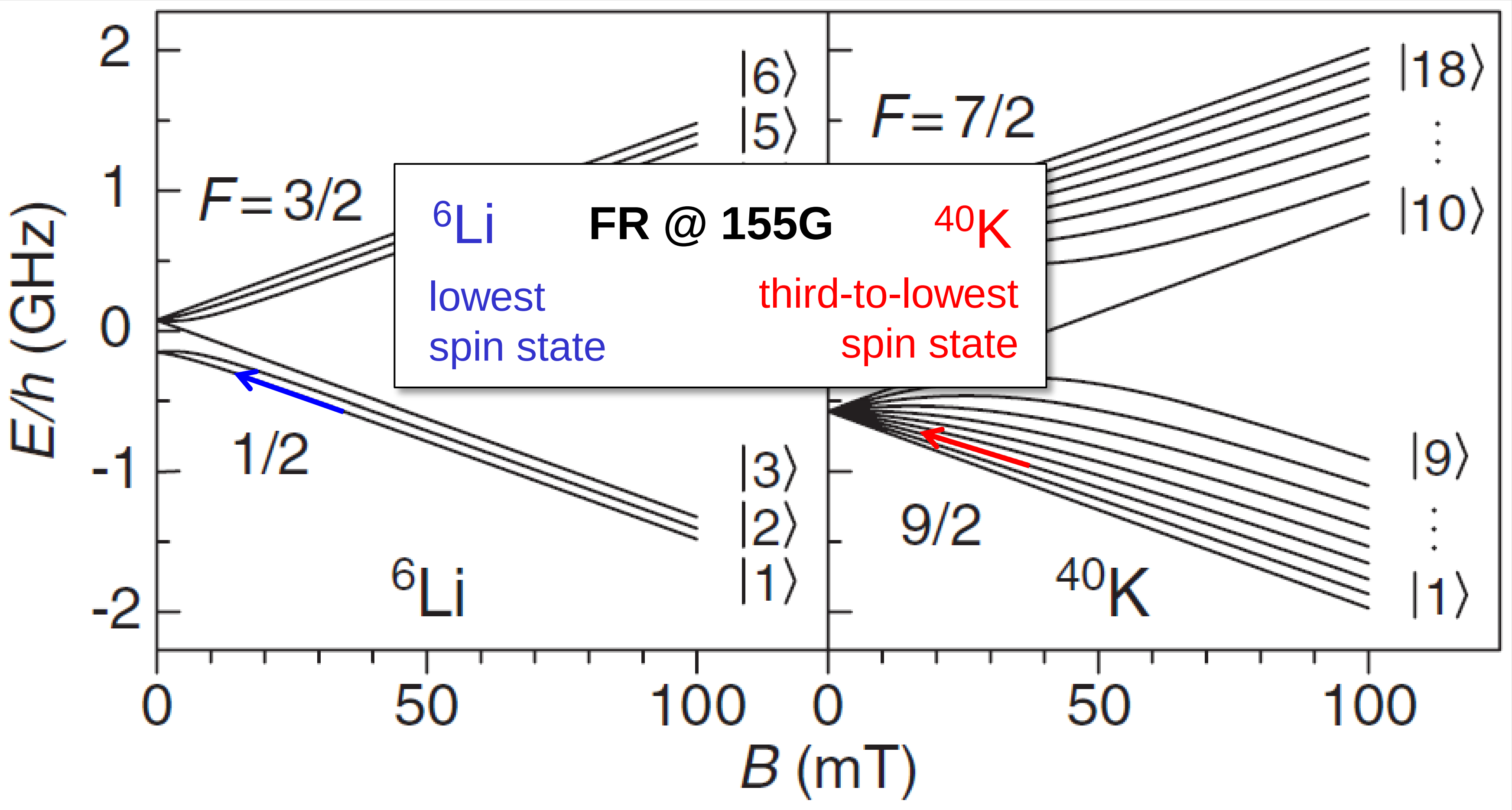
elastic scattering



Li – K
spin
channels

1 – 3
1 – 2

spin channels



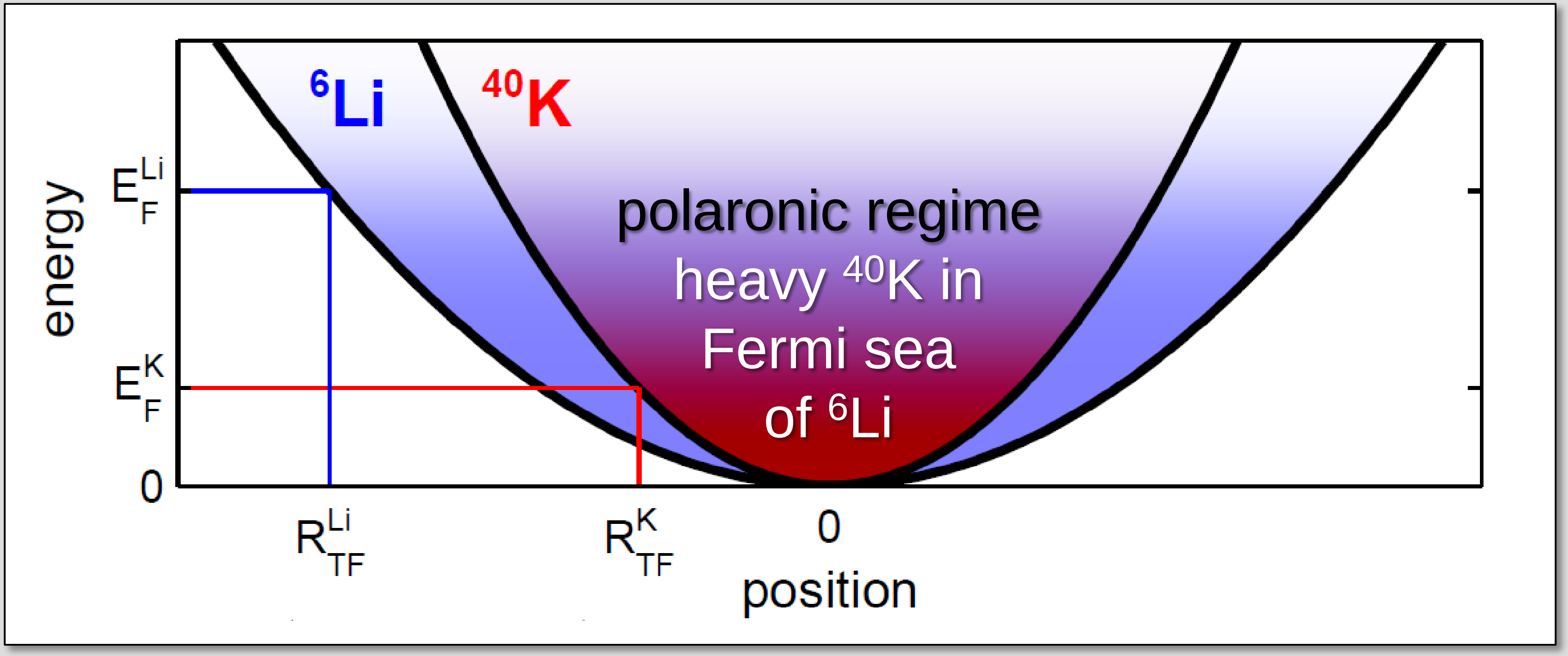
powerful tool-box of radio-frequency transitions

