The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1859-4

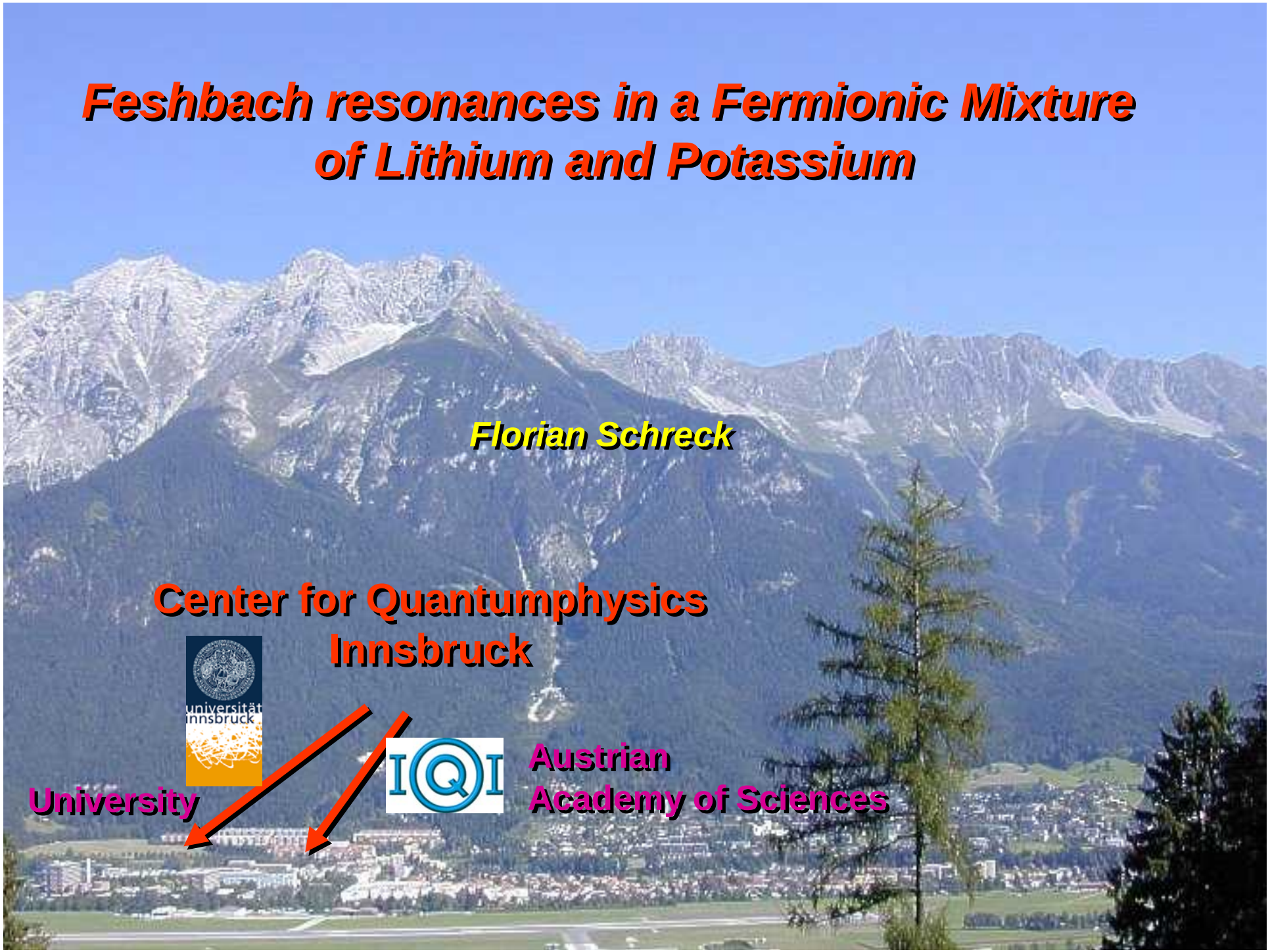
Summer School on Novel Quantum Phases and Non-Equilibrium Phenomena in Cold Atomic Gases

27 August - 7 September, 2007

Experiments with an ultracold 6Li-40K mixture

Florian Schreck
Center for Quantumphysics (IQOQI), Innsbruck

Feshbach resonances in a Fermionic Mixture of Lithium and Potassium



Florian Schreck

Center for Quantumphysics
Innsbruck

University

Austrian
Academy of Sciences

ultracold.atoms

Innsbruck

Cs-Rb GOST (RG & HCN)

Cs LevT (RG & HCN)

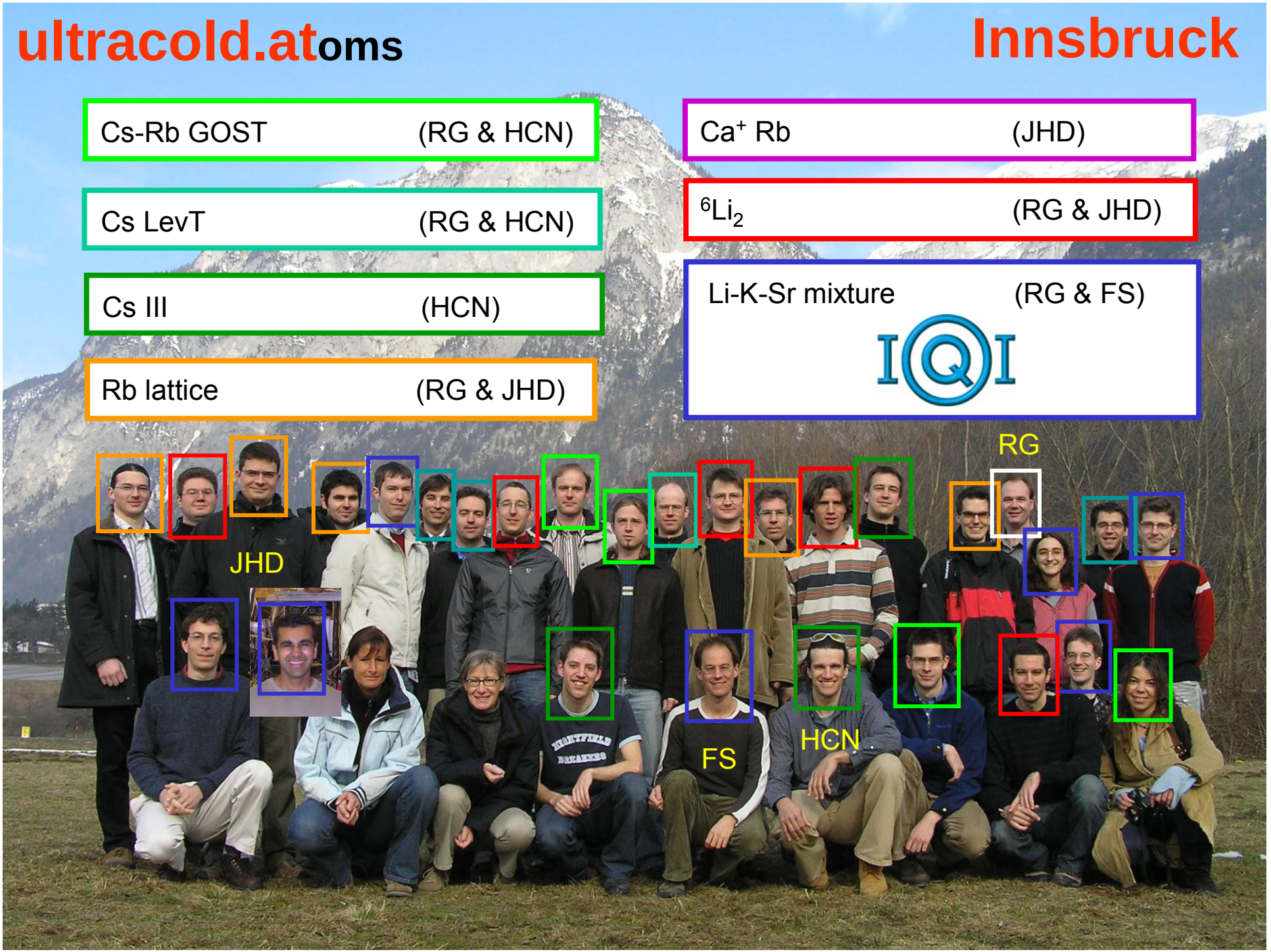
Cs III (HCN)

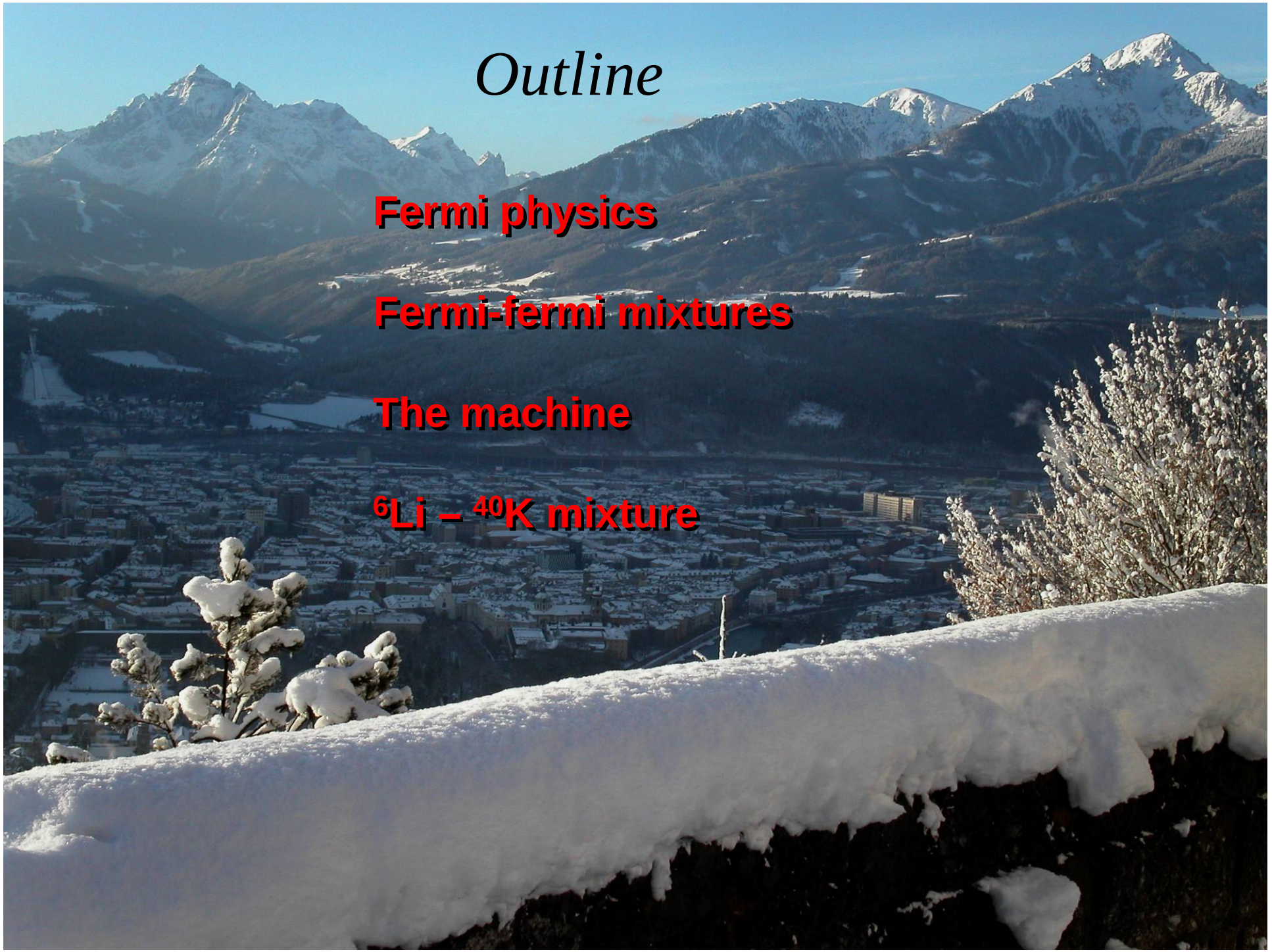
Rb lattice (RG & JHD)

Ca^+ Rb (JHD)

$^6Li_2$ (RG & JHD)

Li-K-Sr mixture (RG & FS)





Outline

Fermi physics

Fermi-fermi mixtures

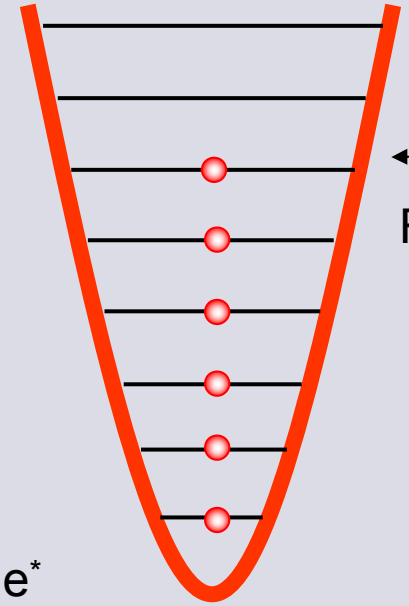
The machine

^{6}Li – ^{40}K mixture

Fermi and Bose statistics

Fermions

half-integer spin



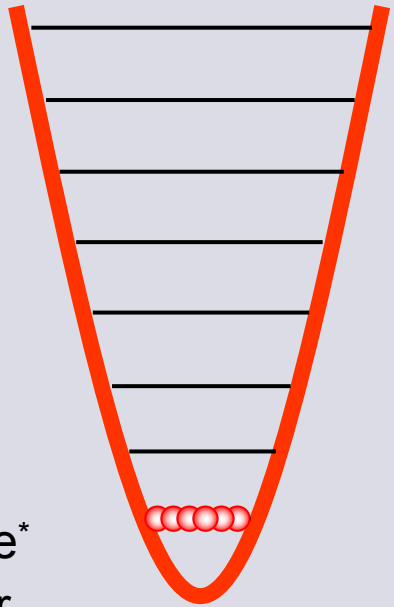
1999
Jin

^{6}Li ^{3}He*
^{40}K ^{173}Yb

degenerate Fermi gas

Bosons

integer spin



^{7}Li
^{23}Na
^{39,41}K ^{1}H
^{87,85}Rb ^{4}He*
^{133}Cs ^{52}Cr
^{170,174,176}Yb

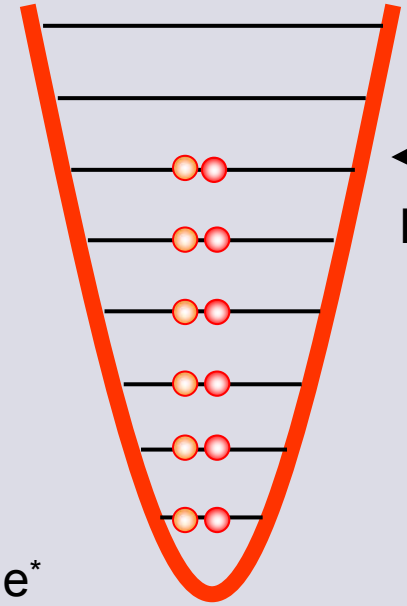
1995
Cornell
Ketterle
Wieman
Hulet

Bose-Einstein condensate

Fermi and Bose statistics

Fermions

half-integer spin



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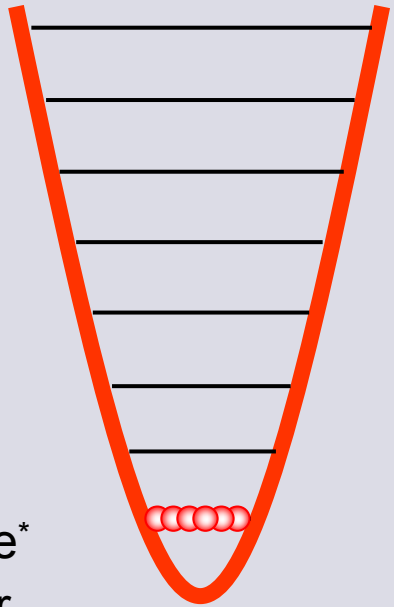

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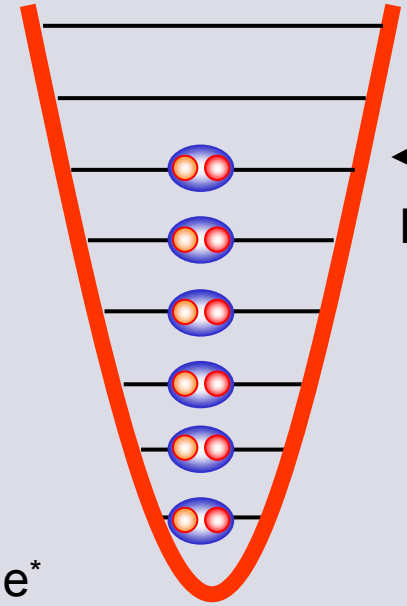

^{6}Li ^{3}He*
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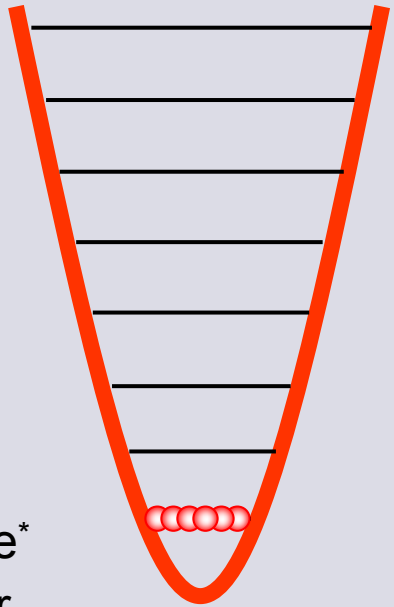
degenerate Fermi gas

Bosons

integer spin



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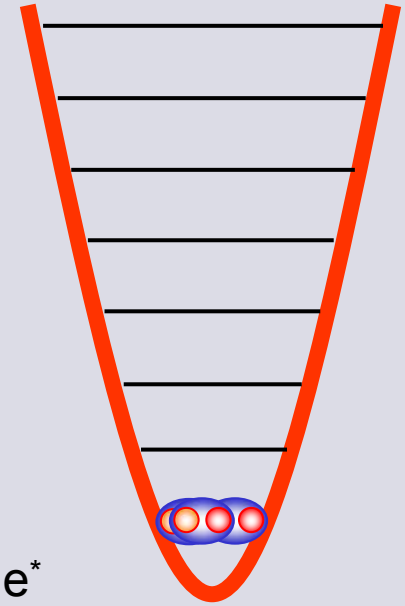


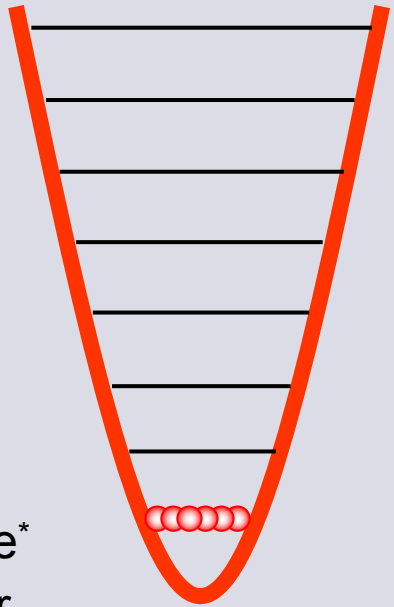
^{6}Li ^{3}He*

^{40}K ^{173}Yb

Molecular BEC !

