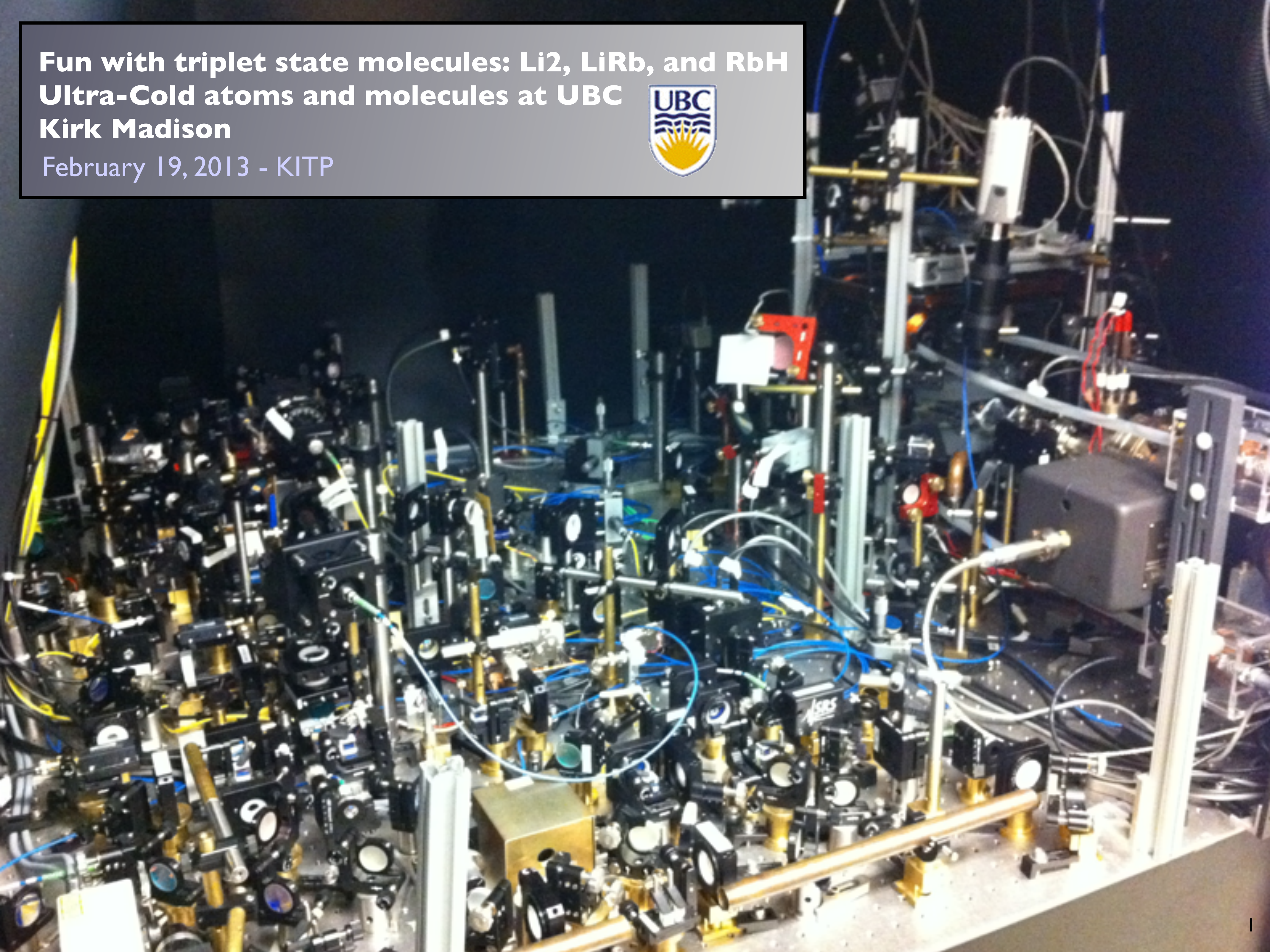
Fun with triplet state molecules: Li2, LiRb, and RbH

Ultra-Cold atoms and molecules at UBC

Kirk Madison

February 19, 2013 - KITP



Li+Rb mixtures

Will Gunton

Mariusz Semczuk

Theory support for Li_2 from Xuan Li[1] and Nike Dattani[2]

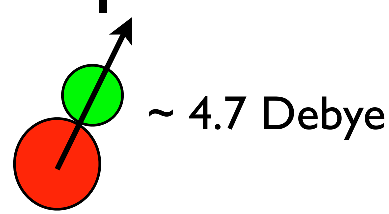
[1]Chemical Science Division, Lawrence Berkeley National Laboratory, Berkeley, USA
[2]Department of Chemistry, University of Oxford, Oxford, UK

CRUCS Canadian Centre for Research on Ultra-Cold Systems

NSERC CRSNG
UBC
British Columbia
CFI
Peter Wall Institute for Advanced Studies
CIFAR CANADIAN INSTITUTE for ADVANCED RESEARCH

Long term goal: production of dense, ultracold ensembles of polar molecules

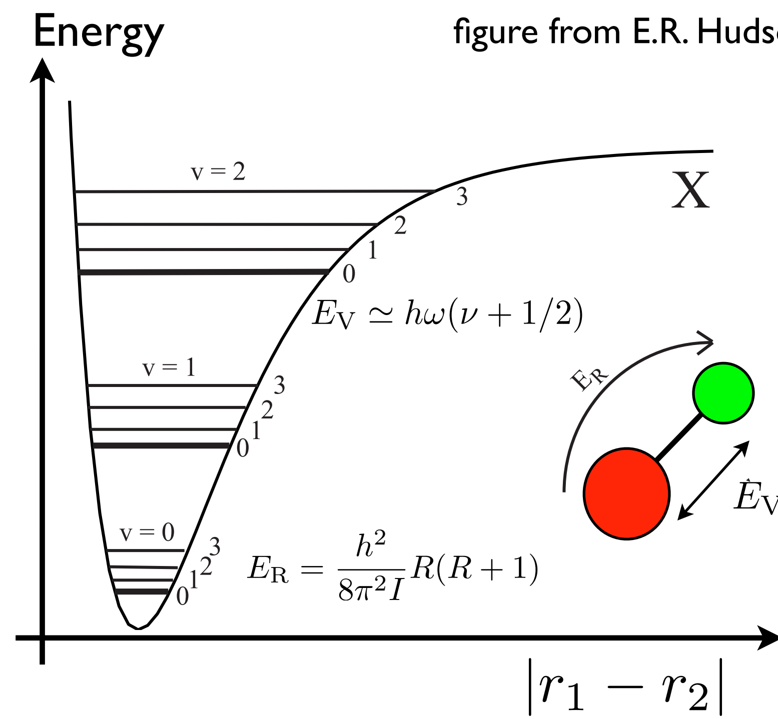
RbLi is a polar molecule



Polar molecules: scientific motivation

Additional **features** not available with atoms:

figure from E.R. Hudson



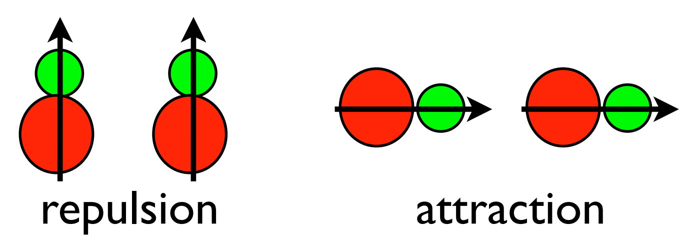
Rich internal structure:

- *rotational, vibrational*

Dipolar interactions:

- *large and long range* $\sim 1/r^3$
- *angular dependence (anisotropic)*

$$U_{\rm dd}^{\rm electric} = \frac{1}{4\pi\epsilon_0} \frac{\mathbf{d_1} \cdot \mathbf{d_2} - 3(\mathbf{d_1} \cdot \hat{r})(\mathbf{d_2} \cdot \hat{r})}{r^3}$$



... and zero at the 'magic angle'

Polar molecules: scientific motivation

Dipolar interactions - *how strong?*

* fully polarized

Inter-particle interactions between RbLi dimers (4.7 Debye)*
~1000x larger than mean field interaction in a BEC
~10,000x larger than magnetic dipolar interactions in Cr

Dipolar interactions - *at what range?*

532 nm optical lattice

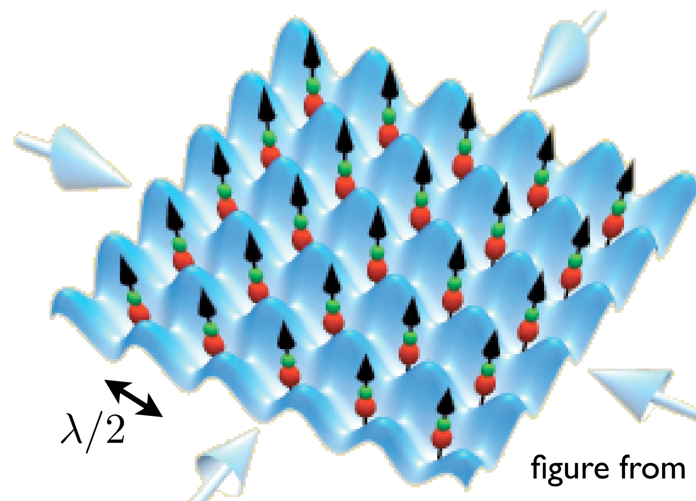


figure from Nature **2**, 341 (2006)

$$U_{\mathrm{dd}} \sim \left.\frac{(4.7\ \mathrm{Debye})^2}{4\pi\epsilon_0 r^3}\right|_{r=0.266\mu\mathrm{m}} = k_{\mathrm{B}} \times 8.5\ \mu\mathrm{K} = h \times 177\ \mathrm{kHz}$$

Polar molecules: scientific motivation

few and many body QM

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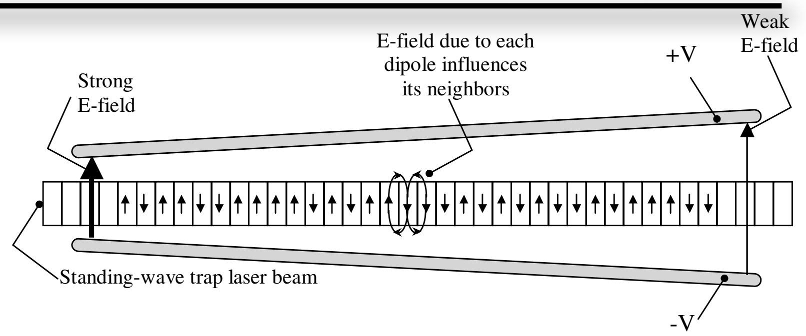

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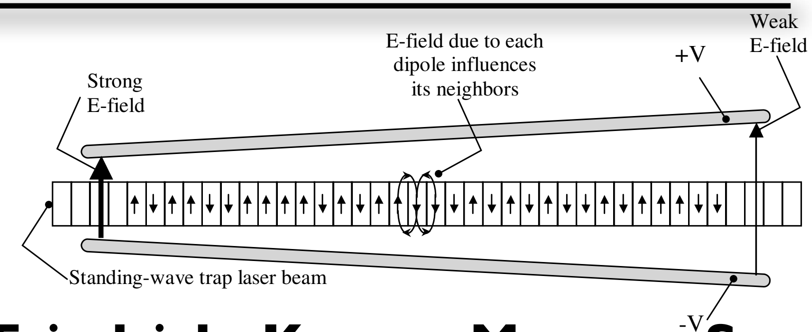

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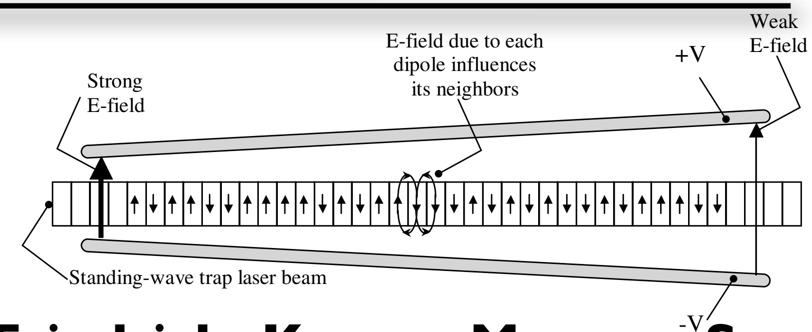

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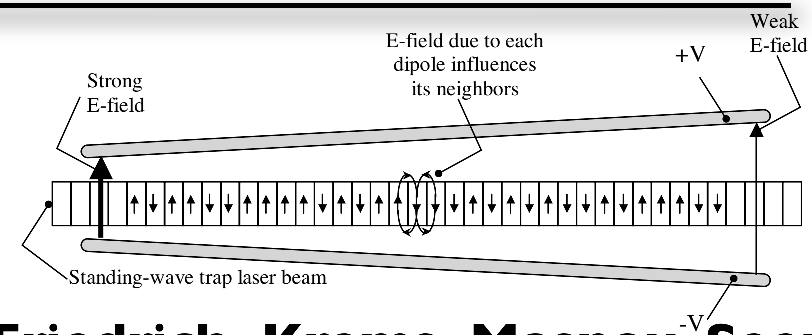

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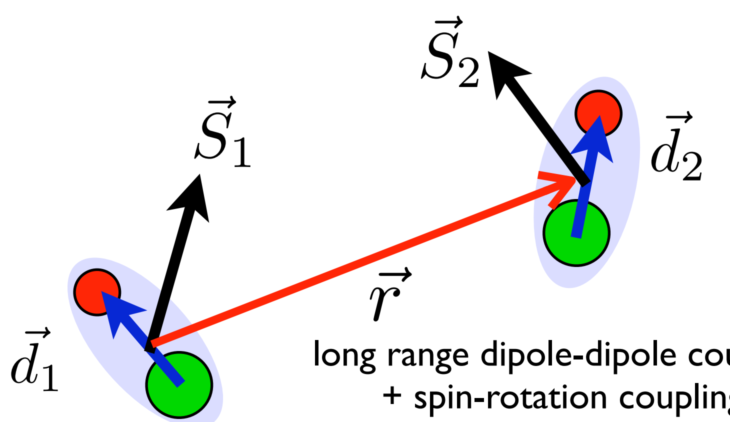
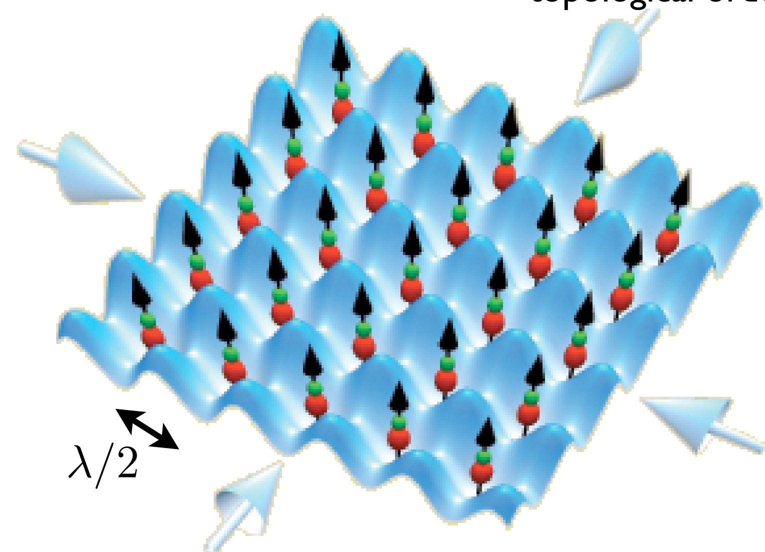
  with polar molecules in an optical lattice dressed with a microwave field, you can realize just about any spin lattice model : 1D xyz, 2D Ising, 3D Heisenberg, Kitaev model, etc...*



long range dipole-dipole coupling
+ spin-rotation coupling
+ microwave field
= effective spin-spin coupling

* topological order



Polar molecules: scientific motivation

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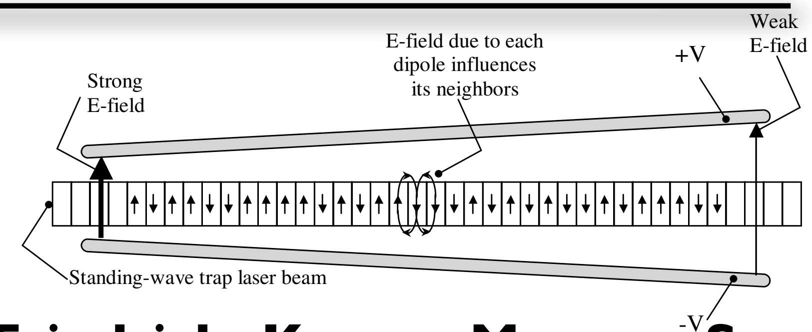

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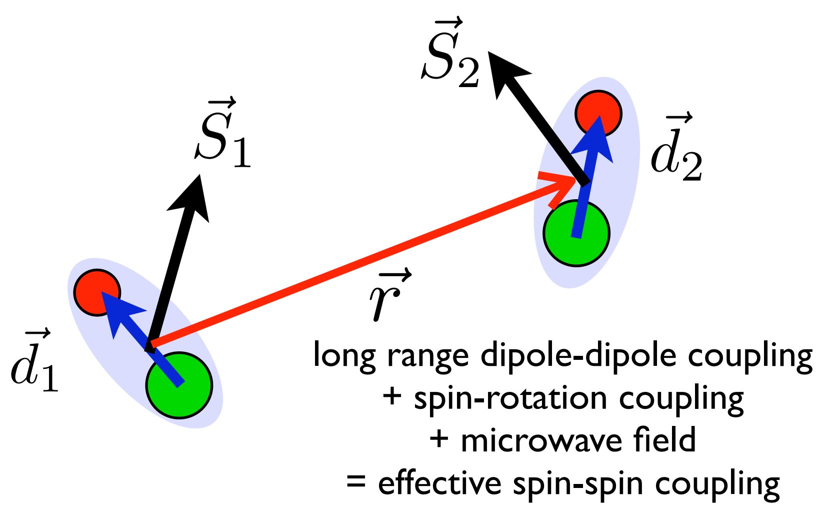

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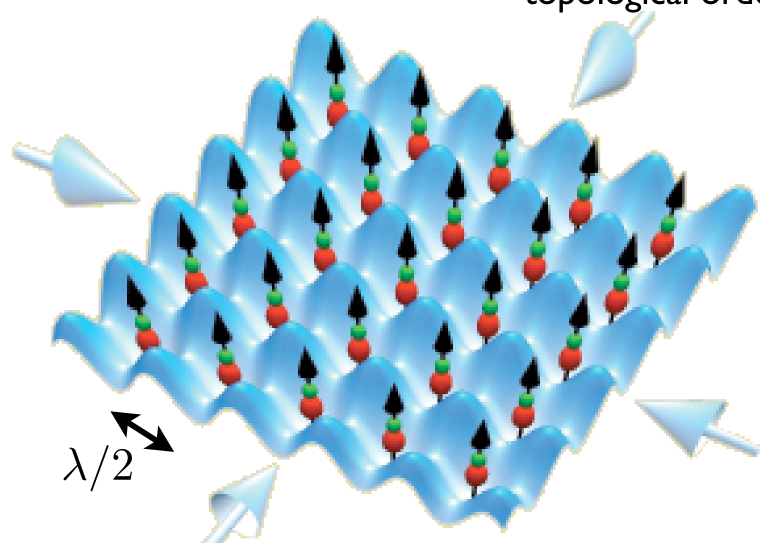
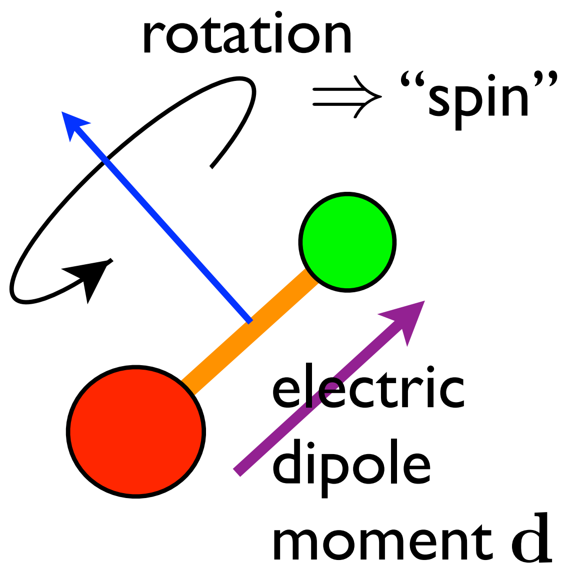


for this, you need paramagnetic, polar molecules !

Polar molecules: scientific motivation

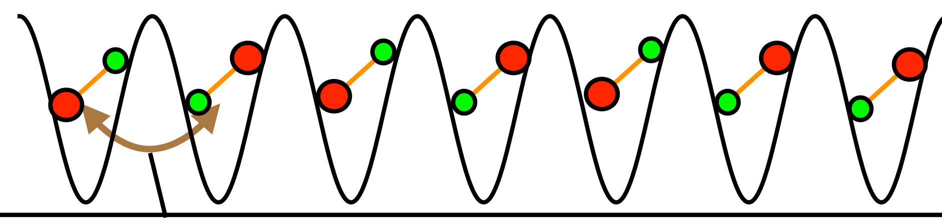
from Alexey V. Gorshkov's Jan. 24th talk, "Topological Phases in Polar-Molecule Quantum Magnets"



highly tunable exotic spin models

Our achievements:

- stronger interactions
- much higher tunability ⇒ exotic physics



dipole-dipole interactions ⇒ "spin-spin" interactions

Barnett et al., PRL (2006)
Micheli, Brennen, Zoller, Nat Phys (2006)
Brennen, Micheli, Zoller, NJP (2007)
Buchler, Micheli, Zoller, Nat Phys (2007)
Watanabe, PRA (2009)
Wall, Carr, NJP(2009)
Pupillo et al, in *Cold Molecules* (2009)
Wall, Carr, PRA (2010)
Schachenmayer et al., NJP (2010)
Perez-Rios, Herrera, Krems, NJP (2010)
Trefzger et al., NJP (2010)
Herrera, Litinskaya, Krems, PRA (2010)
Kestner et al., PRB (2011),
Lemeshko et al, PRL (2012), etc...

for some of these proposals, you need paramagnetic, polar molecules !

Quantum degenerate polar molecules from cold atoms: state of the art

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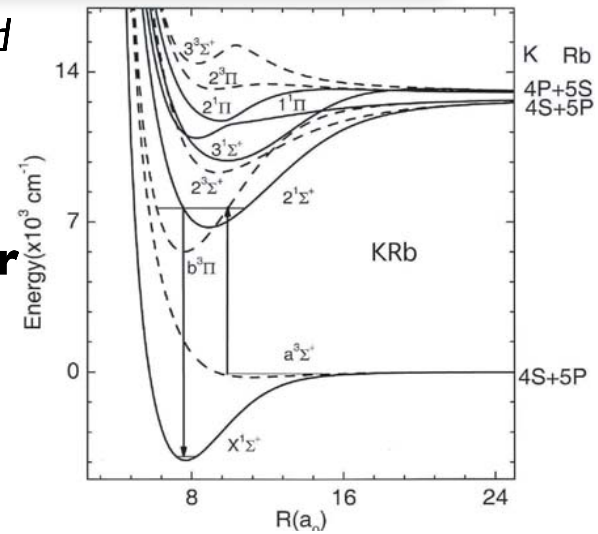

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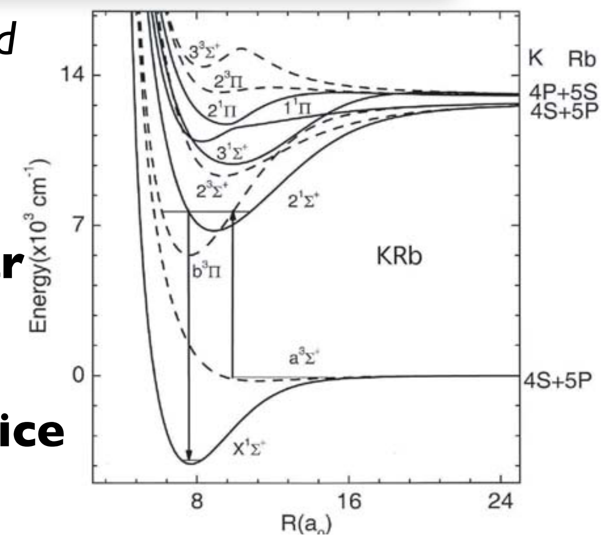

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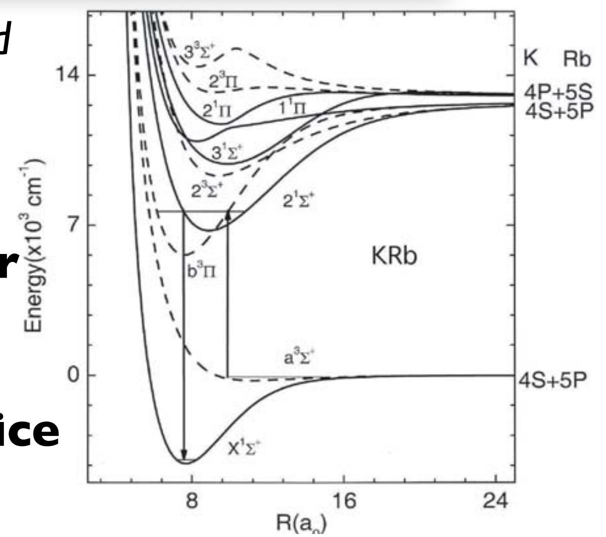

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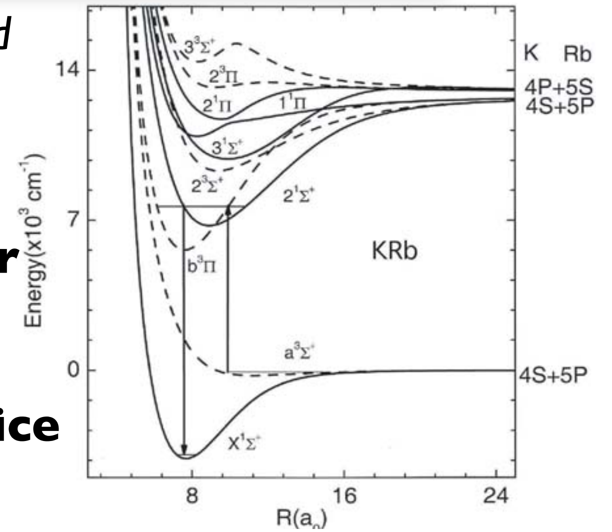

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Dipole moments (Debye)

X \ Y	Na	K	Rb	Cs
Li	0.53 (0.45[a])	3.50 (3.41[b])	4.13 (4.01[c])	5.48
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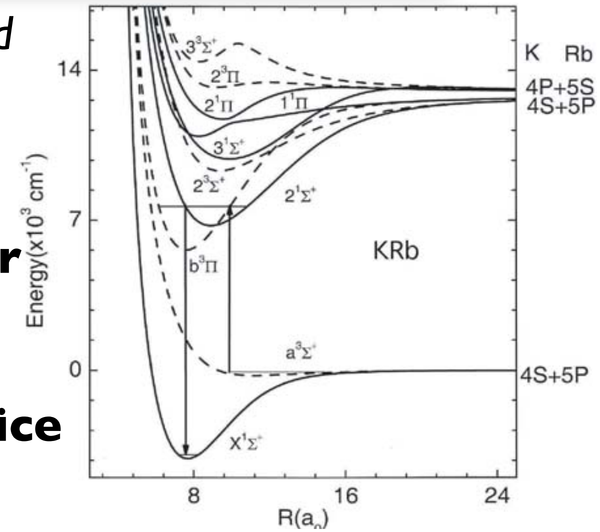

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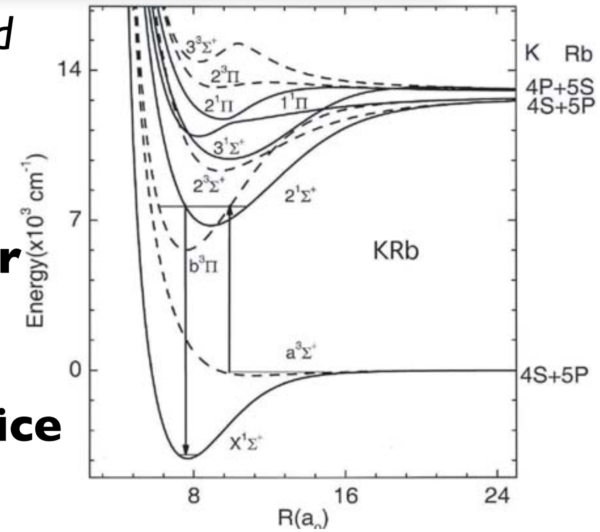

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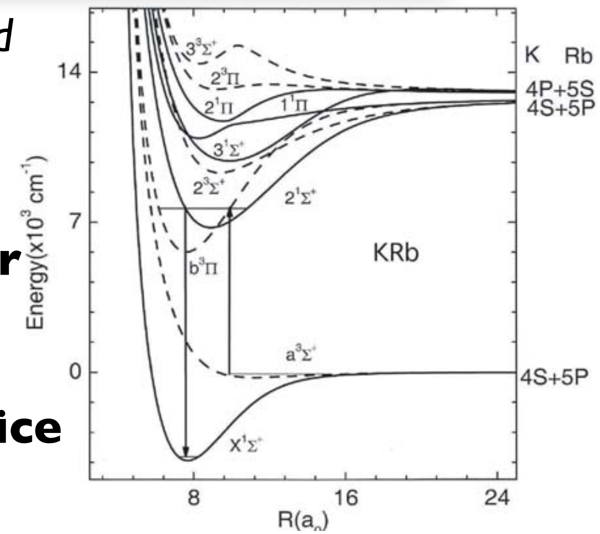

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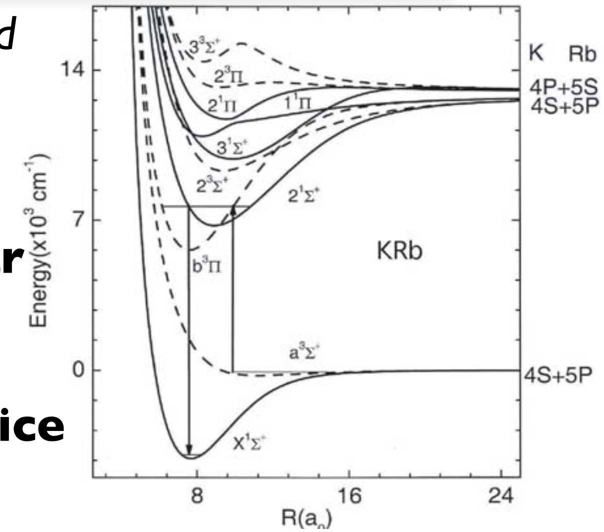

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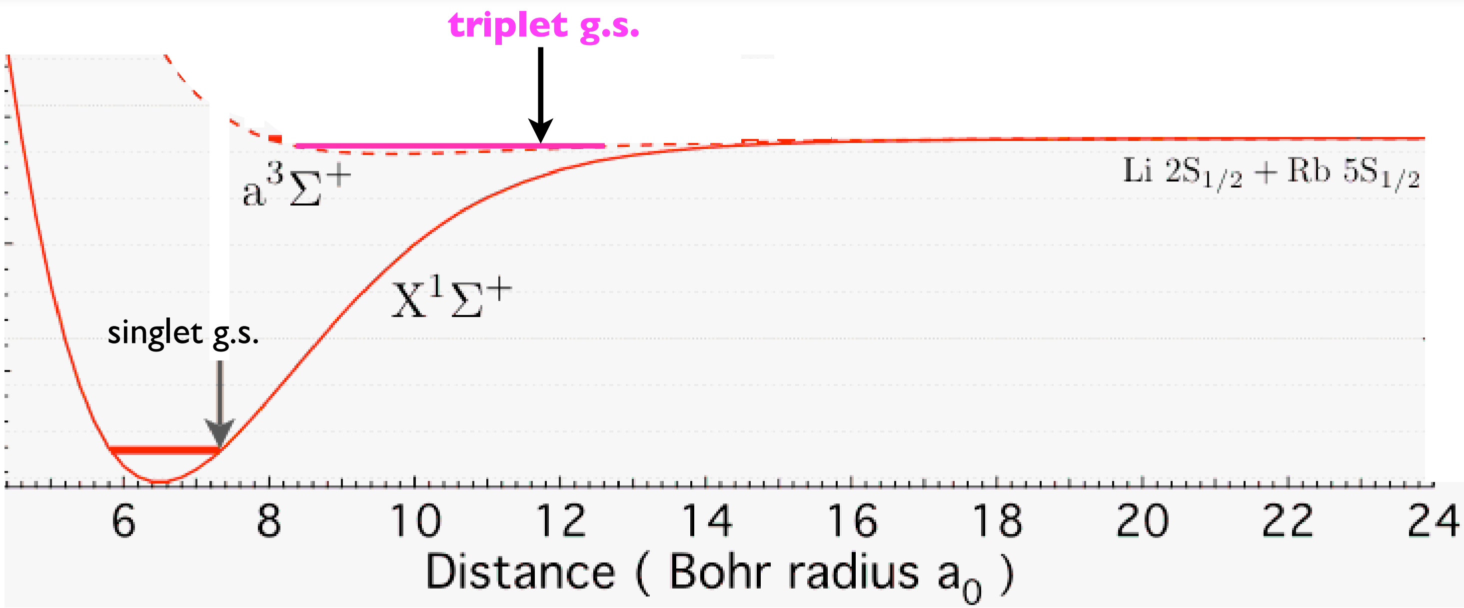
what about the triplet state of a bi-alkali molecule?

What about the lowest triplet state?



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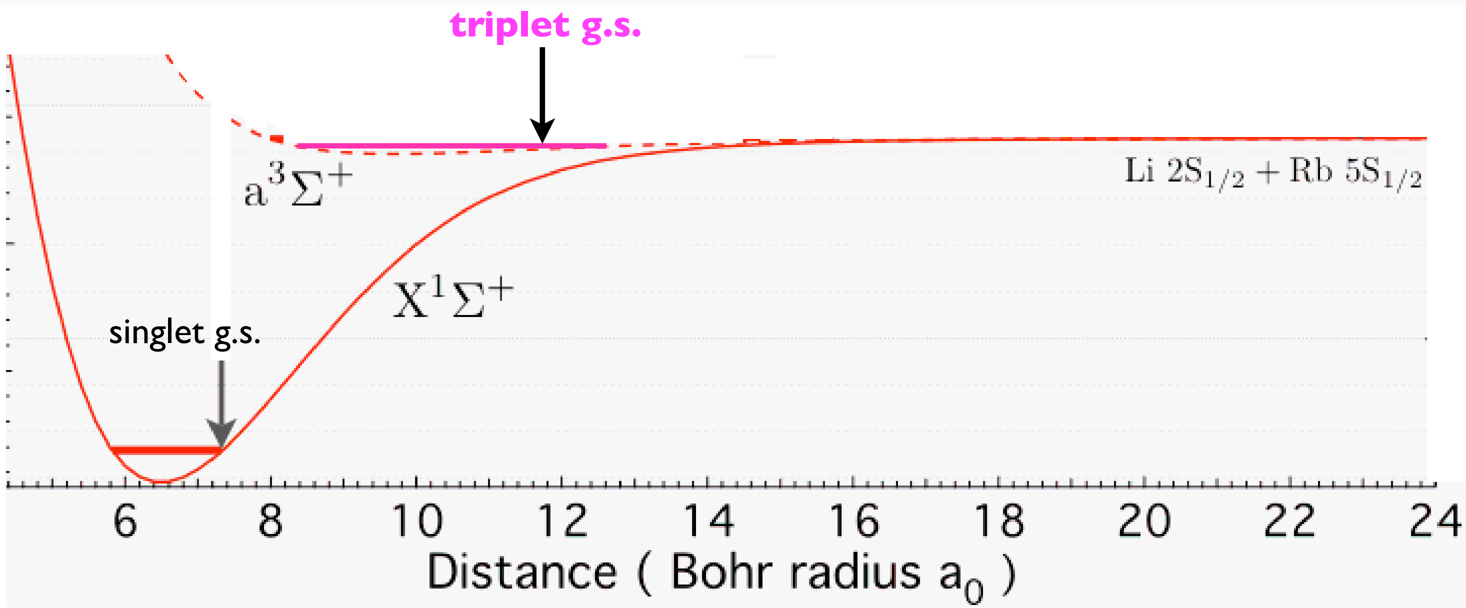

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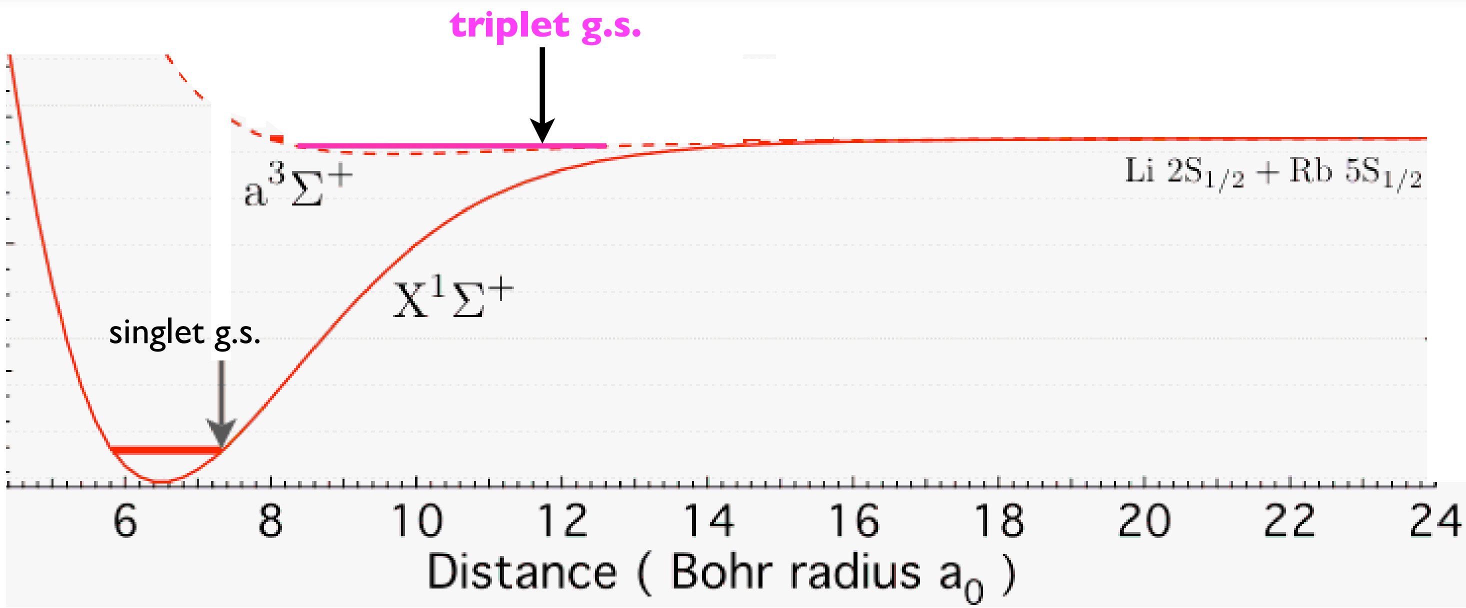

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DM of triplet state LiRb is about 0.4 Debye

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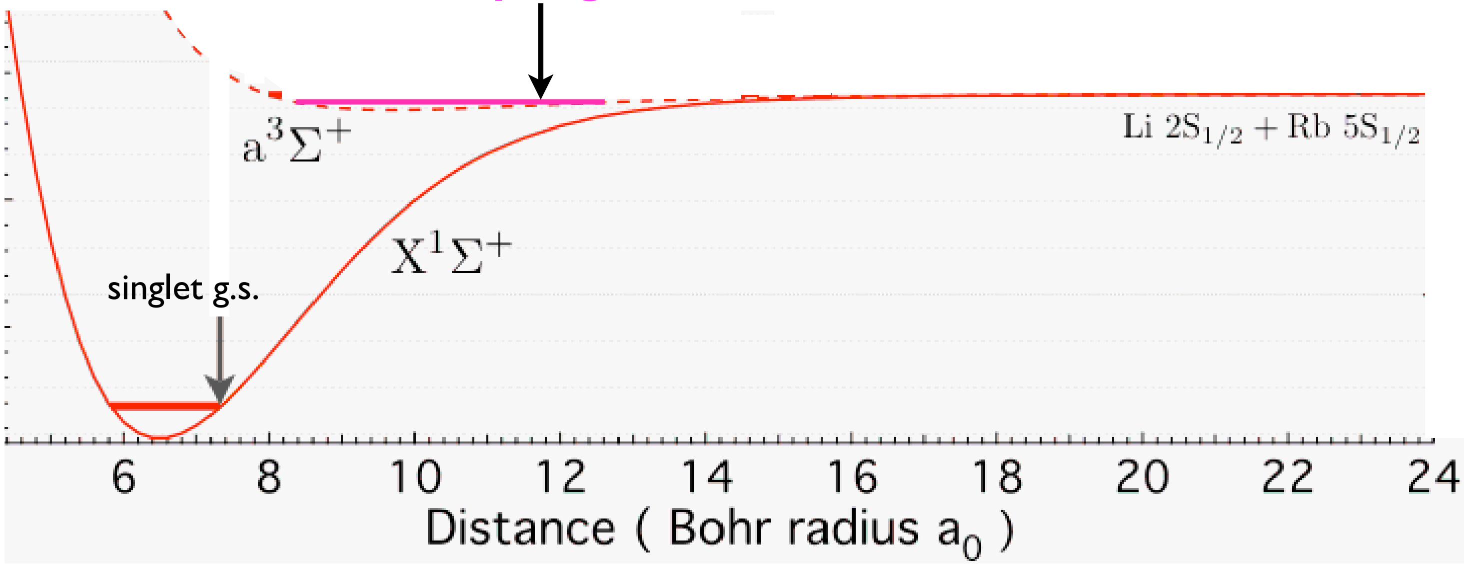

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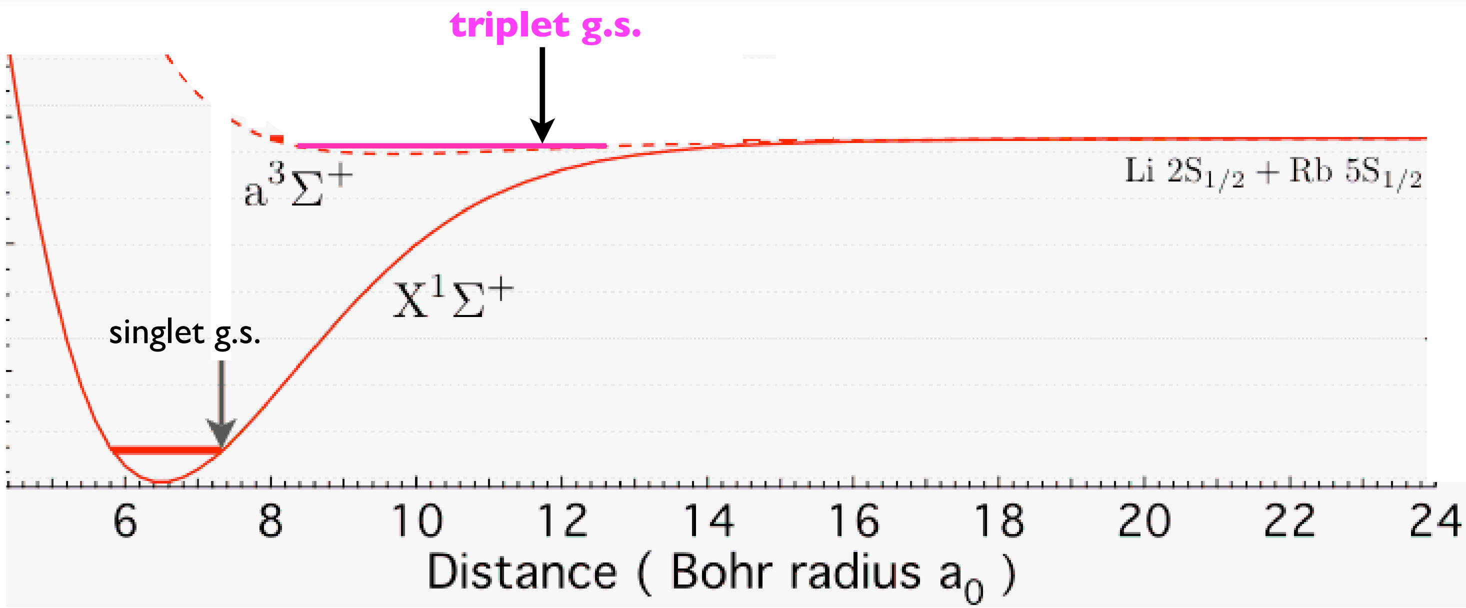

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- **spin relaxation collisions (triplet to singlet coupling) ?**
- **chemical reactivity ?**
- **spontaneous emission ?**

Is the lowest triplet state stable?

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- **chemical reactivity ?**

by some magic*, is the triplet state stable?

** or suitably physical reasons*

- **spontaneous emission ?**

Is the lowest triplet state stable?

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  "Spin-orbit couplings are small in light systems. For Li_2, one wouldn't expect fast relaxation. ... but will be more important in heavy systems (like LiRb), but how important?"

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Cold Controlled Chemistry, PCCP **10**, 4079 (2008). [Krems]

Physical Chemistry Chemical Physics

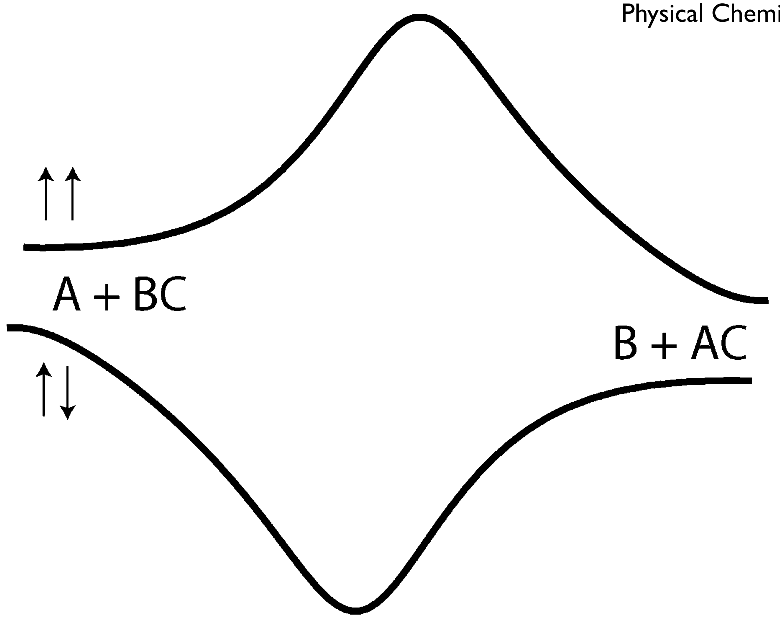

Fig. 4 Schematic illustration of minimum energy profiles for an $A(^2S)$ + $BC(^2\Sigma)$ chemical reaction in the singlet-spin (lower curve) and triplet-spin (upper curve) electronic states. Electric fields may induce non-adiabatic transitions between the different spin states and modify the reaction mechanism.

- **spontaneous emission ?**

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- **chemical reactivity ?**

  "The interactions between 2S atoms and 2S molecules in the triplet spin state are typically characterized by strongly repulsive exchange forces, leading to significant reaction barriers."

  Cold Controlled Chemistry, PCCP **10**, 4079 (2008). [Krems]

  Physical Chemistry Chemical Physics

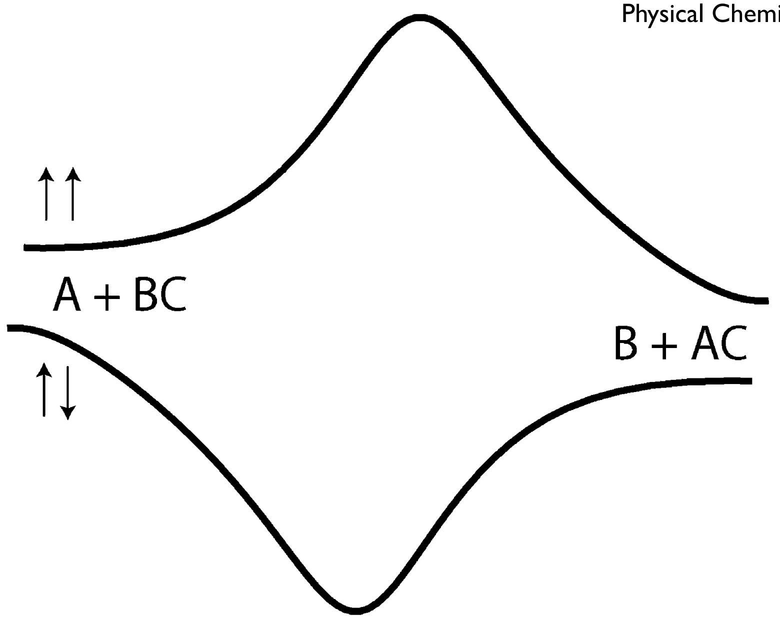


Fig. 4 Schematic illustration of minimum energy profiles for an $A(^2S)$ + $BC(^2\Sigma)$ chemical reaction in the singlet-spin (lower curve) and triplet-spin (upper curve) electronic states. Electric fields may induce non-adiabatic transitions between the different spin states and modify the reaction mechanism.

- **spontaneous emission ?**

Is the lowest triplet state stable?

- **spin relaxation collisions (triplet to singlet coupling) ?**

  "Spin-orbit couplings are small in light systems. For Li_2, one wouldn't expect fast relaxation. ... but will be more important in heavy systems (like LiRb), but how important?"

- **chemical reactivity ?**

  "The interactions between 2S atoms and 2S molecules in the triplet spin state are typically characterized by strongly repulsive exchange forces, leading to significant reaction barriers."

  Cold Controlled Chemistry, PCCP **10**, 4079 (2008). [Krems]

  Physical Chemistry Chemical Physics

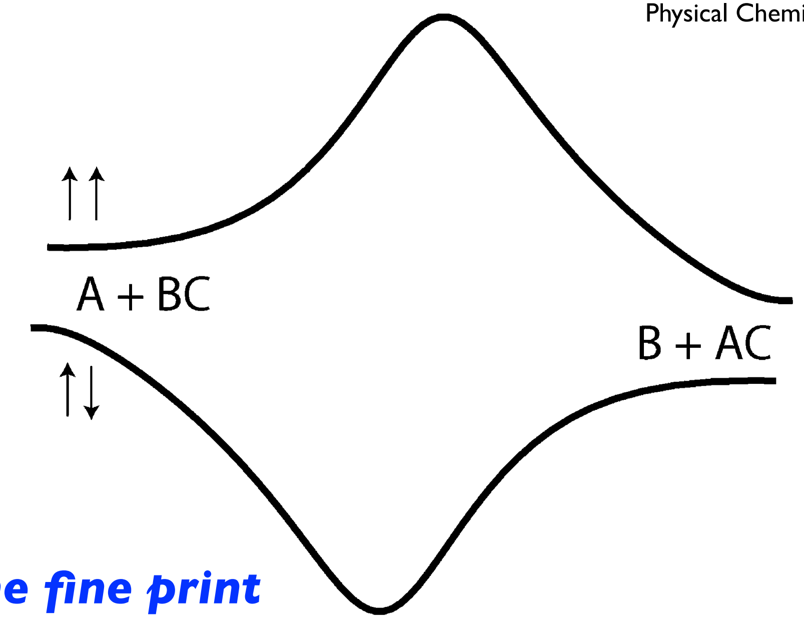


Fig. 4 Schematic illustration of minimum energy profiles for an $A(^2S)$ + $BC(^2\Sigma)$ chemical reaction in the singlet-spin (lower curve) and triplet-spin (upper curve) electronic states. Electric fields may induce non-adiabatic transitions between the different spin states and modify the reaction mechanism.

the fine print

"... non-adiabatic coupling ... may be induced by the spin-rotation interaction and the magnetic dipole–dipole interaction. The latter is negligibly small and ... transitions are determined by the spin-rotation interaction in the open-shell molecule. The spin-rotation interaction can be effectively manipulated with an external electric field."

