INT Workshop on Quantum Simulation, Ap. 14, 2015

Can we control complex species like Er or Dy with dense sets of chaotic overlapping resonances?

A Work in Progress

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NIST and The University of Maryland

Krzysztof Jachymski (U. Warsaw)
Tilman Pfau Group, U. Stuttgart, especially Igor Ferrier
3-body theory by Yujun Wang

http://www.jqi.umd.edu/

Supported by an AFOSR MURI

Collisions of atoms and molecules on the microscale (nm) control quantum phenomena on the macroscale (>>μm) and destructive interactions that set the system lifetime (< ms to >> 1s)

Can we understand and control complex atoms or molecules having collision complexes with dense sets of resonances?

Outline

Review experimental findings—new Dy data, Pfau group

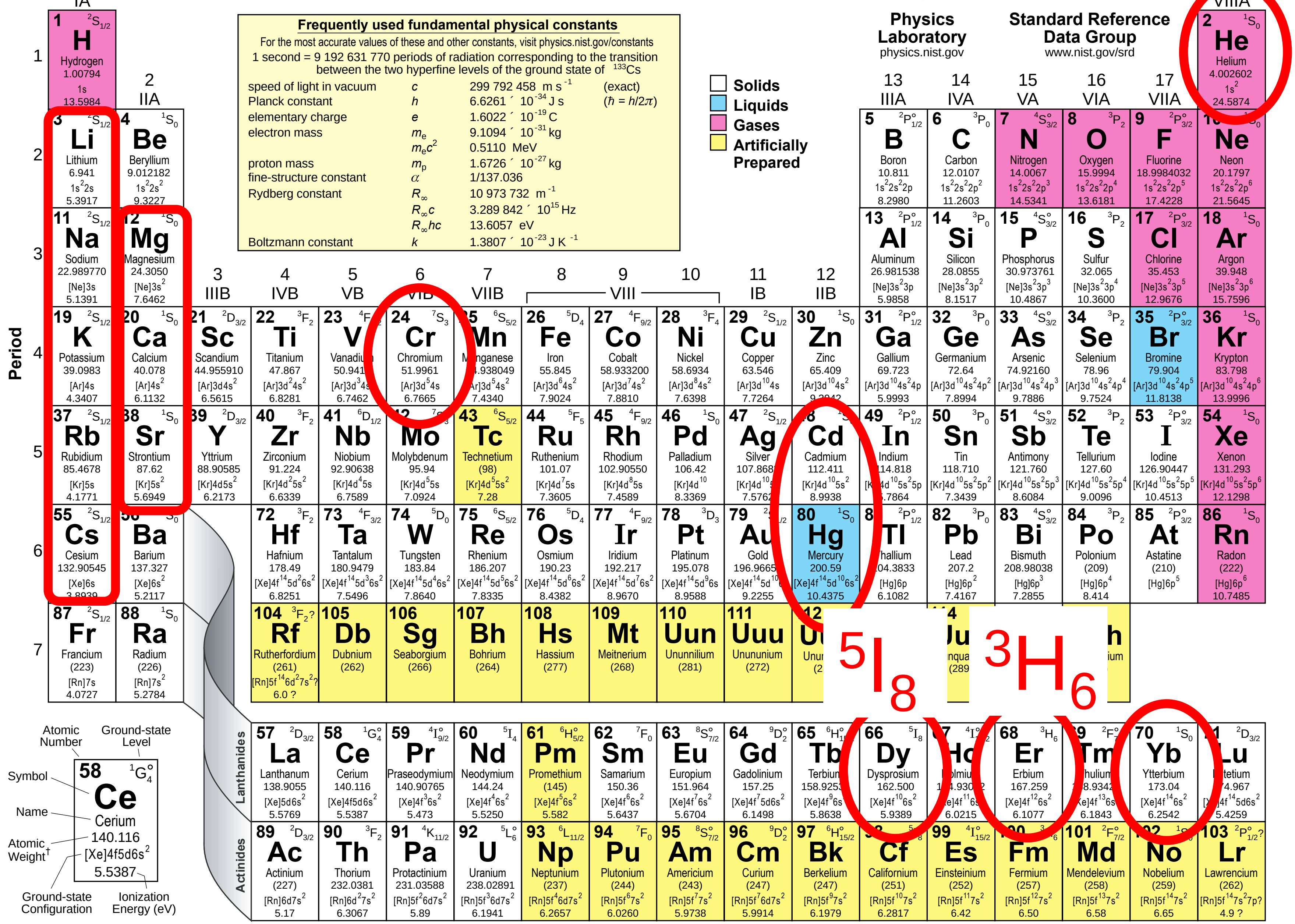
Introduce basic theory of overlapping resonances:
- Cs example
- CC and MQDT models

Some thoughts about what is going on in Er or Dy

PERIODIC TABLE

Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce



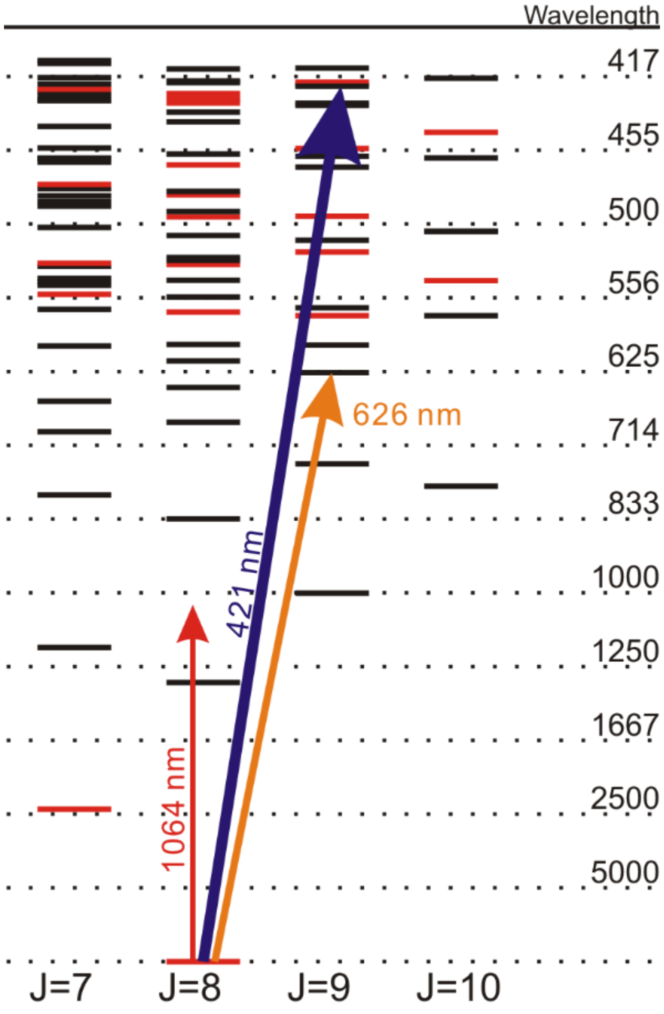
†Based upon 12C. () indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

Properties of Dysprosium

	Dysprosium
Protons	*66*
Stable Isotopes	*^{160}Dy (2%), ^{161}Dy (19%), ^{162}Dy (26%), ^{163}Dy (25%), ^{164}Dy (28%)*
Electronic structure	*[Xe] $4f^{10}\ 6s^2$ → $^5I_8$*
Angular momentum L	*6*
Spin S	*2 (4 unpaired e^-)*
Magnetic moment μ	*10 μ_B*
Nuclear spin	*0 (bosons), 5/2 (fermions)*



Similar Er $^3H_6$

Dy_2: 153 potential curves
Er_2: 91 potential curves

Anisotropic C_6, C_3

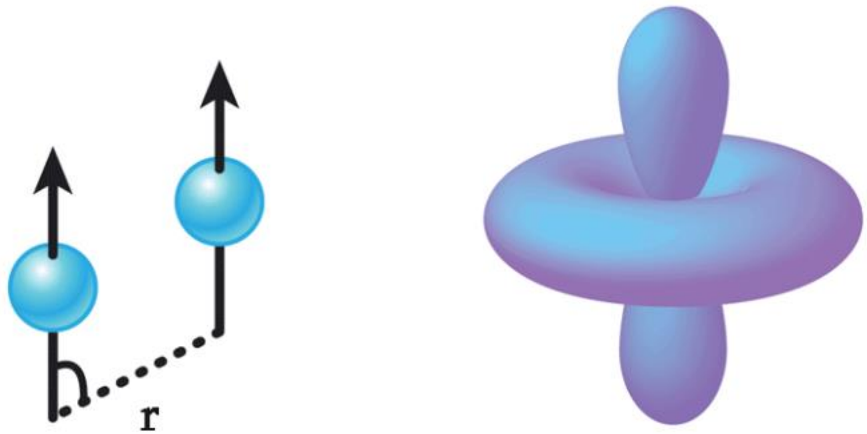
Kotochigova and Petrov, PCCP 13, 19165 (2011)

Laser cooling works!

Slide thanks to Igor Ferrier and Tilman Pfau

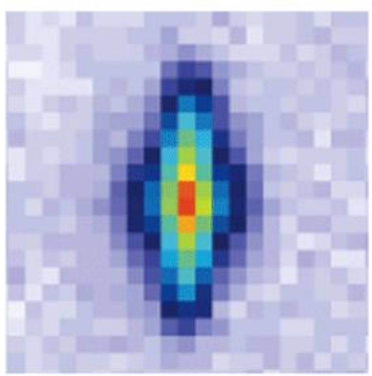
Physics

B. Laburthe-Tolra, Physics 5, 58 (2012)
“Quantum Dipolar Gases in Boson or Fermion Flavor

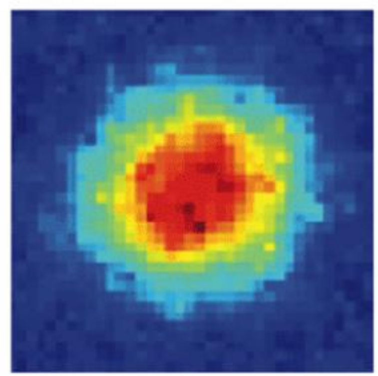


(a)

Ferlaino group
Innsbruck
^{168}Er
30000 atoms
order 100nK



(b)



(c)

