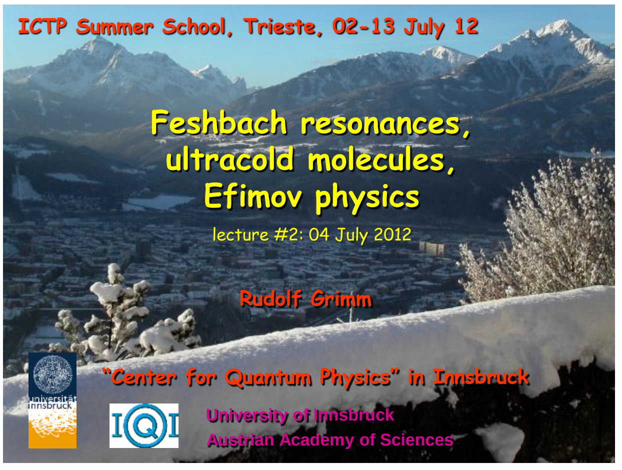
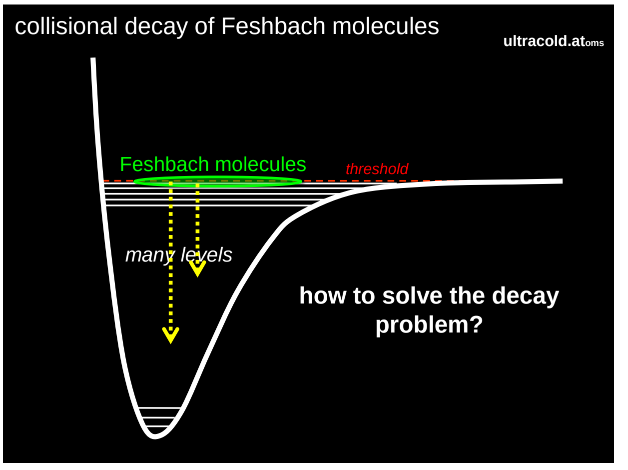
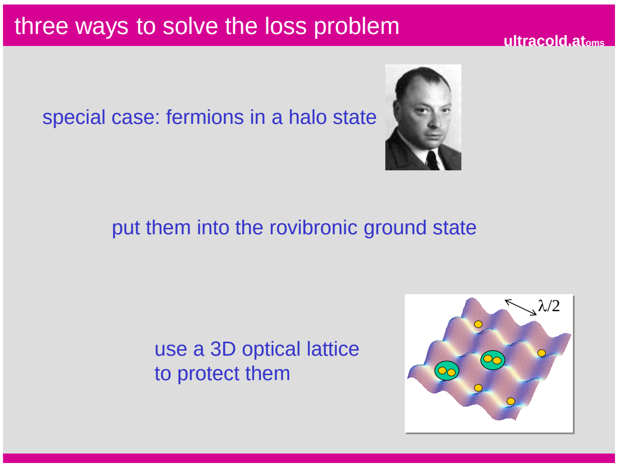
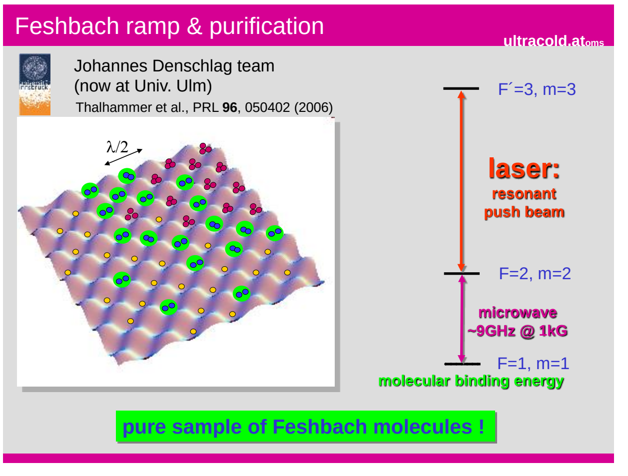
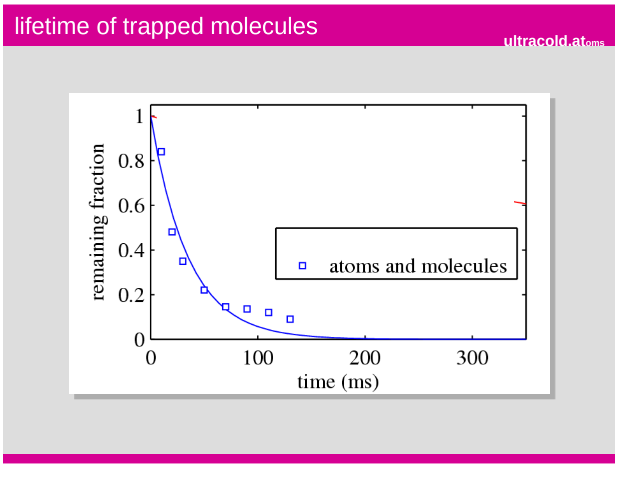
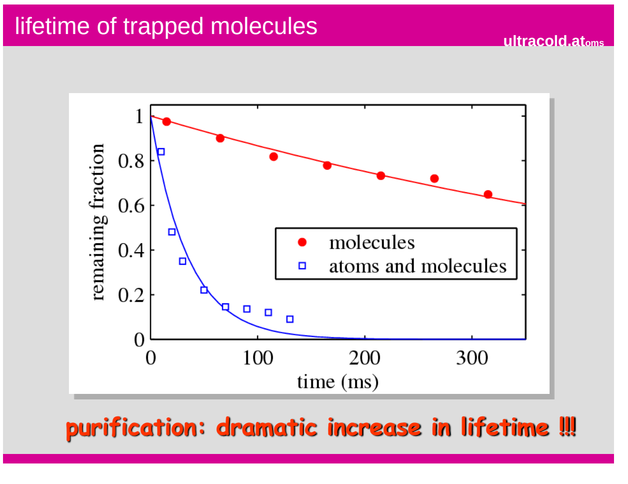