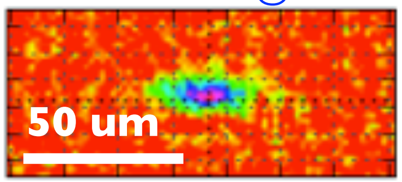
- **spontaneous emission ?**

Experimental goals and results

Li_2

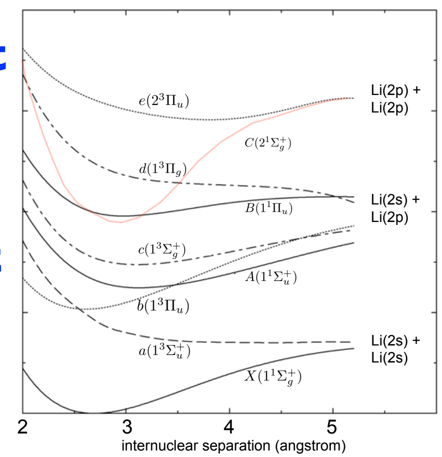
√ **Feshbach resonances and FR molecule production**

BEC of Li dimers @ 300 nK



√ **excited triplet spectroscopy (1-color PA)**

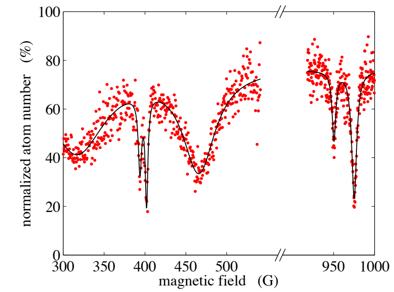
√ **ground triplet spectroscopy (2-color PA)**



STIRAP production of triplet Li_2 from FR molecules

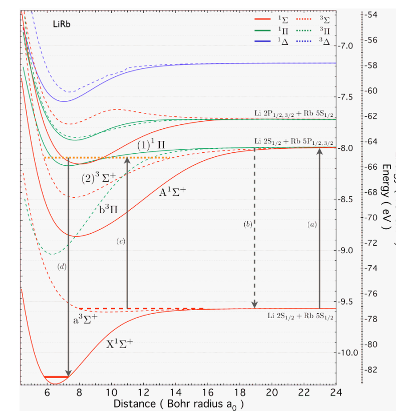
LiRb

√ **Feshbach resonances and FR molecule production**



excited triplet spectroscopy (1-color PA)

ground triplet spectroscopy (2-color PA)



STIRAP production of triplet LiRb from FR molecules

Experimental goals and results

table from Eberhard Tiemann's Jan. 25th talk, "Molecular Properties and Potentials"

Leibniz Universität
Hannover

Overview of results

FR: Feshbach resonances observed a: potential for $a^3\Sigma^+$ determined

	Li	**Na**	**K**	**Rb**	**Cs**
Li	FR				
Na	FR	FR (a)			
K	FR a	FR a	FR a		
Rb	FR (a)	FR a	FR a	FR a	
Cs	FR (a)	a	a	FR a	FR (a)

Experimental goals and results

table from Eberhard Tiemann's Jan. 25th talk, "Molecular Properties and Potentials"

Leibniz Universität Hannover

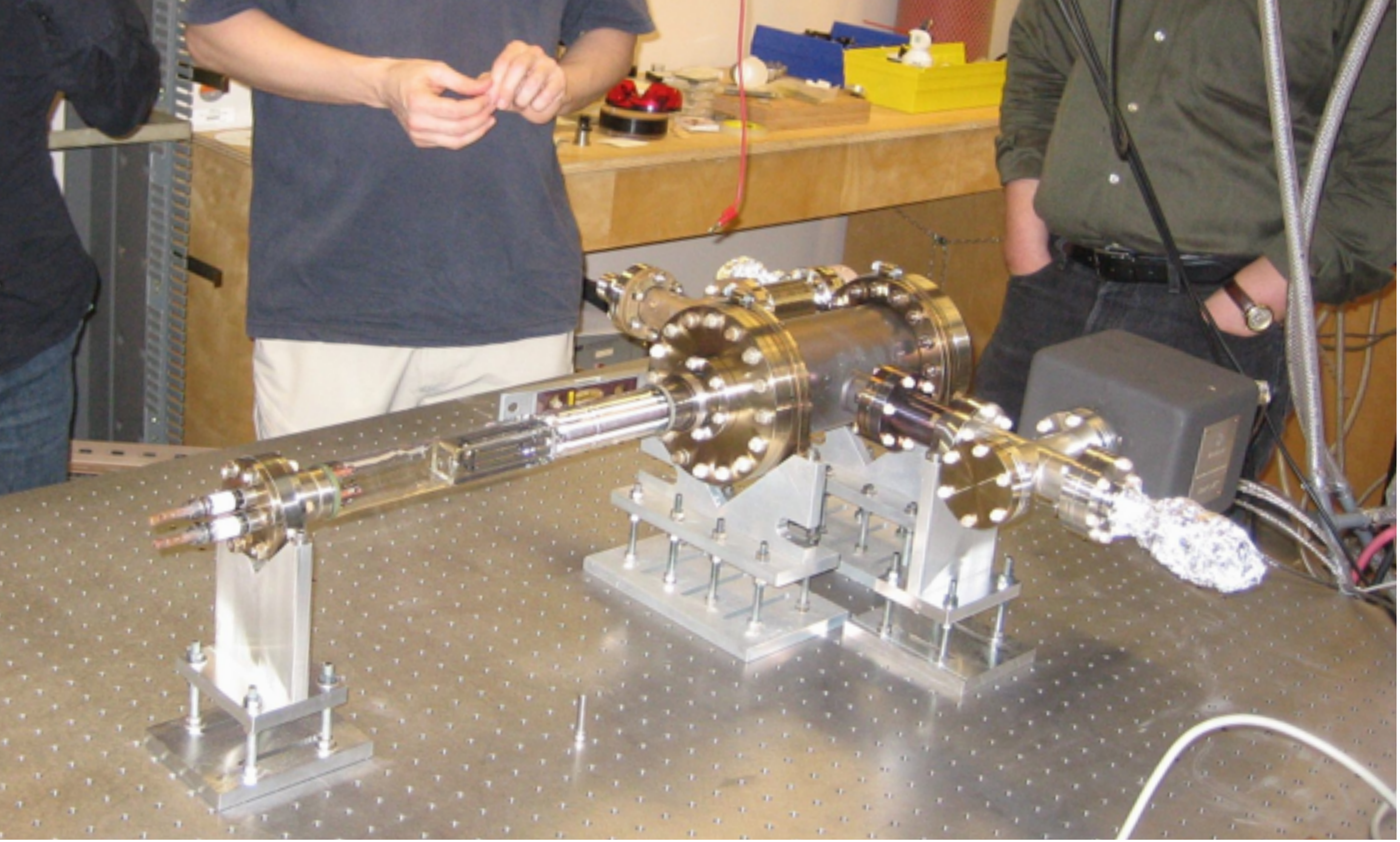
Overview of results

FR: Feshbach resonances observed   a: potential for $a^3\Sigma^+$ determined

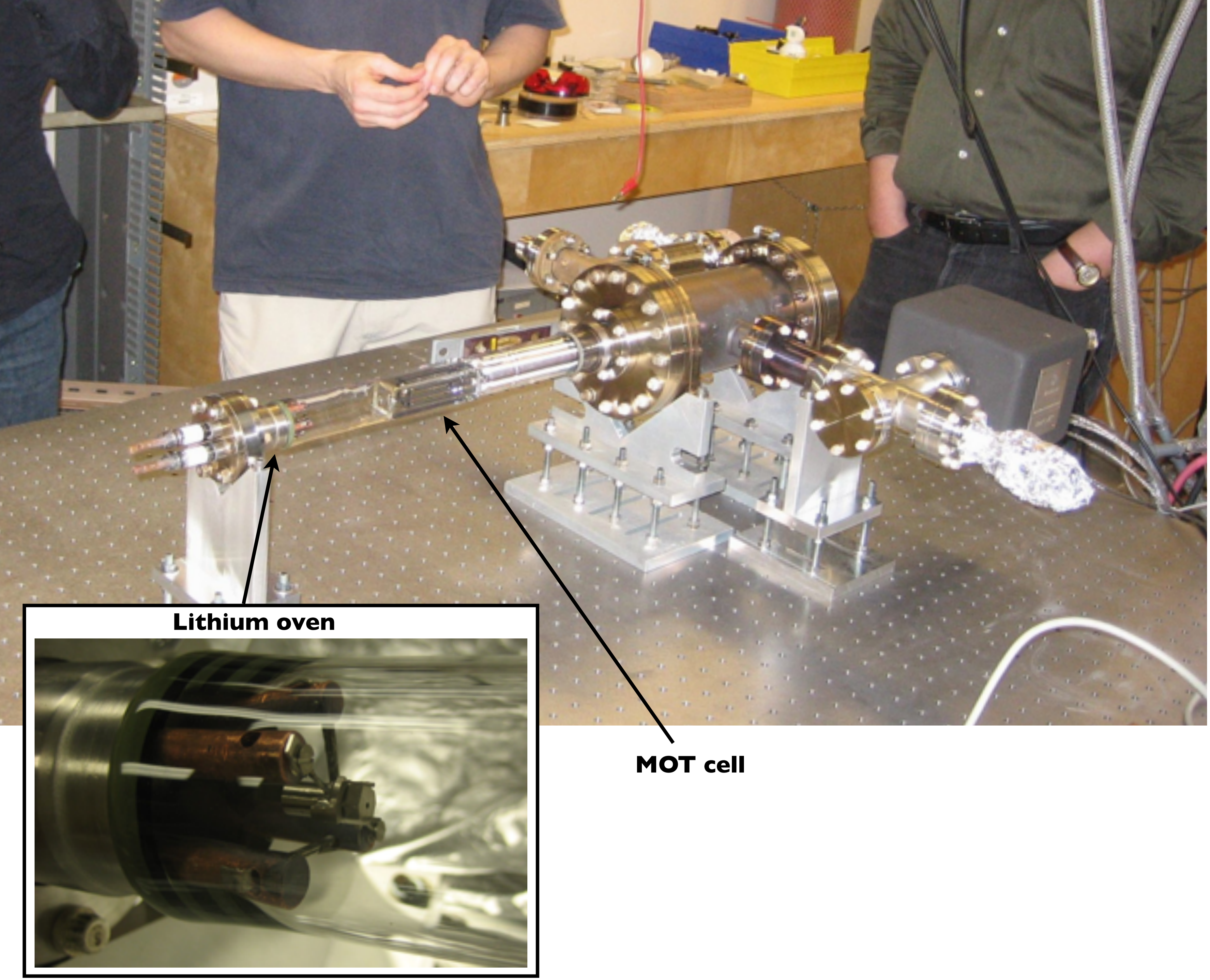
	Li	**Na**	**K**	**Rb**	**Cs**
Li	FR a				
Na	FR	FR (a)			
K	FR a	FR a	FR a		
Rb	FR (a) FR a	FR a	FR a	FR a	
Cs	FR (a)	a	a	FR a	FR (a)

our contributions in blue

pending contributions in red



ultra-cold Li+Rb mixtures



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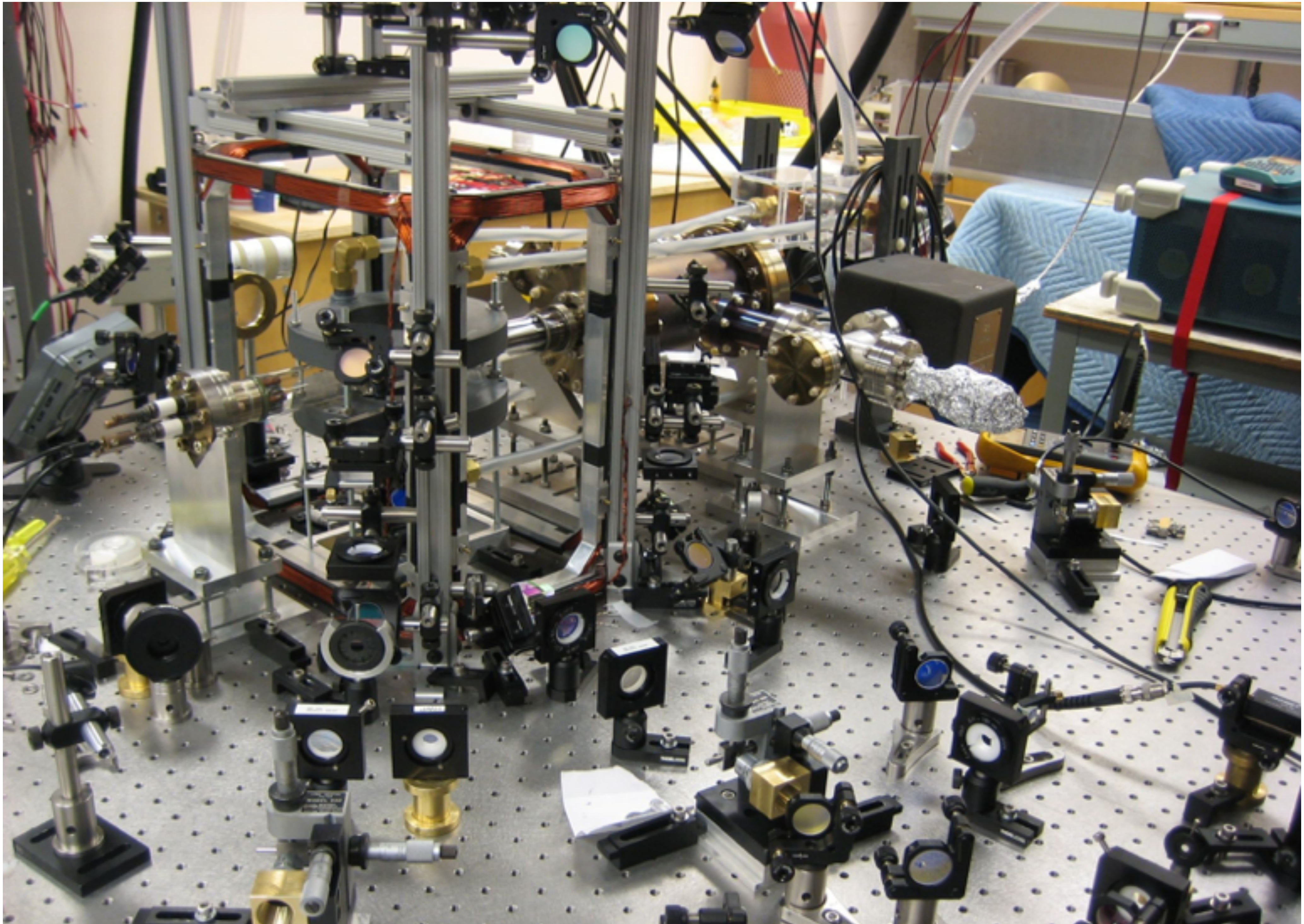

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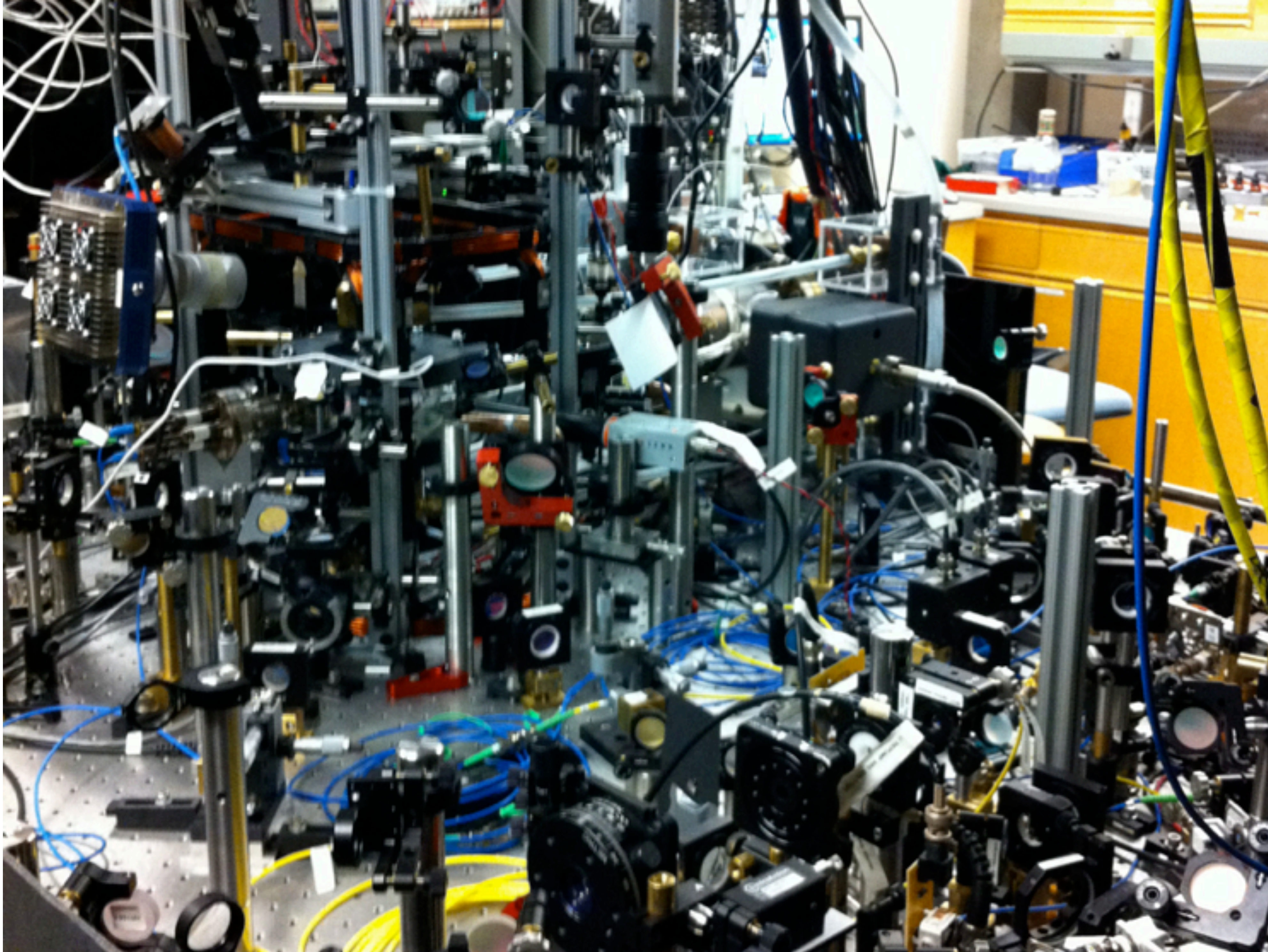

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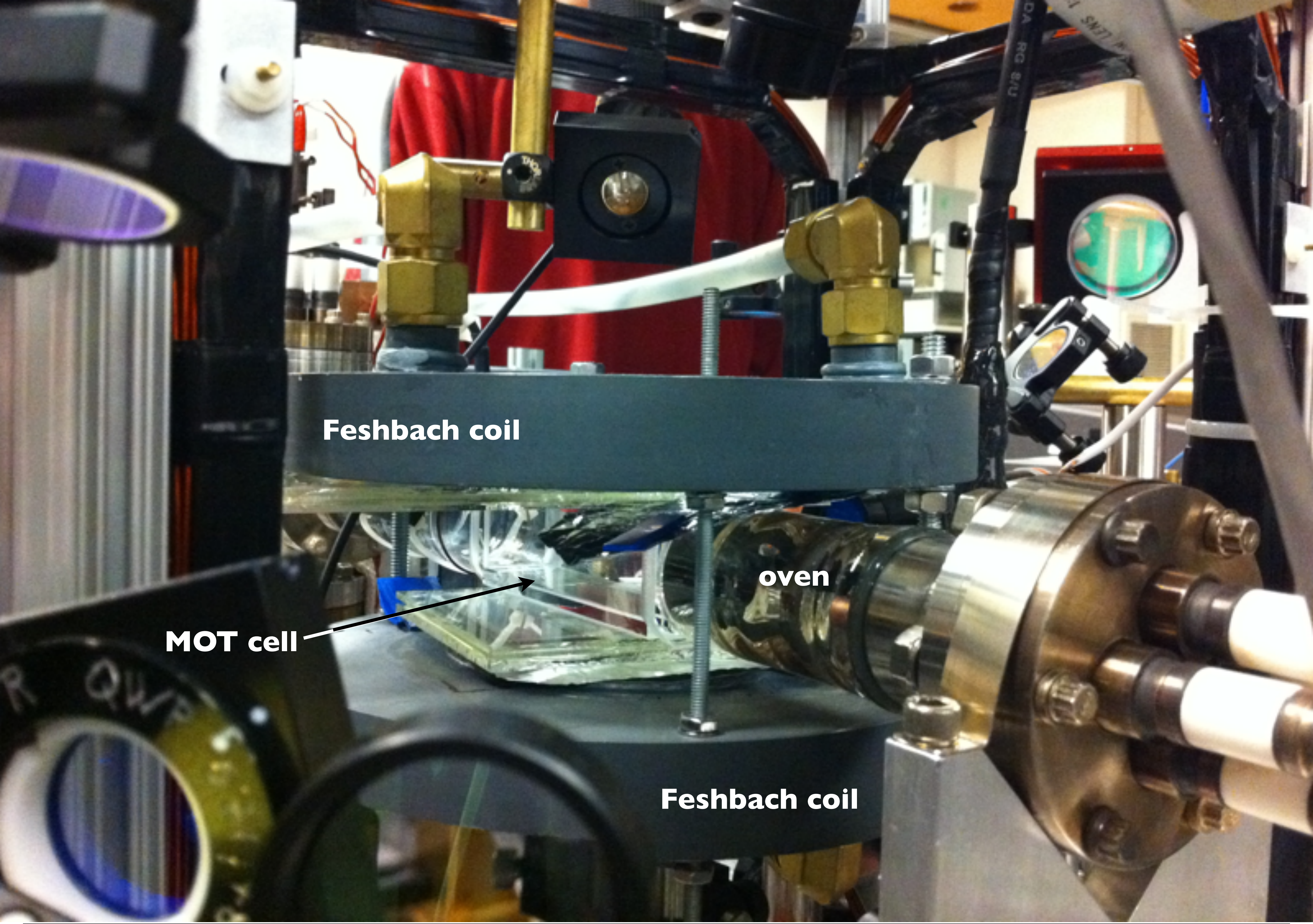

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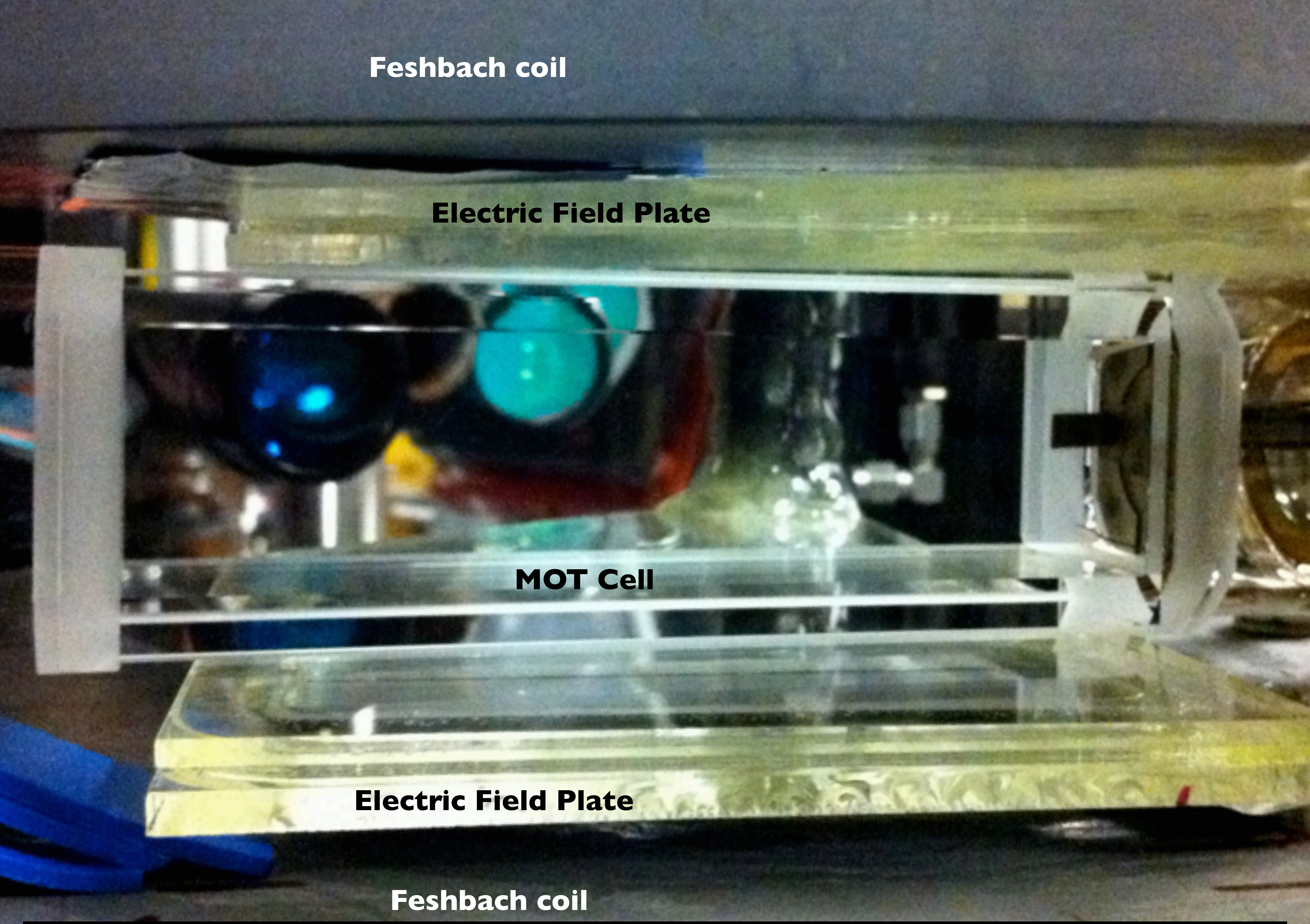
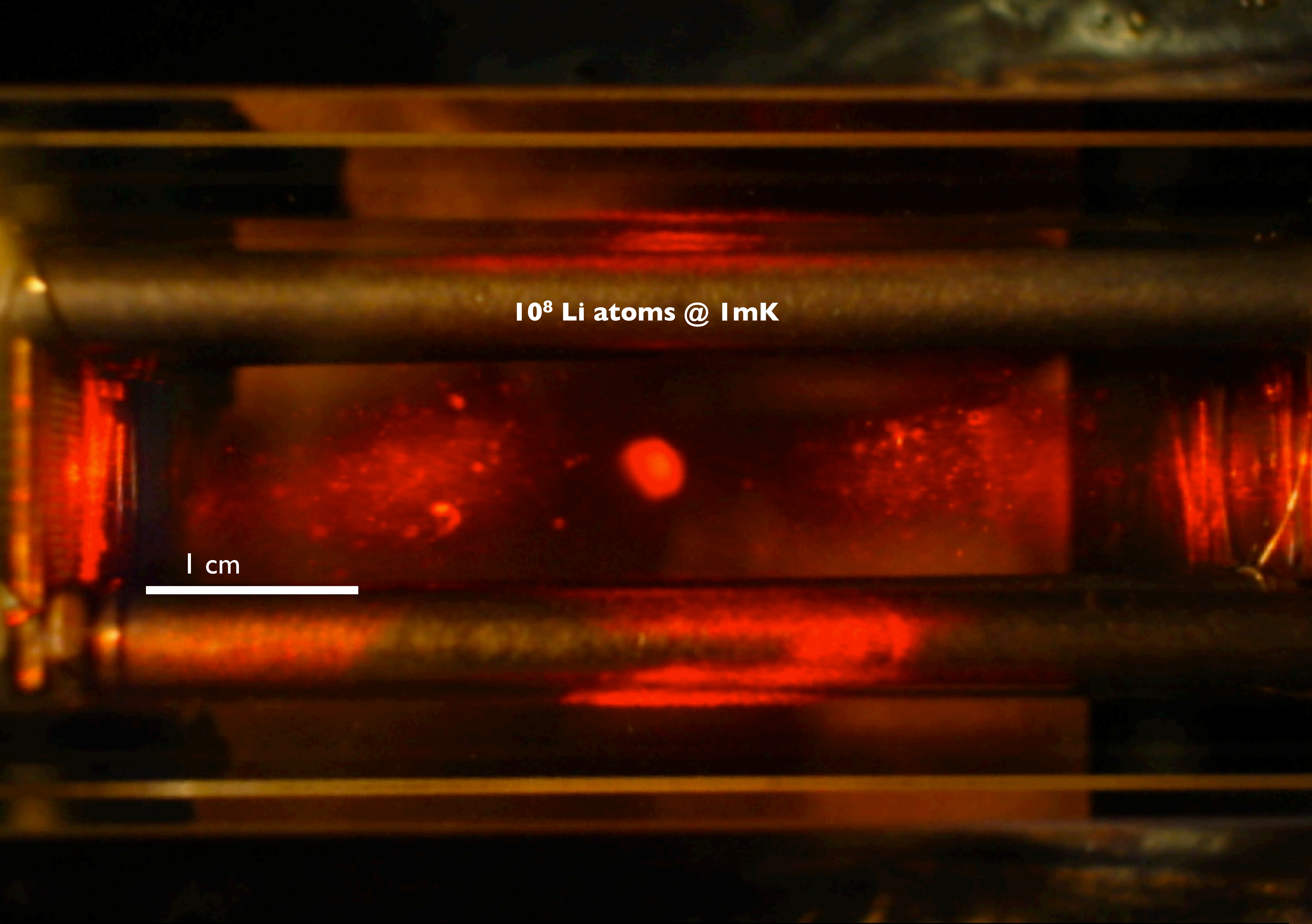
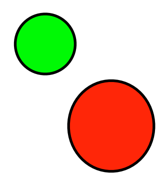


ultra-cold Li+Rb mixtures

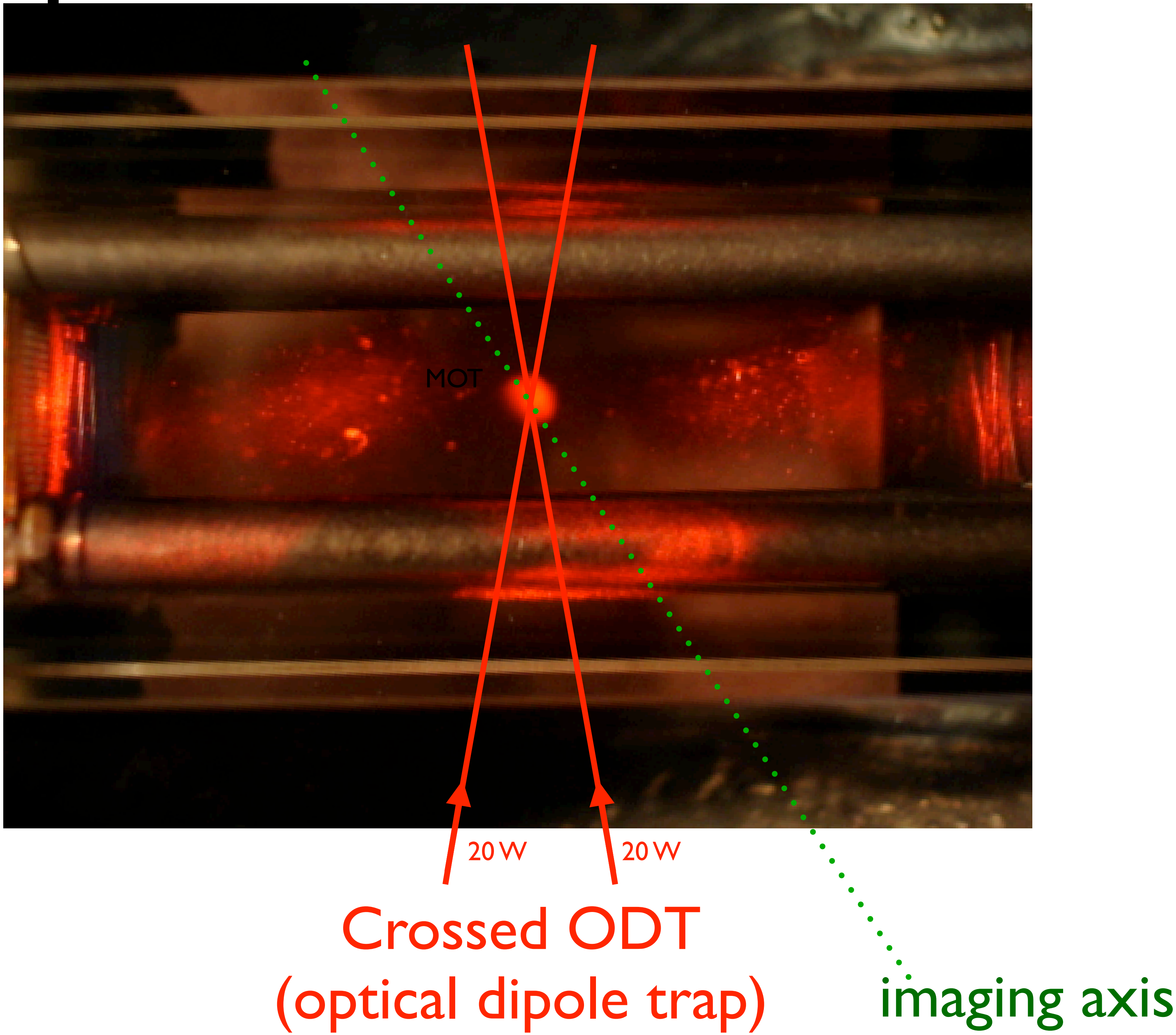


ultra-cold Li+Rb mixtures

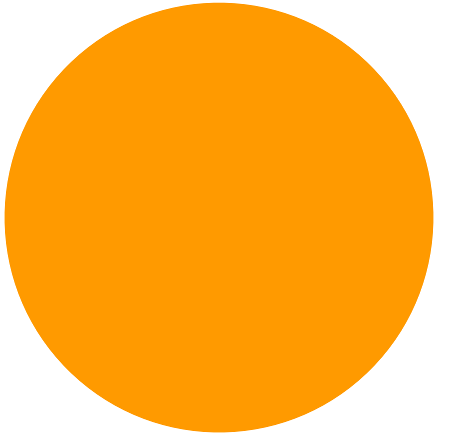
observing Rb+Li Feshbach resonances



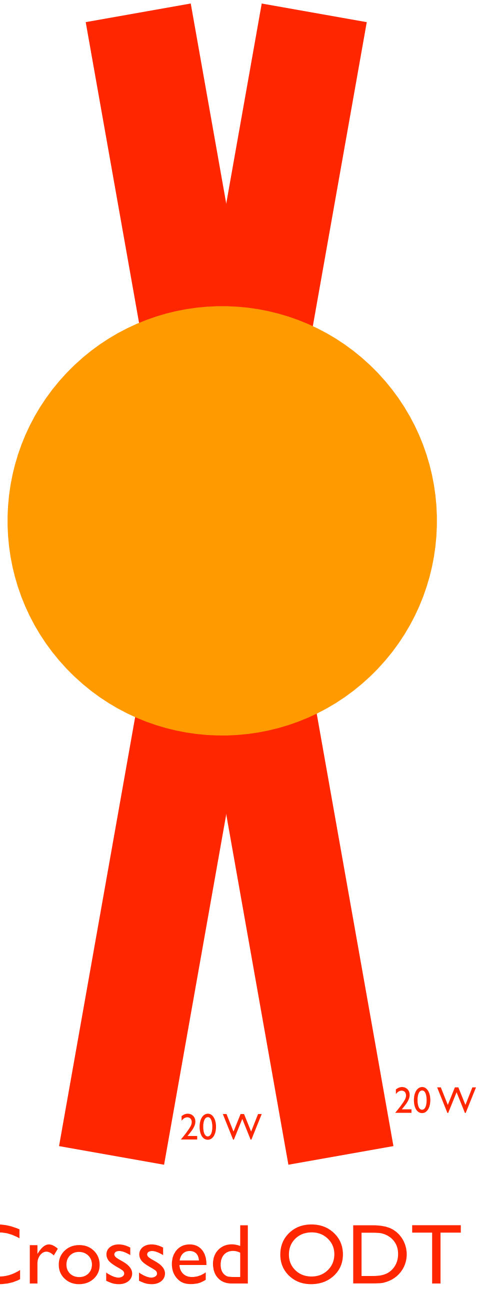
Trap Schematic



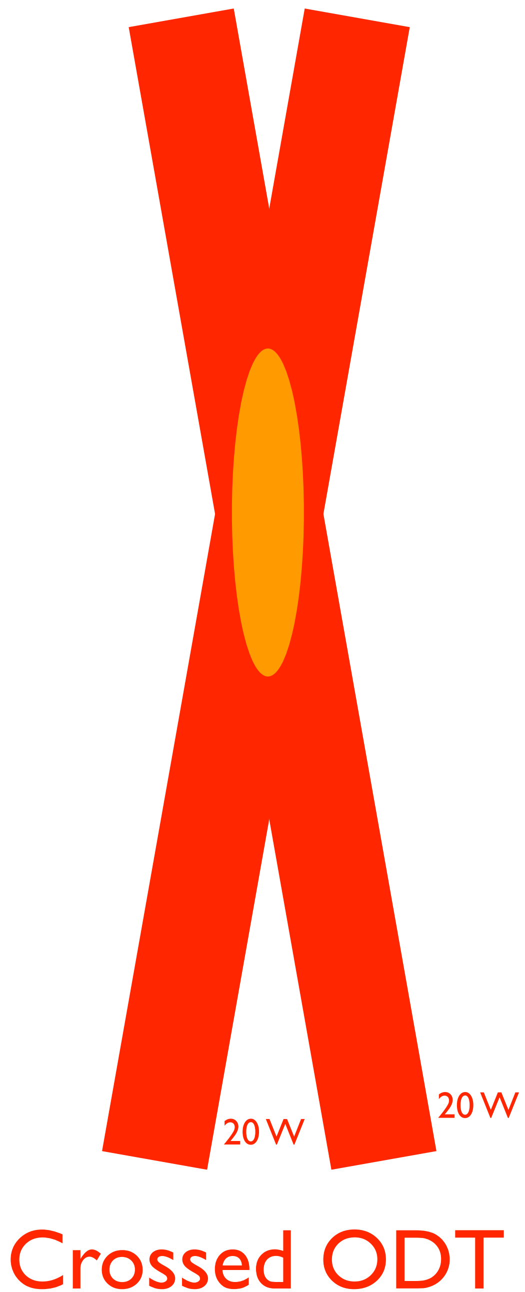
Load Lithium MOT



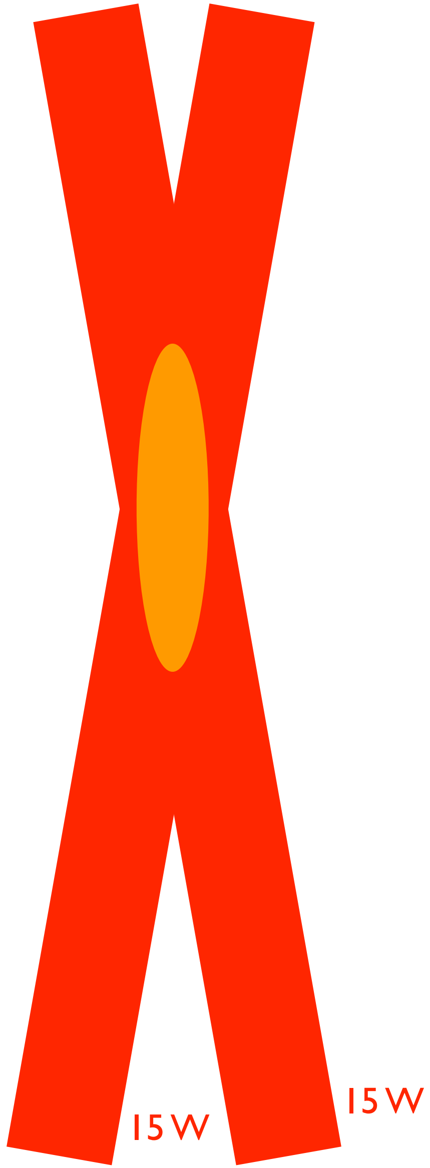
Transfer Li from MOT to crossed trap



Transfer Li from MOT to crossed trap

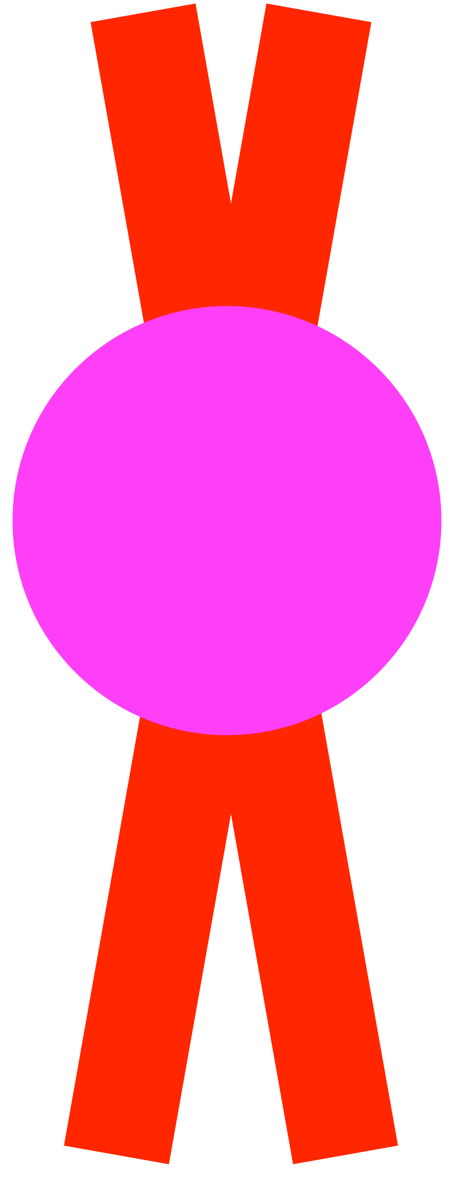


Evaporate Li from crossed trap

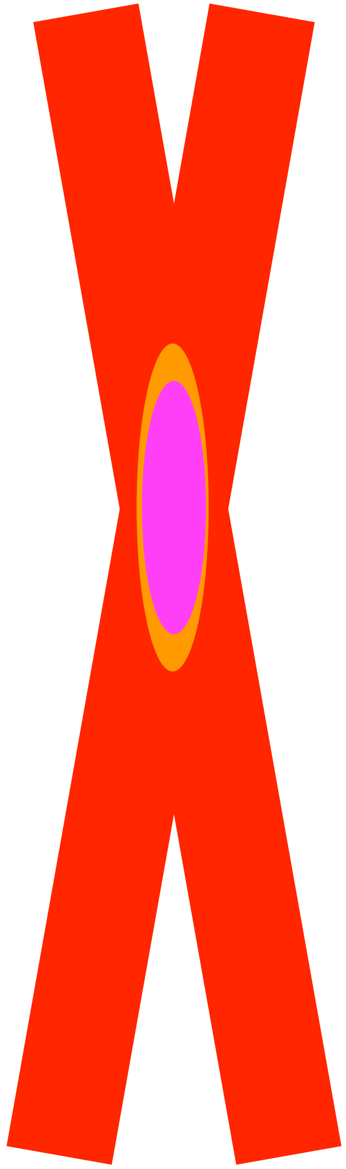


Crossed ODT

Load Rb MOT while holding Li



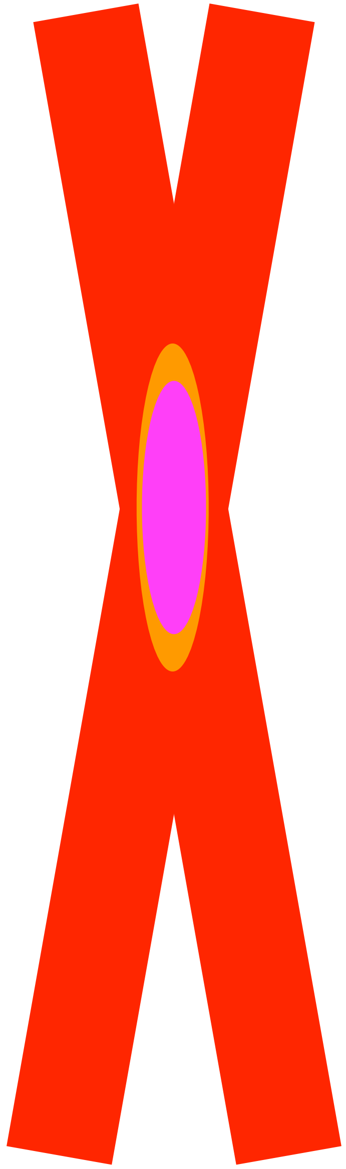
Transfer Rb to crossed trap



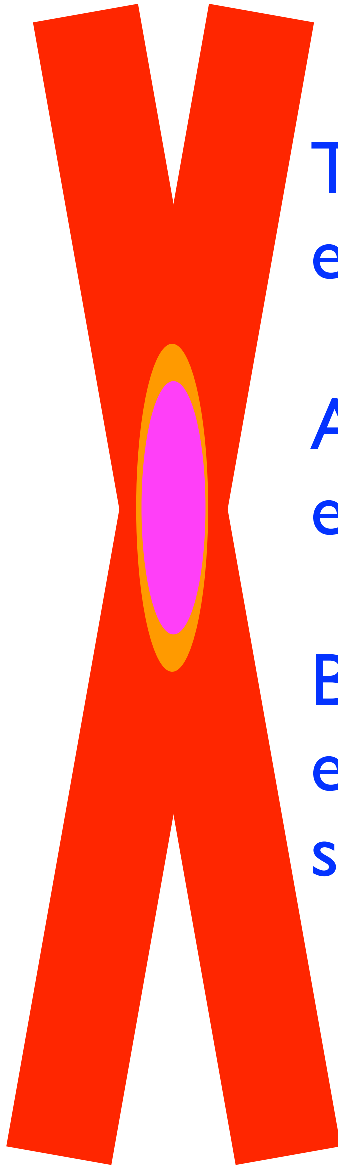
Rb MOT turned off:

In trap: Rubidium and Lithium

Both Rb and Li in trap: *trap depths different*



Simultaneous evaporation of Li and Rb



Trap power lowered to force evaporation losses

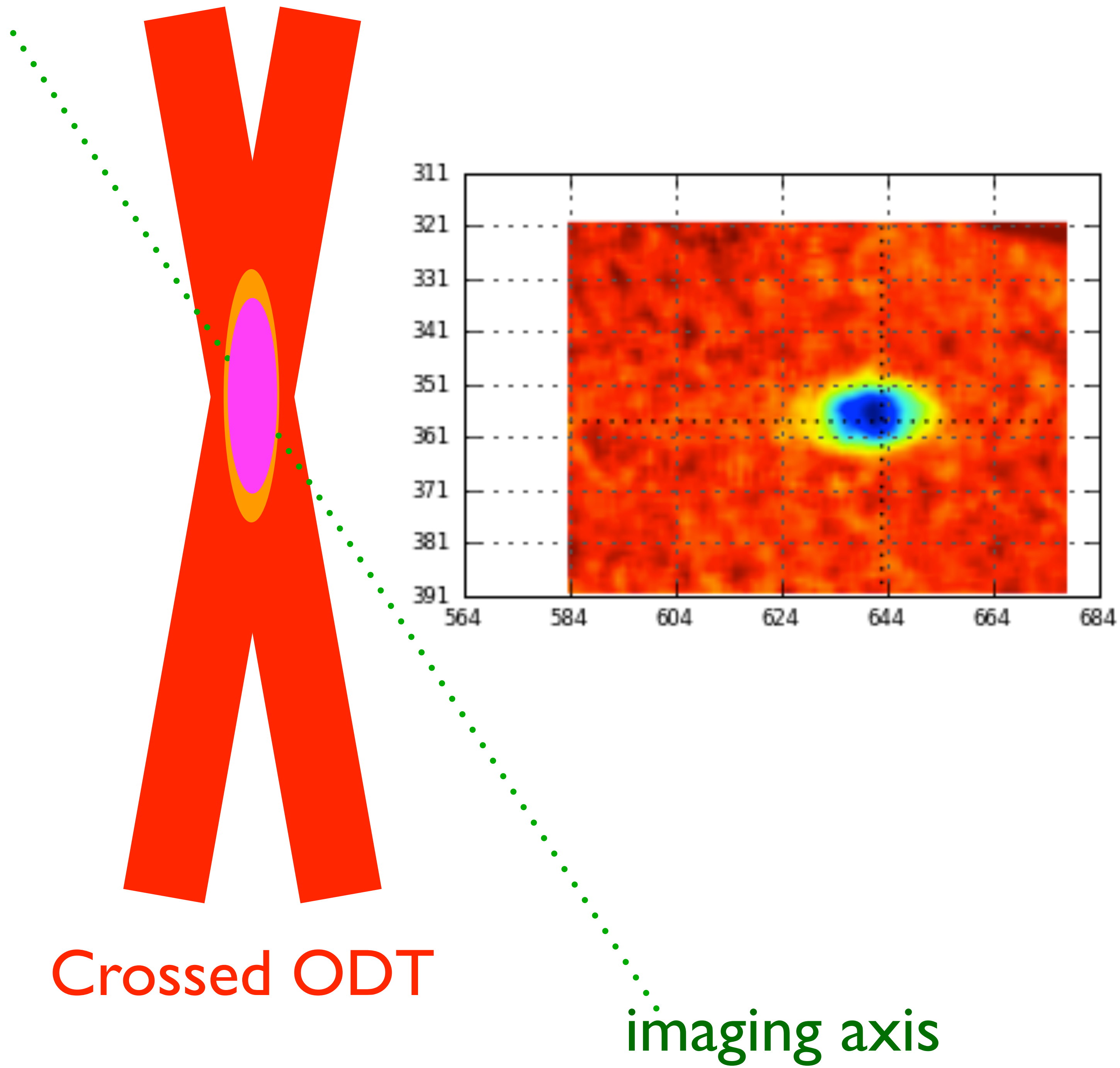
A) If Li+Rb reach thermal equilibrium, Li leaves trap quickly

