S-Wave Interactions in a Two-Species Fermi-Fermi Mixture

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Kioloa, November 30, 2011

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Moved in 2010 from:

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€€€:

Max-Planck-Society
Munich Center for Advanced Photonics (MAP)
DFG Research Unit FOR 801 „Strong Correlations in Multiflavor Ultracold Quantum Gases"

SGD:

National Research Foundation
Ministry of Education

Polar Molecules

Cold polar molecules:

^{133}Cs – ^{7}Li Bose-Bose mixture:

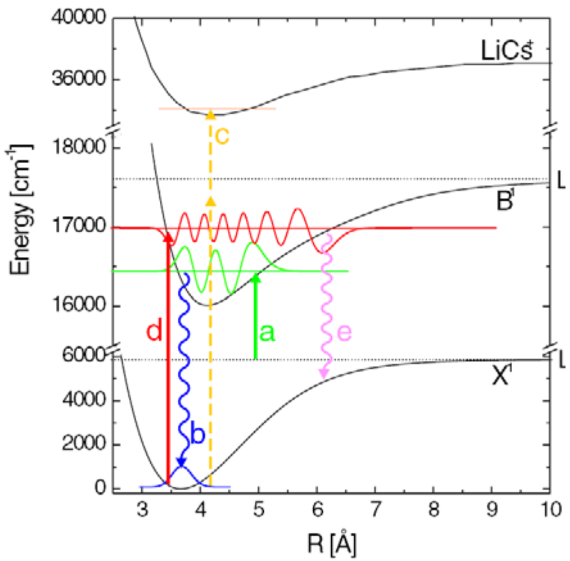
Single step of photoassociation process

*J. Deiglmayr et al., PRL **101**, 133004 (2008)*

^{87}Rb – ^{40}K Bose-Fermi mixture:

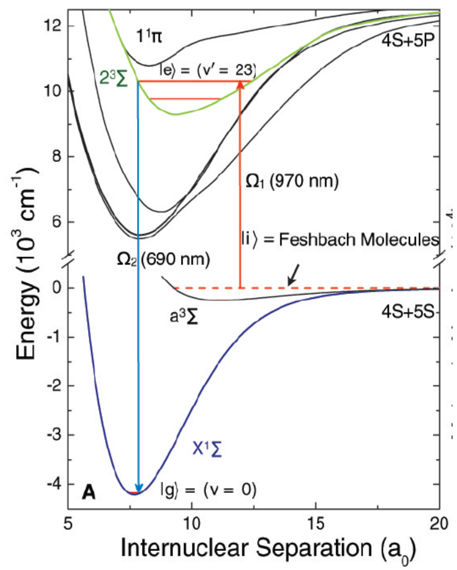
Single step of stimulated Raman transfer

*K.-K. Ni et al., Science **322**, 231 (2008)*



^{6}Li – ^{40}K Fermi-Fermi mixture:

- **Long lifetime** of Feshbach molecules facilitate STIRAP
- **High dipole moment**
  Absolute ground state LiK 3.6 Debye
  *M. Aymar and O. Dulieu, J. Chem.Phys., **122**, 204302 (2005)*
- **Bosonic** molecules



Perspective: longlived BEC of ground state molecules with anisotropic, long-range interaction

Dipole Moments of Ground State Molecules

Dipole moments of vibrational ground state:

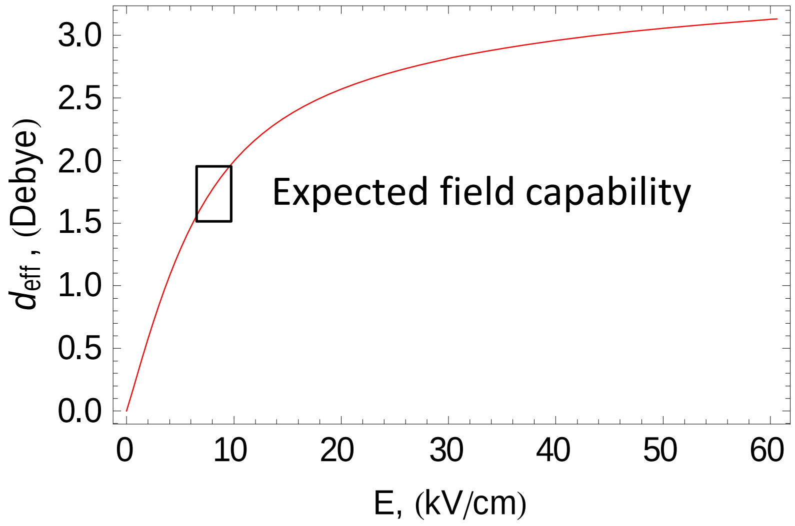
Mixture	[Debeye]
Li-Na	0.56
Li-K	3.6
Li-Rb	4.2
Li-Cs	5.5
Na-K	2.8
Na-Rb	3.3
Na-Cs	4.6
K-Rb	0.6
K-Cs	1.9
Rb-Cs	1.2

M. Aymar and O. Dulieu, J. Chem.Phys., 122, 204302 (2005)

Parity eigenstate have no electric dipole moment

↓

Effective electric dipole by mixing rotational states of opposite parity by electric field.