ICTP Summer School, Trieste, 02-13 July 12
Feshbach resonances, ultracold molecules, Efimov physics
lecture #2: 04 July 2012
Rudolf Grimm
"Center for Quantum Physics" in Innsbruck
University of Innsbruck
Austrian Academy of Sciences


collisional decay of Feshbach molecules
ultracold.atoms
Feshbach molecules
threshold
many levels
how to solve the decay problem?


three ways to solve the loss problem
ultracold.atoms
special case: fermions in a halo state
put them into the rovibronic ground state
use a 3D optical lattice to protect them
λ/2

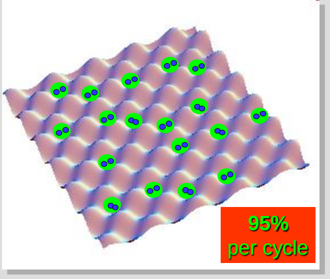

Feshbach ramp & purification
ultracold.atoms
Johannes Denschlag team
(now at Univ. Ulm)
Thalhammer et al., PRL 96, 050402 (2006)
λ/2
F´=3, m=3
laser:
resonant push beam
F=2, m=2
microwave ~9GHz @ 1kG
F=1, m=1
molecular binding energy
pure sample of Feshbach molecules !


lifetime of trapped molecules
ultracold.atoms
remaining fraction
time (ms)
atoms and molecules


lifetime of trapped molecules
ultracold.atoms
remaining fraction
time (ms)
molecules
atoms and molecules
purification: dramatic increase in lifetime !!!

## doing it again and again ...

ultracold.atoms




Thalhammer et al., PRL **96**, 050402 (2006)

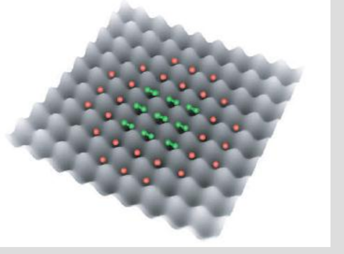
## starting with a Mott insulator

ultracold.atoms

Preparation of a quantum state with one molecule at each site of an optical lattice

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
*e-mail: stephan.duerr@mpq.mpg.de; gerhard.rempe@mpq.mpg.de

Nature Phys. **2**, 692 (2006)



## experimental sequence

ultracold.atoms

quantum gas preparation → FR assoc. → something interesting → FR dissoc. → detection