B) If Li+Rb decoupled, Li evaporatively cools and leaves trap slowly

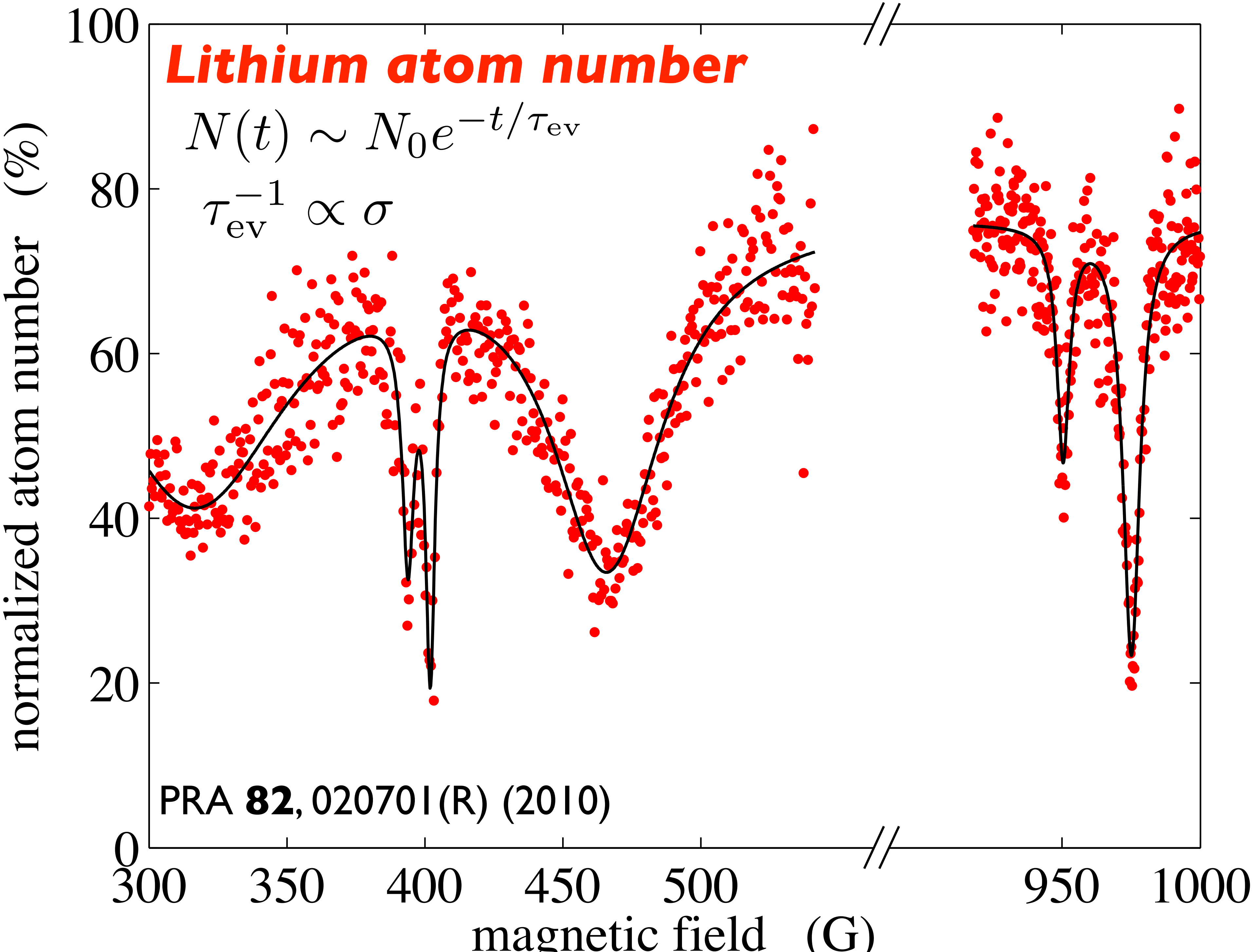
Trap for Li half as deep for Rb

Crossed ODT

Image Li or Rb



Feshbach resonances in $^{6}Li+^{85}Rb$ mixtures



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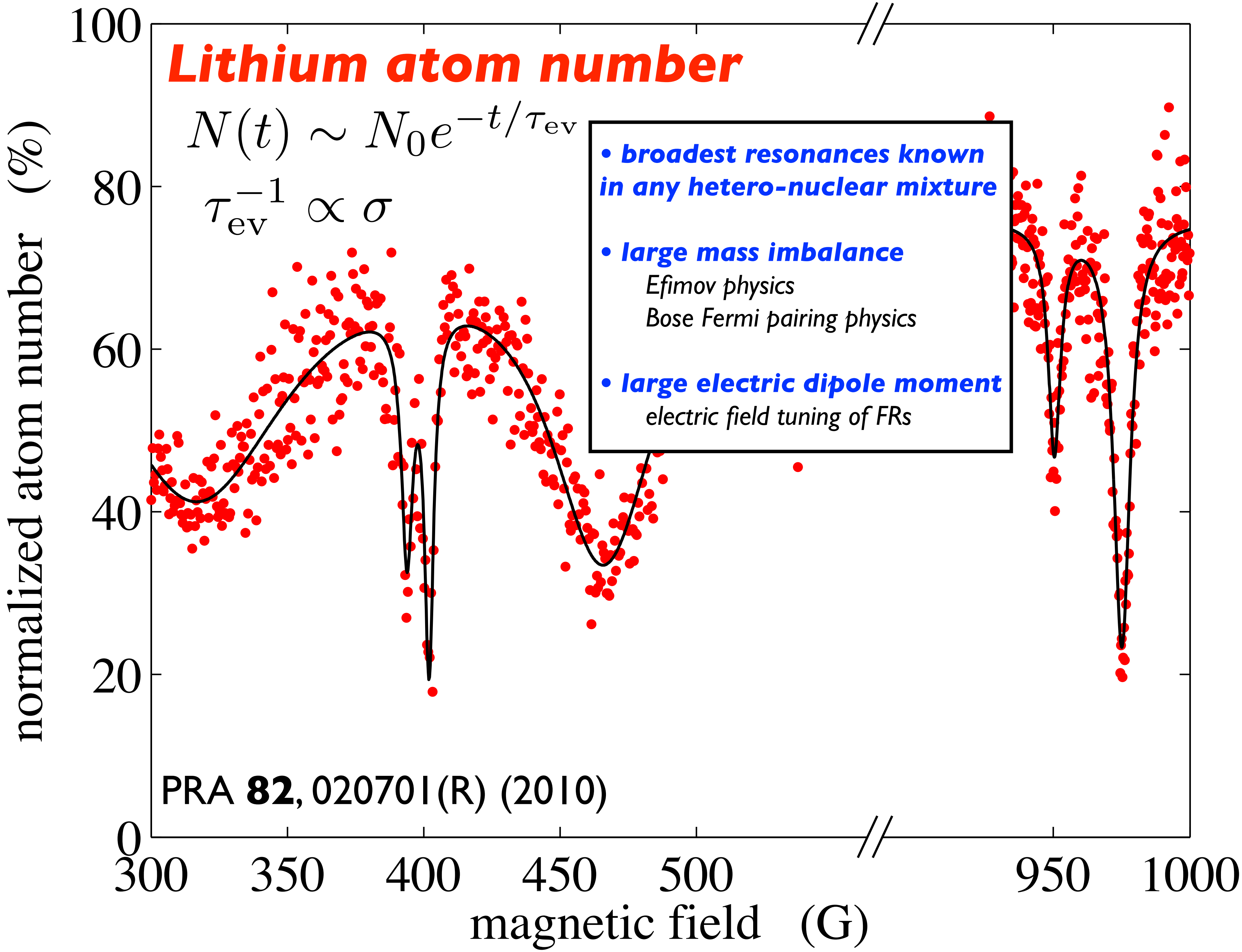
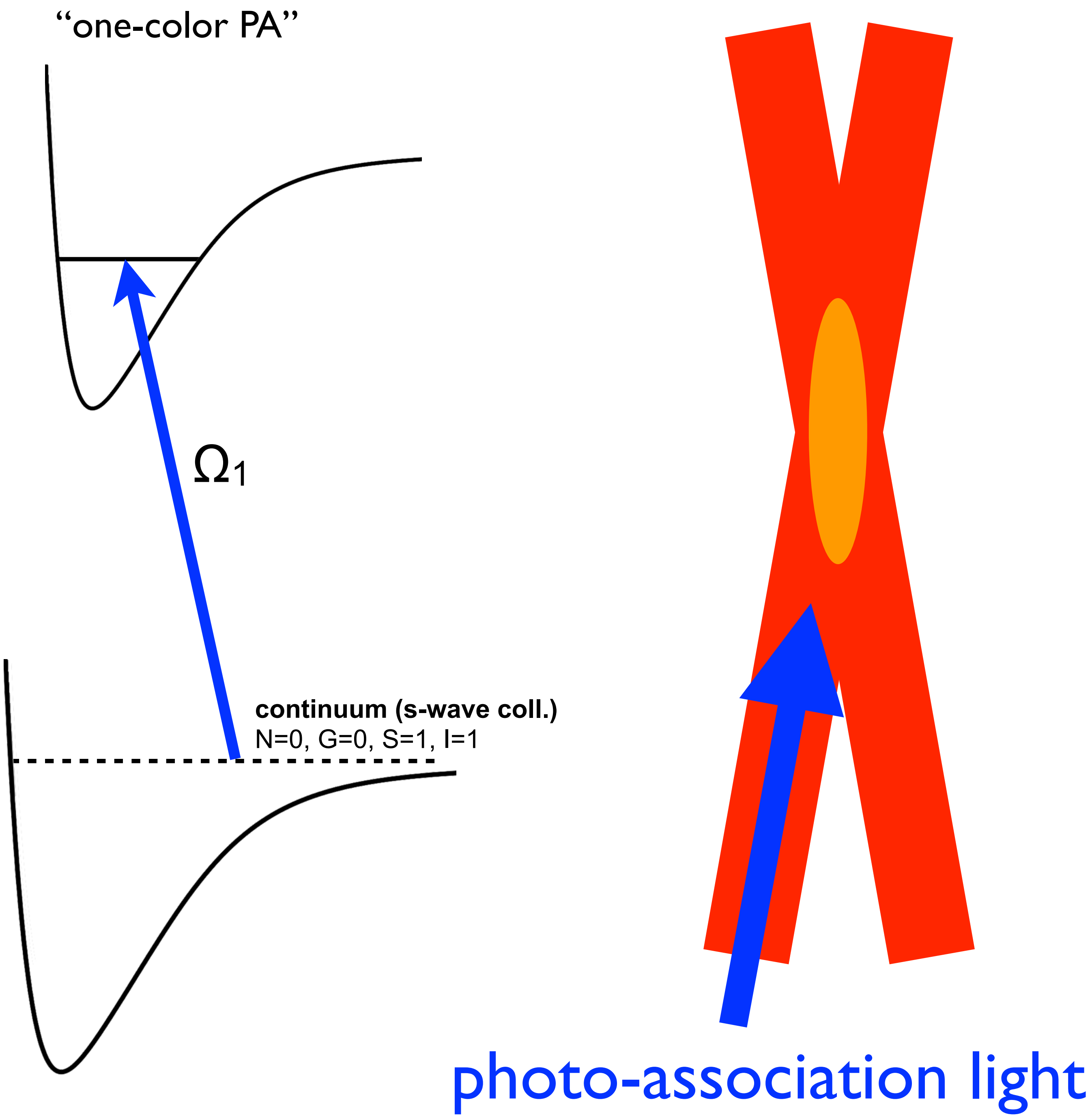


For photo-association, just add additional light



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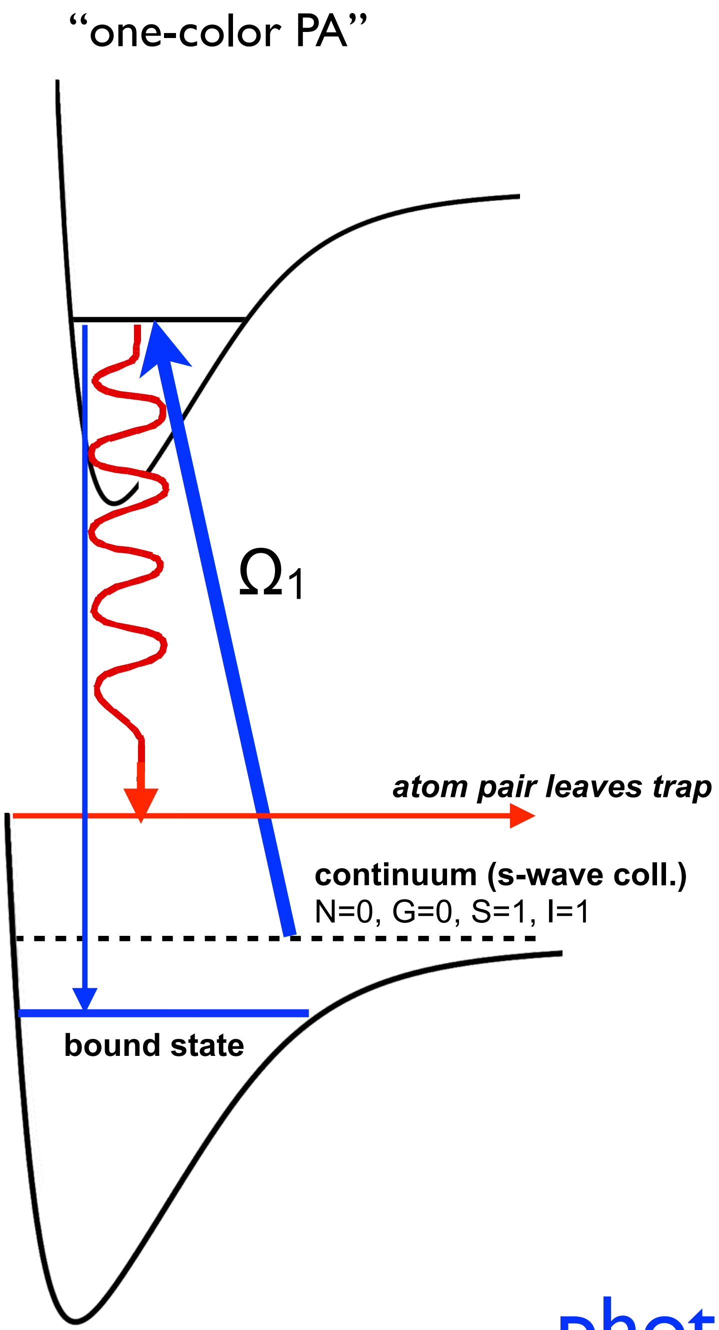


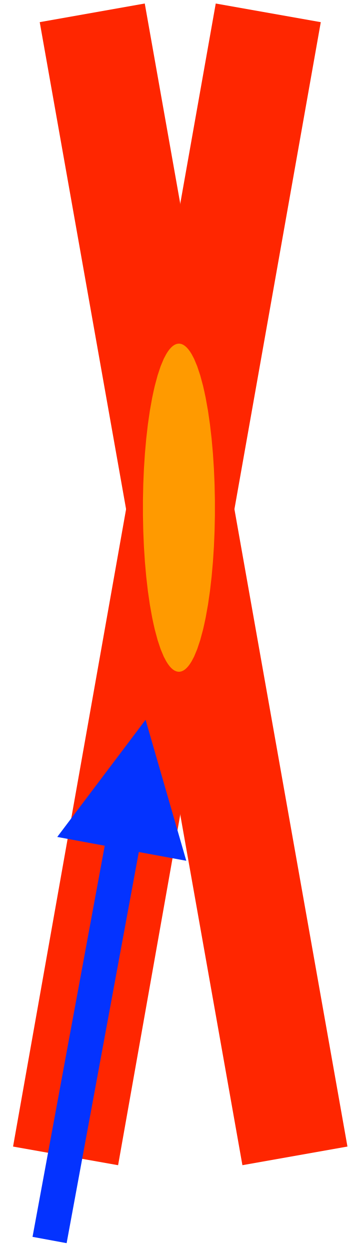
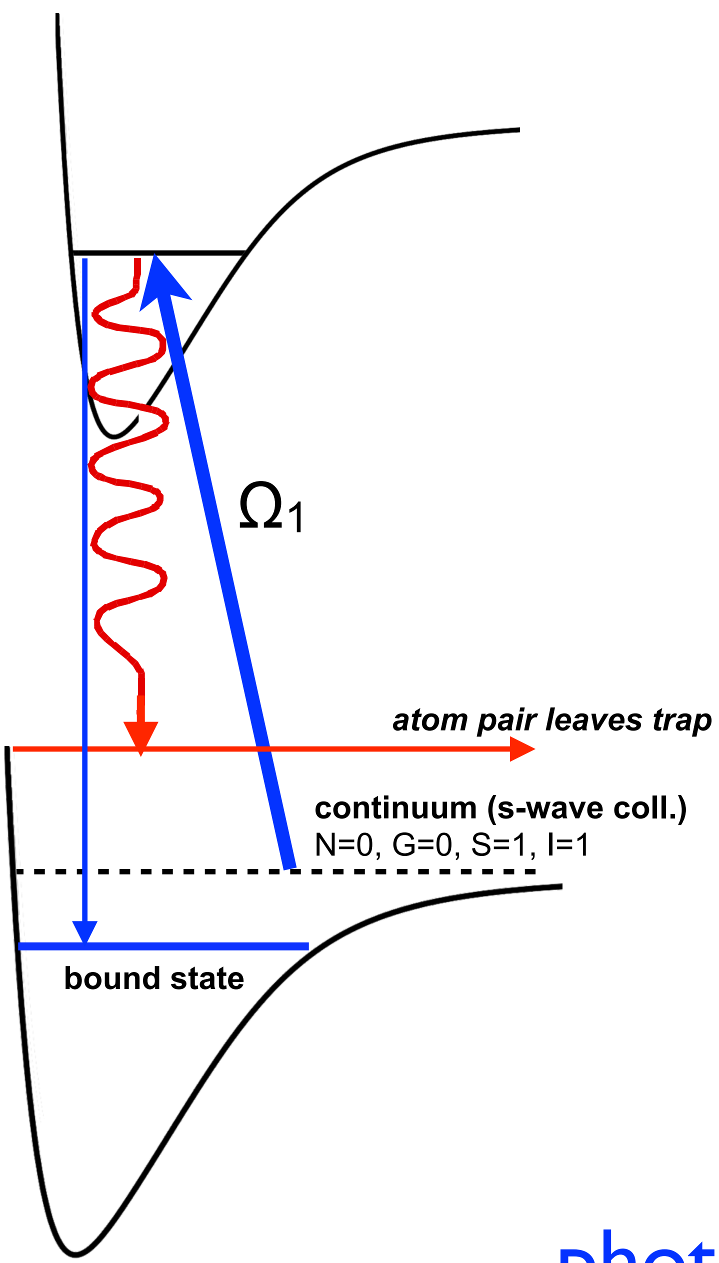


photo-association light

For photo-association, just add additional light



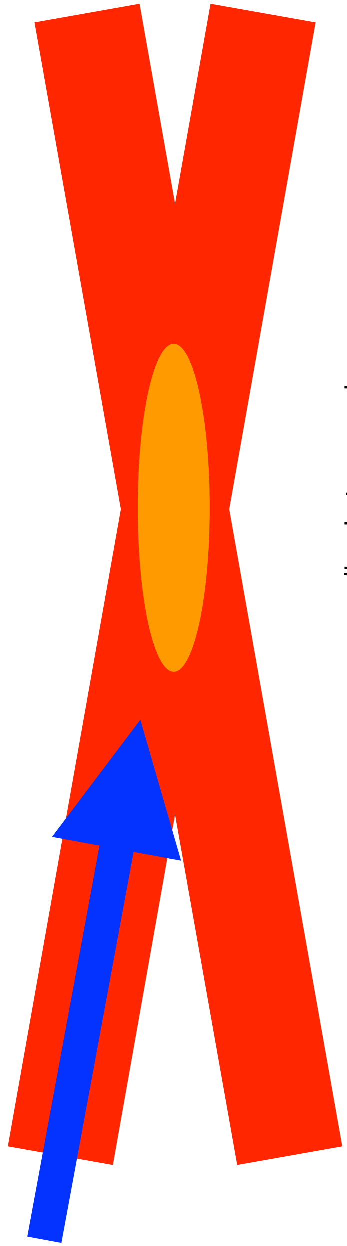
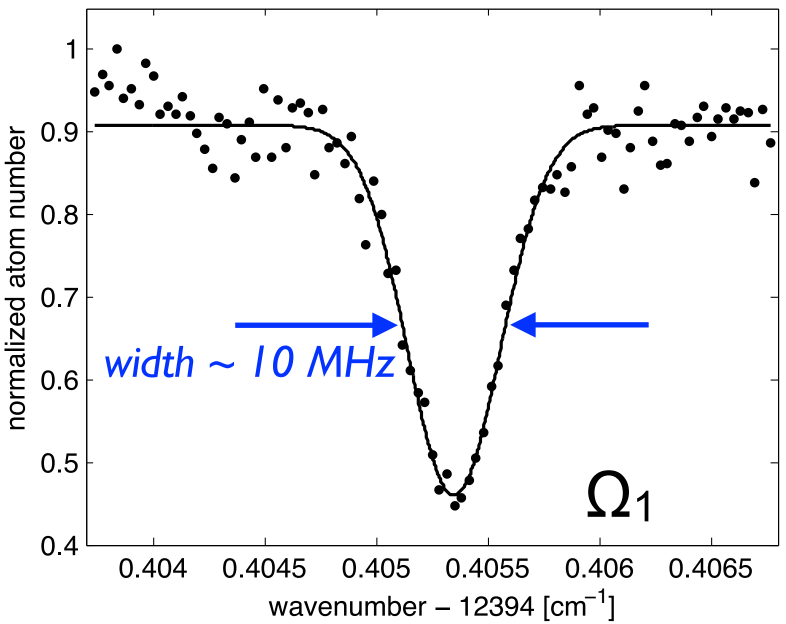


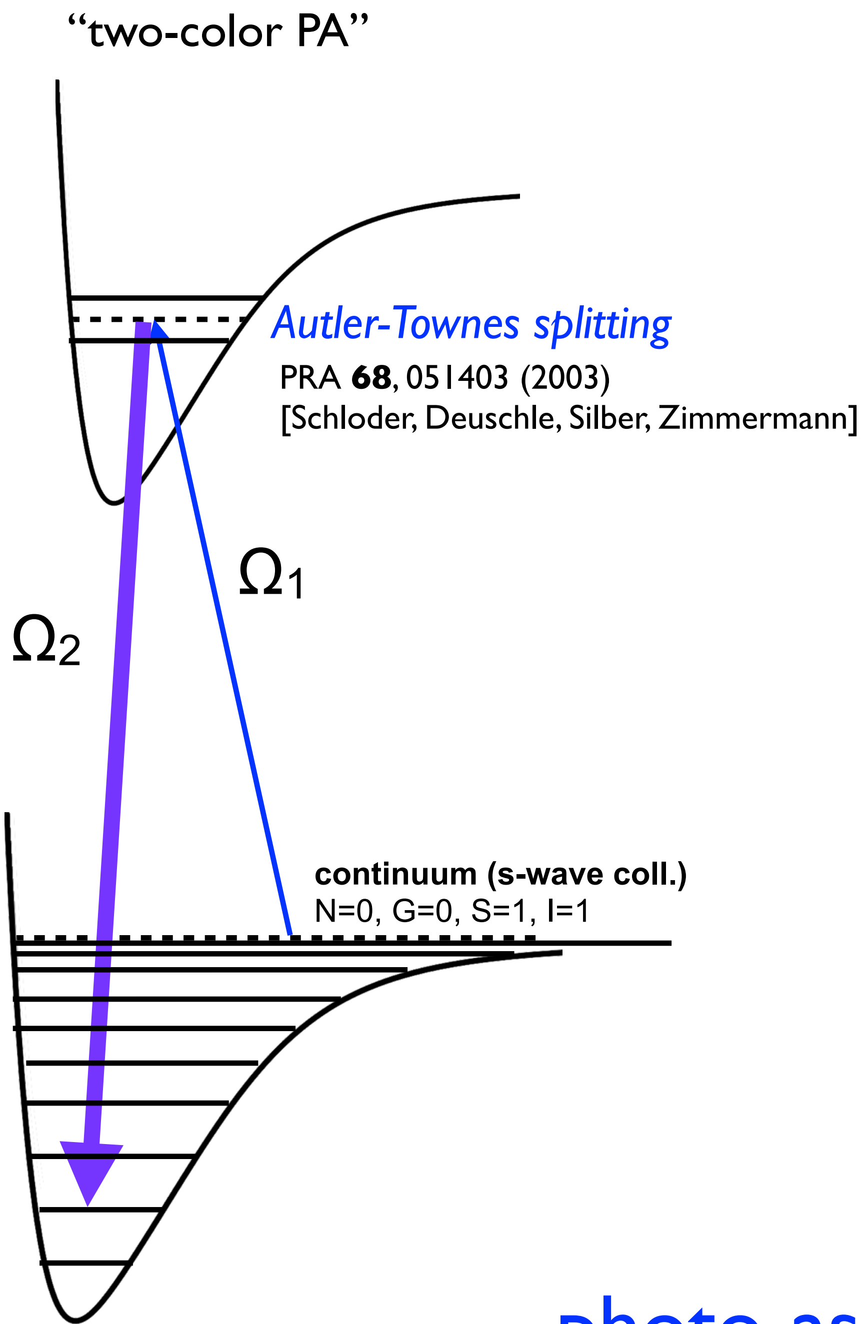
photo-association light

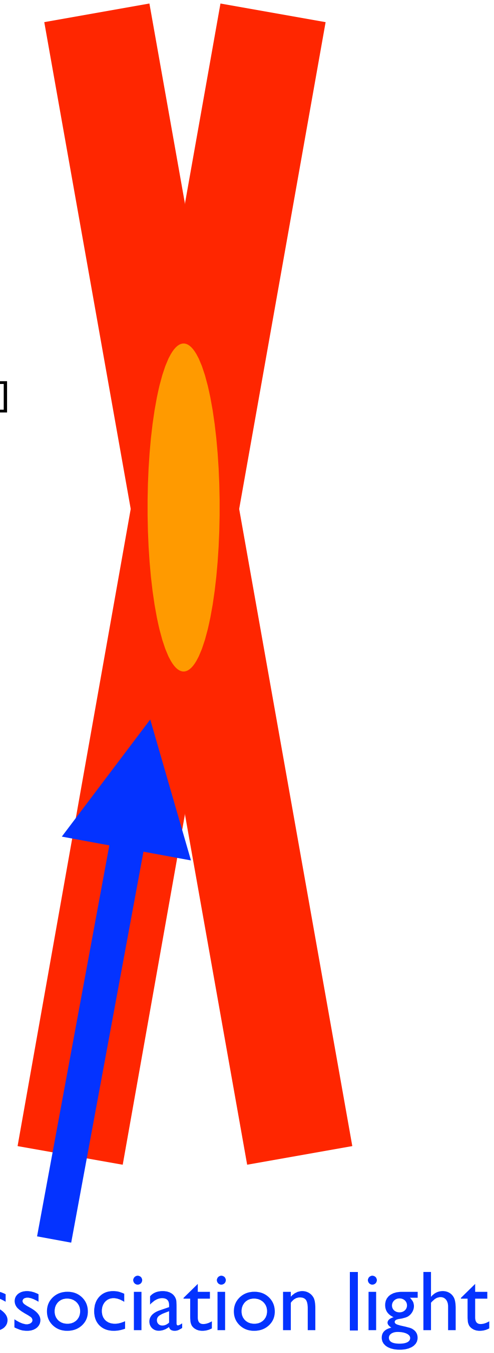
atom loss



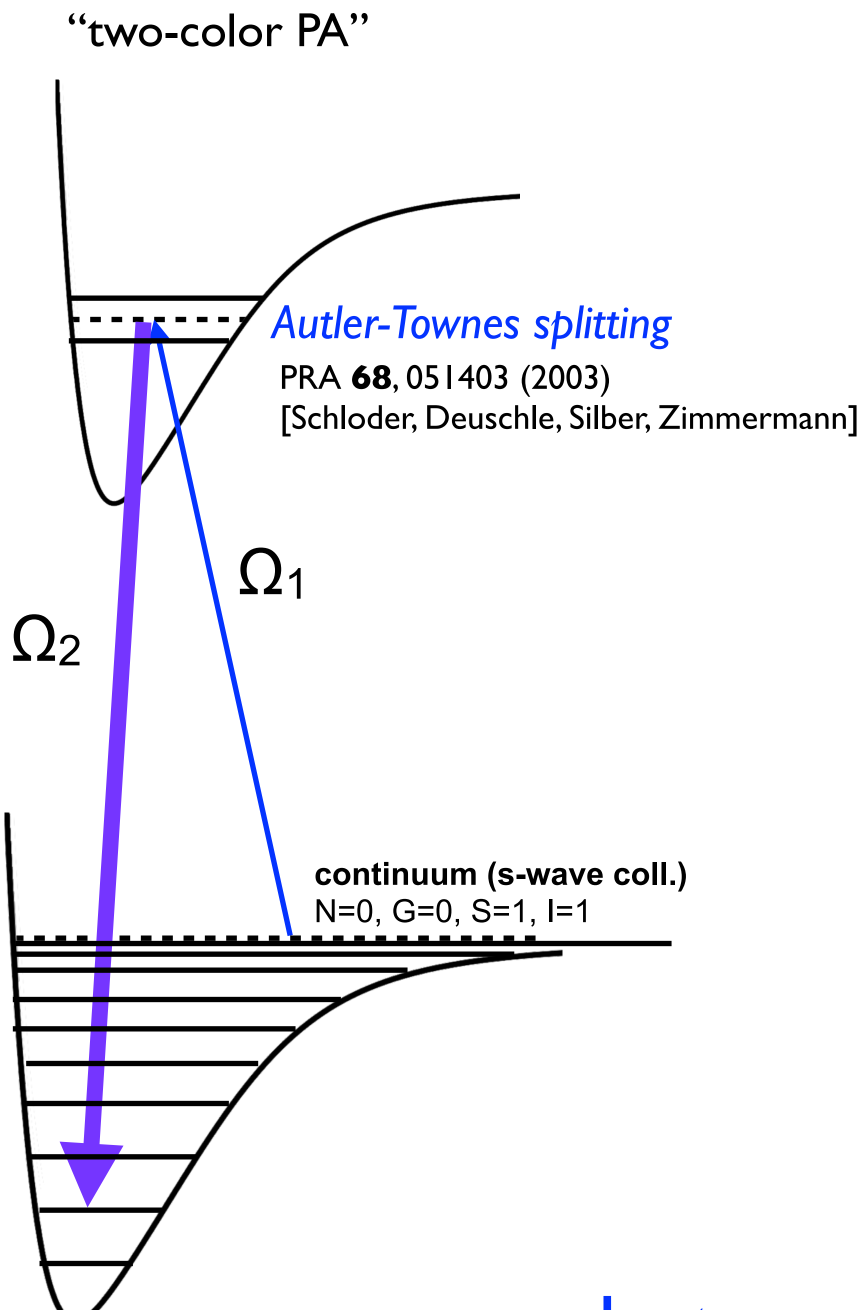
width set by excited state lifetime

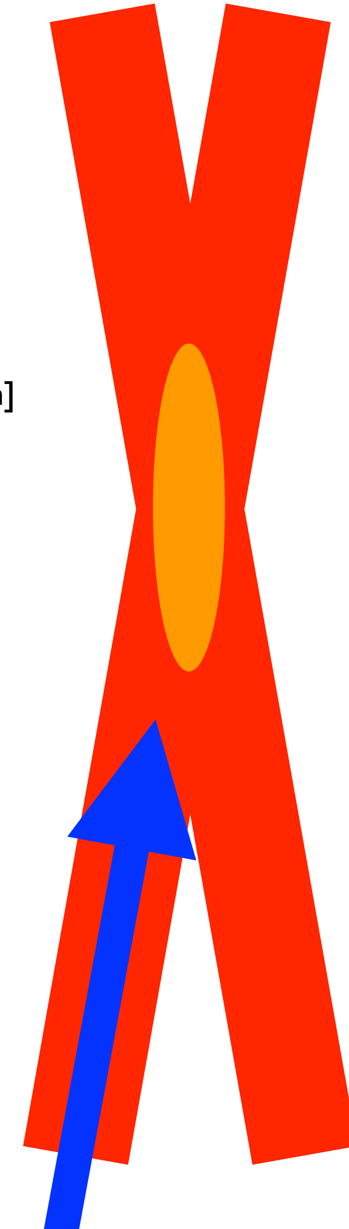
For photo-association, just add additional light



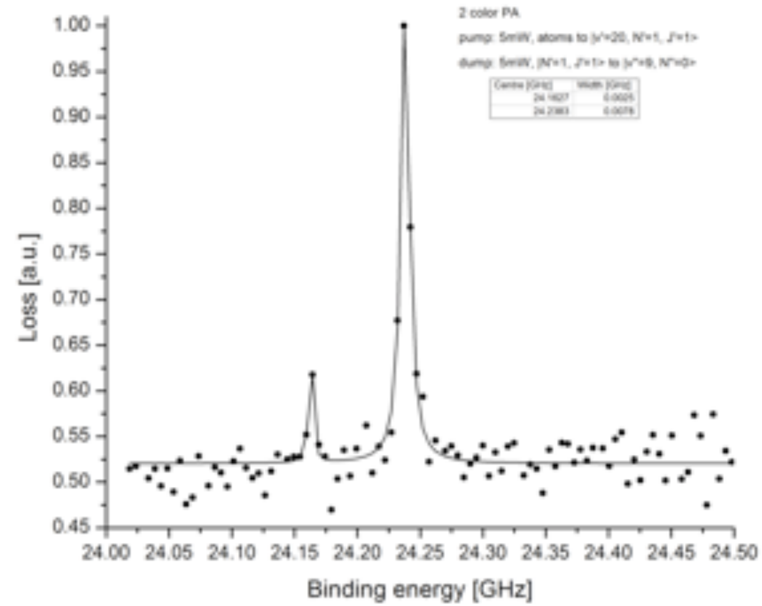


For photo-association, just add additional light





atom loss suppressed

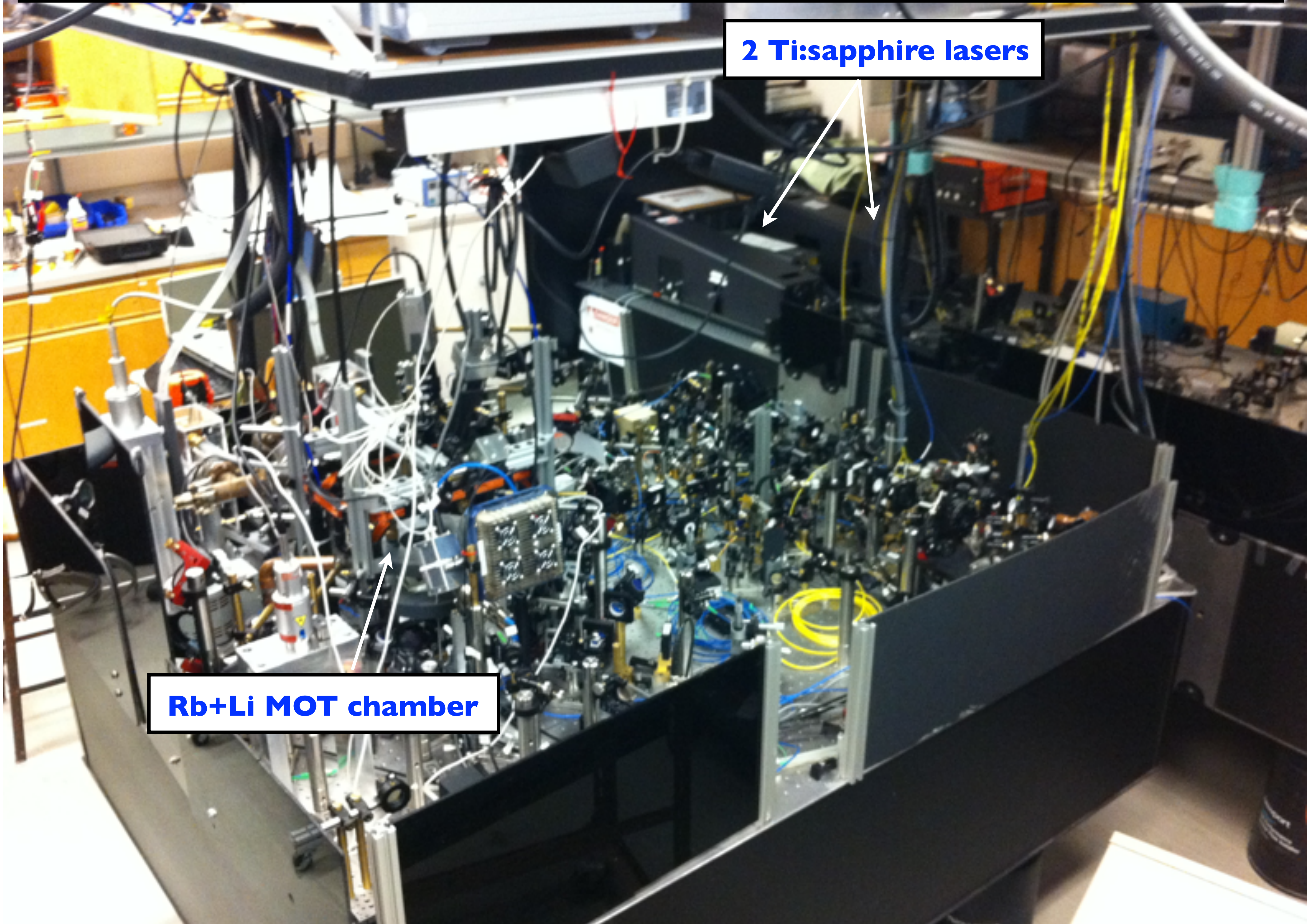


Ω_2 - Ω_1

width set by coupling induced by Ω_2

photo-association light

For photo-association, we just add additional light



For photo-association, we just add additional light

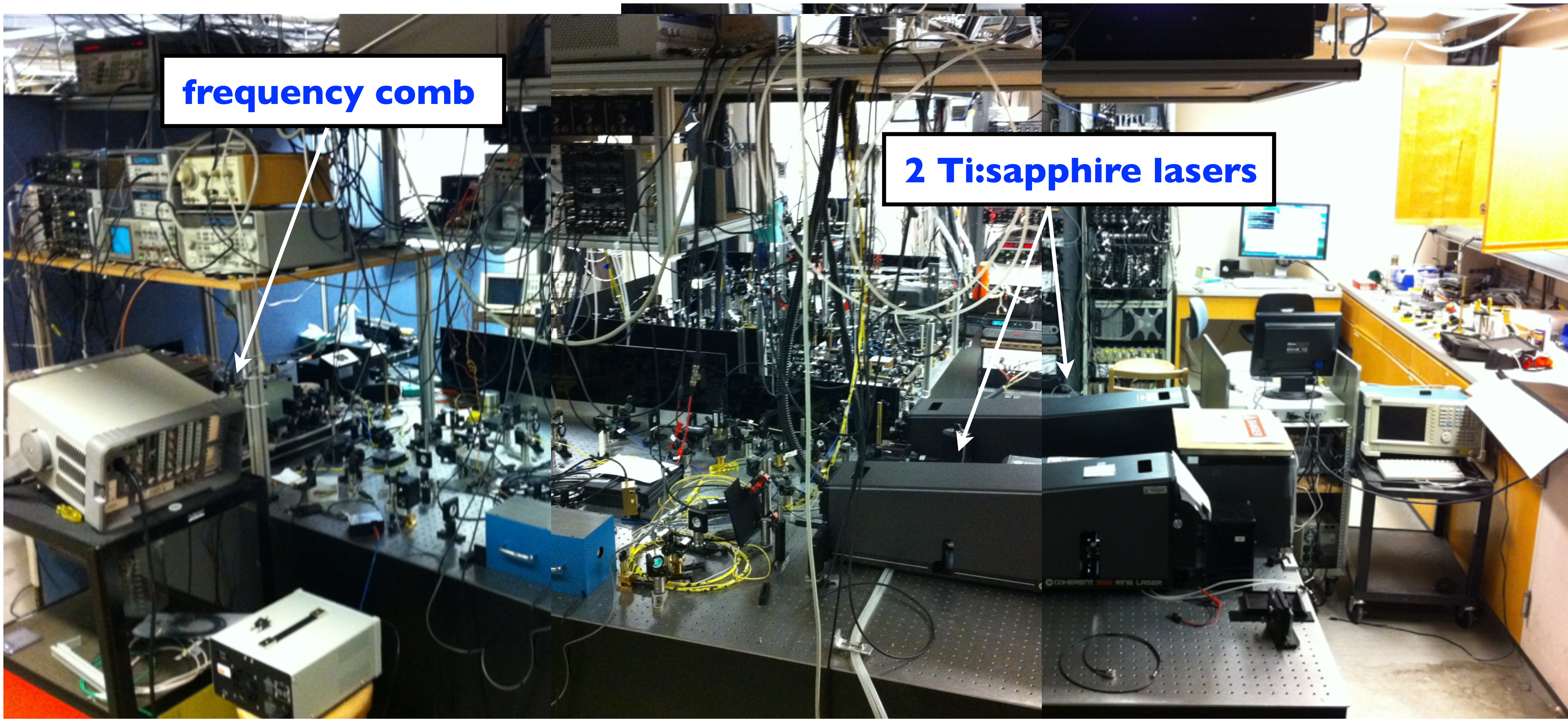
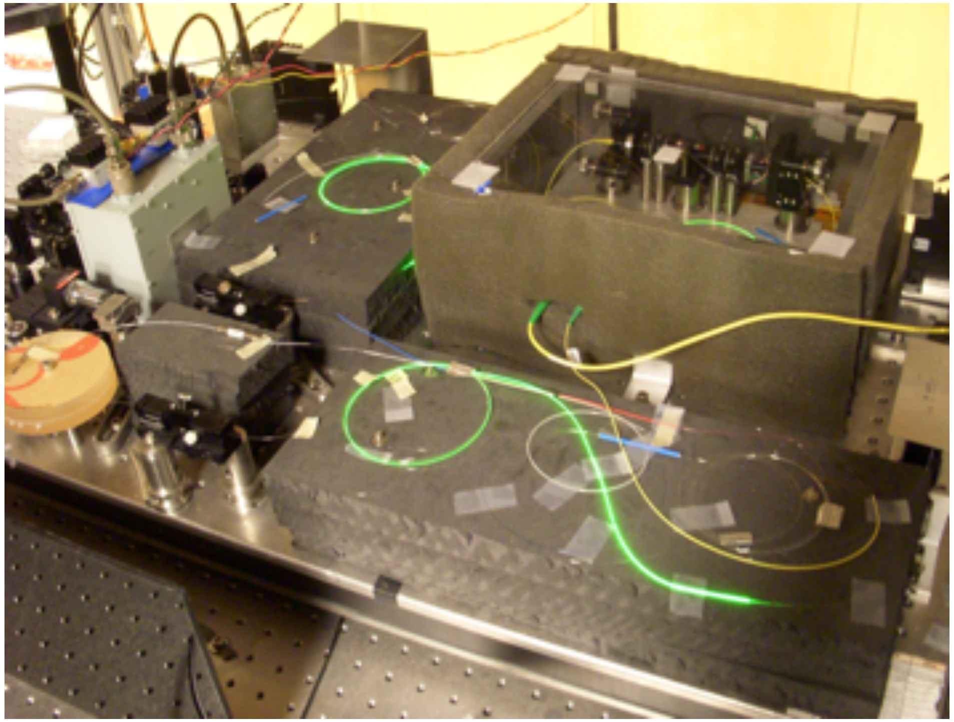
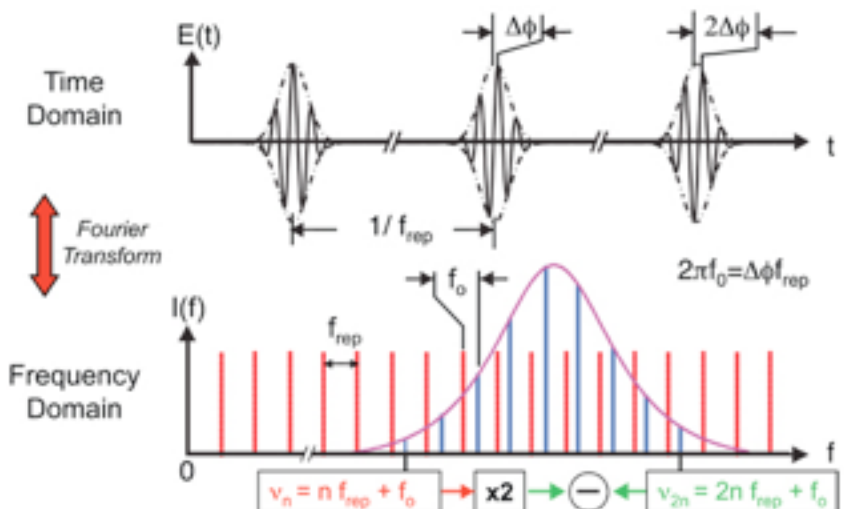


Photo-association (PA) laser system

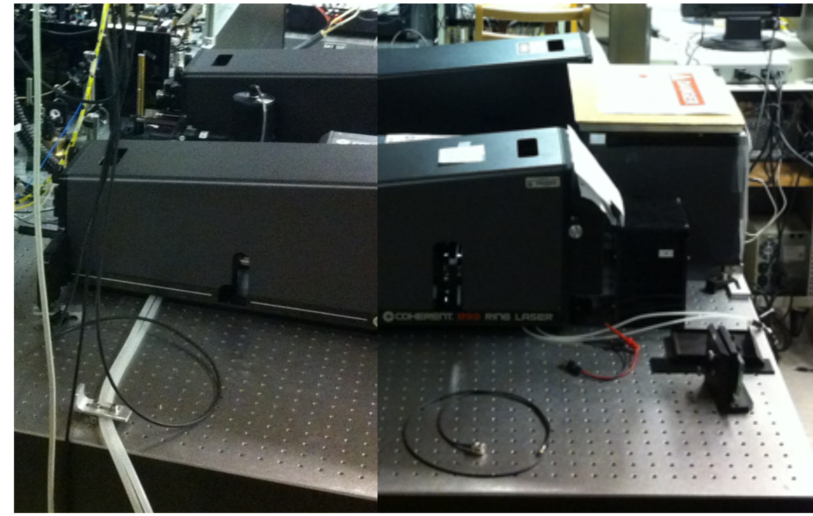
frequency comb





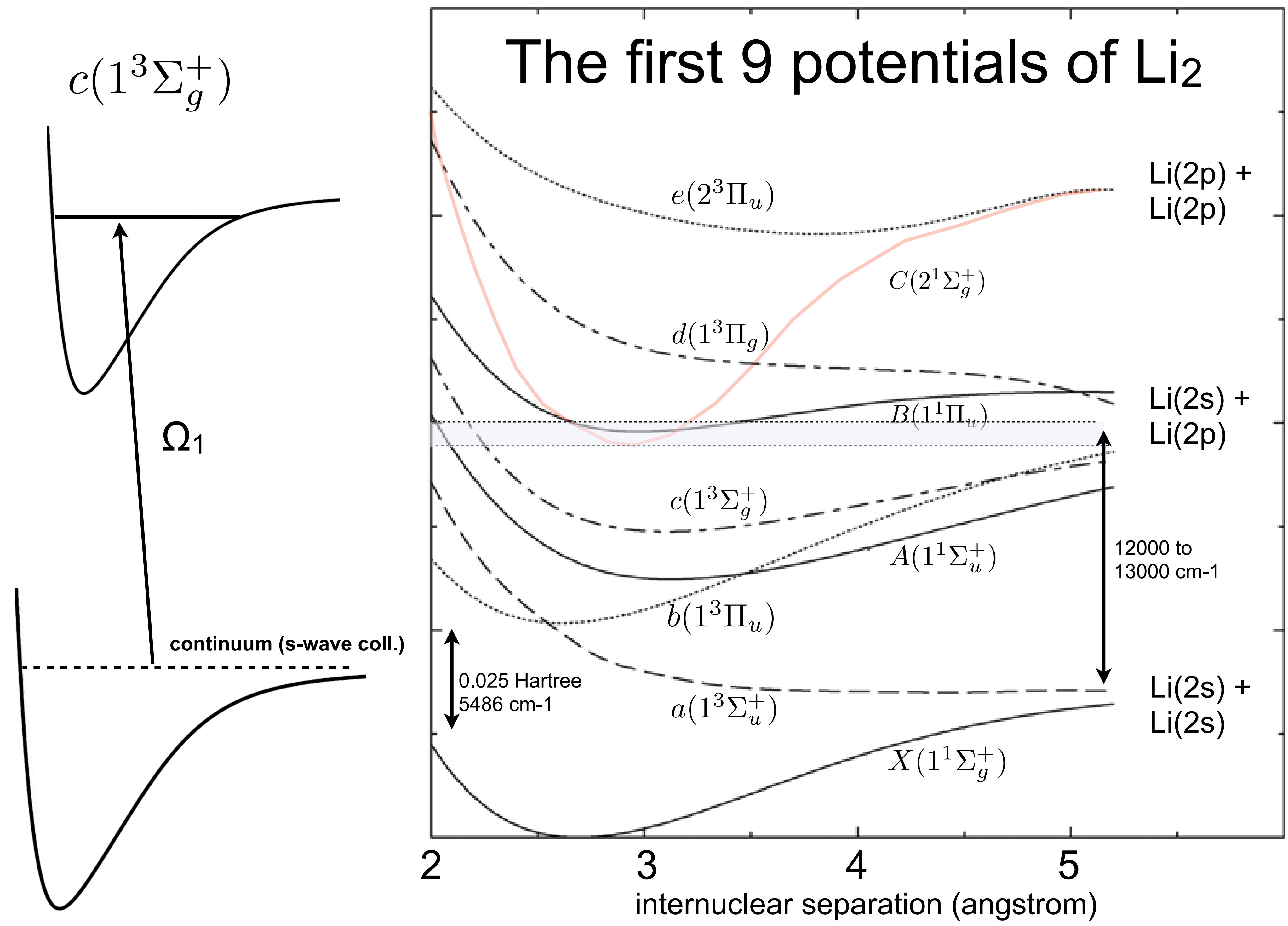
self reference lock

2 Ti:sapphire lasers



When locked to comb:
1) uncertainty on frequency difference < 10 kHz.
2) line width of each Ti:sapphire: ~ 100 kHz
(verified by an independent heterodyne measurement)

1-color PA spectroscopy results



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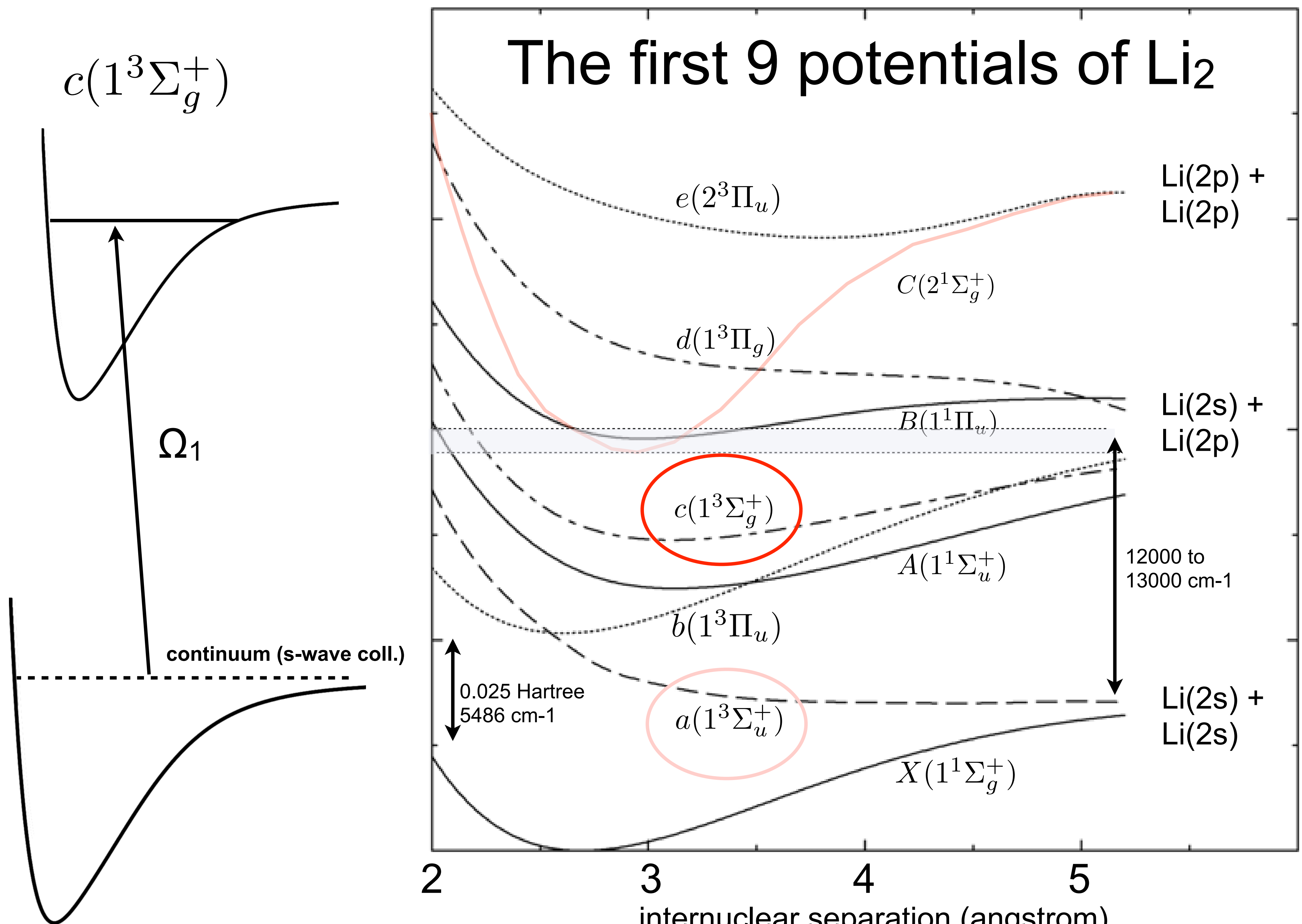

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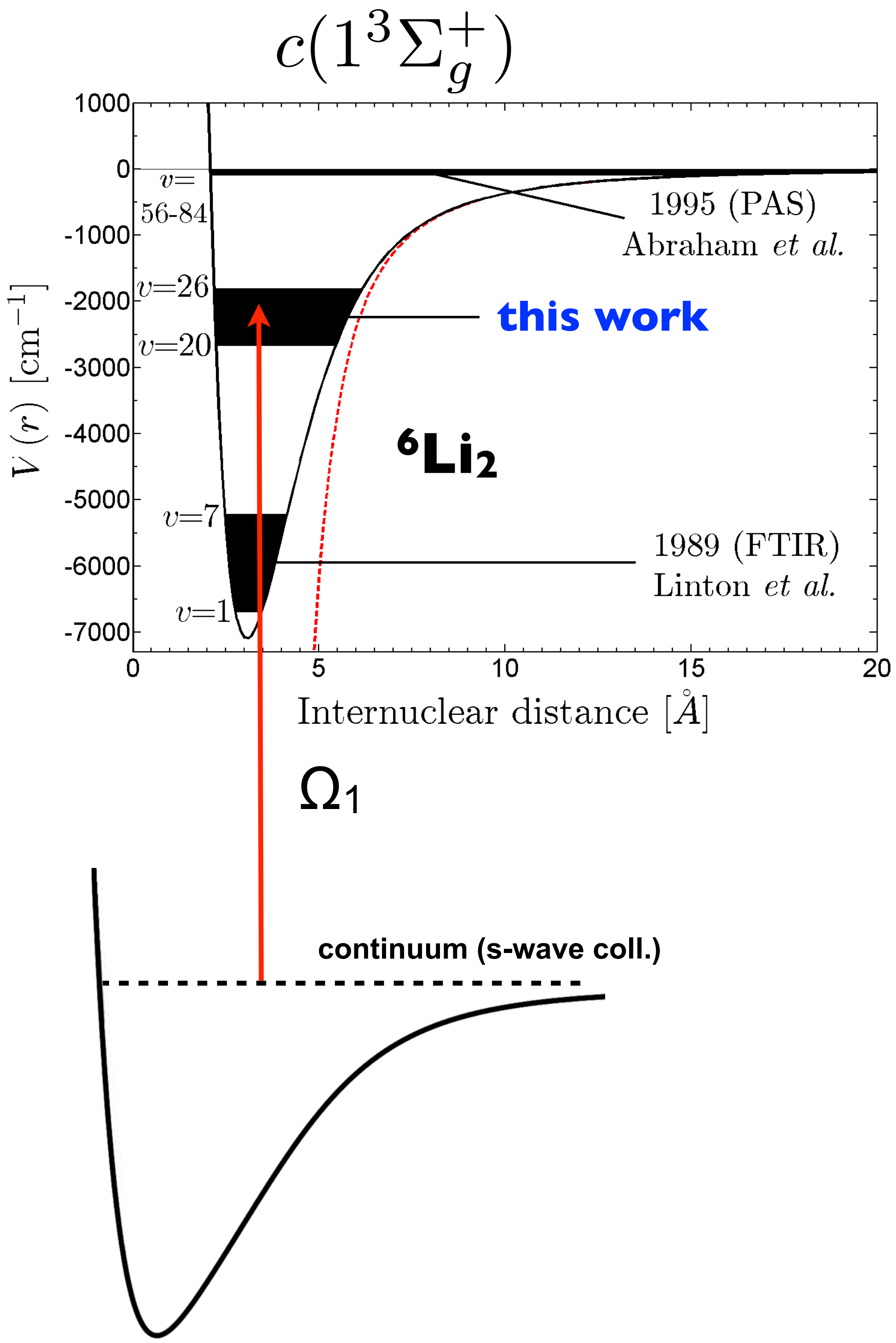