Lev group
Stanford
^{161}Dy
6000 atoms
64nK $T/T_F=0.2$

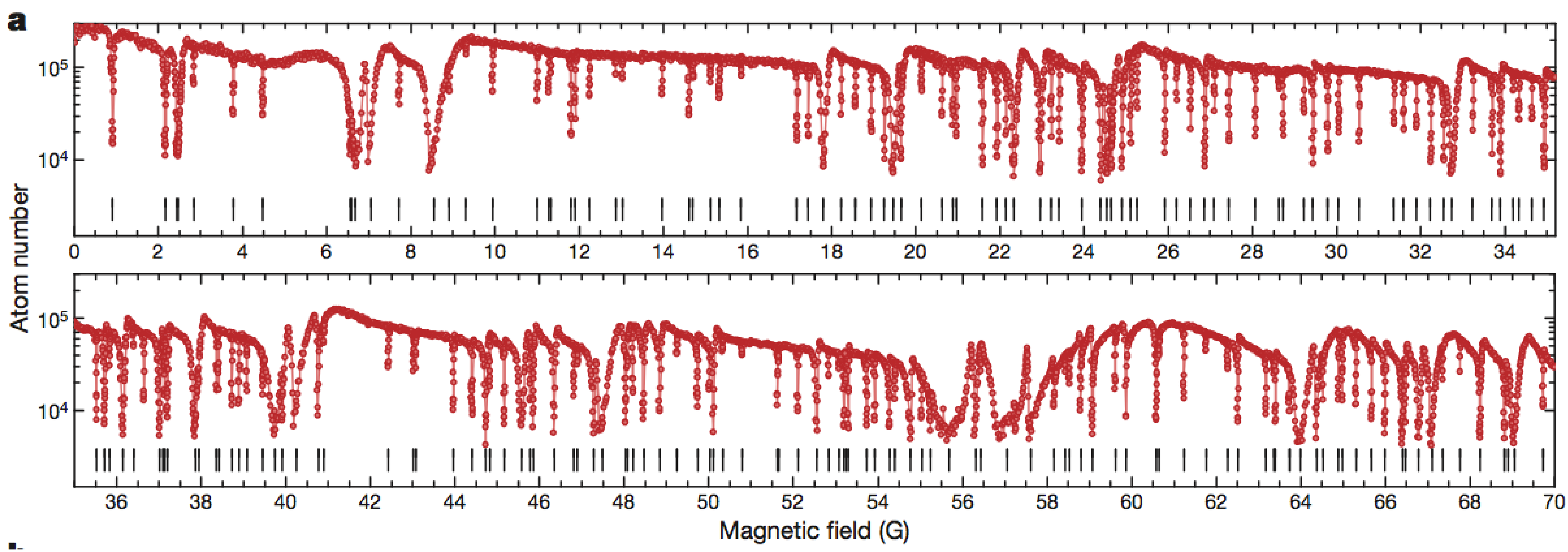
LETTER

Nature online, March 12, 2014

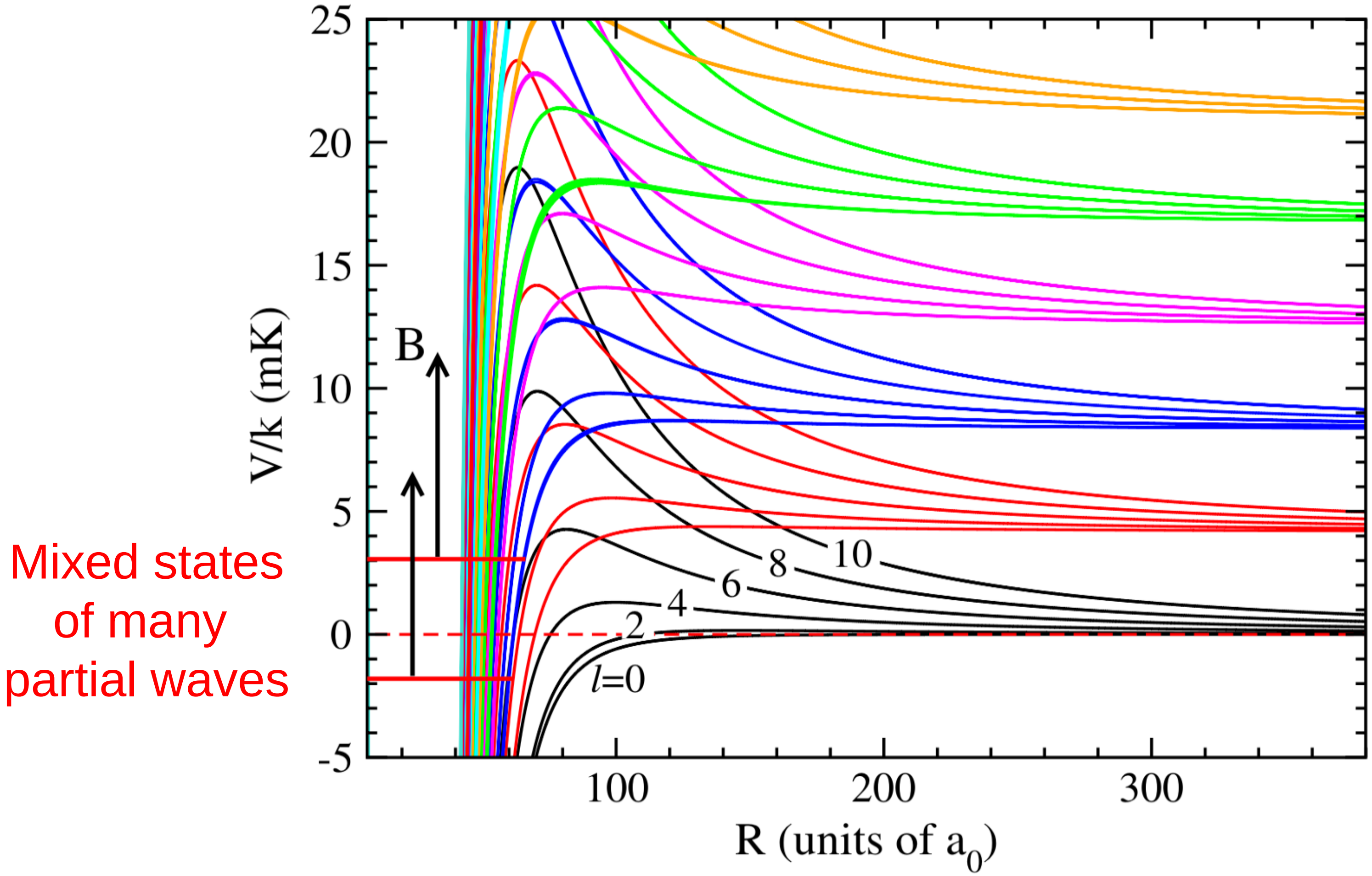
doi:10.1038/nature13137

Quantum chaos in ultracold collisions of gas-phase erbium atoms

Albert Frisch[1], Michael Mark[1], Kiyotaka Aikawa[1], Francesca Ferlaino[1], John L. Bohn[2], Constantinos Makrides[3], Alexander Petrov[3,4,5] & Svetlana Kotochigova[3]



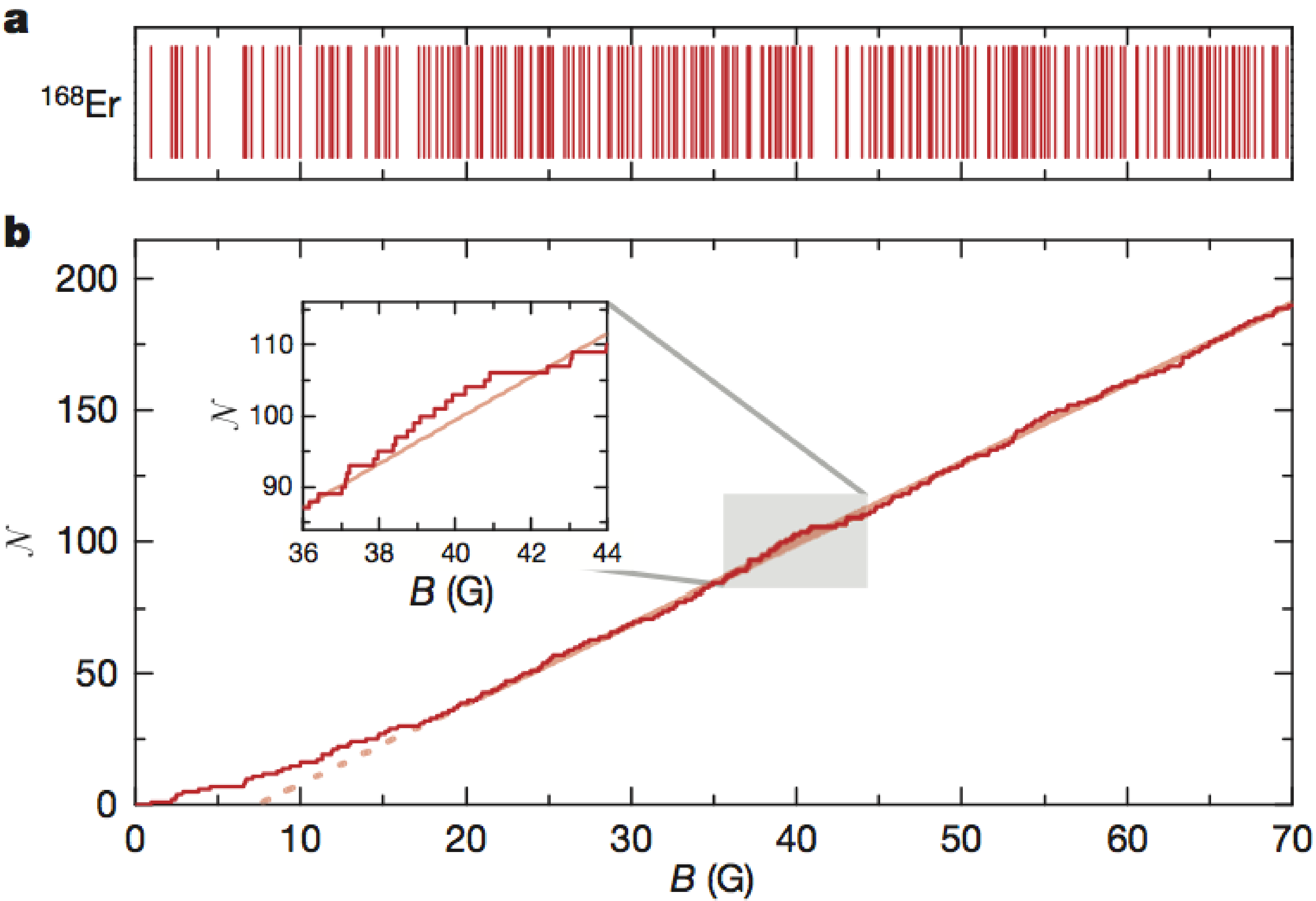
^{168}Er in ground state $^3H_6$(m=-6)



