Quantum Mixtures with Ultracold Atoms, Varenna, 18-23 July 2022

Rudolf Grimm

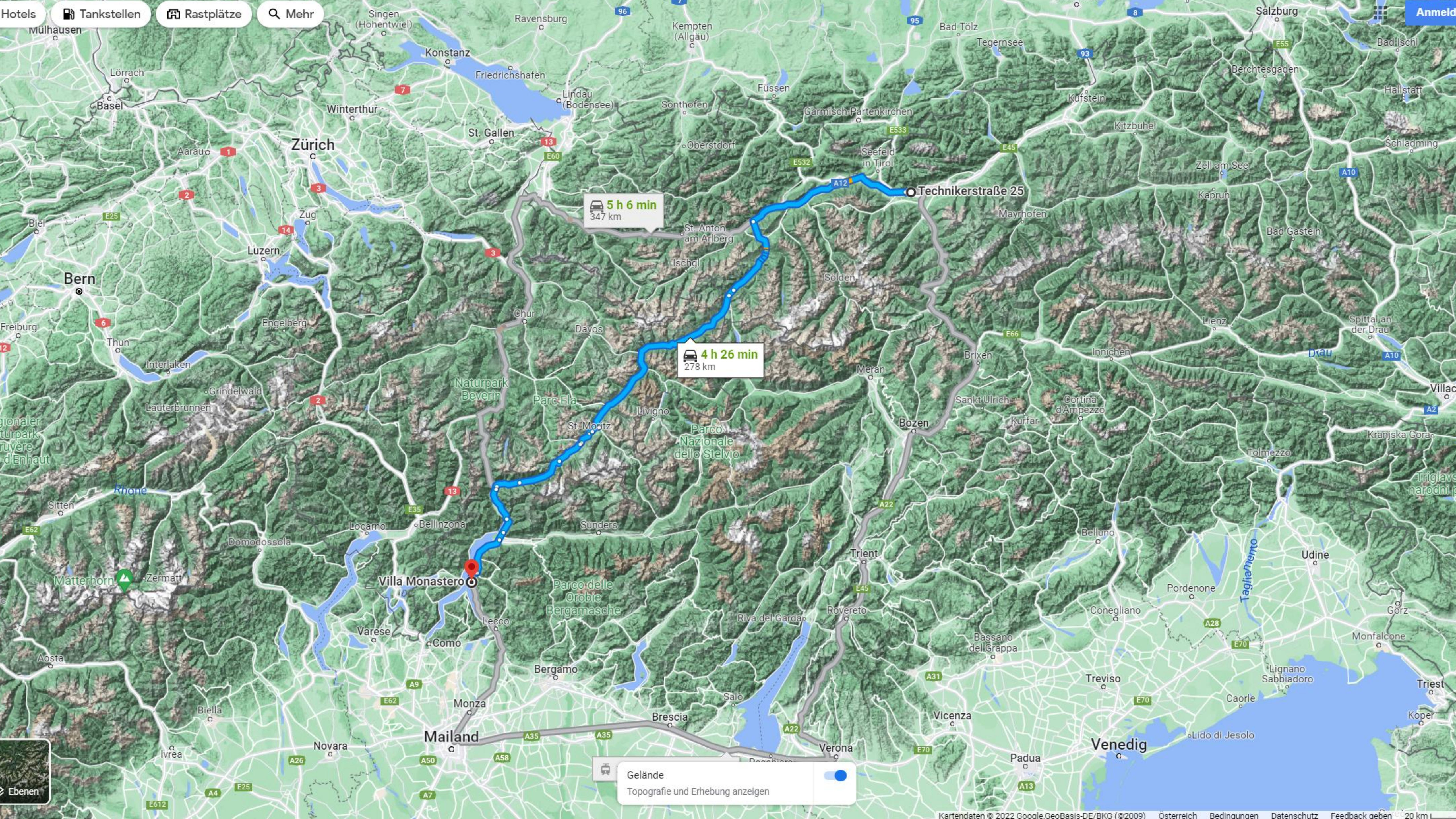
Experiments with quantum mixtures I: General ideas, a bit of history, and...

Austrian Acad. of Sciences

IQI

universität innsbruck

Inst. of Experimental Physics


Hotels
Tankstellen
Rastplätze
Mehr
Technikerstraße 25
Villa Monastero
5 h 6 min
347 km
4 h 26 min
278 km
Zürich
Bern
Basel
Luzern
St. Gallen
Konstanz
Friedrichshafen
Lindau (Bodensee)
Kempten (Allgäu)
Füssen
Garmisch-Partenkirchen
Seefeld in Tirol
Salzburg
Kufstein
Kitzbühel
St. Anton am Arlberg
Chur
Davos
St. Moritz
Livigno
Sölden
Meran
Bozen
Brixen
Lienz
Trient
Rovereto
Bellinzona
Locarno
Como
Lecco
Varese
Bergamo
Monza
Mailand
Brescia
Verona
Vicenza
Padua
Venedig
Treviso
Udine
Zermatt
Matterhorn
Interlaken
Thun
Grindelwald
Lauterbrunnen
Parco Nazionale dello Stelvio
Parco delle Orobie Bergamasche
Naturpark Beverin
Gelände
Topografie und Erhebung anzeigen
Ebenen
Kartendaten © 2022 Google,GeoBasis-DE/BKG (©2009)
Österreich
Bedingungen
Datenschutz
Feedback geben
20 km


Eurovision
SONG CONTEST
TURIN 2022
All 40 songs from Europe's favourite TV show

mixture

combination of two or more pure substances
in which each retains its individual chemical properties
(can separate them by physical means)

pure matter vs. mixture

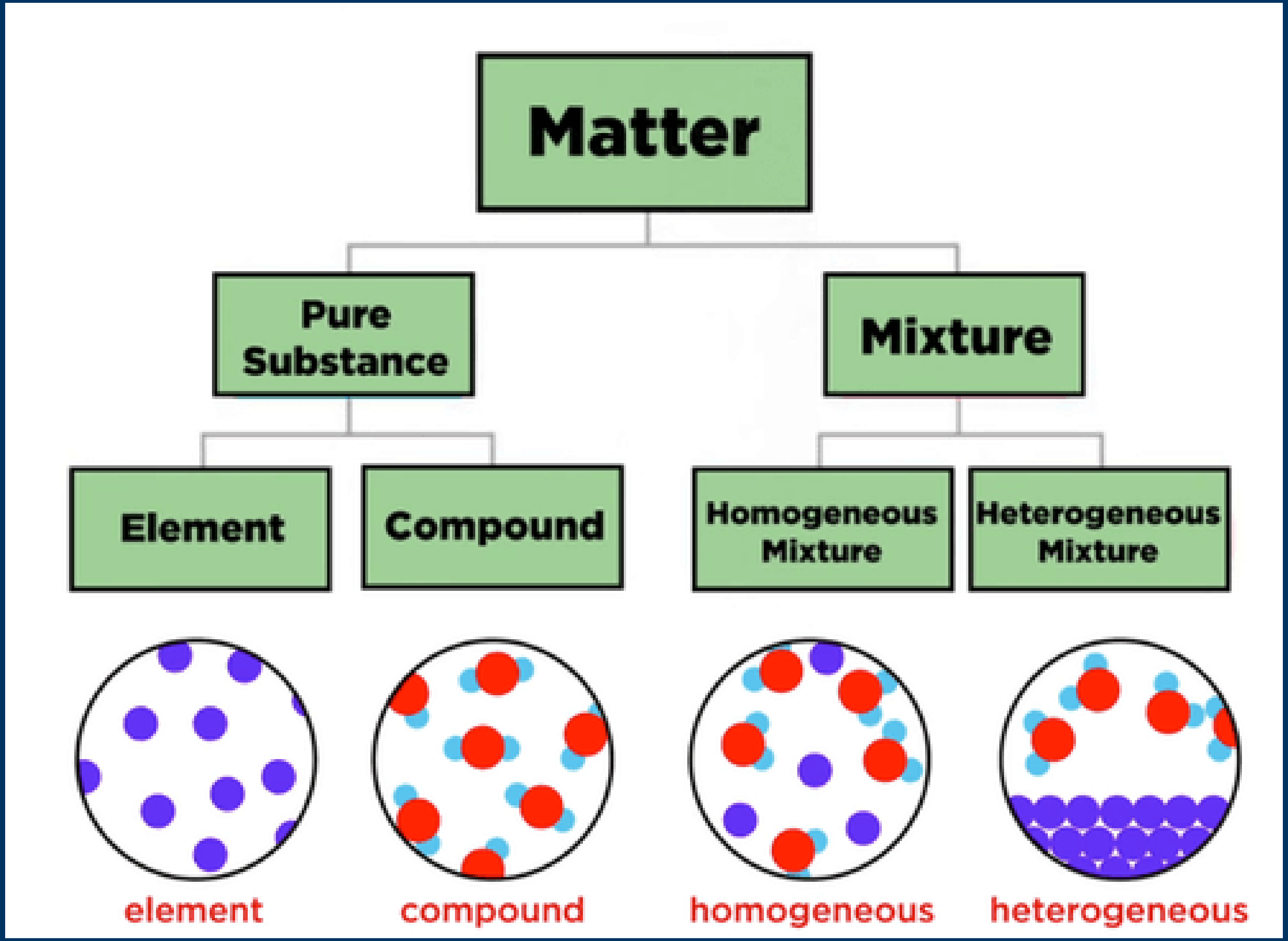


Figure https://www.pinterest.com/pin/660903314050618202/

atomic quantum gases

molec. quantum gases

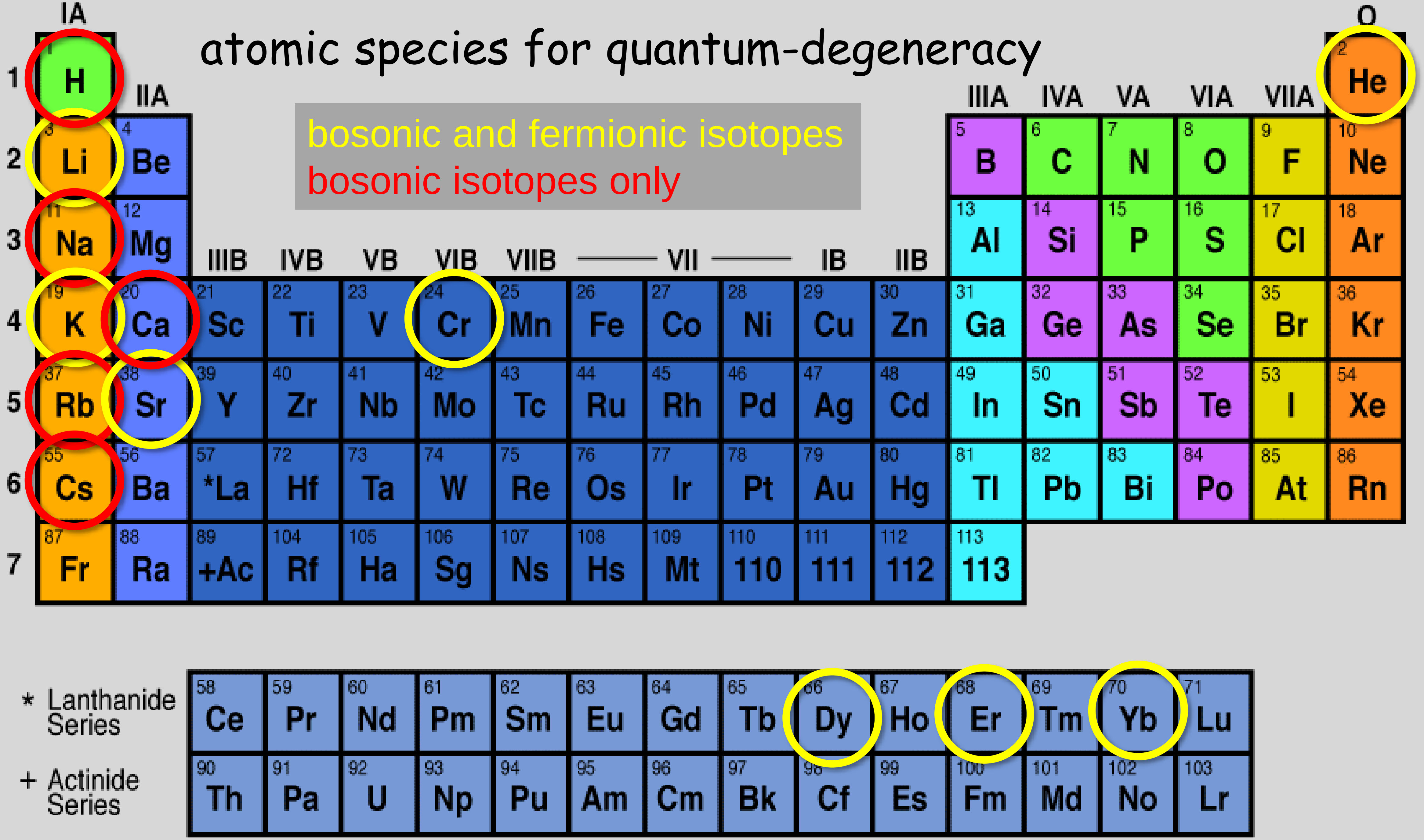
quantum gas mixtures

immiscible quantum gas mixtures

atomic species for quantum-degeneracy

bosonic and fermionic isotopes

bosonic isotopes only



why mixtures – some general arguments

combining different properties

different quantum statistics
BF mixtures

sympathetic cooling

species-specific
optical manipulation

mass imbalance

creating systems with new properties

new quantum phases
in optical lattices

heteronuclear
molecules

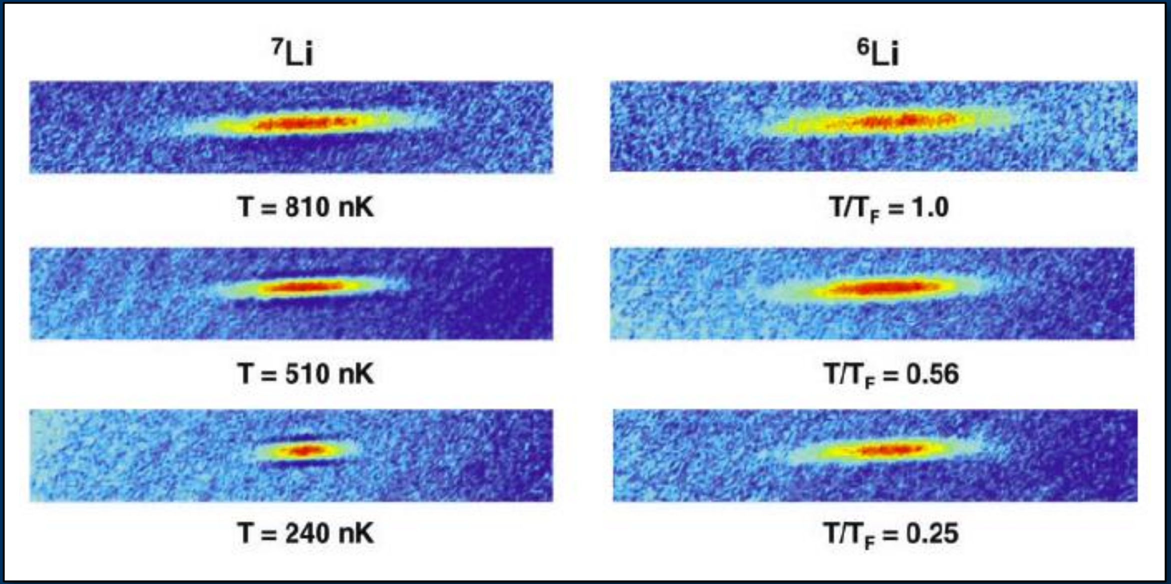
novel superfluids with
mass imbalance

mixtures of three kinds

	quantum statistics	multi-compon.	coherent population control	specific optical potentials	mass imbalance	expt. complexity
spin mixture	BB, FF	yes	yes	no	no	moderate
isotope mixture	BB, (FF), BF	(no)	no	(no)	(no)	medium
species mixture						