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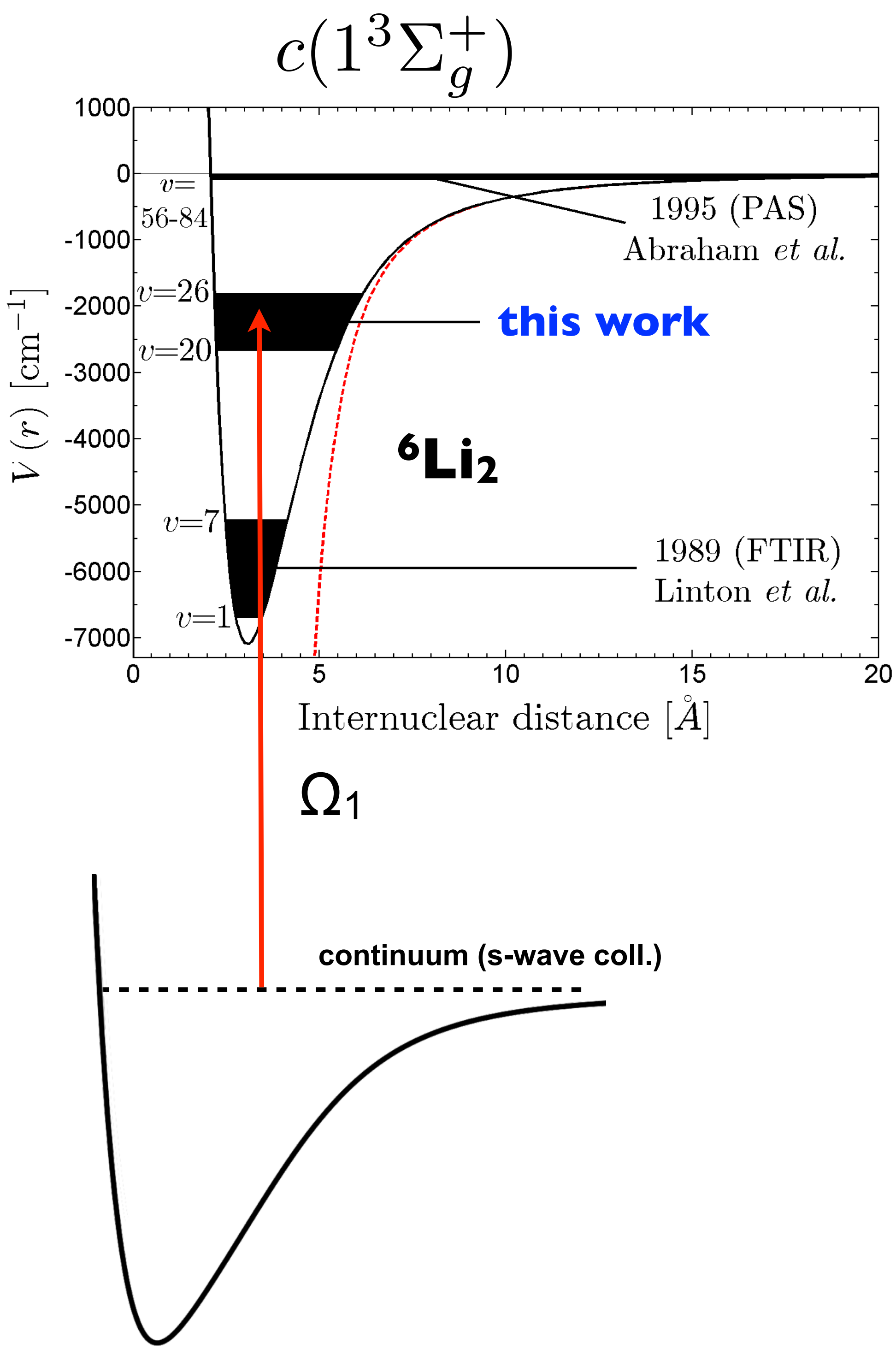
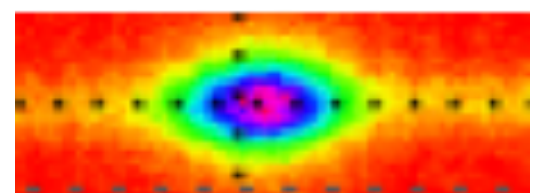


0) To minimize broadening and systematic shifts, we evaporate to very low trap powers and photo-associate a 2-component quantum degenerate Fermi gas ($T/T_F \sim 0.4$)



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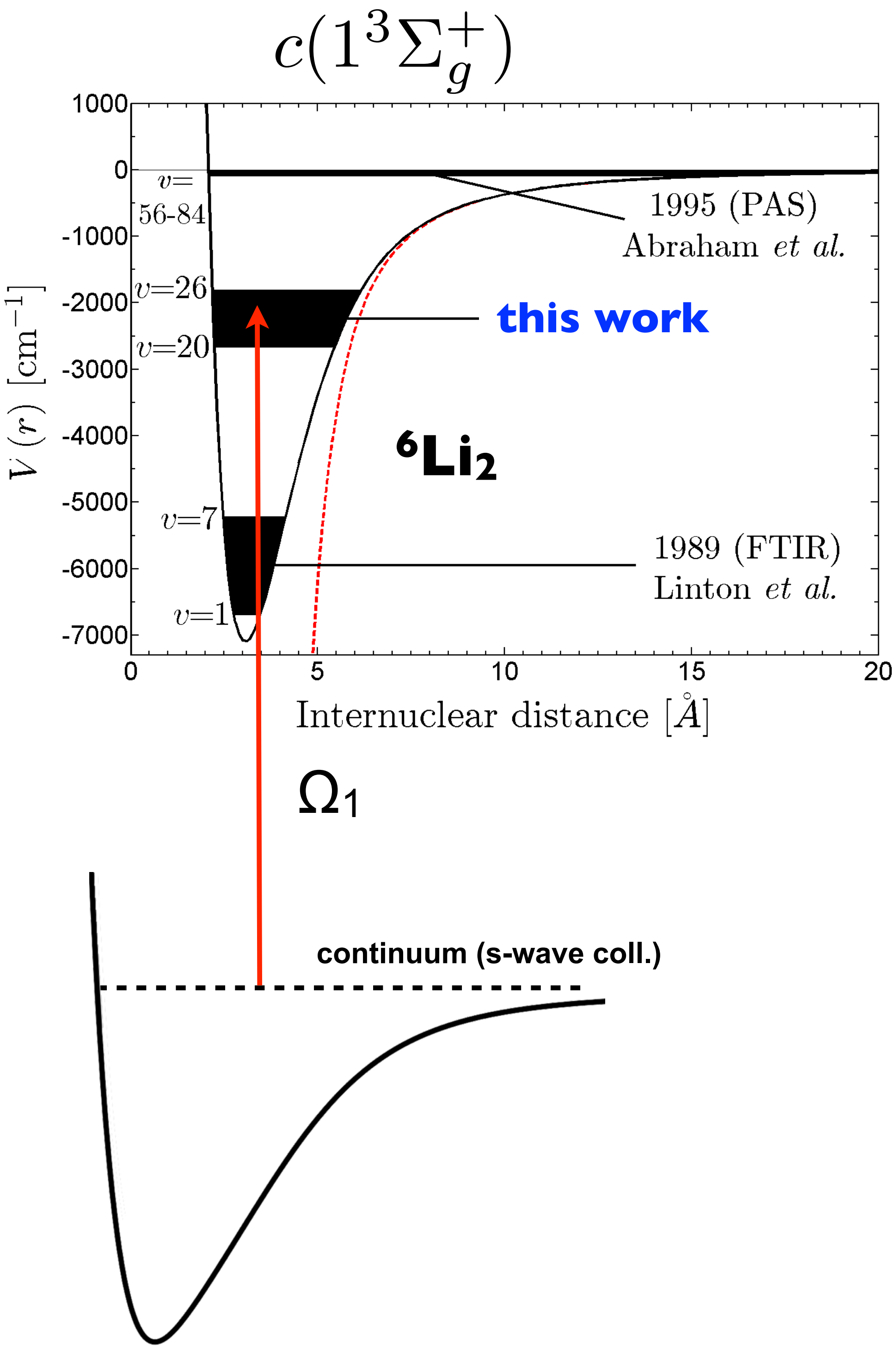

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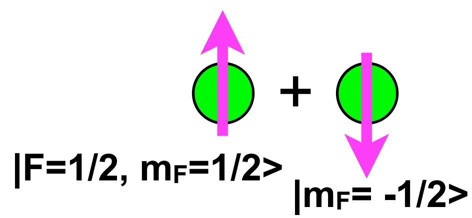
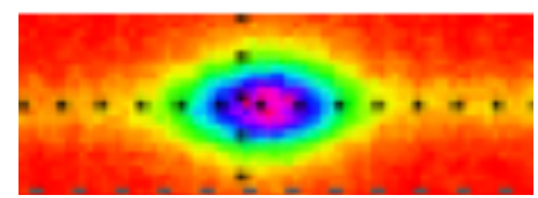


Initial state:
S-wave collision: N=0
Total spin = 0 (G = S+I = 0)
electronic spin = 0, 1



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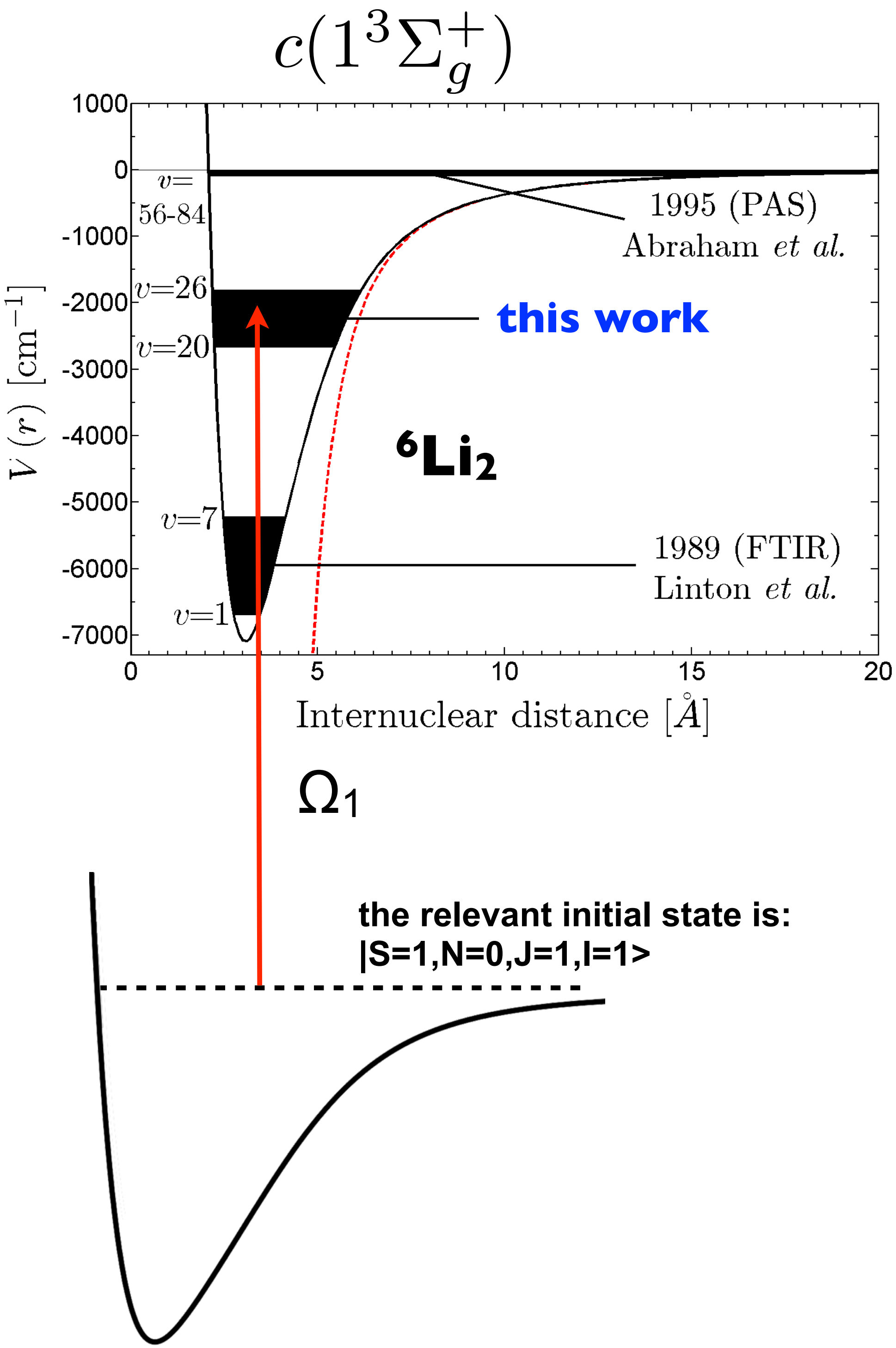

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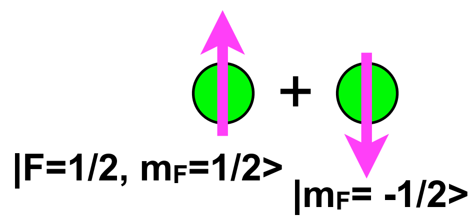

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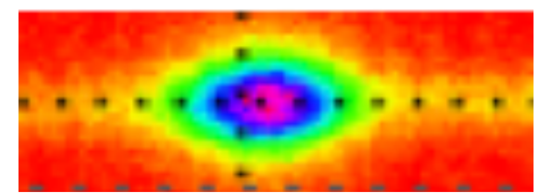
electronic spin = 0, 1

two states are:
|S=0,N=0,J=0,I=0>
|S=1,N=0,J=1,I=1>



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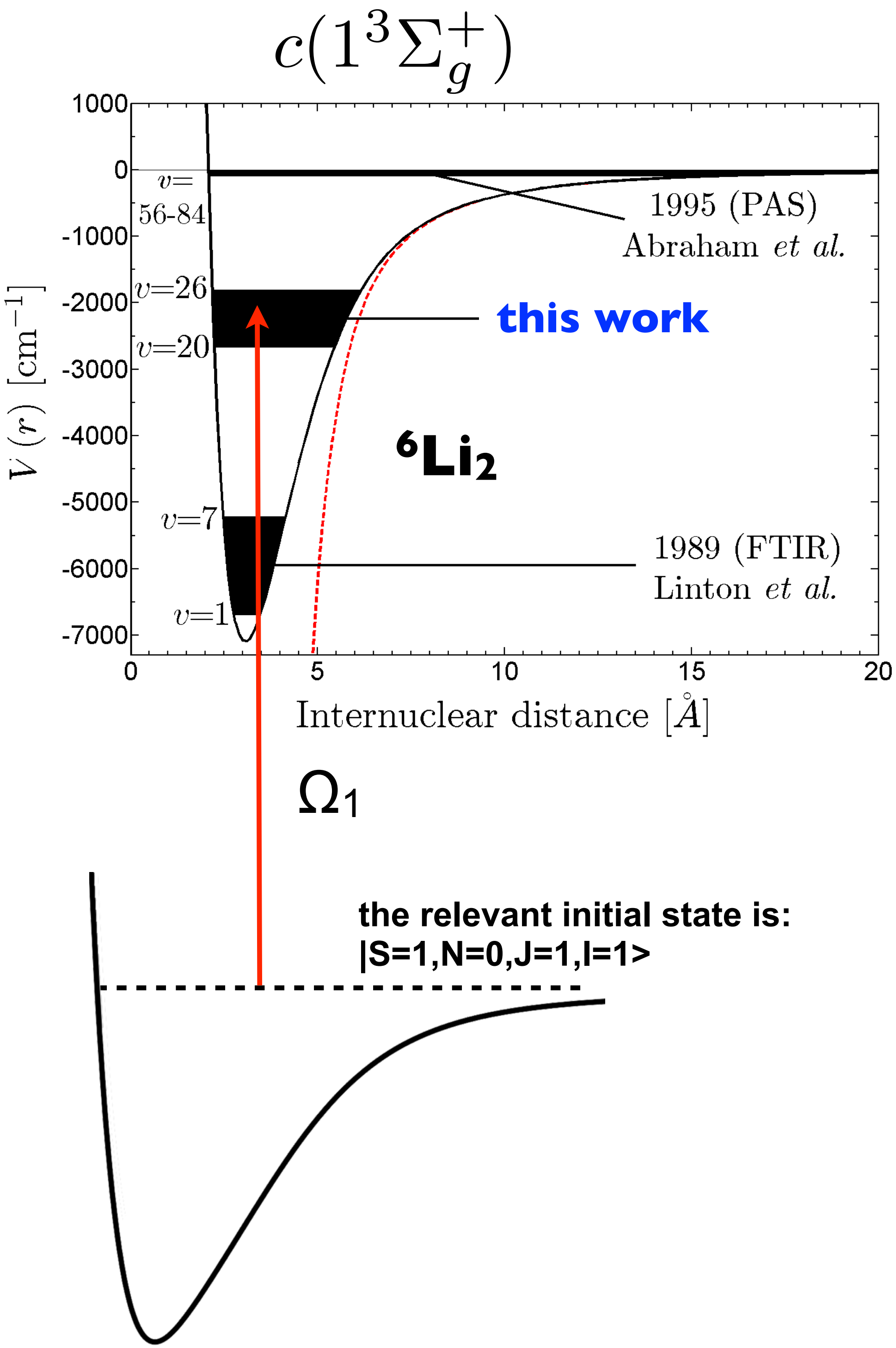

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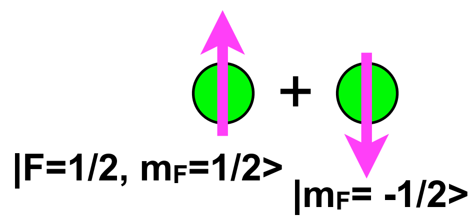


Initial state:
S-wave collision: N=0
Total spin = 0 (G = S+I = 0)
electronic spin = 0, 1

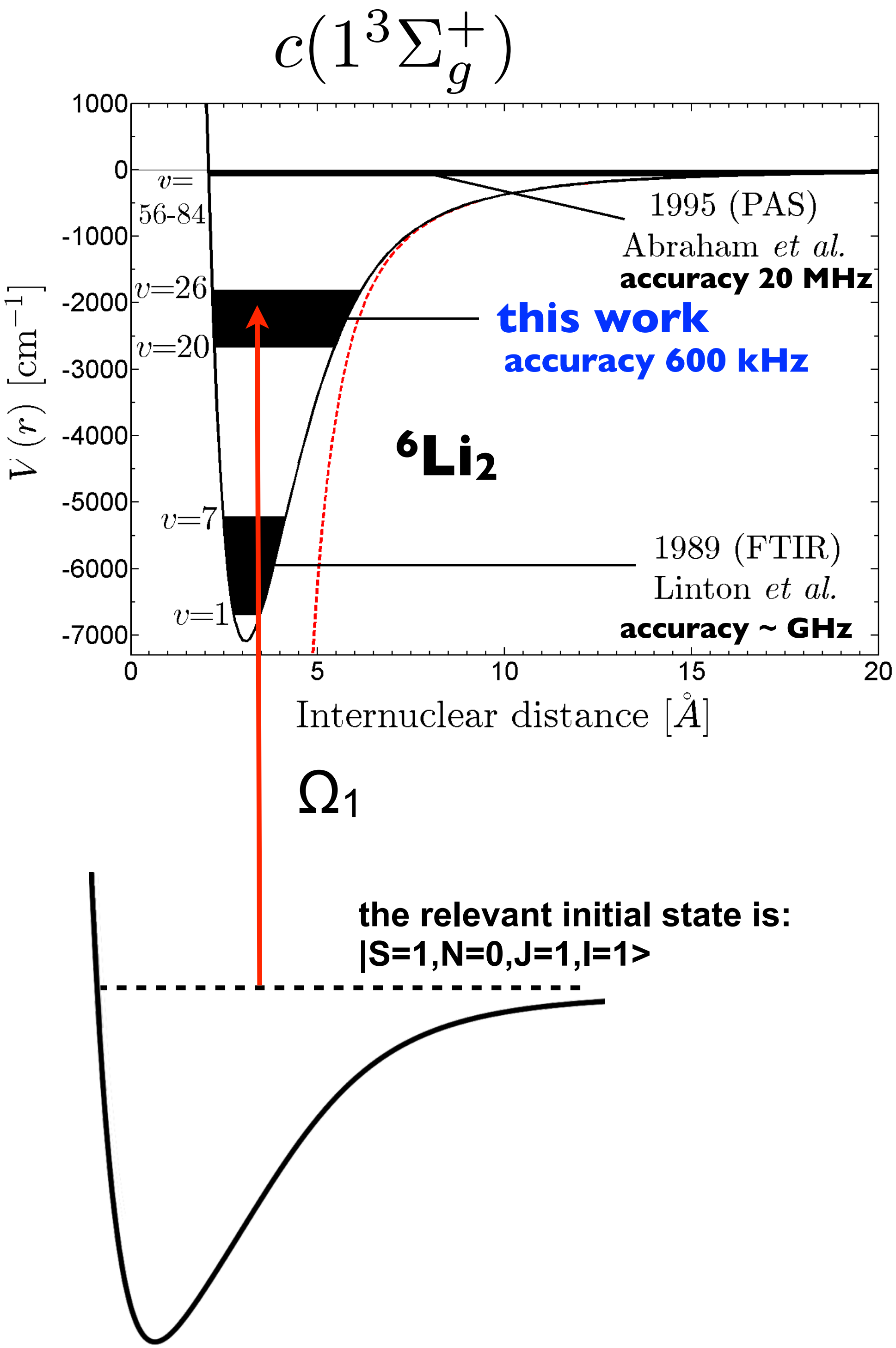
two states are:
|S=0,N=0,J=0,I=0>
|S=1,N=0,J=1,I=1>

1) We measure 7 levels from v'=20 to v'=26 with an absolute accuracy of +/- 600 kHz (+/- 0.00002 cm-1)

2) For each vibrational level, we observe the N'=1 level AND using a p-wave FR at 187.4 G, we observe the N'=0 and N'=2 rotational levels

3) We also characterized the systematic shifts due to magnetic field, and the residual AC Stark shifts of the PA laser and the trapping laser.

1-color PA spectroscopy results



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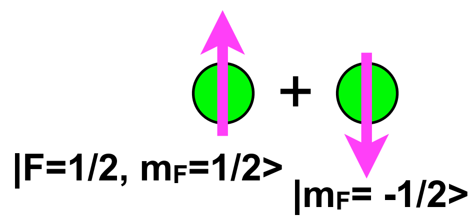

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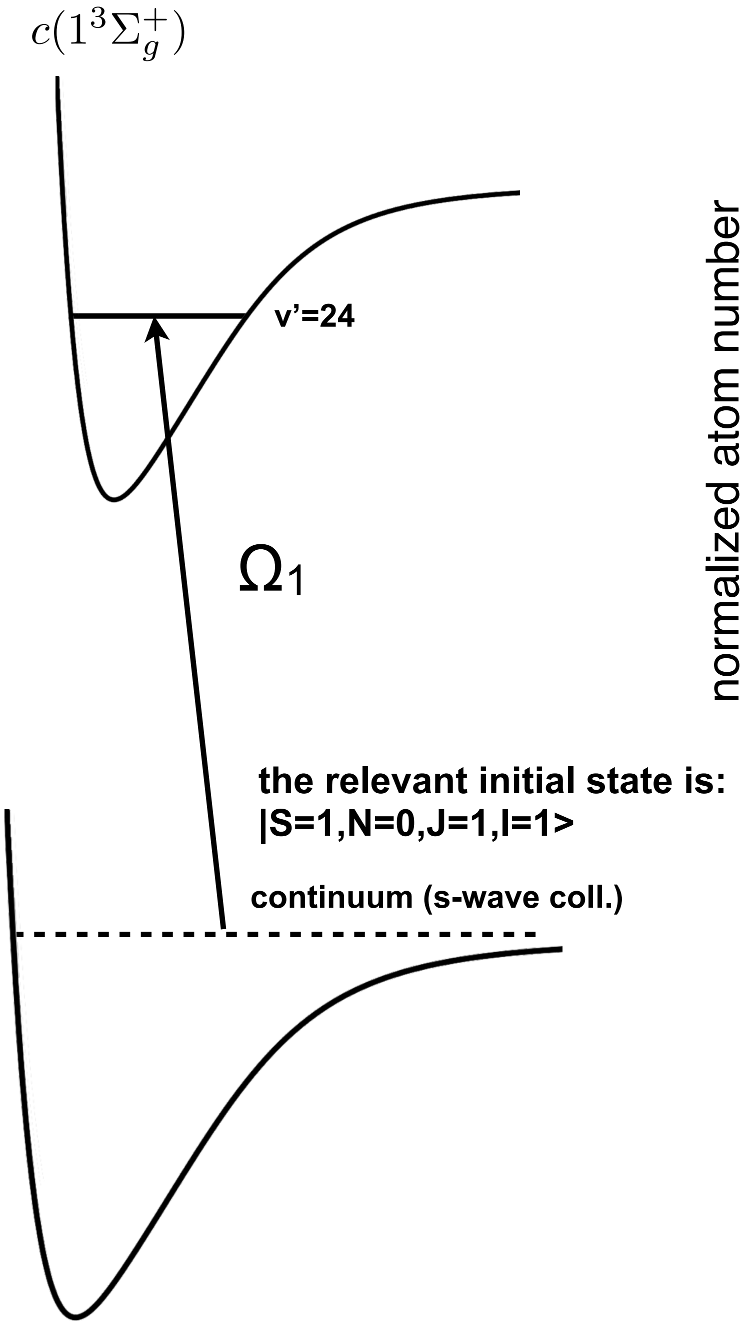
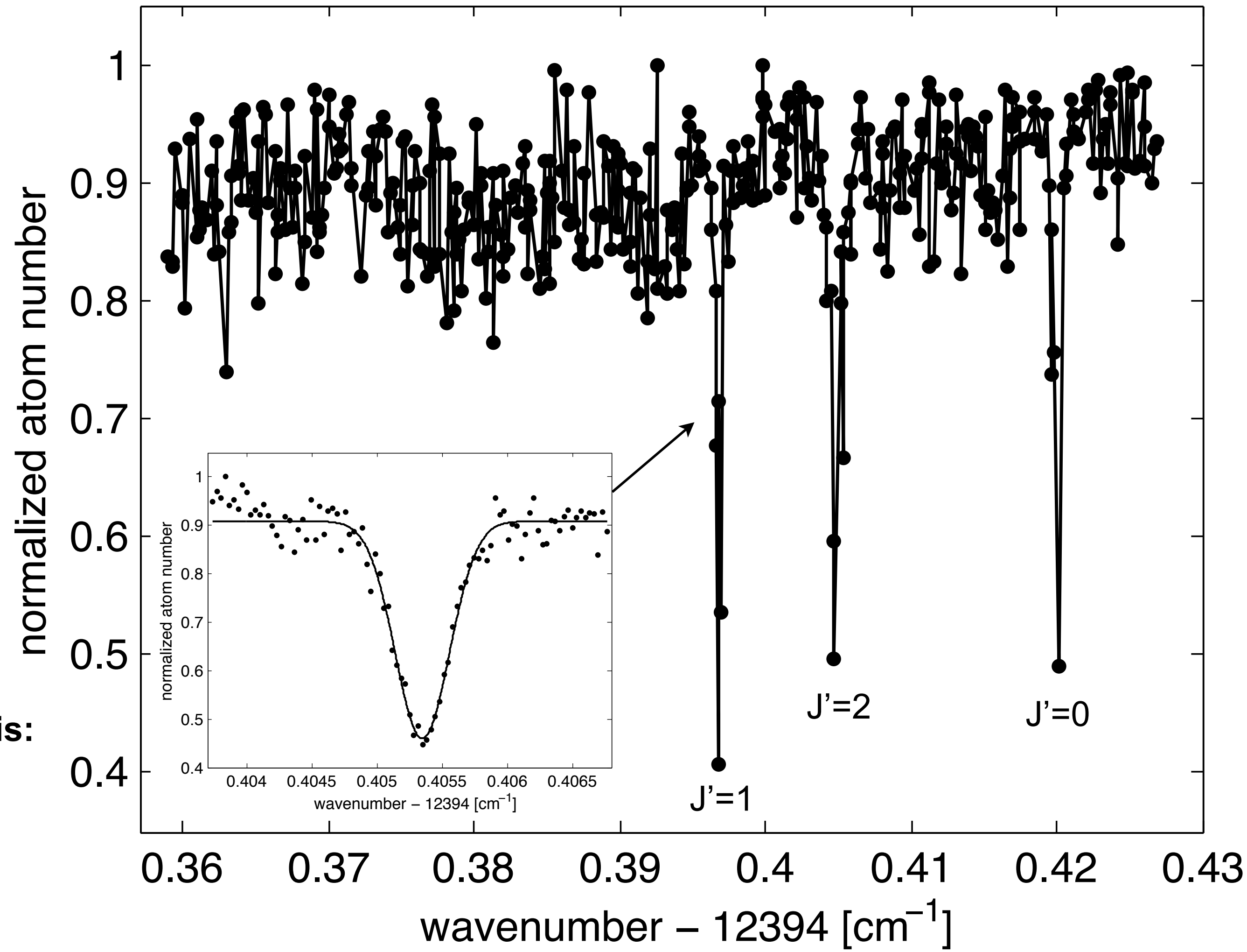
1-color PA spectroscopy results

We resolve three features for each vibrational level





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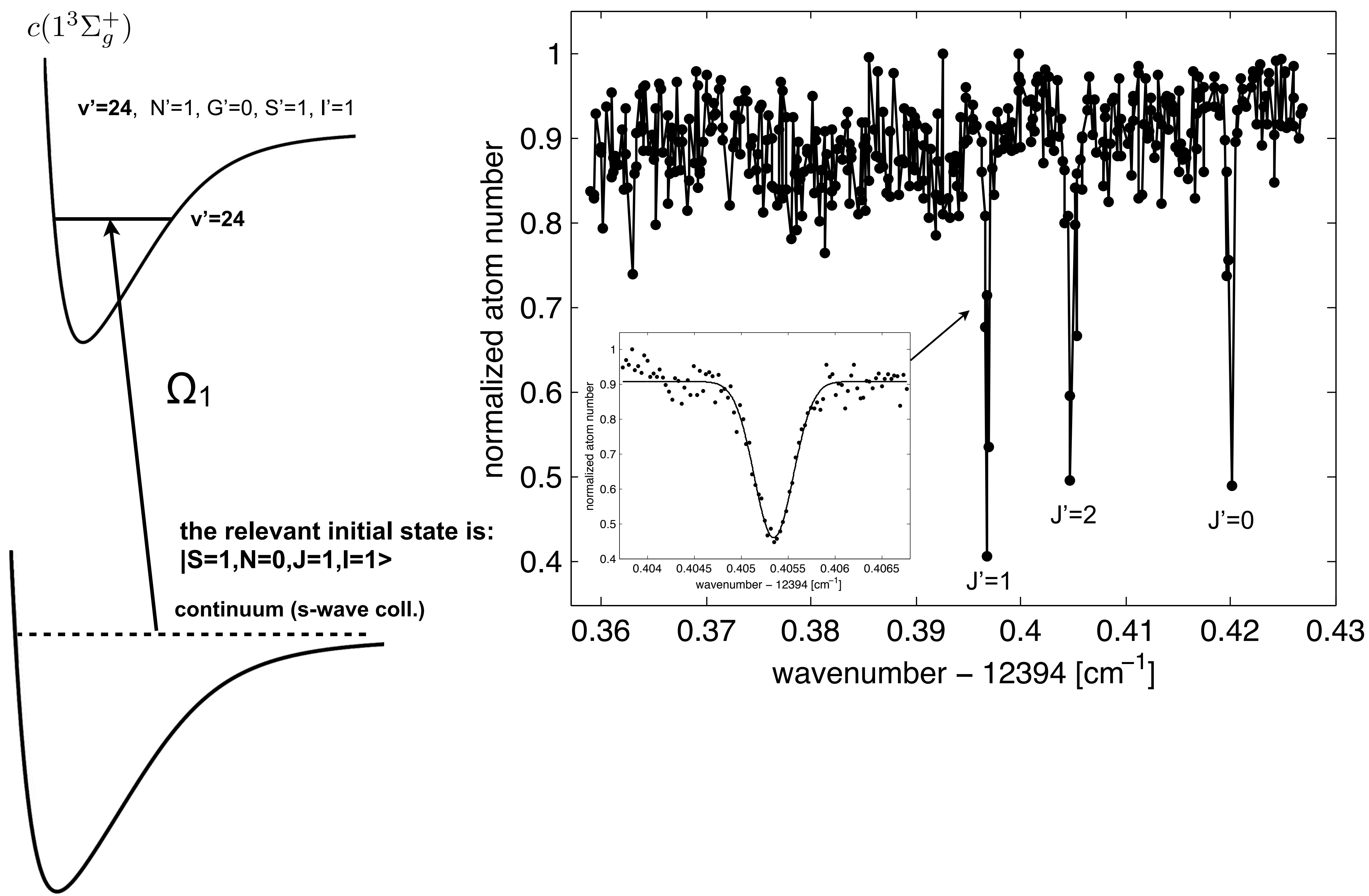
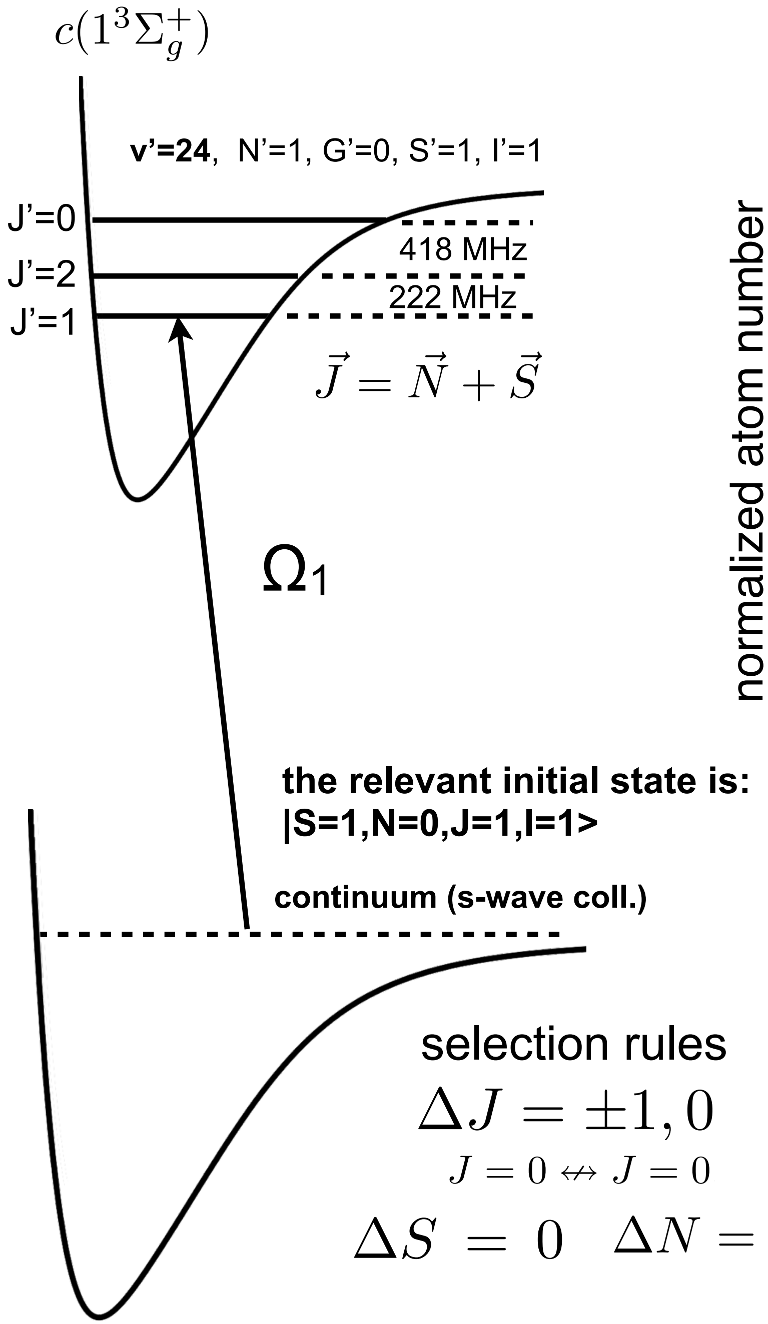
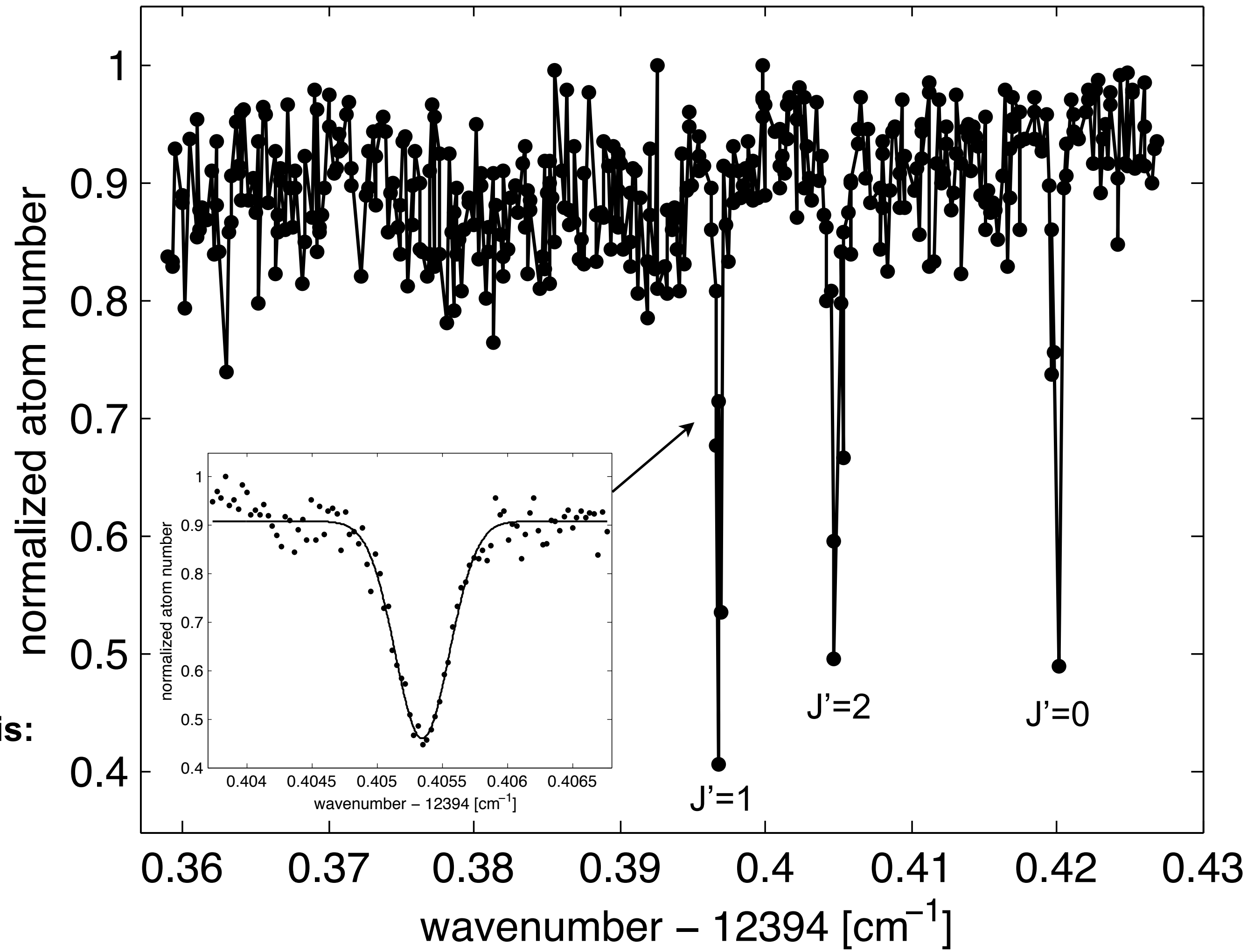


1-color PA spectroscopy results

We resolve three features for each vibrational level split by spin-spin and spin-rotation coupling





selection rules

$$\Delta J = \pm 1, 0$$

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1-color PA spectroscopy results

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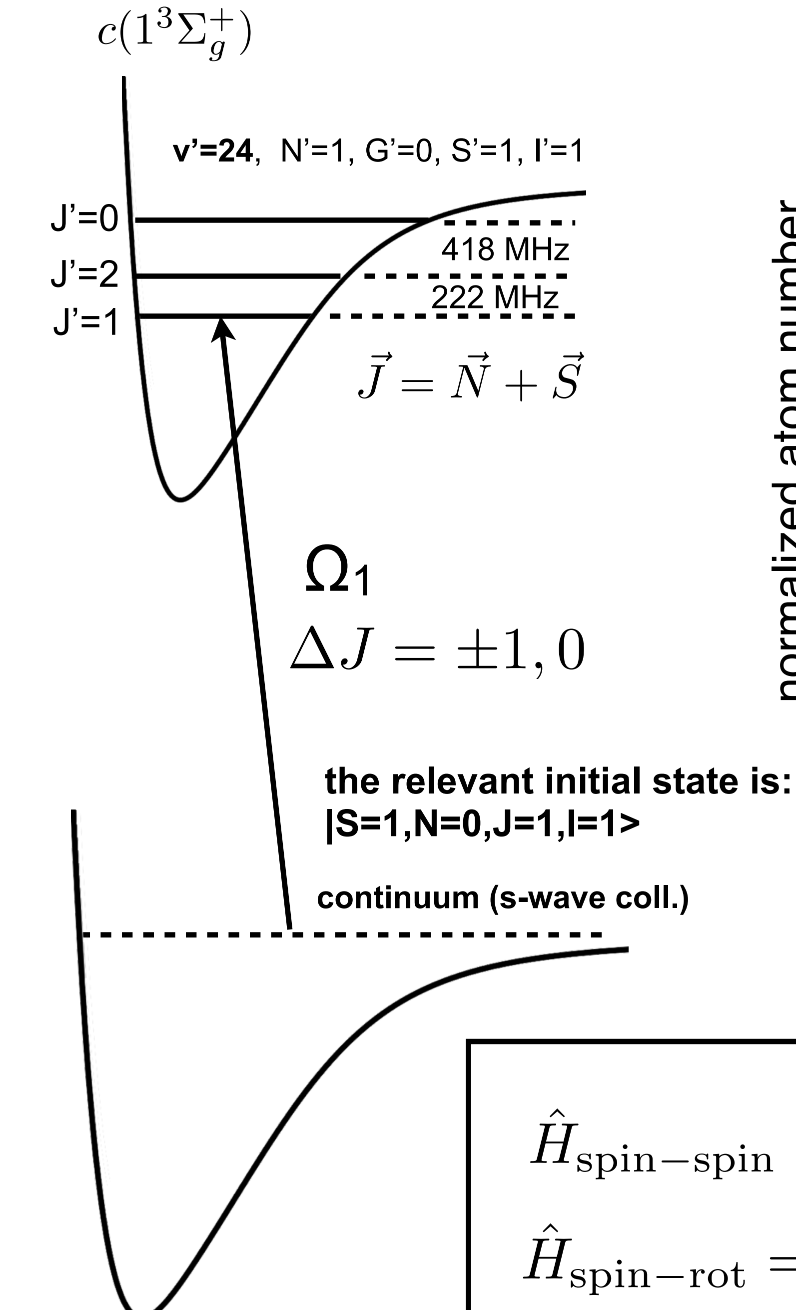
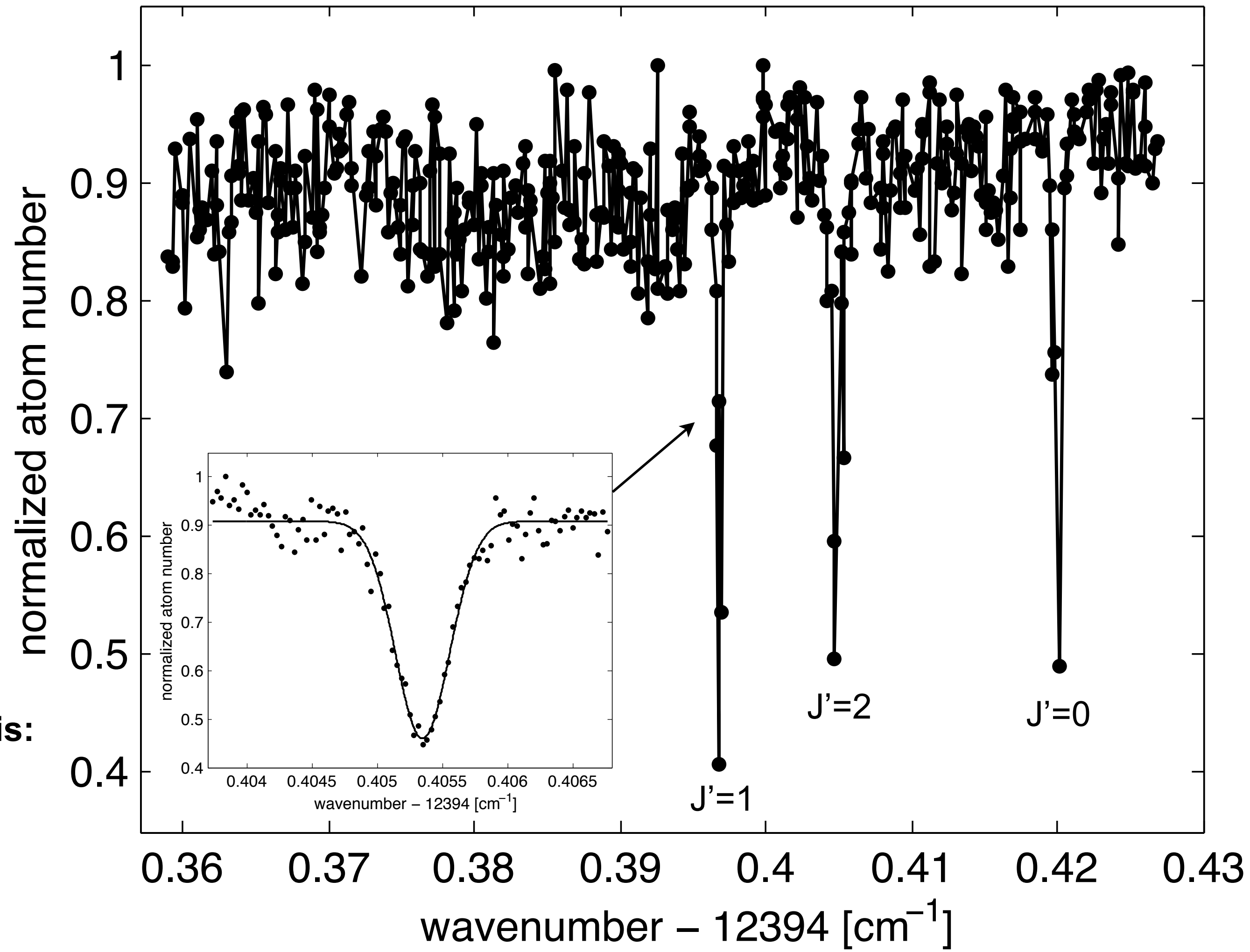


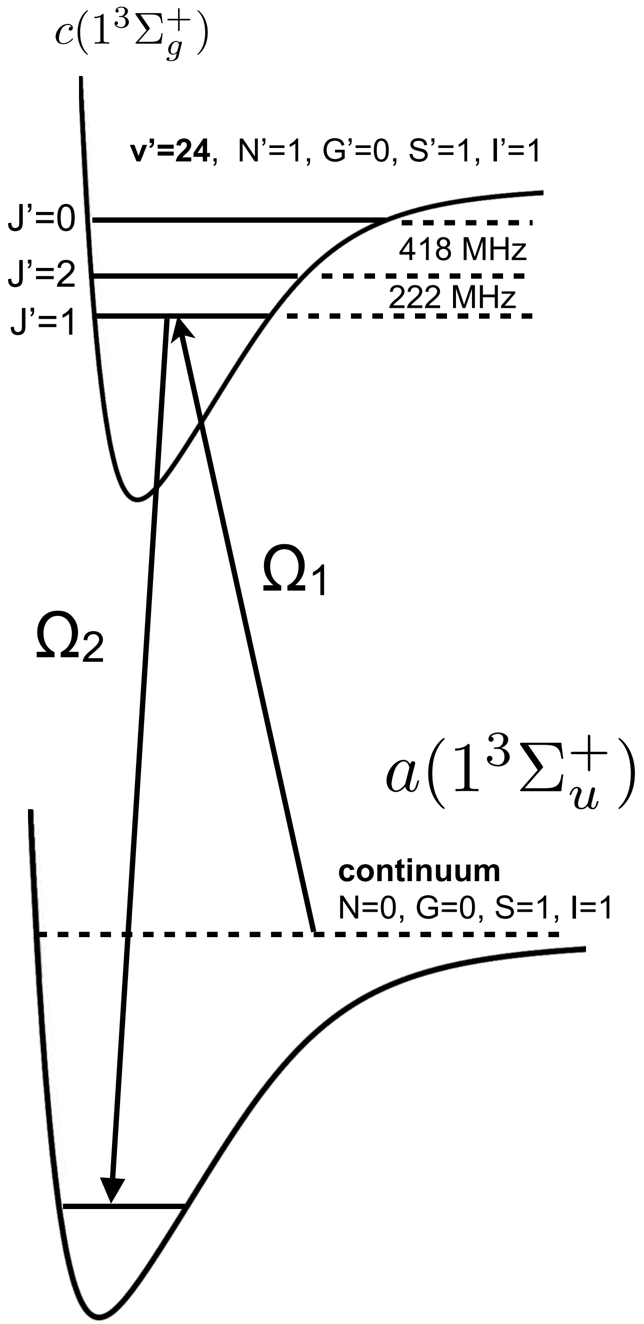


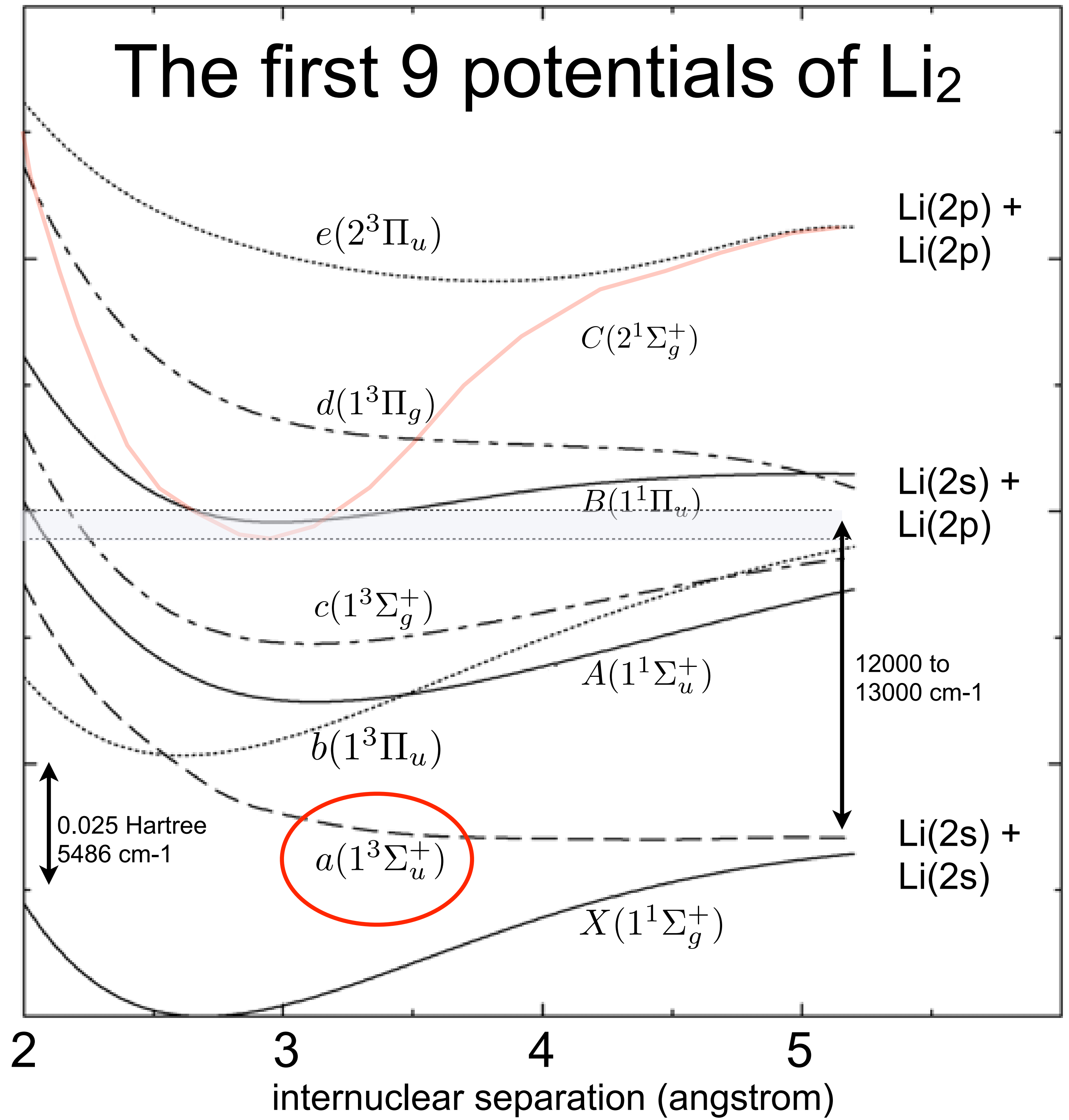
$$\hat{H}_{\rm spin-spin} = 2\lambda_v[\hat{S}_z^2 - \hat{S}^2/3]$$

$$\hat{H}_{\rm spin-rot} = \gamma_v \vec{N}\cdot\vec{S}$$

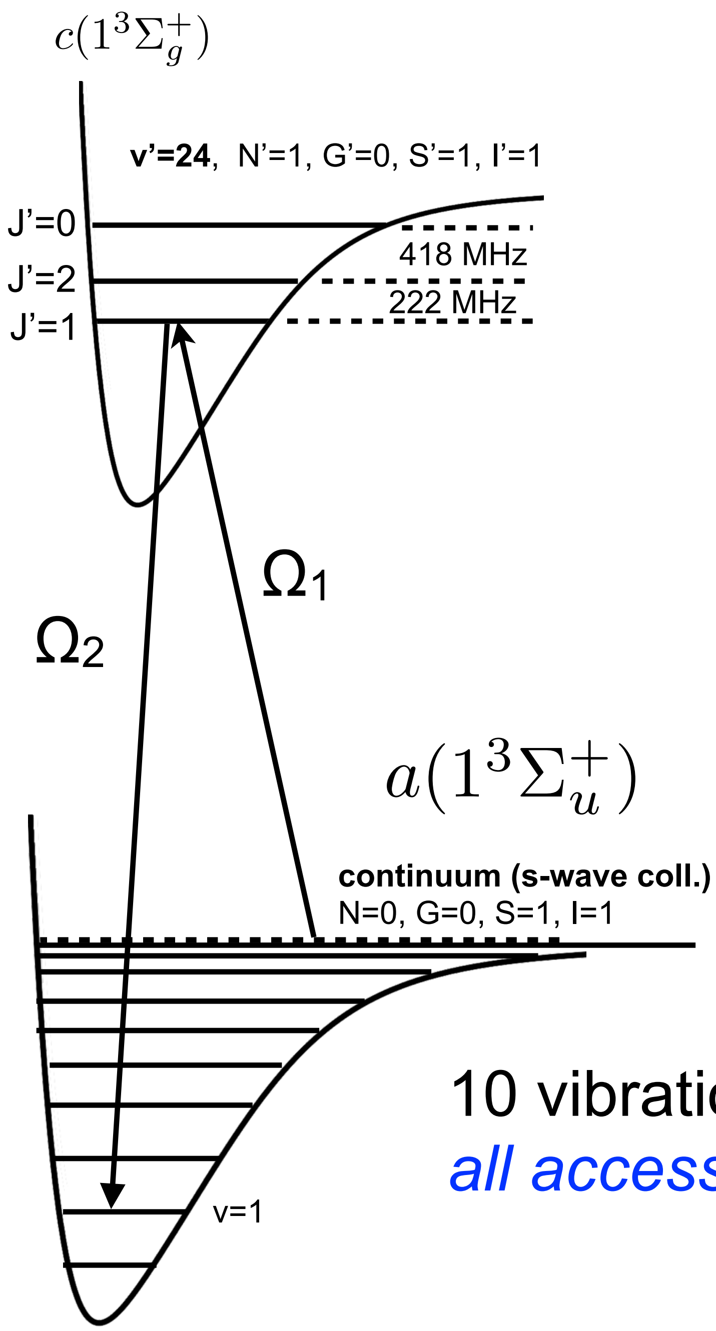
v'	λ_v (MHz)	γ_v (MHz)
20	-348.2	-14.5
21	-339.4	-14.5
22	-331.1	-14.7
23	-321.7	-14.2
24	-312.2	-14.4
25	-309.6	-14.0
26	-294.3	-14.3

