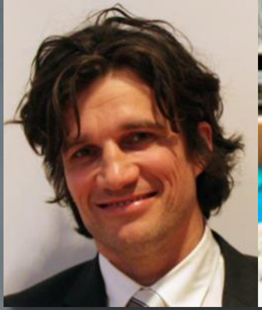
Ultracold dipolar bosonic molecules

Workshop on Quantum Simulations with Ultracold Atoms

ICTP Trieste

Tetsu Takekoshi, 20.07.12


Hanns-Christoph Nägerl (PI)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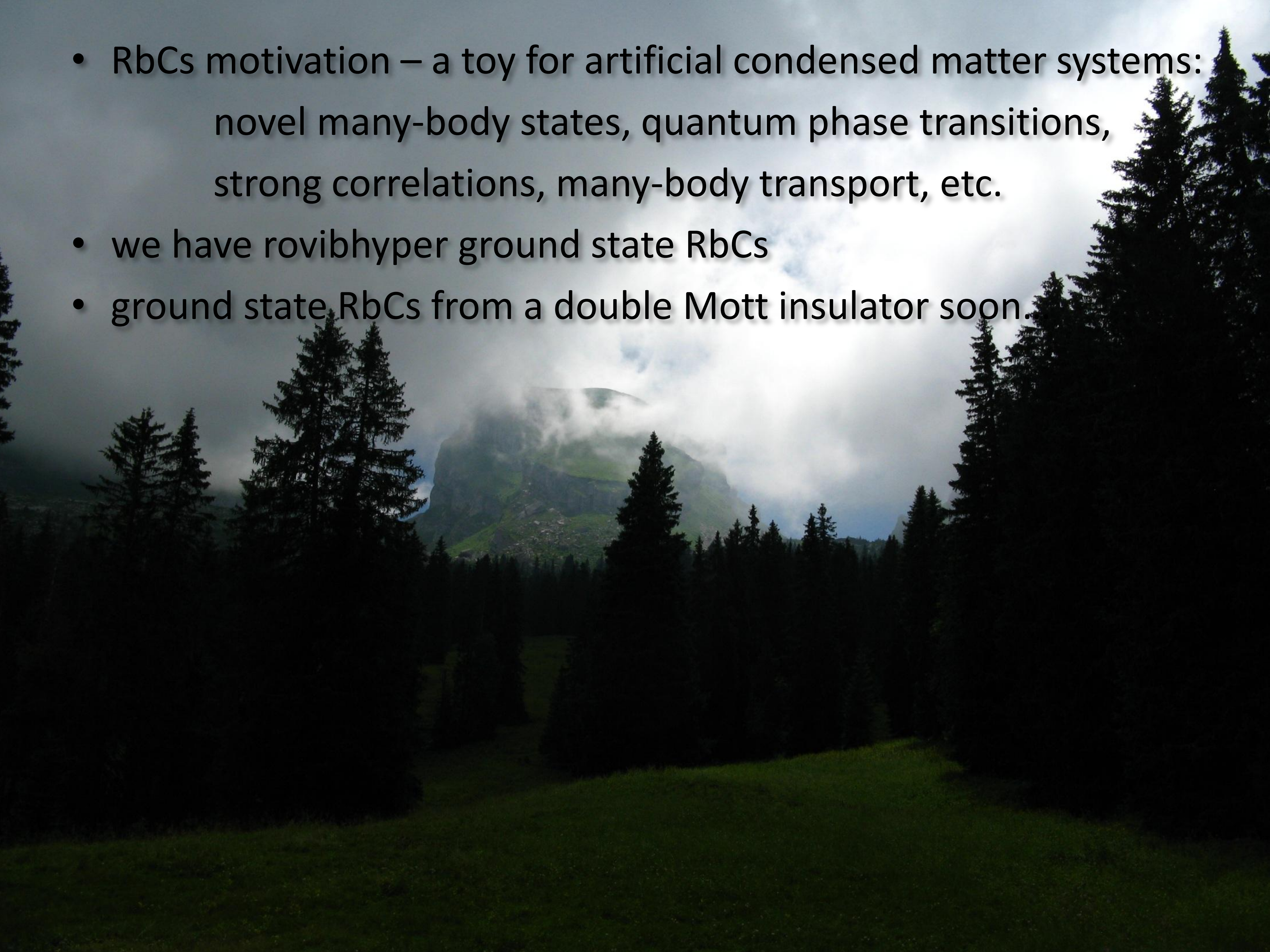
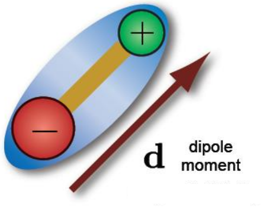
FWF
SFB Foundations and Applications of Quantum Science FoQuS
IQI
universität innsbruck
European Science Foundation

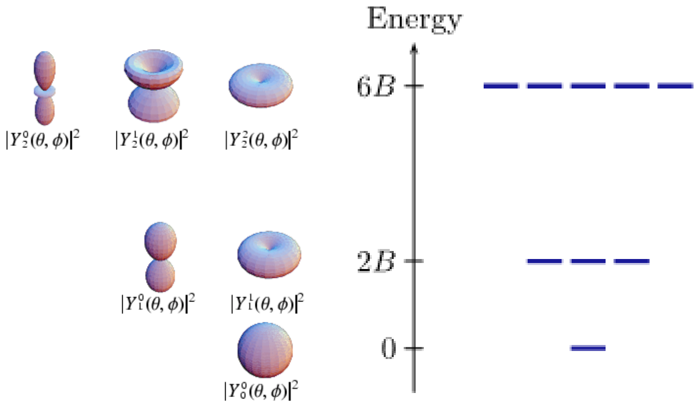


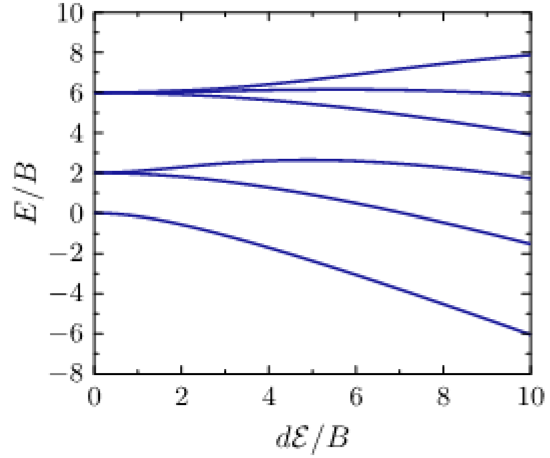
- RbCs motivation – a toy for artificial condensed matter systems:
  novel many-body states, quantum phase transitions,
  strong correlations, many-body transport, etc.
- we have rovibhyper ground state RbCs
- ground state RbCs from a double Mott insulator soon.

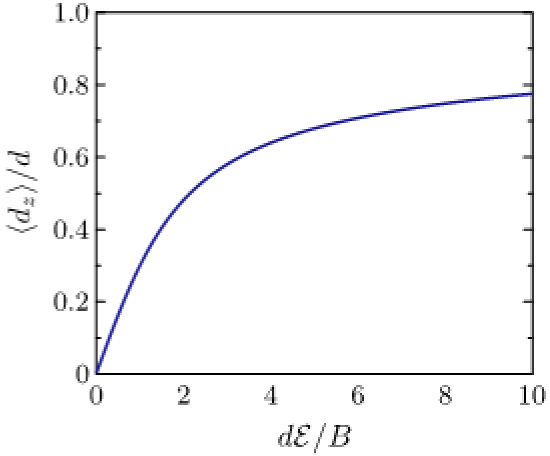
Why degenerate dipolar gases?



$^1\Sigma$ rigid rotor







$$\hat{H}_{\rm rot} = B\hat{\boldsymbol{J}}^2$$

$$\hat{H} = \hat{H}_{\rm rot} - \hat{\boldsymbol{d}} \cdot \boldsymbol{E} = \hat{H}_{\rm rot} - d\mathcal{E}\cos\theta,$$

$$\boldsymbol{E} = \mathcal{E}\boldsymbol{e}_z$$

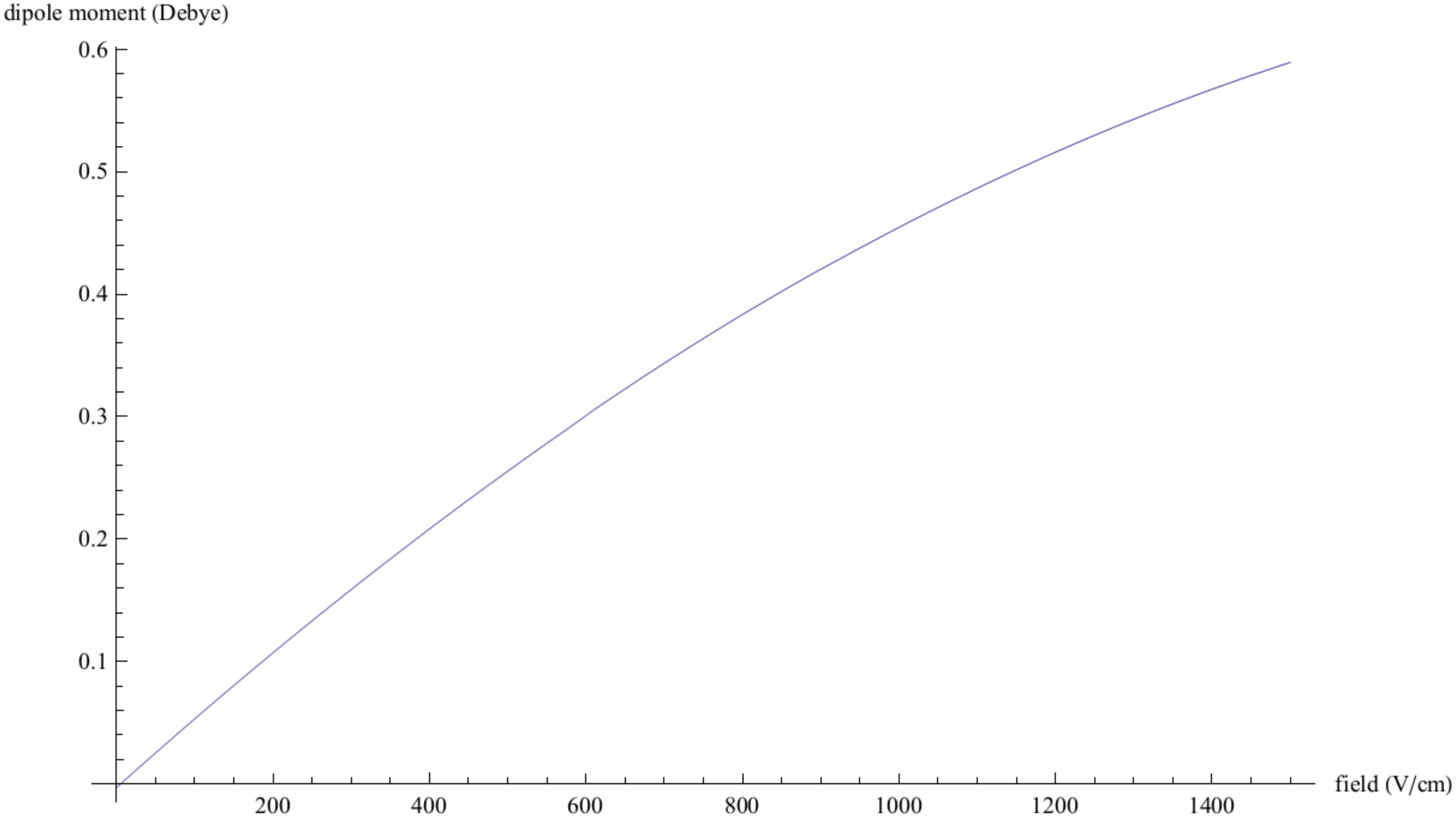
Review articles:

T. Lahaye, C. Menotti, L. Santos, M. Lewenstein, and T. Pfau, Rep. Prog. Phys. **72**, 126401 (2009).

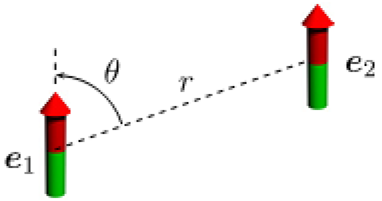
M.A. Baranov, Phys. Rep. **464**, 71 (2008).

Why degenerate dipolar gases?

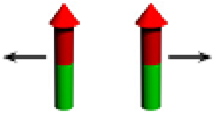
87RbCs lowest rotational level

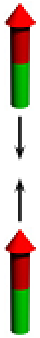


Why degenerate dipolar gases?



$$U_{\mathrm{dd}}(\boldsymbol{r}) = \frac{C_{\mathrm{dd}}}{4\pi}\frac{1-3\cos^2\theta}{r^3}$$





$$C_{dd} = \frac{d^2}{\epsilon_0} \qquad \text{electric dipoles}$$

$$C_{dd} = \mu_0\mu^2 \qquad \text{magnetic dipoles}$$

$$\frac{\mu_0\mu^2}{d^2/\varepsilon_0} \sim \alpha^2 \sim 10^{-4}$$

$$a_{\mathrm{dd}} \equiv \frac{C_{\mathrm{dd}}m}{12\pi\hbar^2} \qquad \varepsilon_{\mathrm{dd}} \equiv \frac{a_{\mathrm{dd}}}{a} = \frac{C_{\mathrm{dd}}}{3g}$$

Review articles:

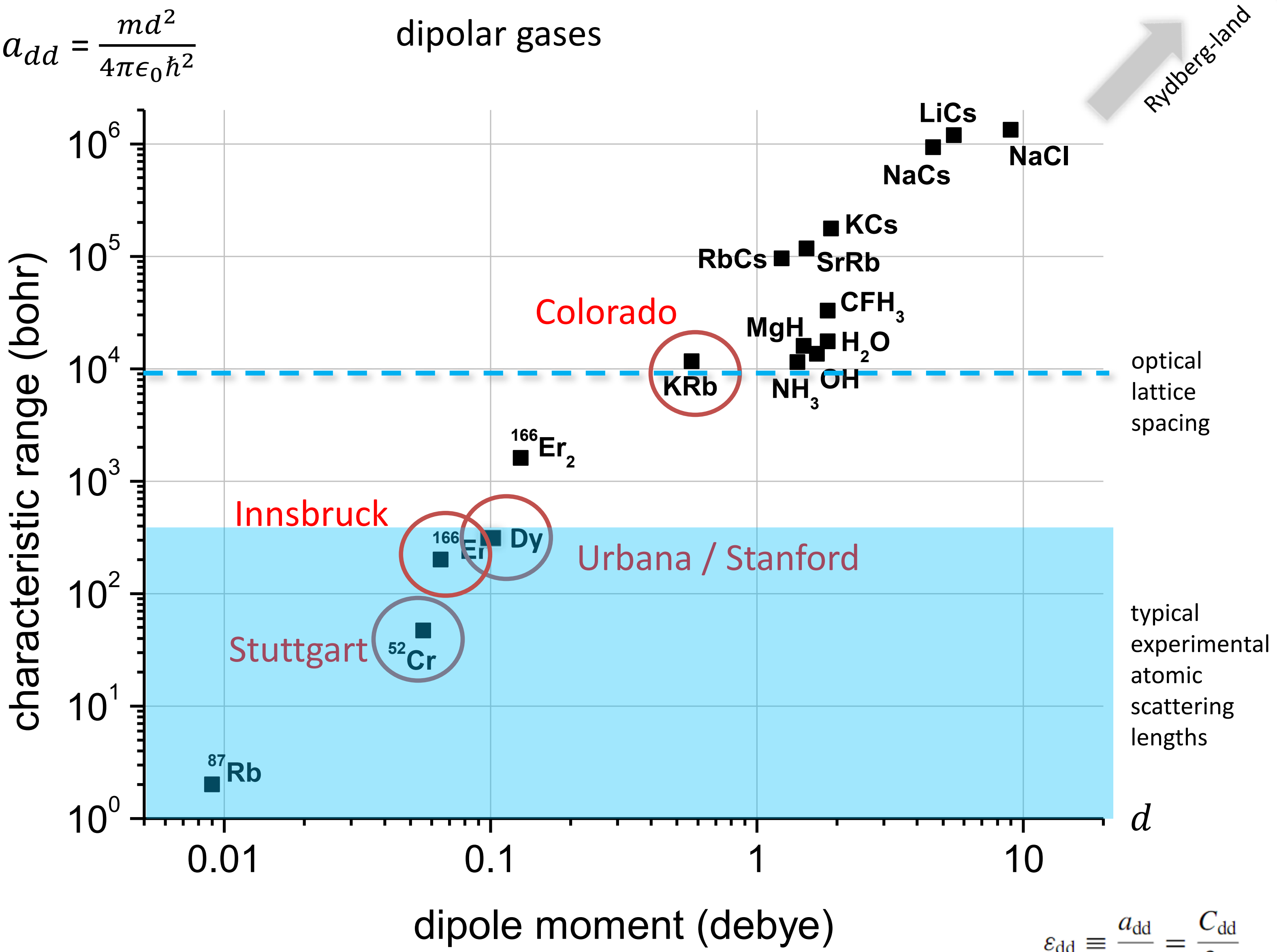
T. Lahaye *et al.*, Rep. Prog. Phys. **72**, 126401 (2009).

M.A. Baranov, Phys. Rep. **464**, 71 (2008).

Why degenerate dipolar gases?

$$a_{dd} = \frac{md^2}{4\pi\epsilon_0\hbar^2}$$

dipolar gases

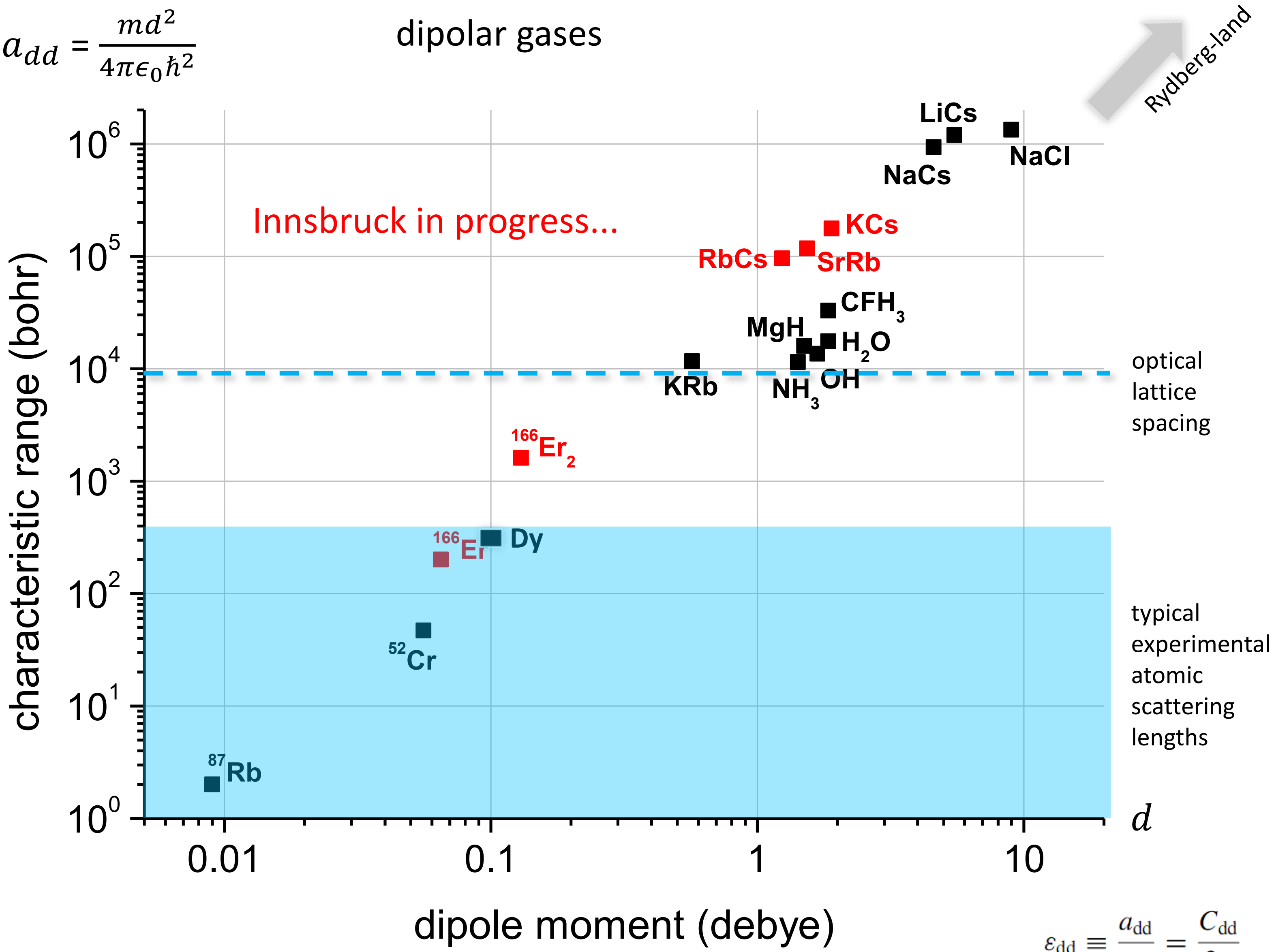


$$\varepsilon_{dd} \equiv \frac{a_{dd}}{a} = \frac{C_{dd}}{3g}$$

Why degenerate dipolar gases?

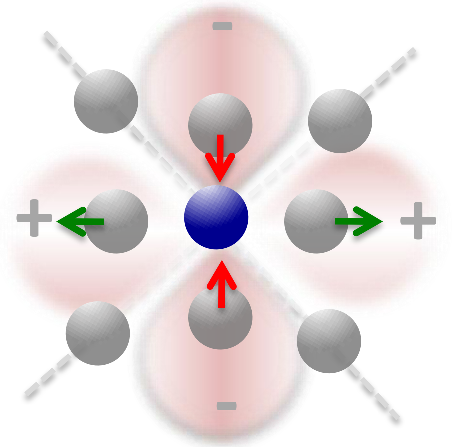
$$a_{dd} = \frac{md^2}{4\pi\epsilon_0\hbar^2}$$

dipolar gases



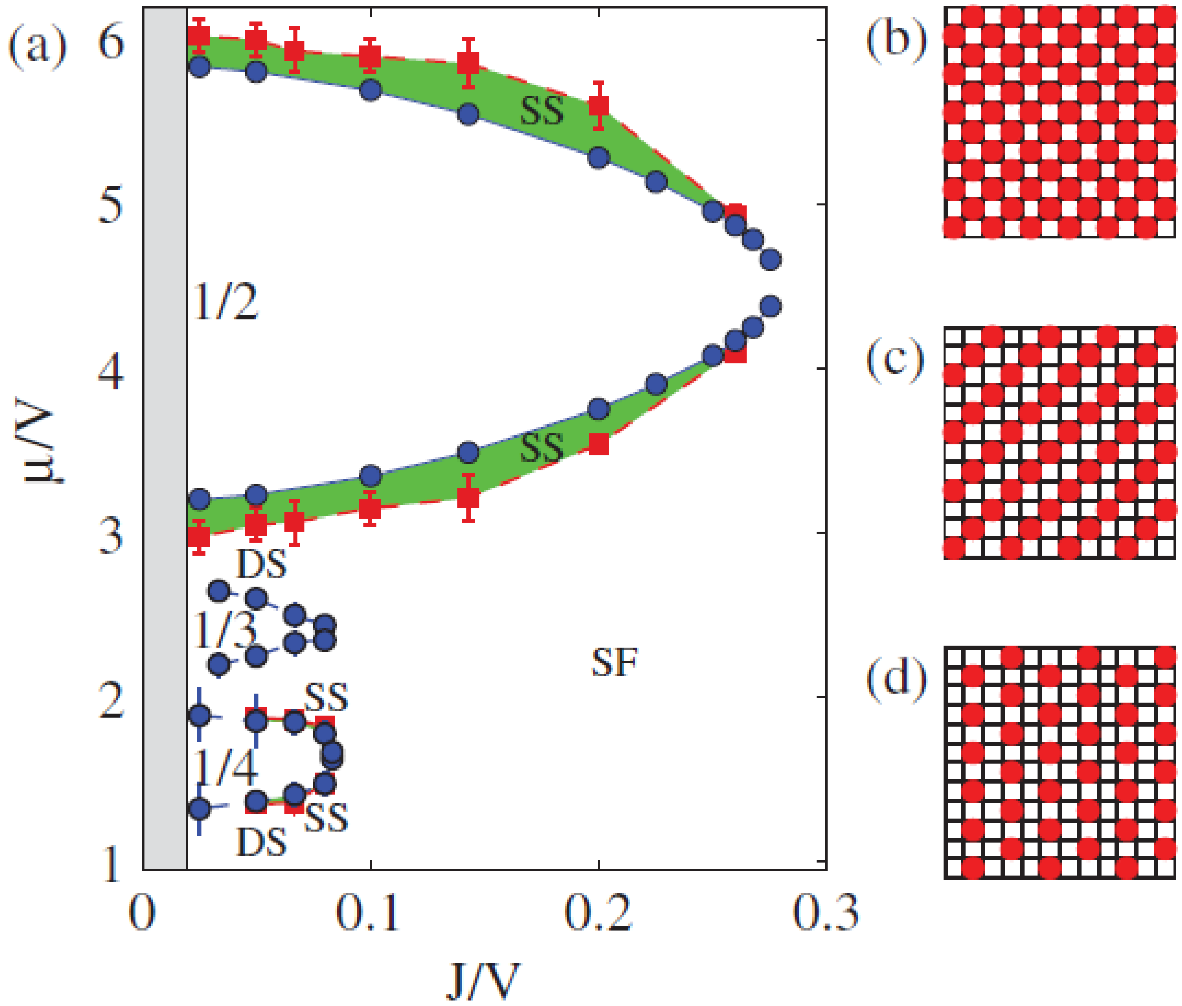
$$\varepsilon_{dd} \equiv \frac{a_{dd}}{a} = \frac{C_{dd}}{3g}$$

Why degenerate dipolar gases?



Novel effects appear – NOT contact interaction!

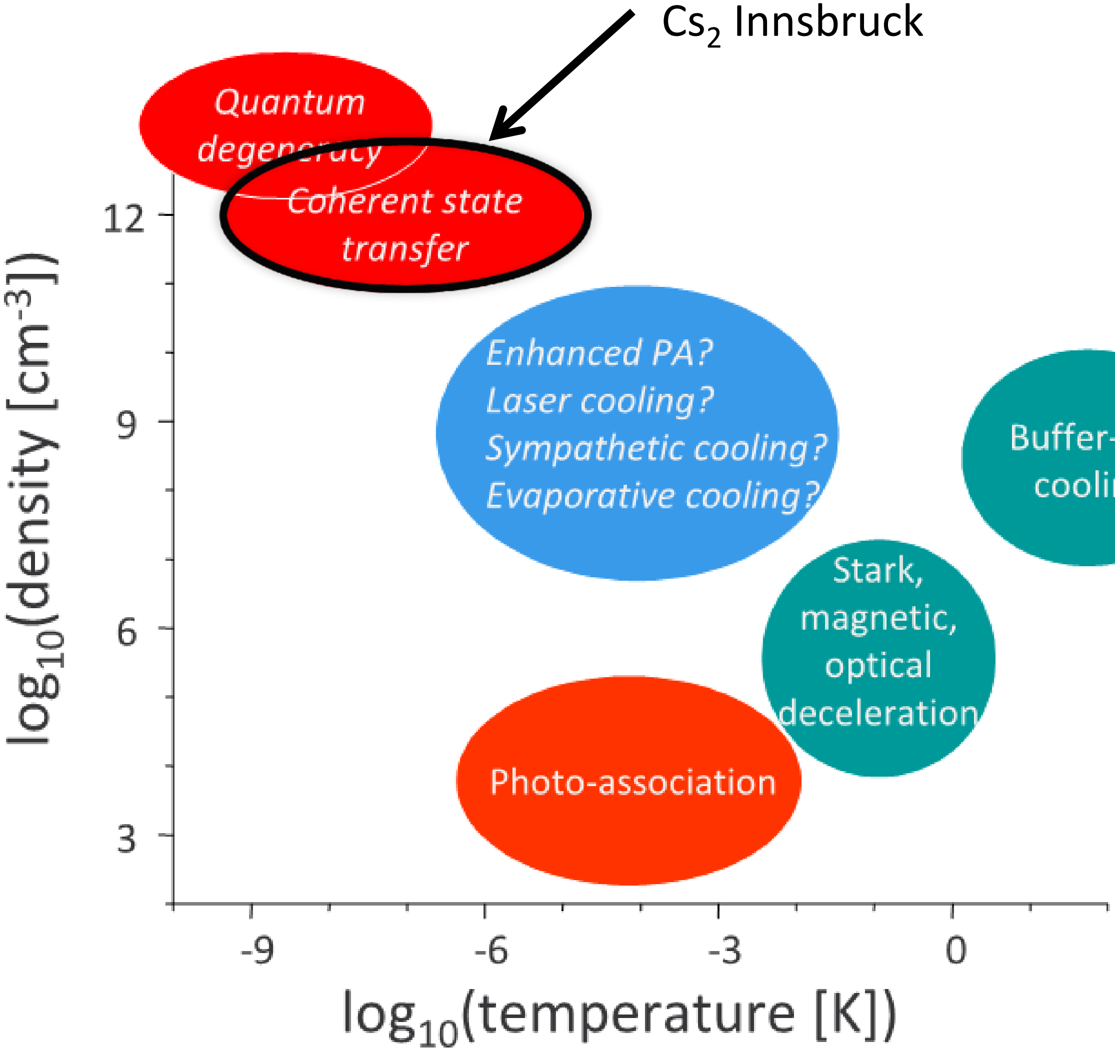
Identical fermions interact • exotic quantum phases •
• novel spectrum of excitations • geometry-dependent interaction • …



B. Capogrosso-Sansone et al.,
Phys. Rev. Lett. **104**, 125301 (2010)

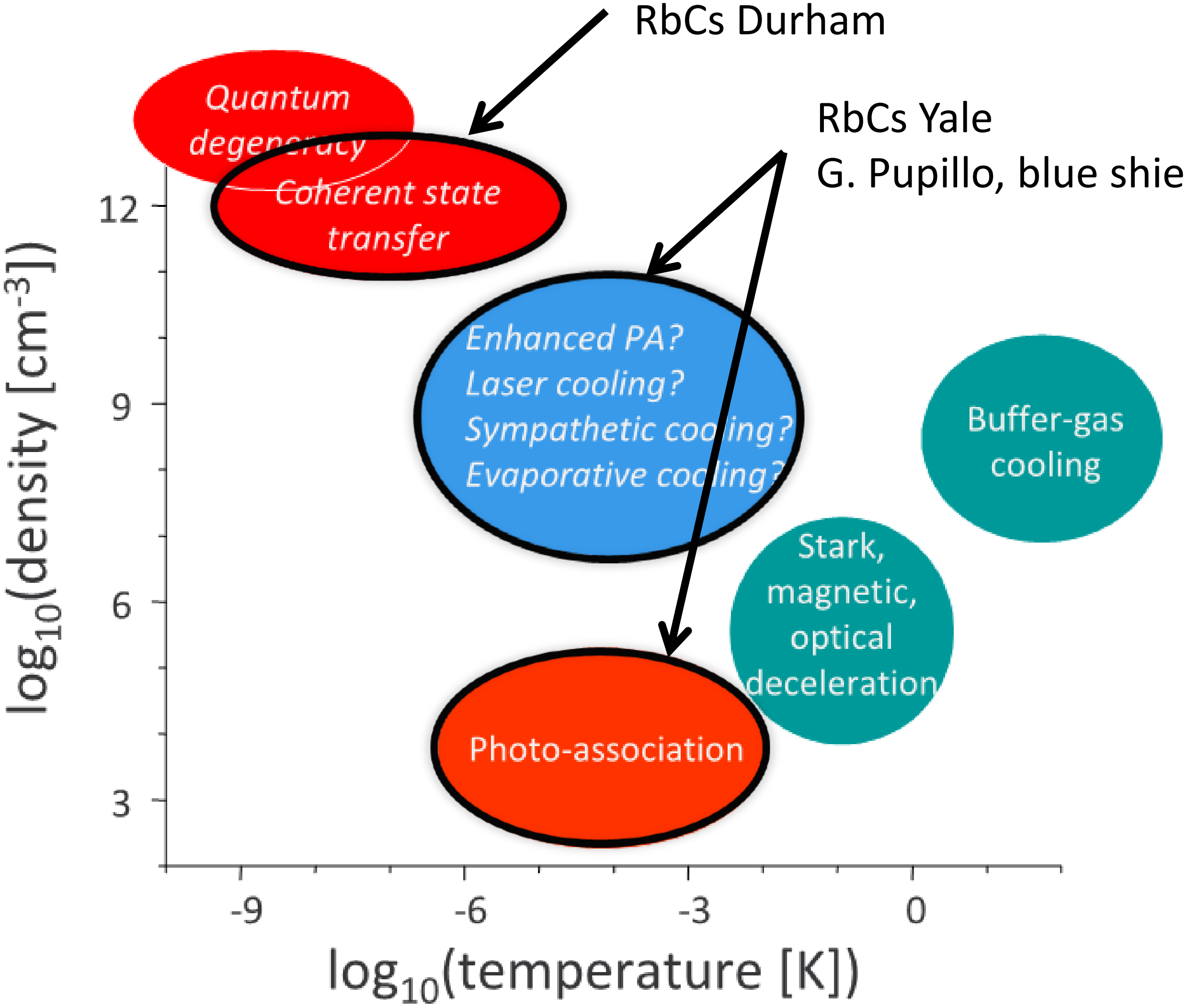
Why degenerate dipolar gases?