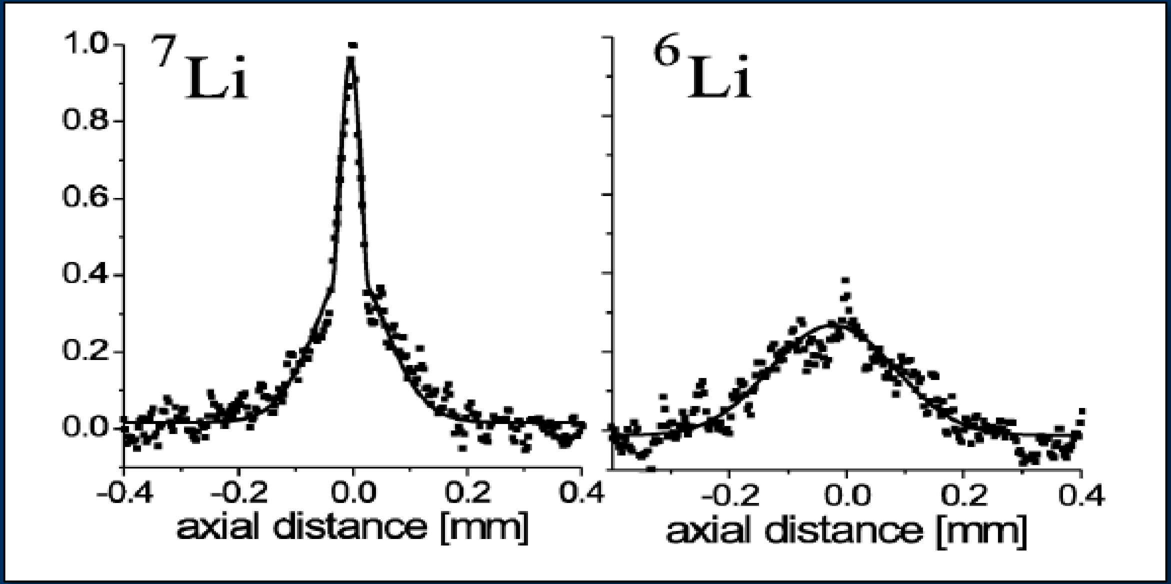
Bose-Fermi isotope mixture of lithium

Rice Univ., Hulet group



Truscott et al., Science 291, 257 (2001)

ENS Paris, Salomon group



Schreck et al., Phys. Rev. Lett. 87, 080403 (2001)

mixtures of three kinds

	quantum statistics	multi-compon.	coherent population control	specific optical potentials	mass imbalance	expt. complexity
spin mixture	BB, FF	yes	yes	no	no	moderate
isotope mixture	BB, (FF), BF	(no)	no	(no)	(no)	medium
species mixture	BB, FF, BF	(no)	no	yes	yes	high

Ultracold mixtures of <u>different species</u>

brief history

cold species mixtures in MOTs

mid-late 90's

bi-alkali combinations

Na-K, Na-Rb (São Paolo, Bagnato group)

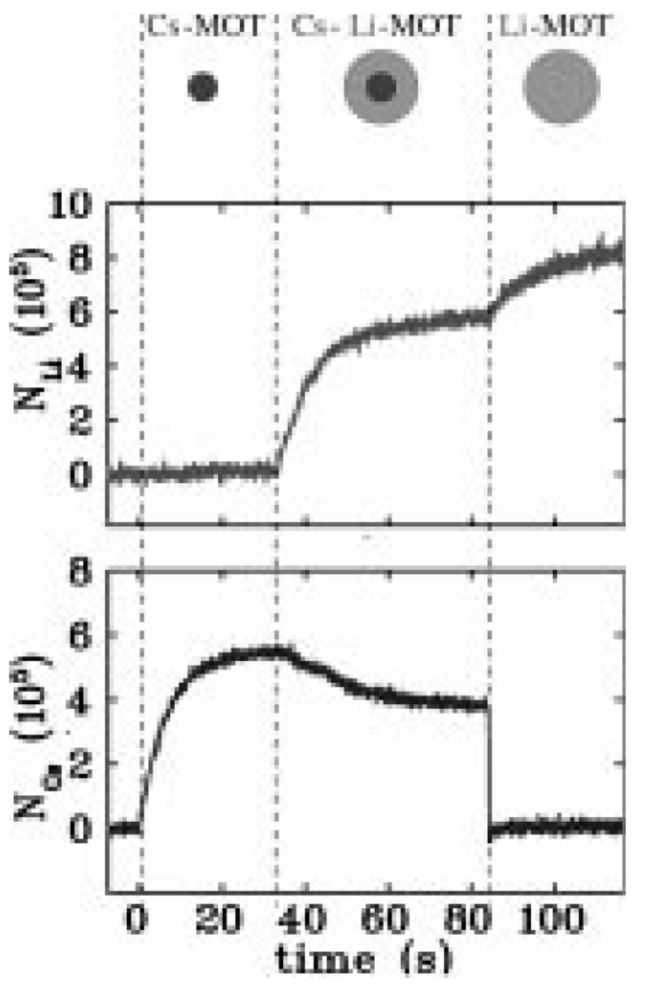
Santos et al., PRA 52, R4340 (1995)
Telles et al., PRA 59, R23 (1998)

Na-Cs (Rochester, Bigelow group)

Shaffer et al., PRL 82, 1124 (1998)

Li-Cs (Heidelberg, Weidemüller/Grimm group)

Schlöder et al., EPJD 7, 331 (1999) →



interest: creation of **heteronuclear molecules**

degenerate species mixtures (first experiments)

early 00's

K-Rb (LENS, Inguscio group)

Modugno et al., Science 294, 1320 (2001)

sympathetic cooling
of ^{41}K to BEC

Li-Na (MIT, Ketterle group)

Hadzibabic et al., PRL 88, 160401 (2002)

K-Rb (LENS, Inguscio group)

Roati et al., PRL 89, 150403 (2002)

sympathetic cooling
of ^{6}Li / ^{40}K to Fermi degeneracy

K-Rb (JILA, Jin group)

Goldwin et al., PRA 70, 021601(R) (2004)

interactions - more than just (in)elastic collisions

2002

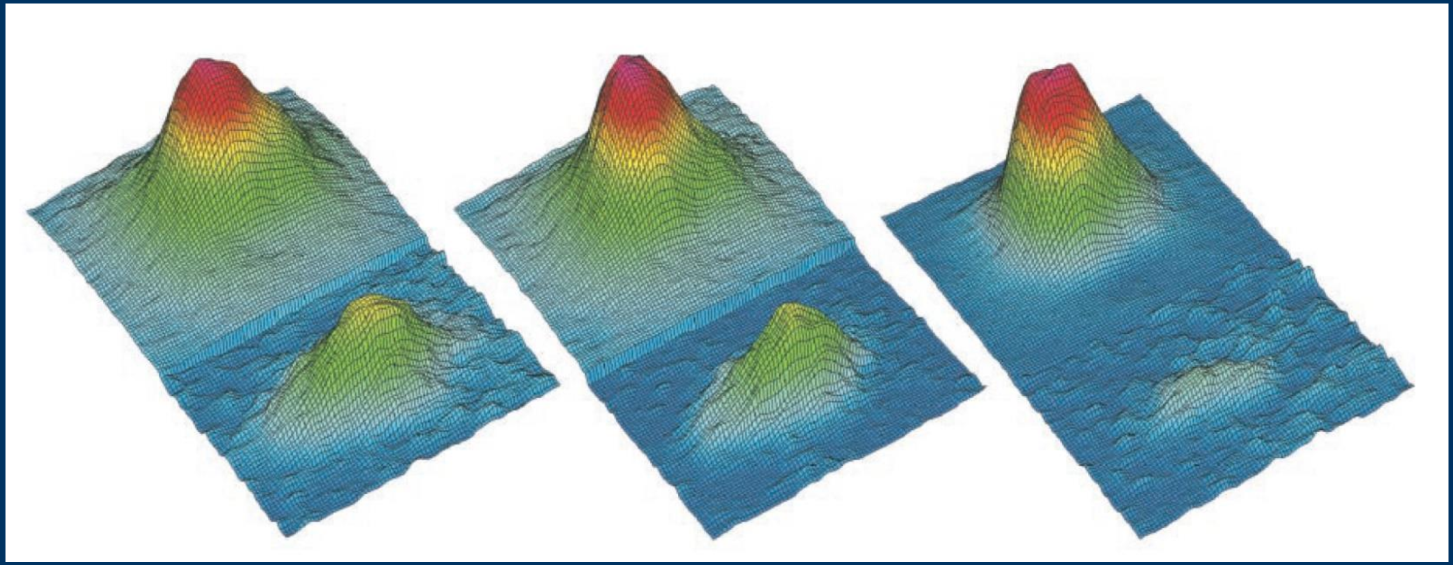
Collapse of a Degenerate Fermi Gas

Giovanni Modugno,* Giacomo Roati, Francesco Riboli, Francesca Ferlaino, Robert J. Brecha, Massimo Inguscio

Science 297, 2240 (2002)

^{87}Rb

^{40}K



evaporative cooling →

onset of BEC

quasi-pure BEC

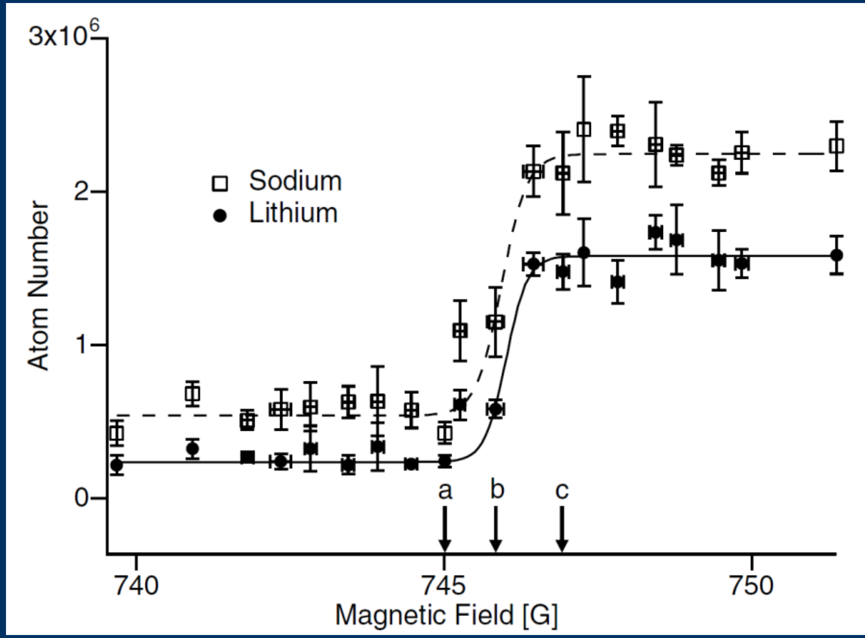
sudden loss of fermions!

heteronuclear Feshbach resonances

mid 00's

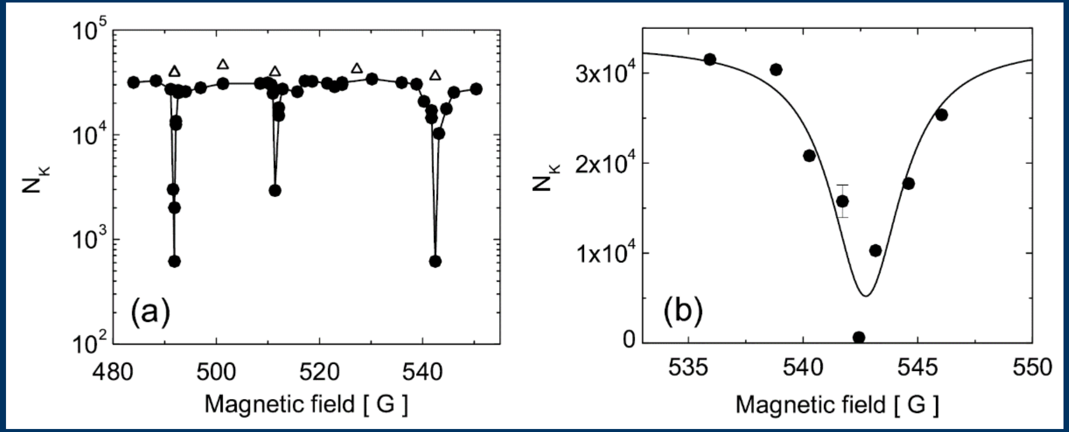
^{6}Li-^{23}Na (MIT, Ketterle group)

Stan et al., PRL 93, 143001 (2004)



^{40}K-^{87}Rb (JILA, Jin group)

Inouye et al., PRL 93, 183201 (2004)



^{40}K-^{87}Rb (LENS, Inguscio group)