Bosons

integer spin



^{7}Li

^{23}Na

^{39,41}K ^{1}H

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^{133}Cs ^{52}Cr

1995

Cornell

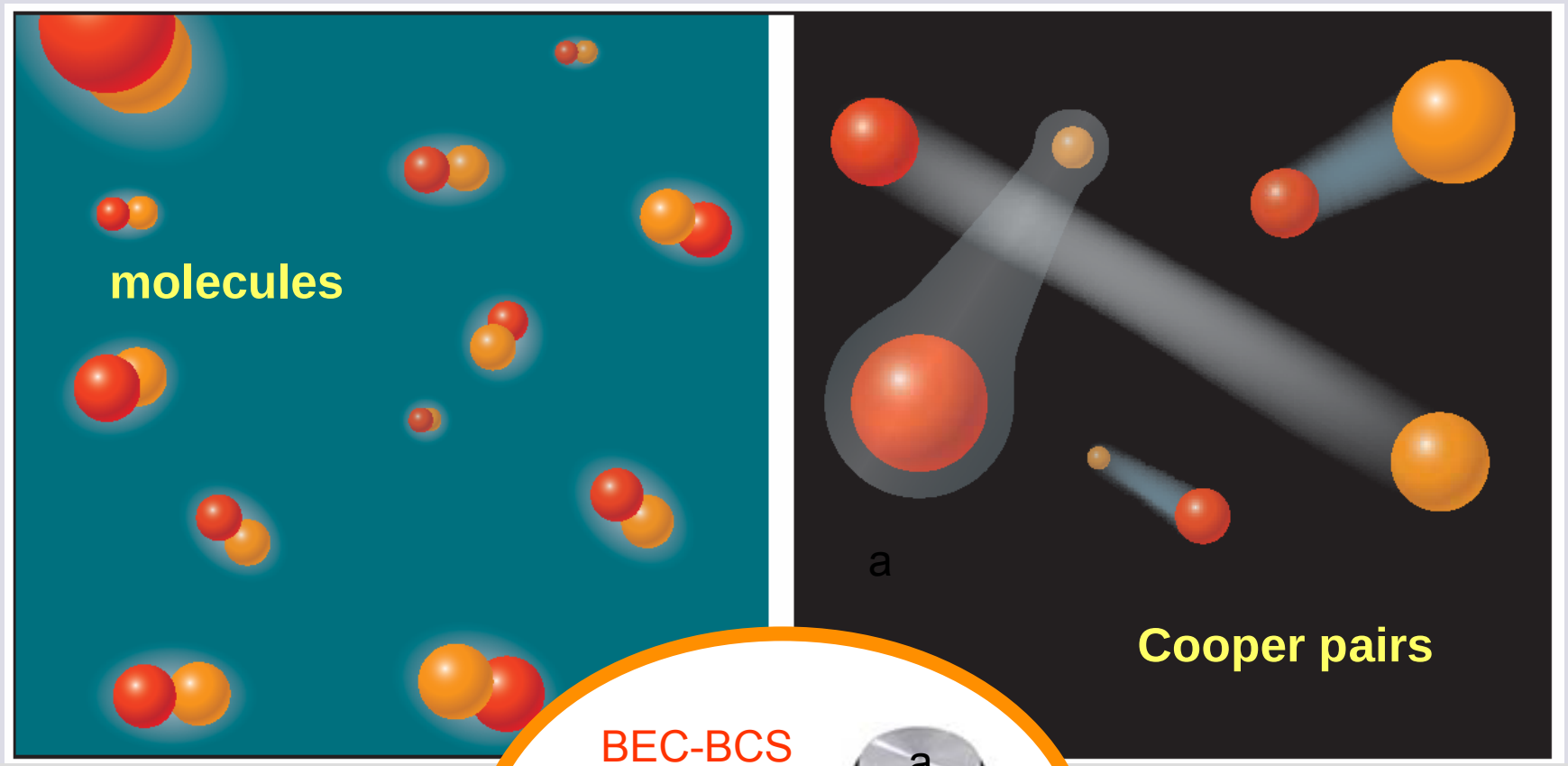
Ketterle

Wieman

Hulet

Bose-Einstein condensate

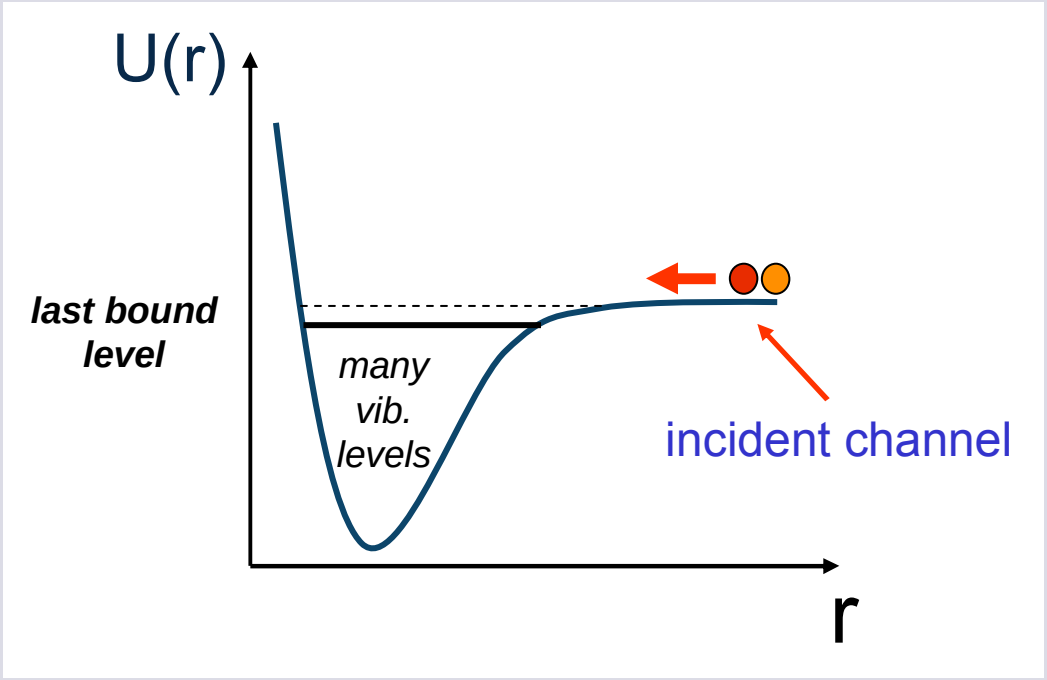
BEC-BCS crossover



BEC-BCS control knob

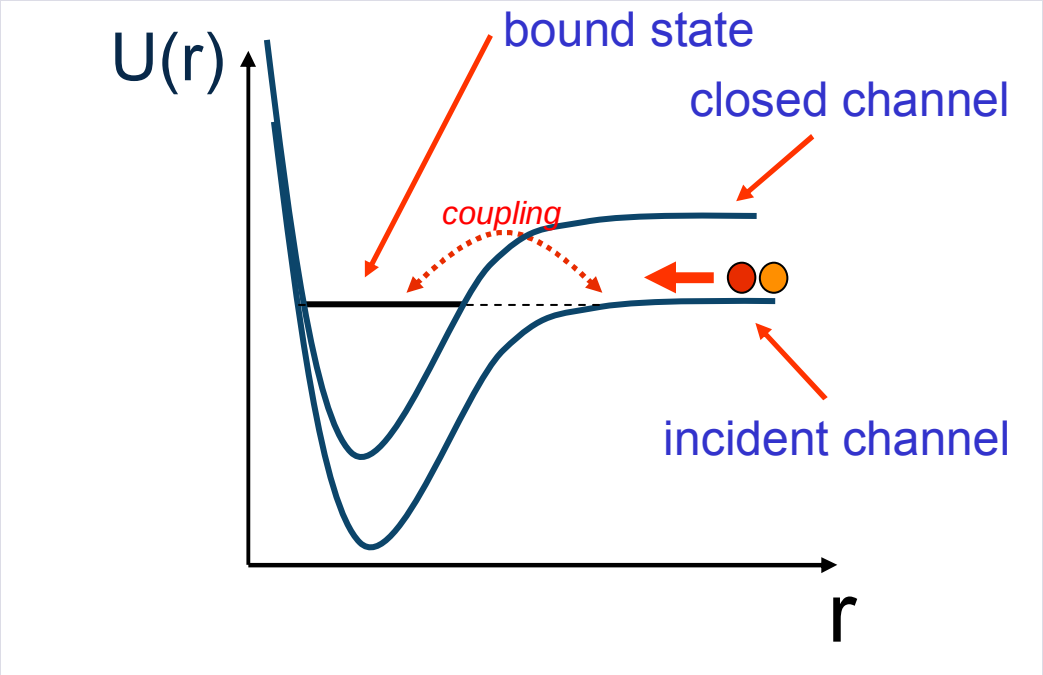
Feshbach resonance

scattering length

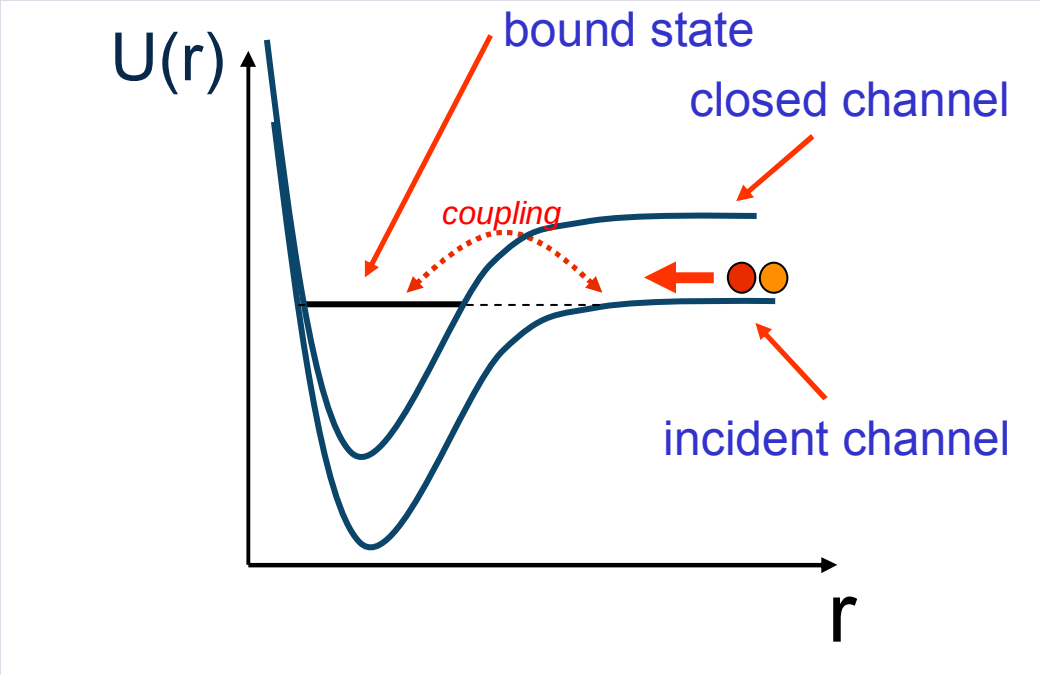


s-wave scattering length *a* determined by last bound level

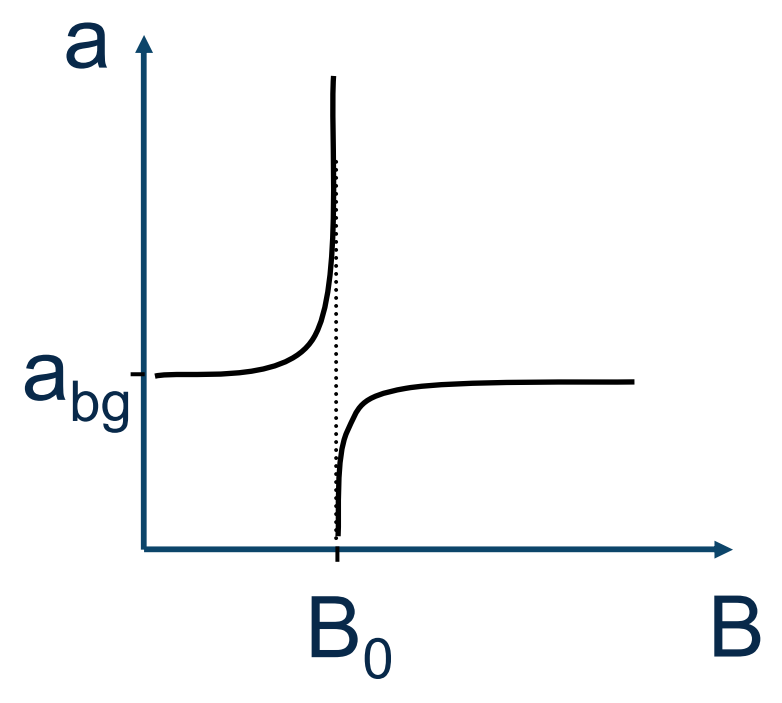
scattering length



Feshbach resonance

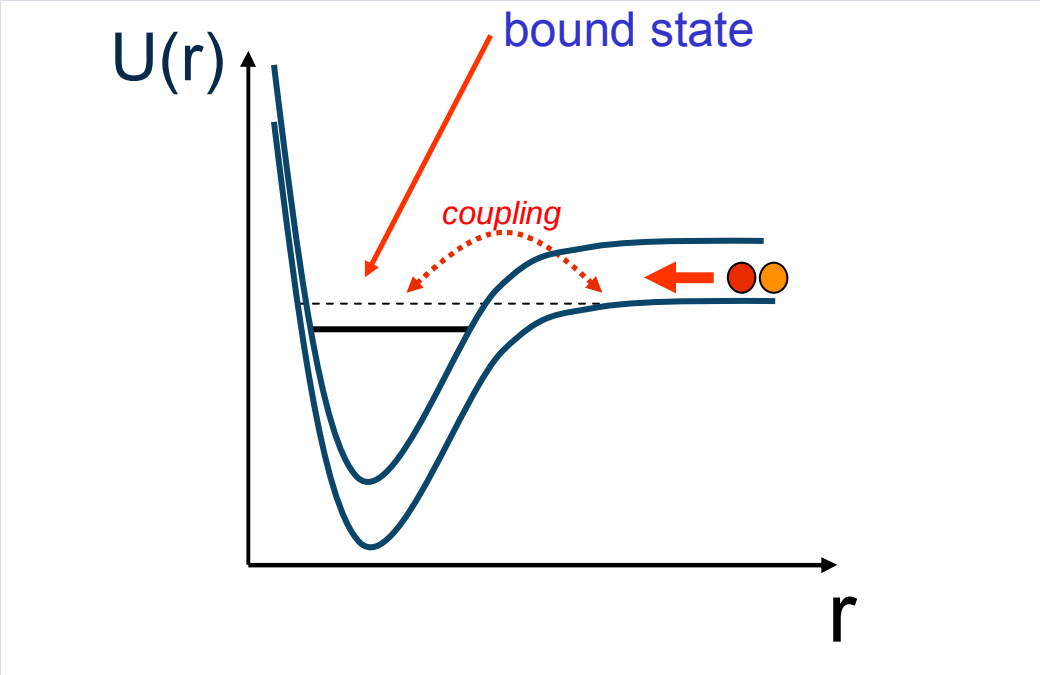


s-wave scattering length a
as a function of magnetic field B

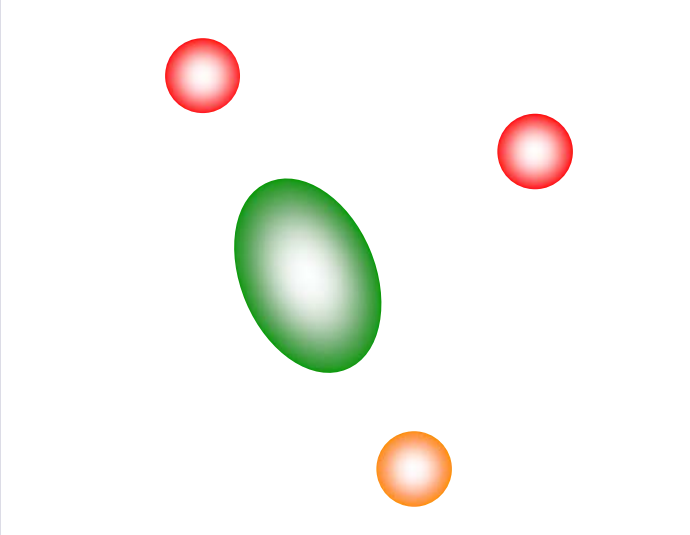


magnetic moment of bound state
differs from the magnetic moment
of the incident channel

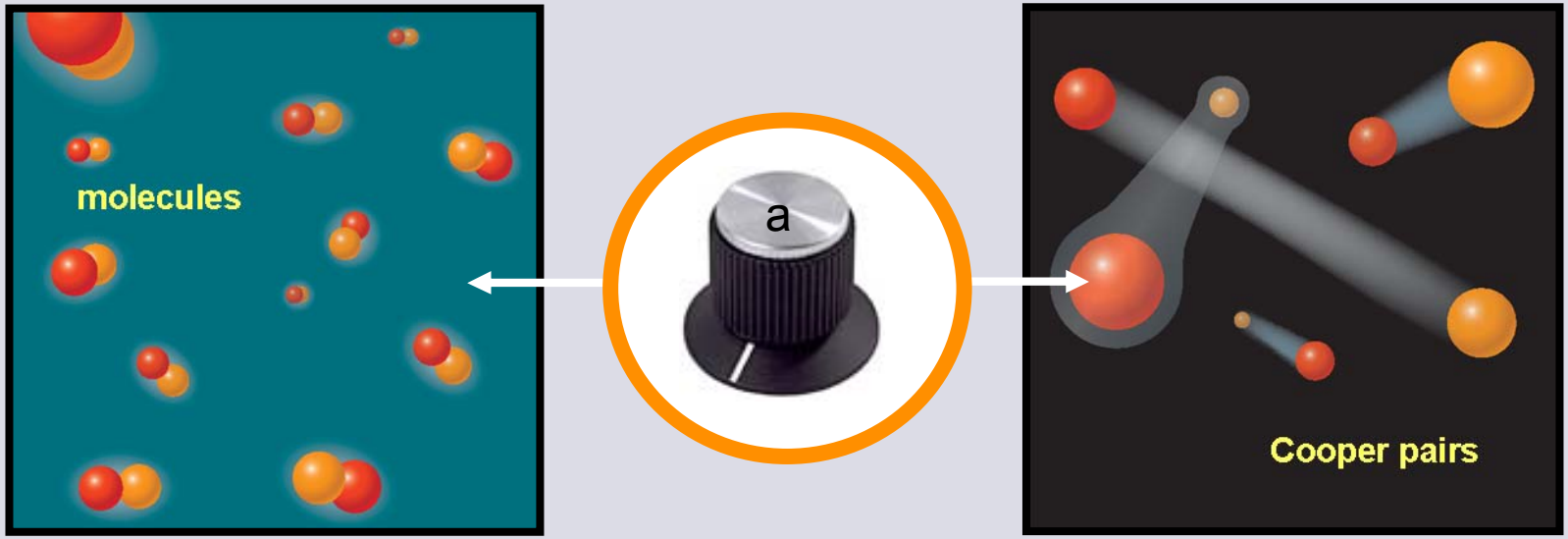
Forming molecules

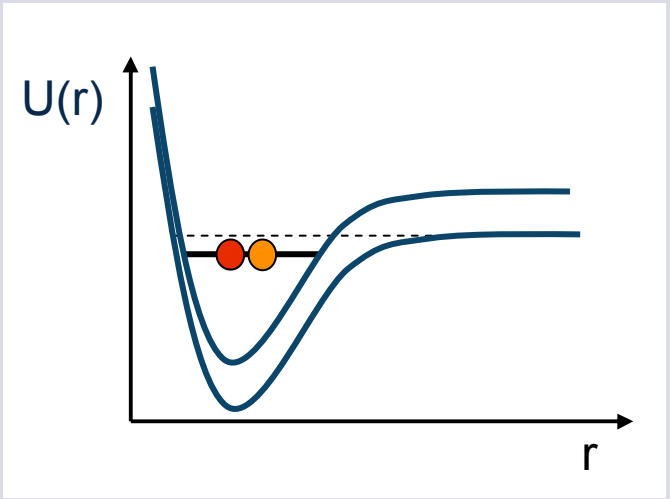


Three body collision:
(Fulfills energy and momentum conservation)

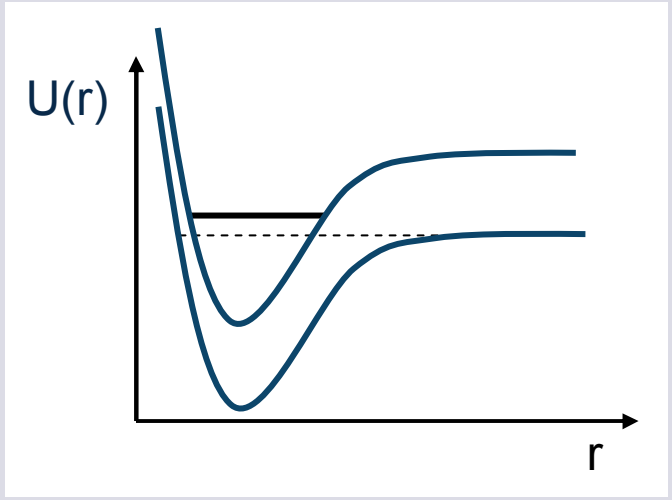


BEC-BCS crossover



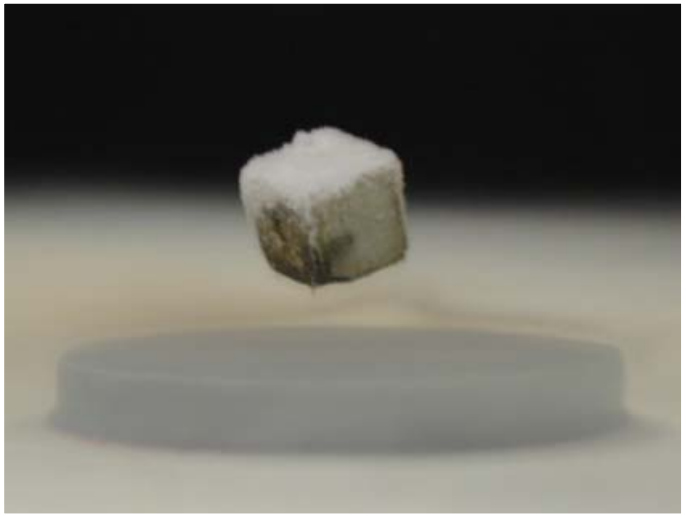


BEC of molecules

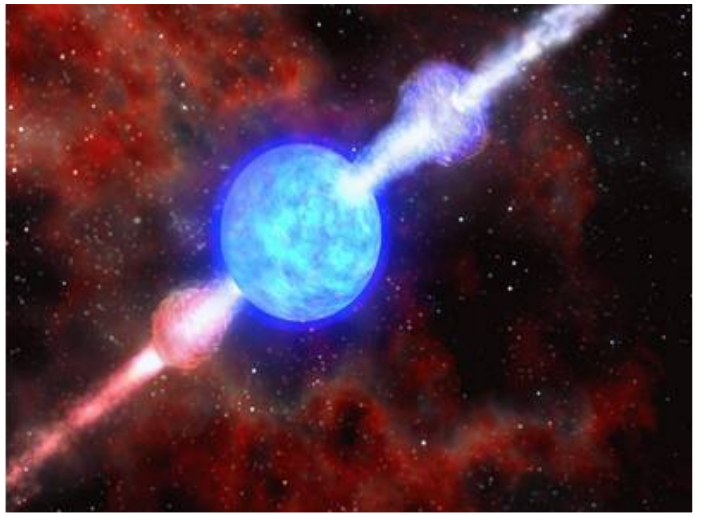


BCS state

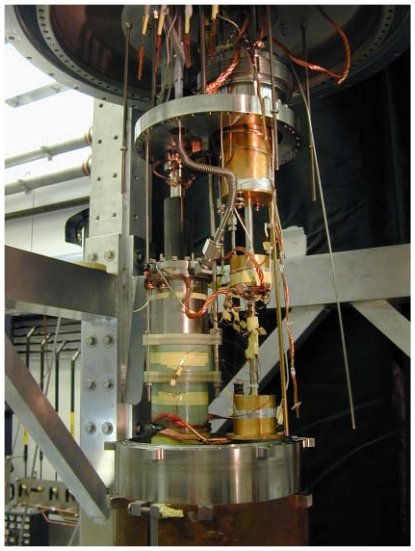
Other fermionic superfluids



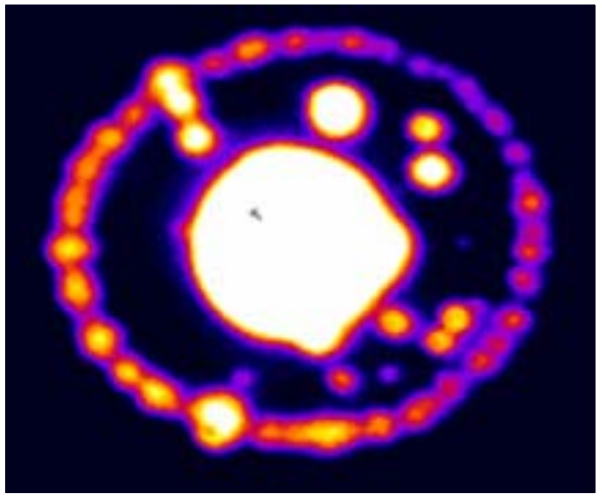
superconductors



dense quark matter



^{3}He

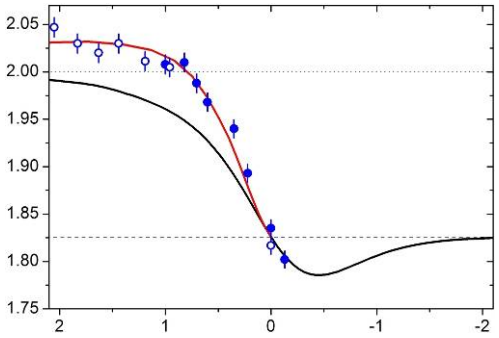


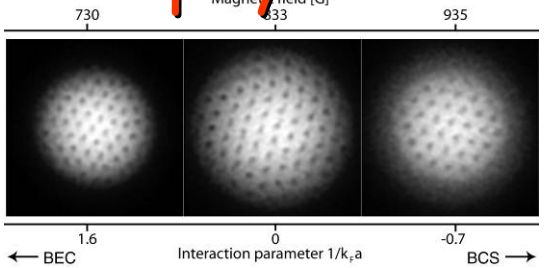
exciton condensation

control knobs (single species)

interaction strength

BEC-BCS crossover physics





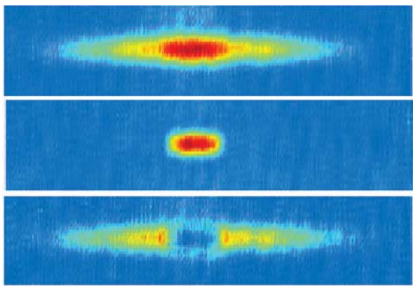
Innsbruck, JILA, MIT, Duke, ENS, Rice

. . .

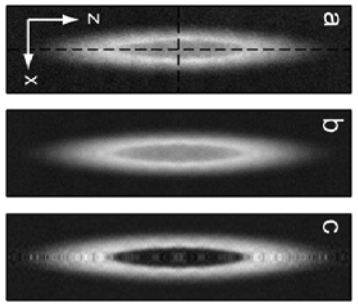
trap parameters:
anisotropy, ellipticity etc. (very flexible!)

spin imbalance

physics of polarized Fermi gases



Rice



MIT

new possibilities in FF mixtures

87/40 = 2.2

40/6 = 6.7

87/6 = 14.5

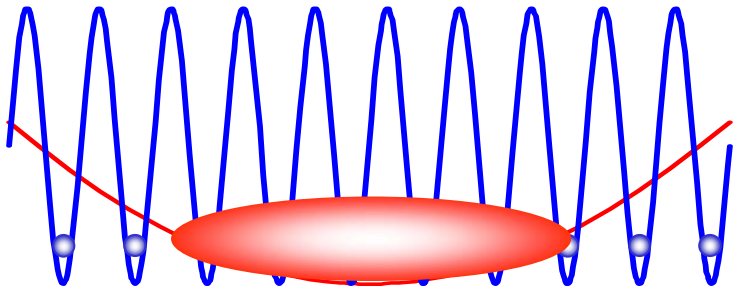
control of mass ratio

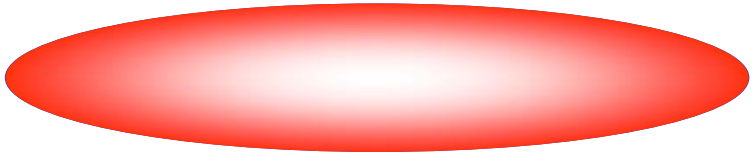
fermion pairing with unequal masses,
stable heteronuclear molecules,
novel quantum phases …

<u>*independent*</u> control of optical potentials

pairing with unequal Fermi surfaces

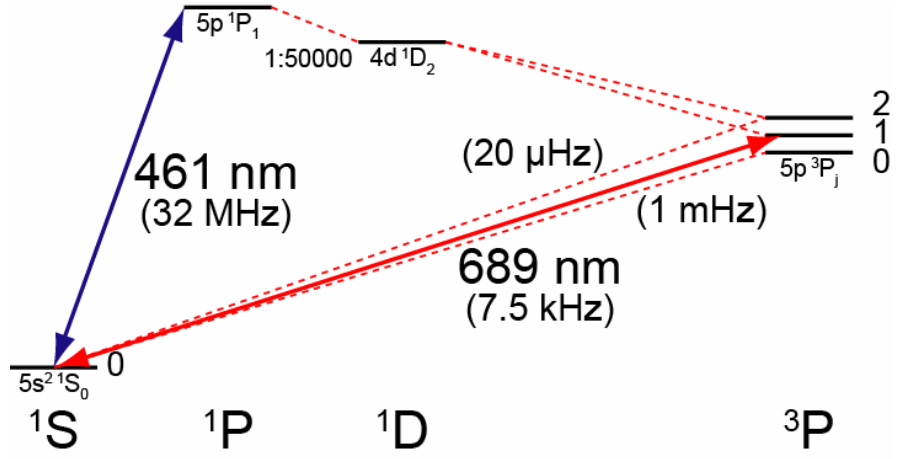
e.g., small trap of ^{40}K in a large trap of ^{6}Li
or optical lattice for ^{87}Sr in a bath of ^{6}Li …





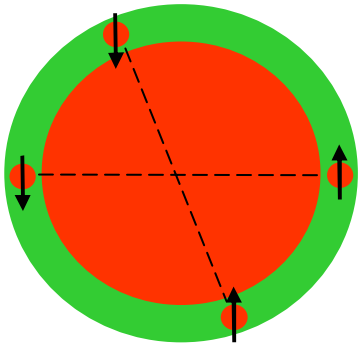
Alkaline / alkaline-earth mixtures

Strontium

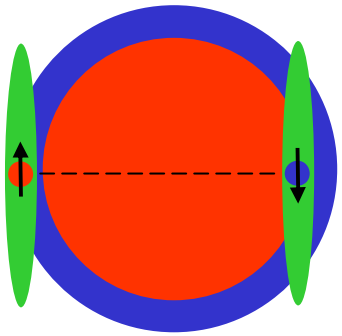


- metastable state
- intercombination line → optical Feshbach resonances
- weak magnetic moment

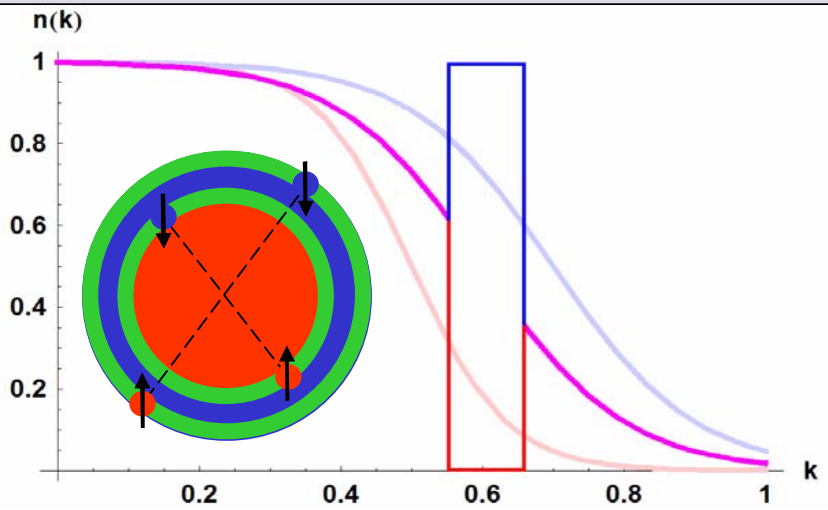
Pairing phases beyond BCS



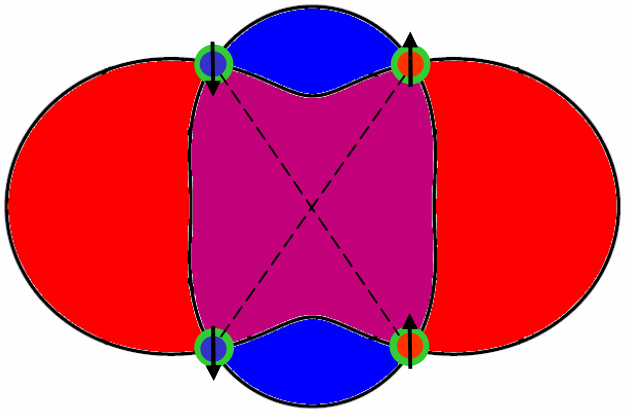
BCS superfluidity
Bardeen, Cooper & Schrieffer (1957)



FFLO superfluidity
Fulde & Ferrell (1964), Larkin & Ovchinnikov (1965)
discussed in $CeCoIn_5$, $ErRh_4B_4$, $HoMo_6S_8$, neutron stars



Breached pair superfluidity
= phase separation in momentum space
Liu & Wilczek (2003)



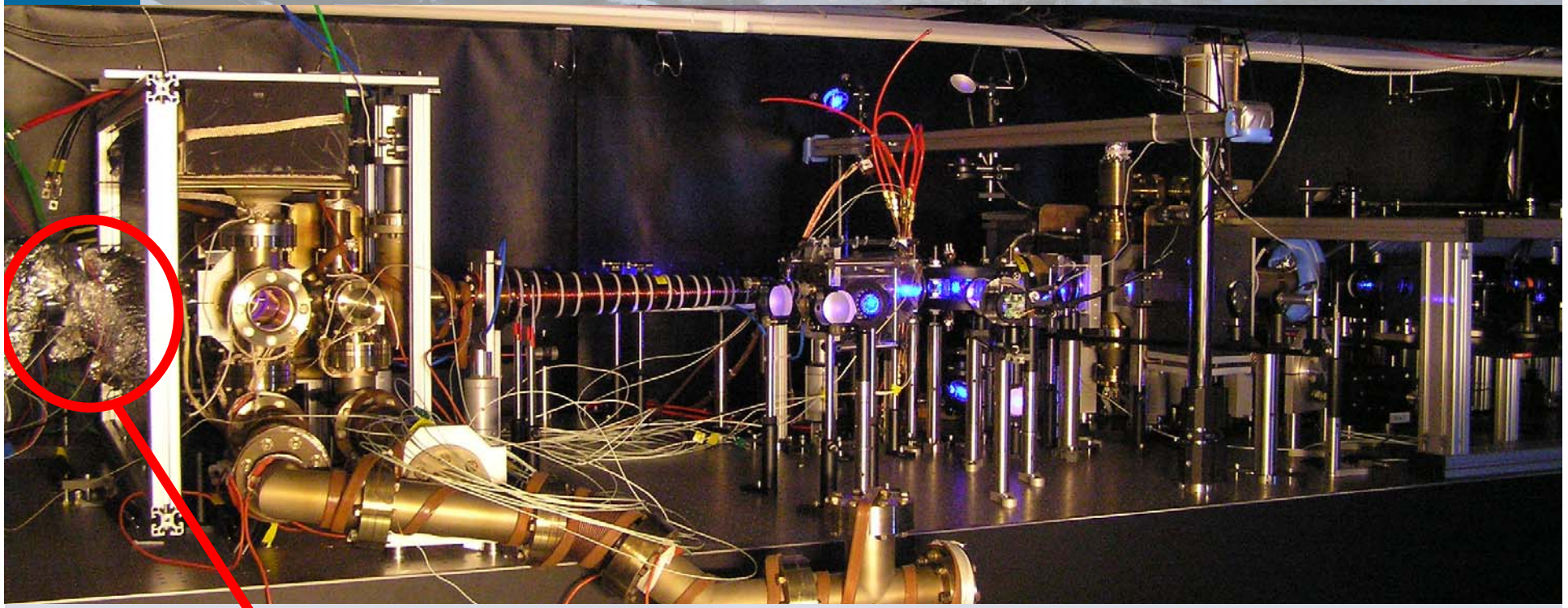
Deformed Fermi surface superfluidity
Müther & Sedrakian (2002)