2-color PA spectroscopy : ground state spectroscopy





2-color PA spectroscopy : ground state spectroscopy



Triplet ground state Li_2

Motivations:

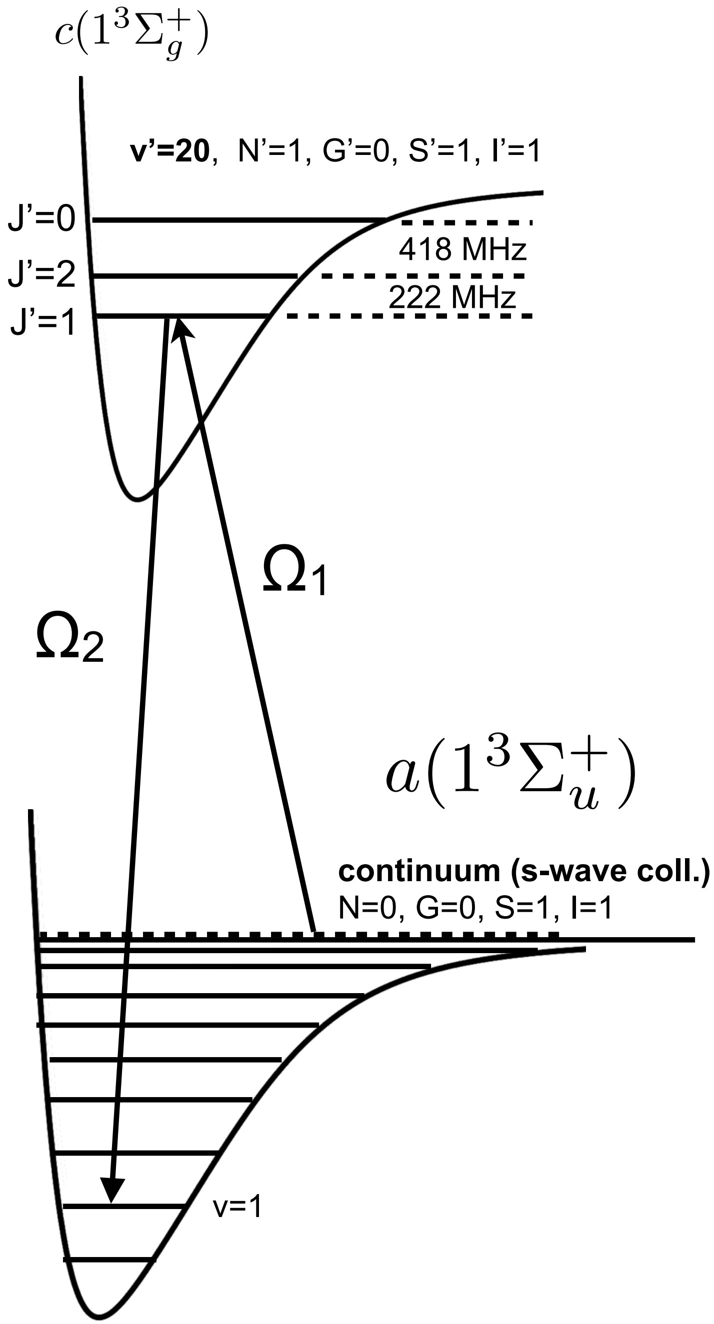
1) Technical: we can access with our lasers.
2) It has a magnetic moment (Molecular FRs !)
3) Make a BEC of ground state molecules
4) Measure the "Spin blockade"
5) Study collision properties of ultra-cold super-rotors (collaboration with Valery Milner)
6) Stepping stone for making triplet LiRb

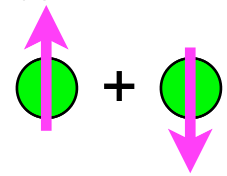
10 vibrational levels

all accessible with our laser system

2-color PA spectroscopy results : here Ω_1 is fixed and Ω_2 is scanned

In the data that follows, the loss of atoms due to photo-association induced by Ω1 is **suppressed** by the AC Stark shift of the excited state levels induced by Ω2. We specify the excited state v' number and the J' number and we specify the ground state v'' number and N'' number.





the relevant initial state is:
|S=1,N=0,J=1,I=1>

the intermediate state is:
|S=1,N=1,J=1,I=1>

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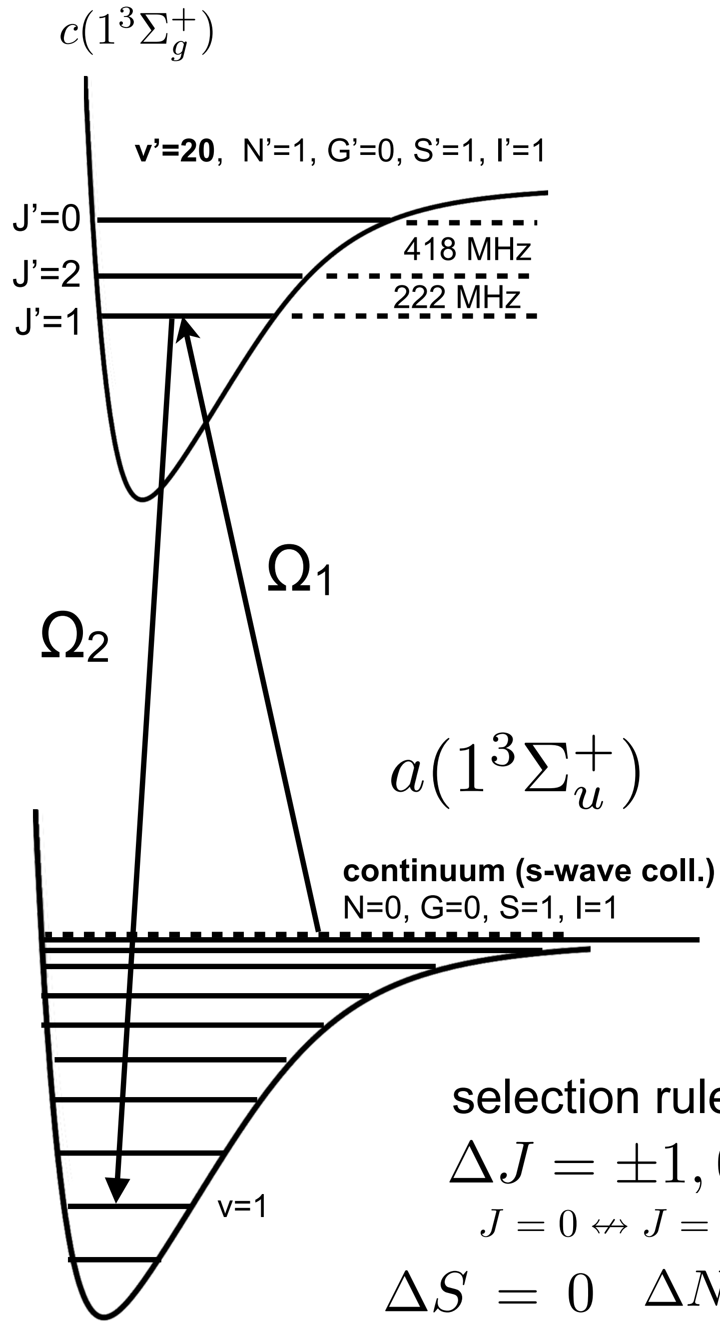

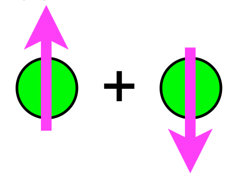

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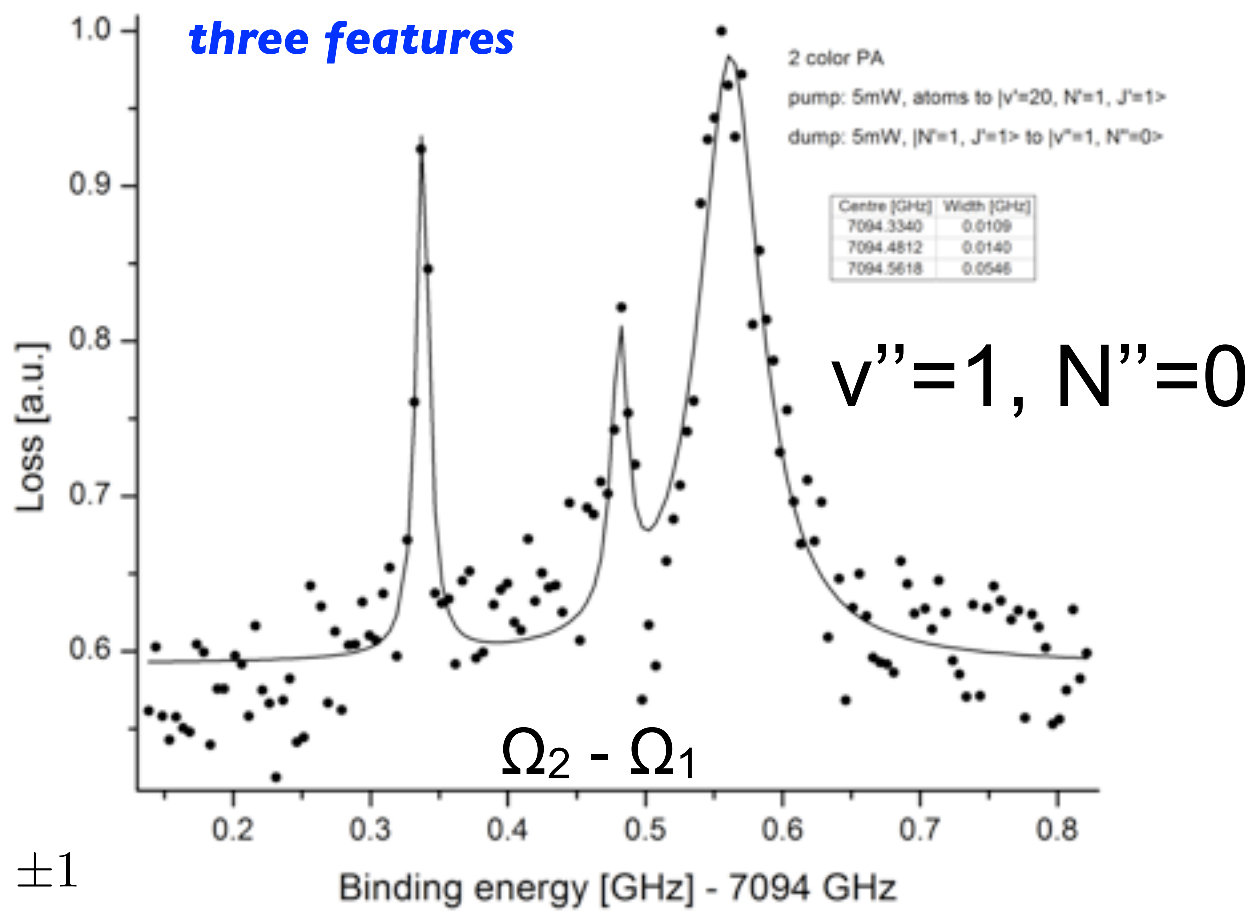
$$\Delta S = 0 \quad \Delta N = \pm 1$$



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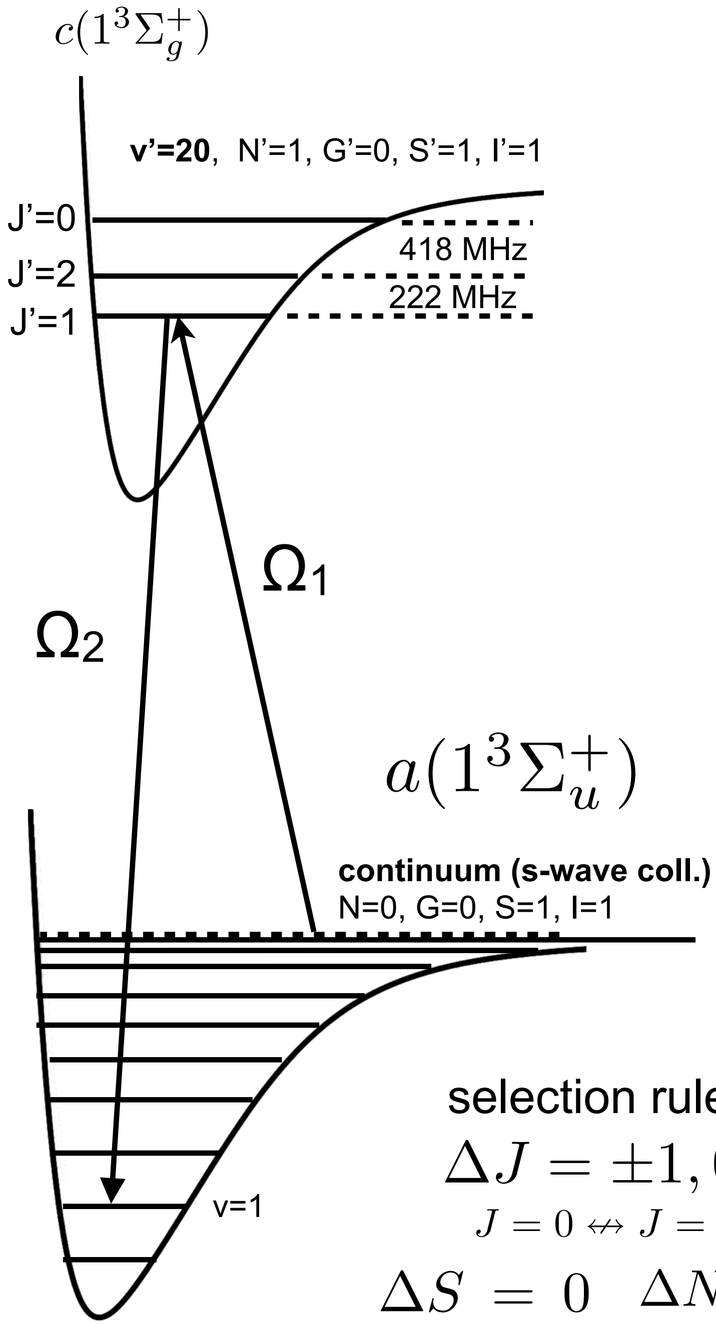

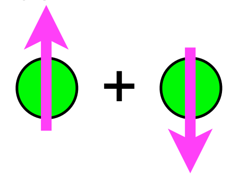

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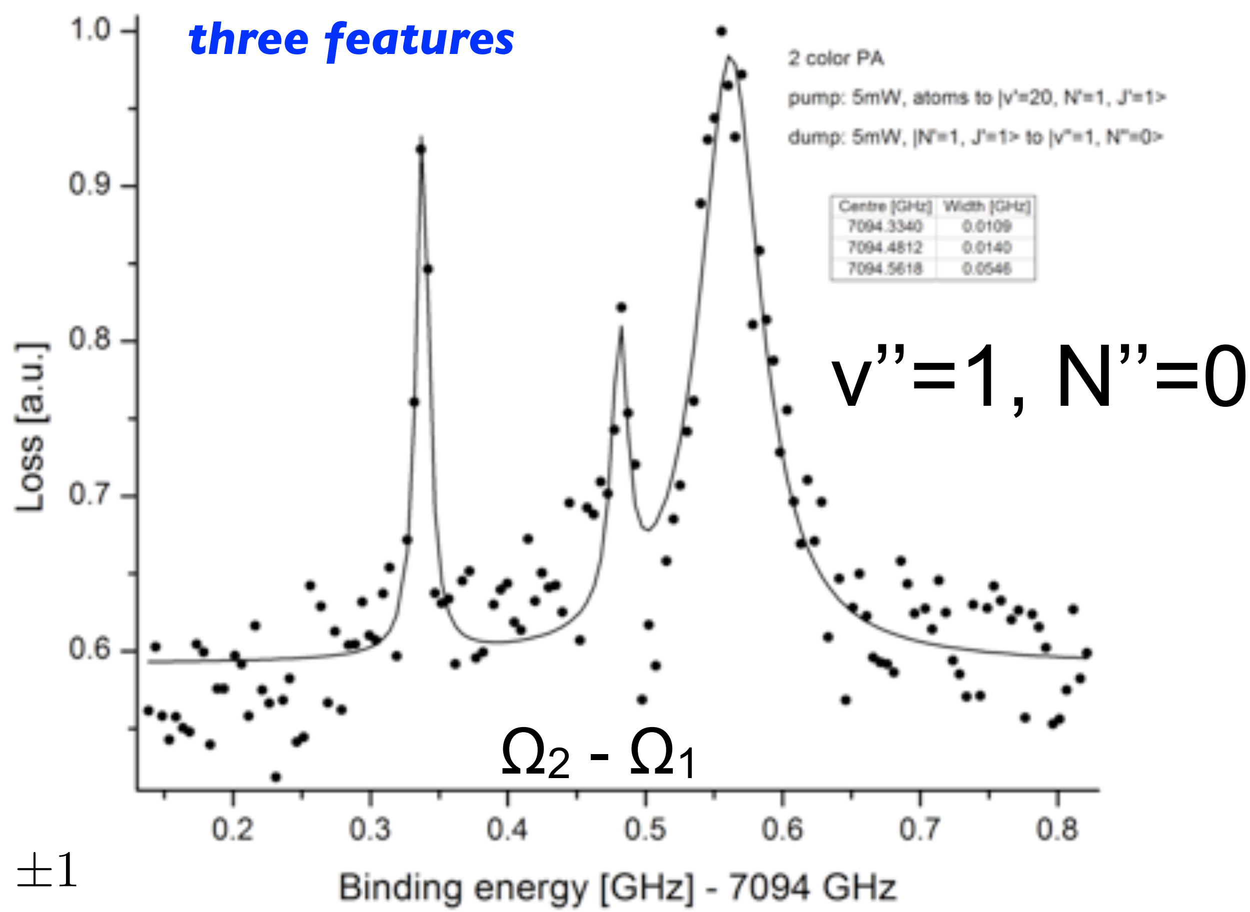
only one value of J



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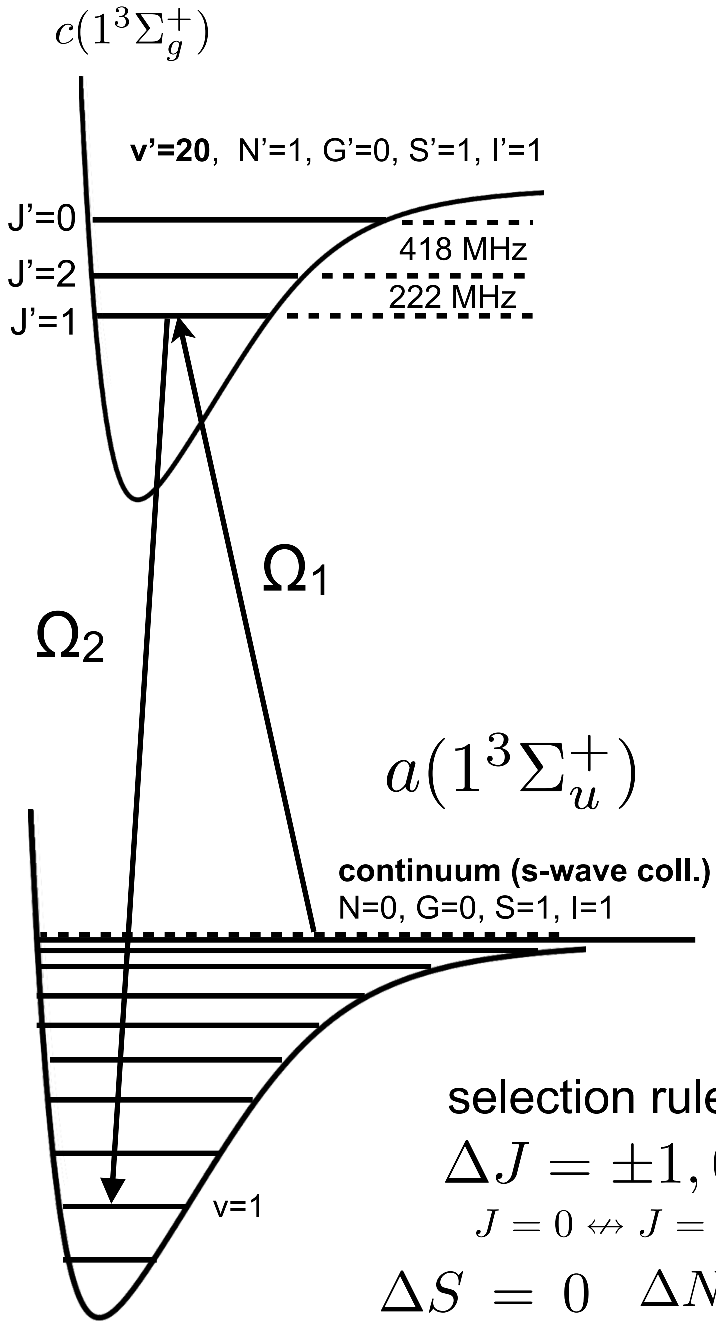

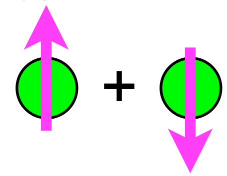

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only one value of J

F = I + S = 0, 1, 2 (expect three hyperfine levels)

selection rules

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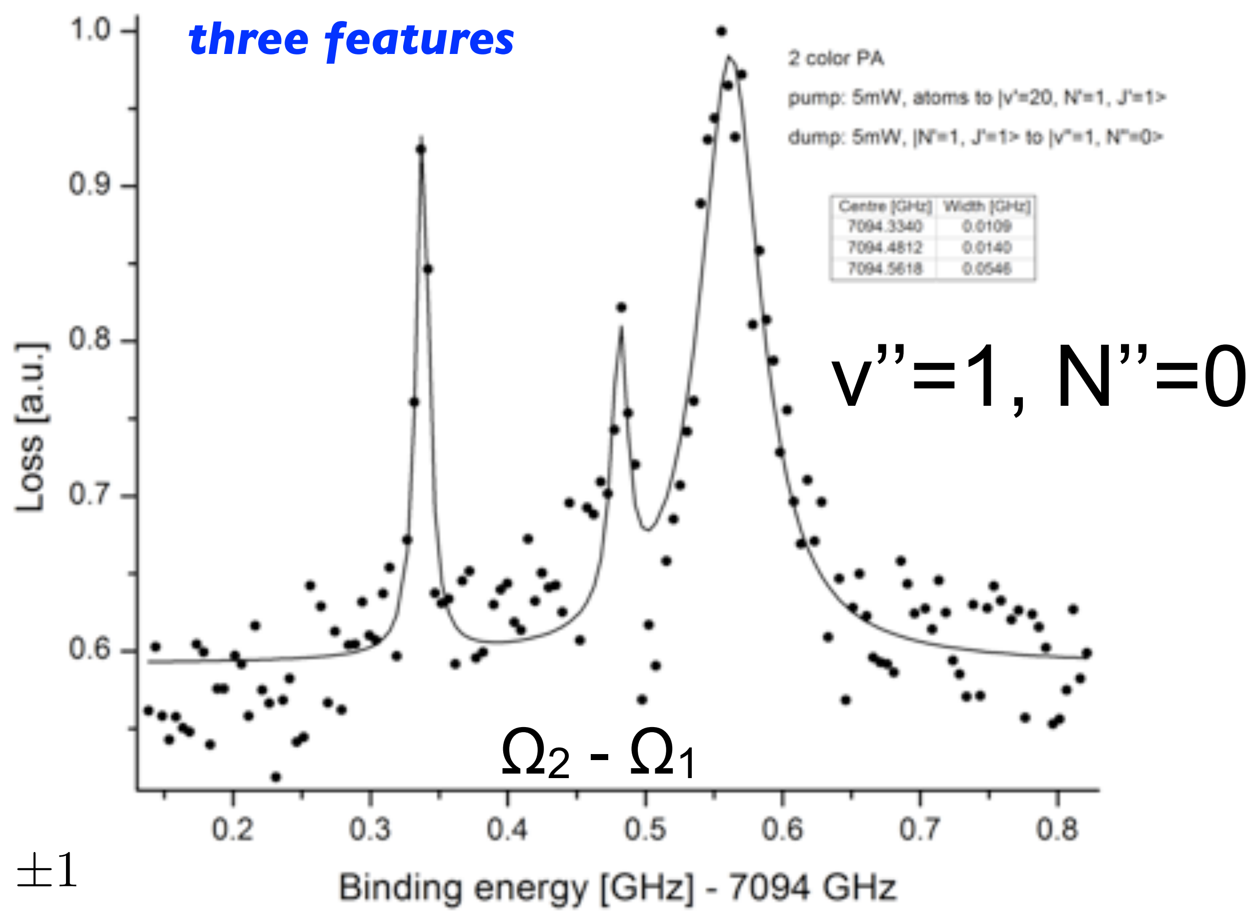

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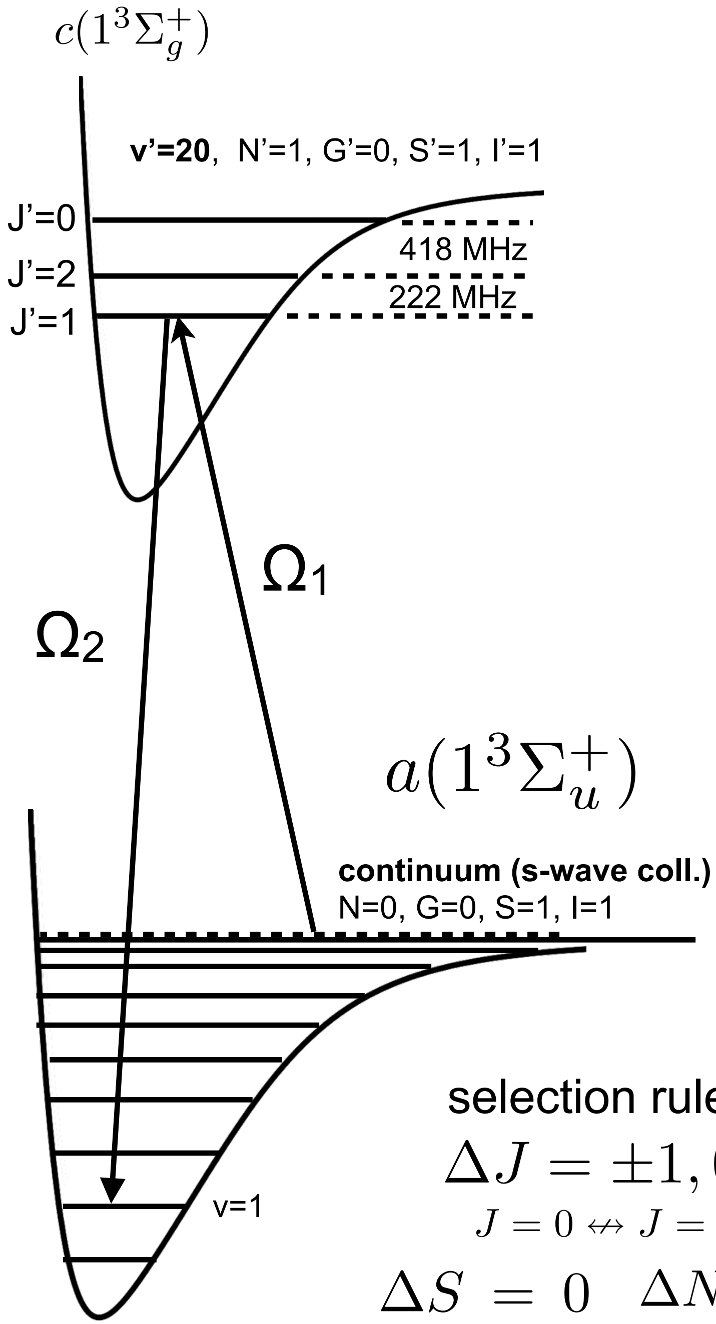

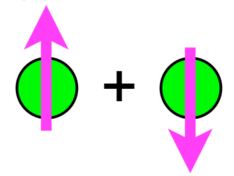

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only one value of J

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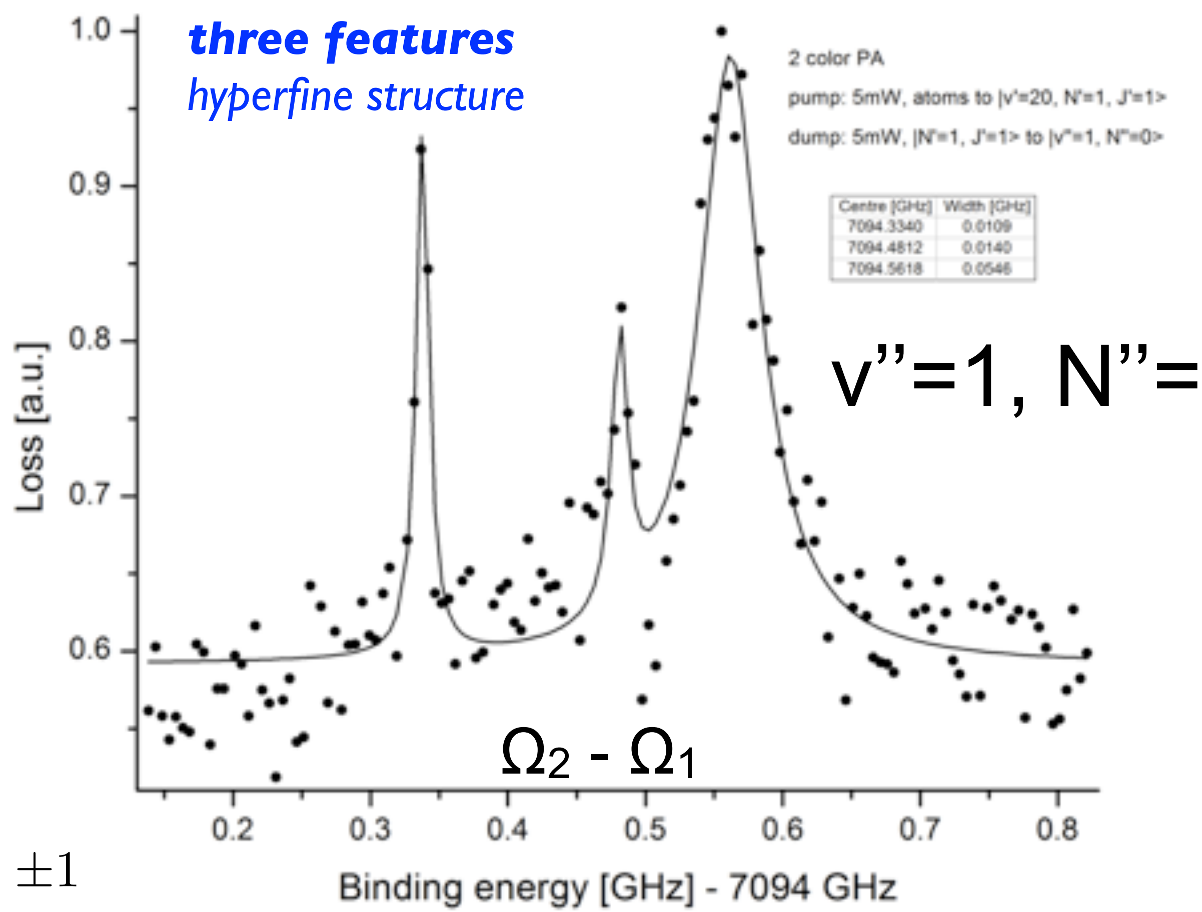

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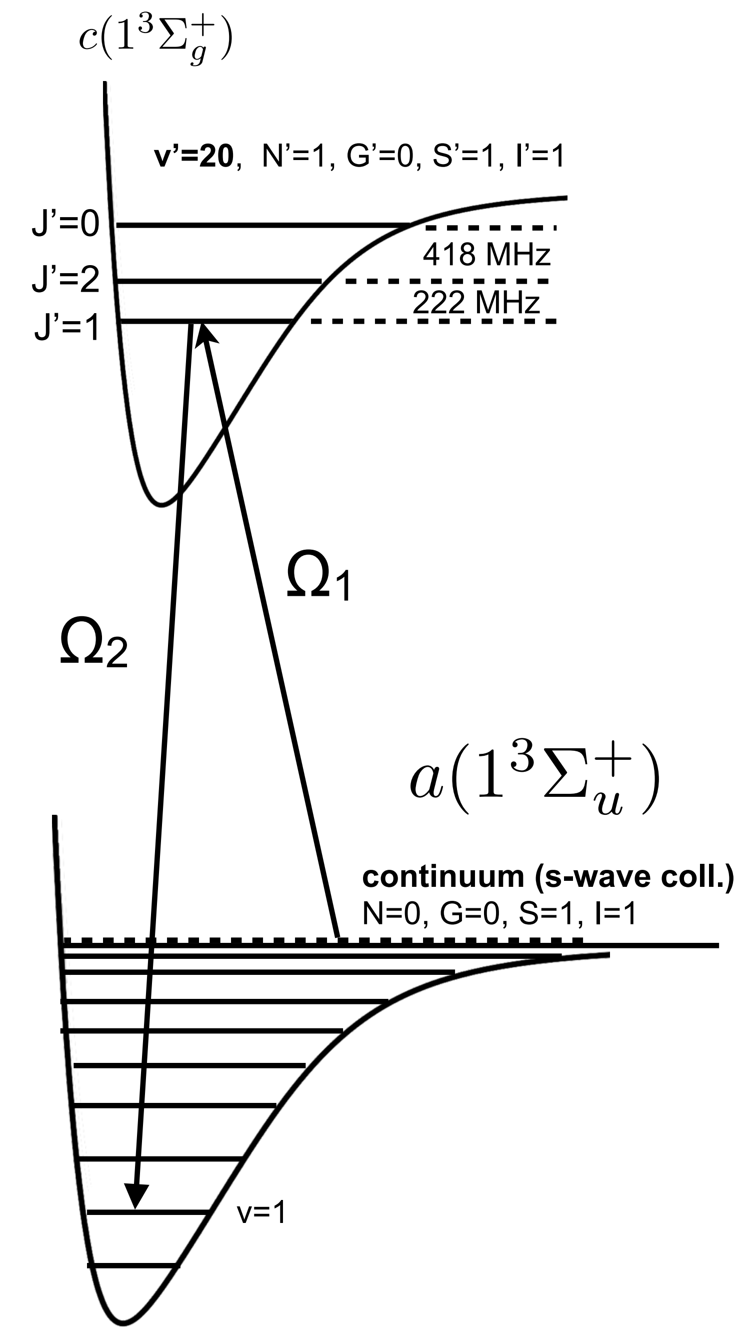

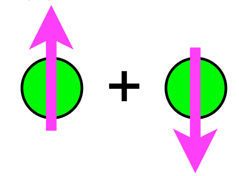

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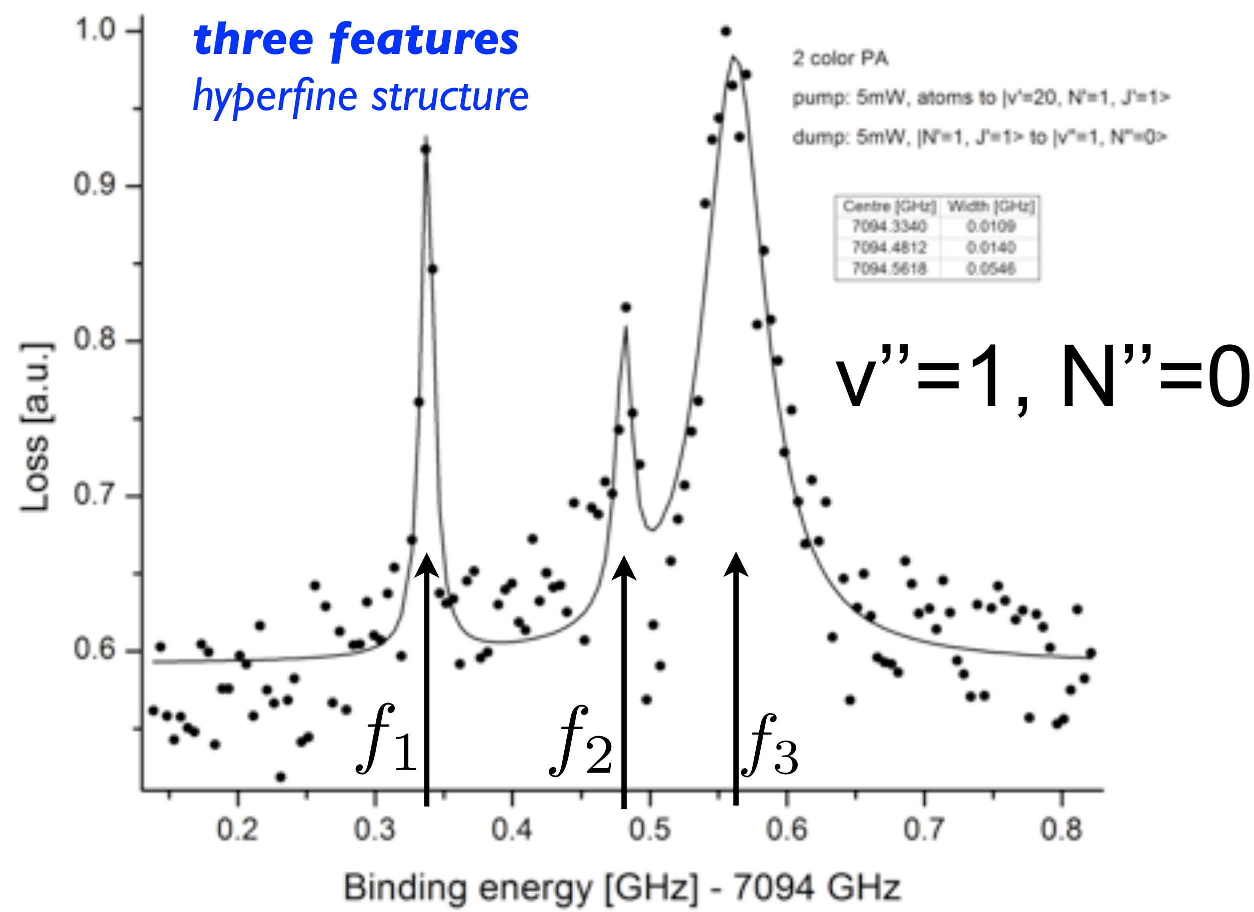
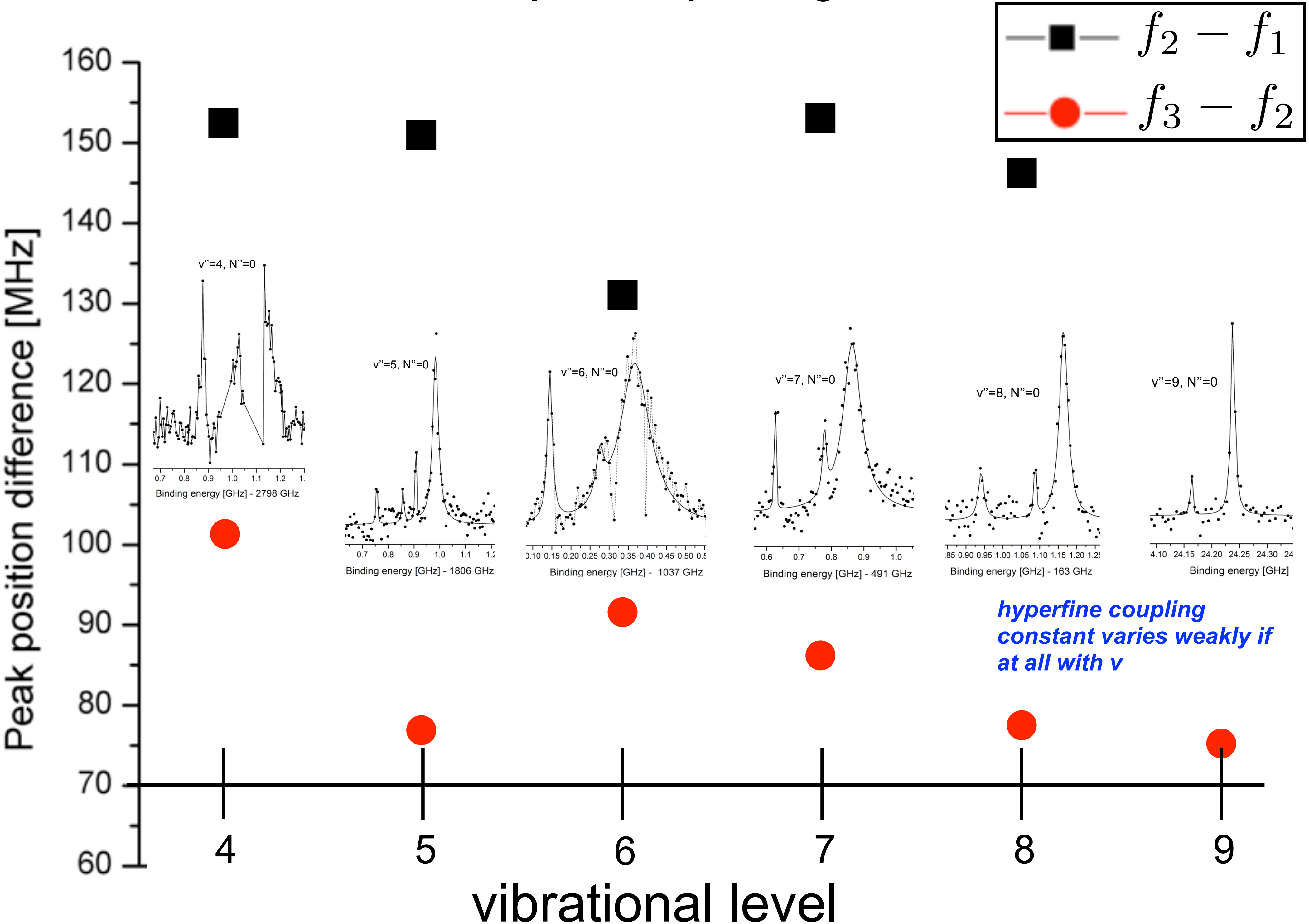


Centre [GHz]	Width [GHz]
7094.3340	0.0109
7094.4812	0.0140
7094.5618	0.0546

N=0 peak splittings



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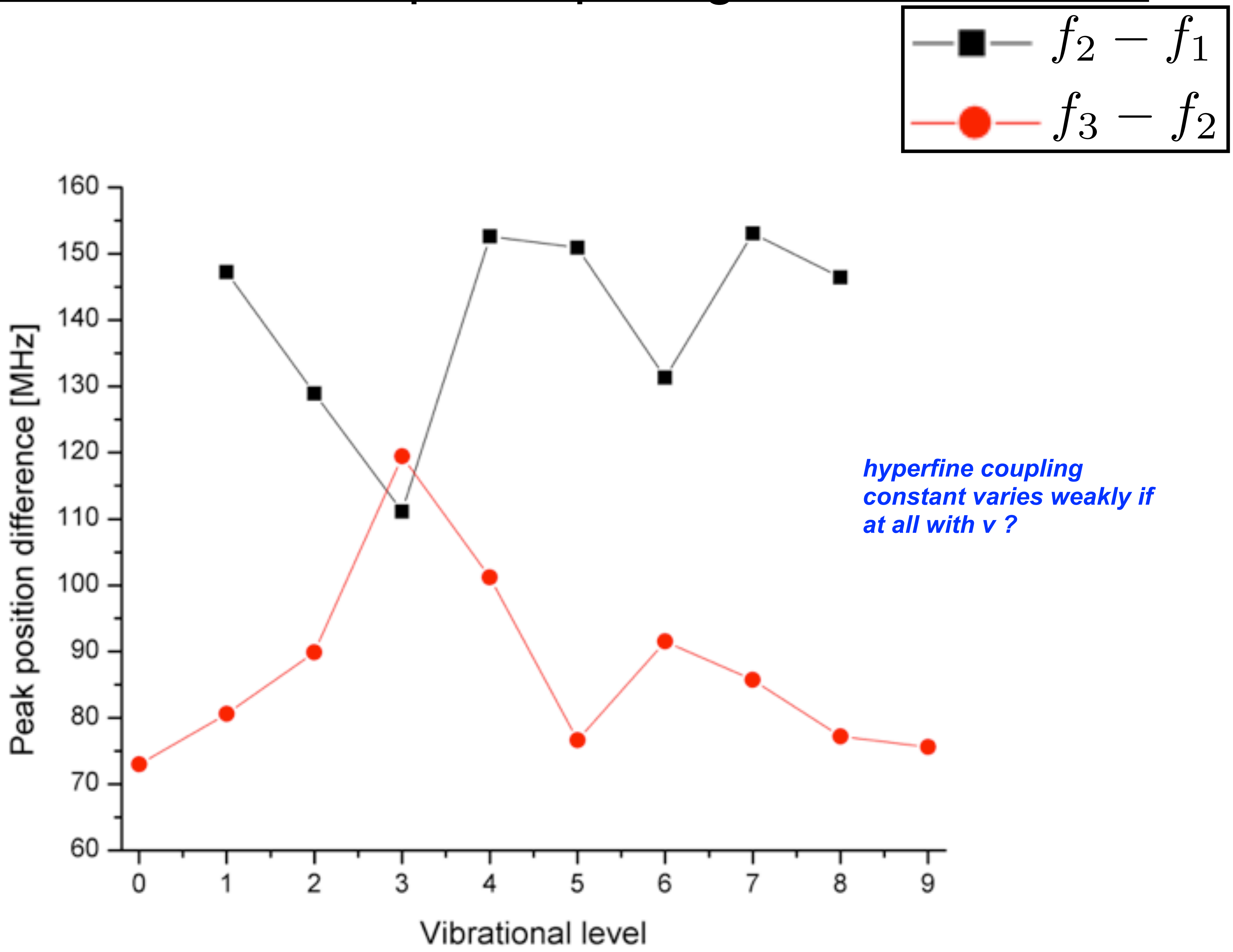
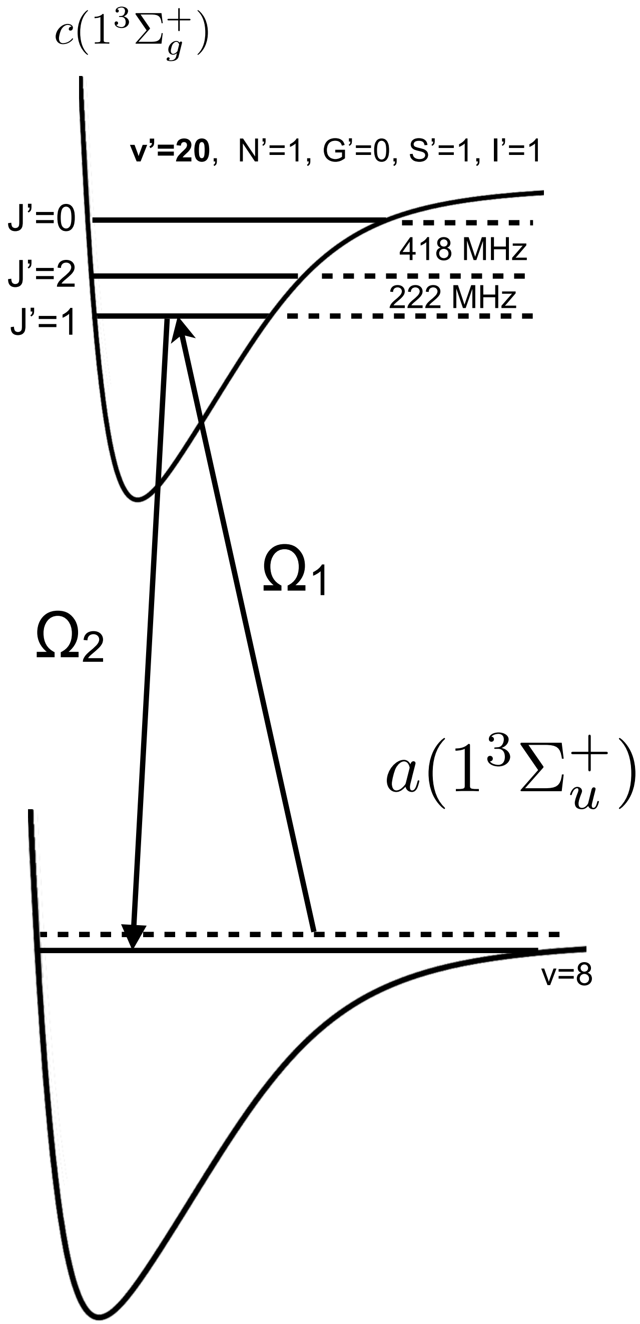
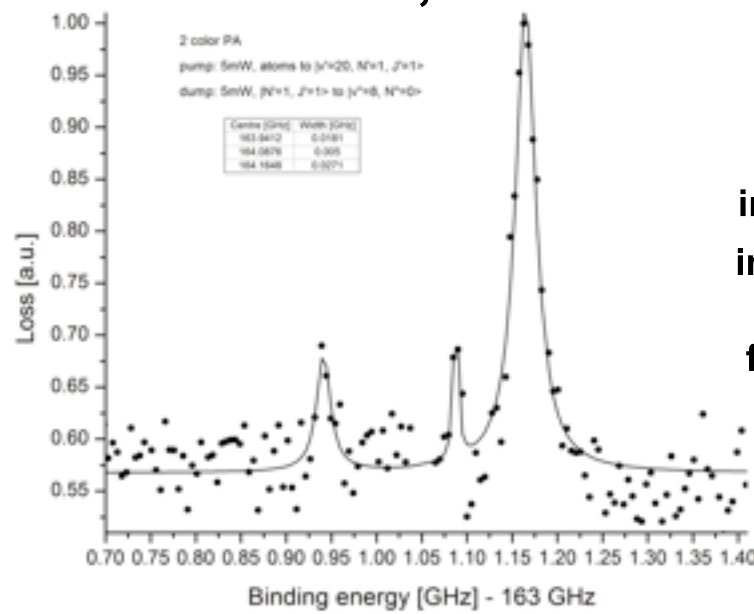


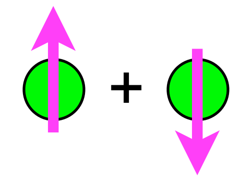
hyperfine coupling constant varies weakly if at all with v ?

