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Ultracold Alkali Metal Atoms and Dimers: A Quantum Paradise

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Thanks to
Eite Tiesinga (NIST), Svetlana Kotochigova (Temple/NIST)
Bo Gao (U. Toledo), Thorsten Köhler (Oxford)
Roman Ciurylo (Torun), Pascal Naidon (NIST)

M. Kitagawa, K. Enomoto, K. Kasa, Y. Takahashi (Kyoto University)

Looking for good students/postdocs
Joint Quantum Institute, NIST/University of Maryland

http://www.jqi.umd.edu/
http://physics.nist.gov/

Cold alkali atoms and molecules

Widely used in forefront experiments

- Ultra-cold Bose or Fermi gases
- Optical lattices and reduced dimensional structures
- Precision measurements
- Multidisciplinary studies and applications

Control interaction properties

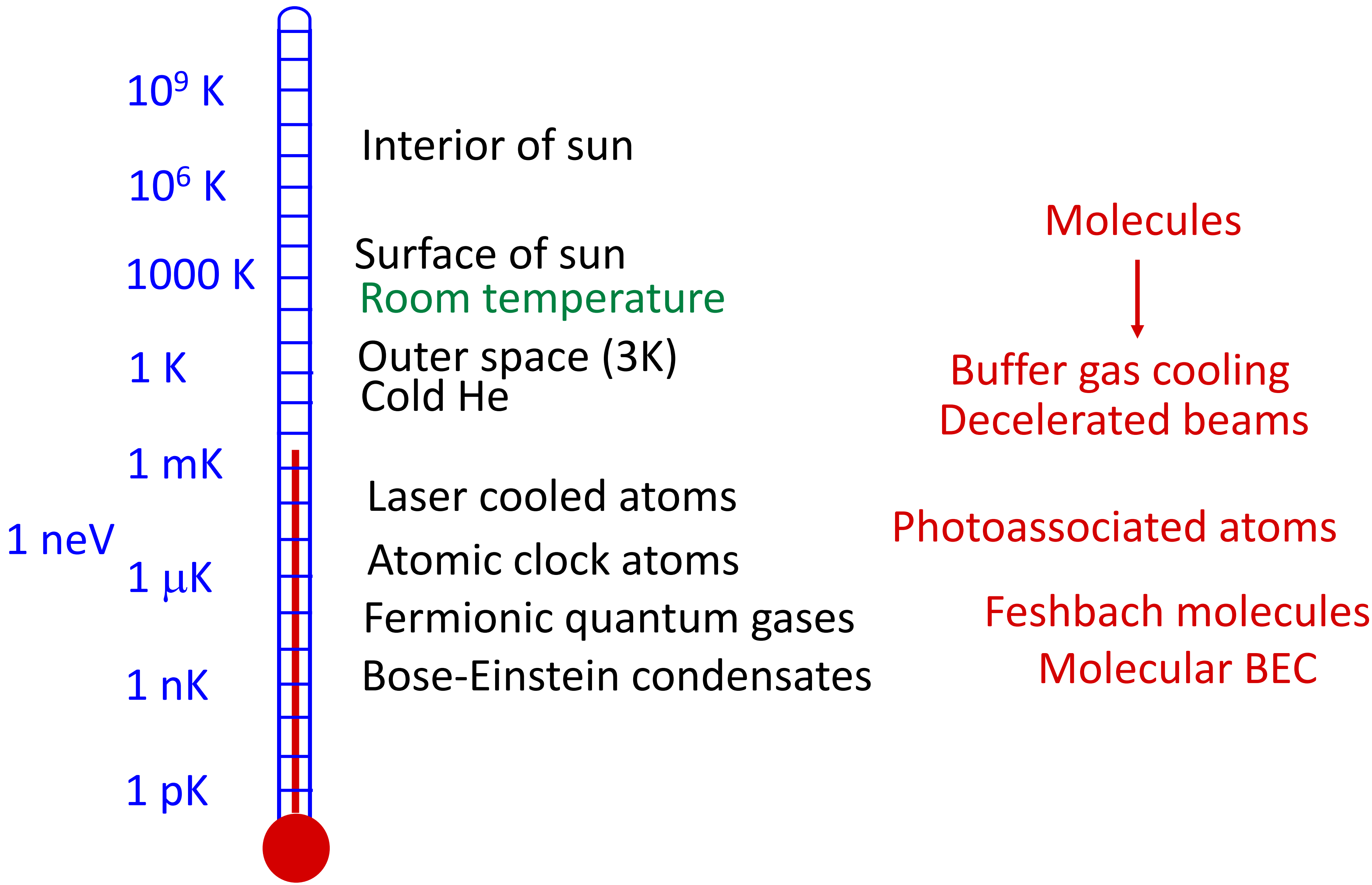
- by static or dynamic electromagnetic fields
- s-wave scattering length (a quantum phase shift)

Complex calculations required

- coupled channels methods
- *ab initio* structure and properties

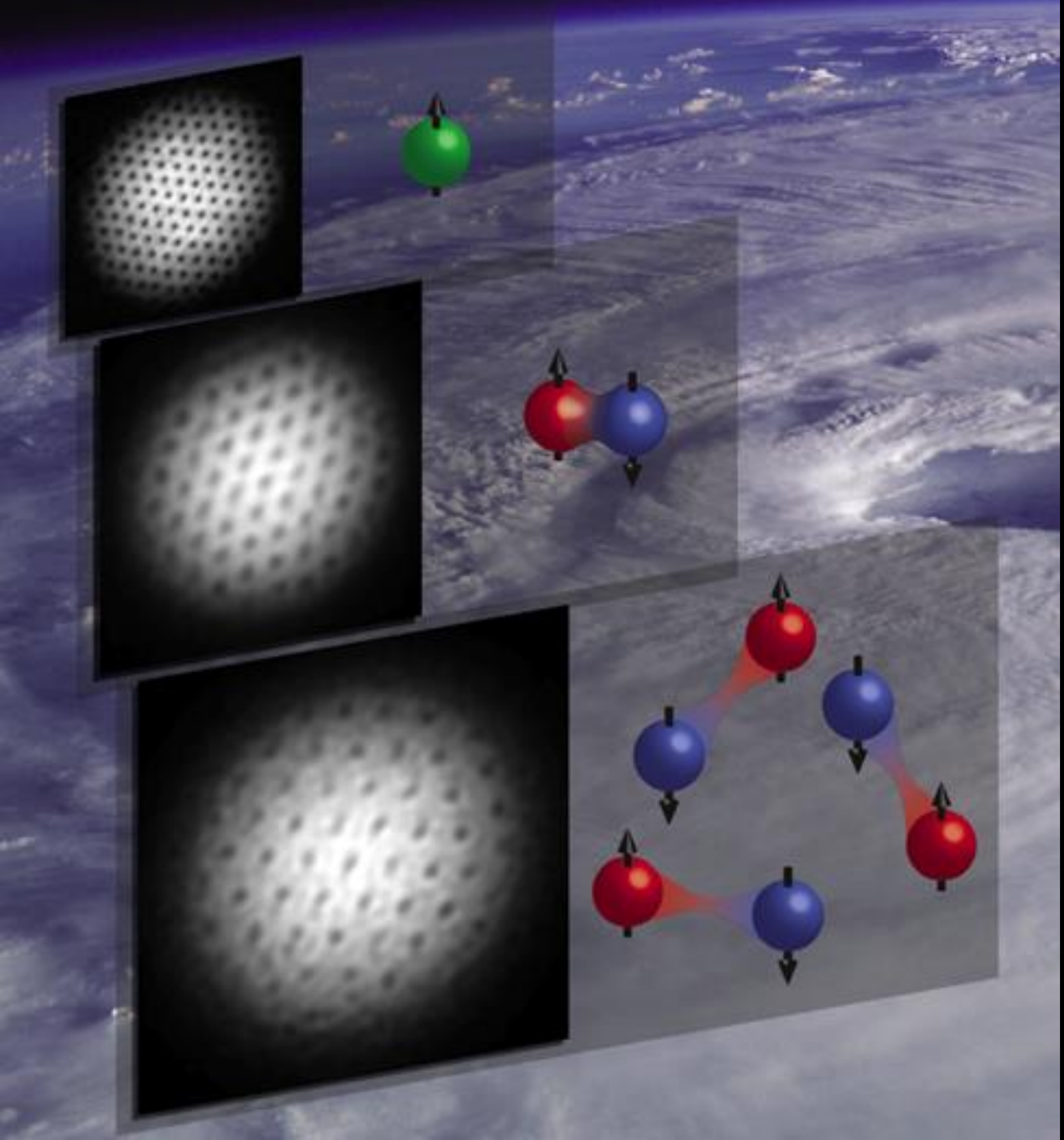
But remain amenable to simple models

- based on long range potentials



10⁹ K
10⁶ K
1000 K
1 K
1 mK
1 neV
1 μK
1 nK
1 pK
Interior of sun
Surface of sun
Room temperature
Outer space (3K)
Cold He
Laser cooled atoms
Atomic clock atoms
Fermionic quantum gases
Bose-Einstein condensates
Molecules
Buffer gas cooling
Decelerated beams
Photoassociated atoms
Feshbach molecules
Molecular BEC