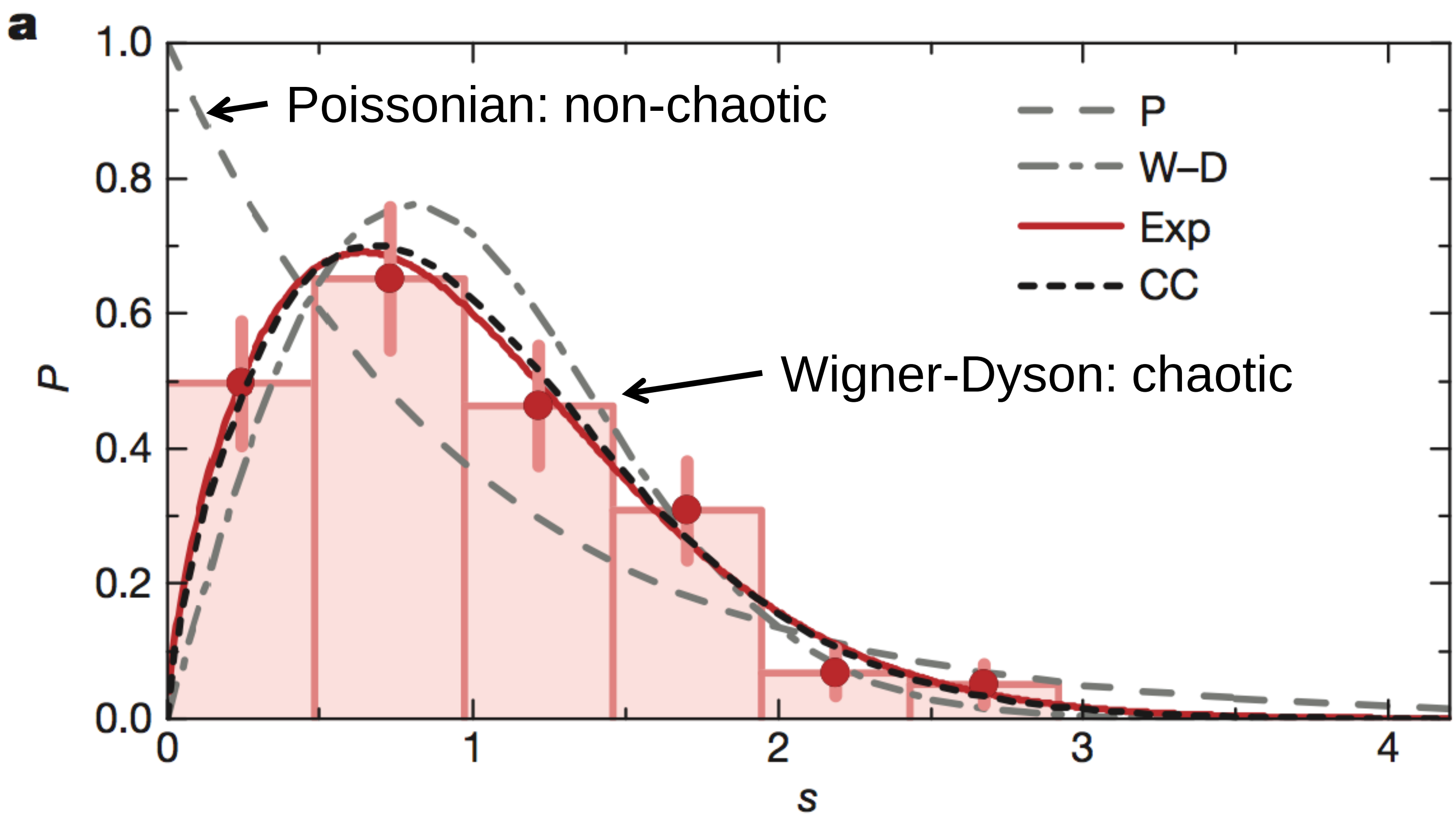
Diagonal potential energy curves for ^{164}Dy + ^{164}Dy at B = 50G

There are 91 curves for channels $|(j_1 j_2) j m_j, l m_l\rangle$, $m_j + m_l = -16$, l up to 10

From Petrov et al, PRL 109, 103002 (2012)



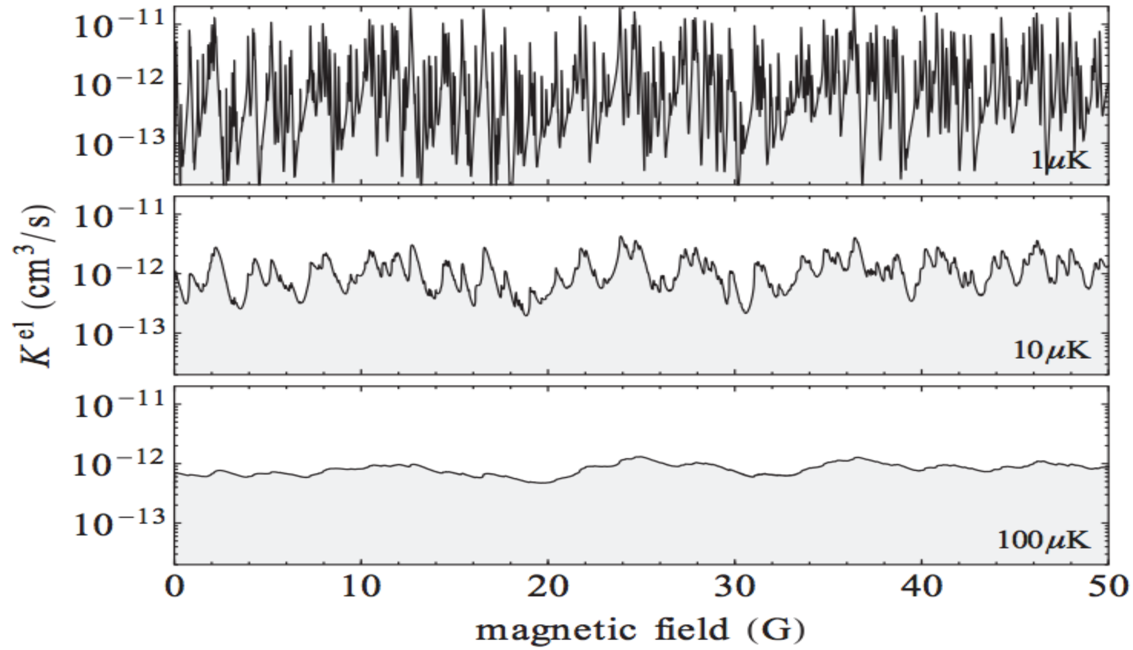
From Frisch et al (2014)



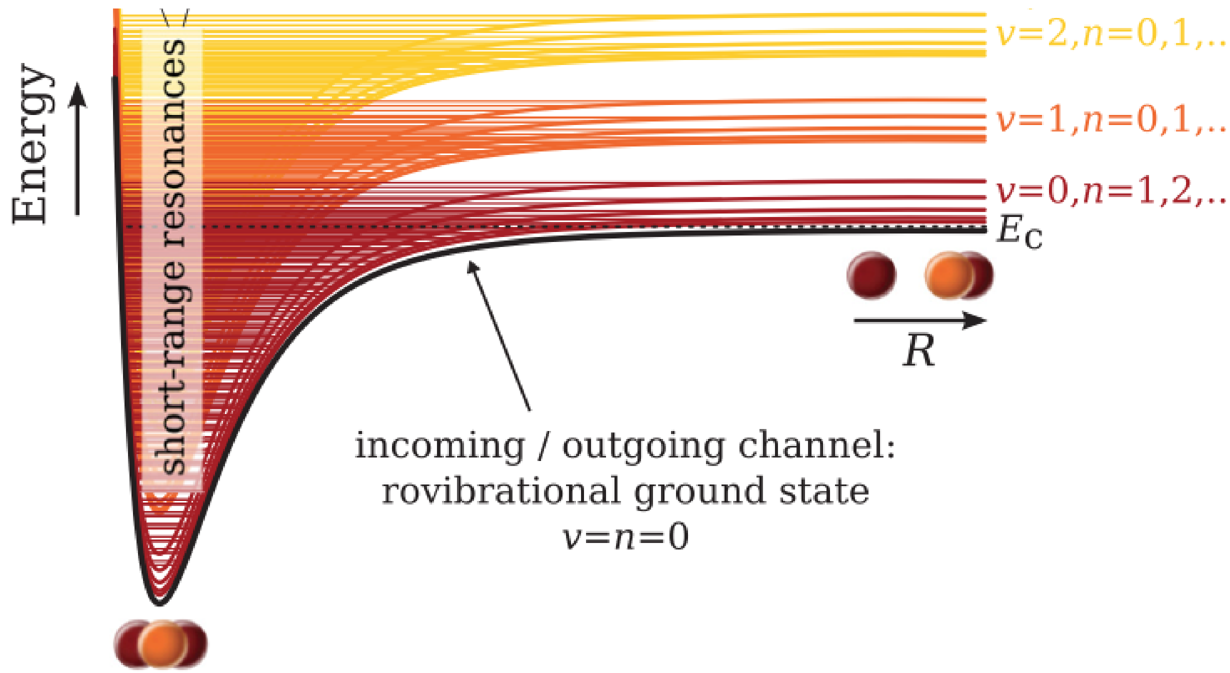
Dense set of overlapping (interacting) resonances:
mixed eigenstates of “random” character

From Frisch et al (2014)

From Mayle, Ruzic, Bohn, Phys. Rev. A 85, 062712 (2012)



Toy Statistical model Rb + KRb

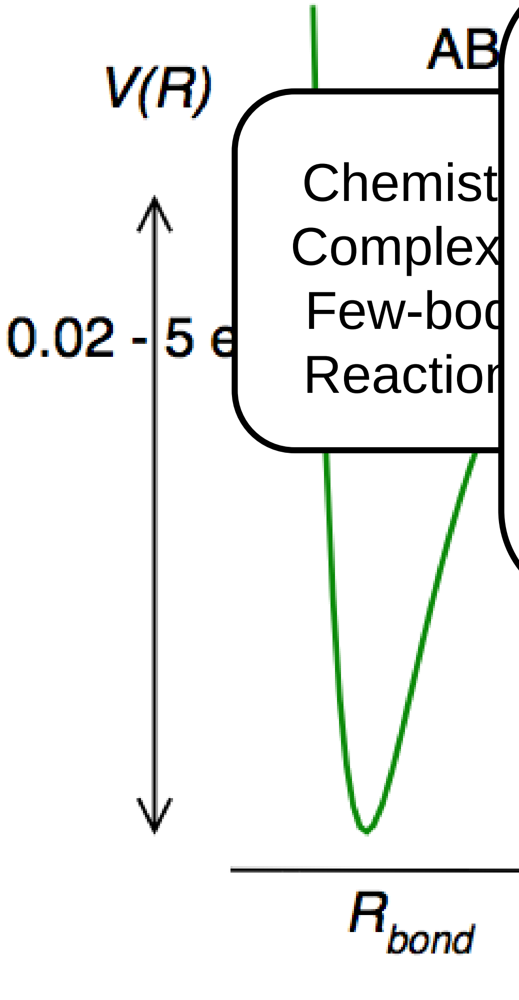


Recent unpublished Dy data deleted,
pending submission of paper

>10 THz (1000K) 10 Ghz (K) 10 kHz (μK)

Short-range Long-range Separated

A,B=Atom or molecule



Chemist
Complex
Few-bod
Reaction

Bridge
Sturdy, but simple
well-understood

Highly controlled
R ≳ 100 nm
Quantum state preparation
Low entropy
Free space
1D, 2D, 3D confined
Many-body
Gauge potentials

Fig. 2, PSJ Faraday Disc 142, 361 (2009)

>10 THz (1000K) 10 Ghz (K) 10 kHz (μK)

Short-range Long-range Separated

A,B=Atom or molecule

A few
parameters

Phase (α)
Feshbach strength (s_{re}
Reactivity (y)

Statistical complexity

Not unique
More than one way
To build a bridge
(Mies/PSJ/Hutson
Greene/Bohn, Gao)

Analytic
Numerical

Highly controlled
$R \gtrsim 100$ nm
Quantum state preparation
Low entropy
Free space
1D, 2D, 3D confined
Many-body
Gauge potentials

