Towards ultracold ground state RbCs molecules

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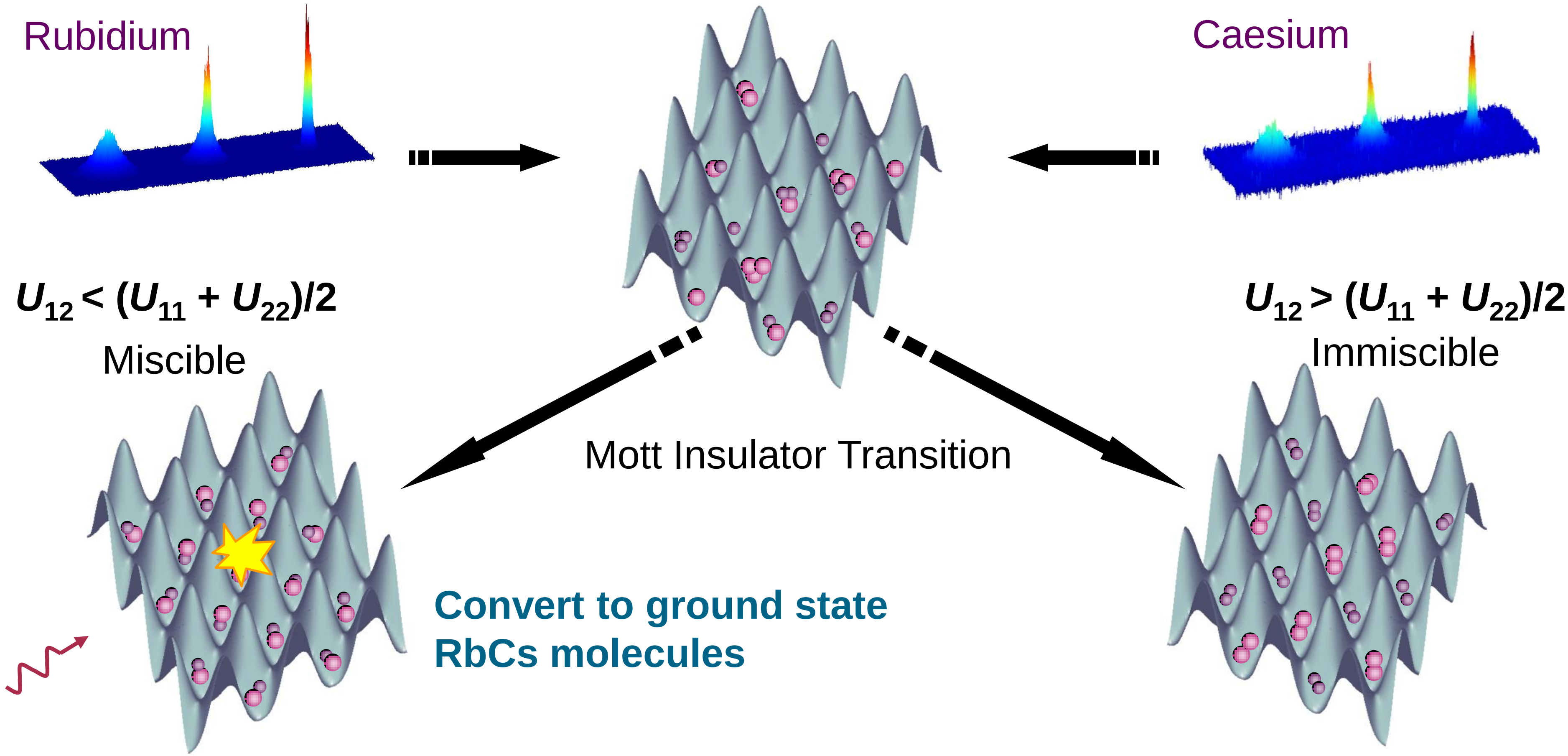
Goal: A quantum array of polar molecules



RbCs: Stable against reactive collisions
d = 1.25 D, B_{rot} = 0.5 GHz
Induced $d_{eff} = d/3$ for E = B_{rot}/d = 0.8 kV / cm

Jaksch *et al.*, PRL **89**, 040402 (2002)
Damski *et al.* PRL **90**, 110401 (2003)

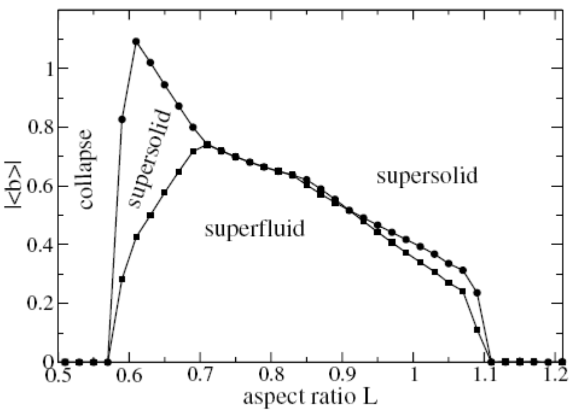
A Bosonic Dipolar Quantum Gas

$$V_{\text{int}} = d_{\text{eff}}^2 \frac{1-3\cos^2\theta}{|\vec{r}-\vec{r}\,'|^3} + \frac{4\pi\hbar^2 a}{M}\delta(\vec{r}-\vec{r}\,')$$

Dipole-dipole interaction

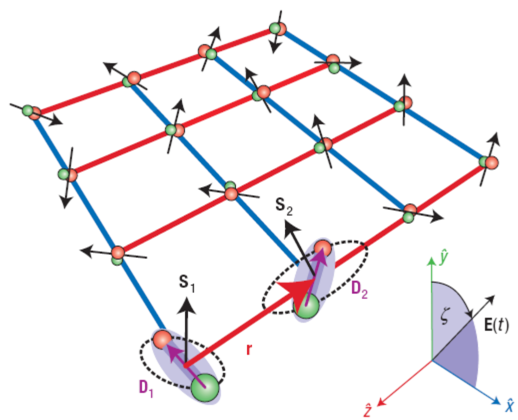
Contact interaction

Novel quantum phases:



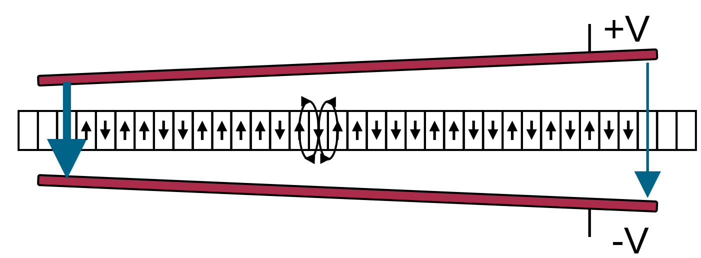
Góral, PRL **88**, 170406 (2002)

Lattice spin models:



Micheli, Nat. Phys. **2**, 341 (2006)

Quantum computation:

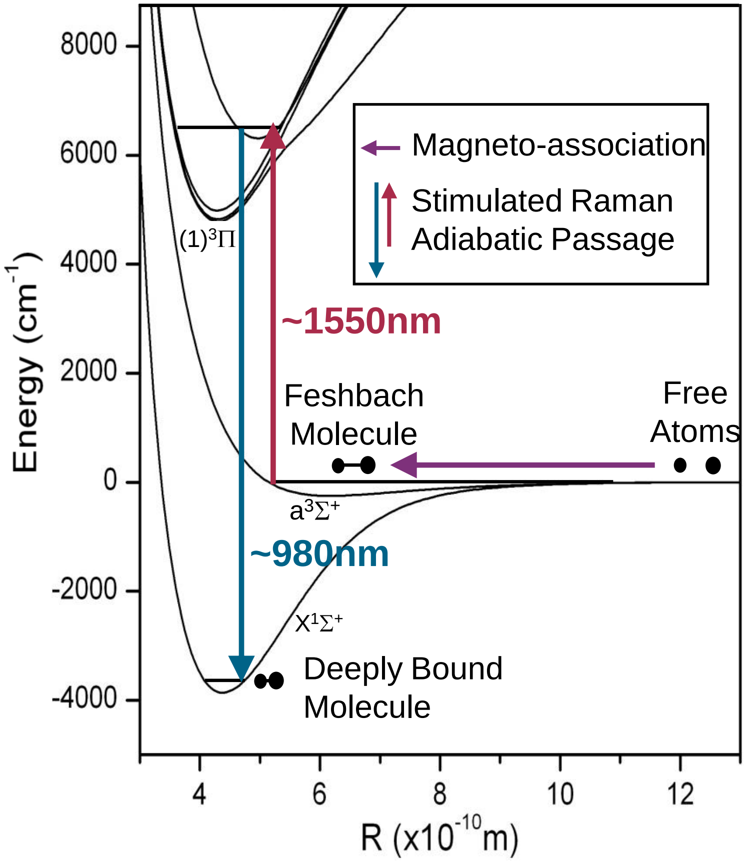


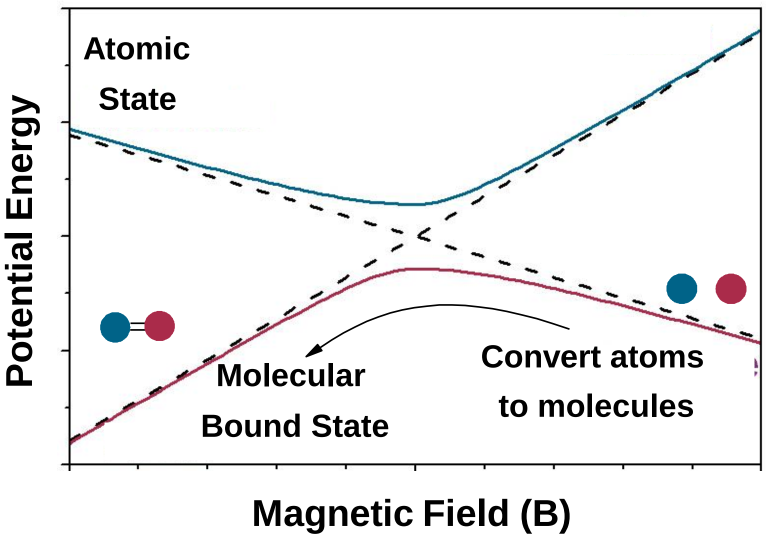
DeMille, PRL **88**, 067901 (2002)

Ultracold chemistry & Precision measurement.

How to produce heteronuclear molecules

1. Create a high phase space density atomic mixture.
2. Associate weakly-bound molecules via an interspecies Feshbach resonance.





3. Transfer Feshbach molecules to the rovibrational ground state using stimulated Raman adiabatic passage (STIRAP).

Cs_2 : J. G. Danzl *et al.*, Science, **321**, 5892, (2008).

Rb_2 : F. Lang *et al.,* PRL, **101**, 133005 (2008).

^{40}K-^{87}Rb : K.-K. Ni *et al.*, Science, **322**, 5899, (2008).

Outline

❶ The Rb Cs experiment

❷ Two species BEC: Immiscibility

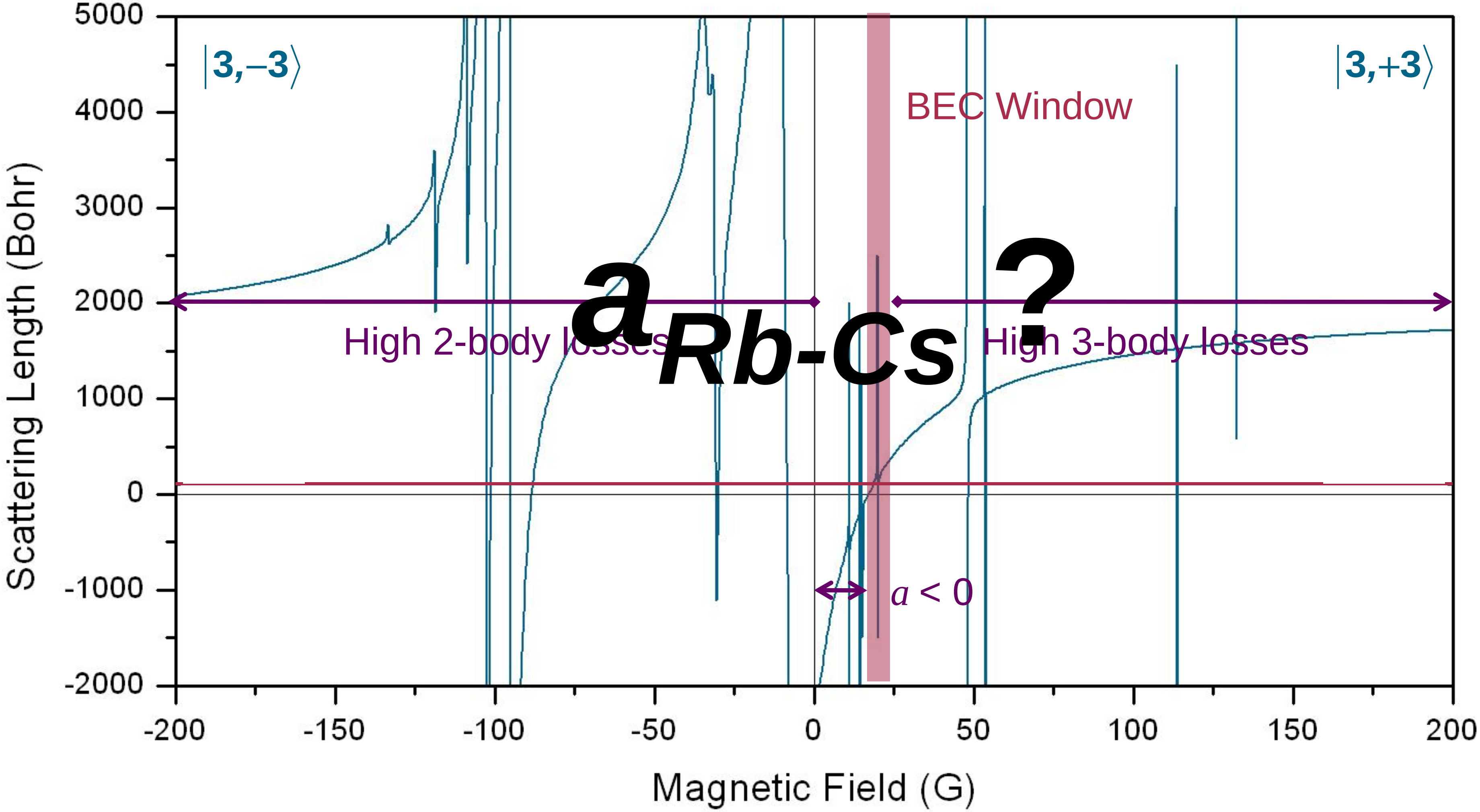
❸ Feshbach spectroscopy of Rb-Cs mixtures

❹ Creation of Cs_2 and RbCs Feshbach molecules

❺ Progress towards ground state molecules.

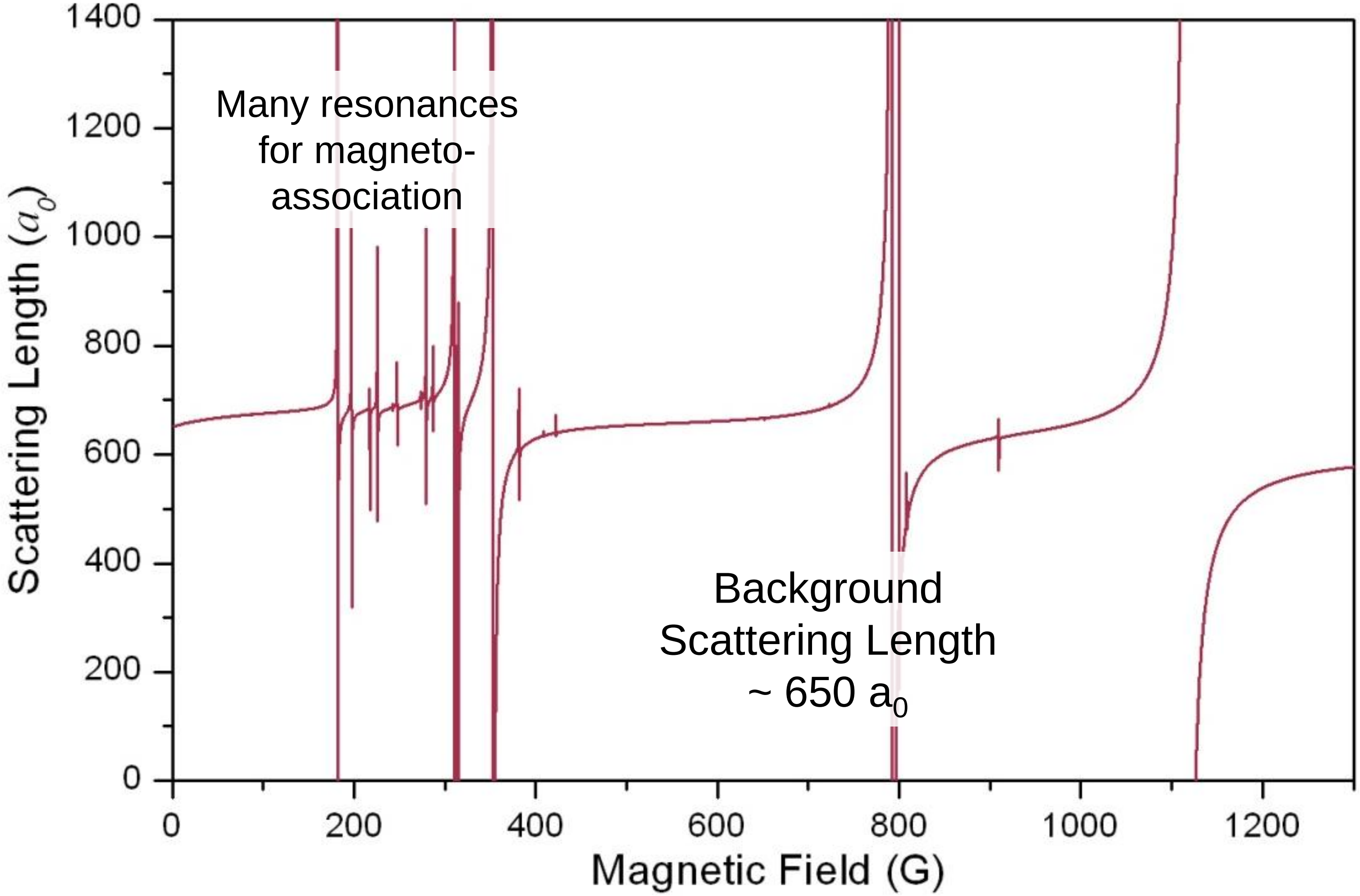
❻ Next generation experiment: YbCs

Rb and Cs scattering lengths



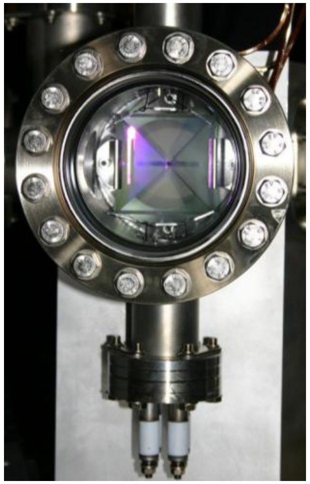
Rb-Cs scattering length

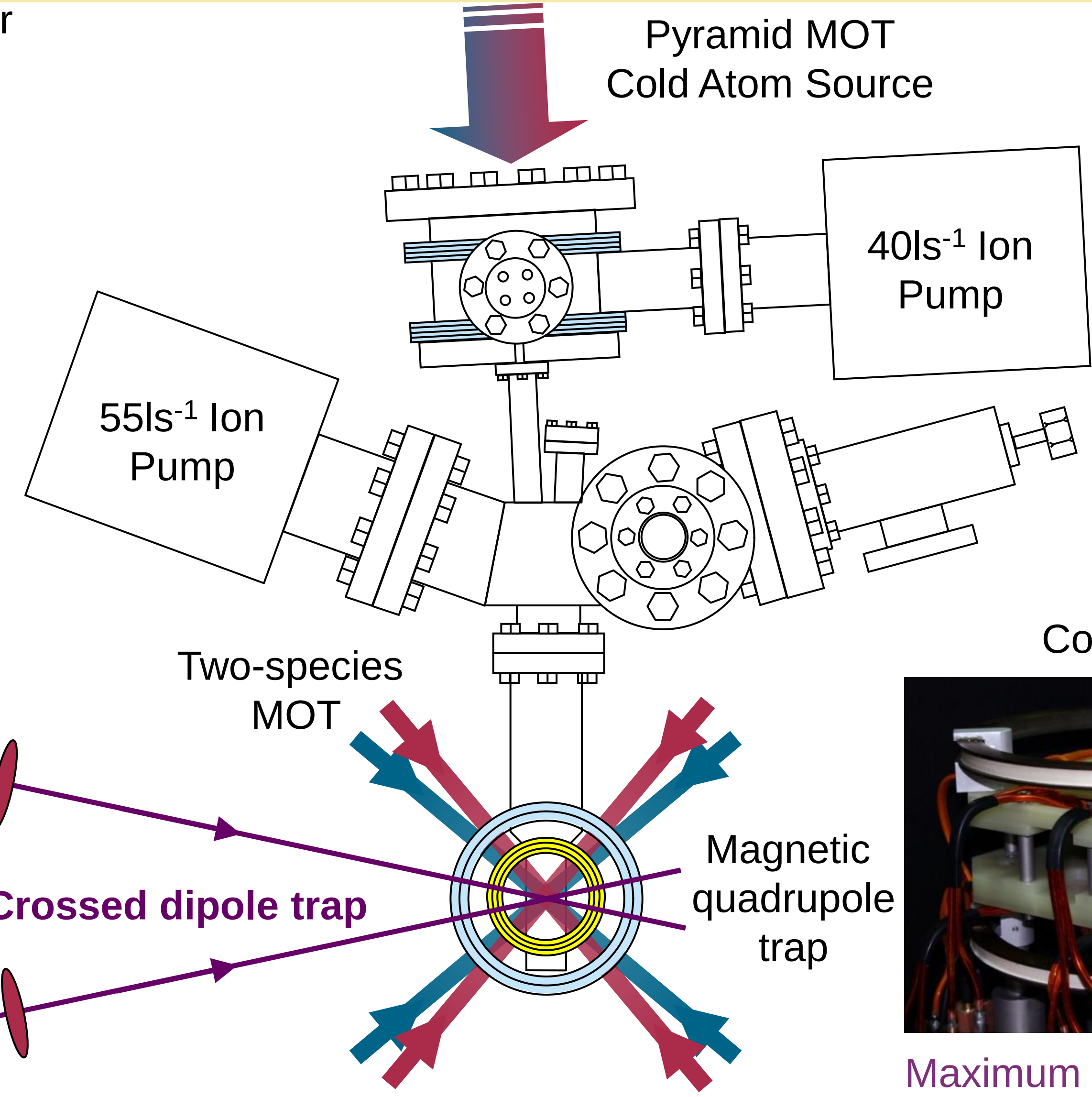
T. Takekoshi *et al.*, PRA **85**, 032506 (2012)
K. Pilch *et al.*, PRA **79**, 042718 (2009)