From Wolfgang Ketterle Group, MIT

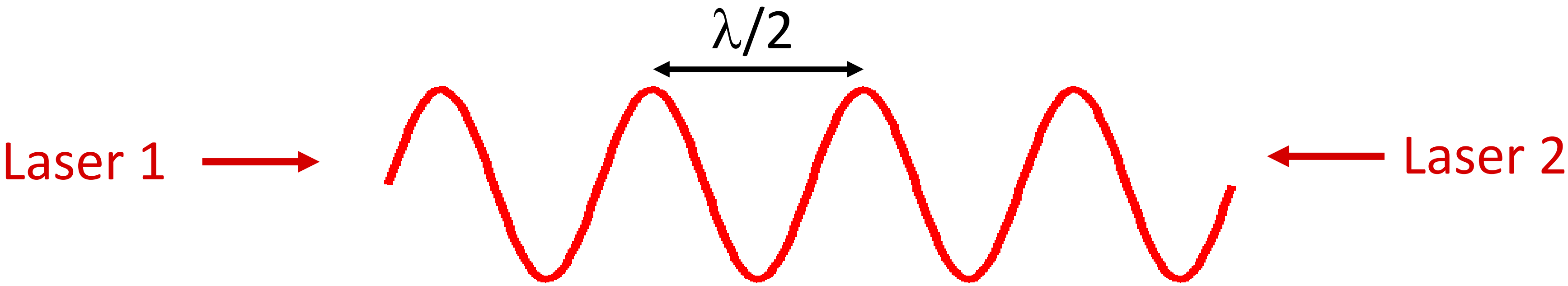


^{23}Na BEC

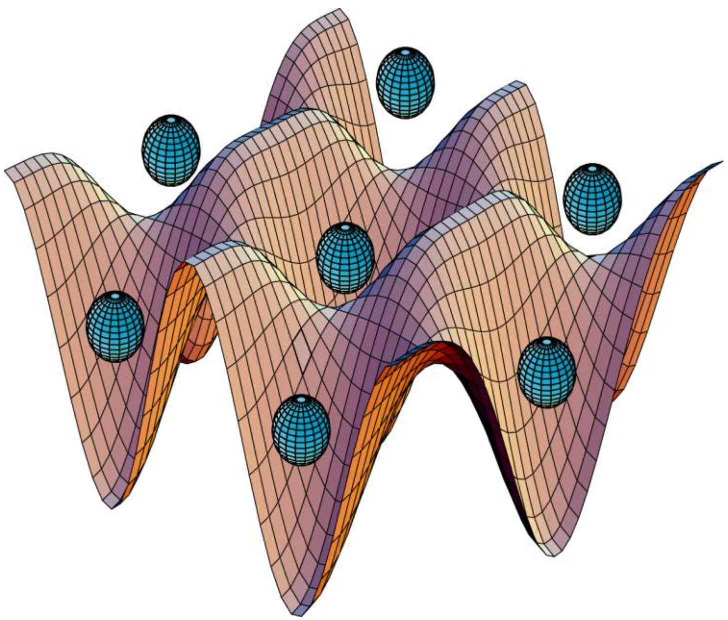
BEC of molecules of paired ^{6}Li

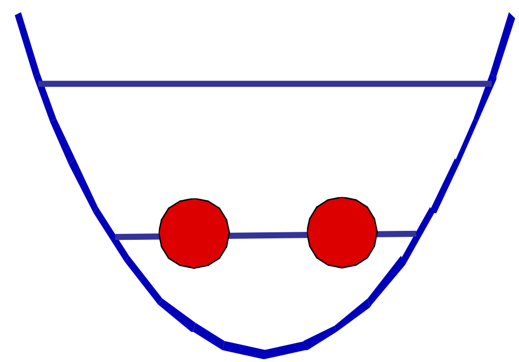
Superfluid pairing of ^{6}Li atoms

An Optical Lattice



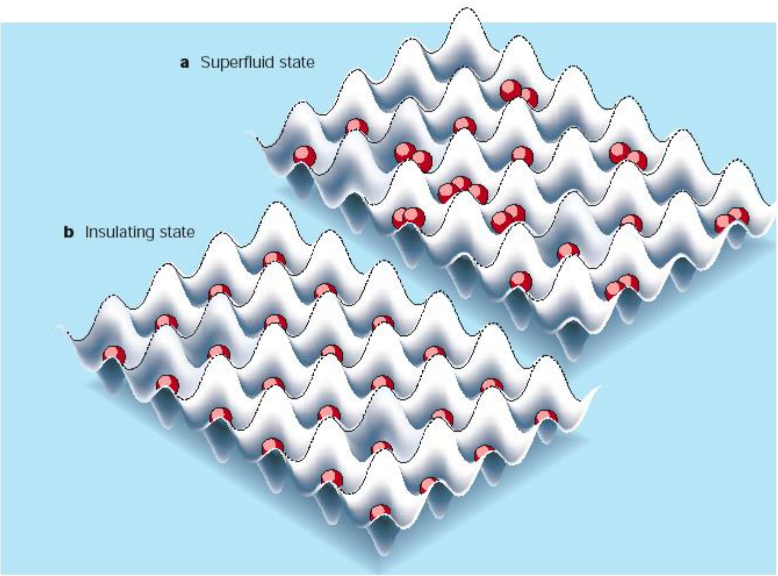
Typical well depth, 100 kHz





2 atoms in a cell

Put a BEC in a Lattice



from H. T. C. Stoof, in News and Views,
Nature **415**, 25 (2002)

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Greiner, Mandel, Esslinger, Haensch, and Bloch
Nature 415, 39, (2002)

PRL **96**, 050402 (2006) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2006

Long-Lived Feshbach Molecules in a Three-Dimensional Optical Lattice

G. Thalhammer,[1] K. Winkler,[1] F. Lang,[1] S. Schmid,[1] R. Grimm,[1,2] and J. Hecker Denschlag[1]
[1]*Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*
[2]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
(Received 27 October 2005; published 8 February 2006)

We have created and trapped a pure sample of $^{87}Rb_2$ Feshbach molecules in a three-dimensional optical lattice.

$^{87}Rb_2$

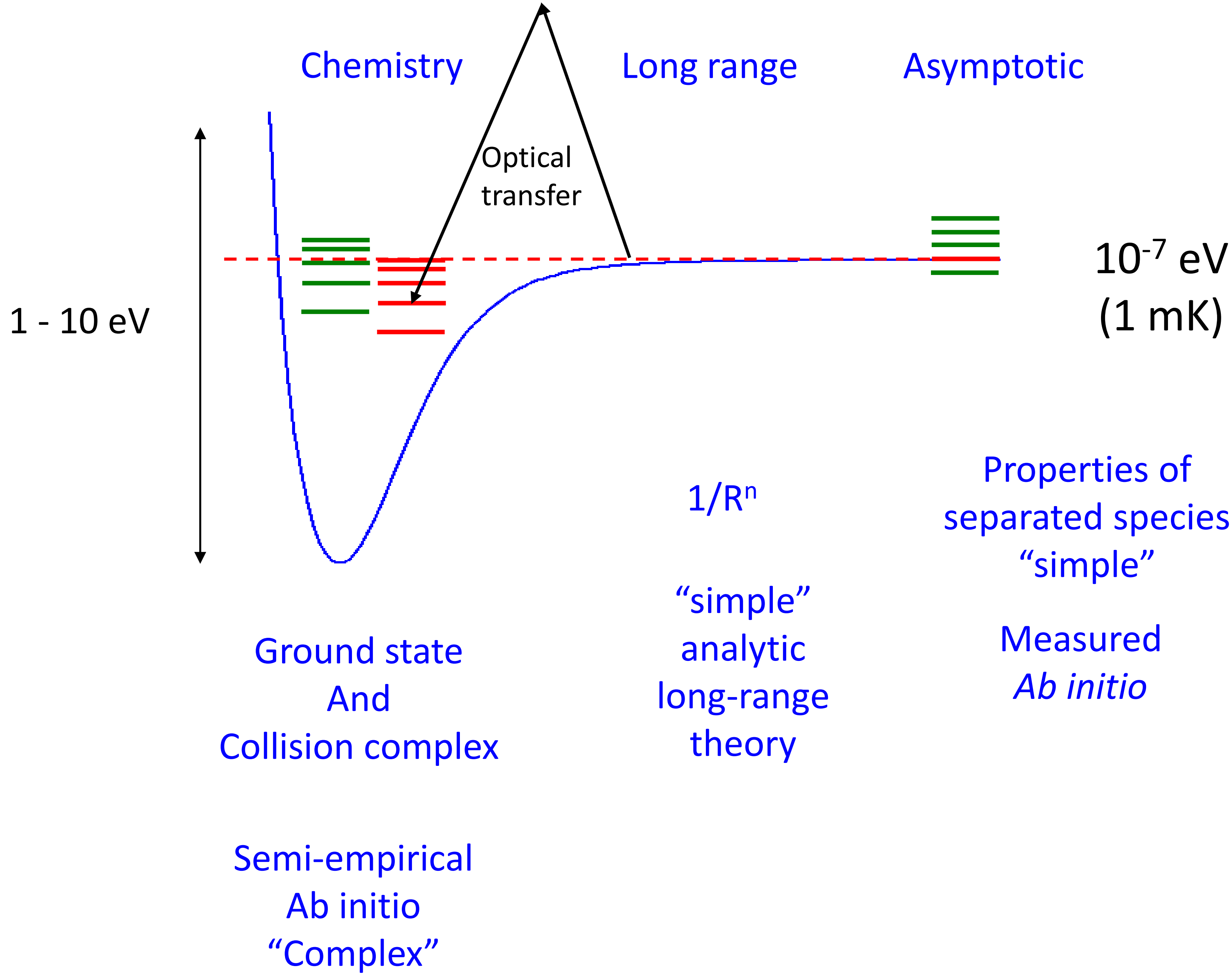
PRL **97**, 120402 (2006) PHYSICAL REVIEW LETTERS week ending 22 SEPTEMBER 2006

Ultracold Heteronuclear Molecules in a 3D Optical Lattice

C. Ospelkaus, S. Ospelkaus, L. Humbert, P. Ernst, K. Sengstock, and K. Bongs
Institut für Laserphysik, Luruper Chaussee 149, 22761 Hamburg, Germany
(Received 22 July 2006; published 18 September 2006)

We report on the creation of ultracold heteronuclear molecules assembled from fermionic ^{40}K and bosonic ^{87}Rb atoms in a 3D optical lattice.

$^{40}K^{87}Rb$



Chemistry
Long range
Asymptotic
Optical transfer
1 - 10 eV
10^{-7} eV
(1 mK)
$1/R^n$
Properties of separated species
“simple”
Ground state
And
Collision complex
“simple”
analytic
long-range
theory
Measured
Ab initio
Semi-empirical
Ab initio
“Complex”

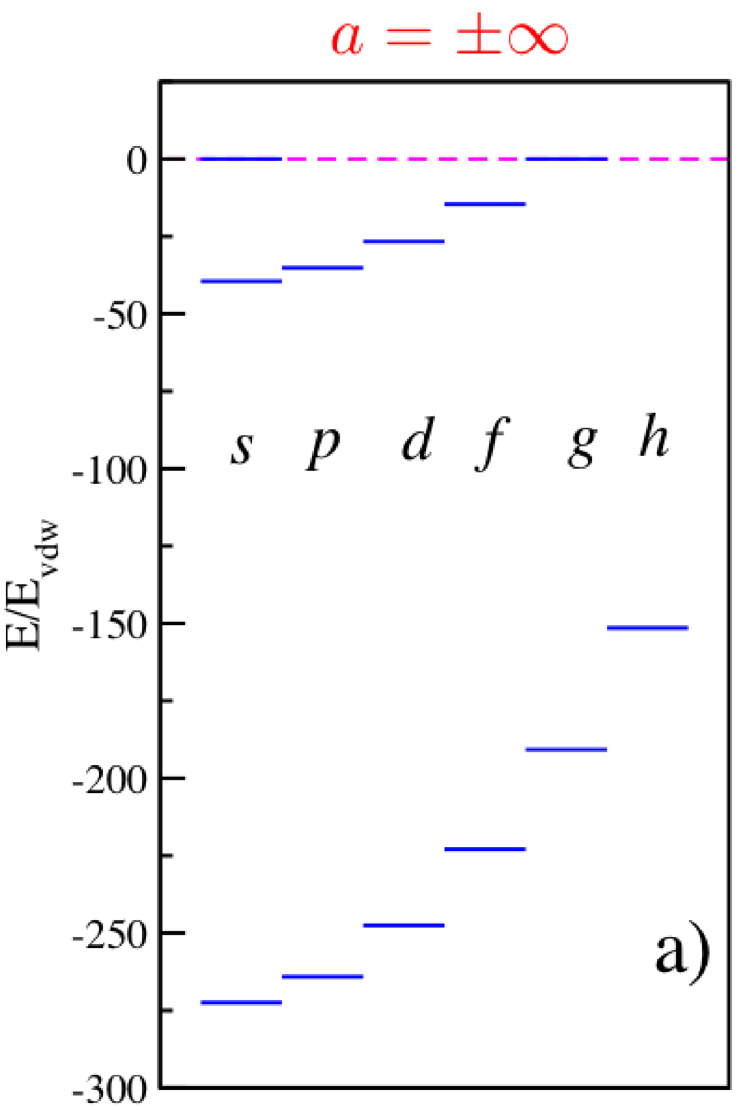
"Size" of $-C_6/R^6$ van der Waals potential V(R)

$$R_{\mathrm{vdw}} = \frac{1}{2}\left(\frac{2\mu C_6}{\hbar^2}\right)^{\frac{1}{4}} \qquad E_{\mathrm{vdw}} = \frac{\hbar^2}{2\mu R_{\mathrm{vdw}}^2}$$