R_{bond} $\bar{a}$

R

Fig. 2, PSJ Faraday Disc 142, 361 (2009)

Long-range potential

p

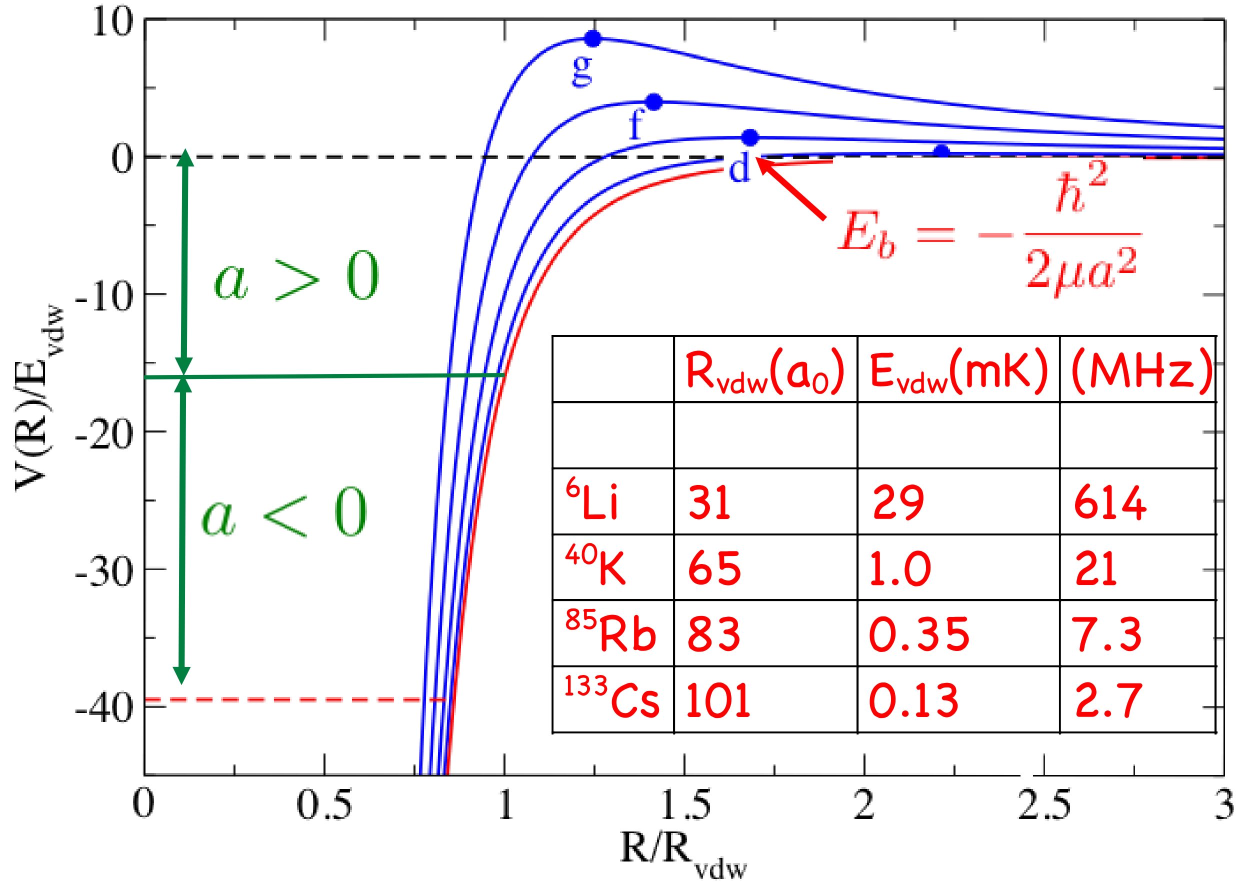
p = 1 Coulomb
p = 2 ion-dipole
p = 3 dipole-dipole, ion-quadrupole
p = 4 ion-neutral (polarization)
p = 5 quadrupole-quadrupole
p = 6 neutral-neutral (van der Waals)

"Universal" potential in E_p, R_p units

$$v(r) = -\frac{1}{r^p} + \frac{\ell(\ell+1)}{r^2}$$

For p=6, we also use $R_{\mathrm{vdW}} = \frac{1}{2} R_6$ or $\bar{a} = 0.478\ldots R_6$

“Size” of vdW potential



	$R_{vdw}(a_0)$	E_{vdw}(mK)	(MHz)
^{6}Li	31	29	614
^{40}K	65	1.0	21
^{85}Rb	83	0.35	7.3
^{133}Cs	101	0.13	2.7

Jones et al, Rev. Mod. Phys. 78, 483 (2006)

REVIEWS OF MODERN PHYSICS, VOLUME 82, APRIL–JUNE 2010

Feshbach resonances in ultracold gases

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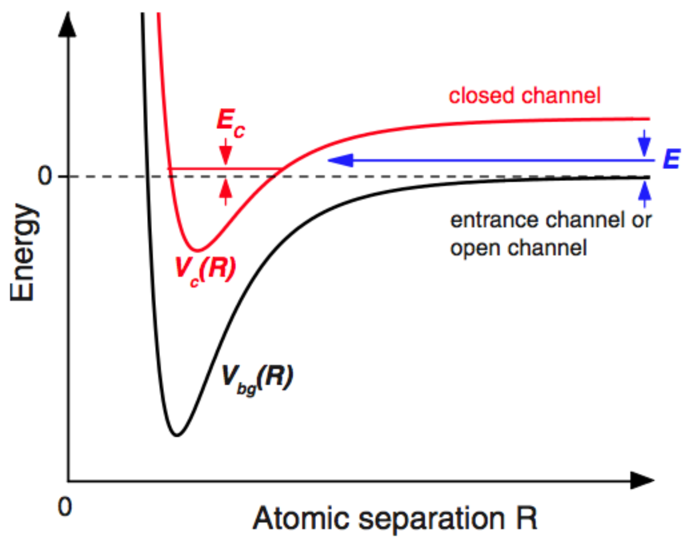
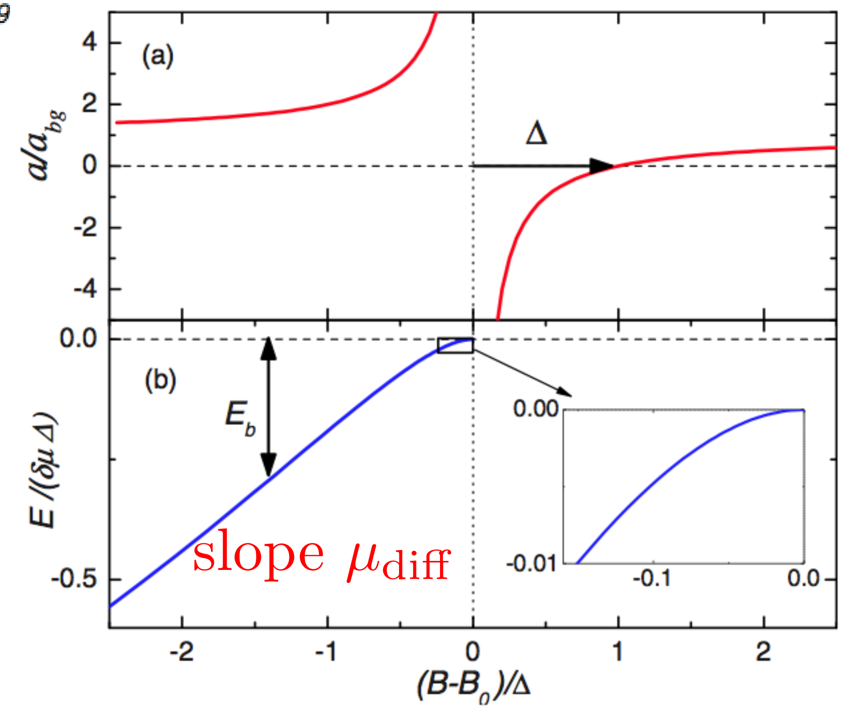
Resonance "pole strength"

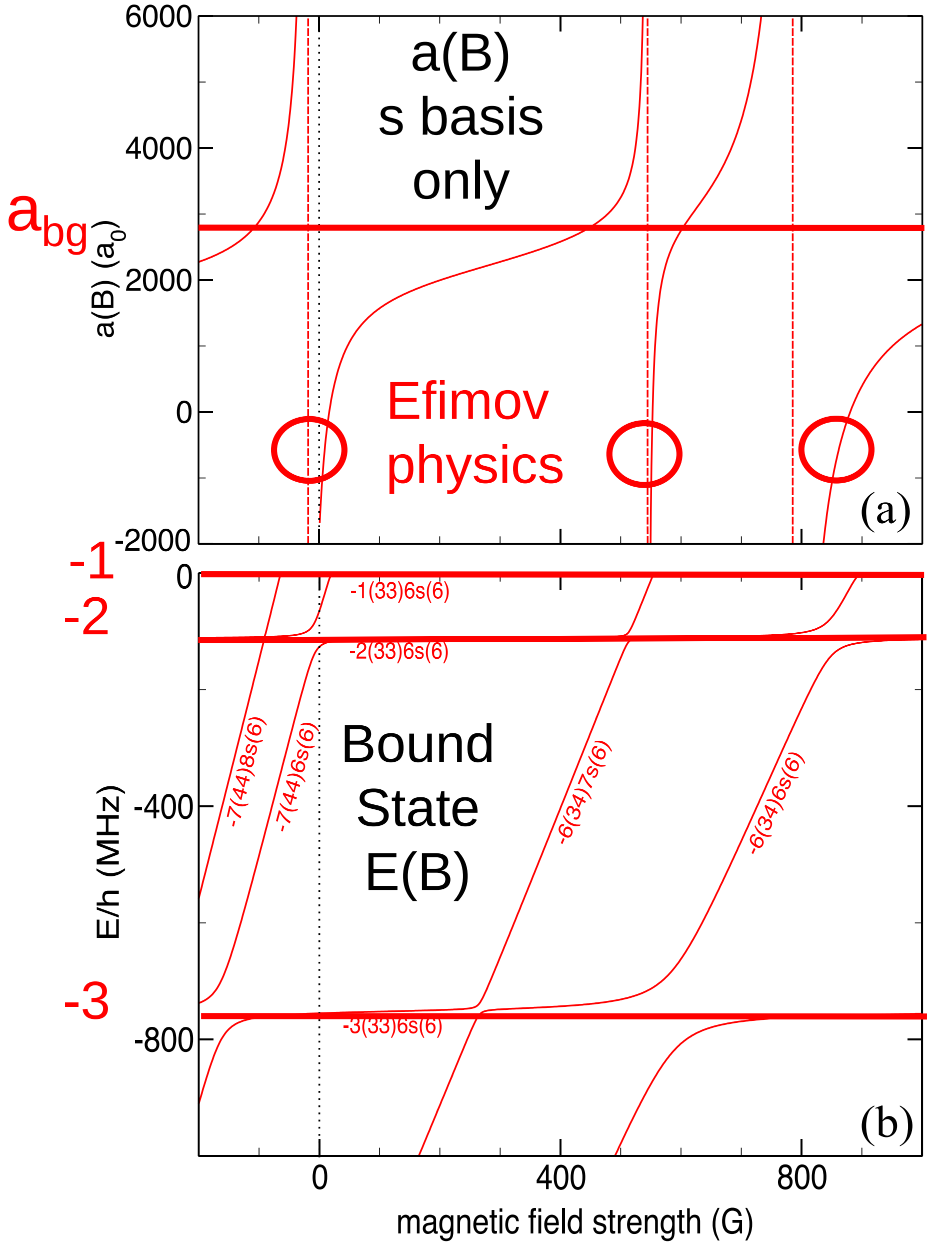
$$s_{\mathrm{res}} = \frac{a_{\mathrm{bg}}}{\bar{a}} \frac{\Delta\mu_{\mathrm{diff}}}{\bar{E}}$$