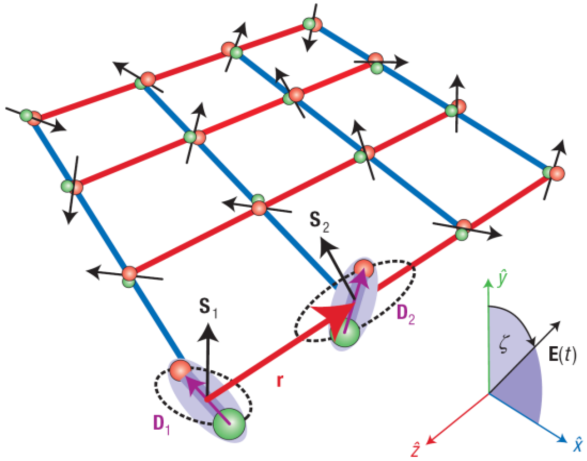
Interaction energy for 532 nm lattice:

^{6}Li^{40}K: 3.6 Debye ~ 13 kHz ~ 0.65 μK

Heteronuclear Fermi-Fermi Mixture

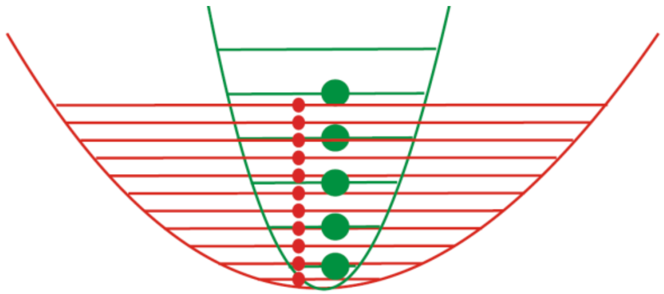
Dipolar molecules:

- Quantum information
- Quantum phase transitions in 2D trap and optical lattices



Heteronuclear Fermi-Fermi mixture in bulk trap:

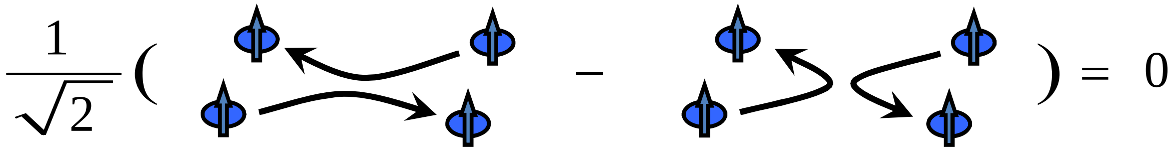
- long life times for fermions
- heteronuclear molecular BEC
- Imbalanced Fermi gases 1D, crystalline phase,…
- Species selective potentials: adiabatic cooling, tunable effective mass, selective detection



Triple Degenerate Mixture

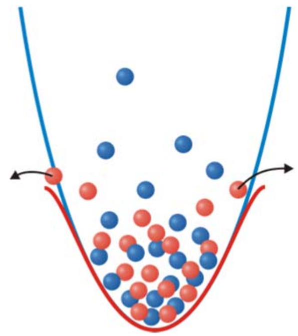
Why Three Species?

- **Fermions in identical states do not interact**



➡ Use of mixtures for sympathetic cooling

Amsterdam, Innsbruck: Li: $|1\rangle \,\&\, |2\rangle$ & K $\left|\frac{9}{2}; -\frac{9}{2}\right\rangle$



- **Fermi-Fermi-Bose mixture**

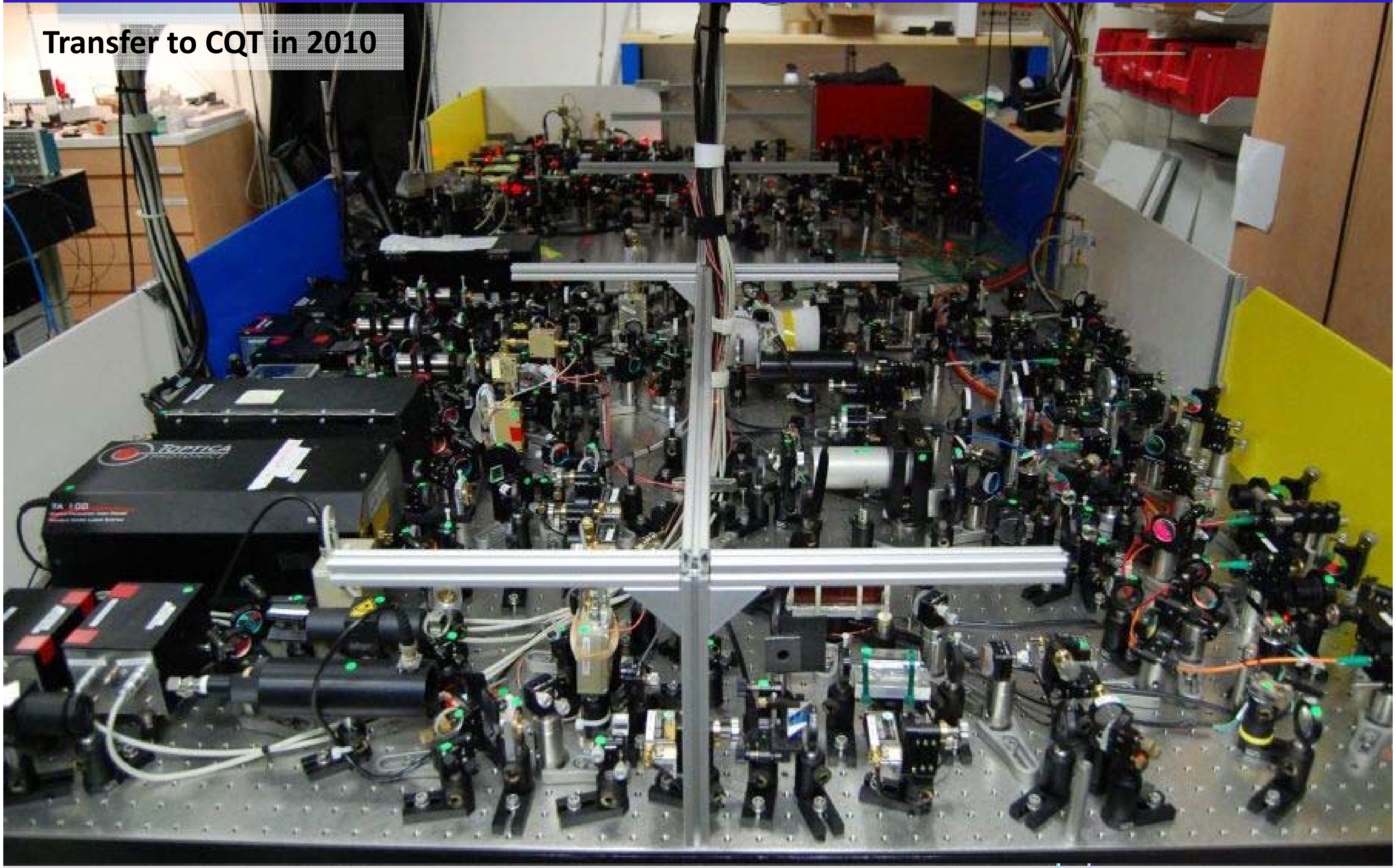
Munich: ^{6}Li (fermion) | ^{40}K (fermion) | ^{87}Rb (boson)