## experimental sequence

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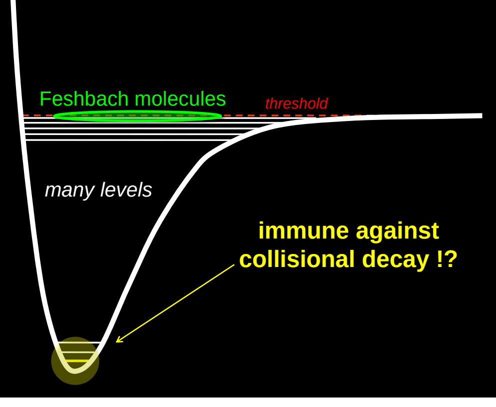
collision studies, spectroscopy....

quantum gas preparation → FR assoc. → purif. → state transf. → **experiment !** → state transf. → FR dissoc. → detection

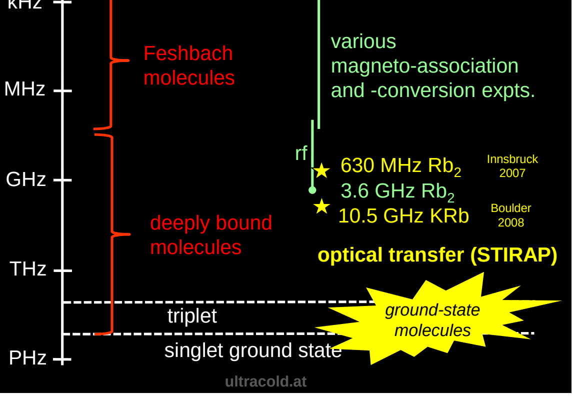
state of main interest:
**rovibronic ground state**

## rovibronic ground-state molecules

ultracold.atoms



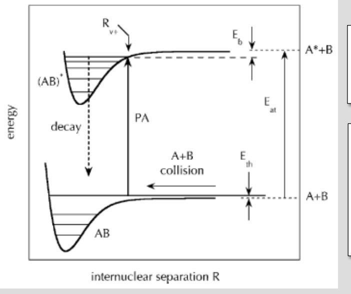

## binding energy scales




## III. Photoassociation (just a short detour)

ultracold.atoms

review: Jones et al., RMP **78**, 0483 (2006)




excitation

$A + B + \gamma \rightarrow (AB)^*$

de-excitation

$(AB)^* \rightarrow A + B + \gamma_d$

or

$(AB)^* \rightarrow AB + \gamma_d$

spontaneous or stimulated process

## III. Photoassociation (just a short detour)

ultracold.atoms

PA molecular spectroscopy:
widely used method, many papers !

molecule formation in MOTs (end 90's, early 00's)
$Cs_2$ Pillet et al., $Rb_2$ Gabannini et al., $K_2$ Swalley/Gould et al., ...

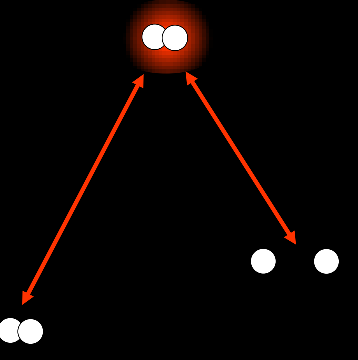
optically trapped molecules: Knize et al. (1998)
molecules in BEC: Heinzen et al. (1999)

creation of *heteronuclear* ground state molecules

KRb Stwalley et al. (2000)
RbCs DeMille et al. (2005)
LiCs Weidemüller et al. (2008)

but quite far from being a quantum gas

## two photons: atom-molecule Raman coupling





## early BEC experiment: two-color photoassociation

Wynar et al., Science 287, 1016 (2000); Heinzen group, Austin, TX

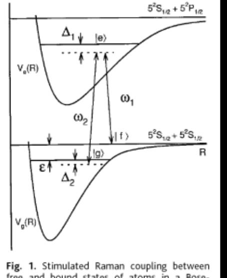
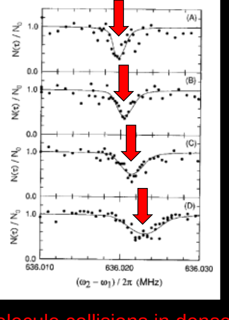