The machine


MELLES GRIOT
MELLES GRIOT
IQI
August 2005

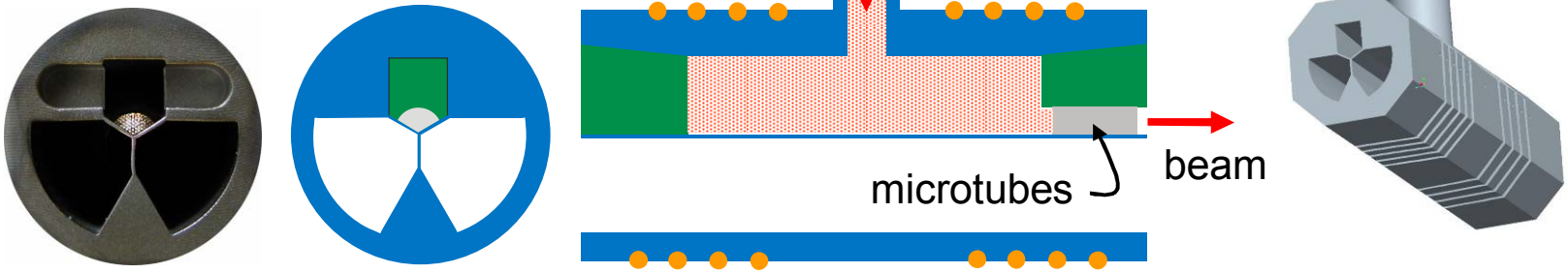

IQI
Februar 2007
MELLES GRIOT

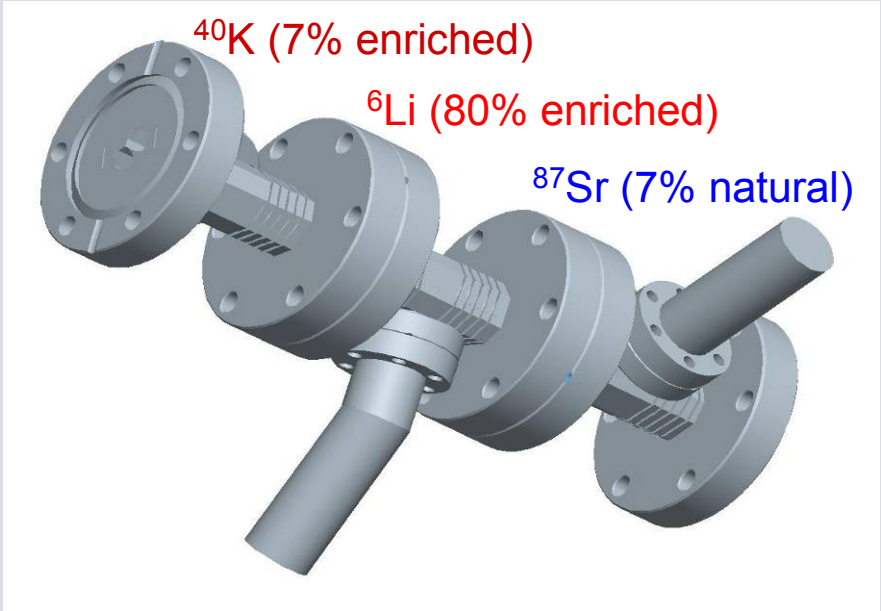
The Lithium-Potassium-Strontium Machine

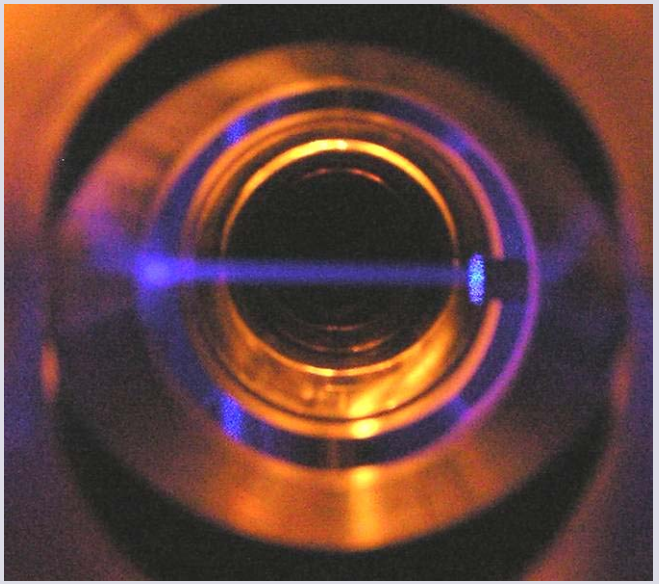


Three species atomic beam source

Three-species oven

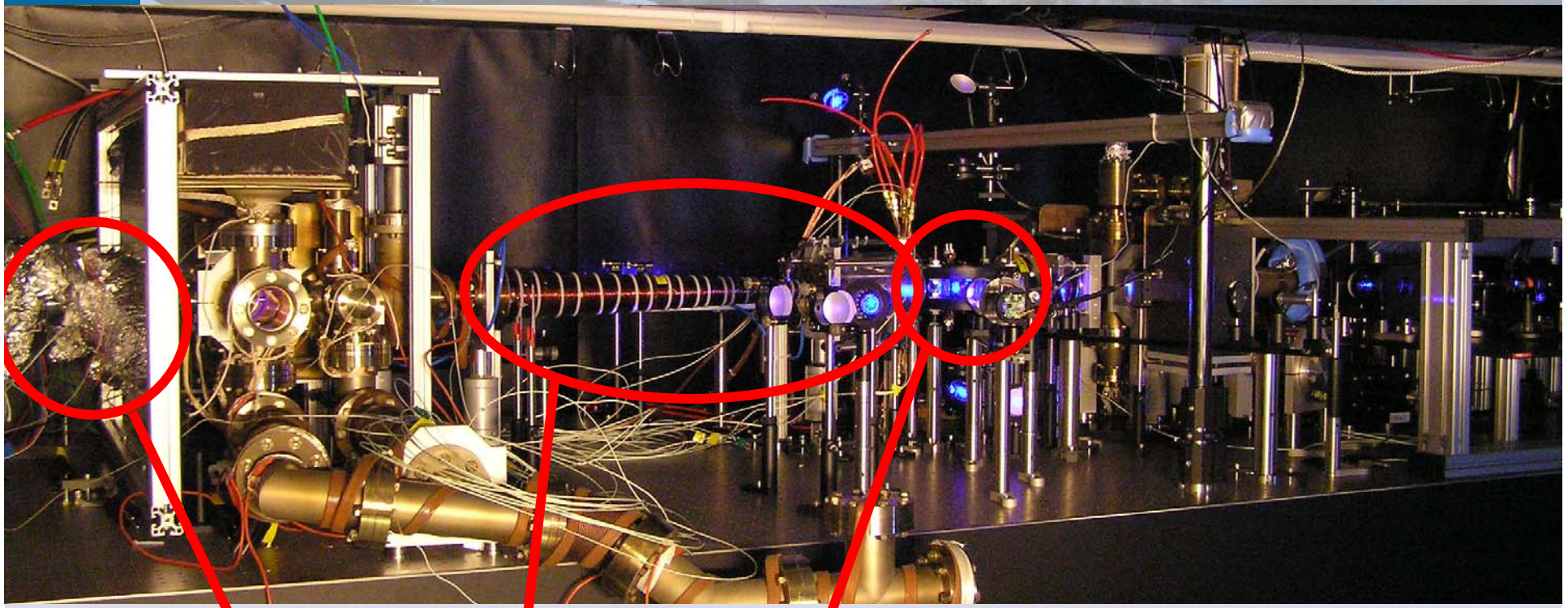






Strontium atomic beam

The Lithium-Potassium-Strontium Machine



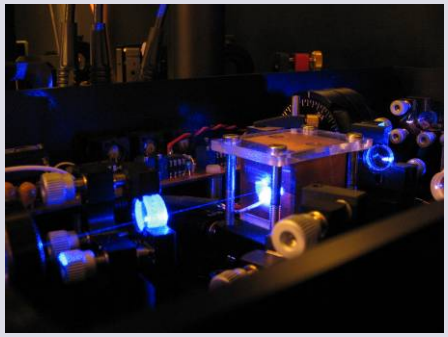
Zeeman slower

Three color cooling lasers

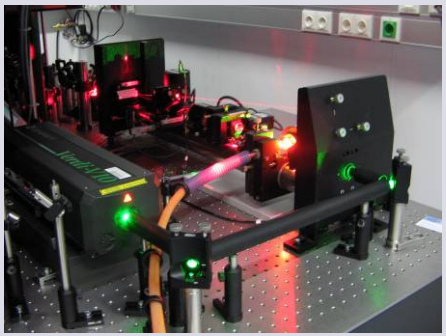
Three species atomic beam source

Cooling laser system

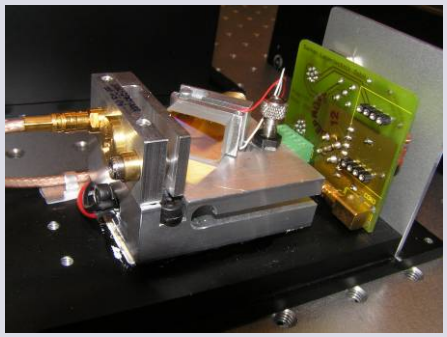
Sr, 461nm: doubled diode laser



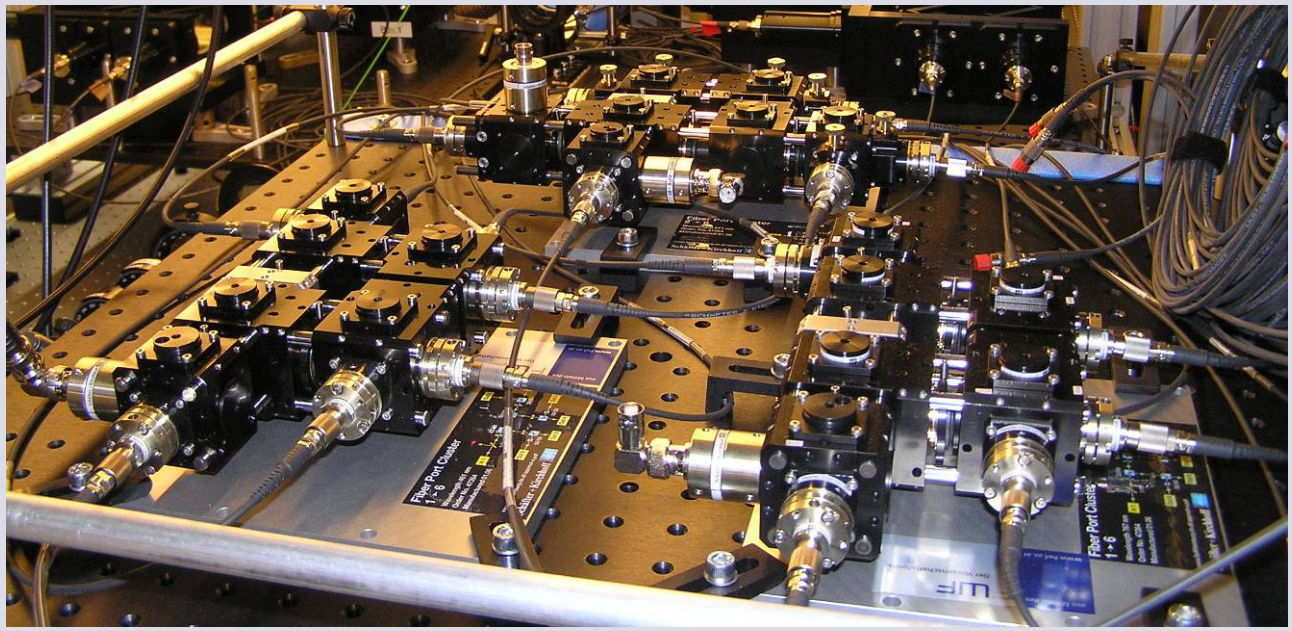
Li, 671nm: dye laser

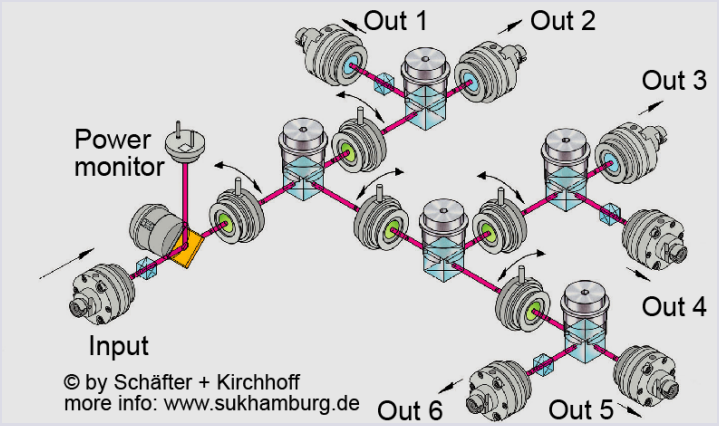


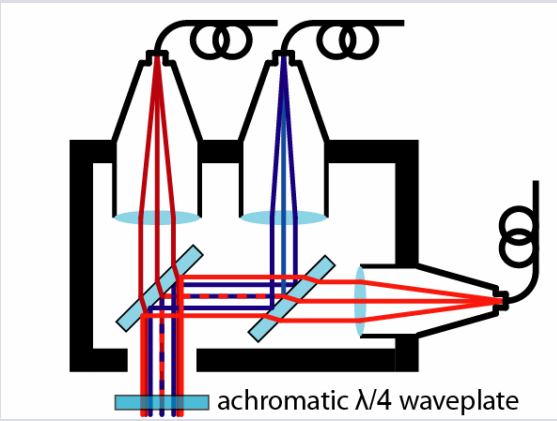
K, 767nm: diode lasers



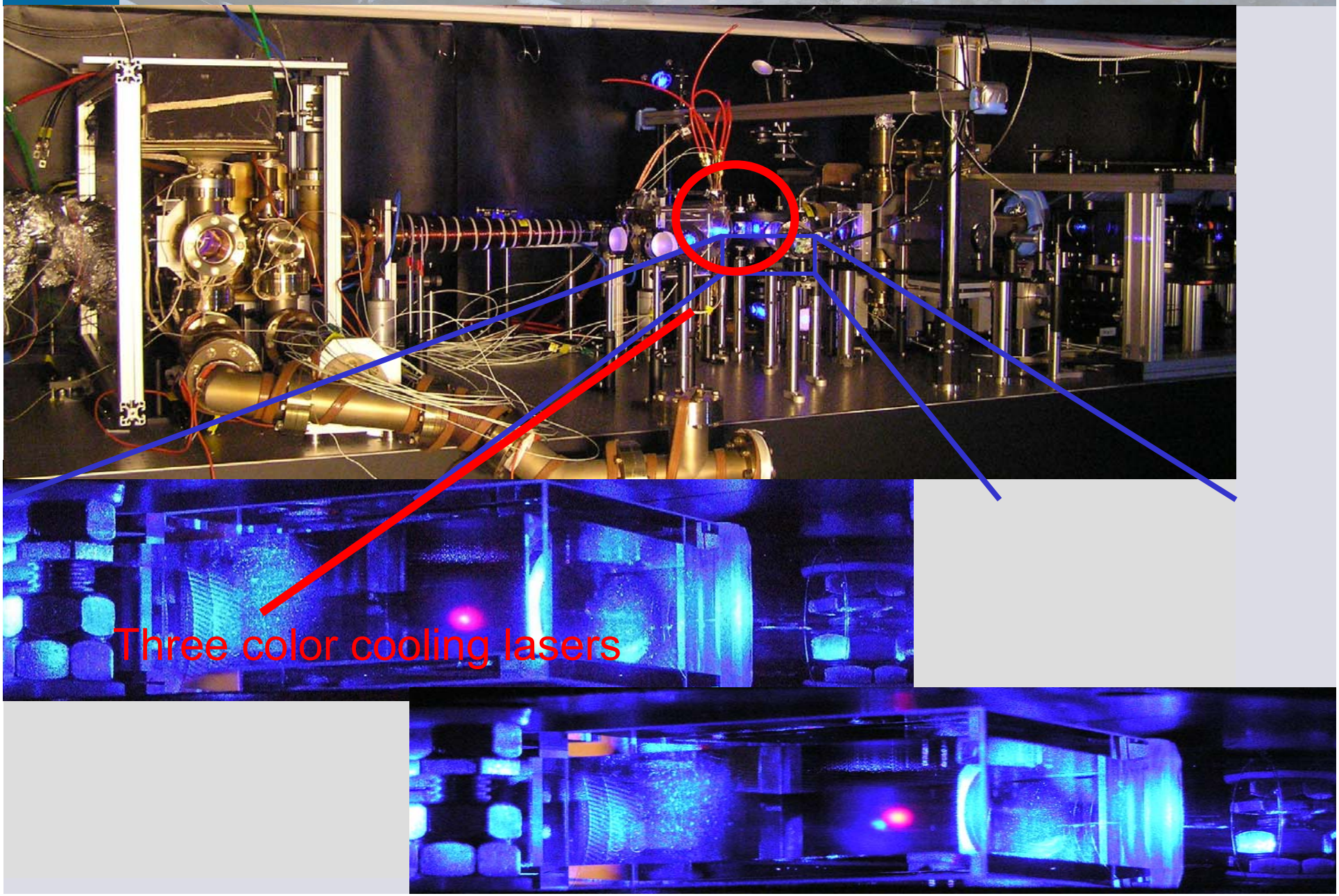
MOT beam delivery:



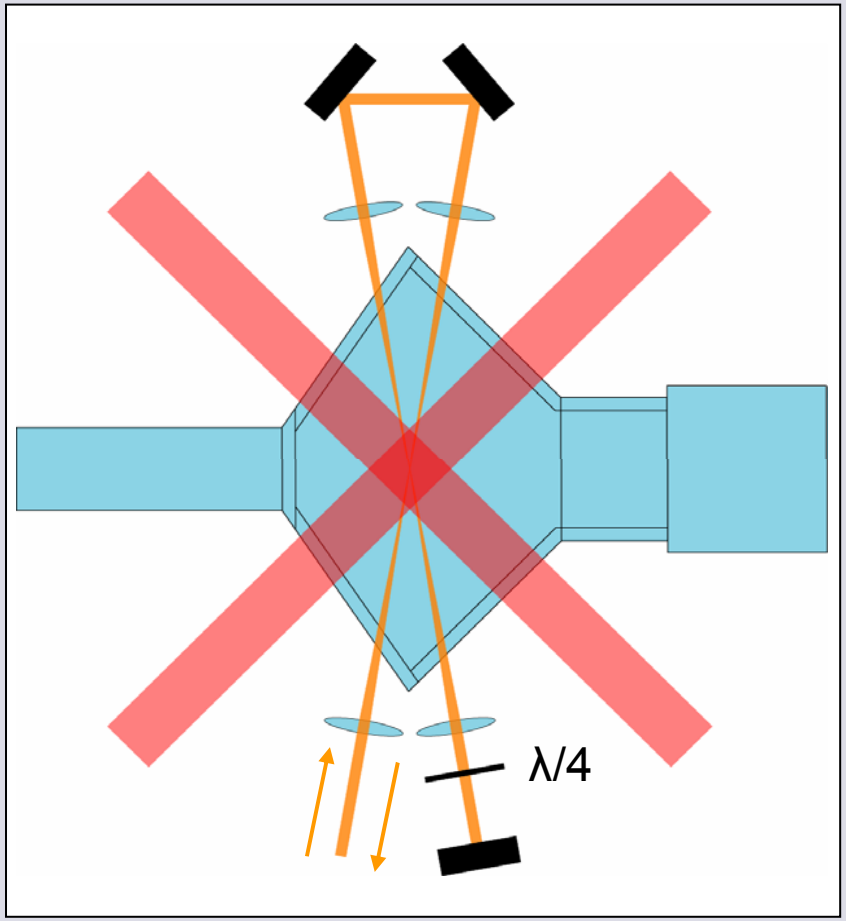




The Lithium-Potassium-Strontium Machine

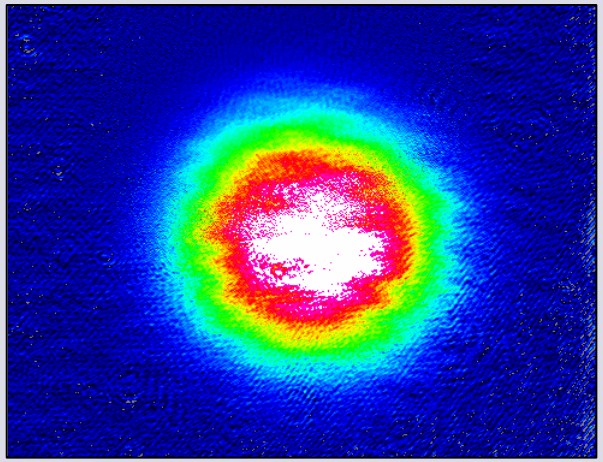


The all-optical way

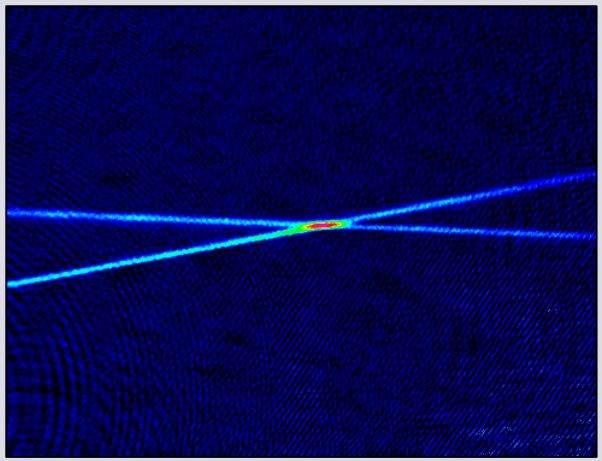


dipole trap (100W 1075nm laser):
U ~ k_B 1 mK
w ~ 60 µm

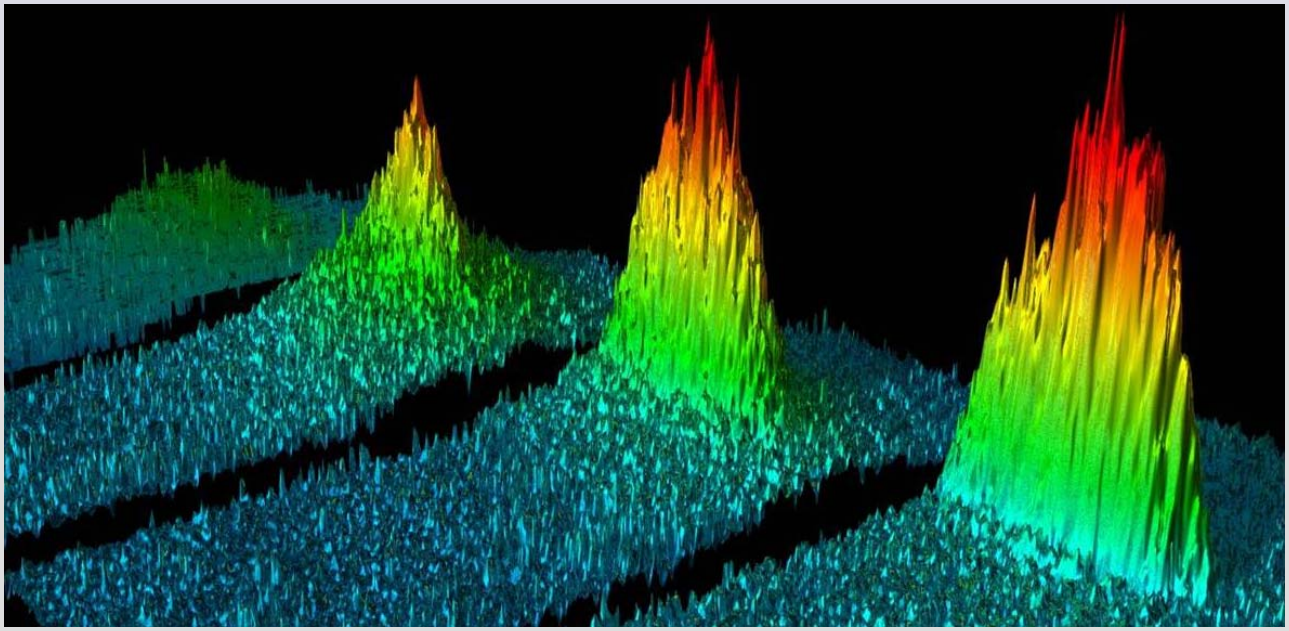
^{6}Li MOT: N ~ 10^9 T ~ 300µK



dipole trap: N > 10^6



$^6Li_2$ molecular Bose condensation

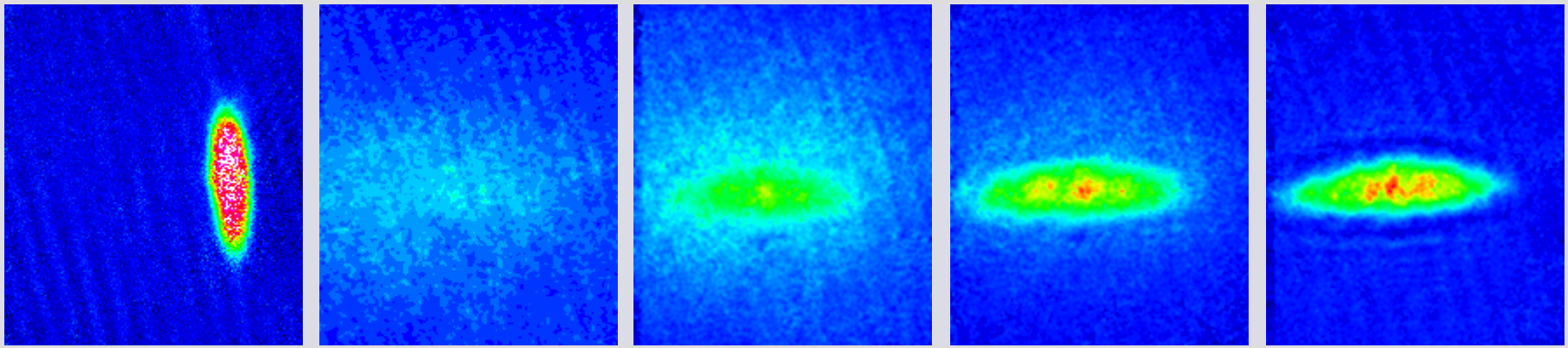


in dipole trap

After 10ms time of flight:

PURE BEC!