experimental parameters

^{6}Li: $N = 1.9 \times 10^5$
$E_F = 1.6\ \mu K$

^{40}K: $N = 1.2 \times 10^4$
$E_F = 400\ nK$

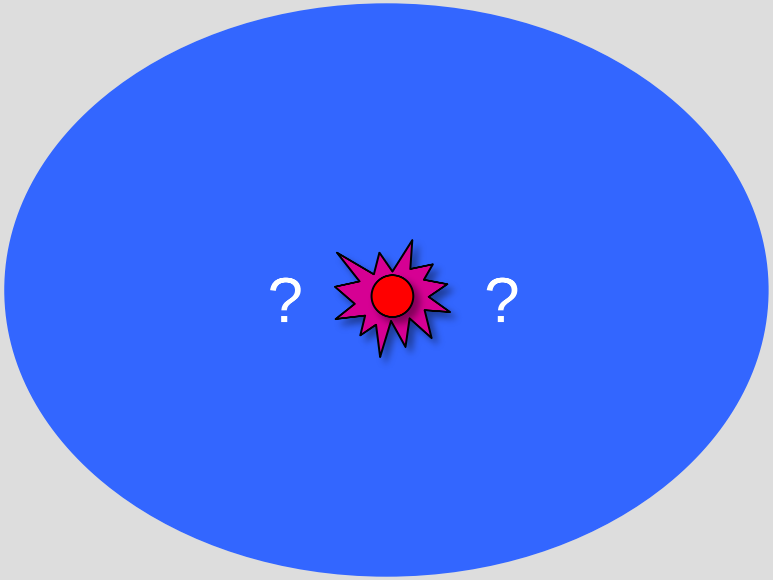
T = 330 nK



Li Fermi energy
our leading energy scale!