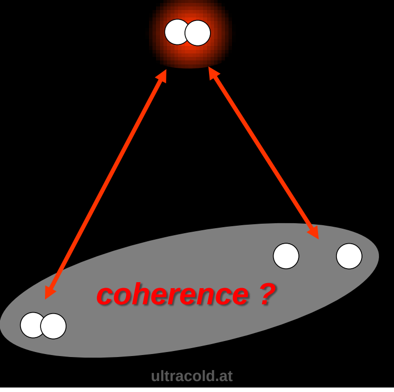

Fig. 1. Stimulated Raman coupling between free and bound states of atoms in a Bose-Einstein condensate.




loss resonance from inelastic molecule collisions in dense BEC

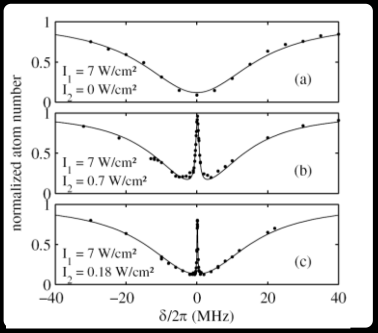


## two photons: atom-molecule Raman coupling




Q

## observation of atom-molecule dark states




**Q**

coupling of atom pairs to second-to-last bound state (636 MHz)

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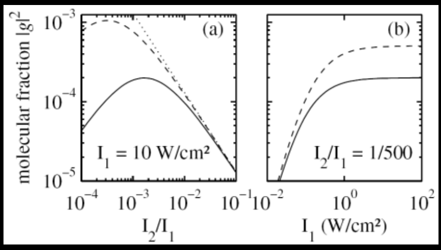
## maximum molecular fraction

theoretical modelling of our Rb experiments based on parameters extracted from dark-resonance measurements




**not really encouraging !**

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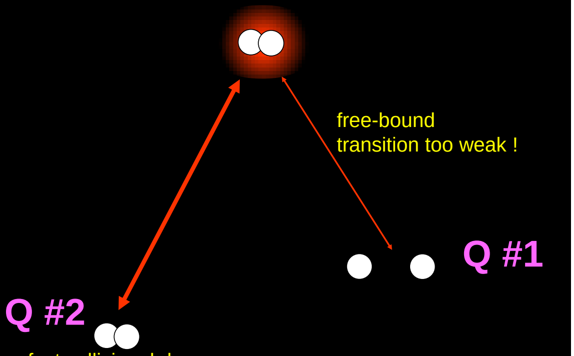
## two main problems

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## IV. Ground-state molecules near degeneracy

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why quantum gases of ground state molecules?

**collisional stability**

**novel interactions**

**novel quantum many-body states**

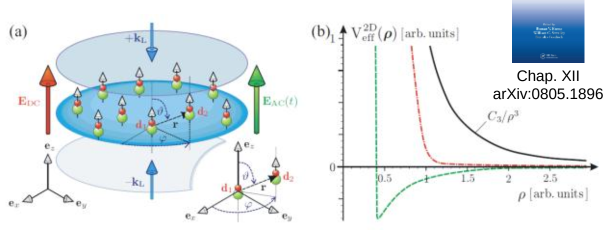
in particular strongly dipolar systems
heteronuclear molecules: large electric dipole moment

## example: highly correlated states

ultracold.atoms

Condensed Matter Physics with Cold Polar Molecules

G. Pupillo[1,2], A. Micheli[1,2], H.P. Büchler[3], and P. Zoller[1,2]




Chap. XII
arXiv:0805.1896

tayloring interactions by DC and AC electric fields

## early proof-of-principle experiment

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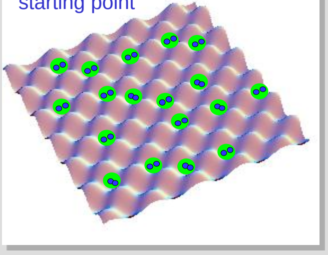
**coherent optical transfer in $Rb_2$**