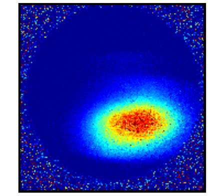
The Rb-Cs apparatus

Pyramid Chamber

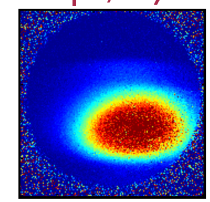




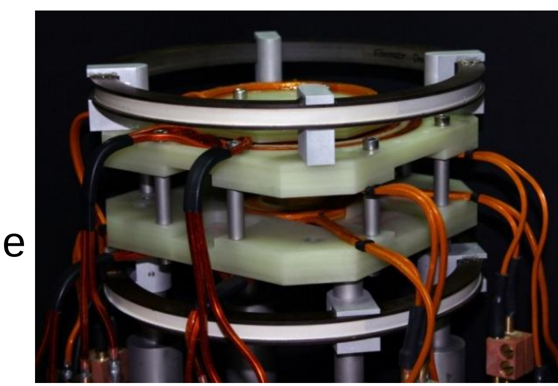
Cs 3x10^{8}
$|3,-3\rangle$



Rb 6x10^{8}
$|1,-1\rangle$



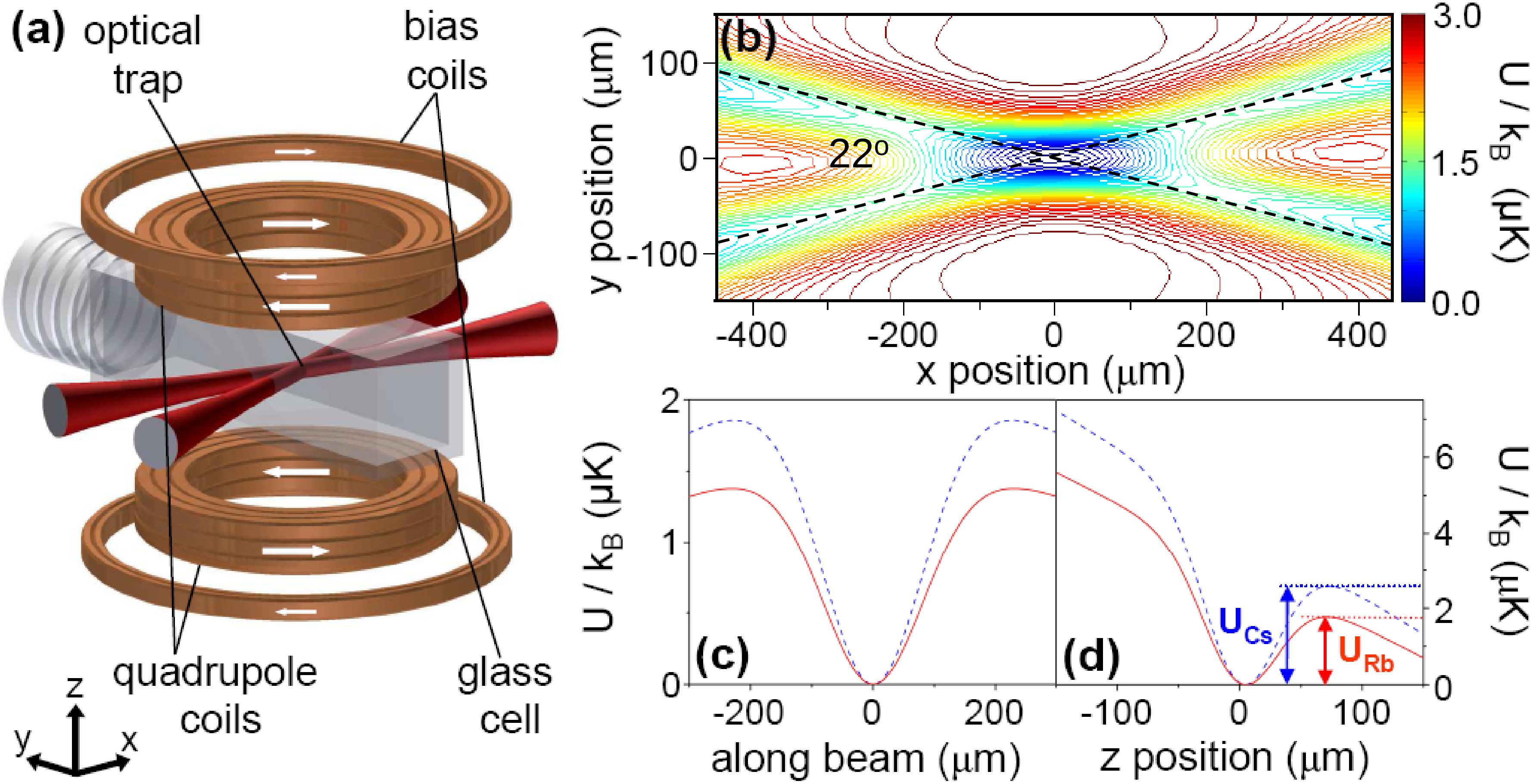
Coil Assembly



Maximum Bias Field **> 1150G**

Levitated crossed dipole trap

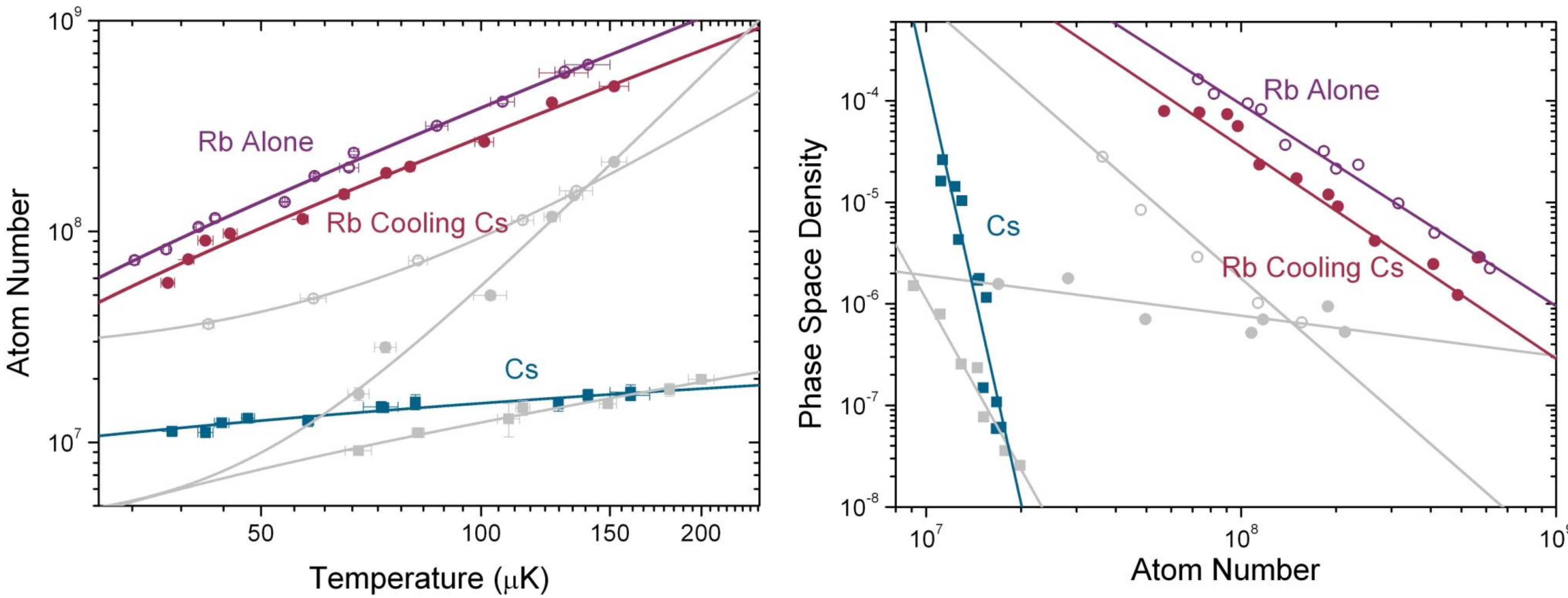
P_0 = 6 W per beam, U_{Rb} = 90 μK, U_{Cs} = 125 μK initially.



Sympathetic cooling in quadrupole trap

Pre-cool the gas before loading dipole trap.

RF Evaporation: Cs trap depth = 3 x Rb trap depth



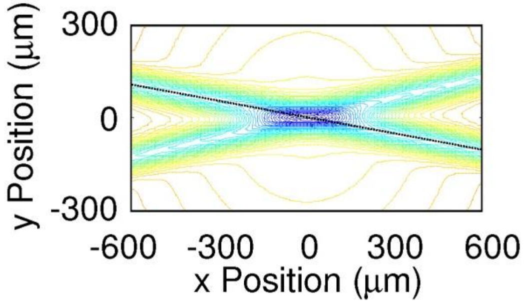
To load dipole trap: simply ramp down quadrupole gradient to ~30 G/cm!

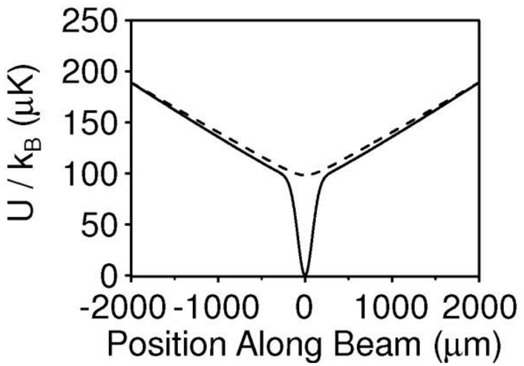
Lin *et al.*, PRA **79**, 063631 (2009)

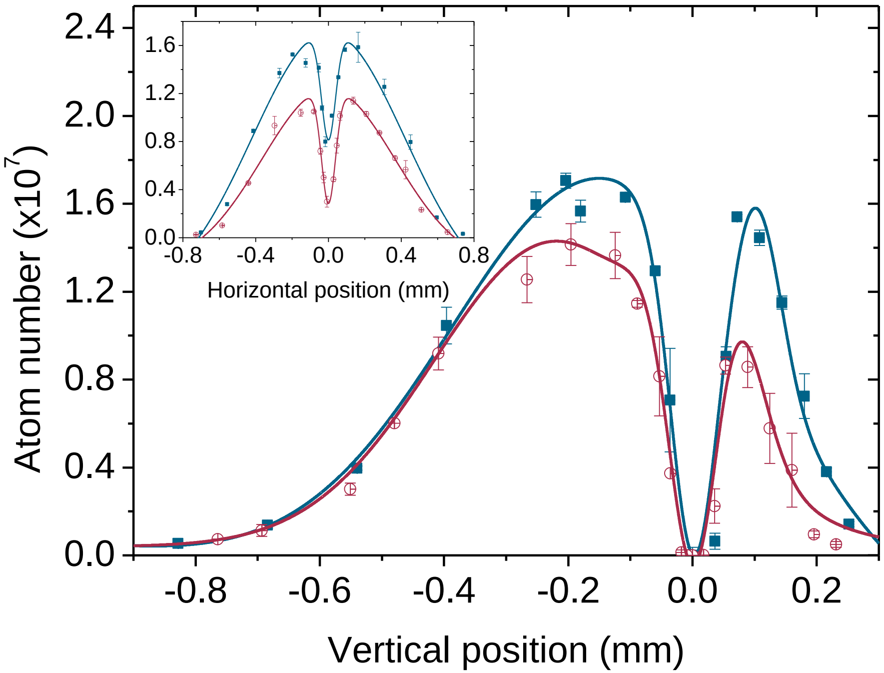
Aligning the dipole trap

At this stage magnetic potential confines atoms along beams.

Hence: single beam forms a trap for magnetically trappable m_F states!







$$\omega_{ax} = \frac{1}{2}\left(\frac{\mu B'_z}{m z_0}\right)^{1/2} \sim 25 \text{ Hz}$$

$$B_0 = B'_z z_0 \sim 0.3 \text{ G}$$

Align each beam w.r.t. quadrupole zero

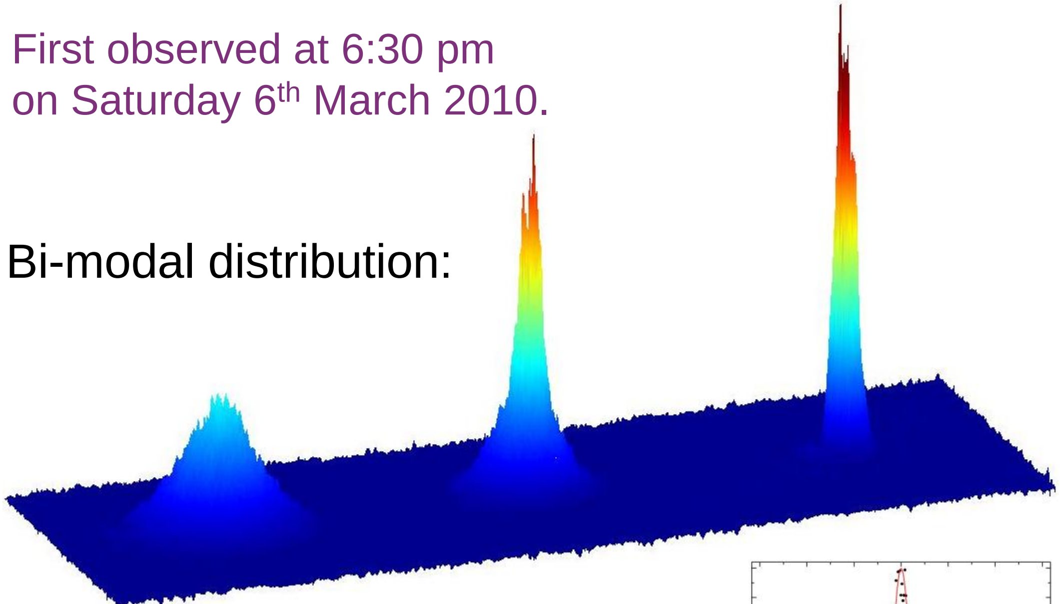
Bose-Einstein Condensation – ^{87}Rb

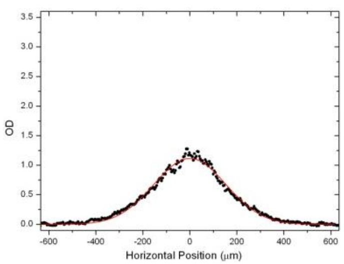
BEC of ^{87}Rb |1,-1⟩ in single beam dipole trap.

c.f. Lin *et al*., PRA **79**, 063631 (2009)

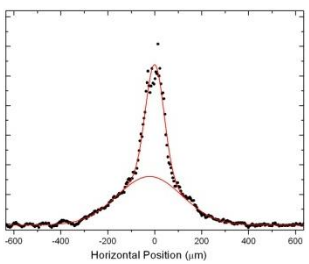
First observed at 6:30 pm
on Saturday 6th March 2010.

Bi-modal distribution:

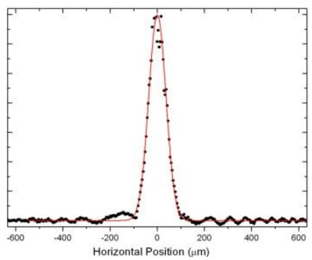




T = 0.57 μK
N ~ 1 x 10^6

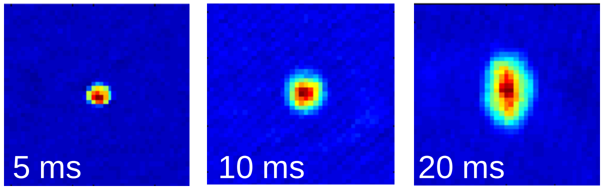


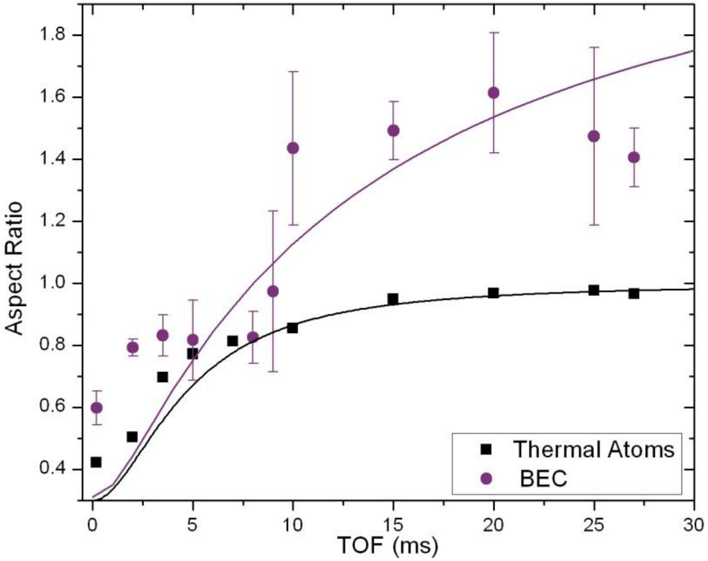
T = 0.50 μK
BEC Fraction ≈ 30 %

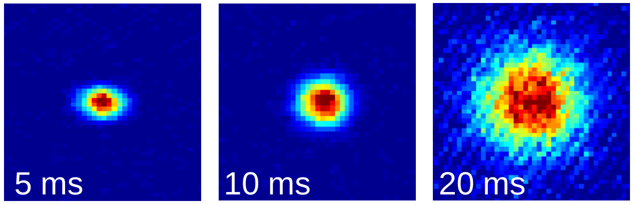


Trap Depth = 2.8 μK
N ~ 2 x 10^5

Anisotropic expansion:

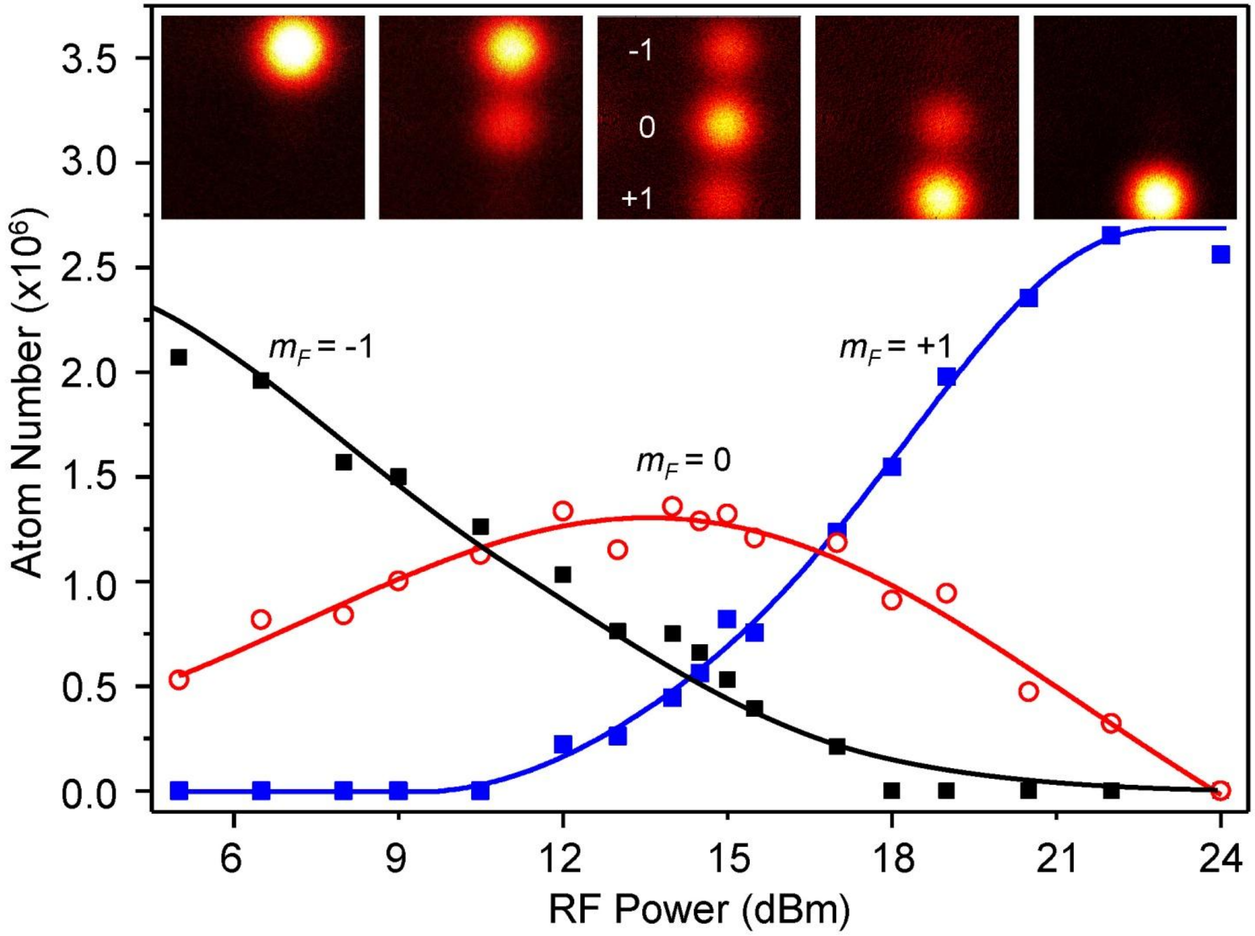






Need to flip the spin to work with Cs

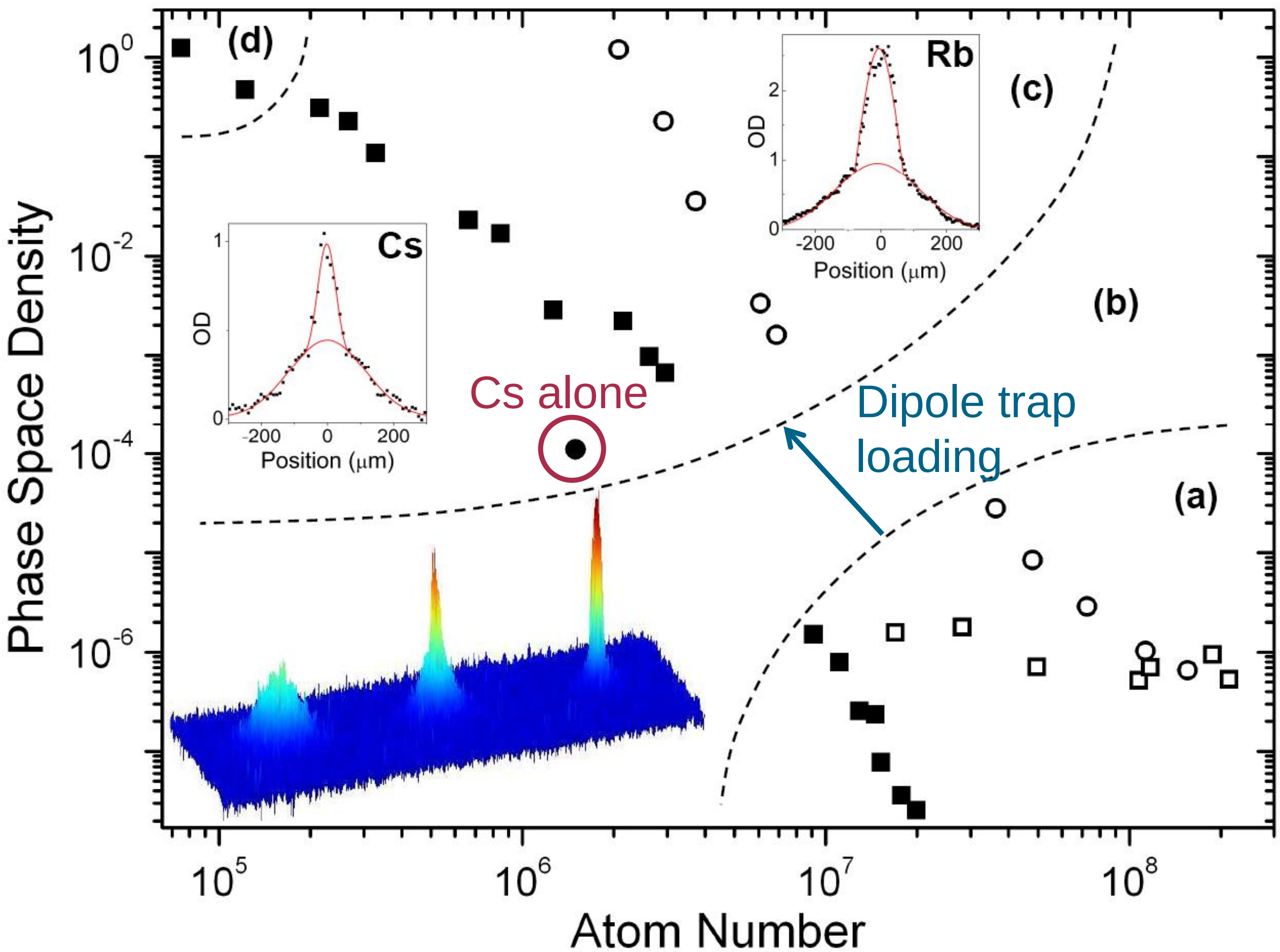
Apply RF at 1.2MHz. Switch on 22G bias field in 18ms.