$1/k_F^{Li} \approx 3000\ a_0$

Impurity in a Fermi sea



weak ($k_F|a|<<1$): simple mean-field description

stronger: *quasi-particle* (polaron)
à la Landau Fermi liquid theory

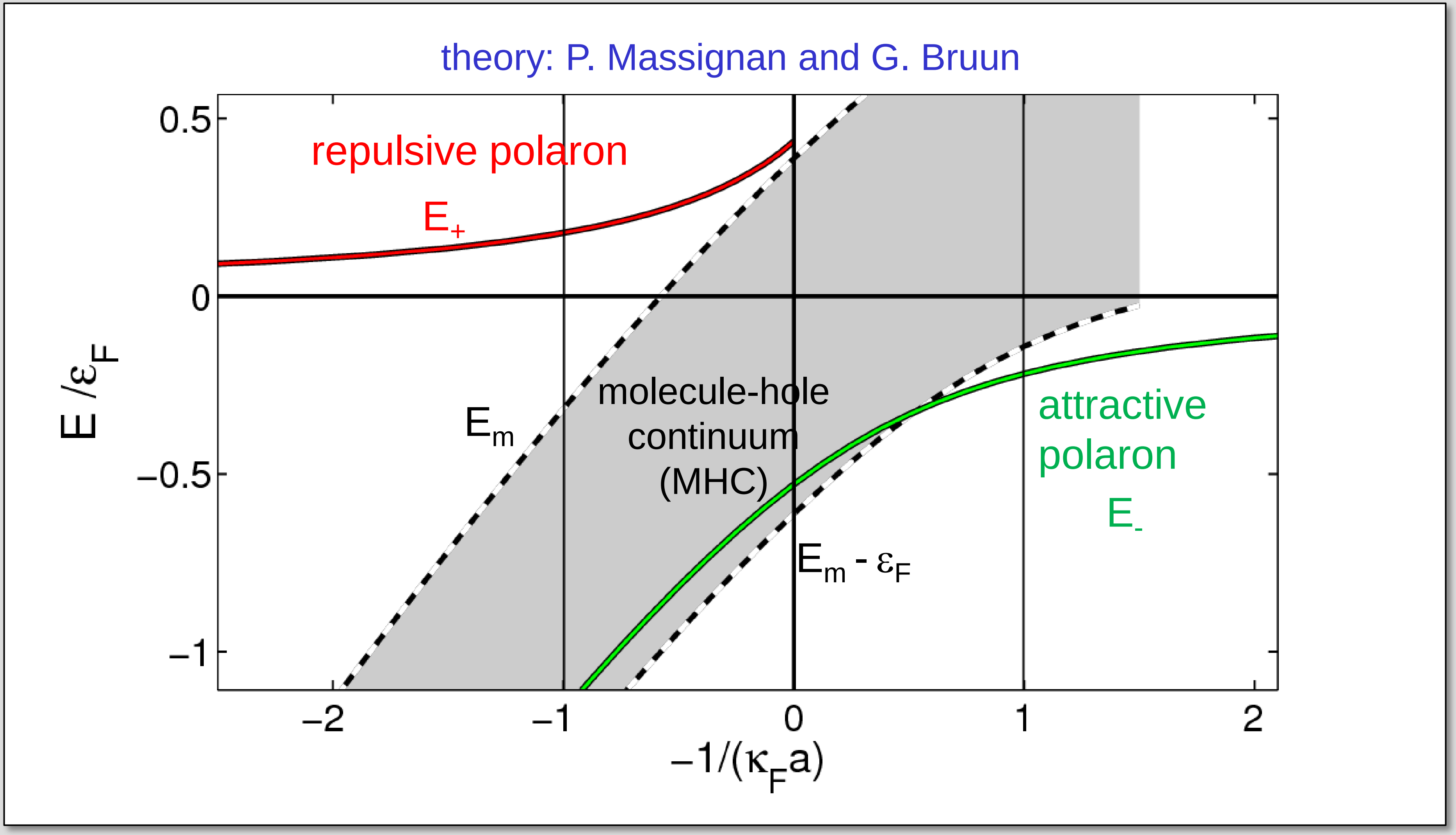
strong ($k_F|a| > 1$): polaron or molecule?

Innsbruck Fermi-Fermi team

Metastability and coherende of ***repulsive polarons*** *in a strongly interacting Fermi mixture*
C. Kohstall et al., Nature, in press; arXiv:1112.0020

theory collaboration

energy diagram (T=0)