KRb Boulder
Cs_2 Innsbruck



Carr DeMille Krems and Ye, NJP **11,** 055049 (2009).

Why degenerate dipolar gases?



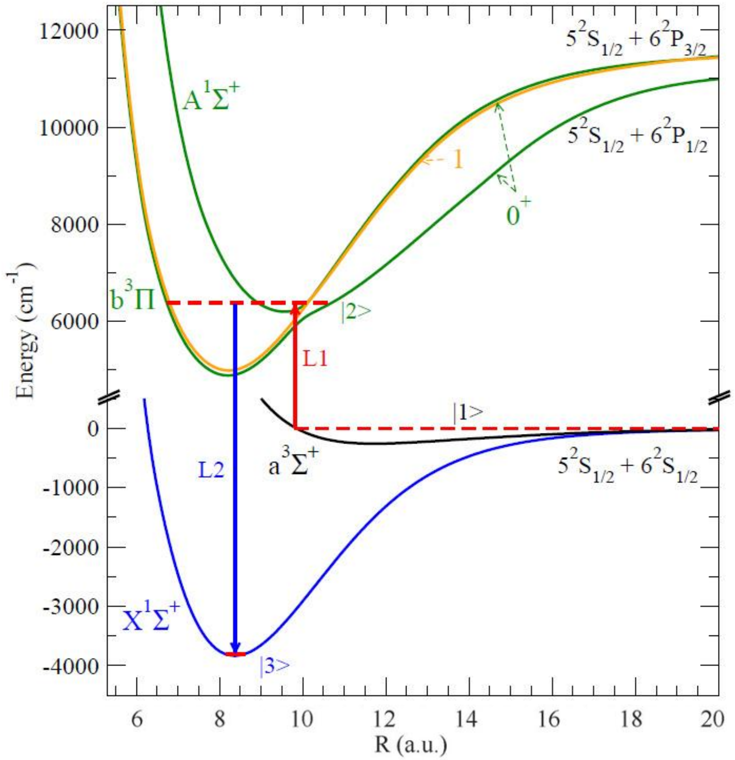
RbCs Innsbruck
RbCs Durham

RbCs Yale
G. Pupillo, blue shielding

Carr DeMille Krems and Ye, NJP **11,** 055049 (2009).

Recipe for high phase-space density dimer gas

degenerate atomic gas(es) → Feshbach molecules → coherent ground state transfer

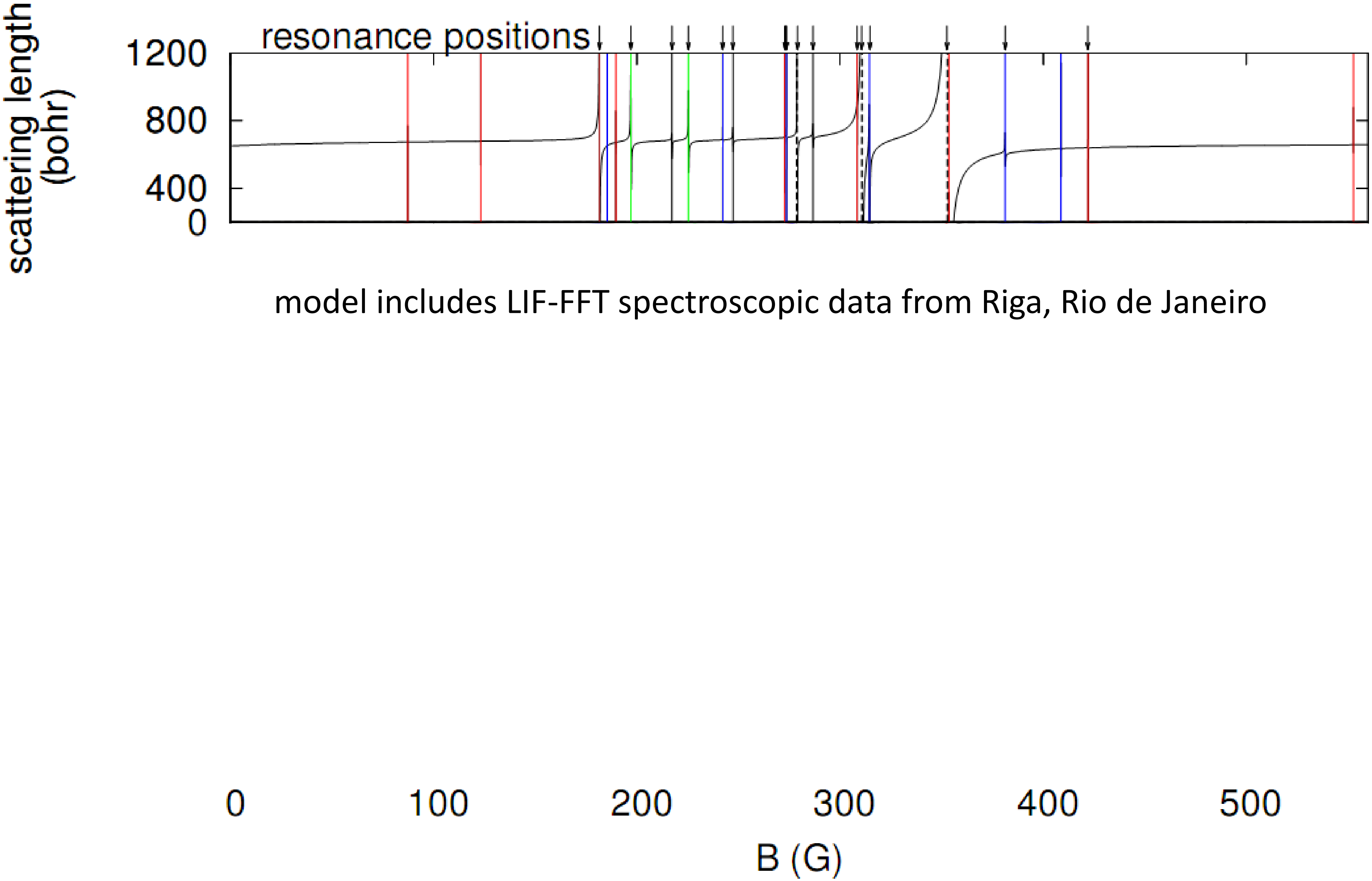


- high phase space density almost guaranteed
- high experimental complexity
- limited to "boring" molecules, i.e. dimers
- successfully applied thus far to

  KRb, Cs_2, Rb_2 ($^3\Sigma$), ...RbCs

The colliding BEC method

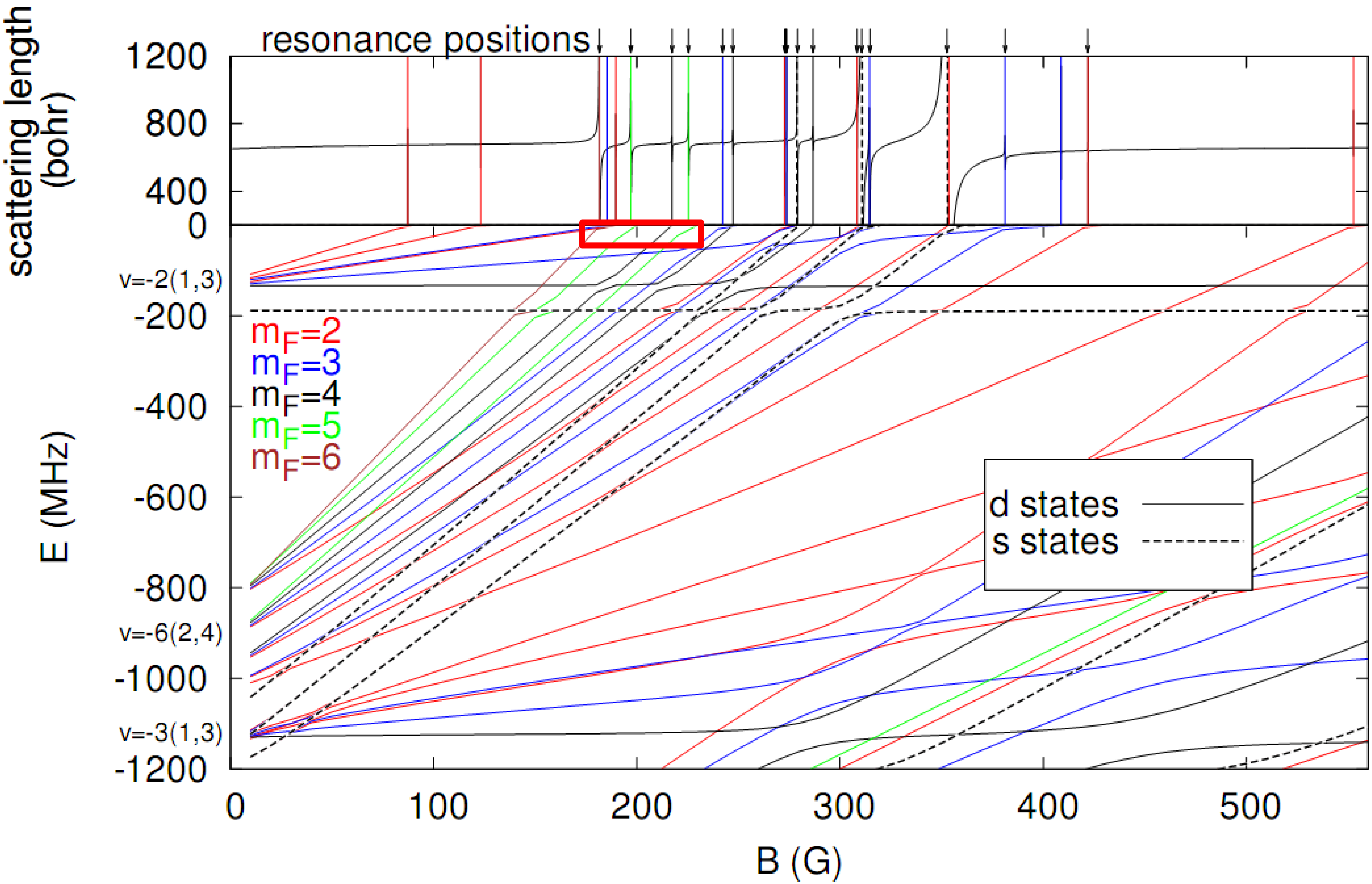
Coupled channel model



model includes LIF-FFT spectroscopic data from Riga, Rio de Janeiro

C.R. LeSueur, J.M. Hutson, P.S. Julienne, S. Kotochigova, E. Tiemann

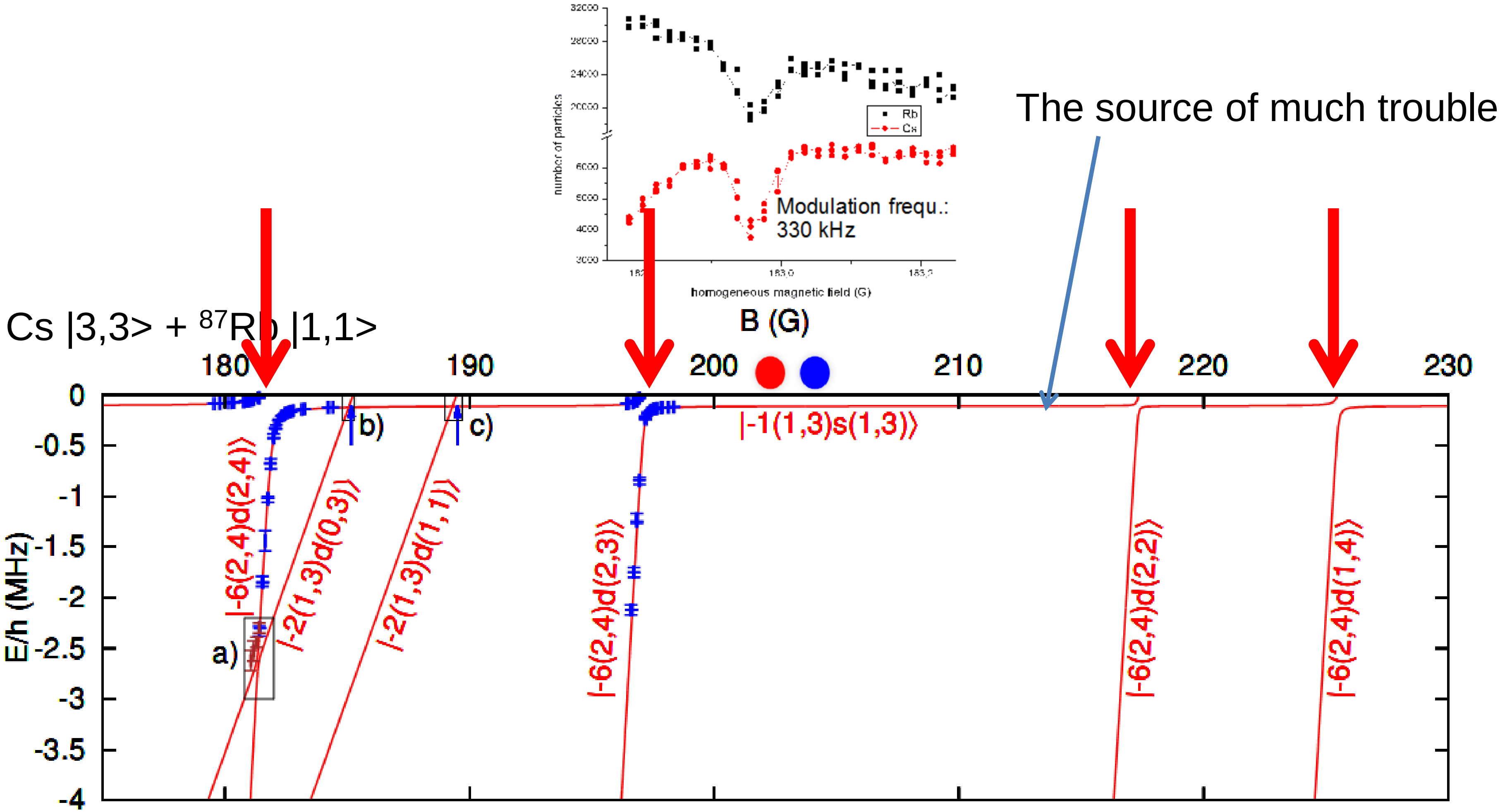
Coupled channel model



C.R. LeSueur, J.M. Hutson, P.S. Julienne, S. Kotochigova, E. Tiemann

Coupled channel model

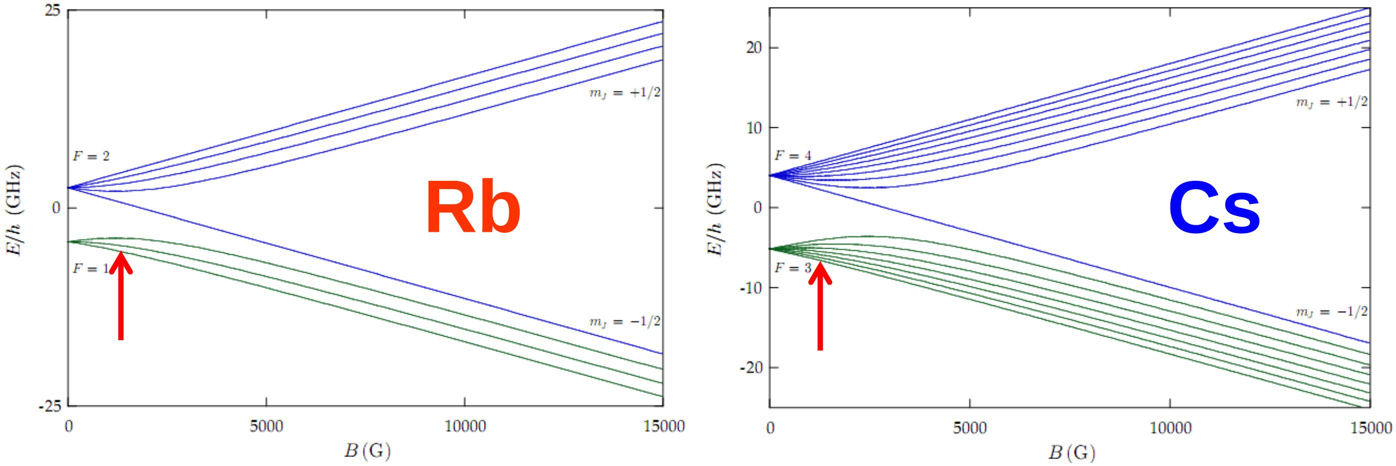
Data for model – Feshbach molecule binding energies through magnetic field modulation



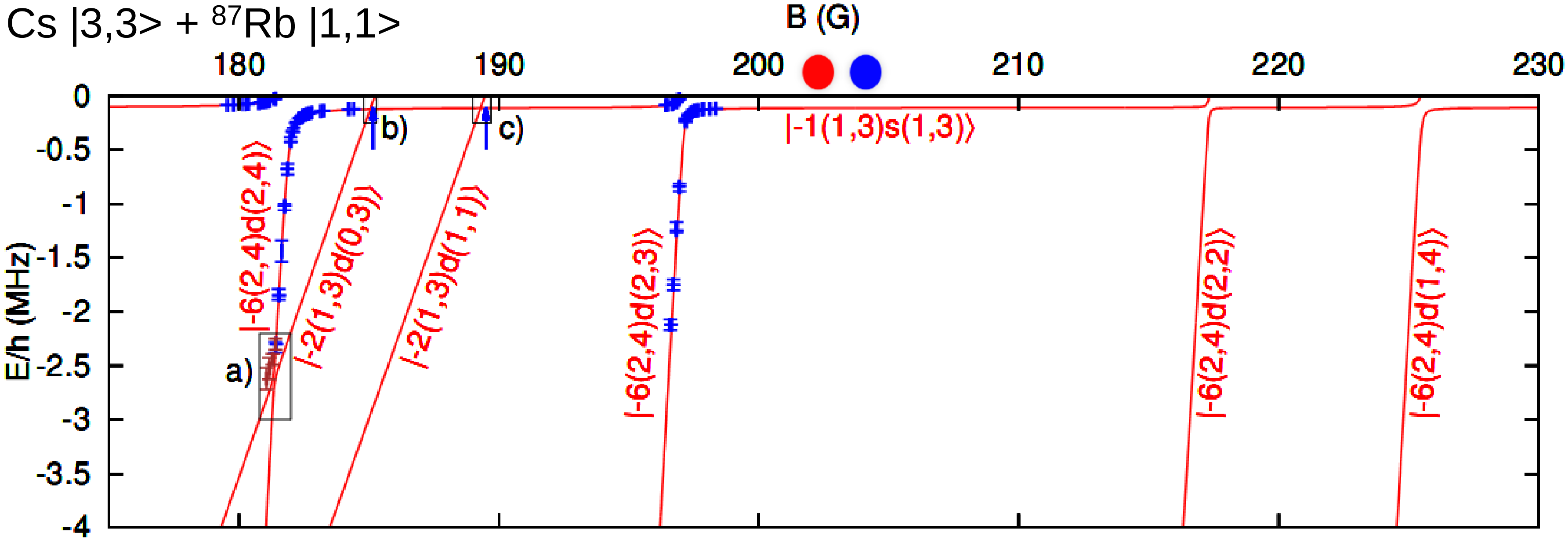
The source of much trouble...

C.R. LeSueur, J.M. Hutson, P.S. Julienne, S. Kotochigova, E. Tiemann

Coupled channel model

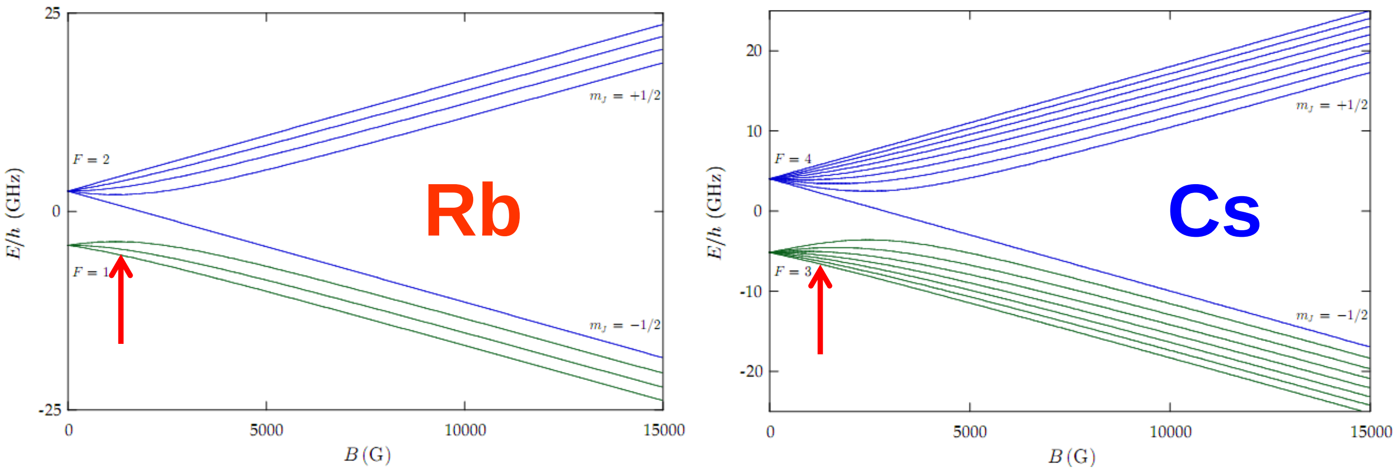


Cs |3,3> + ^{87}Rb |1,1>



C.R. LeSueur, J.M. Hutson, P.S. Julienne, S. Kotochigova, E. Tiemann

Coupled channel model



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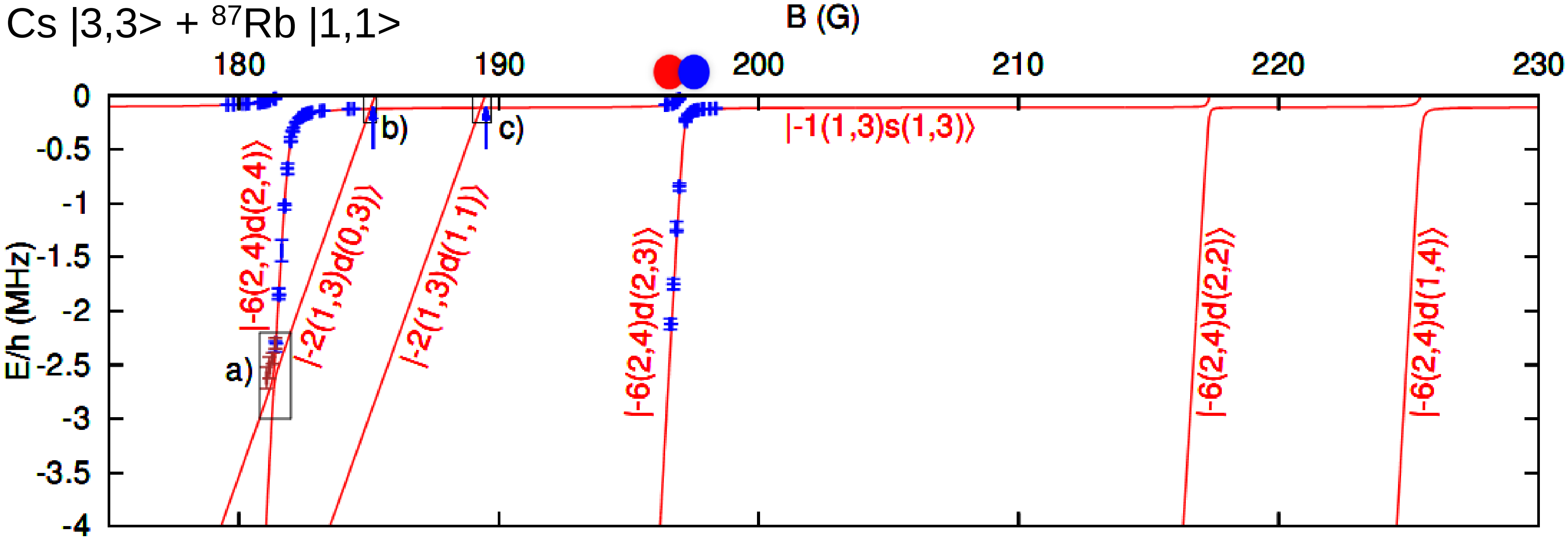
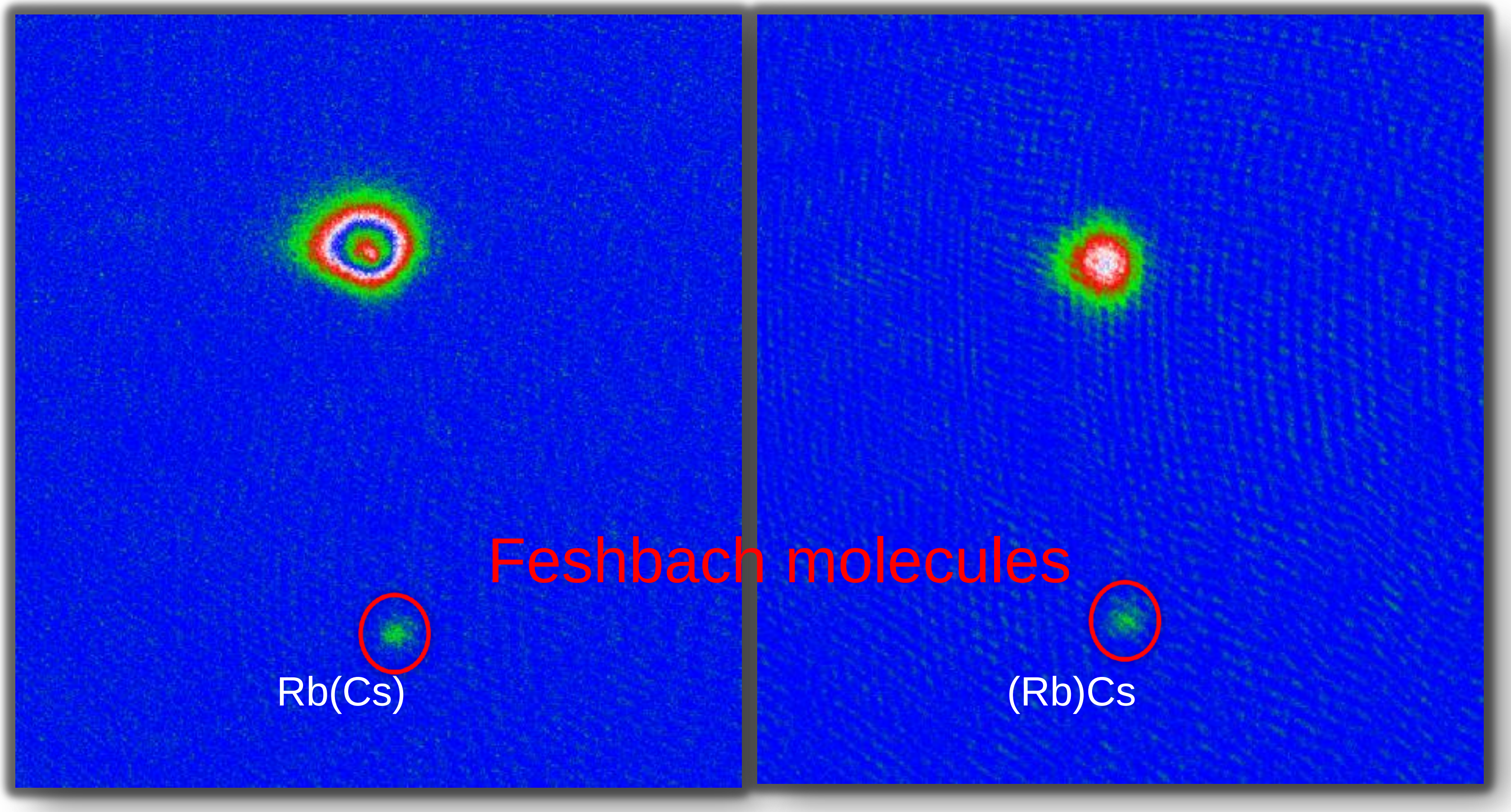