Transfer efficiency ~ 96%

Jenkin *et al*., Eur. Phys. J. D (DOI: 10.1140/epjd/e2011-10720-5)

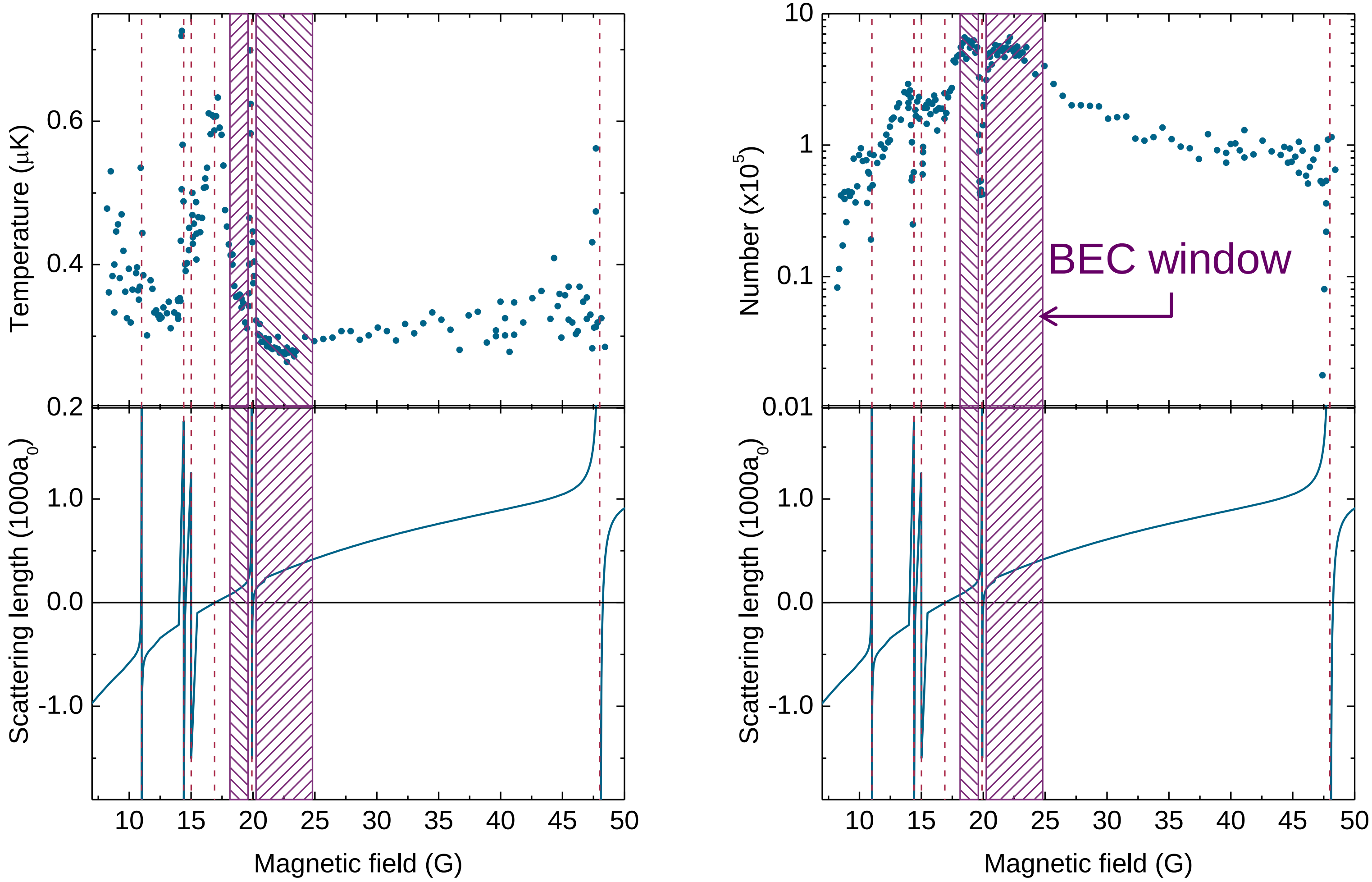
Evaporate Cs to BEC



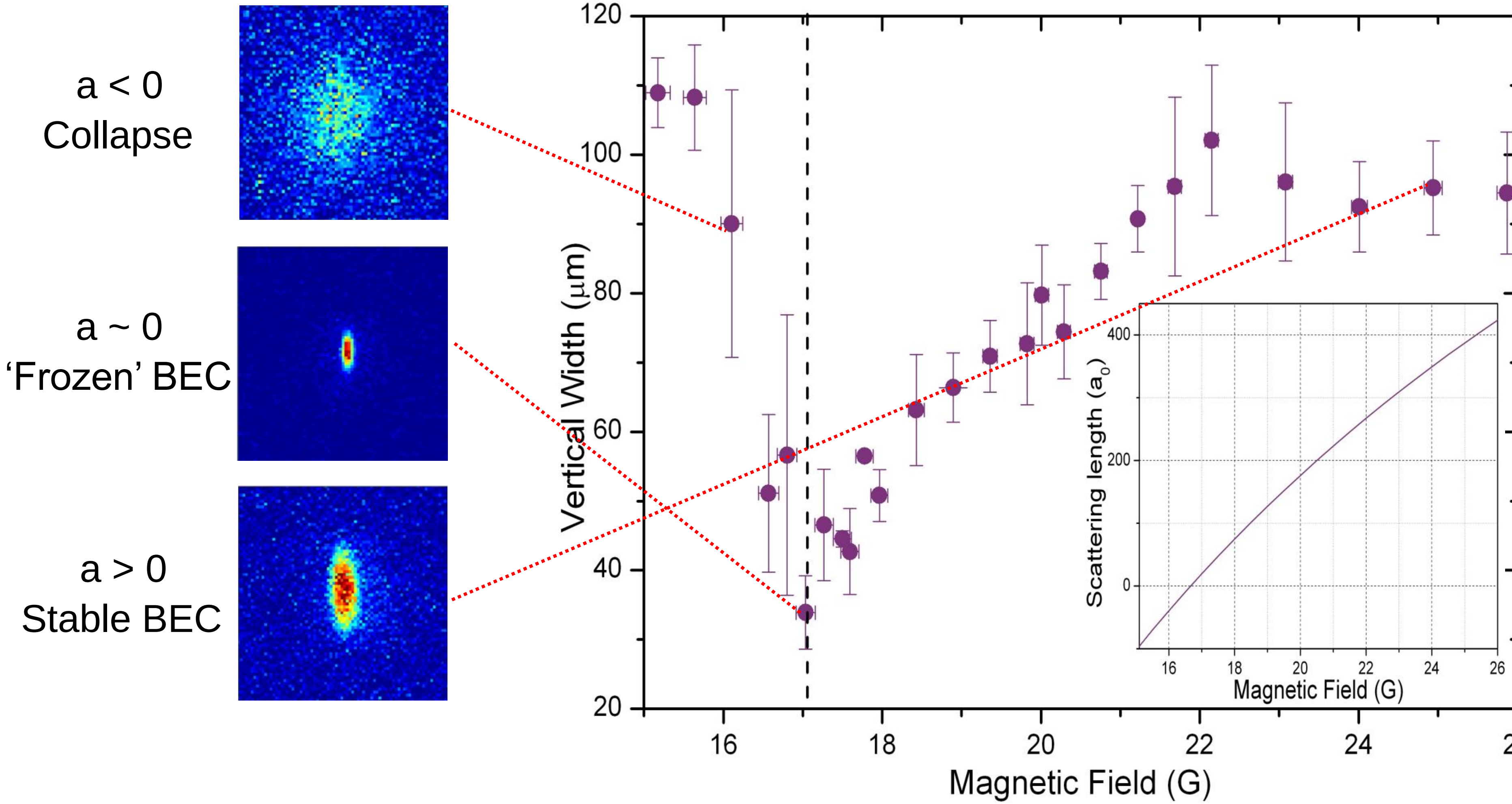
McCarron *et al*., Phys. Rev. A 84 011603 (2011)

Cs Feshbach resonances (6 – 50 G)

Optimising the magnetic field:



Cs BEC - Tunable Interactions

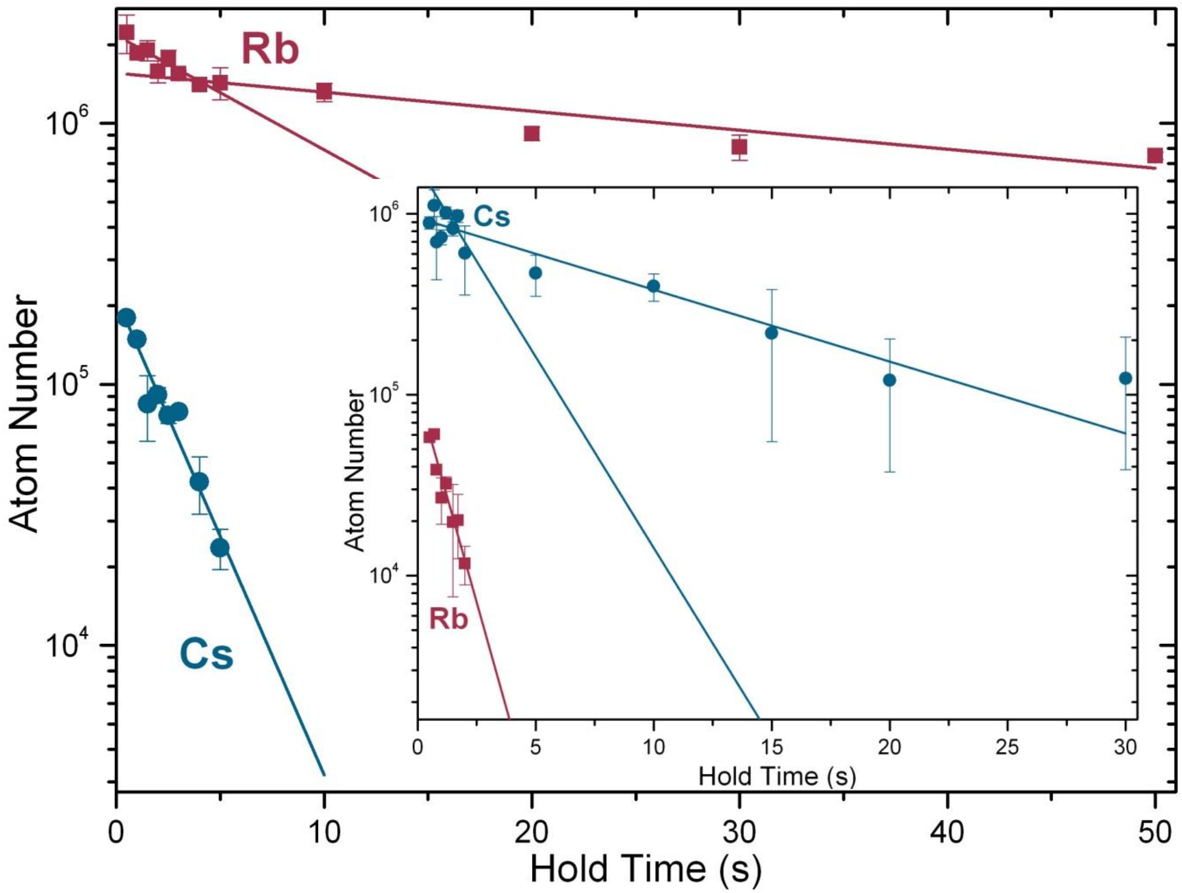


Each image is (630 x 670) μm

c.f. Weber *et al.*, Science, **299**, 232 (2003).

Two-species: interspecies Loss

Strong interspecies 3-body loss is observed in the dipole trap. Bias Field = 22.7 G.



Cs minority:

τ_{Rb1} = 10(2) s,

τ_{Rb2} = 60(5) s,

τ_{Cs} = 2.4(3) s.

Rb minority:

τ_{Cs1} = 2.1(9) s,

τ_{Cs2} = 10(3) s,

τ_{Rb} = 0.9(2) s.

Three body loss coefficient:

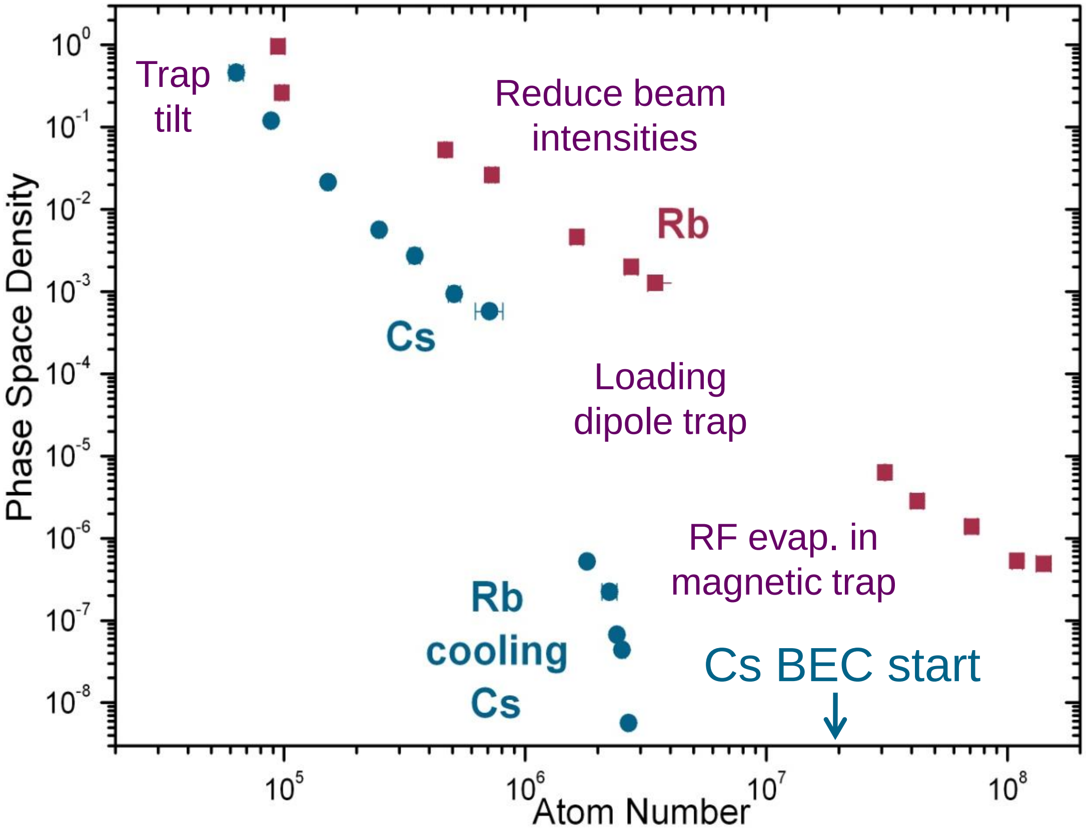
$K_3 \approx 10^{-25}$- 10^{-26} cm^6/sec

Relative fractions of Rb and Cs are controlled using RF during the dipole trap loading.

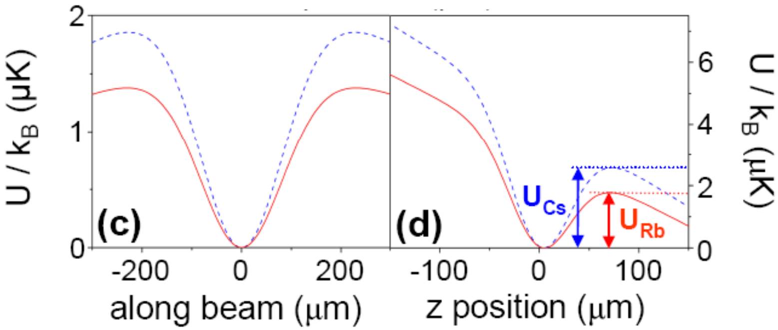
Two-Species BEC

- Reduce the initial Cs number
- Fast (~1s) reduction of dipole trap depth.

See also: Rb Cs double BEC in Innsbruck Lercher *et al.*, arXiv:1101.1409



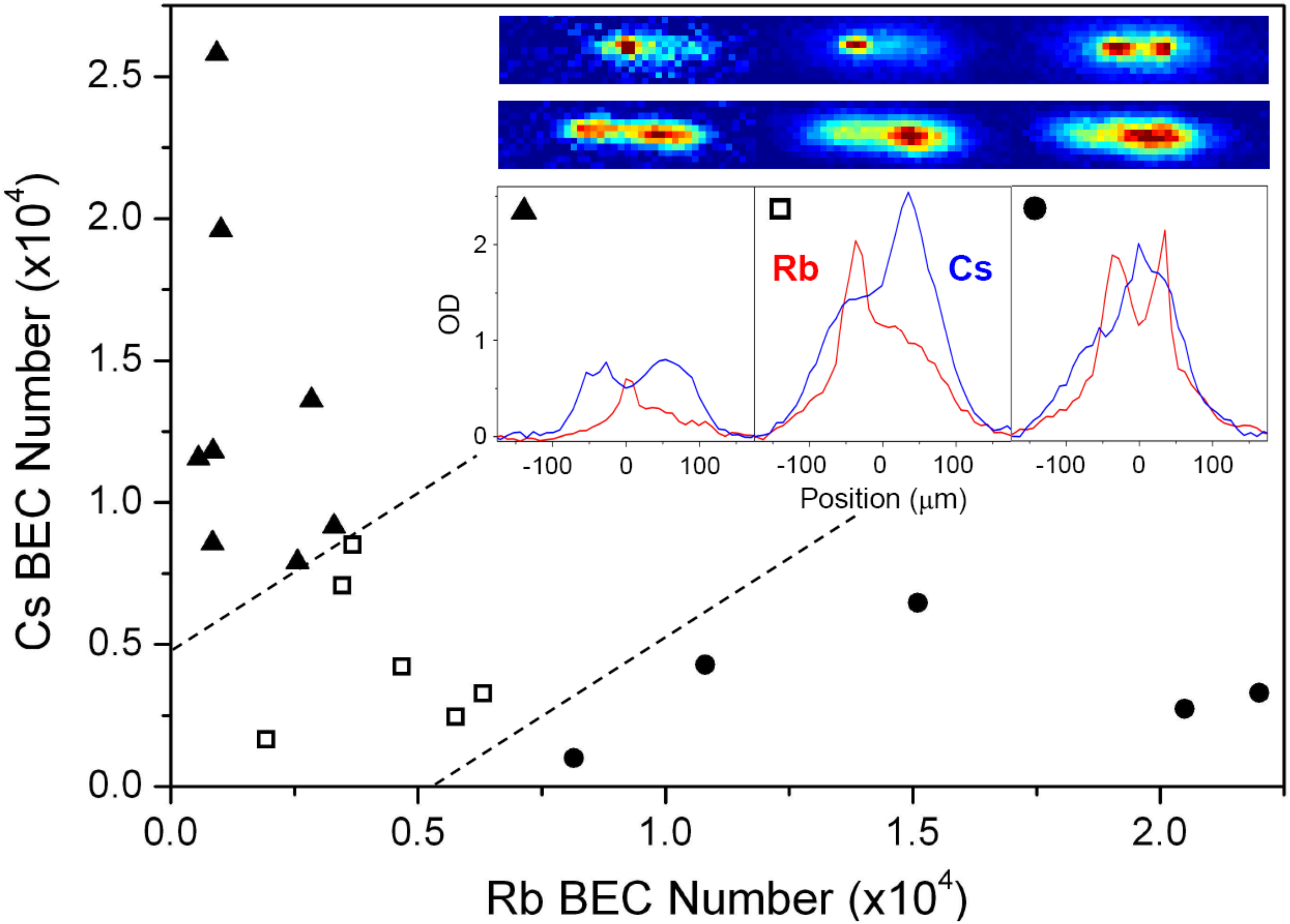
Ratio of polarizabilities ~ 1.3
Sympathetic cooling in dipole trap



