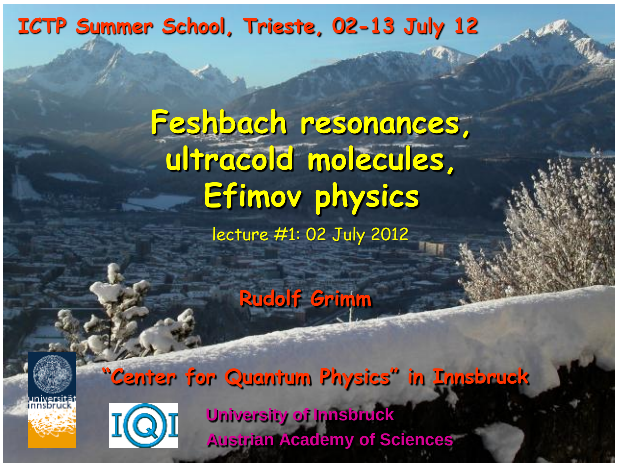
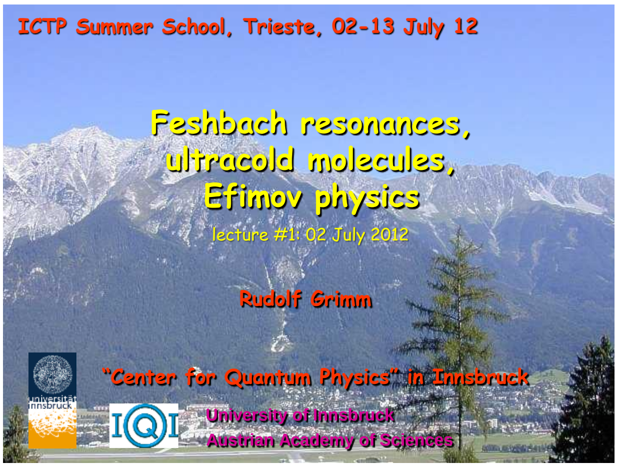


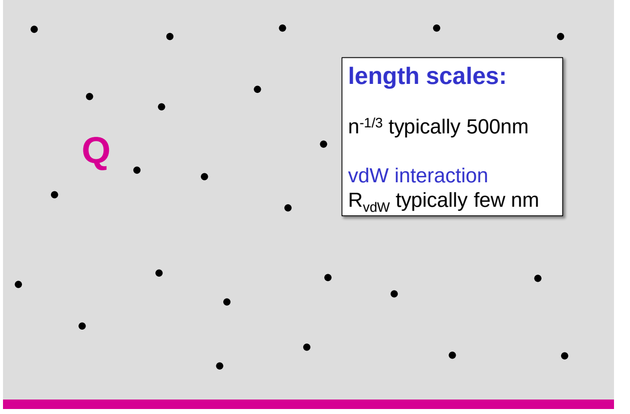


where is Innsbruck?

ultracold.atoms

ultracold gas

ultracold.atoms



length scales:

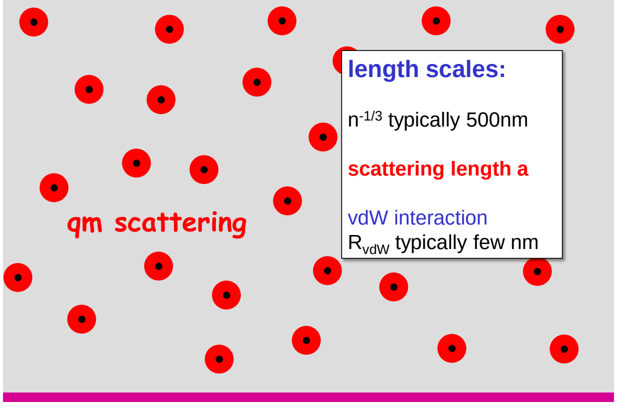
$n^{-1/3}$ typically 500nm

vdW interaction

R_{vdW} typically few nm

ultracold gas

ultracold.atoms



length scales:

$n^{-1/3}$ typically 500nm

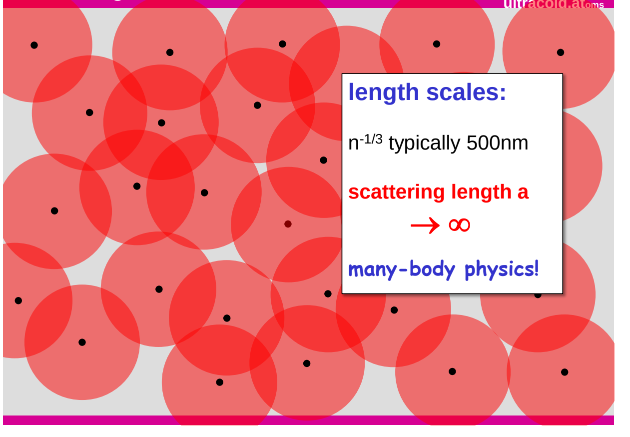
scattering length a

vdW interaction

R_{vdW} typically few nm

ultracold gas

ultracold.atoms



length scales:

$n^{-1/3}$ typically 500nm

scattering length a

$\rightarrow \infty$

many-body physics!

different regimes

ultracold.atoms

$a << n^{-1/3}$ dilute quantum gas

weakly interacting BEC, GP equation, ... (well understood)

$a \geq n^{-1/3}$ strongly interacting quantum gas

$a >> R_0$ universal interactions

($R_0 = R_{vdW}$ or R* to be explained later)

