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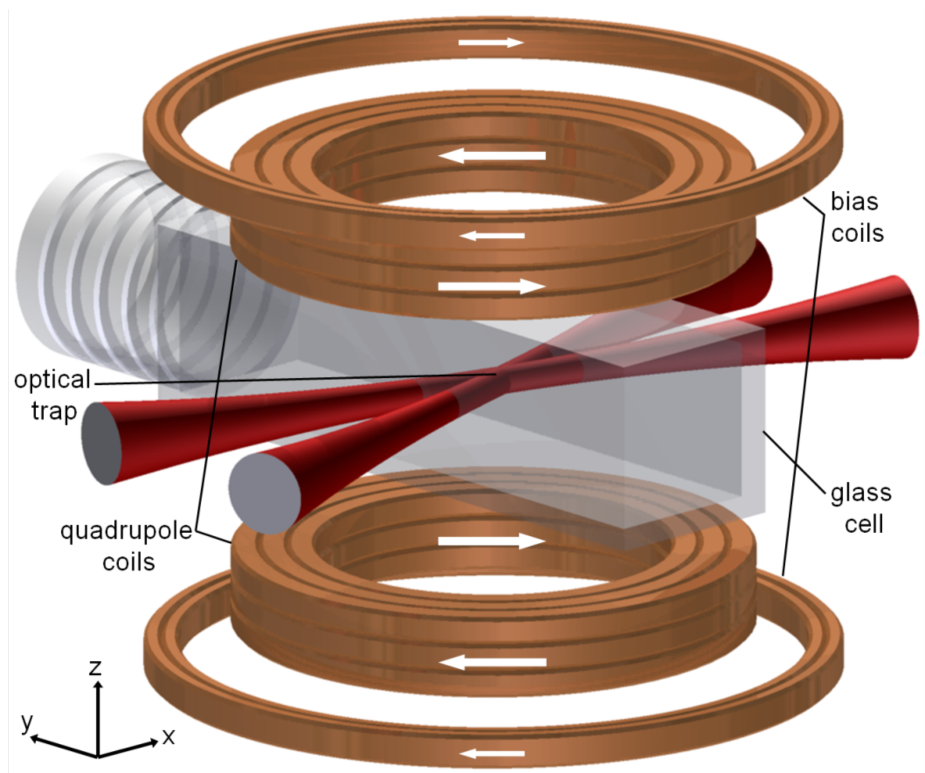
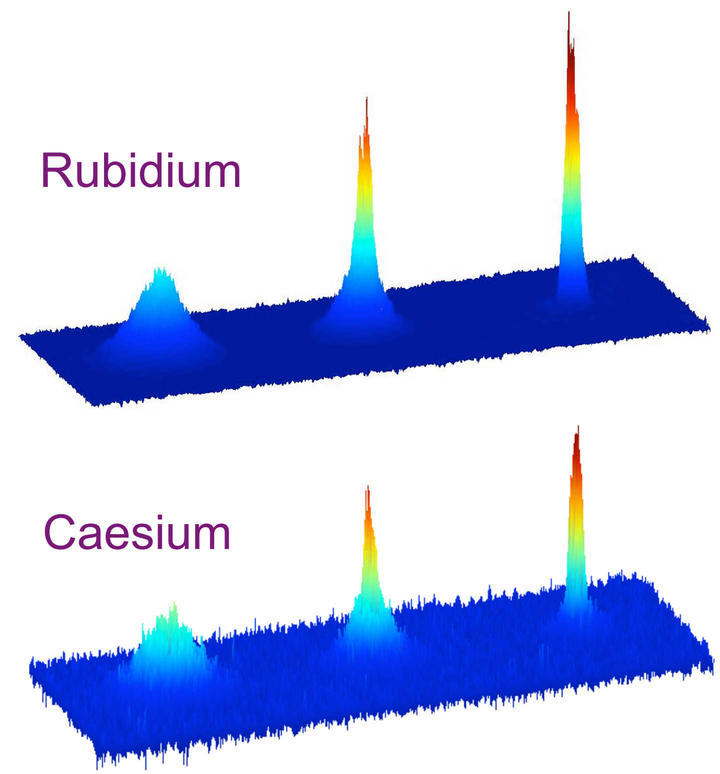
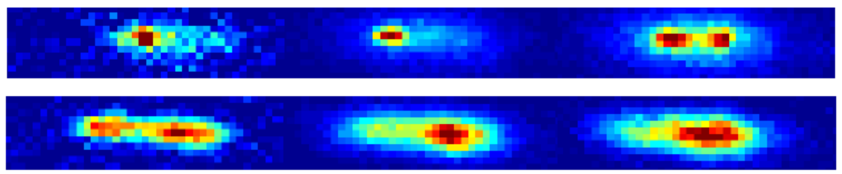
Observation of Feshbach resonances in ultracold ^{87}Rb and ^{133}Cs mixtures at high magnetic field







RbCs

Hung-Wen, Cho

Motivation

- Bialkali molecules in the ground state have a large permanent electric dipole moment
  ex. RbCs d=1.25 Debye

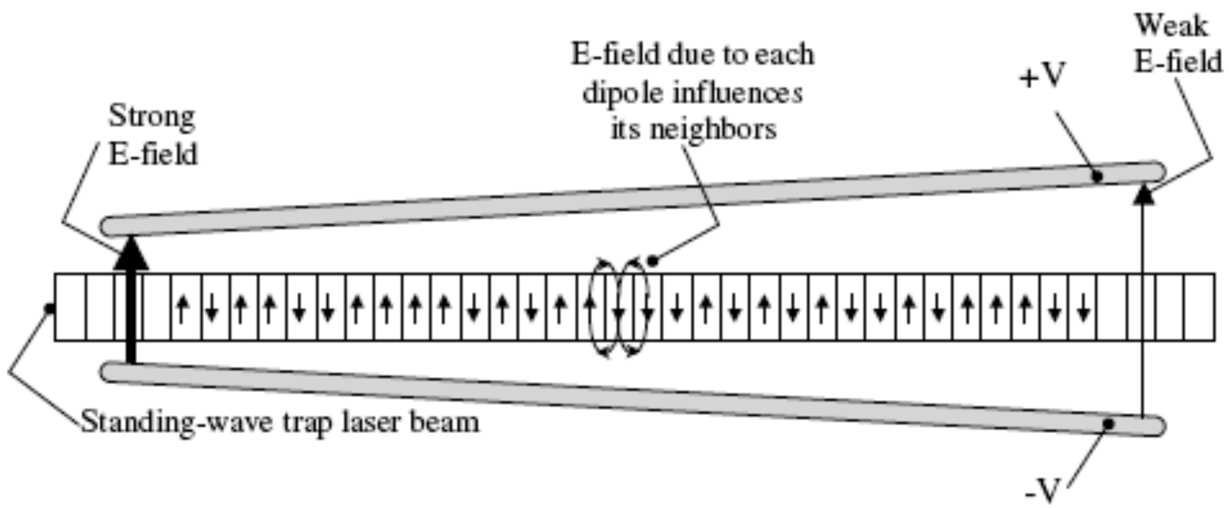
$$V_{int} = d^2 \frac{1 - 3cos^2\theta}{|\vec{r} - \vec{r'}|^3} + \frac{4\pi\hbar^2 a}{M}\delta(\vec{r} - \vec{r'})$$

Dipole-dipole interaction

Contact interaction

^{52}Cr BEC_PRL, 101, 080401 (2008)

- Quantum computation with trapped polar molecules



PRL, 88, 067901 (2002)

- Ultracold chemistry and precision measurement
- Molecules clocks
- Electric dipole moment (EDM) measurement

Nature 473, 493 (2011), Phys. Rev. A 84, 042504 (2011)

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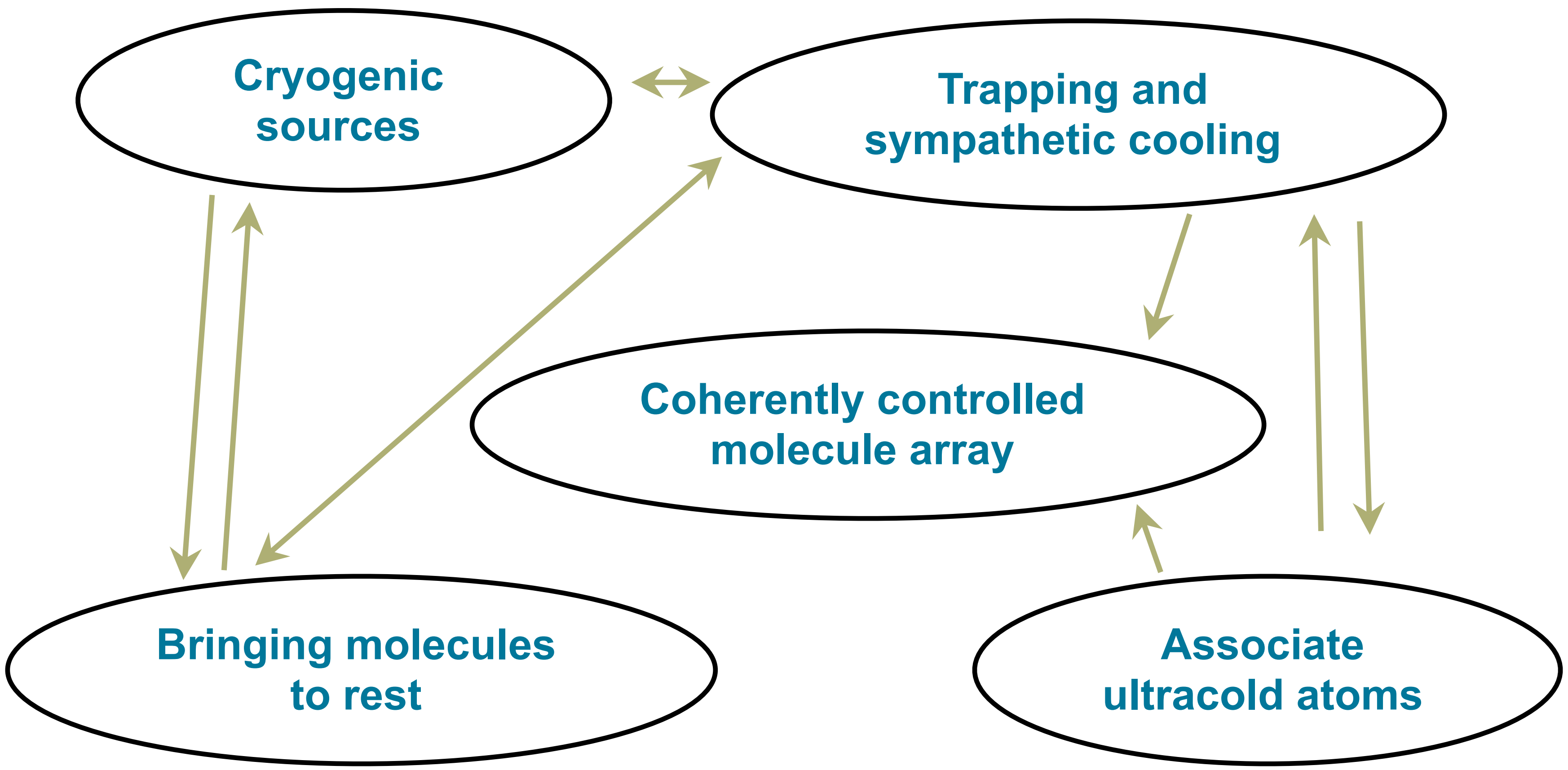
- Helium buffer-gas

- ^{7}Li, Rb
- Microwave cavity trap



- Photostop
- Magnetic decelerator
- Stark decelerator

- RbCs
- YbCs

MMQA_MicroKelvin Molecules in a Quantum Array

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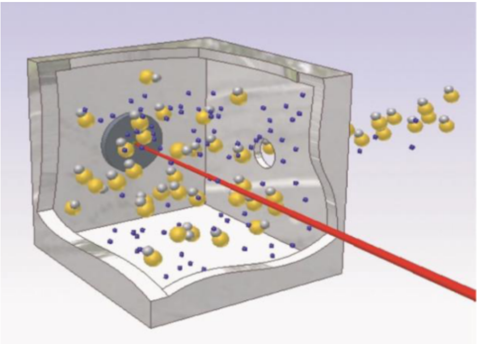
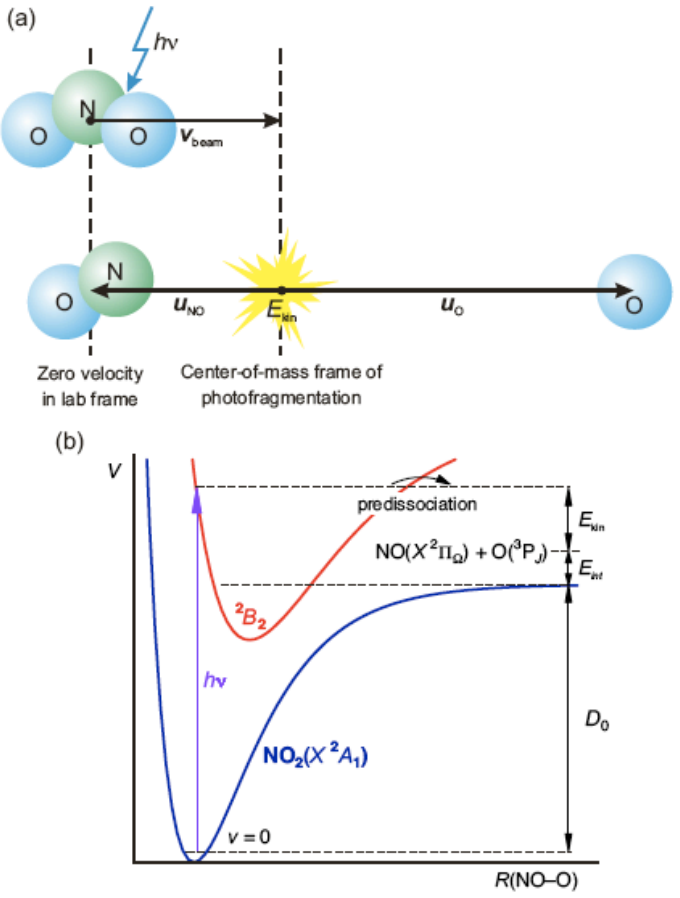
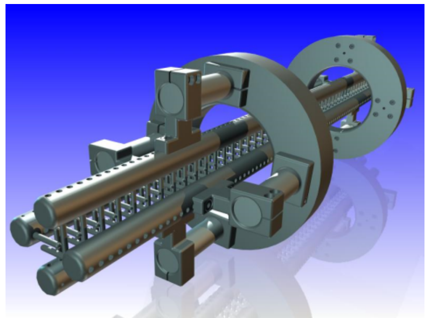
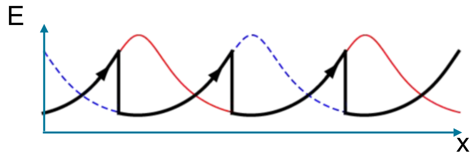
Professor EA Hinds (Physics ICL)
Dr MR Tarbutt (Physics ICL)
Professor JM Hutson (Chemistry Durham)
Dr SL Cornish (Physics Durham)
Dr D Carty (Physics & Chemistry Durham)
Dr E Wrede (Chemistry Durham)



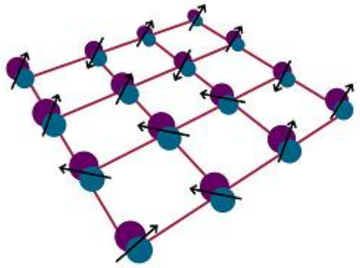


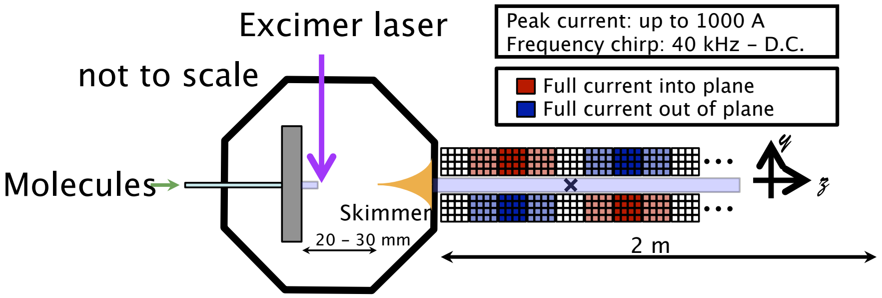




Helium buffer-gas cooling
YbF, T:3K d=10^{17} cm^{-3}
LiH, CaF, SO, OH
Stark decelerator (Electric)
LiH brought to rest
removed 50% of E_{kin} of CaF
Sympathetic cooling
^{7}Li and ^{87}Rb
Li in magnetic trap (300μK), overlap with LiH from Stark decelerator (50mK) ->5mK after 0.6s
try cool Li using rf evaporation

RbCs, CsYb Mixture
Zeeman decelerator (Magnetic)
PhotoStop
Theory





- Bose-Einstein condensations (BECs)
  - ^{87}Rb BEC in a combined magnetic and optical trap
  - ^{133}Cs BEC in a crossed dipole trap
  - A quantum degenerate Bose mixture of ^{87}Rb and ^{133}Cs
- Feshbach molecules
  - The formation background and method
  - ^{87}Rb^{133}Cs Feshbach resonance measurement
- Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon scheme transfers the Feshbach molecules into the rovibronic ground state
- Summary

Atoms in which laser cooling has been demonstrated[1]:

Alkali metals	Alkaline earth metals	Noble Gases	Lanthanide	Others
Li	Mg	He	Dy	Cr
Na	Ca	Ne	Er	Ag
K	Sr	Ar	Tm	Cd
Rb	Ra	Kr	Yb	Hg
Cs	Ba	Xe		Al
Fr				

Feshbach molecules:

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[1](Steele, J. Vac. Sci. Technol. B 28, C6F1 (2010))

Laser cooling & Feshbach resonance

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RbCs is one of the stability of quantum gases of alkali-metal dimers

ex.

$XY+XY \rightarrow X_2+Y_2$

$XY+XY \rightarrow X+XY_2$ or X_2Y+Y

PRA, 81, 060703(R) (2010)

	Na	K	Rb	Cs
Li	−328(2)	−533.9(3)	−618(200)	−415.38(2)
Na		74.3(3)	45.5(5)	236.75(20)
K			−8.7(9)	37.81(13)
Rb				29.1(1.5)

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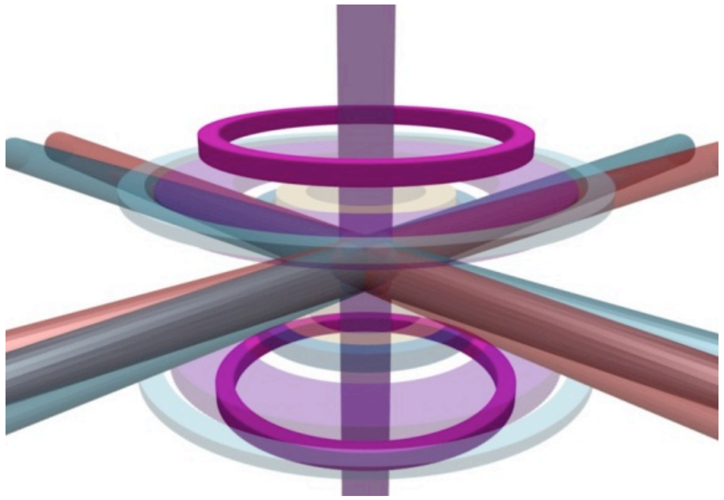
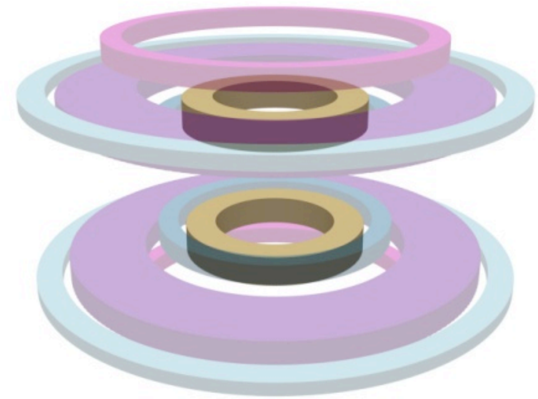
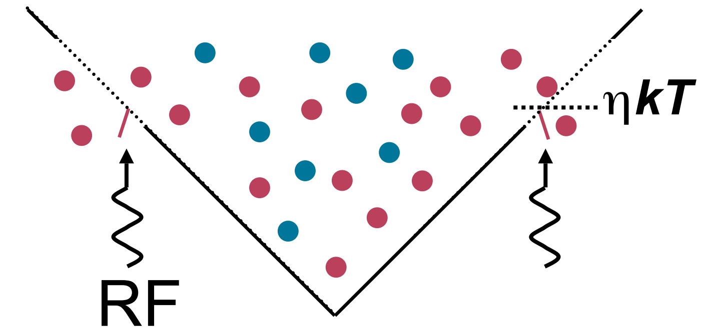
Cooling Process



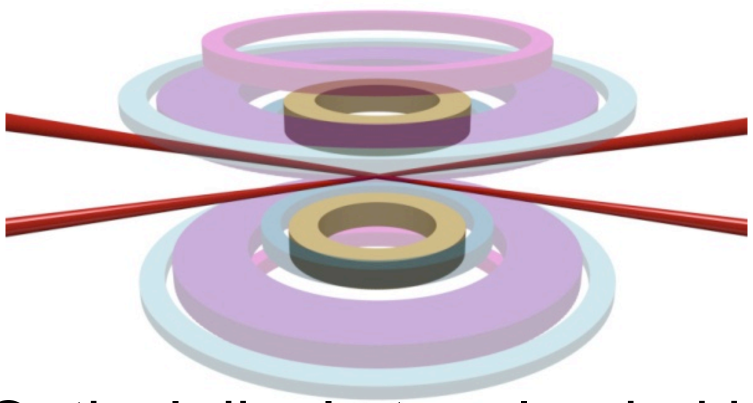
Atoms collected in MOT



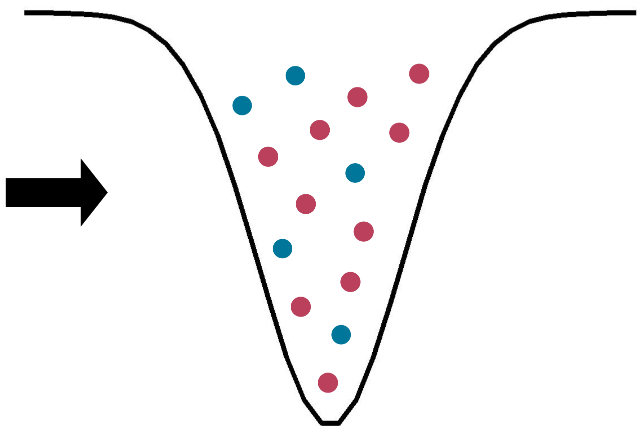
Load magnetic quadrupole trap



Evaporation in quadrupole trap

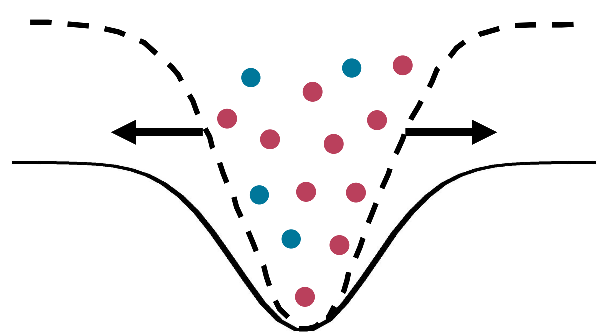


Optical dipole trap loaded by reducing field gradient



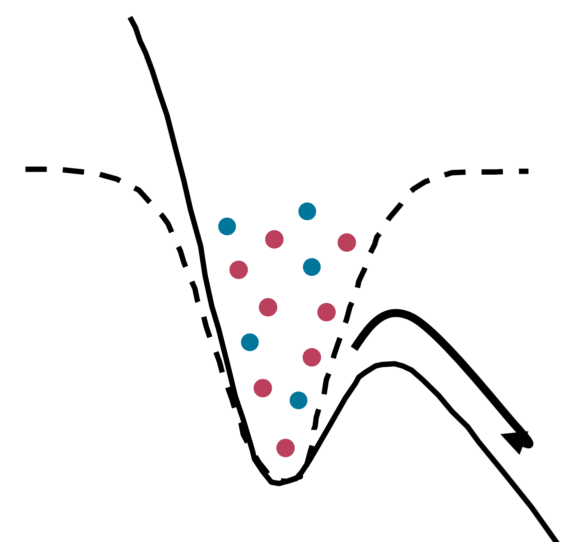
Levitated dipole trap

Final evaporation



Reduce the beam intensity to lower the trap depth

and



Apply a magnetic gradient to tilt the trap

Review

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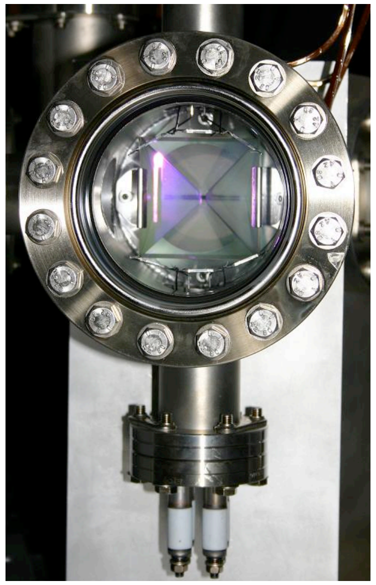
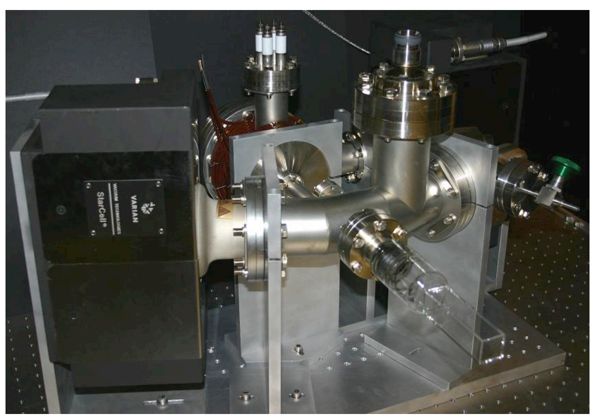
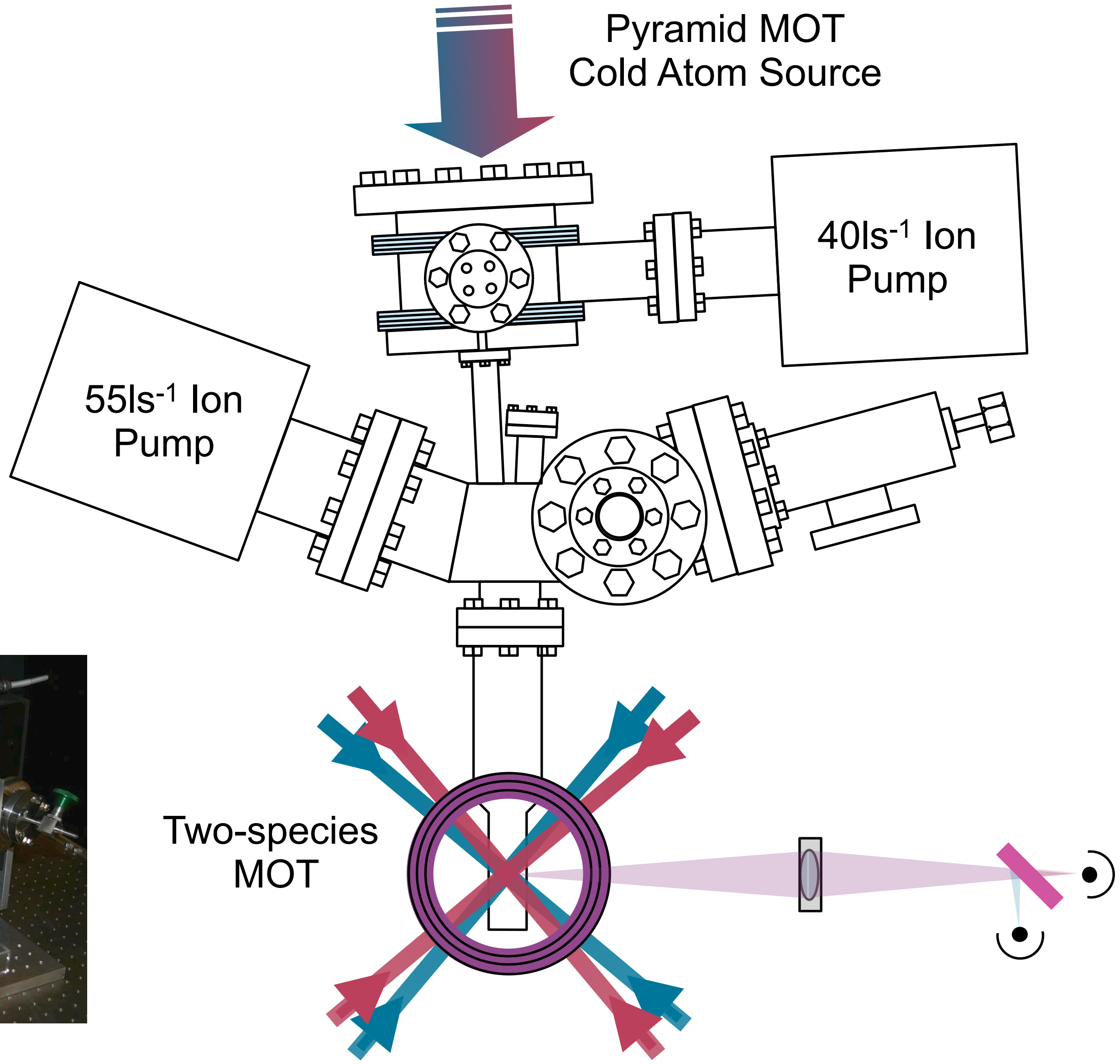


Pyramid Chamber



Vacuum System



- Cold-atomic beams source is created by Pyramid MOT.
- >9x10^{8} ^{87}Rb & 4x10^{8} ^{133}Cs can be obtained by science MOT.
- The optical potential is produced by two laser beams with waists of 70 μm and wavelength 1550nm from a 30 Watt IPG ELR-30-LP-SF

Review

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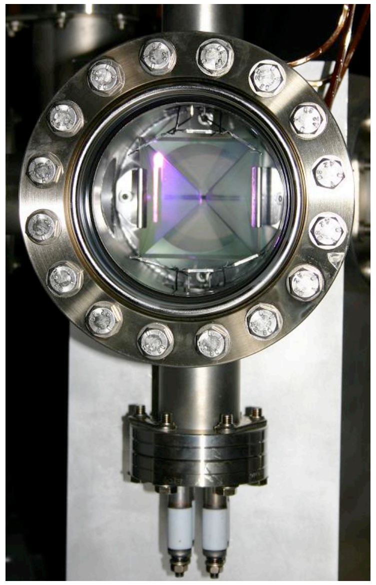

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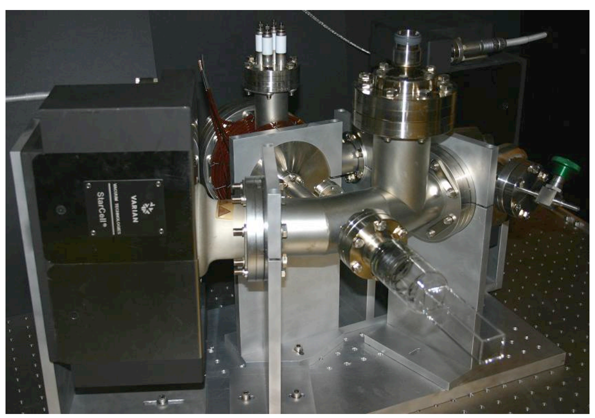

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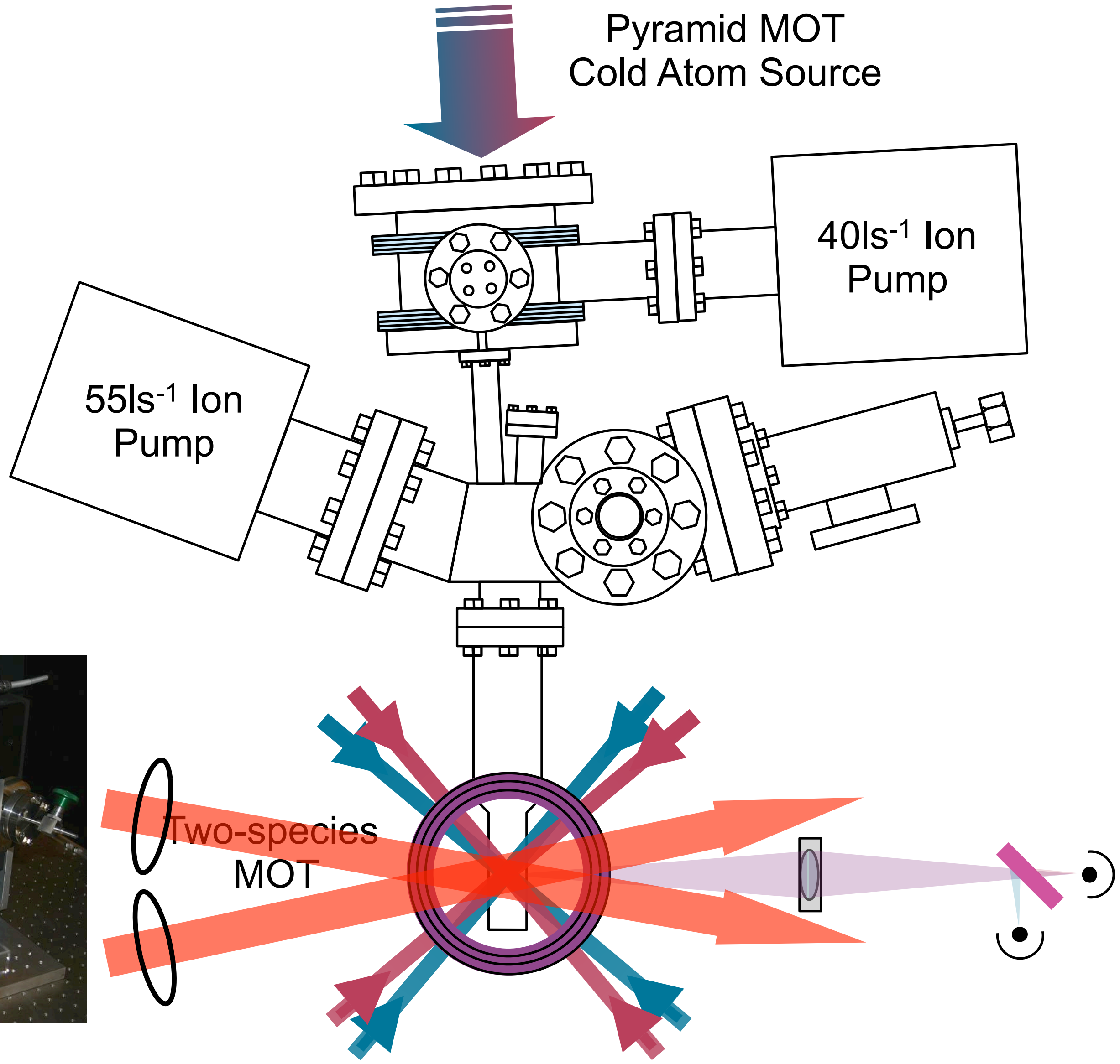