Trap tilt preserves trap frequencies during evaporation†

† Hung *et al.*, PRA **78**, 011604 (2008)

Immiscible 2-species BEC



McCarron *et al*., Phys. Rev. A 84 011603 (2011)

Immiscibility

Interaction coupling constant:

$$g_{ij} = 2\pi\hbar^2 a_{ij}\left(\frac{m_i + m_j}{m_i m_j}\right)$$

Relative strength of interactions:

$$\Delta = \frac{g_{12}}{\sqrt{g_{11}\, g_{22}}} \approx \frac{a_{12}}{\sqrt{a_{11}\, a_{22}}}$$

Immiscibility $\Longrightarrow$ $\Delta > 1$

At 22.4 G: $a_{Rb} = 100\ a_0$, $a_{Cs} = 290\ a_0$

$\Longrightarrow$ $a_{RbCs} > 170\ a_0$

Trippenbach *et al*., J. Phys. B: At. Mol. Opt. Phys. **33** 4017 (2000):

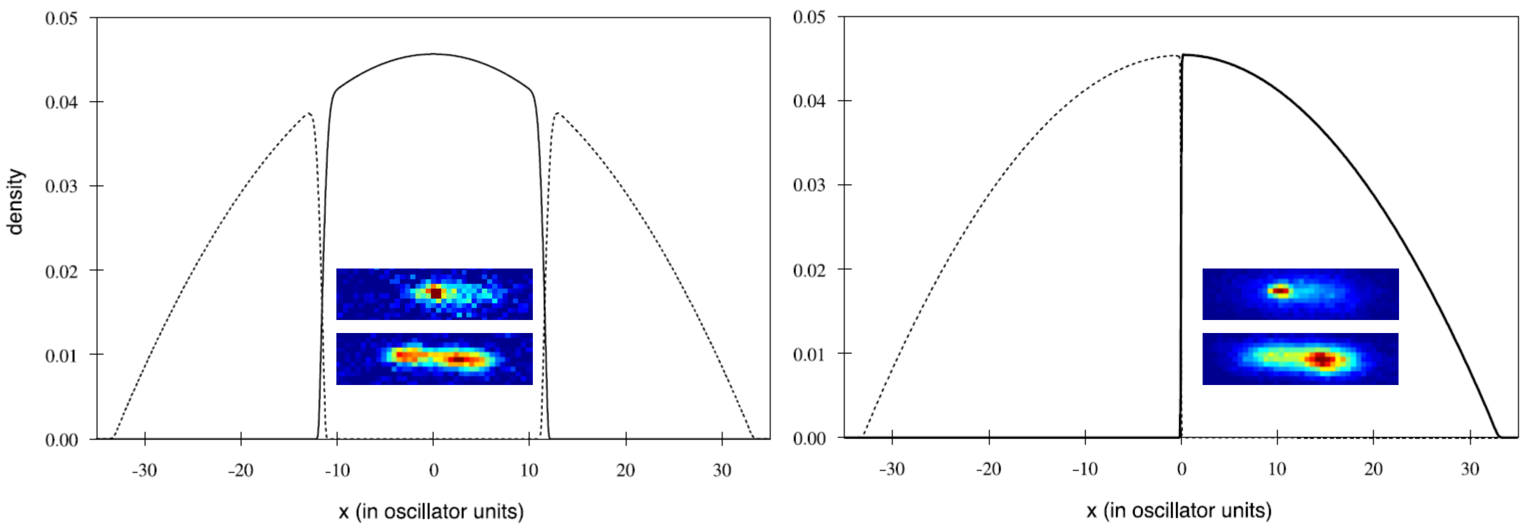


Figure 2. Two types of solutions without overlap: symmetric and asymmetric cases. Densities for the first and second components are plotted as full and broken curves. For both panels, the ratio of the scattering lengths is $U_{11} : U_{12} : U_{22} = 1 : 1.52 : 1.01$ and $N_1 = N_2$. The ratio of the energy of the asymmetric case to the symmetric one is 0.8.

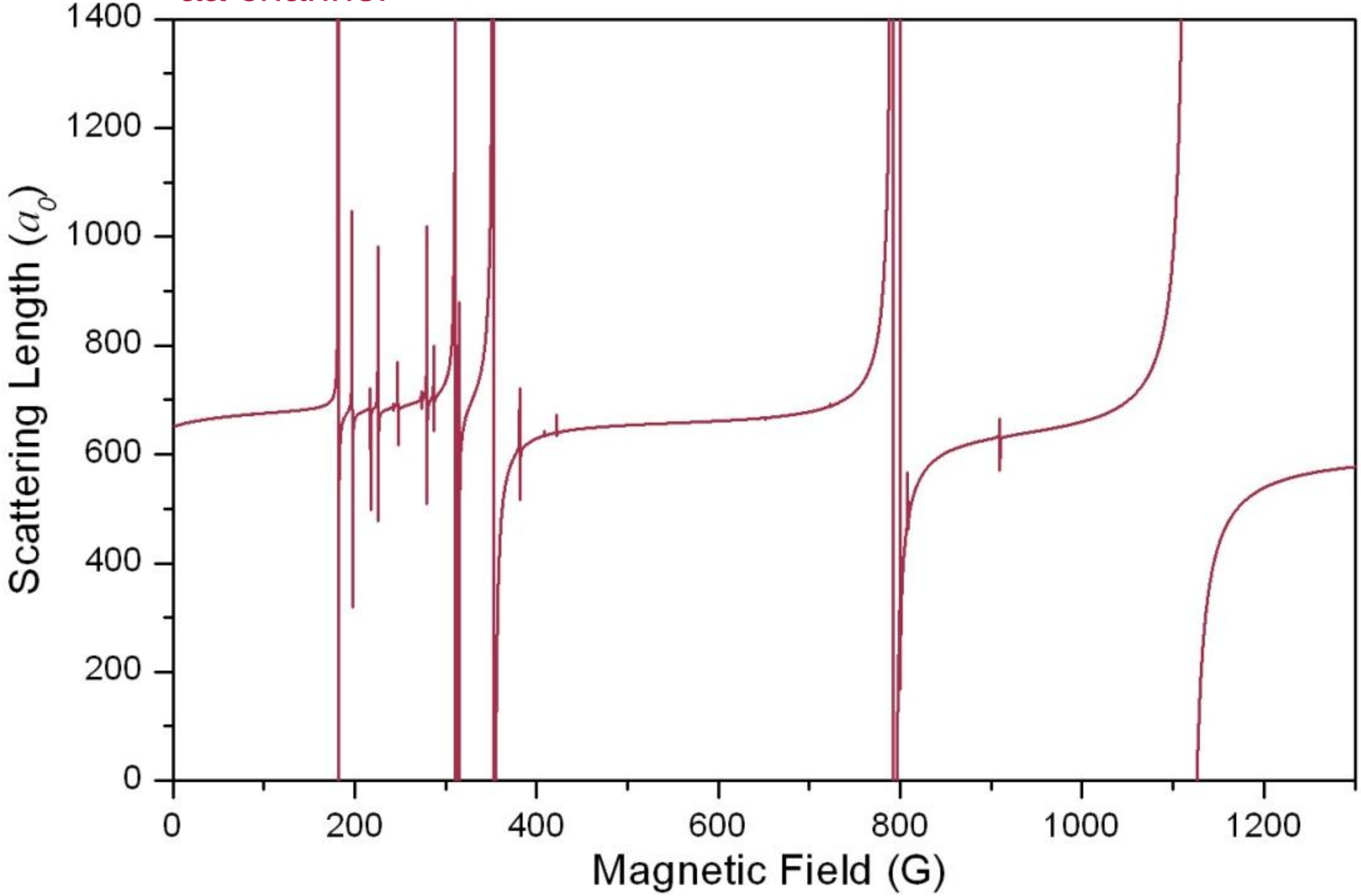
Outline

1. The Rb Cs experiment
2. Two species BEC: Immiscibility
3. **Feshbach spectroscopy of Rb-Cs mixtures**
4. Creation of Cs_2 and RbCs Feshbach molecules
5. Progress towards ground state molecules.
6. Next generation experiment: YbCs

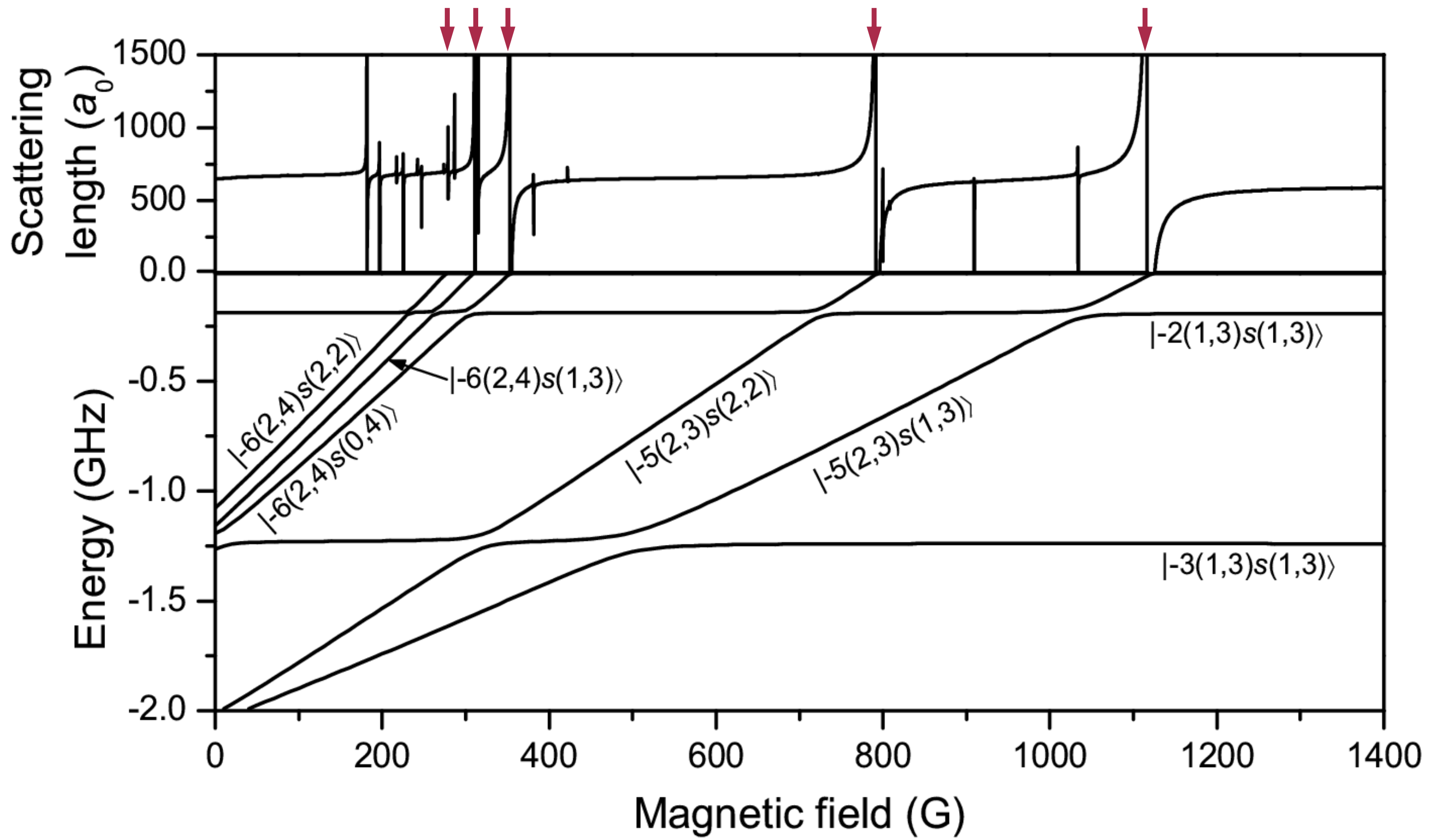
Feshbach Spectroscopy: ^{87}Rb + Cs

T. Takekoshi *et al.*, PRA **85**, 032506 (2012)
K. Pilch *et al.*, PRA **79**, 042718 (2009)

aa channel



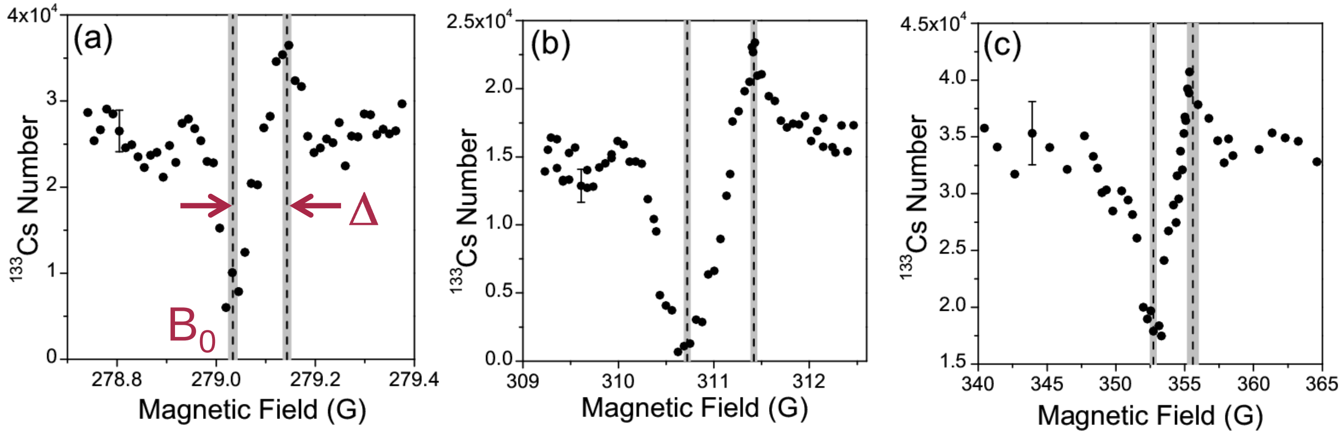
Focus on s-wave resonances



Notation: $\left| n(f_{\mathrm{Rb}}, f_{\mathrm{Cs}})L(m_{\mathrm{Rb}}, m_{\mathrm{Cs}}) \right\rangle$

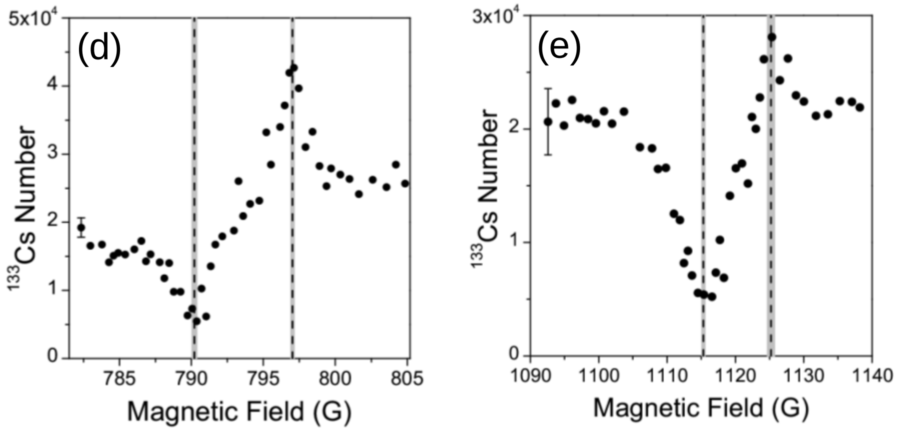
Focus on s-wave resonances

- Load dipole trap with a mixture of ^{87}Rb in the $|1,+1\rangle$ state and Cs in the $|3,+3\rangle$ state.
- Evaporate at specific magnetic field and hold for 0.5s to 1s for different resonances.



N_{Rb} = 9x10^4, T_{Rb} = 210nK

N_{Cs} = 3x10^4, T_{Cs} = 260nK

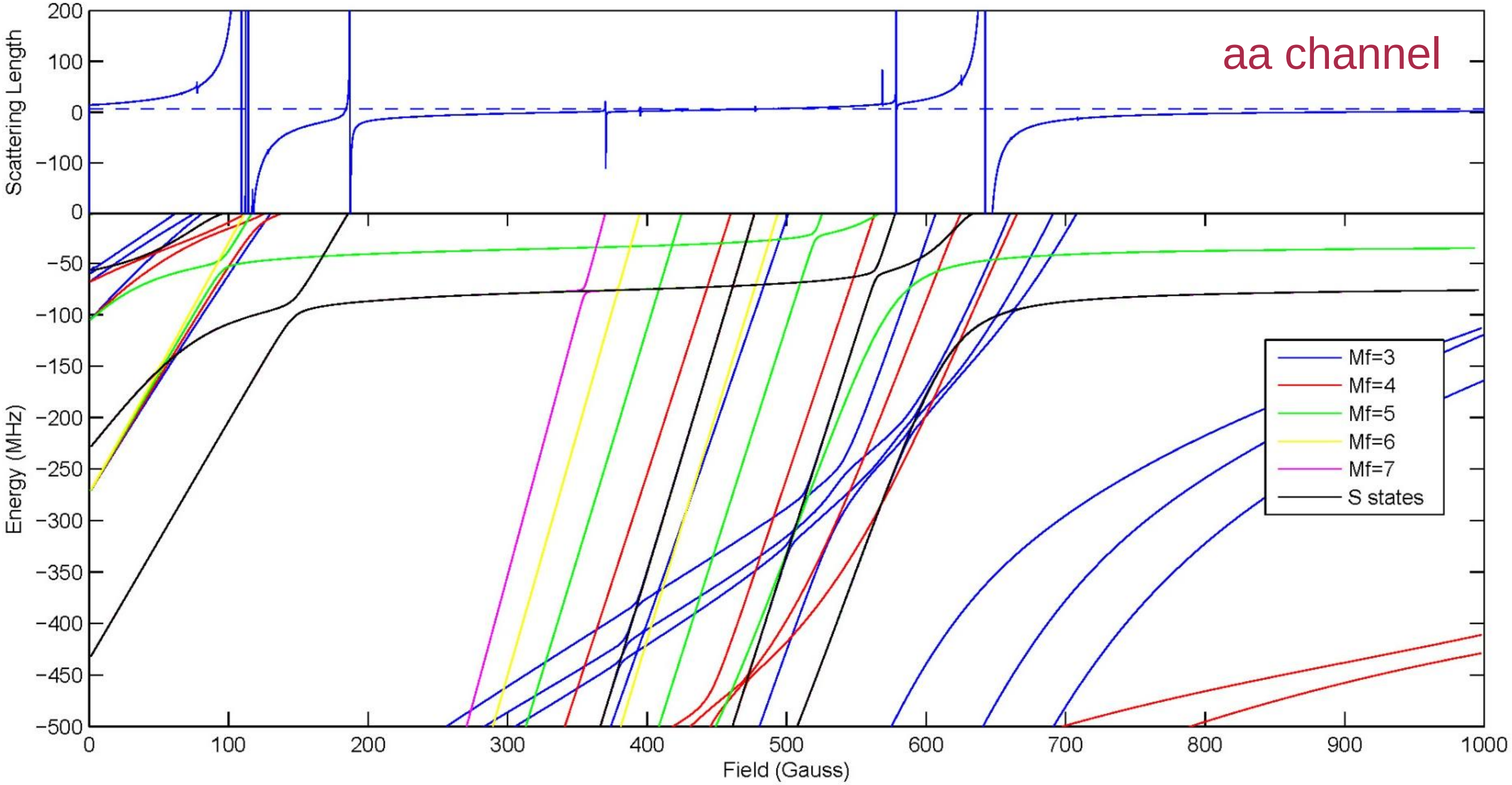


Experiment		Theory		
B_0 (G)	Δ (G)	Quantum labels	B_0 (G)	Δ (G)
279.03(1)	0.11(1)	$\|-6(2,4)s(2,2)\rangle$	278.972	0.034
310.72(2)	0.70(3)	$\|-6(2,4)s(1,3)\rangle$	310.669	0.583
352.7(2)	2.9(5)	$\|-6(2,4)s(0,4)\rangle$	352.706	2.206
790.2(2)	6.8(2)	$\|-5(2,3)s(2,2)\rangle$	791.762	4.220
1115.2(2)	10.0(6)	$\|-5(2,3)s(1,3)\rangle$	1116.554	8.936

Notation: $|n(f_{Rb}, f_{Cs})L(m_{Rb}, m_{Cs})\rangle$

Prediction for ^{85}Rb-Cs interspecies scattering length

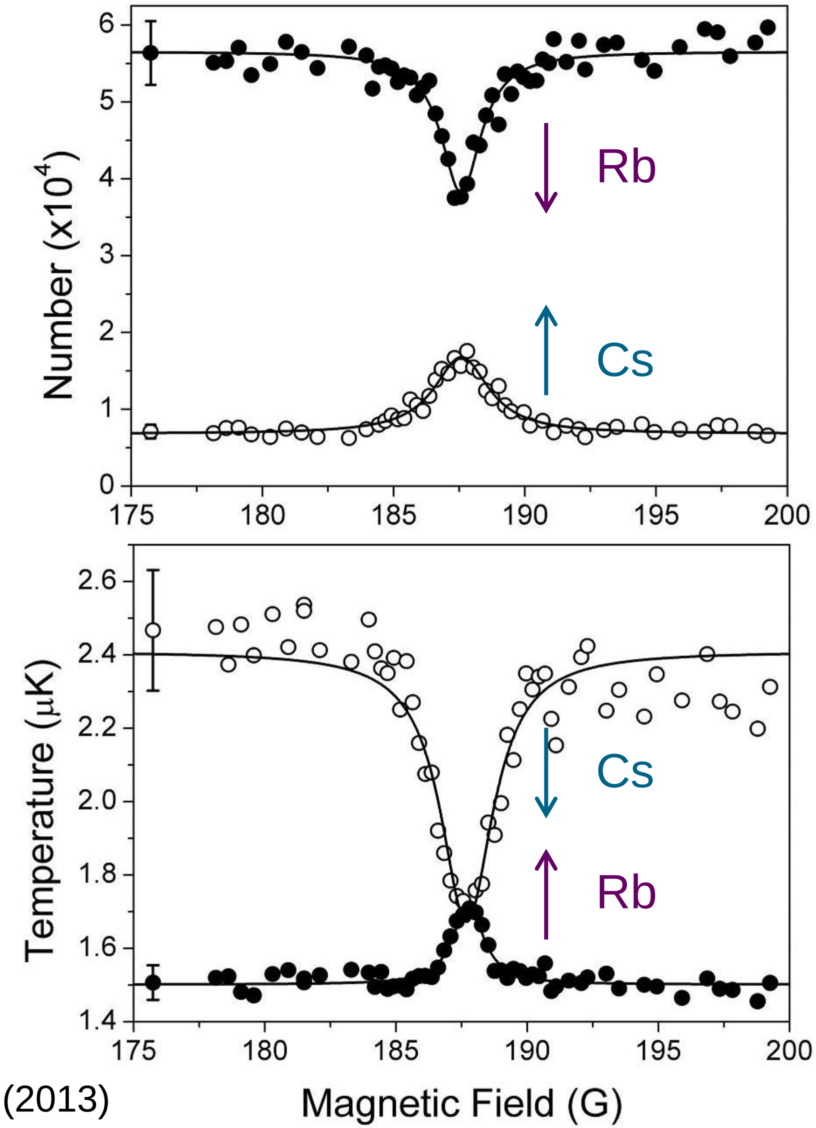
- Mass scaling allows us to re-use the potentials fitted for ^{87}RbCs



Background scattering length ~ zero !