“reverse” rf spectroscopy

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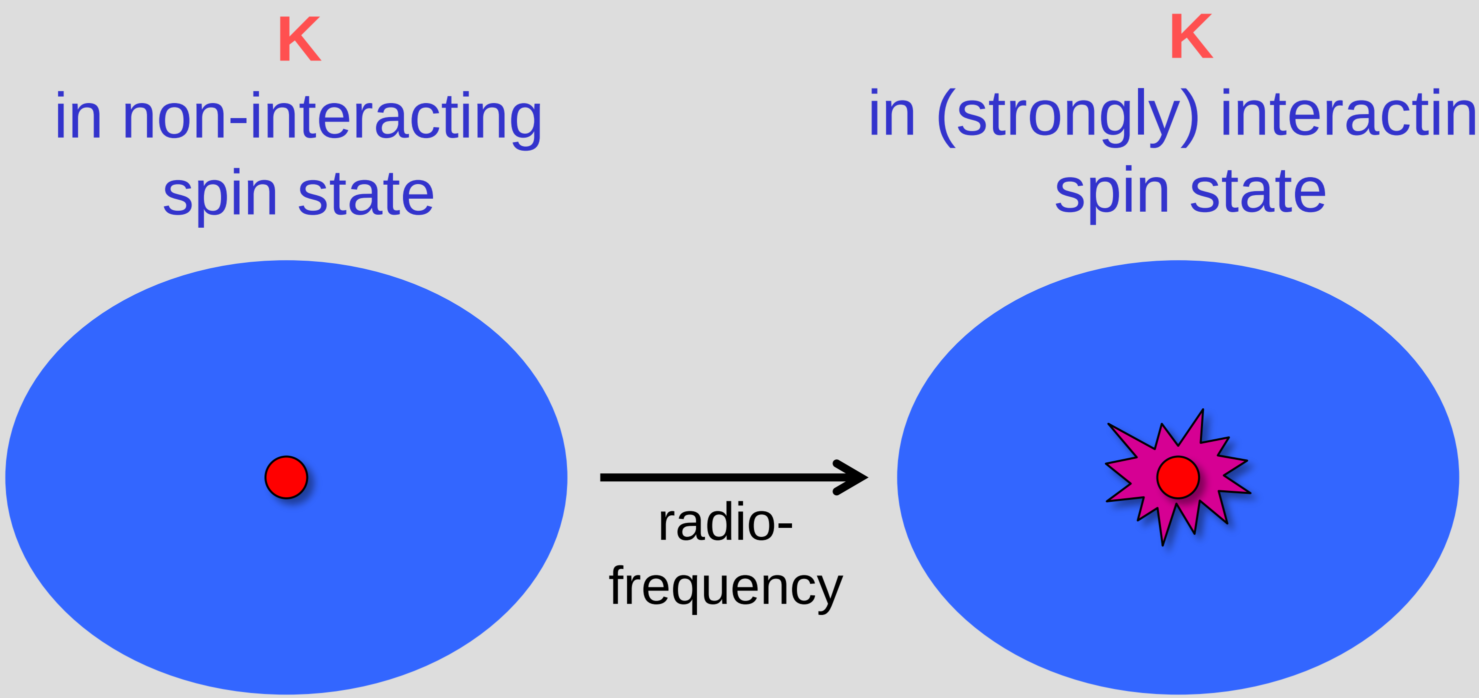
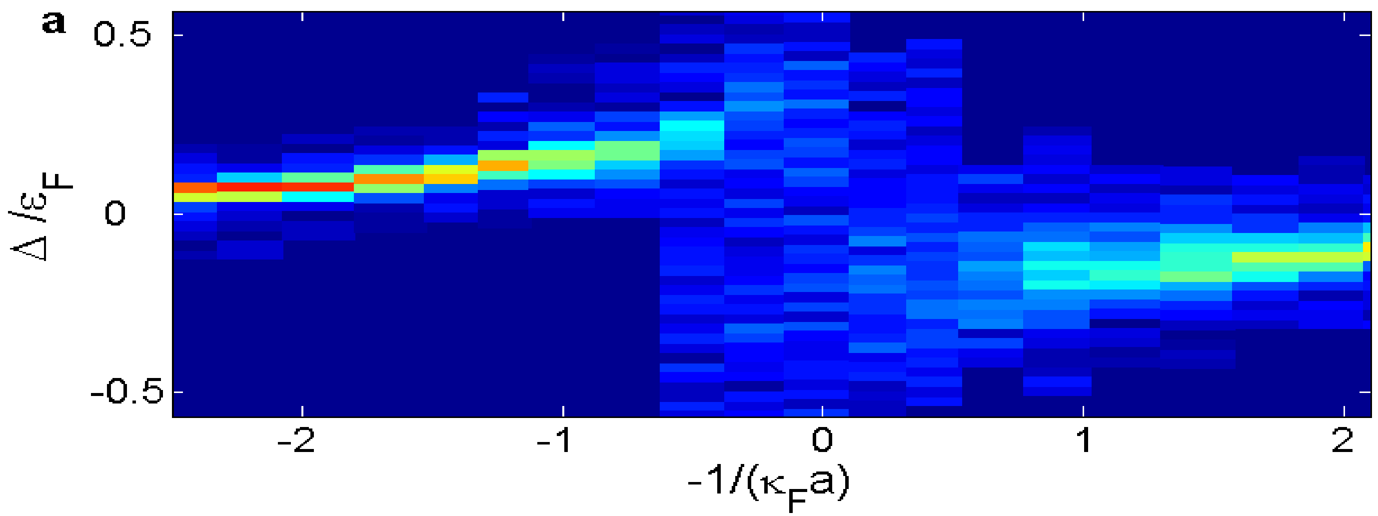