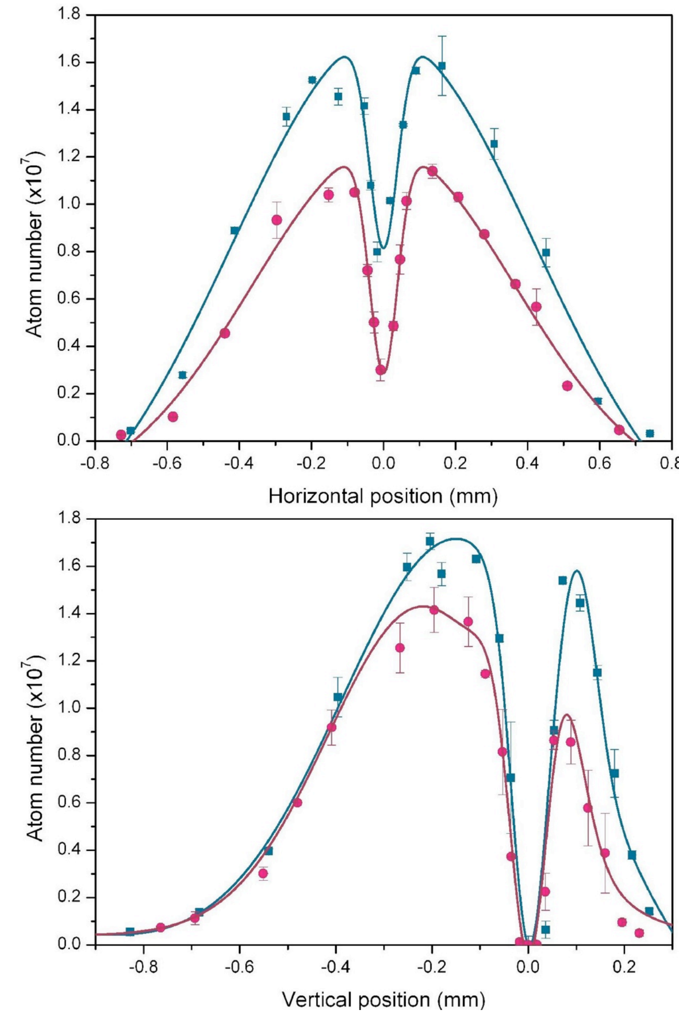

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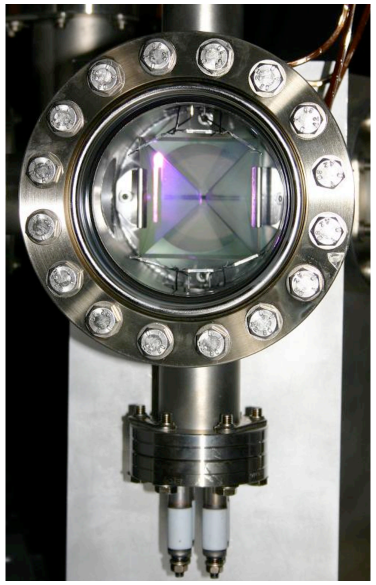

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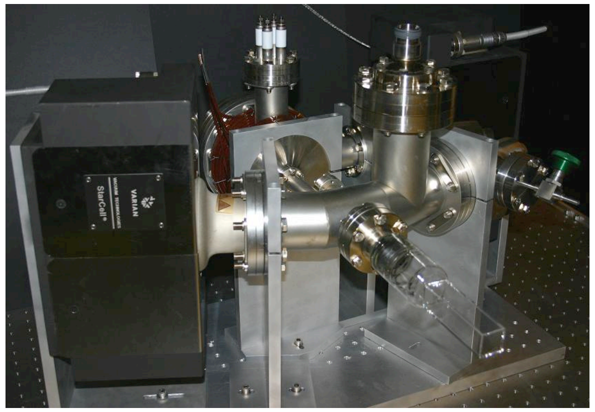

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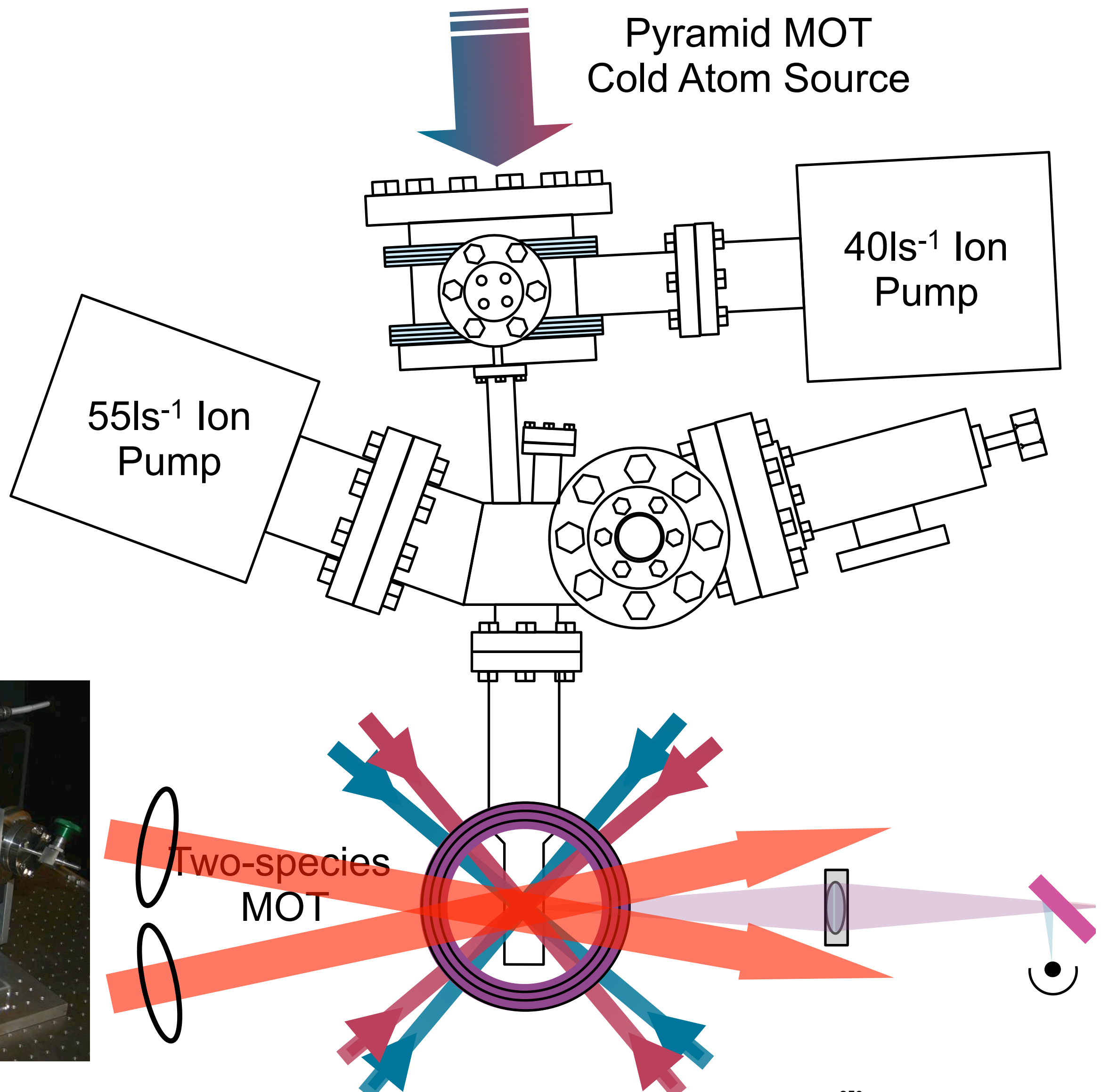

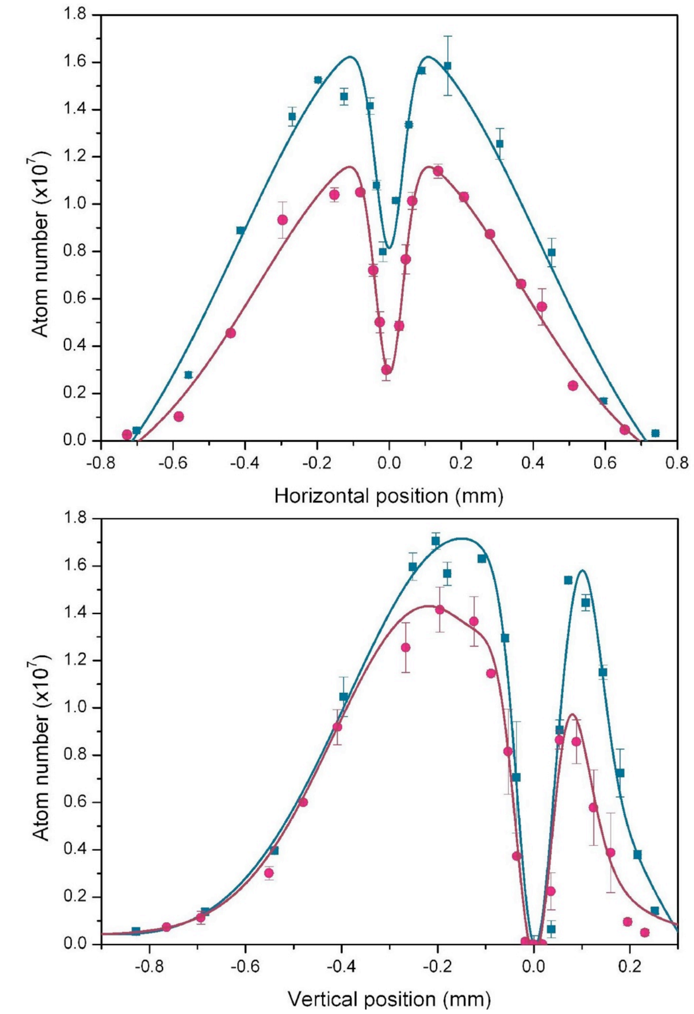

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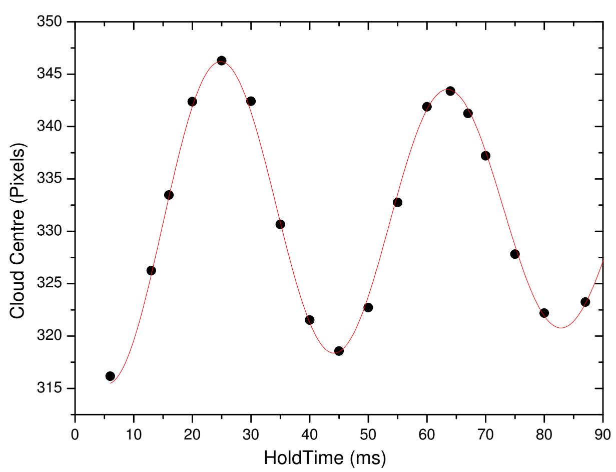
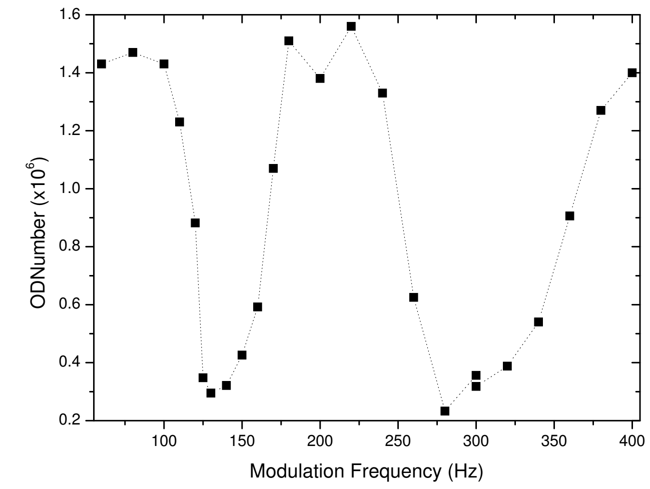
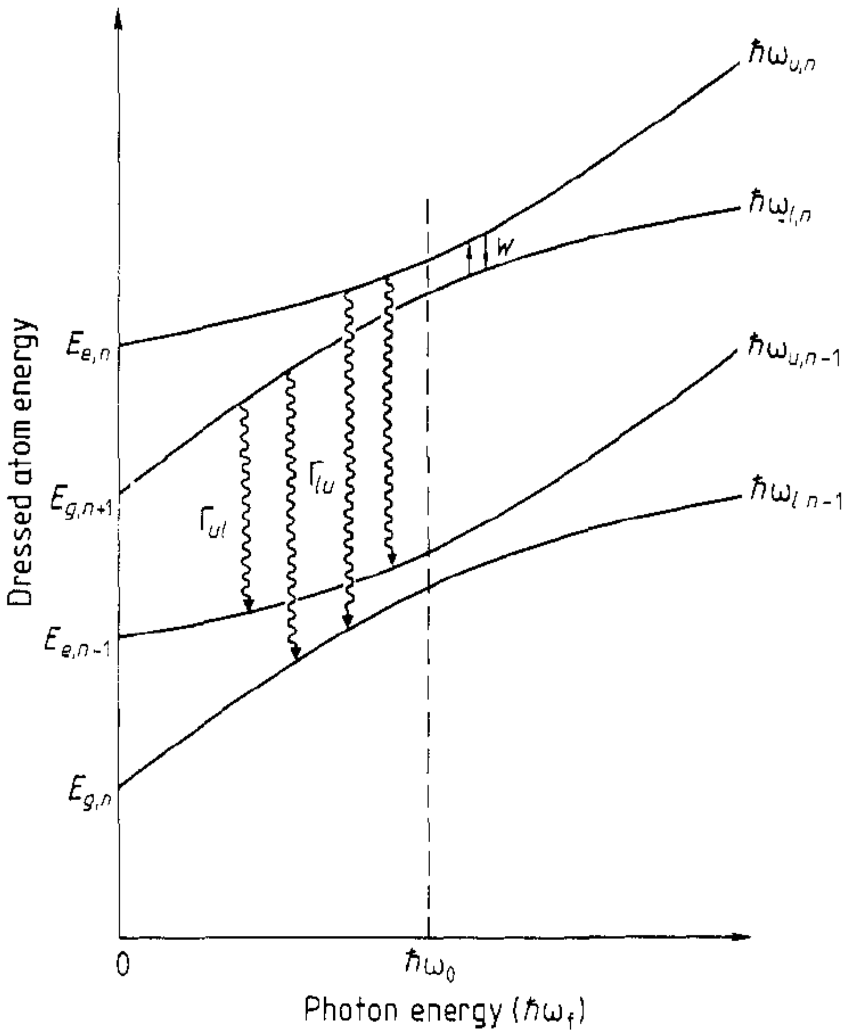




^{87}Rb BEC in a levitated crossed dipole trap

- Atoms are transferred into |1,+1> from |1,-1> by adiabatic rapid passage.
- A 26 x 26 mm square coil of 3 turns are driven to create an RF Filed at 1.5 MHz. A bias field of 22.4 G is then switched on to cross the RF Zeeman resonance at 2.1 G.



$$P_{ad} = 1 - \exp(-\pi\omega_1^2/2|\alpha|)$$

$$\omega_1^2 \gg |\alpha| = (d/dt)|\omega_0 - \omega_f|$$

J. Phys. B: At. Mol. Phys. 17 (1984) 4169-4178

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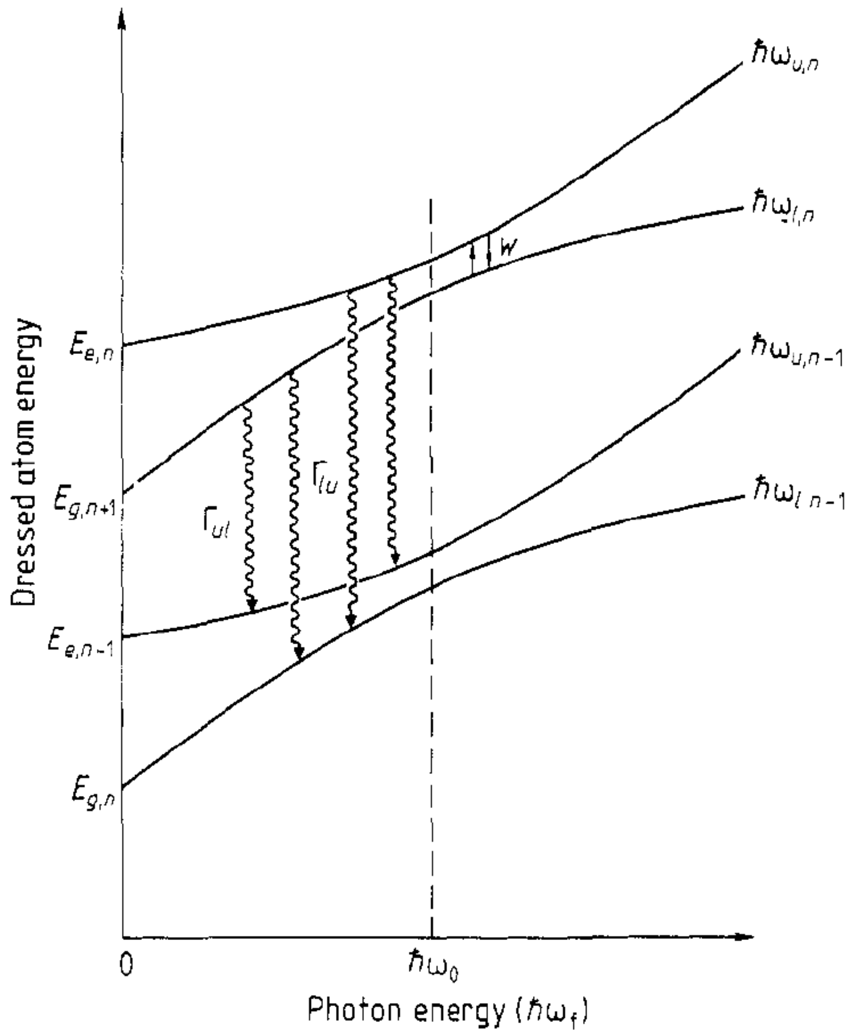

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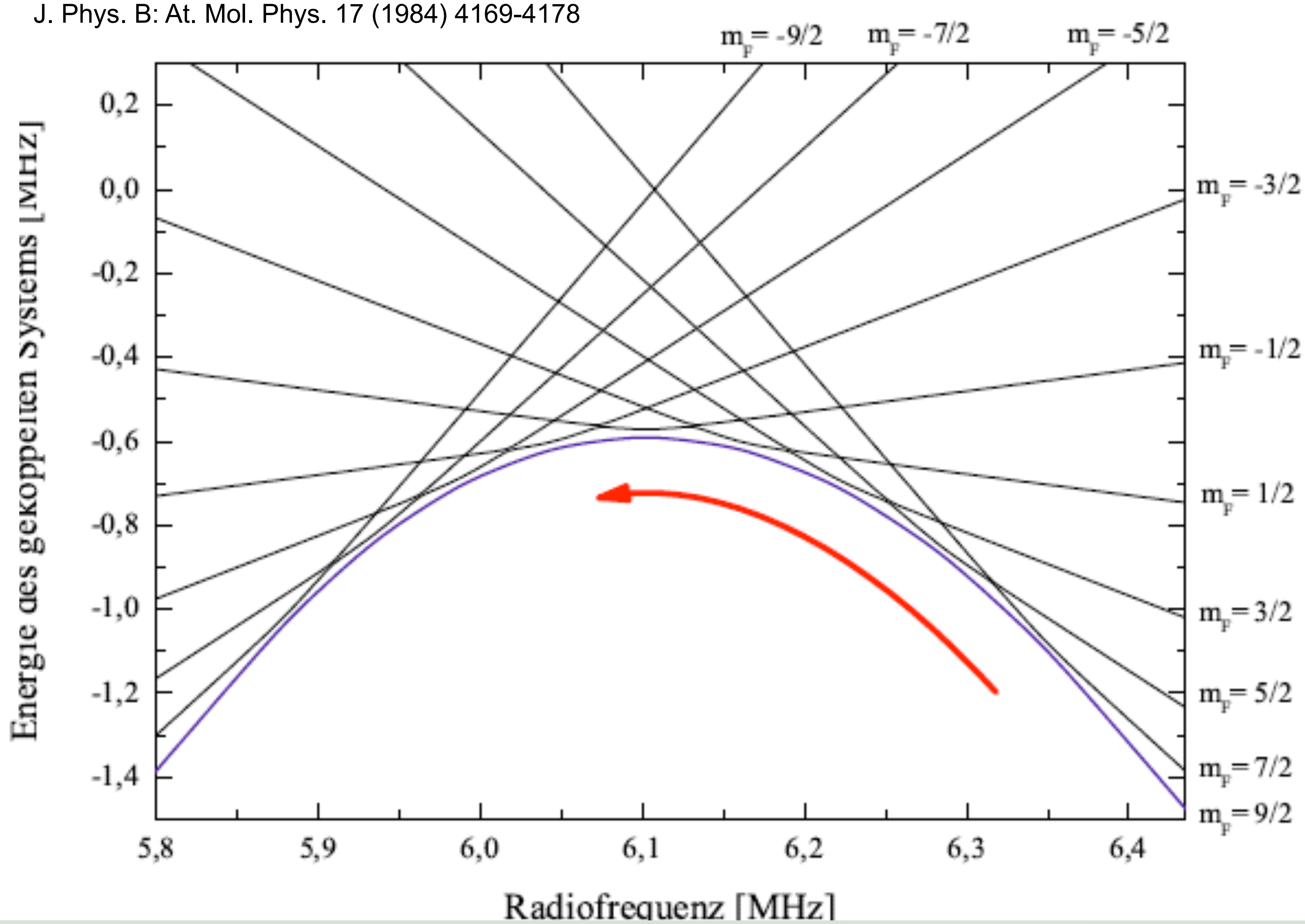

Carsten Klempt Thesis

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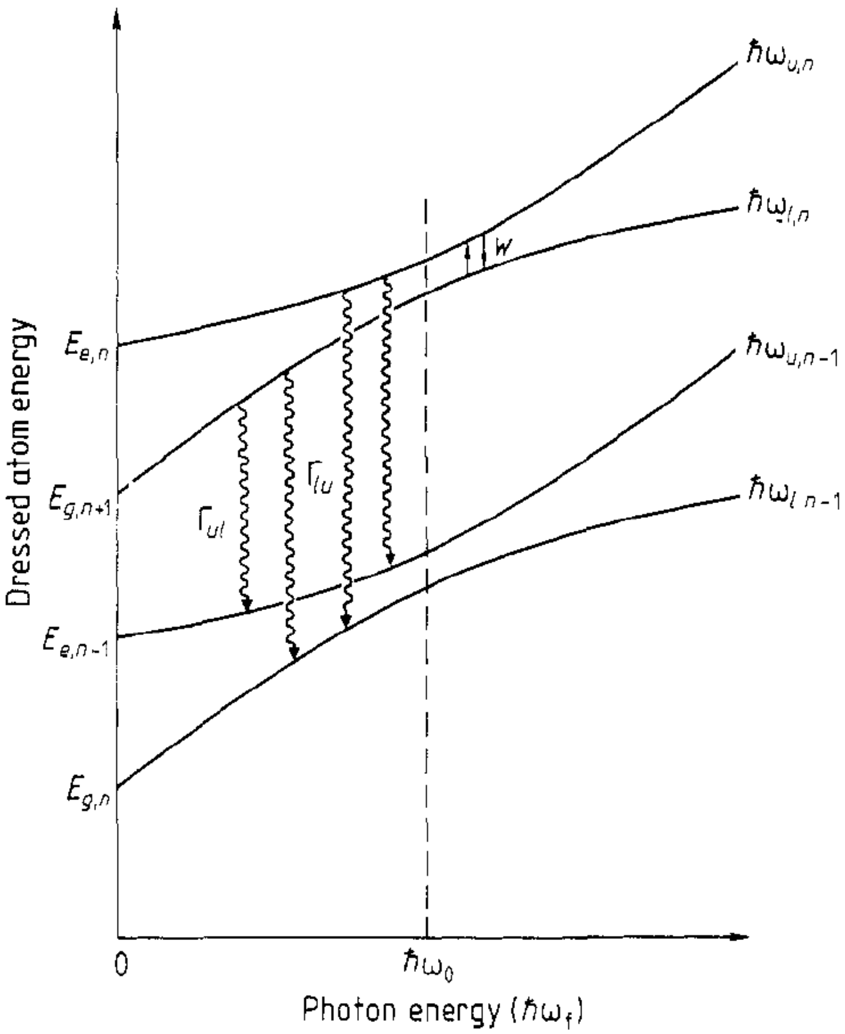

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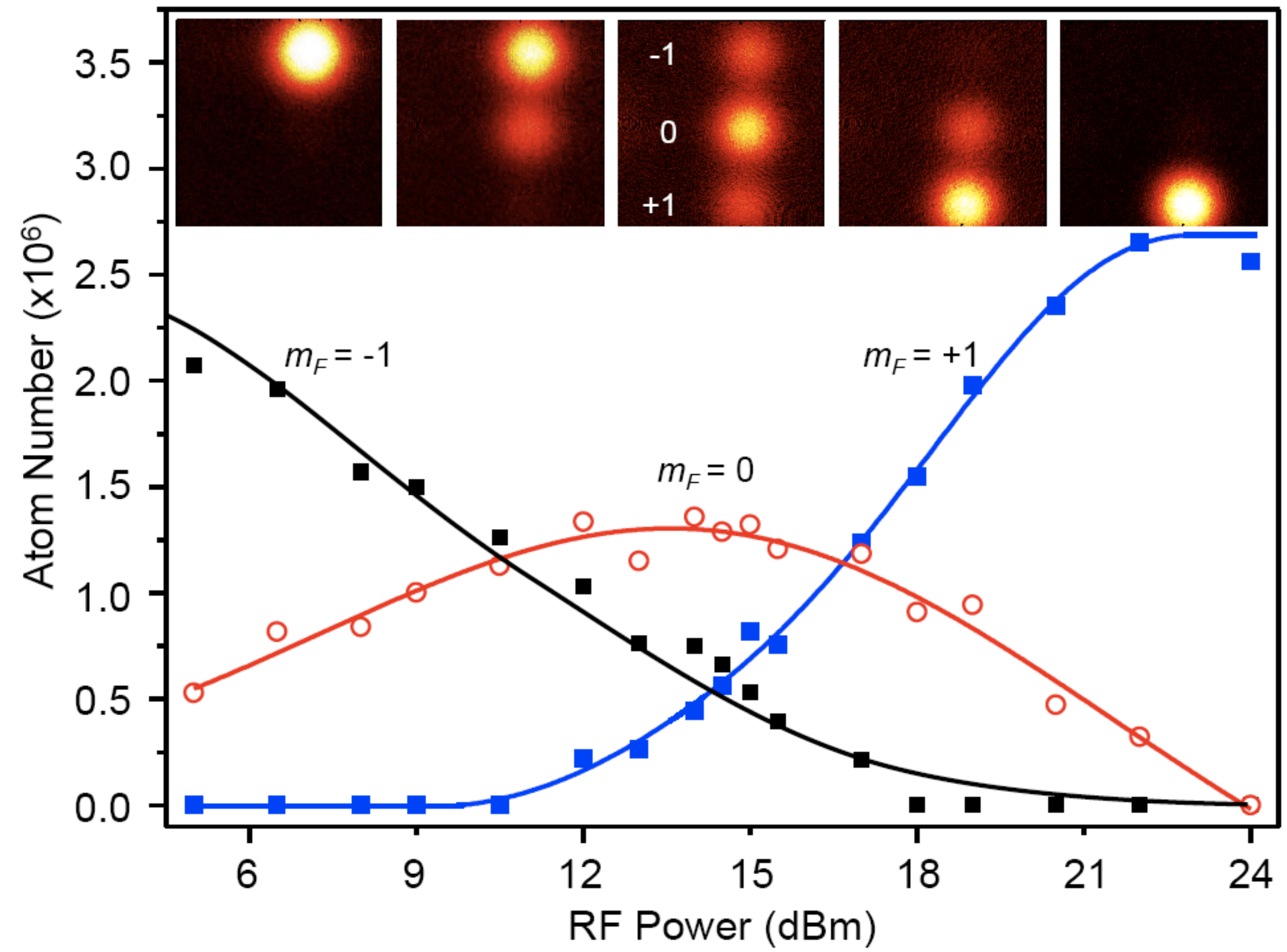

^{87}Rb BEC in a levitated crossed dipole trap

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- The phase-space density trajectory to BEC of ^{87}Rb (|1,+1>) in the cross dipole trap. N_{BEC} = 1 x 10^6
- Control the depth of the levitated crossed dipole trap by manipulating the magnetic field gradient.
  C. Chin, Phys. Rev. A, 78, 011604(R), 2008
- Sympathetic cooling of different spin states in the levitated cross dipole trap by a tilting potential. The inset shows the vertical cross-section through the potential minimum for a beam power of 0.45 W and a magnetic field gradient of 13 G/cm.
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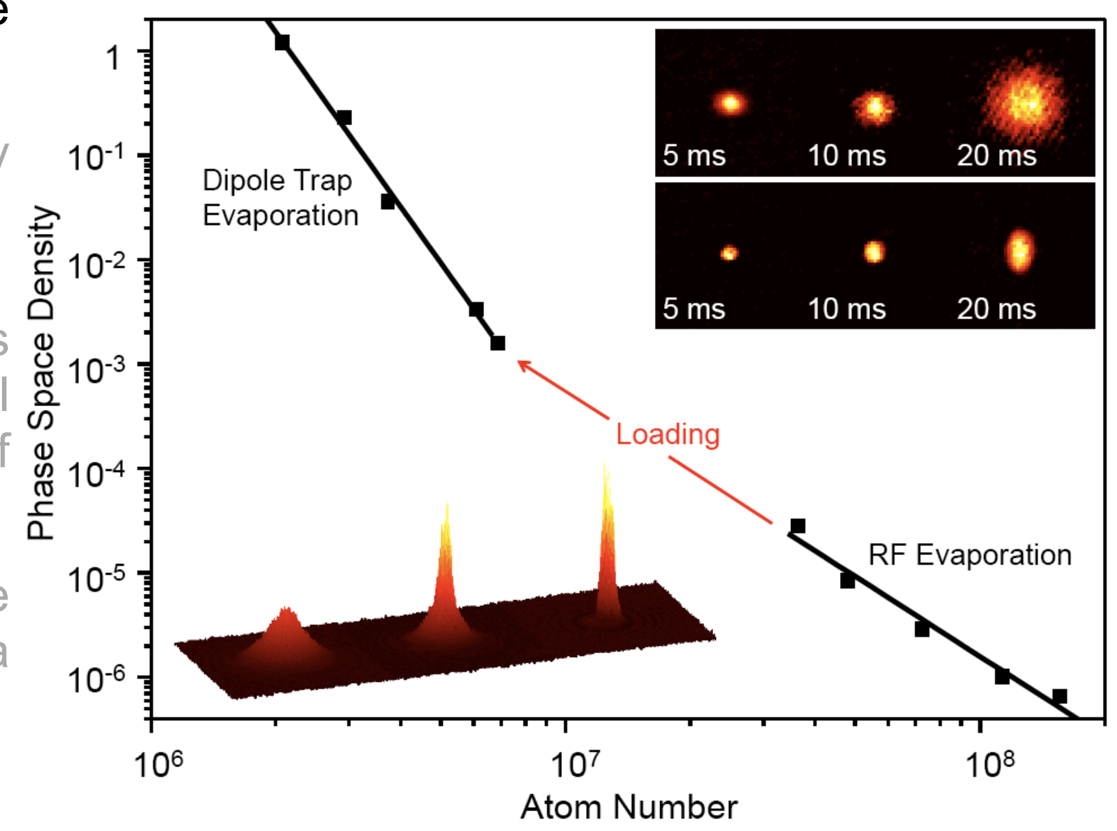

Durham University

Eur. Phys. J. D ((DOI: 10.1140/epjd/e2011-10720-5))

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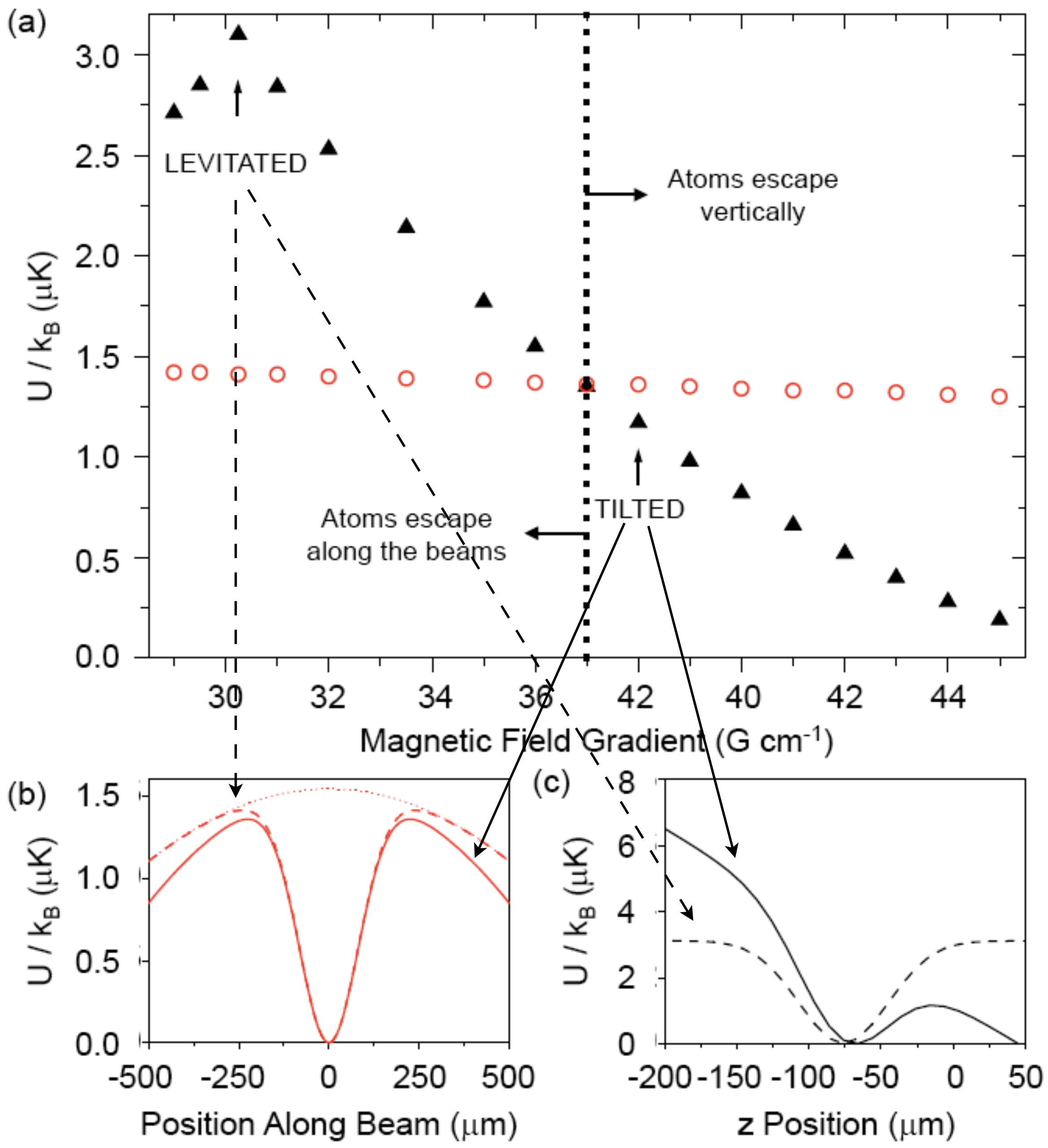

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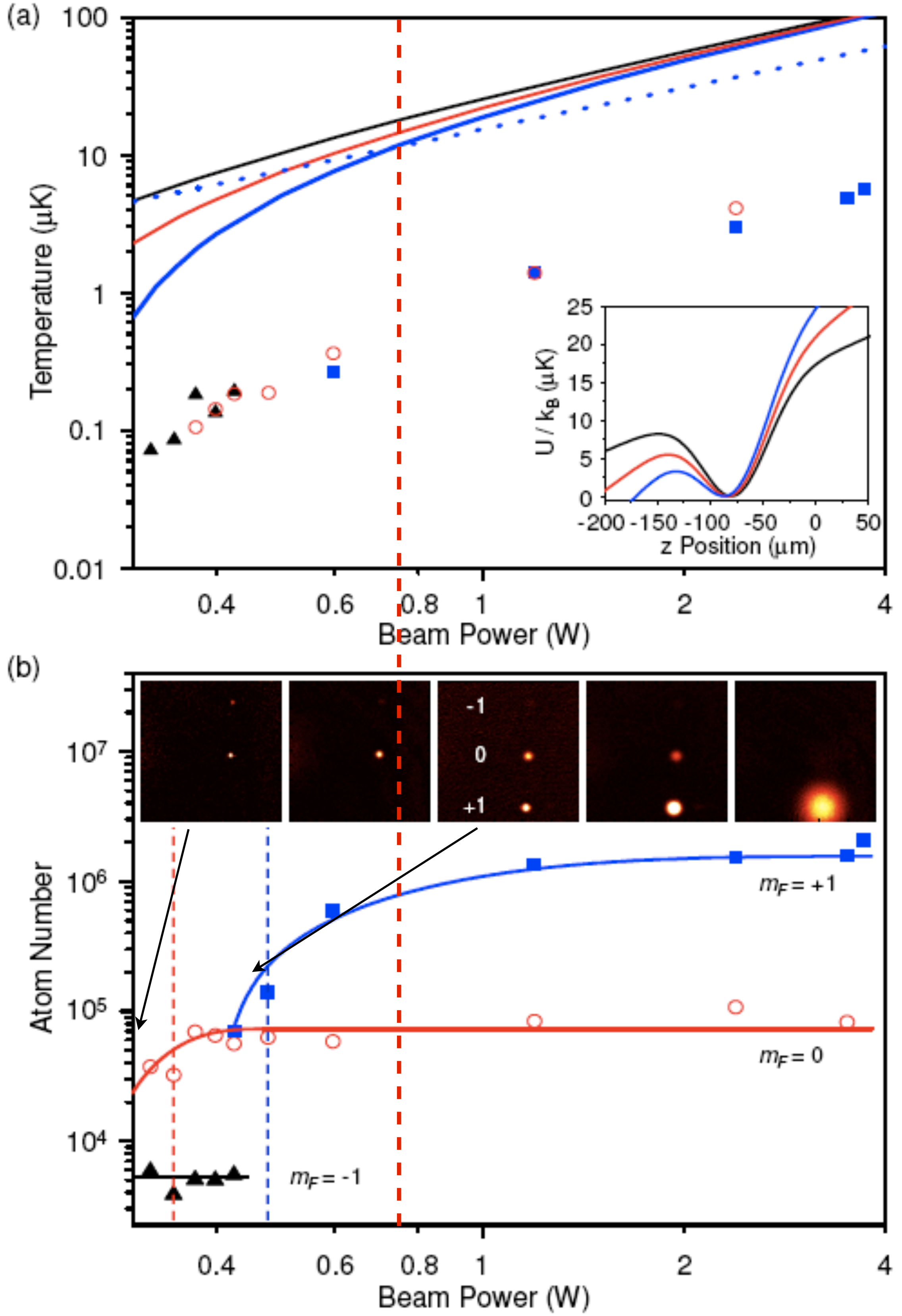
- Application of the experiment to sympathetic cooling of ^{133}Cs. The dipole trap potential corresponds to 100 mW in each beam, a magnetic field gradient of 38 G/cm and a bias field of 22.4 G.