Feshbach Spectroscopy of a ^{85}Rb-Cs mixture

Detect resonances through rethermalisation



Ratio of Trap Depths Rb:Cs = 1:1.4

Before evaporation:

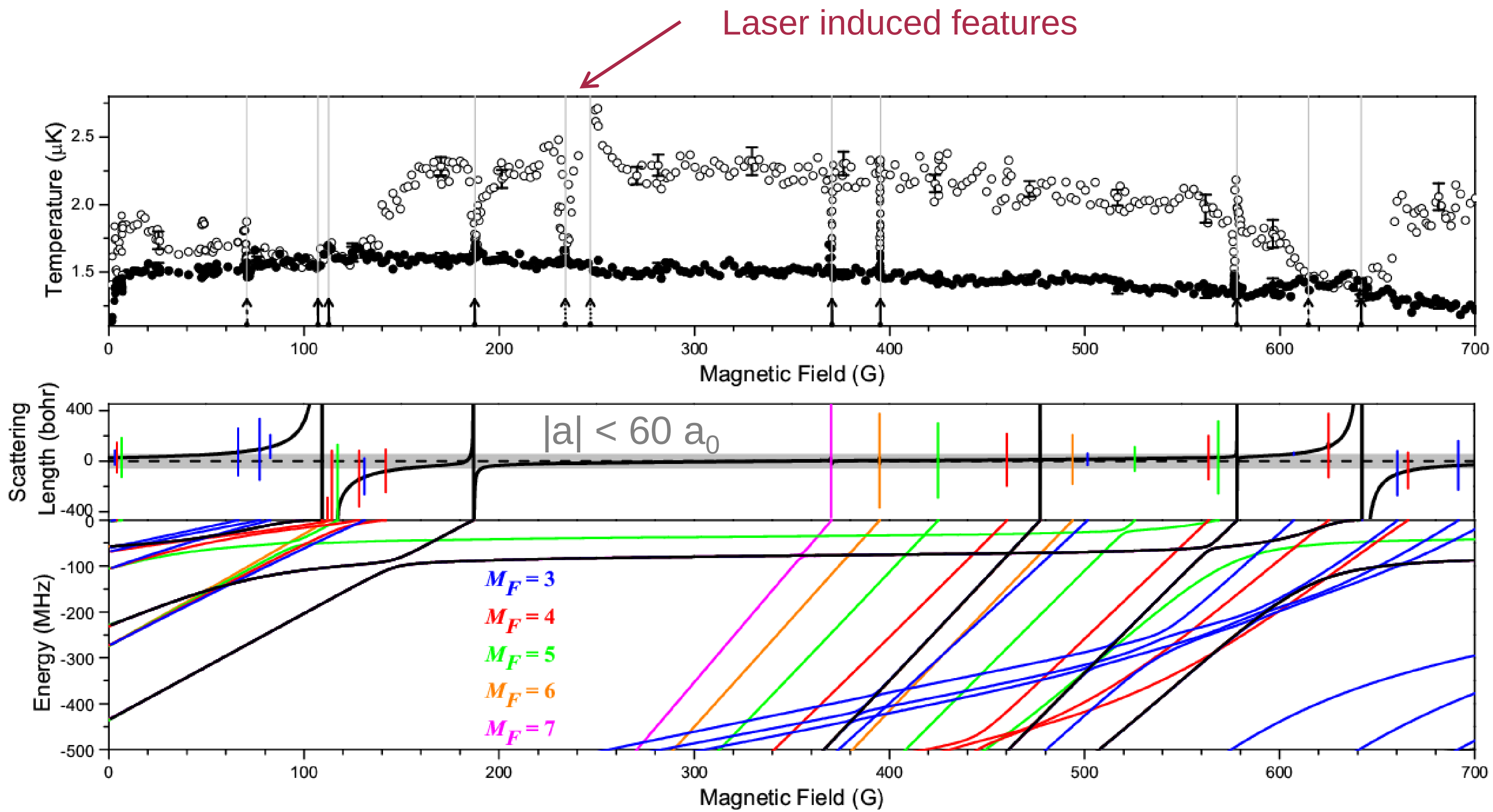
N_{Cs} = 8(2)x10^4
T_{Cs} = 17(2) μK
N_{Rb} = 7(1) x 10^5
T_{Rb} = 13.3(1) μK

After (off resonance):

N_{Cs} ≈ 2 x 10^4
N_{Rb} ≈ 8 x 10^4

Cho *et al.*, PRA **87** 010703(R) (2013)

Feshbach Spectroscopy of a ^{85}Rb-Cs mixture



Cho *et al.*, PRA **87** 010703(R) (2013)

Summary of results

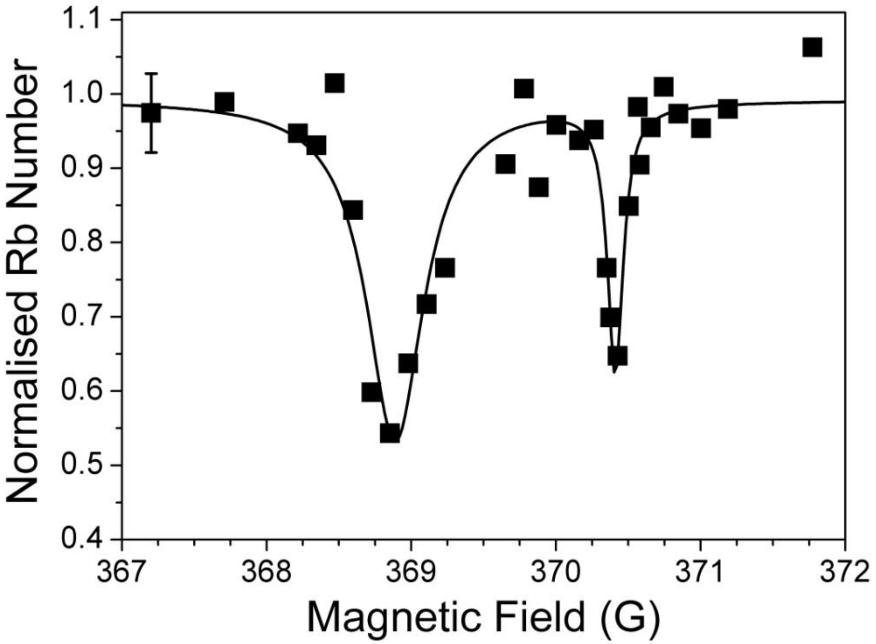
Experiment		Theory							
B_0 (G)	δ (G)	Assignment L_i	L	F	M_F	B_0 (G)	B_* (G)	Δ (G)	a_{bg} (bohr)
70.68(4)	0.8(1)	p	1	-	-	70.54	58.54	-12	-
		s	2	4	3	77.51	77.52	0.010	93.6
107.13(1)	0.6(2)	s	0	5	5	109	350	241	9.6
112.6(4)	28(5)	s	2	6	6	112.29	112.12	-0.17	-628
		s	2	4	4	114.33	114.21	-0.12	-246
		s	2	6	5	117.40	117.35	-0.051	-169
187.66(5)	1.7(3)	s	0	6	5	187.07	182.97	-4.1	-30.3
370.39(1)	0.08(4)	s	2	7	7	370.41	374.31	3.9	1.57
395.20(1)	0.08(1)	s	2	7	6	395.11	395.56	0.45	3.4
		s	2	7	5	425.11	425.16	0.045	6.1
		s	2	5	5	568.62	568.66	0.037	29.8
577.8(1)	1.1(3)	s	0	6	5	578.36	578.7 0	0.34	32.2
614.6(3)	1.1(4)	p	1	-	-	614.98	608.18	-6.8	-
		s	2	5	4	625.29	625.30	0.014	123
641.8(3)	6(2)	s	0	5	5	642	901	259	9.6
		s	2	3	3	708.70	708.68	-0.024	-23.8

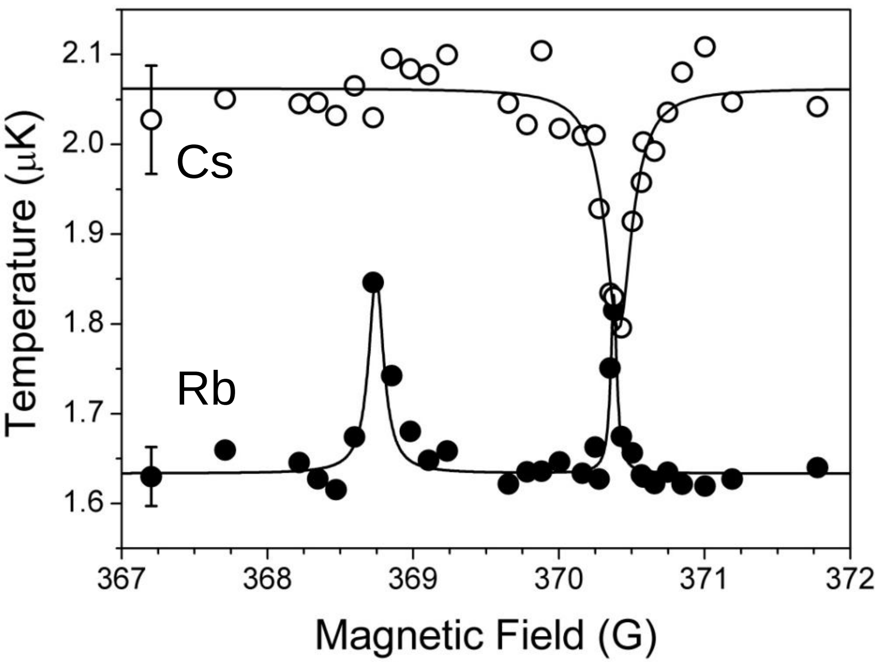
9 resonances identified experimentally

p-wave entrance channel resonances

broad resonances

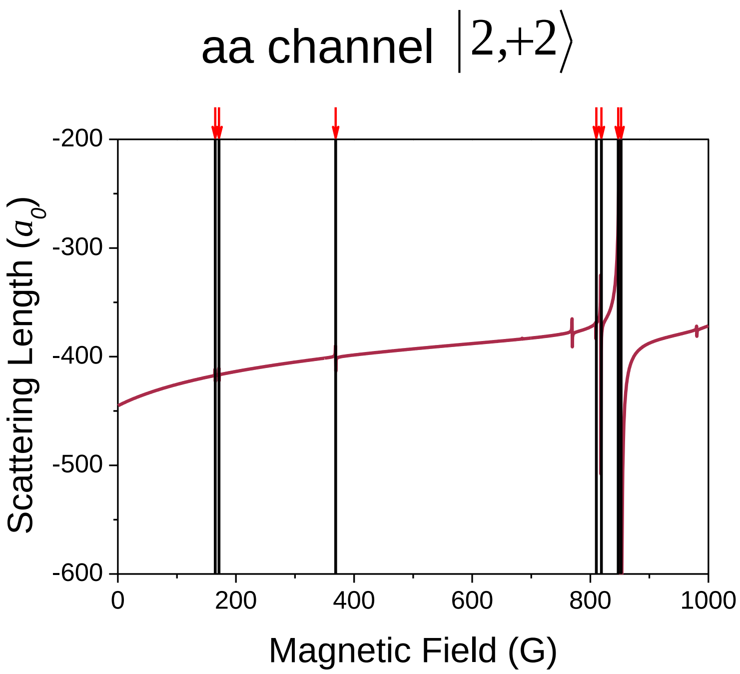
Inter- vs. Intra-species resonances





Feshbach spectroscopy of 85Rb

- Evaporative cooling in the dipole trap and 1s hold at specific magnetic field.
- Typical conditions: T = 1.7 μK , N = 1x10^5



Incoming s-wave (2,2)+(2,2) state								
Experiment		Theory						
B_0 (G)	δ (G)	Assignment L	(f_a, f_b)	F	M_F	B_0 (G)	Δ (mG)	a_{bg} (bohr)
164.74(1)	0.08(2)	2	(2,2)	4	2	164.7	-0.0003	-432
171.36(1)	0.12(2)	2	(2,2)	2	2	171.3	-0.01	-431
368.78(4)	0.4(1)	2	(2,2)	4	3	368.5	-0.03	-413
-	-	2	(2,3)	3	2	594.9	-0.2×10^{-9}	-401
-	-	2	(2,3)	5	3	685.0	-0.2×10^{-4}	-396
-	-	2	(2,3)	5	2	750.8	-0.0002	-392
770.81(1)	0.11(2)	2	(2,3)	5	4	770.6	-0.26	-390
809.65(3)	0.3(1)	2	(2,3)	3	3	809.7	-0.05	-383
819.8(2)	1.1(5)	2	(2,3)	5	5	819.0	-3.14	-380
852.3(3)	1.3(4)†	0	(2,3)	5	4	**851.3**	-1199	-393
-	-	2	(2,3)	2	2	961.8	-0.005	-390
-	-	2	(2,3)	4	4	980.5	-0.38	-387

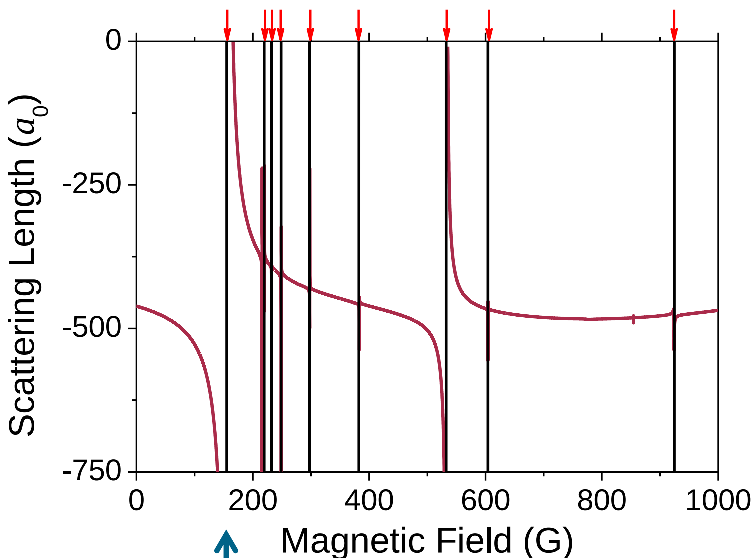
Suitable for BEC production?

Blackley *et al.*, PRA **87** 033611 (2013)

Feshbach spectroscopy of 85Rb

- Evaporative cooling in the dipole trap and 1s hold at specific magnetic field.
- Typical conditions: T = 1.7 μK , N = $1\text{x}10^5$

ee channel $|2,-2\rangle$



'Usual' resonance

Incoming s-wave (2,-2)+(2,-2) state							
Experiment		Theory					
B_0 (G)	δ (G)	Assignment L	Assignment M_F	B_0 (G)	Δ (mG)	a_{res} (bohr)	a_{bg} (bohr)
156(1)	10.5(5)	0	-4	**155.3**	10800	≥10000	-447
-	-	2	-6	215.5	3.1	4000	-374
219.58(1)	0.22(9)	0	-4	**219.9**	9.1	8000	-379
232.25(1)	0.23(1)	2	-4	232.5	2.0	400	-393
248.64(1)	0.12(2)	2	-5	248.9	1.8	5000	-406
297.42(1)	0.09(1)	2	-4	297.7	1.1	5000	-432
382.36(2)	0.19(1)	2	-3	382	-	7	-457
532.3(3)	3.2(1)†	0	-4	**532.9**	2300	≥10000	-474
604.1(1)	0.2(1)	2	-4	604.4	0.1	700	-466
-	-	2	-5	854.3	0.2	25	-481
924.52(4)	2.8(1)	2	-3	924	-	5	-476

Suitable for BEC production?

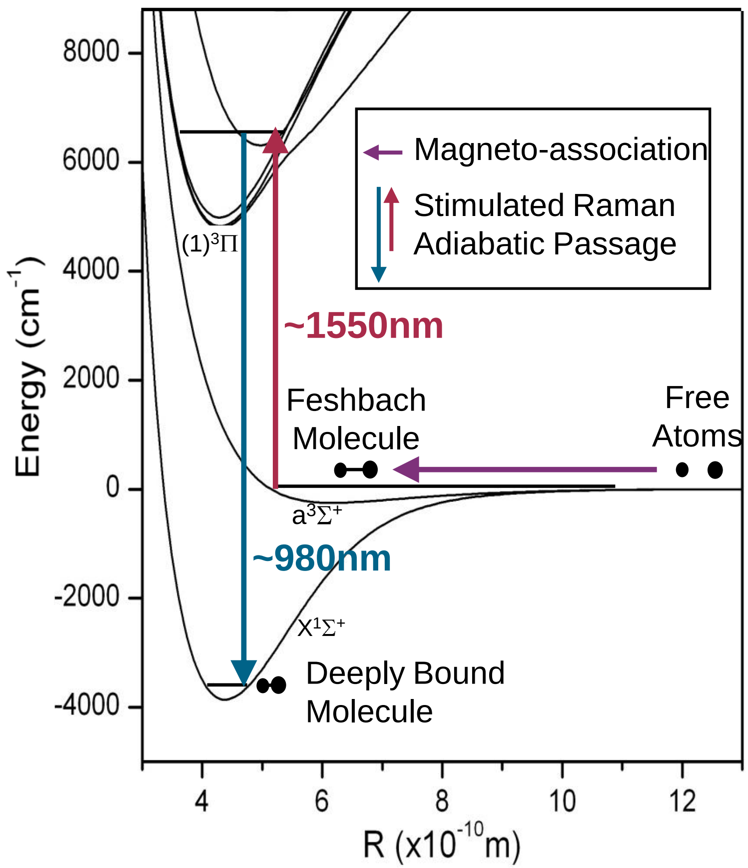
Blackley *et al.*, PRA **87** 033611 (2013)

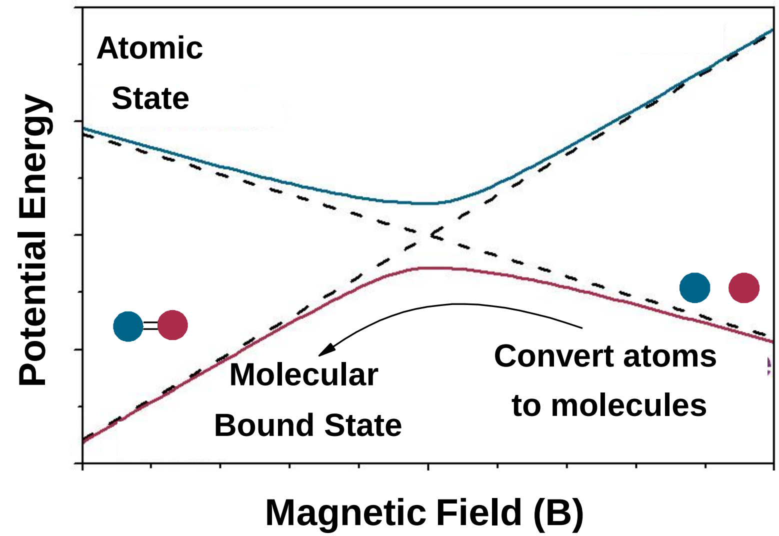
Outline

1. The Rb Cs experiment.
2. Sympathetic cooling of Cs with ^{87}Rb: Cs BEC
3. Two species BEC: Immiscibility
4. Feshbach spectroscopy of ^{87}Rb/^{85}Rb-Cs mixtures
5. **Progress towards ultracold polar molecules.**
6. Next generation experiment: YbCs

How to produce heteronuclear molecules

1. Create a high phase space density atomic mixture.
2. Associate weakly-bound molecules via an interspecies Feshbach resonance.