Ferlaino et al., PRA 73, 040702(R) (2006)

tuning the interspecies interaction

mid 00's

K-Rb

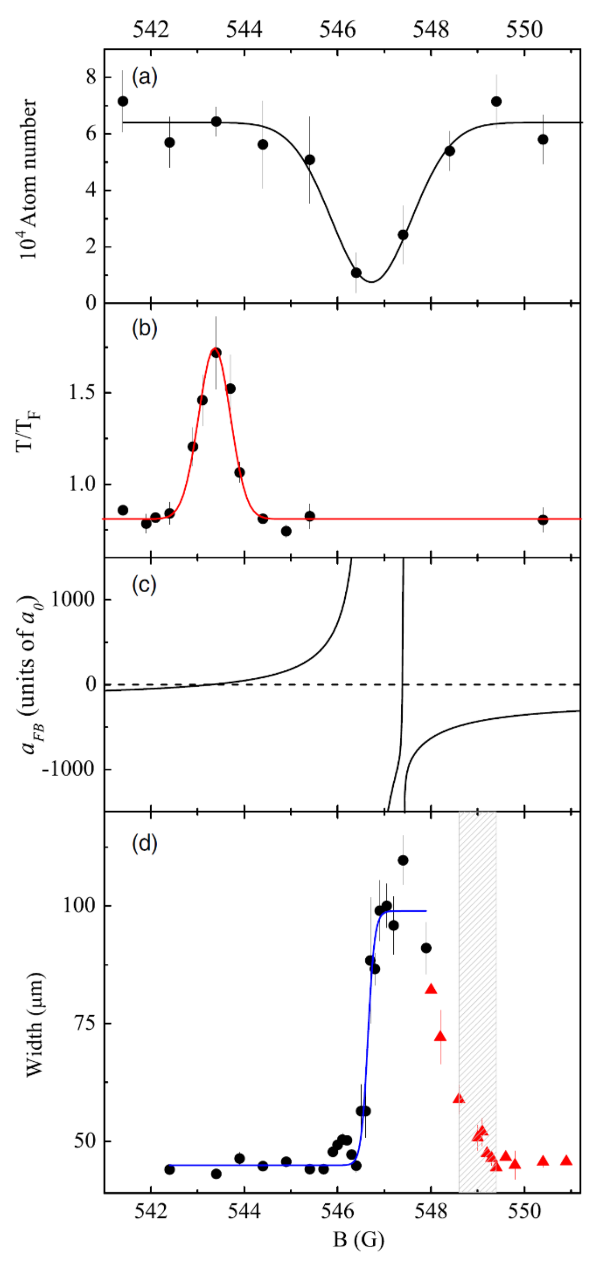
expansion near resonance

LENS, Inguscio group

Zaccanti et al., PRA 74, 041605(R) (2006) →

Hamburg, Sengstock-Bongs group

Ospelkaus et al., PRL 97, 120403 (2006)



resonance center

zero crossing

scattering length

Rb width after TOF expansion

heteronuclear Feshbach molecules

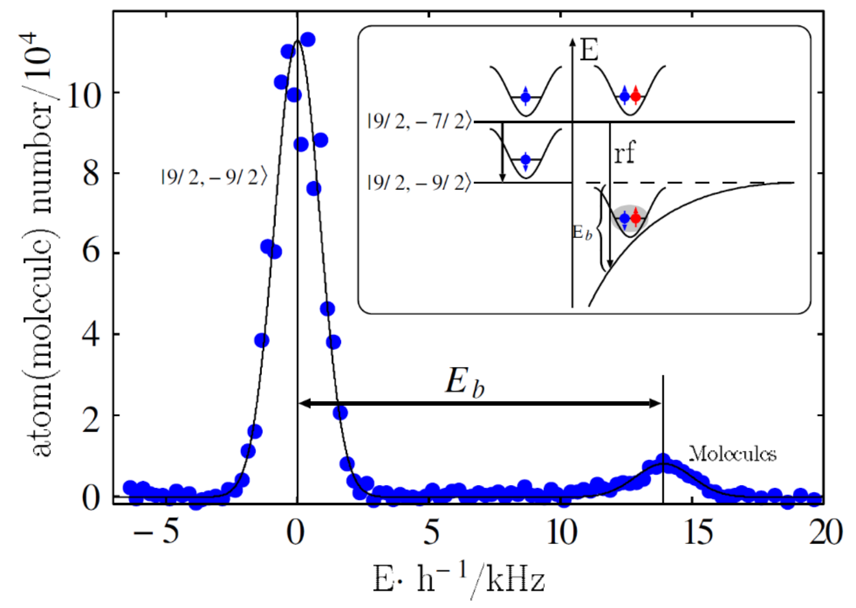
mid-late 00‘s

KRb in an optical lattice

(Hamburg, Bongs-Sengstock group)

Ospelkaus et al., PRL 97, 120402 (2006)

radio-freq. association ⟶

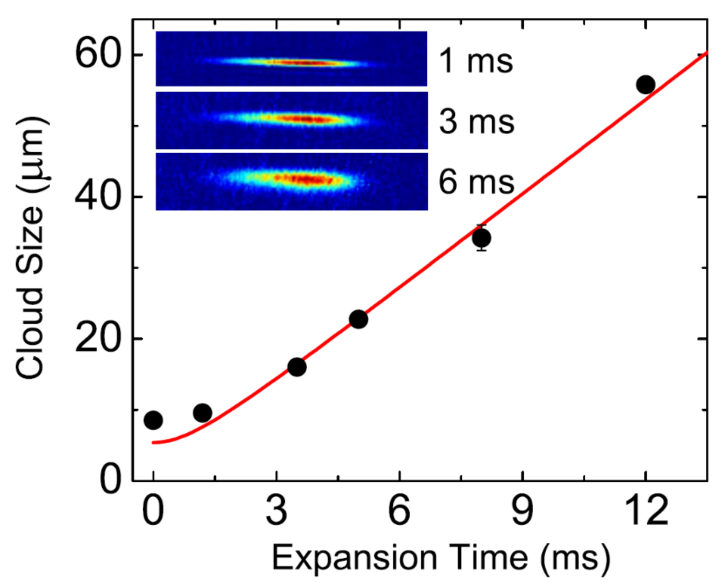


KRb in an optical dipole trap

(JILA, Jin group)

Zirbel et al., PRA 78, 013416 (2008)

time-of-flight expansion ⟶



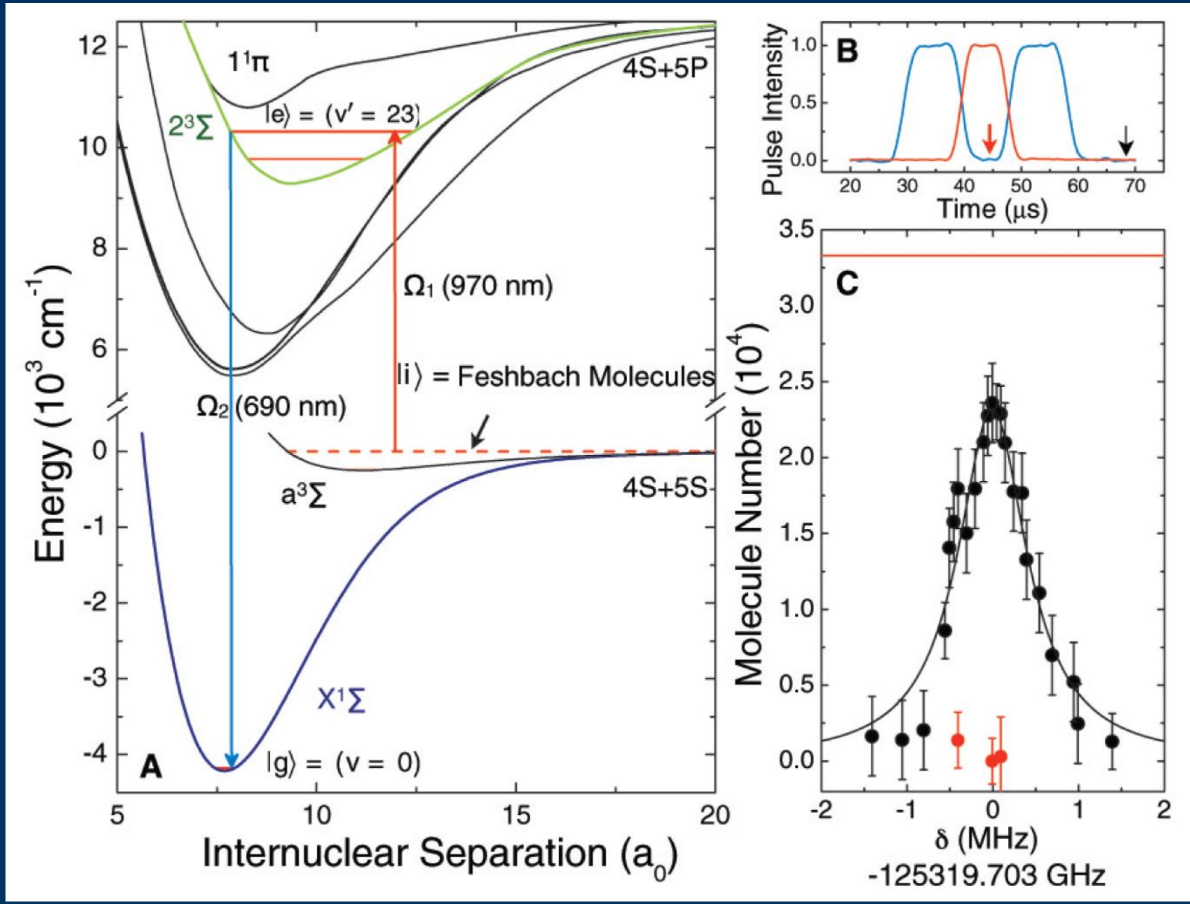
heteronuclear (dipolar) ground state molecules

2008

A High Phase-Space-Density Gas of Polar Molecules

K.-K. Ni,[1*] S. Ospelkaus,[1*] M. H. G. de Miranda,[1] A. Pe'er,[1] B. Neyenhuis,[1] J. J. Zirbel,[1] S. Kotochigova,[2] P. S. Julienne,[3] D. S. Jin,[1†] J. Ye[1†]

Science 322, 231 (2008)



very active research field with
many experiments worldwide
(many bi-alkali systems and other combinations)

related work in Innsbruck on homonuclear molecules

Rb_2: Lang et al., PRL 101, 133005 (2008); Denschlag group

Cs_2: Danzl et al., Science 321, 1062 (2008); Nature Phys. 6, 266 (2010); Nägerl group

species mixtures in Innsbruck

^{6}Li – ^{40}K / ^{41}K — RG group (since 2007)

^{87}Rb – ^{133}Cs

^{39}K – ^{133}Cs

H.-C. Nägerl group

^{87}Rb – ^{84}Sr / ^{88}Sr — (expt. moved to Amsterdam with F. Schreck)

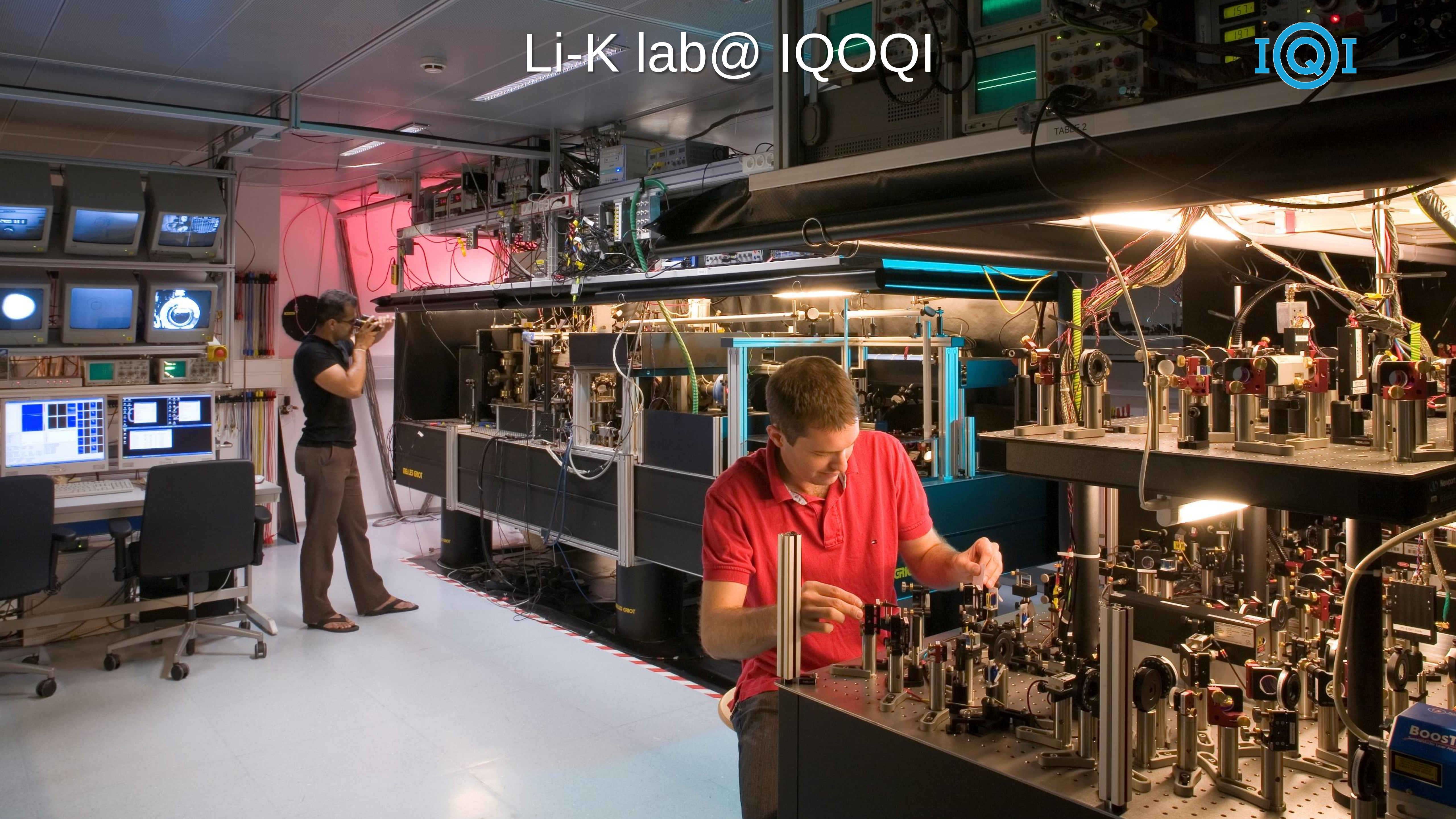
at UvA
since 2013

Er – Dy (5x) — **F. Ferlaino** group

^{40}K – ^{161}Dy — RG group (since 2018)