2-color PA spectroscopy results : here Ω_1 is fixed and Ω_2 is scanned



v''=8, N''=0





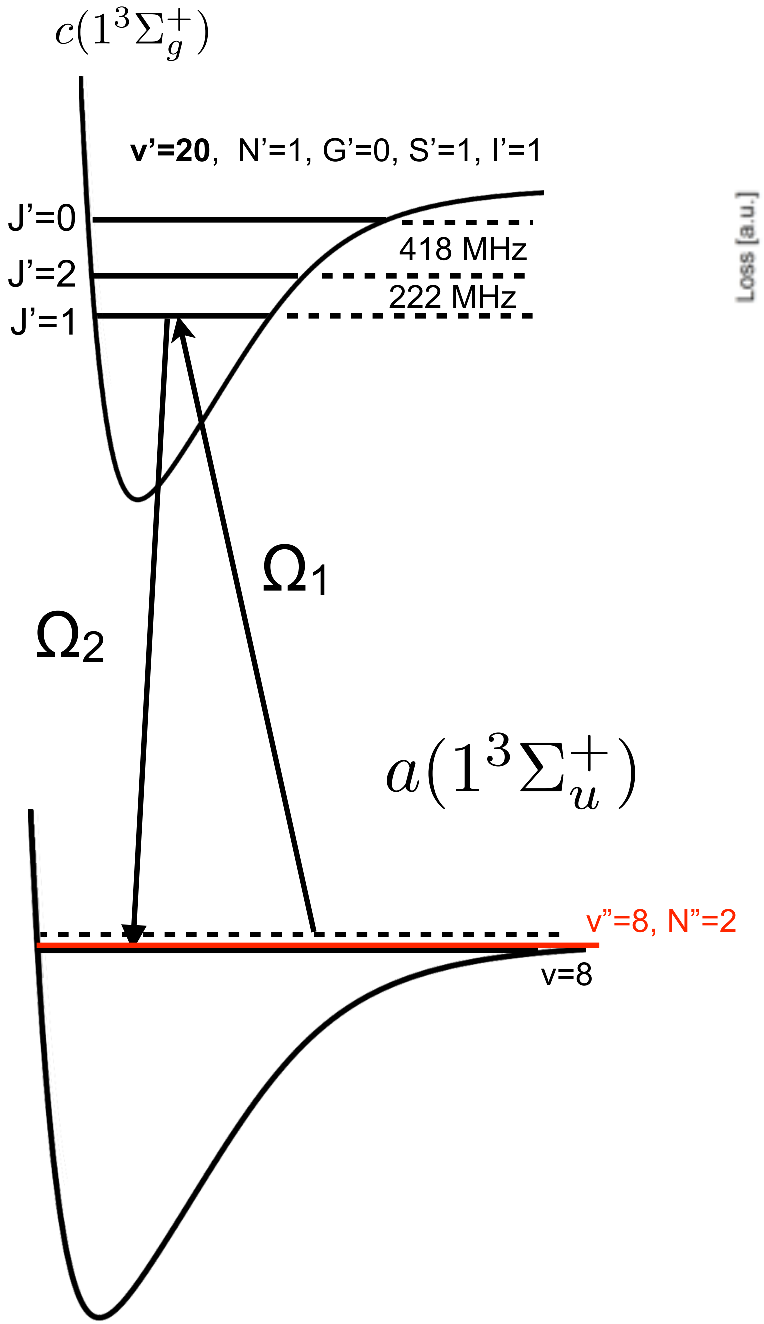
initial state |S=1,N=0,J=1,I=1>

intermediate: |S=1,N=1,J=1,I=1>

final: |S=1,N=0,J=1,I=1>

three features

2-color PA spectroscopy results : here Ω_1 is fixed and Ω_2 is scanned



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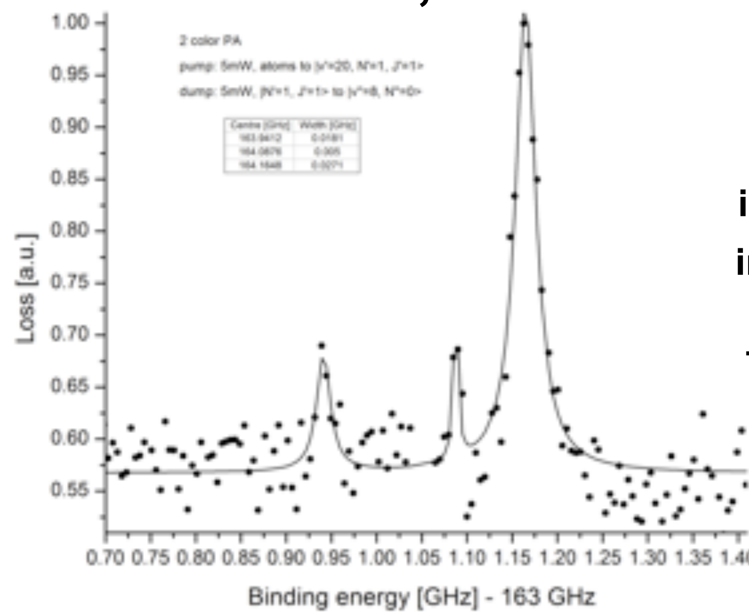
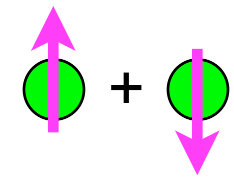




initial state |S=1,N=0,J=1,I=1>

intermediate: |S=1,N=1,J=1,I=1>

final: |S=1,N=0,J=1,I=1>

three features

v''=8, N''=2

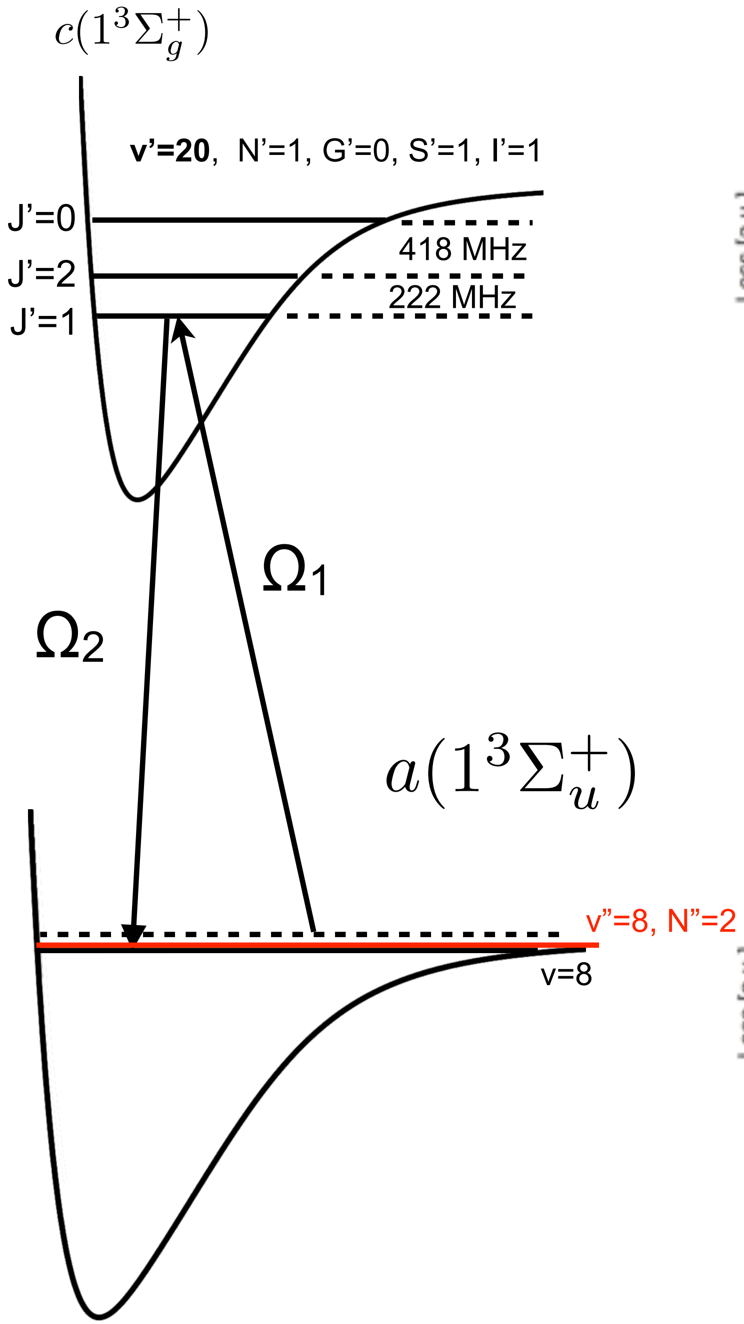
final state:
|S=1,N=2,J=1, I=1>

OR

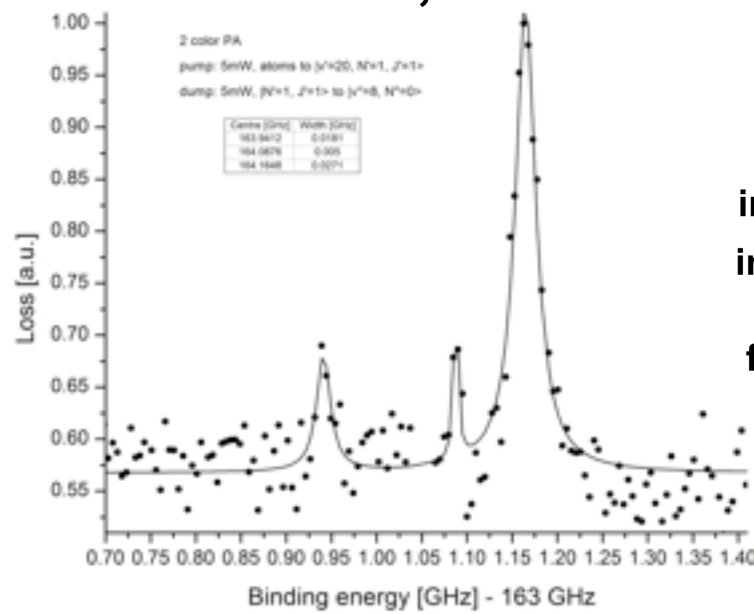
|S=1,N=2,J=2, I=1>

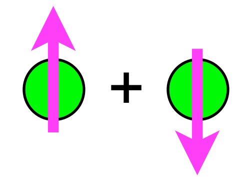
six features ?

2-color PA spectroscopy results : here Ω_1 is fixed and Ω_2 is scanned



v''=8, N''=0





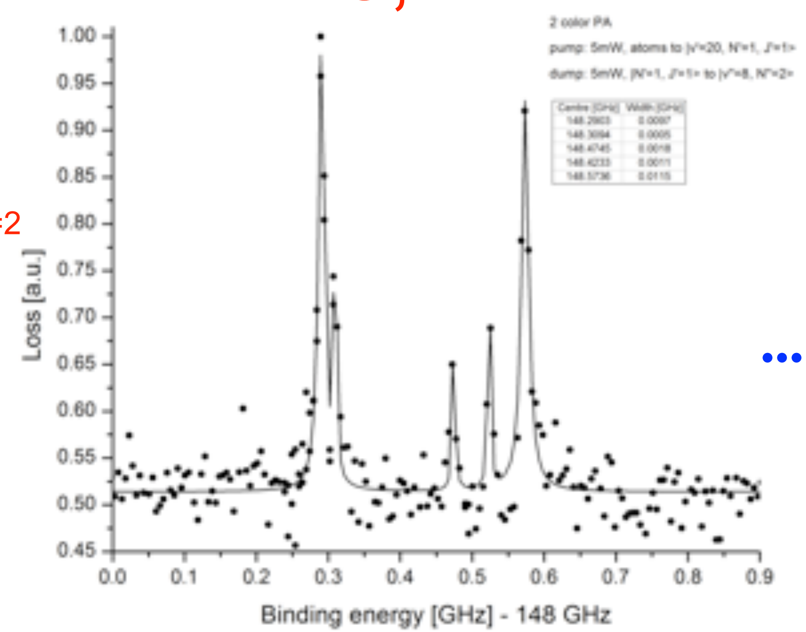
initial state |S=1,N=0,J=1,I=1>

intermediate: |S=1,N=1,J=1,I=1>

final: |S=1,N=0,J=1,I=1>

three features

v''=8, N''=2



final state:
|S=1,N=2,J=1, I=1>

OR

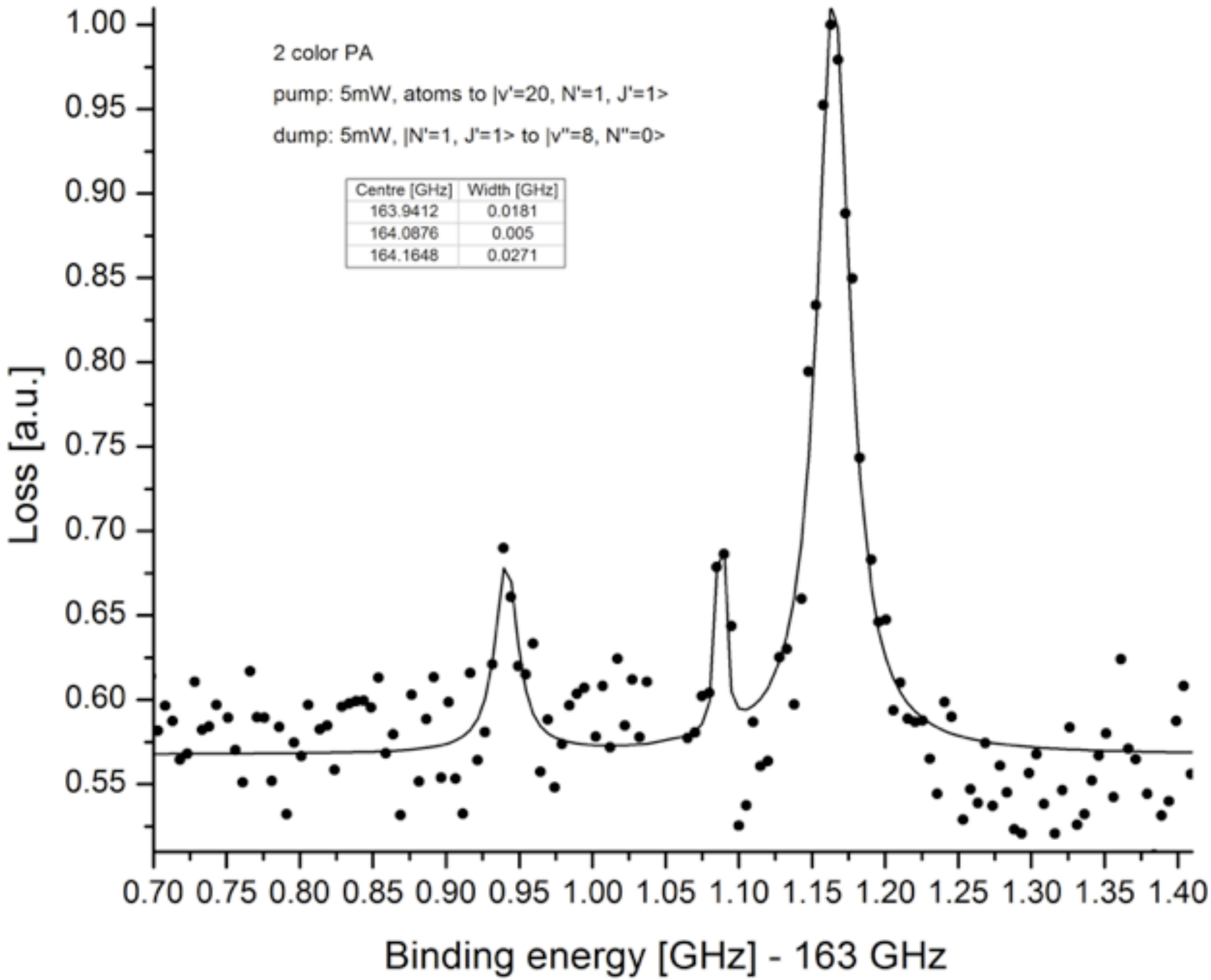
|S=1,N=2,J=2, I=1>

six features ?

... we see five features

2-color PA spectroscopy results : here Ω_1 is fixed and Ω_2 is scanned

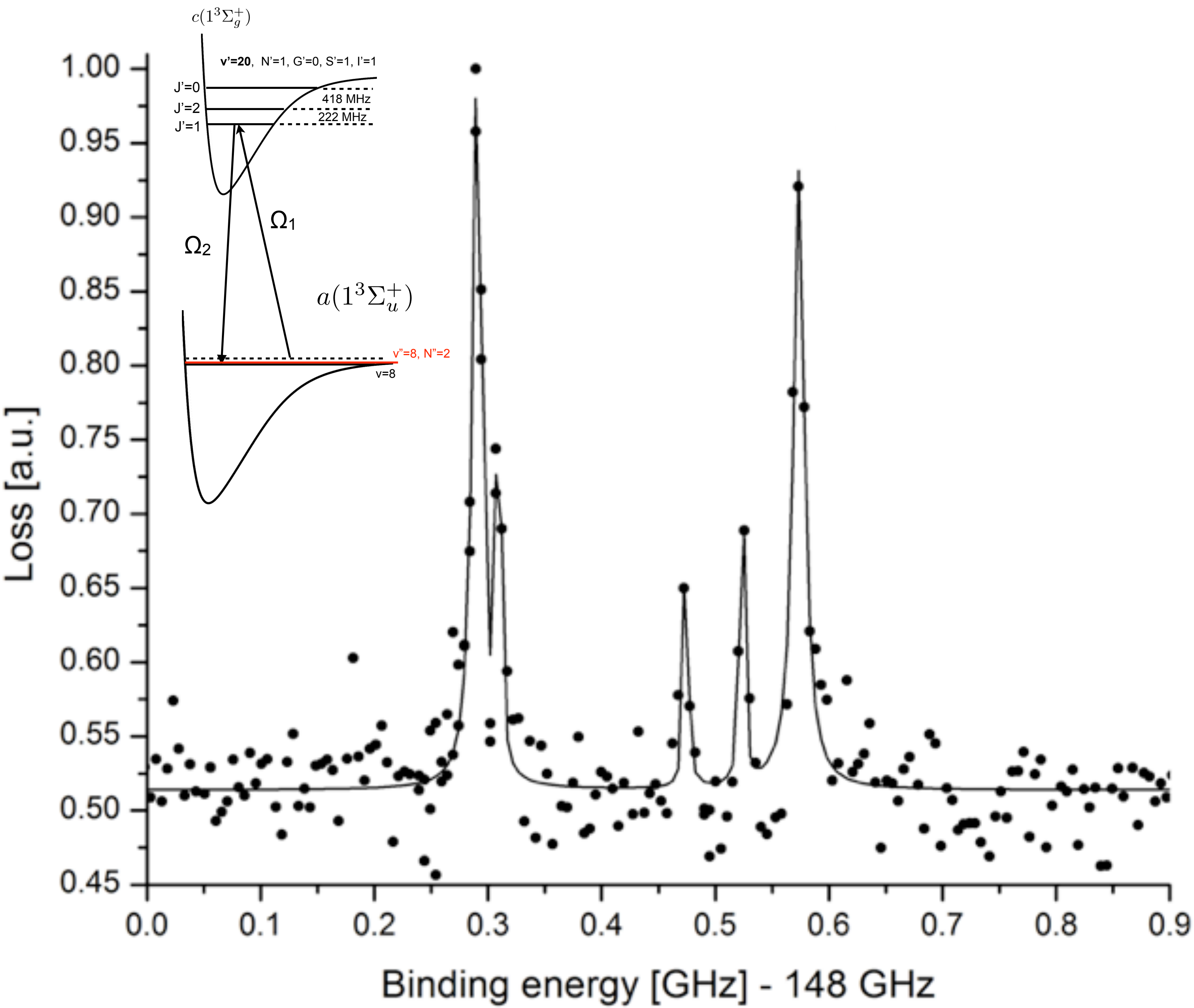
v''=8, N''=0



what follows is unchanged and what was presented, but after the talk Mariusz and Will sent me a correction : the data plotted in red were not obtained with Ω1 tuned to the J=0 state, rather it was obtained with Ω1 tuned to the J=2 state! So the conclusions are, as stated, incorrect.

2-color PA spectroscopy results : here Ω_1 is fixed and Ω_2 is scanned

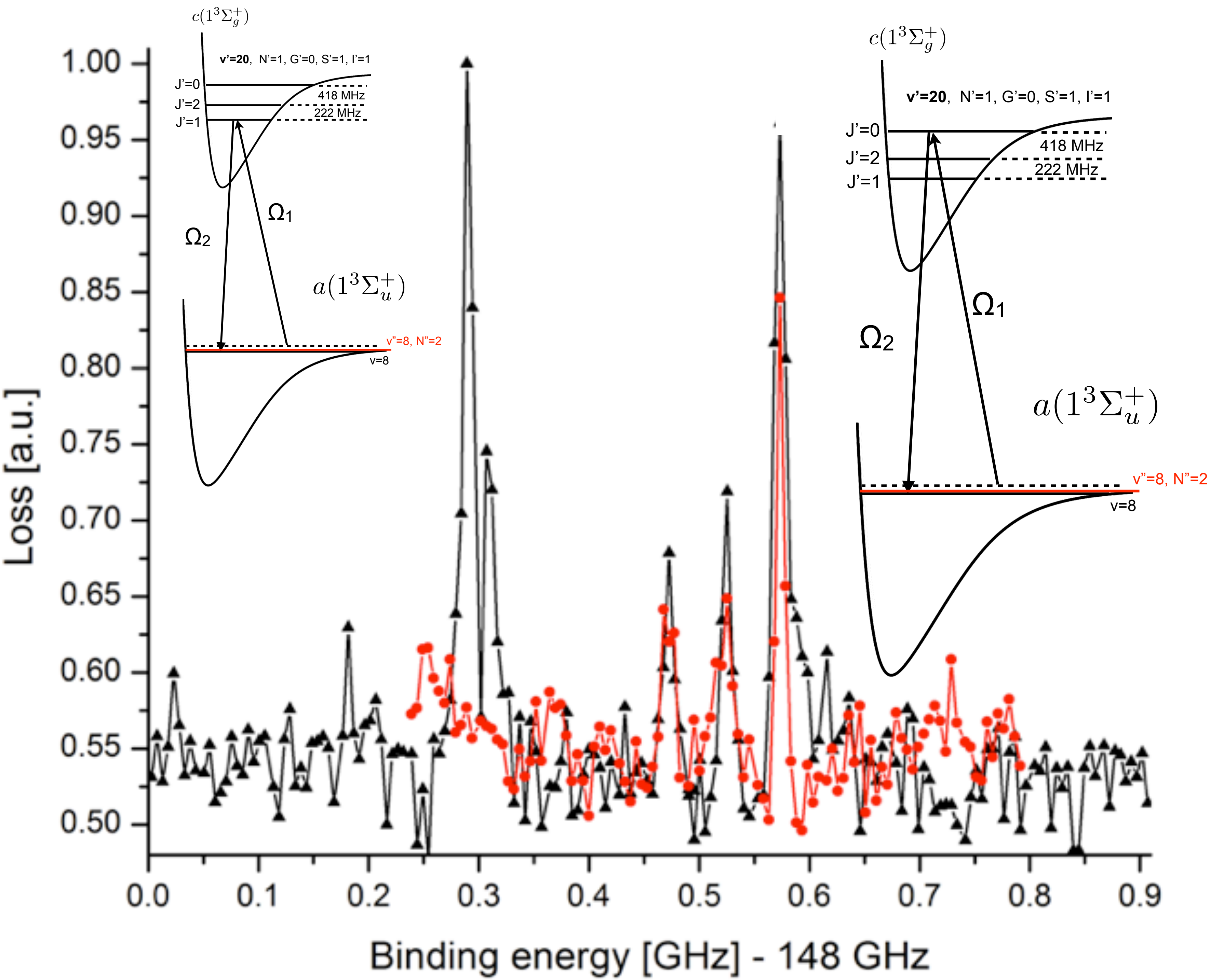
final: |S=1,N=2,J=1 or 2, I=1>



2-color PA spectroscopy results : here Ω_1 is fixed and Ω_2 is scanned

final: |S=1,N=2,J=1 or 2, I=1>

final state ONLY: |S=1,N=2,J=1, I=1>



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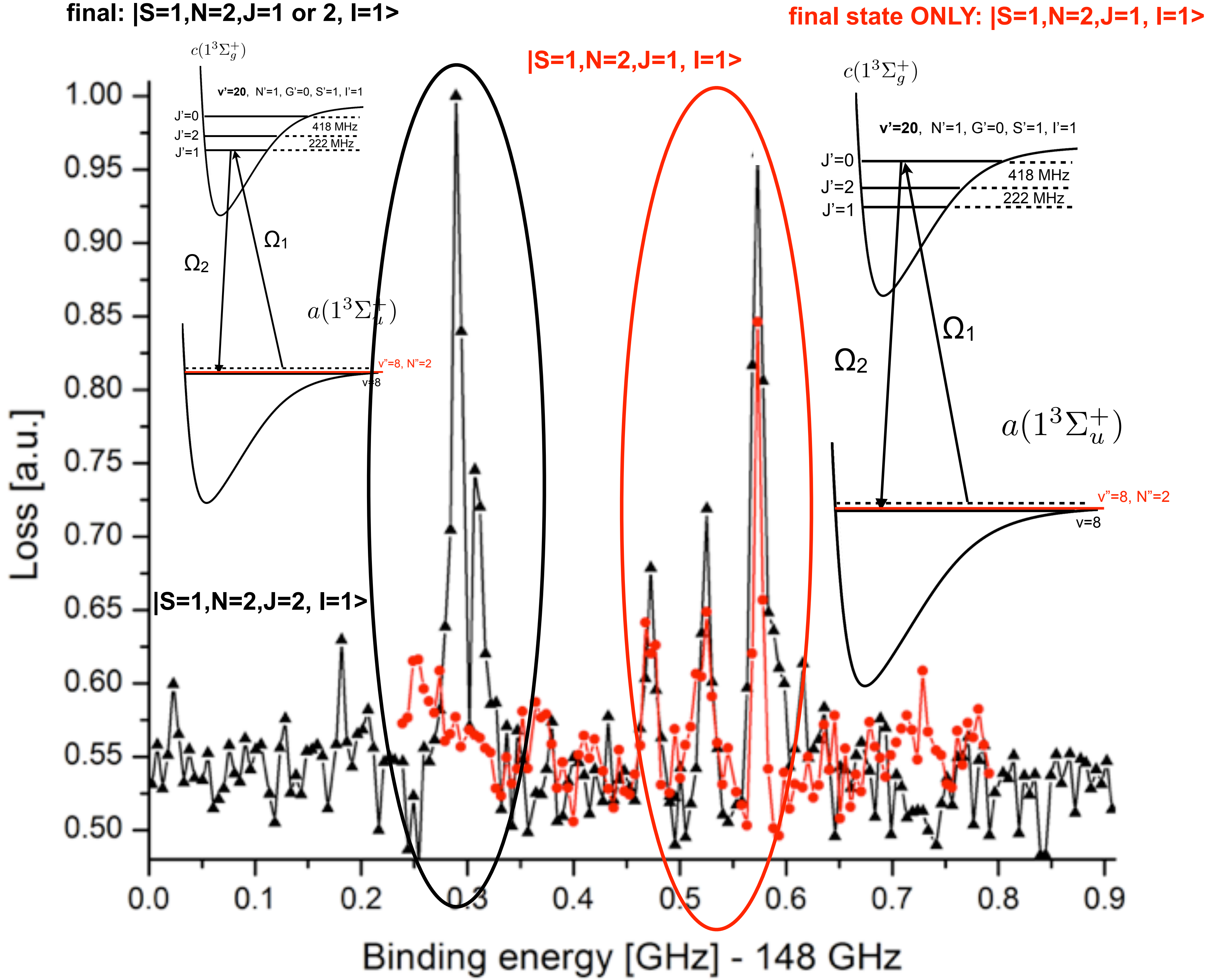

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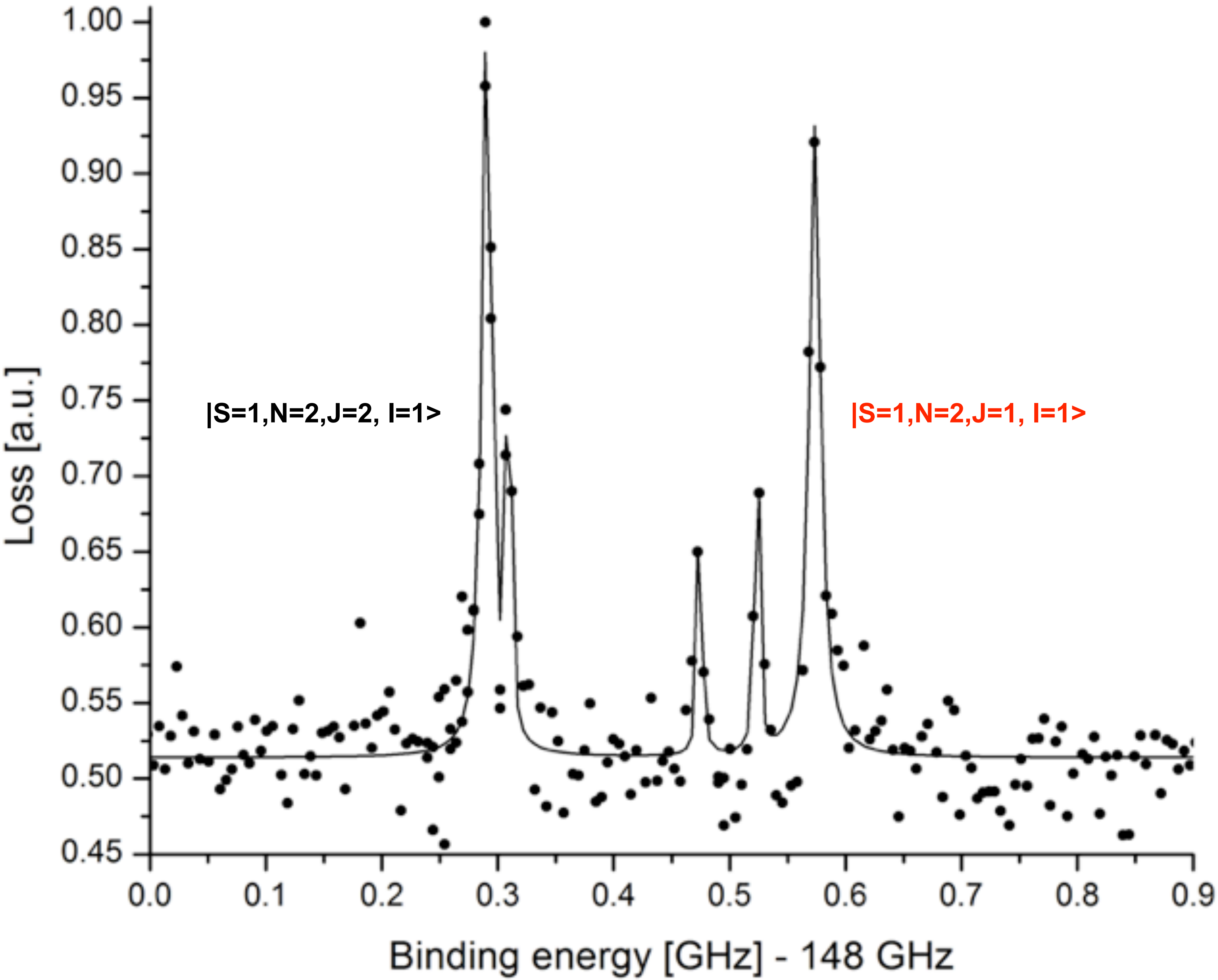
final: |S=1,N=2,J=1 or 2, I=1>



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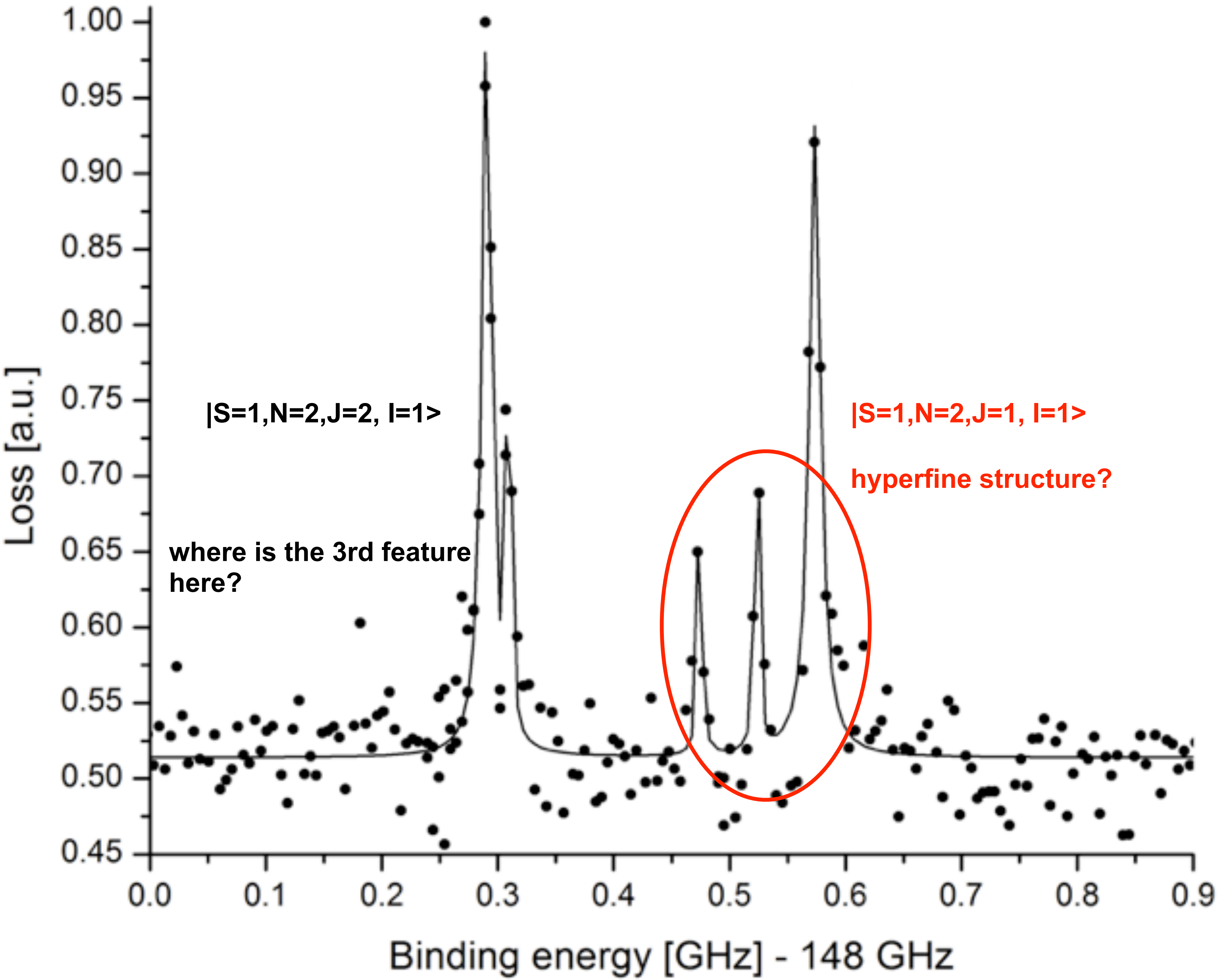

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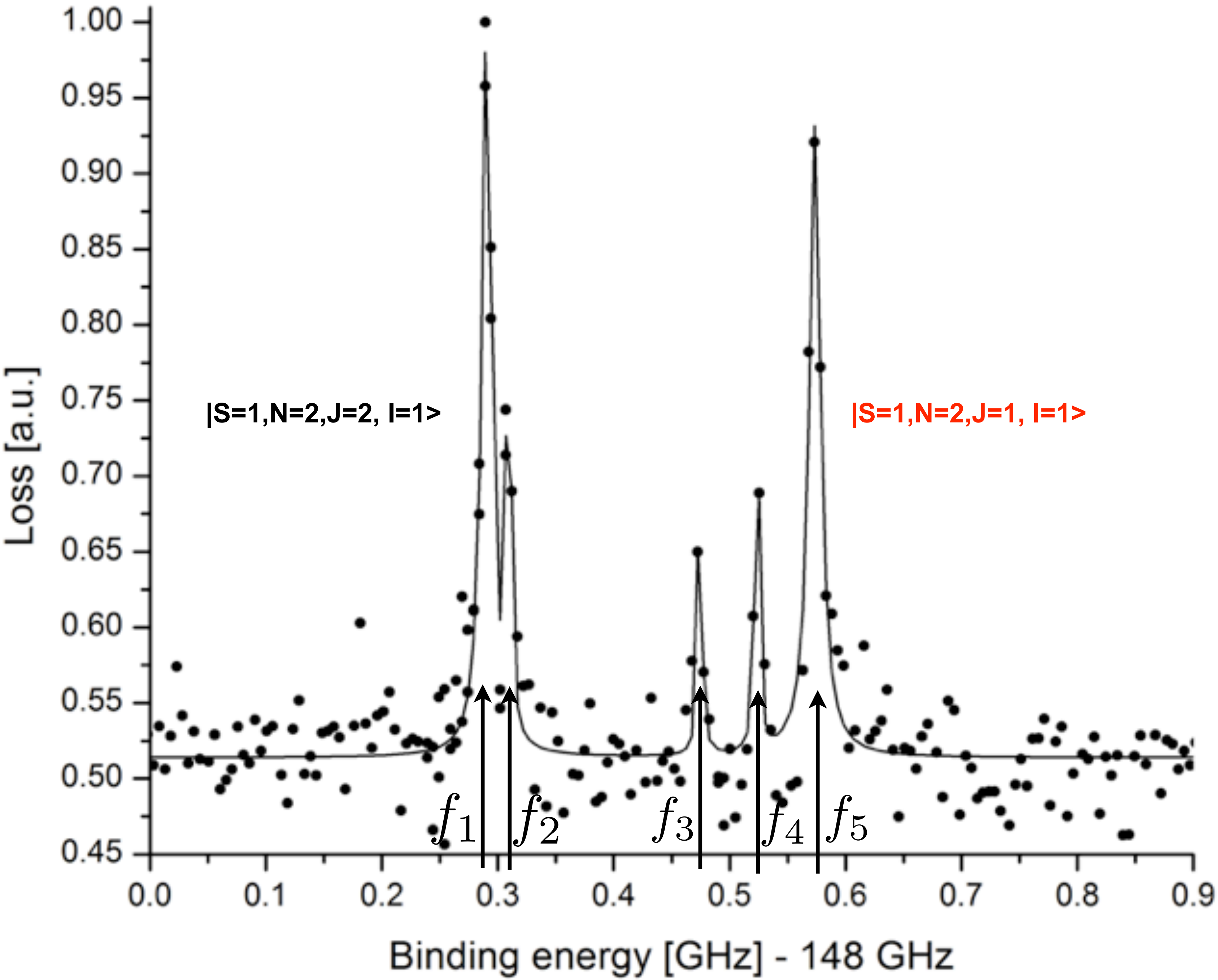
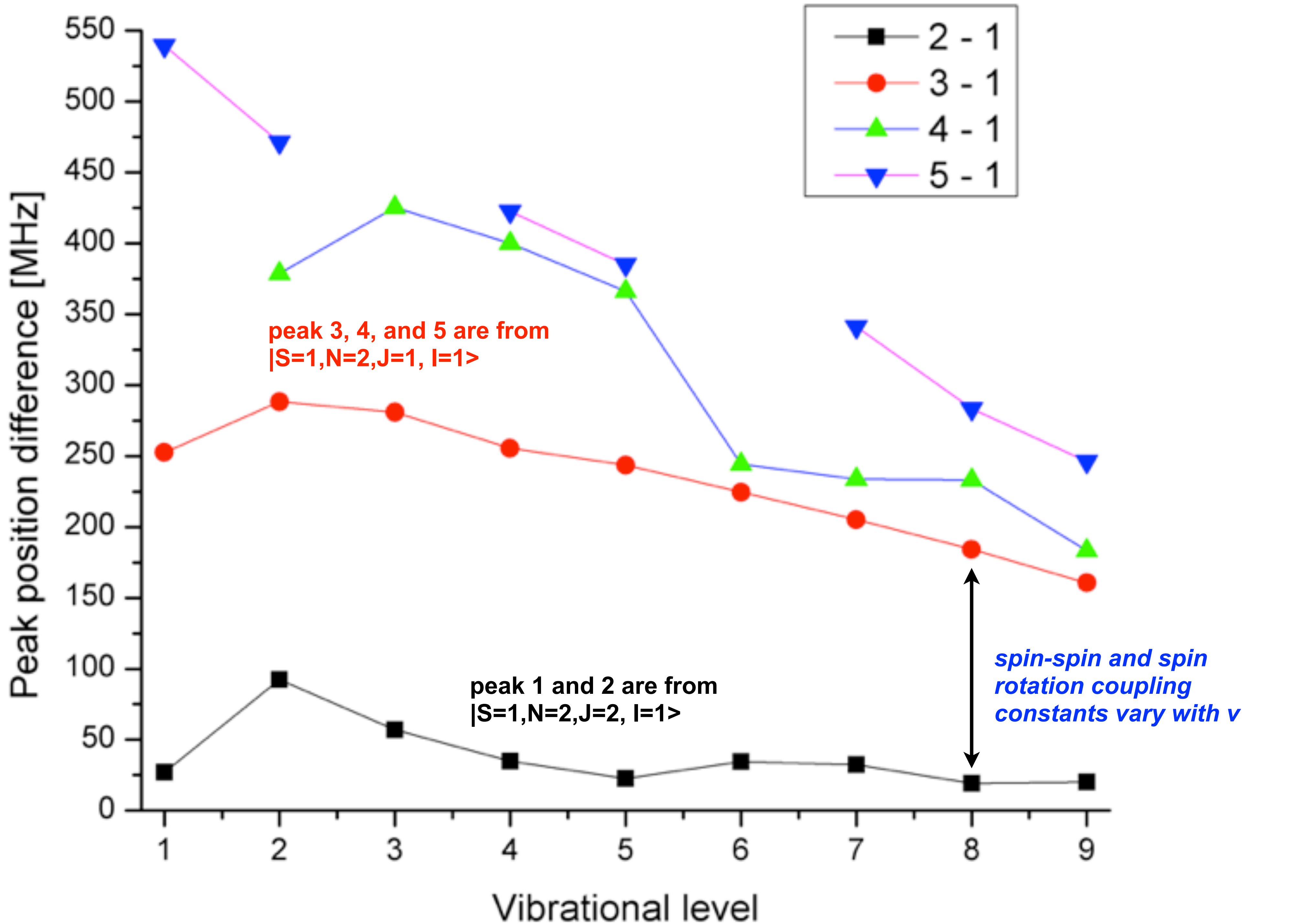
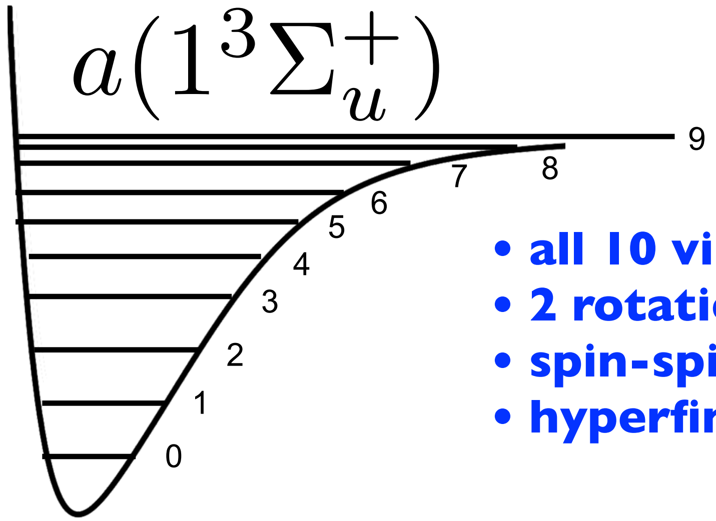




2 - 1
3 - 1
4 - 1
5 - 1
peak 3, 4, and 5 are from
|S=1,N=2,J=1, I=1>
peak 1 and 2 are from
|S=1,N=2,J=2, I=1>
spin-spin and spin
rotation coupling
constants vary with v
Peak position difference [MHz]
Vibrational level
0
50
100
150
200
250
300
350
400
450
500
550
1
2
3
4
5
6
7
8
9

Triplet ground state Li_2

Full characterization of the bound levels of the ground triplet state of $^6Li_2$



- all 10 vibrational levels found
- 2 rotational levels for each vibrational level (N”=0, N”=2)
- spin-spin and spin-rotation splitting of J levels observed
- hyperfine structure resolved

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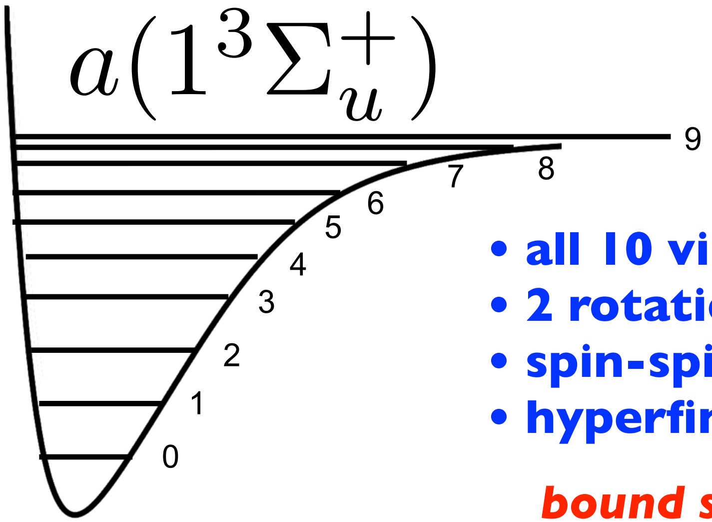
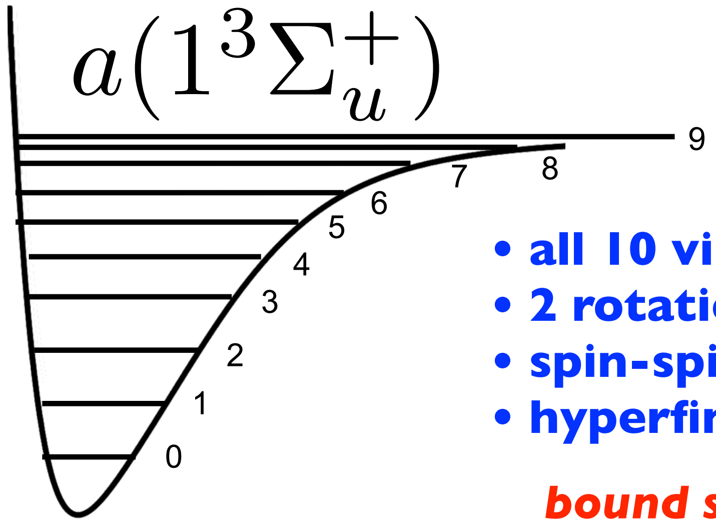


- **all 10 vibrational levels found**
- **2 rotational levels for each vibrational level (N”=0, N”=2)**
- **spin-spin and spin-rotation splitting of J levels observed**
- **hyperfine structure resolved**

bound state energy resolution < 500 kHz (< 100 kHz)

Triplet ground state Li_2

Full characterization of the bound levels of the ground triplet state of $^6Li_2$



- **all 10 vibrational levels found**
- **2 rotational levels for each vibrational level (N”=0, N”=2)**
- **spin-spin and spin-rotation splitting of J levels observed**
- **hyperfine structure resolved**

bound state energy resolution < 500 kHz (< 100 kHz)

the ground triplet state of Li is now the most accurately known molecular potential.