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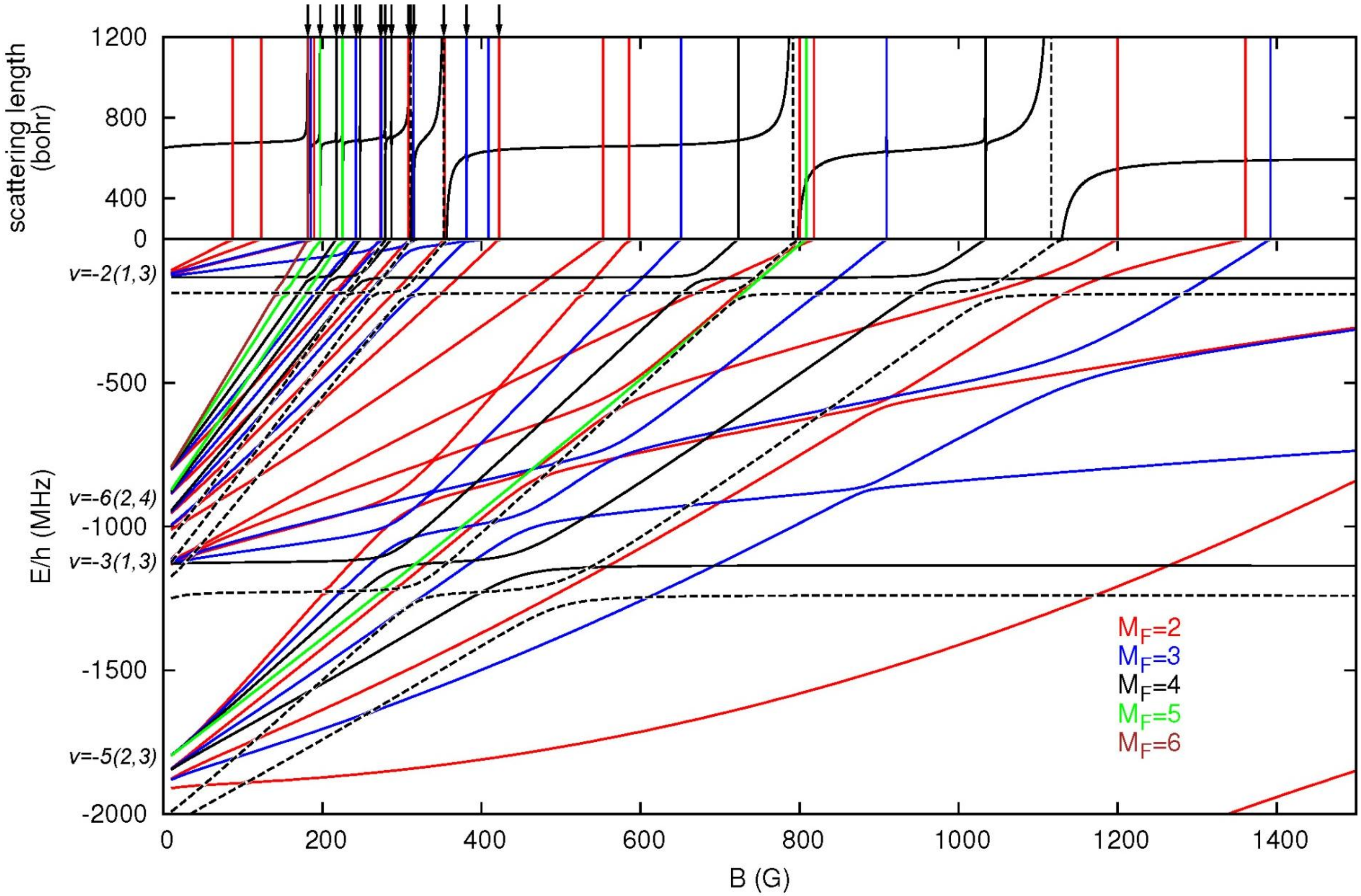
Rb_2 : F. Lang *et al.*, PRL, **101**, 133005 (2008).

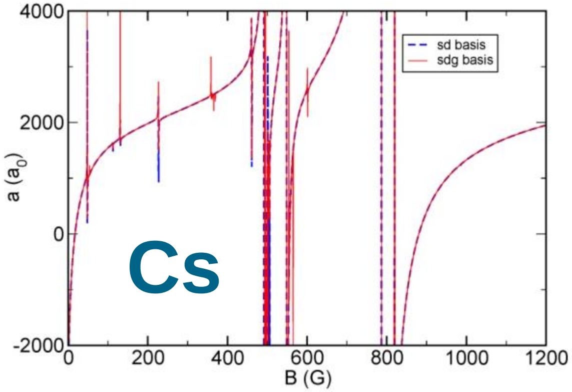
^{40}K-^{87}Rb : K.-K. Ni *et al.*, Science, **322**, 5899, (2008).

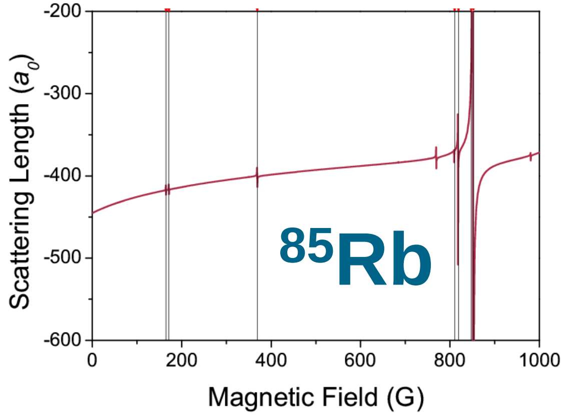
Next step: association

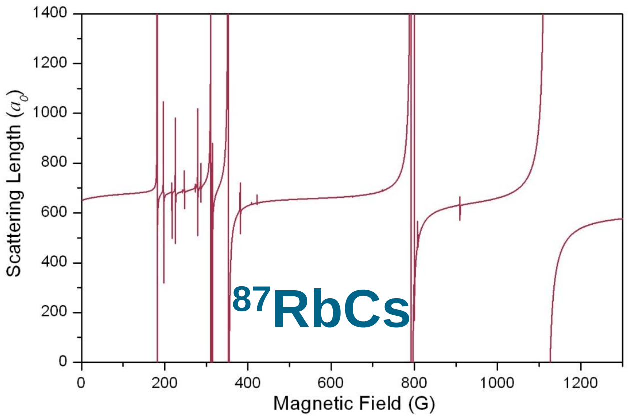


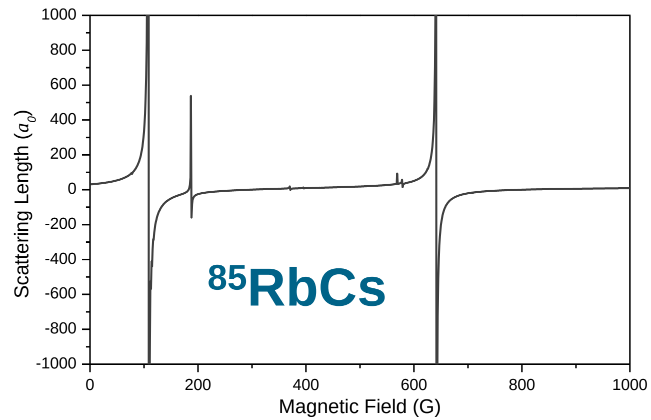
The challenge

Navigating the inter- and intra-species scattering lengths:



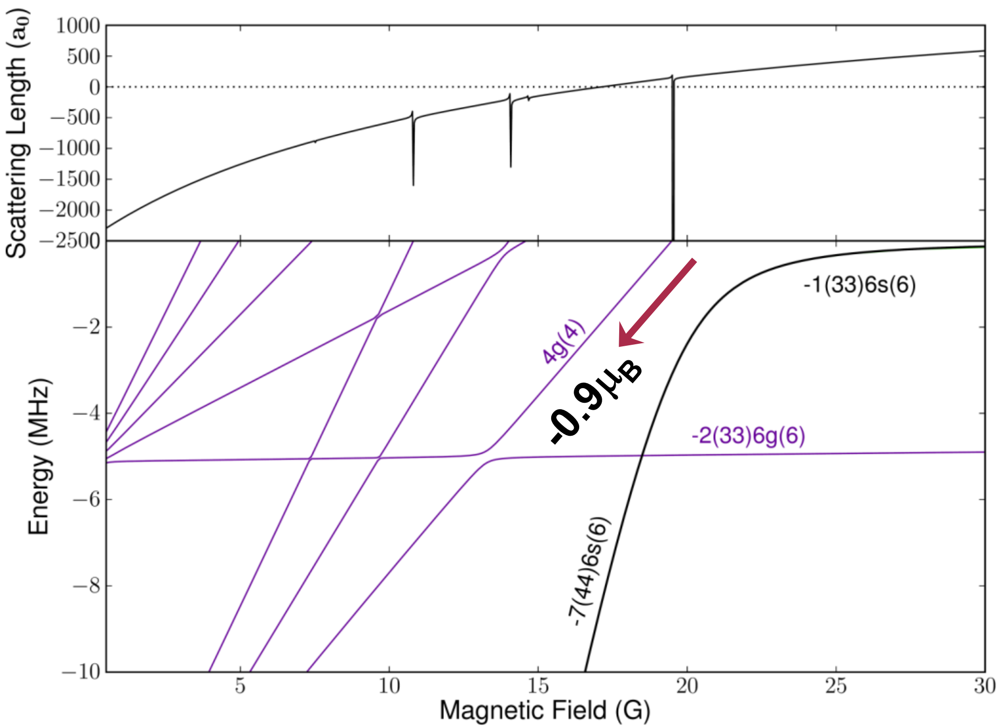


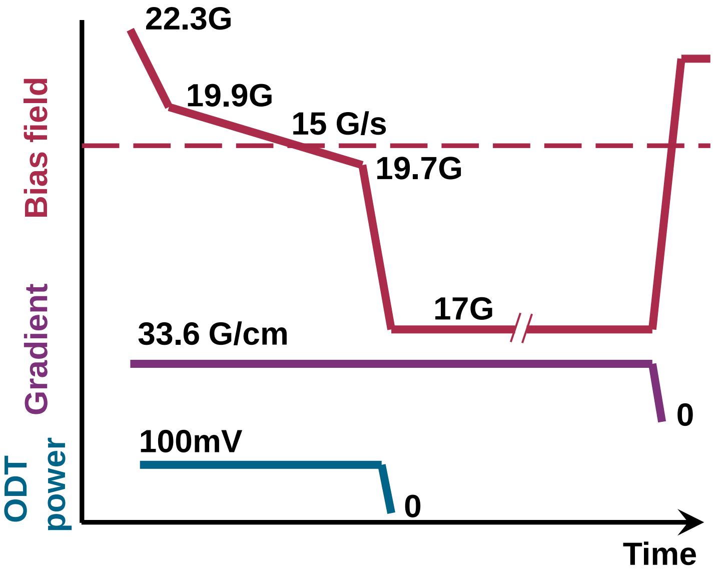




Start with something simple… Cs_2

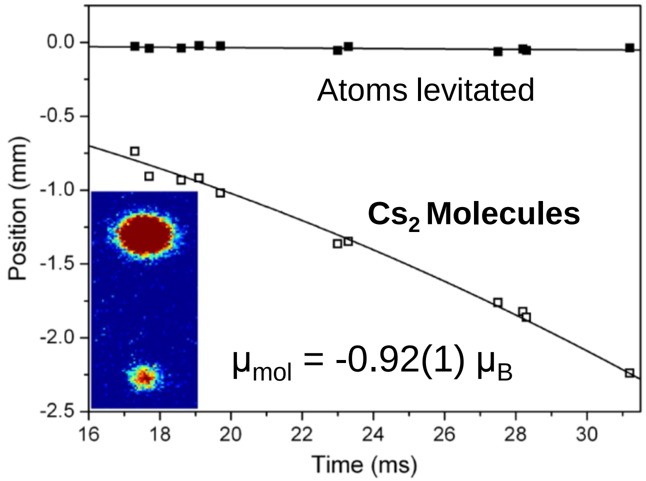
• Use 19.8 G resonance in Cs for magneto-association.





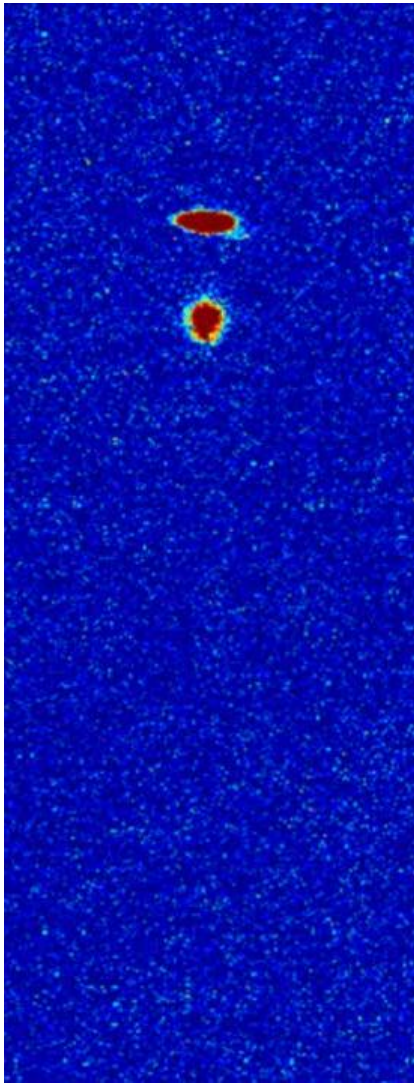
Start with something simple… Cs_2

- Initially: T_{Cs} = 60 nK, N_{Cs} = 1 x 10^5, PSD_{Cs} = 1.5
- N_{Cs_2} = 1.3 x 10^4, Transfer efficiency ~13%



From expansion: T_{Cs_2} = 60nK

Decreasing magnetic field



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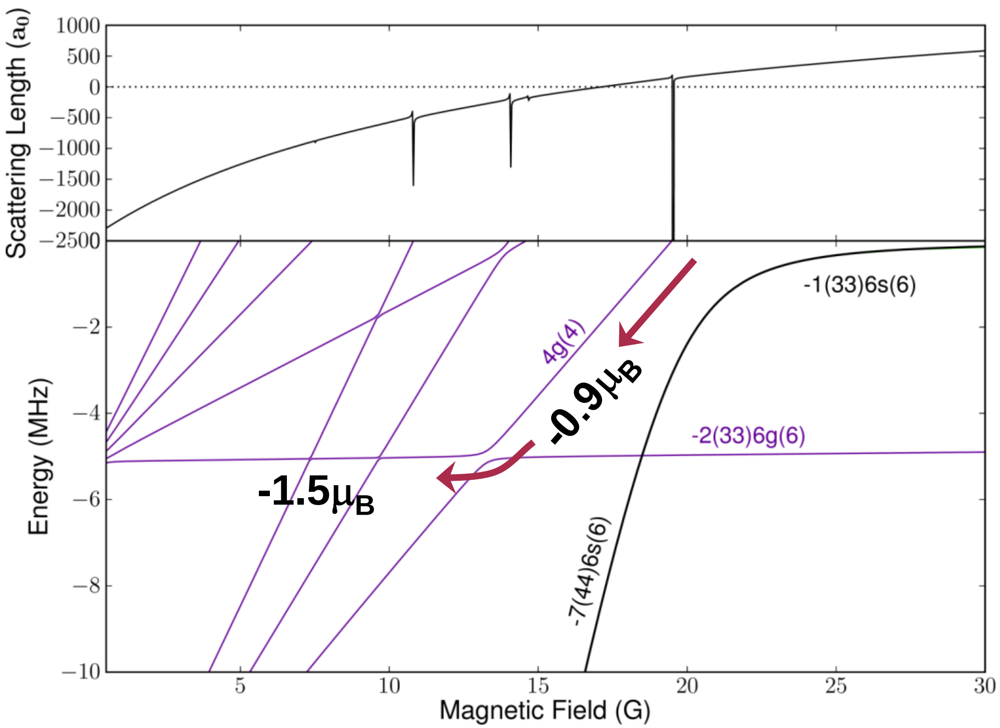
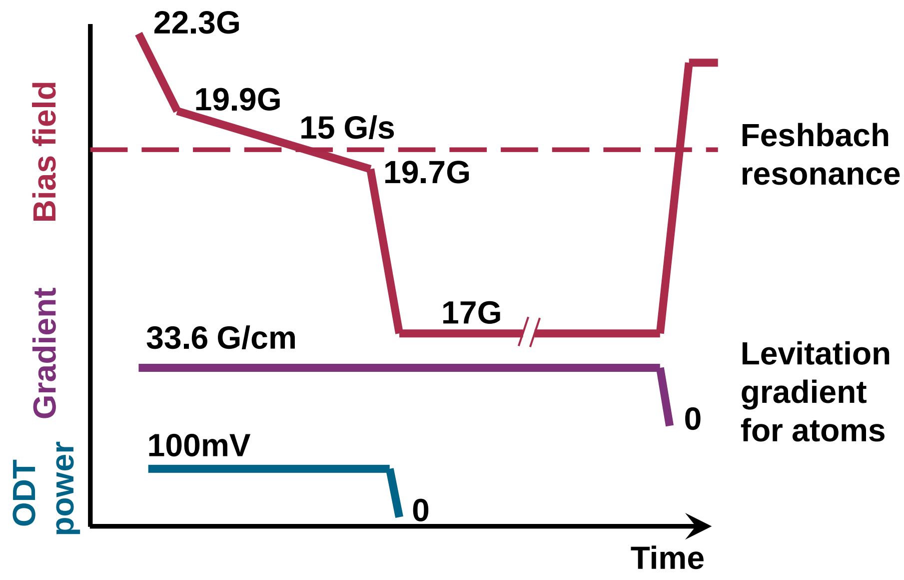
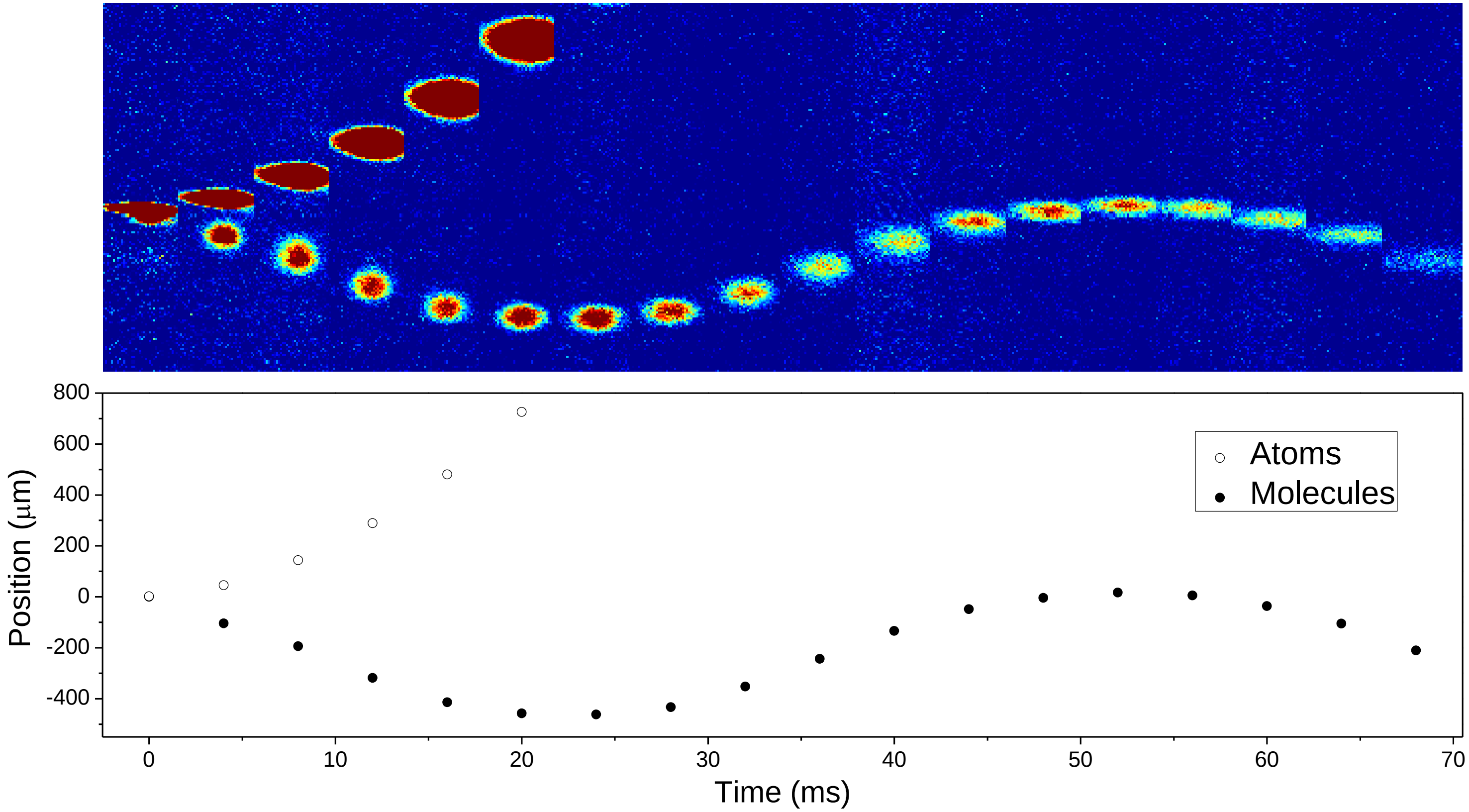
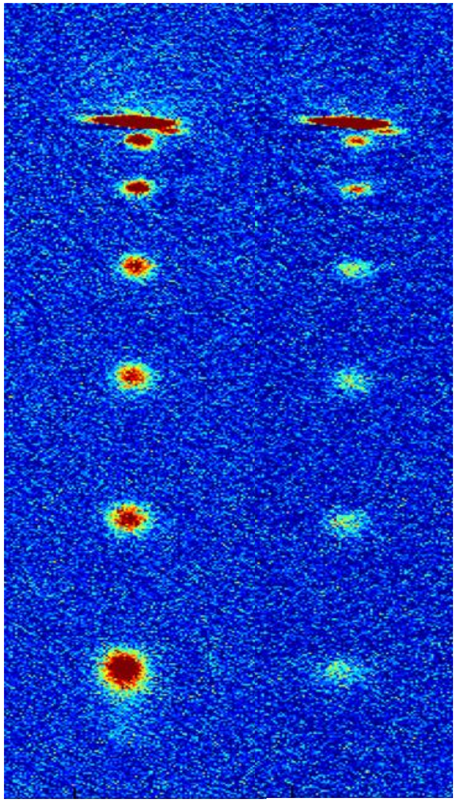