Li-K lab@ IQOQI

IQI



isotopic combinations

our experiments

$$\boxed{\text{6 - fermions}}$$

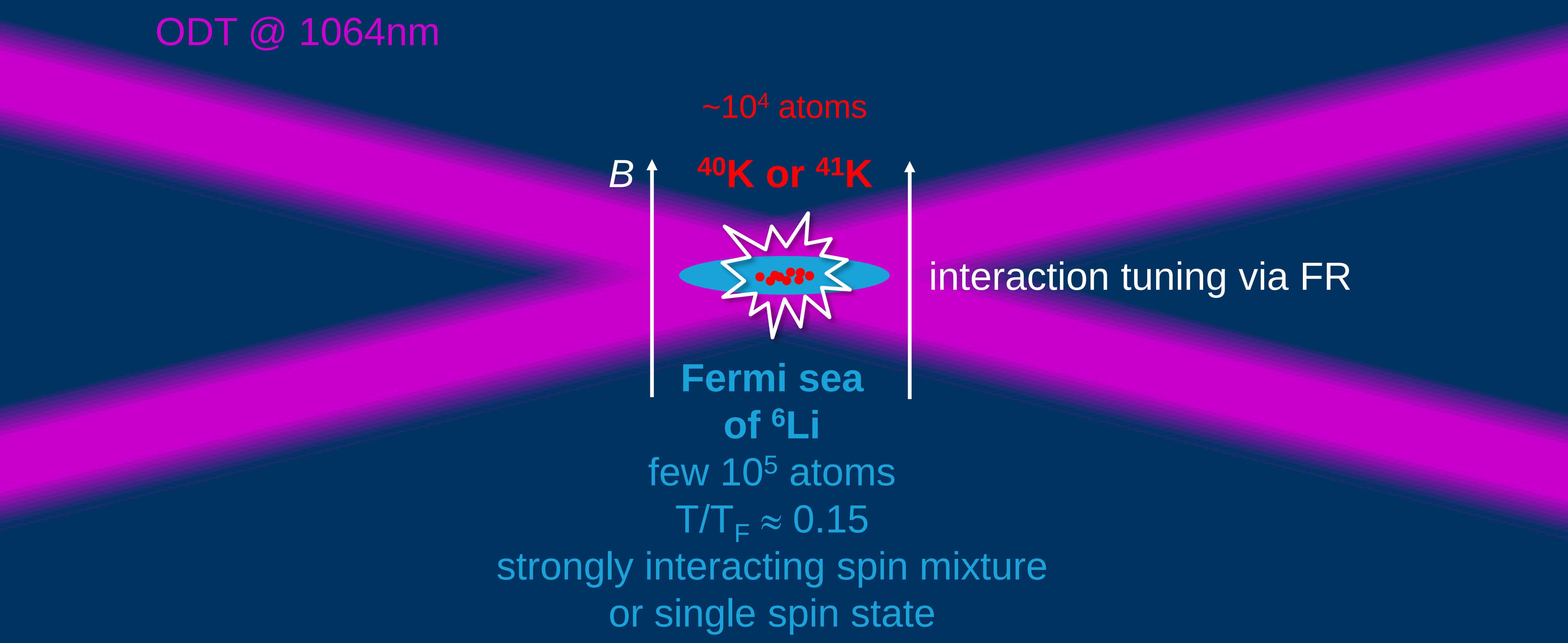
7 - bosons

Li – K

39 - bosons

$$\boxed{\begin{array}{l}\text{40 - fermions}\\ \text{41 - bosons}\end{array}}$$

typical experimental situation



research topics

$^{6}Li - {}^{40}K$

interaction properties

$^{6}Li - {}^{41}K$

strongly interacting
Fermi-Fermi mixture

Fermi gas thermometry

few-body physics

phase separation

quantum impurities

main research topic in last few years

Feshbach spectroscopy on ^{6}Li-^{40}K

PRL **100,** 053201 (2008) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2008

Exploring an Ultracold Fermi-Fermi Mixture: Interspecies Feshbach Resonances and Scattering Properties of ^{6}Li and ^{40}K

E. Wille,[1,2] F. M. Spiegelhalder,[1] G. Kerner,[1] D. Naik,[1] A. Trenkwalder,[1] G. Hendl,[1] F. Schreck,[1] R. Grimm,[1,2] T. G. Tiecke,[3] J. T. M. Walraven,[3] S. J. J. M. F. Kokkelmans,[4] E. Tiesinga,[5] and P. S. Julienne[5]

experiment & theory
together

Feshbach spectroscopy on ^{6}Li-^{40}K

PRL **100**, 053201 (2008) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2008

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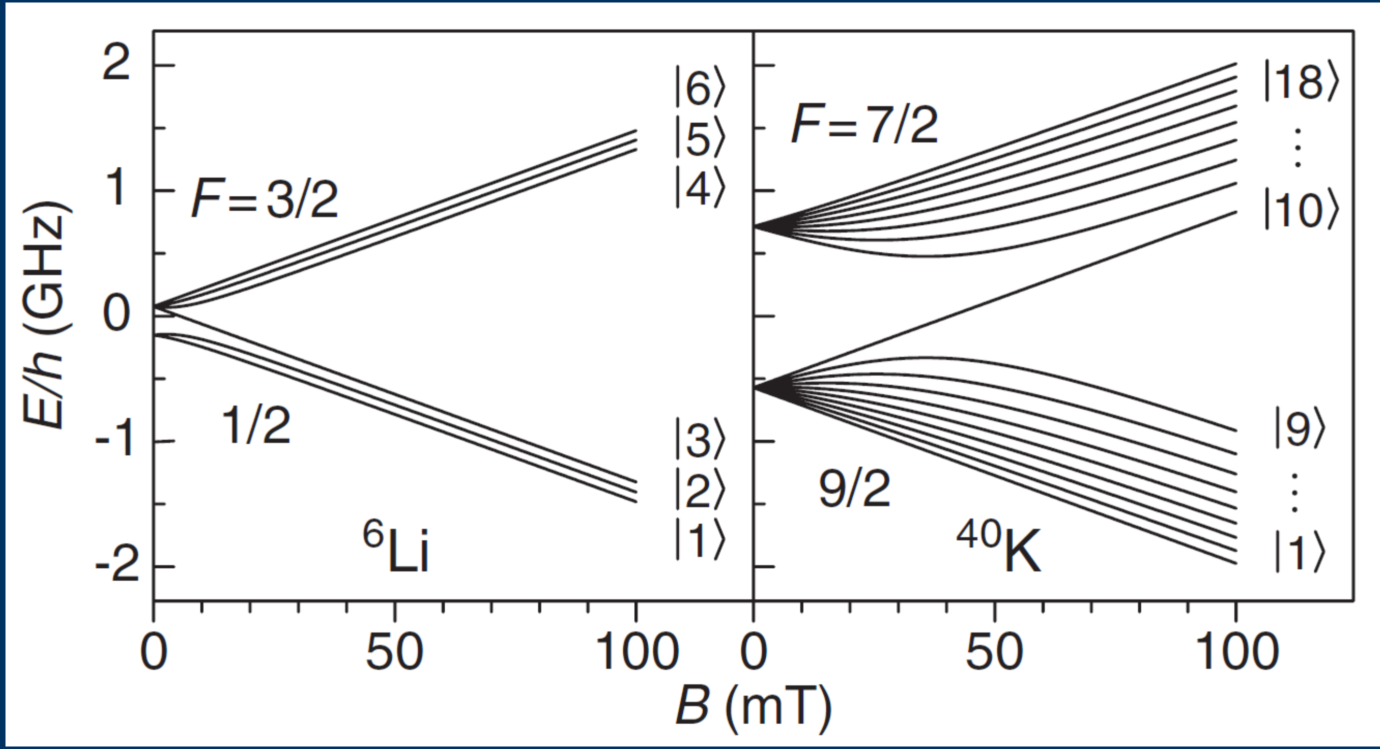
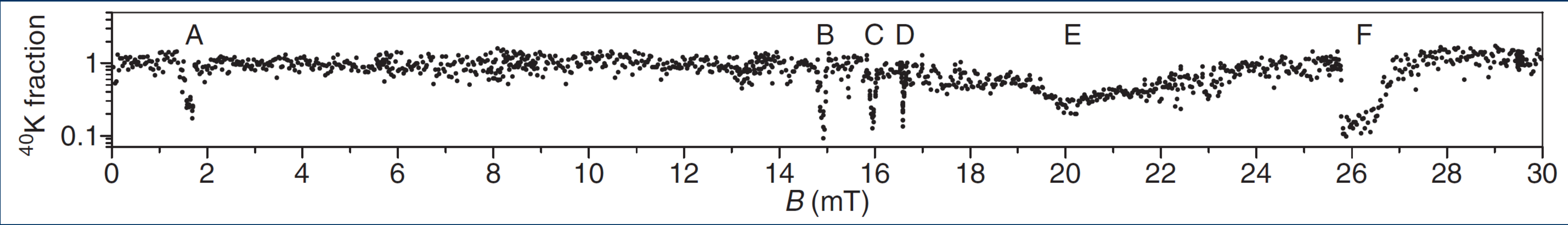
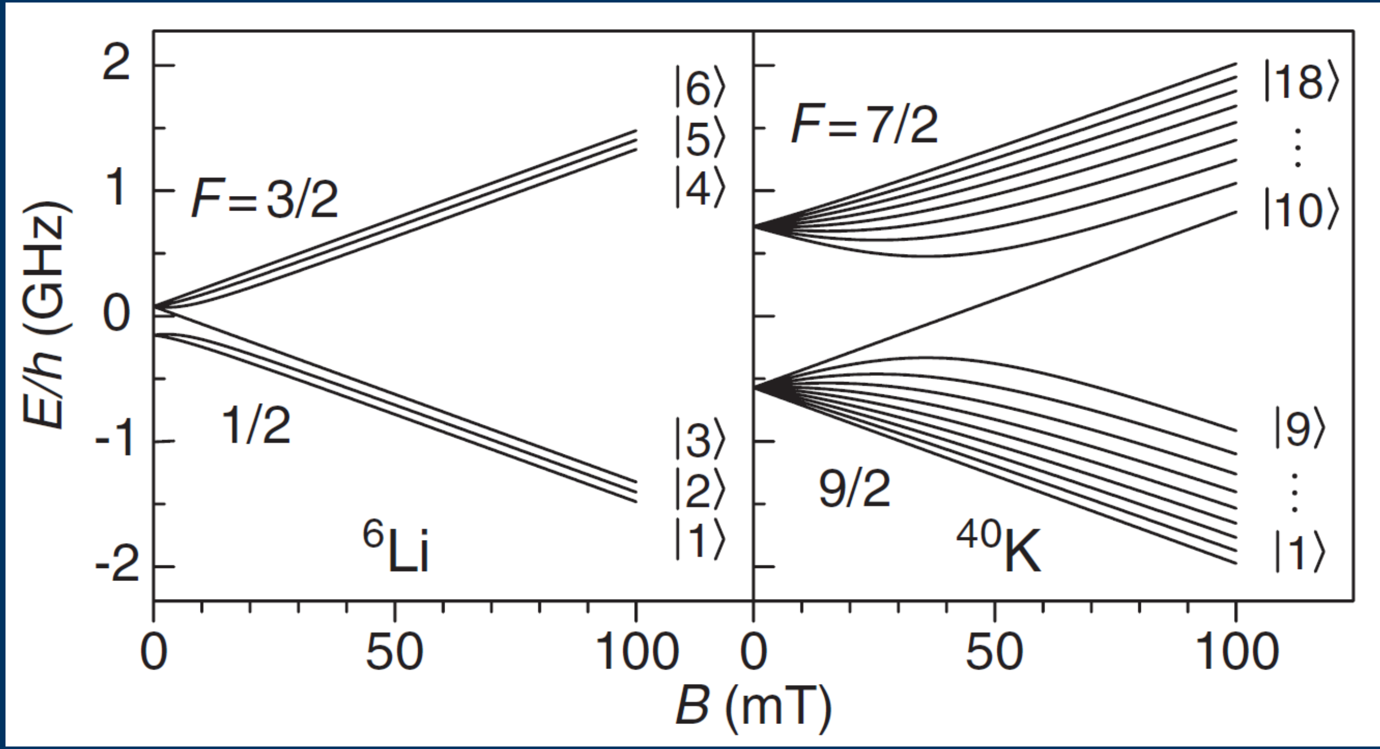