Johannes Denschlag team
(now at Univ. Ulm)

starting point

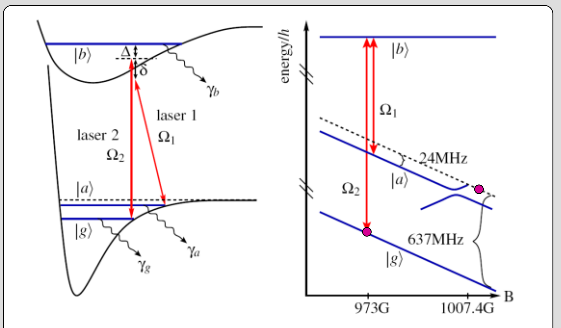


Winkler et al., PRL 98, 043201 (2007)

## STIRAP in $Rb_2$

ultracold.atoms

Winkler et al., PRL 98, 043201 (2007)

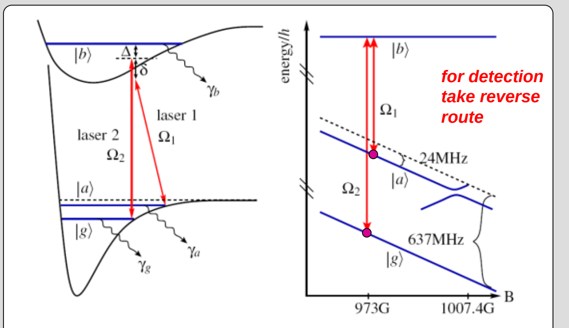



coupling of **last** to **second-to-last** bound level

## STIRAP in $Rb_2$

ultracold.atoms

Winkler et al., PRL 98, 043201 (2007)




coupling of **last** to **second-to-last** bound level

## what is STIRAP?

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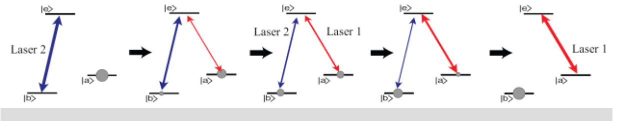
**STI**mulated **R**aman **A**diabatic **P**assage

Bergmann, Theuer, Shore, RMP 70, 1003 (1998)

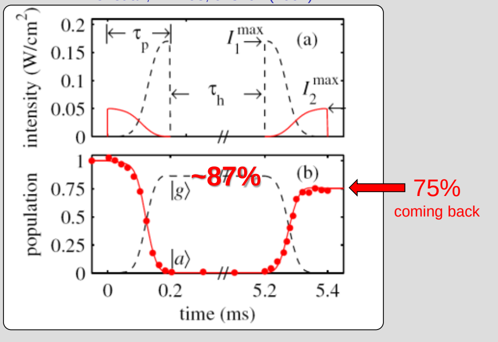



a very efficient and robust
way to implement a two-photon transition
based on a "dark state"

## pulse scheme & efficiency

ultracold.atoms

Winkler et al., PRL 98, 043201 (2007)

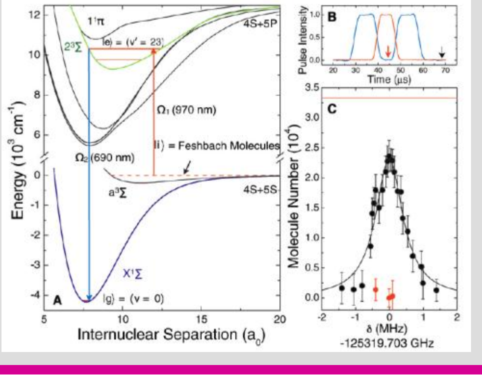



tradeoff between adiabaticity and off-resonant photon scattering

## KRb ground state molecules

ultracold.atoms

Ni et al., Science 322, 231 (2010), group of D. Jin and J. Ye in Boulder




## collisional stability.... now the truth

ultracold.atoms

chemical reactions of ultracold dimers

dimer reactions AB + AB → $A_2$ + $B_2$

P. S. Zuchowski and J. M. Hutson, Phys. Rev. A **81**, 060703 (2010)

two possibilities

AB + AB ✗ $A_2$ + $B_2$ ☺

AB + AB → $A_2$ + $B_2$ + 💥 😐

all reactions making a trimer + an atom are energetically suppressed!

three-molecule collisions?