Eur. Phys. J. D ((DOI: 10.1140/epjd/e2011-10720-5))

^{87}Rb BEC in a levitated crossed dipole trap

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- The phase-space density trajectory to BEC of ^{87}Rb (|1,+1>) in the cross dipole trap. $N_{BEC} = 1 \times 10^6$
- Control the depth of the levitated crossed dipole trap by manipulating the magnetic field gradient.
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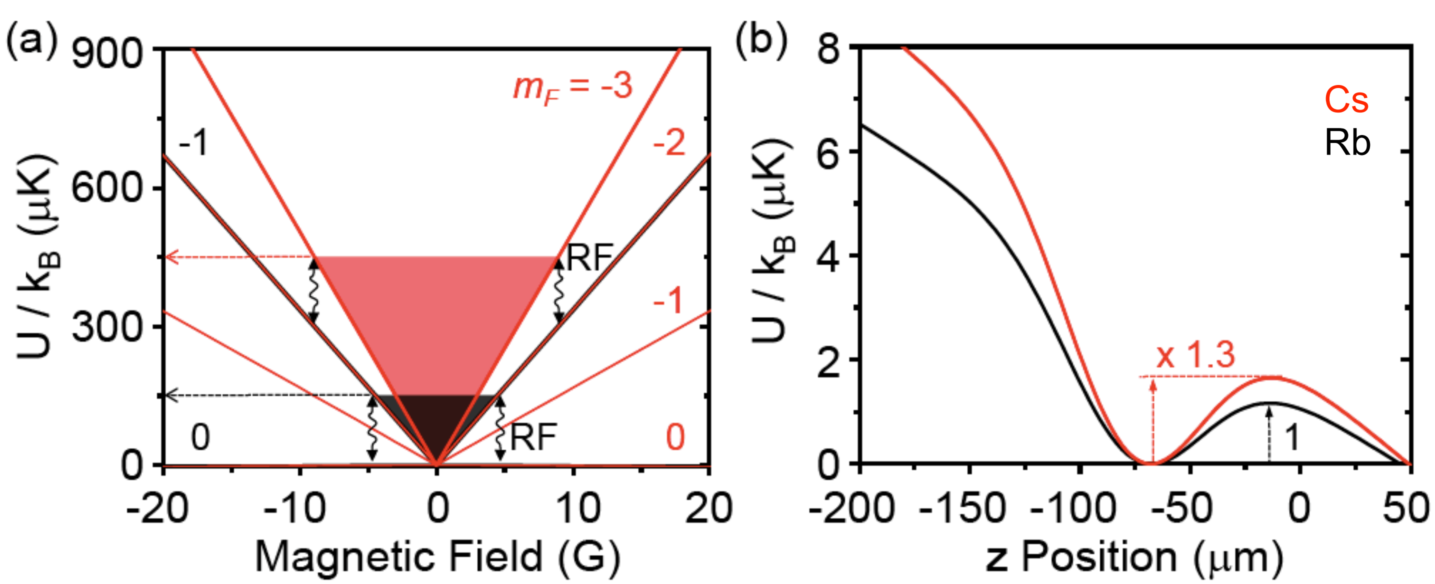

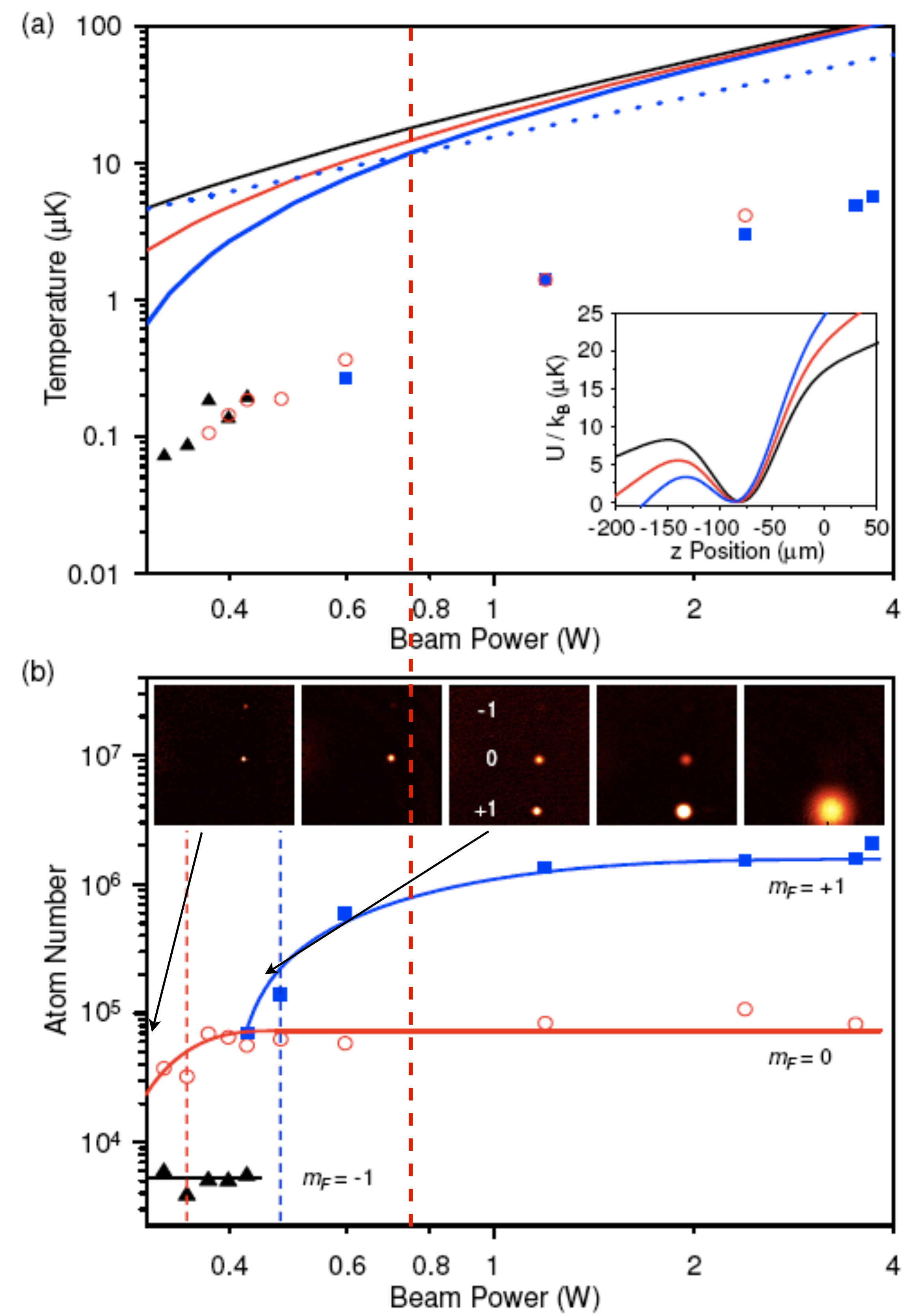

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^{133}Cs BEC in the cross-dipole trap

$$\Gamma_{El} = \langle n\rangle\sigma\langle v_R\rangle \propto \sigma = \frac{8\pi a^2}{1+k^2a^2}\ ,k = \frac{m\langle v_R\rangle}{\hbar}$$

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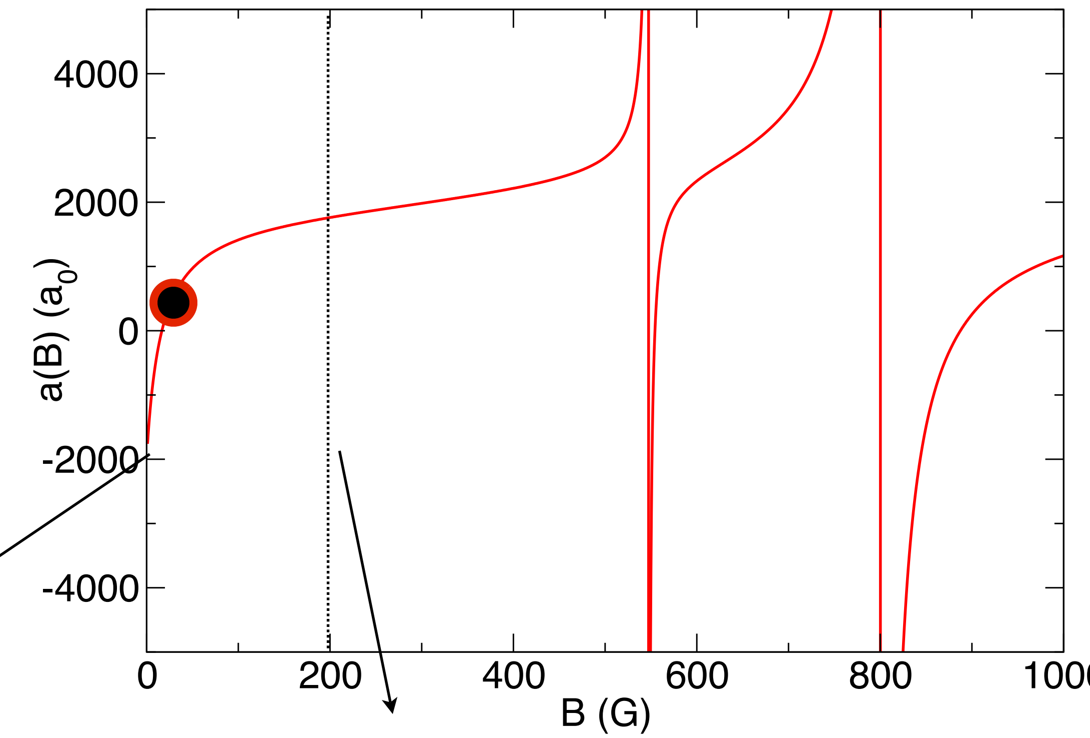

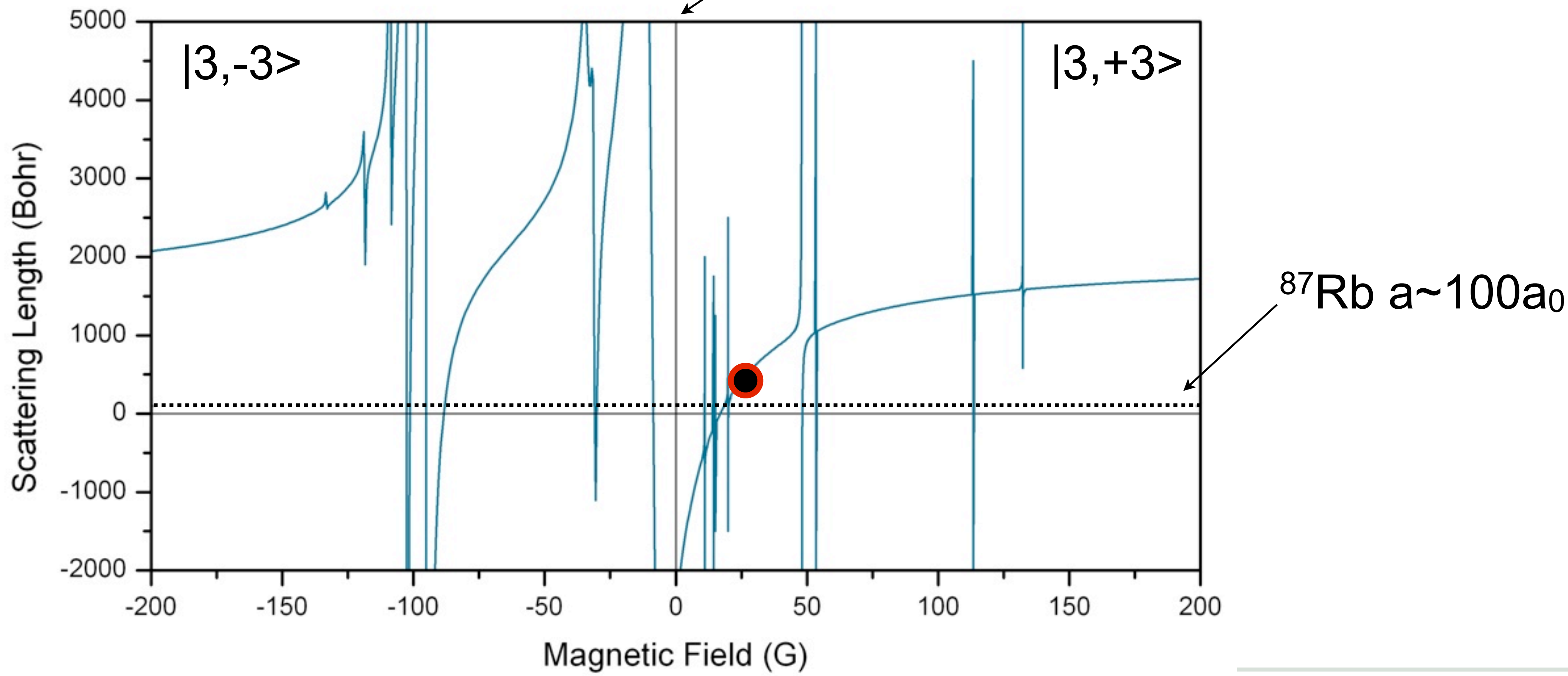

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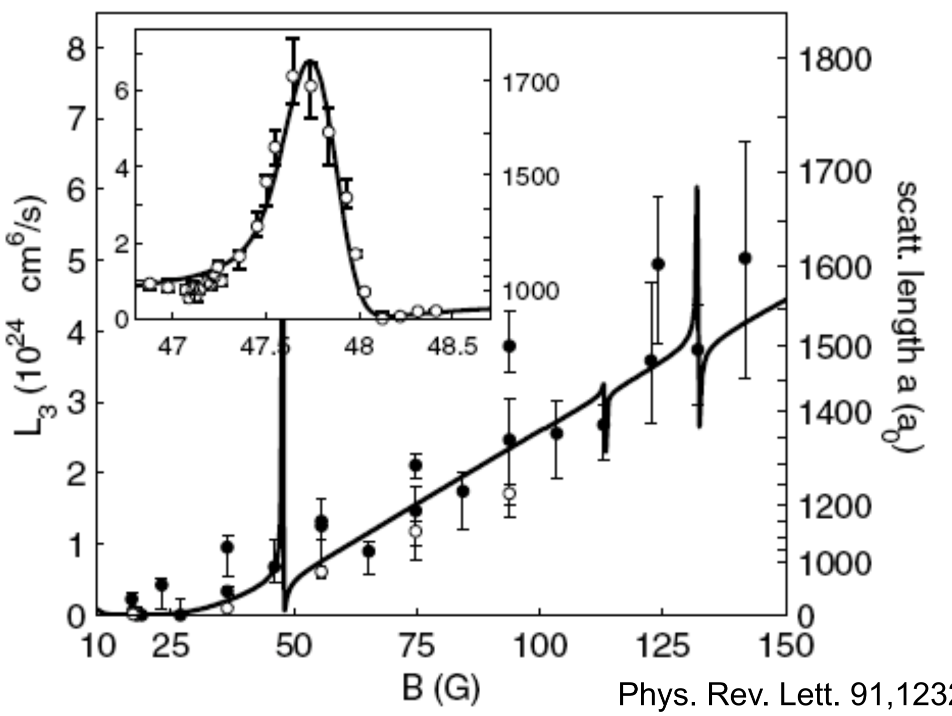
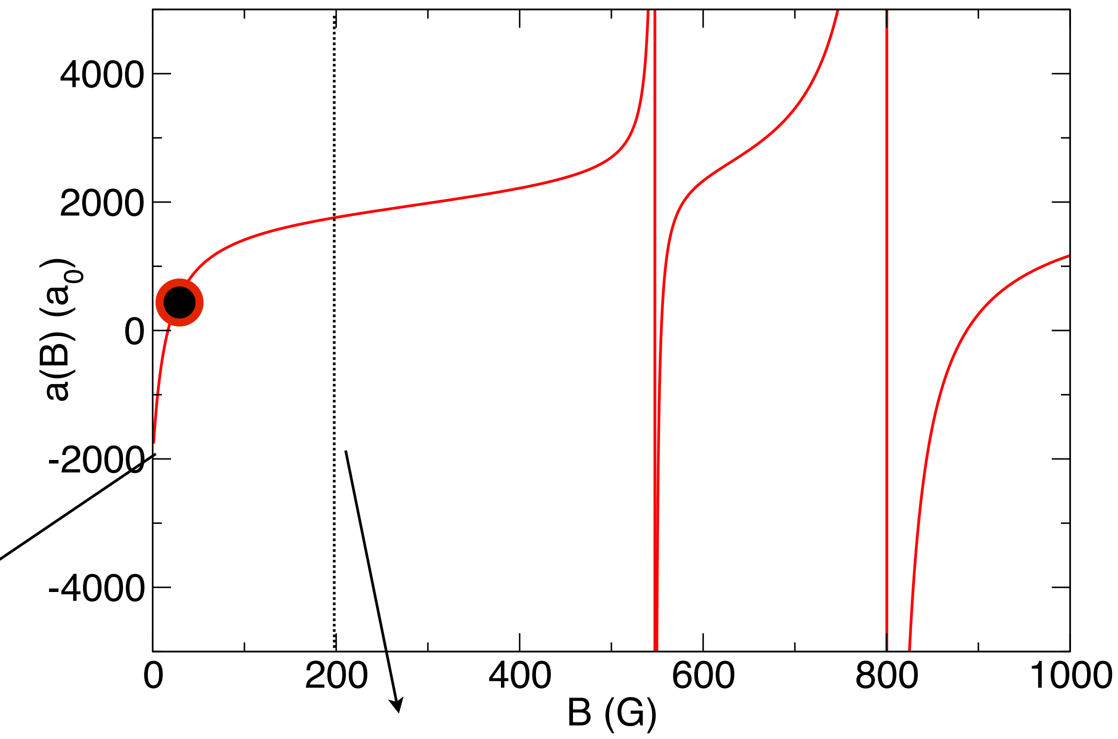
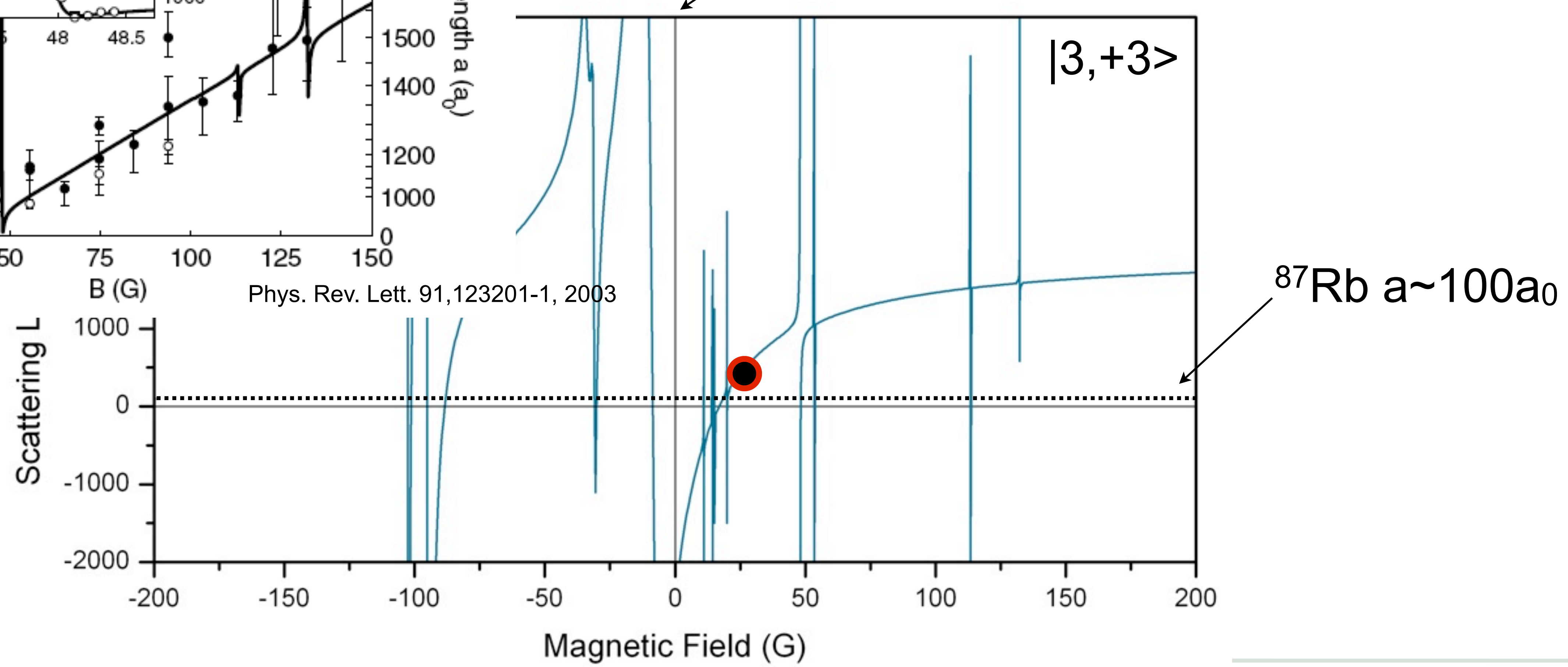


Phys. Rev. Lett. 91,123201-1, 2003





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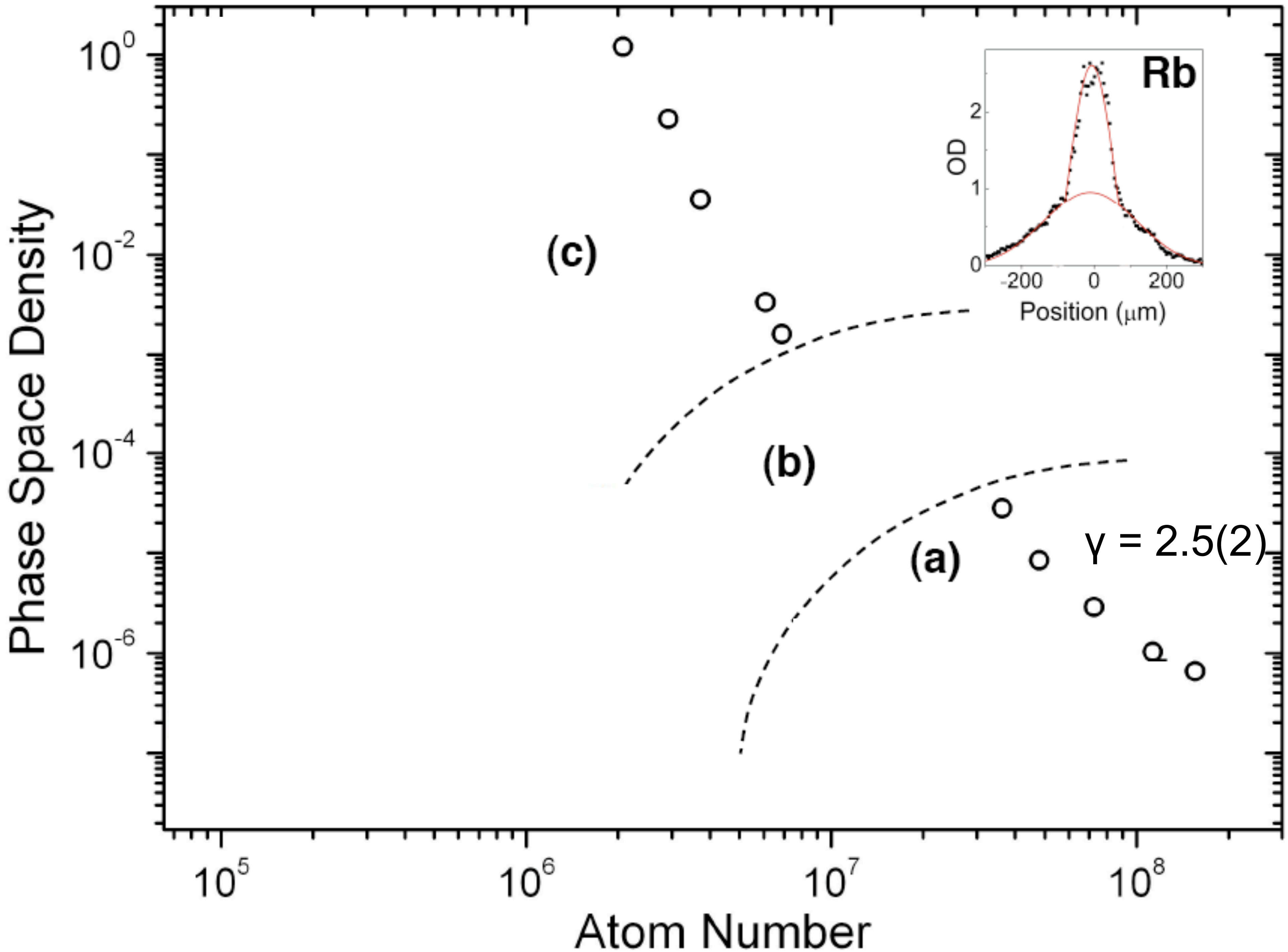

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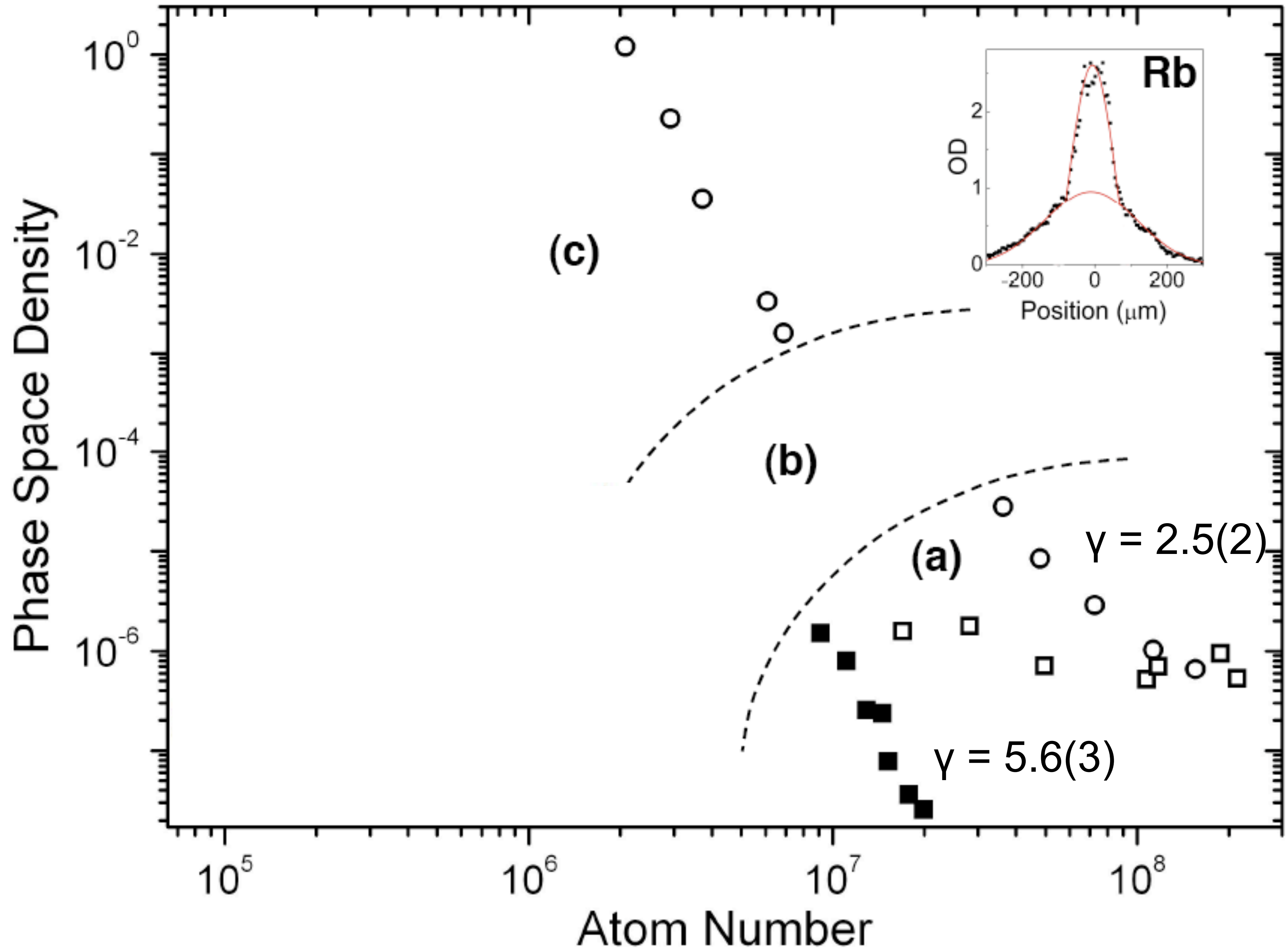
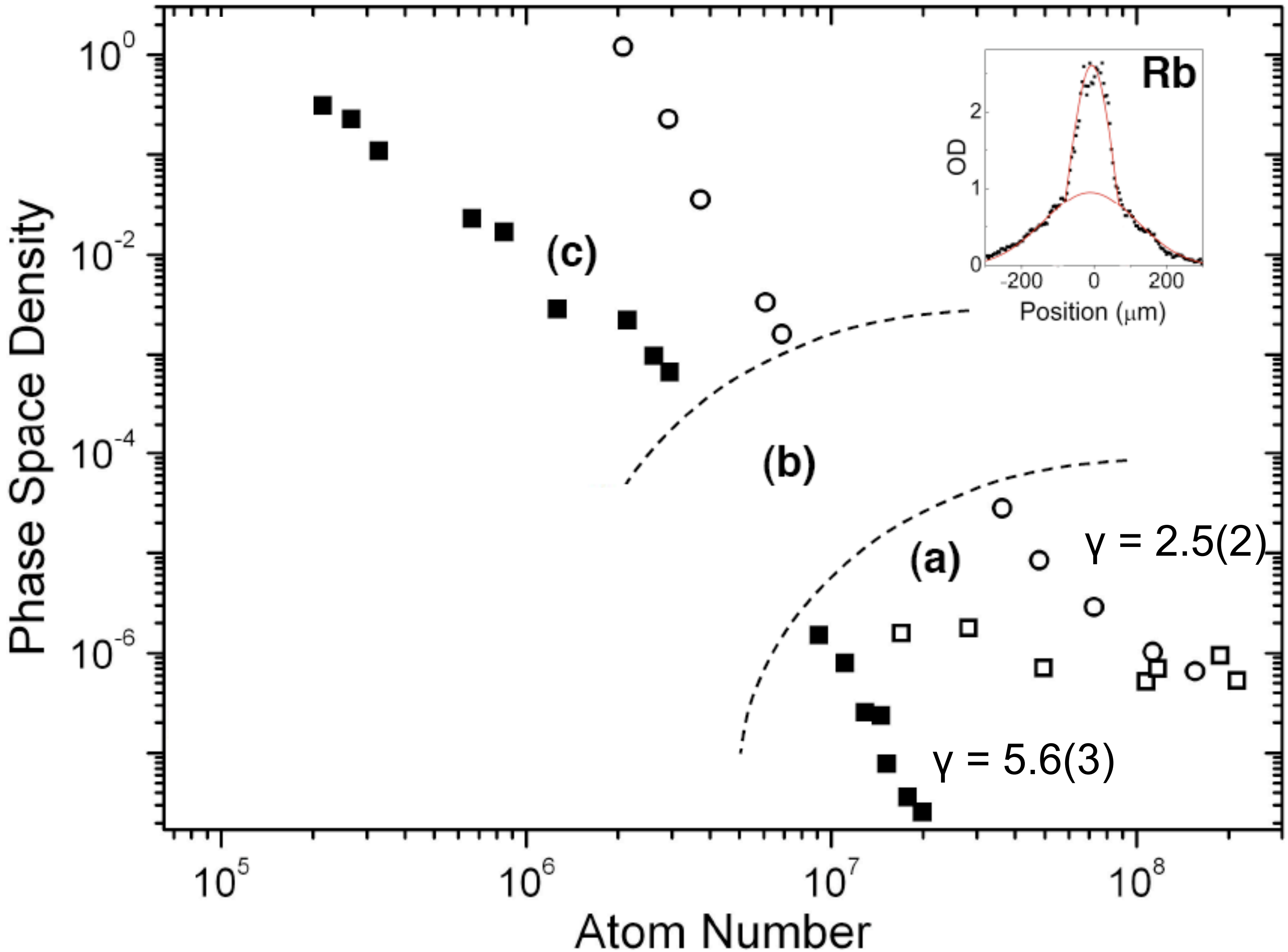


^{133}Cs BEC in the cross-dipole trap

To avoid the interspecies loss and optimise the transfer of ^{133}Cs, lower RF frequency or a resonant light to remove all ^{87}Rb. The resulting loading is highly efficient with ~50% of ^{133}Cs transferred into dipole trap. This is double the atoms number loaded compared to ^{87}Rb absence case.