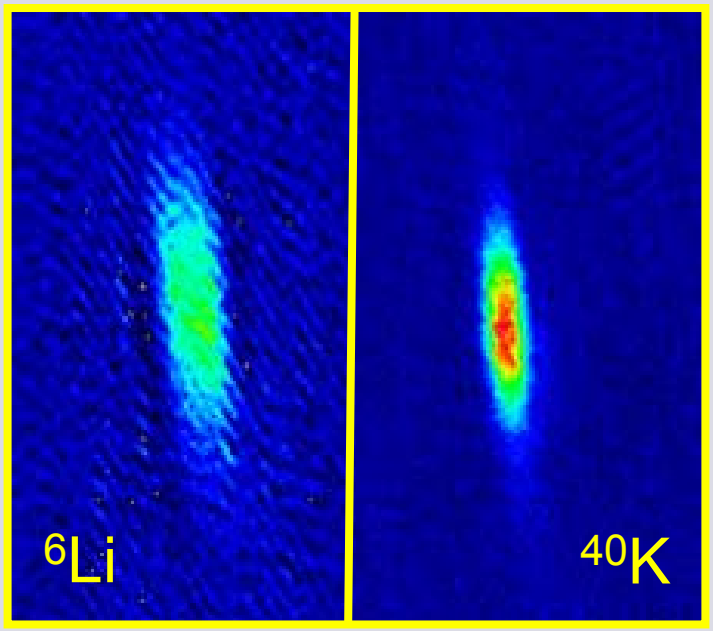
4.3 sec evap **4.7 sec evap** **4.8 sec evap** **5.1 sec evap**



heteronuclear FF mixture !

absorption images of ^{6}Li and ^{40}K atoms

after 3 s of forced evaporative cooling at 750G



26 μK trap depths 55 μK

temperature ~ 4μK

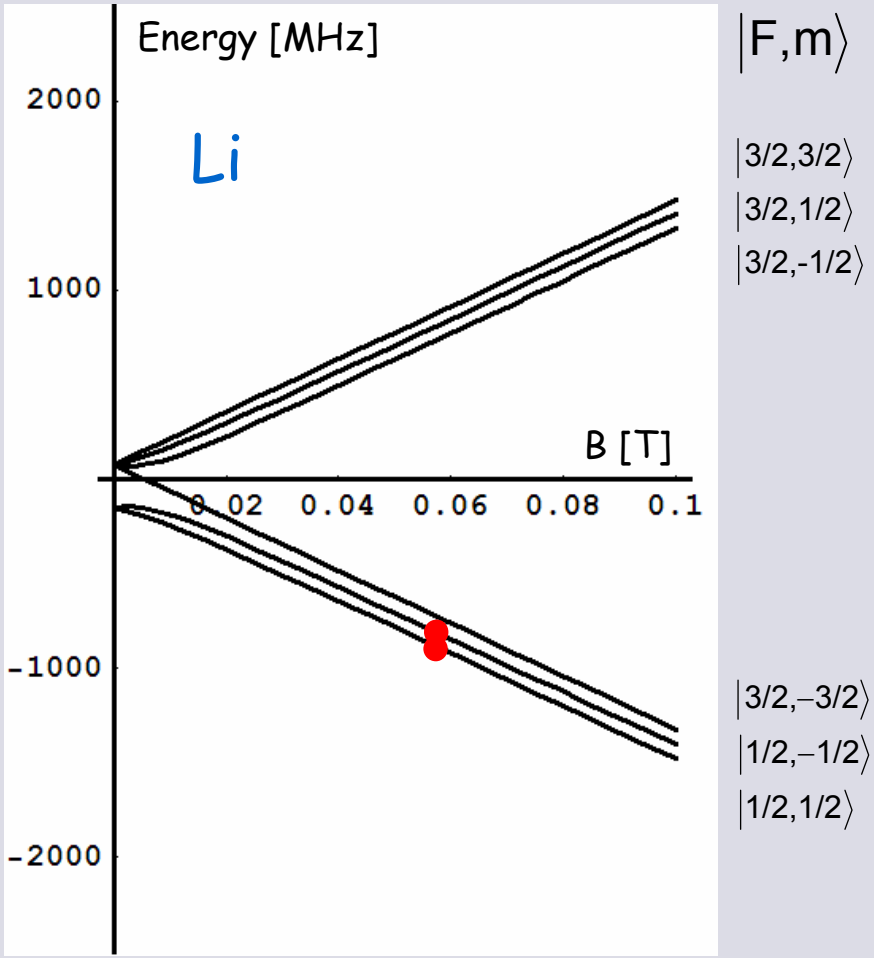
numbers ~ 10^{5}

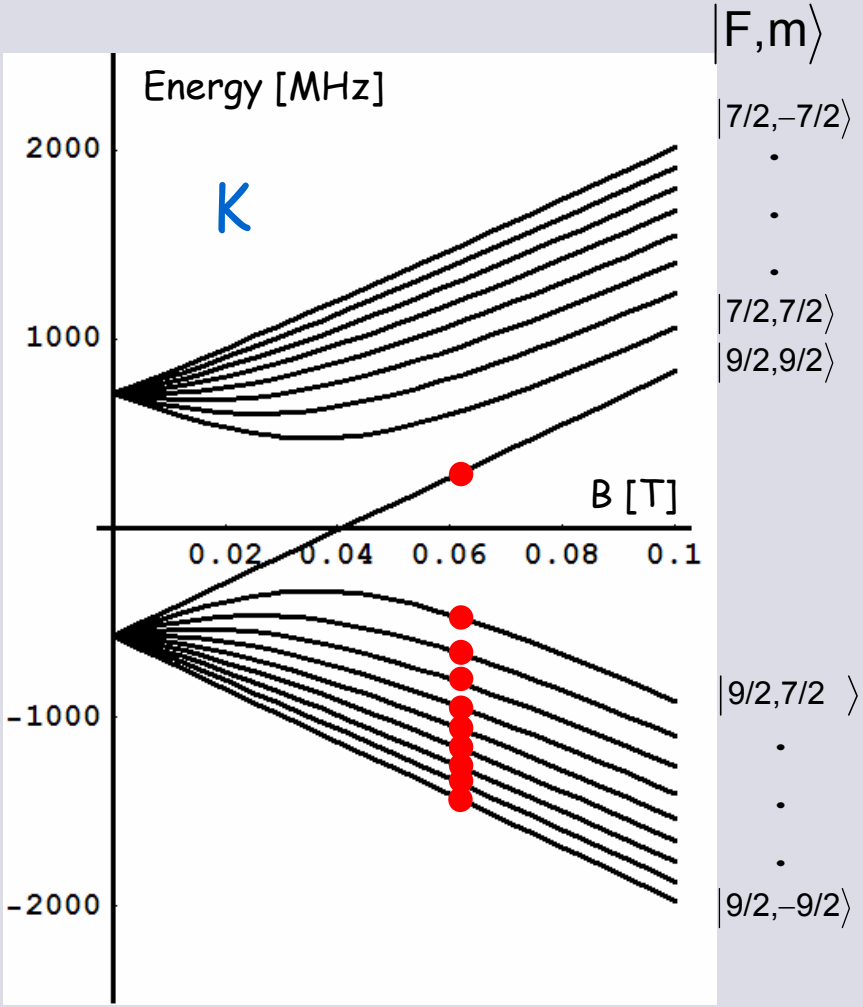
heteronuclear Fermi-Fermi mixture

(stable up to the point where $^{6}Li_2$ dimers are formed)

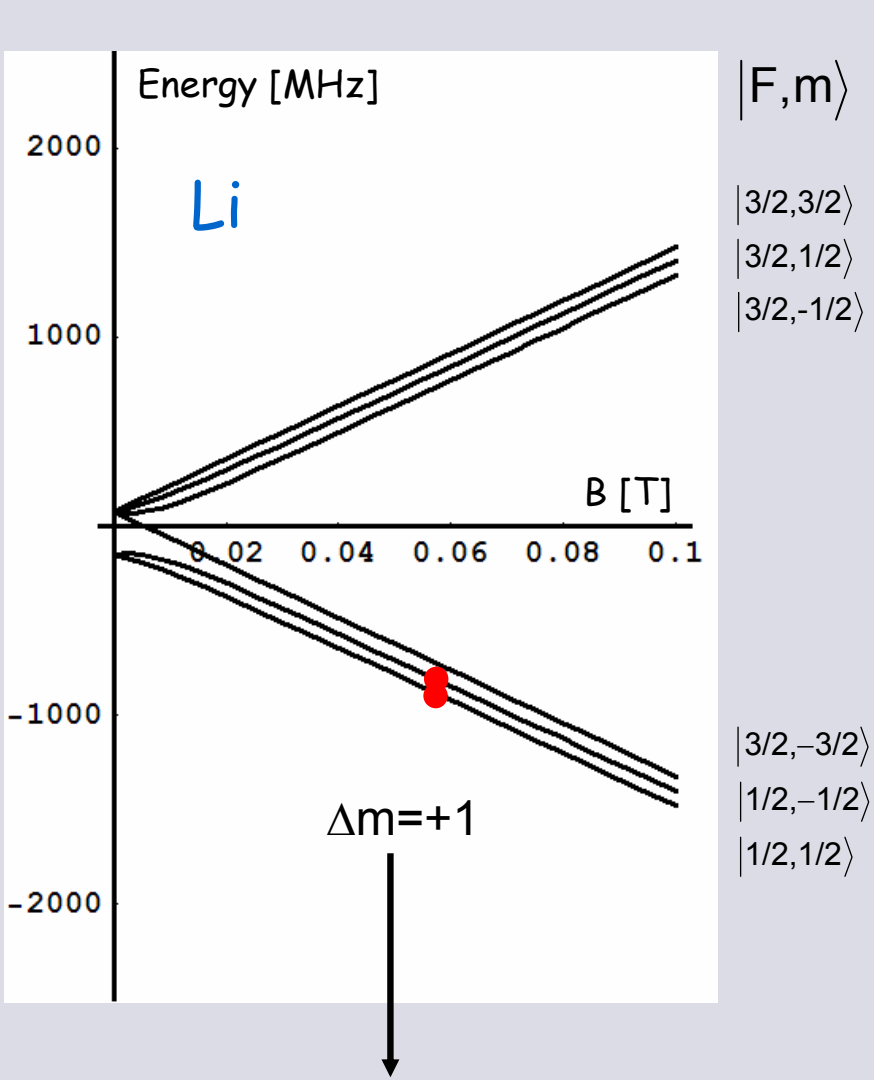

Feshbach resonances

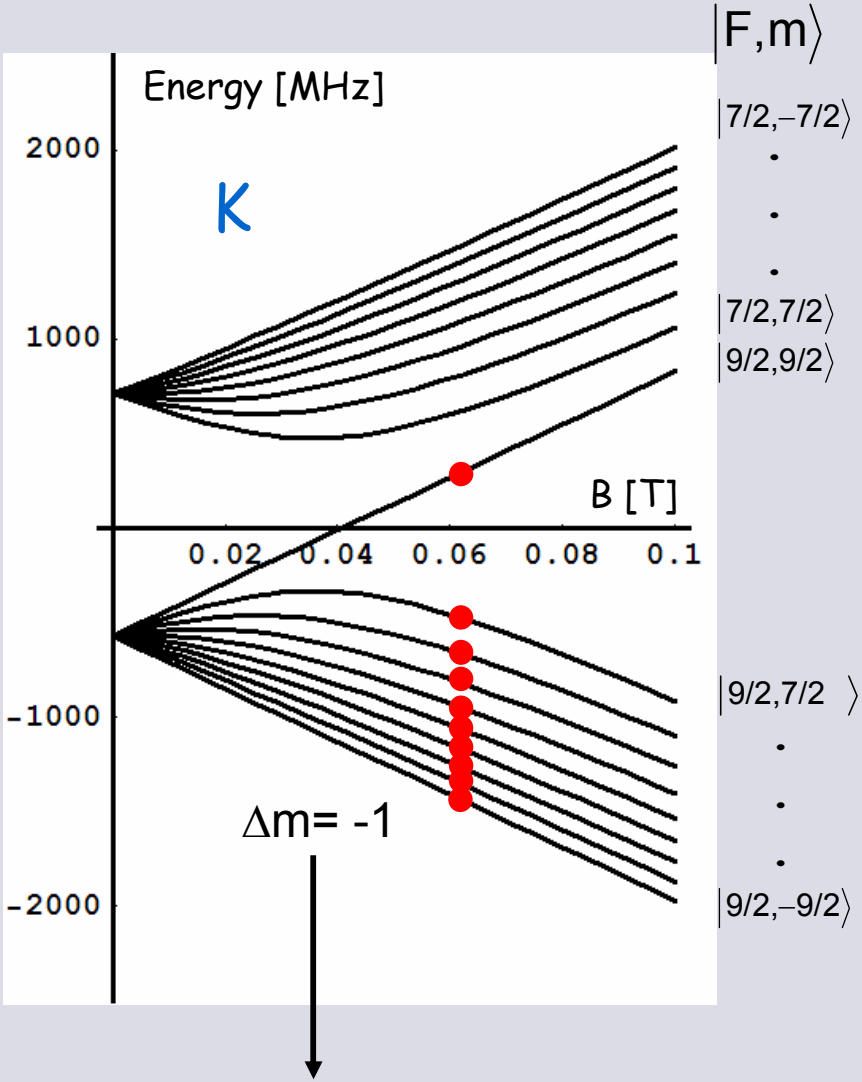
Spin states

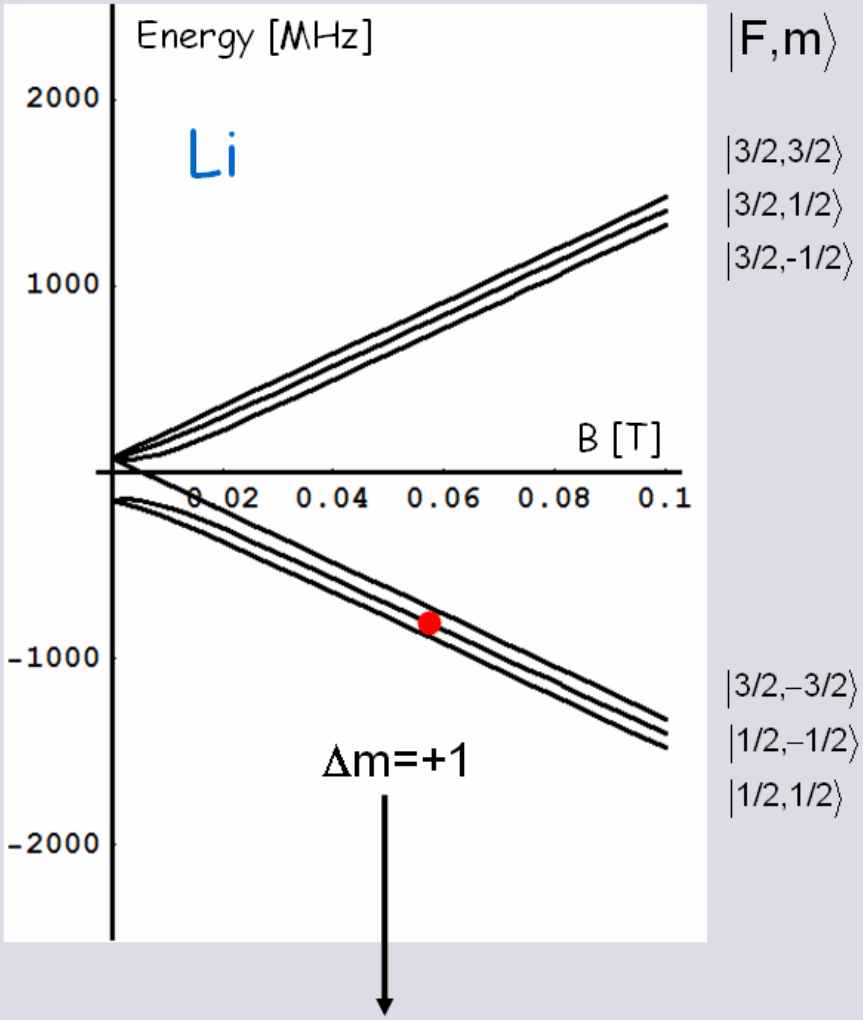

Energy [MHz]
Li
B [T]
2000
1000
-1000
-2000
0.02
0.04
0.06
0.08
0.1
|F,m⟩
|3/2,3/2⟩
|3/2,1/2⟩
|3/2,-1/2⟩
|3/2,–3/2⟩
|1/2,–1/2⟩
|1/2,1/2⟩

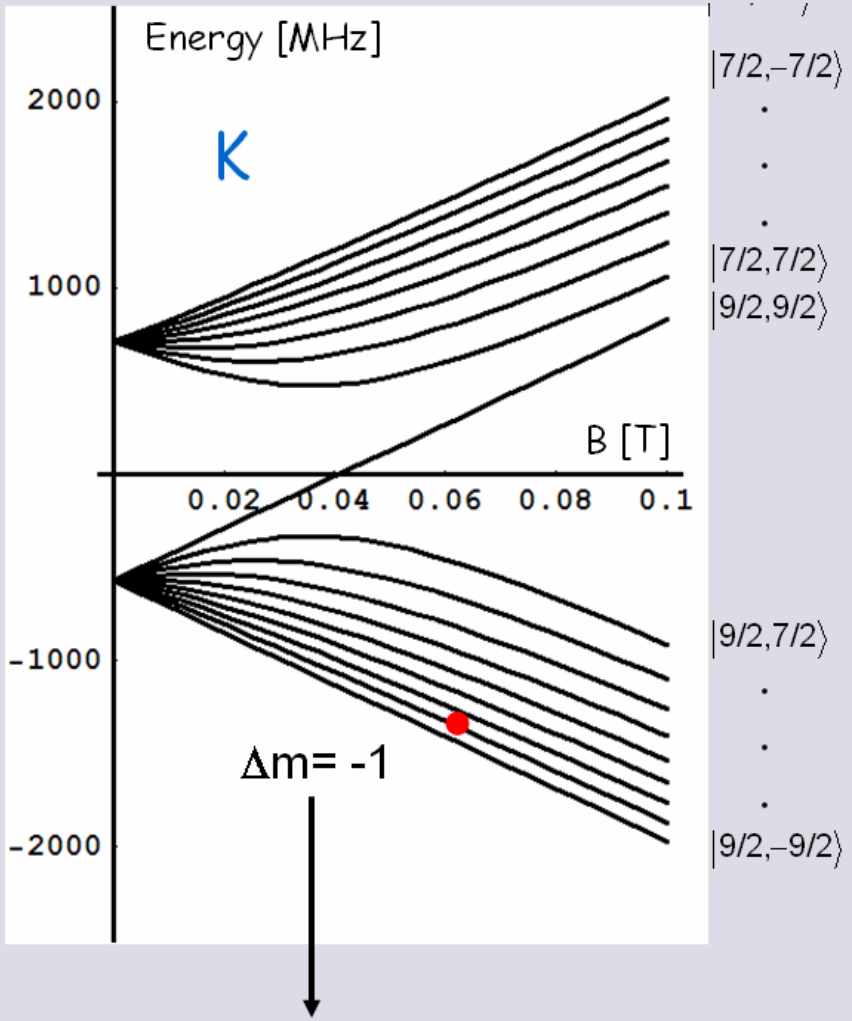

|F,m⟩
Energy [MHz]
K
B [T]
2000
1000
-1000
-2000
0.02
0.04
0.06
0.08
0.1
|7/2,–7/2⟩
|7/2,7/2⟩
|9/2,9/2⟩
|9/2,7/2 ⟩
|9/2,–9/2⟩

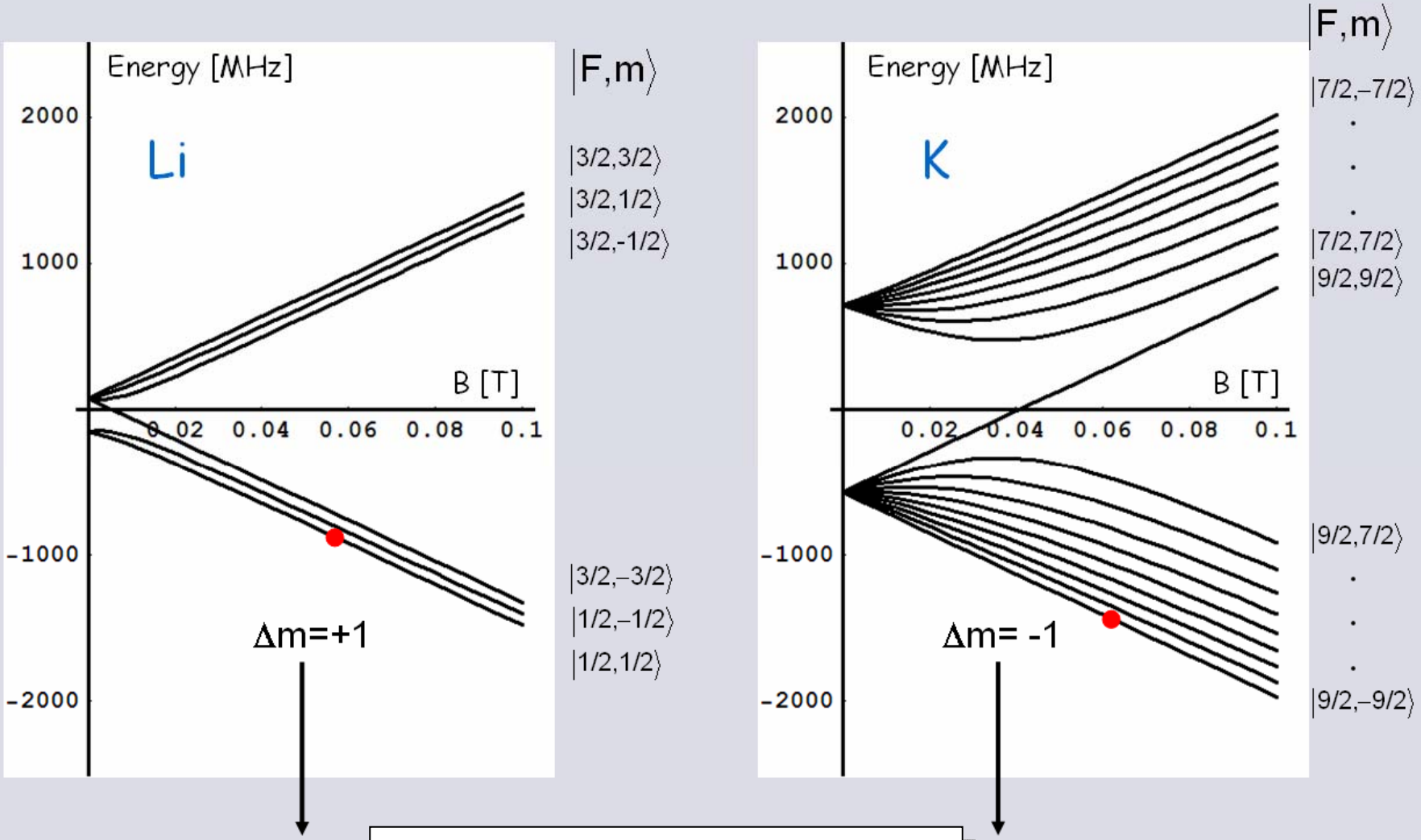
Spin states


Energy [MHz]
2000
1000
-1000
-2000
Li
B [T]
0.02
0.04
0.06
0.08
0.1
Δm=+1
|F,m⟩
|3/2,3/2⟩
|3/2,1/2⟩
|3/2,-1/2⟩
|3/2,−3/2⟩
|1/2,−1/2⟩
|1/2,1/2⟩


Energy [MHz]
2000
1000
-1000
-2000
K
B [T]
0.02
0.04
0.06
0.08
0.1
Δm= -1
|F,m⟩
|7/2,−7/2⟩
|7/2,7/2⟩
|9/2,9/2⟩
|9/2,7/2 ⟩
|9/2,−9/2⟩

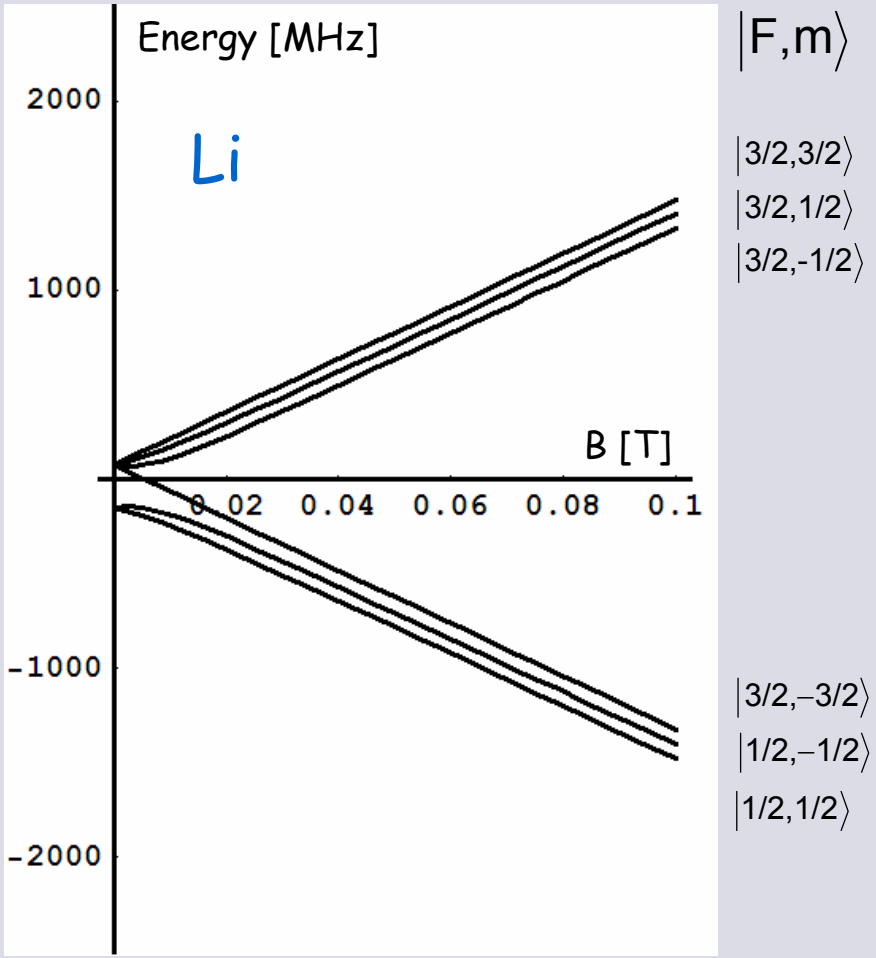

Energy [MHz]
2000
1000
-1000
-2000
Li
B [T]
0.02
0.04
0.06
0.08
0.1
Δm=+1
|F,m⟩
|3/2,3/2⟩
|3/2,1/2⟩
|3/2,-1/2⟩
|3/2,–3/2⟩
|1/2,–1/2⟩
|1/2,1/2⟩

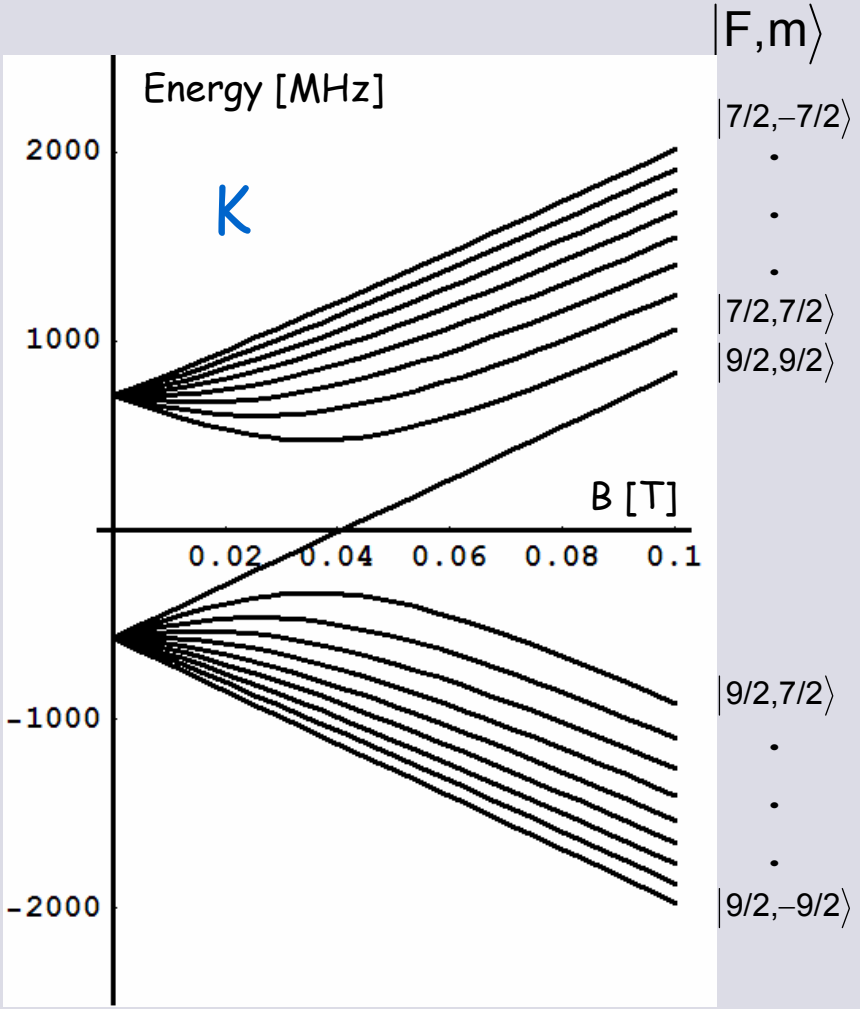

Energy [MHz]
2000
1000
-1000
-2000
K
B [T]
0.02
0.04
0.06
0.08
0.1
Δm= -1
|7/2,–7/2⟩
|7/2,7/2⟩
|9/2,9/2⟩
|9/2,7/2⟩
|9/2,–9/2⟩



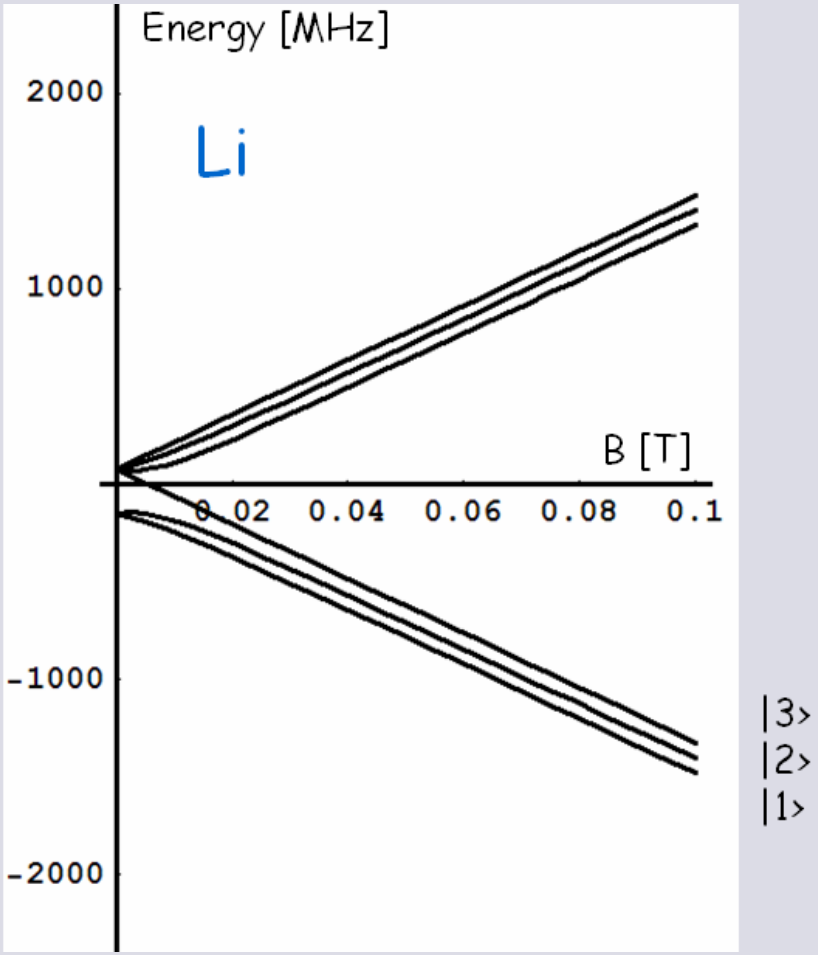
stable mixtures can be created
if one of the species is fully polarized
into the lowest state !