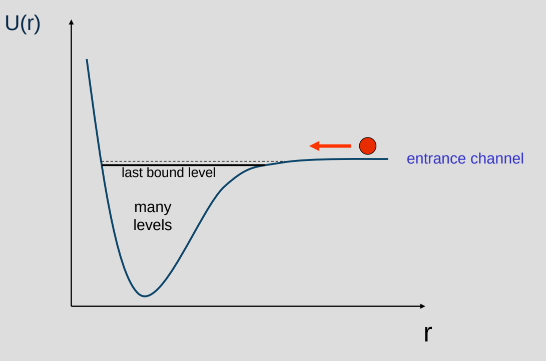
the exciting interaction physics:
few-body physics, many-body physics, universality

experimental control knob?

ultracold.atoms

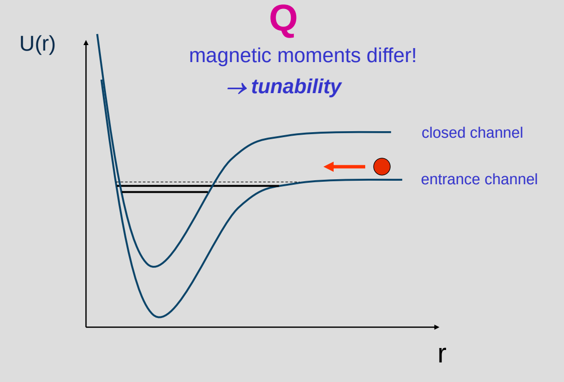
scattering from molecular potential

ultracold.atoms



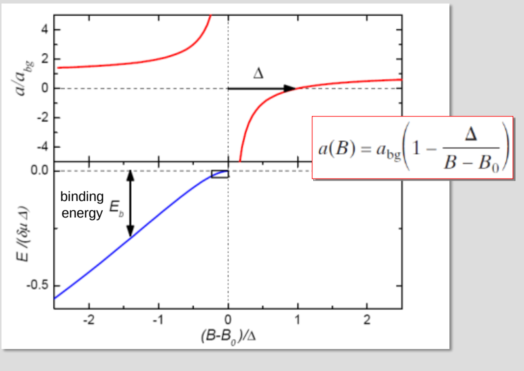
coupling to a closed channel

ultracold.atoms



Feshbach resonance

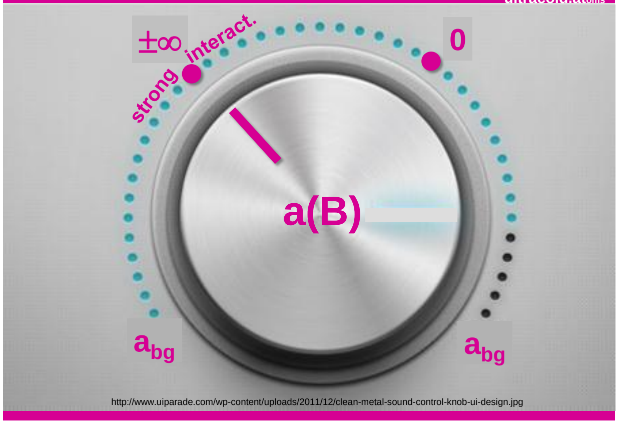
ultracold.atoms



Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

control knob for sc. length (via B field)

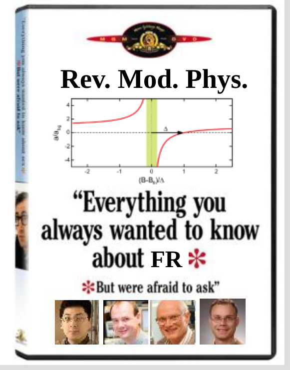
ultracold.atoms



recommended literature

ultracold.atoms

the authors:
Cheng Chin
(U Chicago)
RG (U Innsbruck)
Paul Julienne
Eite Tiesinga
(JQI)



“Feshbach resonances in ultracold gases”

Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

table of Feshbach resonances

ultracold.atoms

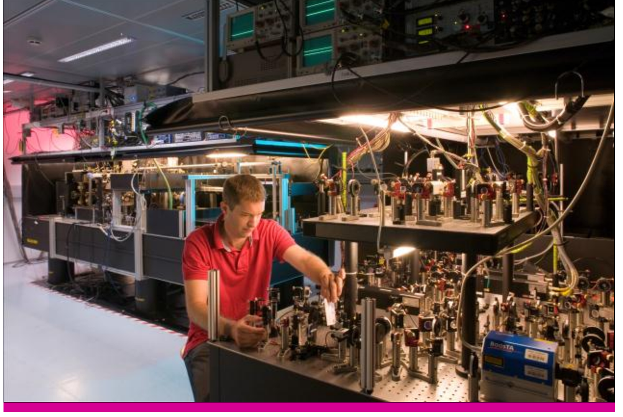
1276 Chin *et al.*: Feshbach resonances in ultracold gases

TABLE IV. Properties of selected Feshbach resonances. The first column describes the atomic species and isotope. The next three columns characterize the scattering and resonance states, which include the incoming scattering channel (ch.), partial wave ℓ, and the angular momentum of the resonance state ℓ_c. This is followed by the resonance location B_0, the width Δ, the background scattering length a_{bg}, the differential magnetic moment $\delta\mu$, the dimensionless resonance strength s_{res}, the background scattering length in van der Waals units $r_{bg}=a_{bg}/\bar{a}$, and the bound state parameter ζ from Eq. (52). Here a_0 is the Bohr radius and μ_B is the Bohr magneton. Definitions are given in Sec. II. The last column gives the source. A string “na” indicates that the corresponding property is not defined. For example a_{bg} is not defined for p-wave scattering.