C.R. LeSueur, J.M. Hutson, P.S. Julienne, S. Kotochigova, E. Tiemann

The colliding BEC method



Typically 60k Cs + 150k Rb gives 4000 RbCs (we detect only atoms)

Ground state transfer

Hamiltonian:

$$H(t) = \frac{\hbar}{2}\begin{array}{cccc} |1\rangle & |2\rangle & |3\rangle & \\ 0 & \Omega_1 & 0 & |1\rangle \\ \Omega_1 & 0 & \Omega_2 & |2\rangle \\ 0 & \Omega_2 & 0 & |3\rangle \end{array}$$

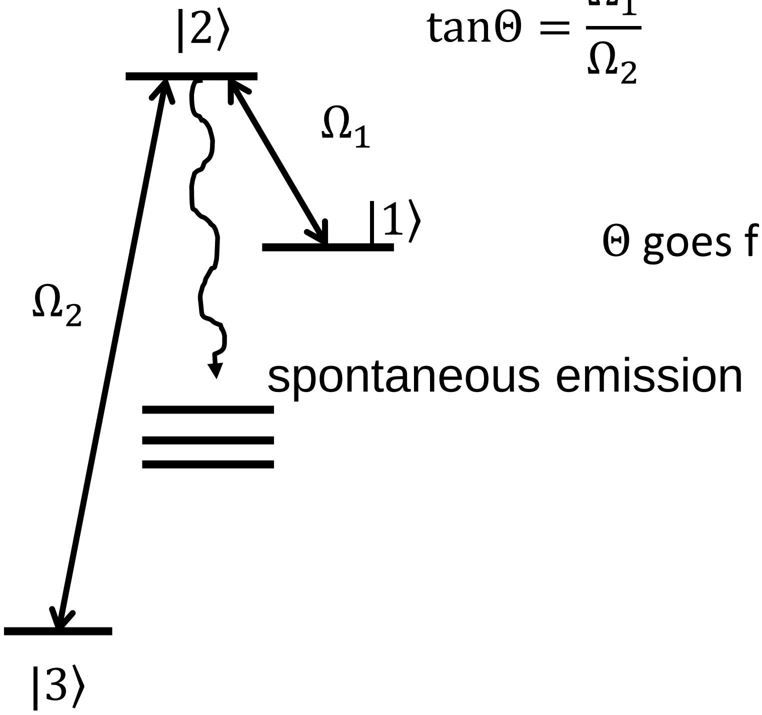
Eigenstates with light on:

$$|a^+\rangle = \sin\Theta\ \sin\Phi|1\rangle + \cos\Phi|2\rangle + \cos\Theta\ \sin\Phi|3\rangle$$

$$|a^0\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle$$ dark state

$$|a^-\rangle = \sin\Theta\ \cos\Phi|1\rangle - \sin\Phi|2\rangle + \cos\Theta\ \cos\Phi|3\rangle$$

$$\tan\Theta = \frac{\Omega_1}{\Omega_2}$$



Θ goes from 0 to Π adiabatically

K. Bergmann, H. Theuer, and B.W. Shore: Rev. Mod. Phys. 70, 1003 (1998)

Ground state transfer

Hamiltonian:

$$H(t) = \frac{\hbar}{2}\begin{array}{c|ccc|c} & |1\rangle & |2\rangle & |3\rangle & \\ \hline & 0 & \Omega_1 & 0 & |1\rangle \\ & \Omega_1 & 0 & \Omega_2 & |2\rangle \\ & 0 & \Omega_2 & 0 & |3\rangle \end{array}$$

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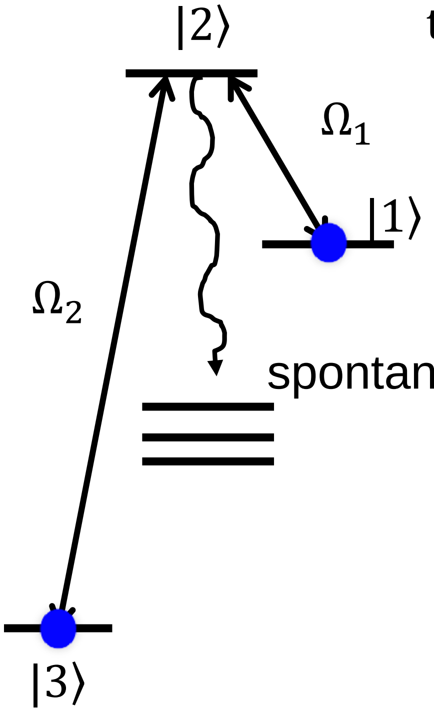

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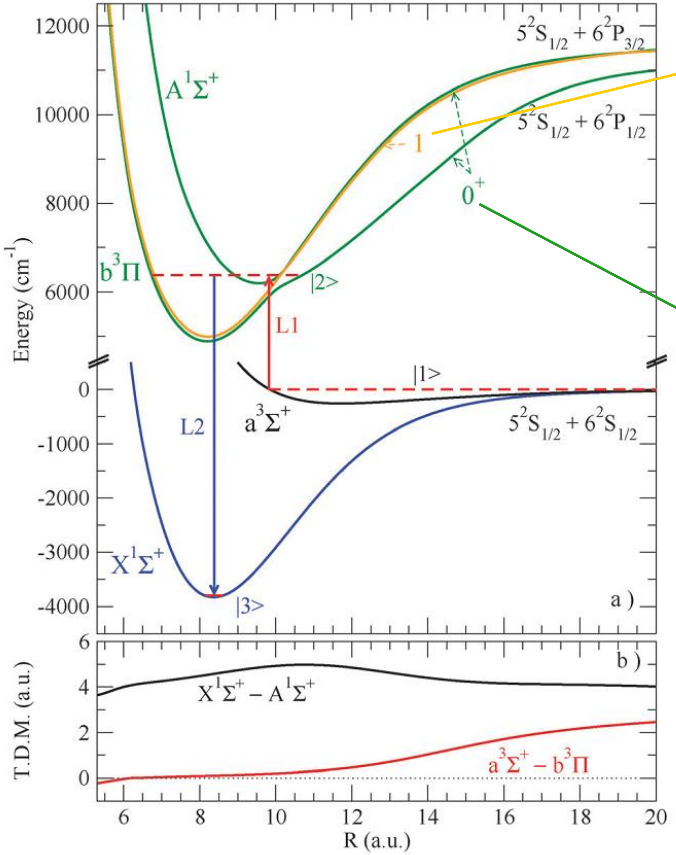
Ground state transfer

Suggested Bergeman *et al.*, PRA **67** 050501 (2003). (Riga, Rio de Janiero)



$S = 1, \Sigma = -1,0,1$

$b^3\Pi_1$

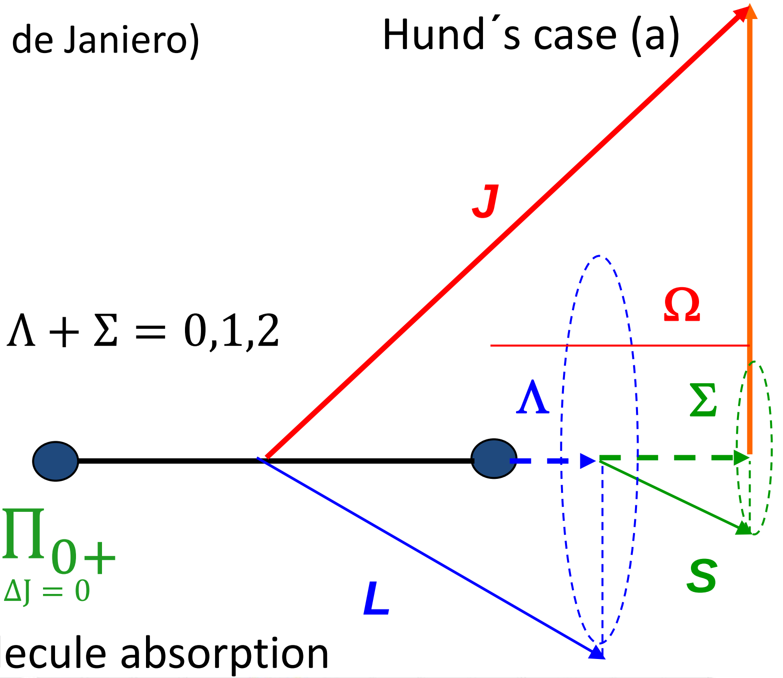
$\Omega = \Lambda + \Sigma = 0,1,2$

$\Lambda = 1$

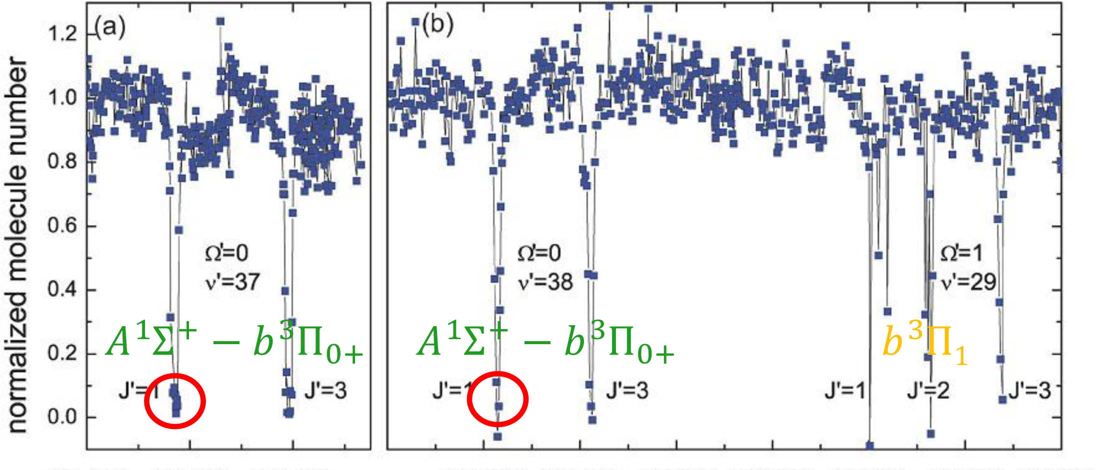
$A^1\Sigma^+ - b^3\Pi_{0+}$

spin-orbit mixing $\Delta\Omega = 0, \Delta J = 0$

Hund´s case (a)



Feshbach molecule absorption

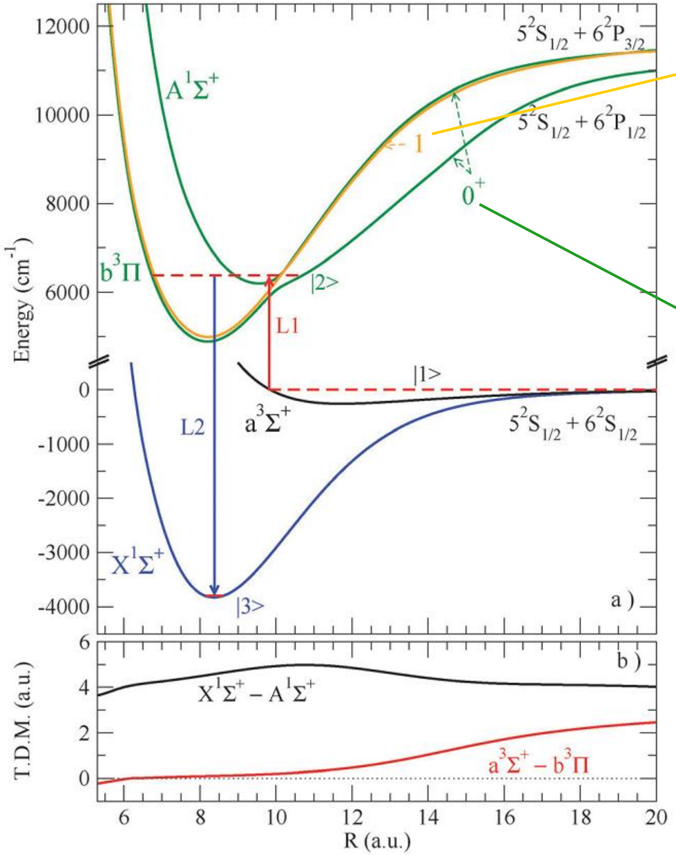


dark states (projection)

Energies and rotational constants agree well with Docenko *et al.*, PRA **81** 042511 (2010). (Riga, Rio de Janiero)

Ground state transfer

Suggested Bergeman *et al.*, PRA **67** 050501 (2003). (Riga, Rio de Janiero)



$$S = 1, \Sigma = -1,0,1$$

$$b^3\Pi_1$$

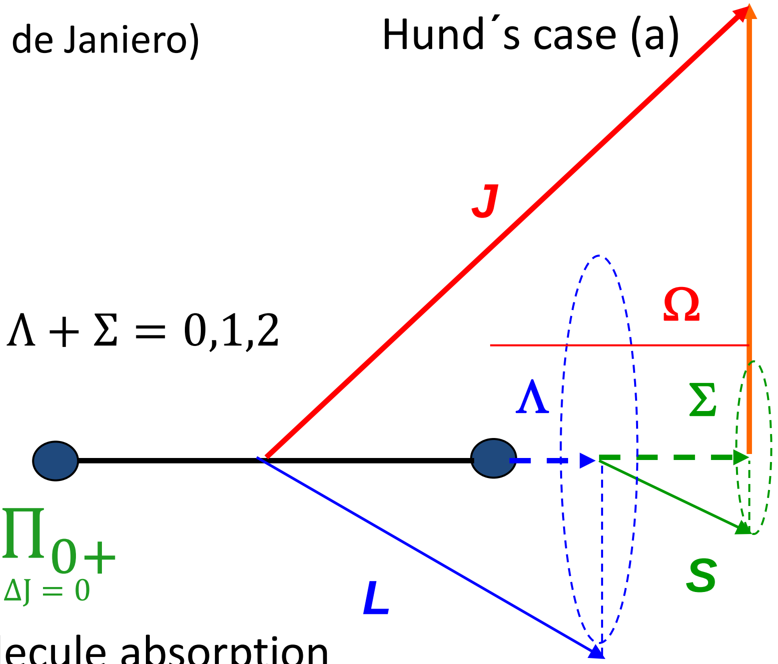
$$\Lambda = 1$$

$$\Omega = \Lambda + \Sigma = 0,1,2$$

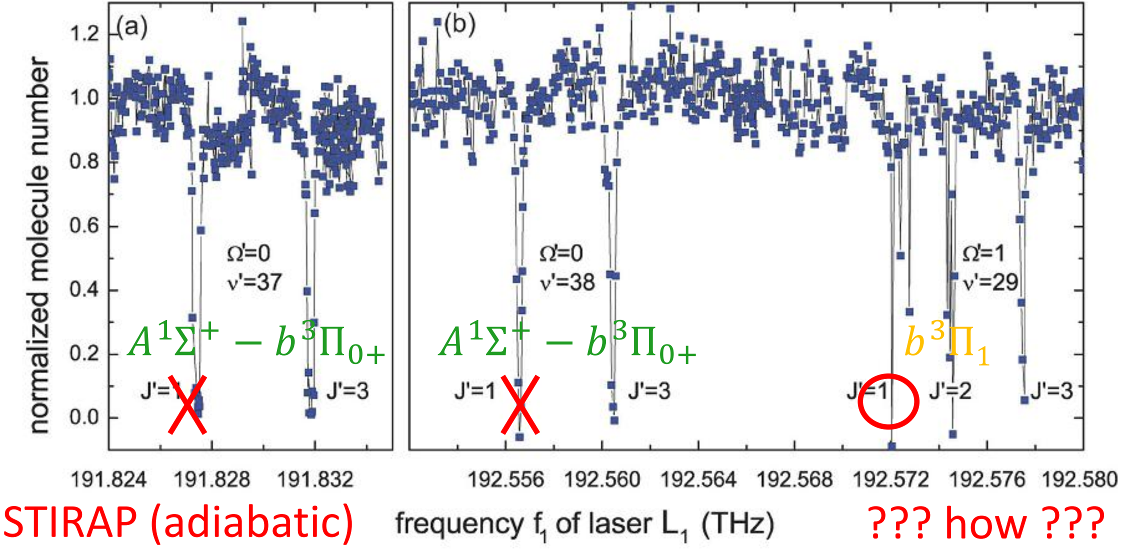
$$A^1\Sigma^+ - b^3\Pi_{0+}$$

spin-orbit mixing $\Delta\Omega = 0, \Delta J = 0$

Hund´s case (a)



Feshbach molecule absorption

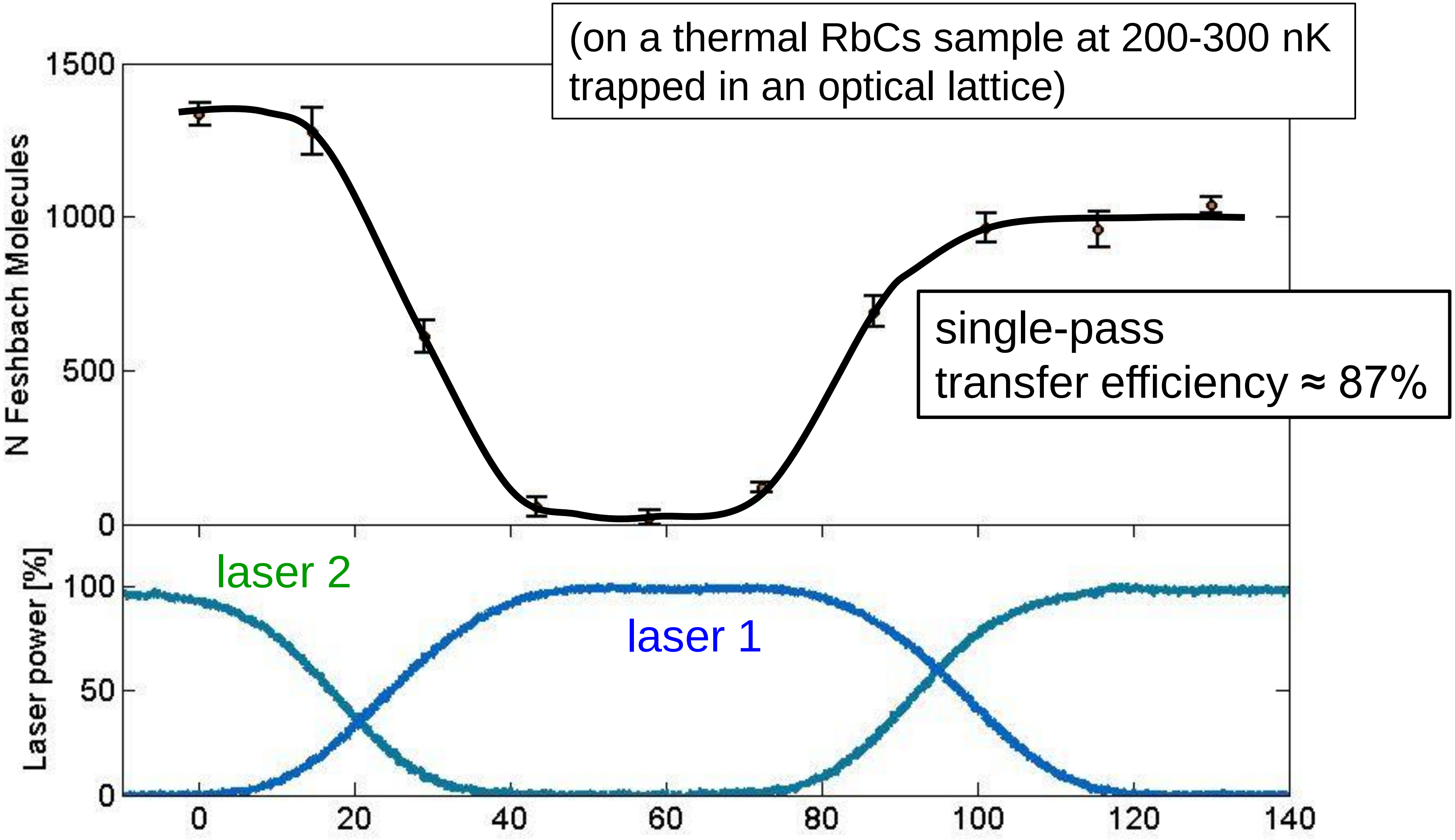


??? why ??? STIRAP (adiabatic) ??? how ???

Energies and rotational constants agree well with Docenko *et al.*, PRA **81** 042511 (2010). (Riga, Rio de Janiero)

Ground state transfer

RbCs two-photon STIRAP to v=0, J=0.



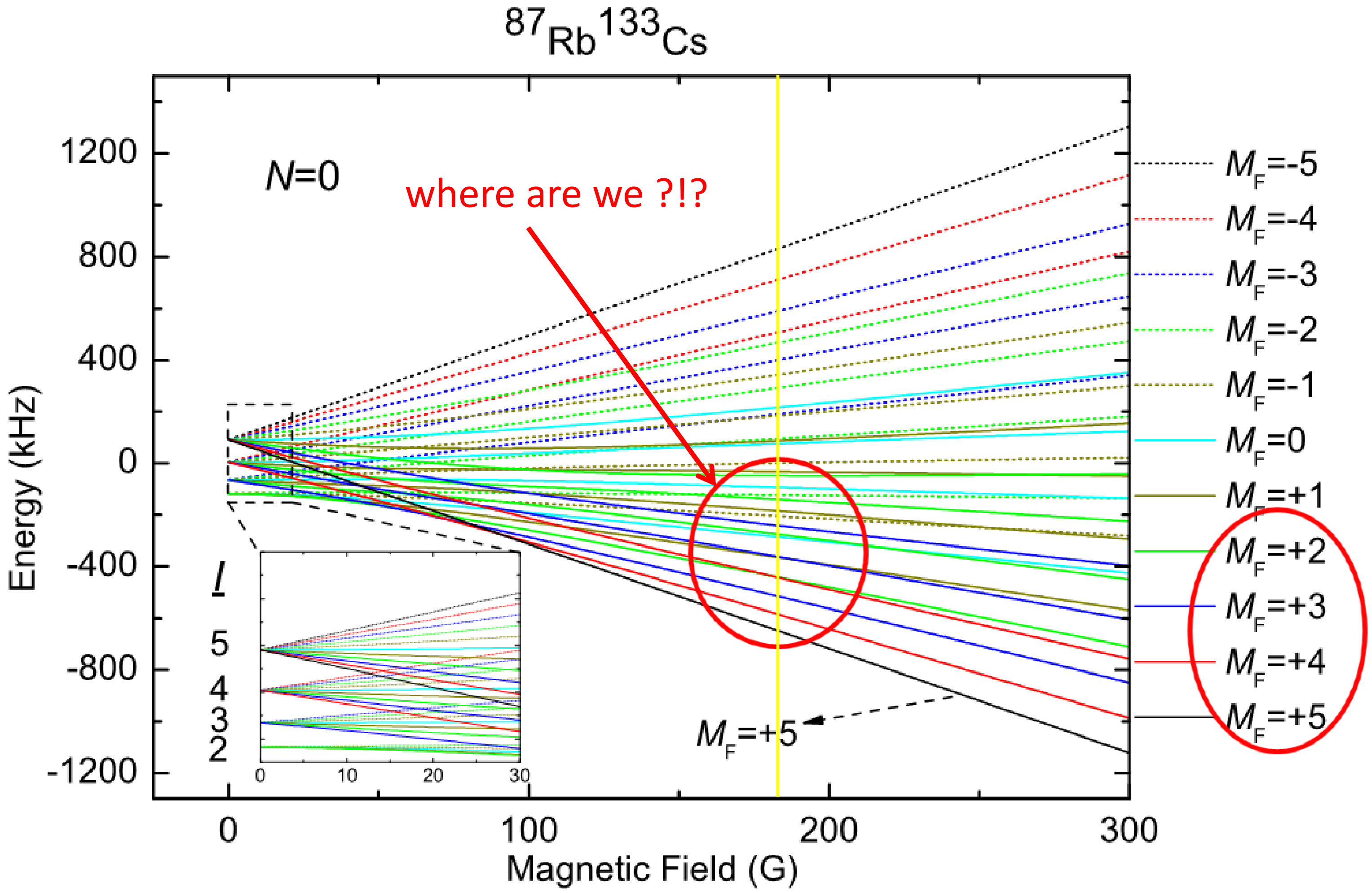
(on a thermal RbCs sample at 200-300 nK trapped in an optical lattice)

single-pass
transfer efficiency ≈ 87%

- we detect only atoms
- STIRAP references -- two optical cavities locked to Cs atomic reference laser
- estimated relative laser linewidth: 5-10kHz

Ground state transfer

Cs |3,3> + ^{87}Rb |1,1> in incoming s-wave collision has M_F=4, therefore, Feshbach molecules also have M_F=4



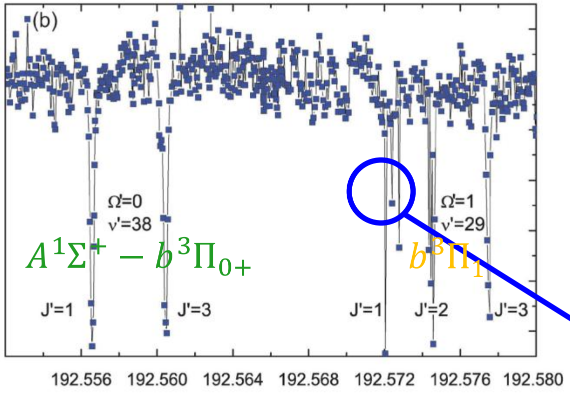
where are we ?!?

all accessible directly through STIRAP (in theory)

dominant terms – scalar nuclear dipole-dipole, nuclear Zeeman

J. Aldegunde (Salamanca) and Jeremy M. Hutson (Durham)

Ground state transfer



Excited state model

(help from Romain Vexieu, Anne Crubelier, Oliver Dulieu)

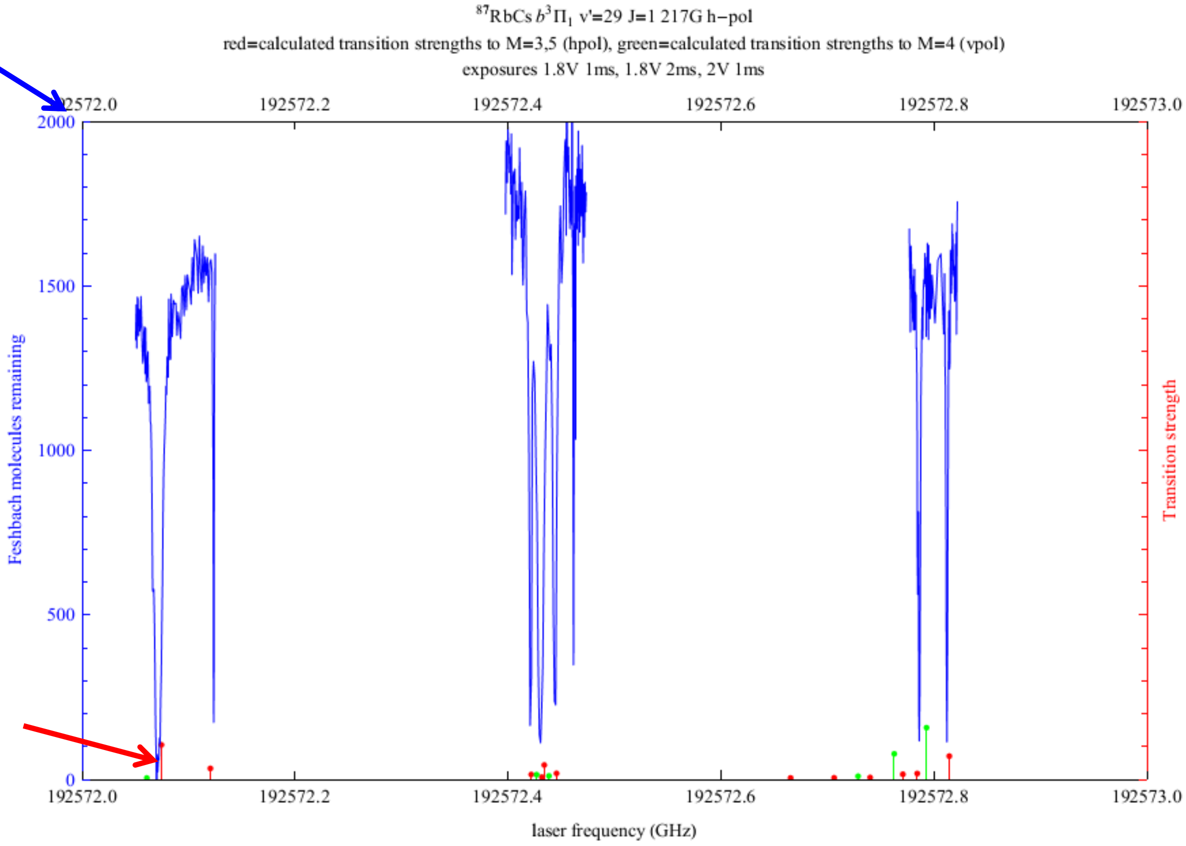


FIG. 3: 217G *Feshbach* → $b\,^3\Pi_1$ $v' = 29$, $J' = 1$ horizontal laser polarization. Red lines indicate calculated transition strengths.

$$H = H_{\text{rotation}} + H_{\text{Zeeman}} + H_{\text{hf}}$$

$$H_{\text{hf}} = a_{Rb}\,\mathbf{i}_{Rb}\cdot\mathbf{L} + a_{Cs}\,\mathbf{i}_{Cs}\cdot\mathbf{L}$$

3 parameter fit to effective Hamiltonian:

a_{Rb} =127 MHz x h

a_{Cs} =74 MHz x h

overall frequency shift

(1st unambiguous observation of orbital hyperfine in bialkalis)

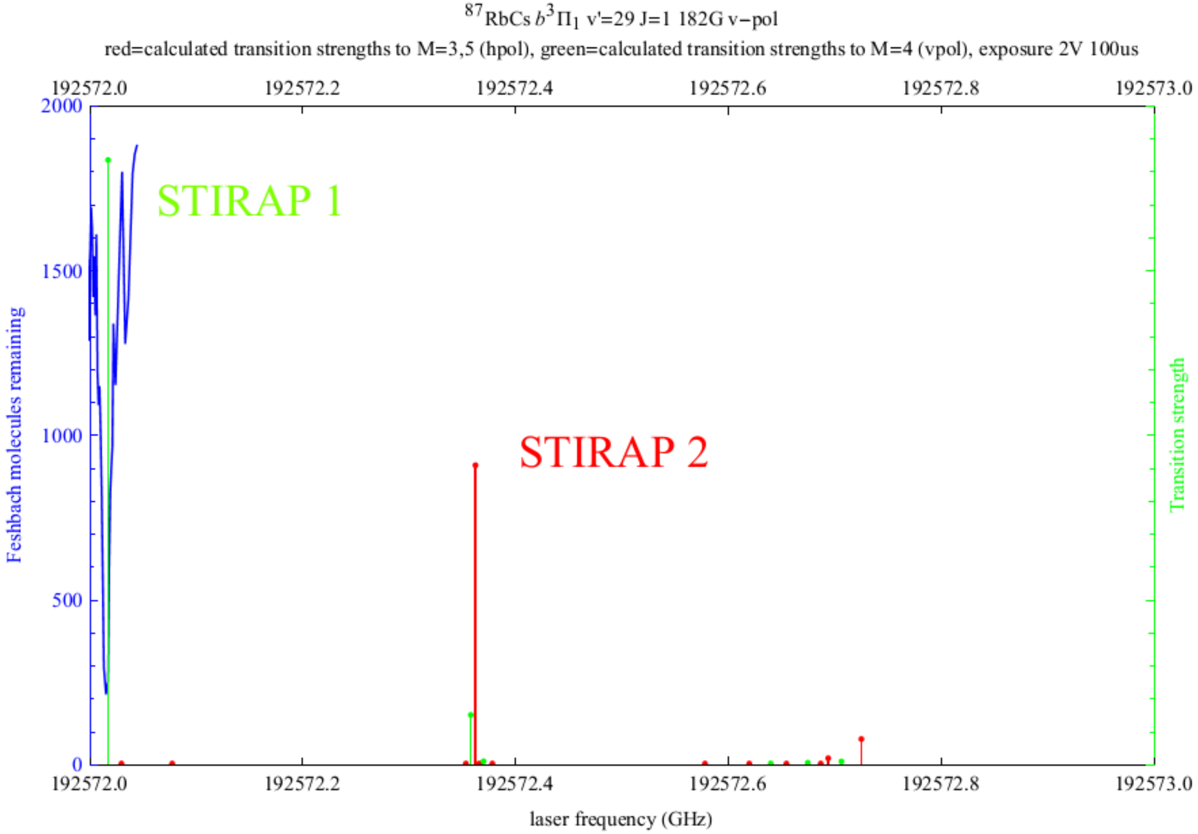


FIG. 4: 182G $Feshbach \to b\,^3\Pi_1$ $v' = 29, J' = 1$ vertical laser polarization. The lowest-frequency peak here (STIRAP 1) is currently used for STIRAP. Green lines indicate calculated transition strengths.