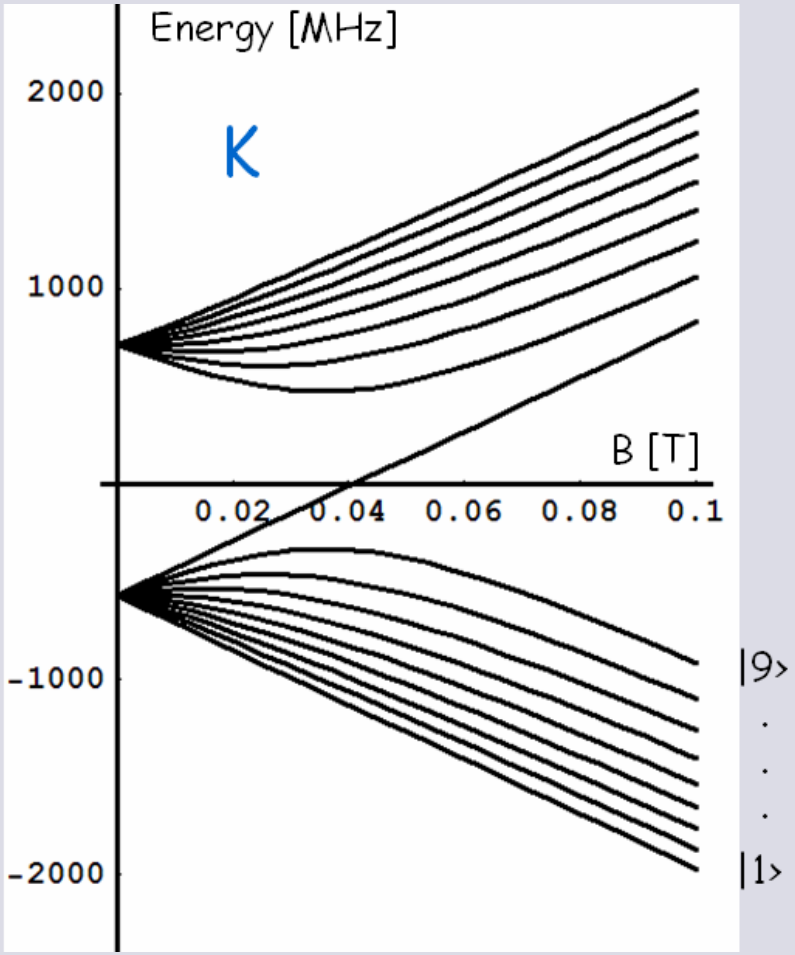
Spin states nomenclature



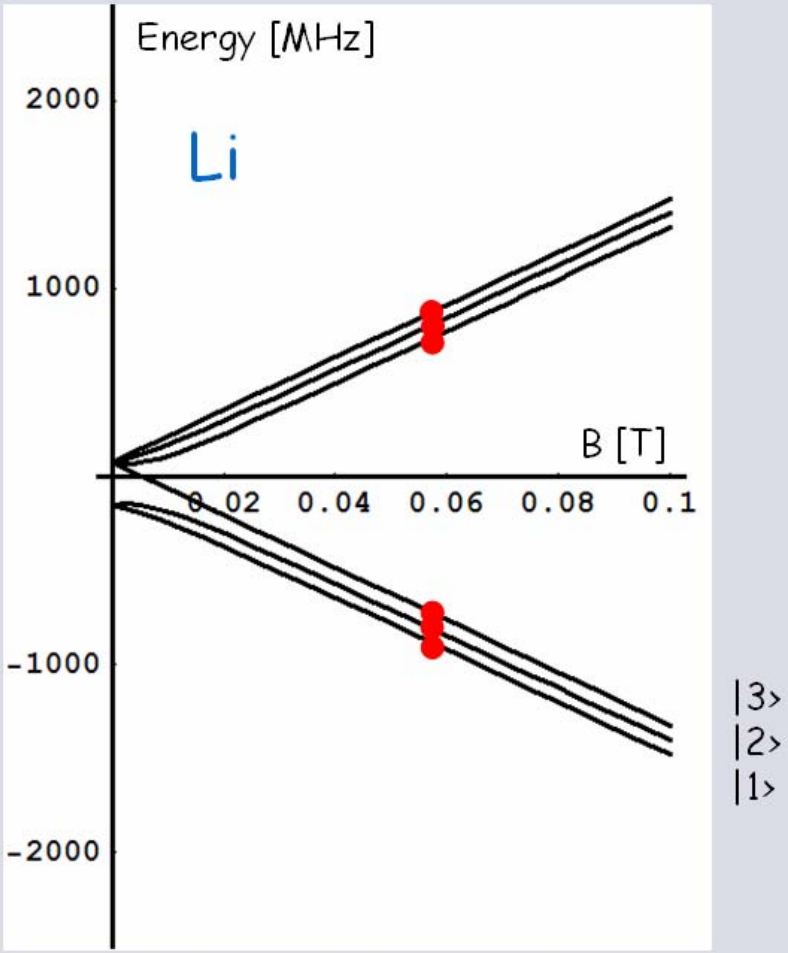


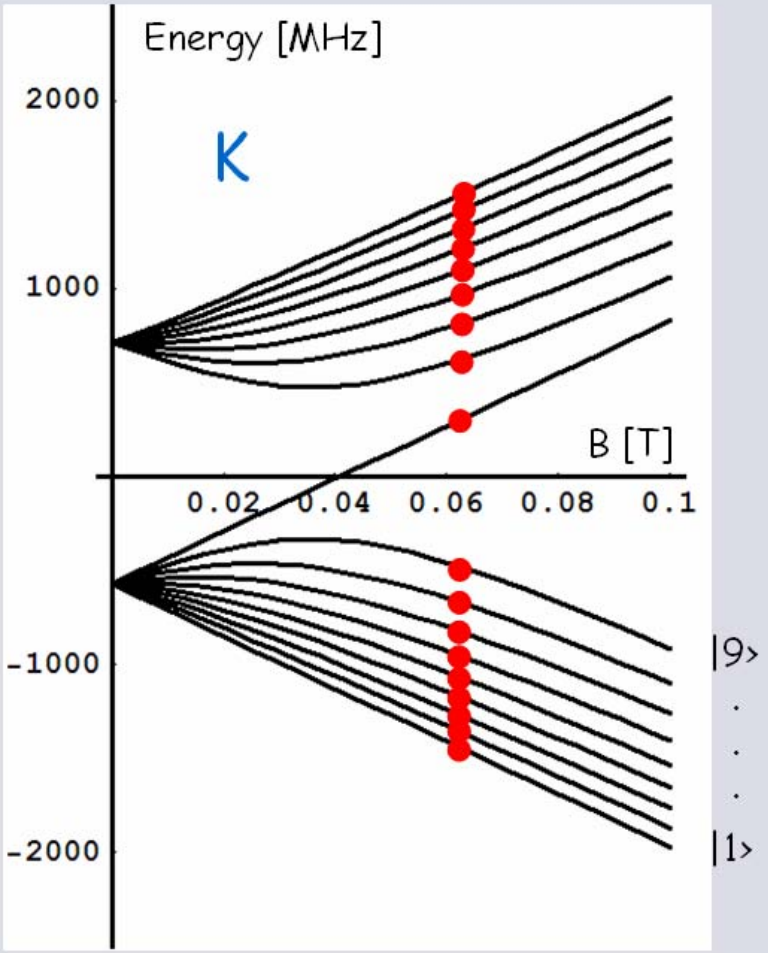
Spin states nomenclature



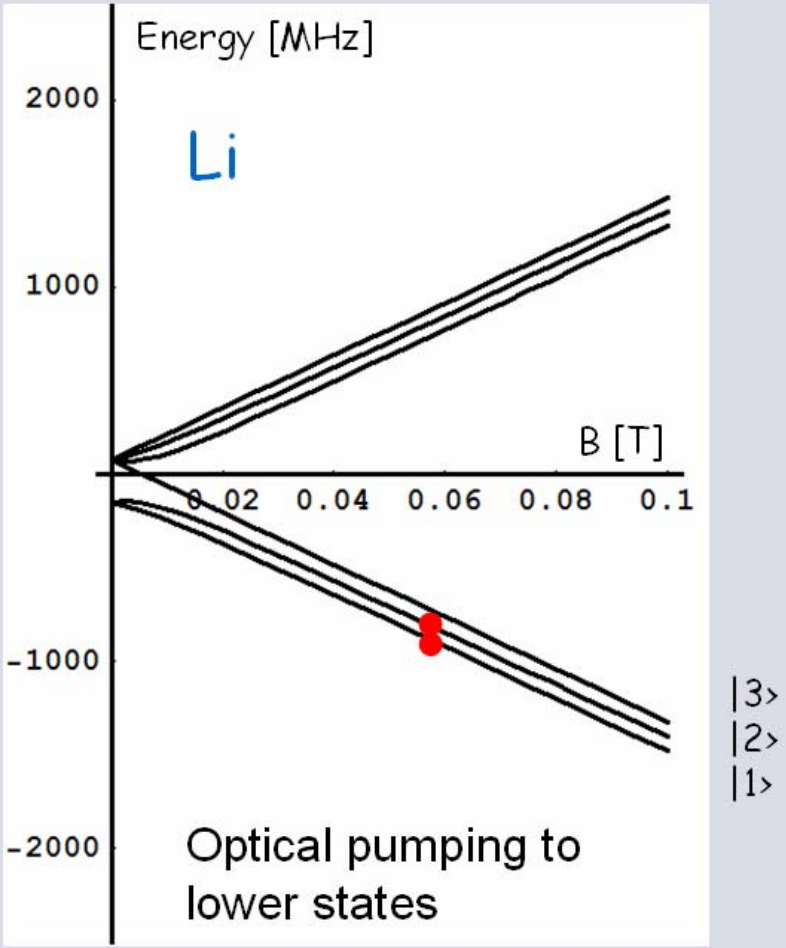


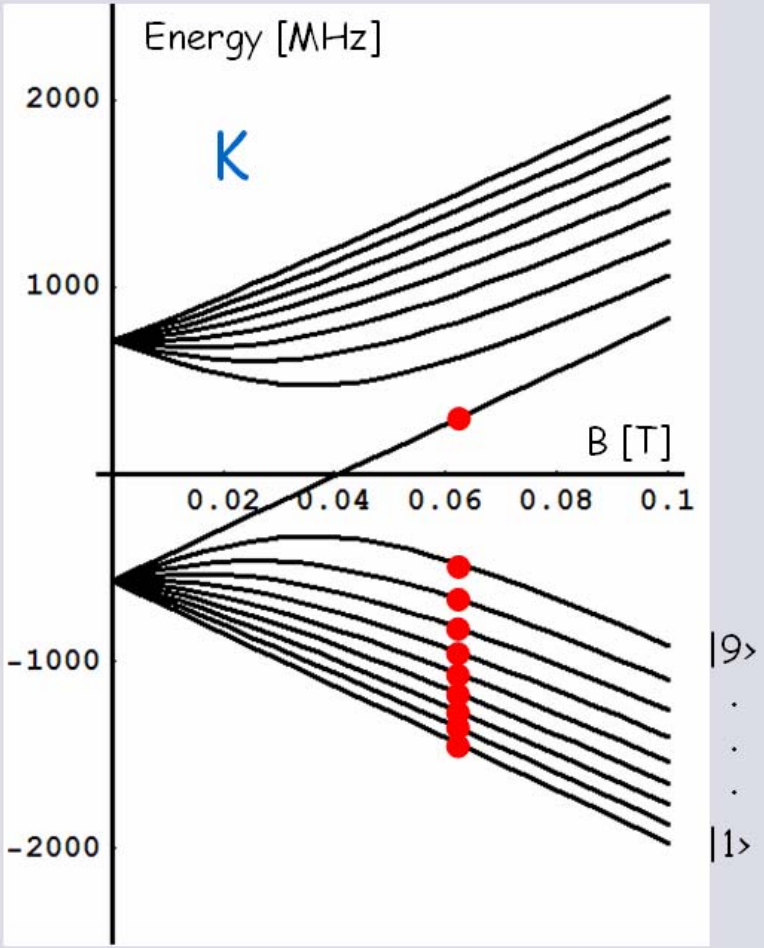
Initial spin state preparation



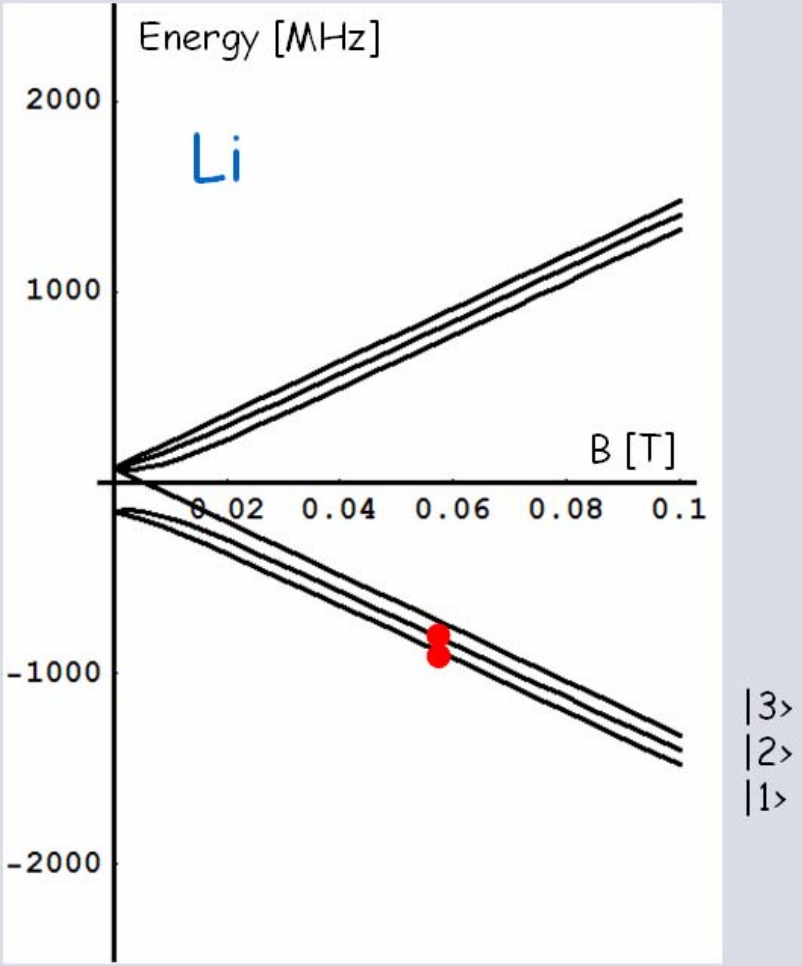


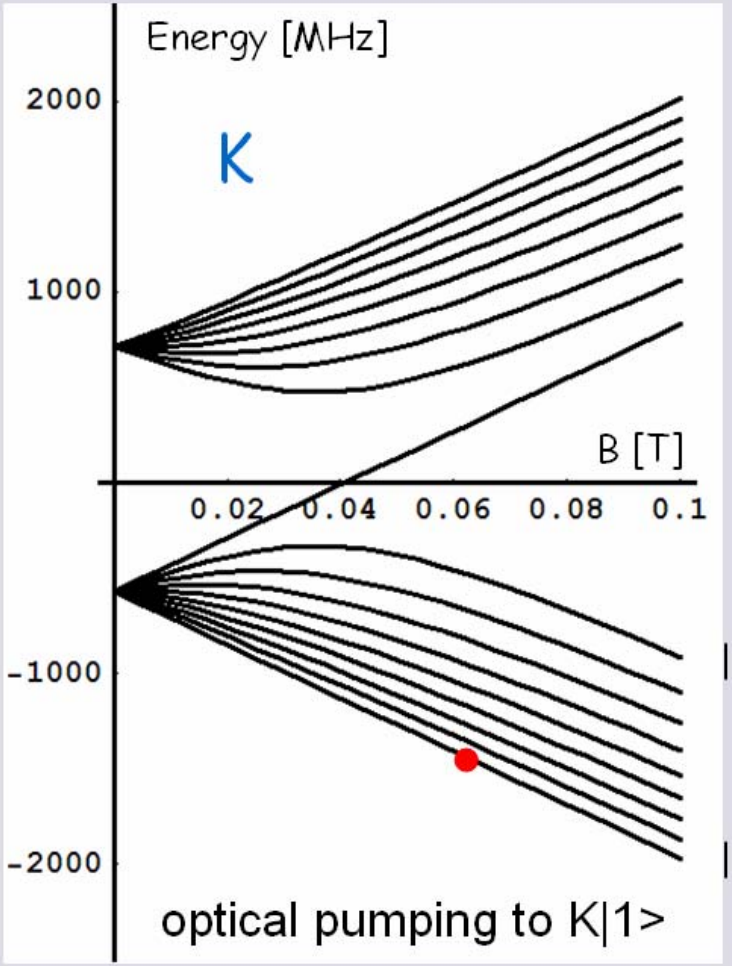
Initial spin state preparation



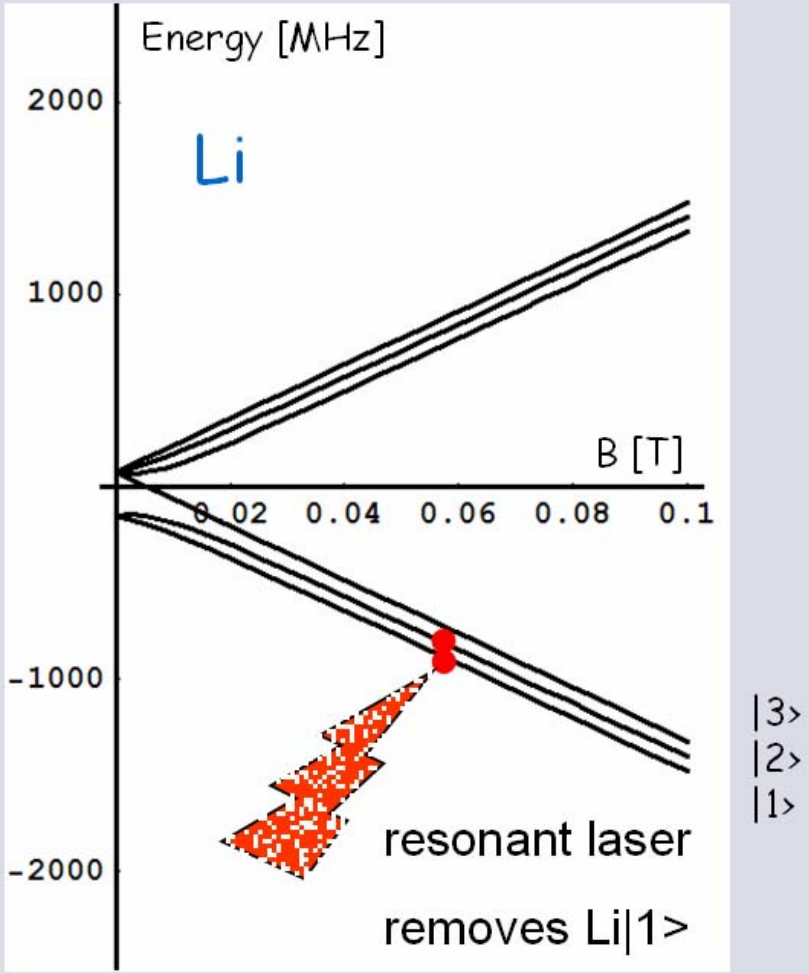


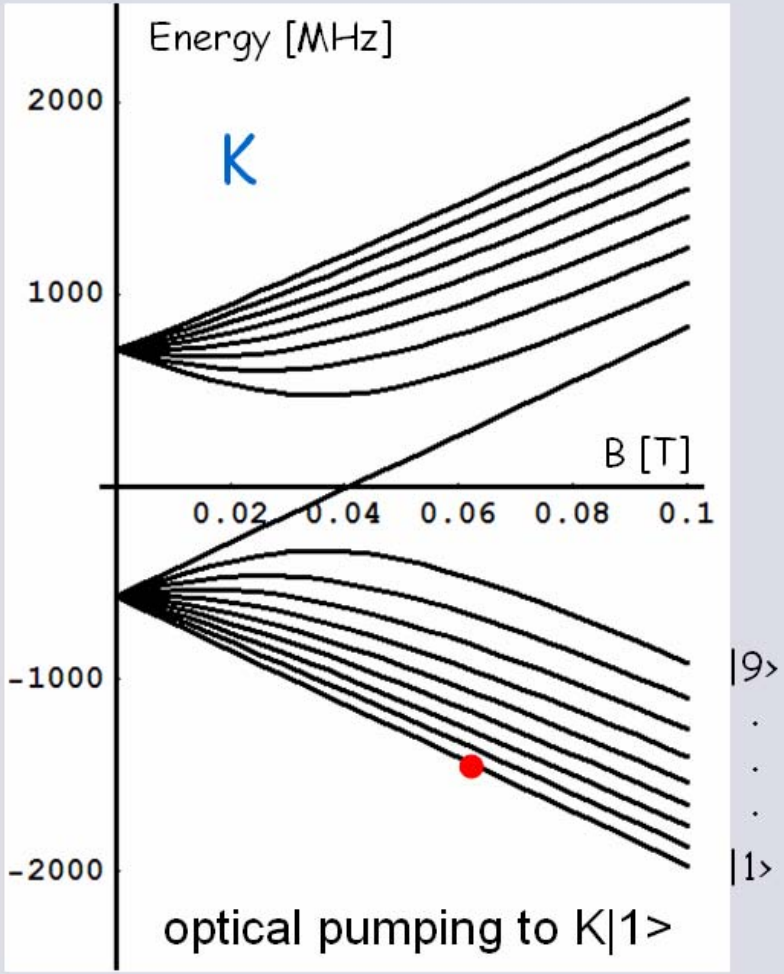
Initial spin state preparation



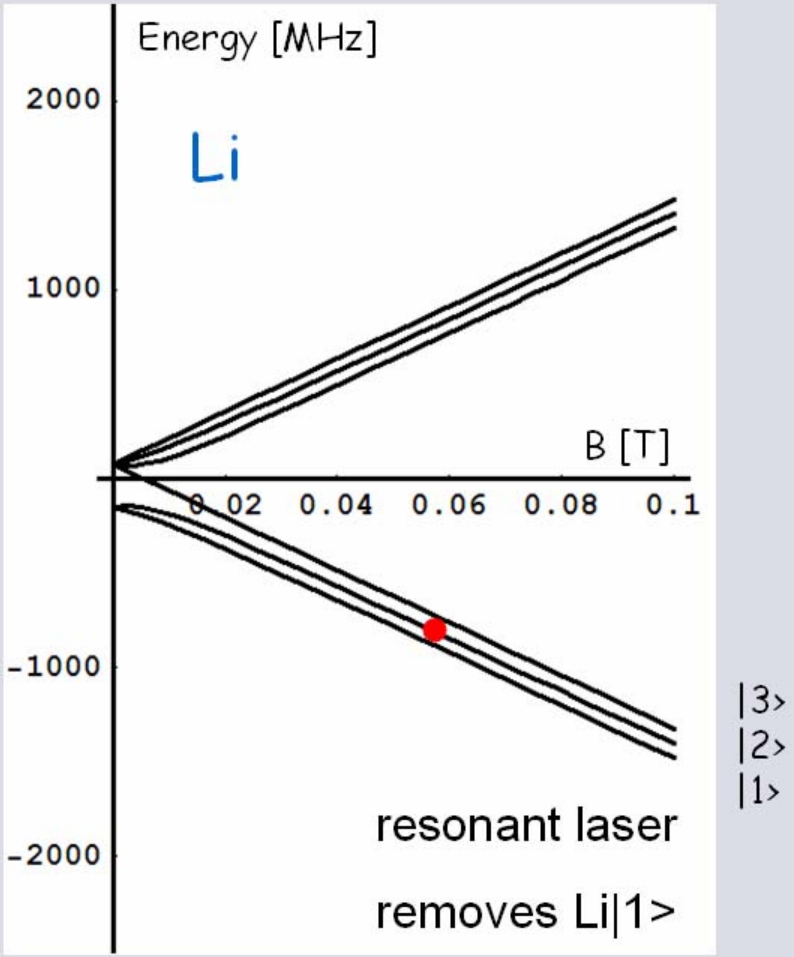


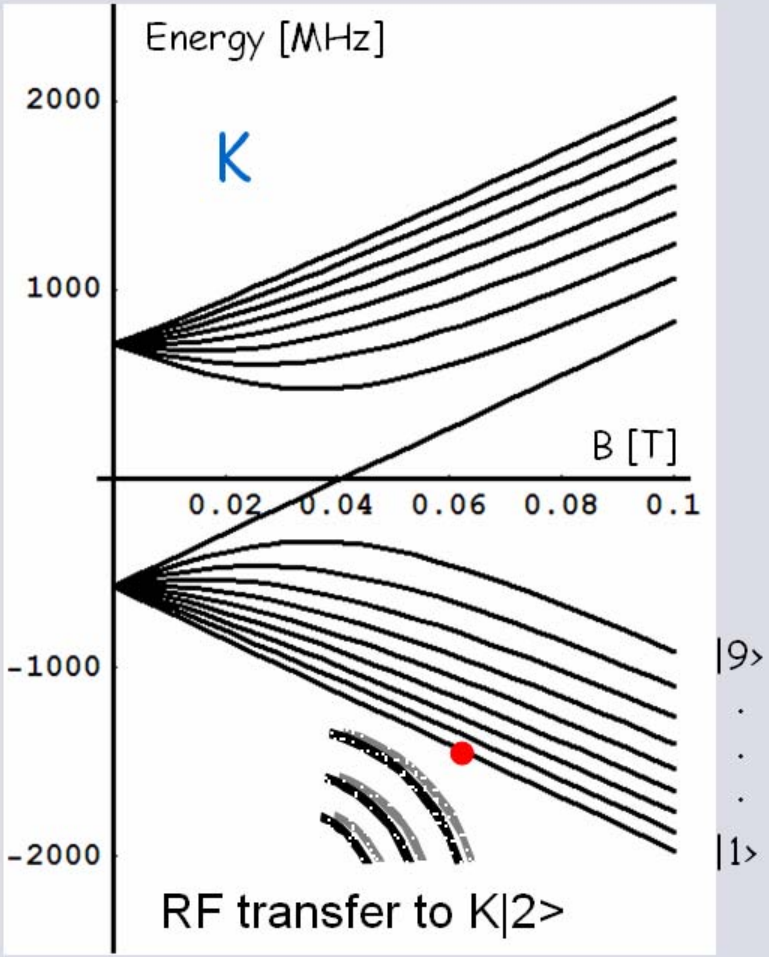
Initial spin state preparation



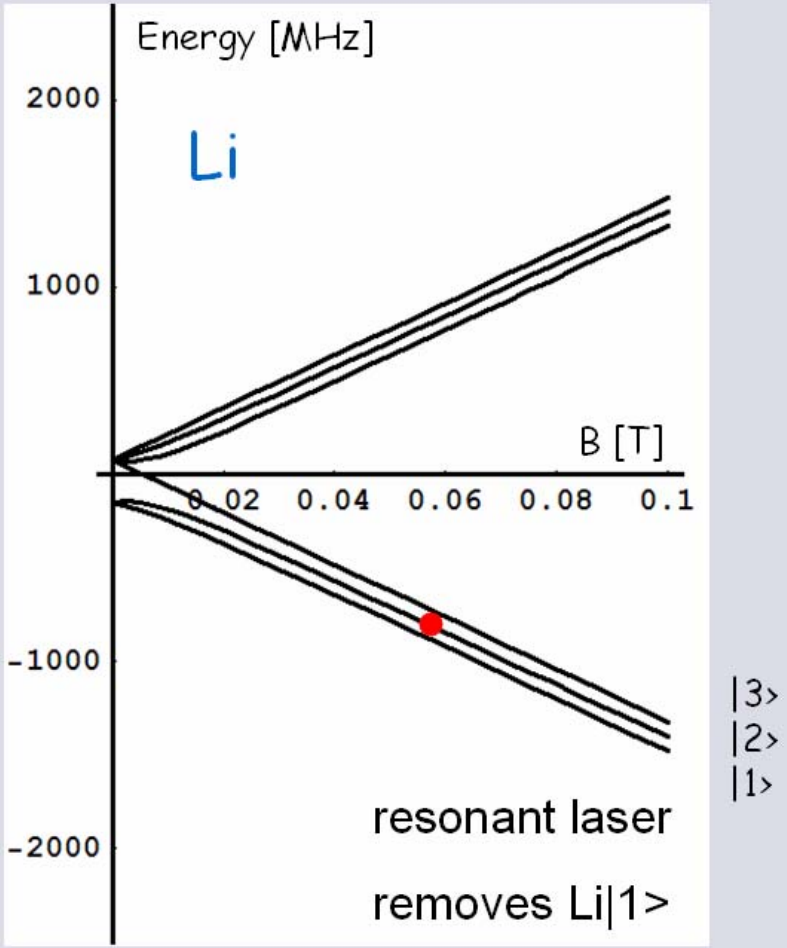


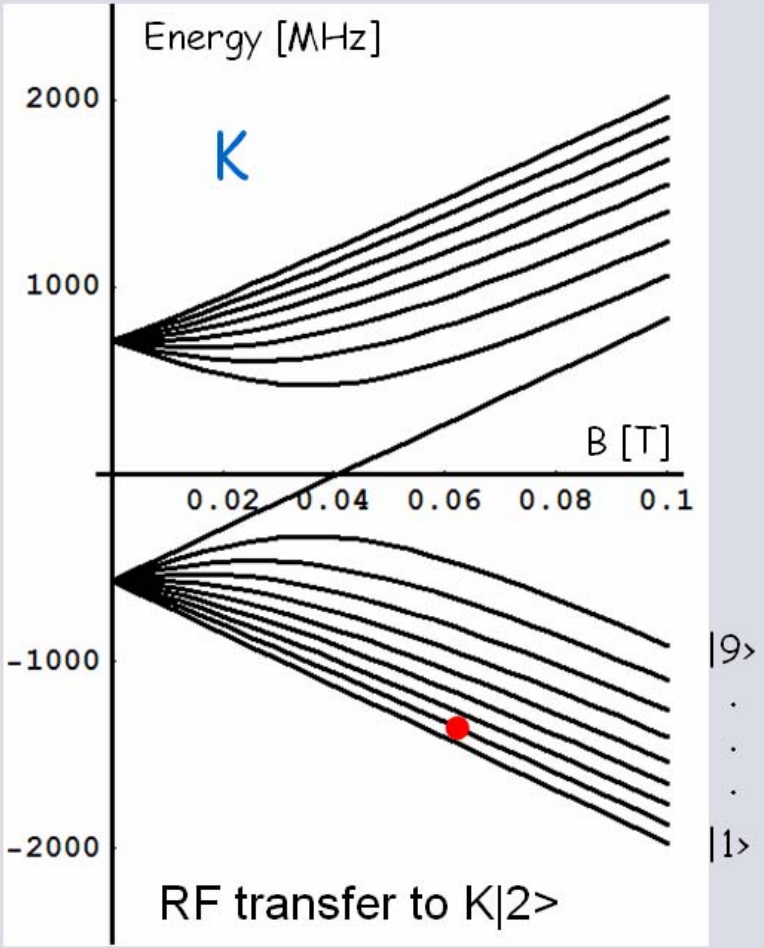
Initial spin state preparation



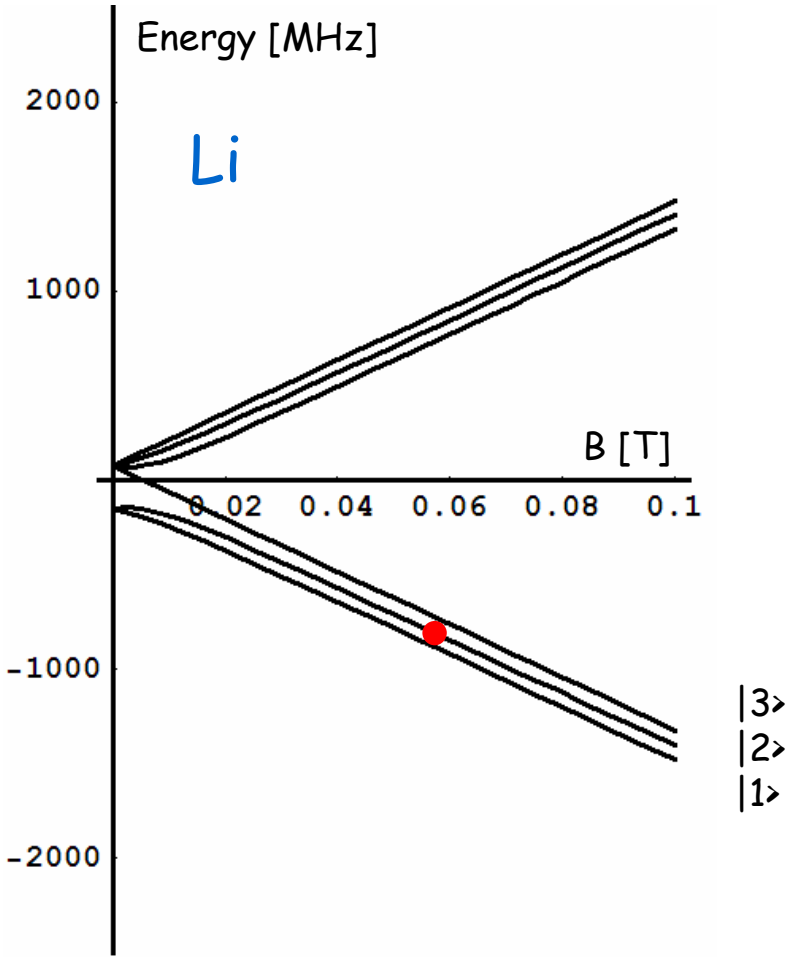