	$R_{vdw}(a_0)$	E_{vdw}(mK)
^{6}Li	31	29
^{40}K	65	1.0
^{85}Rb	83	0.35
^{133}Cs	101	0.13

See Jones, Lett, Tiesinga, Julienne, Rev. Mod. Phys. 78, 483 (2006)

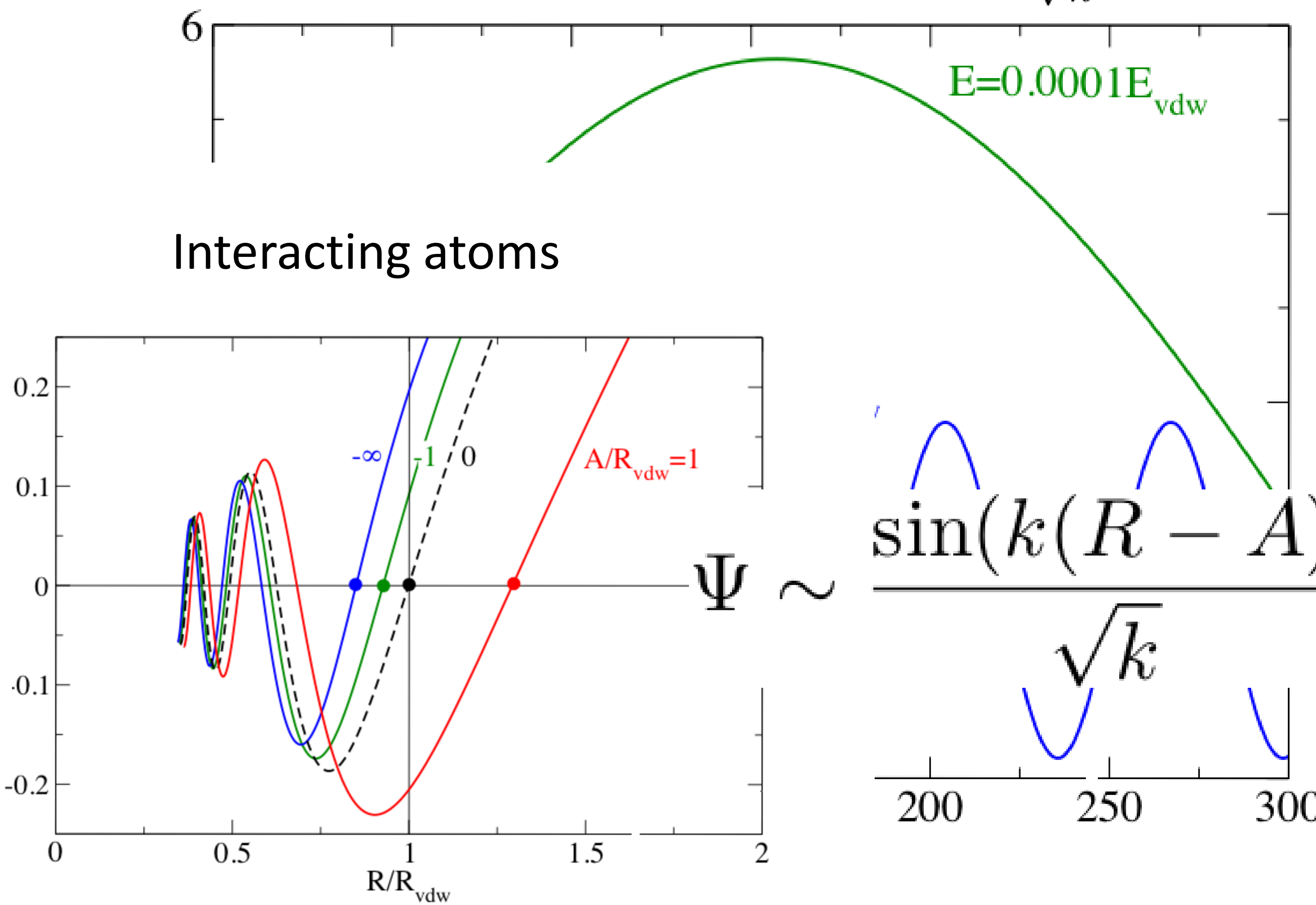
Bound states from van der Waals theory



Adapted from Gao, Phys. Rev. A 62, 050702 (2000); Figure from E. Tiesinga

Noninteracting atoms $\Psi \sim \frac{\sin(kR)}{\sqrt{k}}$

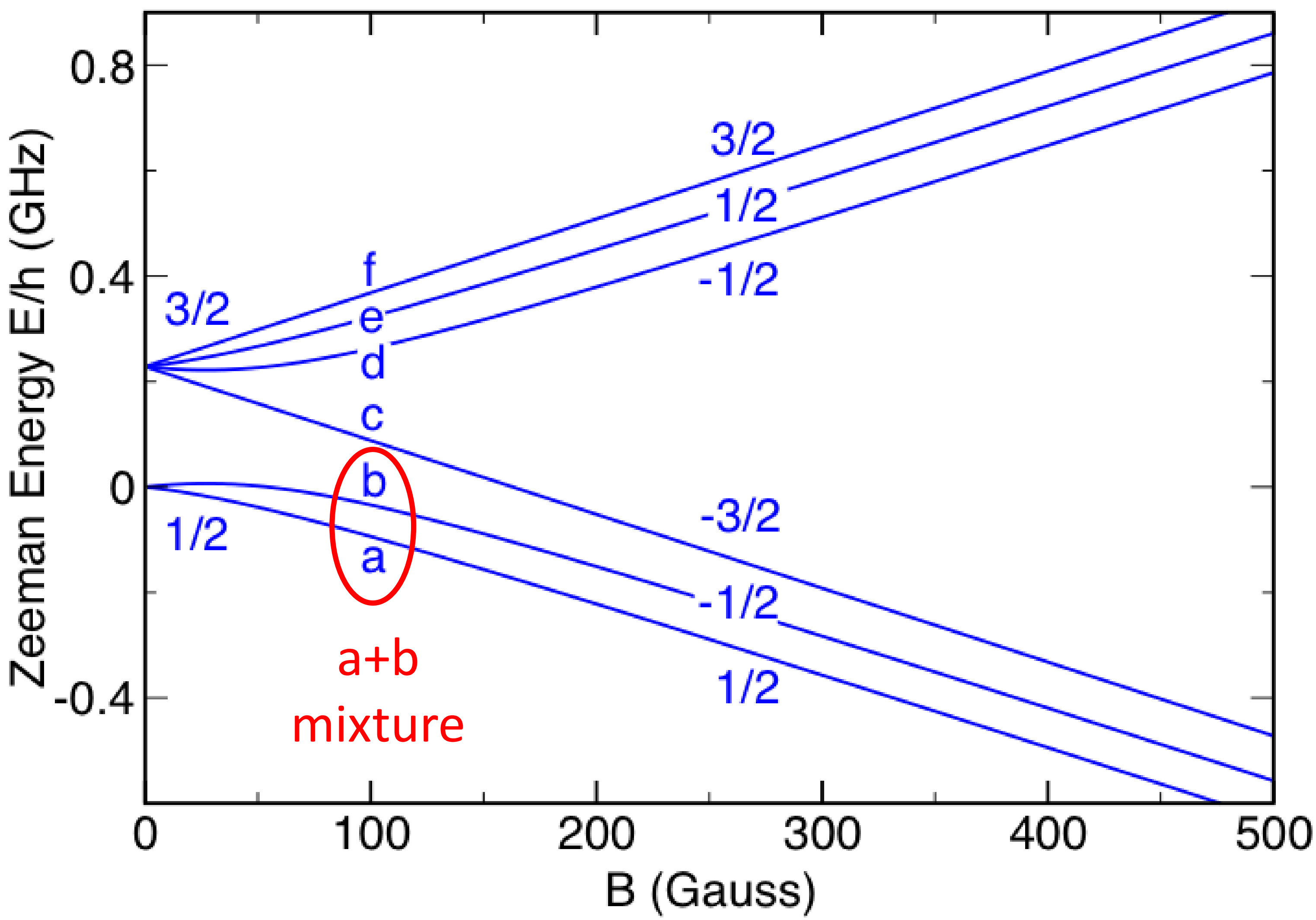