Atom	ch.	ℓ	ℓ_c	B_0 (G)	Δ (G)	a_{bg}/a_0	$\delta\mu/\mu_B$	s_{res}	r_{bg}	ζ	Reference
^{6}Li	*ab*	*s*	*s*	834.1	−300	−1405	2.0	59	−47	1400	Bartenstein *et al.*, 2005
	ac	*s*	*s*	690.4	−122.3	−1727	2.0	29	−58	850	Bartenstein *et al.*, 2005
	bc	*s*	*s*	811.2	−222.3	−1490	2.0	46	−50	1200	Bartenstein *et al.*, 2005
	ab	*s*	*s*	543.25	0.1	60	2.0	0.001	2.0	0.001	Strecker *et al.*, 2003
	aa	*p*	*p*	159.14	na	na	2.0	na	na	na	Zhang *et al.*, 2004; Schunck *et al.*, 2005
	ab	*p*	*p*	185.09	na	na	2.0	na	na	na	Zhang *et al.*, 2004; Schunck *et al.*, 2005
	bb	*p*	*p*	214.94	na	na	2.0	na	na	na	Zhang *et al.*, 2004; Schunck *et al.*, 2005
^{7}Li	*aa*	*s*	*s*	736.8	−192.3	−25	1.93	0.80	−0.79	0.31	Strecker *et al.*, 2002; Pollack *et al.*, 2009[a]
^{23}Na	*cc*	*s*	*s*	1195	−1.4	62	−0.15	0.0050	1.4	0.004	Inouye *et al.*, 1998; Stenger *et al.*, 1999[a]
	aa	*s*	*s*	907	1	63	3.8	0.09	1.5	0.07	Inouye *et al.*, 1998; Stenger *et al.*, 1999[a]
	aa	*s*	*s*	853	0.0025	63	3.8	0.0002	1.5	0.0002	Inouye *et al.*, 1998; Stenger *et al.*, 1999[a]
^{39}K	*aa*	*s*	*s*	402.4	−52	−29	1.5	2.1	−0.47	0.49	D'Errico *et al.*, 2007
^{40}K	*bb*	*p*	*p*	198.4	na	na	0.134	na	na	na	Regal *et al.*, 2003b; Ticknor *et al.*, 2004[a]
	bb	*p*	*p*	198.8	na	na	0.134	na	na	na	Regal *et al.*, 2003b; Ticknor *et al.*, 2004[a]
	ab	*s*	*s*	202.1	8.0	174	1.68	2.2	2.8	3.1	Regal *et al.*, 2004[a]
	ac	*s*	*s*	224.2	9.7	174	1.68	2.7	2.8	3.8	Regal and Jin, 2003[a]
^{85}Rb	*ee*	*s*	*s*	155.04	10.7	−443	−2.33	28	−5.6	80	Claussen *et al.*, 2003
^{87}Rb	*aa*	*s*	*s*	1007.4	0.21	100	2.79	0.13	1.27	0.08	Volz *et al.*, 2003; Dürr, Volz, and Rempe, 2004[a]
	aa	*s*	*s*	911.7	0.0013	100	2.71	0.001	1.27	0.0006	Marte *et al.*, 2002[a]
	aa	*s*	*s*	685.4	0.006	100	1.34	0.006	1.27	0.004	Marte *et al.*, 2002; Dürr, Volz, and Rempe, 2004[a]
	aa	*s*	*s*	406.2	0.0004	100	2.01	0.0002	1.27	0.0001	Marte *et al.*, 2002[a]
	ae	*s*	*s*	9.13	0.015	99.8	2.00	0.008	1.27	0.005	Widera *et al.*, 2004

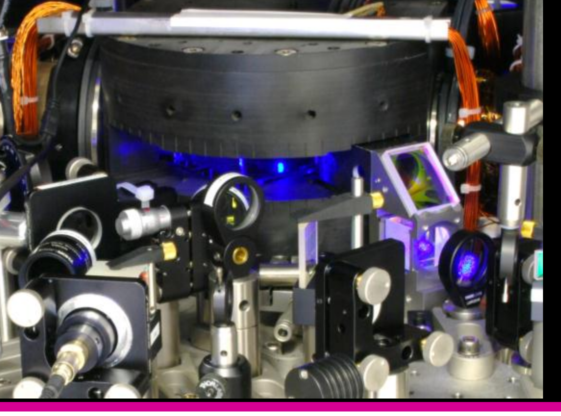
table-top set up

ultracold.atoms



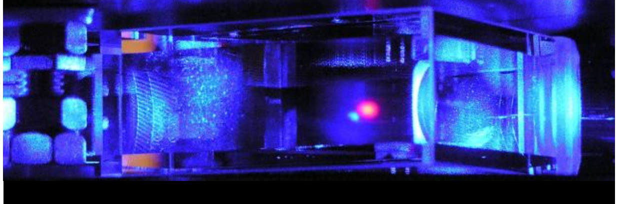
magneto-optically trapped Sr atoms (461nm)

ultracold.atoms



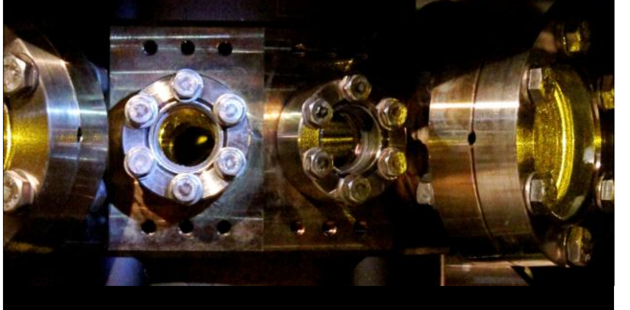
Sr and Li: two-species MOT (461nm and 671nm)