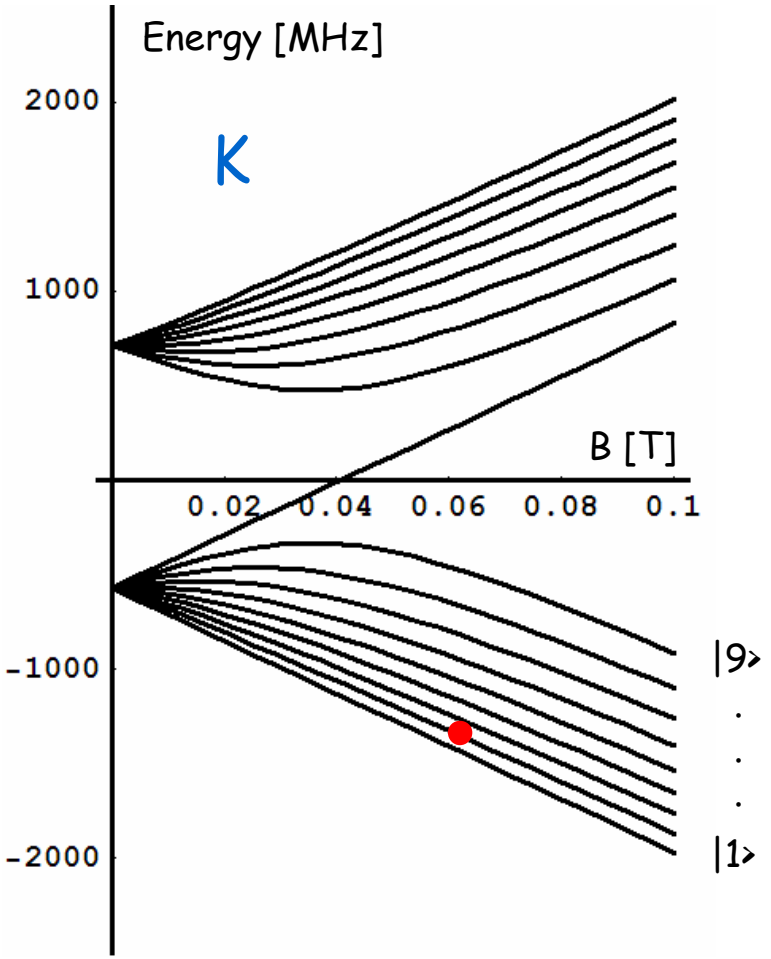
Initial spin state preparation



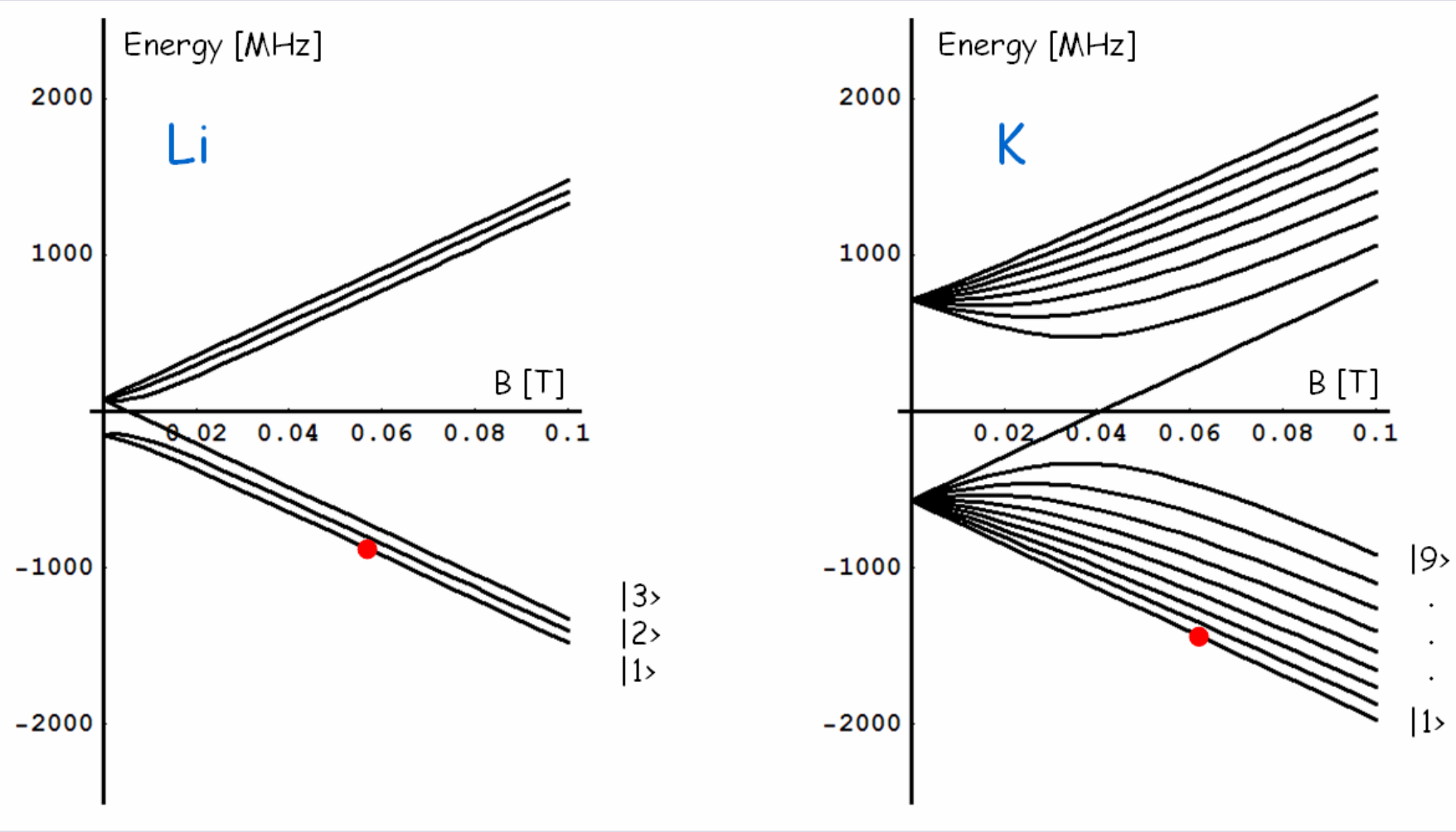


Spin relaxation

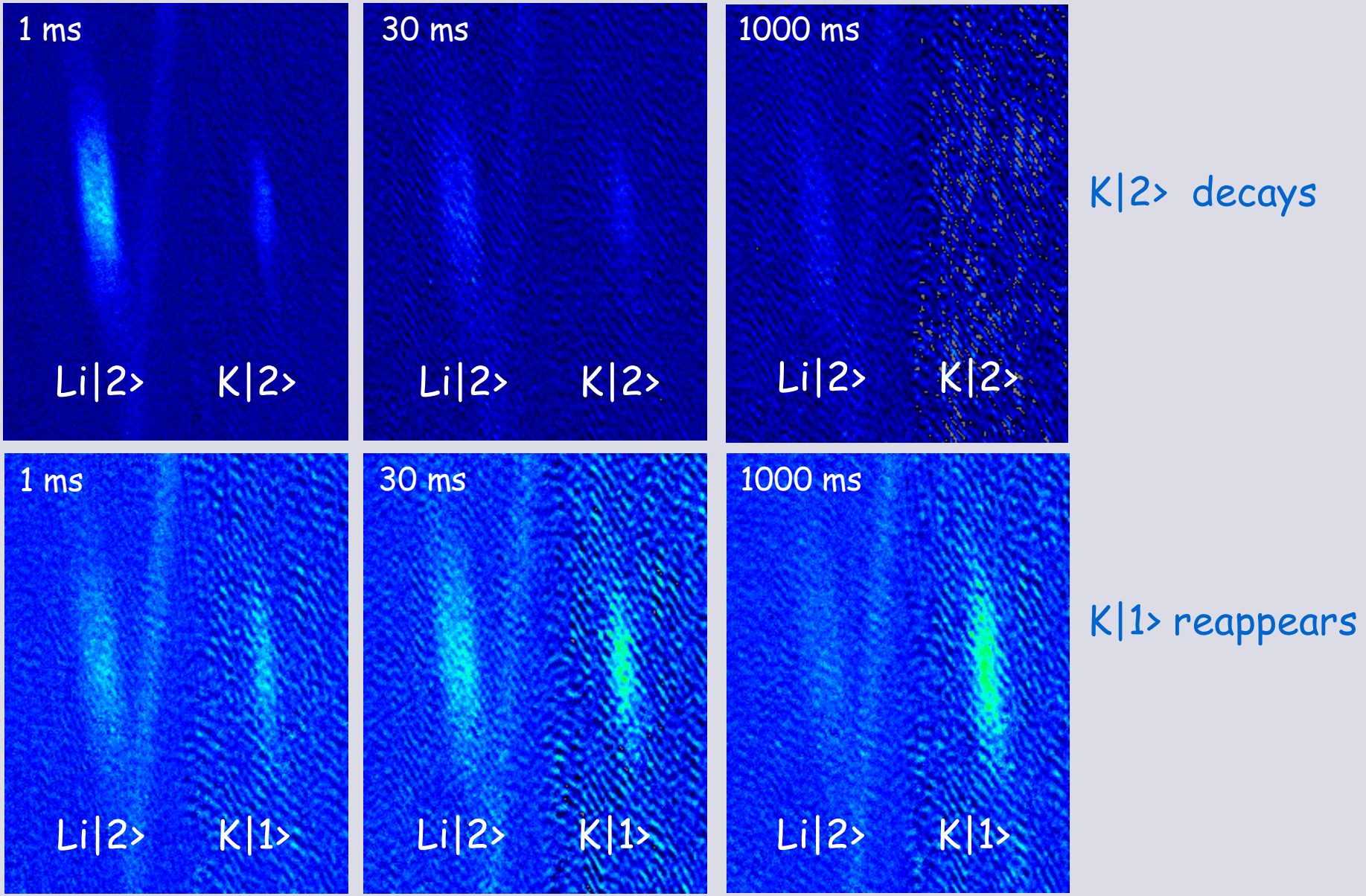




Spin relaxation



Spin relaxation



Towards Feshbach Resonances

- we have full control of initial spin states

- start looking for Feshbach resonances
  → need stable mixtures (no spin relaxation):

Li|1> + K|1> Li|2> + K|1> Li|3> + K|1>

Li|1> + K|2>

Li|1> + K|3>

.

.

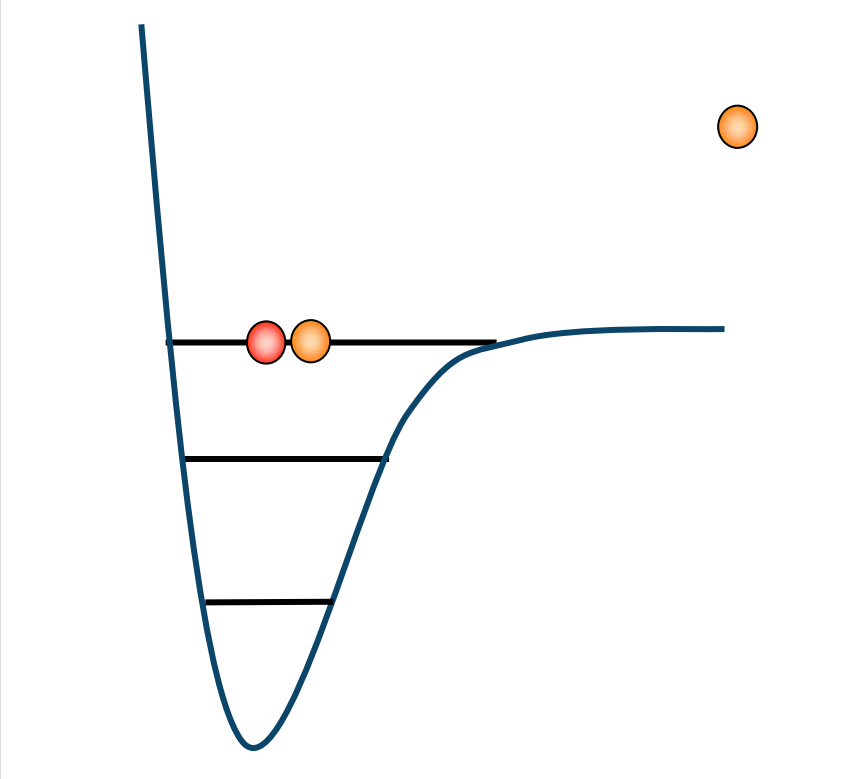
.

Finding Feshbach Resonances

How do we know where they are?

Molecules form at resonance

Decay to lower state in 3-body collision leads to atom/molecule loss:



→ Measure loss in dependance of magnetic field!

Feshbach resonances

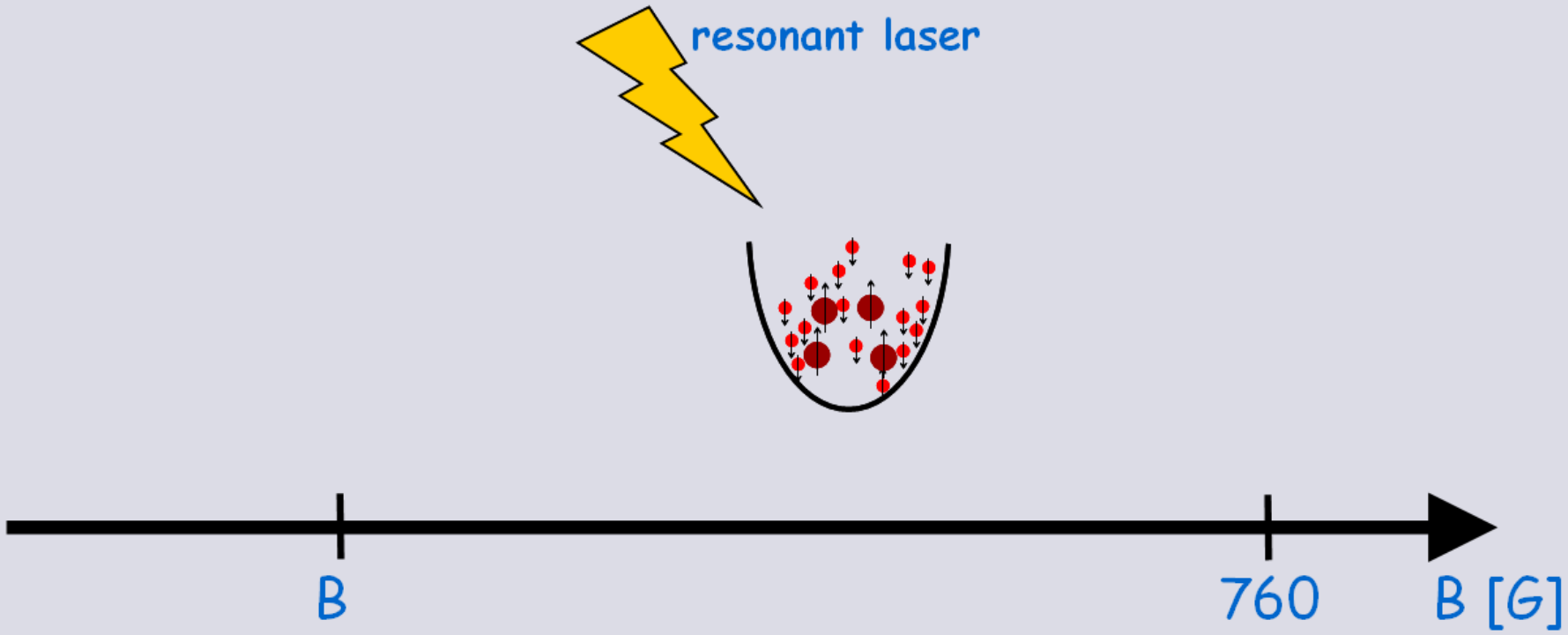
prepare mixture of K|1> and Li |1,2> in IR trap