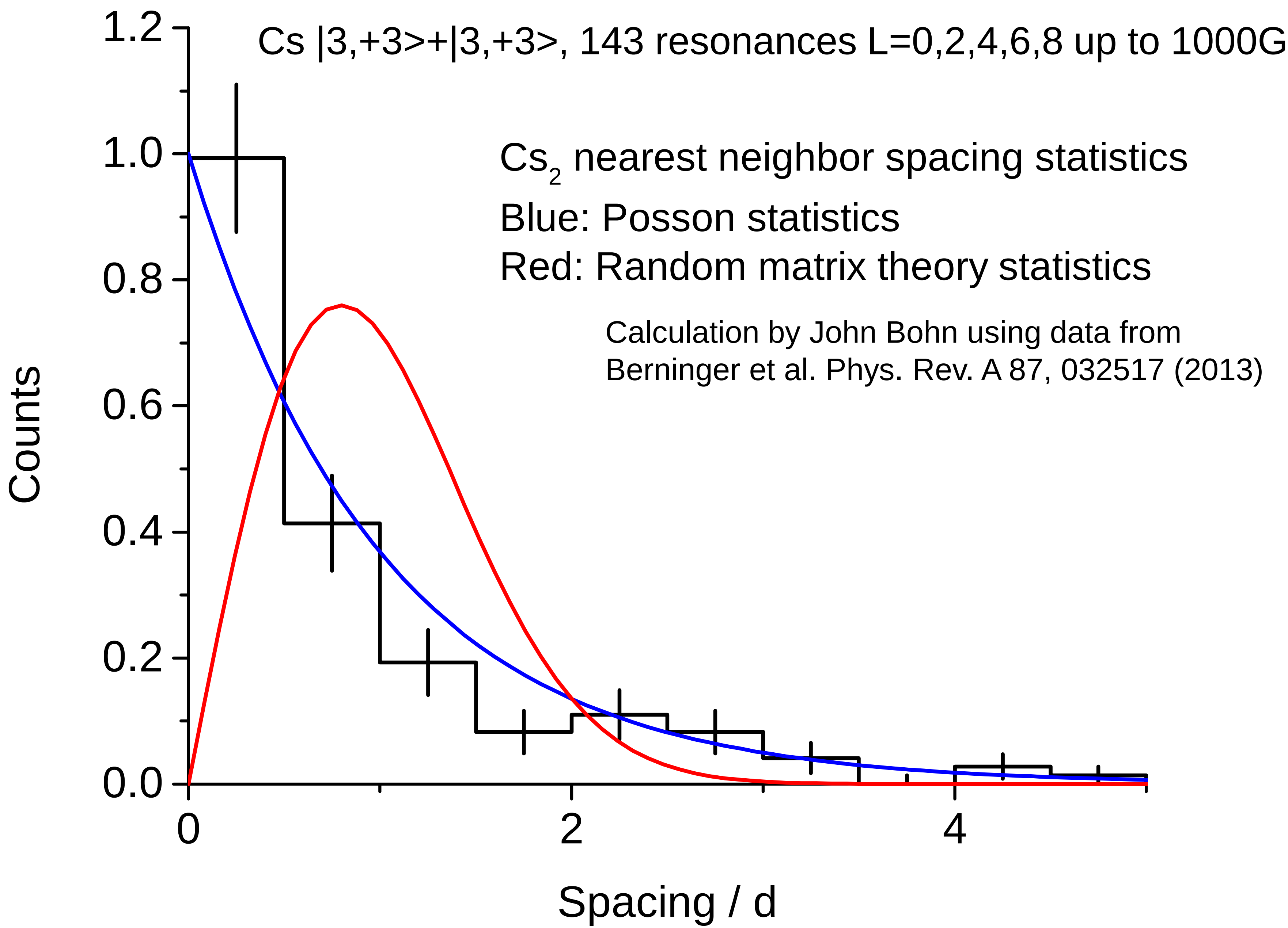
$$a = a_{\mathrm{bg}}\left(1 - \frac{\Delta}{B - B_0}\right)$$



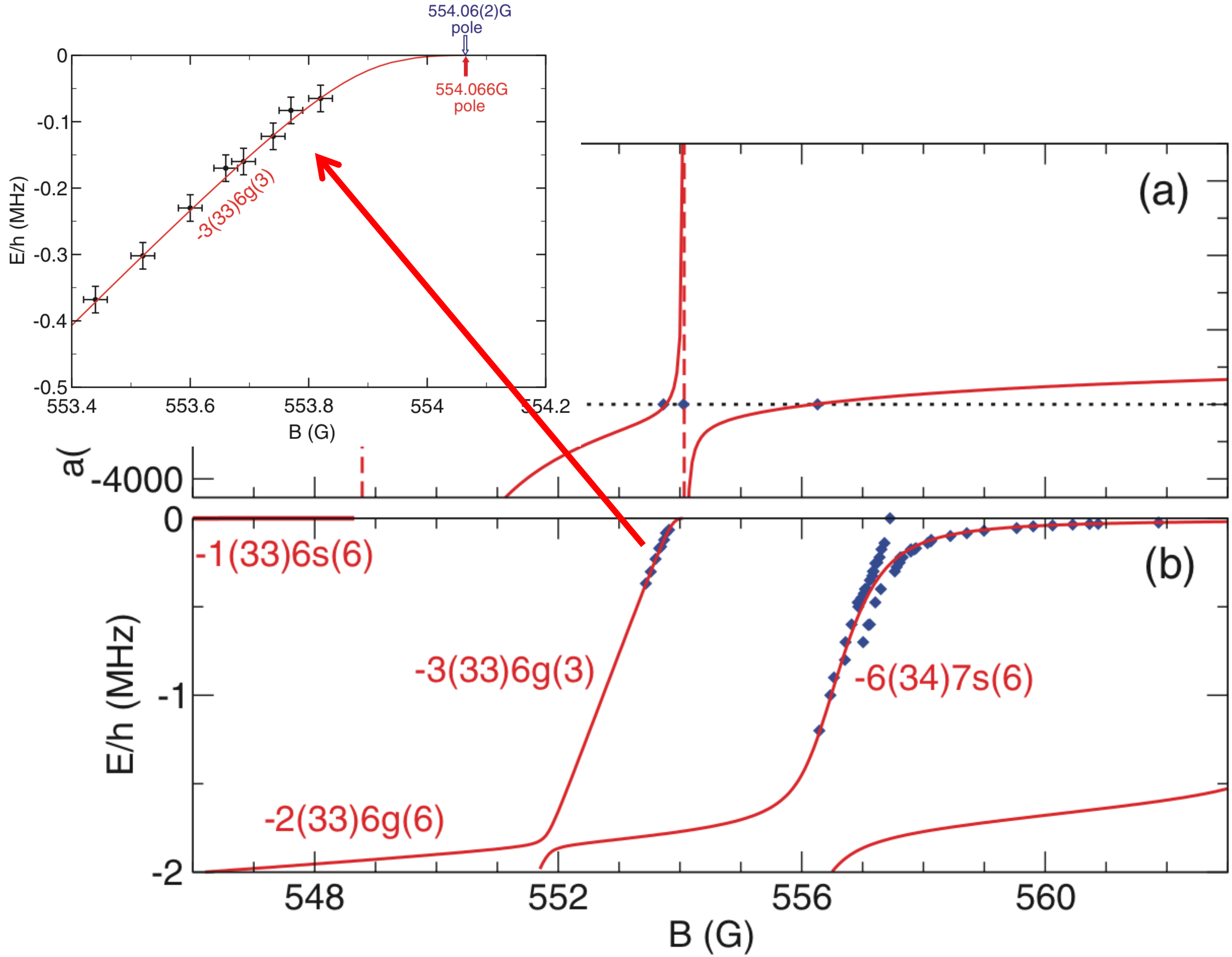


Cs+Cs Innsbruck Berninger et al, Phys. Rev. A 87, 032517 (2013)

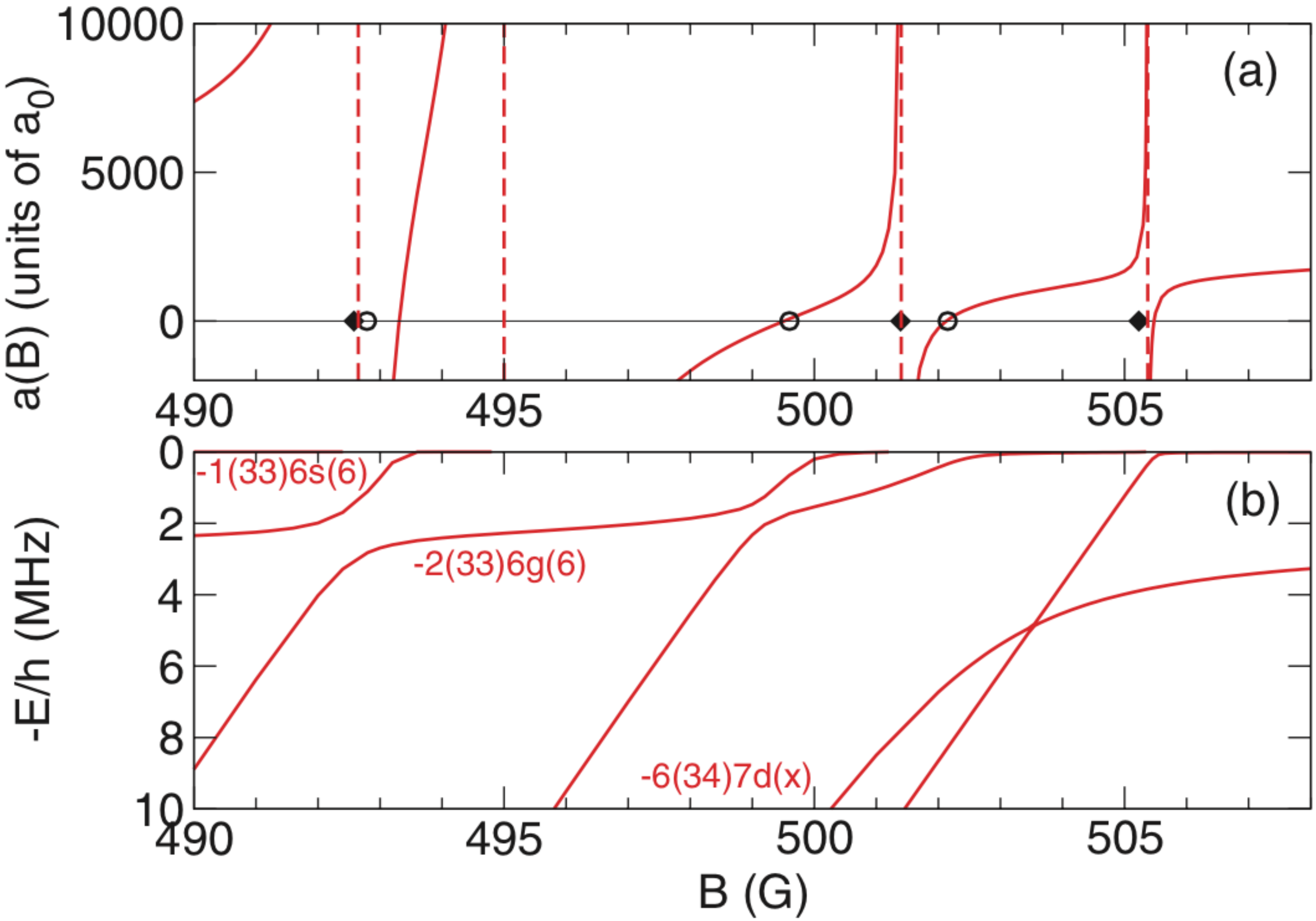




Cs |3,+3>+|3,+3>, 143 resonances L=0,2,4,6,8 up to 1000G
Cs2 nearest neighbor spacing statistics
Blue: Posson statistics
Red: Random matrix theory statistics
Calculation by John Bohn using data from
Berninger et al. Phys. Rev. A 87, 032517 (2013)
Counts
Spacing / d
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4