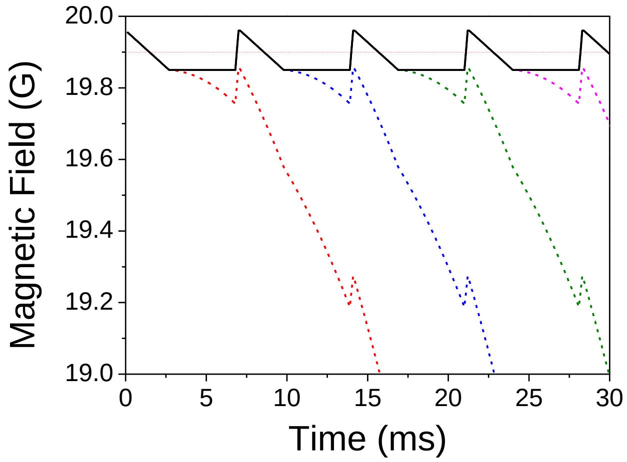


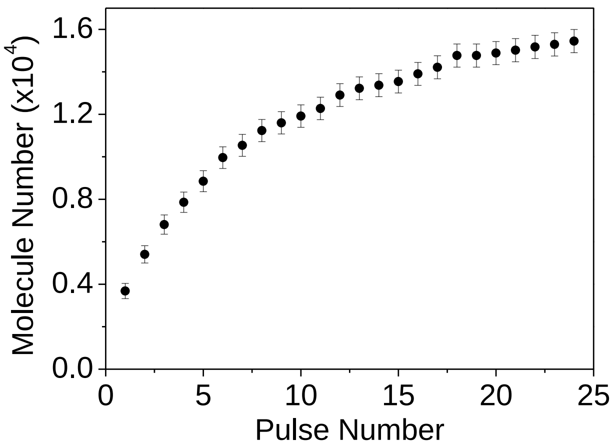
“Bouncing” Cs_2 molecules

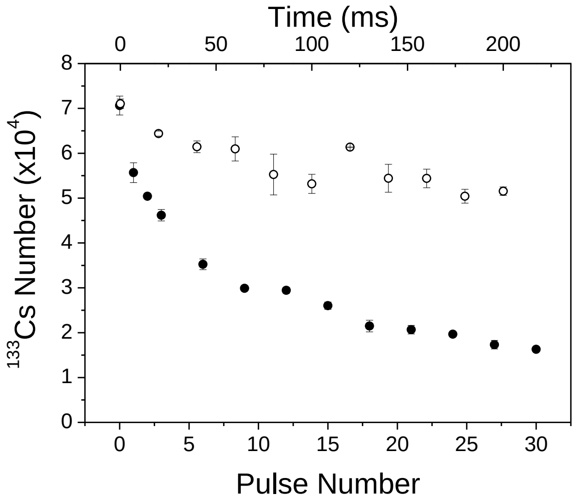


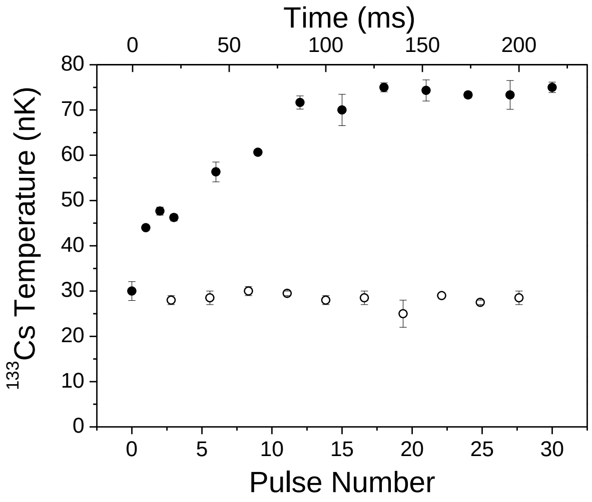
Repeated output coupling of molecules







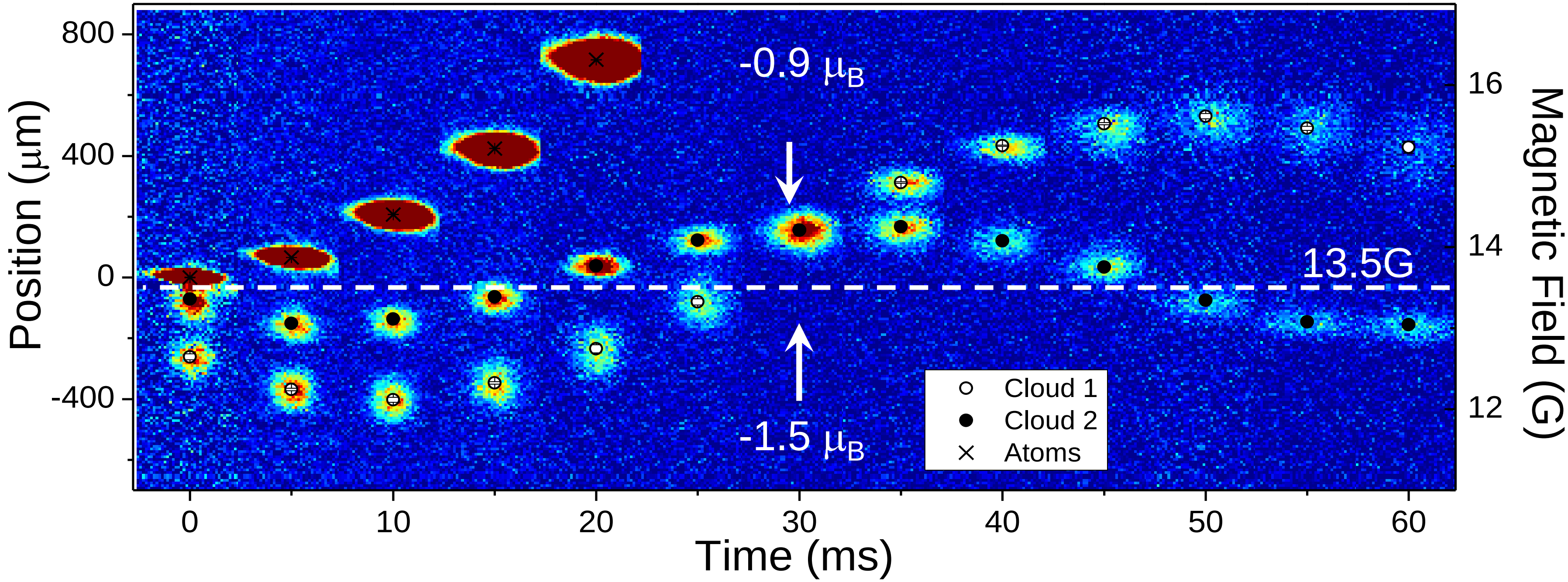




What happens if we combine the two effects…?

'Collision' of two molecular clouds

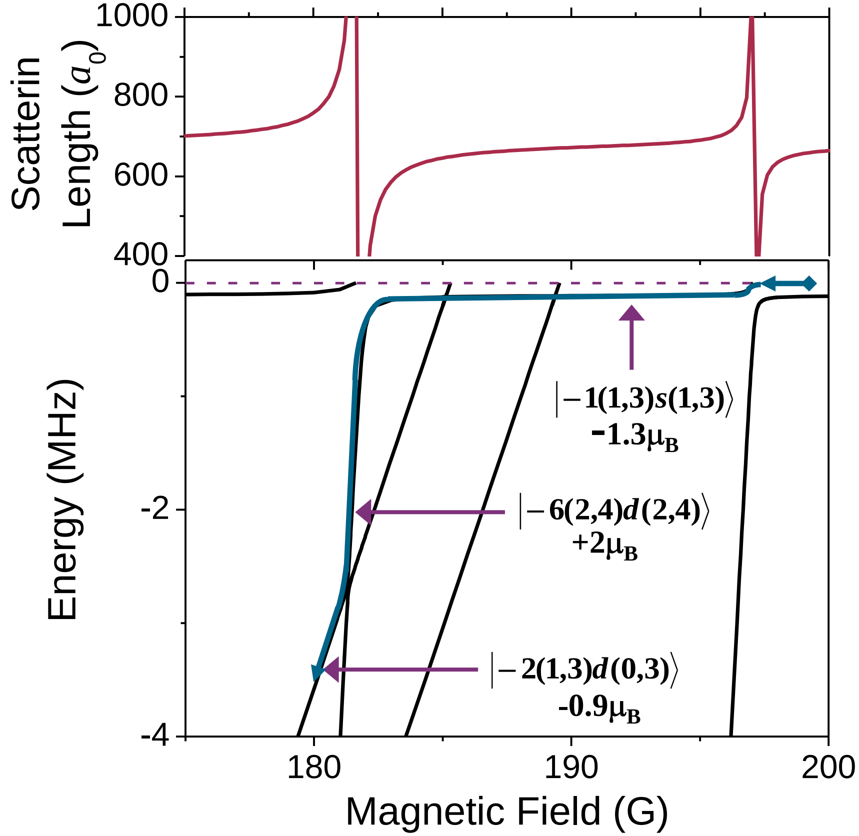
• Increase gradient to 40 G/cm and jump magnetic field close to the avoided crossing at 13.5 G after coupling out two molecular clouds.

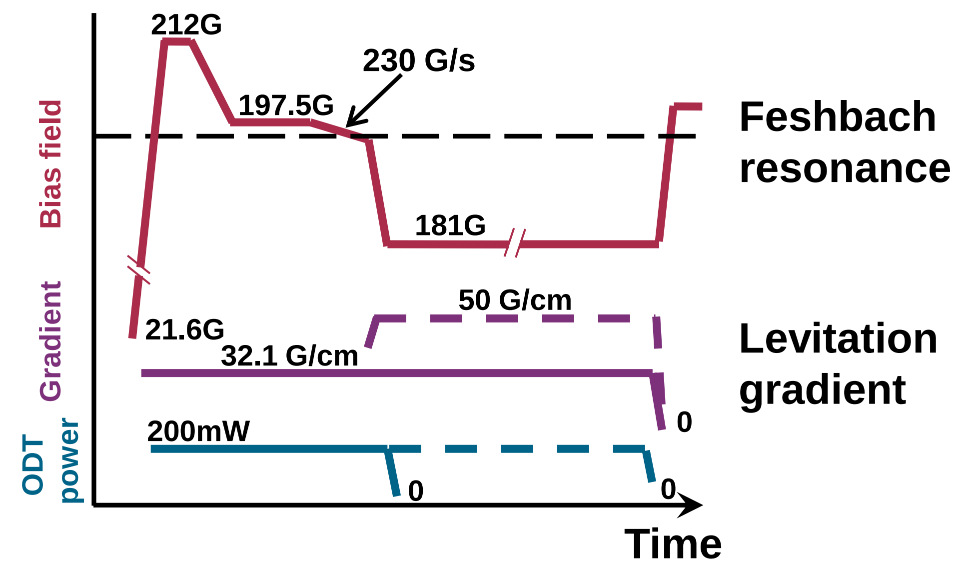


At 'collision' density
~ 4 x 10^9 cm^{-3}

Creation of ^{87}RbCs molecules

Complicated by near threshold bound state (large background scattering length)

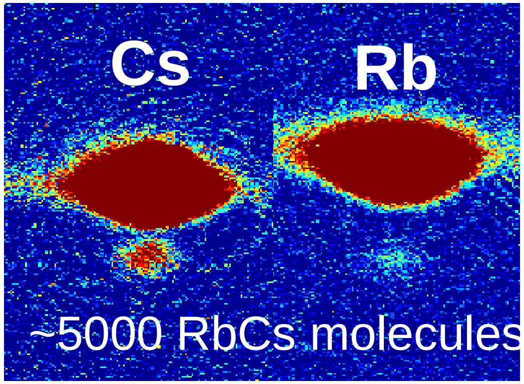




Creation of ^{87}RbCs molecules

Initial conditions:

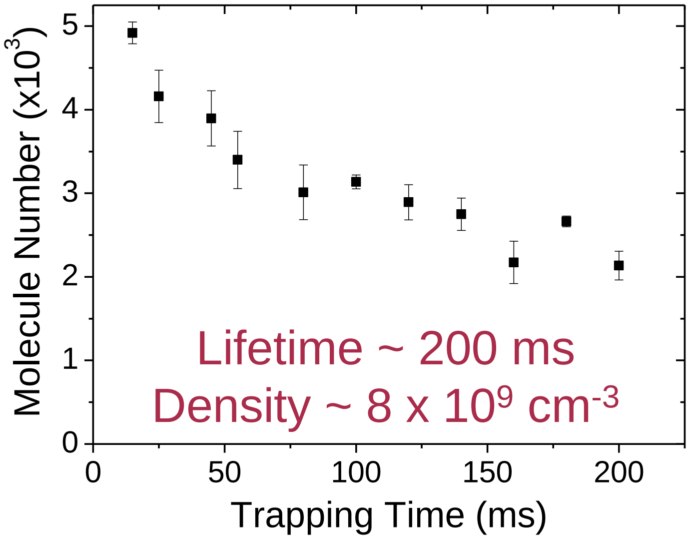
- $N_{Rb} = 3x10^5$, $T_{Rb} = 0.32\mu K$, $PSD_{Rb} = 0.2$
- $N_{Cs} = 2x10^5$, $T_{Cs} = 0.33\mu K$, $PSD_{Cs} = 0.1$



Conversion efficiency ~2%,

$\mu_{mol\ ,181G} = -0.84(1)\ \mu_B$

Optically trapped molecules:



ODT power :100 mW

Field gradient: 49.8 G/cm

Atoms not trapped!

How to produce heteronuclear molecules

1. Create a high phase space density atomic mixture.
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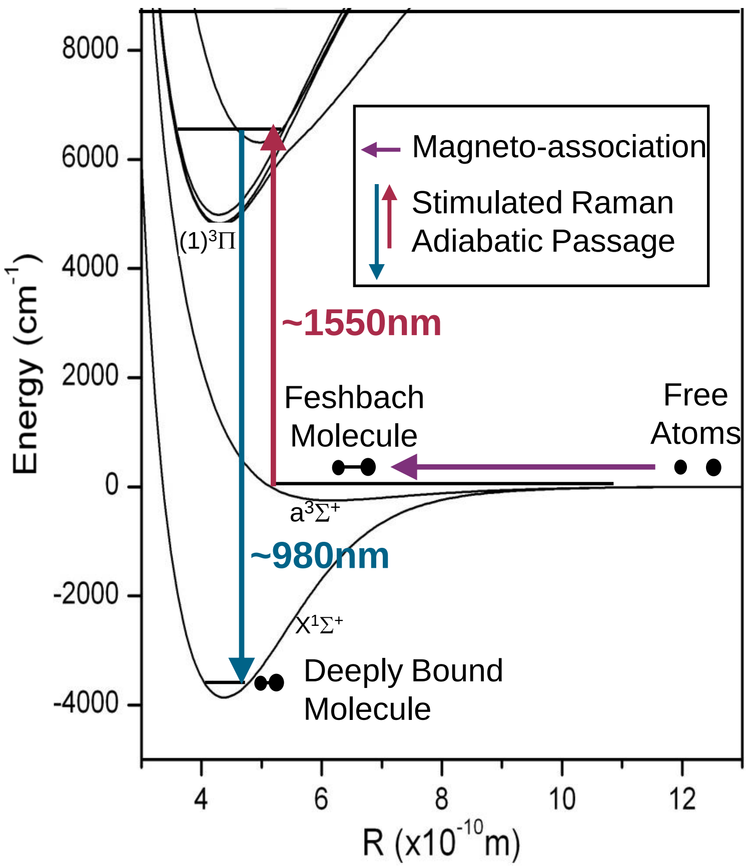

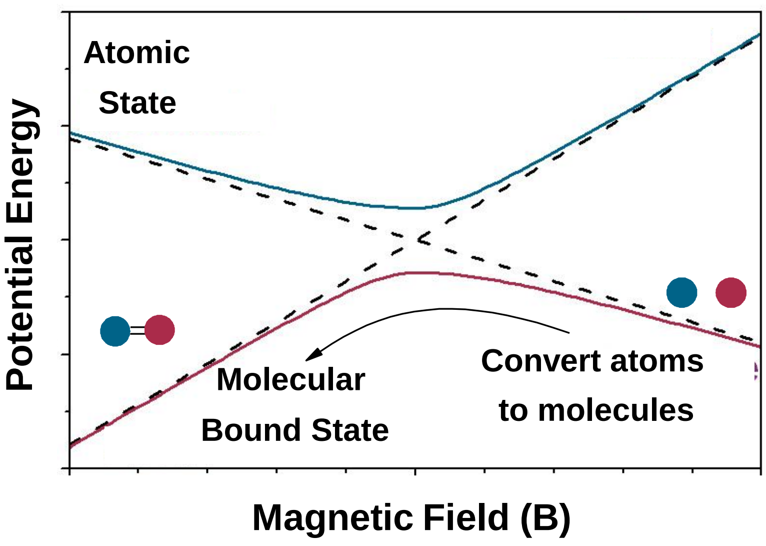

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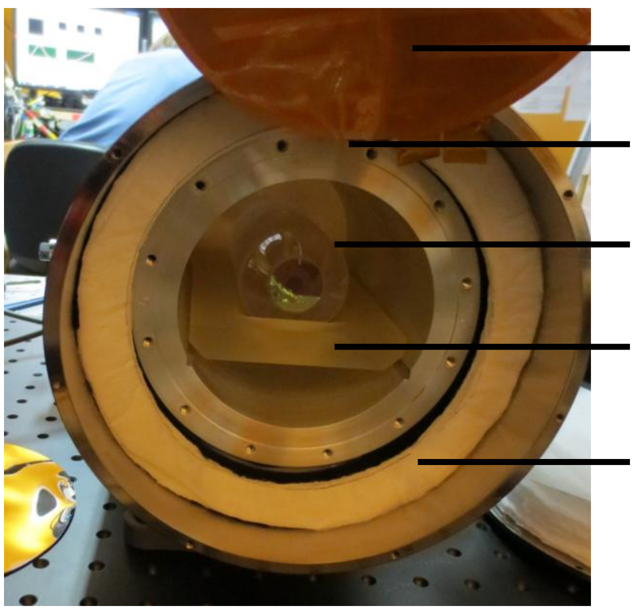
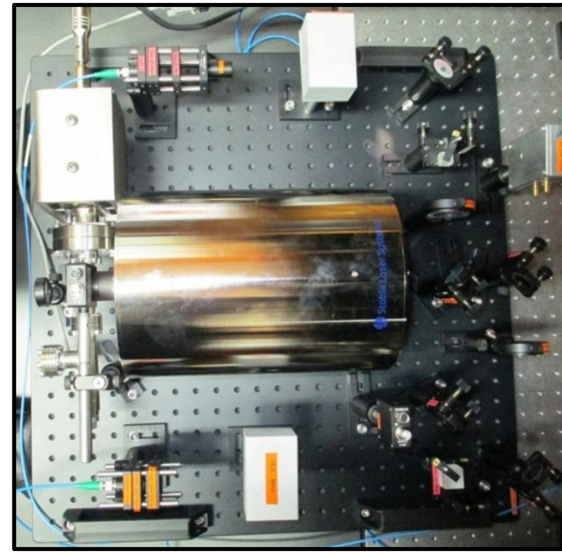
Rb_2 : F. Lang *et al.*, PRL, **101**, 133005 (2008).

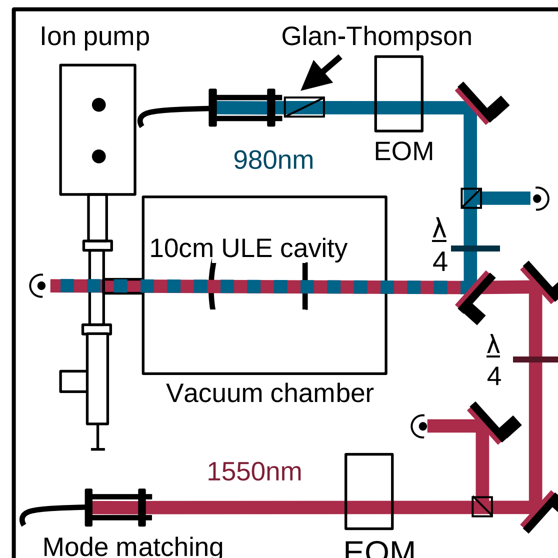
^{40}K-^{87}Rb : K.-K. Ni *et al.*, Science, **322**, 5899, (2008).

Next step: STIRAP

- Lasers referenced to ULE cavity[15] stabilised to 35°C zero-expansion point.
- FSR = 1.5 GHz; drift < 50 kHz/day.
- FWHM = 130 kHz@1550nm, 80 kHz@980nm.







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❶ The Rb Cs experiment.

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❸ Two species BEC: Immiscibility

❹ Feshbach spectroscopy of ^{87}Rb/^{85}Rb-Cs mixtures

❺ Progress towards ultracold polar molecules.

❻ Next generation experiment: YbCs

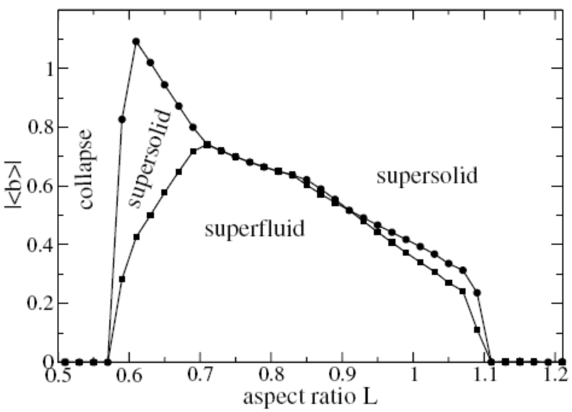
A Bosonic Dipolar Quantum Gas

$$V_{\text{int}} = d_{\text{eff}}^2 \frac{1-3\cos^2\theta}{|\vec{r}-\vec{r}'|^3} + \frac{4\pi\hbar^2 a}{M}\delta(\vec{r}-\vec{r}')$$

Dipole-dipole interaction

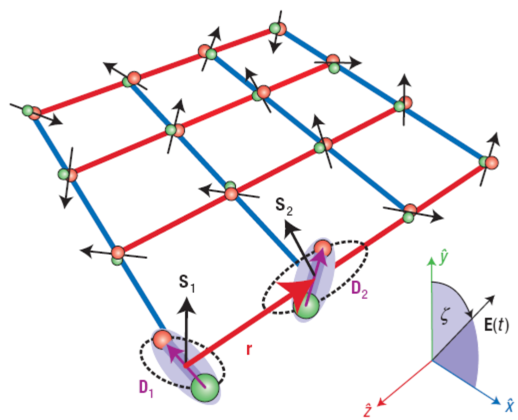
Contact interaction

Novel quantum phases:



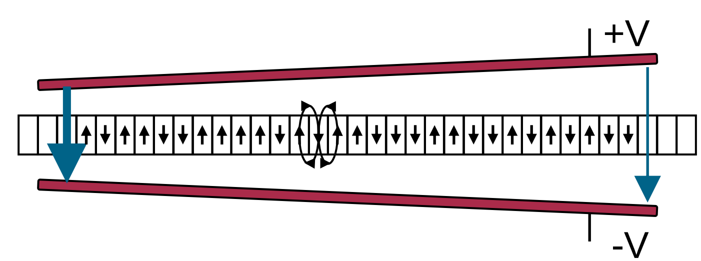
Góral, PRL **88**, 170406 (2002)

Lattice spin models:



Micheli, Nat. Phys. **2**, 341 (2006)

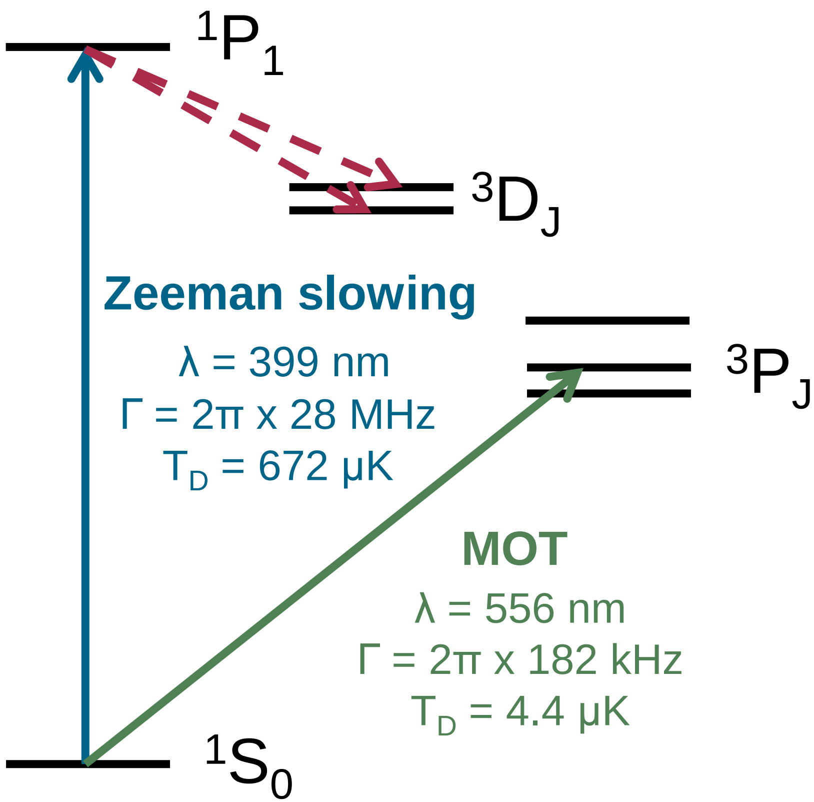
Quantum computation:



DeMille, PRL **88**, 067901 (2002)

Ultracold chemistry & Precision measurement.