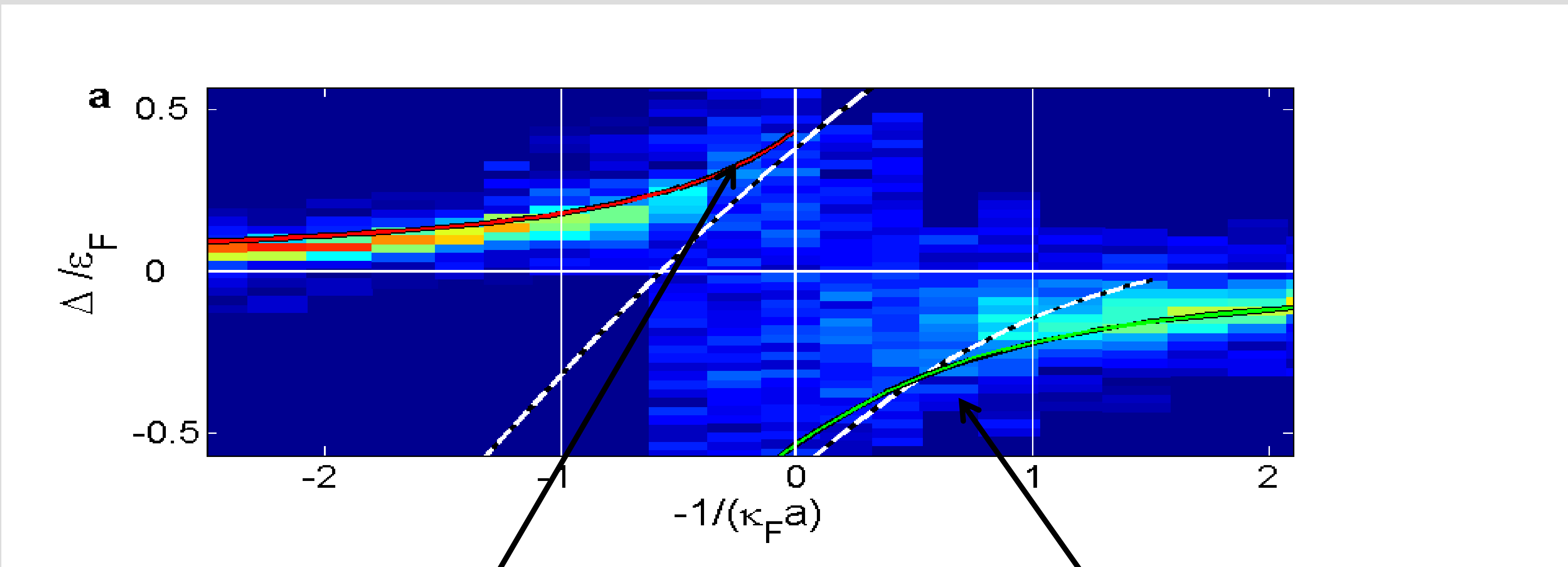
NB: different from standard rf probing !

spectral response

1 ms π-pulse (w/o interaction)



1 ms π-pulse (w/o interaction)