TABLE II: 182G $b\,^3\Pi_1$ $v' = 29, J' = 1$ expectation values. (Green lines from left to right in Fig. 4.)

$\langle \hat{m}_{i_{Rb}} \rangle$	1.45827	1.10556	0.79239	-0.21970	0.64279	1.21344
$\langle \hat{m}_{i_{Cs}} \rangle$	3.46557	2.80281	3.1212	3.25451	2.43313	1.91451
$\langle \hat{m}_J \rangle$	-0.92384	0.09163	0.08642	0.96519	0.92408	0.87205
$\langle \hat{M} \rangle$	4	4	4	4	4	4
$\langle \hat{P}(\delta) \rangle$	0.92671	0.06771	0.00303	0.00019	0.00130	0.00268
$\langle \hat{P}(\epsilon) \rangle$	0.04354	0.23208	0.57752	0.03096	0.08868	0.02533
$\langle \hat{P}(\zeta) \rangle$	0.03590	0.51521	0.31557	0.00686	0.00002	0.12472
$\langle \hat{P}(\theta) \rangle$	0.00089	0.02827	0.07236	0.70694	0.16983	0.01726
$\langle \hat{P}(\iota) \rangle$	0.00201	0.09986	0.00123	0.22289	0.40956	0.25803
$\langle \hat{P}(\kappa) \rangle$	0.00065	0.04539	0.02830	0.02986	0.32579	0.56352

(δ) denotes projection onto $m_{J'} = -1, m_{i_{Rb}} = \frac{3}{2}, m_{i_{Cs}} = \frac{7}{2}$
(ϵ) denotes projection onto $m_{J'} = 0, m_{i_{Rb}} = \frac{1}{2}, m_{i_{Cs}} = \frac{7}{2}$
(ζ) denotes projection onto $m_{J'} = 0, m_{i_{Rb}} = \frac{3}{2}, m_{i_{Cs}} = \frac{5}{2}$
(θ) denotes projection onto $m_{J'} = 1, m_{i_{Rb}} = -\frac{1}{2}, m_{i_{Cs}} = \frac{7}{2}$
(ι) denotes projection onto $m_{J'} = 1, m_{i_{Rb}} = \frac{1}{2}, m_{i_{Cs}} = \frac{5}{2}$
(κ) denotes projection onto $m_{J'} = 1, m_{i_{Rb}} = \frac{3}{2}, m_{i_{Cs}} = \frac{3}{2}$

Ground state transfer

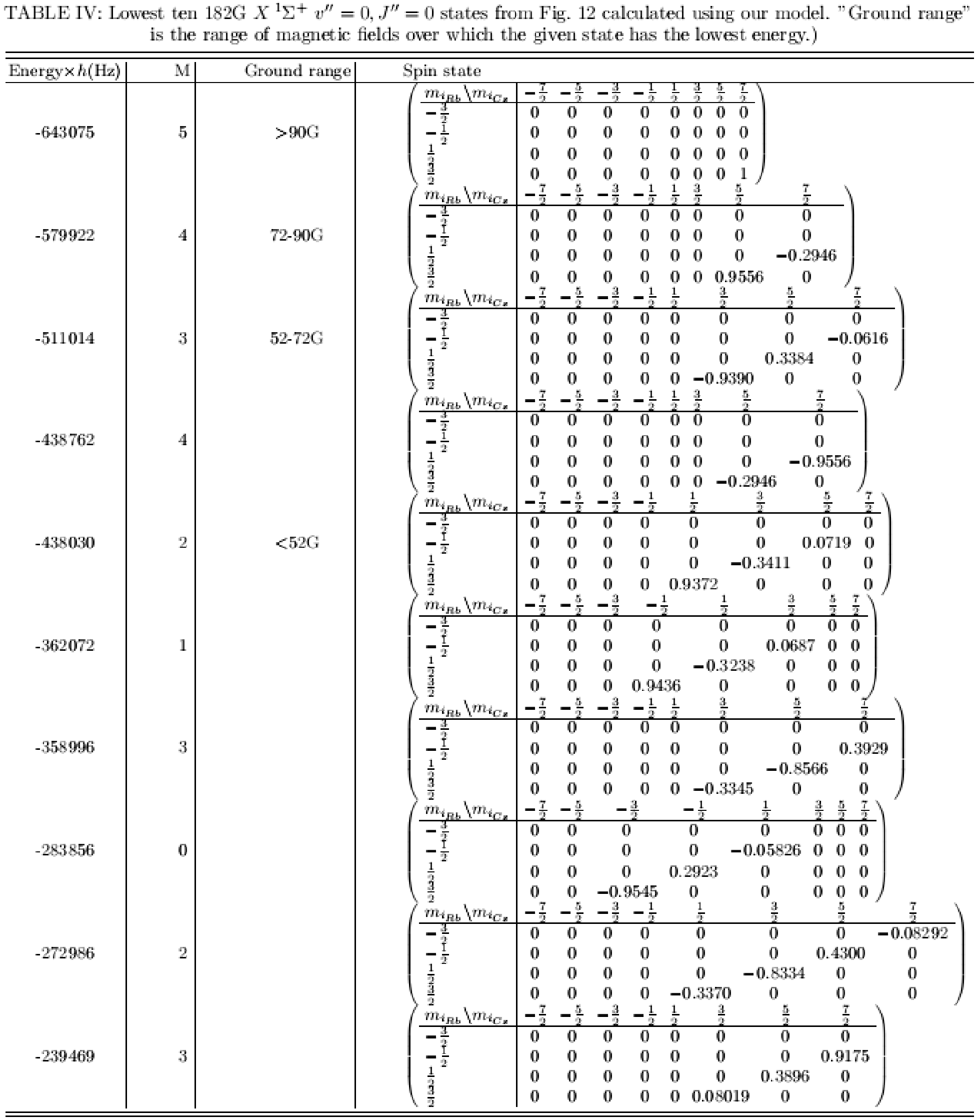
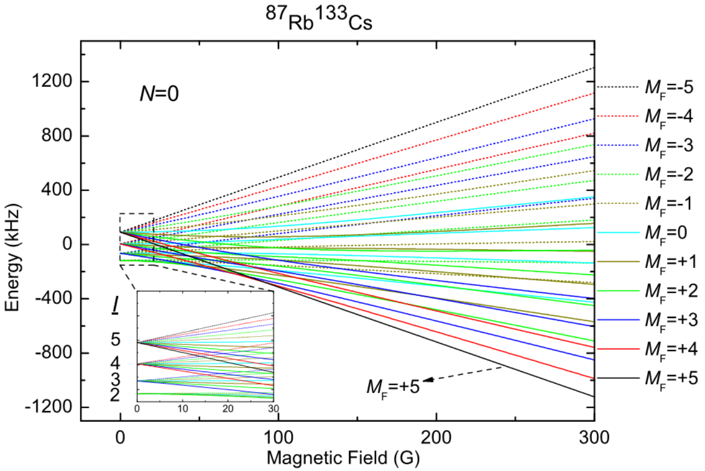


TABLE IV: Lowest ten 182G $X\,{}^1\Sigma^+\ v''=0,\ J''=0$ states from Fig. 12 calculated using our model. "Ground range" is the range of magnetic fields over which the given state has the lowest energy.)

Energy×h(Hz)	M	Ground range	Spin state
-643075	5	>90G	$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}\right)$
-579922	4	72-90G	$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.2946 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0.9556 & 0 \end{array}\right)$
-511014	3	52-72G	$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0616 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0.3384 & 0 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & 0 & -0.9390 & 0 & 0 \end{array}\right)$
-438762	4		$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.9556 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & -0.2946 & 0 \end{array}\right)$
-438030	2	<52G	$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0.0719 & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & -0.3411 & 0 & 0 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & 0.9372 & 0 & 0 & 0 \end{array}\right)$
-362072	1		$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0.0687 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & -0.3238 & 0 & 0 & 0 \\ \frac{3}{2} & 0 & 0 & 0 & 0.9436 & 0 & 0 & 0 & 0 \end{array}\right)$
-358996	3		$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.3929 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & -0.8566 & 0 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & 0 & -0.3345 & 0 & 0 \end{array}\right)$
-283856	0		$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & -0.05826 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0.2923 & 0 & 0 & 0 & 0 \\ \frac{3}{2} & 0 & 0 & -0.9545 & 0 & 0 & 0 & 0 & 0 \end{array}\right)$
-272986	2		$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.08292 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0.4300 & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & -0.8334 & 0 & 0 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & -0.3370 & 0 & 0 & 0 \end{array}\right)$
-239469	3		$\left(\begin{array}{c@{\;\vert\;}cccccccc} m_{i_{Rb}}\backslash m_{i_{Cs}} & -\frac{7}{2} & -\frac{5}{2} & -\frac{3}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{3}{2} & \frac{5}{2} & \frac{7}{2} \\ \hline -\frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9175 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0.3896 & 0 \\ \frac{3}{2} & 0 & 0 & 0 & 0 & 0 & 0.08019 & 0 & 0 \end{array}\right)$



Ground state model

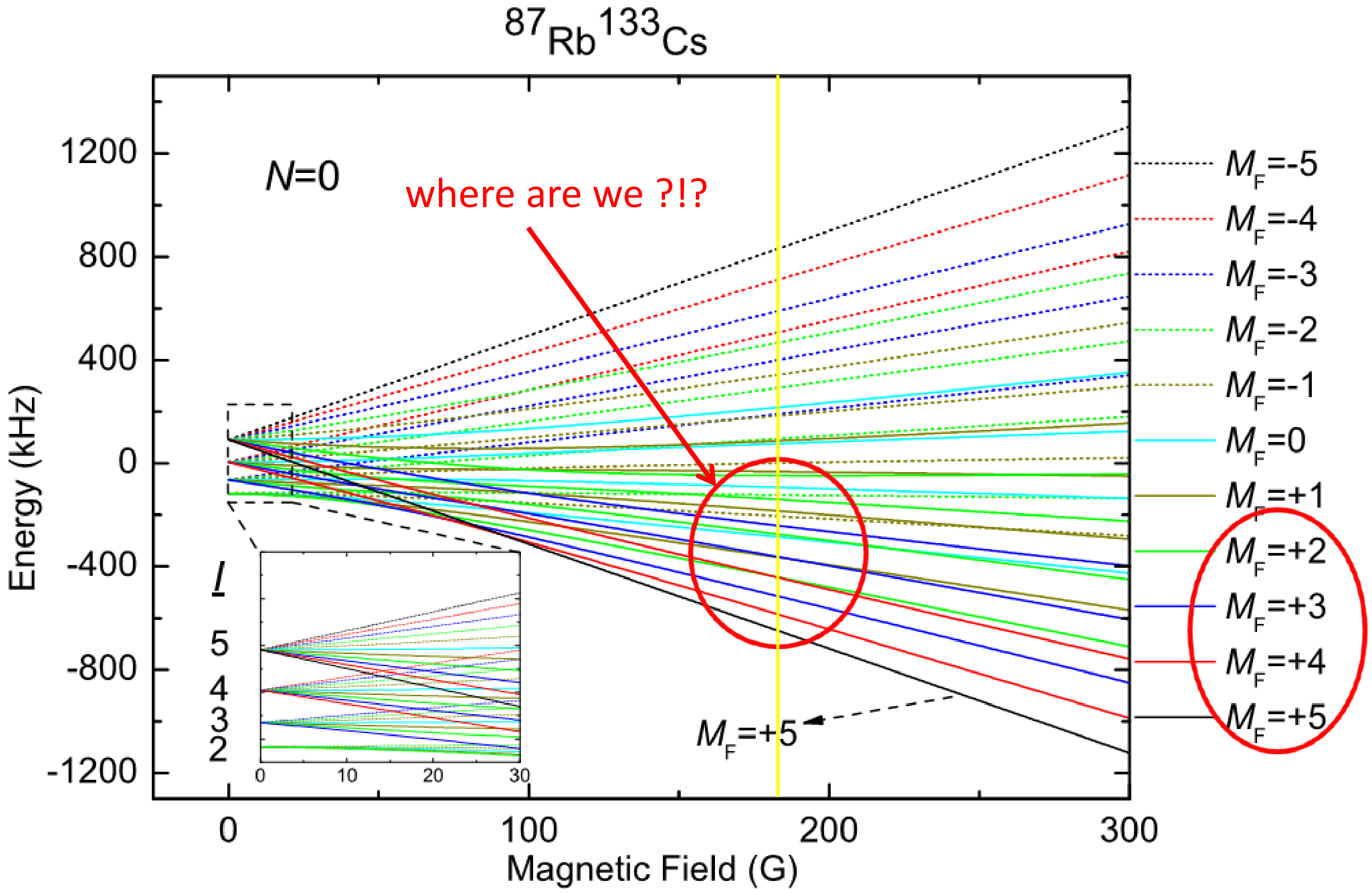
reproduced from
Aldegunde *et al*, PRA **78** 033434 (2008).

182G is intermediate Zeeman regime.

Stark shifts added for future dipolar expts.

Ground state transfer

Cs |3,3> + ^{87}Rb |1,1> in incoming s-wave collision has M_F=4,
therefore, Feshbach molecules also have M_F=4

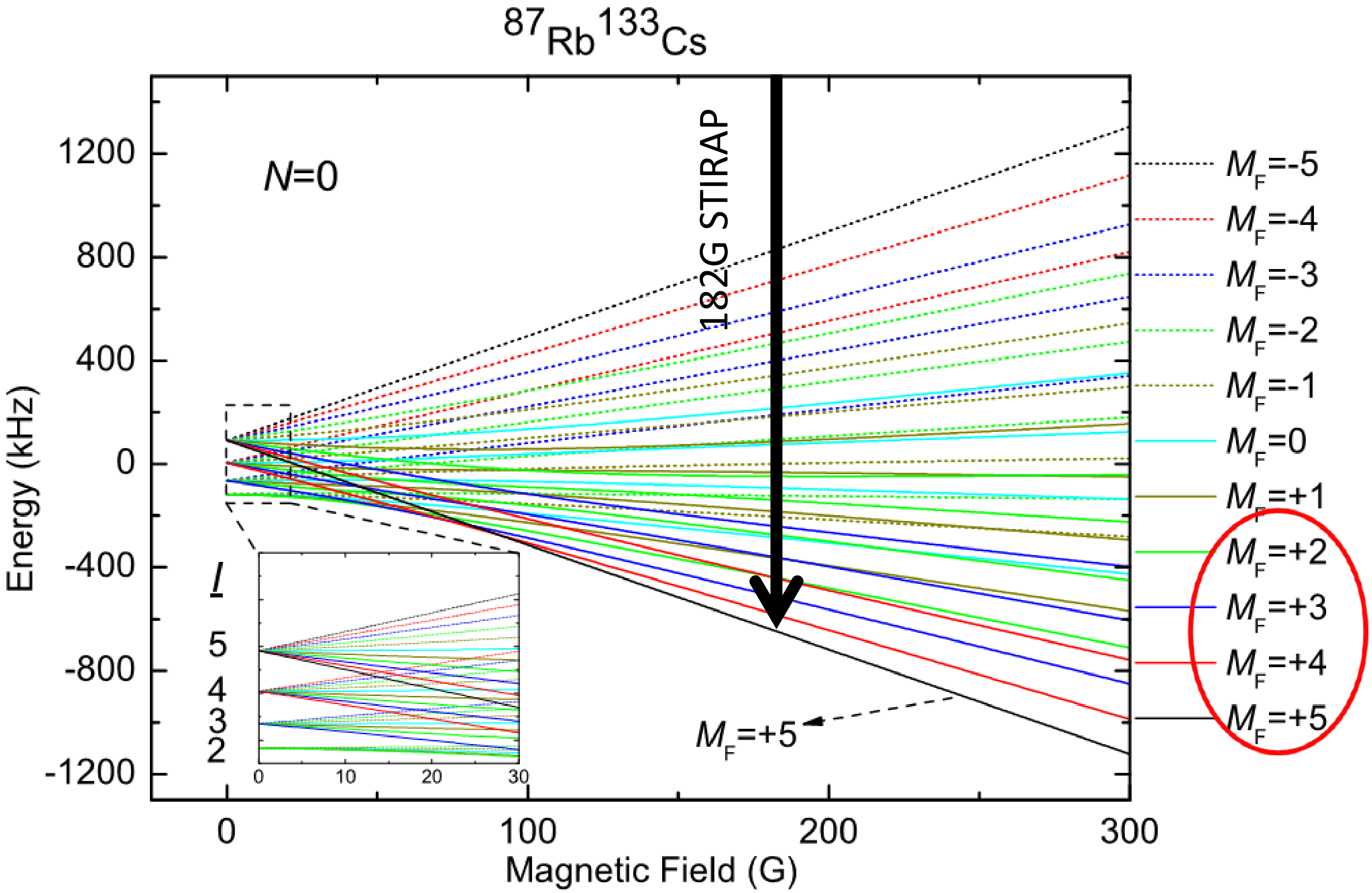


all accessible directly through STIRAP (in theory)

dominant terms – scalar nuclear dipole-dipole, nuclear Zeeman
J. Aldegunde (Salamanca) and Jeremy M. Hutson (Durham)

Ground state transfer

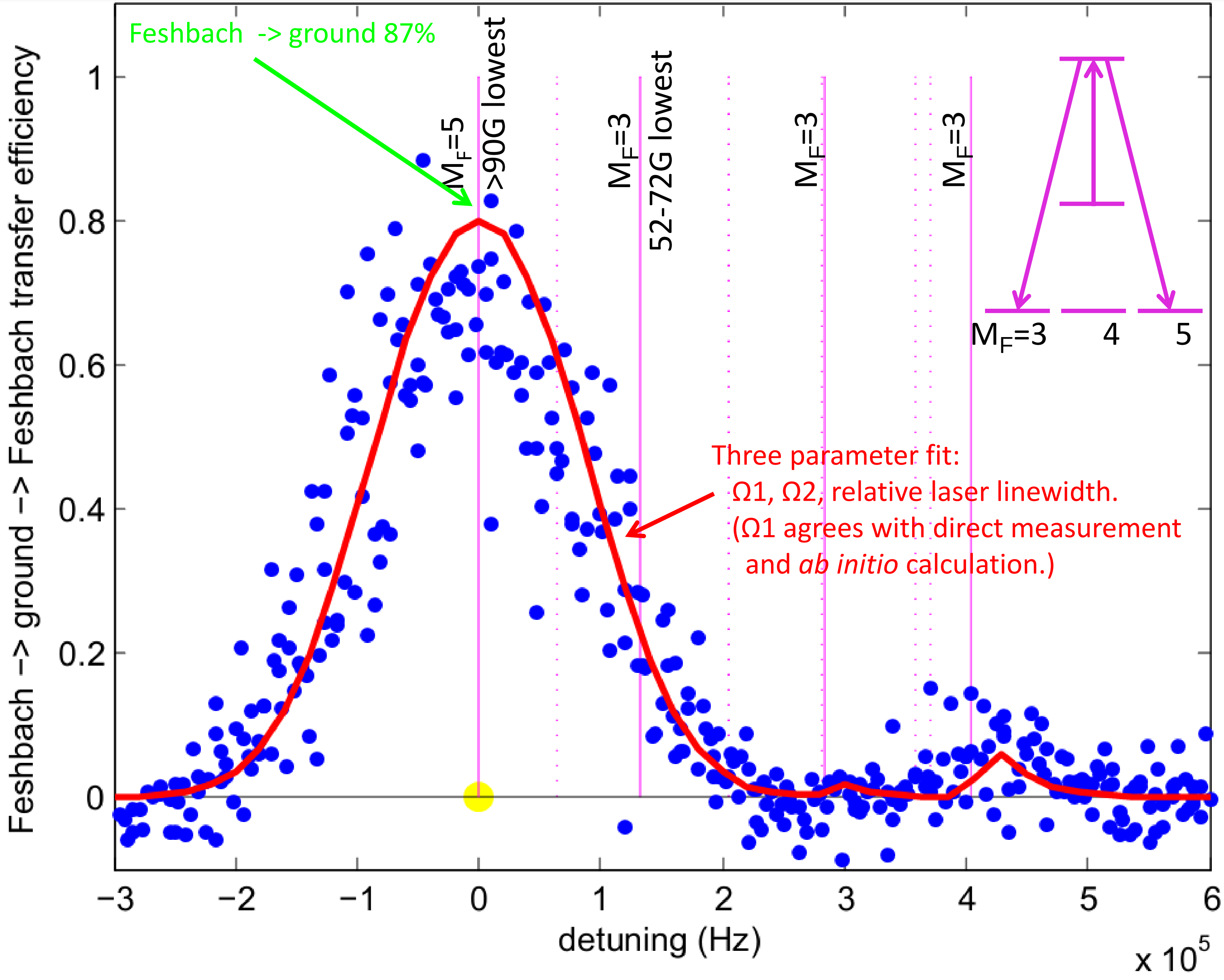
Cs |3,3> + ^{87}Rb |1,1> in incoming s-wave collision has M_F=4, therefore, Feshbach molecules also have M_F=4



all accessible directly through STIRAP (in theory)

J. Aldegunde (Salamanca) and Jeremy M. Hutson (Durham)

Ground state transfer

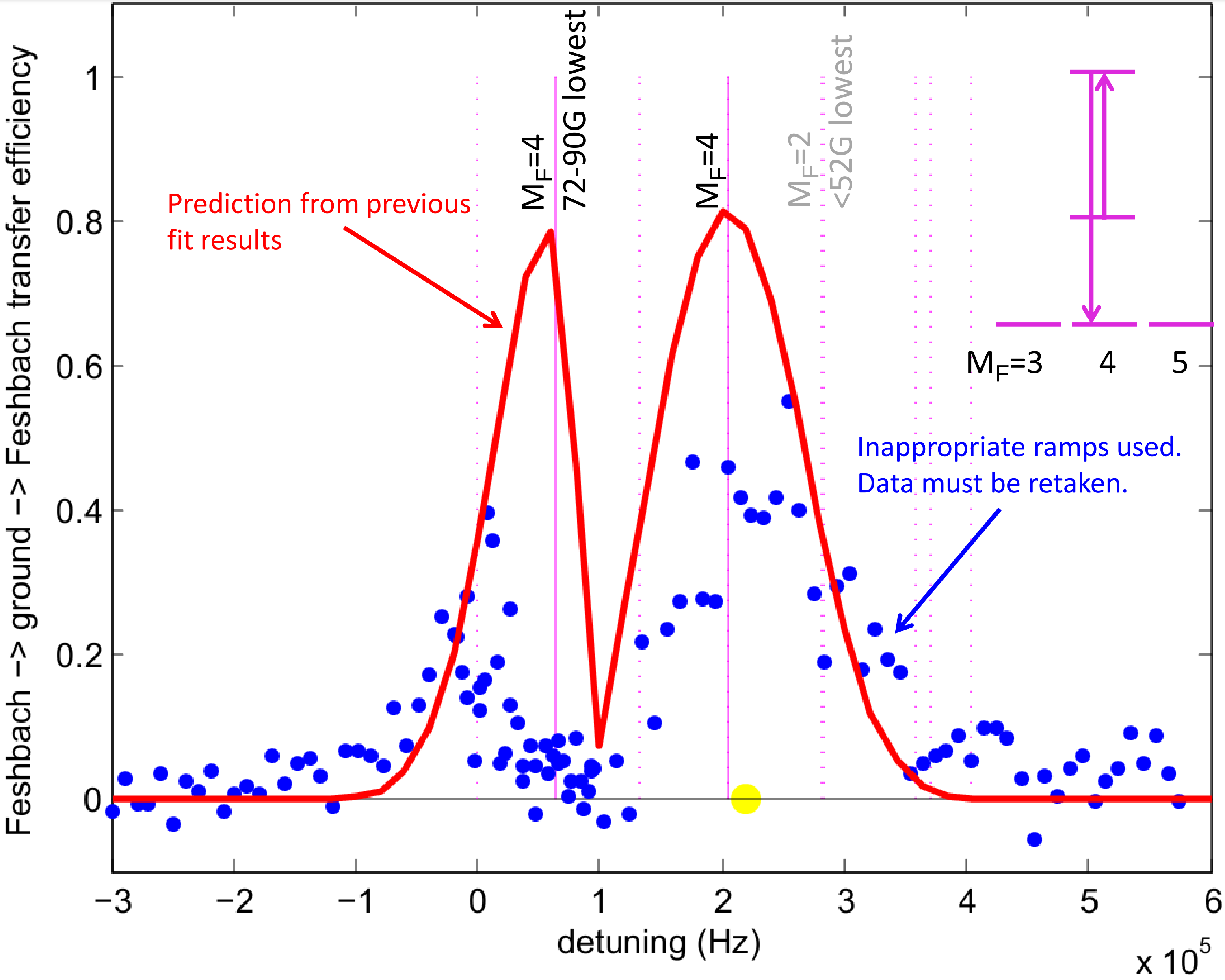


Feshbach -> ground 87%

Three parameter fit:
Ω1, Ω2, relative laser linewidth.
(Ω1 agrees with direct measurement and *ab initio* calculation.)

VH polarization 182G, excited state M_F=4.

Ground state transfer



Prediction from previous fit results

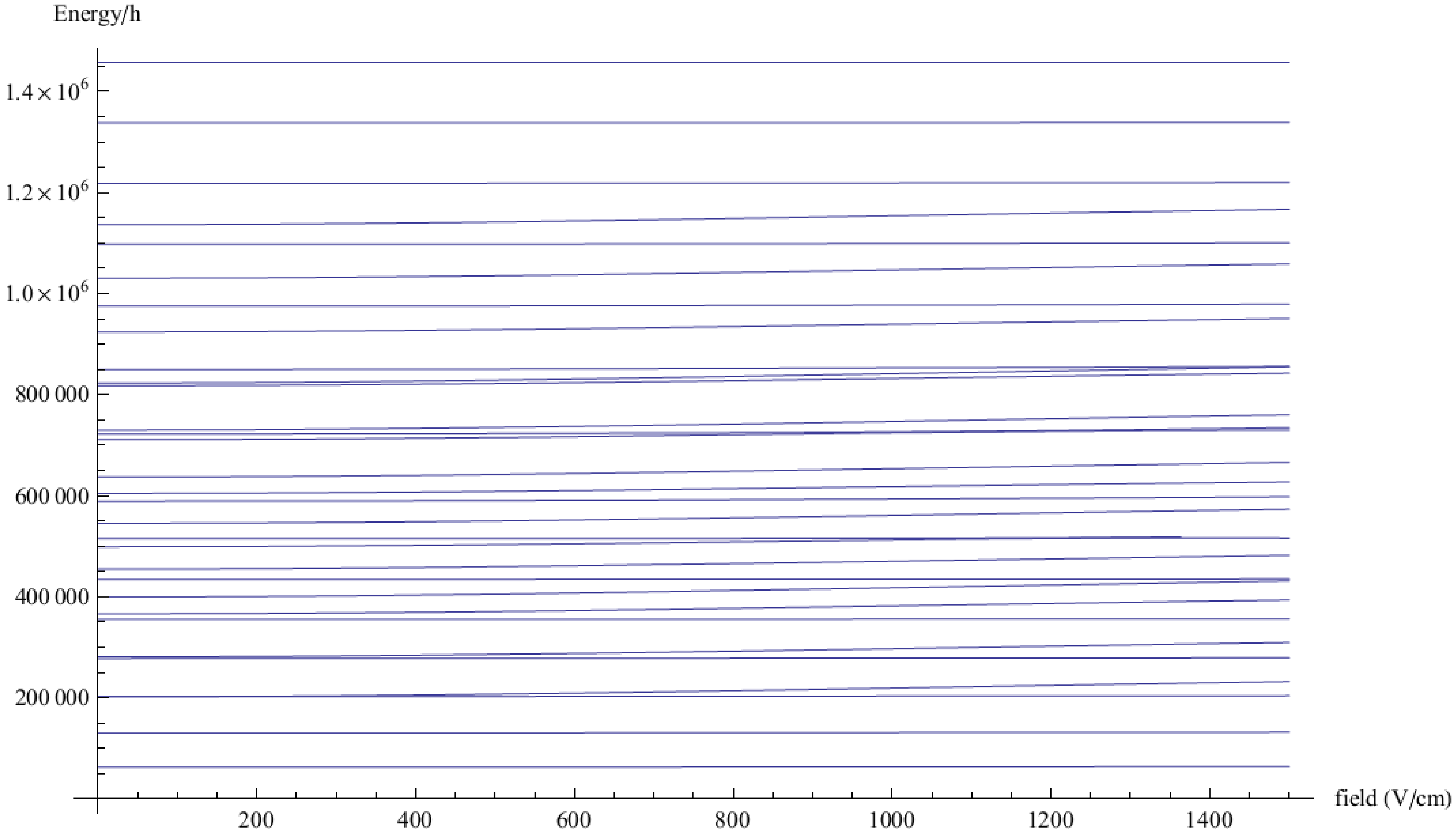
Inappropriate ramps used. Data must be retaken.