sympathetic cooling with
large and stable ^{87}Rb reservoir

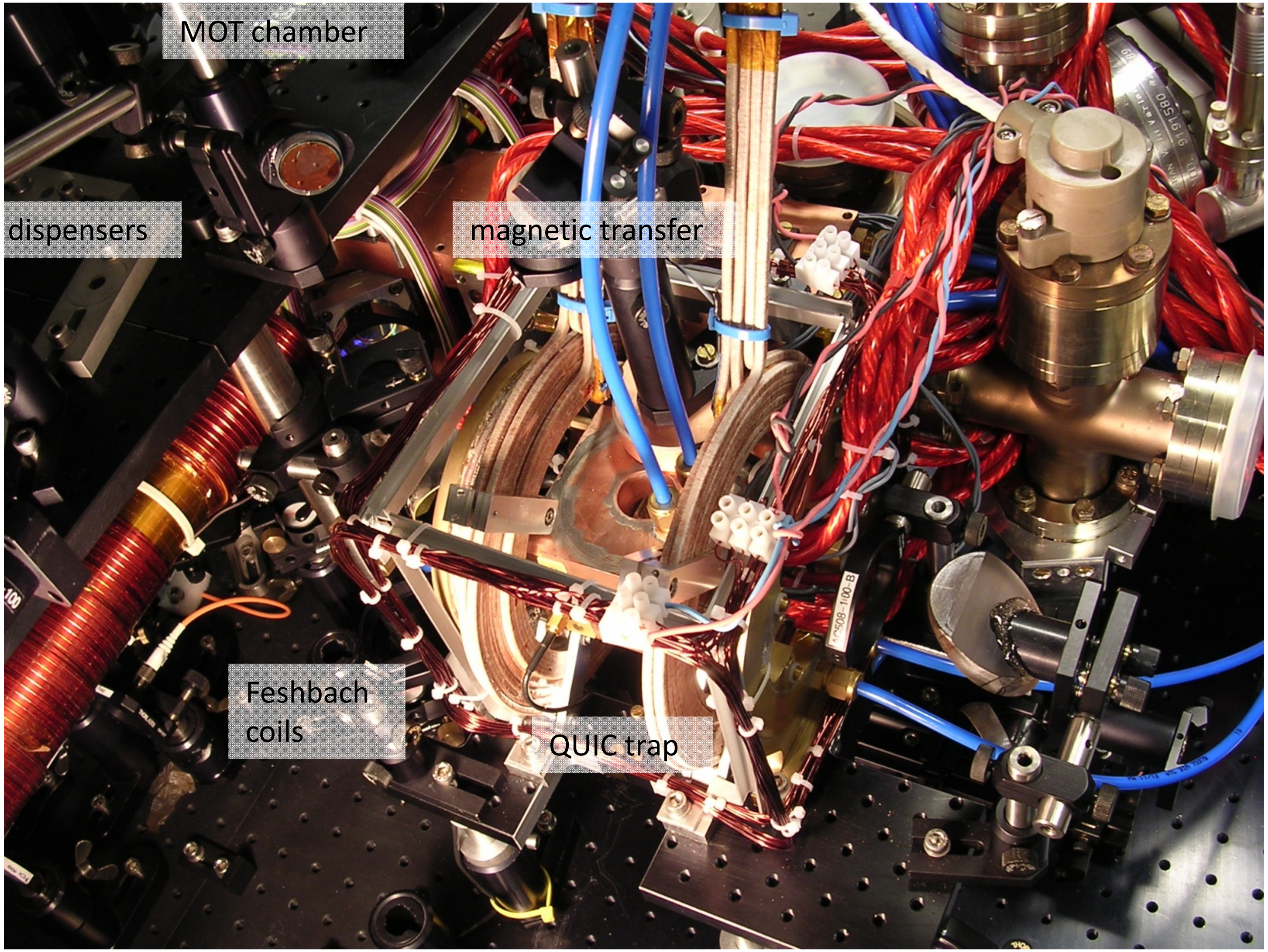
Advantages:

- Fermions are not evaporated: lower initial fermion atom numbers are sufficient
- No doubled Pauli blocking when cooling into quantum degeneracy
- Flexibility: to study Fermi-Fermi and Fermi-Bose mixtures

Laser Systems



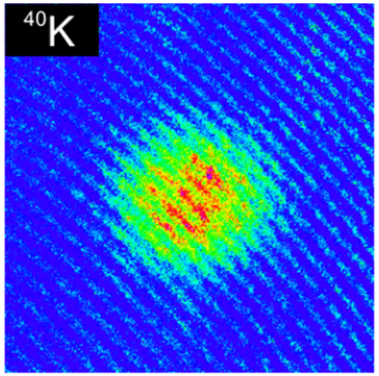
Science Chamber

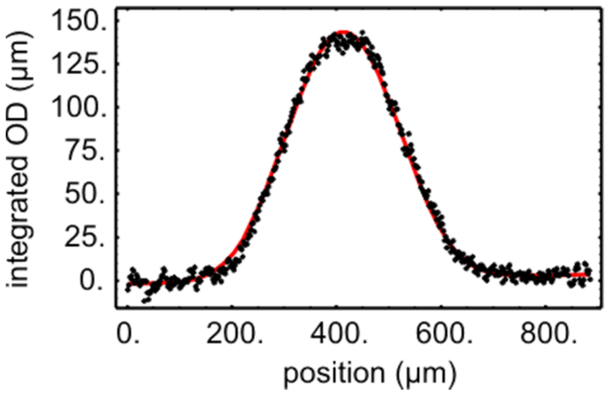


Triple Degeneracy

M.Taglieber, A.-C. Voigt, T. Aoki, T.W. Hänsch, and K. Dieckmann, PRL 100, 010401 (2008)