From Berninger et al, Phys. Rev. A 87, 032517 (2013)



Data indicated for 3-body loss maxima (solid) and minima (open).

From Berninger et al, Phys. Rev. A 87, 032517 (2013)

PHYSICAL REVIEW A **88**, 052701 (2013)

Analytical model of overlapping Feshbach resonances

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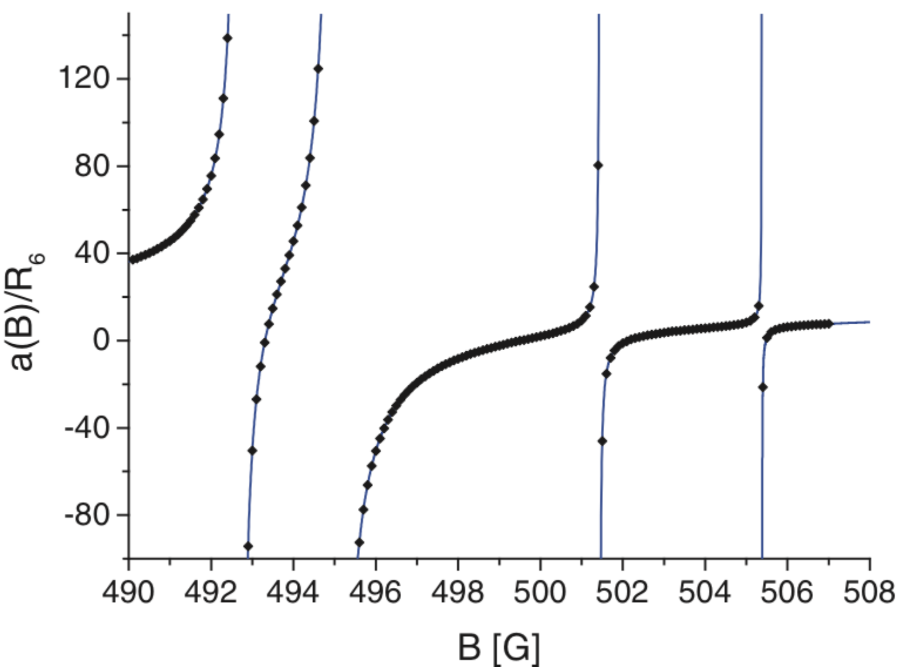
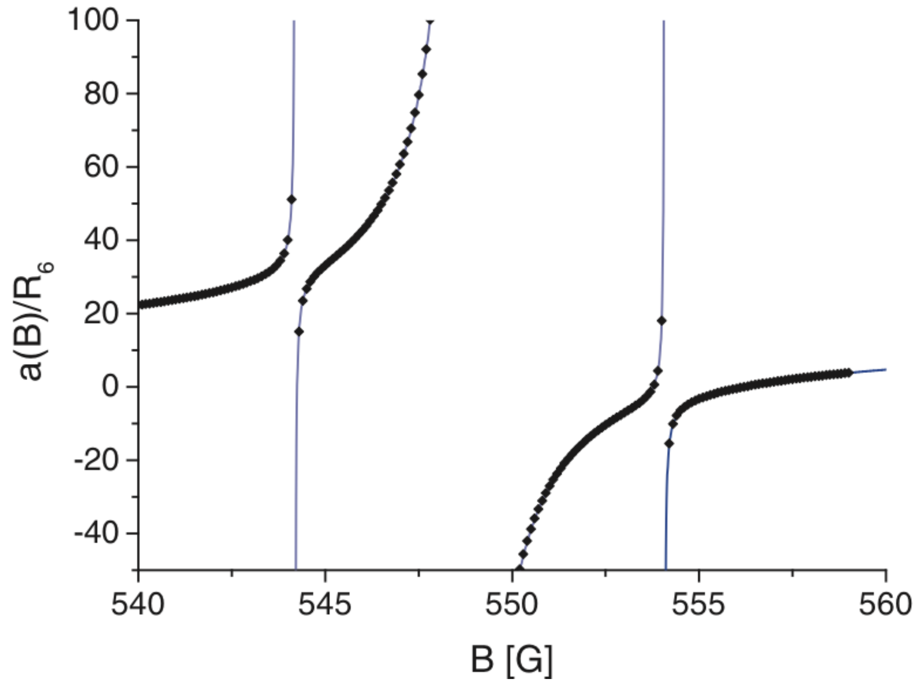
(Received 3 August 2013; published 6 November 2013)

$$a(B) = a_{bg} \prod_{i=1}^{N} \left(1 - \frac{\tilde{\Delta}_i}{B - B_i^{\mathrm{res}}}\right)$$





$$a(B) = a_{\rm bg} - \sum_{i=1}^{N} P_i(B)$$

$$P_i(B) = \frac{\frac{1}{2}\frac{\hat{\Gamma}_i}{\delta\mu_i} C^{-2}(E)/k}{B - B_i - \frac{1}{2}\tan\lambda(E)\left(\frac{\hat{\Gamma}_i}{\delta\mu_i} - \sum_{j\neq i}\frac{B-B_i}{B-B_j}\frac{\hat{\Gamma}_j}{\delta\mu_j}\right)}$$

"global" background

Short-range coupling

$$a(B) = a_{bg}\left(1 - \sum_i \frac{\Delta_i}{B - B_i - \delta B_i - \sum_{j\neq i}\frac{B-B_i}{B-B_j}\delta B_j}\right)$$

Interaction shift

$$a(B) = a_{bg}\prod_{i=1}^{N}\left(1 - \frac{\tilde{\Delta}_i}{B - B_i^{\rm res}}\right)$$

$$a(\text{near } B_i) = \tilde{a}_{bg,i}\left(1 - \frac{\tilde{\Delta}_i}{B - B_i^{\rm res}}\right)$$

$$\tilde{a}_{bg,i} = a_{bg}\prod_{j\neq i}^{N}\left(1 - \frac{\tilde{\Delta}_j}{B_i^{\rm res} - B_j^{\rm res}}\right)$$

"local" background

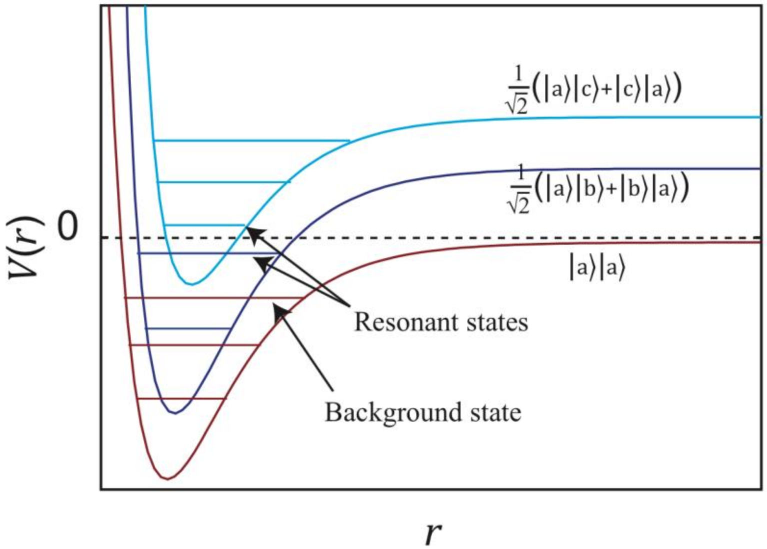
3-Body recombination of 3 alkali-metal atoms