## dipolar ground-state molecules

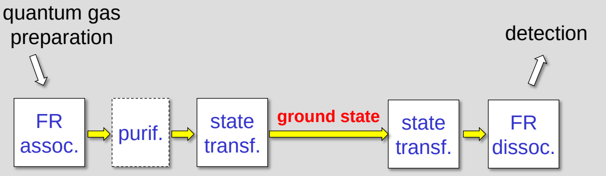

electric dipole moments (debye)
of bi-alkali molecules

| | Li | Na | K | Rb | Cs |
|---|---|---|---|---|---|
| Li | 0 | 0.57 | 3.56 | 4.16 | 5.52 |
| Na | 0.57 | 0 | 2.58 | 3.31 | 4.61 |
| K | 3.56 | 2.58 | 0 | 0.62 | 1.91 |
| Rb | 4.16 | 3.31 | 0.62 | 0 | 1.24 |
| Cs | 5.52 | 4.61 | 1.91 | 1.24 | 0 |

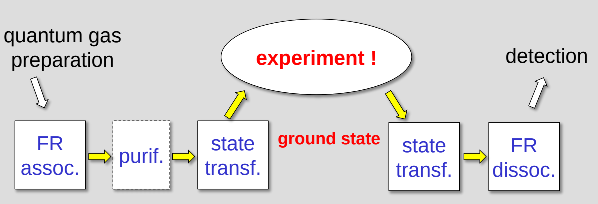
reactive
stable

Deiglmayr et al.,
J. Chem. Phys. 129, 064309 (2008)

## experimental sequence


## experimental sequence

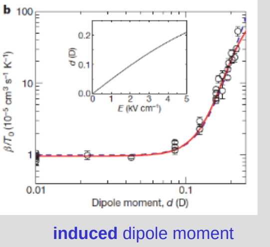



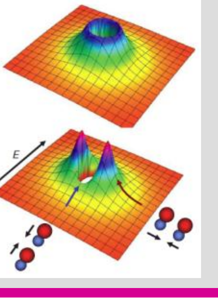

## chemical reactions of KRb molecules


$^{40}K^{87}Rb$ **fermionic** molecule: interactions in *p*-waves

inelastic loss needs tunneling through *p*-wave barrier:
strong suppression as compared to bosonic reactive molecules

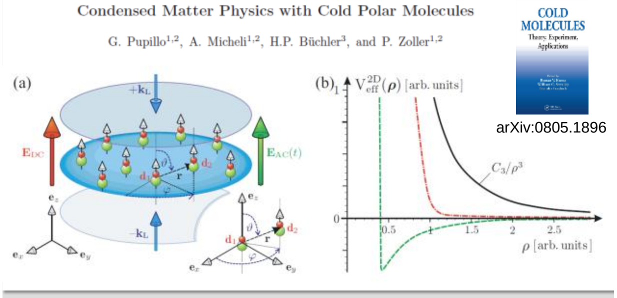
Ni et al., Nature 464, 1324 (2010)




**induced** dipole moment
controlled by external E field

## dipolar molecules in 2D


suppression of reactive loss in 2D recently demonstrated
by Boulder group Nature Phys. **7**, 502 (2011)

## V. Outlook: current trends and new possibilities


attainment of quantum degeneracy (in KRb ?)

bi-alkali molecules with large dipole moments (LiCs, ...)
stronger long-range interaction and
better suppression of reactive losses

chemically stable bi-alkali molecules (RbCs, NaK, ...)

BEC of homo- and heteronuclear molecules ($Cs_2$, RbCs, ...)

molecules of alkali and earth-alkali-like atoms
(LiYb, RbSr, ....) both electric and magnetic dipole moment

more exotic molecules
(LiCr, LiEr, YbF, ....) we'll see.... let's dream!