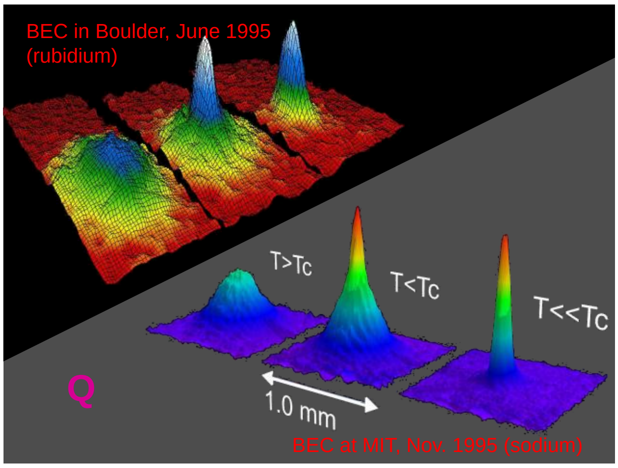
ultracold.atoms

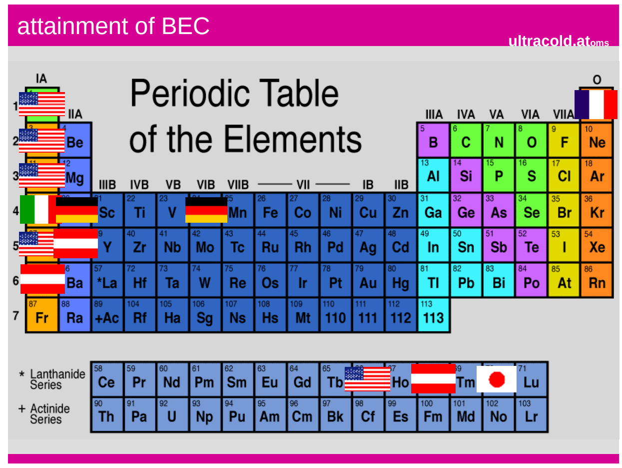


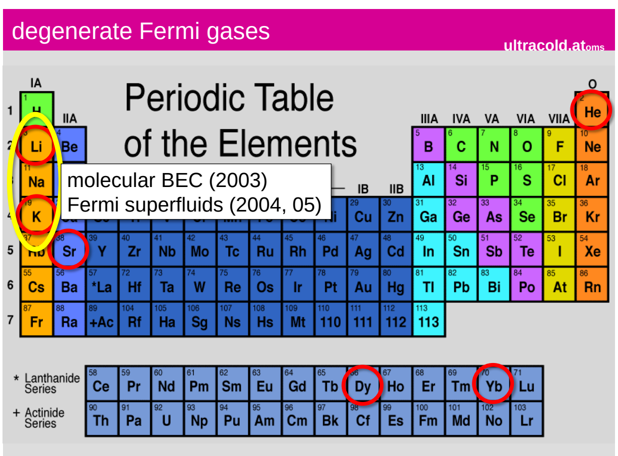
magneto-opically trapped erbium (583nm)

ultracold.atoms



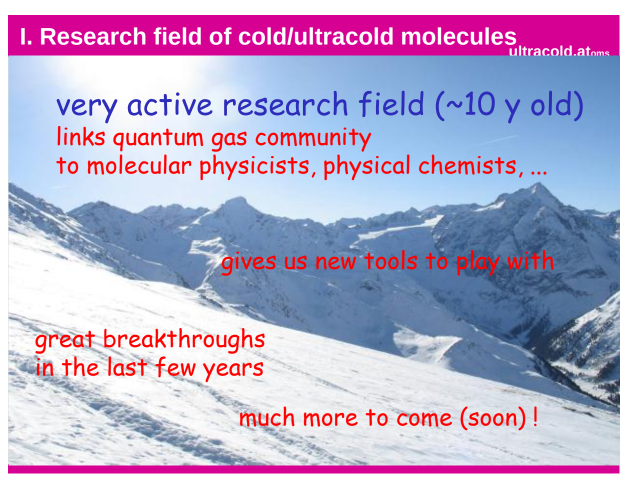

BEC in Boulder, June 1995
(rubidium)
T>Tc
T<Tc
T<<Tc
1.0 mm
BEC at MIT, Nov. 1995 (sodium)


attainment of BEC
ultracold.atoms
Periodic Table
of the Elements
Lanthanide Series
Actinide Series


degenerate Fermi gases
ultracold.atoms
Periodic Table
of the Elements
molecular BEC (2003)
Fermi superfluids (2004, 05)
Lanthanide Series
Actinide Series

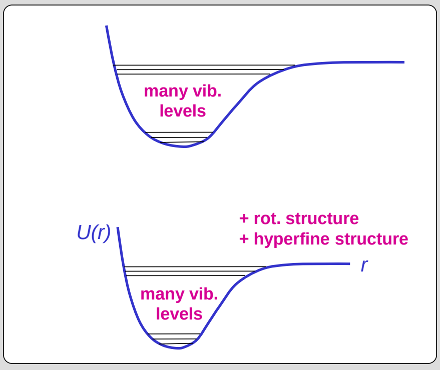

lecture
ultracold.atoms
ultracold molecules


what you will hear in this lecture
ultracold.atoms
I. overview of research field
II. ultracold Feshbach molecules
IV. quantum gases of ground-state molecules
III. few words on photoassociation
V. outlook


I. Research field of cold/ultracold molecules
ultracold.atoms
very active research field (~10 y old)
links quantum gas community
to molecular physicists, physical chemists, ...
gives us new tools to play with
great breakthroughs
in the last few years
much more to come (soon) !

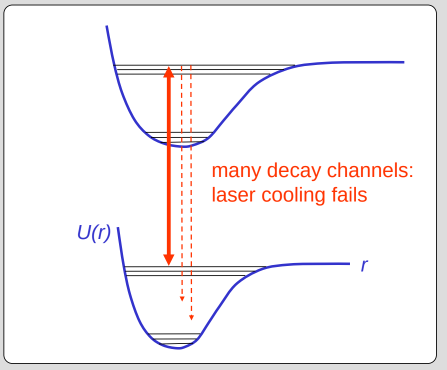
molecules are very rich

ultracold.atoms



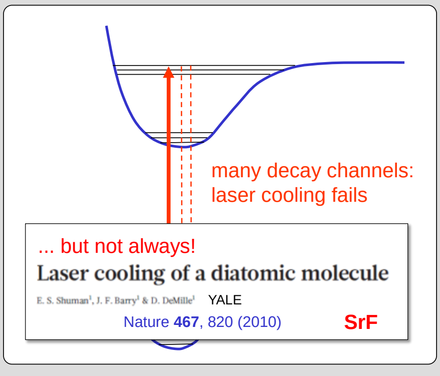
laser cooling not available

ultracold.atoms



laser cooling not available

ultracold.atoms



... but not always!