Feshbach spectroscopy on ^{6}Li-^{40}K



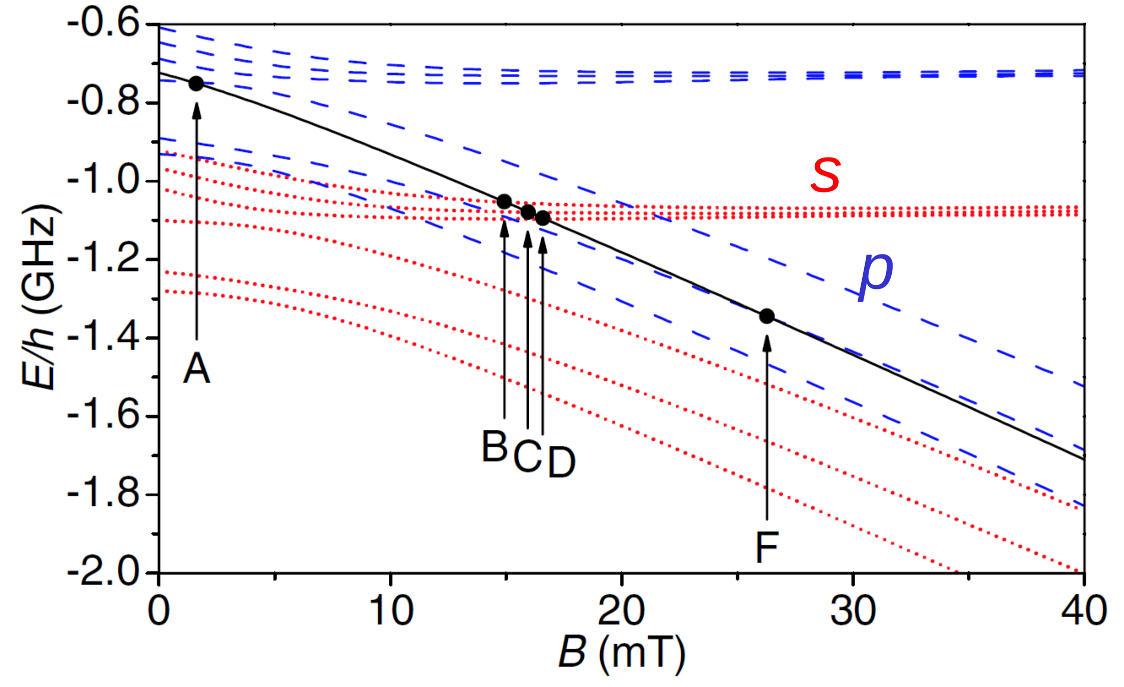
1-2 spin channel



many resonances

i, j	M_F	Experiment B_0 (mT)	Experiment ΔB (mT)	ABM B_0 (mT)
2, 1	−5	21.56[a]	0.17	21.67
1, 1	−4	15.76	0.17	15.84
1, 1	−4	16.82	0.12	16.92
1, 1	−4	24.9	1.1	24.43
1, 2	−3	1.61	0.38	1.39
1, 2	−3	14.92	0.12	14.97
1, 2	−3	15.95[a]	0.17	15.95
1, 2	−3	16.59	0.06	16.68
1, 2	−3	26.3	1.1	26.07
1, 3	−2	Not observed		1.75
1, 3	−2	14.17	0.14	14.25
1, 3	−2	15.49	0.20	15.46
1, 3	−2	16.27	0.17	16.33
1, 3	−2	27.1	1.4	27.40

asymptotic bound state model



variation of two binding energy parameters
(for known C_6 coefficient)

coupled-channels calculation for all spin states

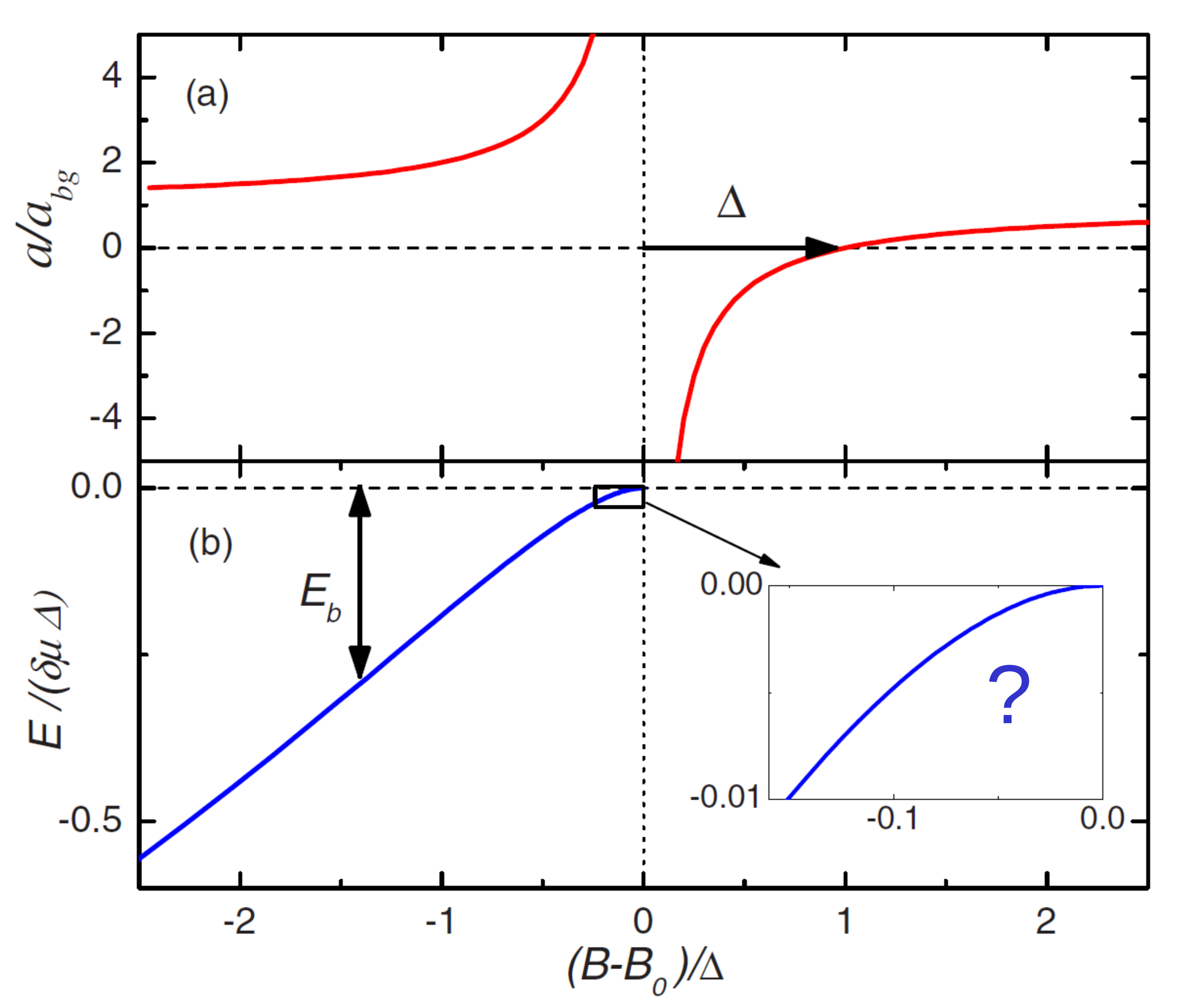
			Experiment			Coupled channels						
Channel	M_{tot}	Group	B_0 (G)	Δ (G)	Ref.	B_0 (G)	Δ (G)	a_{bg}/a_0	$\delta\mu/h$ (MHz/G)	a_{res} ($10^6\ a_0$)	s_{res}	γ_B (μG)
ba	–5	△	215.6		[4]	215.52	0.27	64.3	2.4	160	0.0048	0.11
aa	–4	○	157.6		[4]	157.50	0.14	65.0	2.3		0.0023	0
		◇	168.170(10)		[8]	168.04	0.13	63.4	2.5		0.0023	0
ab	–3	○	149.2		[4]	149.18	0.23	67.0	2.1	14	0.0037	1.1
		□	159.5		[4]	159.60	0.51	62.5	2.4	5.3	0.0086	6.1
		◇	165.9		[4]	165.928	2×10^{-4}	58	2.5	0.3	3.3×10^{-6}	0.04
ac	–2	○	141.7		[4]	141.46	0.25	67.6	2.1	7.5	0.0040	2.3
		□	154.707(5)	0.92(5)	this work	154.75	0.88	63.0	2.3	4.0	0.014	14
		◇	162.7		[4]	162.89	0.09	56.4	2.5	0.89	0.0014	5.7
ad	–1	○				134.08	0.24	68.7	2.0	4.5	0.0038	3.7
		□				149.40	1.06	63.8	2.2	3.3	0.017	20
		◇				159.20	0.33	55.8	2.45	1.4	0.0051	13
ae	0	○				127.01	0.22	68.5	2.05	2.8	0.0035	5.4
		□				143.55	1.20	65.7	2.2	2.8	0.020	29
		◇				154.81	0.69	55.1	2.4	1.6	0.010	24
af	1	○				120.33	0.20	66.8	2.1	1.7	0.0031	7.9
		□				137.23	1.19	65.3	2.2	2.2	0.019	35
		◇				149.59	1.14	53.6	2.4	1.6	0.016	37
ag	2	○				114.18	0.14	67.4	2.1	0.97	0.0023	9.7
		□				130.49	1.07	66.4	2.2	1.8	0.018	40
		◇				143.39	1.57	54.4	2.4	1.6	0.023	53
ah	3	○				108.67	0.098	66.6	2.2	0.48	0.0016	14
		□				123.45	0.86	68.4	2.3	1.3	0.015	44
		◇				135.90	1.87	55.9	2.45	1.5	0.029	72
ai	4	○				104.08	0.06	65.9	2.25	0.19	0.0010	21
		□				116.38	0.54	68.6	2.4	0.98	0.010	38
		◇				126.62	1.97	54.7	2.6	1.3	0.032	83
aj	5	○				100.90	0.02	64.3	2.3	0.03	3.2×10^{-4}	43
		◇	114.47(5)	1.5(5)	[7]	114.78	1.81	57.3	2.3	1.08	0.027	96

Naik et al.,
EPJD 65, 55 (2011)

complete understanding of two-body interaction physics!

(by mass scaling also for all other isotopic combinations)

“best” resonance (Li1 – K3 channel)



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

$$B_0 = 154.699(1)\,\mathrm{G}$$
$$a_{\rm bg} = 63.0\,a_0$$
$$\Delta = 880\,\mathrm{mG}$$

$$\delta\mu/h = 2.35(2)\,\mathrm{MHz/G}$$

range parameter

$$R^* = \frac{\hbar^2}{2m_{\rm r}a_{\rm bg}\,\delta\mu\,\Delta} = 2650(25)\,a_0$$

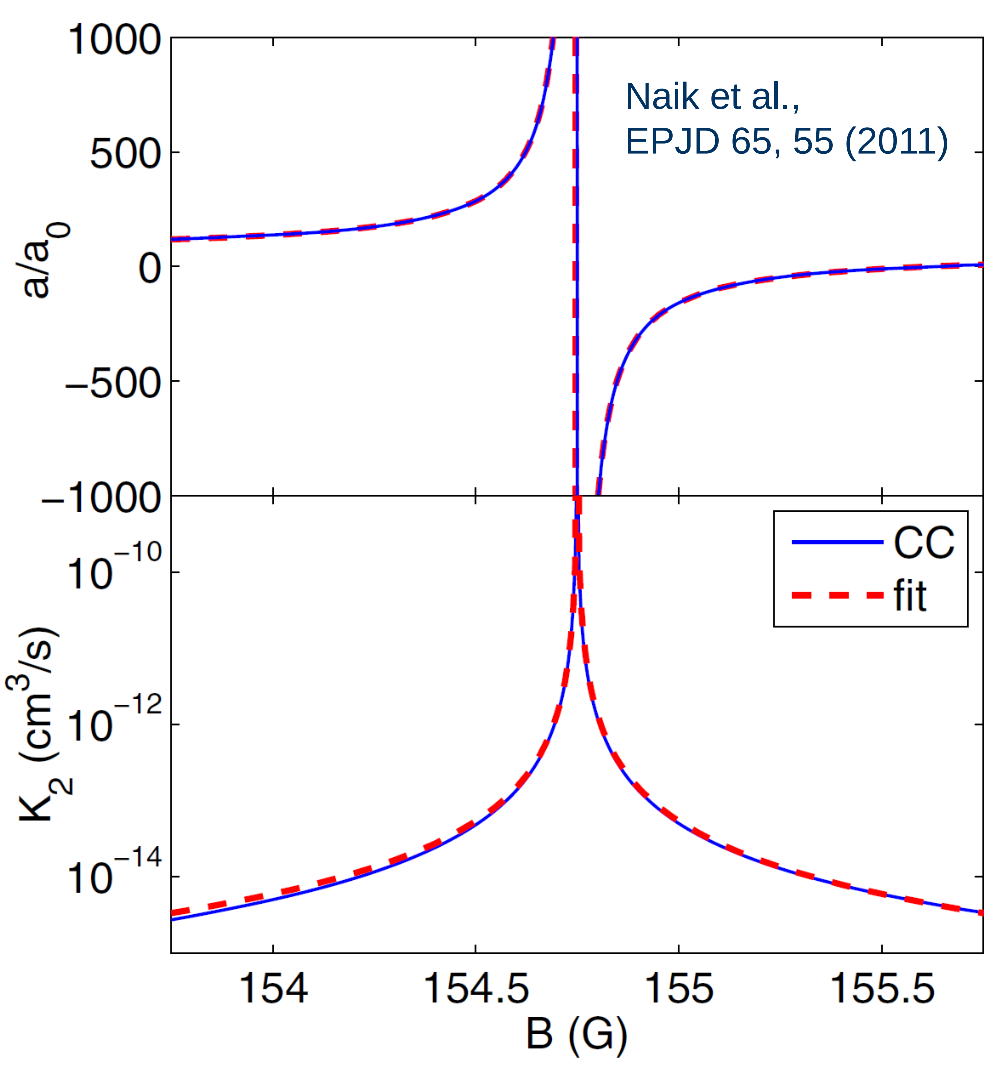
universal range

$$|a| \gg R^* \;\rightarrow\; |\Delta| \ll 20\,\mathrm{mG}$$

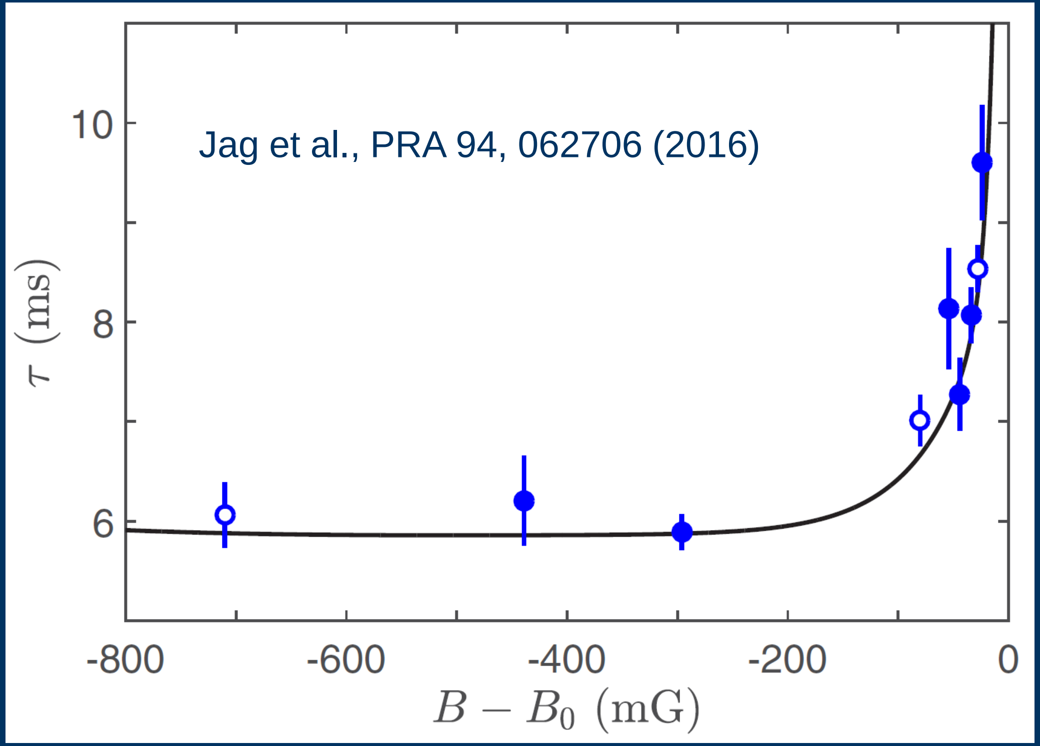
Chin et al., RMP 82, 1225 (2010)