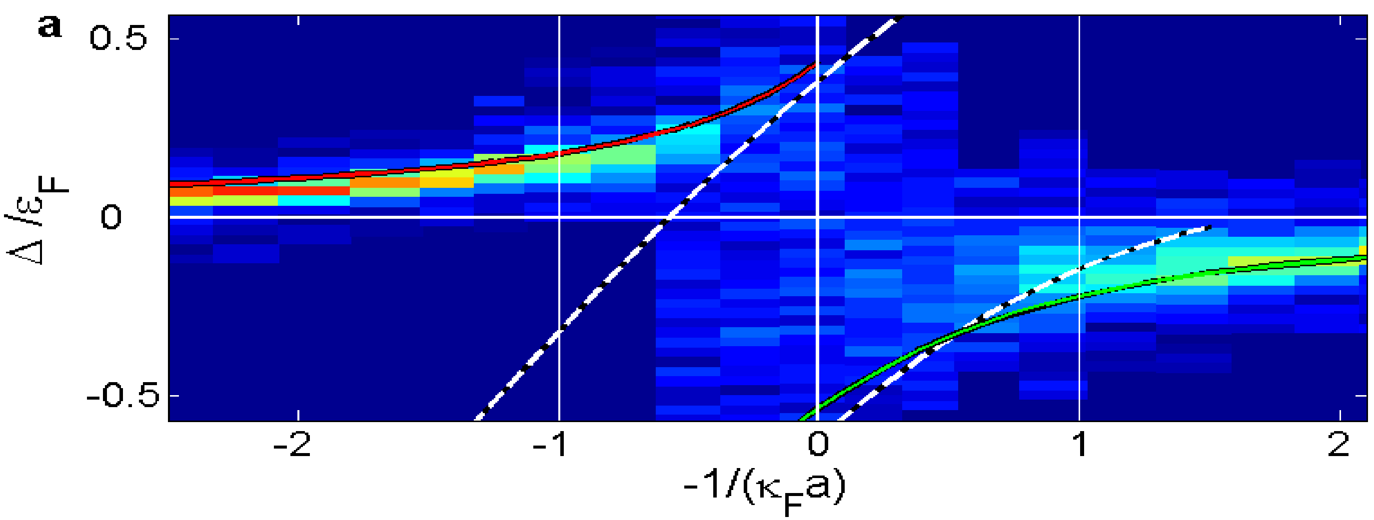


repulsive polaron observed up to $-1/\kappa_F a = -0.3$

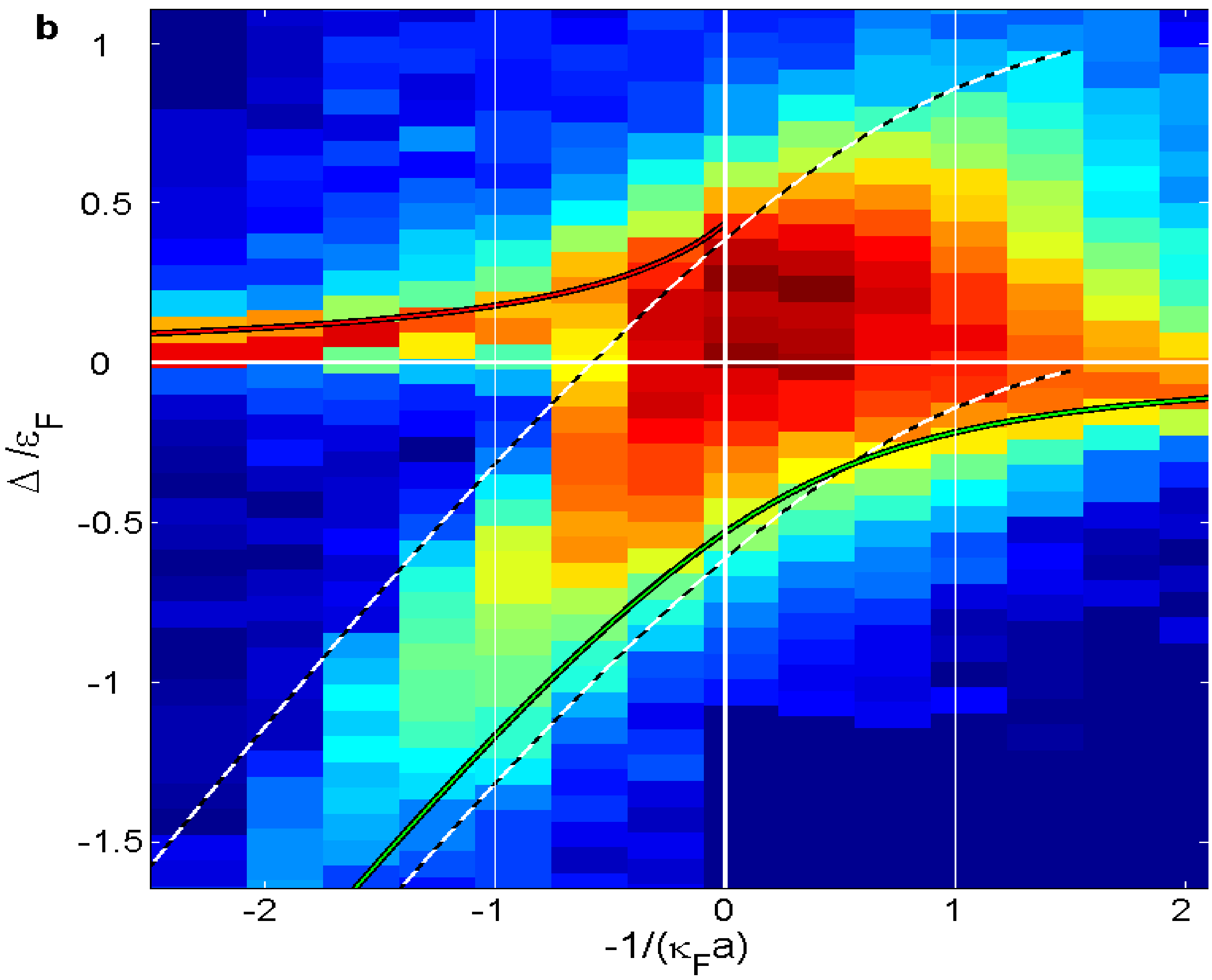
polaron-molecule transition $-1/\kappa_F a = 0.6$