Triplet ground state Li_2

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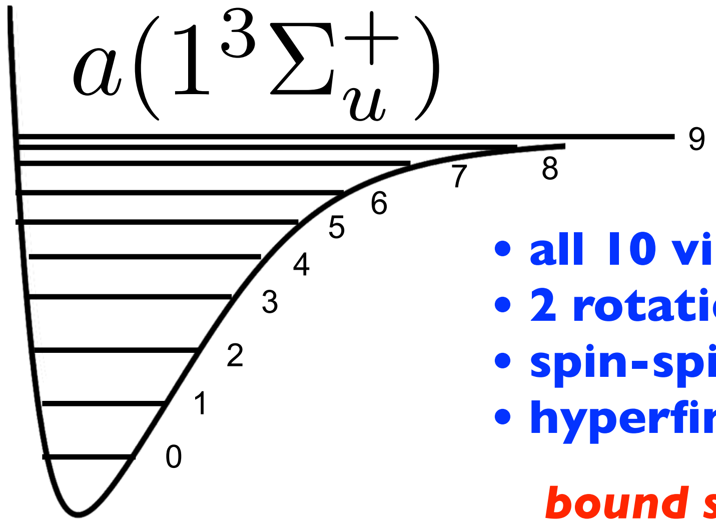

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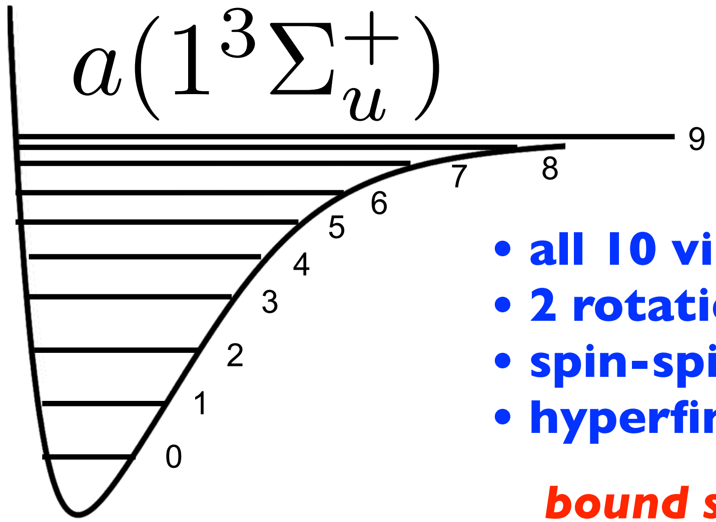

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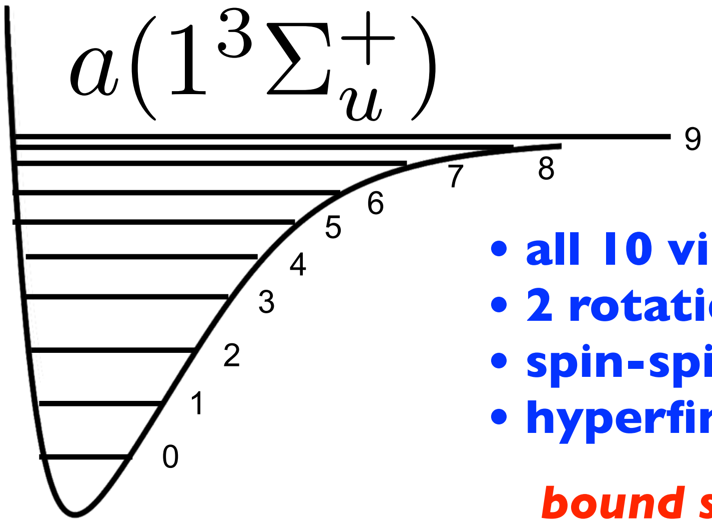

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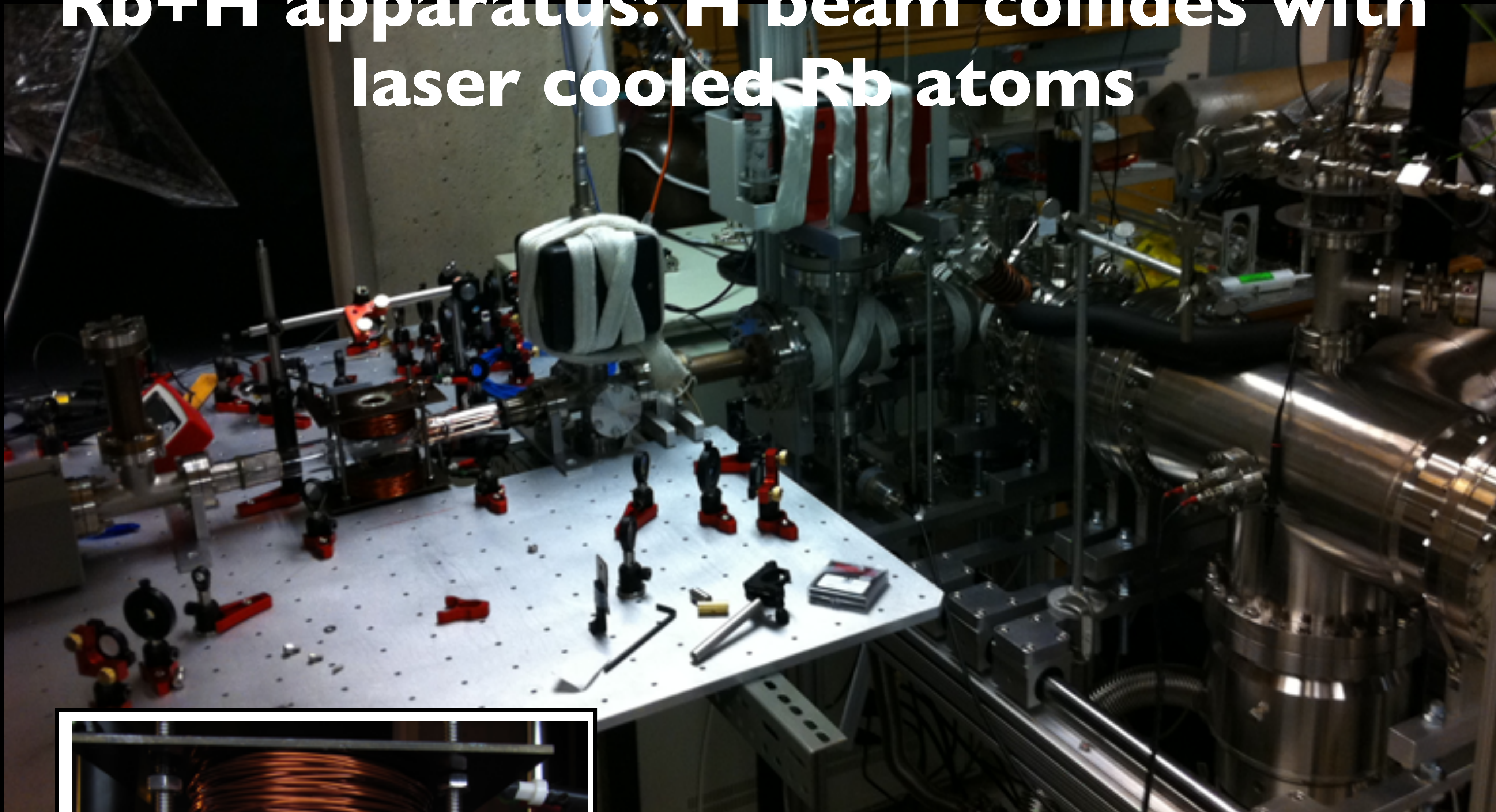
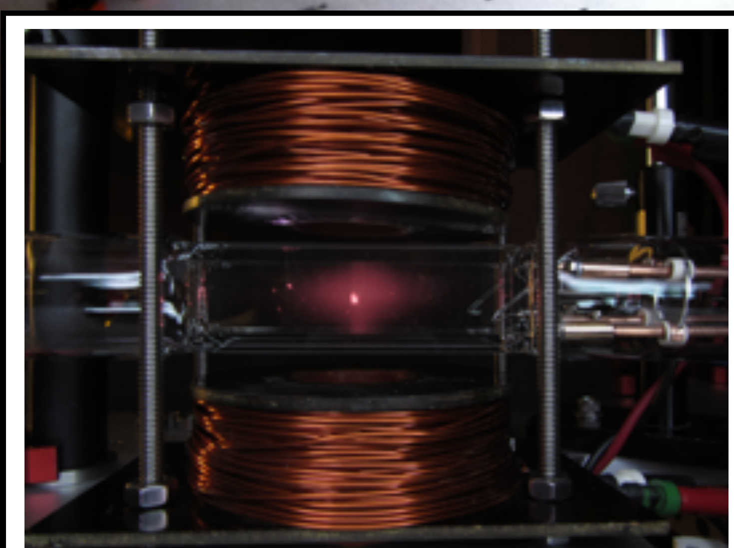
fin

Rb+H apparatus: H beam collides with laser cooled Rb atoms





Collaboration with
Takamasa Momose (UBC CHEM)

A new twist on Feshbach resonances: *polar* collision + *electric* field

PRL **96,** 123202 (2006) PHYSICAL REVIEW LETTERS week ending 31 MARCH 2006

Controlling Collisions of Ultracold Atoms with dc Electric Fields

R. V. Krems*
Department of Chemistry, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada

PHYSICAL REVIEW A **75**, 032709 (2007)

Electric-field-induced Feshbach resonances in ultracold alkali-metal mixtures

Z. Li and R. V. Krems*
Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

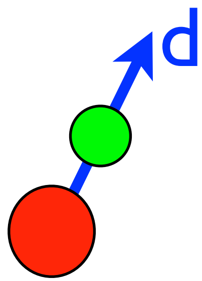
PHYSICAL REVIEW A **79**, 042711 (2009)

Effects of electric fields on heteronuclear Feshbach resonances in ultracold ^{6}Li-^{87}Rb mixtures

Z. Li[1] and K. W. Madison[2]

... a new twist on Feshbach resonances

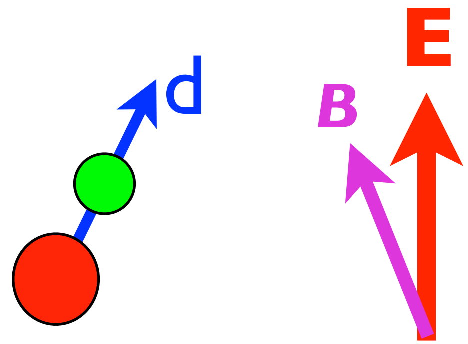
polar collision



A heteronuclear collision complex has an instantaneous electric dipole moment

... a new twist on Feshbach resonances

polar collision + electric field



A heteronuclear collision complex has an instantaneous electric dipole moment

... and this electric dipole is coupled to an external electric field

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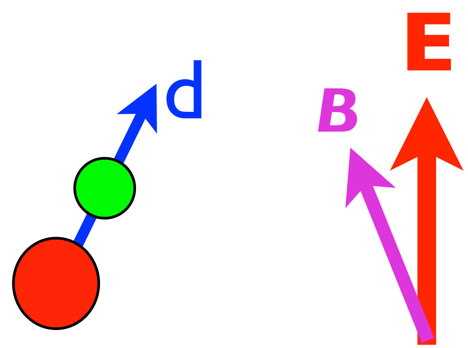
polar collision + electric field



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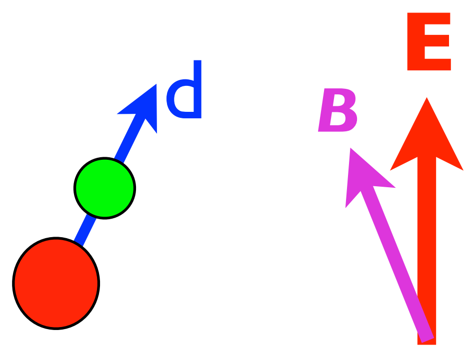
... and this electric dipole is coupled to an external electric field

$$\hat{V}_E(R) = -\vec{E} \cdot \vec{d} = -E(\hat{e}_E \cdot \hat{e}_d) \sum_S \sum_{M_S} |S M_S\rangle d_S(R) \langle S M_S|$$

this operator couples different partial wave states: $l = l' \pm 1$

... a new twist on Feshbach resonances

polar collision + electric field



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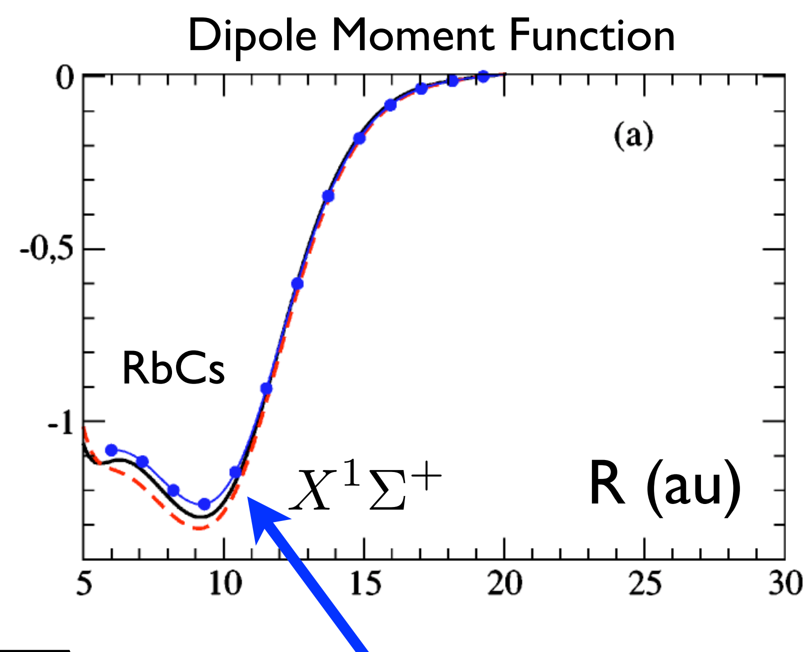

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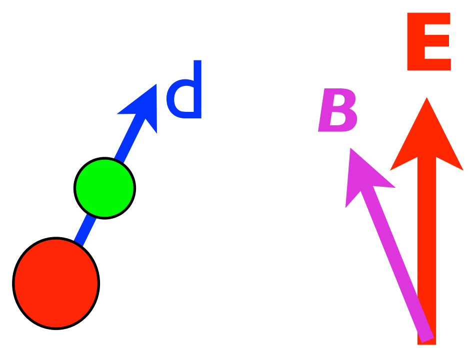


- induce new Feshbach resonances

  mixing of partial waves

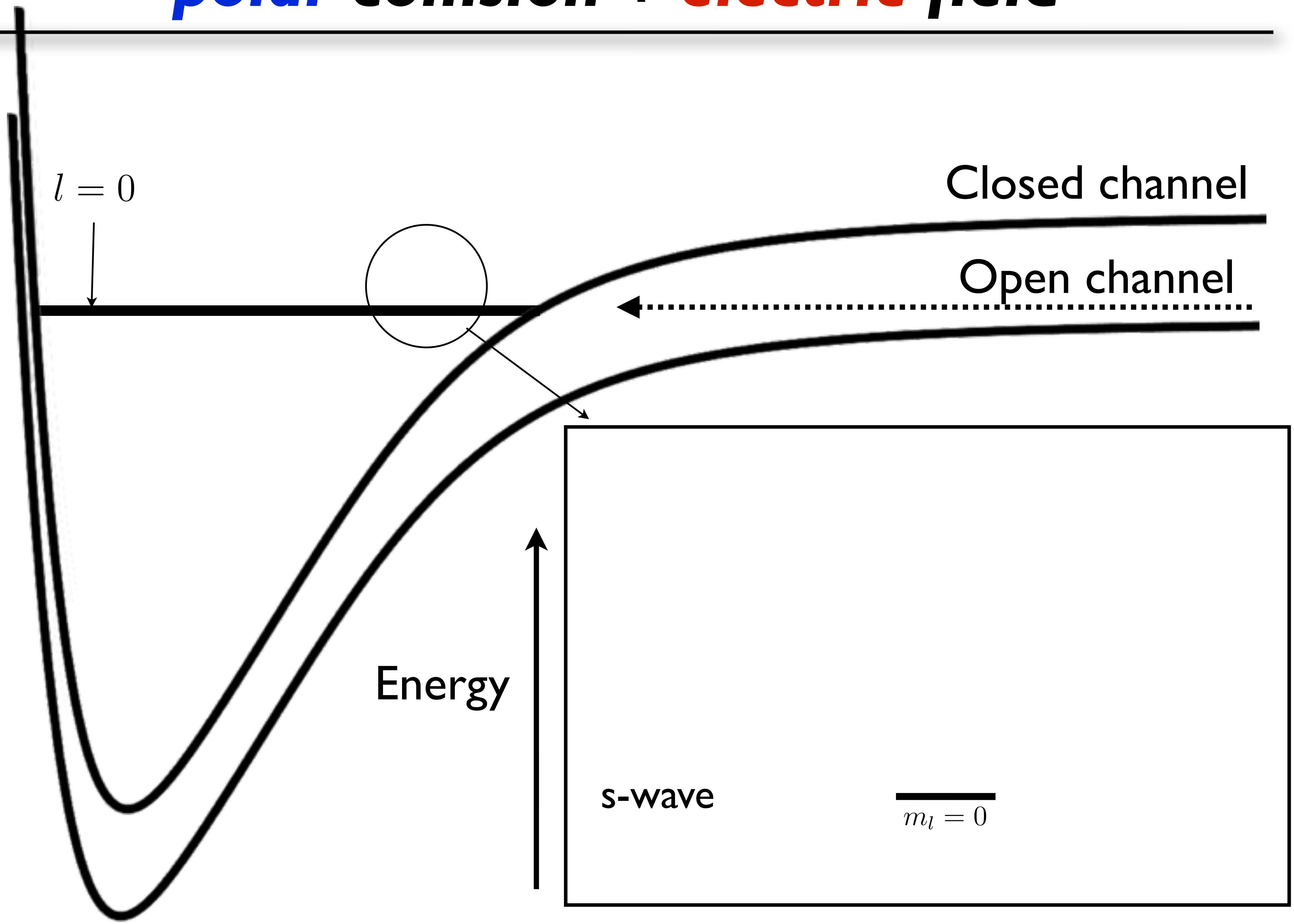
- shift position of intrinsic resonances

  bound state level repulsion

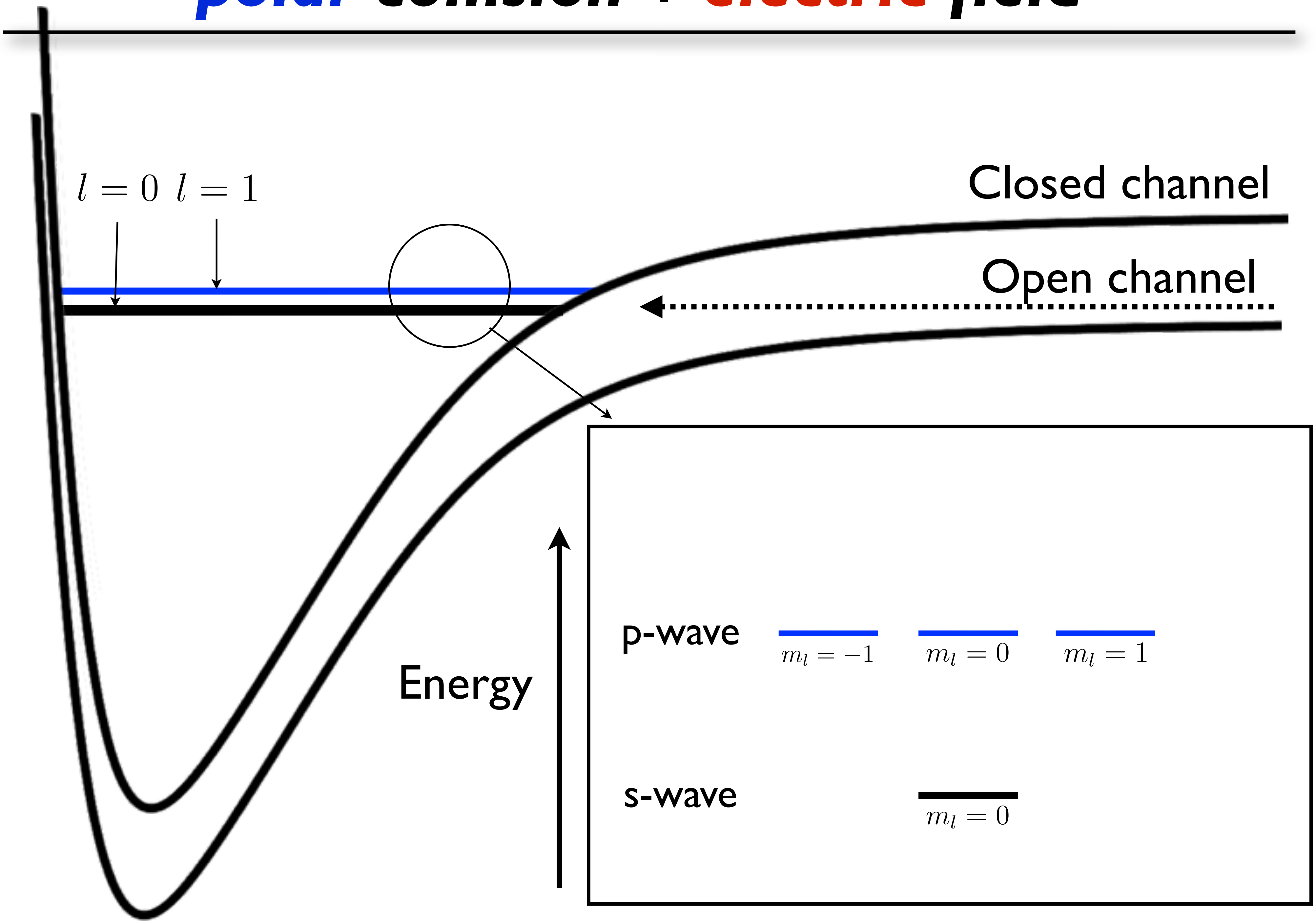
- split resonances into l+1 multiplets

tunable anisotropic interactions

A new twist on Feshbach resonances: *polar* collision + *electric* field



A new twist on Feshbach resonances:
polar collision + *electric field*



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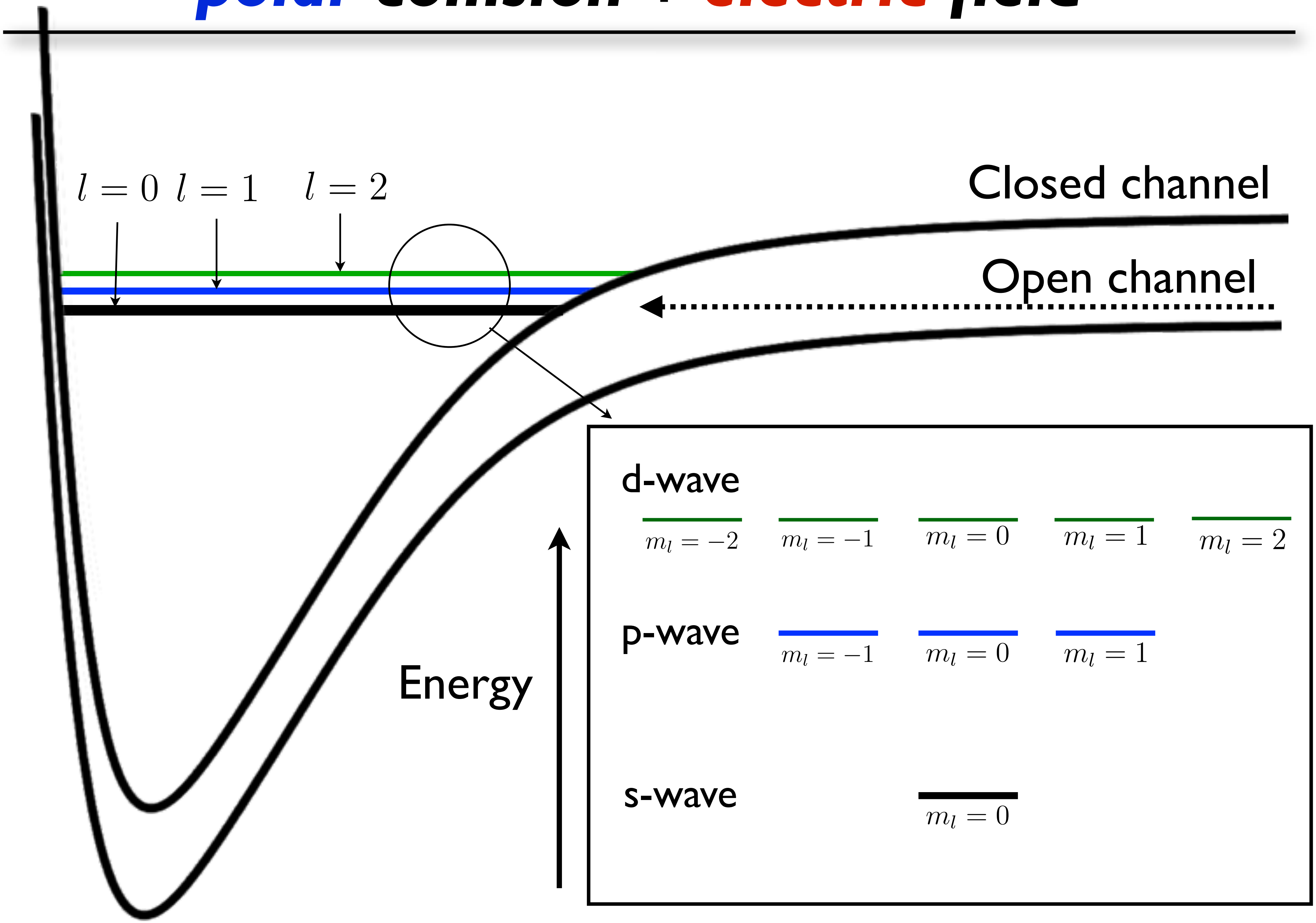

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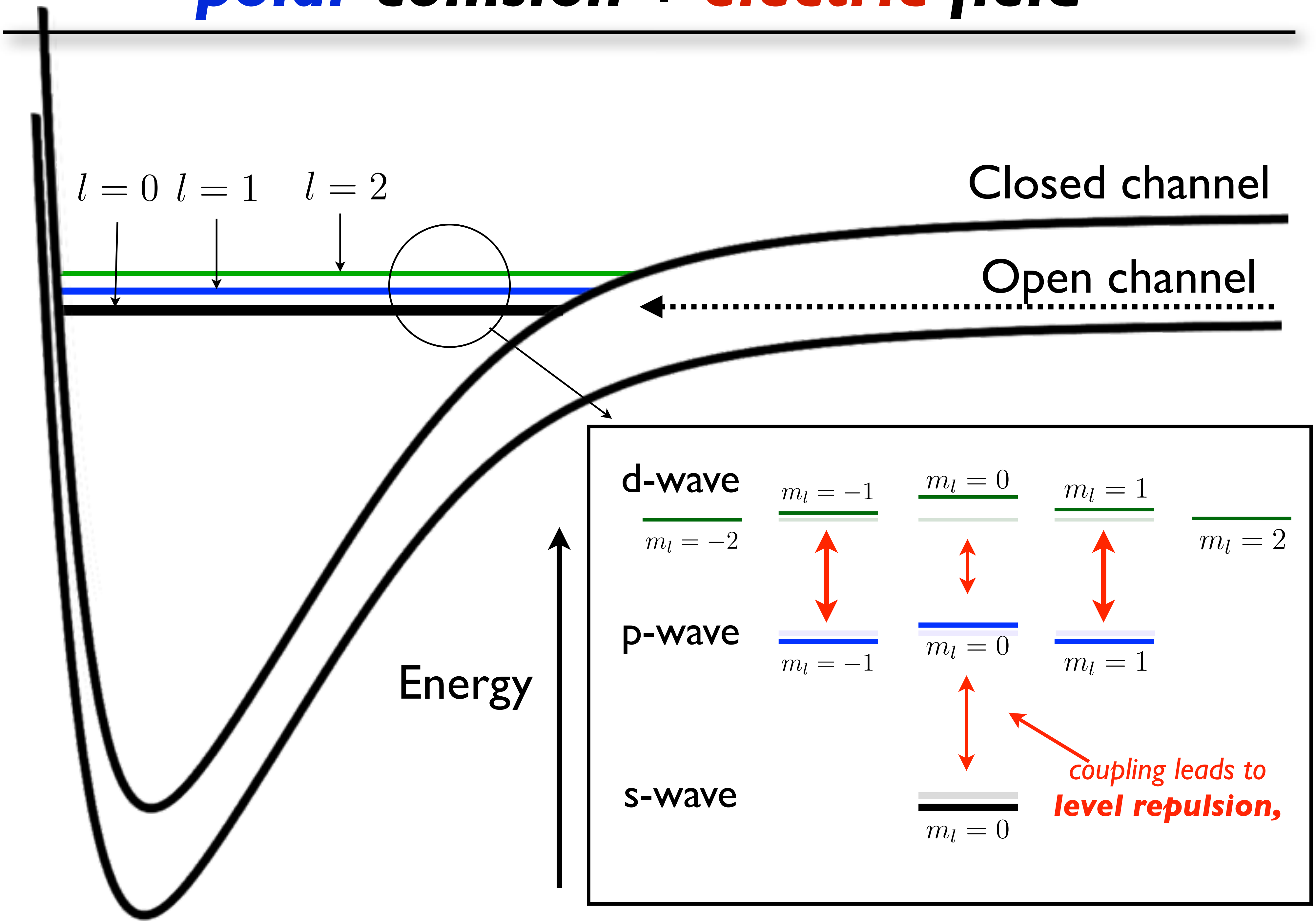

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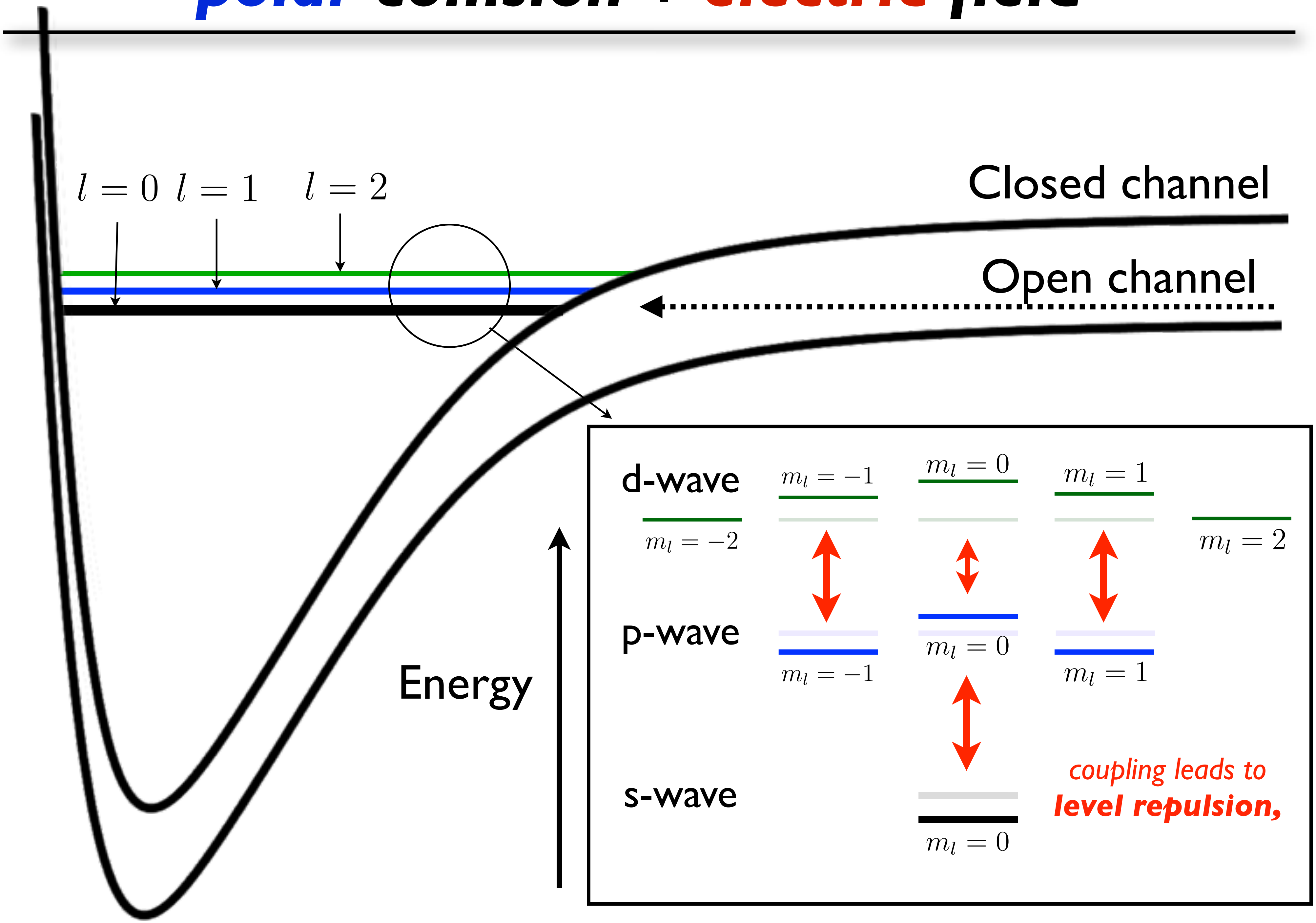

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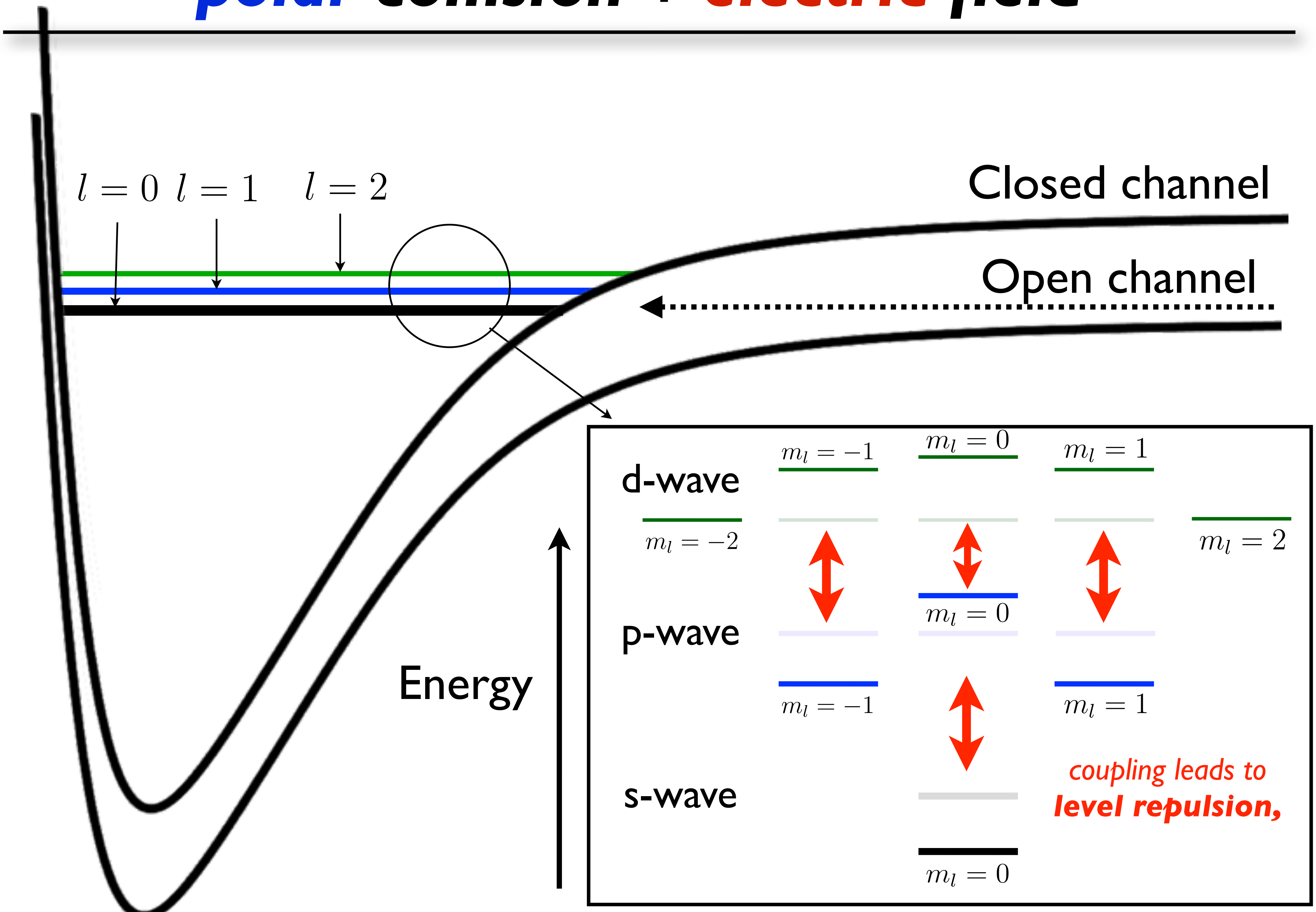

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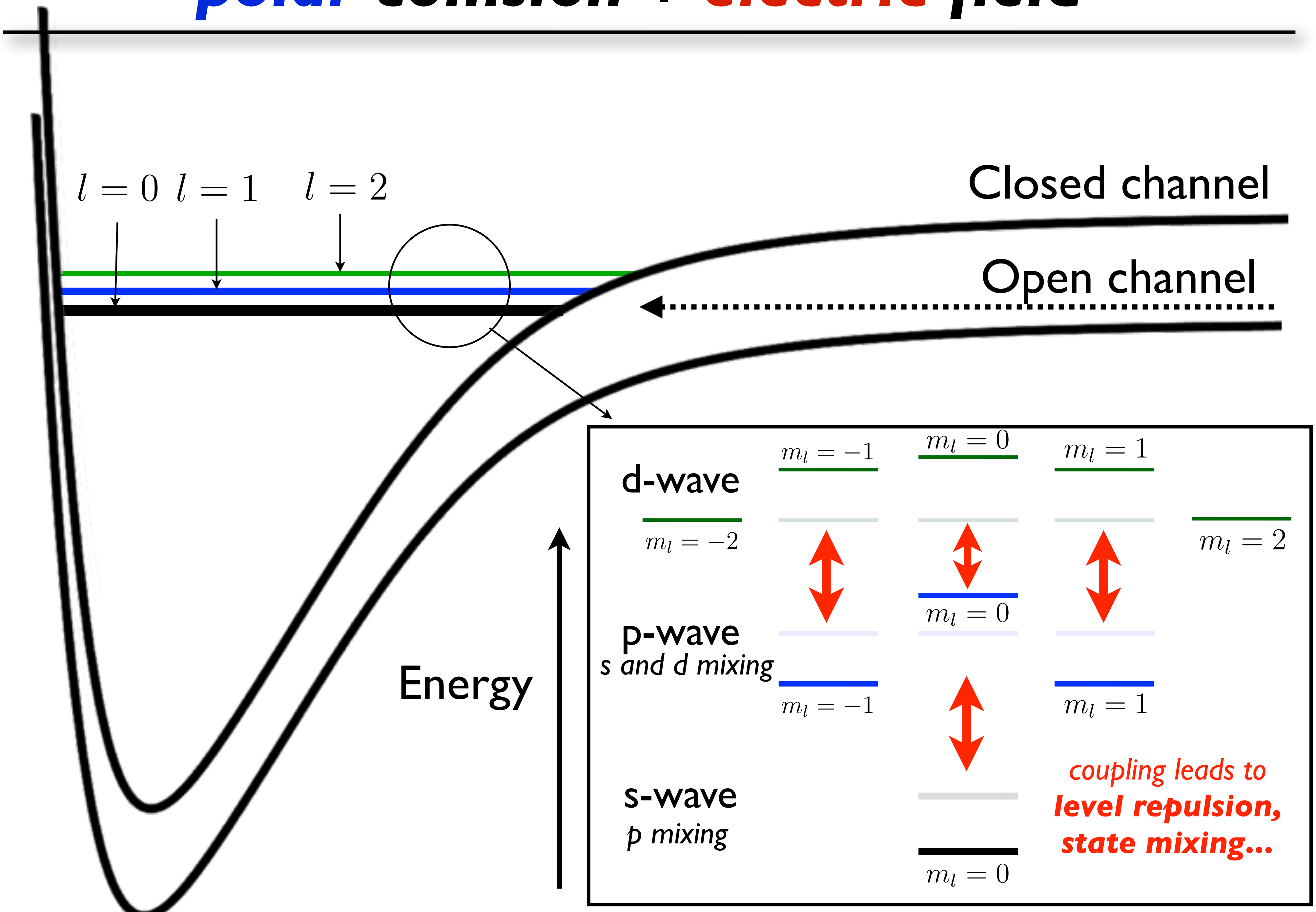

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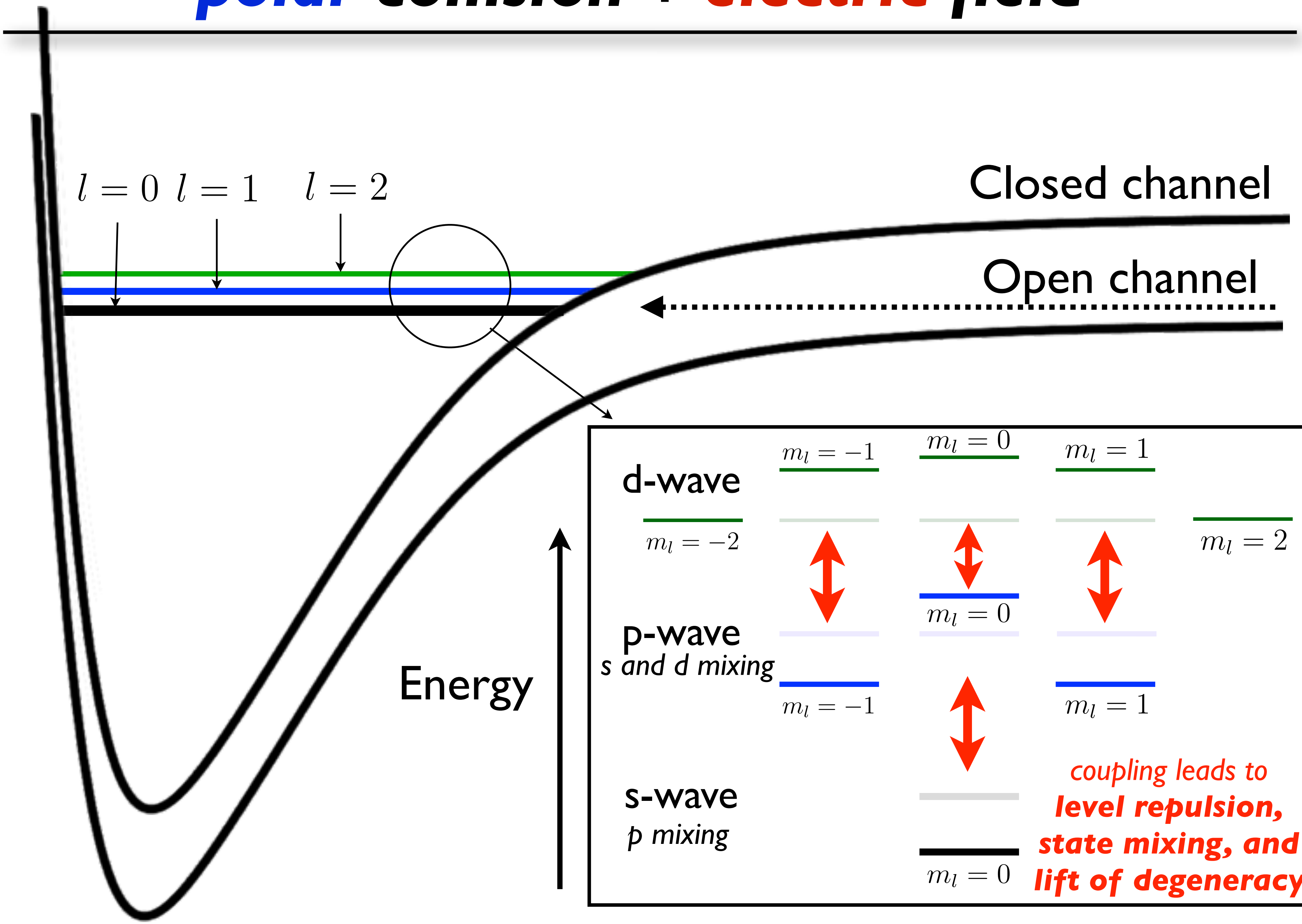
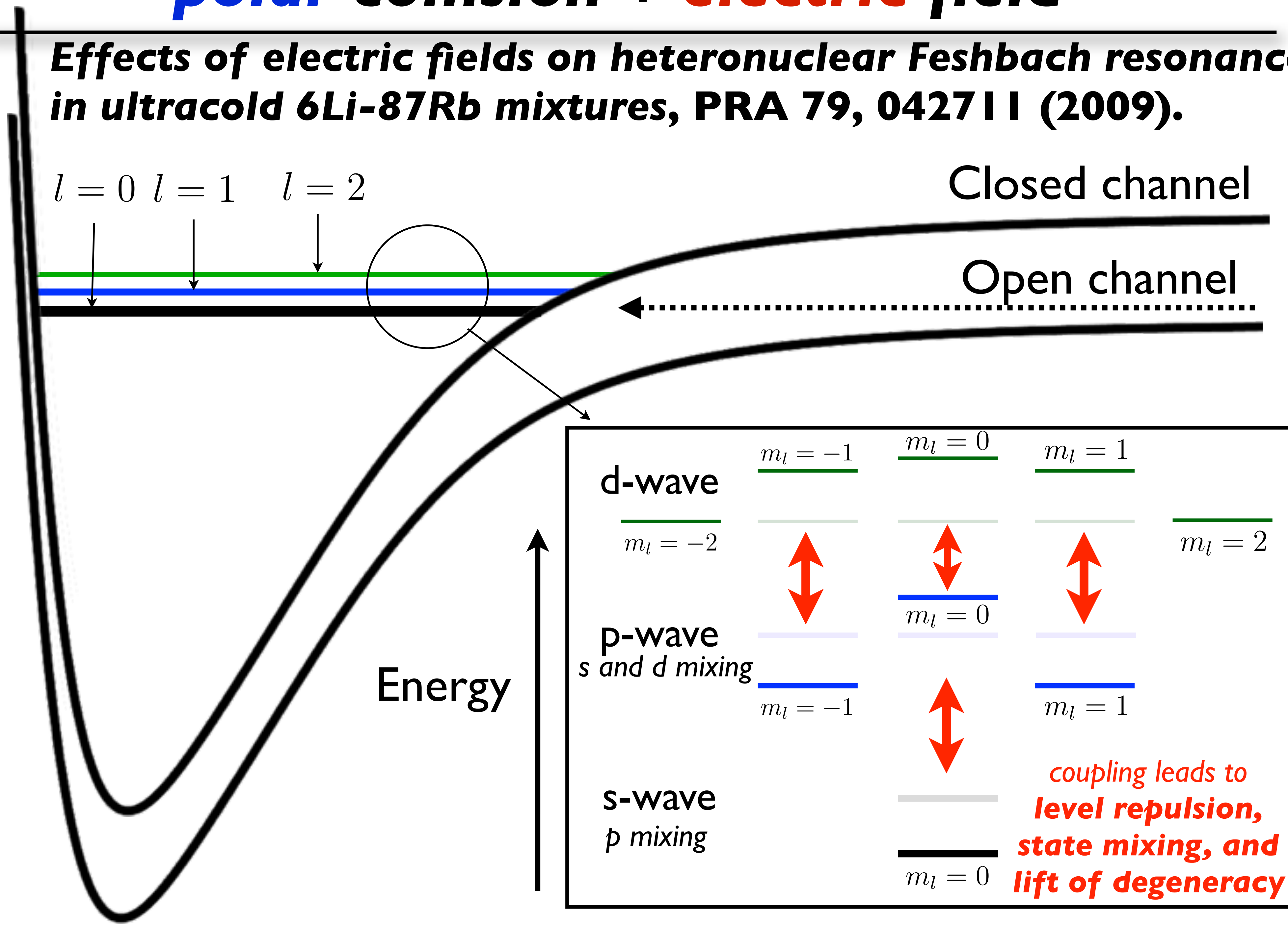


A new twist on Feshbach resonances: *polar* collision + *electric* field

***Effects of electric fields on heteronuclear Feshbach resonances in ultracold 6Li-87Rb mixtures*, PRA 79, 042711 (2009).**



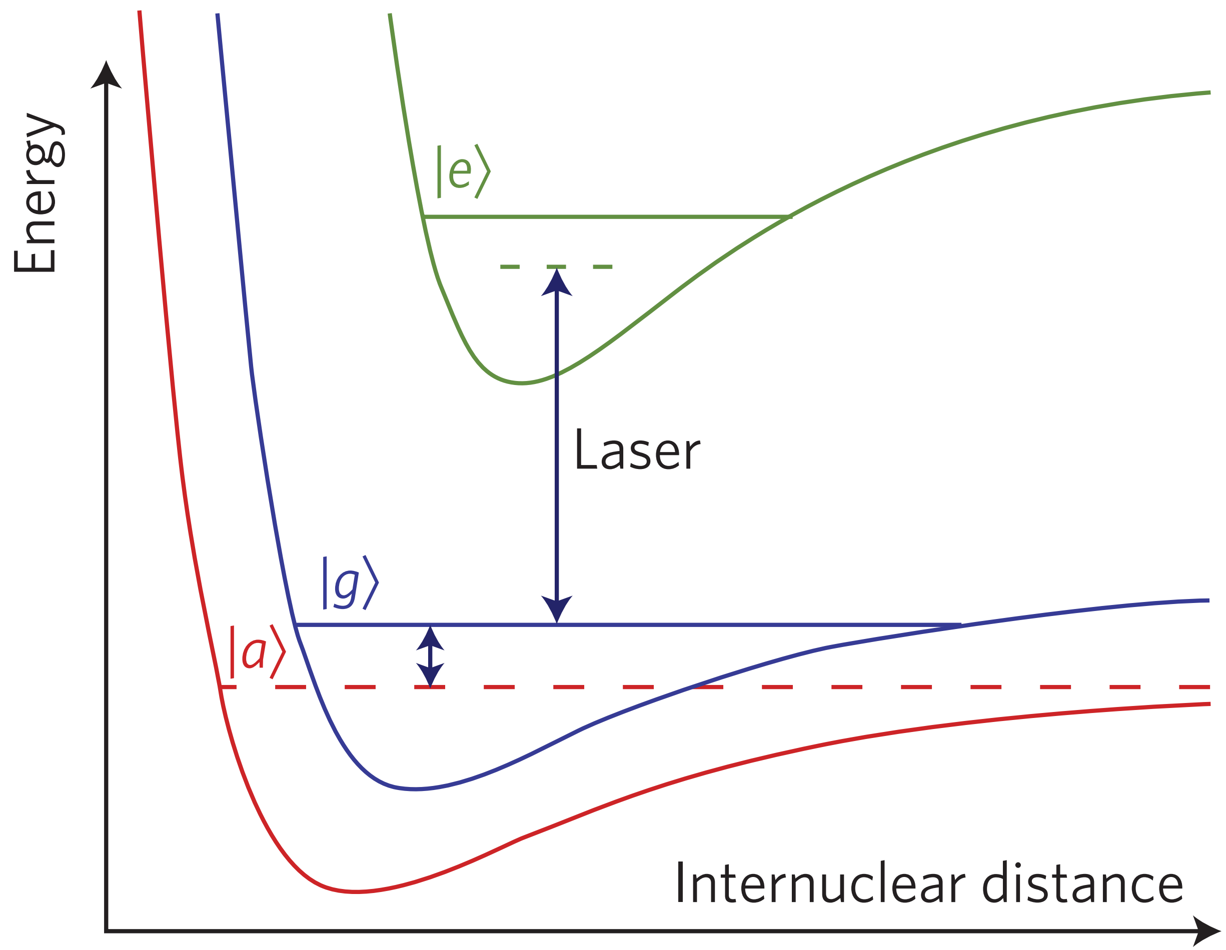
nature physics

LETTERS

PUBLISHED ONLINE: 6 APRIL 2009 | DOI: 10.1038/NPHYS1232

Control of a magnetic Feshbach resonance with laser light

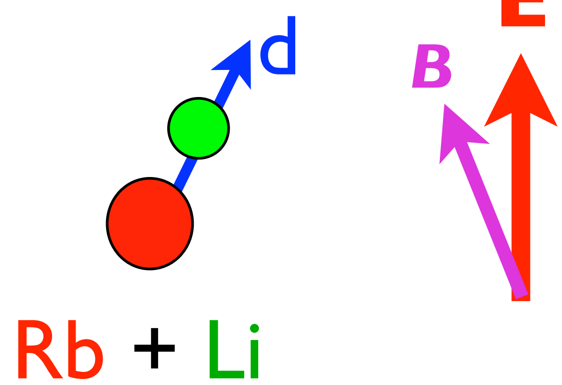
Dominik M. Bauer, Matthias Lettner, Christoph Vo, Gerhard Rempe and Stephan Dürr*



A new twist on Feshbach resonances:

***Effects of electric fields on heteronuclear Feshbach resonances in ultracold 6Li-87Rb mixtures*, PRA 79, 042711 (2009).**

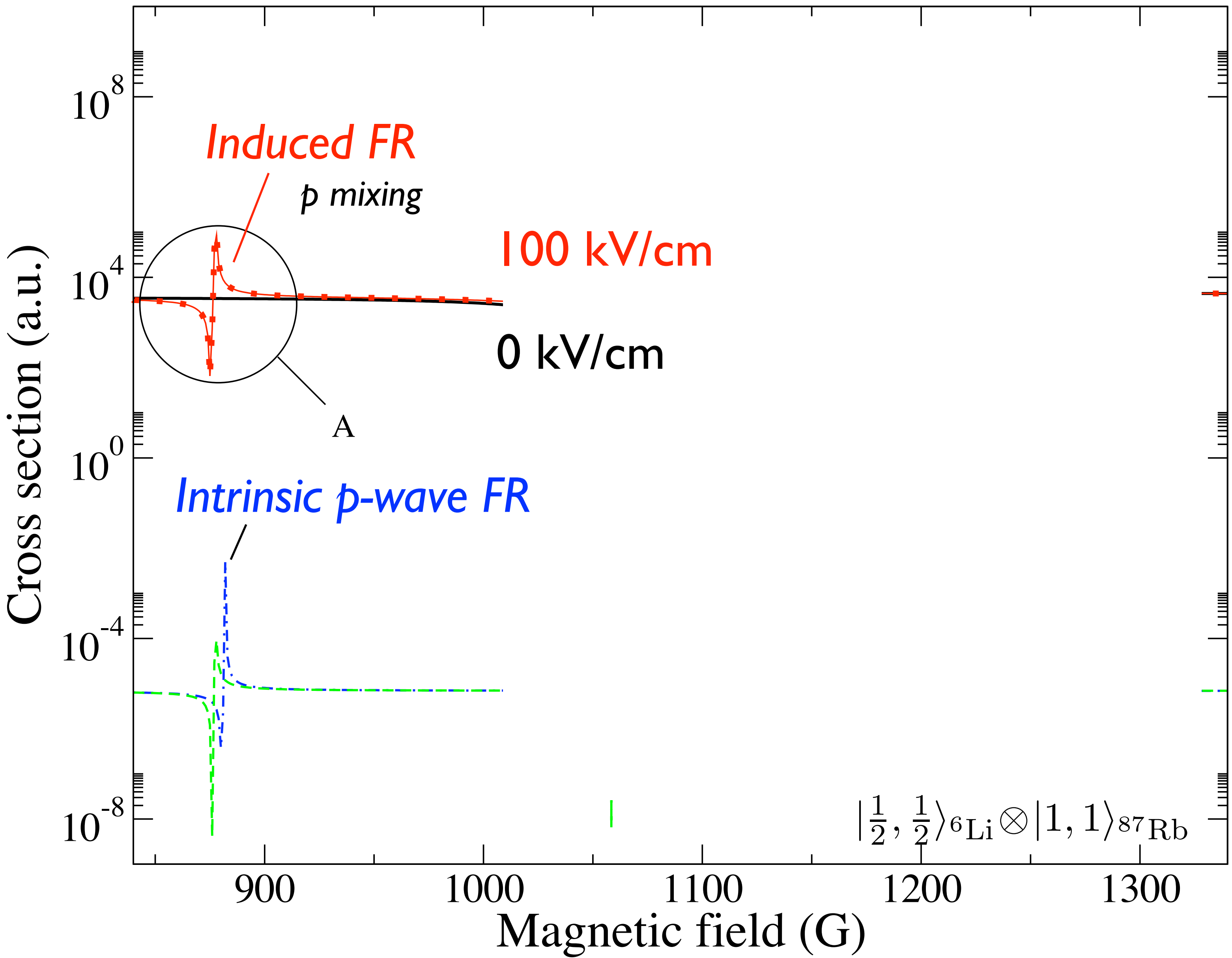
polar collision + electric field



- shift position of intrinsic Feshbach resonances
  bound state level repulsion
- induce new Feshbach resonances
  mixing of partial waves
- split resonances into $l+1$ multiplets
  tunable anisotropic interactions

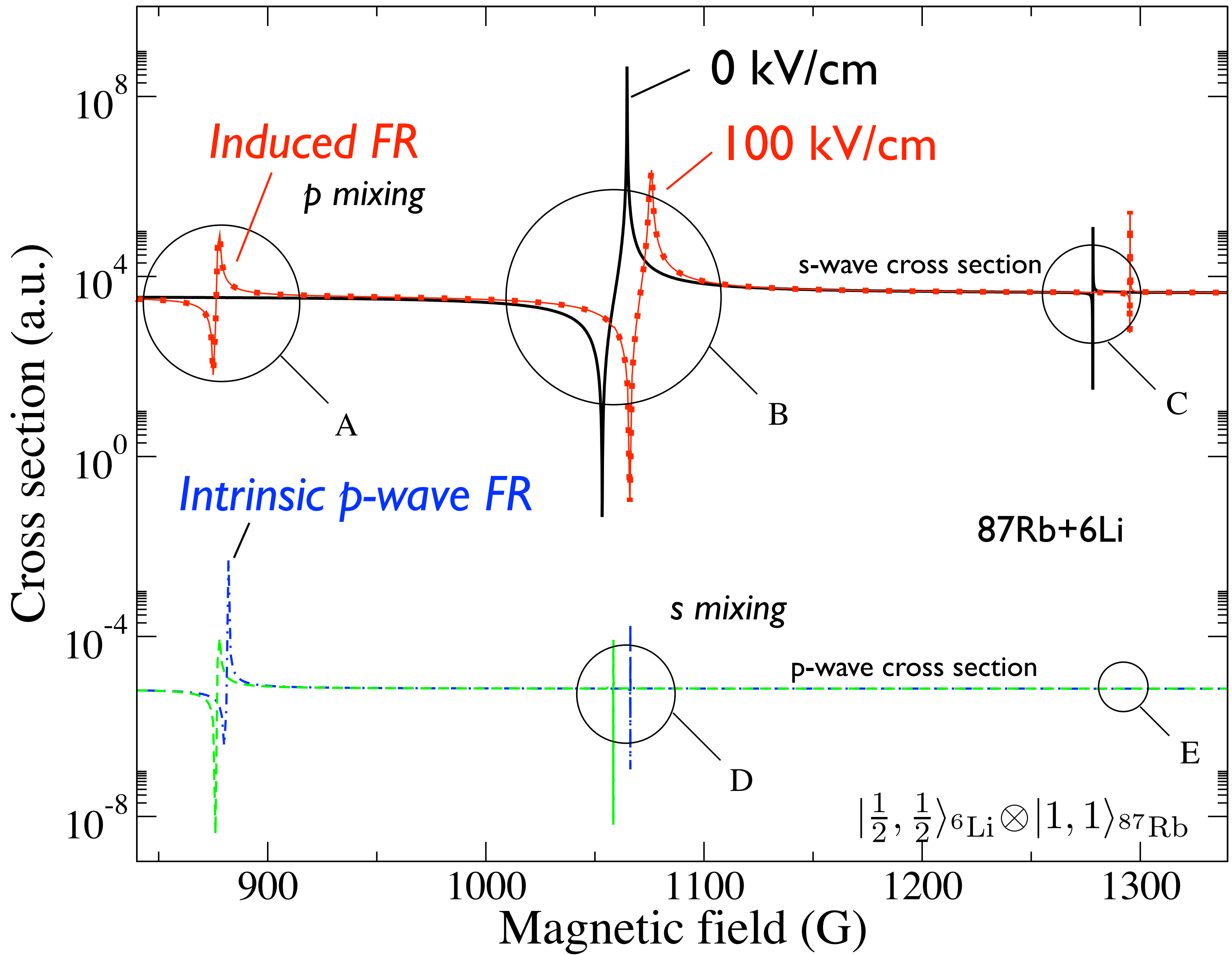
A new twist on Feshbach resonances: *Induced resonances*

new s-wave resonances appear at the location of intrinsic (E=0) p-wave resonances... and vice-versa