Computer codes and calculations by Yujun Wang

Y. Wang & PSJ, Nat. Phys. 10, 768 (2014)

$$\mathrm{Cs + Cs + Cs \rightarrow Cs_2 + Cs}$$

Three-channel Cs + Cs interaction： “Exact” 2-body Feshbach model



2-channel numerical model using s_{res}, α_{bg} for Cs-Cs

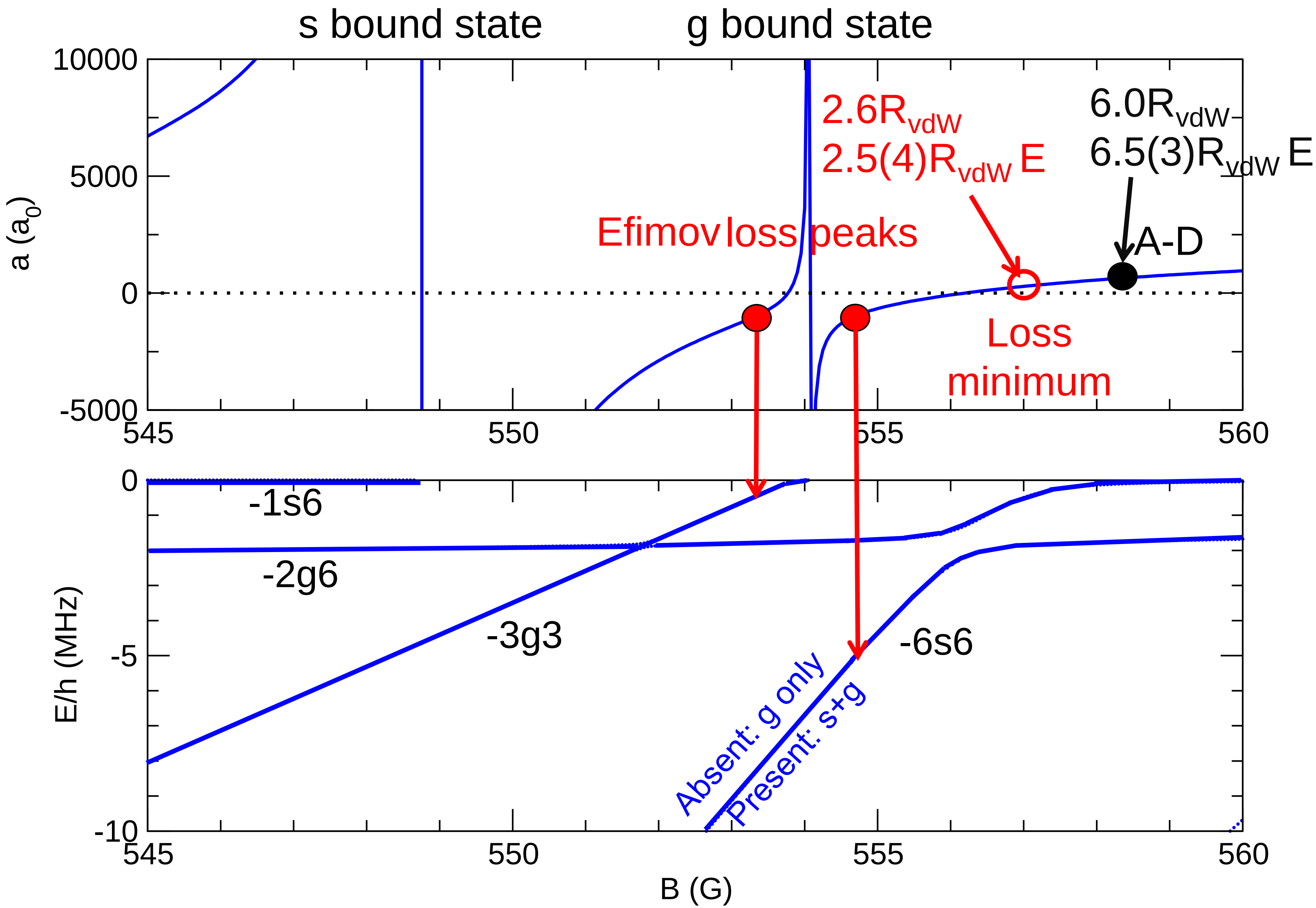
6-12 Lennard-Jones potentials
+ short-range coupling
Mies (2000), PSJ(2006)

Number of bound states can be varied, N = 2 to 4.

Given “exact” 2-body model parameterized by known $s_{\mathrm{res}}, \alpha_{\mathrm{bg}}, m_{\mathrm{dif}}$

plus 3-body interactions as a sum of 2-body ones,

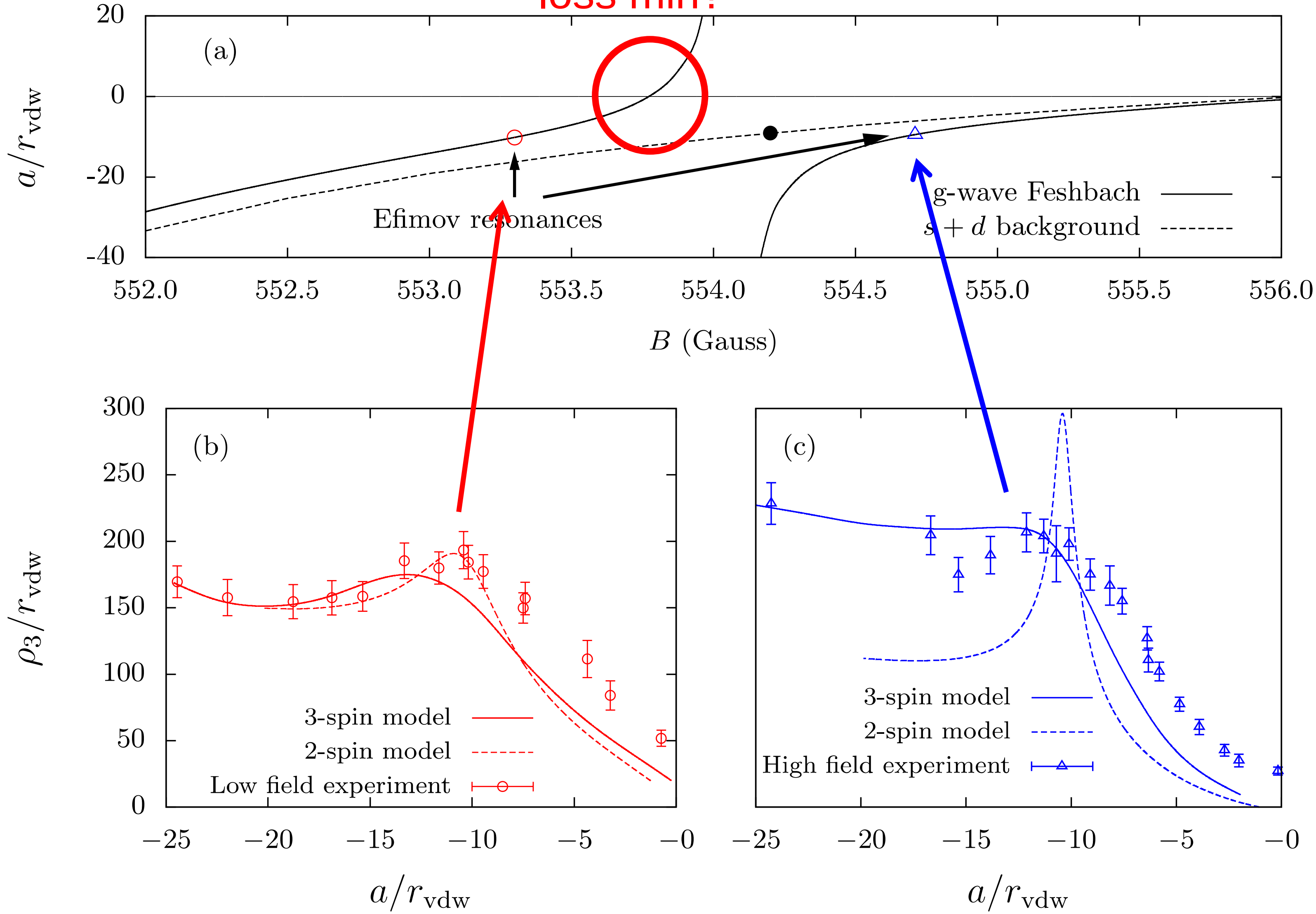
numerically solve 3B equations in hyperspherical basis



Cs coupled channels model from Berninger, et al, Phys. Rev. A 87, 032517 (2013)

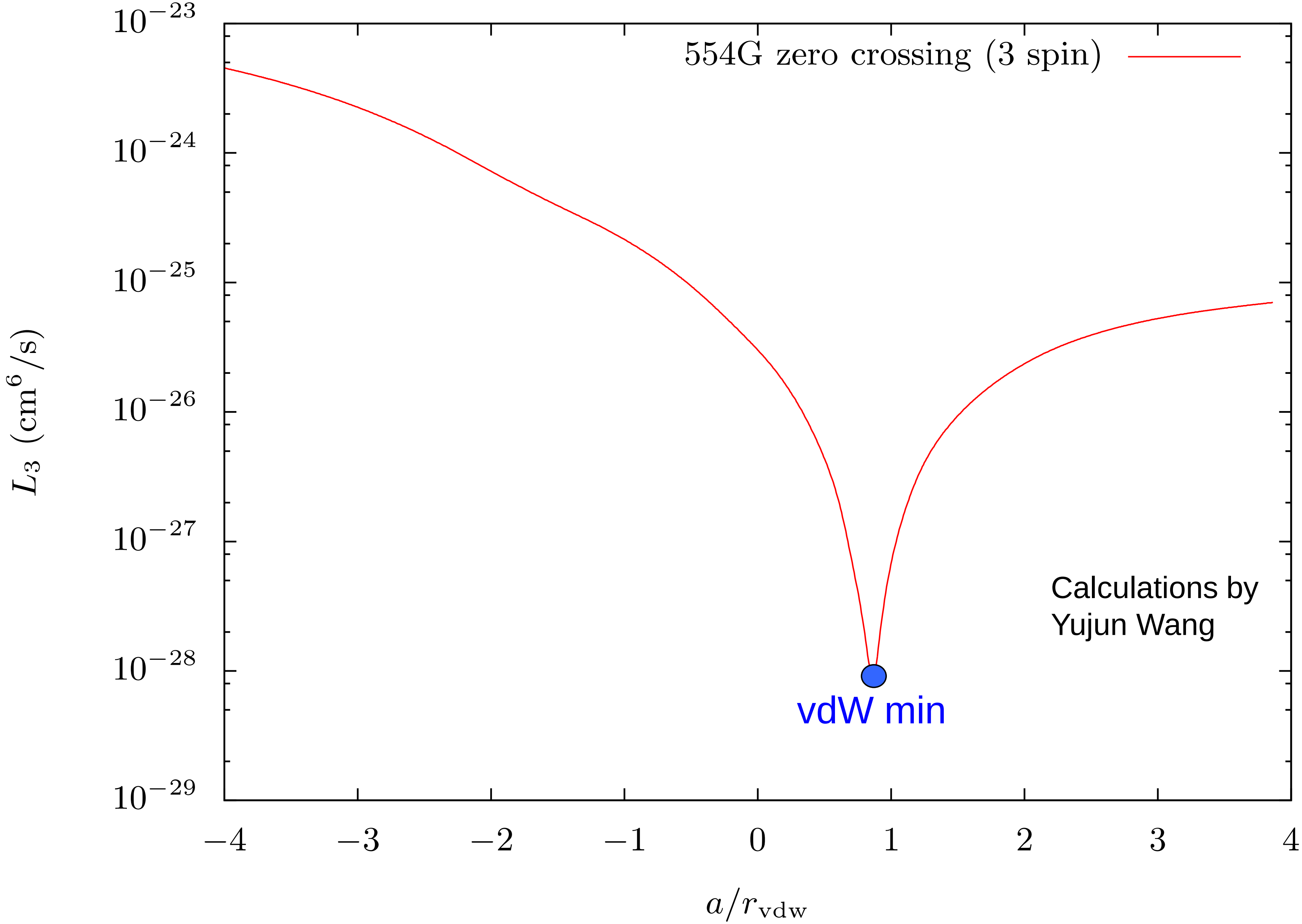
Cs overlapping resonances (multiple s_{res}): Jachymski, PSJ, PRA 88, 052701(2013)

What about loss min?