Ytterbium



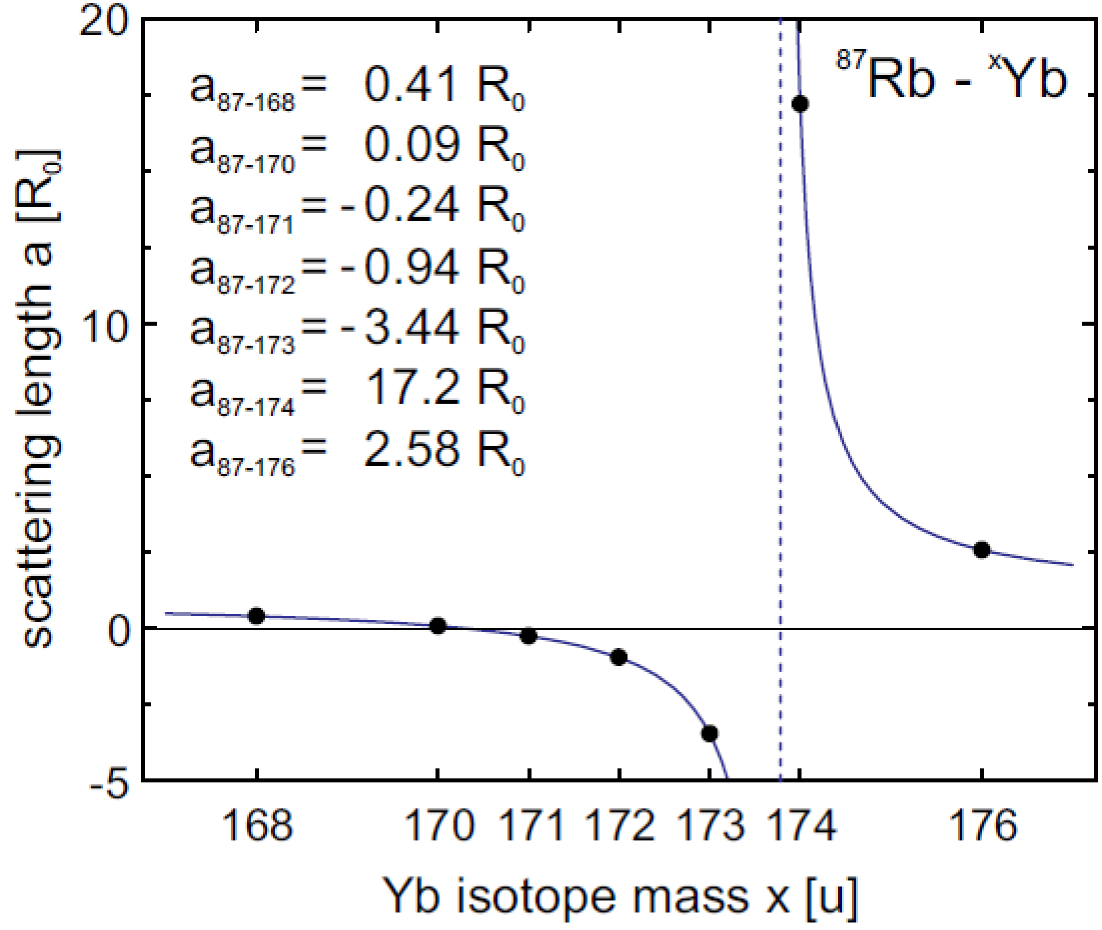
- 7 stable isotopes
- Bosons & fermions
- Low MOT temperature

Isotope	Abundance (%)	Nuclear spin	Scattering length (nm)
168	0.13	0	13.33(18)
170	3.05	0	3.38(11)
171	14.3	$^1/_2$	-0.15(19)
172	21.9	0	-31.7(3.4)
173	16.12	$^5/_2$	10.55(11)
174	31.8	0	5.55(8)
176	12.7	0	-1.28(23)

Why YbCs?

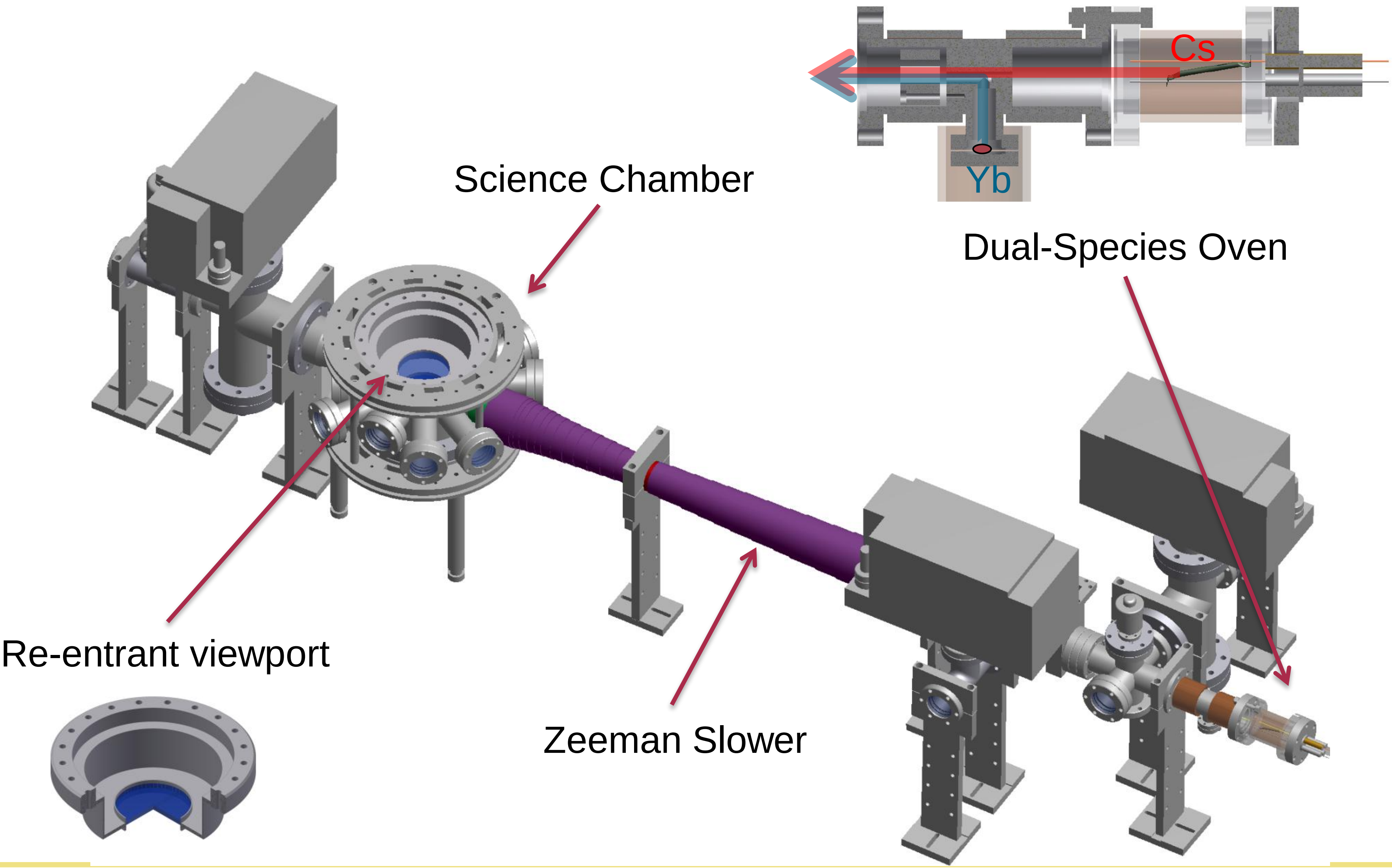
- Reduced mass tuning of scattering length

E.g.



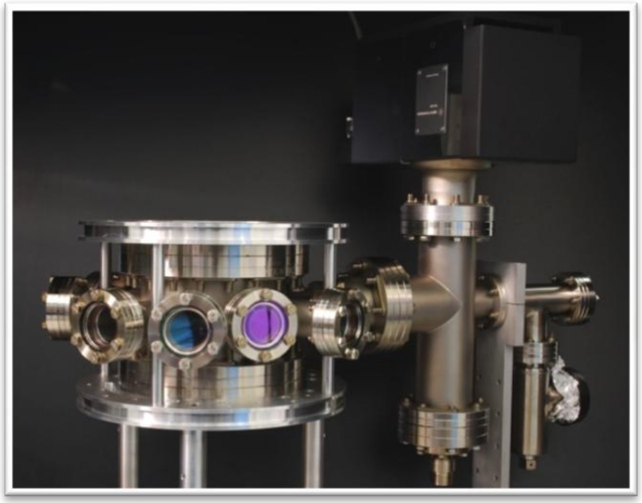
Baumer, F., Thesis, *Heinrich-Heine-Universitat Düsseldorf,* 2010

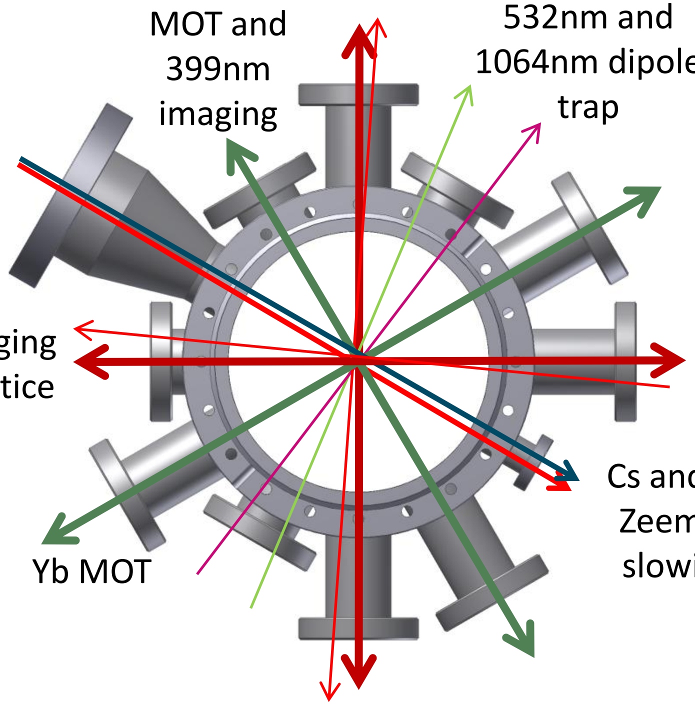
Vacuum system



The science chamber

- Use degenerate Raman sideband cooling for Cs
- Load both species into bichromatic optical trap
- Re-entrant flanges for high magnetic fields

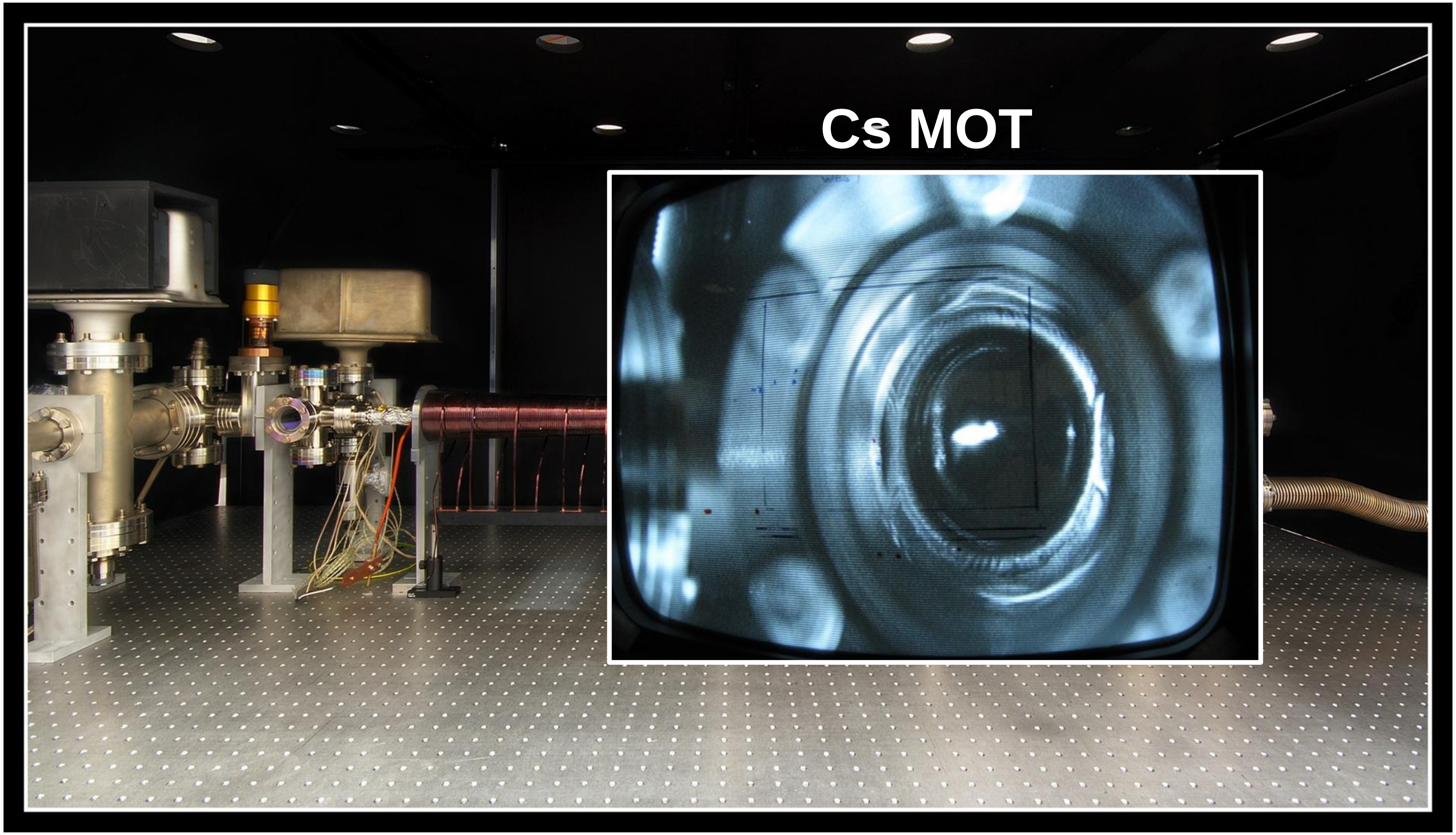




Polarisabilities for **bichromatic optical trap**

	532nm (a_0^3)	1064nm (a_0^3)
Yb	260.6	158.0
Cs	-223.8	1136.5

The assembled system



Feshbach resonances?

Zuchowski, Aldegunde & Hutson PRL **105**, 153201 (2010)

For alkalis – Hamiltonian:

$H = T + \xi_a i_a.s_a + \xi_b i_b.s_b + H_{zeeman}$

$+ \Sigma |S> V_S(R) <S| + V_{dipolar}(R)$

↑

Singlet and triplet potentials – couples atomic And molecular states: Feshbach resonances

For alkali + ^{1}S atom – only one potential $^2\Sigma$

$H = T + V(R) + \xi i.s + B_z(g_i i_z + g_s s_z)$

BUT hyperfine coupling constant is R dependent
- **coupling and Feshbach resonances**

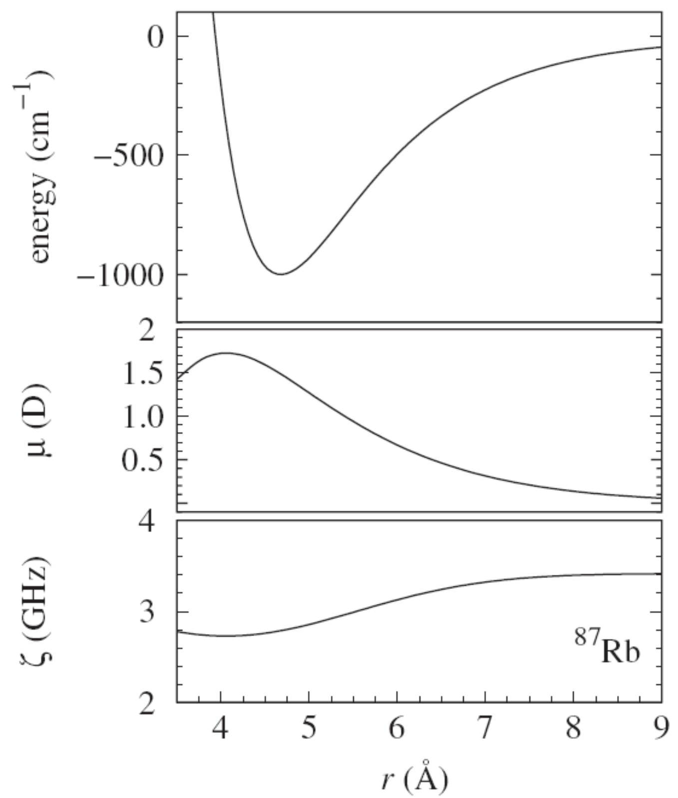
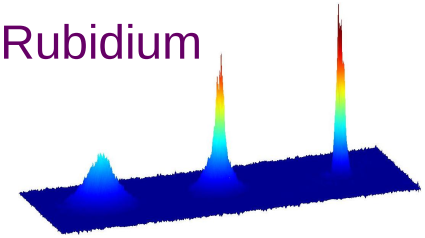


FIG. 1. Interaction potential $V(r)$ (top) with dipole moment $\mu(r)$ (middle) and hyperfine coupling constant $\zeta(r)$ (bottom). The binding energy and equilibrium distance are calculated to be 1000 cm^{-1} and 4.67 Å, respectively.

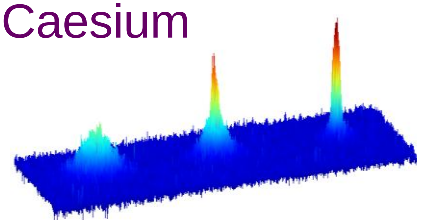
Summary

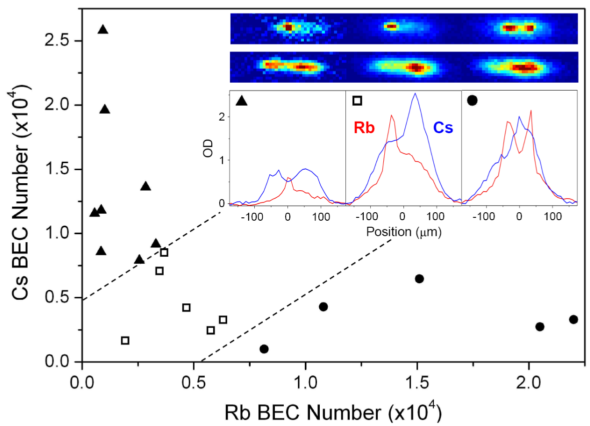
1. Bose-Einstein condensation of Rb and Cs!
2. Immiscible two species BEC.
3. Interspecies Feshbach resonances located.
4. Magneto-association demonstrated.
5. STIRAP transfer under development.
6. YbCs experiment nearly online.

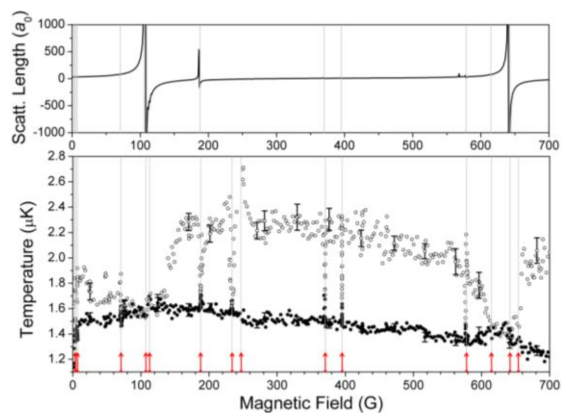
Rubidium

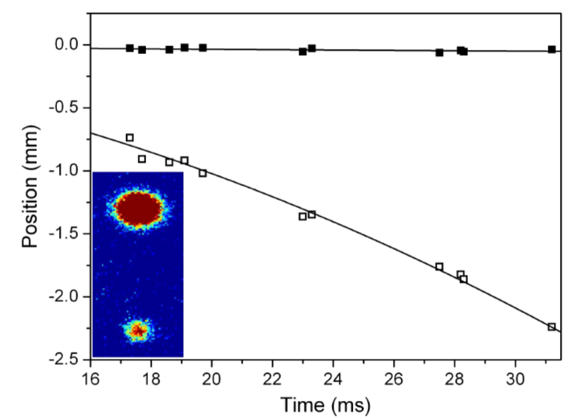


Caesium









Acknowledgements: my (levitated) group

+ Hung-Wen Cho, Caroline Blackley, Ruth Le Sueur and **Jeremy Hutson**

+ Ruben Freytag, Mike Tarbutt and Ed Hinds

Durham University
EPSRC Engineering and Physical Sciences Research Council
THE ROYAL SOCIETY
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Joint Quantum Centre WWW.JQC.ORG.UK