VV polarization 182G, excited state M=4

Ground state transfer

87RbCs lowest rotational level

182G



RbCs from a double Mott insulator

Our current estimated phase-space density ~0.01?
A new method is necessary to get us to 1.

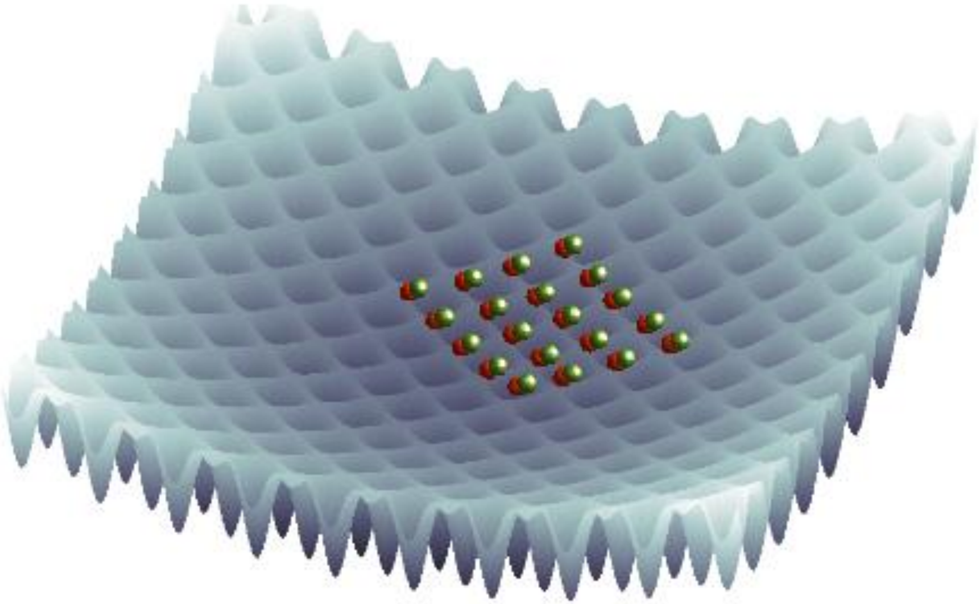
RbCs from a double Mott insulator

We really want something like this! (atom pairs)

VOLUME 90, NUMBER 11 PHYSICAL REVIEW LETTERS week ending 21 MARCH 2003

Creation of a Dipolar Superfluid in Optical Lattices

B. Damski,[1,2] L. Santos,[1] E. Tiemann,[3] M. Lewenstein,[1] S. Kotochigova,[4] P. Julienne,[4] and P. Zoller[5]



Noah Bray-Ali and Carl Williams
preliminary calculations

J. Freericks
numerical simulations starting

RbCs from a double Mott insulator

$$\hat{H} = -J\sum_{\langle ij\rangle}\hat{a}_i^\dagger\hat{a}_j - \sum_i \mu\hat{n}_i + \sum_i \frac{U}{2}\hat{n}_i(\hat{n}_i - 1)$$

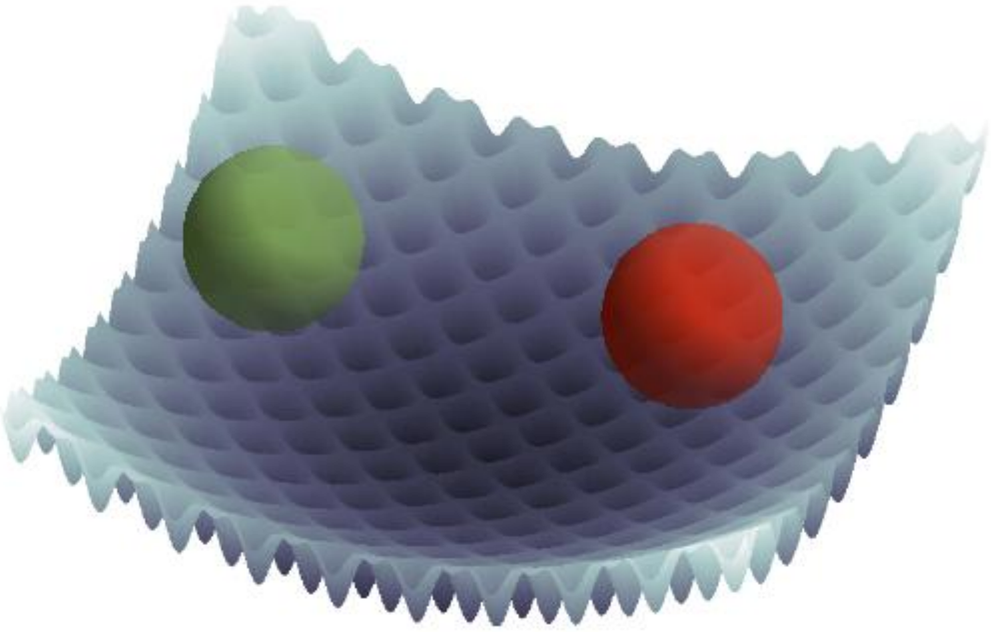
$$U \propto \frac{4\pi h^2 a}{m}$$

a_{CsCs} = 1700 a_0

a_{RbRb} = 100 a_0

a_{RbCs} = tunable

(0.2 G wide Feshbach resonance)

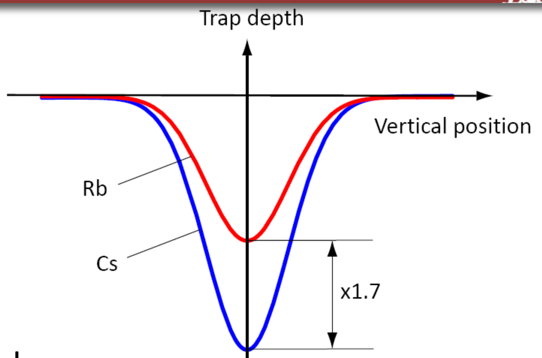


$U_0{}^{RbRb}/J_{Rb}$ << 35 $U_0{}^{CsCs}/J_{Cs}$ << 35

2 superfluids

RbCs from a double Mott insulator

$$\hat{H} = -J\sum_{\langle ij\rangle}\hat{a}_i^\dagger \hat{a}_j - \sum_i \mu \hat{n}_i + \sum_i \frac{U}{2}\hat{n}_i(\hat{n}_i - 1)$$

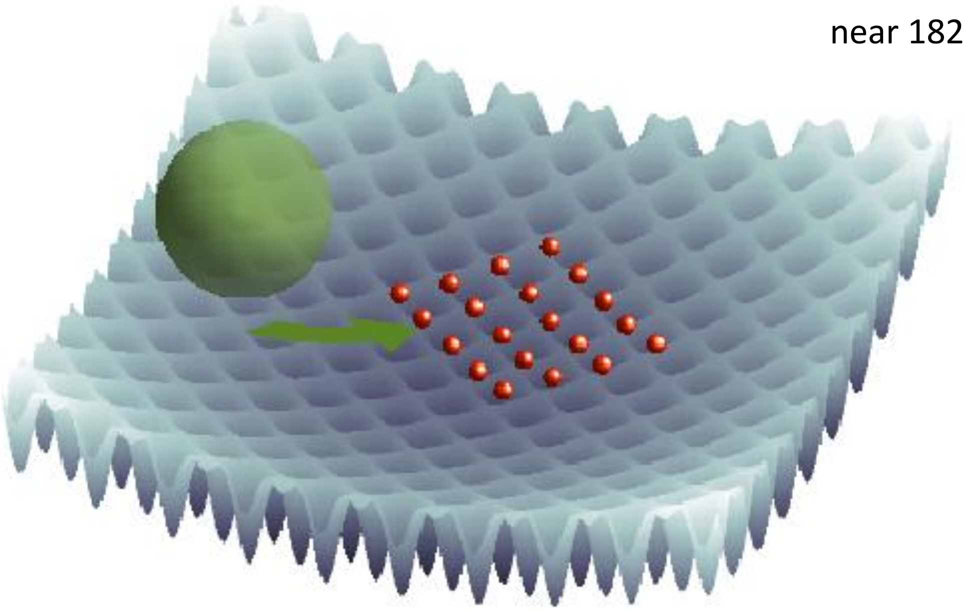


near 182G Feshbach resonance

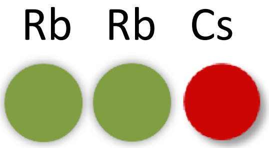
U_{RbRb} ~ $+k_{\text{B}} \times 15$ nK ($h \times 300$ Hz)

U_{CsCs} ~ $+k_{\text{B}} \times 400$ nK ($h \times 8000$ Hz)

U_{RbCs} = tunable, make negative?



Need to prevent site occupation by:



→ three body loss

want $U_{\text{RbRb}} + U_{\text{RbCs}} > 0$

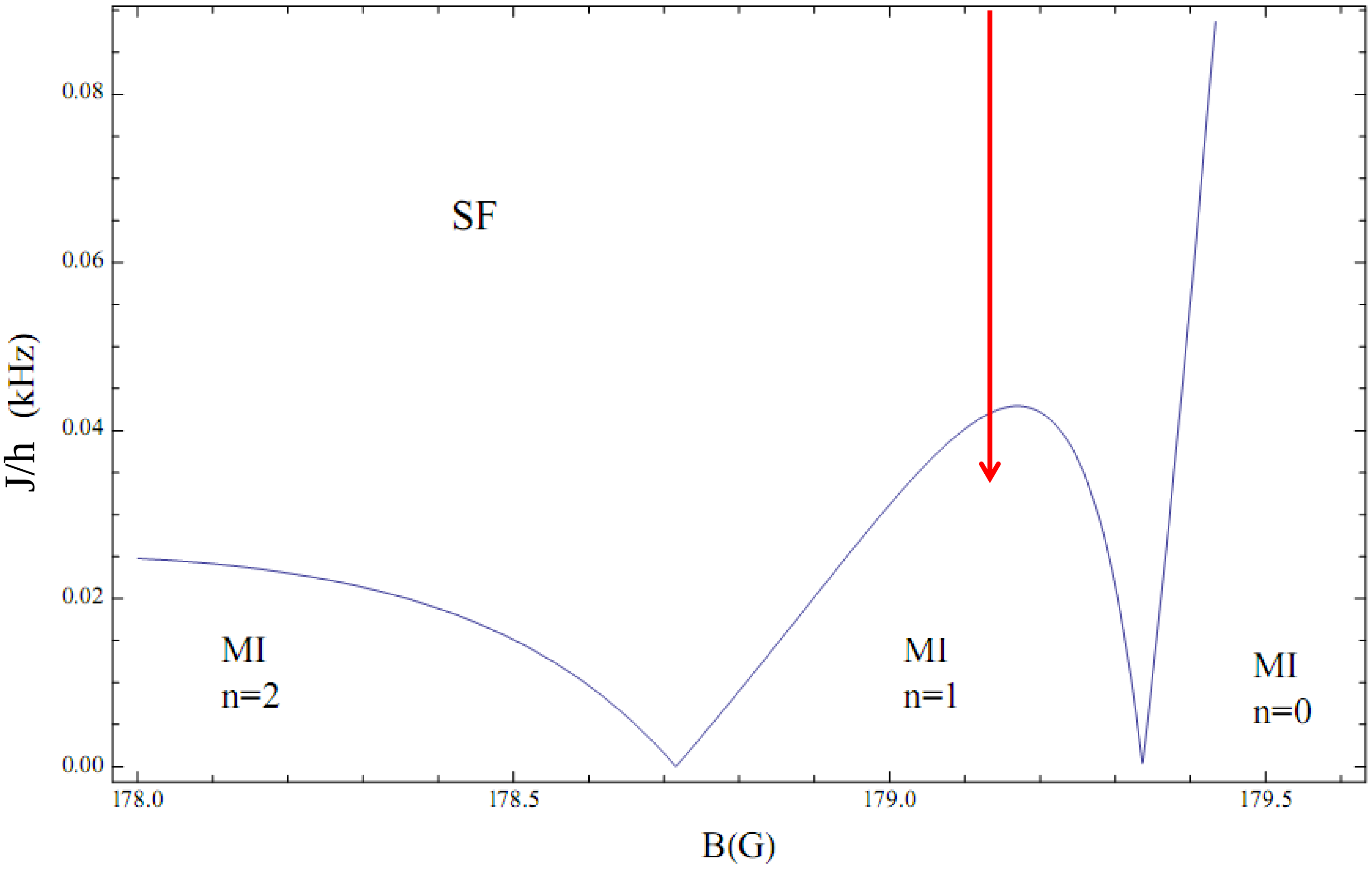
$U_0{}^{RbRb}/J_{Rb}$ =2500 $\quad U_0{}^{CsCs}/J_{Cs} = 4.3$

$$\frac{\Delta a_{RbCs}}{\Delta B} = \frac{a_{RbCs}{}^{background}}{\Delta} = \frac{649a_0}{0.2\ G} = 3.3\ \frac{a_0}{mG}$$

5−10 mG noise measured in lab → Δa_{RbCs} = 17-33a_0

- Freeze out Cs
- Rb superfluid flows onto Cs
- Use onsite interactions U to prevent 3 particles per lattice site

RbCs from a double Mott insulator



Rb-Cs
Feshbach
resonance

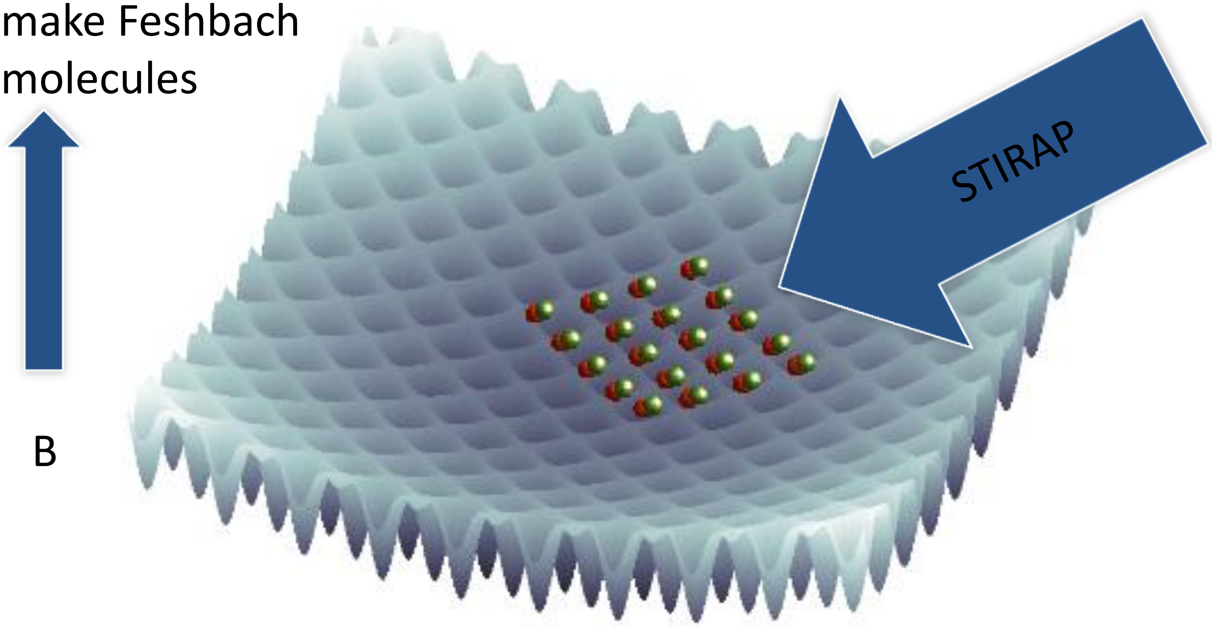
Mean-field phase diagram of Rb atoms in an optical lattice resonantly interacting with a Cs Mott insulator. J/h is the Rb tunneling rate. (Noah Bray-Ali, Carl Williams)

RbCs from a double Mott insulator

$$\hat{H} = -J\sum_{\langle ij\rangle}\hat{a}_i^\dagger \hat{a}_j - \sum_i \mu \hat{n}_i + \sum_i \frac{U}{2}\hat{n}_i(\hat{n}_i - 1) + \frac{U_{\mathrm{NN}}}{2}\sum_{\vec{\ell}}\sum_{\langle\langle ij\rangle\rangle_{\vec{\ell}}} \frac{1}{|\vec{\ell}\,|^3}\hat{n}_i \hat{n}_j$$

dipolar lattice physics !
(or melt for RbCs BEC)

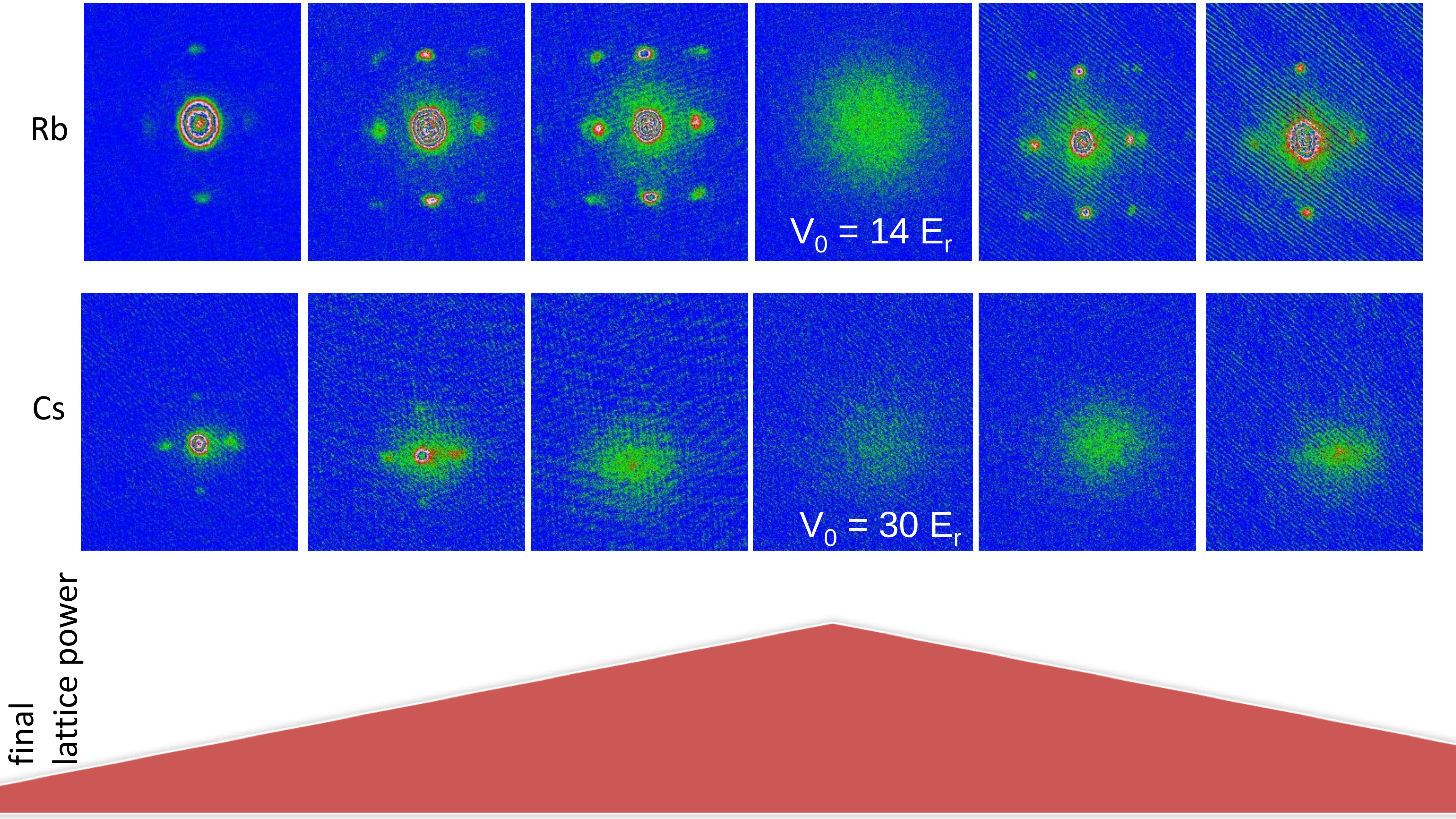
make Feshbach molecules



Now make Feschbach molecules, and do STIRAP (Much simpler version works for Rb_2, Cs_2)
Lower lattice adiabatically for molecular superfluid

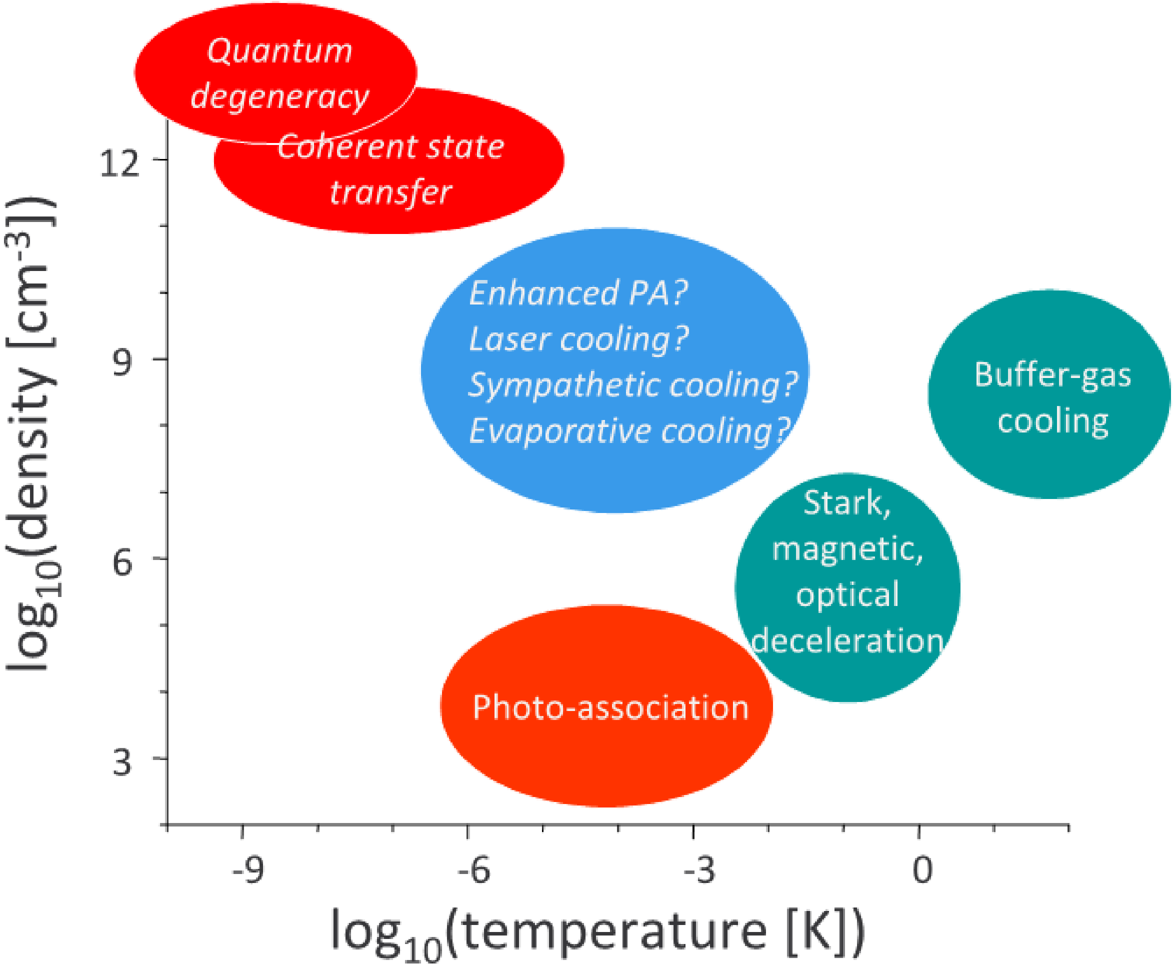
RbCs from a double Mott insulator

Dual species SF-MI: same lattice but not yet overlapped



RbCs from a double Mott insulator

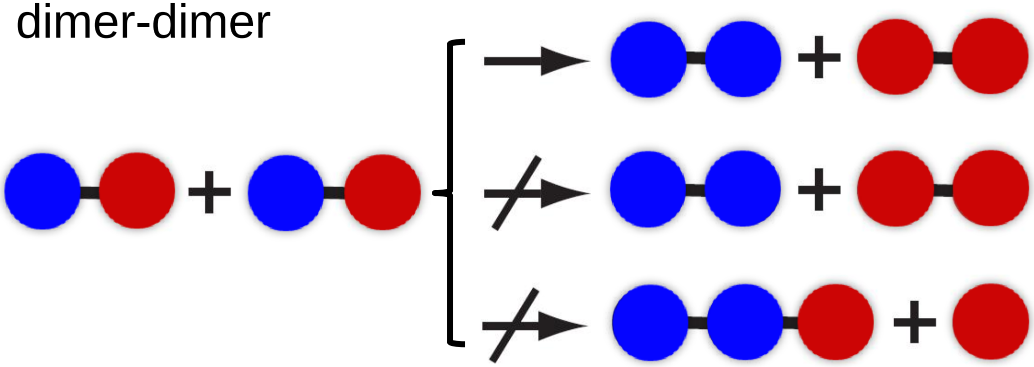
What if this is not enough for degeneracy?
(KRb currently at 1.5T_F, PSD 0.1)



RbCs from a double Mott insulator

What if this is not enough for degeneracy?
3D Evaporative cooling of ground state RbCs with no electric field?

dimer-dimer



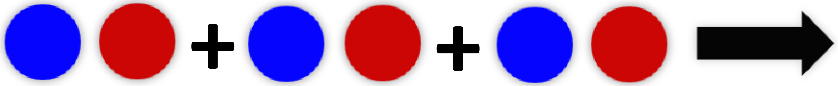
LiNa, LiK, LiRb, LiCs and KRb

NaK, NaRb, NaCs, **KCs** and **RbCs**

all

Piotr S. Zuchowski and Jeremy M. Hutson PRA **81**, 060703 (2010).

Three body loss?



- Spin changing collisions driven by collision anisotropy
- Centrifugal barrier ~ $\mu^{-3/2}C_6^{-1/2}$

$C_6 = 140000a_o$ calculated for RbCs

Kotochigova NJP **12**, 073041 (2010).

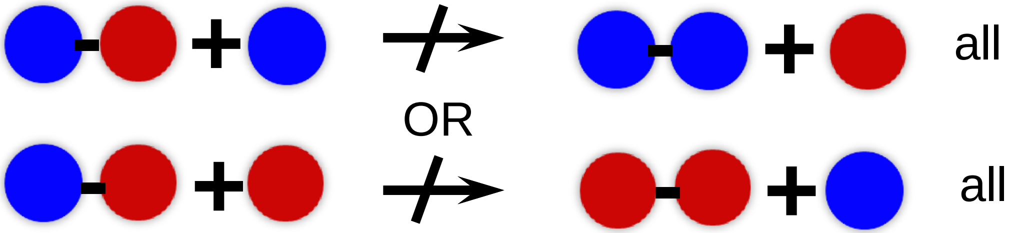
RbCs from a double Mott insulator

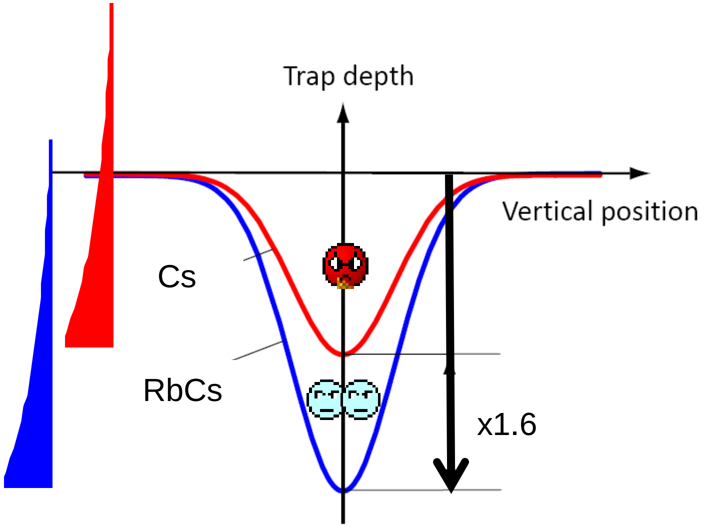
Evaporative cooling of molecules:

ground state molecules are precious.