spectral response

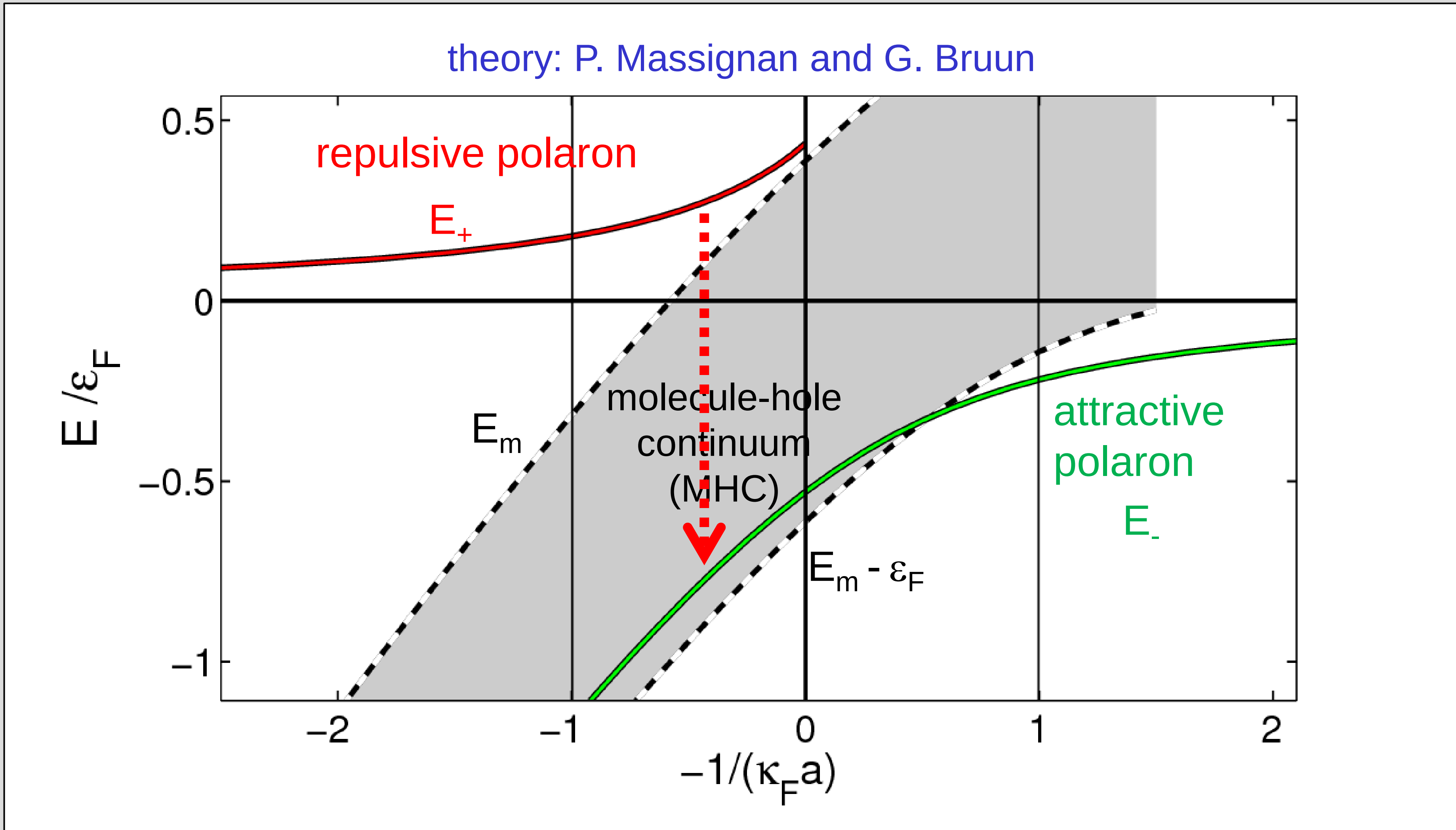
let‘s crank up the rf power (100 x)