Feshbach resonances

evaporative cooling at 760 G

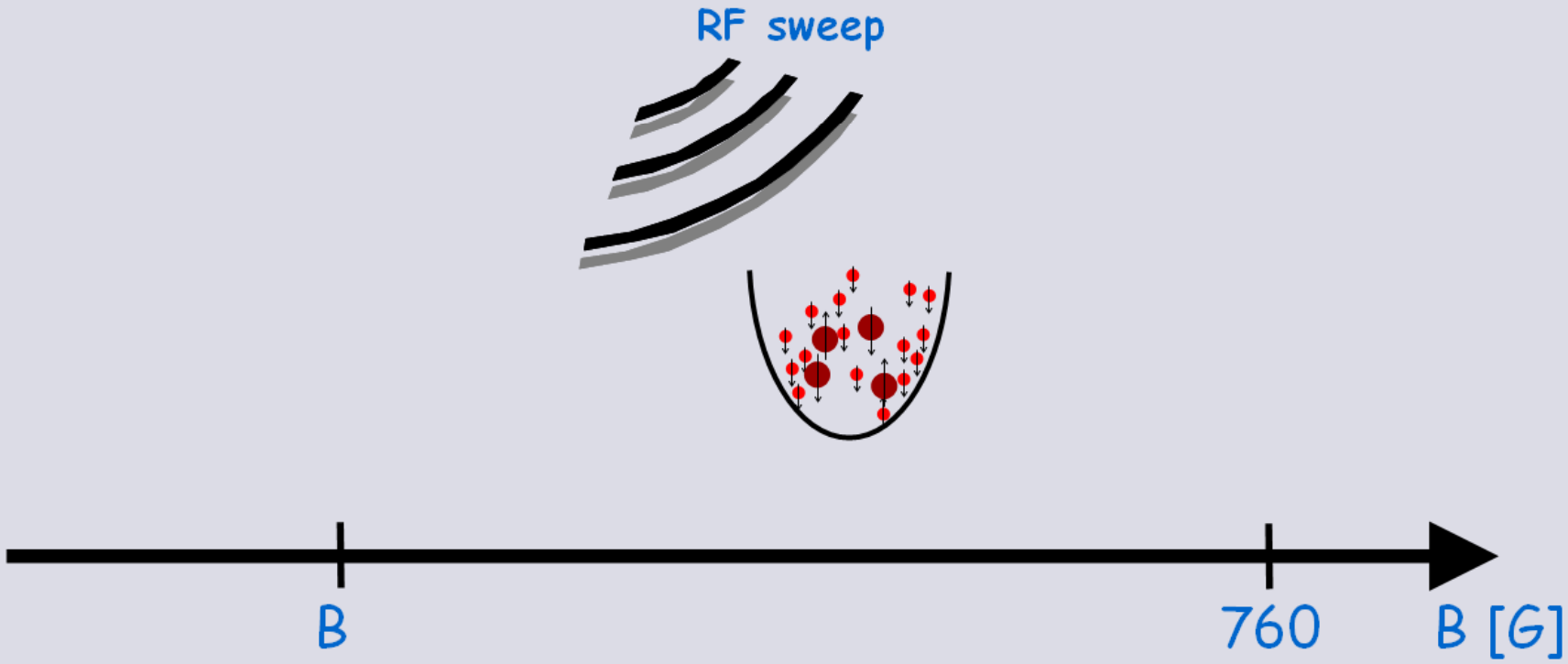
Feshbach resonances

Spin prepare Li



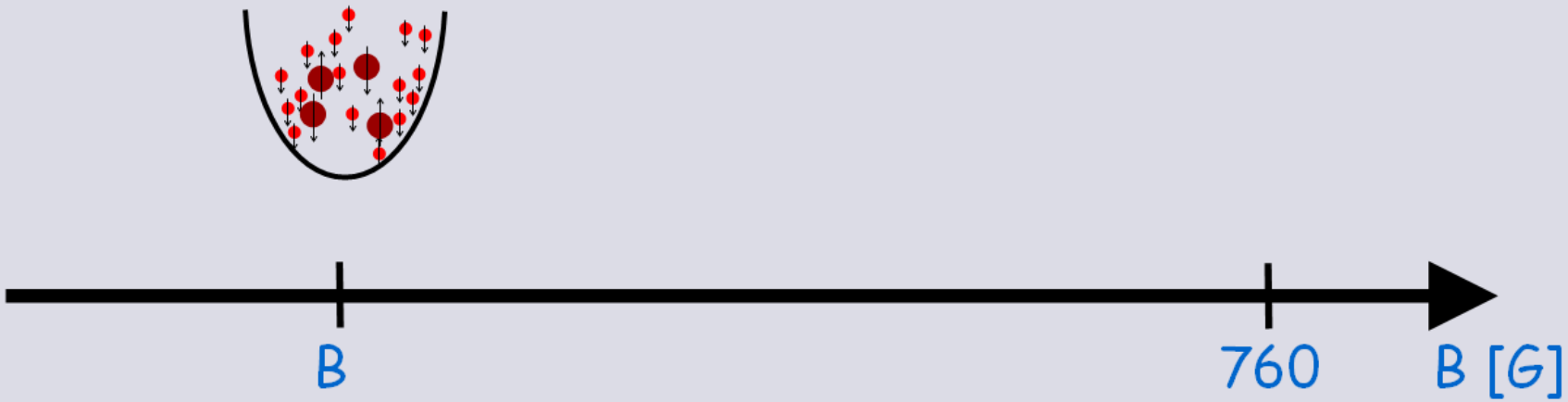
Feshbach resonances

RF preparation of K



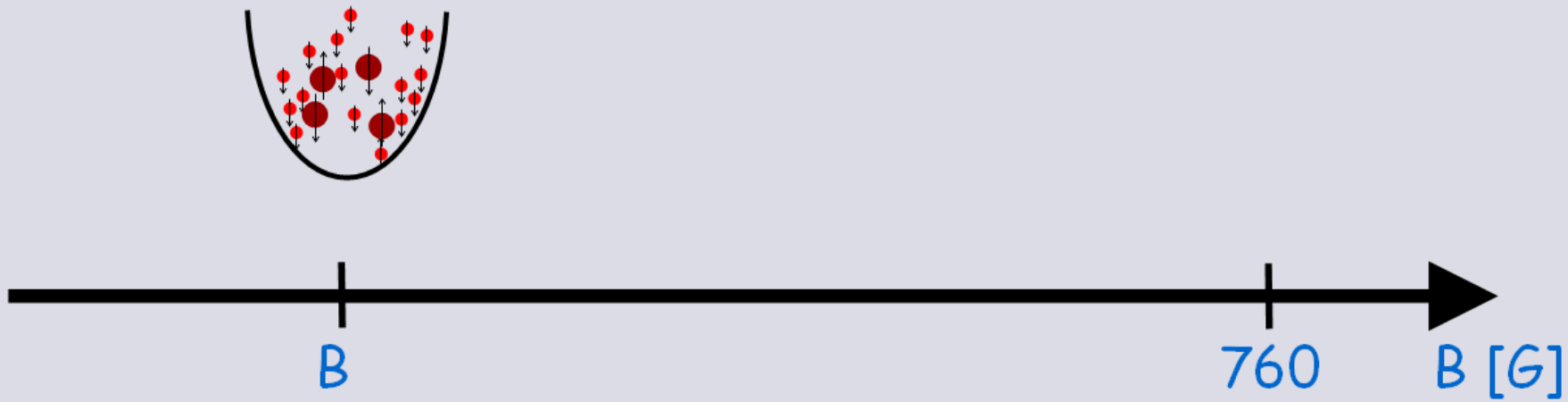
Feshbach resonances

ramp to B field



Feshbach resonances

wait 10 s

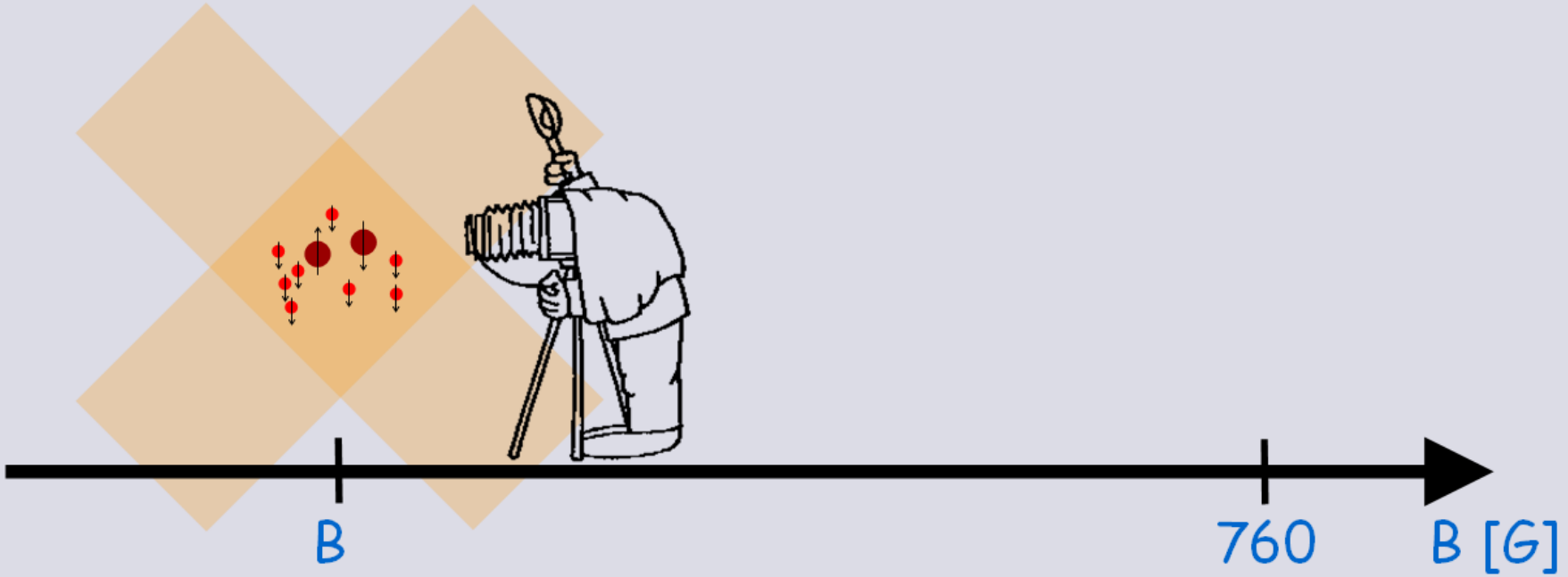


Feshbach resonances

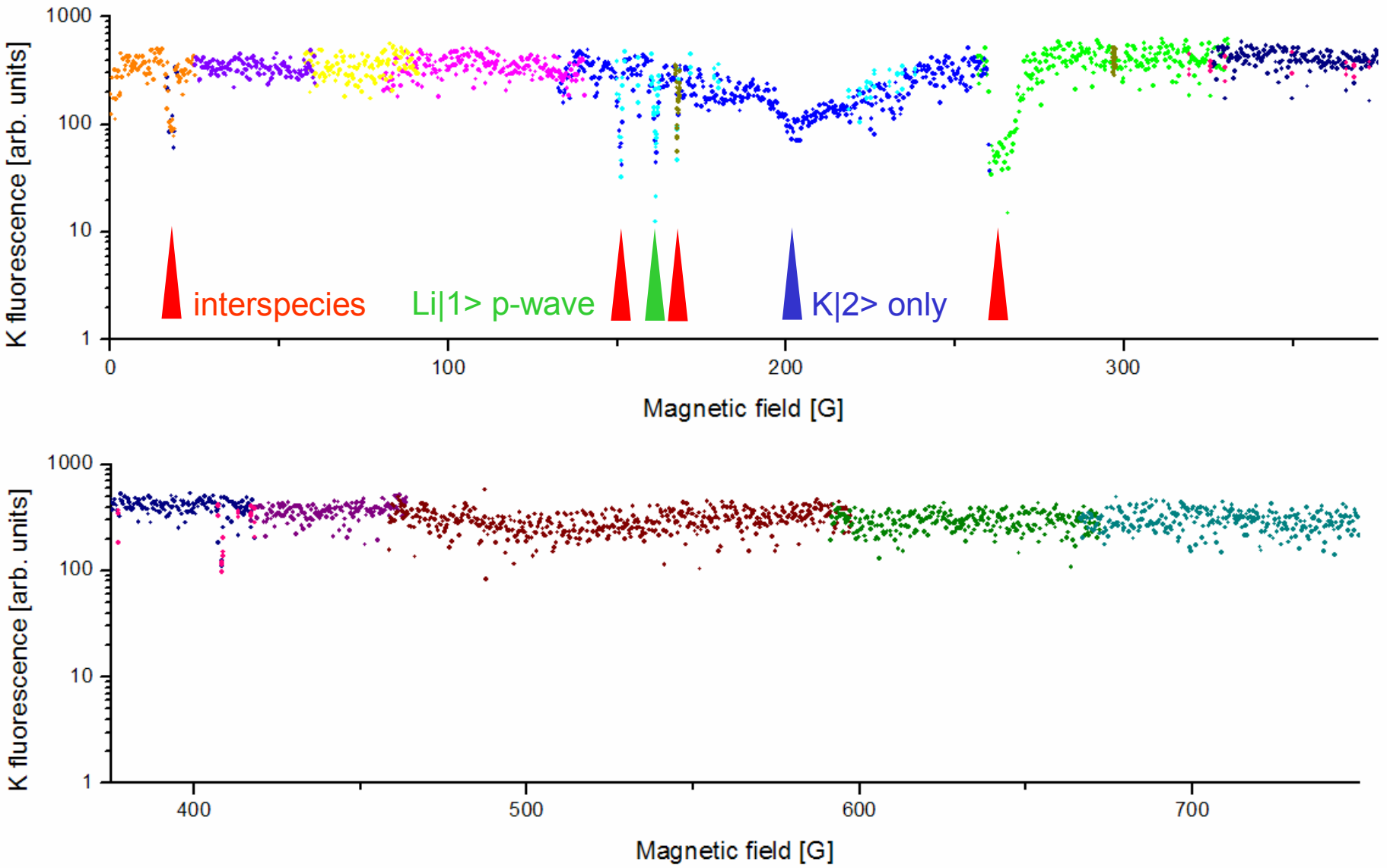
losses occur

Feshbach resonances

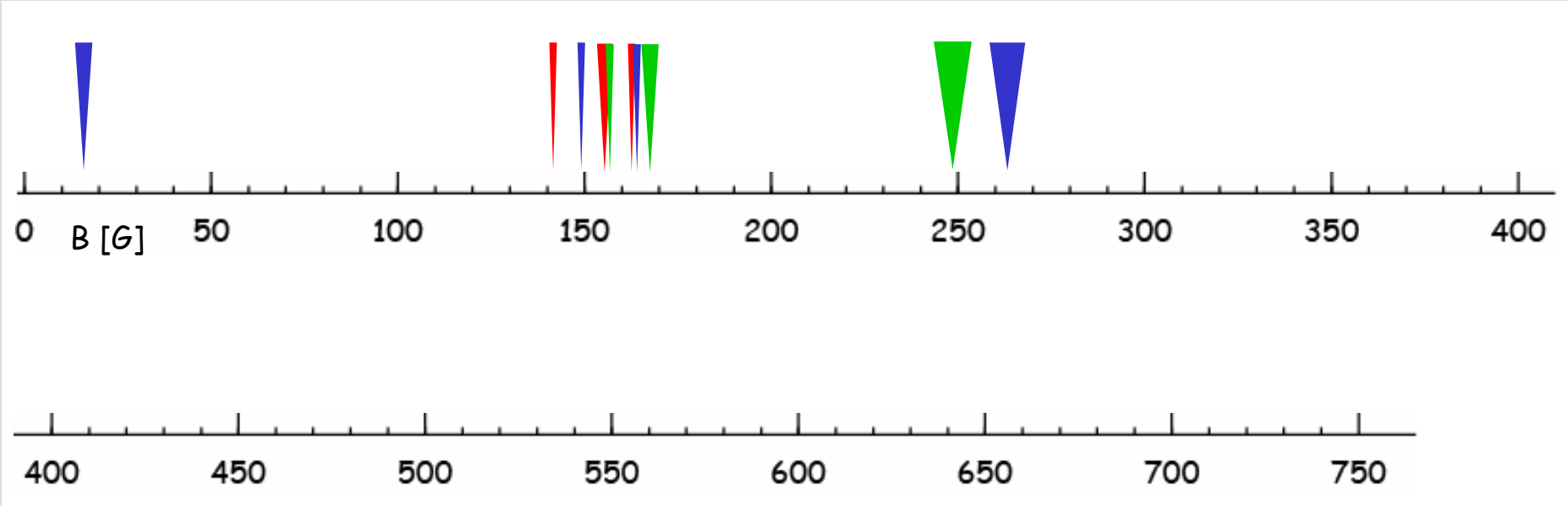
recapture to MOT
and observe remaining fluorescence



Li|1> K|2> scan


1000
100
10
1
K fluorescence [arb. units]
0
100
200
300
Magnetic field [G]
interspecies
Li|1> p-wave
K|2> only
1000
100
10
1
K fluorescence [arb. units]
400
500
600
700
Magnetic field [G]

Interspecies Feshbach resonances



channel	position [G]	width [G]
Li|2> + K|1>	none found	
Li|1> + K|1>	157.6	0.1
Li|1> + K|1>	168.2	1.4
Li|1> + K|1>	249.1	10.4
Li|1> + K|2>	16.2	1.4
Li|1> + K|2>	149.2	0.87
Li|1> + K|2>	165.9	0.3
Li|1> + K|2>	262.8	9.8
Li|1> + K|3>	141.7	0.87
Li|1> + K|3>	154.9	1.7
Li|1> + K|3>	162.7	0.87

What do we learn?

channel	position [G]	width [G]
Li|2> + K|1>	none found	
Li|1> + K|1>	157.6	0.1
Li|1> + K|1>	168.2	1.4
Li|1> + K|1>	249.1	10.4
Li|1> + K|2>	16.2	1.4
Li|1> + K|2>	149.2	0.87
Li|1> + K|2>	165.9	0.3
Li|1> + K|2>	262.8	9.8
Li|1> + K|3>	141.7	0.87
Li|1> + K|3>	154.9	1.7
Li|1> + K|3>	162.7	0.87

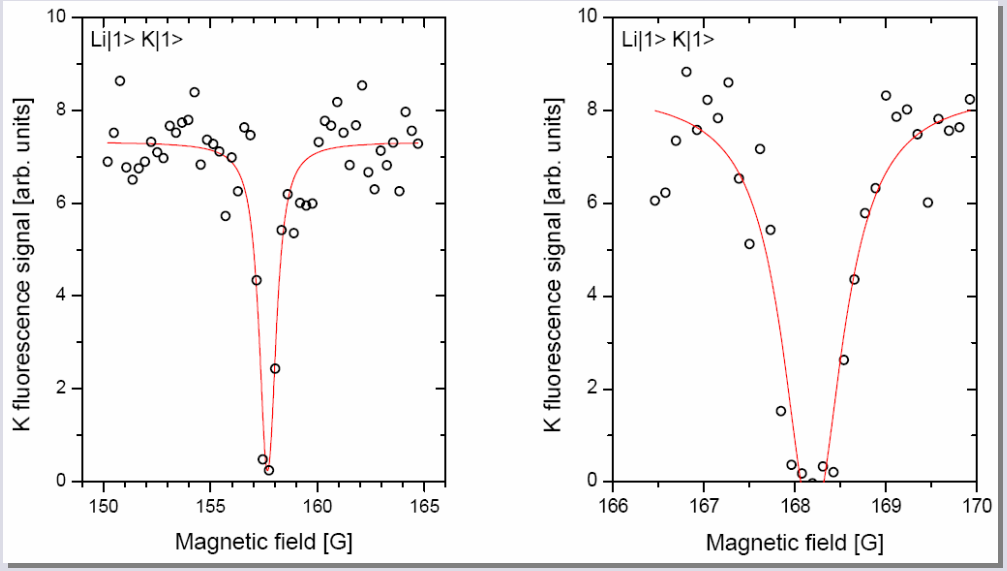
Theorists Paul Julienne, Eite Tiesinga and Servaas Kokkelmans interpret data

Only two free parameters fit model to data:
position of last bound state in singlet and triplet potential ($\hat{=}$ a_S and a_T)

New information from model:
- All Feshbach resonances, also outside the field region and mixtures scanned
- Knowledge of closed channels
- Help to choose optimal resonance for molecule creation

interspecies Feshbach resonances

channel ^{6}Li|1> + ^{40}K|1> (most stable combination)

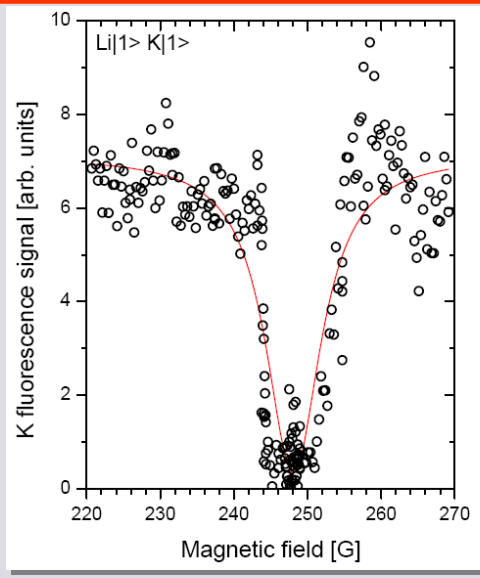


157.6 G
width ~0.1G

168.2G
width ~1G

interaction tuning !

249.1 G
width ~10G

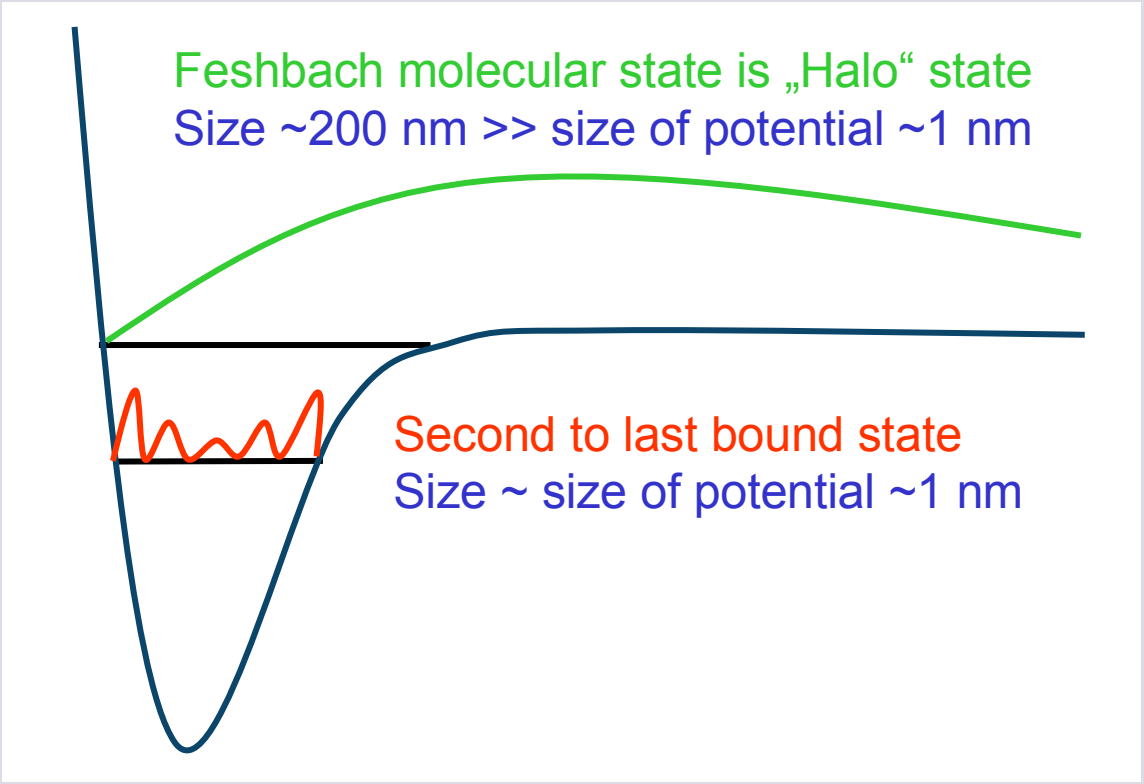


stable
heteronuclear molecules
&
strongly interacting
two-component Fermi gas

Stable Molecules

Same mechanisme responsible for molecule formation and decay to lower state:
3-atom collision

Why can molecules form and then remain stable?



3-atom collision needs 3 atoms closer than size of endstate

In 2 fermion mixture Pauli principle inhibits two of the three atoms to get close

Big Feshbach molecules can still be formed, but decay to tight last bound state highly suppressed!

→ Molecules of Fermions much more stable than molecules of bosons!

Conclusions

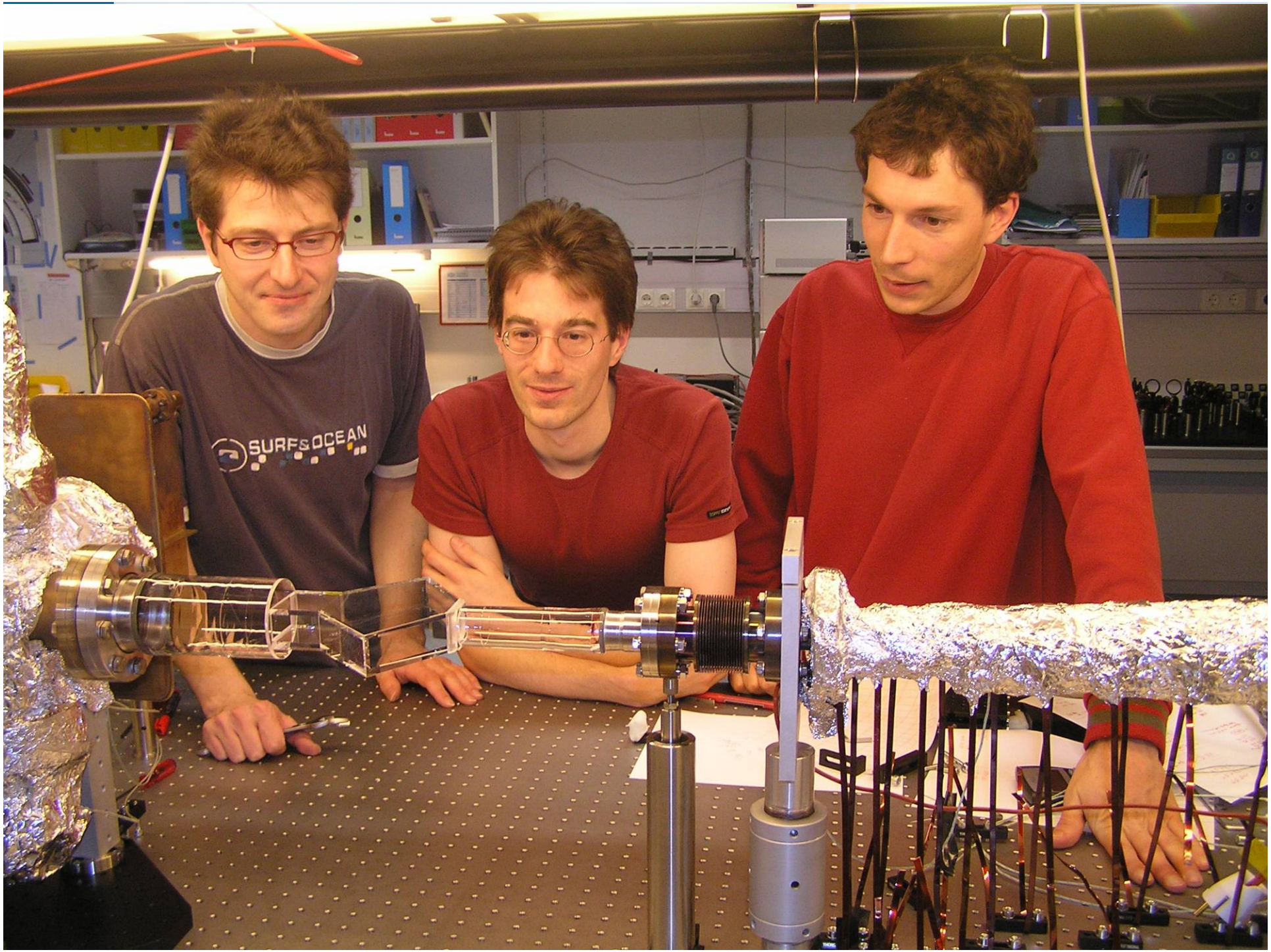
first Fermi-Fermi mixture available in the lab!

several interspecies resonances observed !

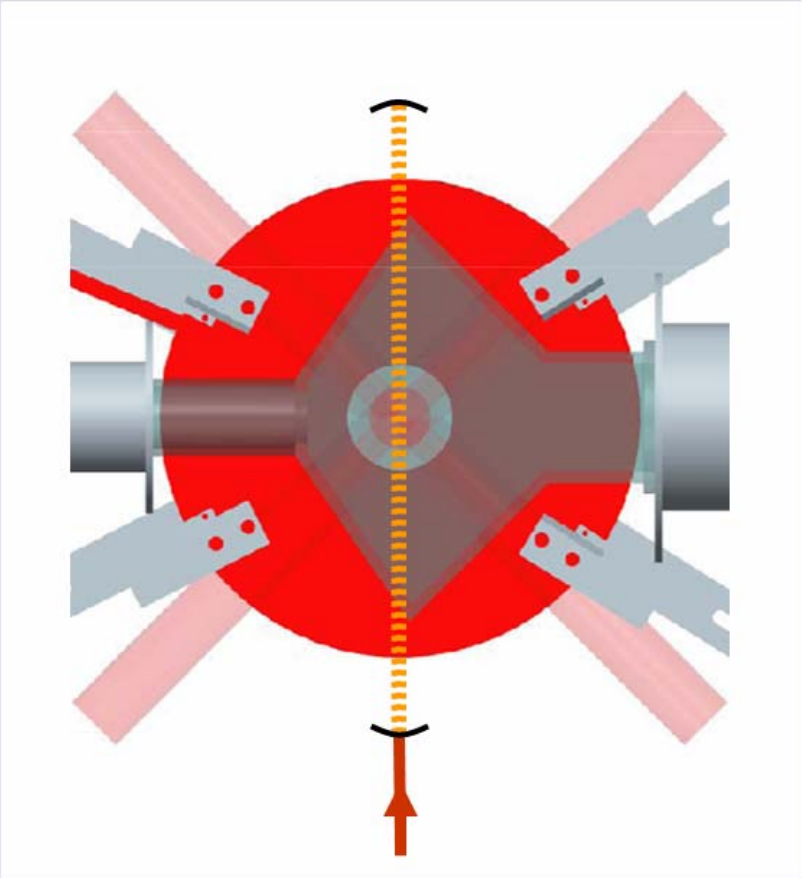
we´ll soon understand the scattering properties

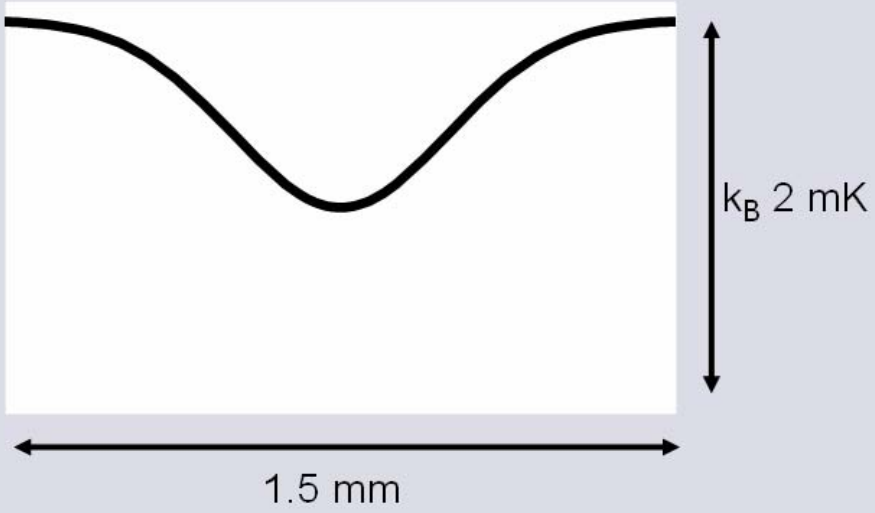
interesting resonance identified
for
creation of heteronuclear molecules
and strongly interacting two-component Fermi gases


Outlook


SURF&OCEAN

Future optical dipole traps



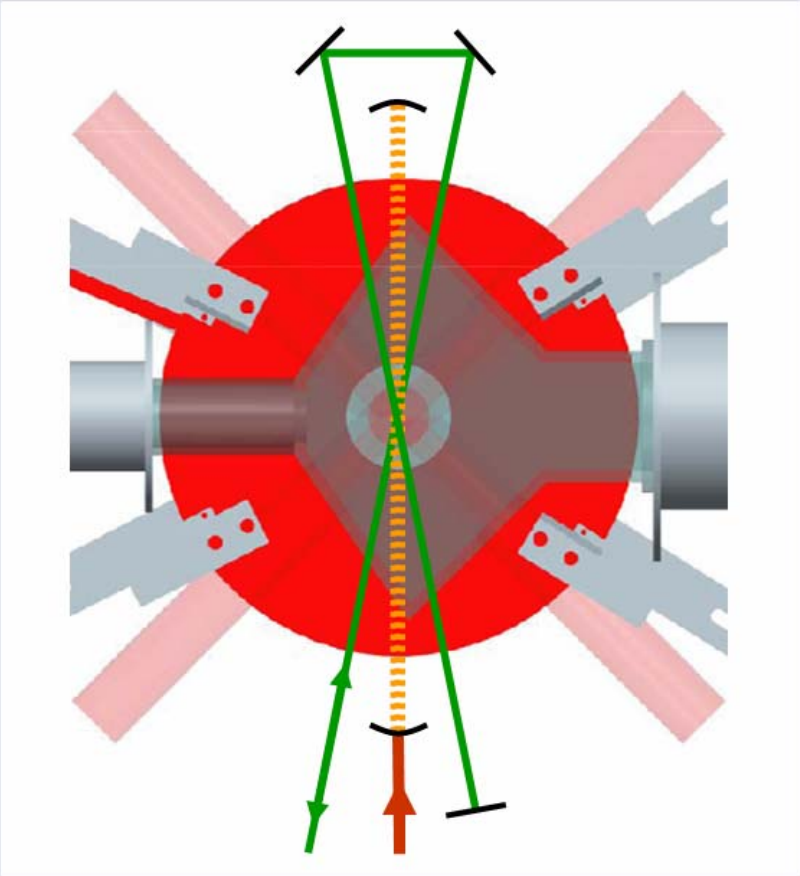


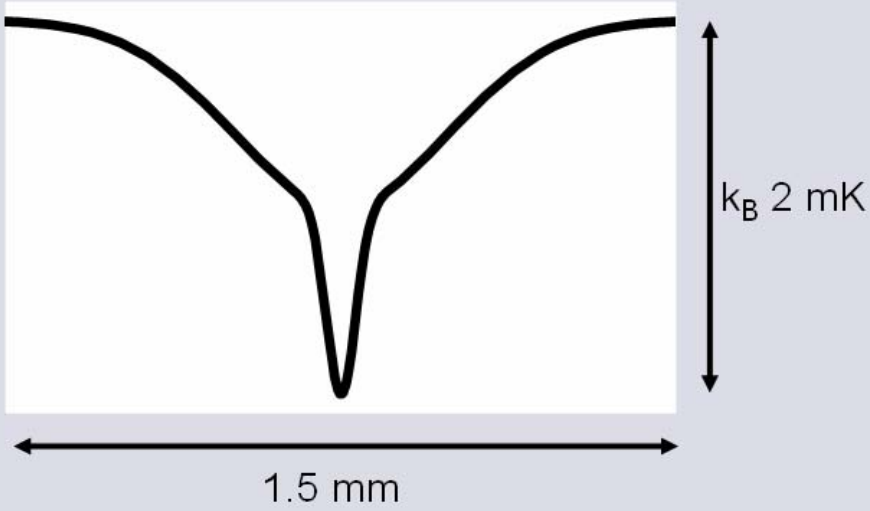
Resonator optical dipole trap (25 W ELS):