## dipolar ground-state molecules

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electric dipole moments (debye)
of bi-alkali molecules

| | Li | Na | K | Rb | Cs |
|---|---|---|---|---|---|
| Li | 0 | 0.57 | 3.56 | 4.16 | 5.52 |
| Na | 0.57 | 0 | 2.58 | 3.31 | 4.61 |
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| Rb | 4.16 | 3.31 | 0.62 | 0 | 1.24 |
| Cs | 5.52 | 4.61 | 1.91 | 1.24 | 0 |

reactive

stable

Deiglmayr et al.,
J. Chem. Phys. 129, 064309 (2008)

## towards a chemically stable, strongly dipolar BEC

Rb-Cs

ground state with dipole moment D = 1.25 Debye

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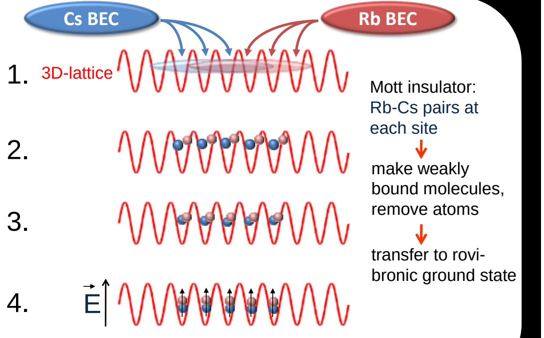
## towards a strongly dipolar BEC




Then: leave in lattice, or „melt“ to form molecular BEC

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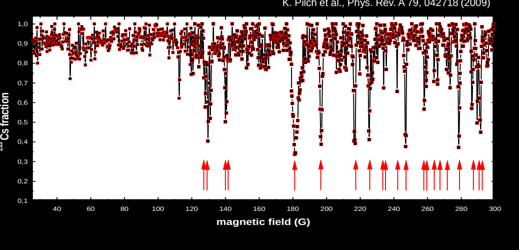
## Rb-Cs mixture: inter-species Feshbach resonances

K. Pilch et al., Phys. Rev. A 79, 042718 (2009)




assignment ALMOST done !!!

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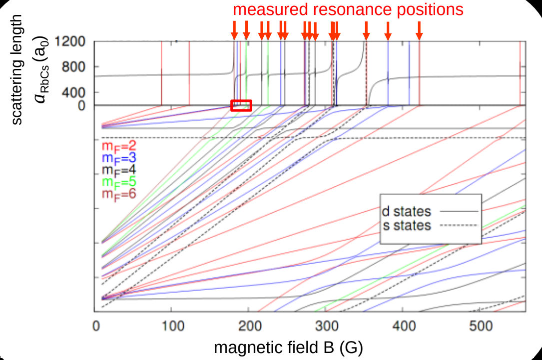
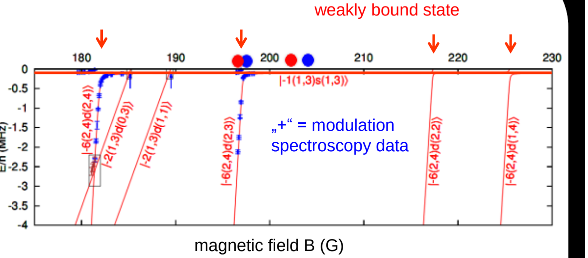
## Rb-Cs mixture: inter-species Feshbach resonances for $a_{RbCs}$