Petrov, PRL 93, 143201 (2004)

spin relaxation (not in the lowest spin channel)



resonant two-body losses

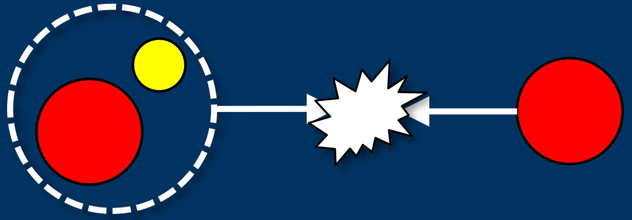


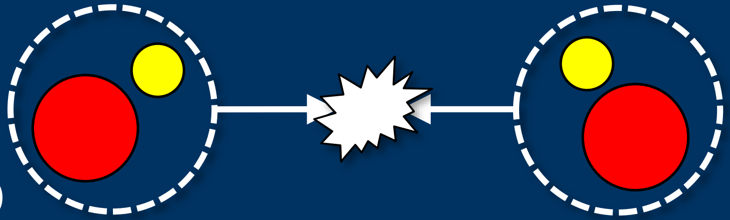
spontaneous dissociation
of Feshbach molecules

^{6}Li – ^{40}K

do experiments fast (few ms)
and with precise magnetic control

glimpse into the few-body world

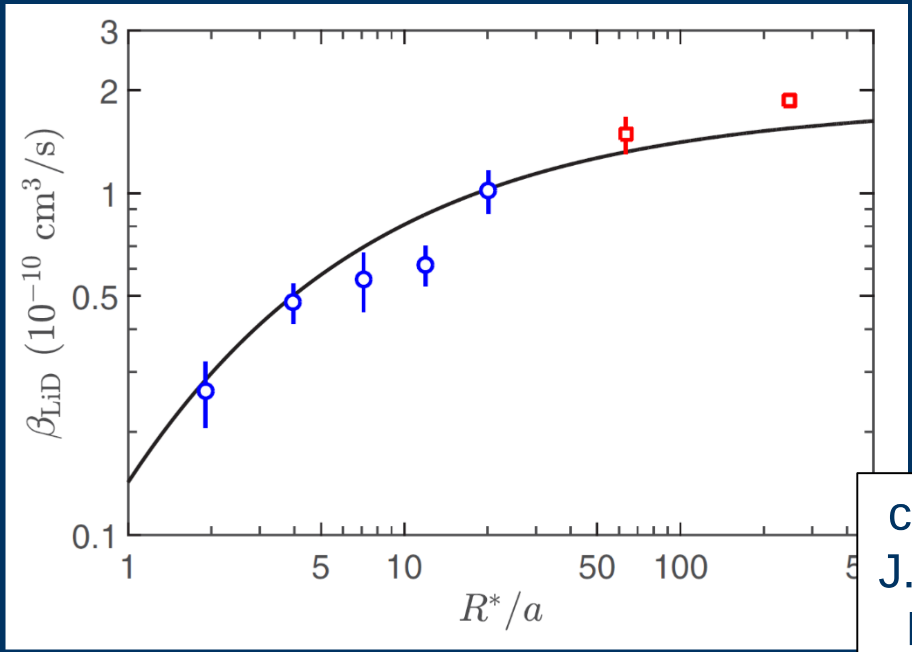




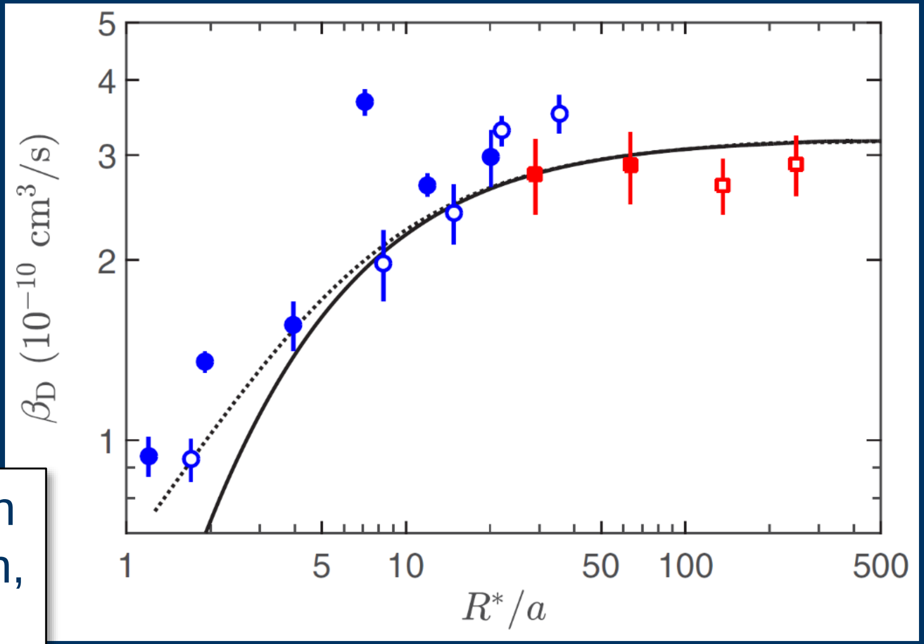
Jag et al.,
PRA 94, 062706 (2016)

atom-dimer collisions

dimer-dimer collisions



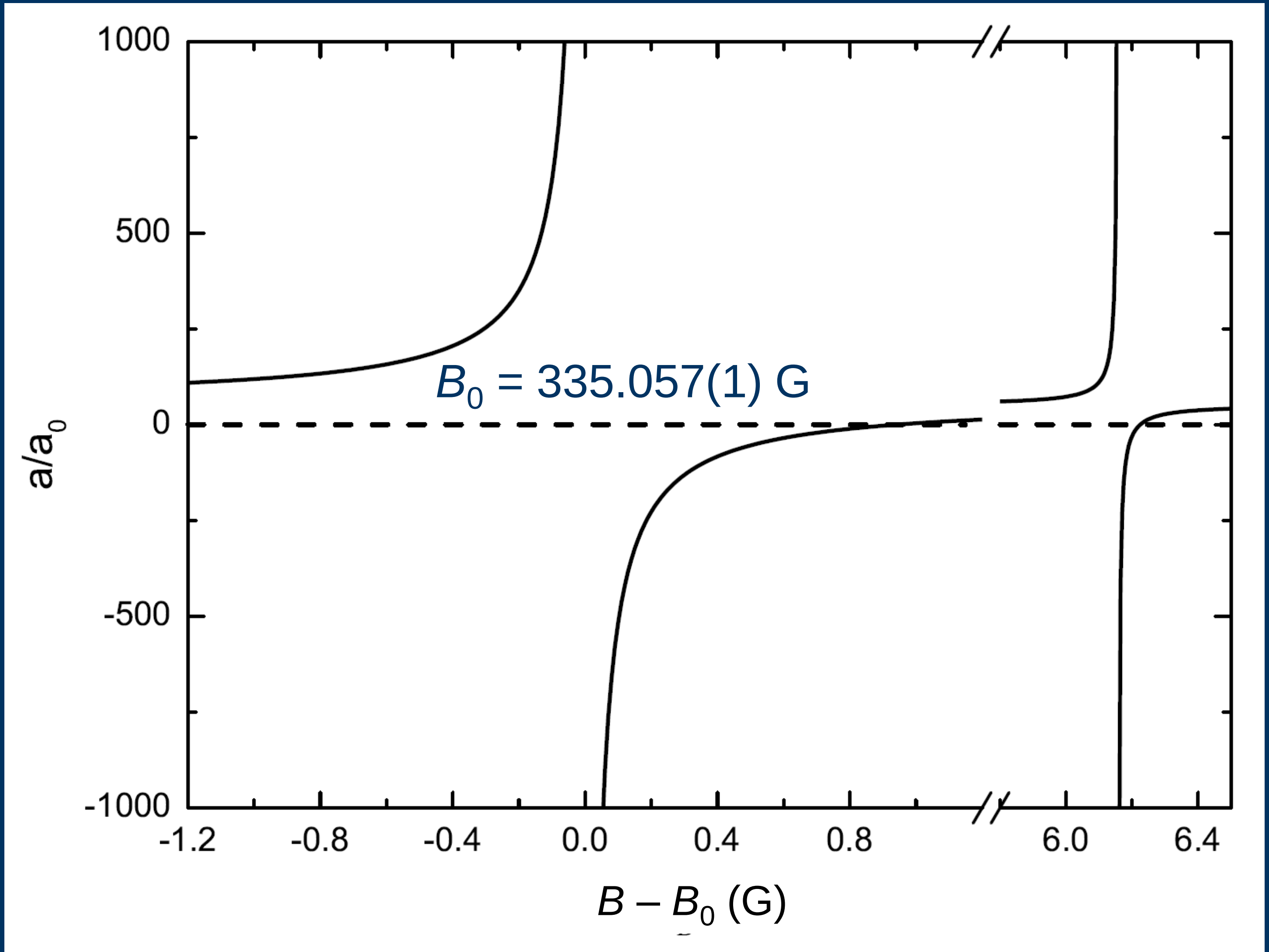
collab. with
J. Levinsen,
D. Petrov



Pauli suppression at work, see Petrov, Salomon, Shlyapnikov, PRL 93, 090404 (2004),
but only very close to resonance

Feshbach resonance in the Fermi-Bose mixture

$^{6}Li - ^{41}K$



lowest spin channel:
no two-body decay

resonance width and a_bg
very similar to
the Fermi-Fermi case:

facilitates direct comparison
between FF and FB system

Lous et al.,
PRL 120, 243403 (2018)

degenerate Bose-Fermi mixture

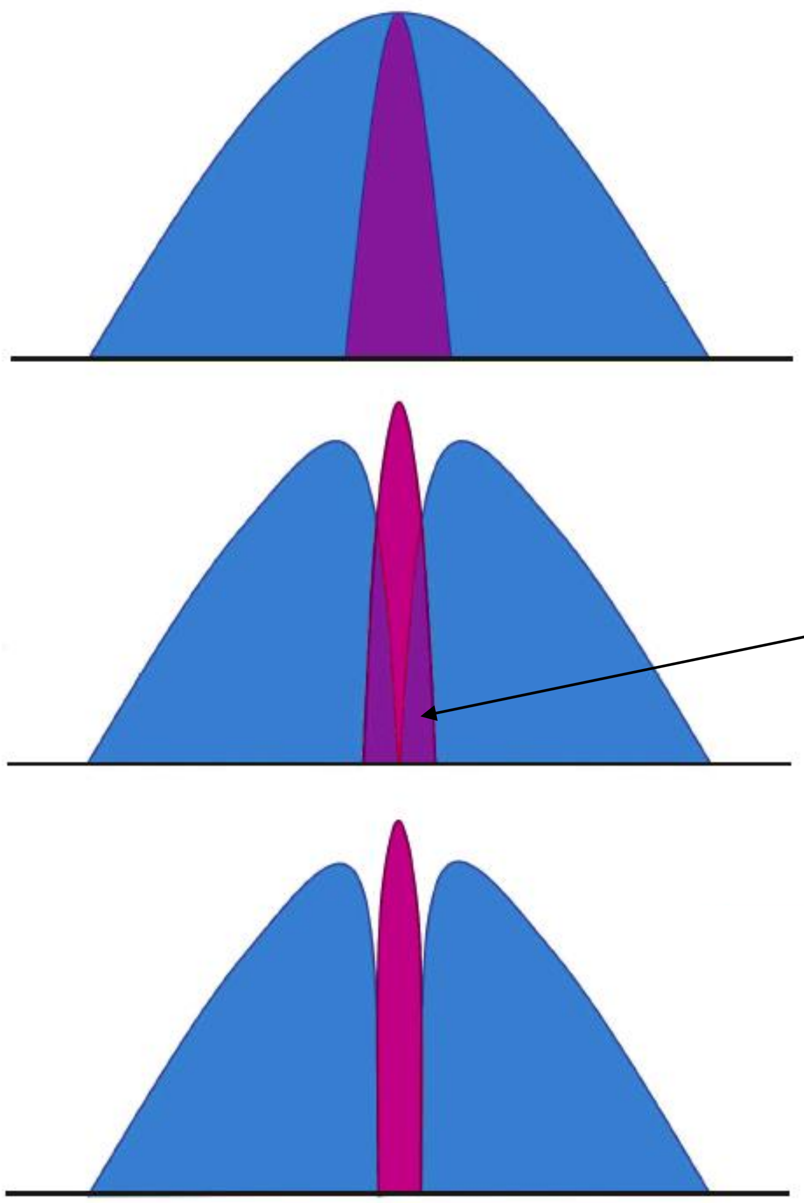
small BEC immersed in a large Fermi sea

"fermionic reservoir approximation"
BEC effect on fermion chemical potential negligible

tunable BF interactions!!!

repulsive interaction

increasing
interspecies
scattering length
a



reduced overlap

phase separation !

$$a > 1.14\sqrt{a_b/k_F}$$

Viverit et al., PRA 61, 053605 (2000)