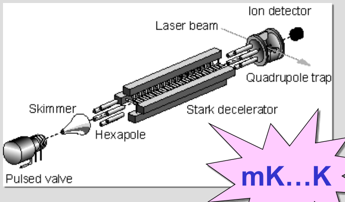
Laser cooling of a diatomic molecule

E. S. Shuman[1], J. F. Barry[1] & D. DeMille[1] YALE

Nature **467**, 820 (2010) **SrF**

slowing and cooling of molecules

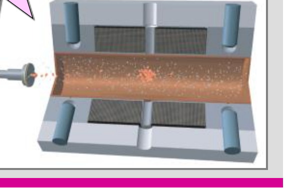
ultracold.atoms



Stark deceleration:
(non-dissipative)
G. Meijer et al.

polar molecules

mK...K

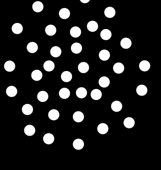


Buffer gas cooling
(dissipative)
J. Doyle et al.

molecules with
large magnetic dipole moment

ultracold molecules: the association trick

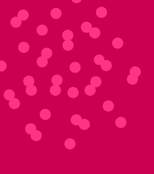
ensemble of
ultracold atoms



ultracold.at

ultracold molecules: the association trick

ensemble of
ultracold atoms



ultracold molecules

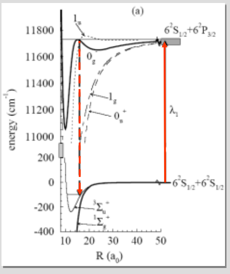
temperature set by atoms: µK (laser cooled), nK (BEC)

ultracold.at

two ways of association

ultracold.atoms

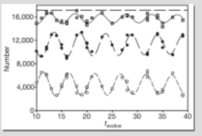
photoassociation



Fioretti et al., PRL 80, 4402 (1998)

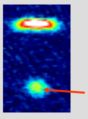
molecules @ 300µK
from a laser-cooled atom gas

„Feshbach"-association



Donley et al., Nature 417, 529 (2002)

coherent atom-molecule coupling



atomic BEC

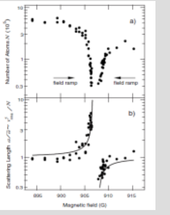
molecules @ few nK
molecular quantum gas

Herbig et al., Science 301, 1510 (2003)

II. Ultracold Feshbach molecules

ultracold.atoms

Feshbach resonance phenomenon



first observed in hydrogen in 1986
and in ultracold gases in 1998
(related observations in at. and mol. physics before)

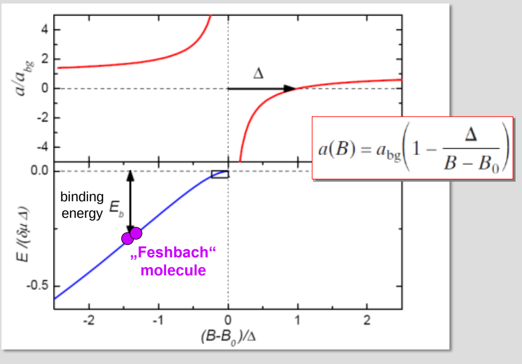
hydrogen: Reynolds et al., PRB **34**, 4912 (1986)
Na BEC: Inouye et al., Nature **392**, 151 (1998)
Rb thermal gas: Courteille et al., PRL **81**, 69 (1998)

nowadays used in many present experiments
to control interactions in quantum gases

recent review:
Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

Feshbach resonance

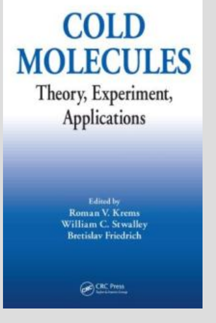
ultracold.atoms



Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

recommended literature

ultracold.atoms

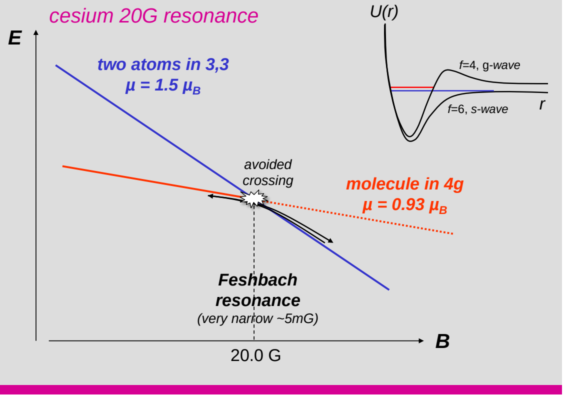


arXiv:0809.3920

Chap IX: "*Ultracold Feshbach molecules*", Ferlaino et al.