Interacting atoms



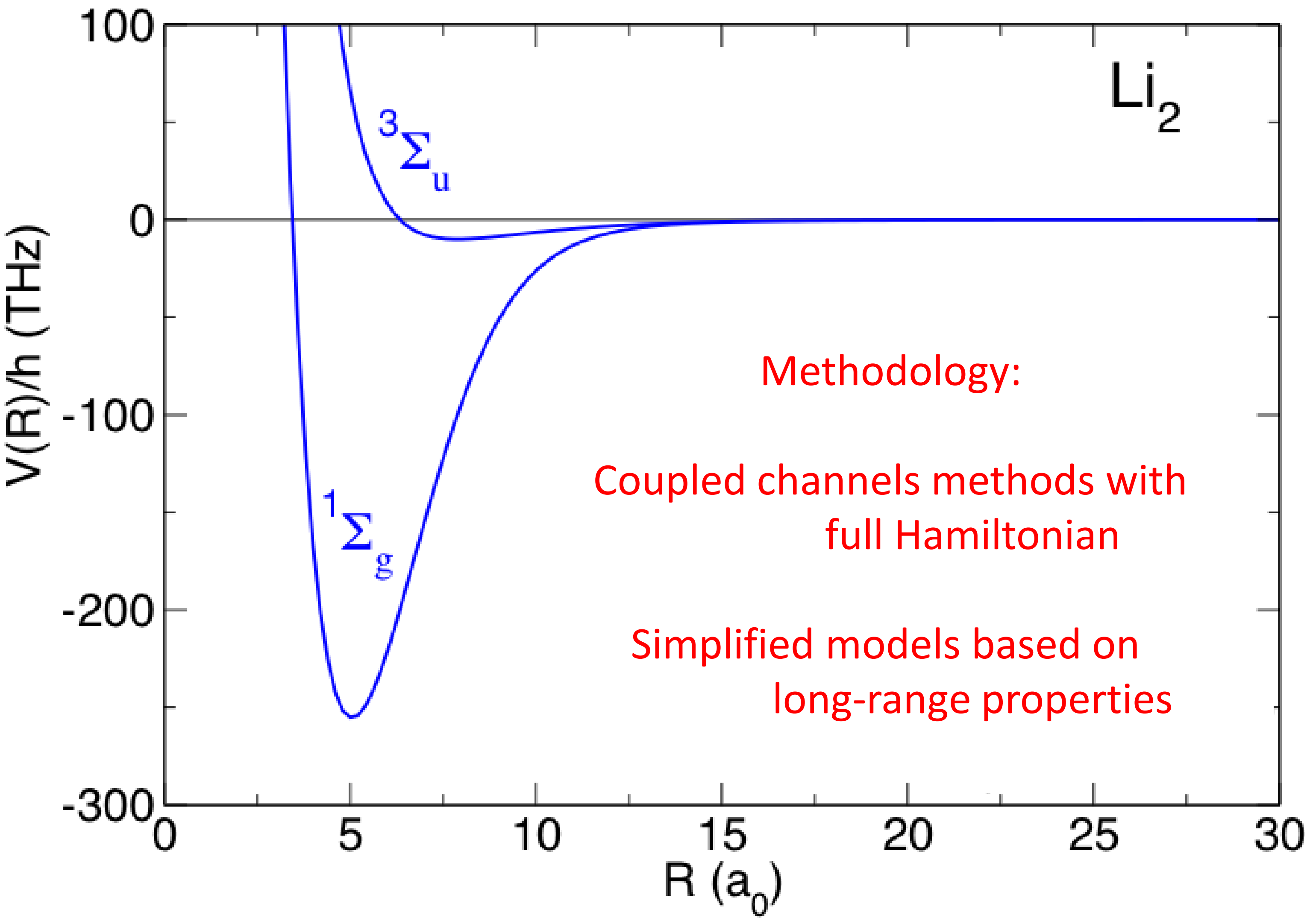
$$\Psi \sim \frac{\sin(k(R-A))}{\sqrt{k}}$$

See Jones, Lett, Tiesinga, Julienne, Rev. Mod. Phys. 78, 483 (2006)

^{6}Li



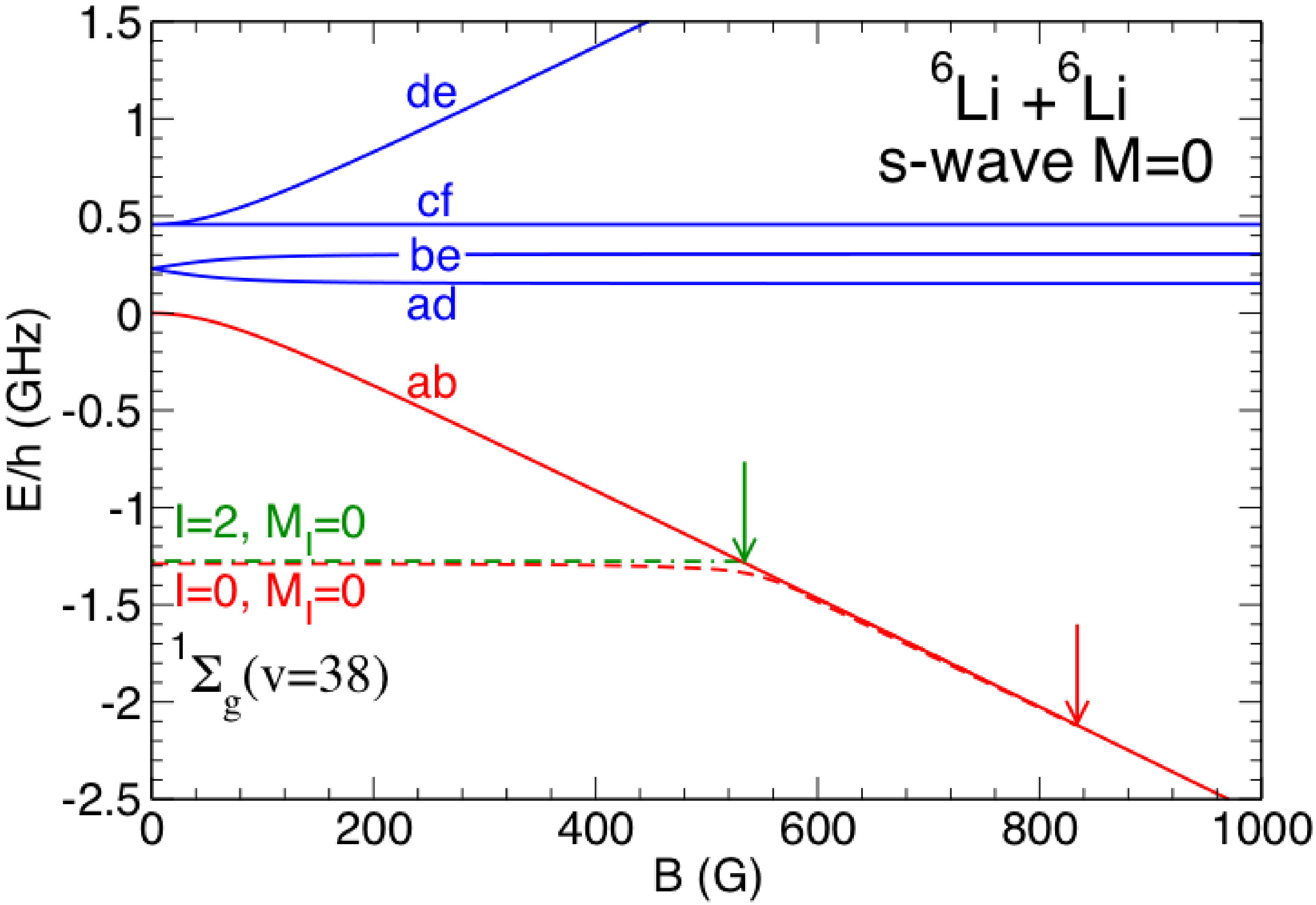
Zeeman Energy E/h (GHz)
0.8
0.4
0
-0.4
0
100
200
300
400
500
B (Gauss)
3/2
1/2
f
e
d
c
b
a
3/2
1/2
-1/2
-3/2
-1/2
1/2
a+b
mixture



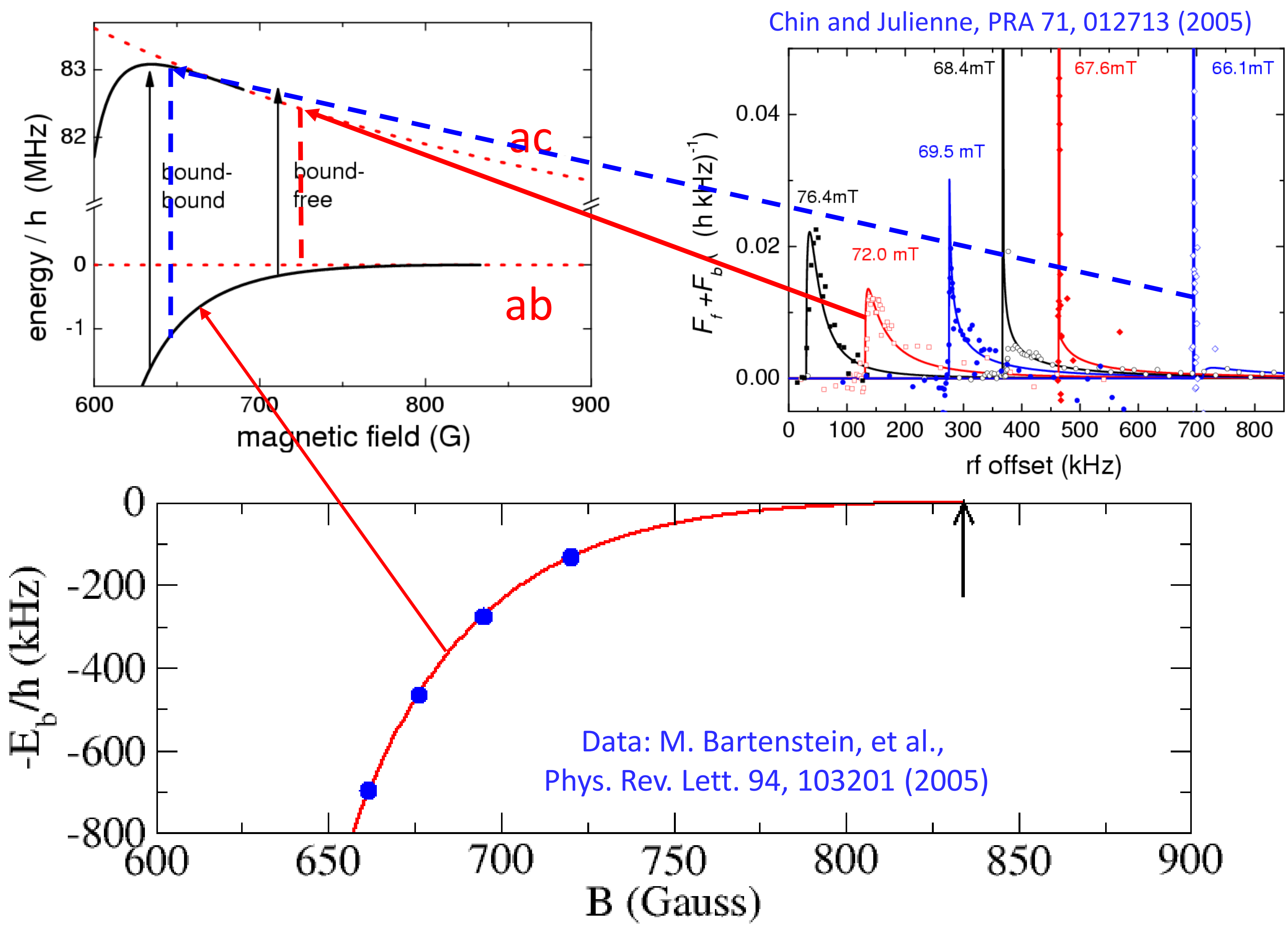
Methodology:

Coupled channels methods with full Hamiltonian

Simplified models based on long-range properties



^{6}Li + ^{6}Li
s-wave M=0
de
cf
be
ad
ab
I=2, M$_I$=0
I=0, M$_I$=0
$^1\Sigma_g$(v=38)
E/h (GHz)
B (G)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
200
400
600
800
1000



Chin and Julienne, PRA 71, 012713 (2005)
energy / h (MHz)
83
82
0
-1
600
700
800
900
magnetic field (G)
bound-bound
bound-free
ac
ab
68.4mT
67.6mT
66.1mT
69.5 mT
76.4mT
72.0 mT
$F_f + F_b$ (h kHz)$^{-1}$)
0.04
0.02
0.00
0 100 200 300 400 500 600 700 800
rf offset (kHz)
$-E_b/h$ (kHz)
0
-200
-400
-600
-800
600 650 700 750 800 850 900
B (Gauss)
Data: M. Bartenstein, et al.,
Phys. Rev. Lett. 94, 103201 (2005)

From M. Bartenstein, et al., Phys. Rev. Lett. 94, 103201 (2005)

Atoms (MHz)	B (mT)	Molecules (MHz)	Theory (MHz)
82.96808(20)	66.1436(20)	83.6645(3)[a]	83.6640(10)
82.83184(30)	67.6090(30)	83.2966(5)[a]	83.2973(10)
82.66686(30)	69.4826(40)	82.9438(20)[b]	82.9422(13)
82.45906(30)	72.0131(40)	82.5928(20)[b]	82.5910(13)

[a] bound-bound transition frequency.

[b] bound-free transition threshold.

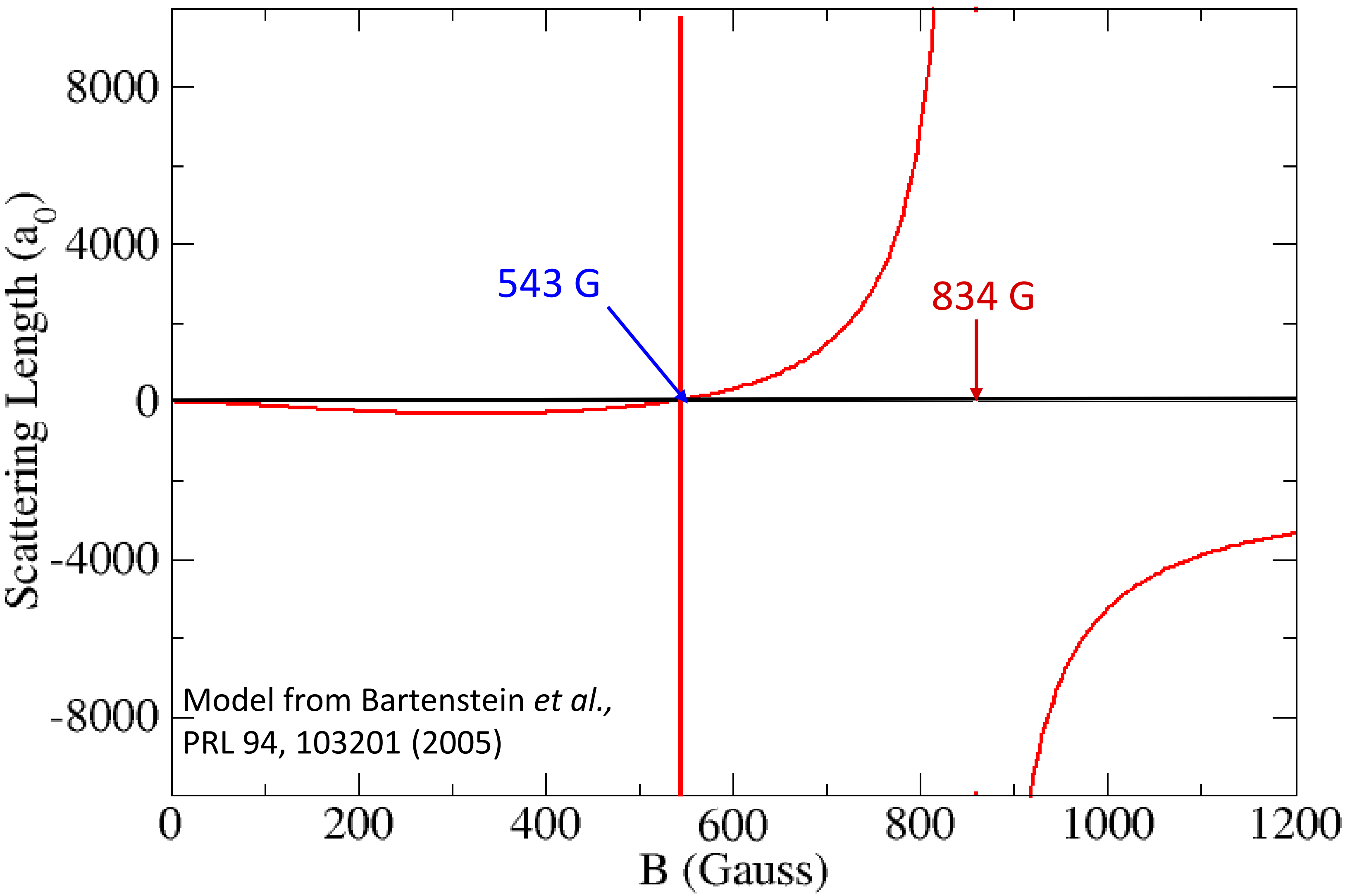
${}^1\Sigma_g^+$ scattering length: 45.167(8) a_0