TOF = 15ms

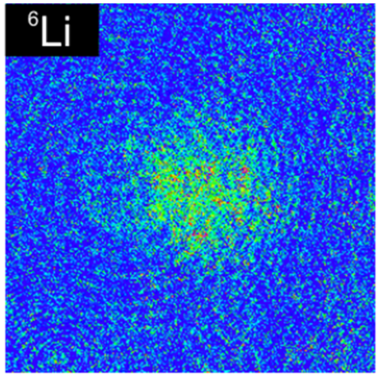


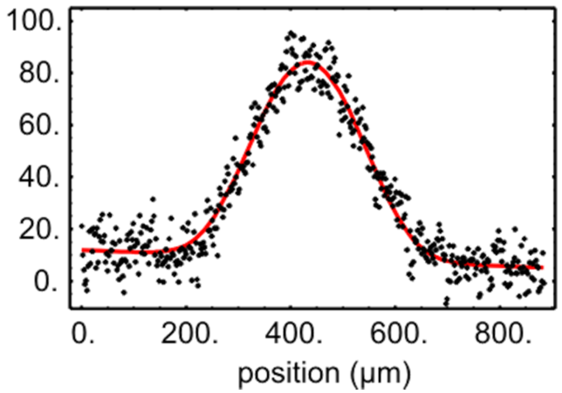


$N = 1.3 \times 10^5$

$T = 184\, nK = 0.35\, T_F$

TOF = 4ms

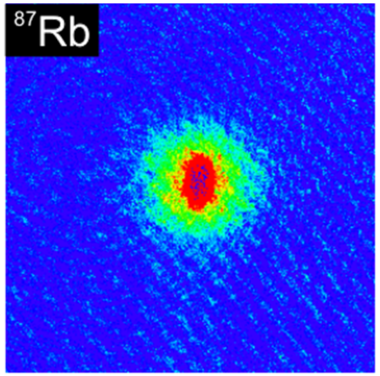


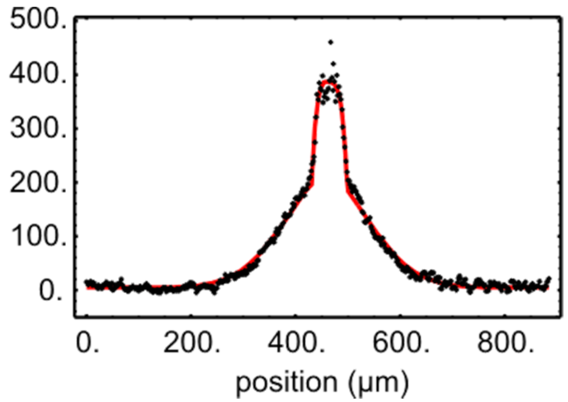


$N = 0.9 \times 10^5$

$T = 313\, nK = 0.27\, T_F$

TOF = 20ms





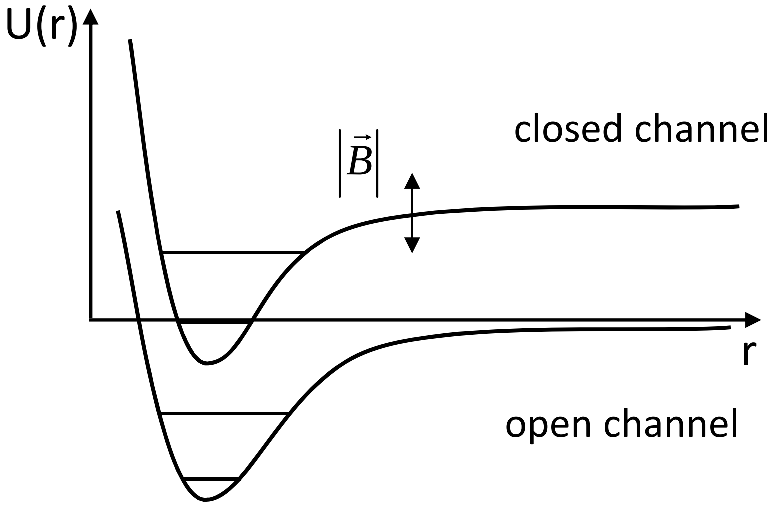
$N_{total} = 2.0 \times 10^5$

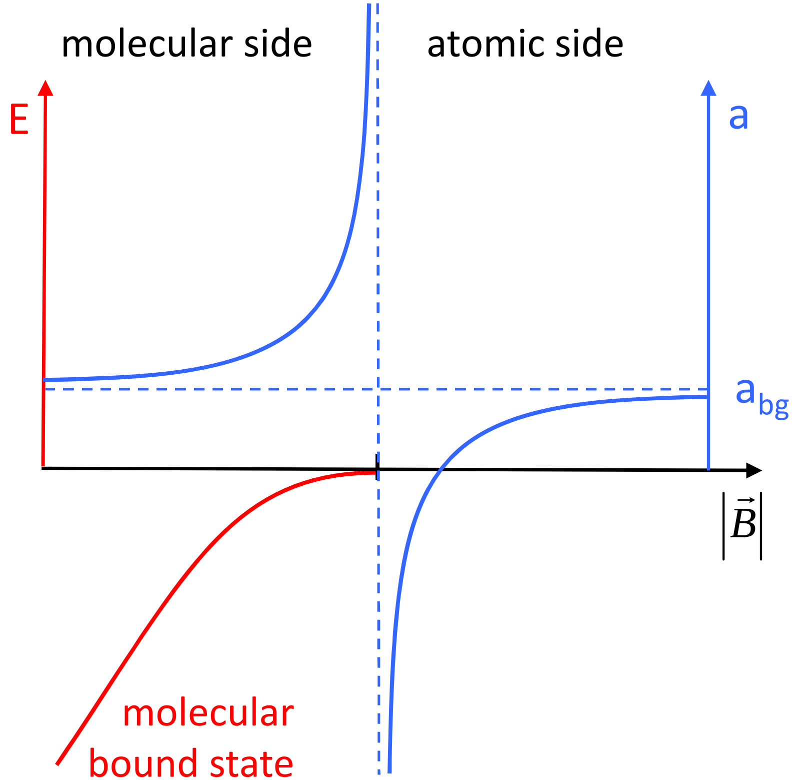
$T = 189\, nK = 0.9\, T_c$

➡ First quantum degenerate mixture of 3 different atomic species

^{6}Li-^{40}K Molecules

Feshbach Resonances





2-body universal regime close to resonance:

$$E_{\text{bind.}} << E_0$$

$$a = a_{\text{bg}}\left(1 - \frac{\Delta B}{B - B_0}\right); \; E_{\text{bind.}} = -\frac{\hbar^2}{m a^2}$$

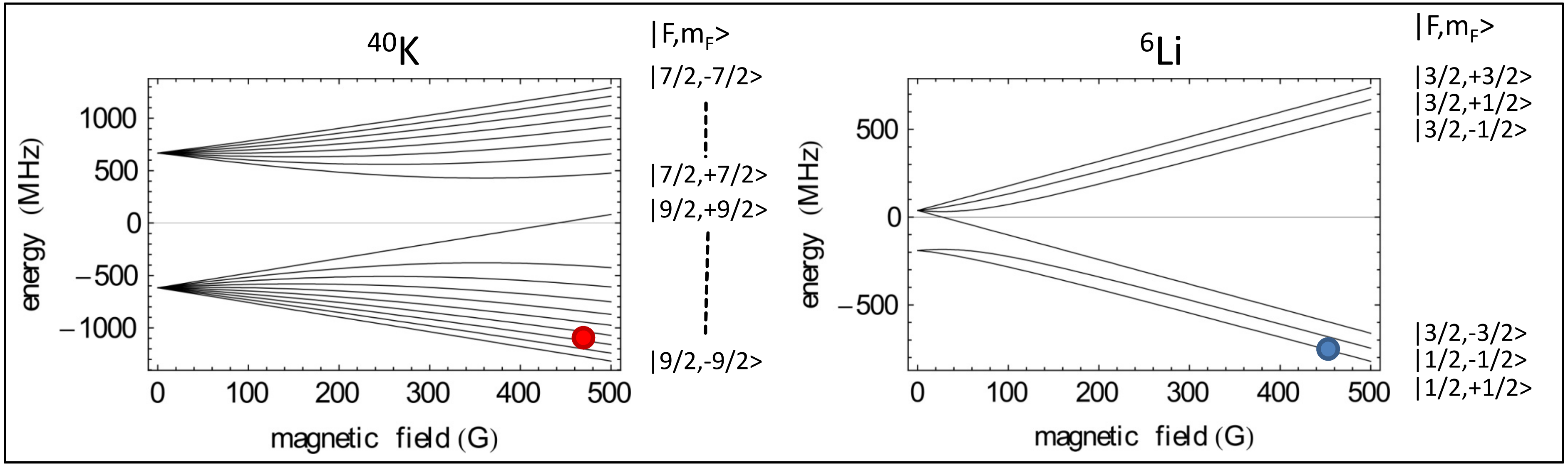
Strongly interacting regime:

$$k_F \, a \approx 1$$

$E_F << E_0$ Many body universal regime / broad resonance

$E_F >> E_0$ Narrow resonance

Levels of Li and K



Stable mixtures:

Selection rule for spin exchange collisions: $\Delta F_z = \Delta\left(m_F^{\mathrm{Li}} + m_F^{\mathrm{K}} + m_F^{\mathrm{Rb}}\right) = 0$

- Stable mixture (doubly polarized states):

  $\mathrm{Li}\ \left|3/2;\ 3/2\right\rangle\ \&\ \mathrm{K}\ \left|9/2;\ 9/2\right\rangle\ \&\ \mathrm{Rb}\ \left|2;\ 2\right\rangle$

- Additional stable mixture for Li-Rb experiments (maximally stretched states):

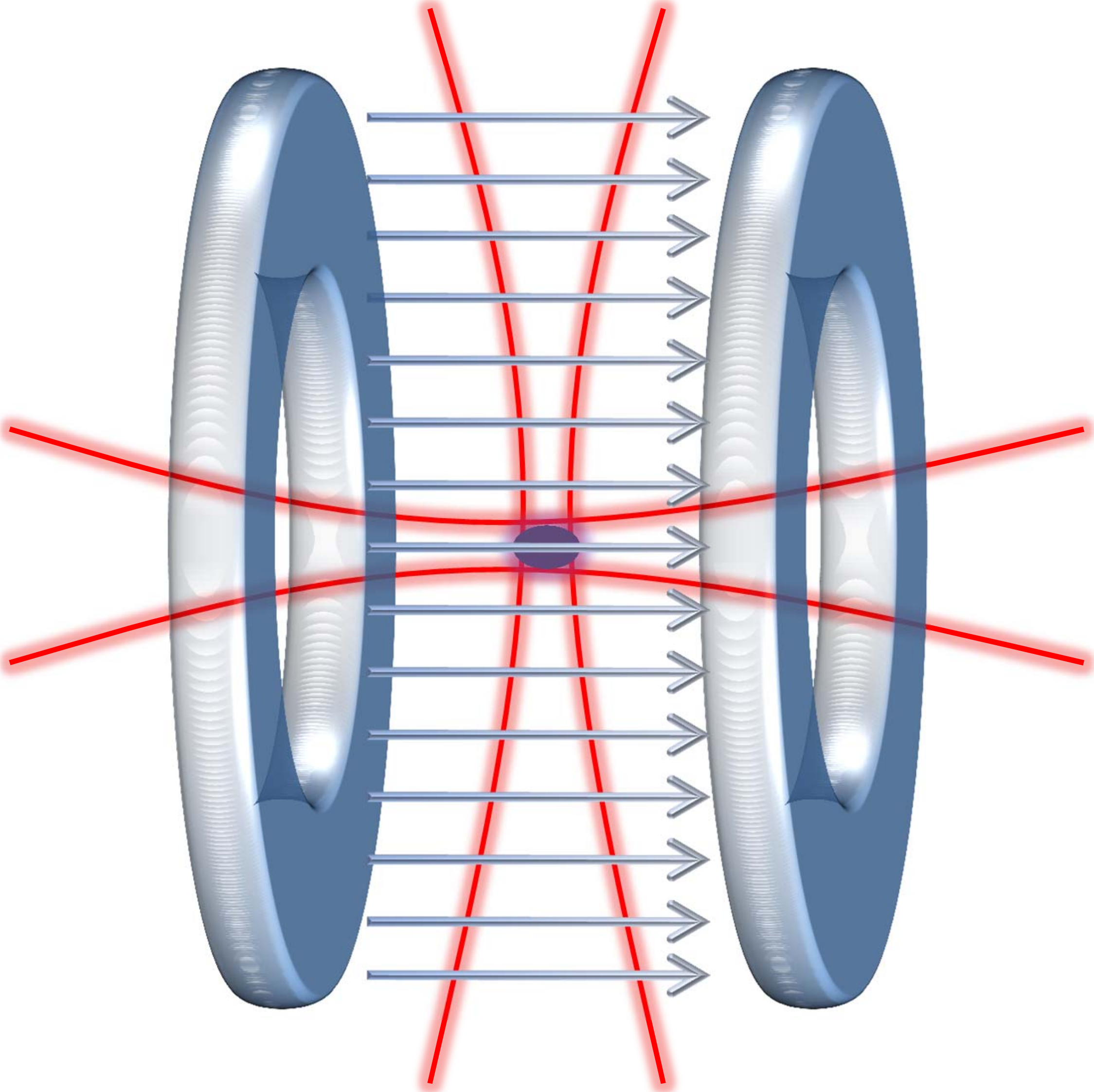
  $\mathrm{Li}\ \left|1/2;\ -1/2\right\rangle\ \&\ \mathrm{Rb}\ \left|1;\ -1\right\rangle$

  But unstable for K-Rb and in Li-K-Rb mixture (inverted HFS of ^{40}K).

- All states trappable in optical dipole trap. Interesting stable examples:

  $\mathrm{Li}\ \left|1/2;\ 1/2\right\rangle\ \&\ \mathrm{K}\ \left|9/2;\ m_F\right\rangle$ $\quad$ $\mathrm{Li}\ \left|1/2;\ m_F\right\rangle\ \&\ \mathrm{K}\ \left|9/2;\ -9/2\right\rangle$

Optical Trap and Magn. Coils



Crossed optical dipole trap:

- 1064 nm
- waists: 50 μm, 55 μm
- Trap frequencies:
  Li: 725 Hz
  K: 1245 Hz

Feshbach coils:

- almost Helmholtz configuration
- hollow, water-cooled wire

Parameters (for I=500A):
$B = 930$ G
$B'' = 7$ G/cm^2
$P = 6.6$ kW

Maximum B-field inhomogeneity at FBR : < ±5 mG

Li-K Feshbach Resonances in Innsbruck

Loss measurement in non-degenerate mixture: *E. Wille et al., PRL 100, 053201 (2008)*

i, j	M_F	Experiment B_0 (mT)	Experiment ΔB (mT)	ABM B_0 (mT)	Coupled channels B_0 (mT)	Coupled channels ΔB_s (mT)	type
2, 1	-5	21.56[a]	0.17	21.67	21.56	0.025	s
1, 1	-4	15.76	0.17	15.84	15.82	0.015	s
1, 1	-4	16.82	0.12	16.92	16.82	0.010	s
1, 1	-4	24.91	1.07	24.43	24.95	-	p
1, 2	-3	1.61	0.38	1.39	1.05	-	p
1, 2	-3	14.92	0.12	14.97	15.02	0.028	s
1, 2	-3	15.95[a]	0.17	15.95	15.96	0.045	s
1, 2	-3	16.59	0.06	16.68	16.59	0.0001	s
1, 2	-3	26.28	1.07	26.07	26.20	-	p
1, 3	-2	not observed		1.75	1.35	-	p
1, 3	-2	14.17	0.14	14.25	14.30	0.036	s
1, 3	-2	15.49	0.20	15.46	15.51	0.081	s
1, 3	-2	16.27	0.17	16.33	16.29	0.060	s
1, 3	-2	27.09	1.38	27.40	27.15	-	p

Molecules in Munich

Tiemann:
Not predicted in
Revised theory

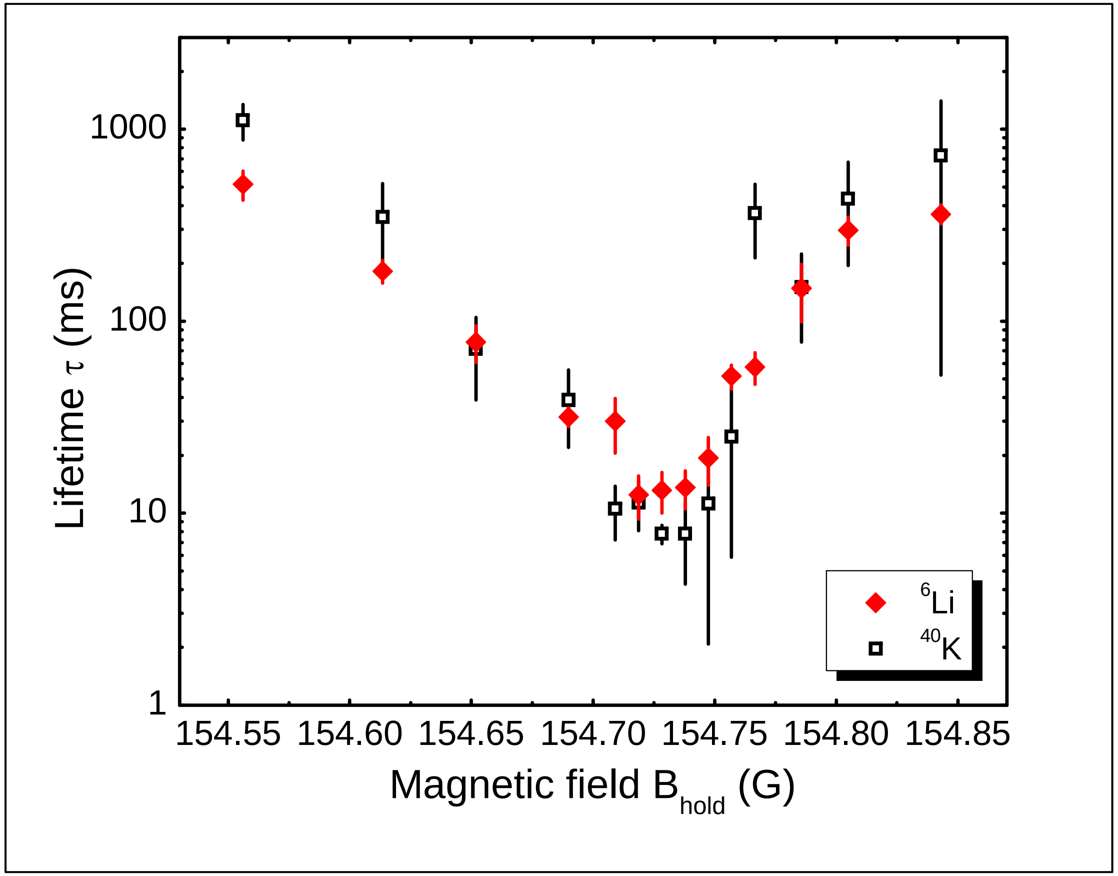
Molecules Munich

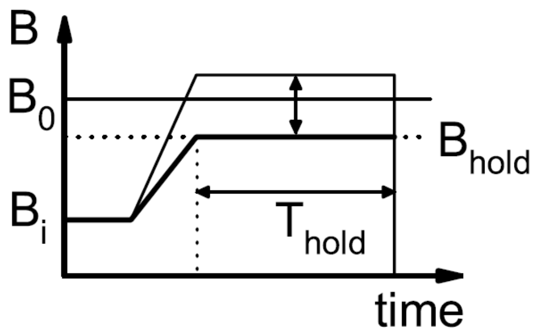
s-wave resonances expected to be narrow , close channel dominated

Mapping the Resonance via Lifetime

Typical initial conditions: ^{6}Li: |1/2,+1/2> $n_{Li} \approx 2 \cdot 10^{13} cm^{-3}$ $T/T_F^{Li} = 0.6$