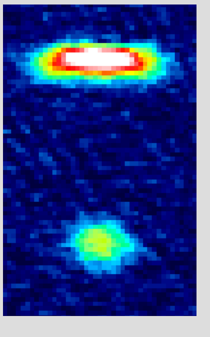
Feshbach ramp: association and detection

ultracold.atoms



atoms & molecules

ultracold.atoms



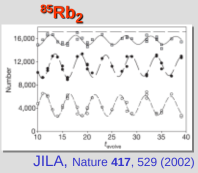
25.000
atoms

3000
dimer molecules

Herbig et al., Science **301**, 1510 (2003)

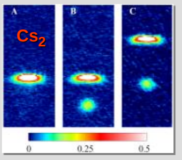
making Feshbach molecules from BECs

ultracold.atoms

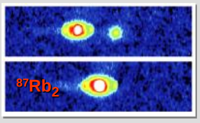


JILA, Nature **417**, 529 (2002)

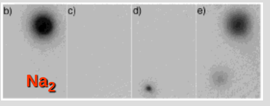
breakthroughs 2002/03



Innsbruck, Science **301**, 1510 (2003)



MPQ, PRL **92**, 020406 (2004)



MIT, PRL **91**, 210402 (2003)

Feshbach molecules from fermionic atoms
$^{40}K_2$ JILA, $^{6}Li_2$ ENS, Rice, Innsbruck 2003

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ultracold.atoms

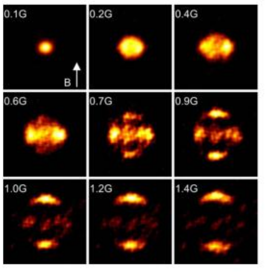

FIG. 36. (Color online) Dissociation patterns of $^{87}Rb_2$ molecules, showing the interference of *s*- and *d*-partial waves. At small magnetic field offsets $B-B_0$ (values given in the upper left corners), the *s*-wave pattern dominates; at large offsets, *d* waves are strongly enhanced due to a *d*-wave shape resonance. From Volz *et al.*, 2005.

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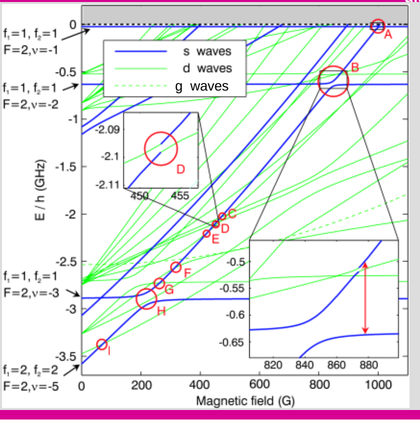
molecular structure near threshold

ultracold.atoms

Rb_2



Lang et al,. Nature Phys. **4**, 223 (2008)

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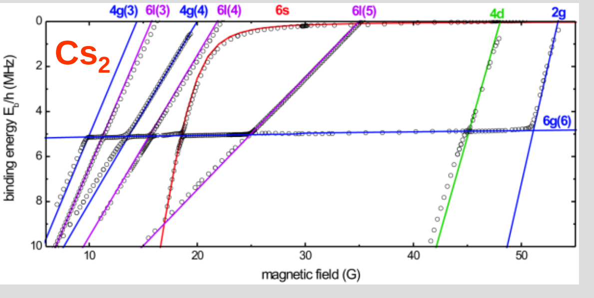
molecular structure near threshold

ultracold.atoms



Mark et al, Phys. Rev. A **76**, 042514 (2007)

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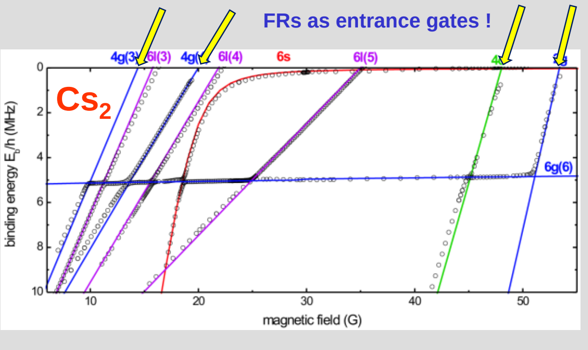
how to enter the molecular world ?

ultracold.atoms

FRs as entrance gates !



Mark et al, Phys. Rev. A **76**, 042514 (2007)

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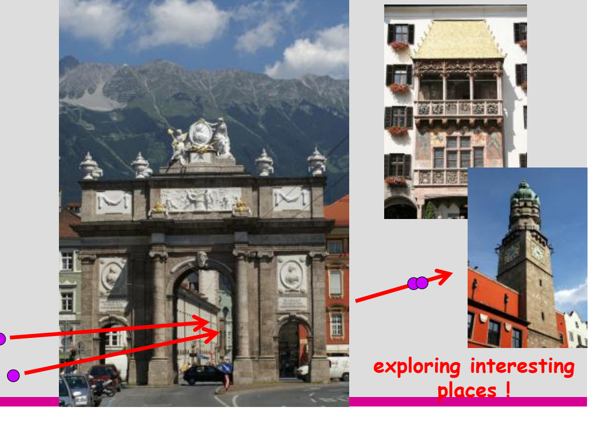
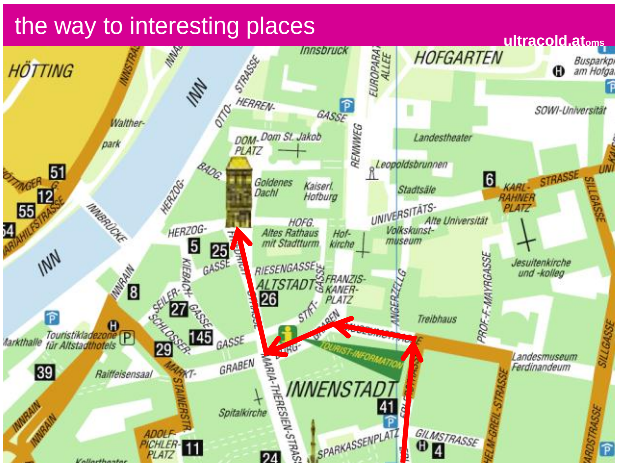
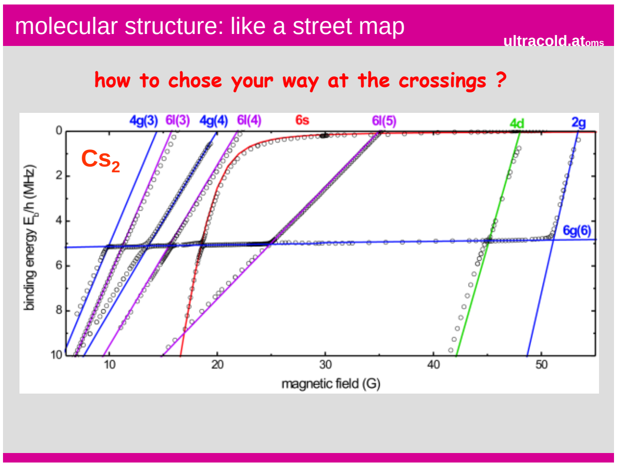
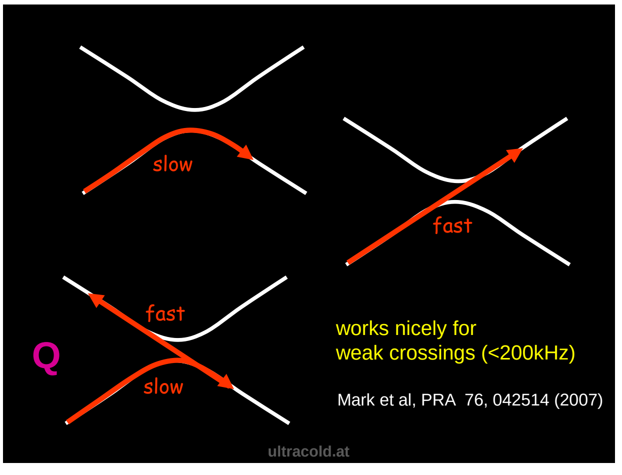
entrance gate