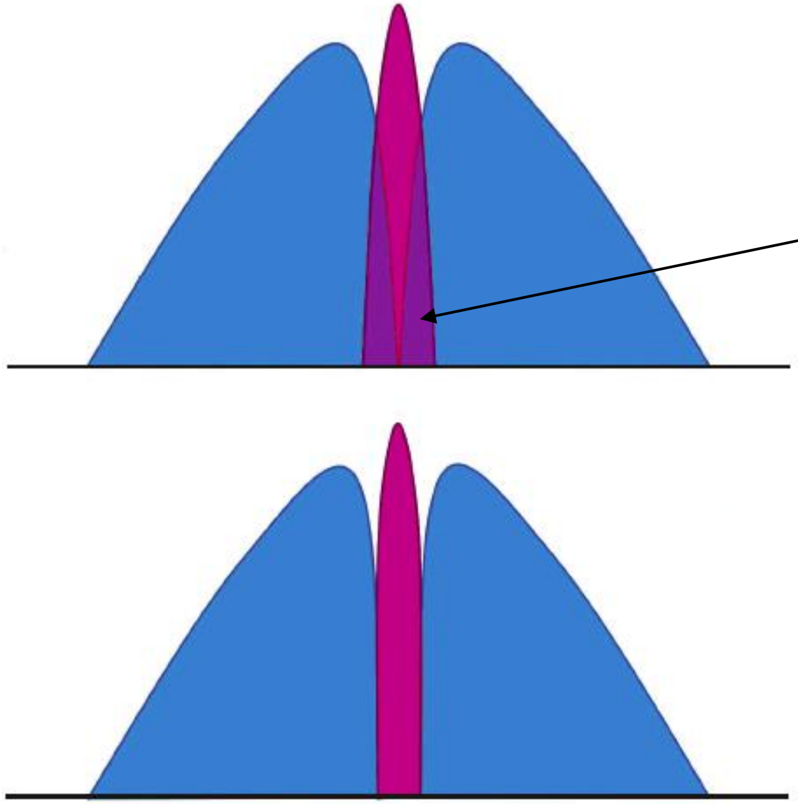
Probing the Interface of a Phase-Separated State in a Repulsive Bose-Fermi Mixture

Rianne S. Lous,[1,2] Isabella Fritsche,[1,2] Michael Jag,[1,2,*] Fabian Lehmann,[1,2] Emil Kirilov,[2]
Bo Huang (黄博),[1,†] and Rudolf Grimm[1,2]
[1]*Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[2]*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

PRL 120, 203043 (2008)

increasing interspecies scattering length

a



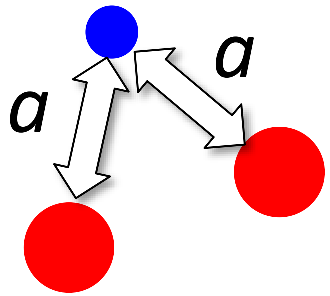
reduced overlap

phase separation !

$$a > 1.14 \sqrt{a_b/k_F}$$

Viverit et al., PRA 61, 053605 (2000)