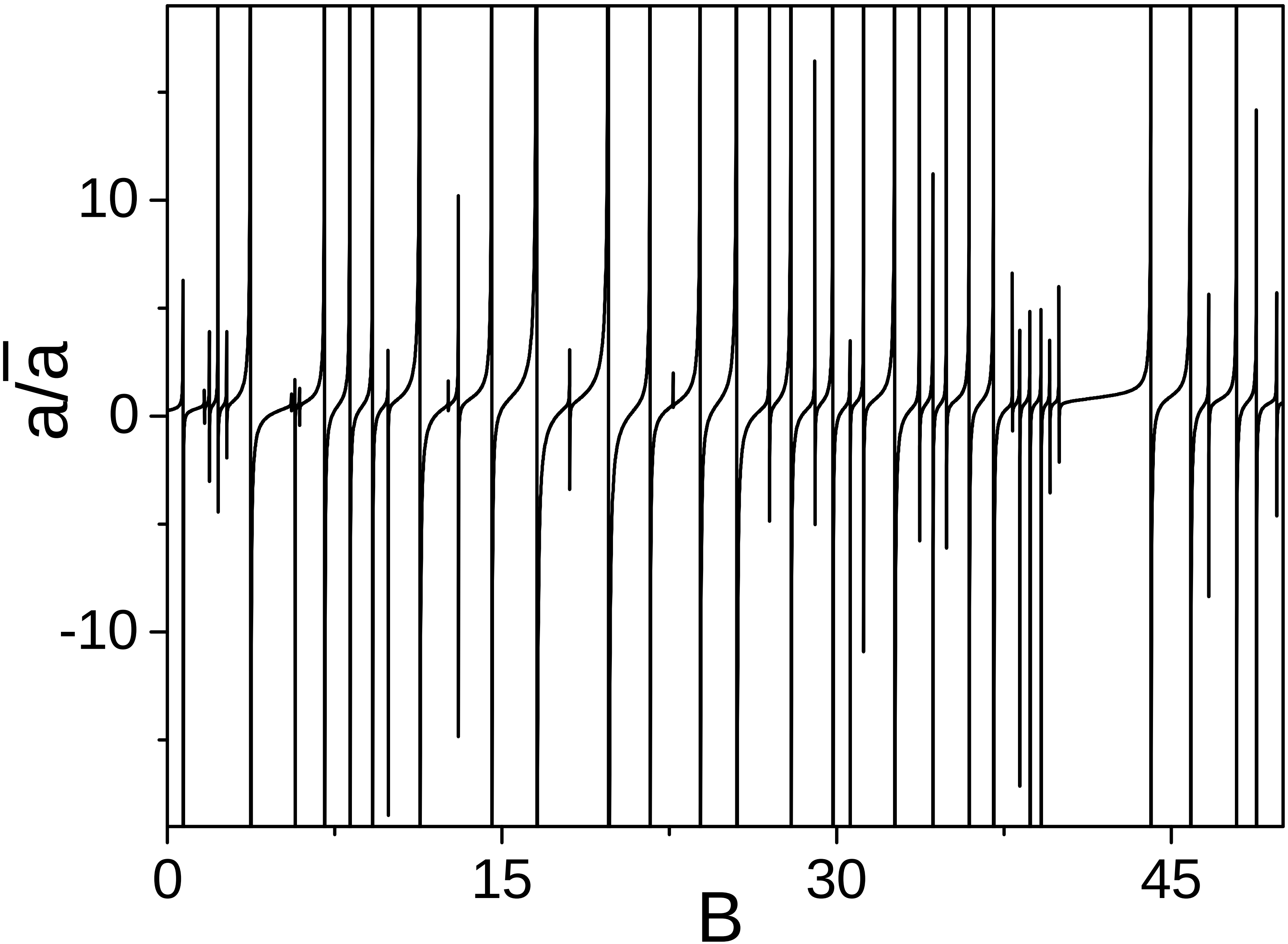


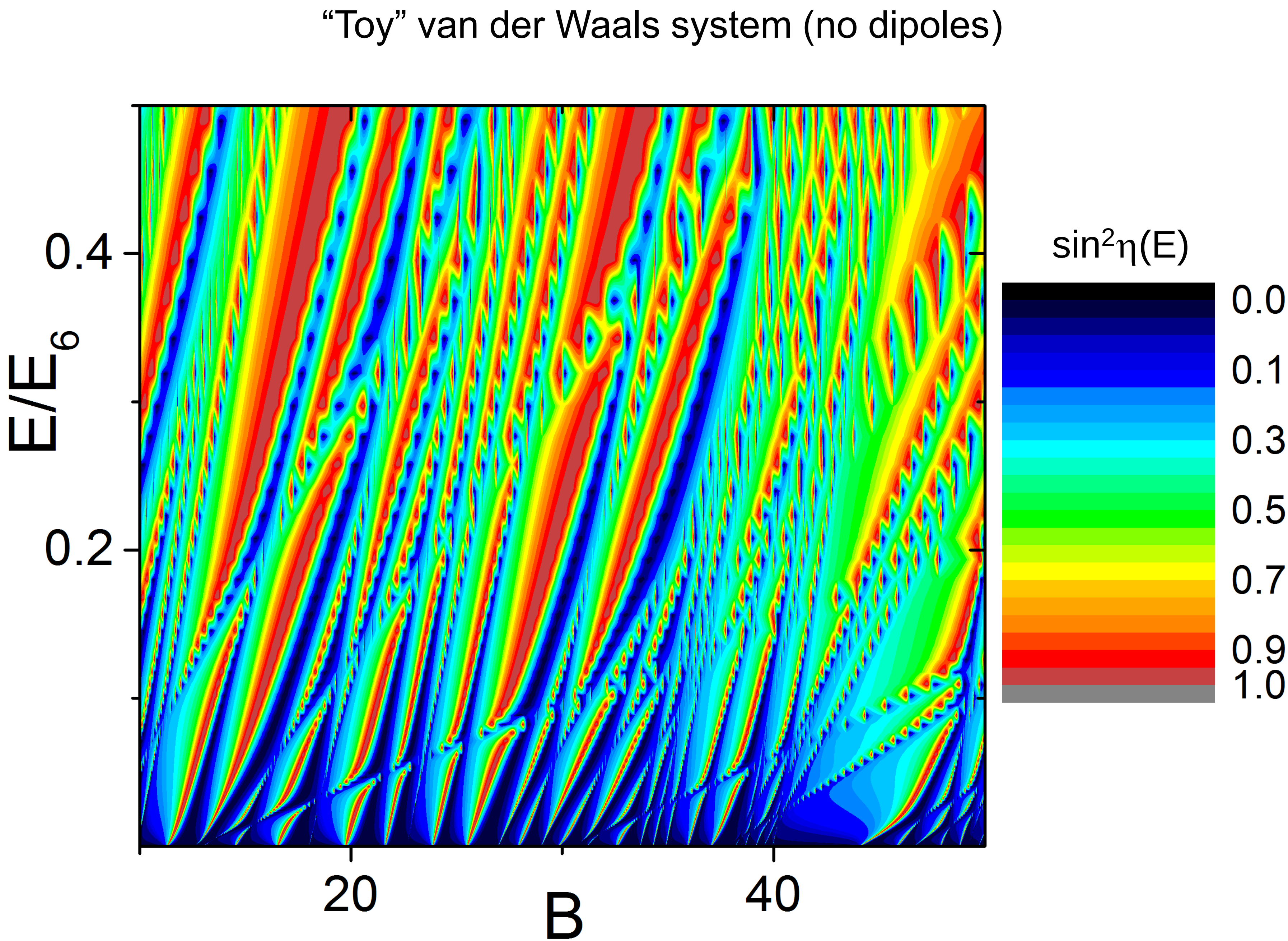
Calculations: no adjustable parameters

Wang and PSJ, Nat. Phys. 10, 768 (2014)

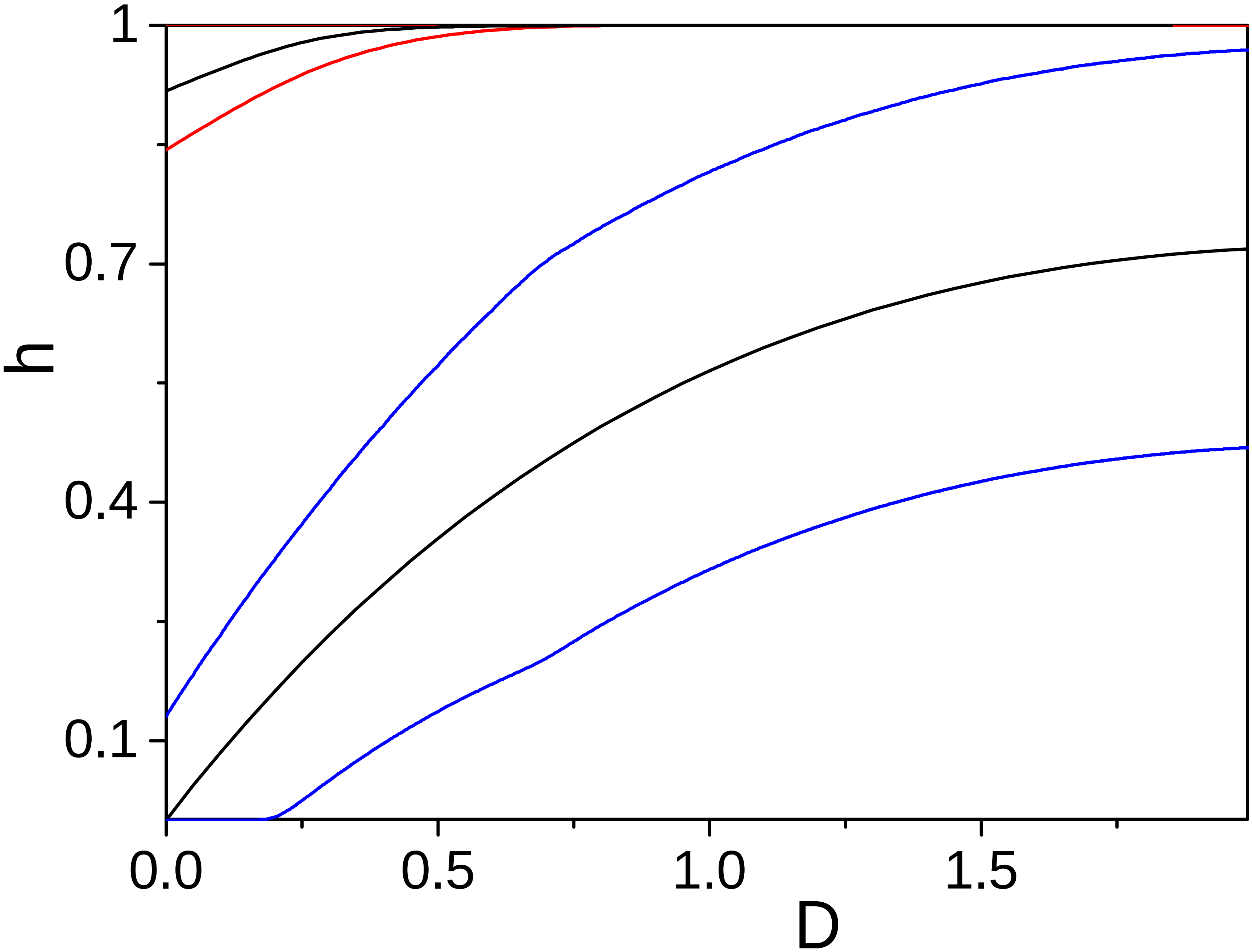


554G zero crossing (3 spin)
Calculations by
Yujun Wang
vdW min
L_3 (cm^6/s)
$a/r_{\rm vdw}$
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
−4
−3
−2
−1
0
1
2
3
4


10
0
-10
a/ā
0
15
30
45
B



"Toy" van der Waals system (no dipoles)
E/E6
0.4
0.2
B
20
40
sin²η(E)
0.0
0.1
0.3
0.5
0.7
0.9
1.0



1
0.7
0.4
0.1
h
0.0
0.5
1.0
1.5
D

The End