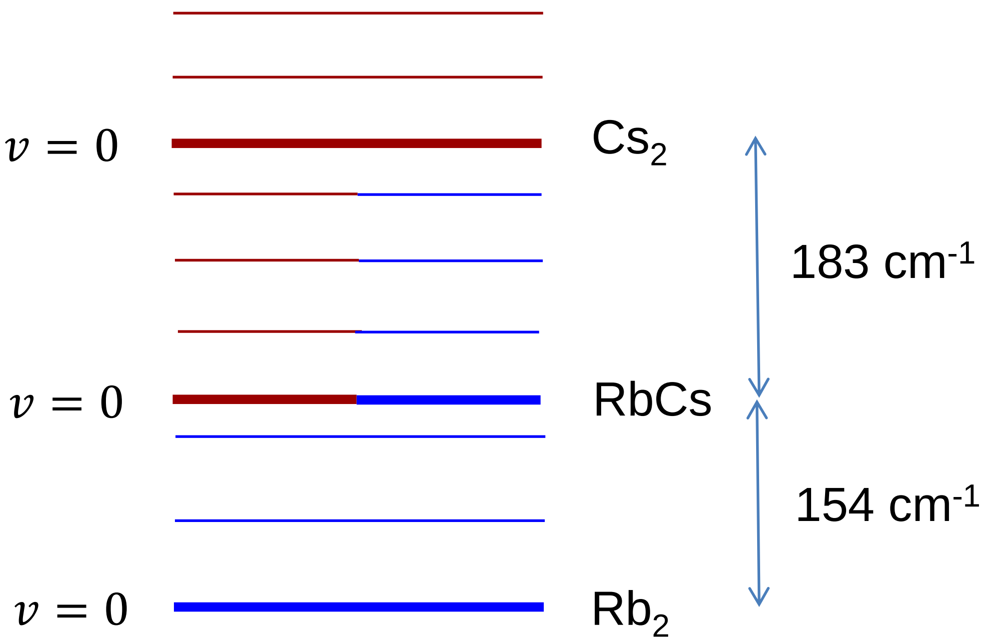
perhaps one can use atoms instead?

dimer-monomer collisions: one will be forbidden

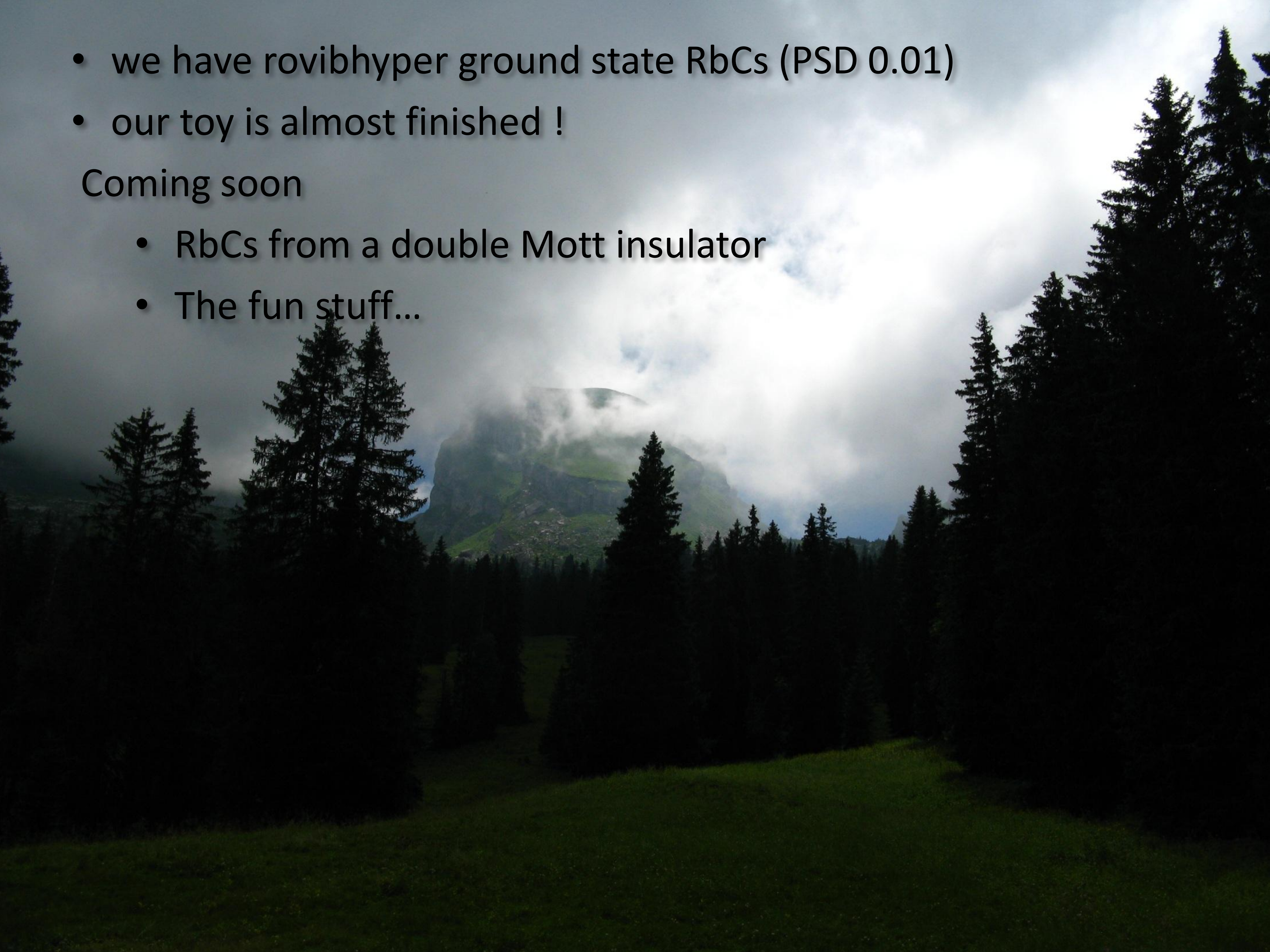




Use Cs atoms as a coolant



- requires high Cs-Cs, RbCs-Cs thermalization rates
- requires low Cs-Cs-Cs, RbCs-RbCs-RbCs, RbCs-RbCs-Cs, RbCs-Cs-Cs three body recombination rates (may need to goto 20G!)



- we have rovibhyper ground state RbCs (PSD 0.01)
- our toy is almost finished !

Coming soon

  - RbCs from a double Mott insulator
  - The fun stuff…

universität innsbruck

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European Science Foundation

Conference on

Cold and Ultracold Molecules

November 18-23, 2012
University Center Obergurgl (“near” Innsbruck)

- Direct and indirect cooling techniques
- Controlled quantum chemistry
- Ultracold molecules for tests of quantum physics
- Molecular quantum gases
- Frontiers in molecular quantum control
- …

Organizers: Guido Pupillo (chair), Francesca Ferlaino, Hanns-Christoph Nägerl

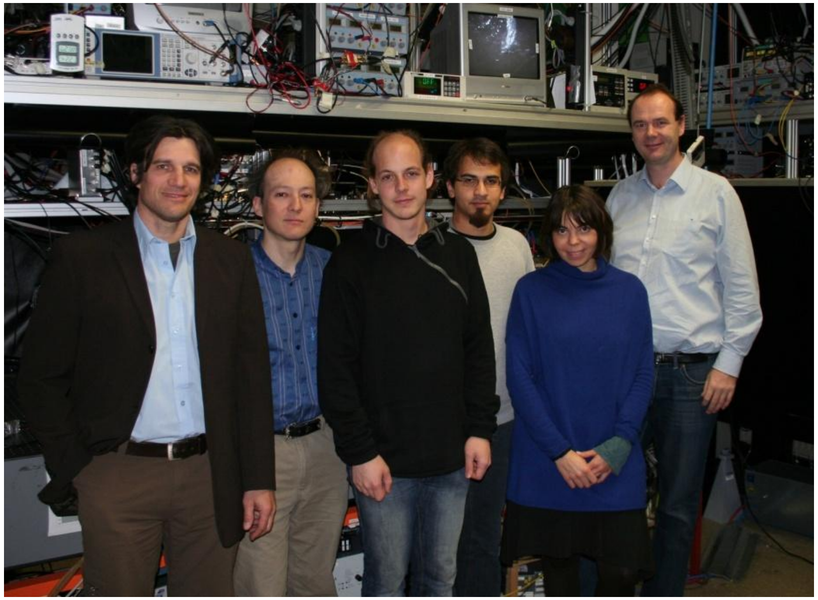
More to come…

http://www.esf.org/index.php?id=9144

SFB FoQuS Foundations and Applications of Quantum Science

FWF

ÖAW Austrian Academy of Sciences



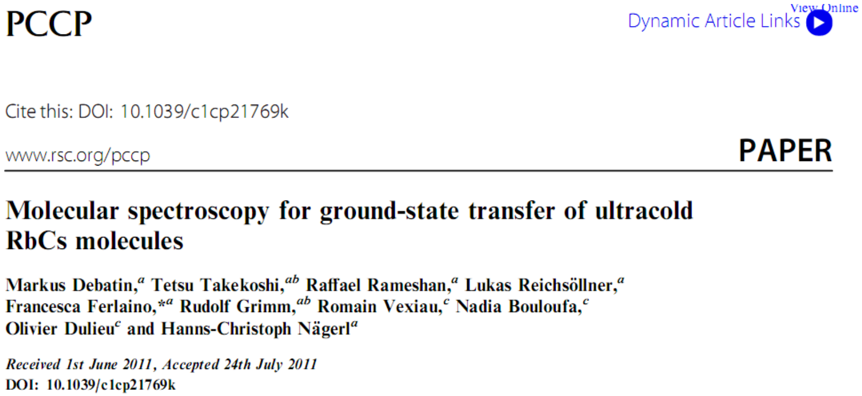
Eur. Phys. J. D (2011)
DOI: 10.1140/epjd/e2011-20015-6

THE EUROPEAN
PHYSICAL JOURNAL D

Regular Article

Production of a dual-species Bose-Einstein condensate of Rb and Cs atoms

A.D. Lercher[1], T. Takekoshi[1,a], M. Debatin[1], B. Schuster[1], R. Rameshan[1], F. Ferlaino[1],
R. Grimm[1,2], and H.-C. Nägerl[1]



PCCP

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Cite this: DOI: 10.1039/c1cp21769k

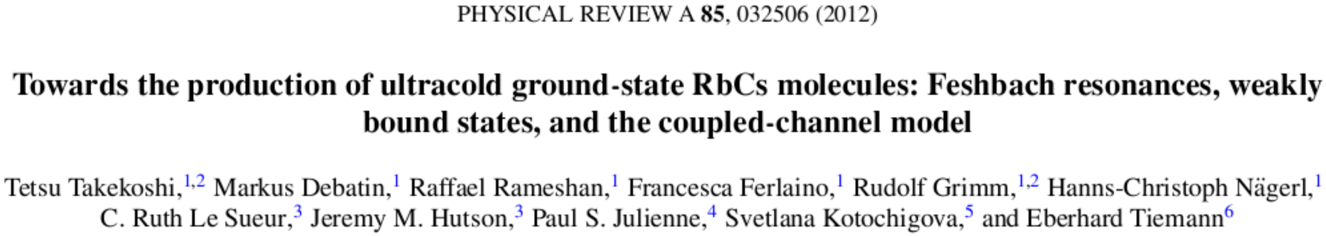
www.rsc.org/pccp

PAPER

Molecular spectroscopy for ground-state transfer of ultracold RbCs molecules

**Markus Debatin,[a] Tetsu Takekoshi,[ab] Raffael Rameshan,[a] Lukas Reichsöllner,[a]
Francesca Ferlaino,*[a] Rudolf Grimm,[ab] Romain Vexiau,[c] Nadia Bouloufa,[c]
Olivier Dulieu[c] and Hanns-Christoph Nägerl[a]**

Received 1st June 2011, Accepted 24th July 2011
DOI: 10.1039/c1cp21769k



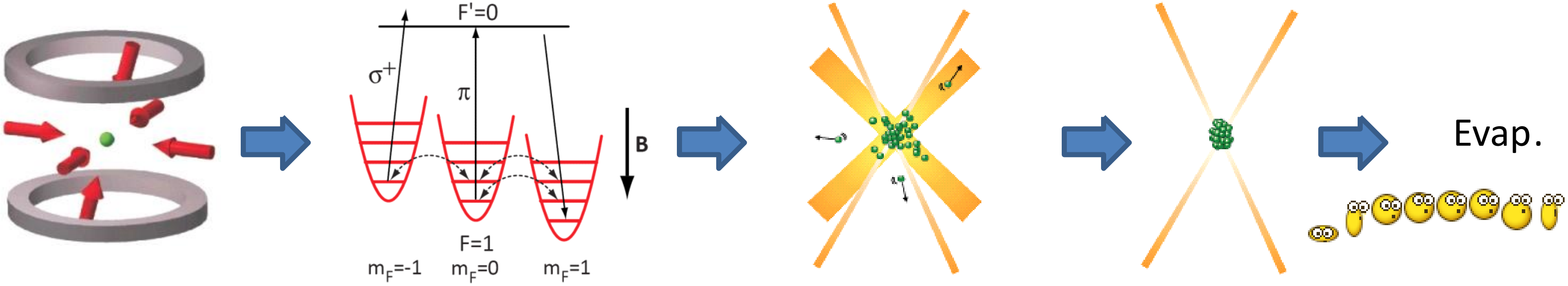
PHYSICAL REVIEW A **85**, 032506 (2012)

Towards the production of ultracold ground-state RbCs molecules: Feshbach resonances, weakly bound states, and the coupled-channel model

Tetsu Takekoshi,[1,2] Markus Debatin,[1] Raffael Rameshan,[1] Francesca Ferlaino,[1] Rudolf Grimm,[1,2] Hanns-Christoph Nägerl,[1]
C. Ruth Le Sueur,[3] Jeremy M. Hutson,[3] Paul S. Julienne,[4] Svetlana Kotochigova,[5] and Eberhard Tiemann[6]

The colliding BEC method

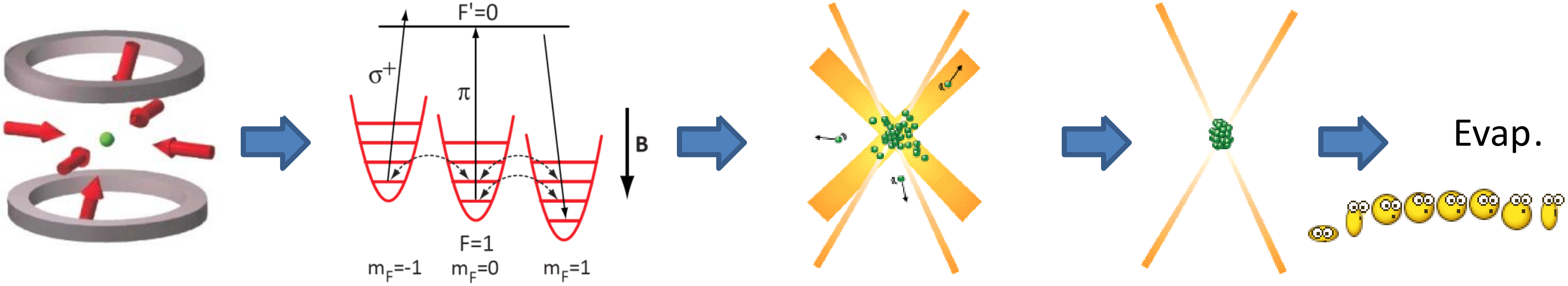
Cs BEC requires optical traps.
Optical BEC of Rb makes dual species apparatus simpler.



Cs |3,3> or ^{87}Rb |1,1>

The colliding BEC method

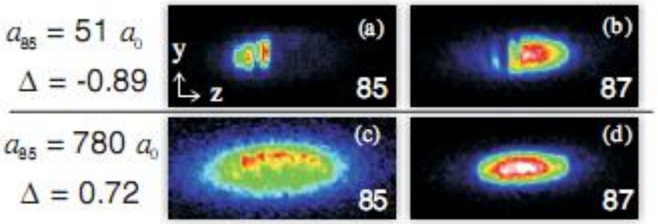
Cs BEC requires optical traps.
Optical BEC of Rb makes dual species apparatus simpler.



Evap.

Cs |3,3> or ^{87}Rb |1,1>

Our dream:
like ^{87}Rb ^{85}Rb mixture



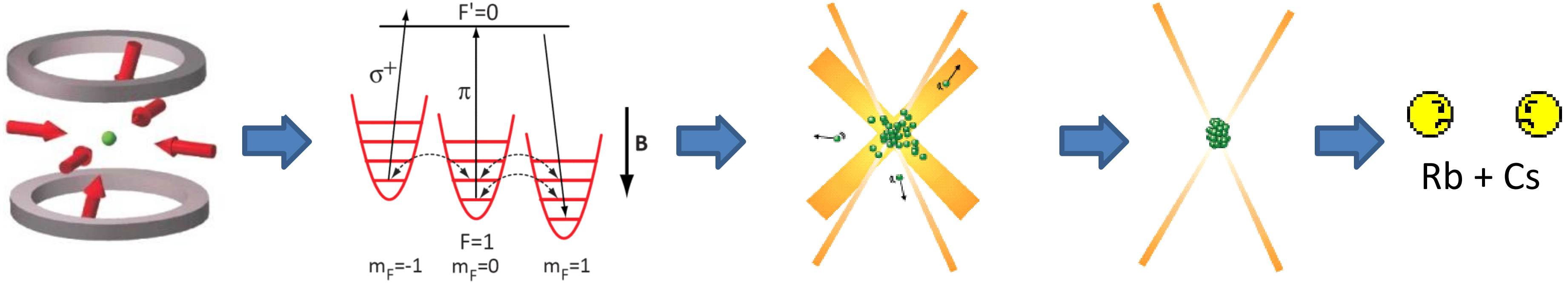
S.B. Papp, J.M. Pino, C.E. Wieman PRL **101** 040402 (2008).

The colliding BEC method

Making Feshbach molecules requires a high phase space density mixture.

mixture problems bad, but not insurmountable

really bad mixture problems



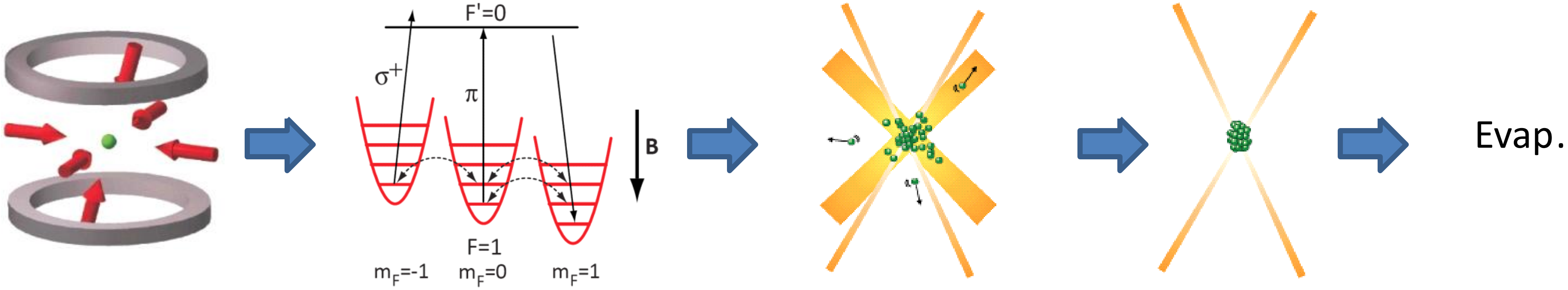
The colliding BEC method

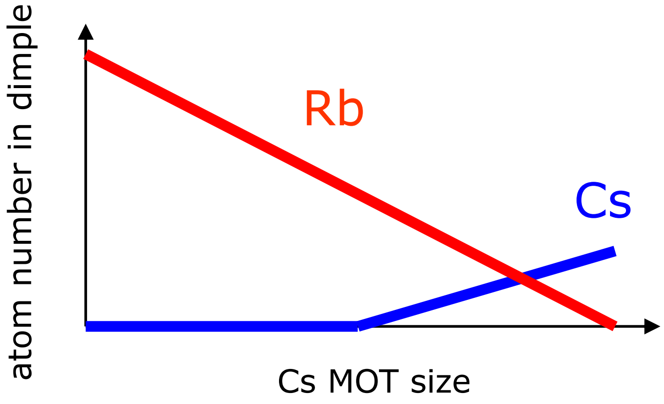
Starting point: all-optical Cs BEC
Making Feshbach molecules requires a high phase space density mixture

mixture problems bad, but
not insurmountable

really bad mixture problems

Rb + Cs

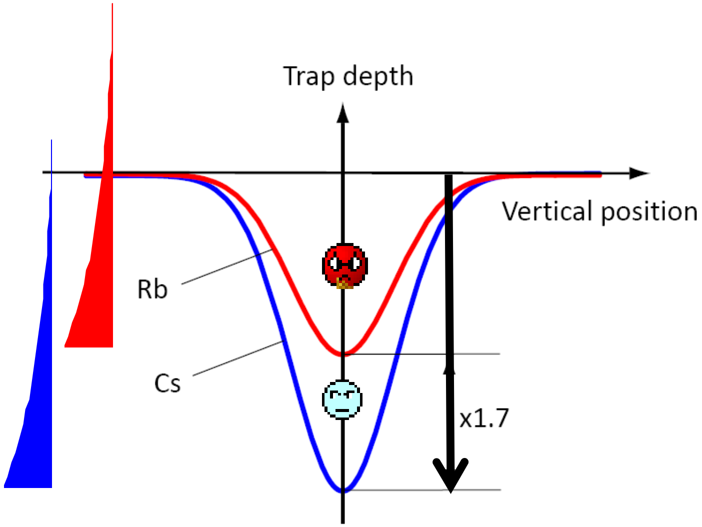




The colliding BEC method

Important for Rb-Cs mixtures:

Traps are deeper for Rb than for Cs.
(evaporative heat load mostly on Rb)



high Rb/Cs thermalization

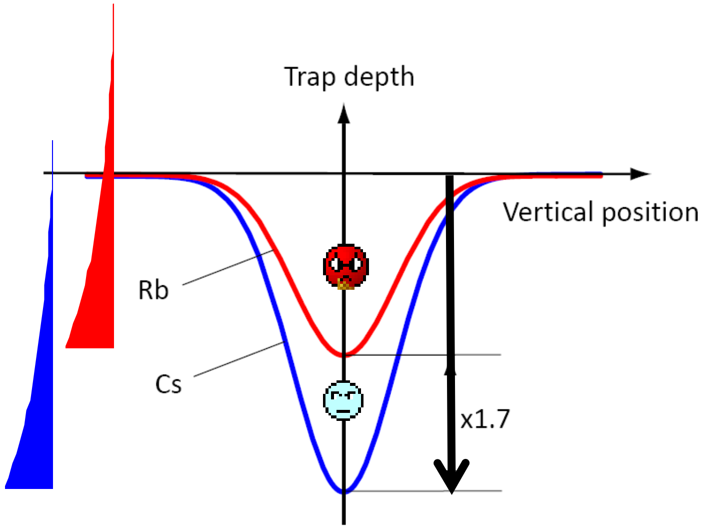
Bad for simultaneous evaporation
Good for Cs cooling! (efficient)

Bad luck #1

The colliding BEC method

Important for Rb-Cs mixtures:

Traps are deeper for Rb than for Cs.
(evaporative heat load mostly on Rb)



high Rb/Cs thermalization

Bad for simultaneous evaporation
Good for Cs cooling! (efficient)

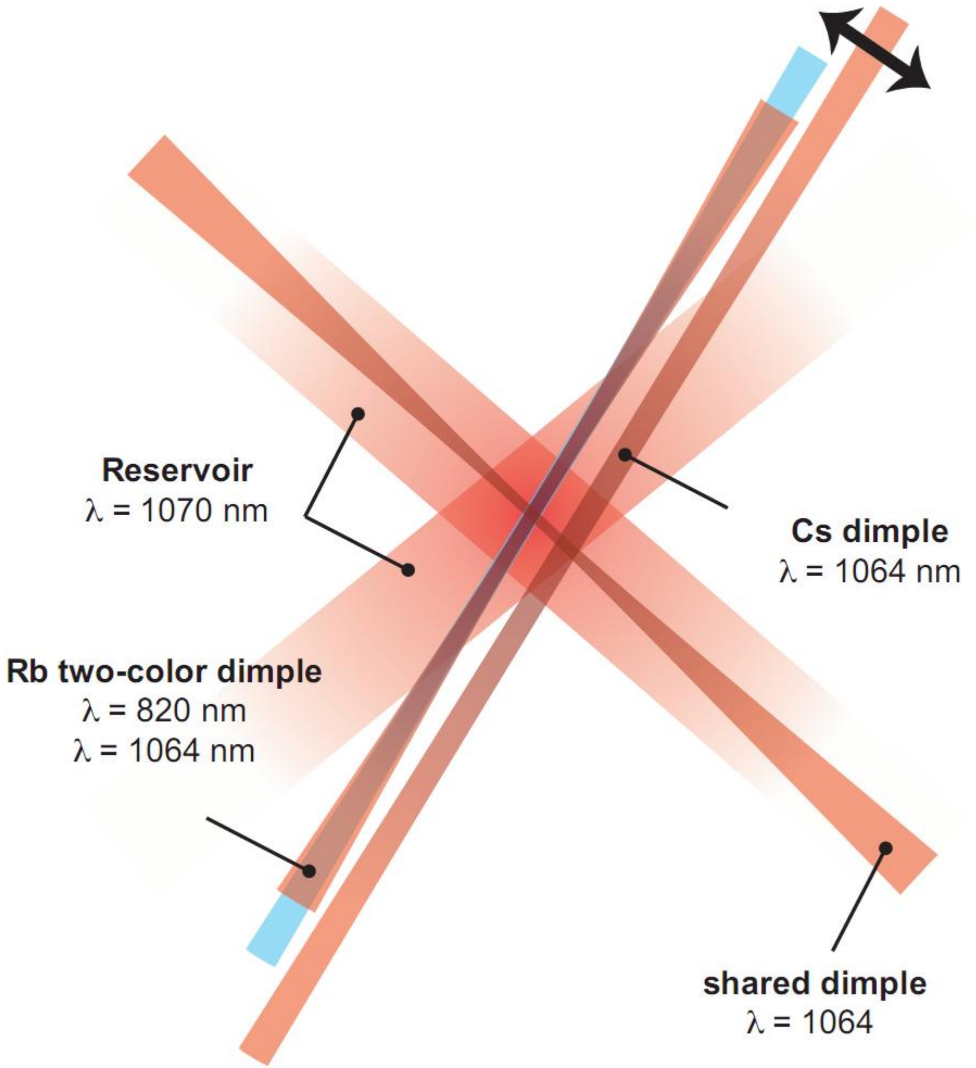
Large interspecies background scattering length
(a_{RbCs}~$649a_0$ from coupled channel model)

Large three-body recombination rates
For example $K_{RbRbCs} \sim |a_{RbCs}|^4 \approx 10^{-24}$ $cm^6 s^{-1}$
(measured)

Ratio of „good" to „bad" collisions
$= 4\pi a_{RbCs}^2 / (K_{RbRbCs} n_{Rb})$

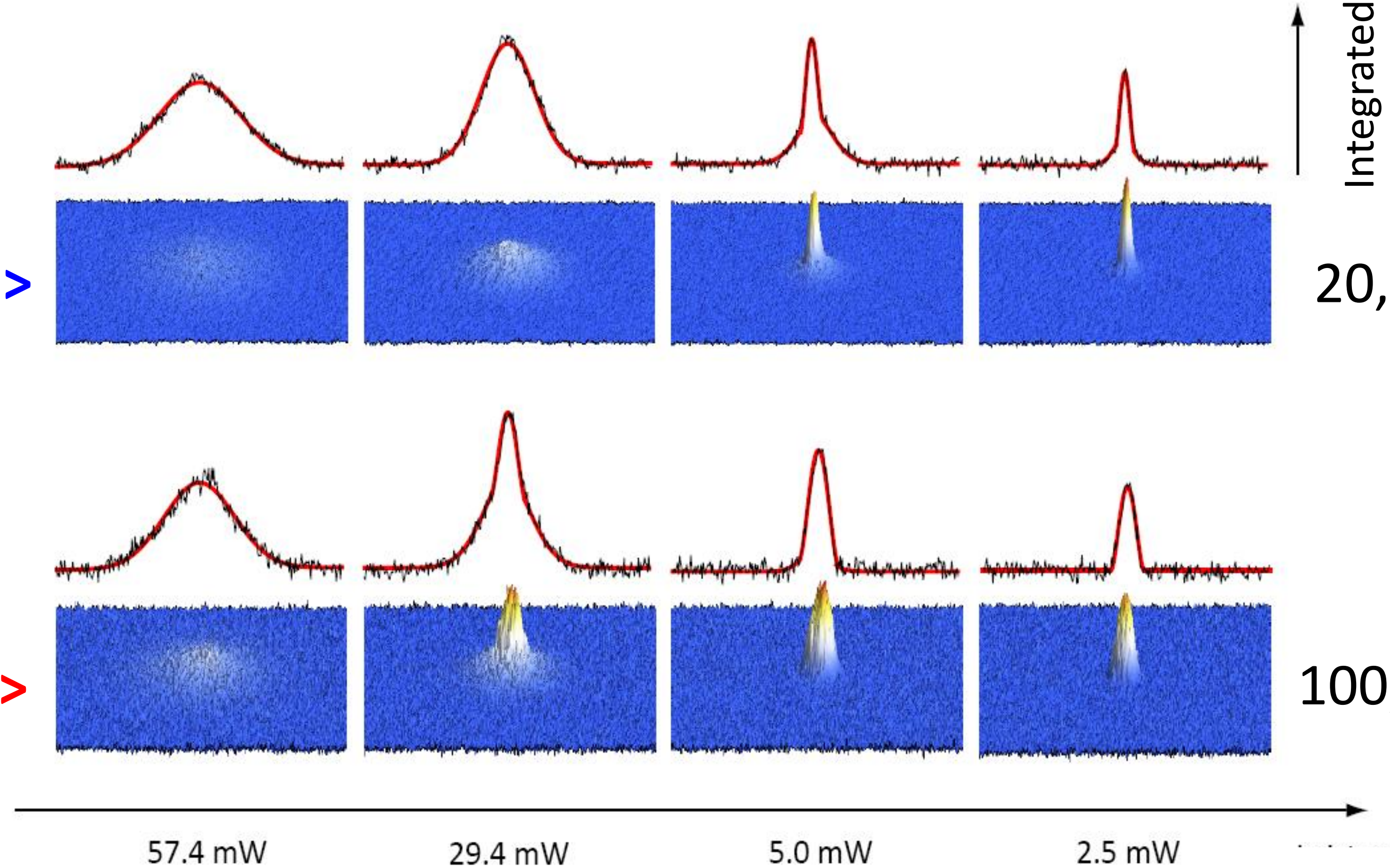
Bad luck #2

The colliding BEC method



- Raman cooling
- reservoir (spin filter)
- separate dimples

The colliding BEC method



Integrated density

Cs
|3,3>

20,000 atoms

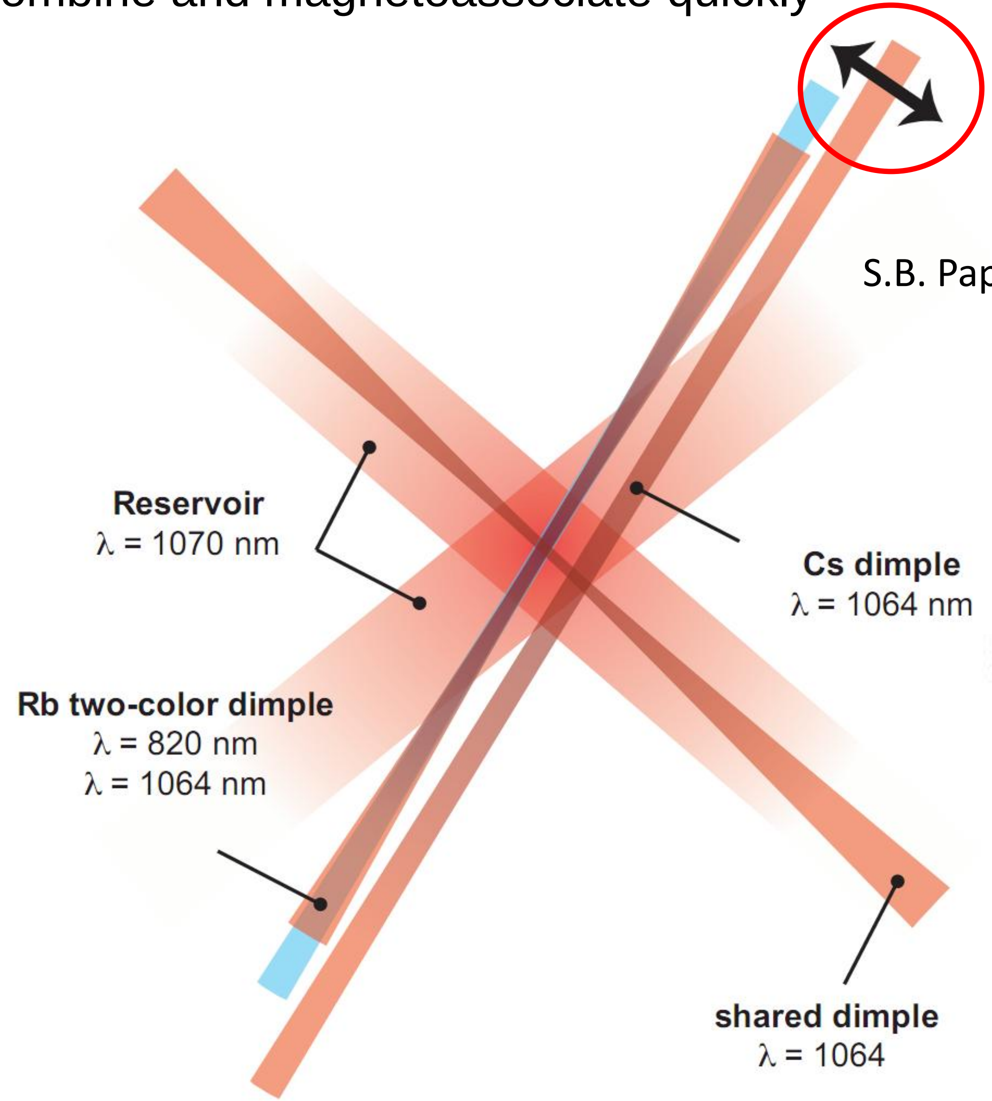
Rb
|1,1>

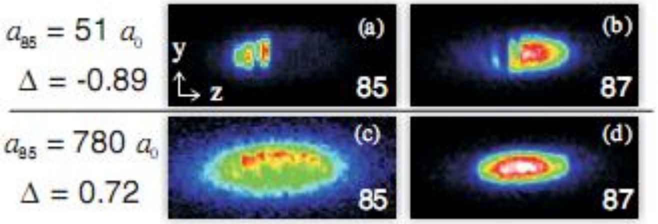
100,000 atoms

dimple power

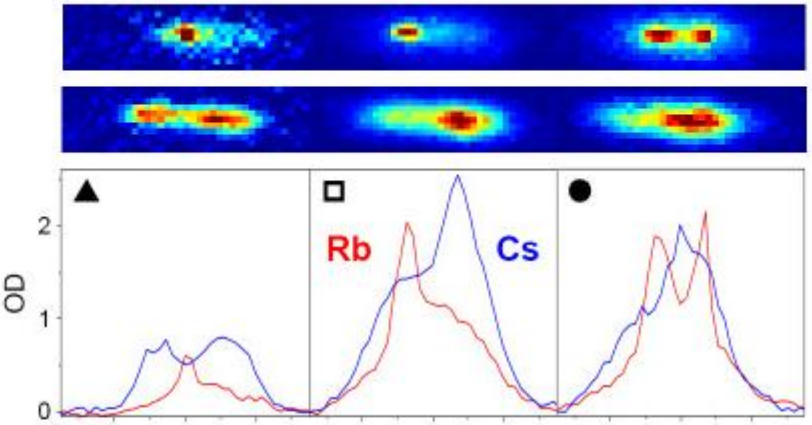
The colliding BEC method

Combine and magnetoassociate quickly





S.B. Papp, J.M. Pino, C.E. Wieman PRL **101** 040402 (2008).