${}^3\Sigma_u^+$ scattering length: -2140(18) a_0

ab resonance: 834.1(1.5) Gauss

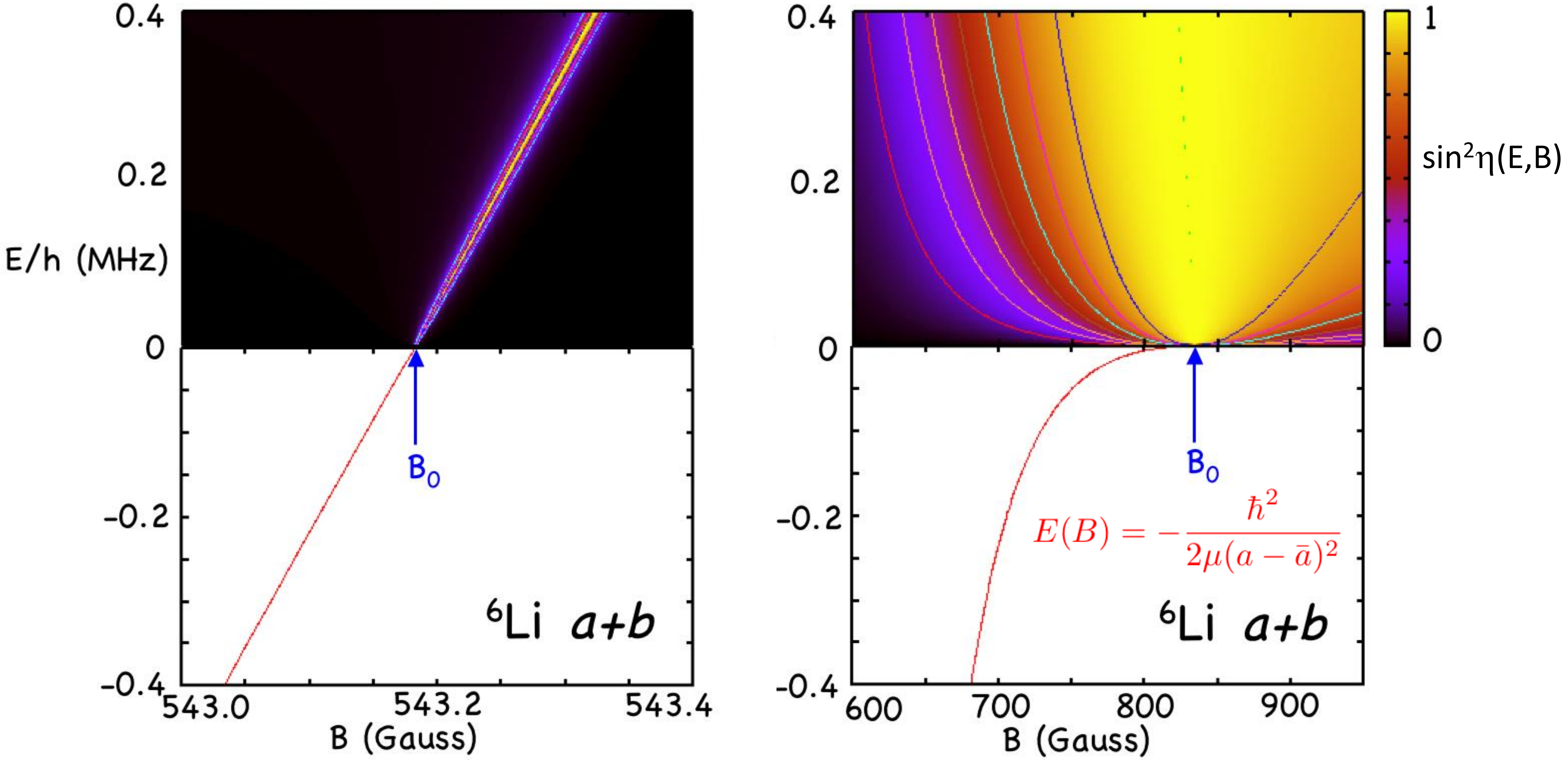
ac resonance: 690.4(5) Gauss

^{6}Li *a+b* Scattering Length vs. B



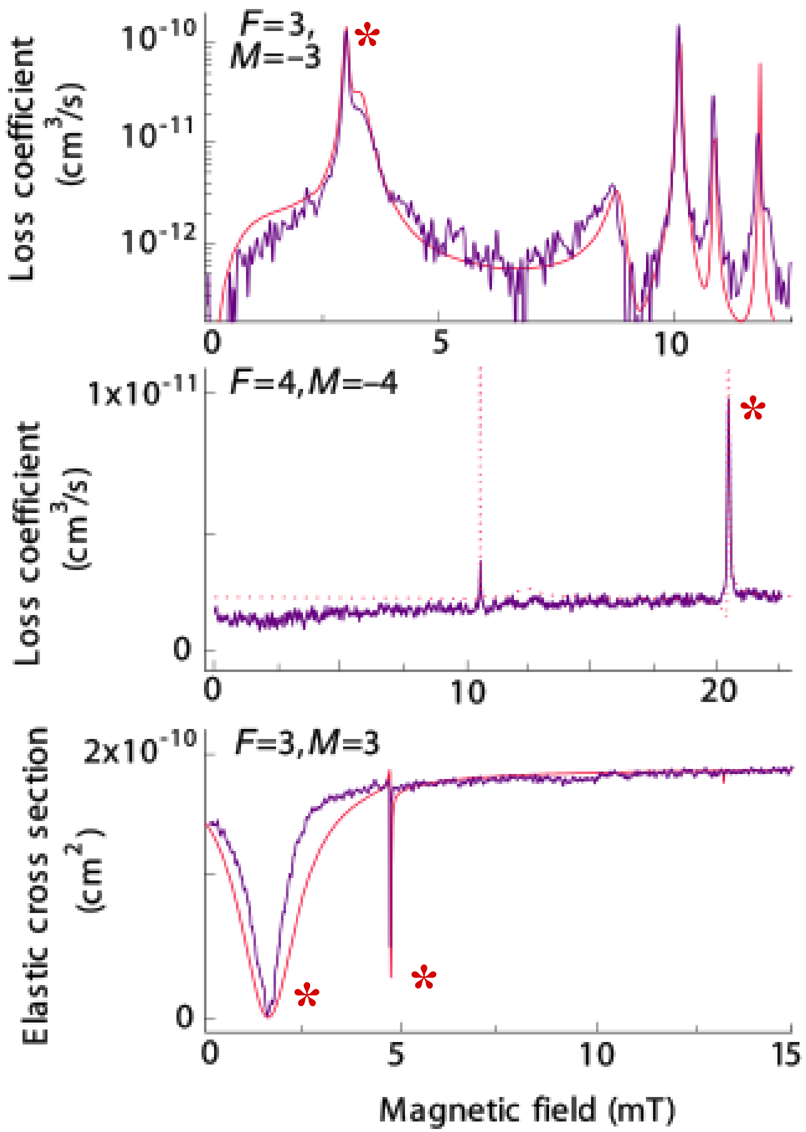
Closed channel dominated

Open channel dominated



Julienne and Gao, Atomic Physics 20, AIP, (2006) and physics/0609013

Cesium threshold resonance spectroscopy



5 mK trap

Tune magnetic field

Measure collision rates

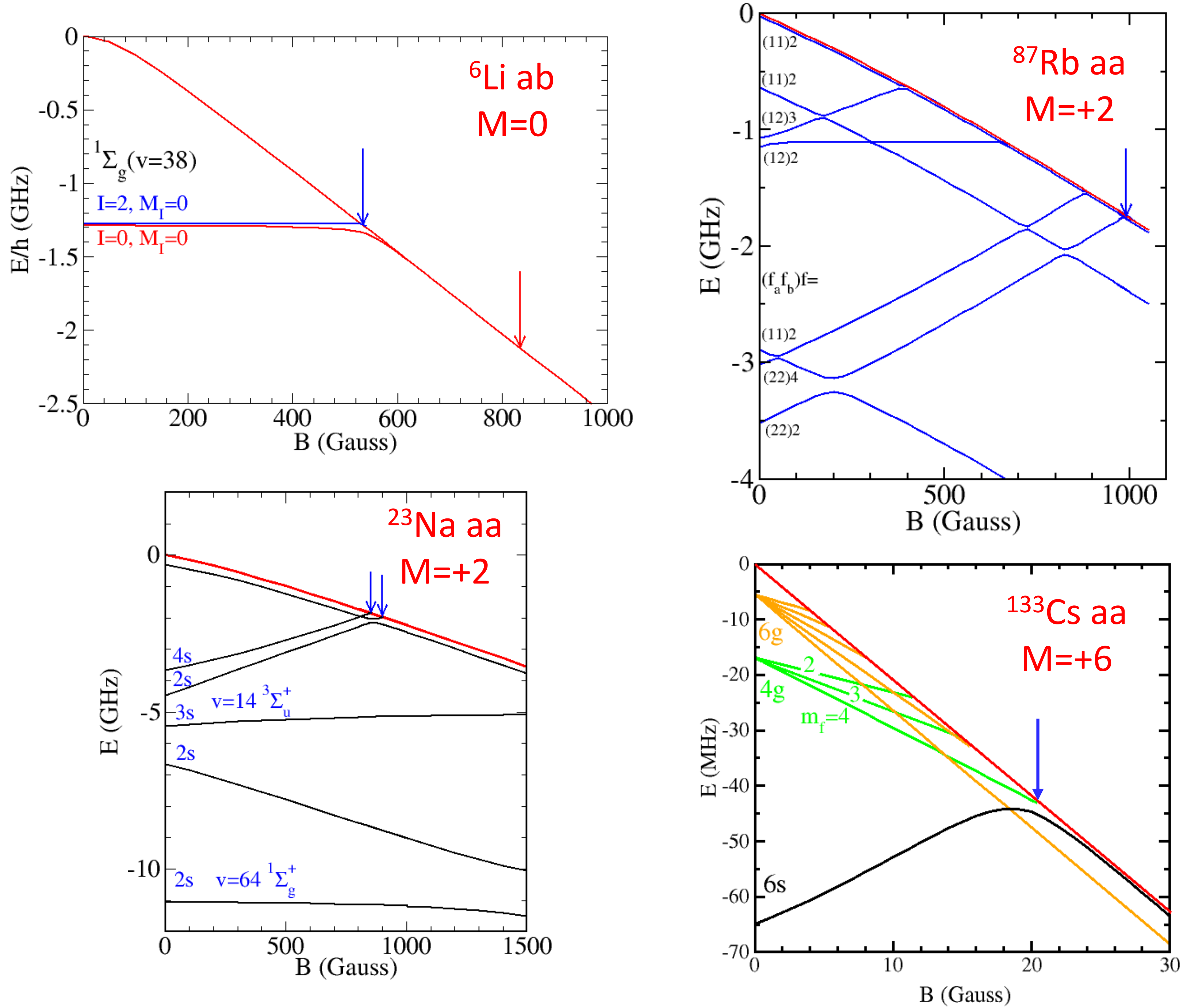
Fit theoretical model parameters *

$A(^1\Sigma_g^+) = +280(10)\ a_0$

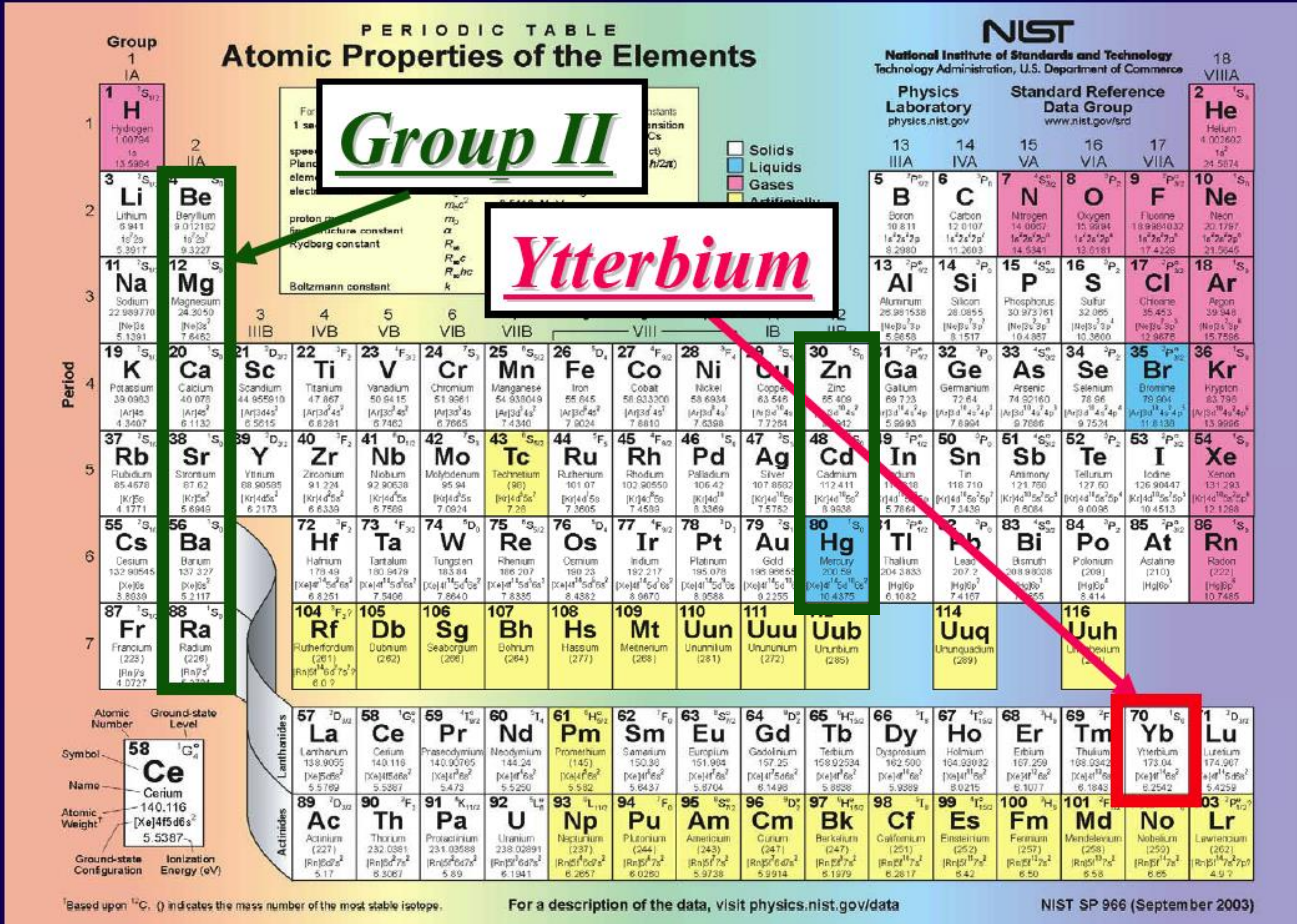
$A(^3\Sigma_u^+) = +2400(100)\ a_0$

$C_6 = 6890(35)$ a.u.