three-body loss from ^{41}K BEC



dominant
3-body process

$$\dot{N} = -\tfrac{1}{2} L_3 \int n_b^2 n_f \, \mathrm{d}V$$

our observable

overlap intergral

$$= -\tfrac{1}{2} L_3 \, \Omega \int \tilde{n}_b^2 \tilde{n}_f \, \mathrm{d}V$$

overlap integral (no FB interaction),
straightforward to calculate

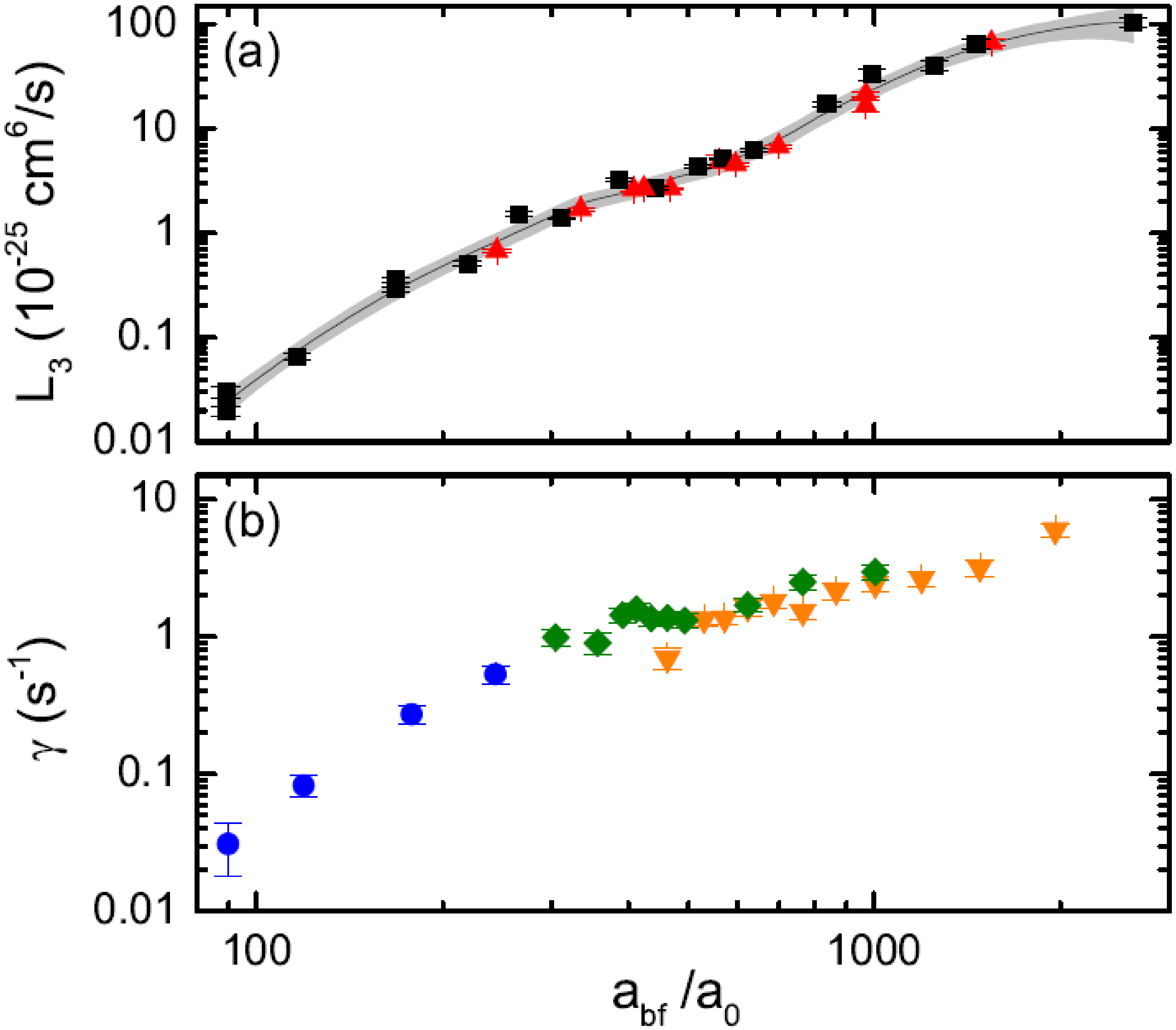
$$L_3(a)$$

can be measured in
non-condensed regime

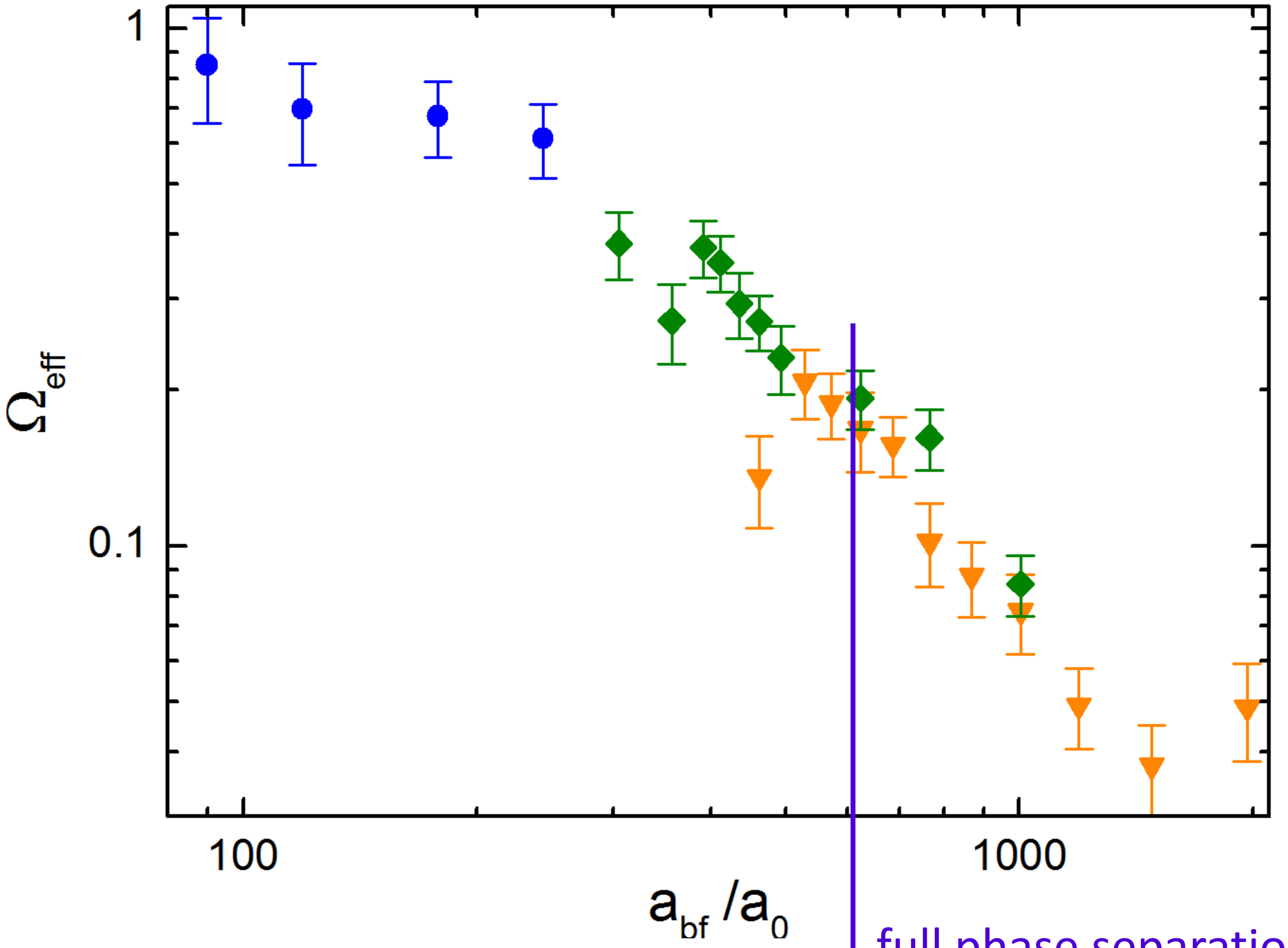
$$\Omega(a)$$

“overlap factor”
characterizes overlap
reduction by FB interaction

observables: L_3 and total loss rate

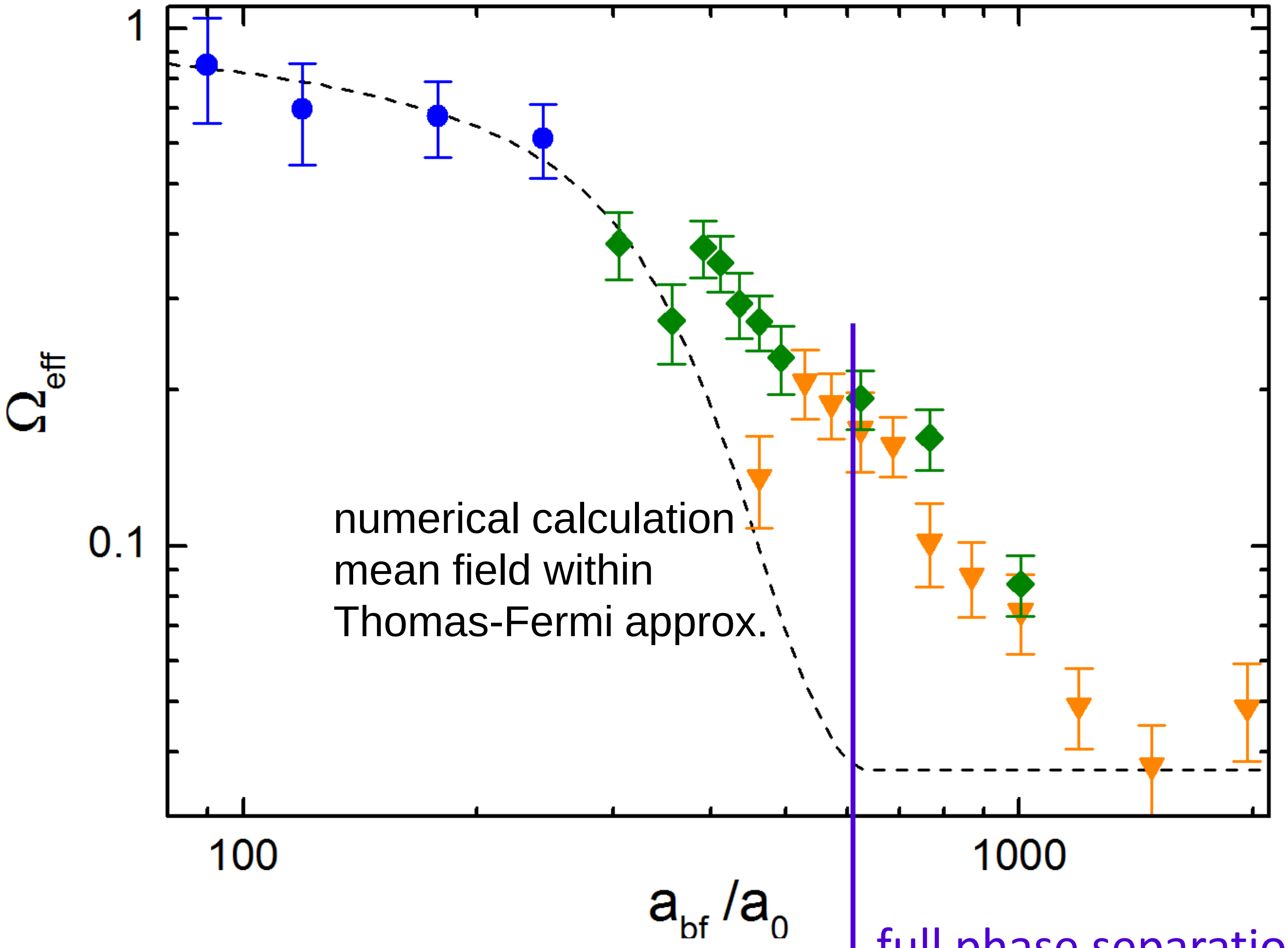


measured overlap factor



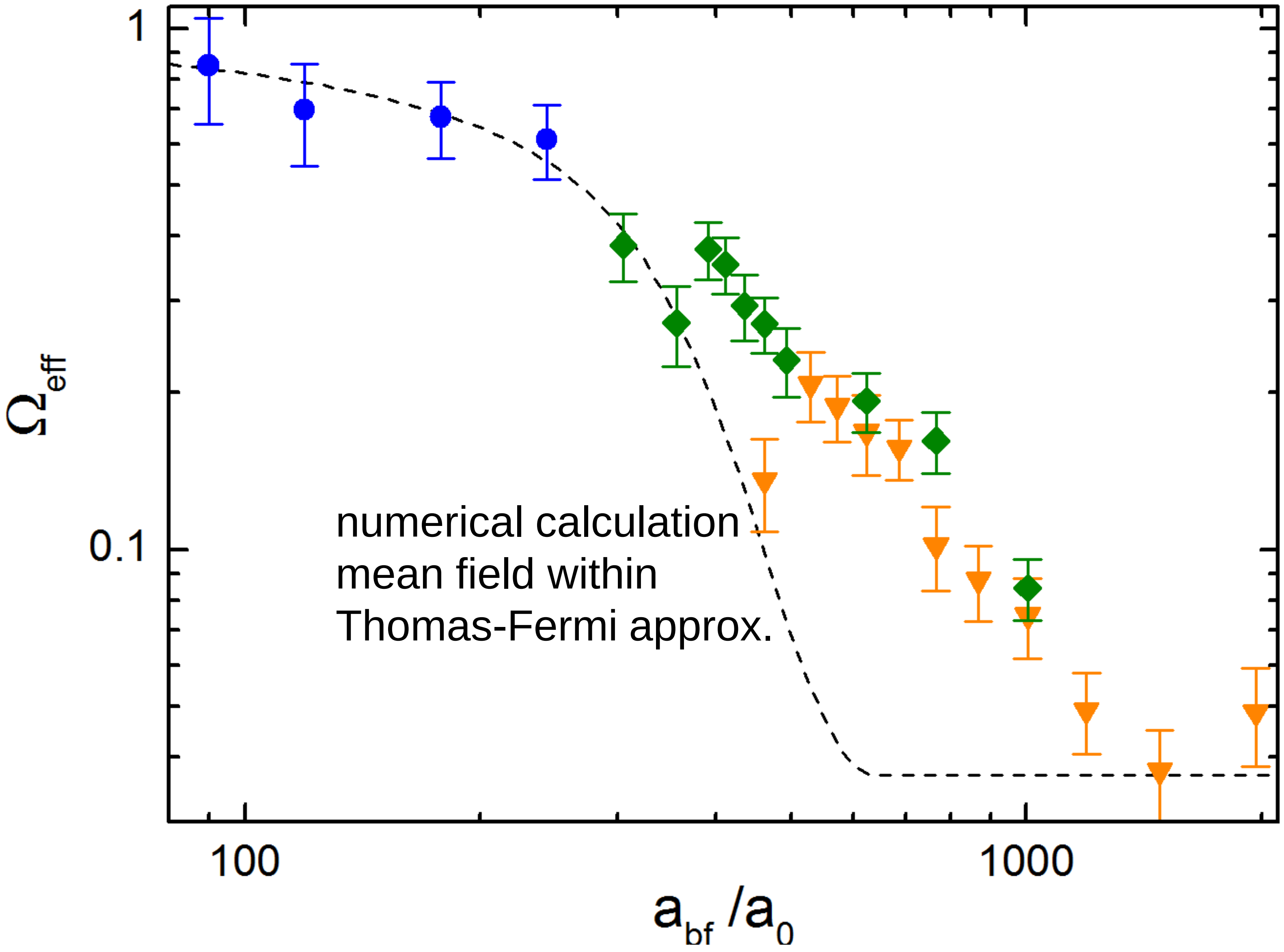
full phase separation ($a > 600a_0$) ???

measured overlap factor

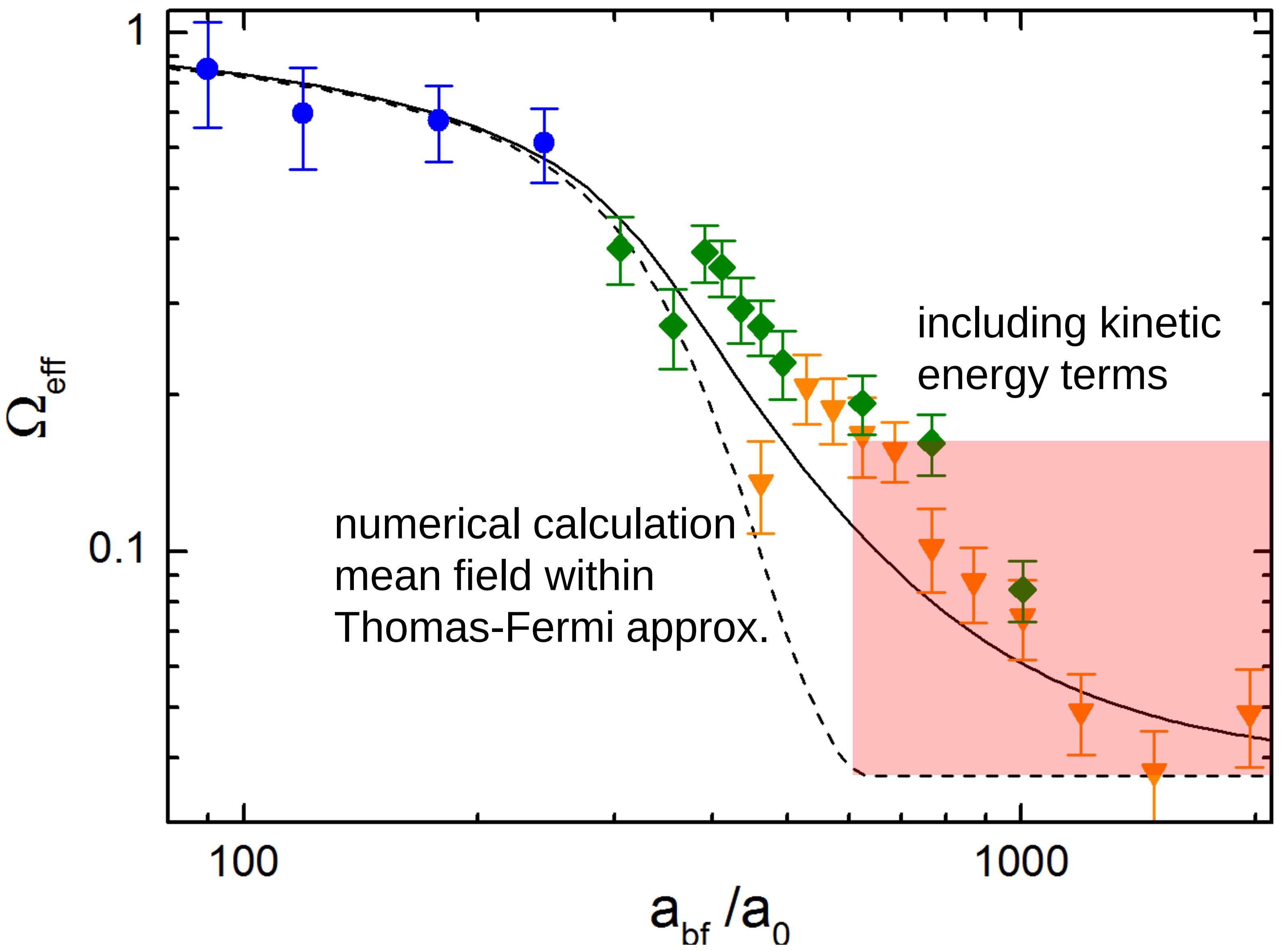


full phase separation ($a > 600a_0$) ???

measured overlap factor

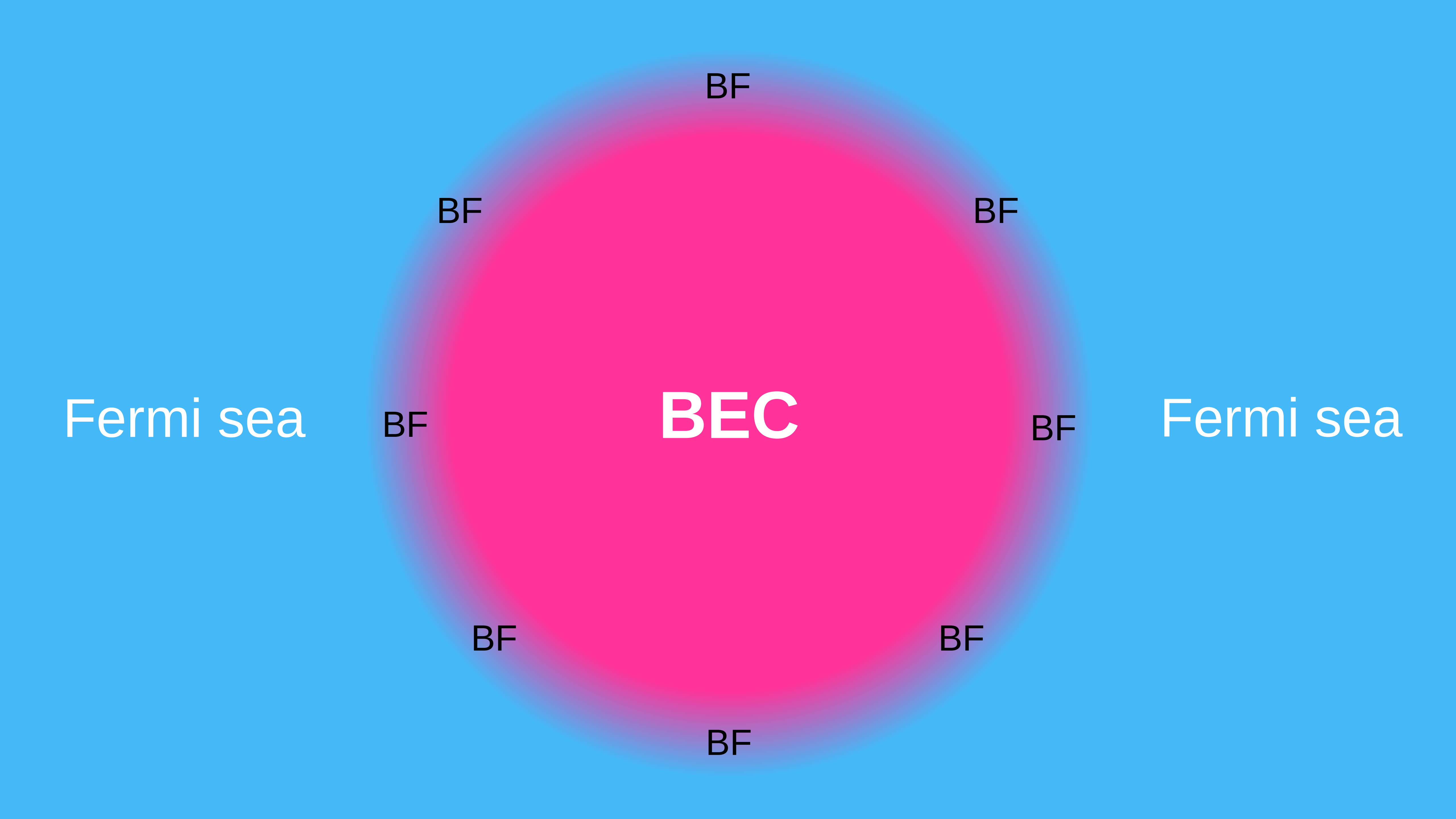


measured overlap factor



still some
overlap for
strong repulsion


Fermi sea
BEC
Fermi sea


BF
BF
BF
Fermi sea
BF
BEC
BF
Fermi sea
BF
BF
BF

interesting questions

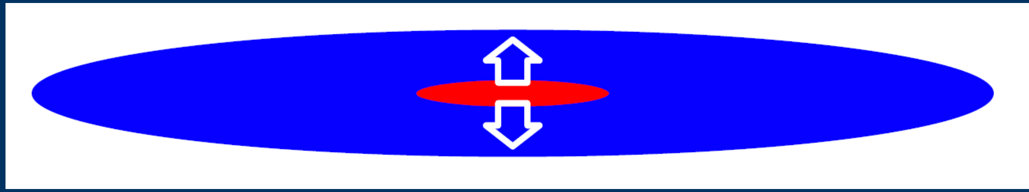
quantum nature of the interface

beyond mean-field approach (strongly interacting B-F mixture)

2D effects

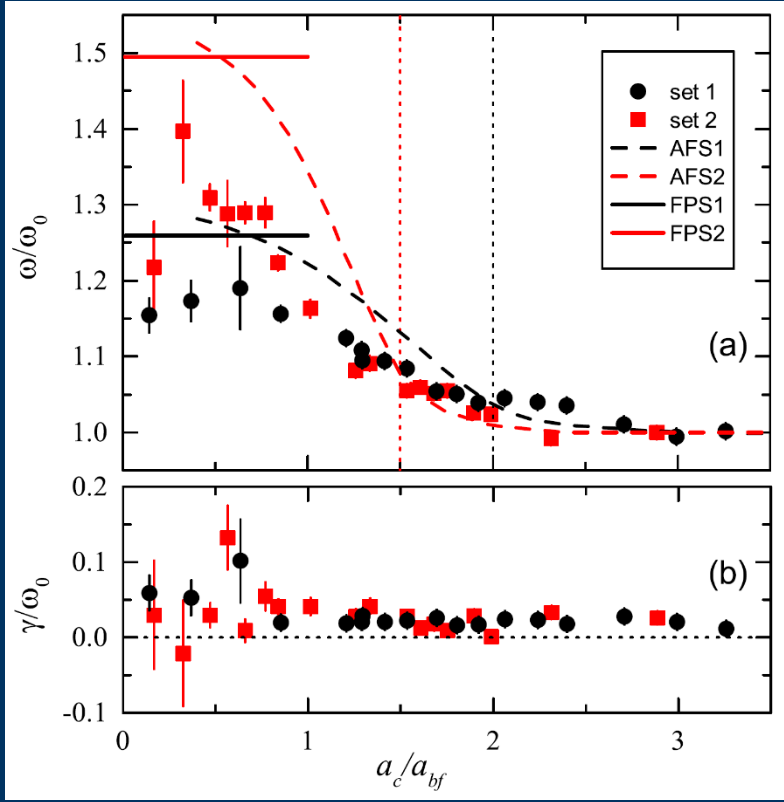
elementary excitations (ripplons...)

collective behavior of the compressed BEC



compression modes

surface modes and surface tension



Huang et al., PRA 99, 041602(R) (2019)