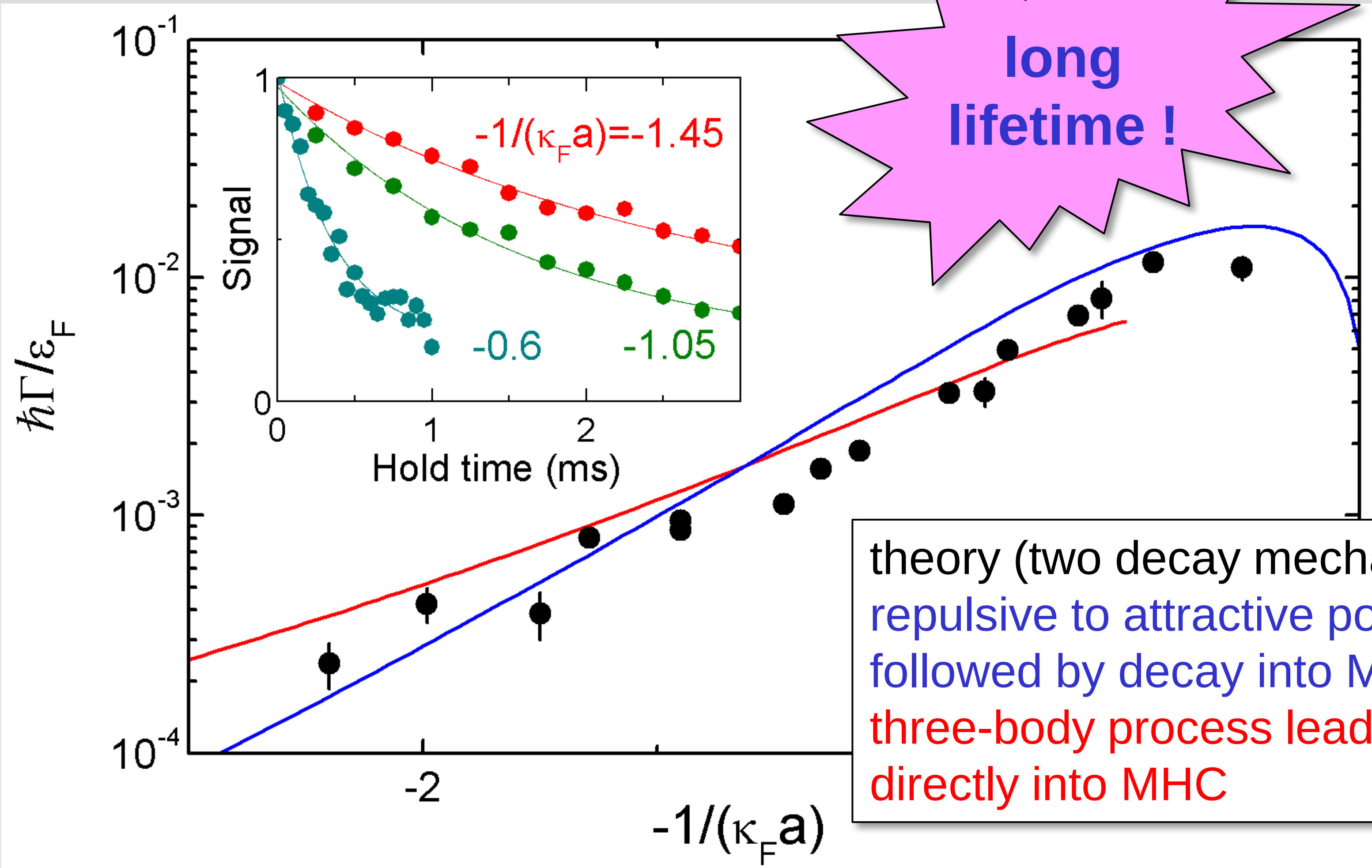
spectral response



energy diagram (T=0)



measured decay rates



long lifetime !

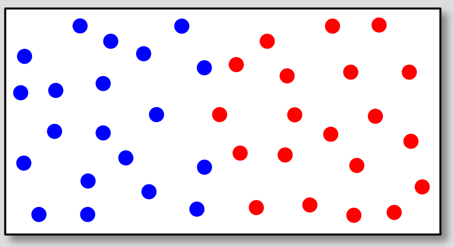
theory (two decay mechanisms)

repulsive to attractive polaron, followed by decay into MHC

three-body process leading directly into MHC

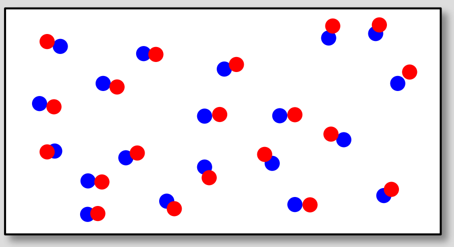
the big question

phase separation
(ferromagnetism)



?

molecules



general conclusion

ultracold atoms: unique, well-controllable model systems for a wide range of phenomena

- strongly interacting quantum matter
- condensed-matter physics
- few-body and many-body physics
- ....

exquisite benchmarks for quantum many-body theories

FWF
Der Wissenschaftsfonds.
SFB
FoQuS
Foundations and Applications of Quantum Science

thank you for your attention !

universität innsbruck

IQI

FWF
Der Wissenschaftsfonds.

SFB FoQuS
Foundations and Applications of Quantum Science

how long?

ultracold.atoms

60 min (incl. disc.) seminar talk
talk way too long!!
could have stopped after the Efimov part (50min)
general intro took 20min.
could only rush through fermion part