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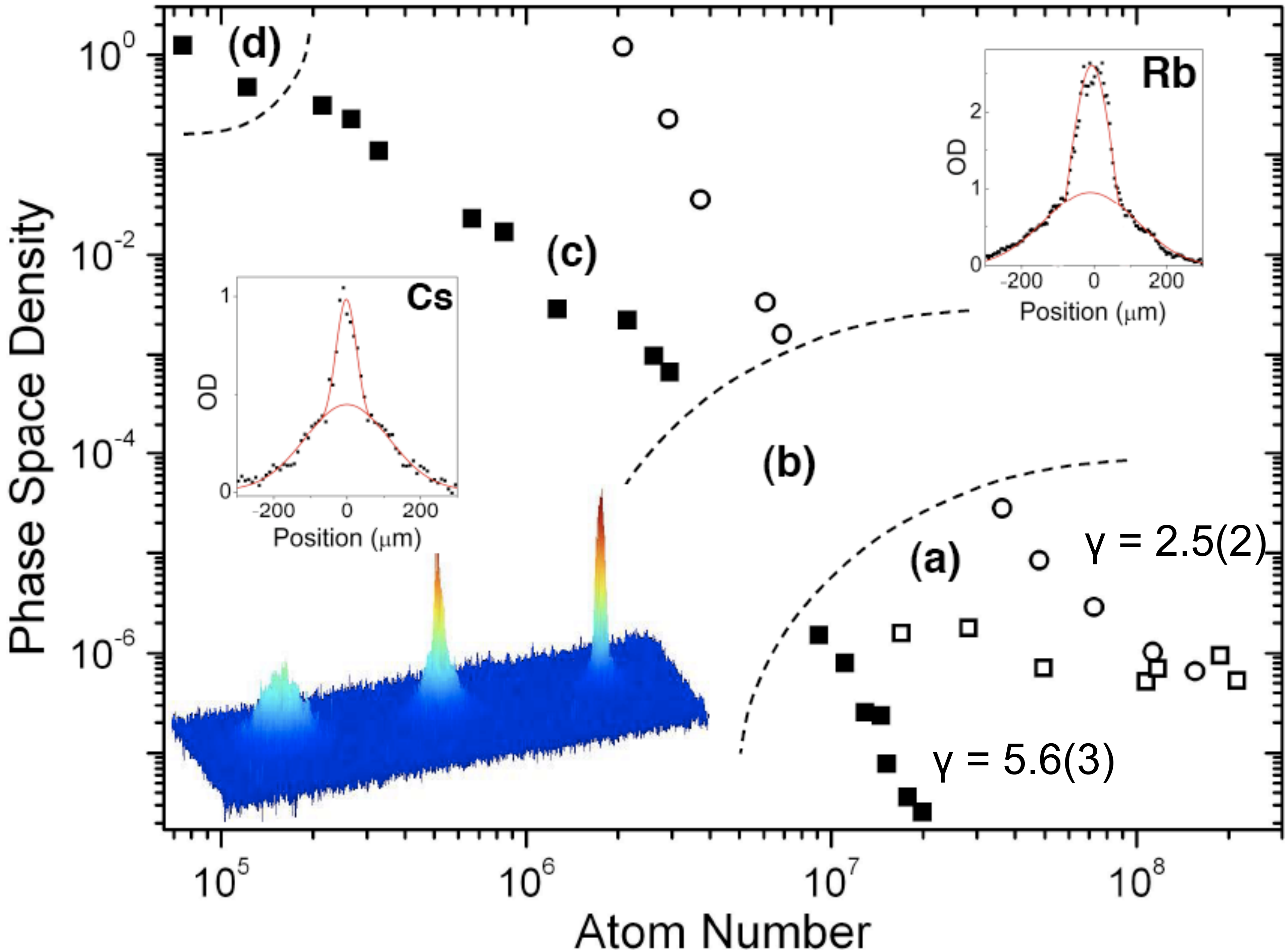

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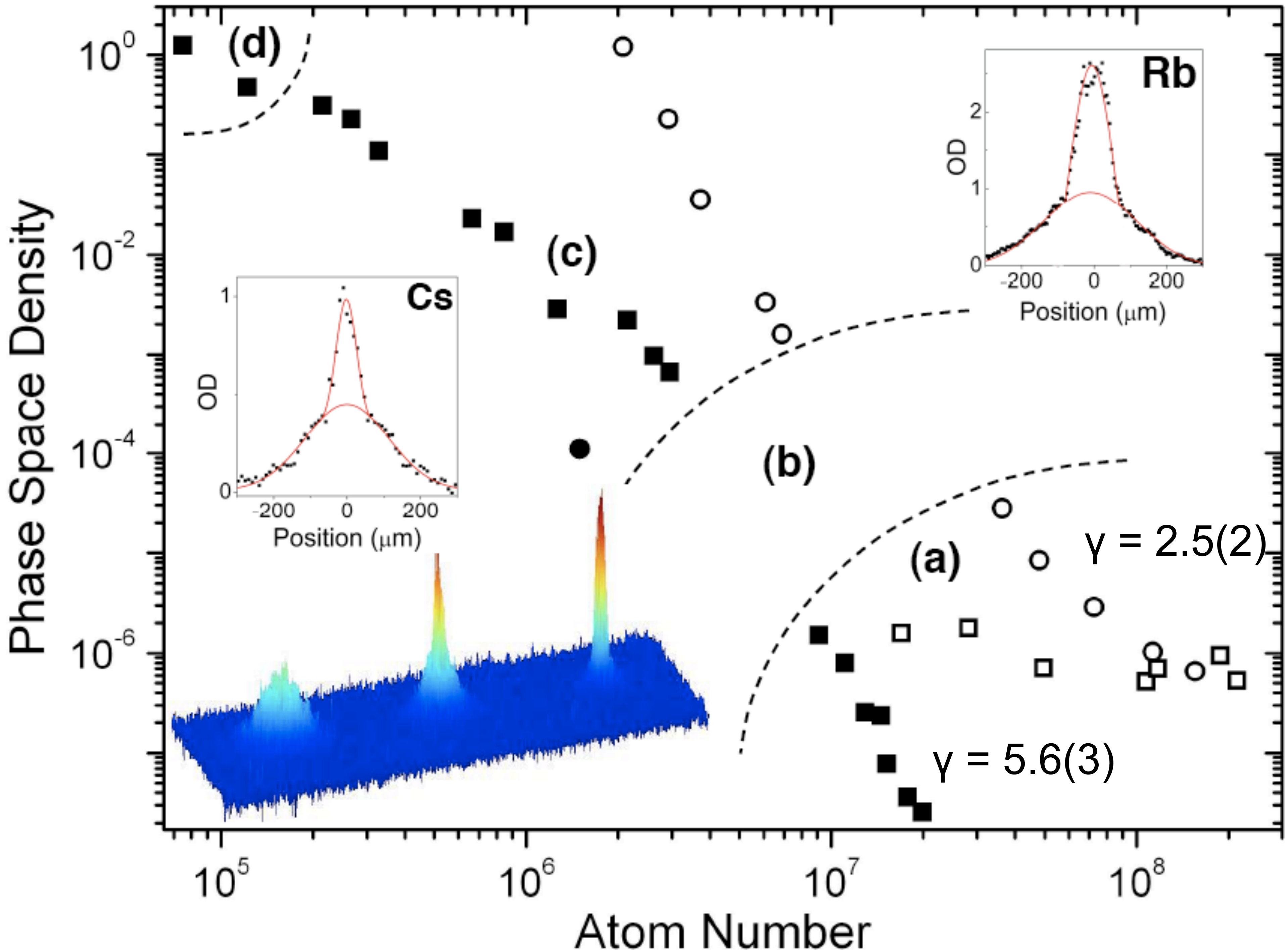

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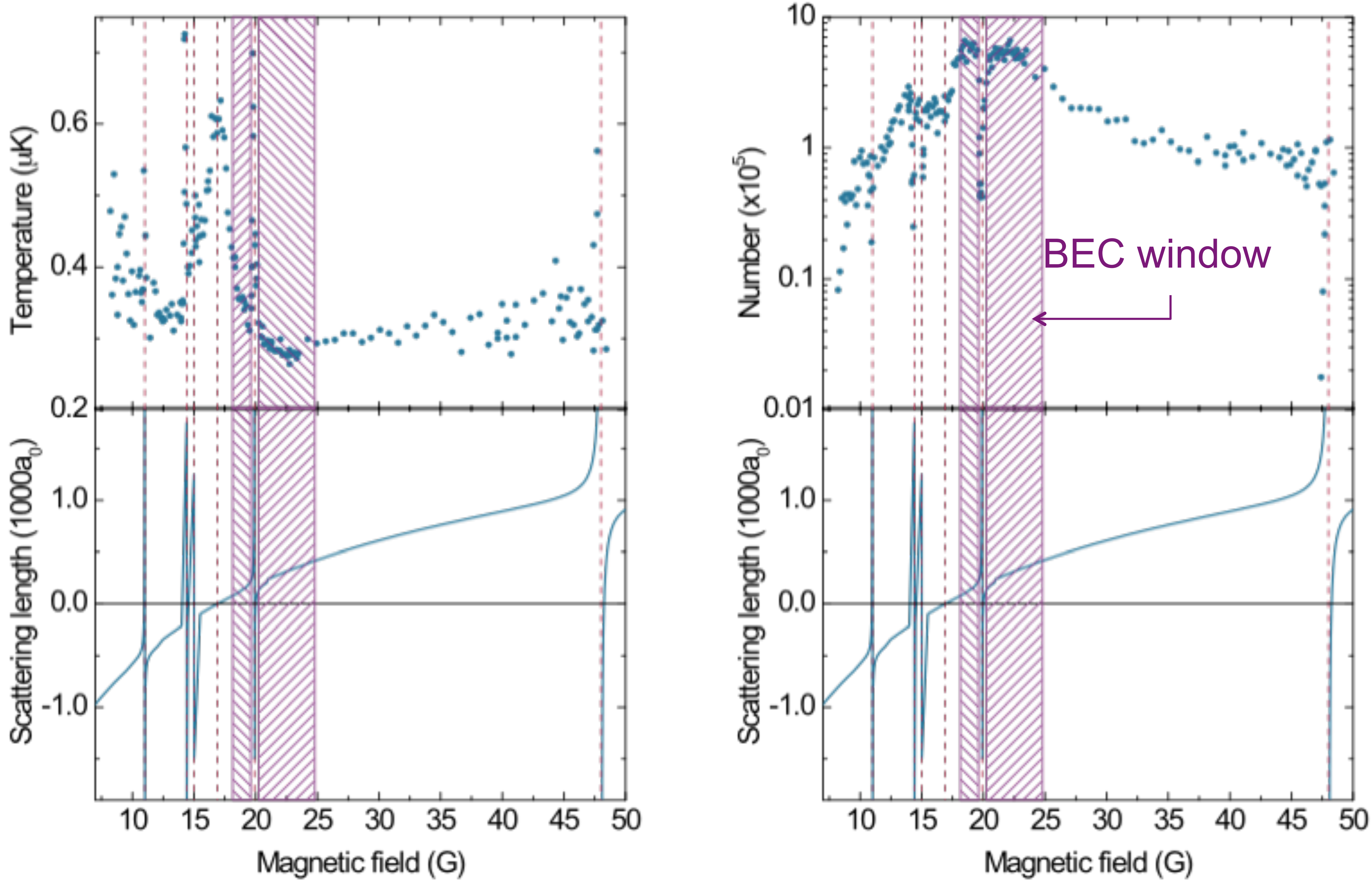
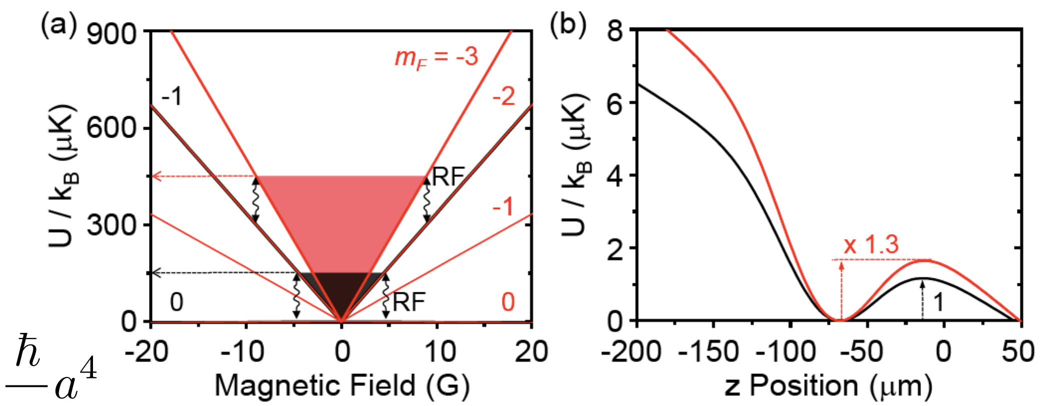
Optimising the magnetic field:



Toward Dual BEC

1) The calculated polarisabilities in atomic unit are ~ 572 a_0^3 for ^{133}Cs and ~ 425 a_0^3 for ^{87}Rb at 1550 nm. Phys. Rev. A, 73, 022505, 2006.



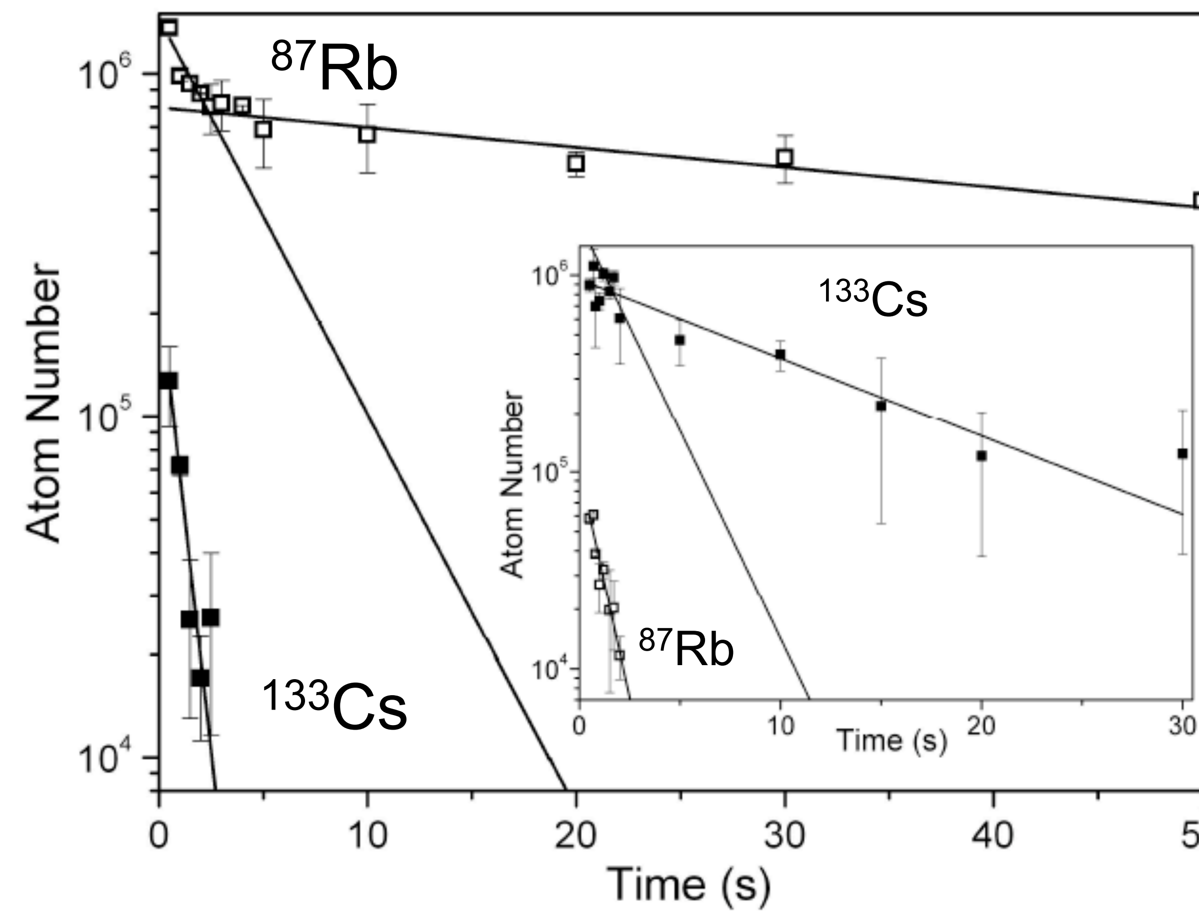
2) A strong interspecies loss after loading into the levitated dipole trap.

- τ_{Cs}= 0.8(1) s, τ_{Rb}= 4(1) & 70(10) s.
- τ_{Rb}= 0.9(2) s, τ_{Cs}= 2(1) & 10(3) s.

lower 3 body loss by reduce the peak density

$$\frac{\dot{N}}{N} = -L\langle n^2\rangle \ , L_3 = n_l C \frac{\hbar}{m} a^4$$

- change to a larger beam waist
- decompress trap



Eur. Phys. J. D (DOI: 10.1140/epjd/e2011-20015-6)
Phys. Rev. A **84** 011603(R) (2011)

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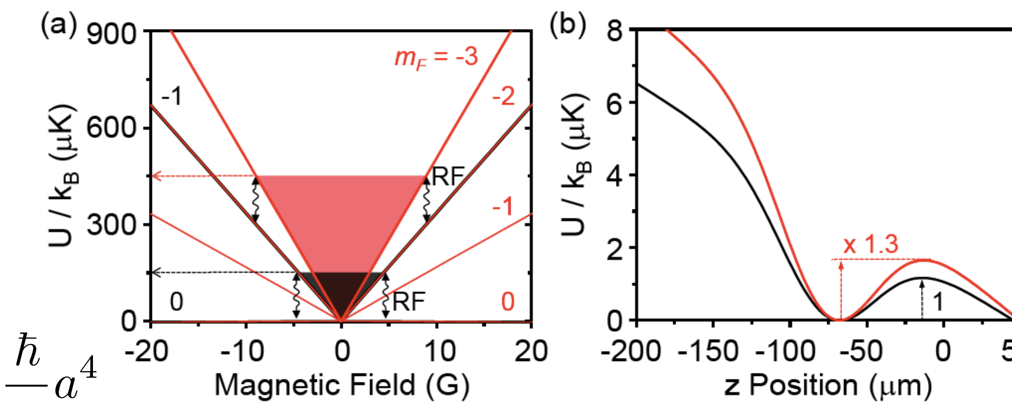

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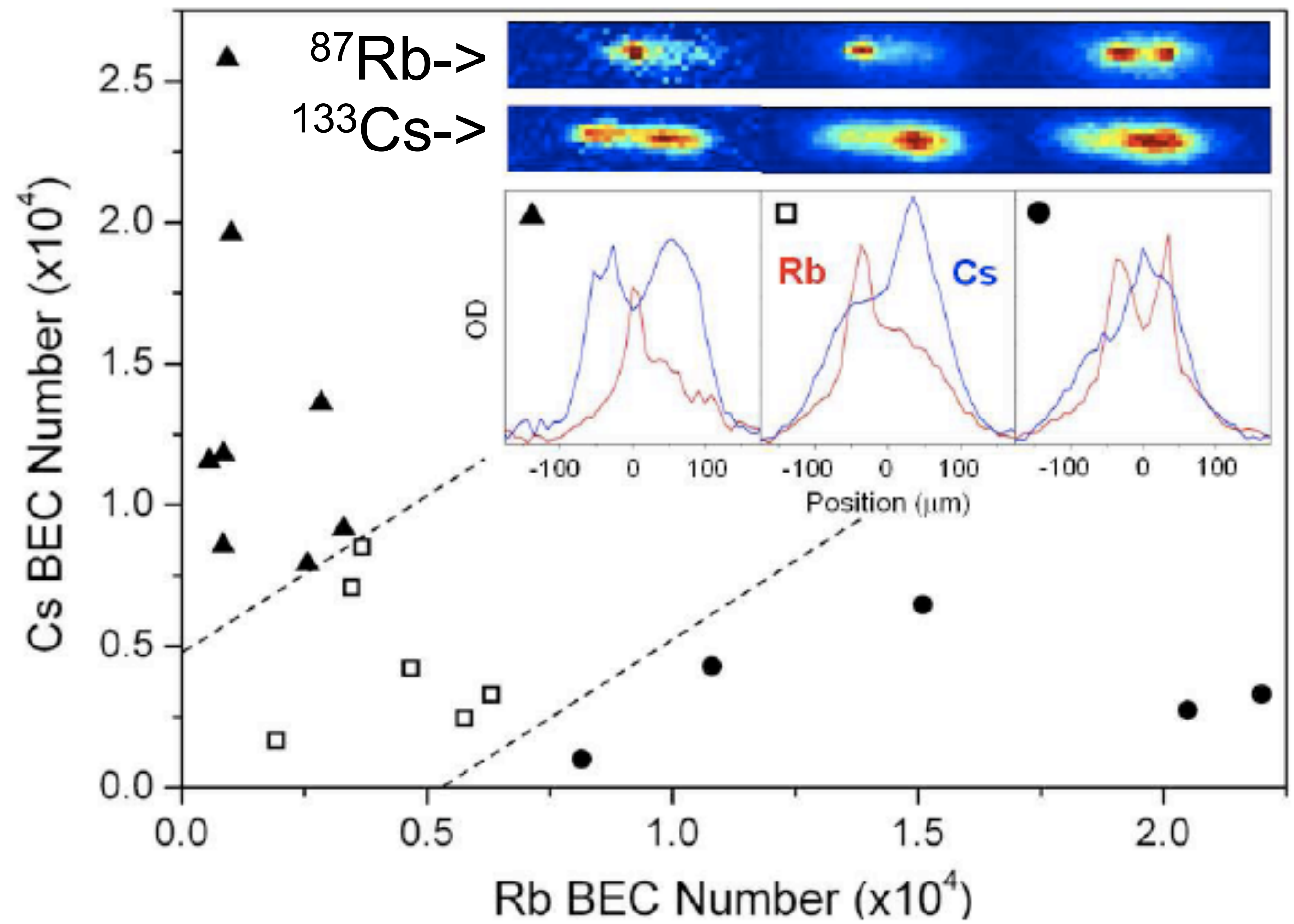
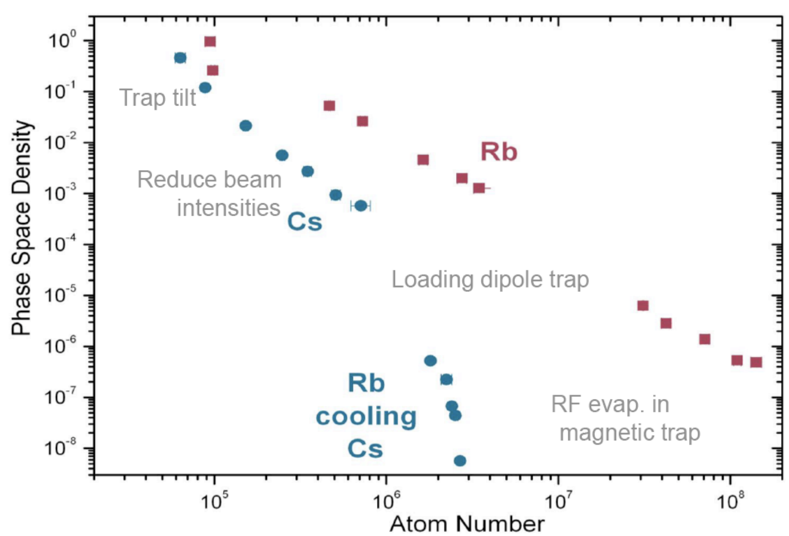
Immiscible quantum degenerate mixture:
the relative strength of the atomic interactions

$$\Delta = \frac{g_{RbCs}}{g_{Rb} g_{Cs}} > 1, g_{ij} = 2\pi\hbar^2 a_{ij} \left(\frac{m_i + m_j}{m_i m_j}\right)$$

Phys.Rev. A, 65, 063614, 2002

In our case, B = 22.4 G, a_{Rb} = 100a_0 and a_{Cs} = 280a_0, the observation of immiscibility require a_{RbCs} > 165a_0. a_{RbCs} = 650a_0 (J. Hustson, private communication 2011)





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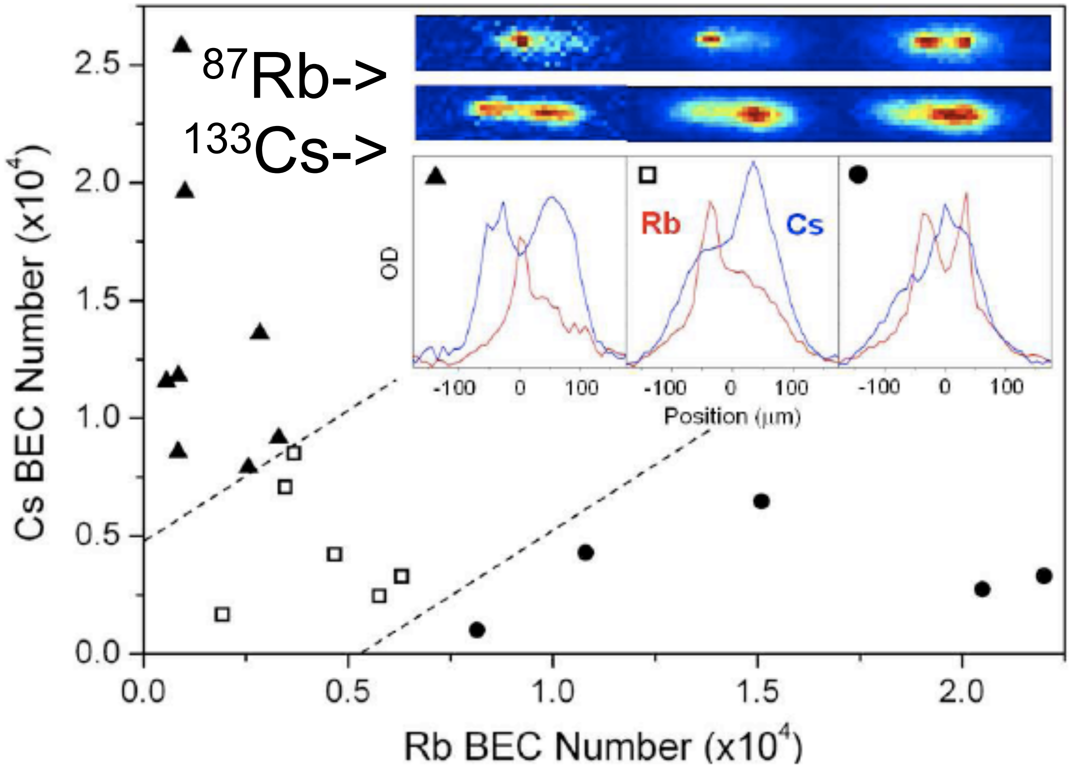

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I. K. Liu, paper in preparation

stochastic projected Gross-Pitaevskii equation

NTUE L. K. Liu and Prof. S. C. Gou

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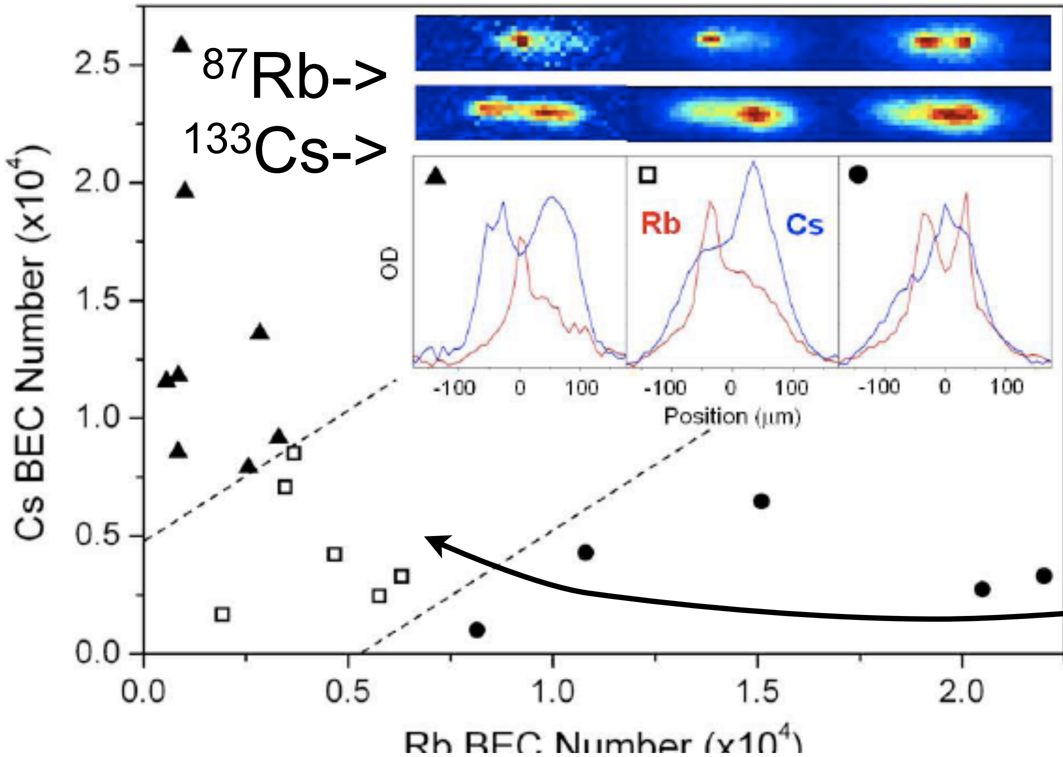

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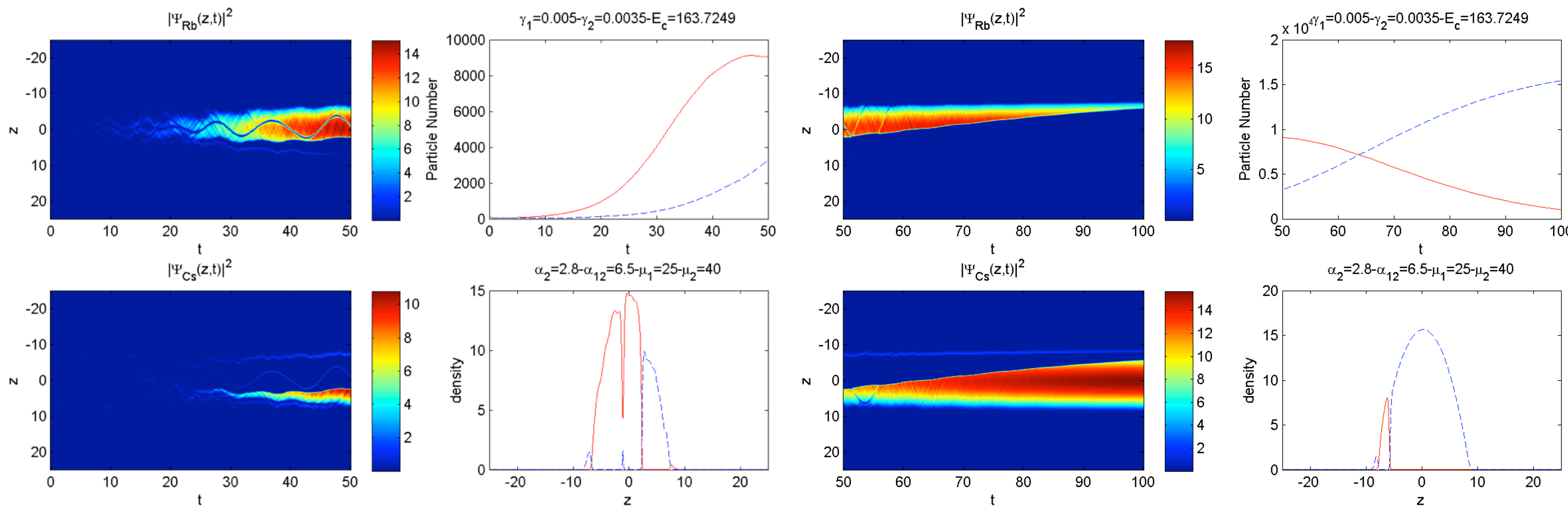

Durham University

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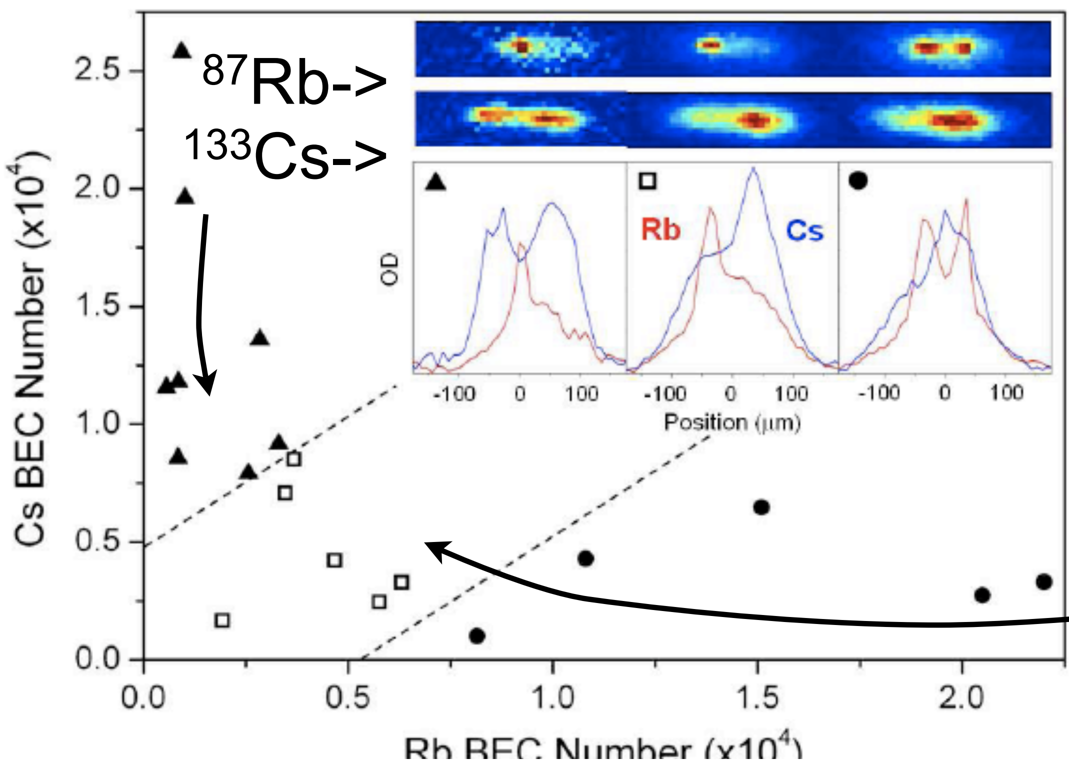