Durham group PRA **84** 011603 (2011).

$$\frac{a_{RbRb} - aCsCs}{a_{RbCs}{}^{2}} - 1 > 0 \quad \text{miscible}$$

Bad luck #3

The colliding BEC method

RbCs from a double Mott insulator

Rb superfluid-Mott insulator transition

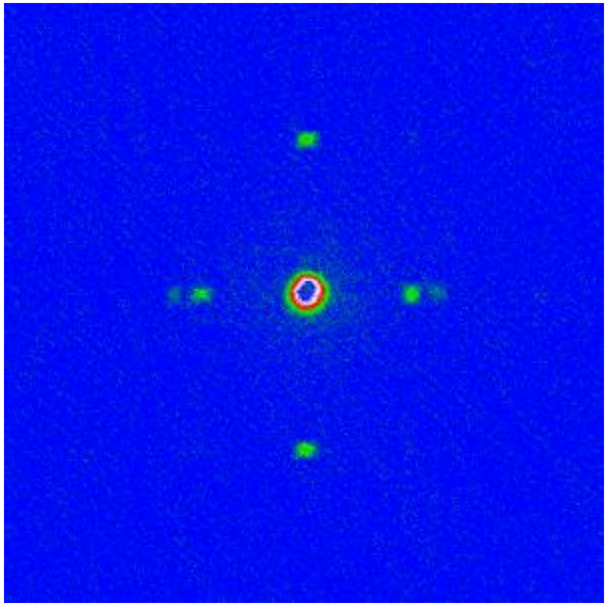
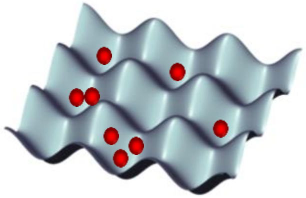


Image after expansion – matter wave interference

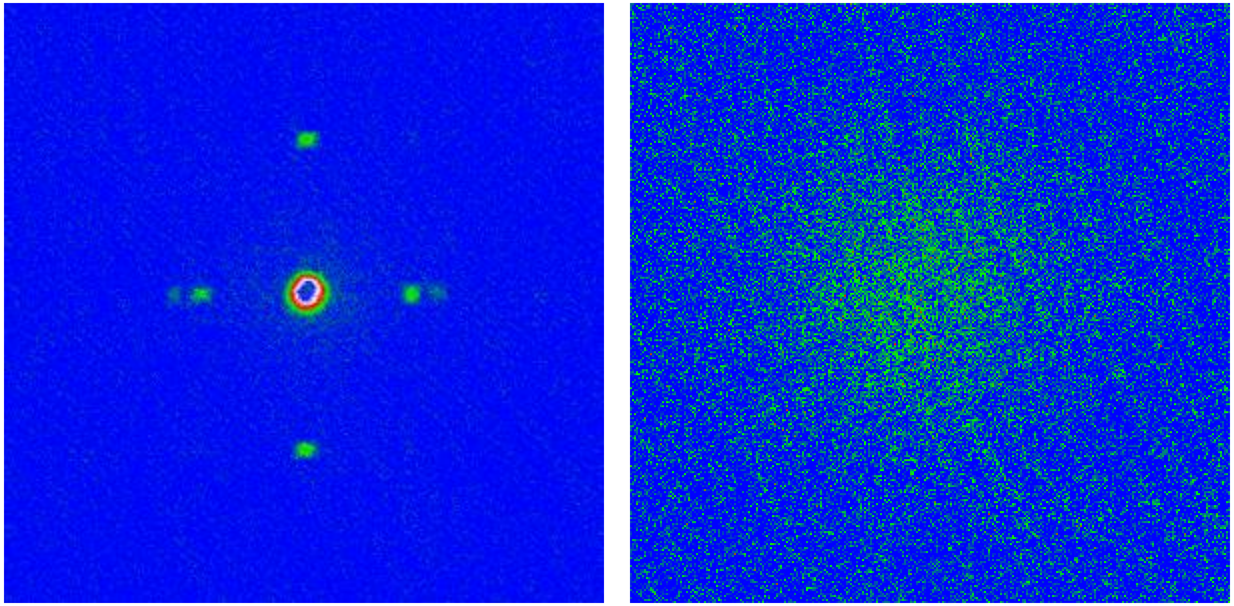


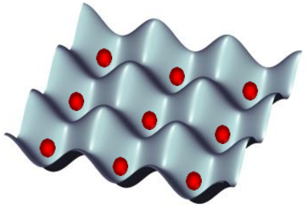
Superfluid state J>>U

- delocalised
- poissonian distribution
- phase coherence
- interference pattern

RbCs from a double Mott insulator

Rb superfluid-Mott insulator transition



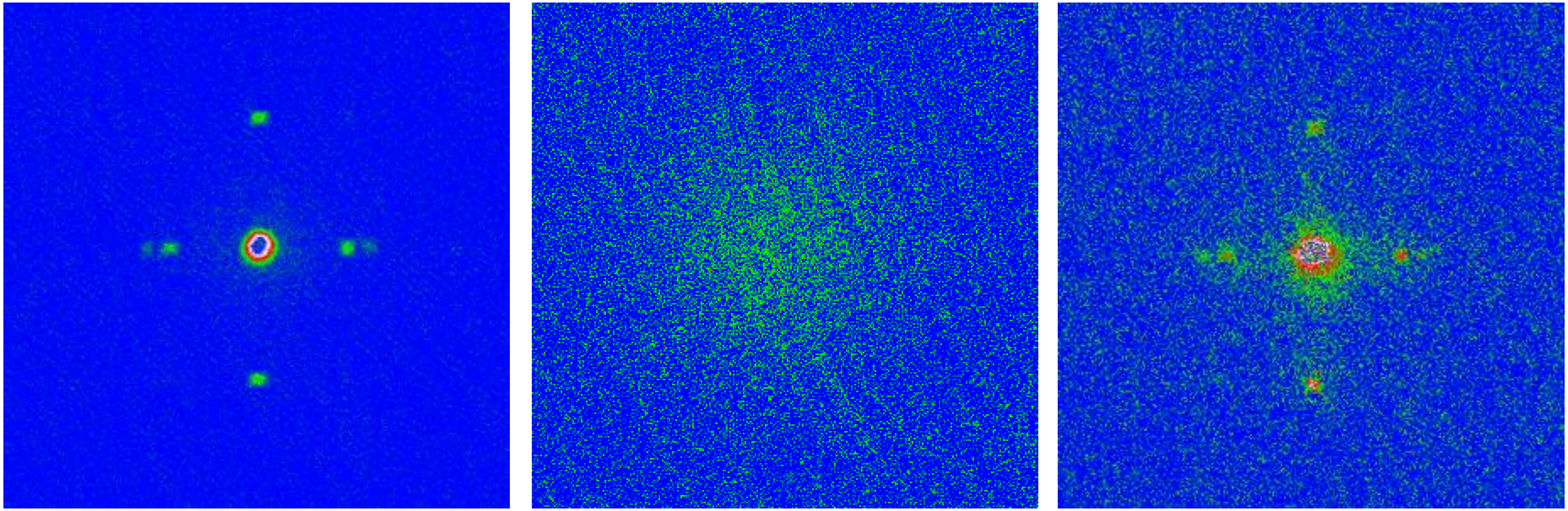


Mott insulator state J<<U

- localized atoms
- no phase coherence
- no interference pattern
- fixed atom number per site

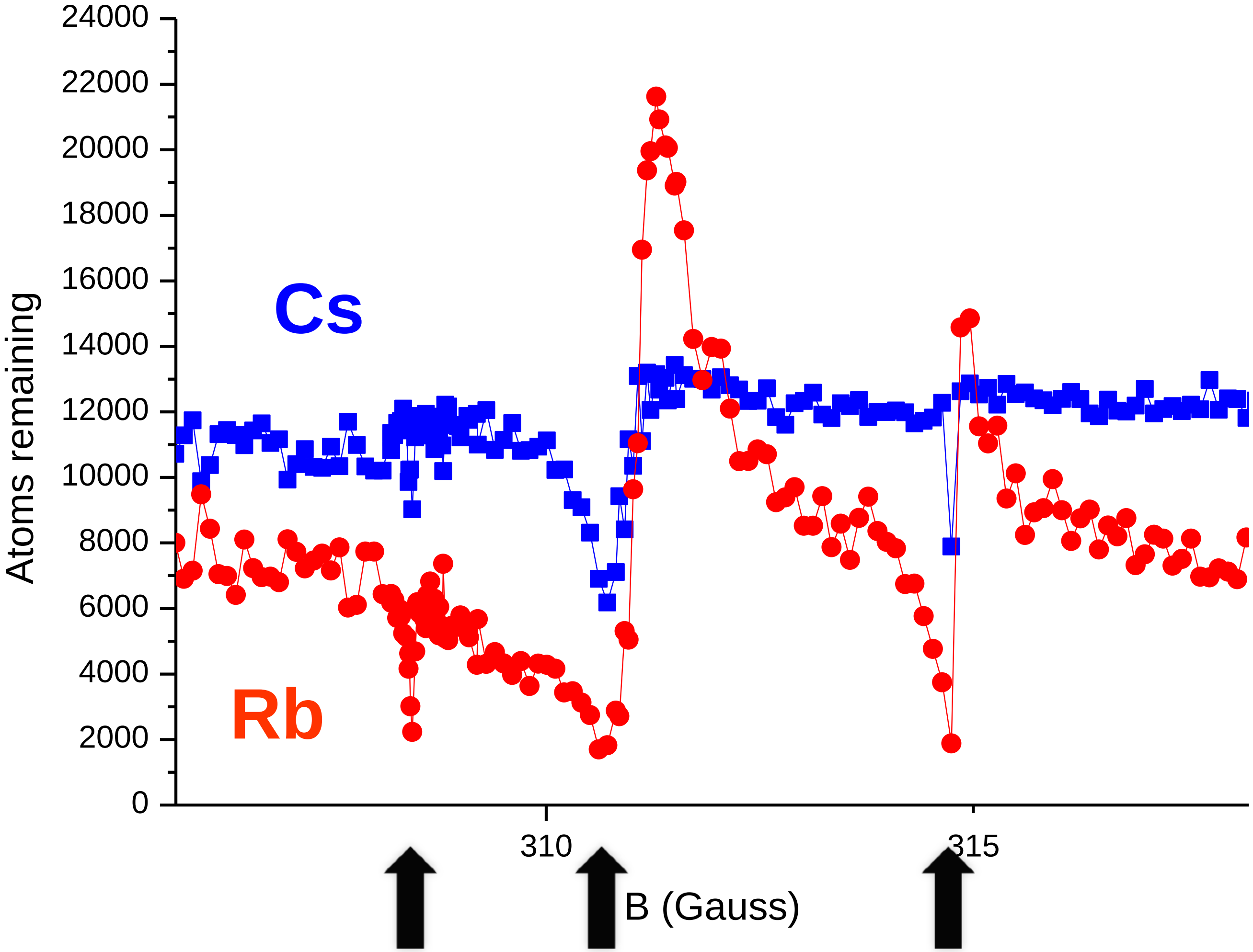
RbCs from a double Mott insulator

Rb superfluid-Mott insulator transition



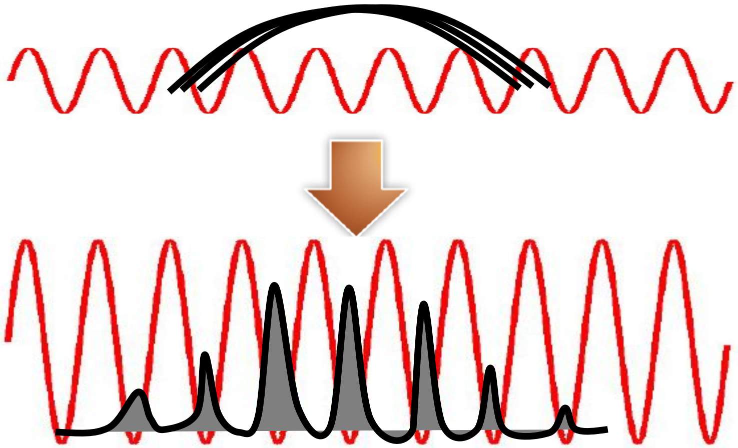
Coupled channel model

Data for model – Feshbach resonances



RbCs from a double Mott insulator

atomic **BEC**



atomic **Mott insulator**

Increasing the lattice depth

Phase transition

from **the superfluid BEC**

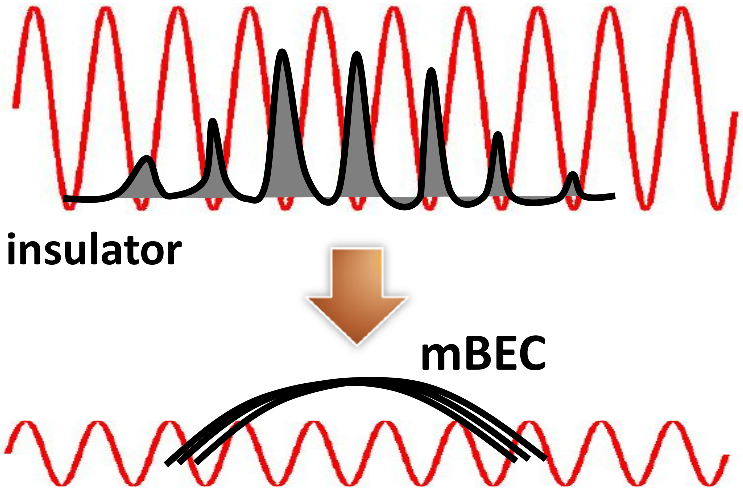
to a localized

Mott-insulator state

Proposal: P. Zoller et al., 1998

This should also work the other way round!!!

molecular Mott insulator



mBEC

Reduction of lattice depth:

Phase transition

from a localized

Mott-insulator state

of molecules

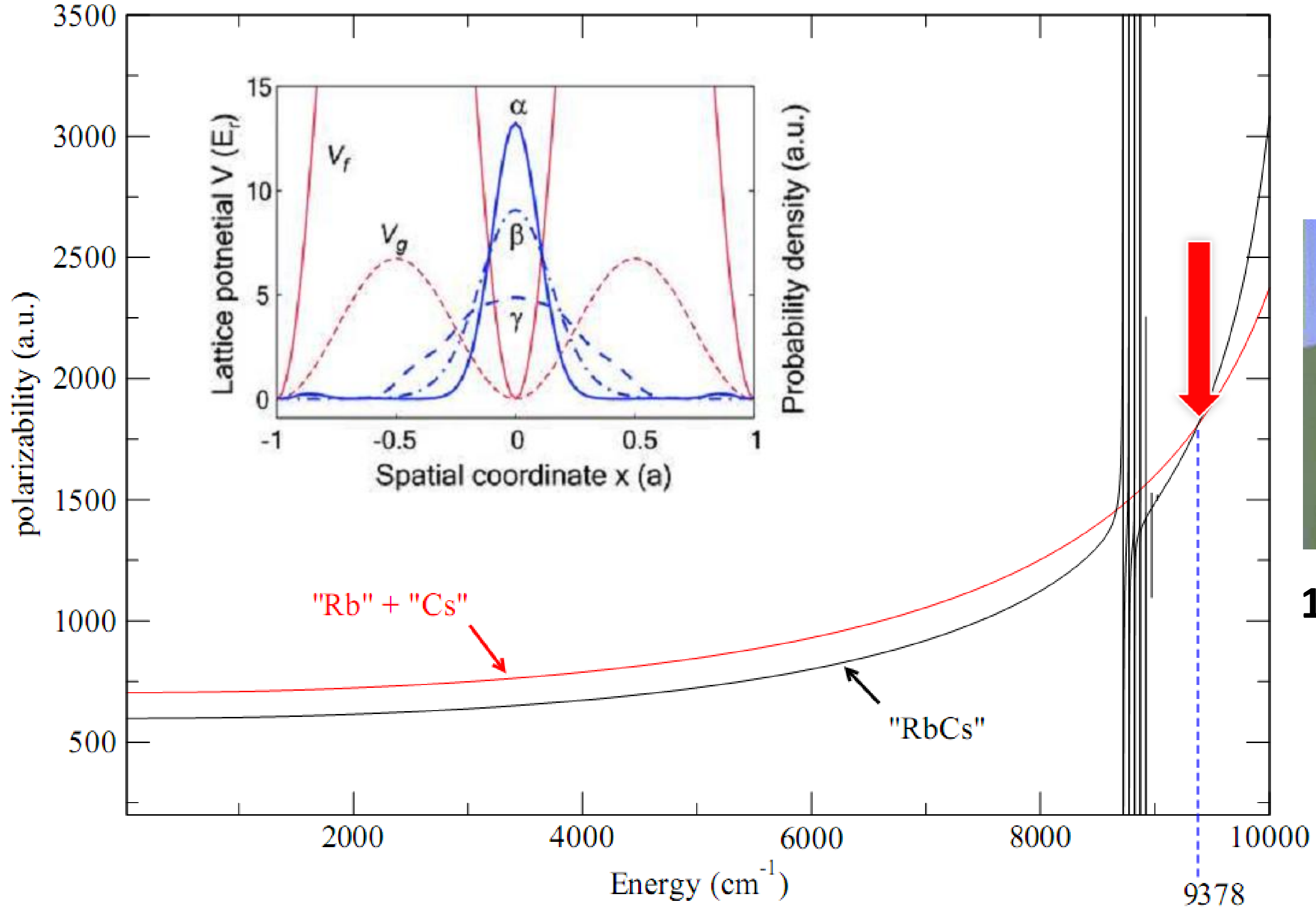
to a **molecular**

BEC („**mBEC**“)

Proposal: P. Zoller et al., 2002

Ground state transfer

Romain Vexieu, Nadia Bouloufa, Oliver Dulieu



magic wavelength

Luck!!

1/1064nm = 9398 cm^{-1}

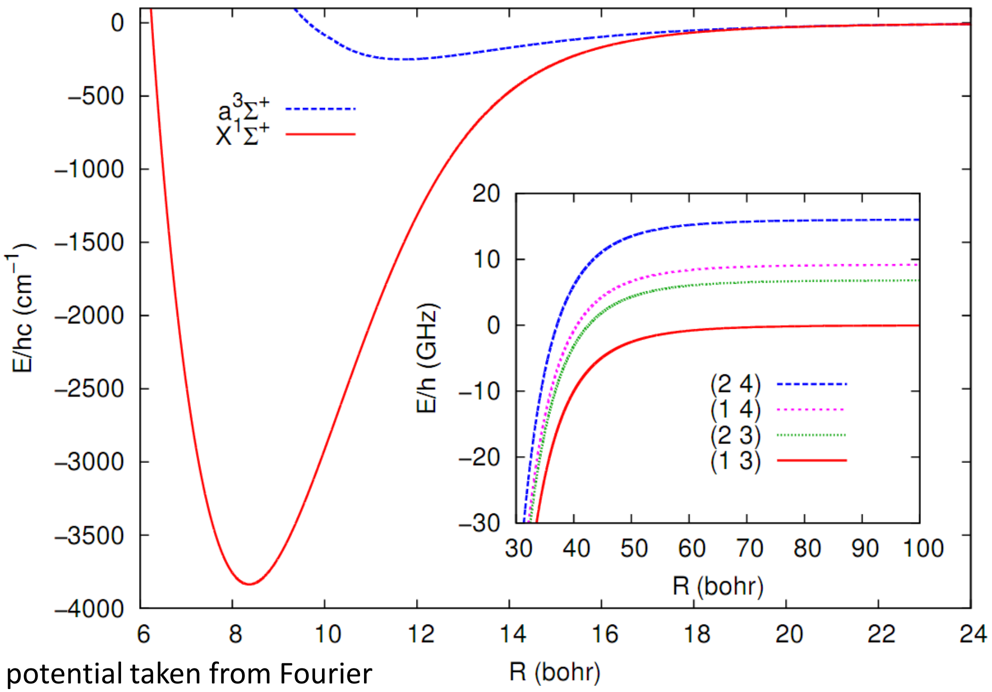
Coupled channel model

$$V_S^{\mathrm{SR}}(R) = A_S + B_S[R_S^{\mathrm{SR}}/a_0]^N$$

$$N = -7.31737405186660705$$

$$V_S(R) = \sum_{i=0}^{n} a_i \xi^i(R) \qquad \xi(R) = \frac{R - R_\mathrm{m}}{R + bR_\mathrm{m}}$$

$$V_S^{\mathrm{LR}}(R) = -C_6/R^6 - C_8/R^8 - C_{10}/R^{10} \pm V_\mathrm{exch}(R)$$



C. Ruth LeSueur, Jeremy M. Hutson (Durham)
Paul S. Julienne (JQI, NIST, UMD)
Svetlana Kotochigova (Temple)
Eberhard Tiemann (Hannover)

Initial medium range potential taken from Fourier transform spectroscopy study (Riga)
O. Docenko *et al*., PRA **83**, 052519 (2011).
level energies accurate to ~ 1GHz x h

Short range

spin-spin and 2nd order spin-orbit (avoided crossing strengths)

Long range

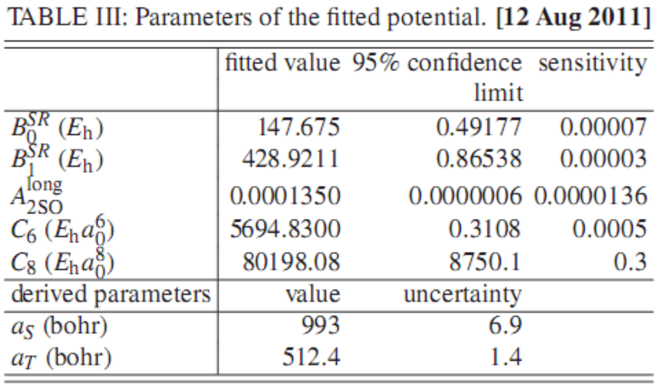


TABLE III: Parameters of the fitted potential. **[12 Aug 2011]**

	fitted value	95% confidence limit	sensitivity
B_0^{SR} (E_h)	147.675	0.49177	0.00007
B_1^{SR} (E_h)	428.9211	0.86538	0.00003
$A_{2\mathrm{SO}}^{\mathrm{long}}$	0.0001350	0.0000006	0.0000136
C_6 ($E_\mathrm{h}a_0^6$)	5694.8300	0.3108	0.0005
C_8 ($E_\mathrm{h}a_0^8$)	80198.08	8750.1	0.3
derived parameters	value	uncertainty	
a_S (bohr)	993	6.9	
a_T (bohr)	512.4	1.4	

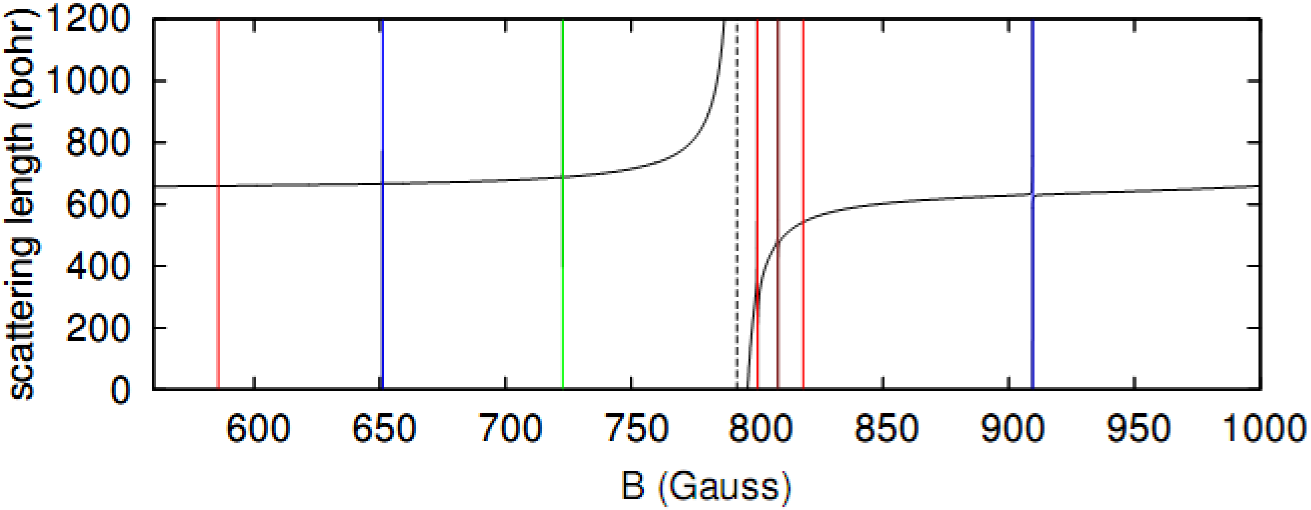
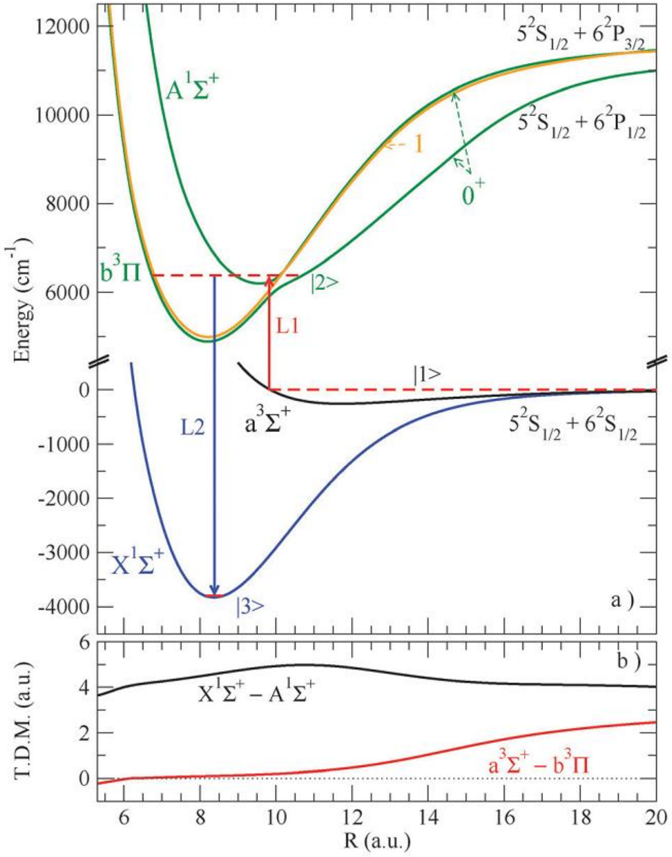
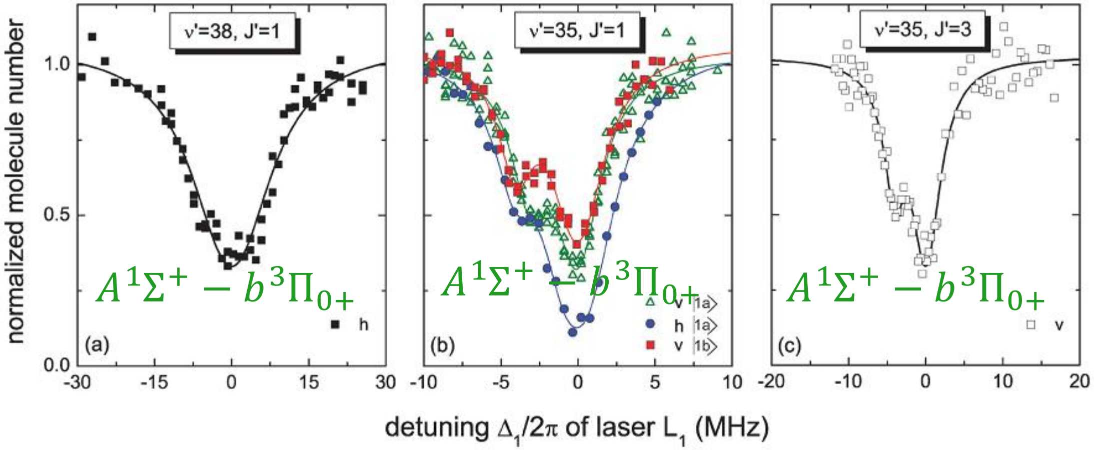


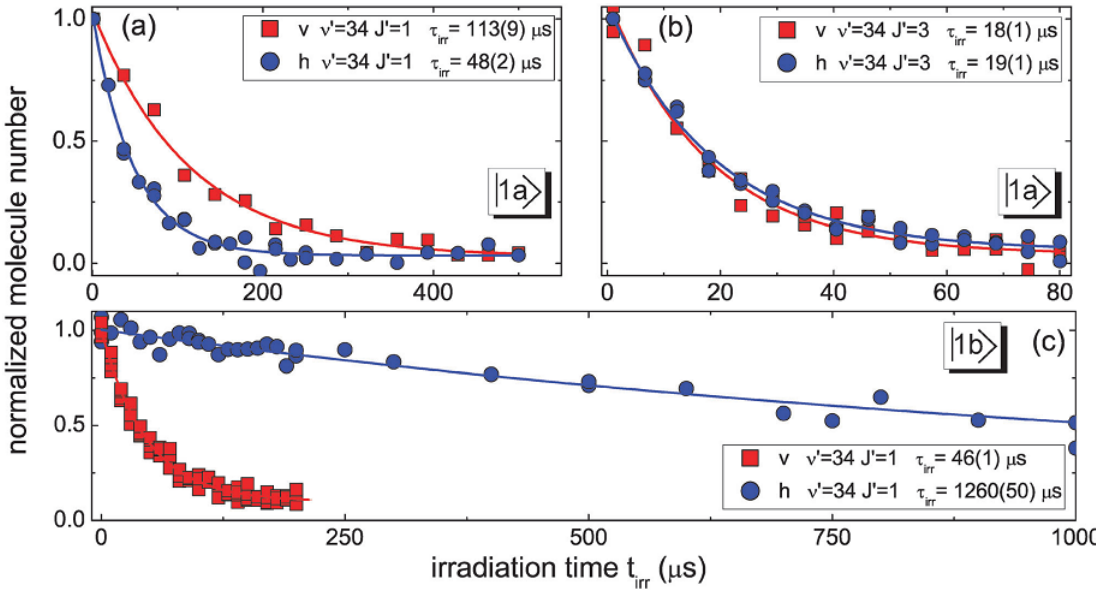
FIG. 10: [Color online.] RbCs scattering length at the $|1,1\rangle + |3,3\rangle$ threshold at fields above 560 G, calculated using the final fitted potential at $E = 160$ nK. Resonance positions are marked by vertical lines, with the value of M_F of the corresponding bound state indicated using the same color scheme as in Fig. 7.