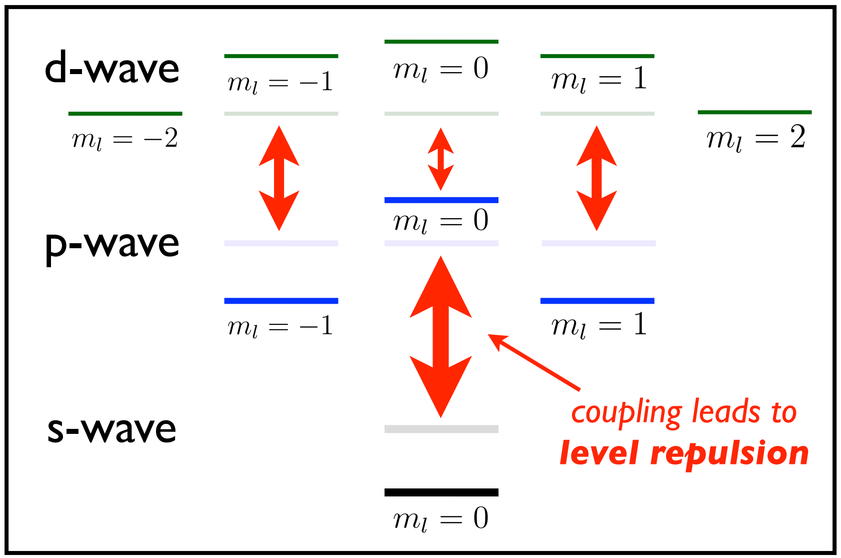
A new twist on Feshbach resonances: *shift of resonances*

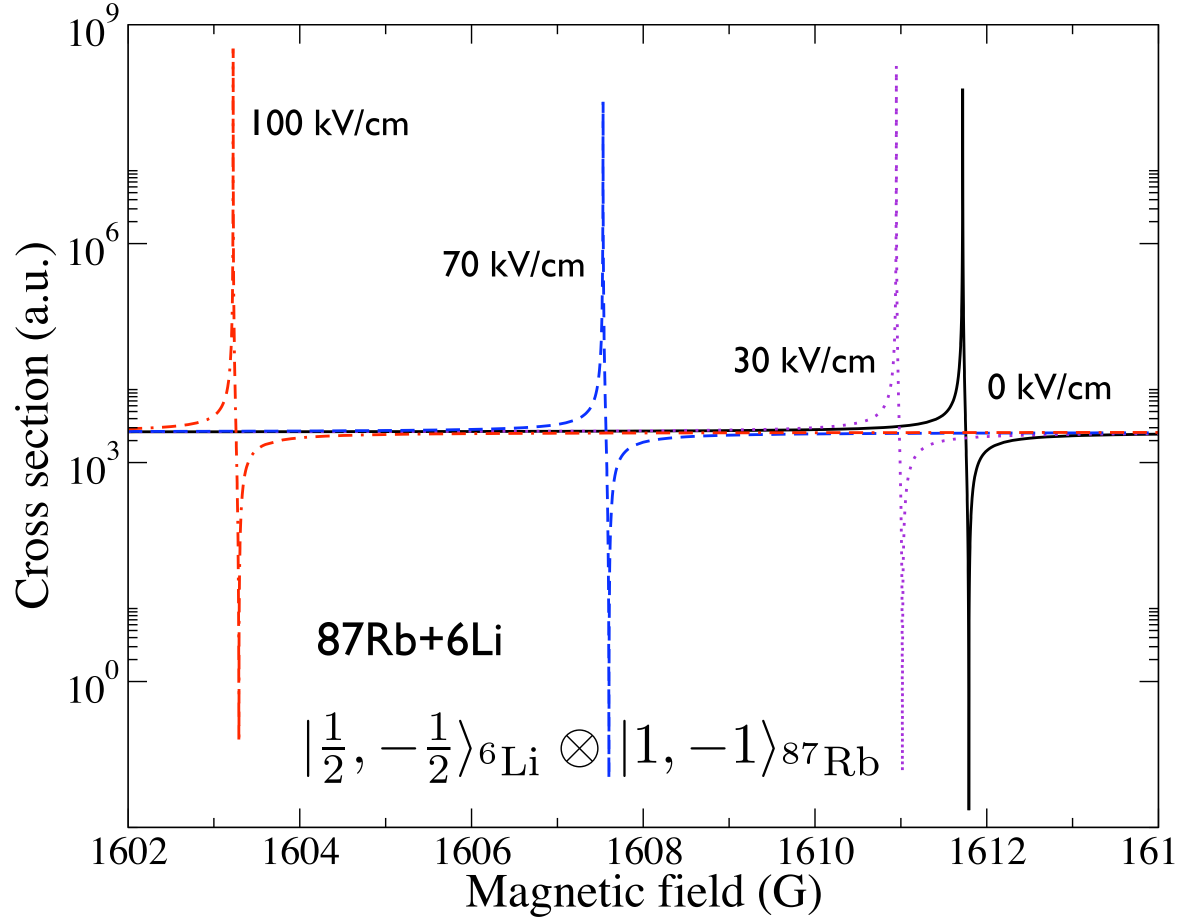
intrinsic s-wave resonances shift with applied electric field



Shift of resonances:

intrinsic (E=0) resonances shift in position as magnitude of electric field increased





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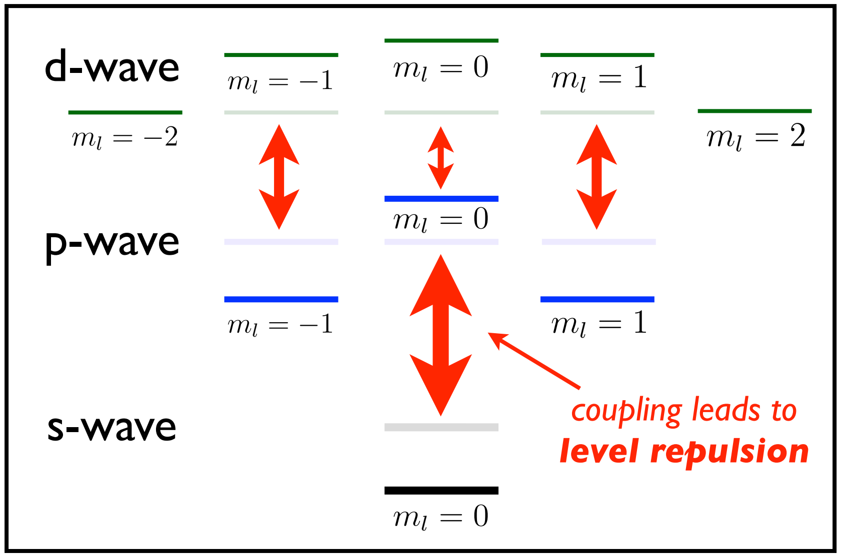
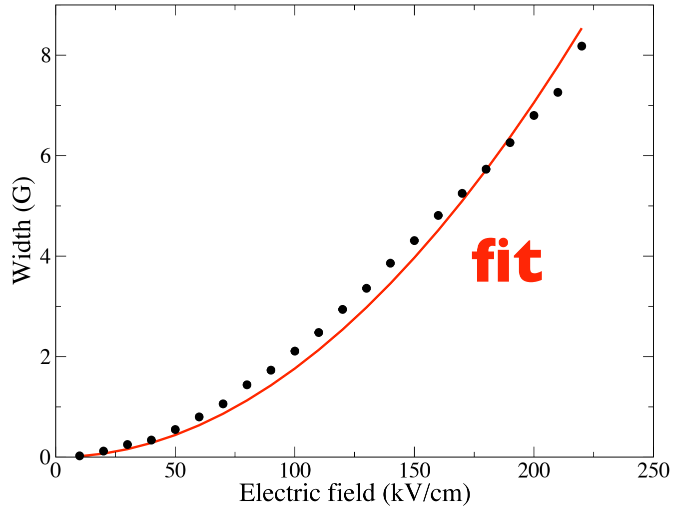
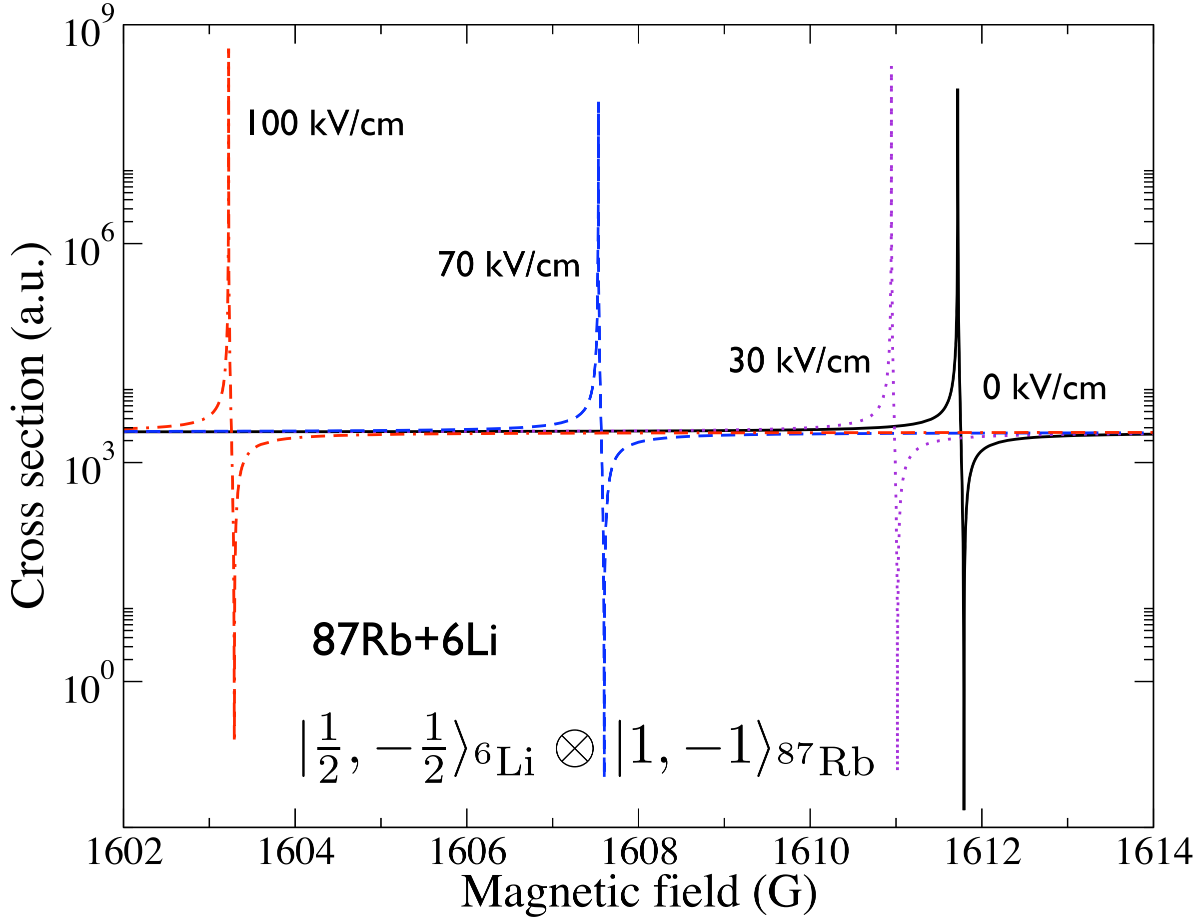


FR ***shift*** and induced FR ***width*** are both quadratic in E

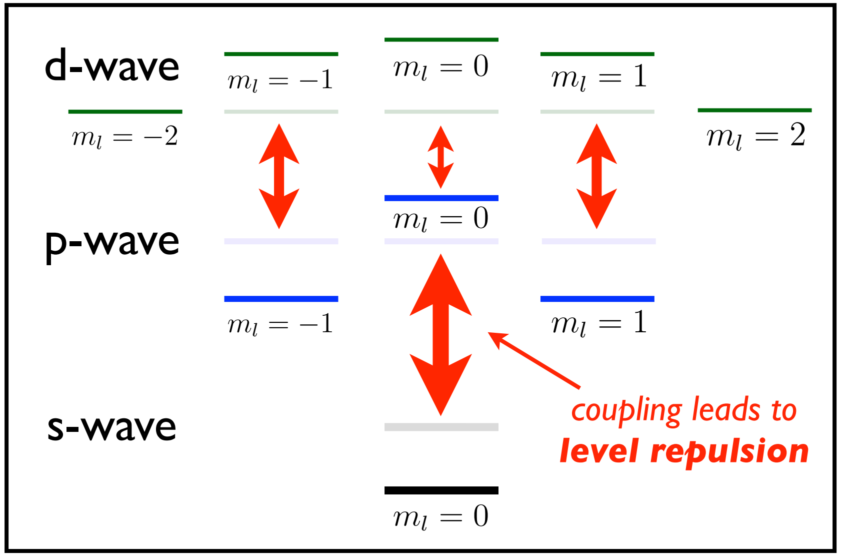




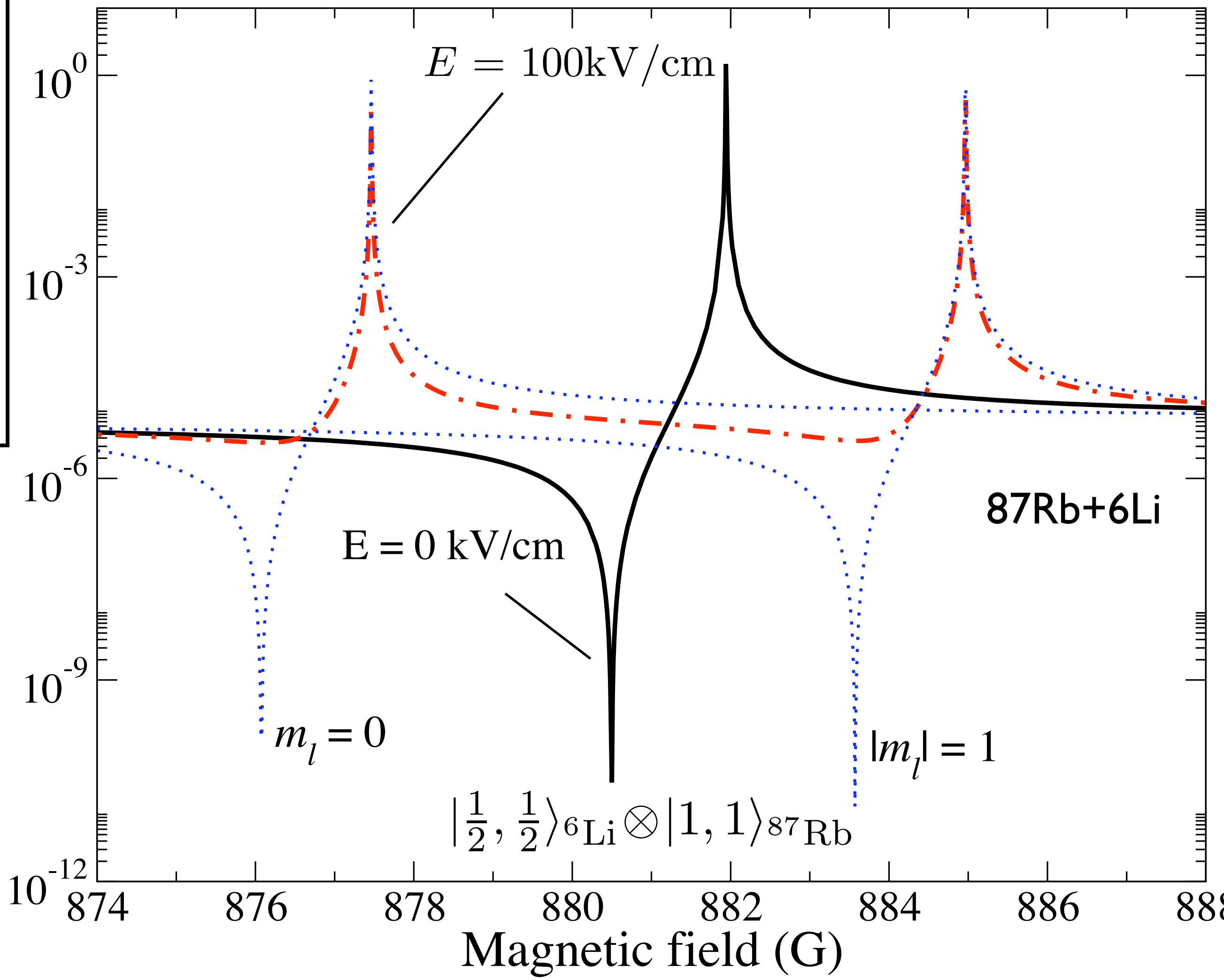
FRs with tunable positions and widths

Splitting of resonances:

partial wave resonances split into
l+1 distinct resonances



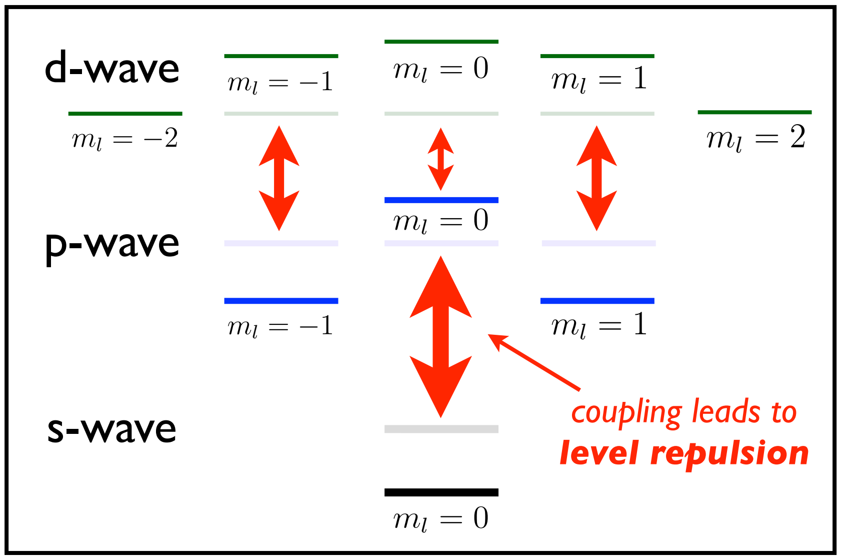
p-wave resonance

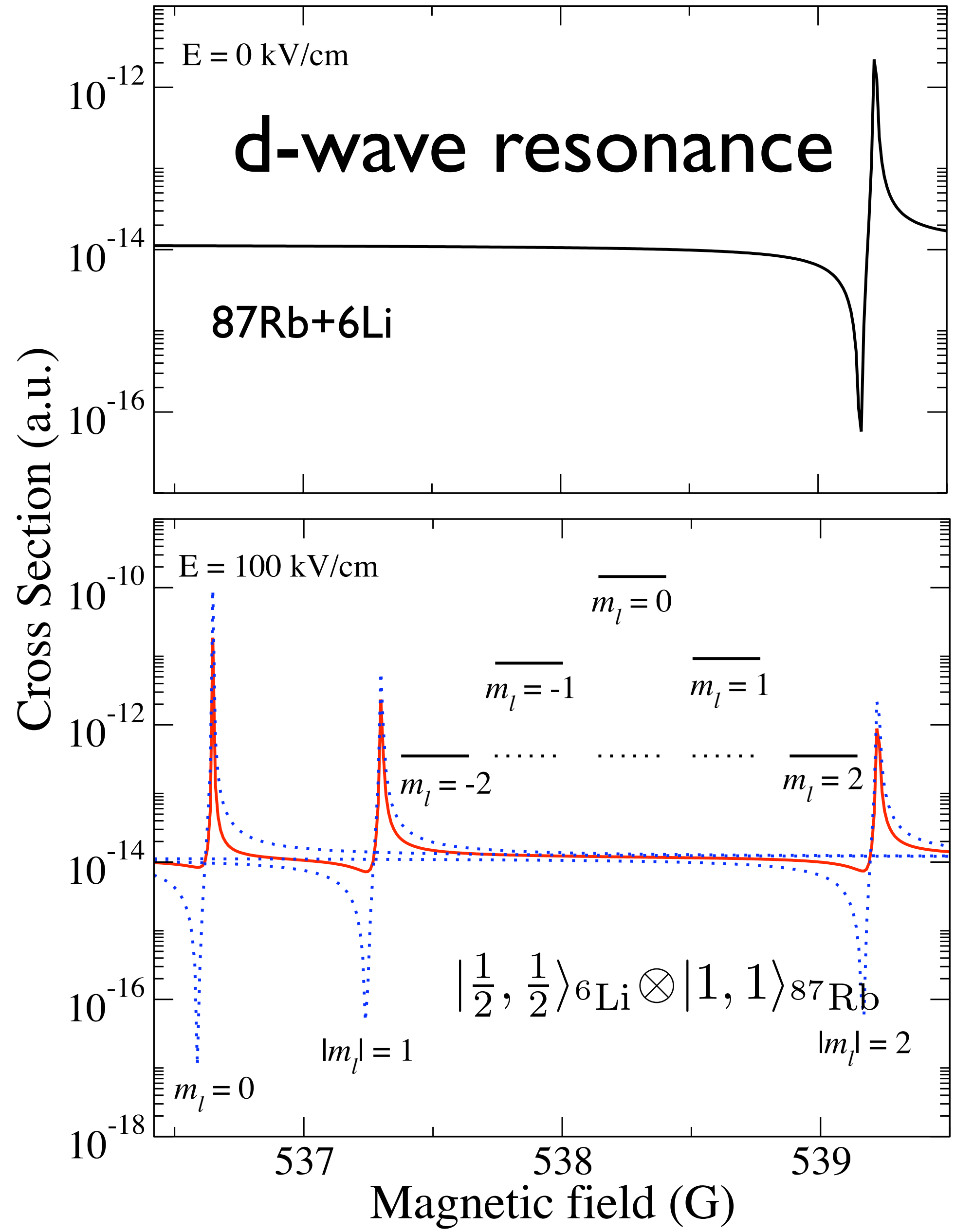


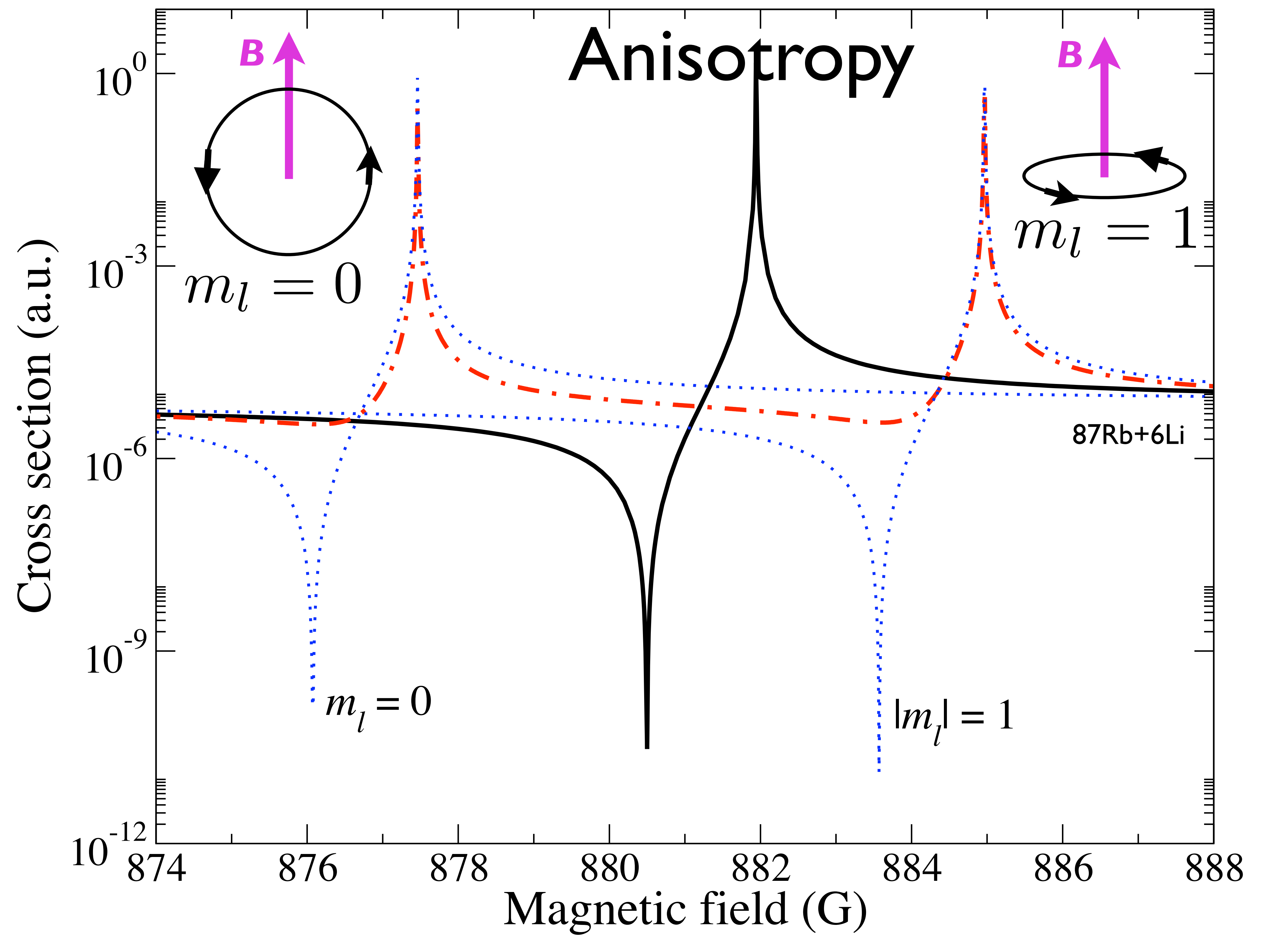
this is similar to splitting due to dipole-dipole coupling
Regal, Ticknor, Bohn, Jin, PRL **90**, 053201 (2003), and PRA **69**, 042712 (2004).

Splitting of resonances:

partial wave resonances split into
l+1 distinct resonances

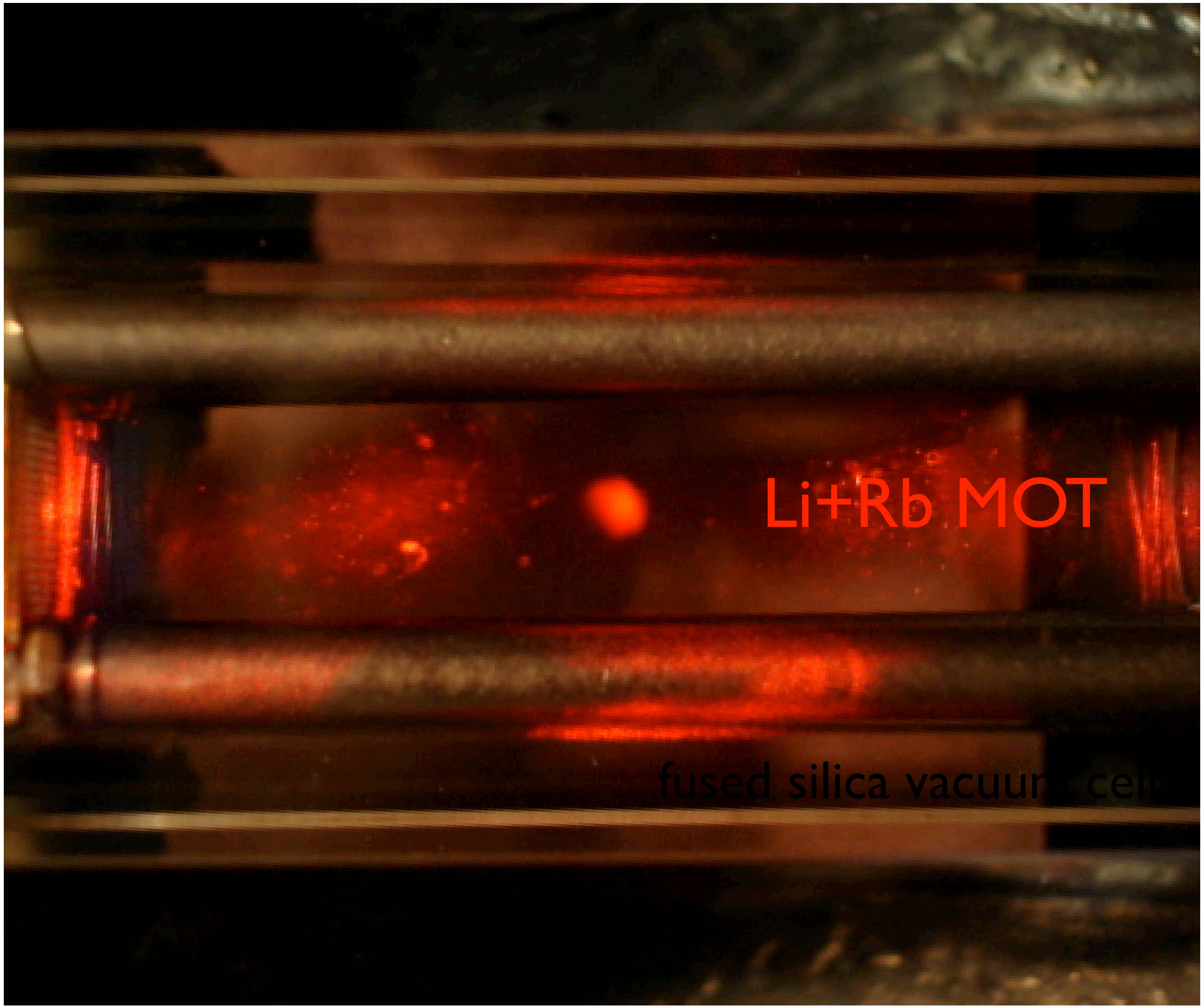






Anisotropy
B
B
$m_l = 0$
$m_l = 1$
87Rb+6Li
$m_l = 0$
$|m_l| = 1$
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
874
876
878
880
882
884
886
888
Cross section (a.u.)
Magnetic field (G)

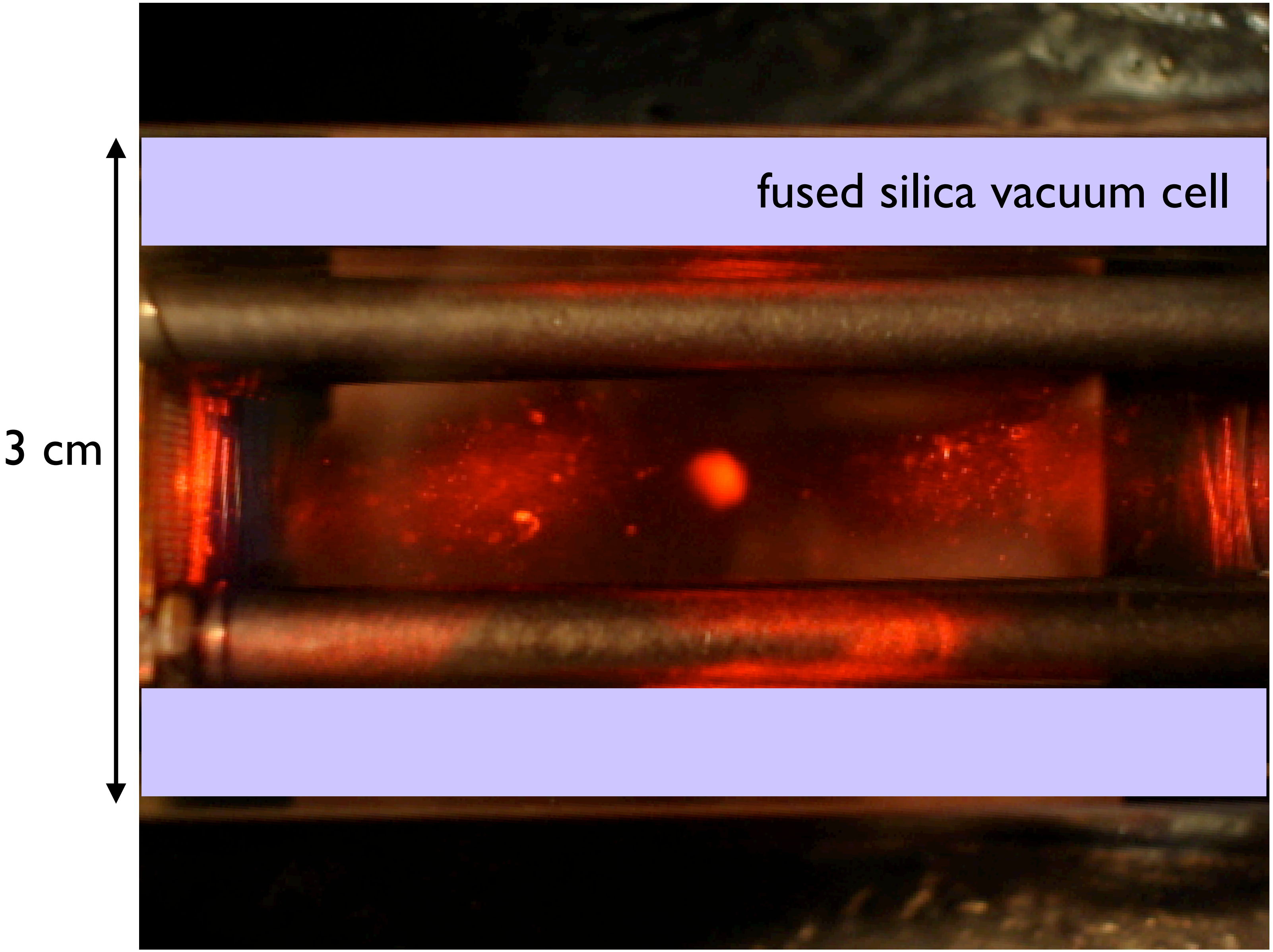
Experimental challenge: adding the E field



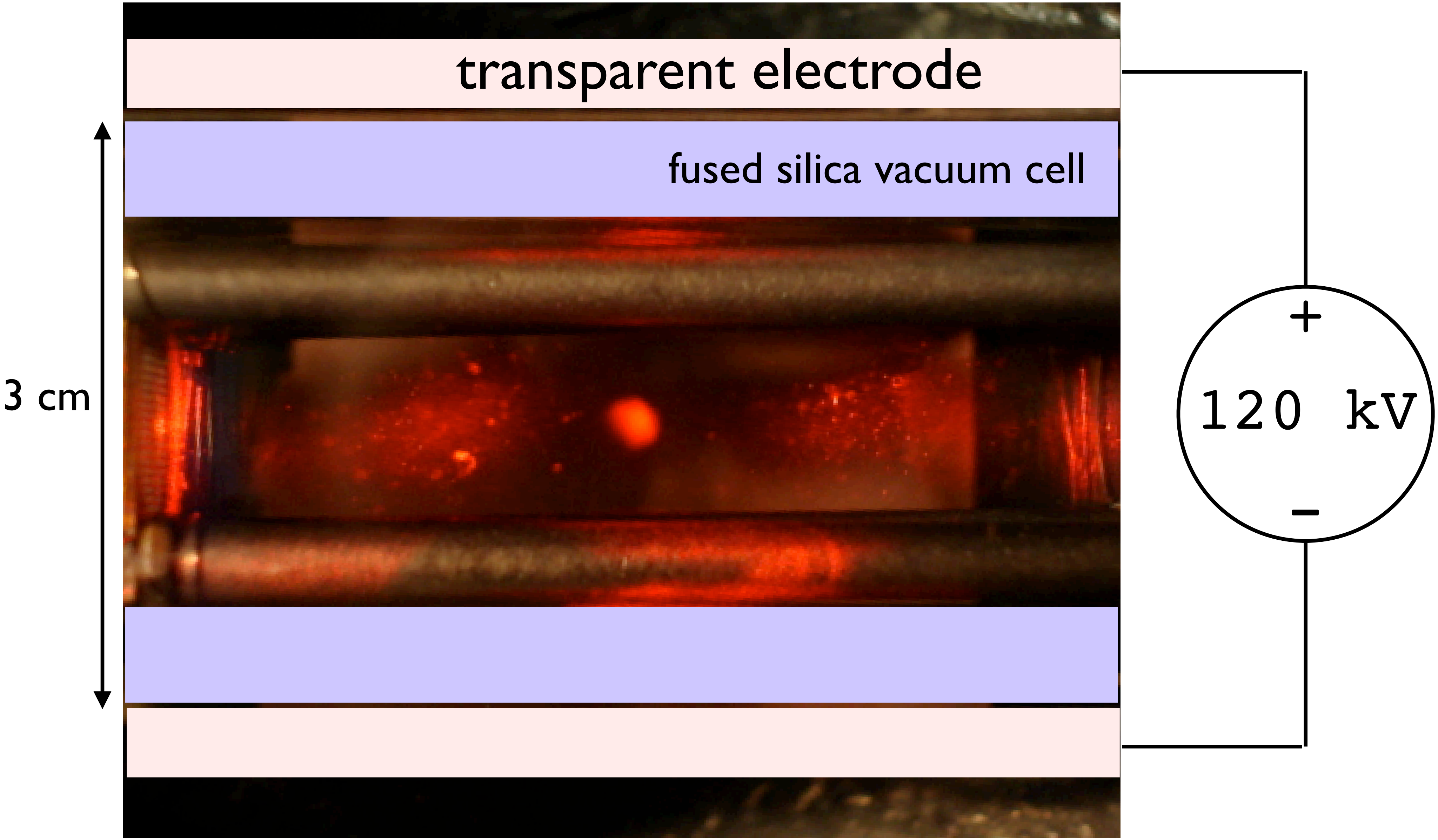
we want a field of about 30 kV/cm

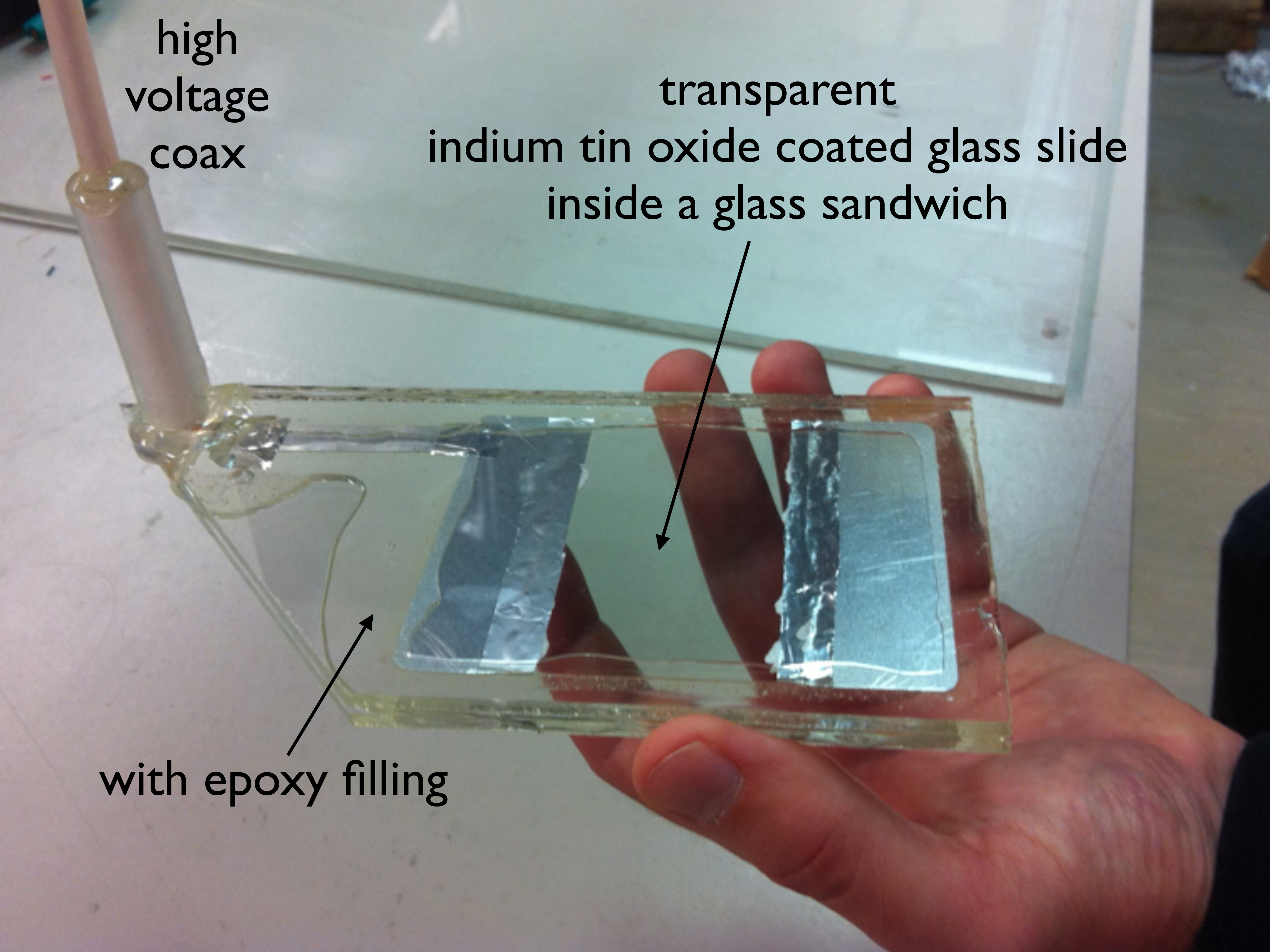
how to add electrodes while keeping good optical access?

Experimental challenge: adding the E field



Experimental challenge: adding the E field




high
voltage
coax
transparent
indium tin oxide coated glass slide
inside a glass sandwich
with epoxy filling

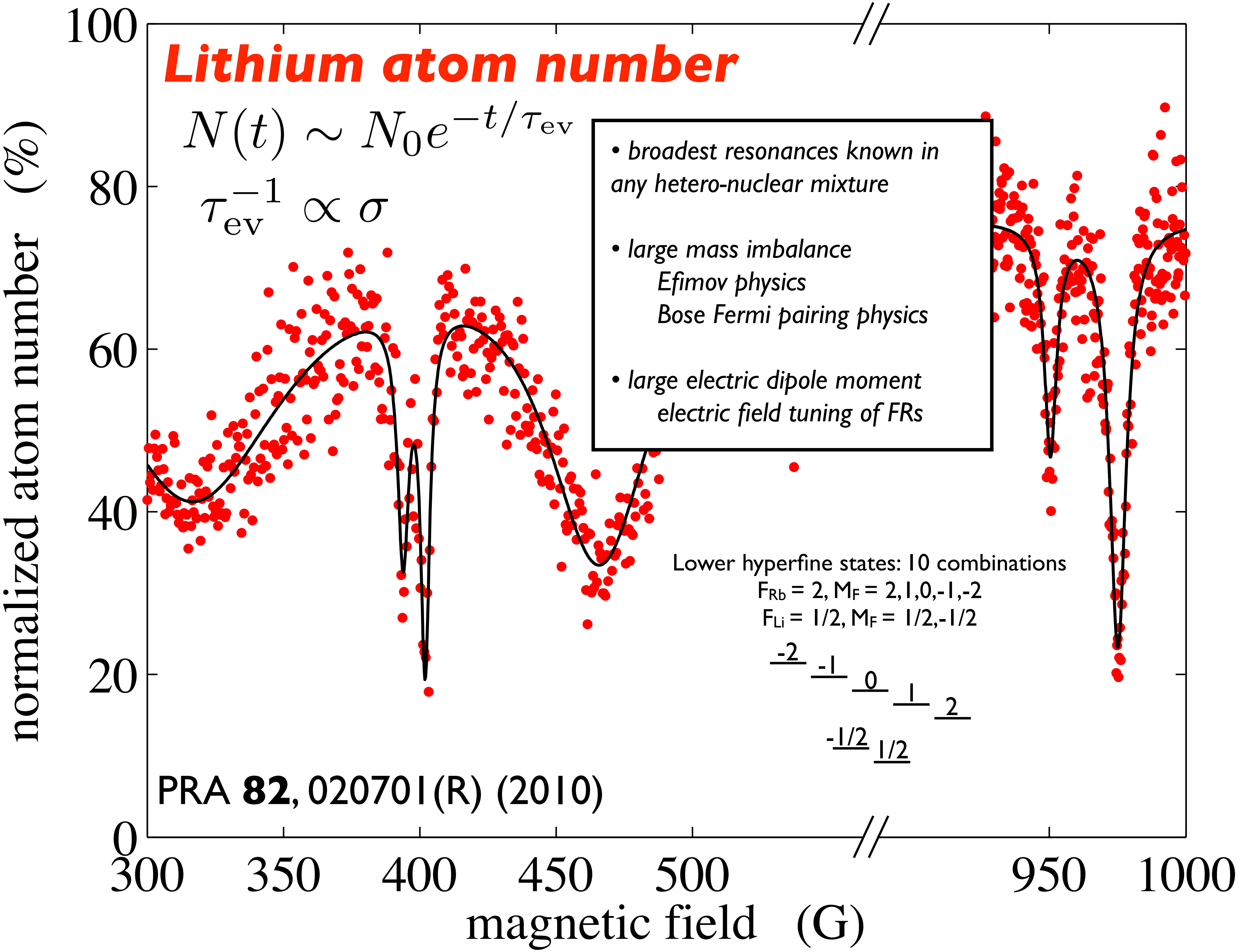
Experimental challenges and mysteries

Status:
We have generated and verified fields of 18kV/cm and have another factor of 2 in voltage.

Mysteries:
1) Field peculiarities (evidence of shielding)
2) Trap loss associated with energizing plates

Feshbach resonances in $^6Li+^{85}Rb$ mixtures
the strength of resonances

Feshbach resonances in $^6Li+^{85}Rb$ mixtures



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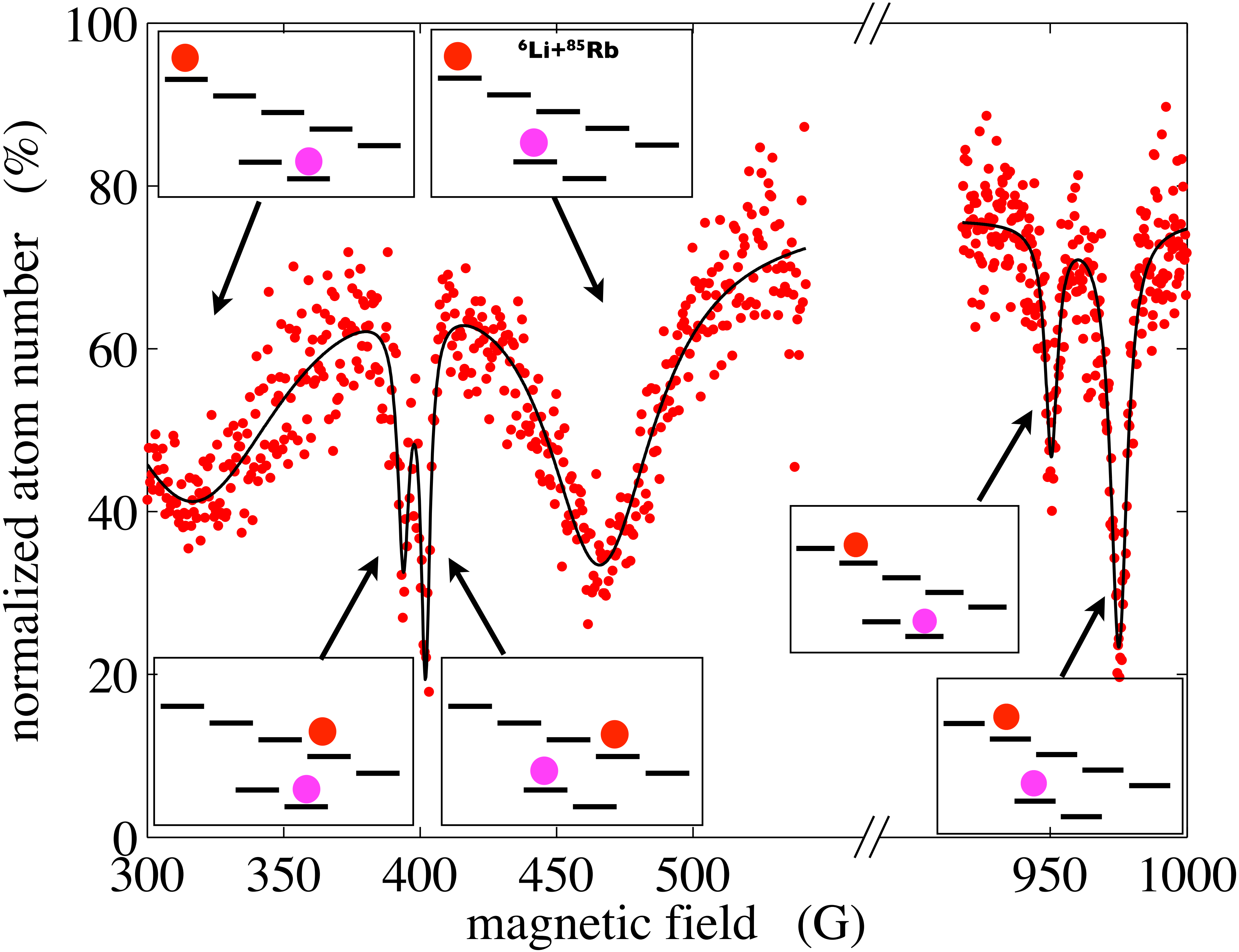
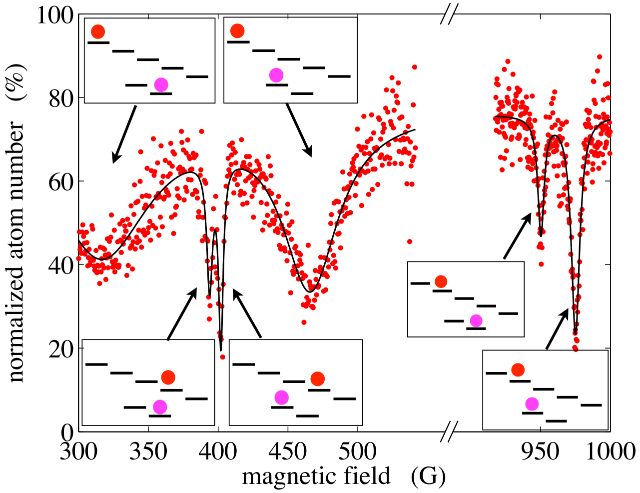


Feshbach resonances in ^{6}Li+^{85}Rb mixtures



effective range: $r_e = \hbar^2/(2m_R|a_{bg}|\mu_{rel}\Delta B)$

resonance strength: $E_{res} = \hbar^2/(2m_R r_e^2)$

TABLE II. The calculated characteristics of seven large FRs for stable Fermi-Bose mixtures of ^{6}Li-^{85}Rb and ^{6}Li-^{87}Rb. The background scattering length a_{bg} and effective range of the resonance r_e are given in units of the Bohr radius, a_0. The value for μ_{rel}, the difference in the magnetic moments of the closed channel (molecule) and the open-channel threshold, is given in units of the Bohr magneton $\mu_B = 9.27400915(23)$ J T^{-1}. For each FR, the magnetic fields at which the mixture is energetically stable with respect to two-body spin relaxation is provided. In some cases, because of nearby resonances, we can only provide an approximate lower bound on the resonance width.

Atomic states $\lvert f,m_f\rangle \otimes \lvert f,m_f\rangle$	B_0 (G)	ΔB (G)	μ_{rel} (μ_B)	a_{bg} (a_0)	r_e (a_0)	Stability (G)
			^{6}Li-^{85}Rb			
$\lvert\frac{1}{2},\frac{1}{2}\rangle \otimes \lvert 2,2\rangle$	40.7	>40	1.66	−14.9	<231	ground state
$\lvert\frac{1}{2},-\frac{1}{2}\rangle \otimes \lvert 2,1\rangle$	402.5	27.3	1.58	−14.9	358	$\geqslant$149
$\lvert\frac{1}{2},-\frac{1}{2}\rangle \otimes \lvert 2,0\rangle$	643.7	61.0	1.34	−14.9	189	$\geqslant$141
$\lvert\frac{1}{2},-\frac{1}{2}\rangle \otimes \lvert 2,-1\rangle$	961.3	75.6	1.81	−14.7	113	$\geqslant$133
$\lvert\frac{1}{2},-\frac{1}{2}\rangle \otimes \lvert 2,-2\rangle$	466.7	>100	0.58	−14.8	<264	$\geqslant$0
			^{6}Li-^{87}Rb			
$\lvert\frac{1}{2},\frac{1}{2}\rangle \otimes \lvert 1,1\rangle$	1065.0	11.5	2.36	−19.0	442	ground state
$\lvert\frac{1}{2},-\frac{1}{2}\rangle \otimes \lvert 1,1\rangle$	1108.6	11.0	2.36	−19.0	463	$\geqslant$75

PRA **82**, 020701(R) (2010)