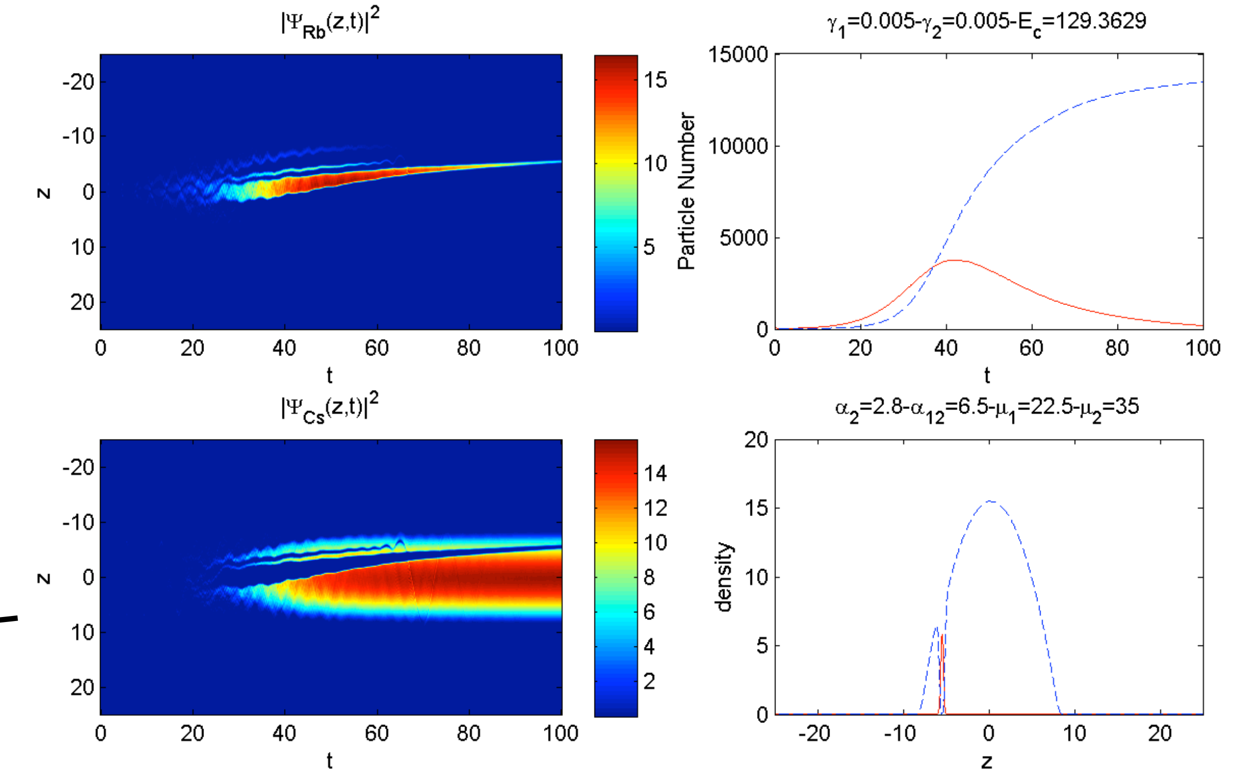

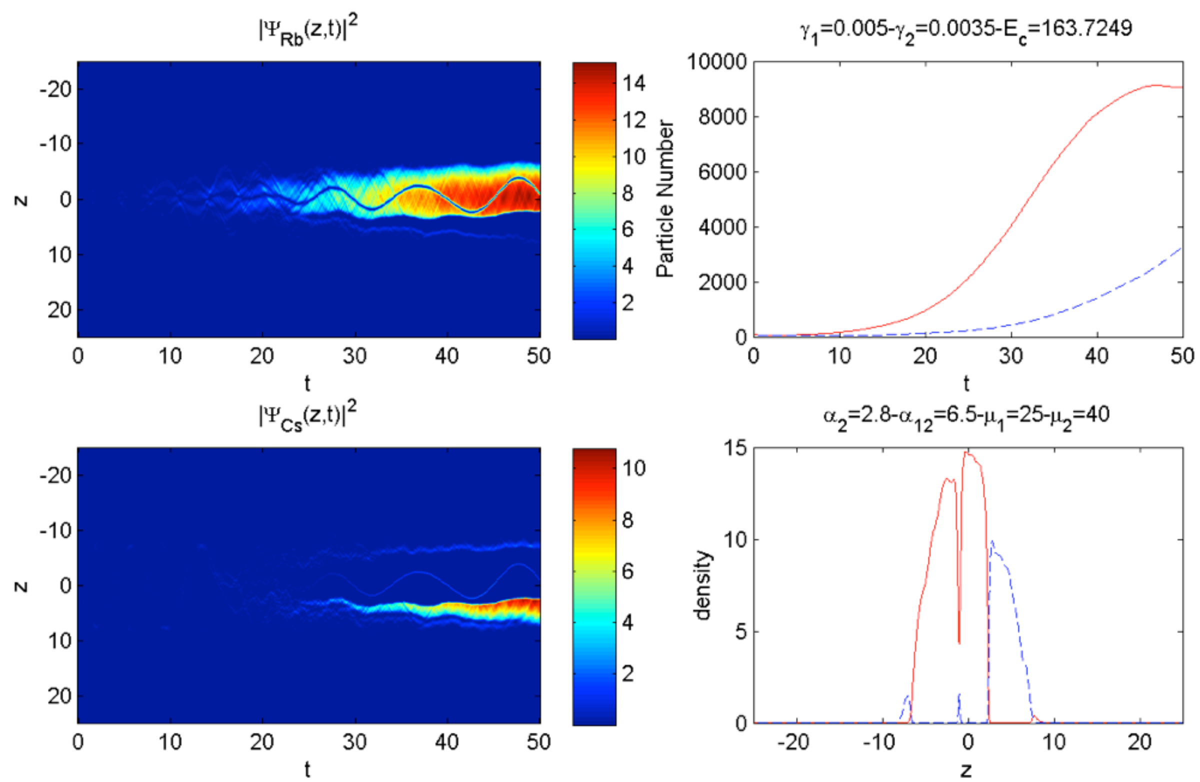

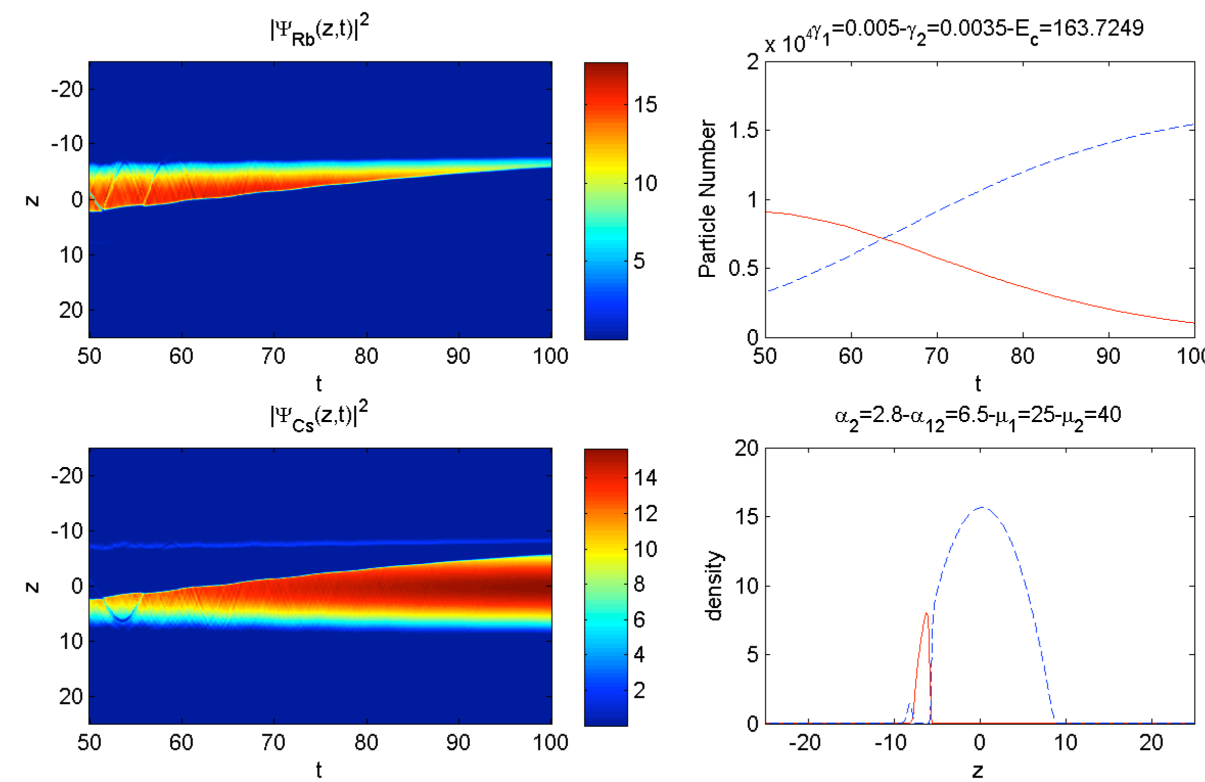

Durham University

Outline

- Bose-Einstein condensations (BECs)
  - ^{87}Rb BEC in a combined magnetic and optical trap
  - ^{133}Cs BEC in a crossed dipole trap
  - A quantum degenerate Bose mixture of ^{87}Rb and ^{133}Cs
- Feshbach molecules
  - The formation background and method
  - ^{87}Rb^{133}Cs Feshbach resonance measurement
- Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon scheme transfers the Feshbach molecules into the rovibronic ground state
- Summary

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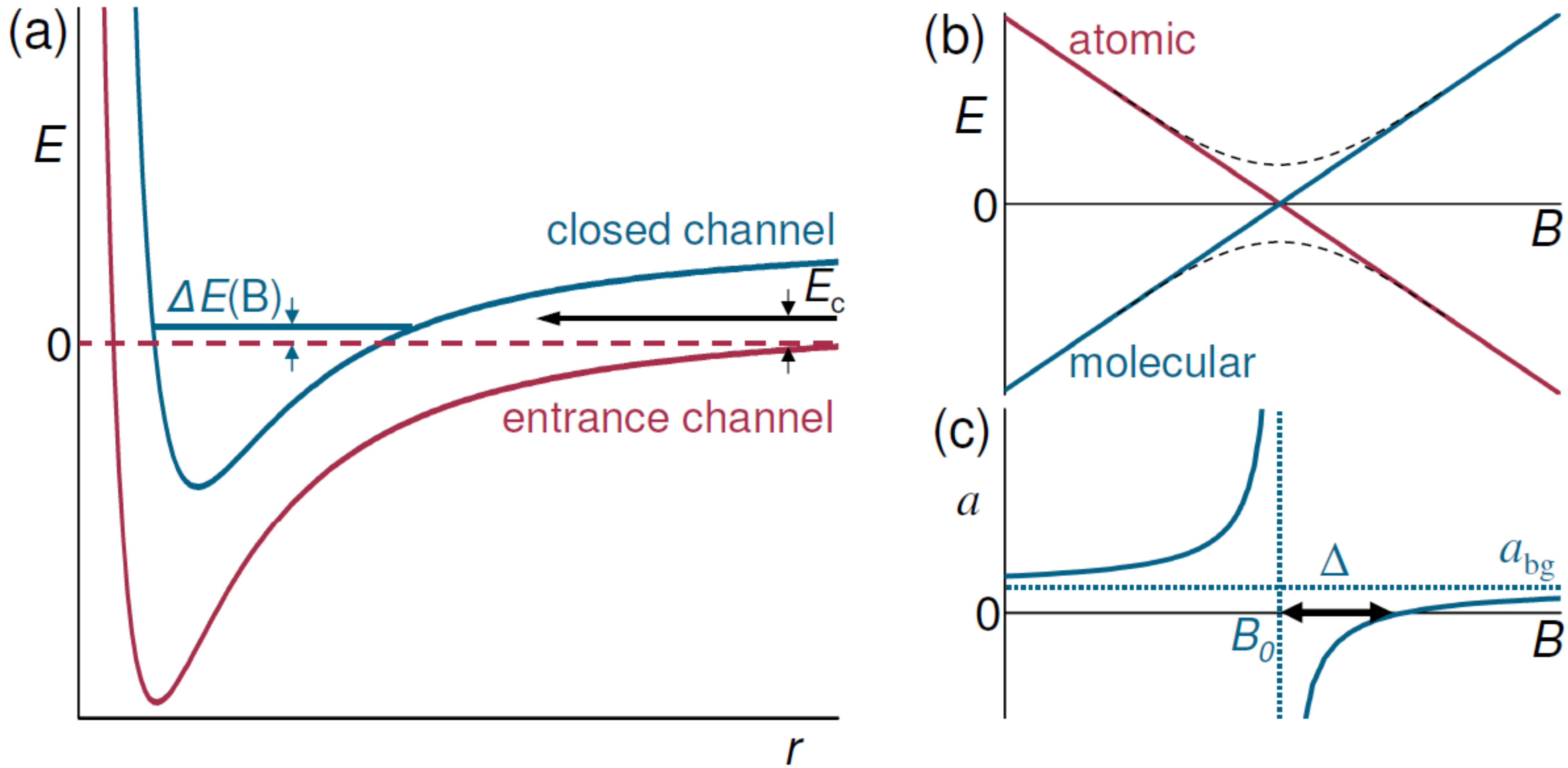
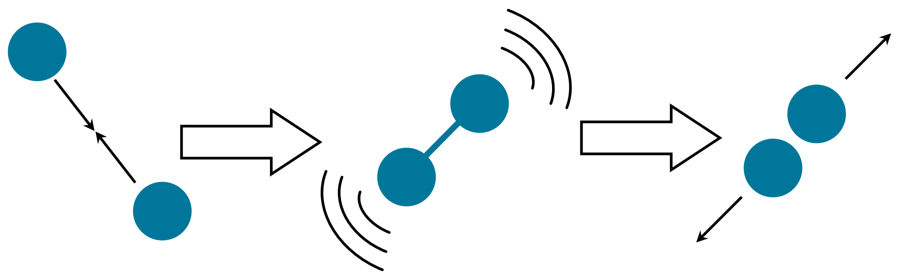
Feshbach resonances:

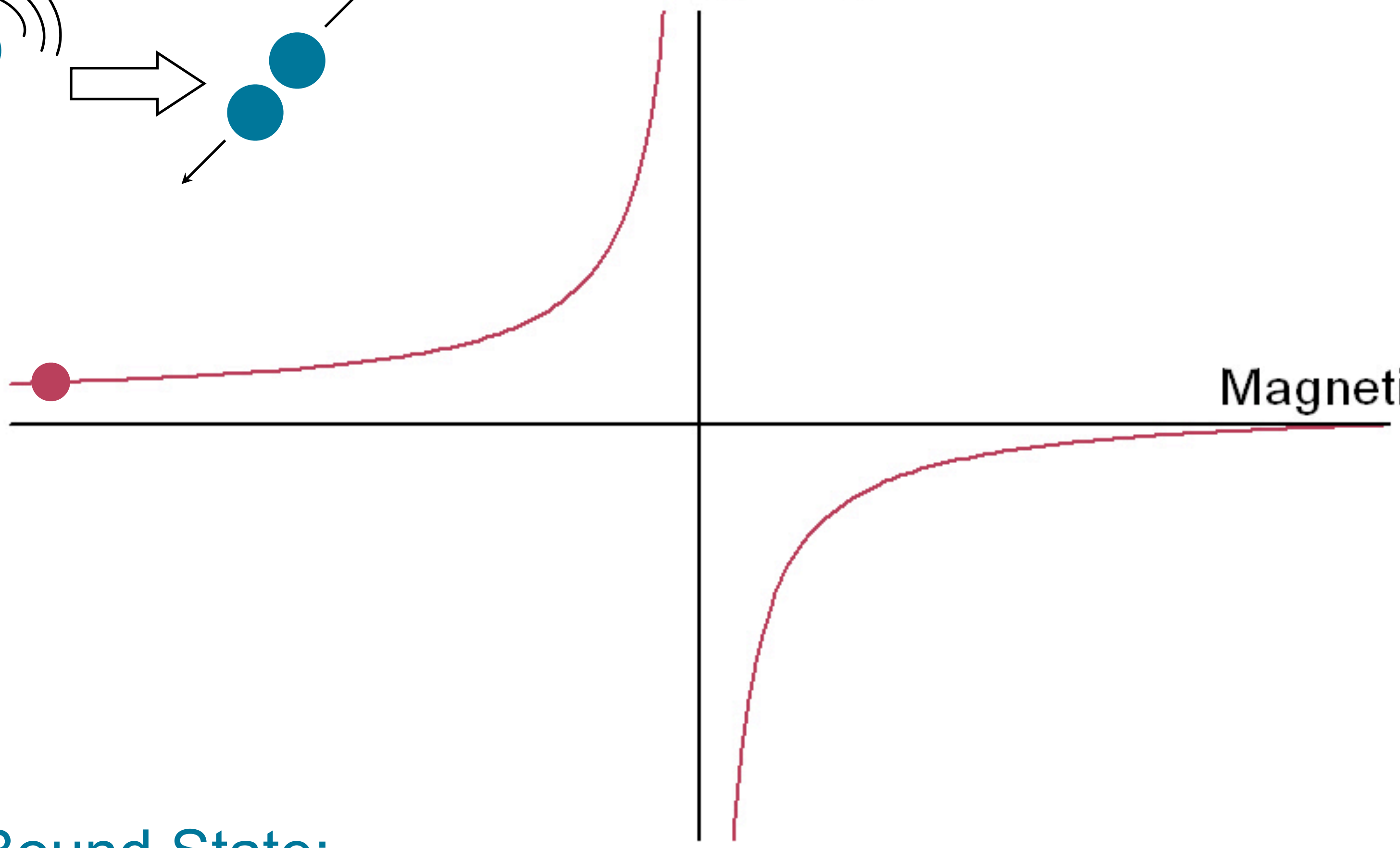


$$a(B) = a_{\mathrm{bg}}\left(1 - \frac{\Delta}{B - B_0}\right)$$

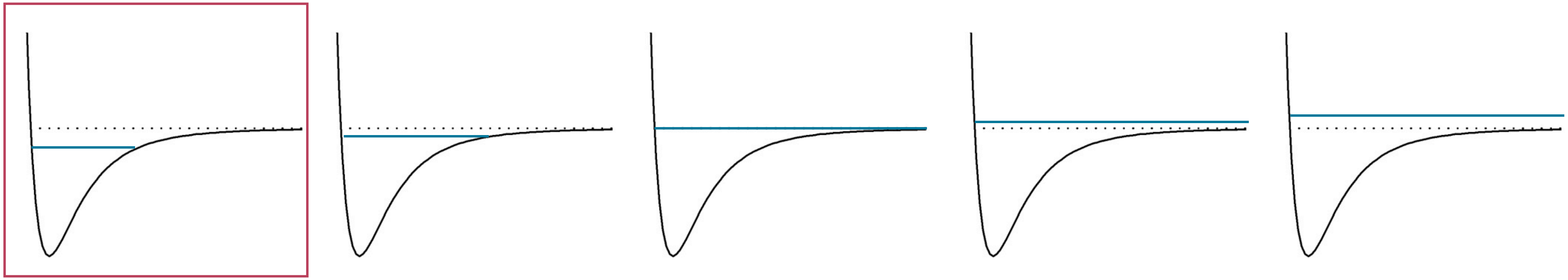
C. Chin, Rev. Mod. Phys. 82, 1225-1286 (2010)
F. Ferlaino *et al.*, arXiv: 0809.3920 (2009)

Feshbach resonances





Position of Last Bound State:



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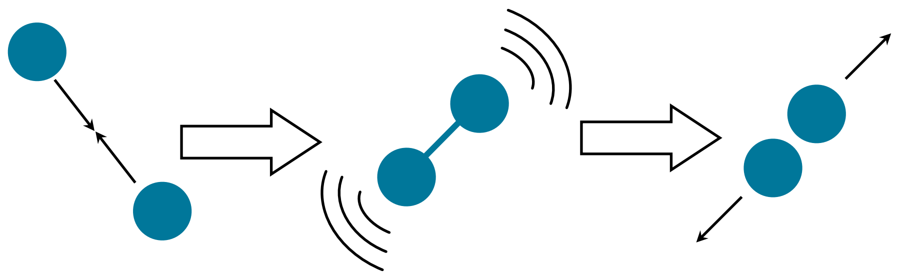

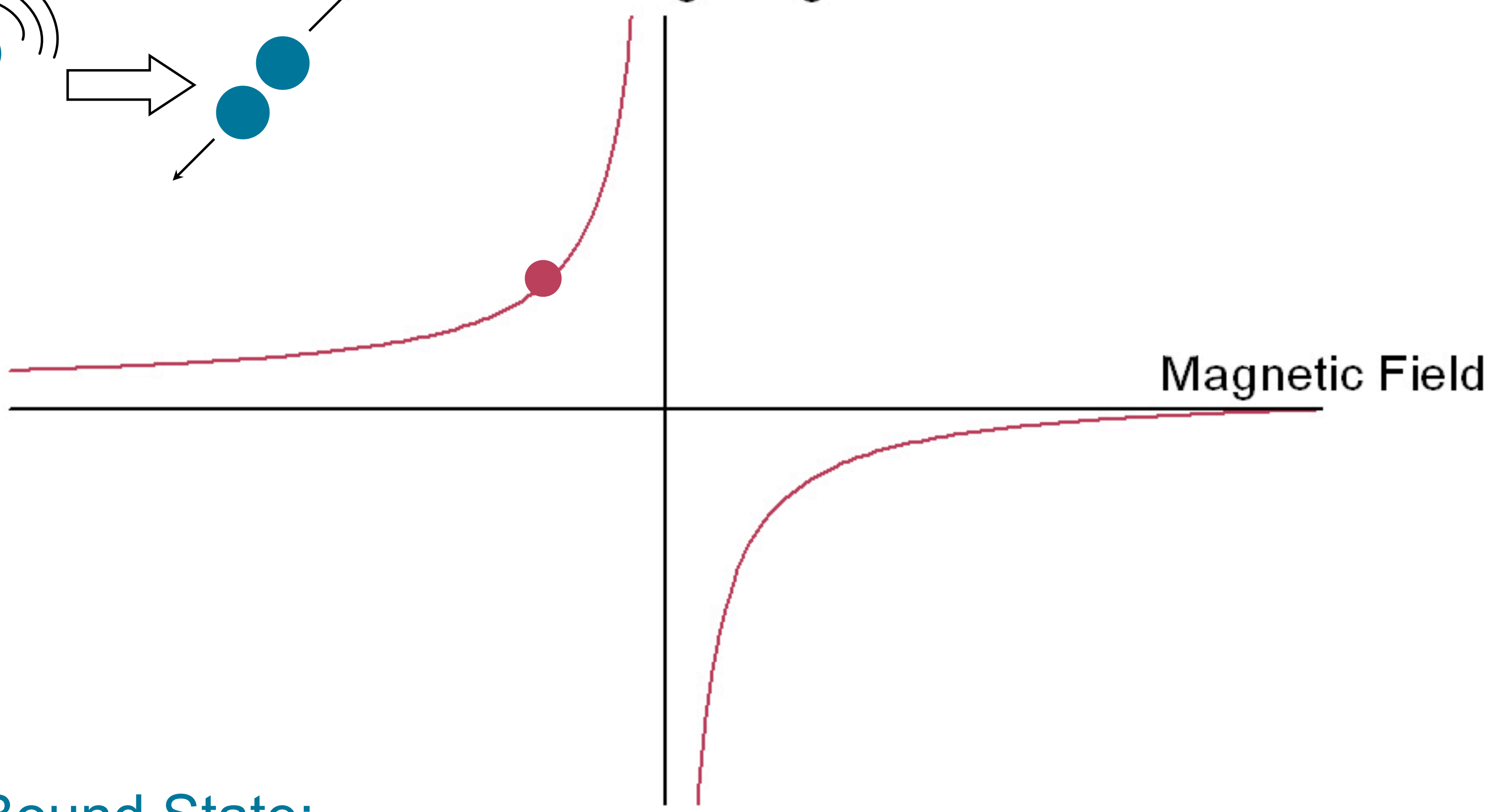

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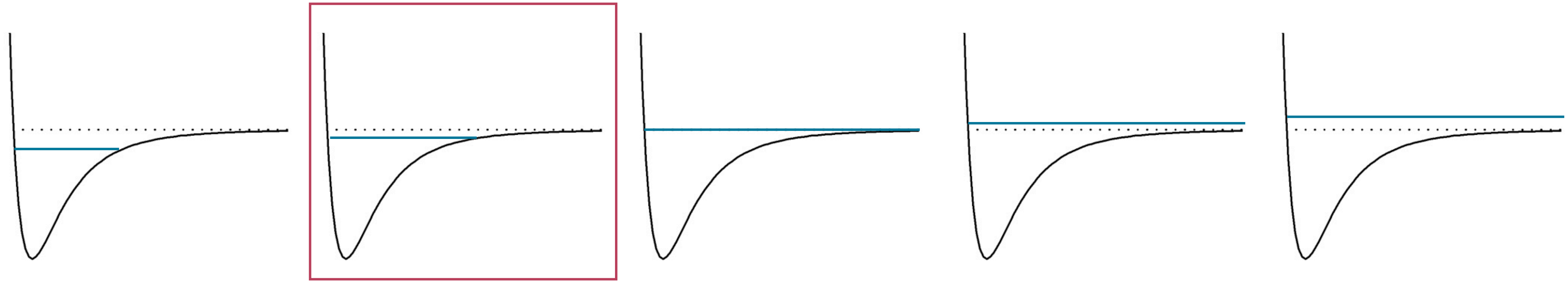

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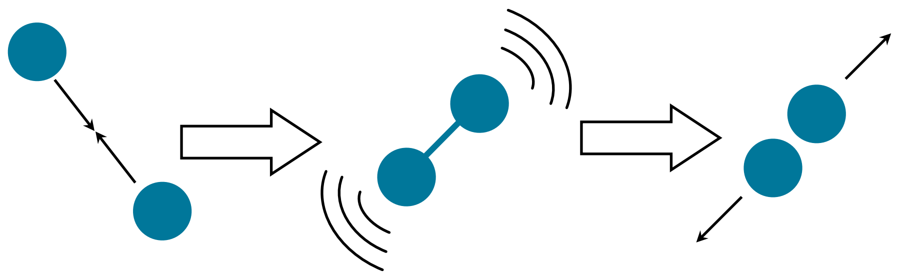

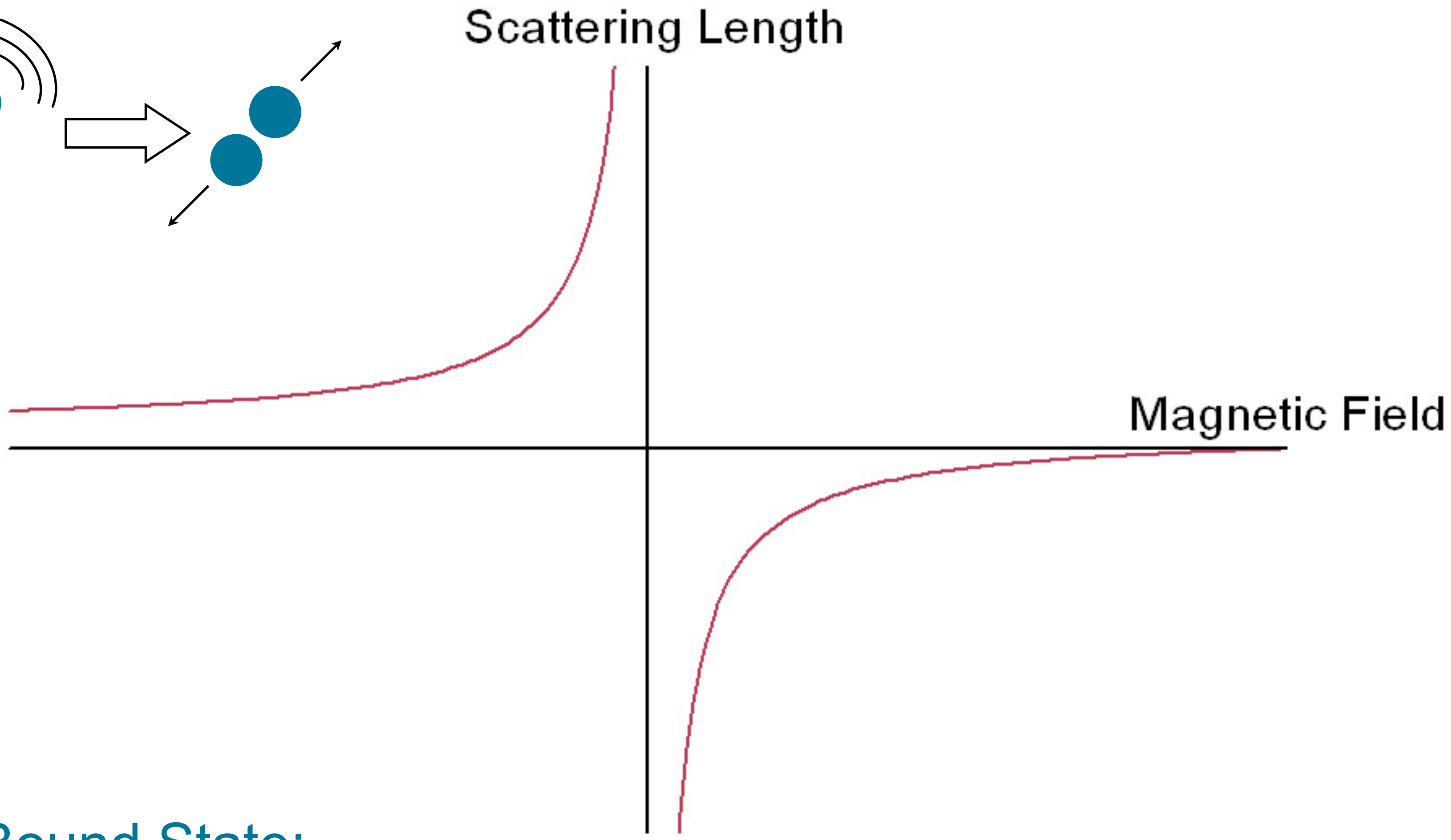

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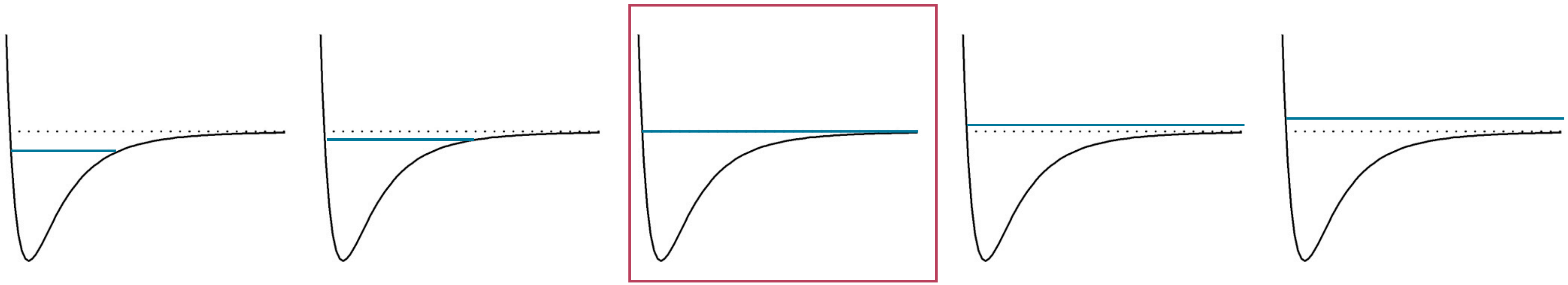

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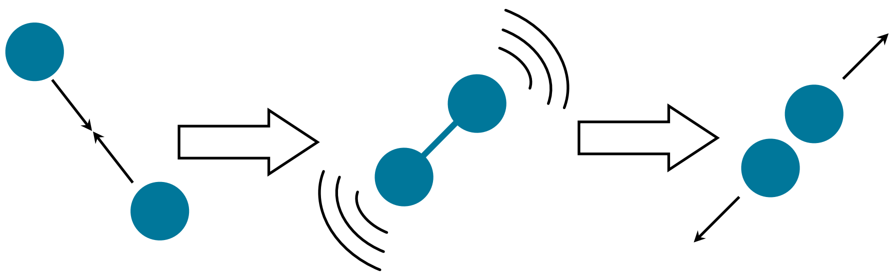

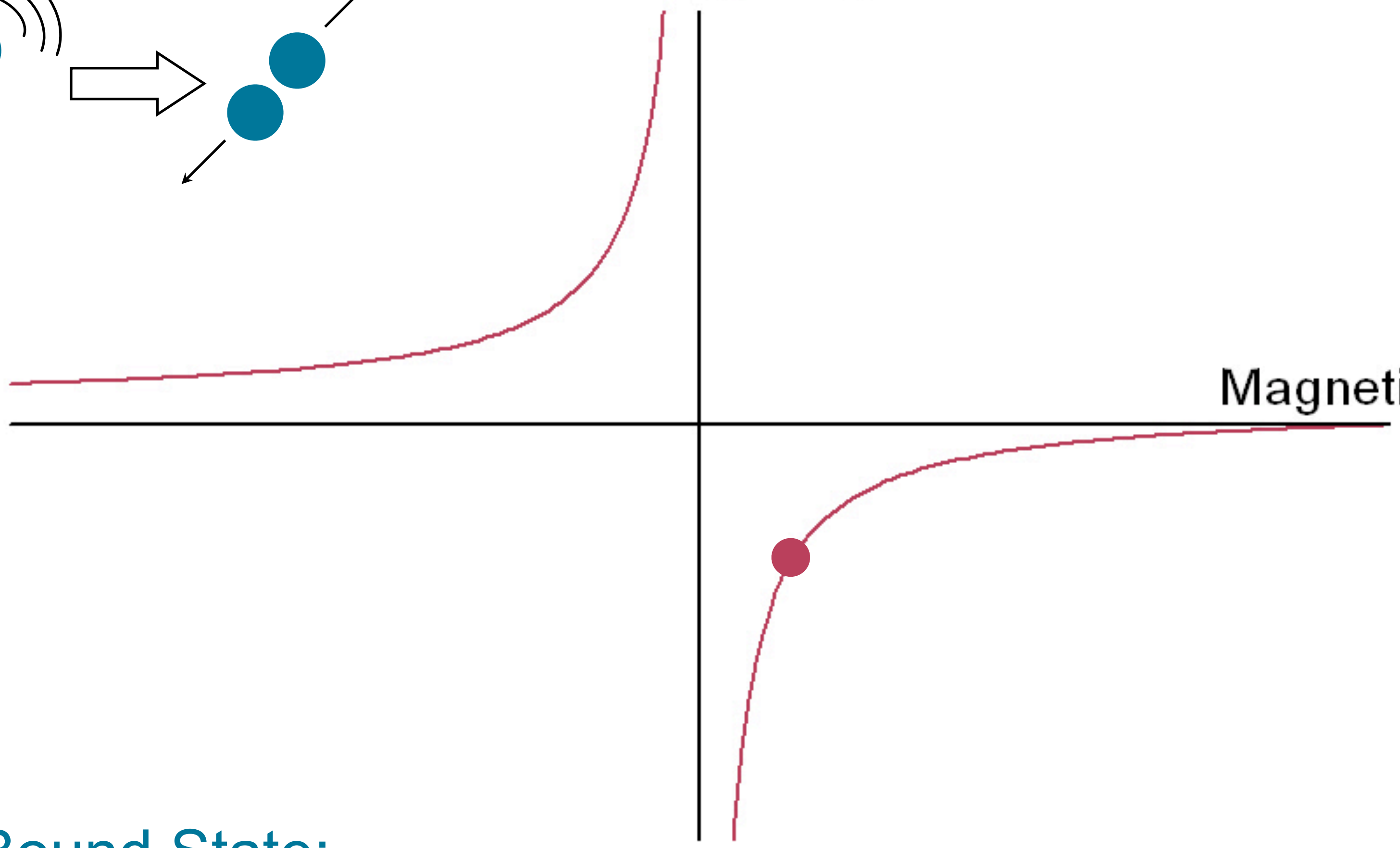

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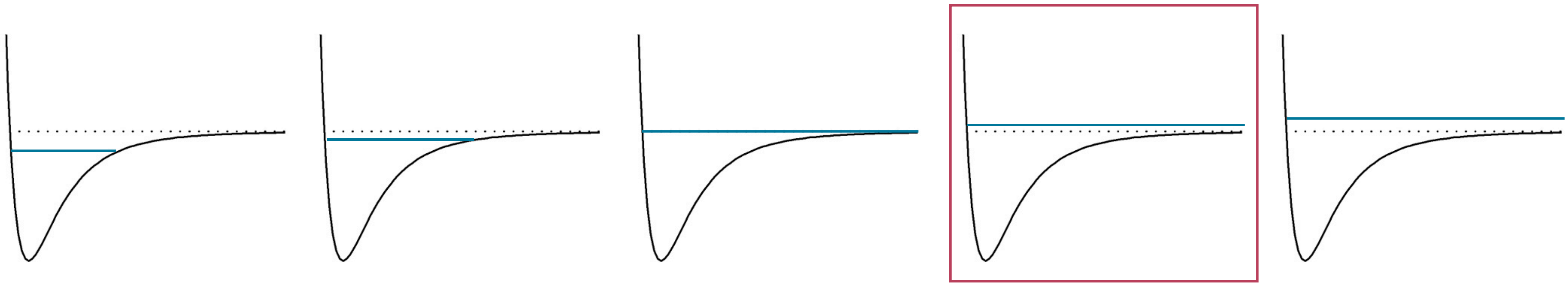