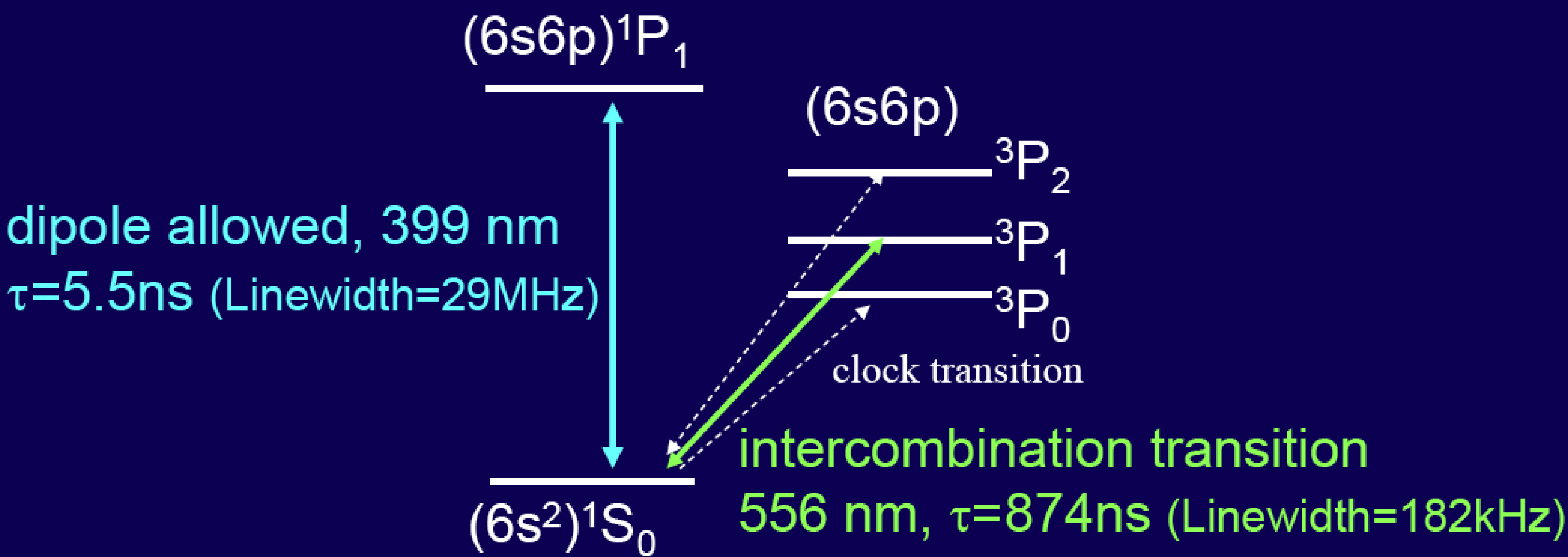
Leo, Williams, Julienne, *Phys. Rev. Lett.* **85**, 2721 (2000)
Vuletic, Kerman, Chin, Chu, *Phys. Rev. Lett*. **85**, 2717 (2000))



6Li ab
M=0
1Σg(v=38)
I=2, MI=0
I=0, MI=0
E/h (GHz)
B (Gauss)
87Rb aa
M=+2
(11)2
(11)2
(12)3
(12)2
(fafb)f=
(11)2
(22)4
(22)2
E (GHz)
B (Gauss)
23Na aa
M=+2
4s
2s
3s
v=14 3Σu+
2s
2s
v=64 1Σg+
E (GHz)
B (Gauss)
133Cs aa
M=+6
6g
2
4g
3
mf=4
6s
E (MHz)
B (Gauss)


PERIODIC TABLE
Atomic Properties of the Elements
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
physics.nist.gov
Standard Reference Data Group
www.nist.gov/srd
Group II
Ytterbium
Solids
Liquids
Gases
Based upon ¹²C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

Level Diagram of Yb

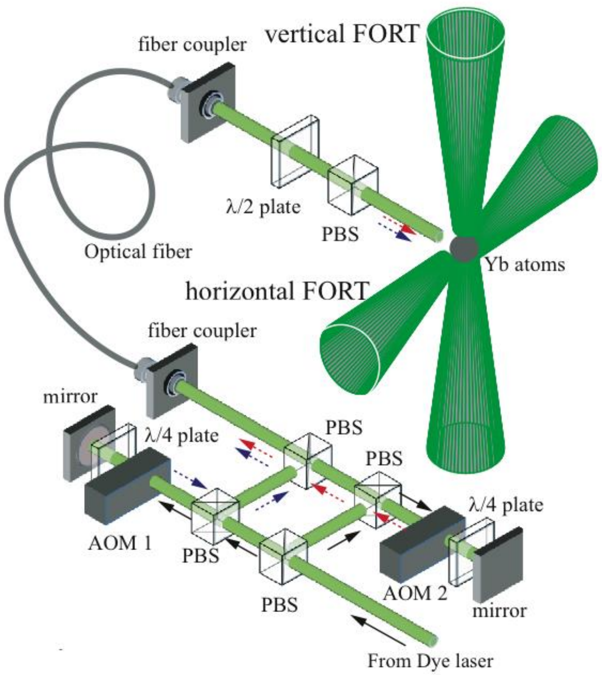


From M. Kitagawa, K. Enomoto, K. Kasa, Y. Takahashi (Kyoto University)

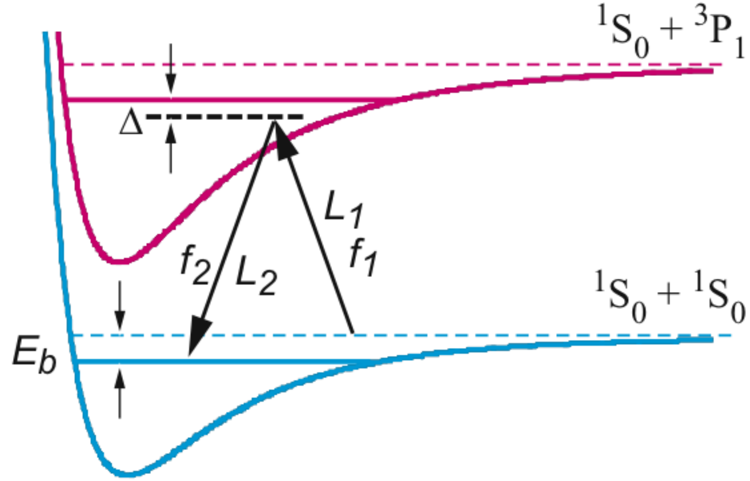
Mass number	168	170	171	172	173	174	176
Nuclear spin *i*	0	0	1/2	0	5/2	0	0
Abundance(%)	0.13	3.05	14.3	21.9	16.2	31.8	12.7