Ground state transfer





broader than expected from calculations (Vexieau, Bouloufa, Dulieu)



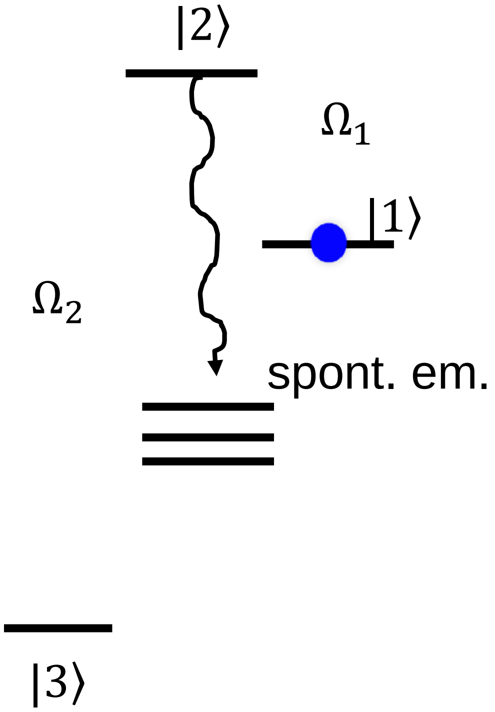
$$\Omega_1 = (\Gamma/\tau_{\mathrm{irr}})^{1/2}$$

$$= \vec{\mu}\cdot\vec{E}/\hbar$$

Ground state transfer

Ground state spectroscopy:

$$H(t) = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 0 & \Omega_2 \\ 0 & \Omega_2 & 0 \end{bmatrix}$$



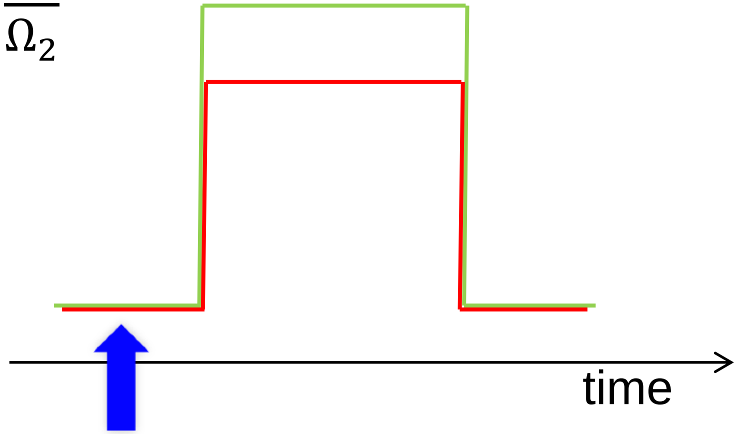
Eigenstates with light on:

$$|a^+\rangle = \sin\Theta\,\sin\Phi|1\rangle + \cos\Phi|2\rangle + \cos\Theta\,\sin\Phi|3\rangle$$

$$|a^0\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle$$

$$|a^-\rangle = \sin\Theta\,\cos\Phi|1\rangle - \sin\Phi|2\rangle + \cos\Theta\,\cos\Phi|3\rangle$$

$$tan\Theta = \frac{\Omega_1}{\Omega_2}$$

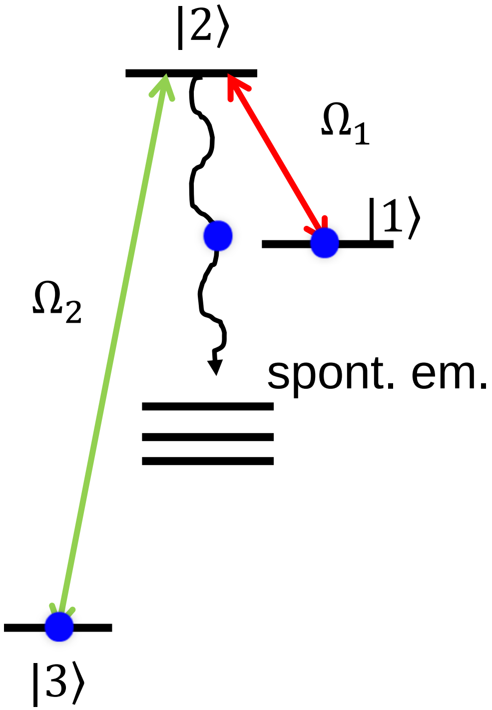


K. Bergmann, H. Theuer, and B.W. Shore: Rev. Mod. Phys. 70, 1003 (1998)

Ground state transfer

Ground state spectroscopy:

$$H(t) = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 0 & \Omega_2 \\ 0 & \Omega_2 & 0 \end{bmatrix}$$



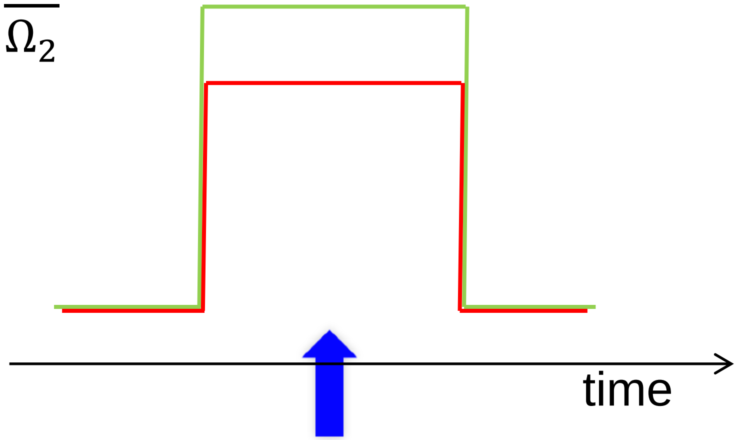
Eigenstates with light on:

$$|a^{+}\rangle = \sin\Theta\ \sin\Phi|1\rangle + \cos\Phi|2\rangle + \cos\Theta\ \sin\Phi|3\rangle$$

$$|a^{0}\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle$$

$$|a^{-}\rangle = \sin\Theta\ \cos\Phi|1\rangle - \sin\Phi|2\rangle + \cos\Theta\ \cos\Phi|3\rangle$$

$$tan\Theta = \frac{\Omega_1}{\Omega_2}$$



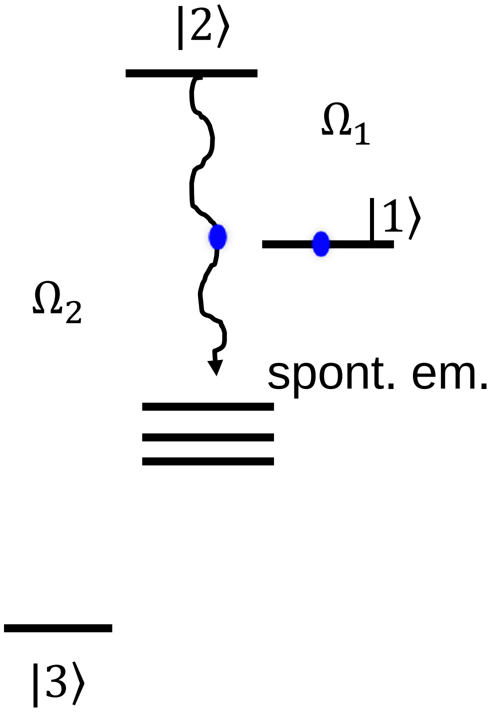
projection $cos\Theta$ onto dark state

K. Bergmann, H. Theuer, and B.W. Shore: Rev. Mod. Phys. 70, 1003 (1998)

Ground state transfer

Ground state spectroscopy:

$$H(t) = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 0 & \Omega_2 \\ 0 & \Omega_2 & 0 \end{bmatrix}$$



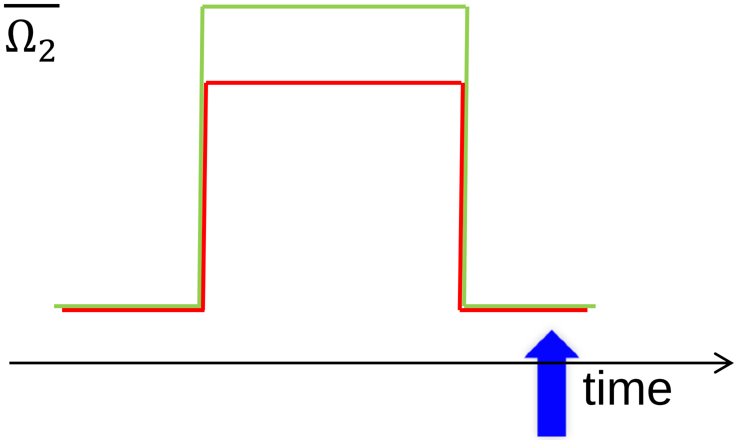
Eigenstates with light on:

$$|a^+\rangle = \sin\Theta\ \sin\Phi|1\rangle + \cos\Phi|2\rangle + \cos\Theta\ \sin\Phi|3\rangle$$

$$|a^0\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle$$

$$|a^-\rangle = \sin\Theta\ \cos\Phi|1\rangle - \sin\Phi|2\rangle + \cos\Theta\ \cos\Phi|3\rangle$$

$$tan\Theta = \frac{\Omega_1}{\Omega_2}$$



projection $cos\Theta$ onto $|1>$

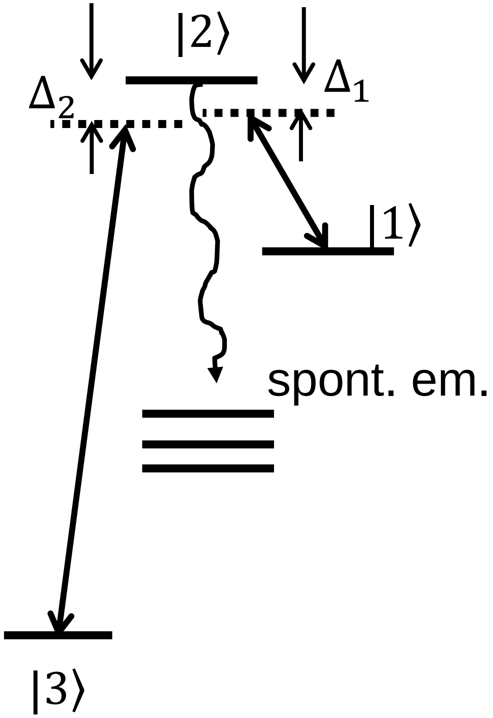
$$P_{1\to a^0\to 1} = P_{1\to a^0}P_{a^0\to 1} = \cos^4\Theta = \frac{\Omega_1^4}{(\Omega_1^2+\Omega_2^2)^2}$$

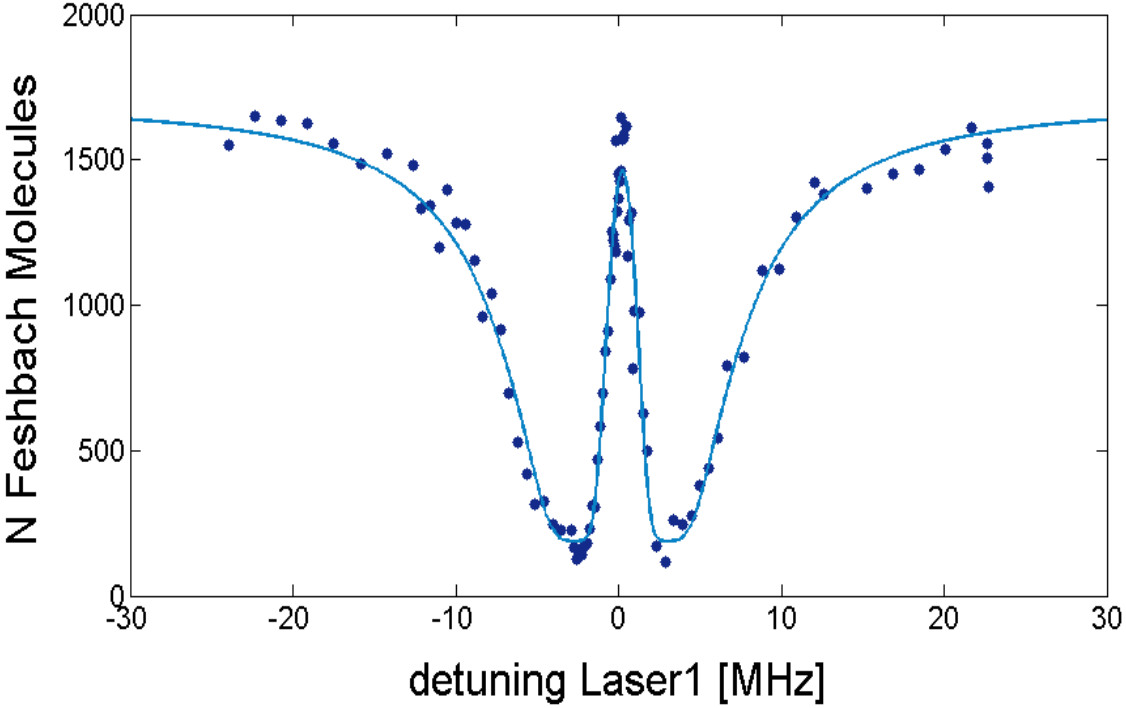
K. Bergmann, H. Theuer, and B.W. Shore: Rev. Mod. Phys. 70, 1003 (1998)

Ground state transfer

Ground state spectroscopy:

$$H(t) = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 2\Delta_1 & \Omega_2 \\ 0 & \Omega_2 & 2(\Delta_1 - \Delta_2) \end{bmatrix}$$

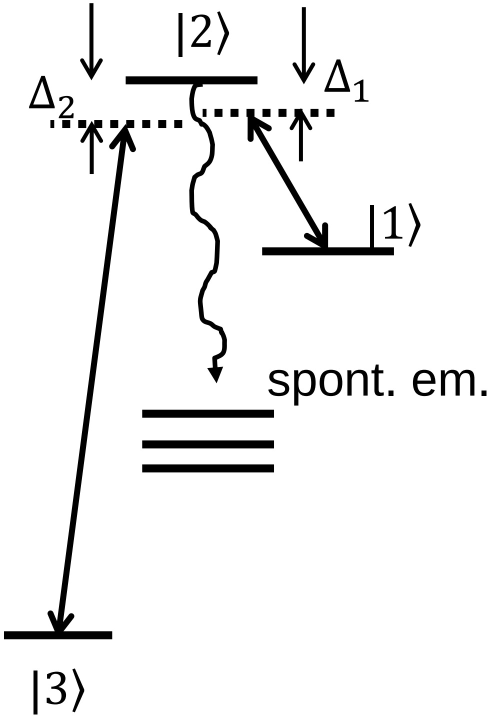


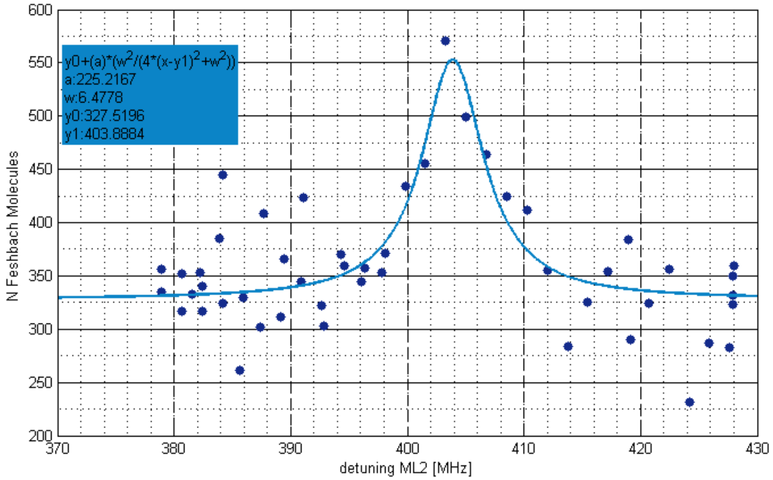


Ground state transfer

Ground state spectroscopy:

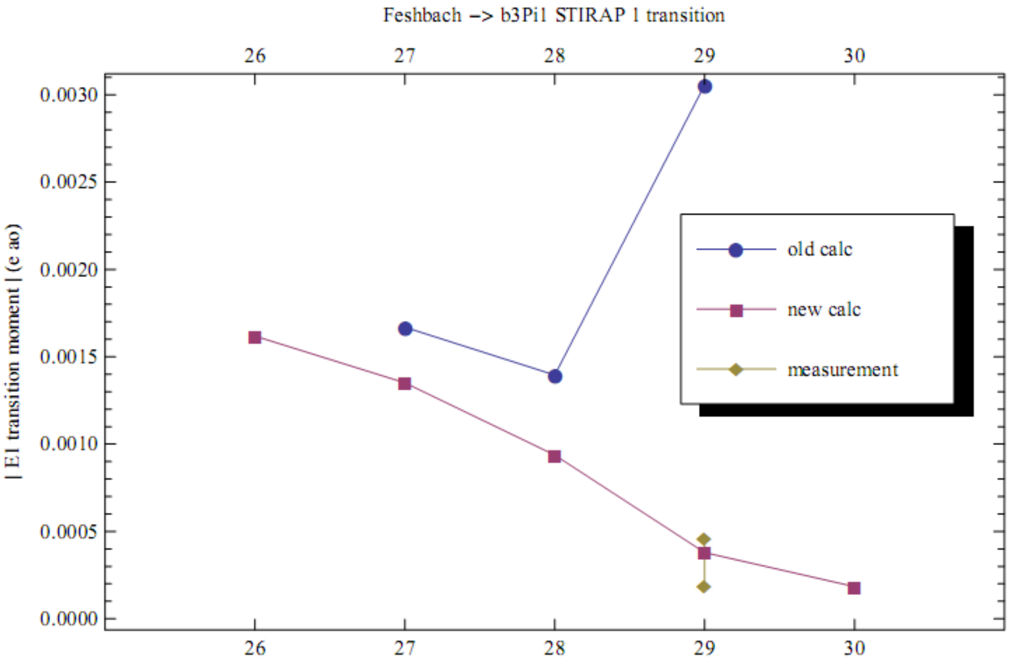
$$H(t) = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_1 & 0 \\ \Omega_1 & 2\Delta_1 & \Omega_2 \\ 0 & \Omega_2 & 2(\Delta_1 - \Delta_2) \end{bmatrix}$$



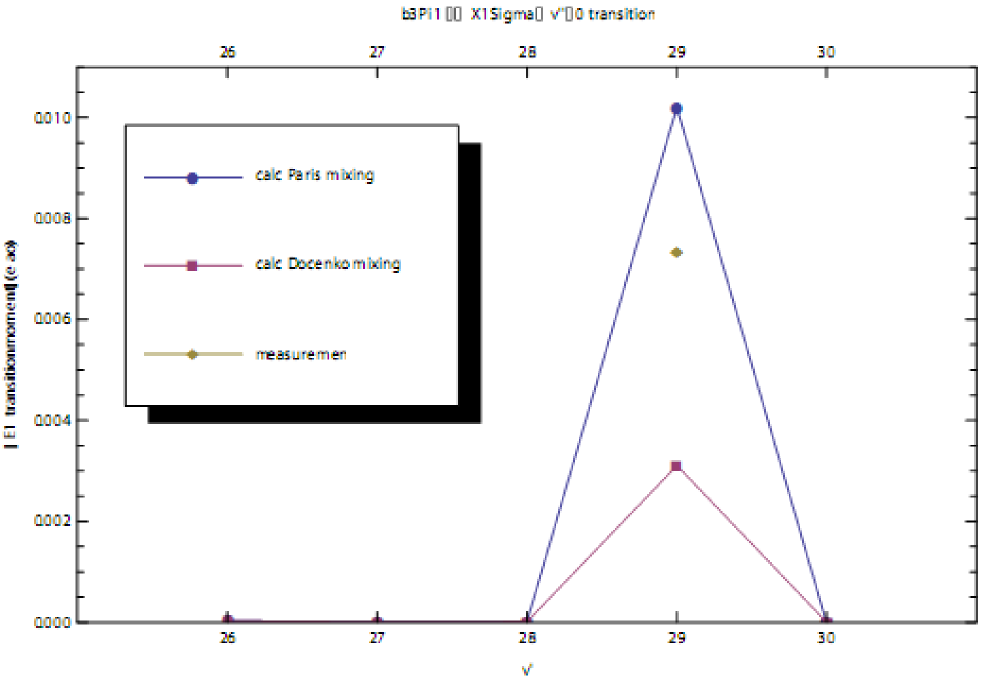


- Have mapped out ground state v=0 N=0,2.
- Rotational constants agree very well with Fourier transform spectroscopy experiments

iso	J	N	s	n	Trm(cm-1)	<R>(Ang)	Fr(A)	Fr(b0)	Fr(b1)	Fr(b2)	(cm-1)
2	1	52	2	27	10019.87	4.69195	0.23704	0.76296	0	0	6208.30
2	1	53	3	24	10023.59	4.51642	0	0	1	0	6212.01
2	1	54	2	28	10057.53	4.73666	0.29303	0.70697	0	0	6245.95
2	1	55	1	0	10060.47	5.04516	0.89831	0.10169	0	0	6248.89
2	1	56	3	25	10070.94	4.525	0	0	1	0	6259.36
2	1	57	2	29	10094.18	4.76101	0.31243	0.68757	0	0	6282.60
2	1	58	1	1	10108.55	5.0381	0.88108	0.11892	0	0	6296.98
2	1	59	3	26	10118.18	4.53366	0	0	1	0	6306.60
2	1	60	2	30	10130.05	4.78599	0.33485	0.66515	0	0	6318.47
2	1	61	1	2	10157.9	5.03051	0.85921	0.14079	0	0	6346.32
2	1	62	3	27	10165.3	4.54241	0.00001	0.00001	0.99998	0	6353.72
2	1	63	2	31	10165.42	4.80475	0.34841	0.65157	0.00001	0	6353.84
2	1	64	2	32	10200.1	4.84594	0.40076	0.59924	0	0	6388.52
2	1	65	1	3	10208.36	5.00023	0.79685	0.20315	0	0	6396.78
2	1	66	3	28	10212.3	4.55122	0	0	1	0	6400.73
2	1	67	2	33	10234.73	4.85737	0.39963	0.60037	0	0	6423.16
2	1	68	1	4	10259.03	4.99905	0.78569	0.21395	0.00036	0	6447.45
2	1	69	3	29	10259.19	4.56026	0.00029	0.00007	0.99964	0	6447.62
2	1	70	2	34	10269.07	4.87554	0.41192	0.58808	0	0	6457.50
2	1	71	2	35	10303.22	4.89033	0.41885	0.58115	0	0	6491.65
2	1	72	3	30	10305.96	4.56905	0	0	1	0	6494.39
2	1	73	1	5	10309.96	4.99505	0.76648	0.23352	0	0	6498.38
2	1	74	2	36	10337.24	4.91178	0.43766	0.56234	0	0	6525.67
2	1	75	3	31	10352.62	4.57806	0	0	1	0	6541.04
2	1	76	1	6	10360.75	4.97269	0.70972	0.29028	0	0	6549.18
2	1	77	2	37	10371.33	4.94569	0.48286	0.51714	0	0	6559.76
2	1	78	3	32	10399.15	4.58713	0	0	1	0	6587.58
2	1	79	2	38	10404.19	4.90554	0.4046	0.5954	0	0	6592.62
2	1	80	1	7	10412.55	5.02509	0.77545	0.22455	0	0	6600.97

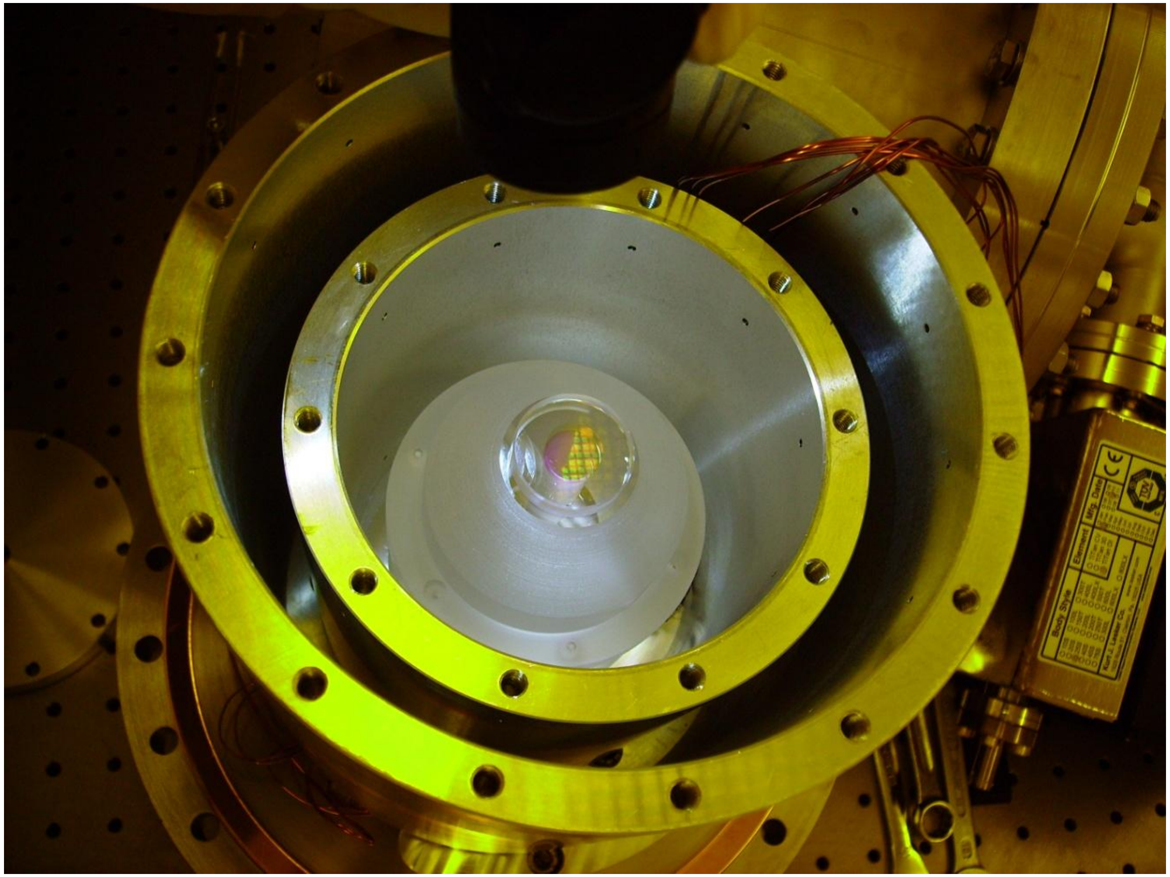


Feshbach –> b3Pi1 STIRAP 1 transition



b3Pi1 □□ X1Sigma□ v''□0 transition

Supercavities!



- sub-Hz laser stabilities possible (cavities themselves are the reference)
- limited by acoustics
- finesse ~200000
- narrow linewidth diode lasers also being built