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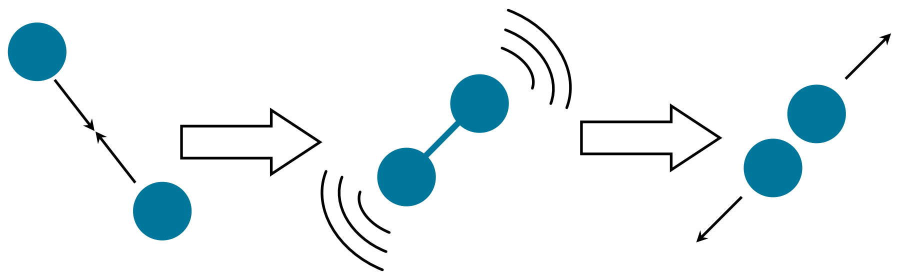

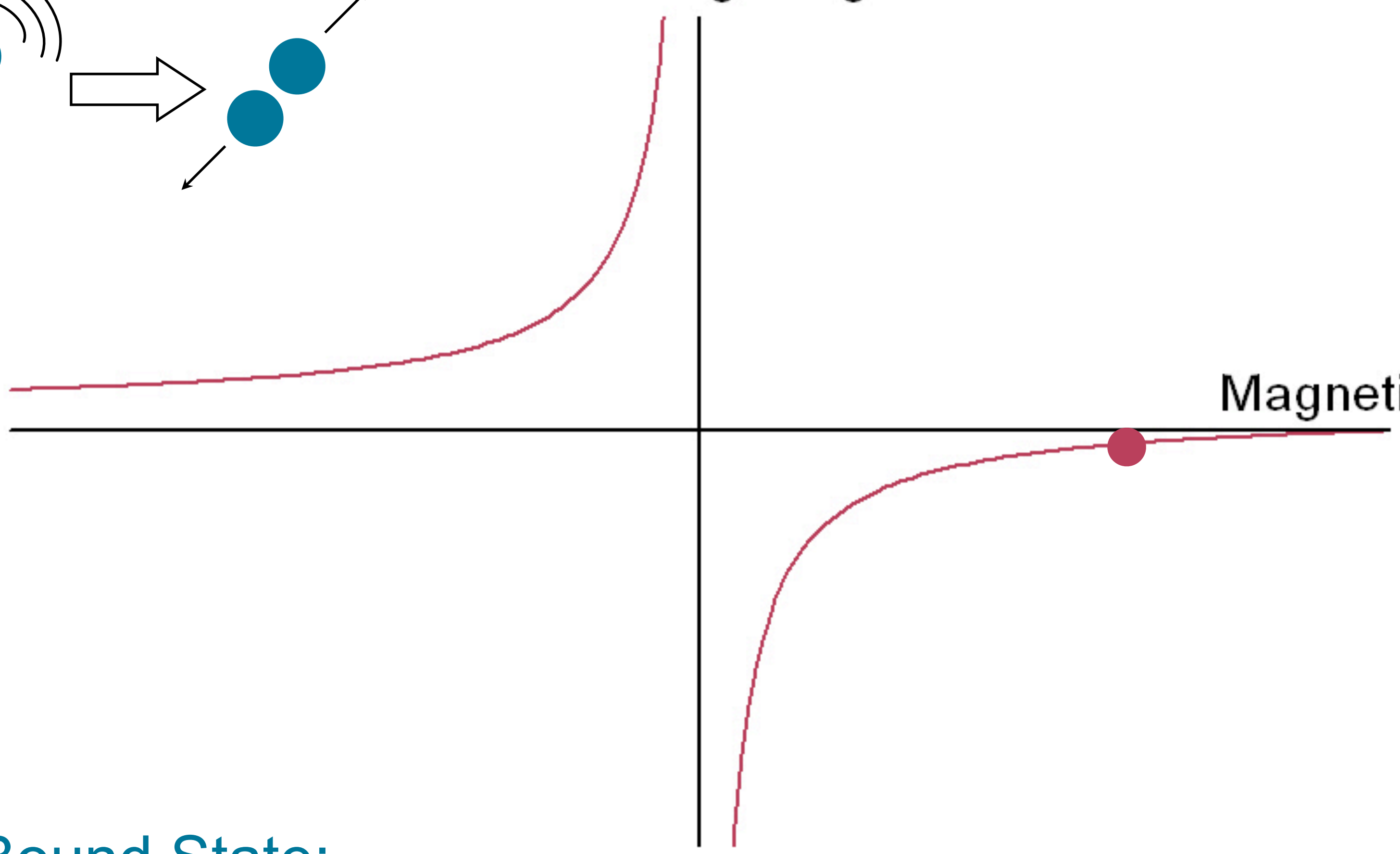

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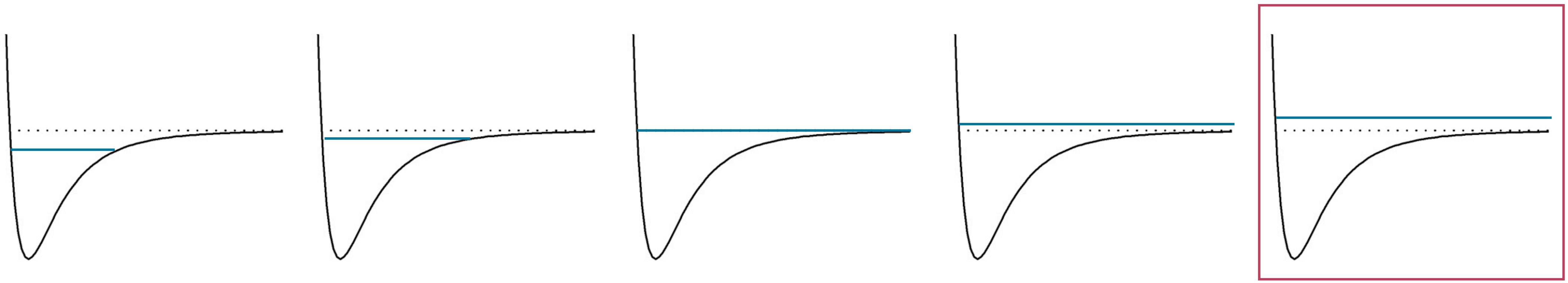
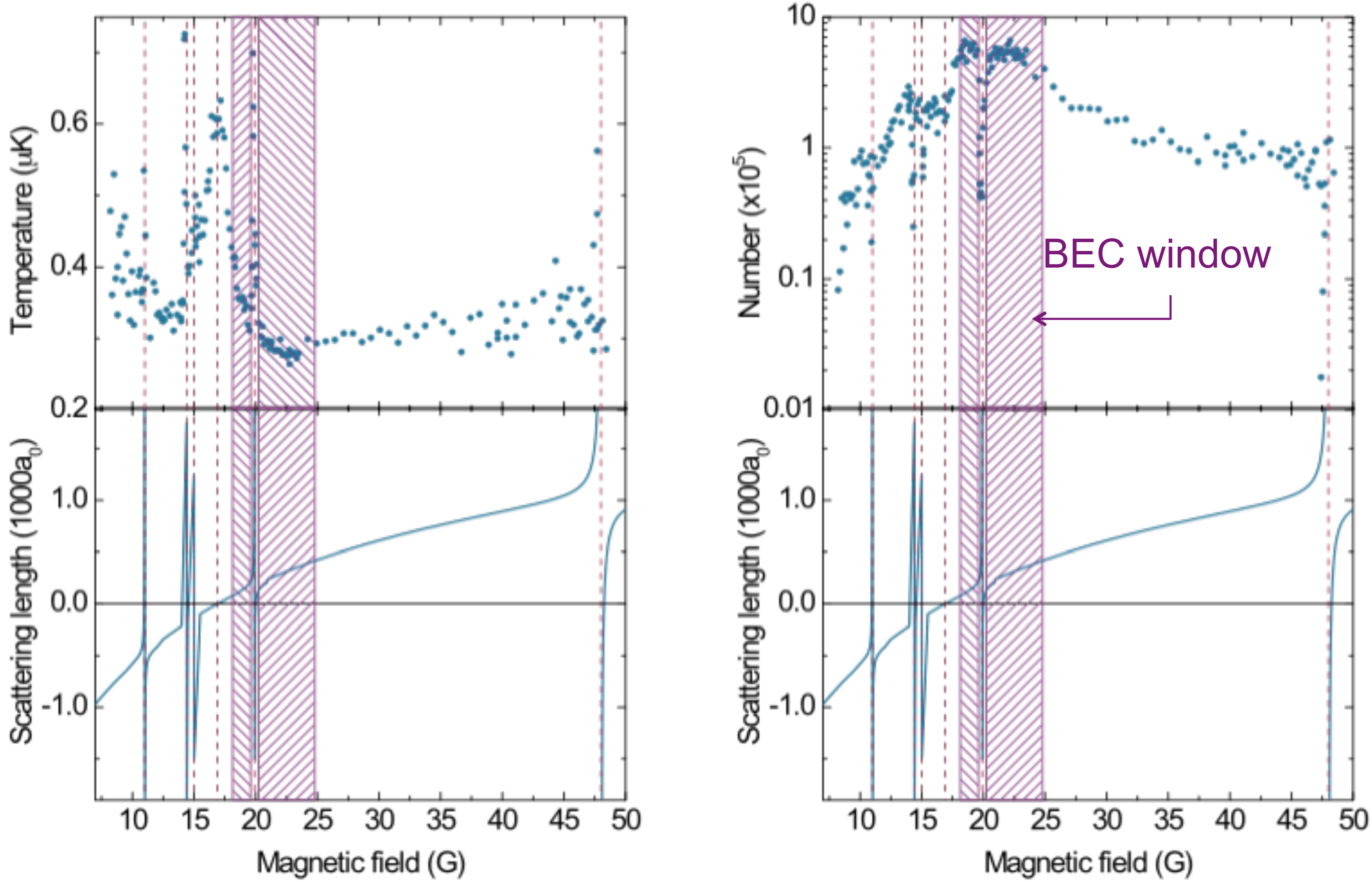


Cs Feshbach resonances (6 – 50 G)

Optimising the magnetic field:



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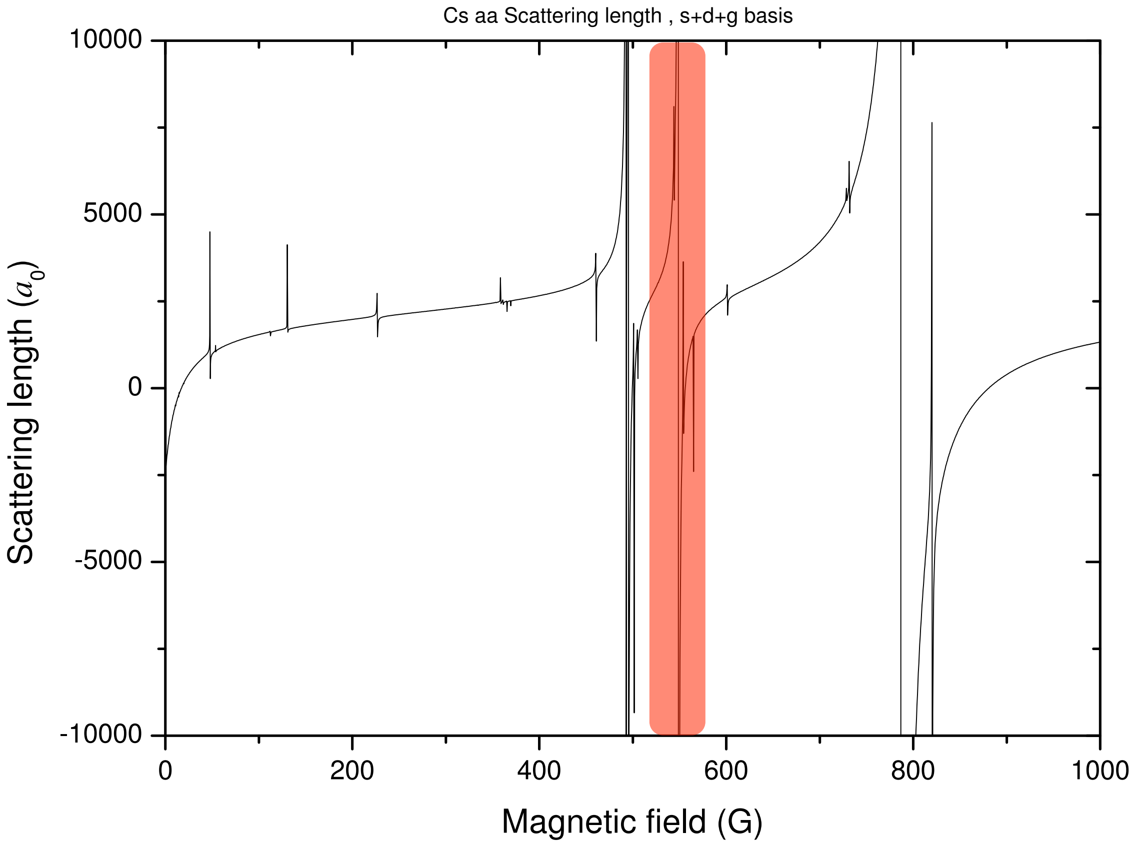
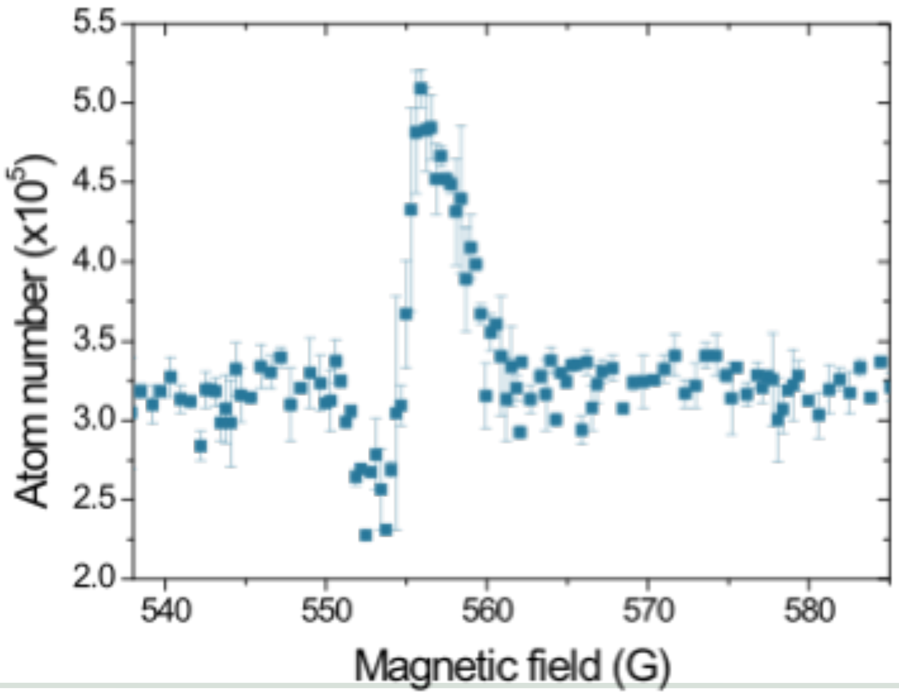
Cs evaporation at high fields:





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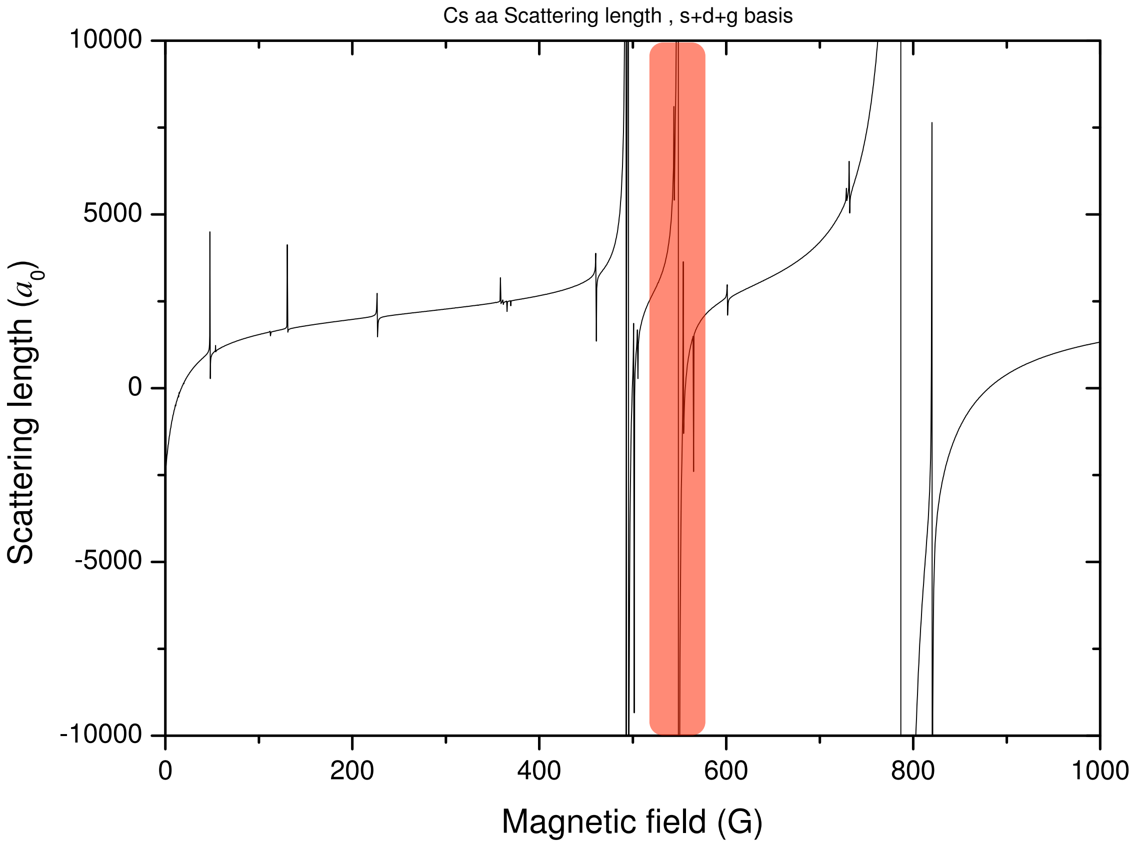

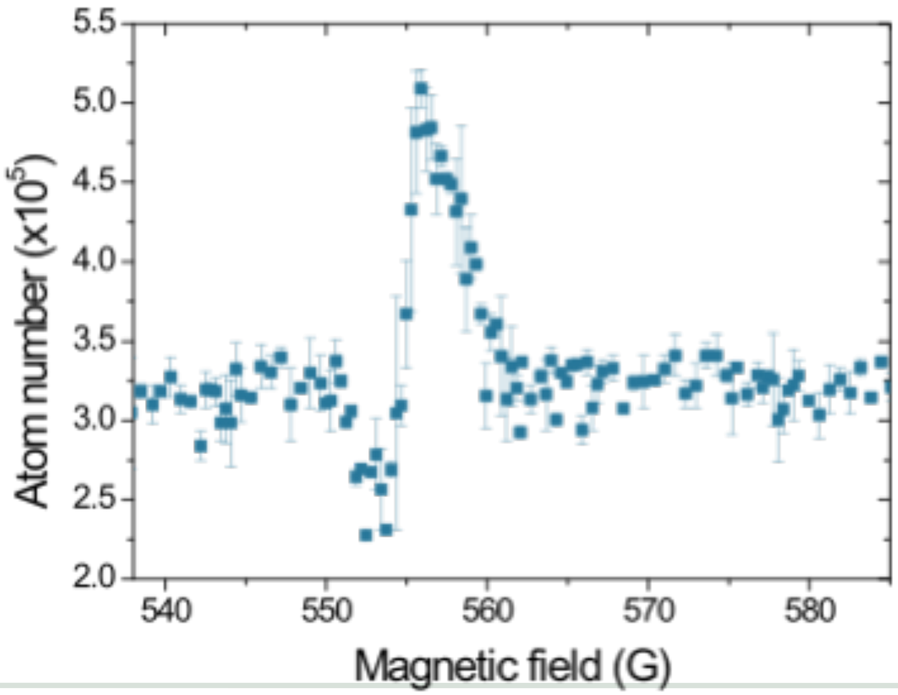

unitarity limit

Few-Body Syst (2011 51: 113-133)

Working at High Magnetic Fields

Preliminary Data

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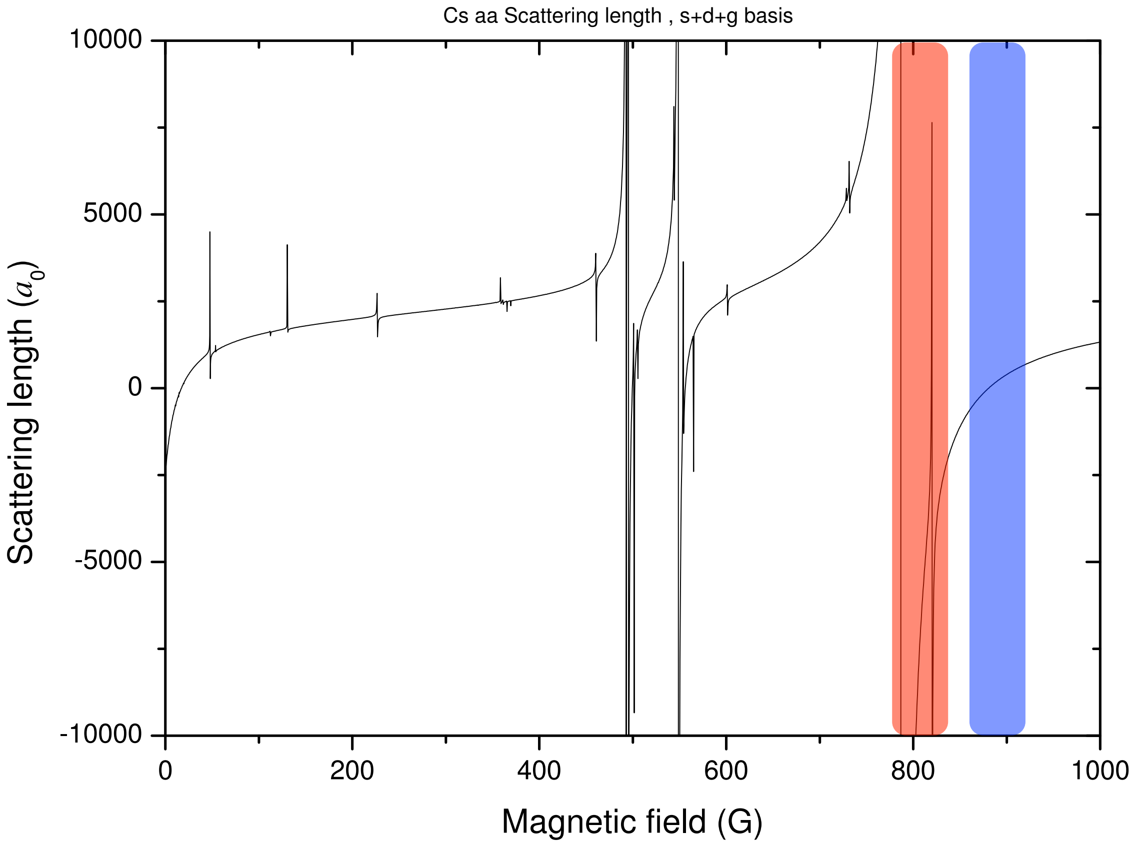
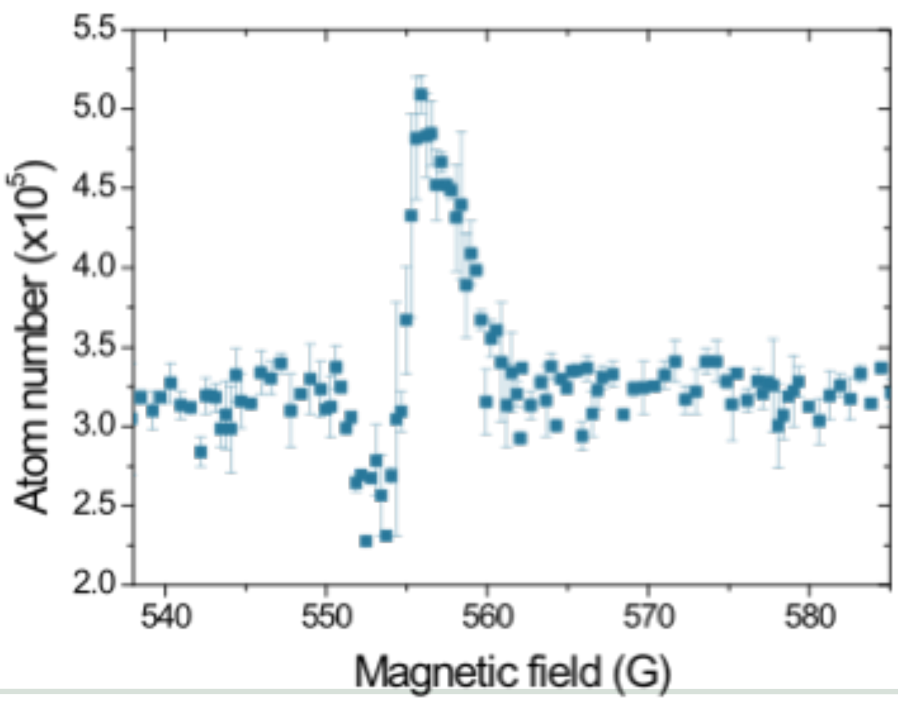
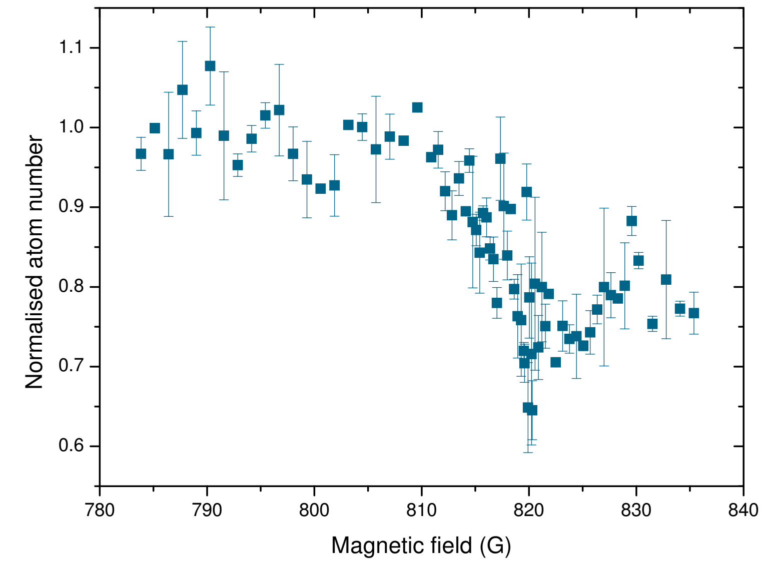
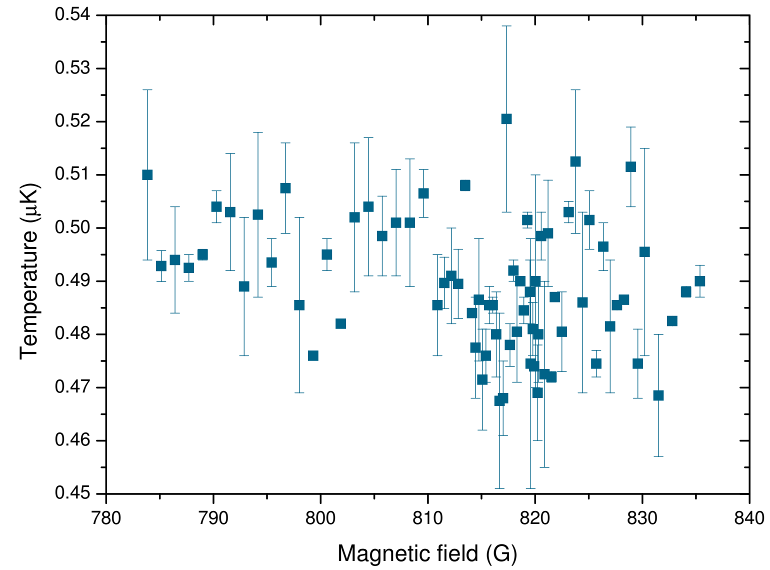


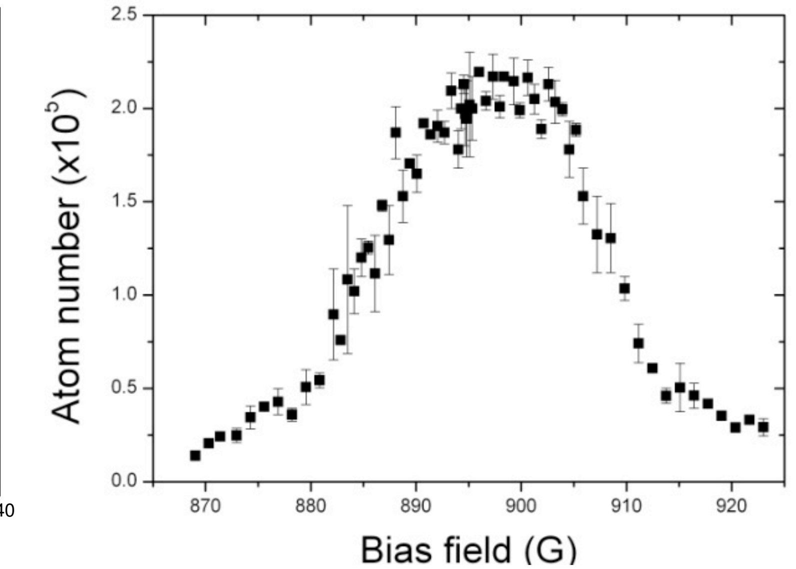


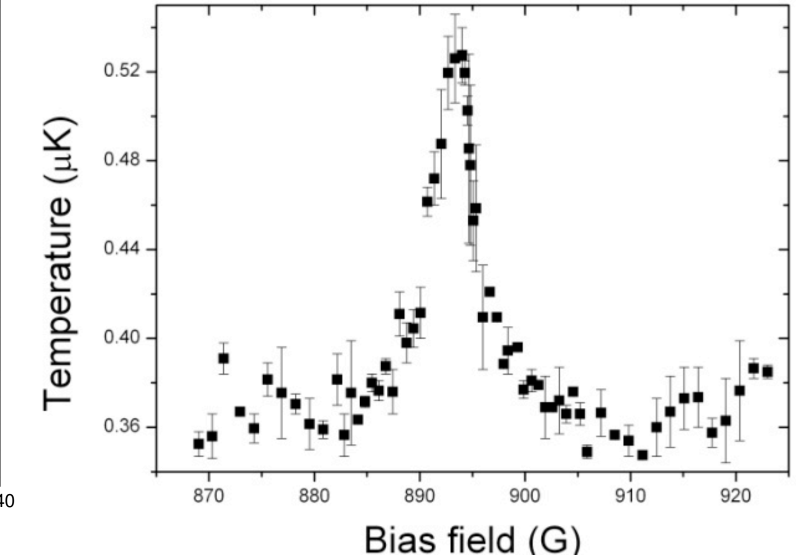
Loss vs Field





Cooling efficiency vs Field





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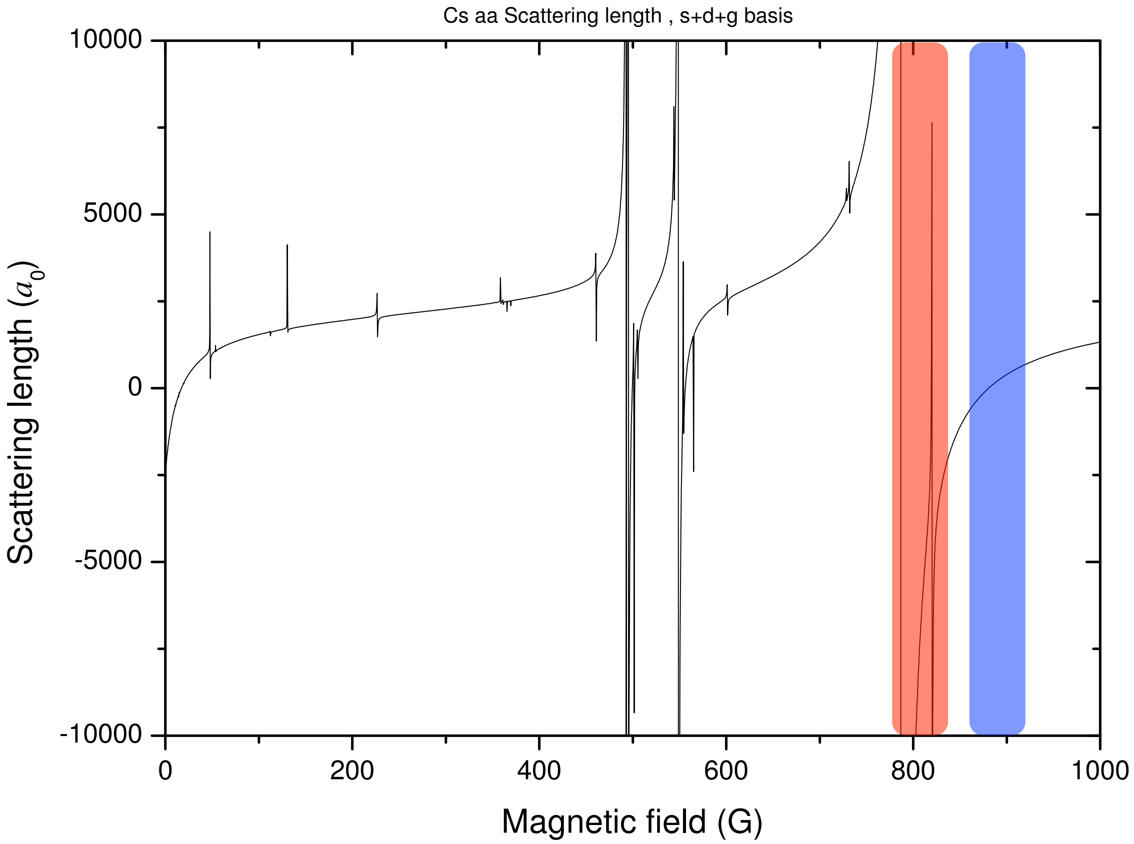
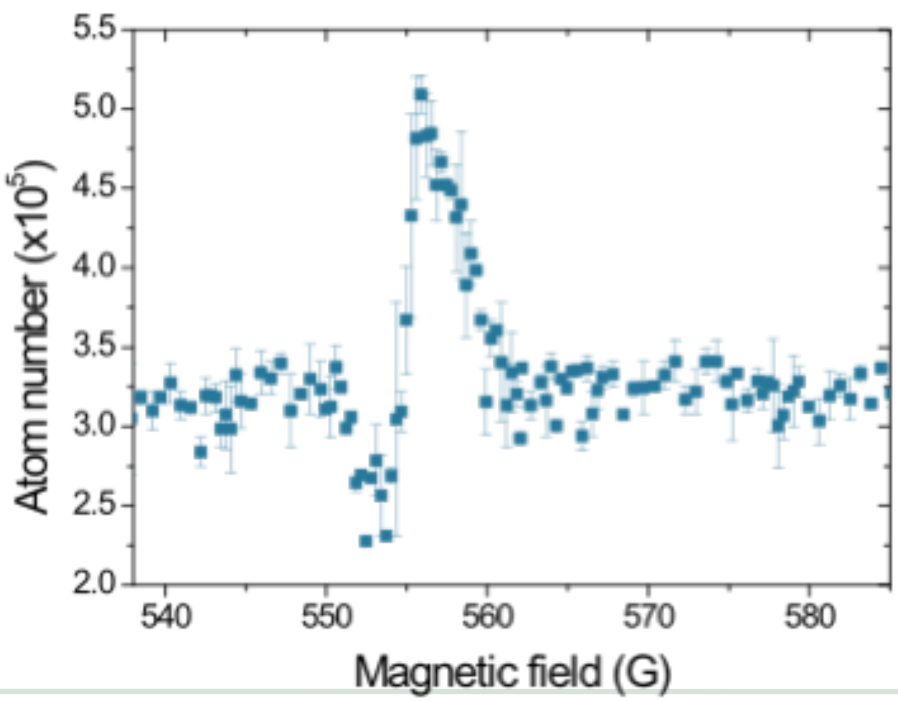
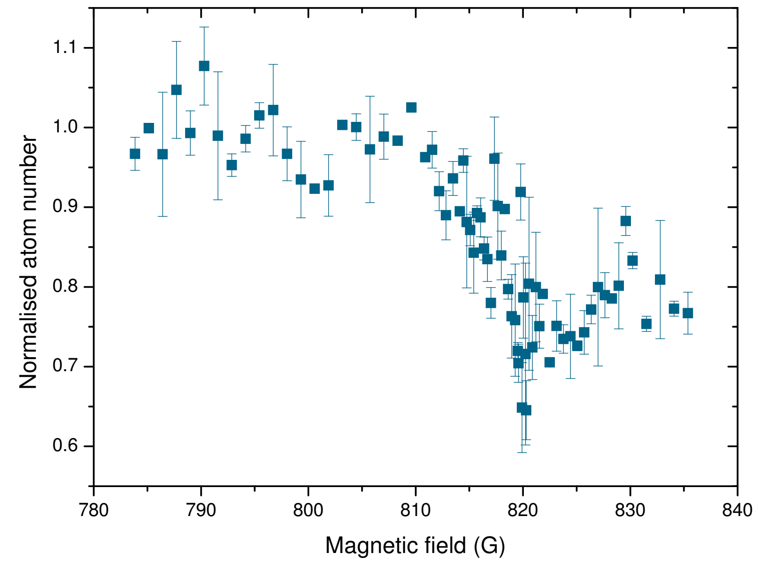
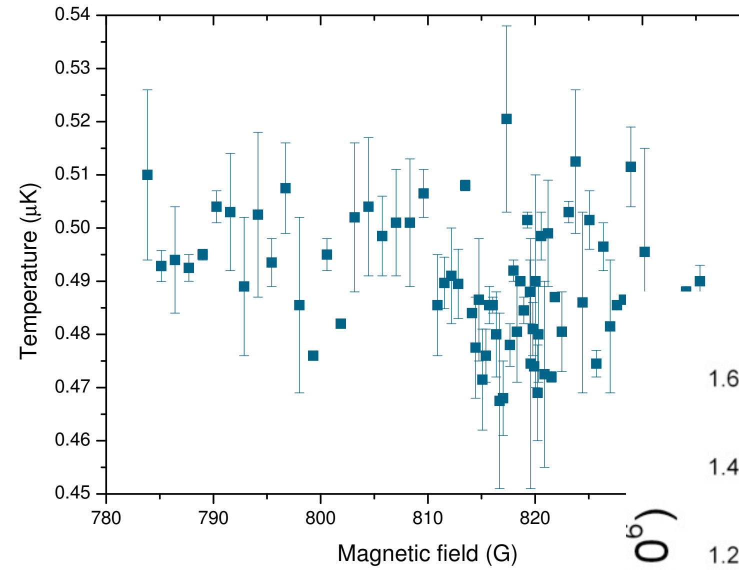
Cs evaporation at high fields:





Loss vs Field

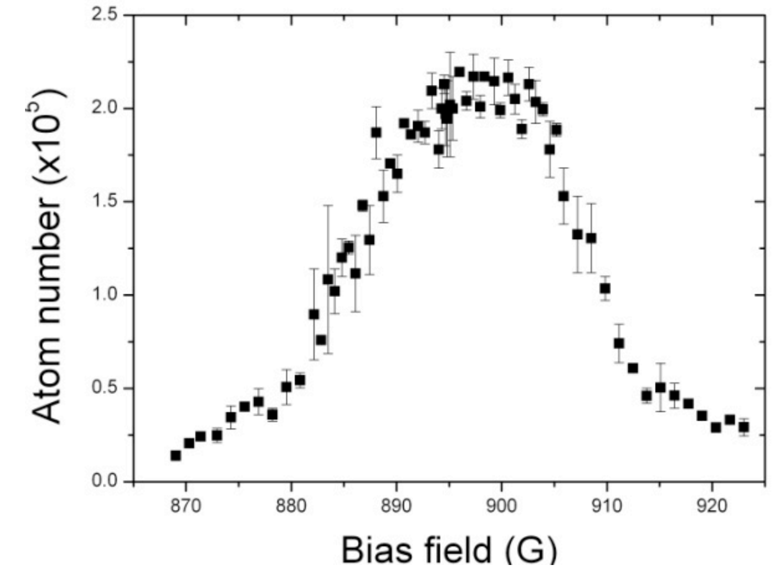


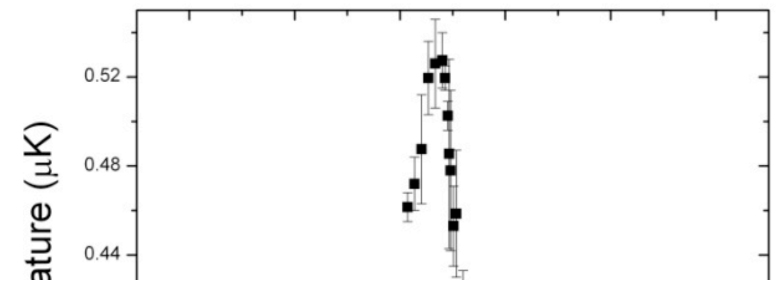


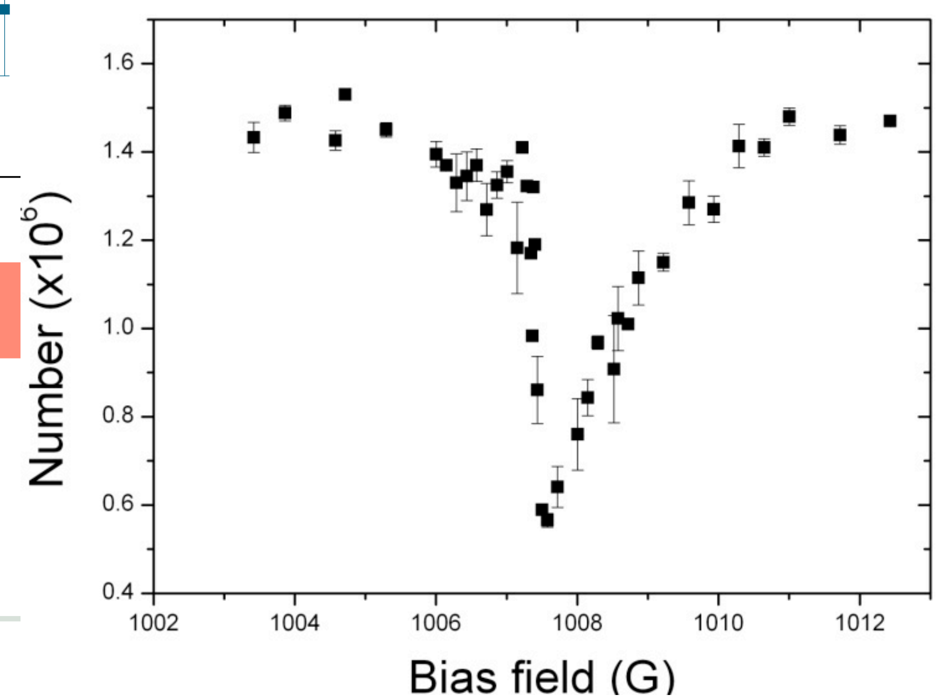
unitarity limit

Few-Body Syst (2011 51: 113-133)

Cooling efficiency vs Field







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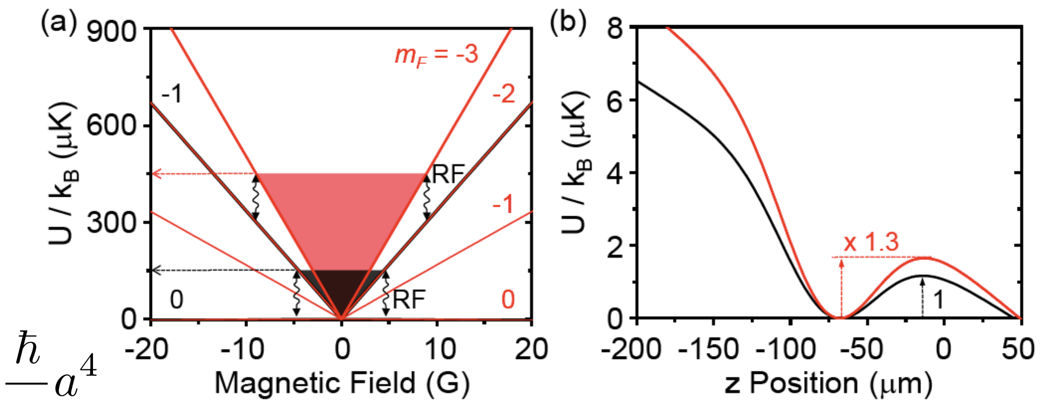
Toward Dual BEC

1) The calculated polarisabilities in atomic unit are ~ 572 a_0^3 for ^{133}Cs and ~ 425 a_0^3 for ^{87}Rb at 1550 nm. Phys. Rev. A, 73, 022505, 2006.



2) A strong interspecies loss after loading into the levitated dipole trap.
- τ_{Cs}= 0.8(1) s, τ_{Rb}= 4(1) & 70(10) s.
- τ_{Rb}= 0.9(2) s, τ_{Cs}= 2(1) & 10(3) s.

lower 3 body loss by reduce the peak density

$$\frac{\dot{N}}{N} = -L\langle n^2\rangle \ , L_3 = n_l C\frac{\hbar}{m}a^4$$

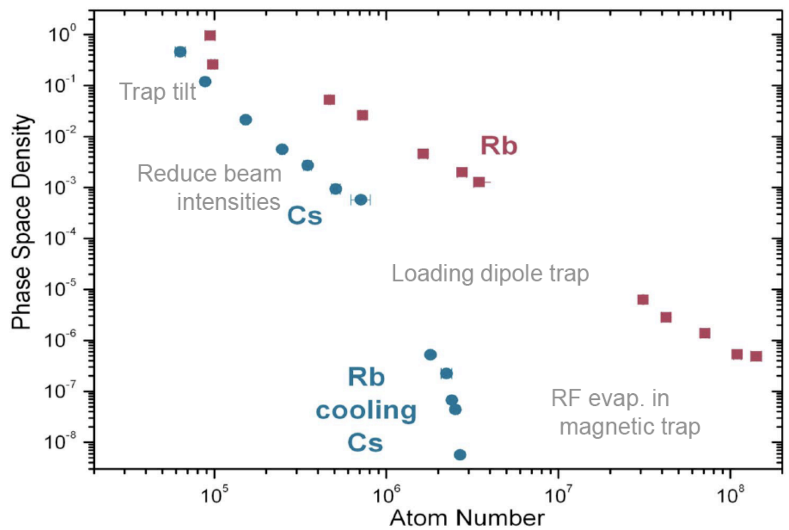
- change to a larger beam waist
- decompress trap

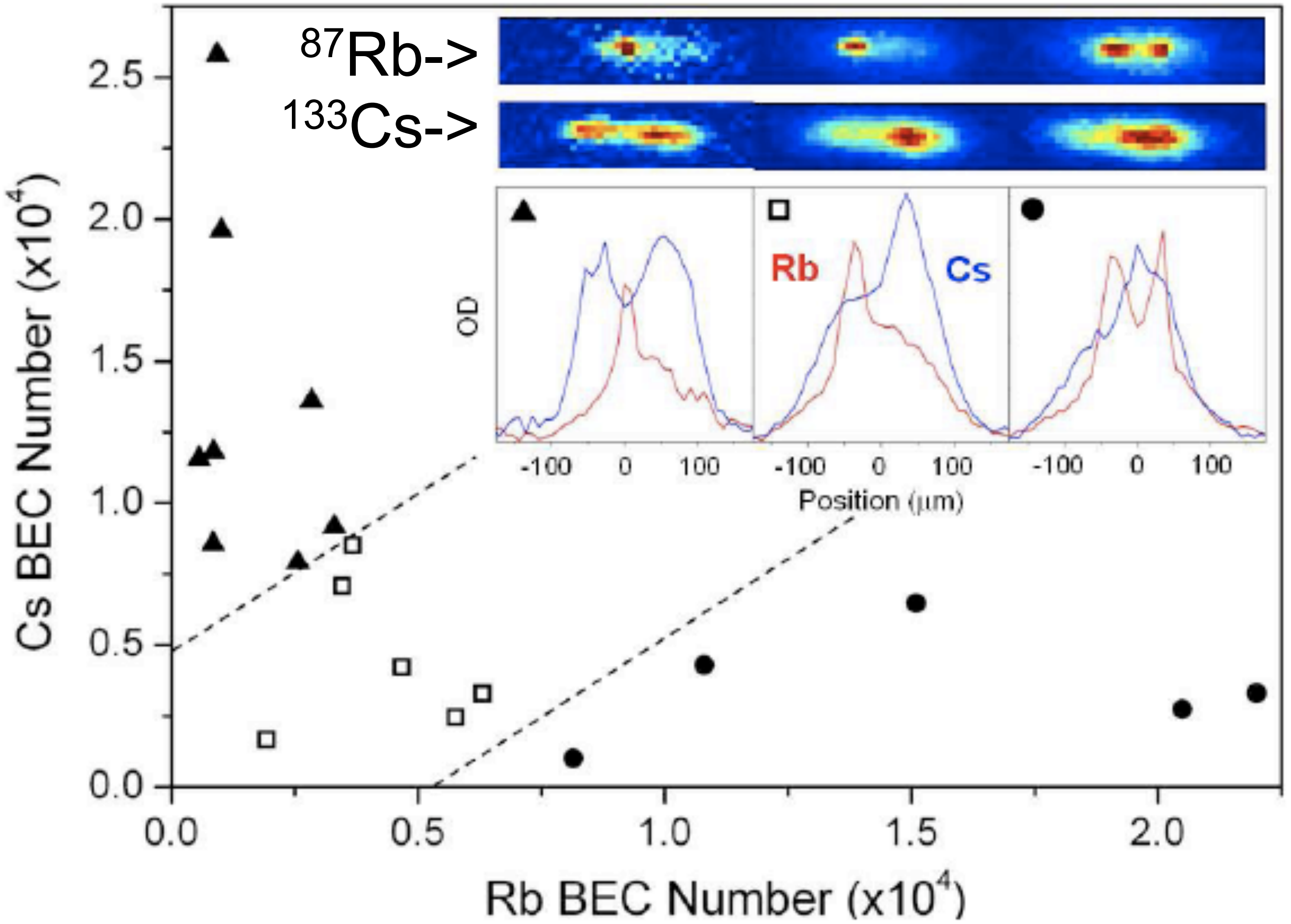
Immiscible quantum degenerate mixture:
the relative strength of the atomic interactions

$$\Delta = \frac{g_{RbCs}}{g_{Rb}g_{Cs}} > 1, g_{ij} = 2\pi\hbar^2 a_{ij}(\frac{m_i+m_j}{m_i m_j})$$

Phys.Rev. A, 65, 063614, 2002

In our case, B = 22.4 G, a_{Rb} = 100a_0 and a_{Cs} = 280a_0, the observation of immiscibility require a_{RbCs} > 165a_0. a_{RbCs} = 650a_0 (J. Hutson, private communication 2011)





Phys. Rev. A **84** 011603(R) (2011)

Preliminary Data

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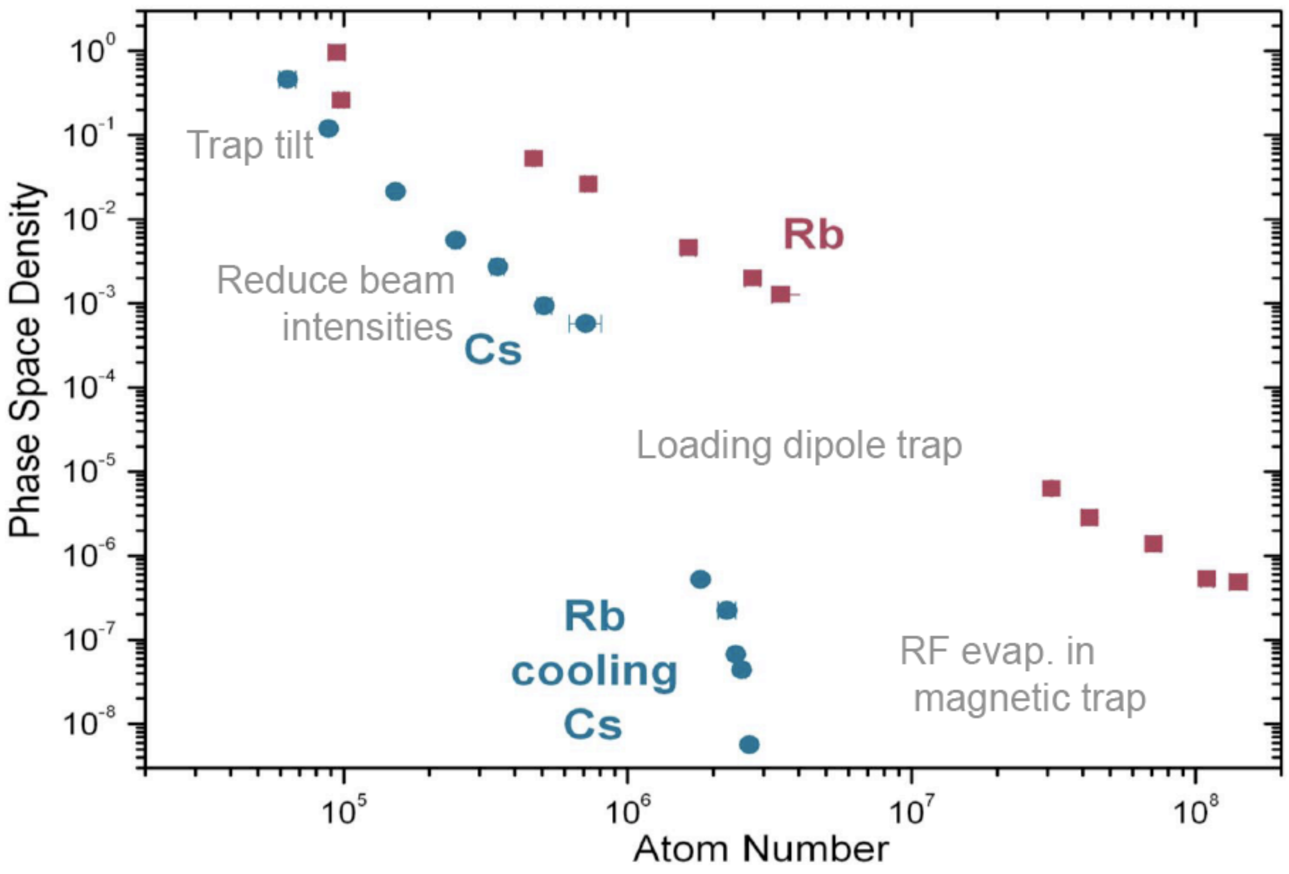
^{87}RbCs Feshbach resonances



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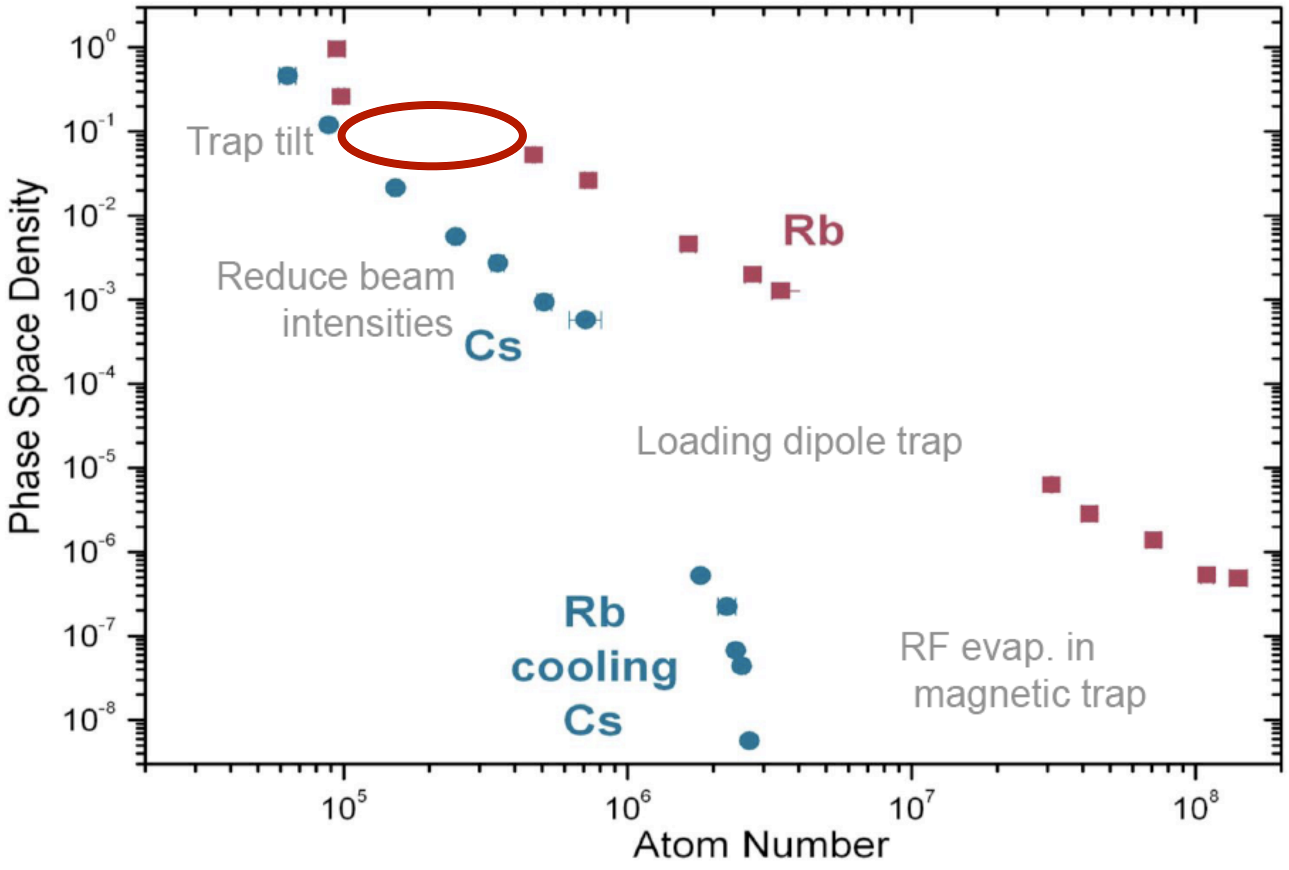

RbCs Feshbach Resonance

Preliminary Data

AtMol. Durham Atomic & Molecular Physics

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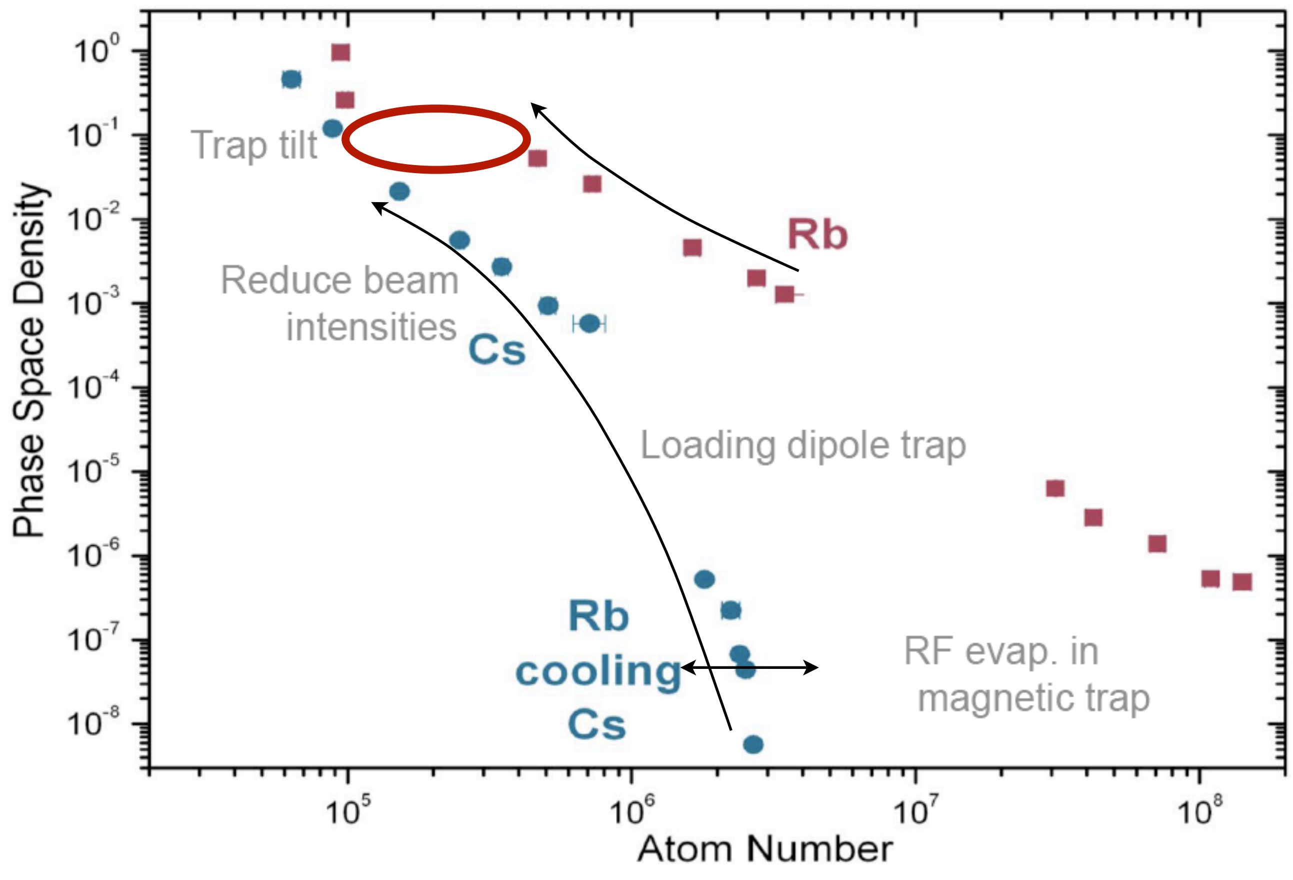

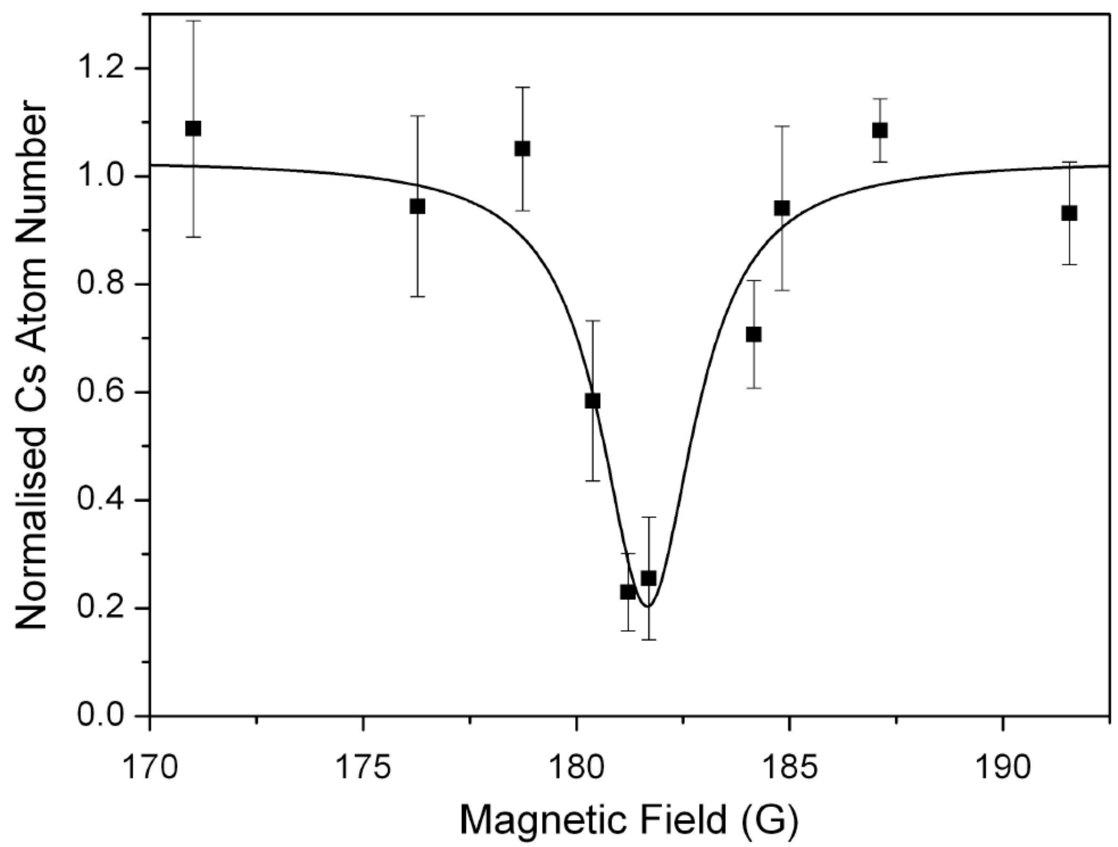

Peak densities of ^{87}Rb and ^{133}Cs are 1.6(1) x 10^{12} cm^{-3} and 3.1(4) x 10^{11} cm^{-3}.

The mixture contains 3.0(3) x 10^5 ^{87}Rb and 2.6(4) x 10^4 ^{133}Cs at 0.32(1) μK

- the temperature is well below the p-wave threshold (k_B x 56 μK based upon C_6, Phys. Revs A 59, 390, 1999)
- The presented Feshbach spectrum near 180 G is measured by evolving the mixture at a specific homogeneous magnetic field for 5 sec and each data point corresponds to an average of 3-5 measurements.

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RbCs Feshbach Resonance

Preliminary Data

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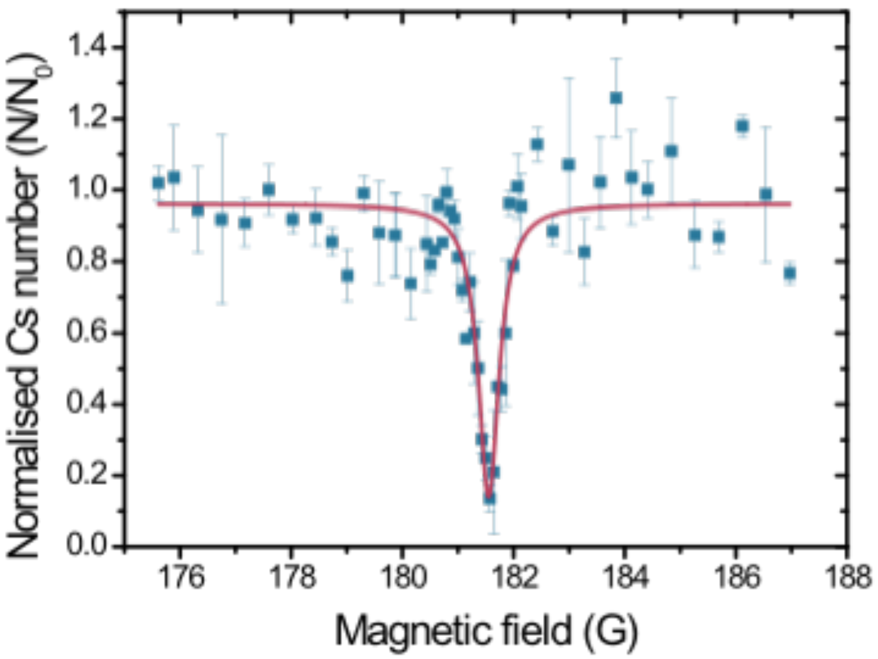
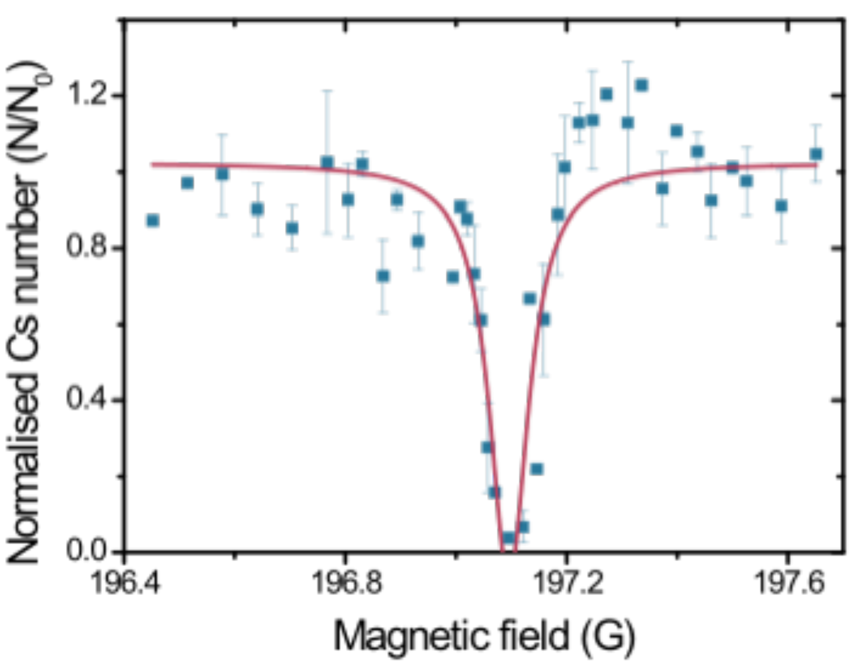
^{87}RbCs Feshbach resonances



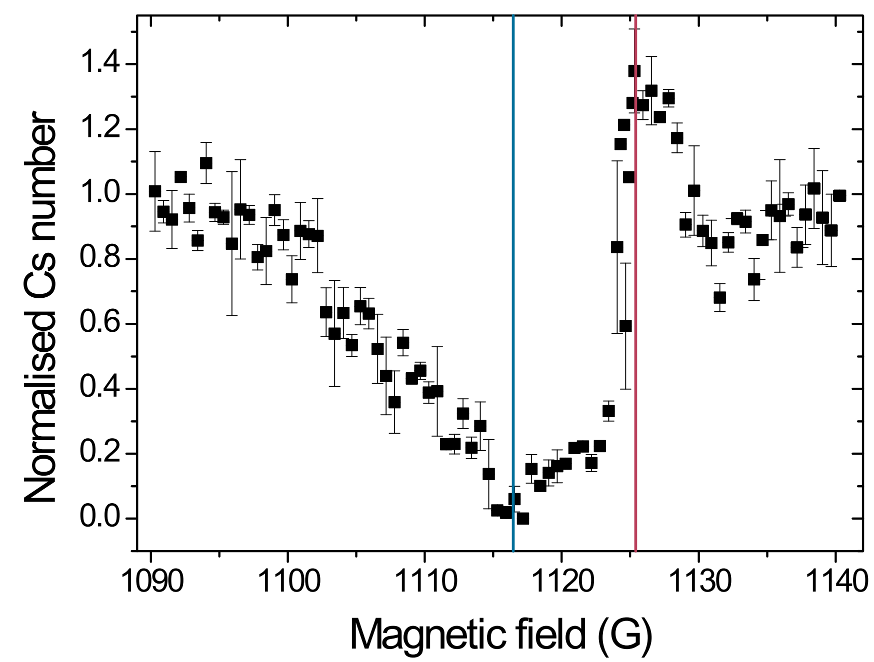
Position: 181.55(2) G
Width: 0.45(7) G

Theor. pos.:
181.65 G



Position: 197.095(4) G
Width: 0.09(1) G

Theor. pos.:
197.067 G



Theor. pos.:

Zero crossing: 1125.4 G

Pole: 1116.46 G

J. Hutson, private communication (2011)

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^{87}RbCs Feshbach resonances