All-optical Yb trap

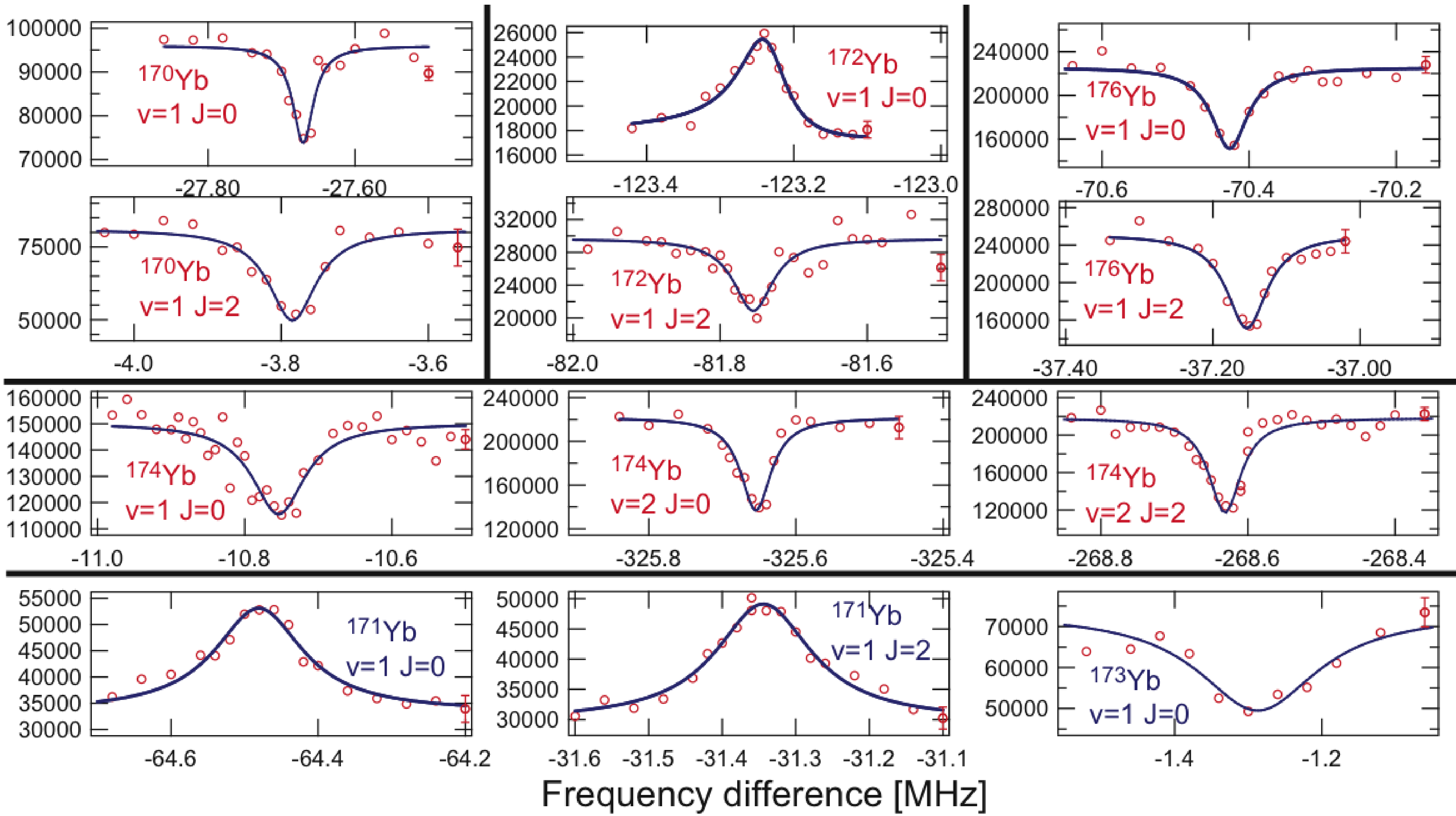
Few μK



2-color photoassociation



12 PA lines among 6 different isotopes

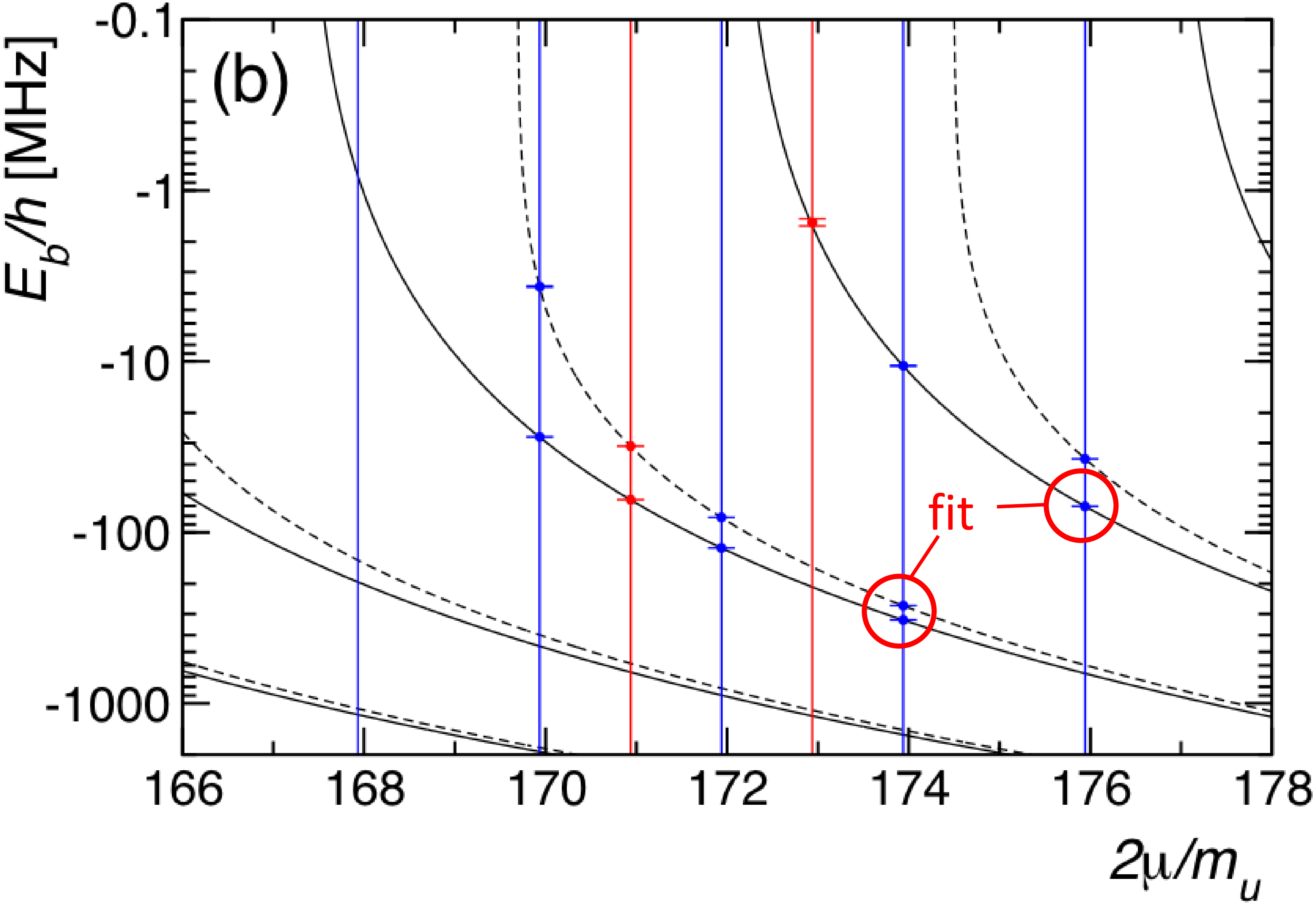


Model: LJ 6-12 + C_8 van der Waals
1 potential + reduced mass

C_6=1932(15) au C_8=1.9(5)x10^5 au N=72 bound states in $^{174}Yb_2$

	isotope	v	J	method	E_b (MHz) experiment	E_b (MHz) theory	Difference (MHz)
	^{170}Yb	1	0	R	-27.661(23)	-27.755	0.094
			2	R	-3.651(26)	-3.683	0.032
	^{171}Yb	1	0	AT	-64.418(40)	-64.548	0.130
			2	AT	-31.302(50)	-31.392	0.090
	^{172}Yb	1	0	AT	-123.269(26)	-123.349	0.080
			2	R	-81.786(19)	-81.879	0.093
	^{173}Yb	1	0	R	-1.539(74)	-1.613	0.074
	^{174}Yb	1	0	R	-10.612(38)	-10.642	0.030
		1	0	AT	-10.606(17)	-10.642	0.036
C_6 + N		2	0	R	-325.607(18)	-325.607	0.000
C_8		2	2	R	-268.575(21)	-268.576	0.001
	^{176}Yb	1	0	R	-70.404(11)	-70.405	0.001
		1	2	R	-37.142(13)	-37.118	-0.024

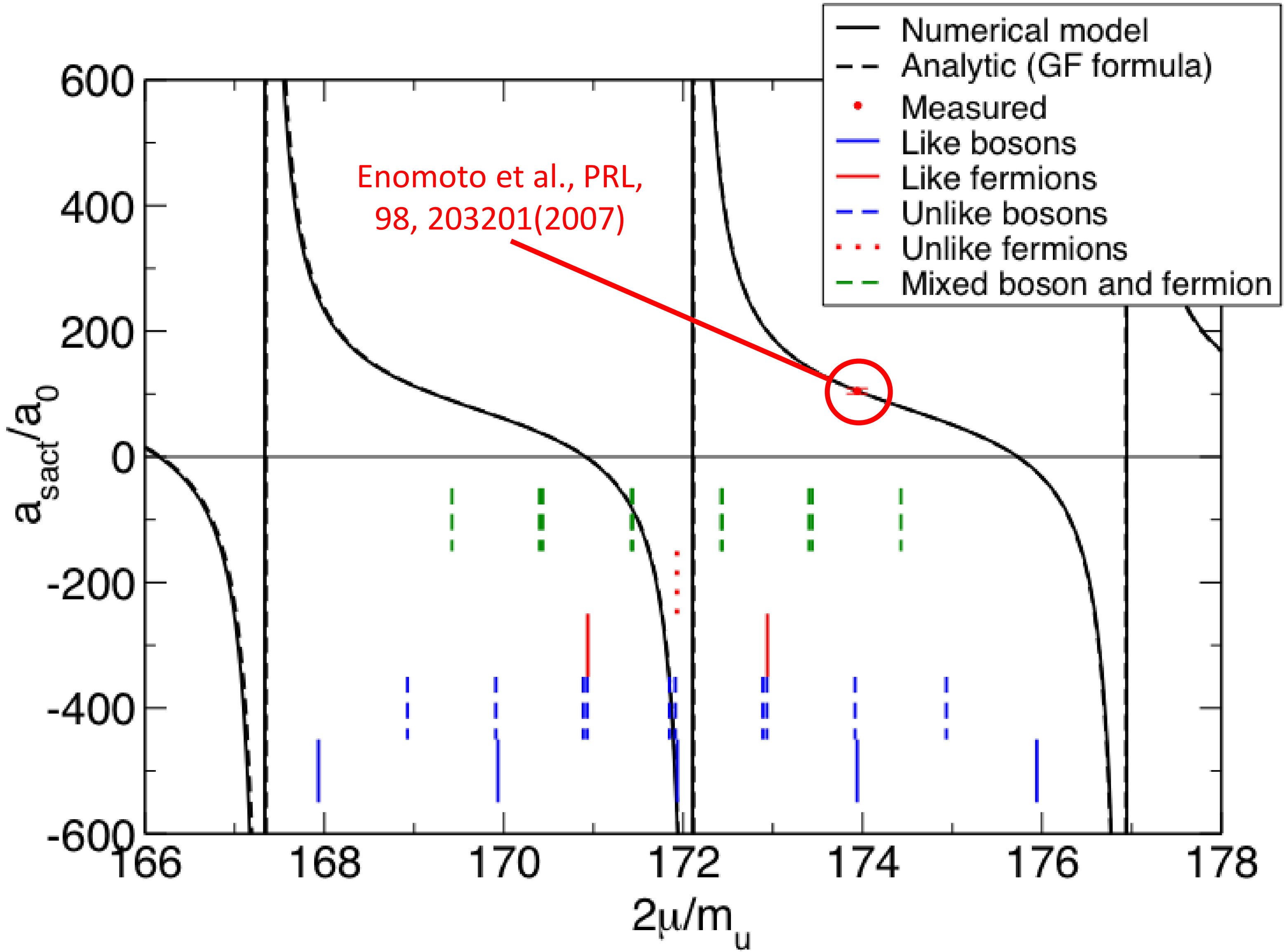
Last bound state energies versus mass
Solid: J=0
Dashed: J=2



Scattering lengths for Yb ground state model (in a_0 units)

	168	170	171	172	173	174	176
168	252(6)	117(1)	89(1)	65(1)	39(1)	2(2)	−360(30)
170	117	64(1)	37(1)	−2(2)	−81(4)	−520(50)	209(4)
171	89	37	−3(2)	−84(5)	−580(60)	430(20)	142(2)
172	65	−2	−84	−600(60)	420(20)	201(3)	106(1)
173	39	−81	−580	420	199(3)	139(2)	80(1)
174	2	−520	430	201	139	105(1)	55(1)
176	−360	209	142	106	80	55	−24(2)

Variation of scattering length with mass



Gribakin and Flambaum

Phys. Rev. A 48, 546 (1993)

$$a = \bar{a}\left(1 - \tan\left(\Phi - \frac{\pi}{8}\right)\right)$$

$$\bar{a} = \frac{1}{2^{3/2}} \frac{\Gamma(3/4)}{\Gamma(5/4)} \left(\frac{2\mu C_6}{\hbar^2}\right)^{1/4}$$

$$\Phi = \int_{r_{in}}^{\infty} \left(\frac{2\mu}{\hbar^2}(-V(R)\right)^{1/2} dR$$

Number of bound states in V(R) = $\mathrm{Int}\left[\frac{\Phi}{\pi} - \frac{5}{8}\right] + 1$

Pure van der Waals theory

(Gribakin-Flambaum and B. Gao)

$$V(R) = -\frac{C_6}{R^6} \text{ for } R_{in} < R \leq \infty$$

$$V(R) = \infty \text{ for } 0 < R \leq R_{in}$$

Species	Spin	% Abundance
^{84}Sr	0	0.6
^{86}Sr	0	9.9
^{87}Sr	9/2	7.0
^{88}Sr	0	82.6
^{130}Ba	0	0.1
^{132}Ba	0	0.1
^{134}Ba	0	2.4
^{135}Ba	3/2	6.6
^{136}Ba	0	7.9
^{137}Ba	3/2	11.2
^{138}Ba	0	71.7

Species	Spin	% Abundance
^{106}Cd	0	1.3
^{108}Cd	0	0.9
^{110}Cd	0	12.5
^{111}Cd	1/2	12.8
^{112}Cd	0	24.1
^{113}Cd	1/2	12.2
^{114}Cd	0	28.7
^{116}Cd	0	7.5
^{196}Hg	0	0.2
^{198}Hg	0	10.0
^{199}Hg	1/2	16.9
^{200}Hg	0	23.1
^{201}Hg	3/2	13.2
^{202}Hg	0	29.9
^{204}Hg	0	6.9