U ~ k_B 1 mK

w ~ 450 µm

Future optical dipole traps





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Dimple trap (100 W IPG fiberlaser):
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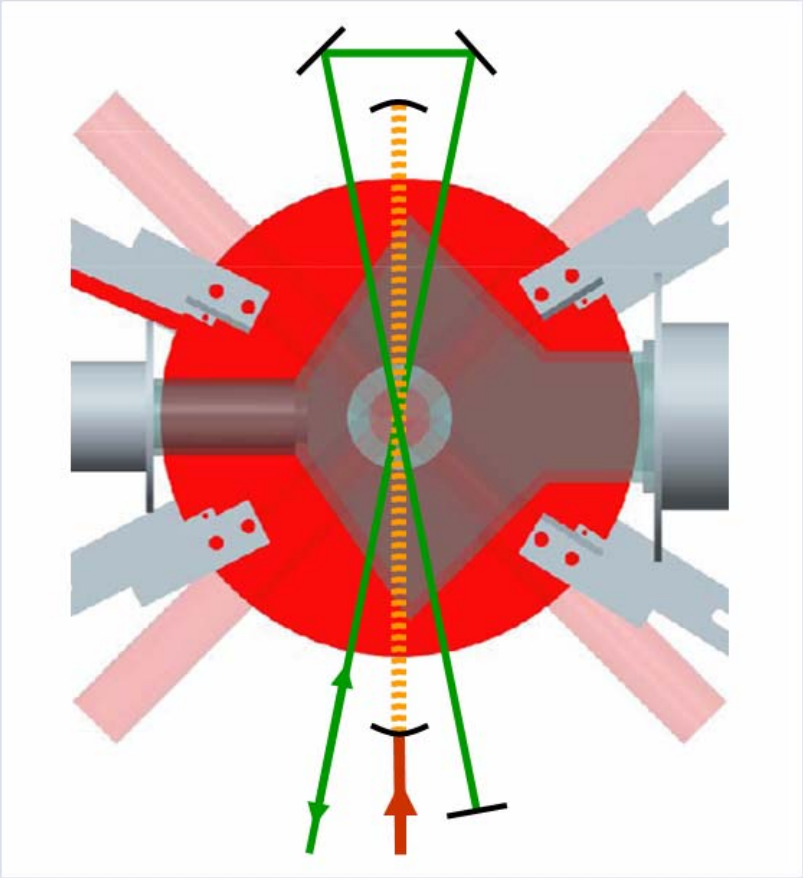
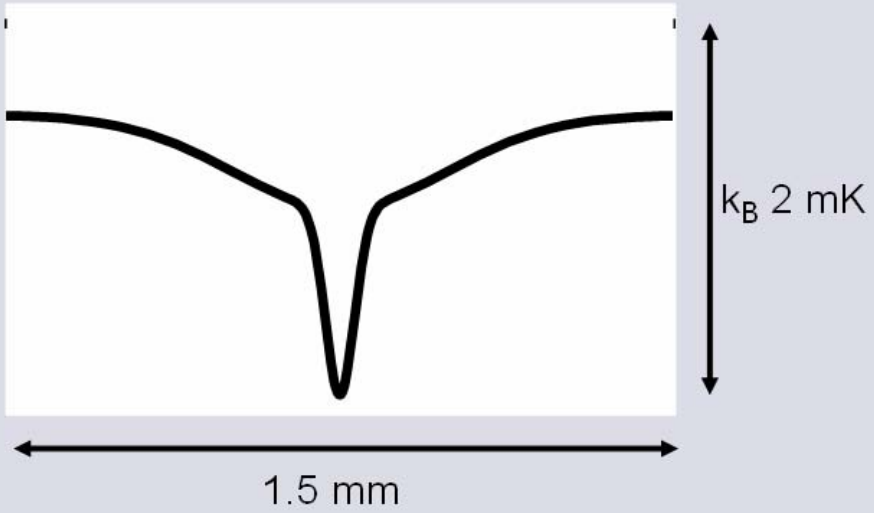
Future optical dipole traps





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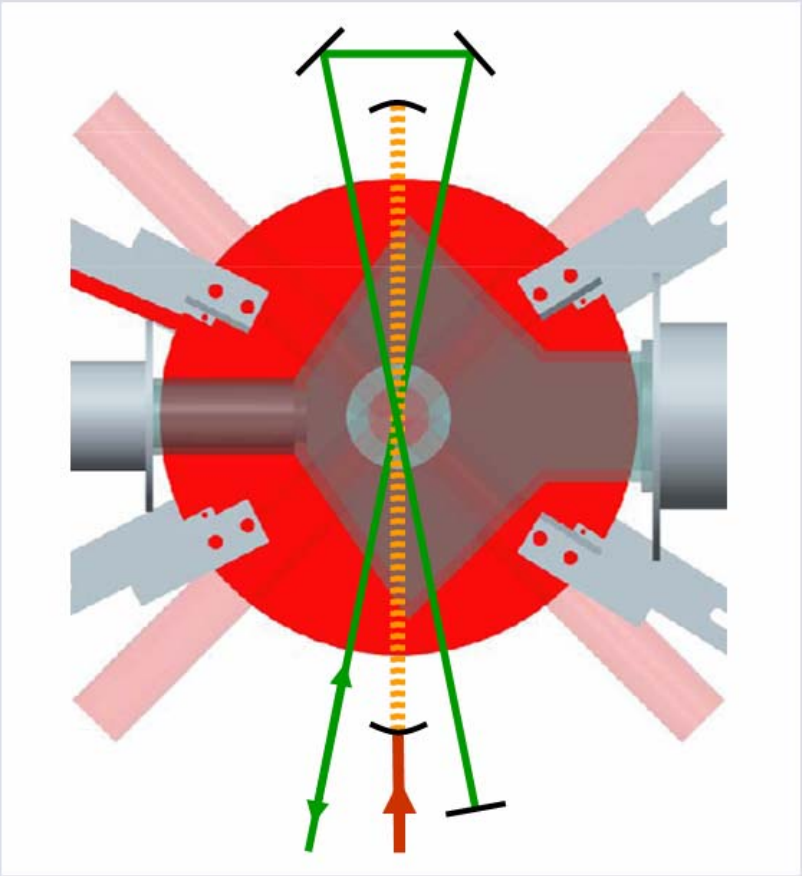

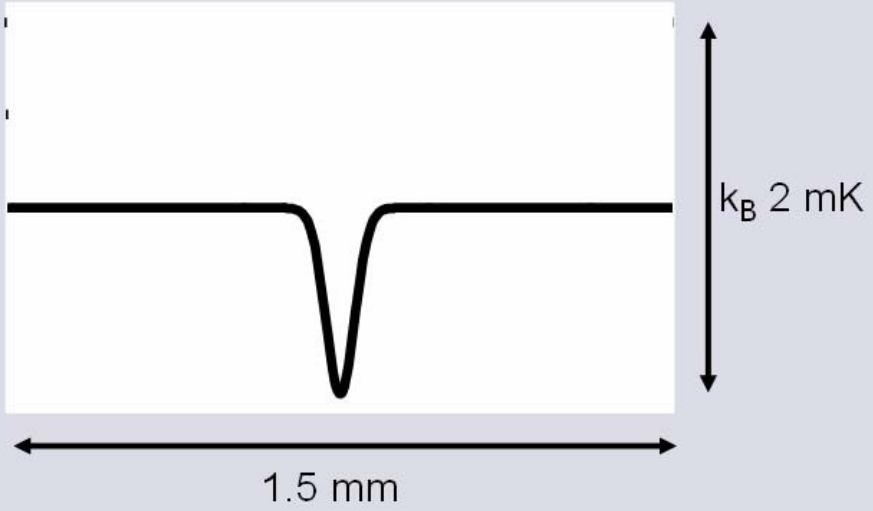

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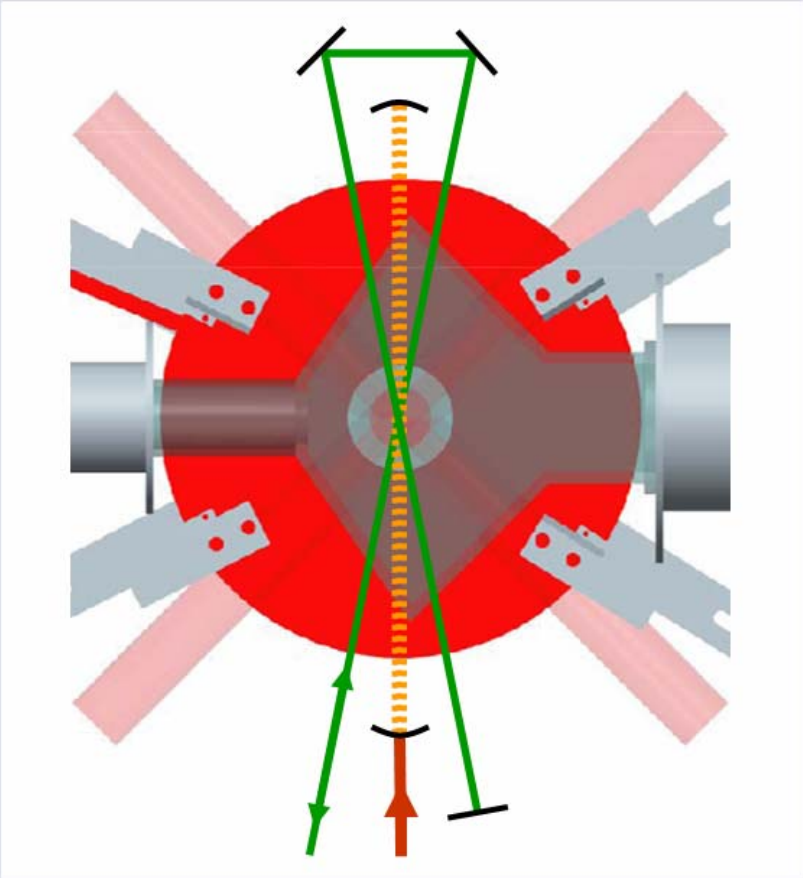

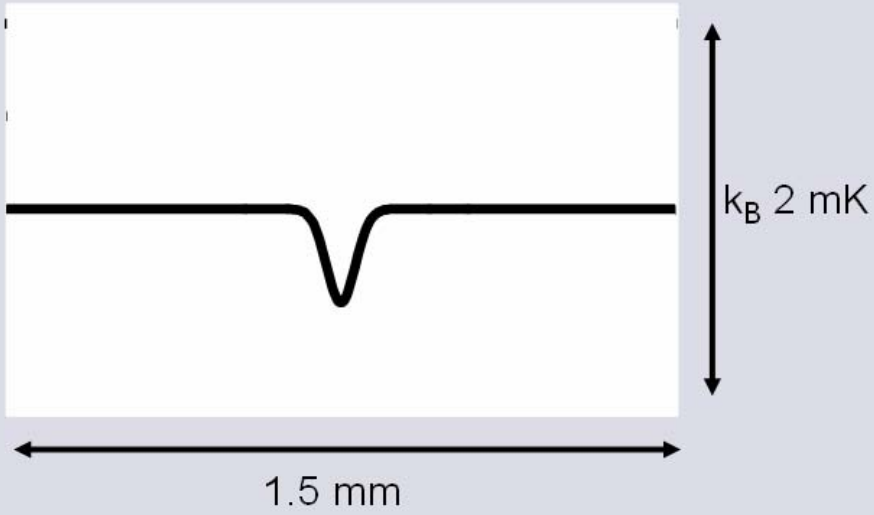

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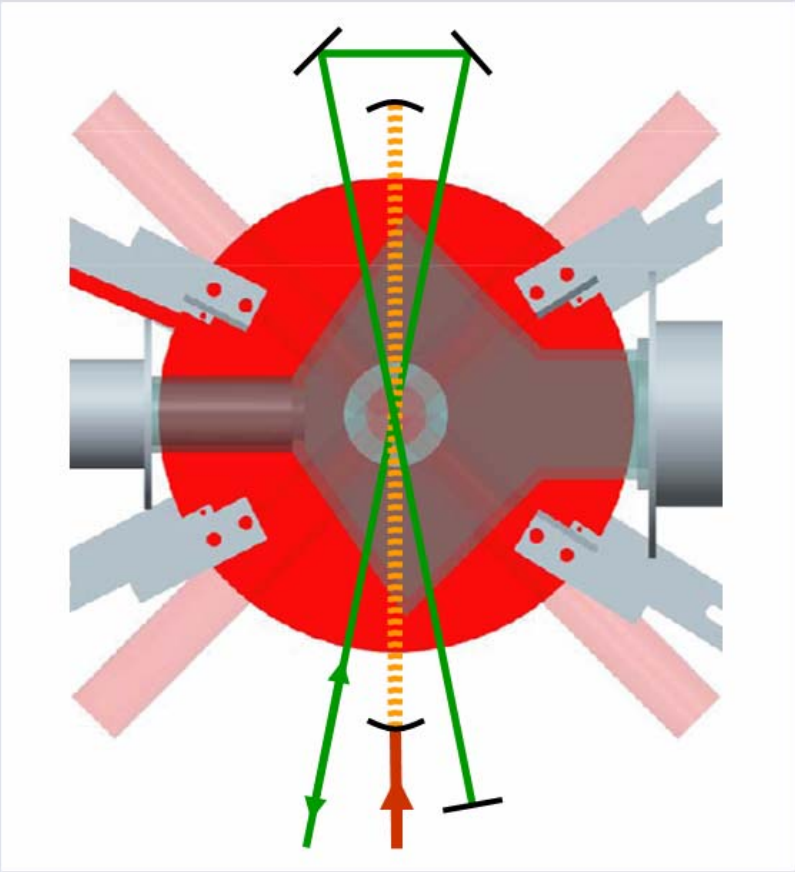

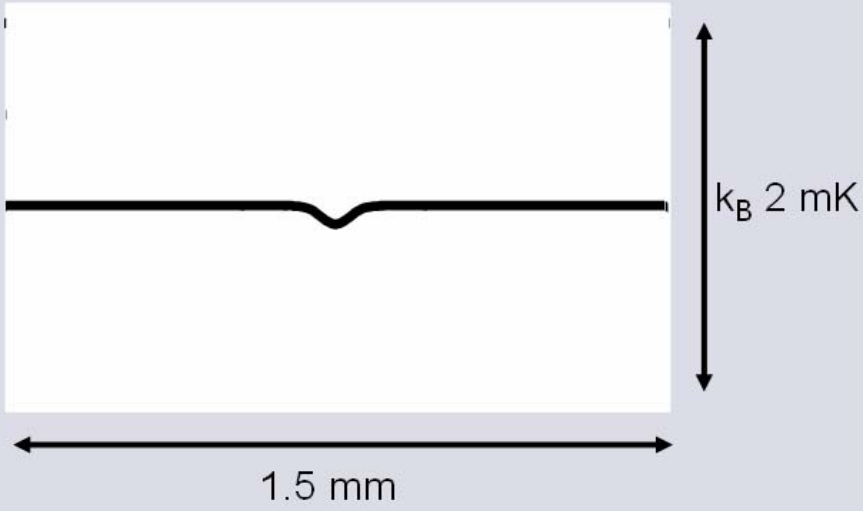

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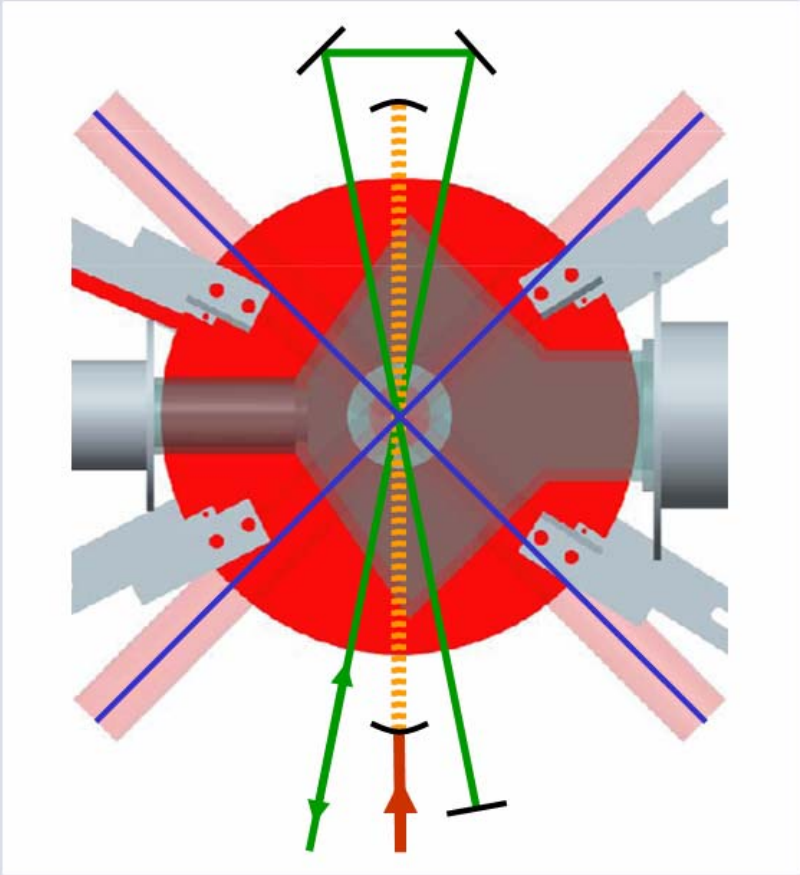

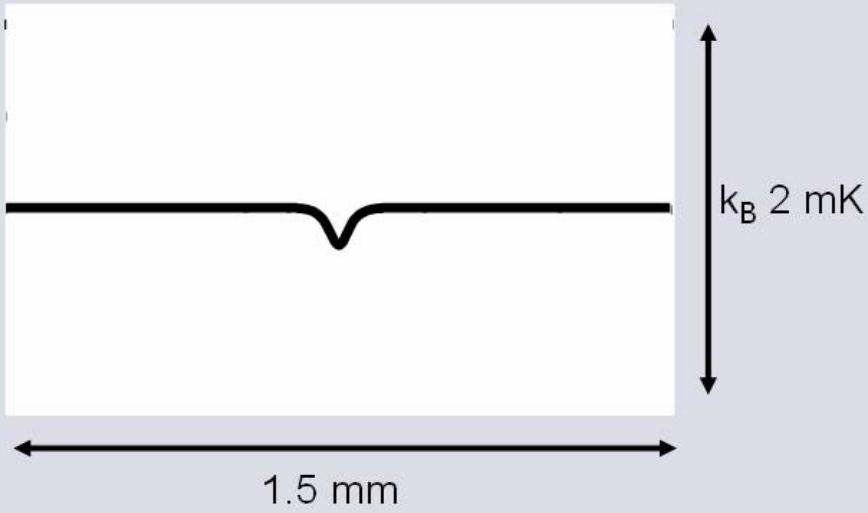

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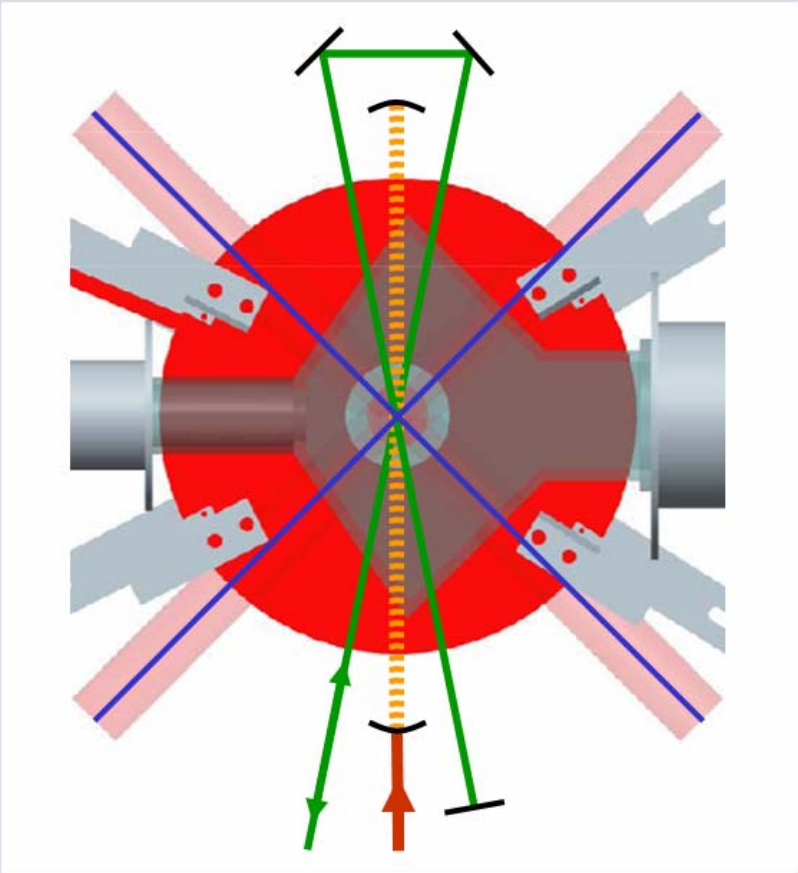
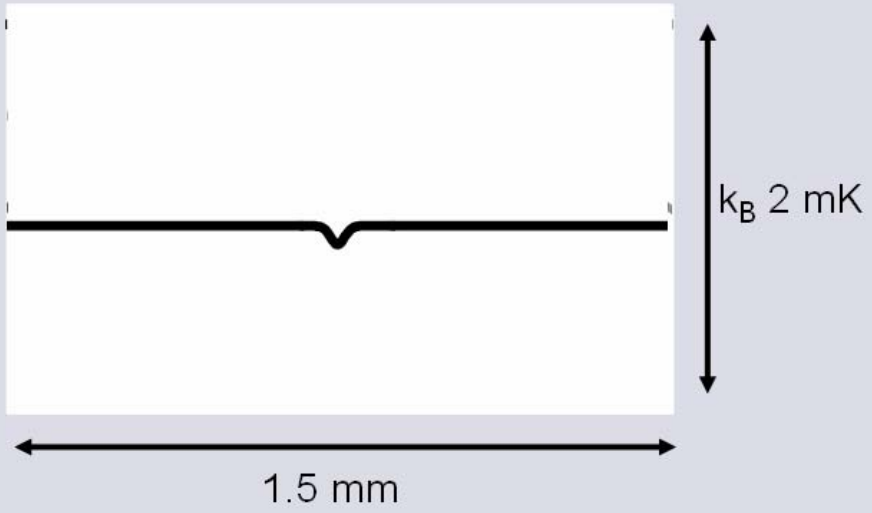
Science trap (5 W IPG fiberlaser):
- U ~ kB 10 µK
- w ~ 30 µm

scanning possible
-> oscillations, vortices,...

Future optical dipole traps





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scanning possible
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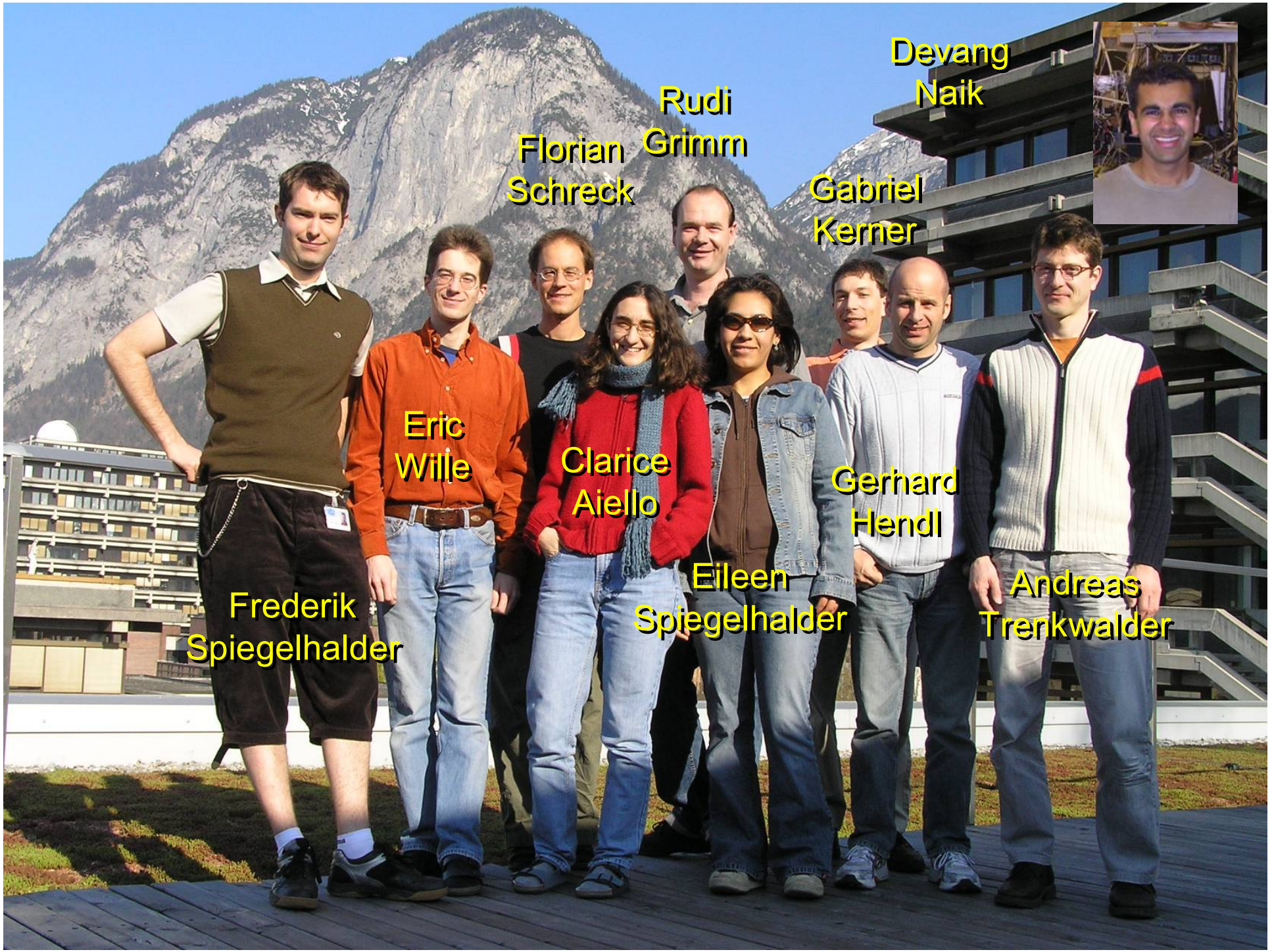
Future

Next steps:
- heteronuclear molecules
- study heteronuclear BEC-BCS crossover

Huge playground beyond BEC-BCS:
- sympathetic cooling of ^{86,87,88}Sr, ^{39,41}K
- ^{86,88}Sr BEC
- optical Feshbach resonances using Sr intercomb. line
- Bose-Fermi and Bose-Bose mixtures
- three element Fermi mixtures
- ...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Eric Wille
Clarice Aiello
Gerhard Hendl
Eileen Spiegelhalder
Andreas Trenkwalder
Frederik Spiegelhalder