Theor. pos.:
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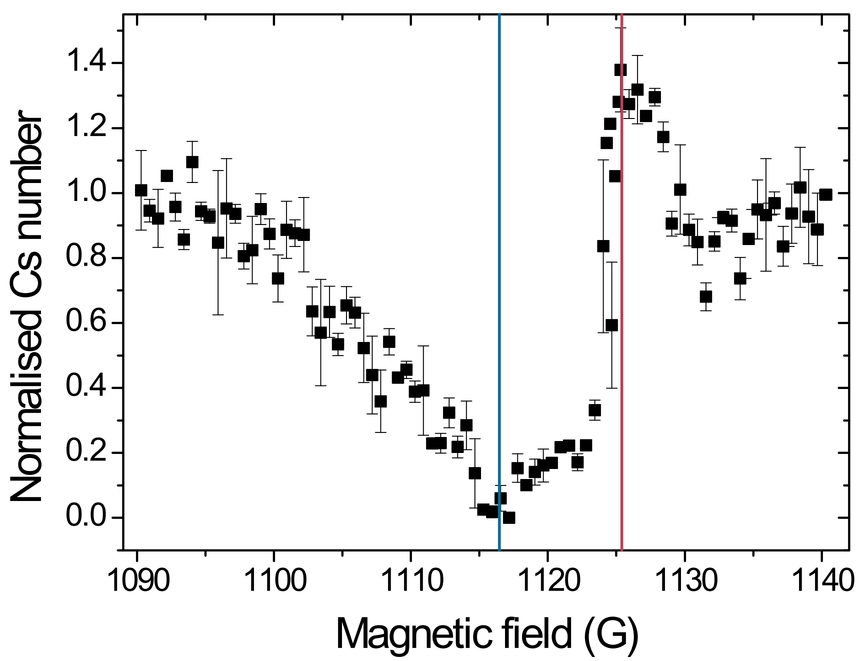

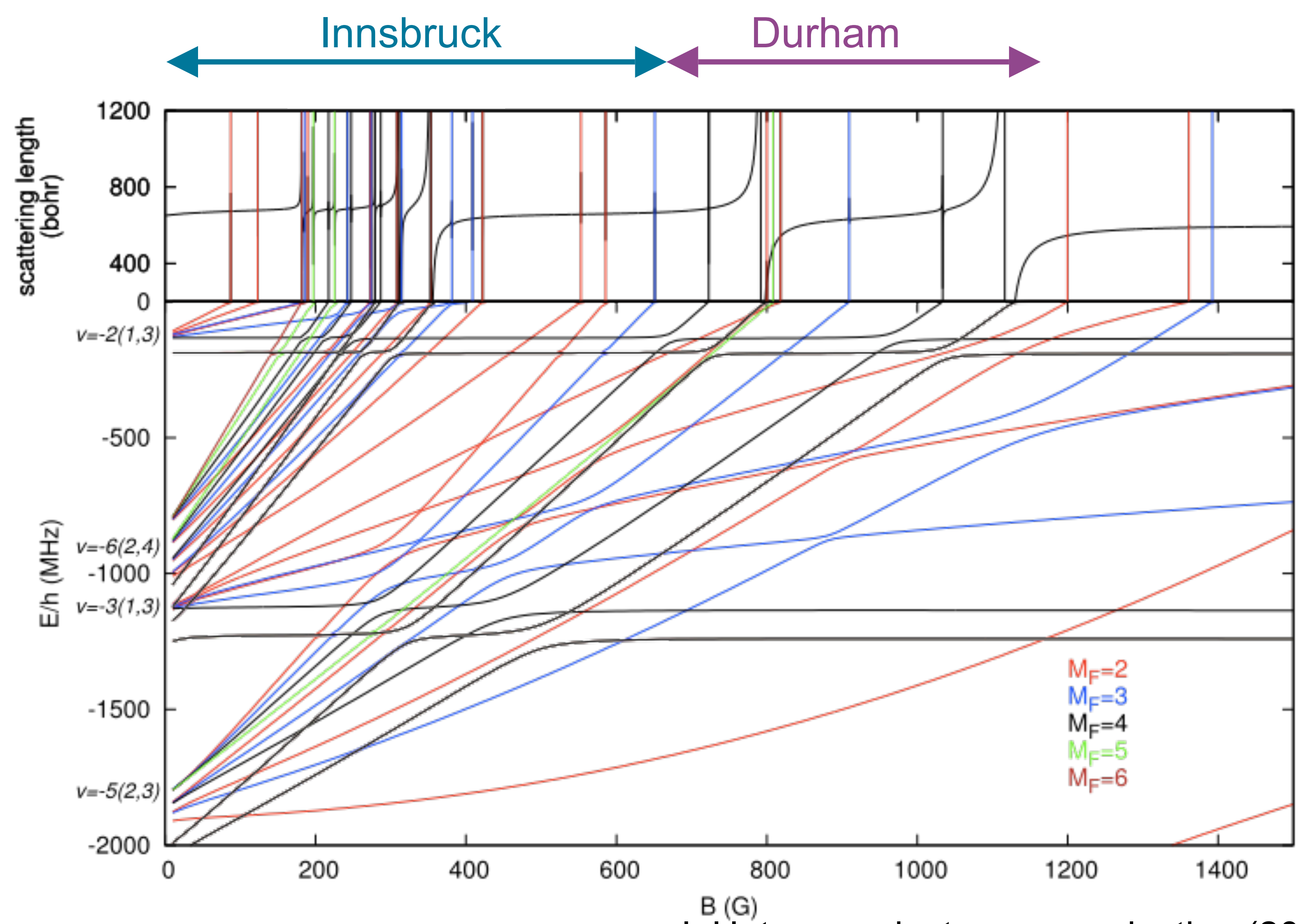

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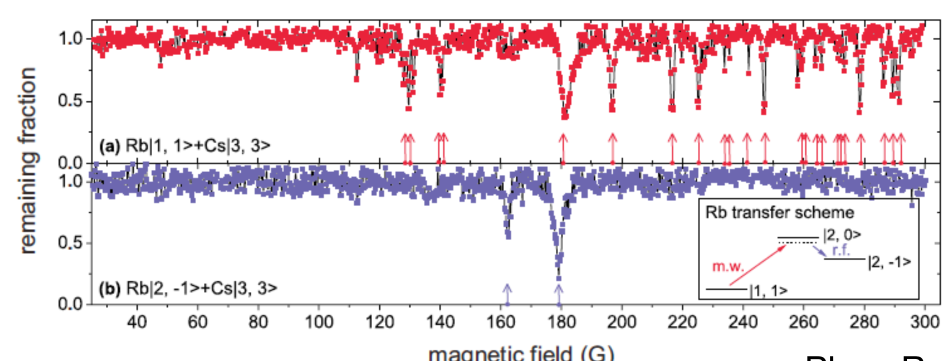

Phys. Rev. A 79 042718 (2009)

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^{87}RbCs Feshbach resonances

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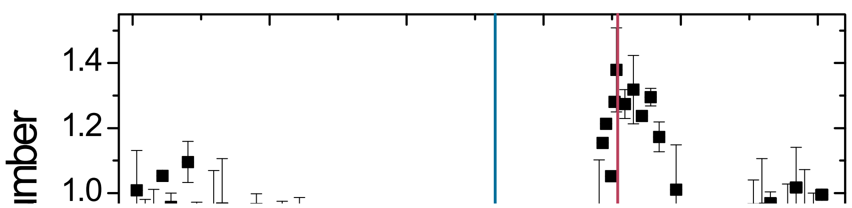

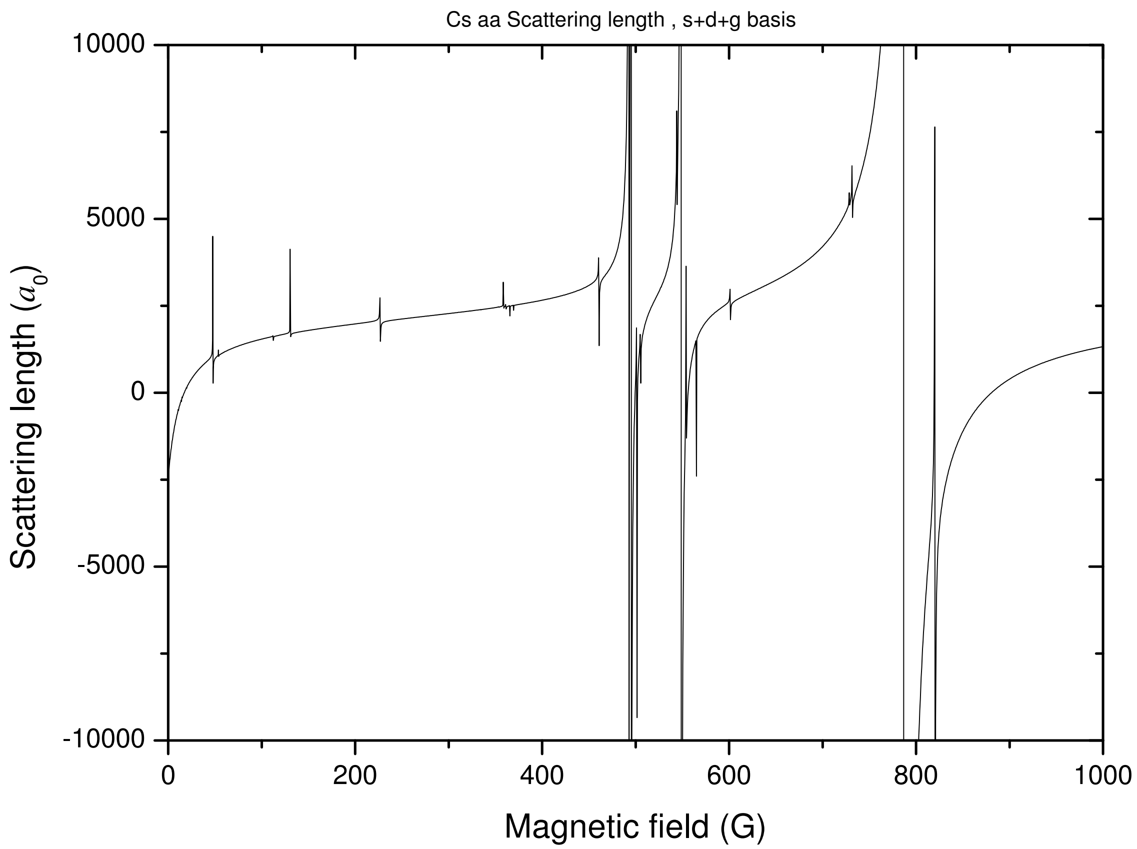

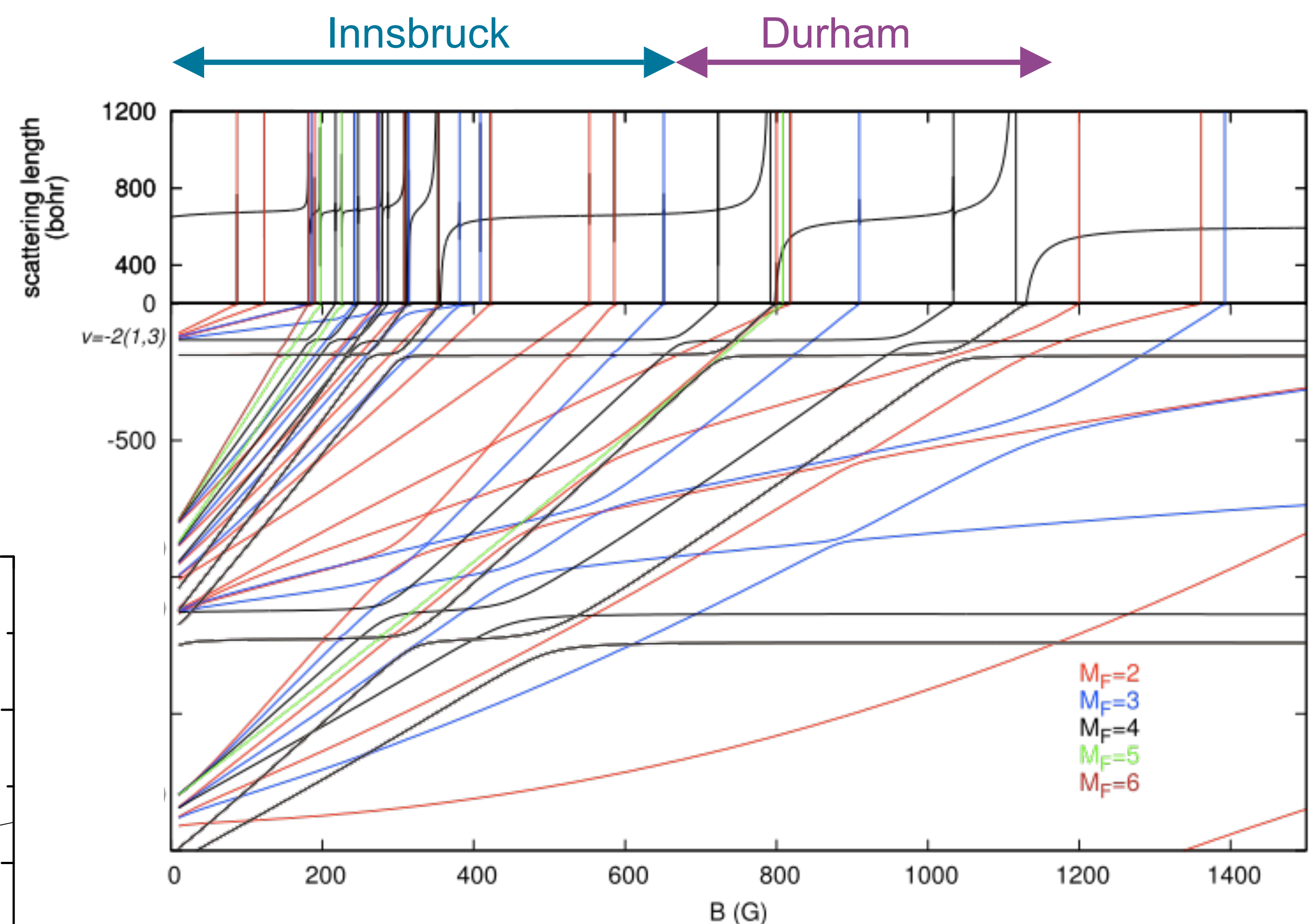

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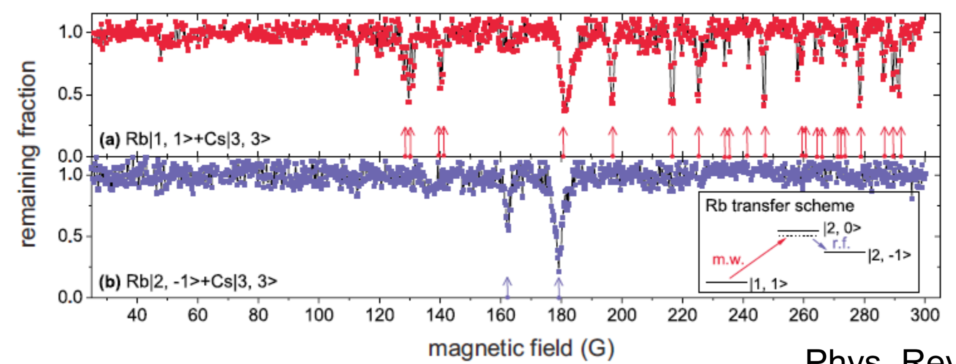

Phys. Rev. A 79 042718 (2009)

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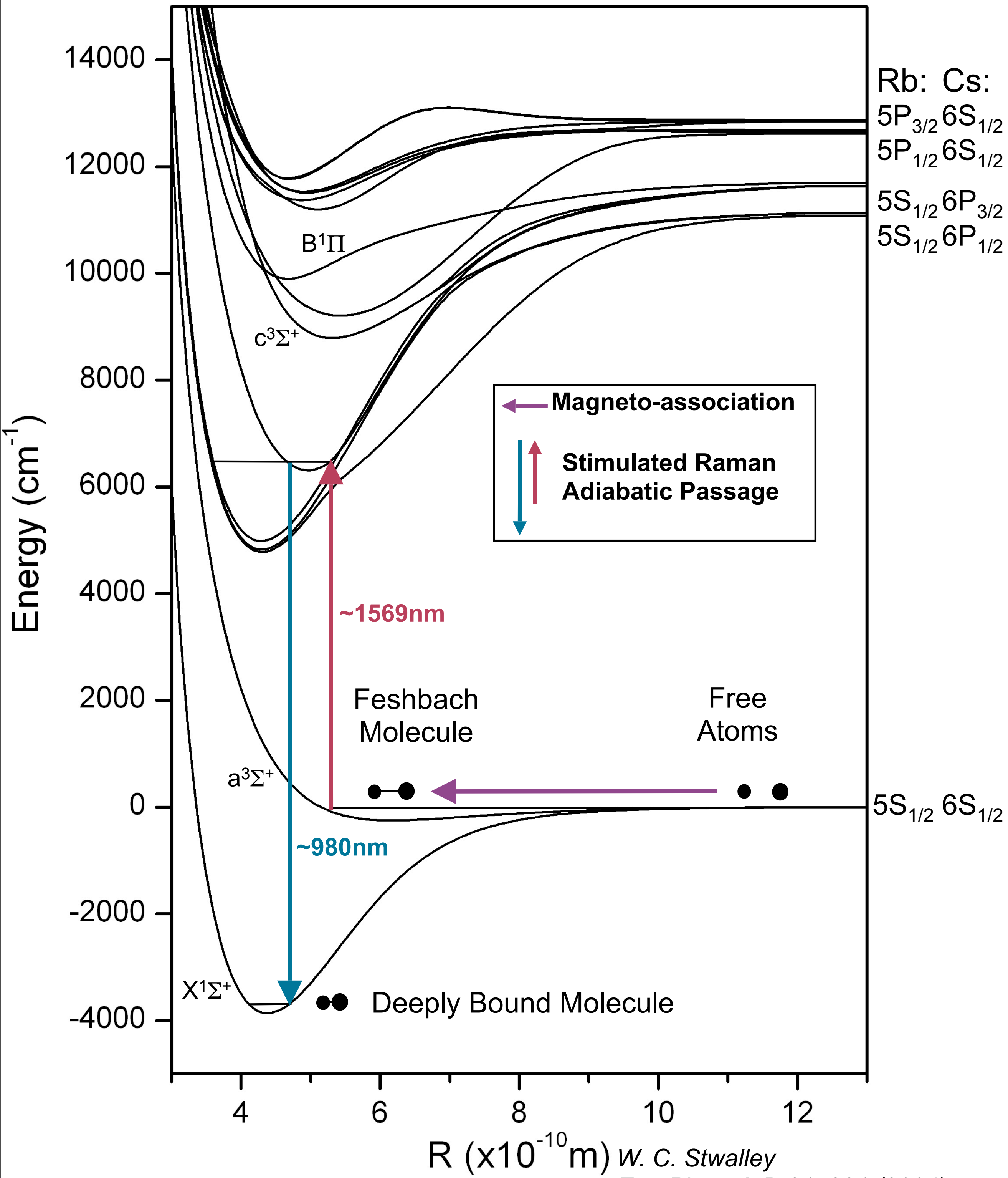
Outline

- Bose-Einstein condensations (BECs)
  - ^{87}Rb BEC in a combined magnetic and optical trap
  - ^{133}Cs BEC in a crossed dipole trap
  - A quantum degenerate Bose mixture of ^{87}Rb and ^{133}Cs
- Feshbach molecules
  - The formation background and method
  - ^{87}Rb^{133}Cs Feshbach resonance measurement
- Stimulate Raman adiabatic passage (STIRAP)
  - a two-photon scheme transfers the Feshbach molecules into the rovibronic ground state
- Summary

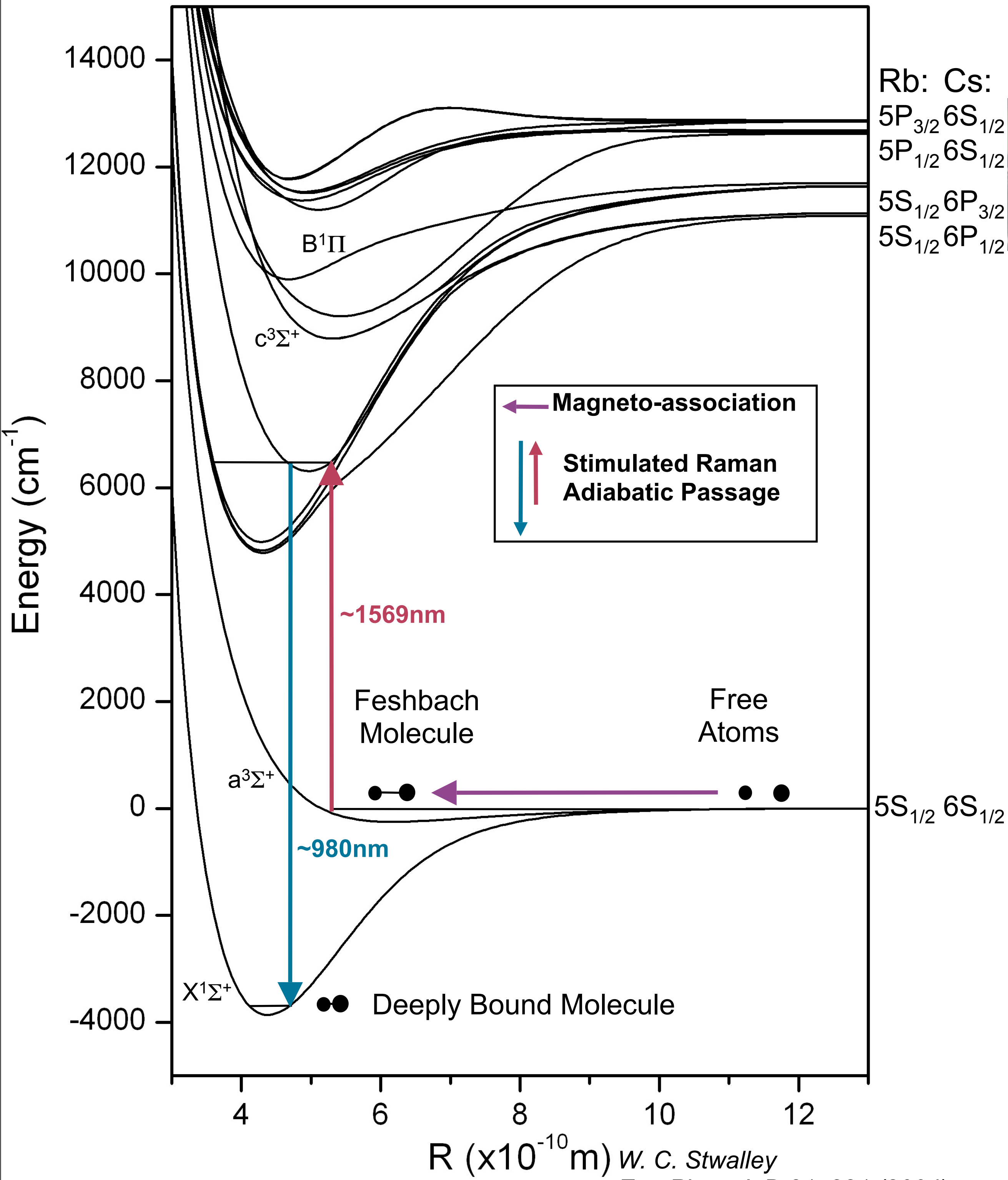
Stimulate Raman adiabatic passage (STIRAP)



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

Phys. Chem. Chem. Phys. 13 18926 (2011)

Stimulate Raman adiabatic passage (STIRAP)



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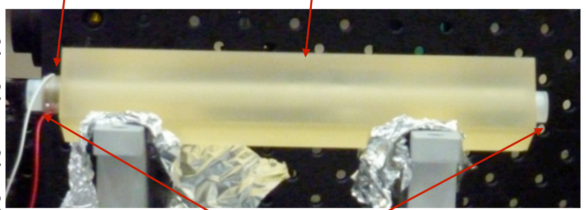
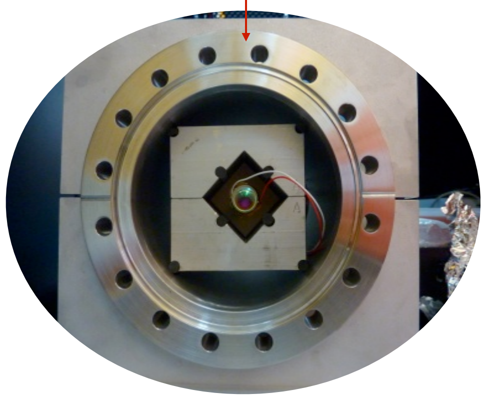
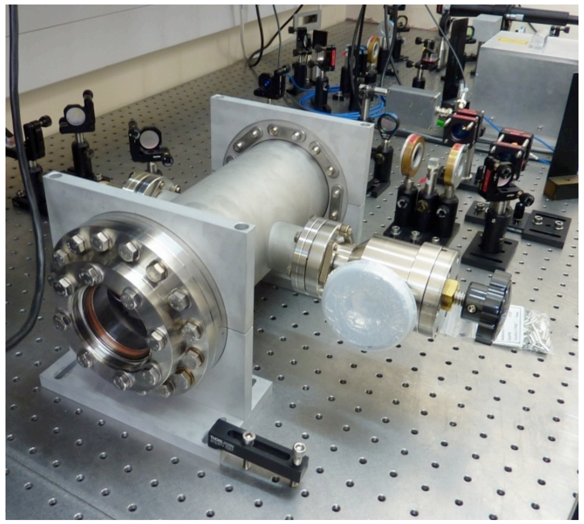
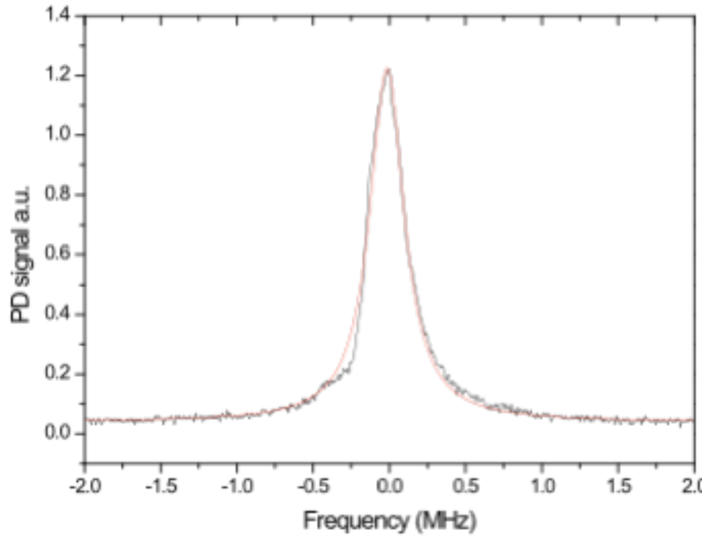
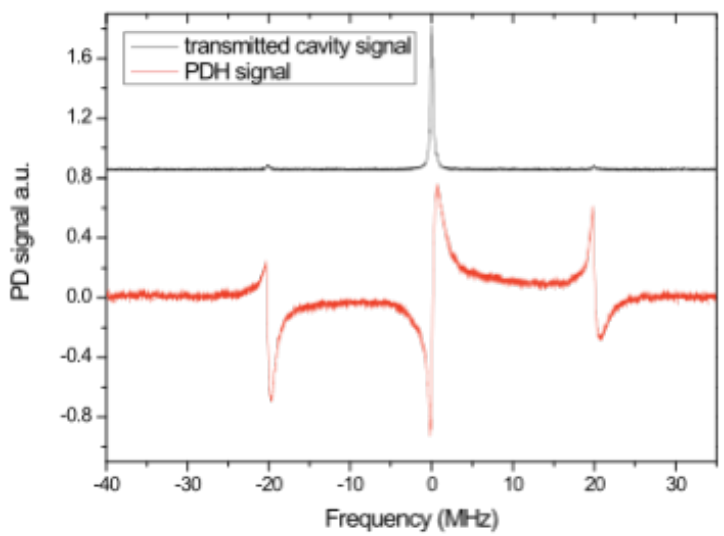










FWHM: 270 kHz
FSR: 750 MHz
Finesse: ~ 3000

Phys. Chem. Chem. Phys. 13 18926 (2011)

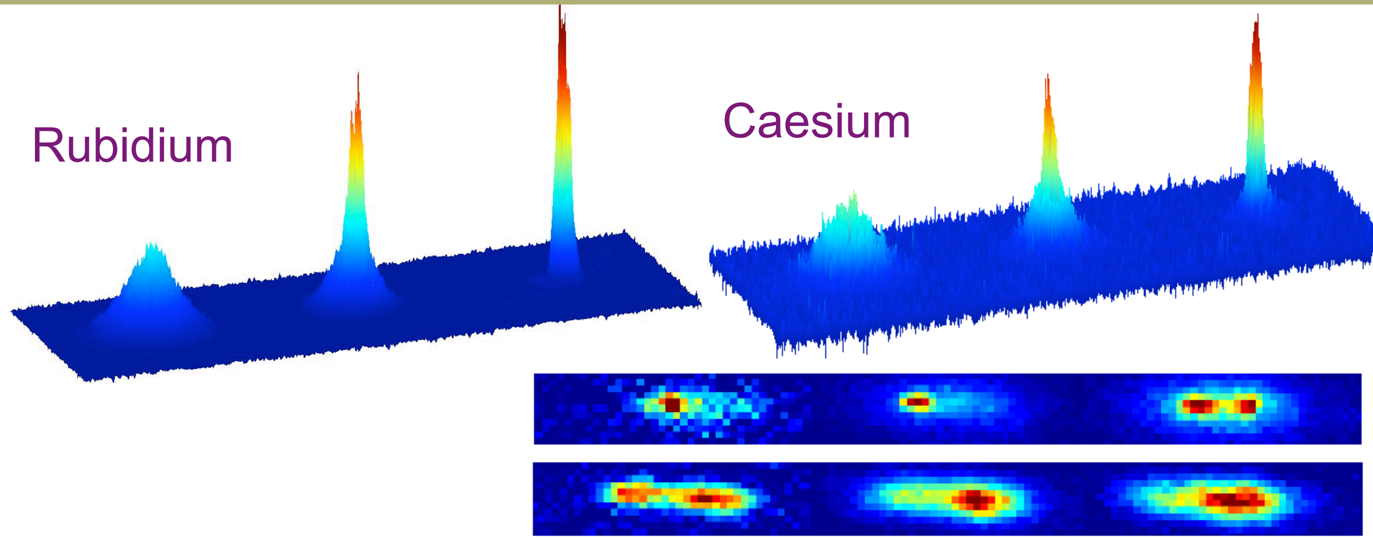
Summary

- Bose-Einstein condensations (BECs)

  ^{87}Rb BEC in a combined magnetic and optical trap

  ^{133}Cs BEC in a crossed dipole trap

  A quantum degenerate Bose mixture of ^{87}Rb and ^{133}Cs



- Feshbach molecules

  The formation background and method

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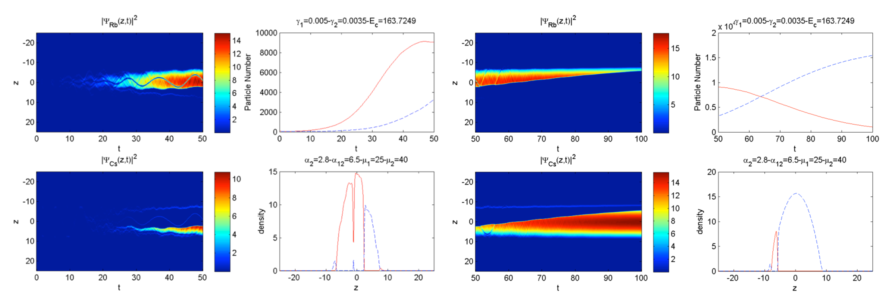

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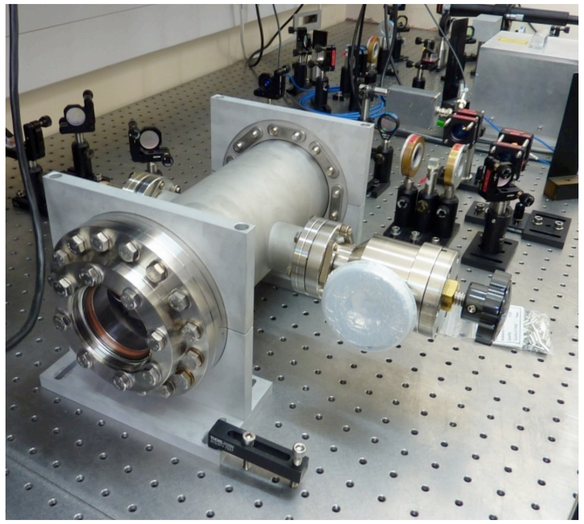

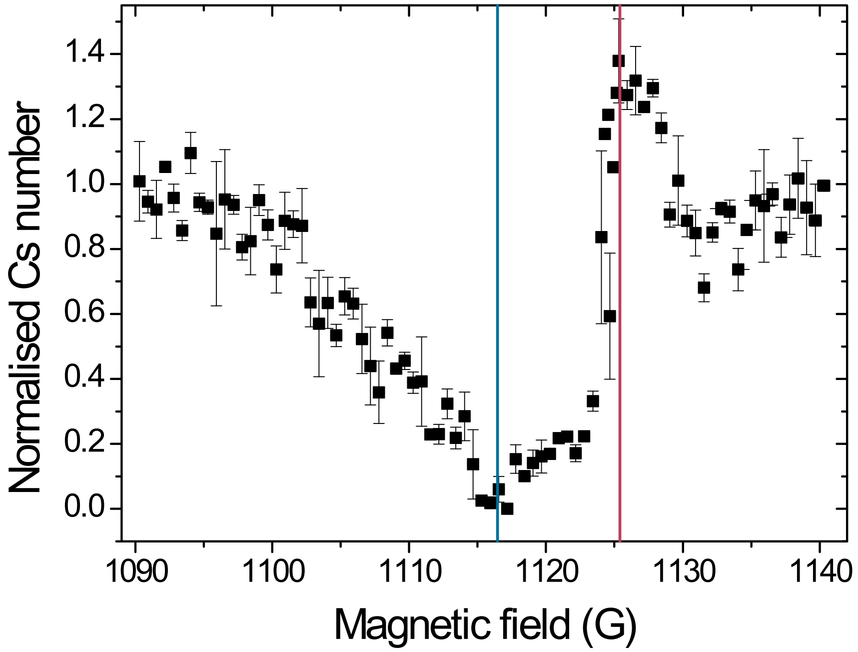

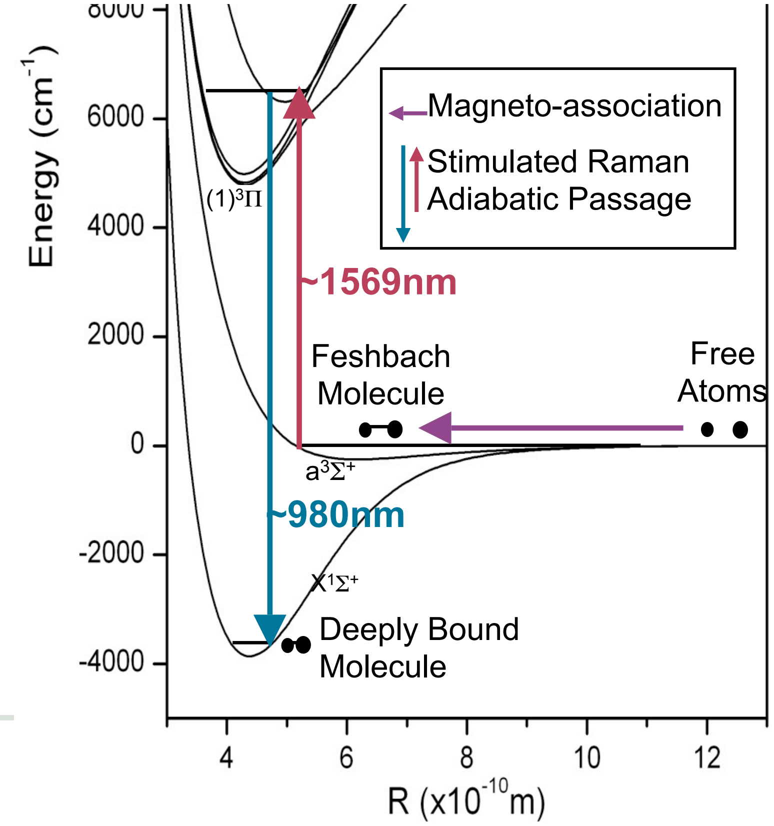

Thanks

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