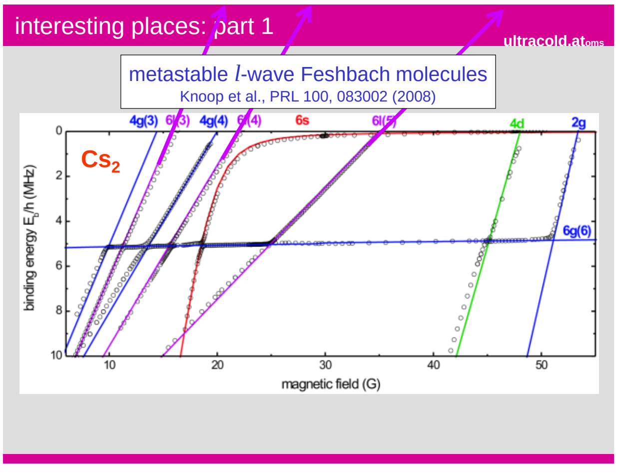
ultracold.atoms

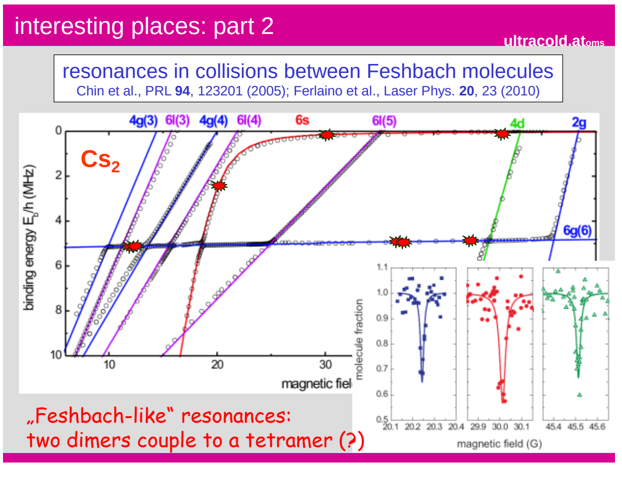


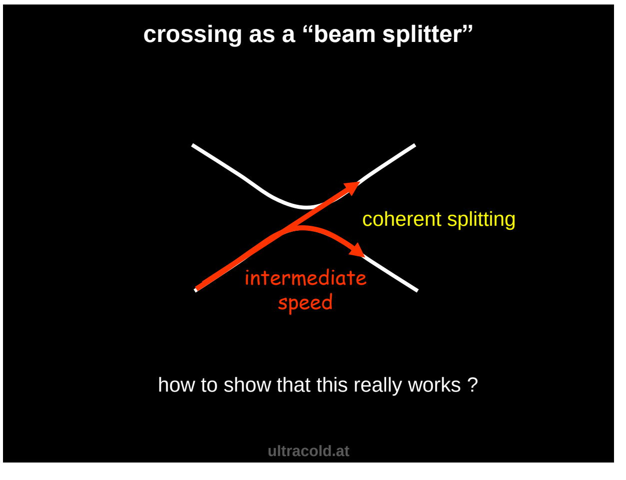

the way to interesting places
ultracold.atoms
HÖTTING
HOFGARTEN
INN
ALTSTADT
INNENSTADT


molecular structure: like a street map
ultracold.atoms
how to chose your way at the crossings ?
Cs2
4g(3) 6l(3) 4g(4) 6l(4) 6s 6l(5) 4d 2g
6g(6)
binding energy Eb/h (MHz)
magnetic field (G)


slow
fast
fast
slow
Q
works nicely for
weak crossings (<200kHz)
Mark et al, PRA 76, 042514 (2007)
ultracold.at


interesting places: part 1
ultracold.atoms
metastable l-wave Feshbach molecules
Knoop et al., PRL 100, 083002 (2008)
Cs2
4g(3) 6l(3) 4g(4) 6l(4) 6s 6l(5) 4d 2g
6g(6)
binding energy Eb/h (MHz)
magnetic field (G)