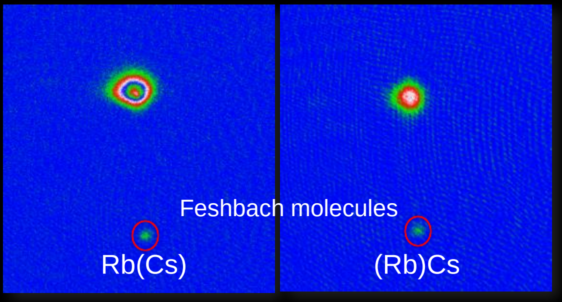

Takekoshi et al., PRA 2012

## Rb-Cs mixture: Feshbach molecules



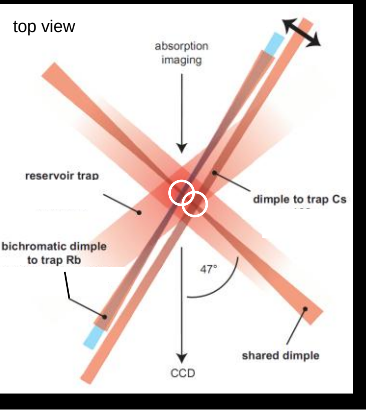

Typically, 60k Cs + 150k Rb gives 4000 RbCs at T=200 nK

## Rb-Cs mixture: RbCs-production



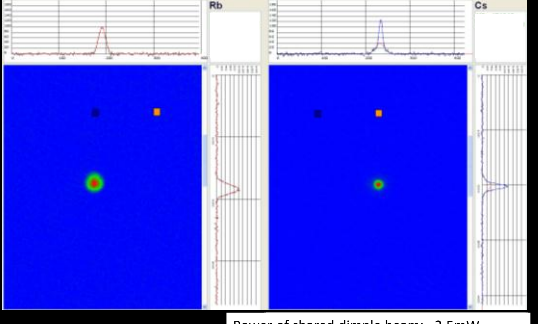

- typically 4000 molecules
- atom clouds are near-degenerate (~200nK)
- magneto-association is faster than 3-body heating
- efficiency ~5%, i.e. still low, as expected

## Rb-Cs mixture: separate BEC-production in two separate traps




comparatively strong three-body loss: $L_3=10^{-24}cm^6/s$

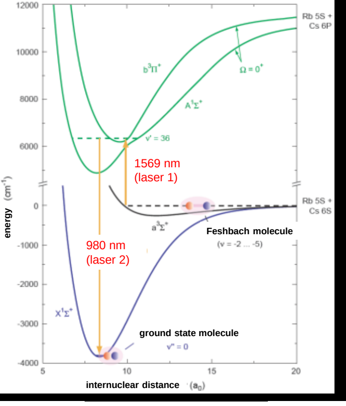
## Rb-Cs mixture: separate BEC-production




Power of shared dimple beam: 2.5mW
pure condensates with Rb 20k, Cs 10k atoms

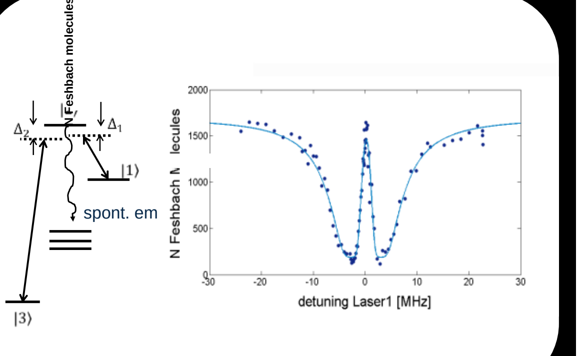
A. D. Lercher et al., EPJD 65, 3 (2011)

## Spectroscopy and stimulated transfer for RbCs



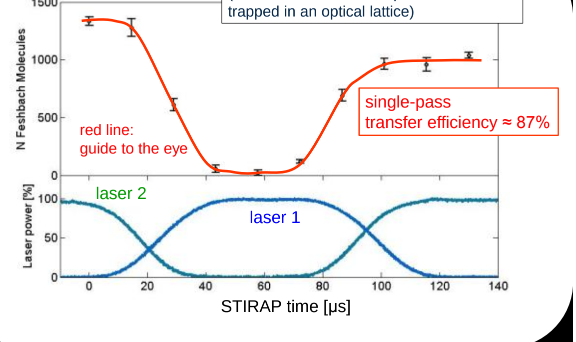

W.C. Stwalley, Eur. Phys. J. D **31**, 221 (2004)

## two-photon spectroscopy to v=0, J=0

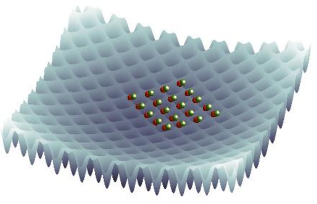



M. Debatin et al., Phys. Chem. Chem. Phys. **13**, 18926 (2011)

## RbCs two-photon STIRAP to v=0, J=0 (data from February)



How do we mix two degenerate samples?



Now make Feshbach molecules, and do STIRAP

## our group in Innsbruck

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## ultracold experiments in Innsbruck

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Hanns-Christoph Nägerl

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

Florian Schreck

Francesca Ferlaino

**Sr** - quantum simulations
**RbSr** - ground state molecules

**Er** - new, strongly dipolar quantum gas

RG's experiments

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

**Li** - fermionic spin mixtures