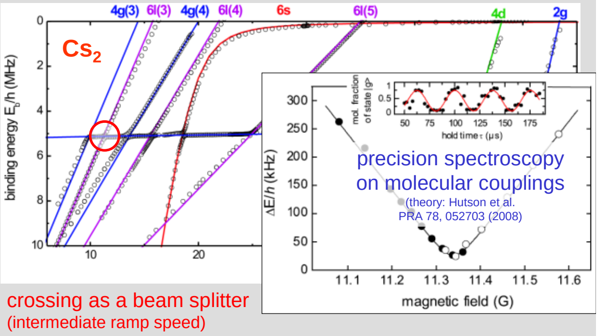

interesting places: part 2
ultracold.atoms
resonances in collisions between Feshbach molecules
Chin et al., PRL 94, 123201 (2005); Ferlaino et al., Laser Phys. 20, 23 (2010)
Cs2
4g(3) 6l(3) 4g(4) 6l(4) 6s 6l(5) 4d 2g
6g(6)
binding energy Eb/h (MHz)
magnetic fiel
molecule fraction
magnetic field (G)
„Feshbach-like" resonances:
two dimers couple to a tetramer (?)


crossing as a "beam splitter"
coherent splitting
intermediate
speed
how to show that this really works ?
ultracold.at

interesting places: part 3

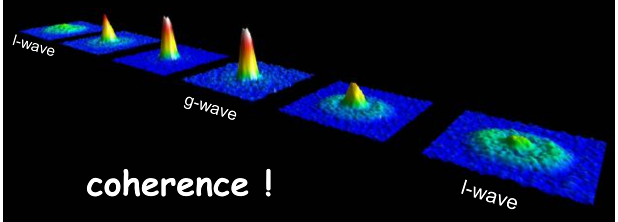
ultracold.atoms

"Stückelberg interferometry" with ultracold molecules
Mark et al., PRL 99, 113201 (2007)



crossing as a beam splitter
(intermediate ramp speed)

Stückelberg oscillations in dissociation pattern



coherence !

interesting places: part 4

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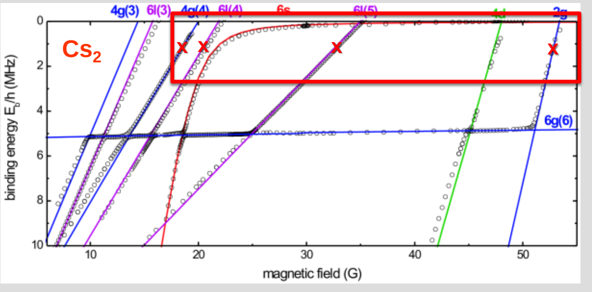
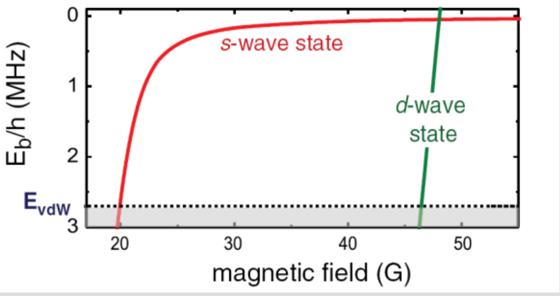


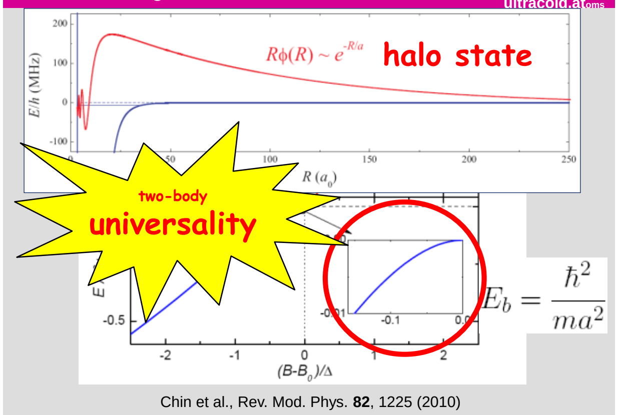
universal *s*-wave state

ultracold.atoms



universal range

ultracold.atoms



Chin et al., Rev. Mod. Phys. **82**, 1225 (2010)

inelastic loss (bad news)

ultracold.atoms

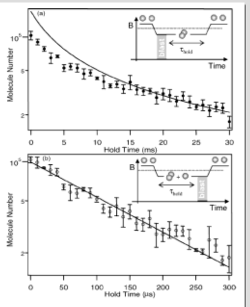


FIG. 4. Decay of ultracold molecules trapped alone (a) or together with atoms (b). The solid lines in (a) and (b) are fits of Eqs. (9) and (10) to data, which assume vibrational relaxation in the collision of m olecules (a) or collisions between molecules and atoms (b). The insets illustrate the experimental sequences. MIT, PRL **92**, 180402 (2003)

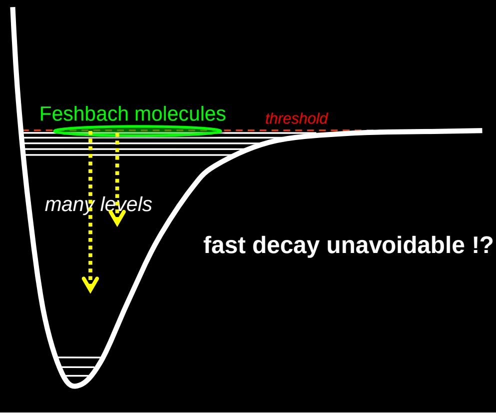
molecule-molecule collisions

typ. rate coefficient
~ 5 x 10^{-11} cm^3/s

atom-molecule collisions

collisional decay of Feshbach molecules

ultracold.atoms



fast decay unavoidable !?

three ways to solve the loss problem

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special case: fermions in a halo state

put them into the rovibronic ground state

use a 3D optical lattice
to protect them