^{40}K: |9/2,-5/2> $n_K \approx 1 \cdot 10^{14} cm^{-3}$ $T/T_F^{Li} = 0.4$

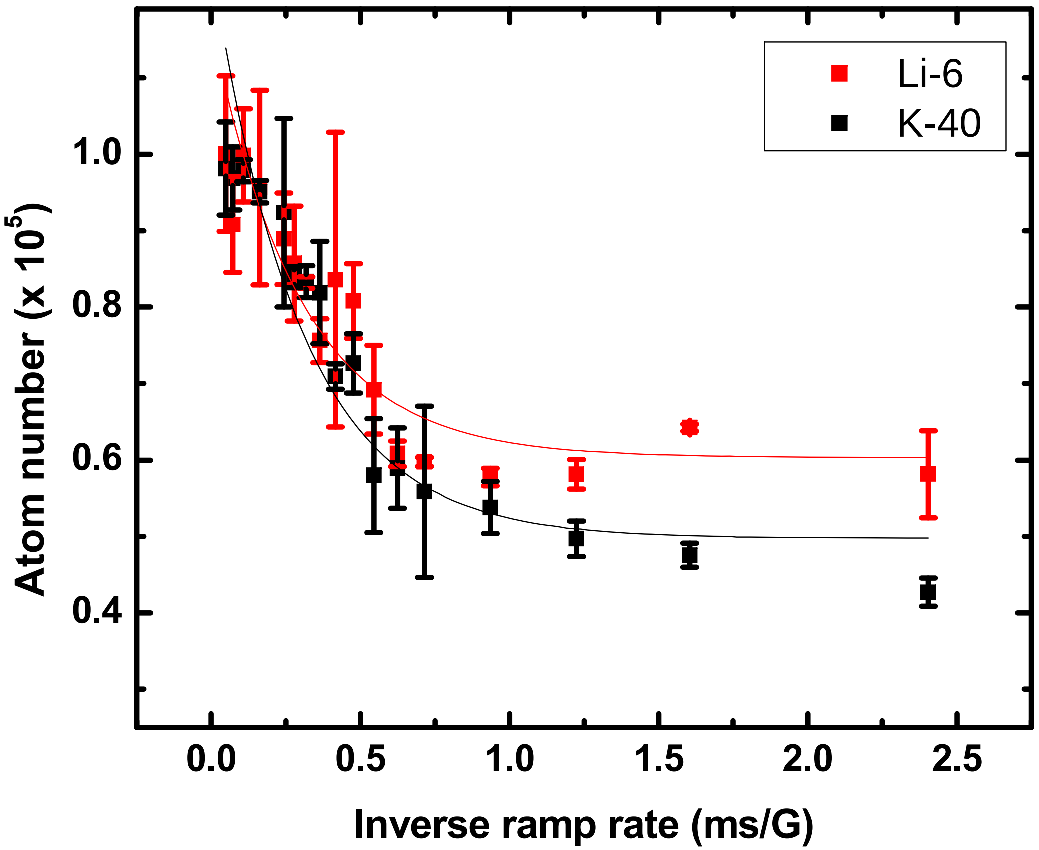


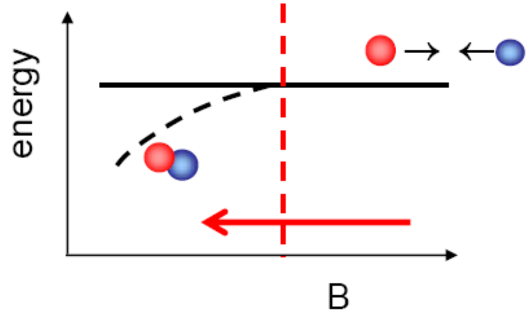


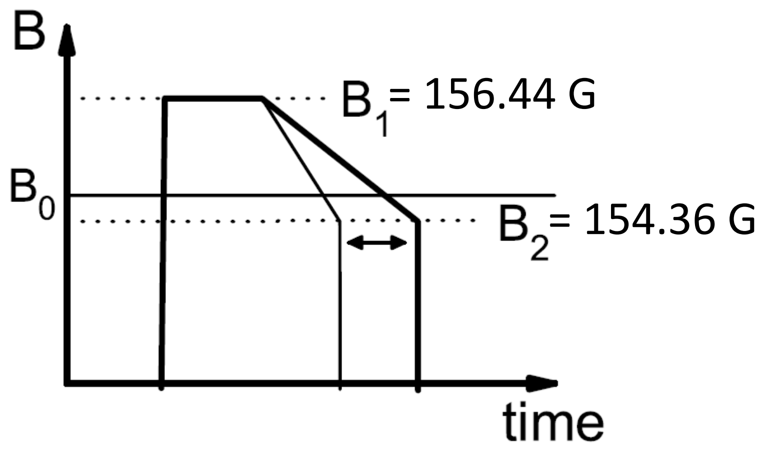
$B_0 = 154.72(5)$ G

$\Delta B_{3dB} = 50$ mG (Innsbruck: 2 G)

Feshbach Association Ramp Speed



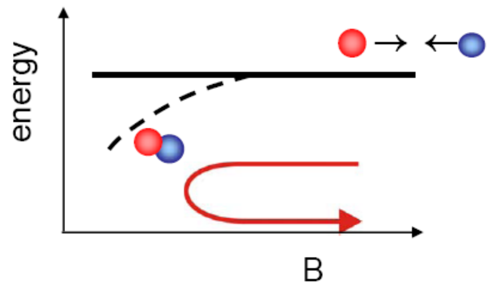


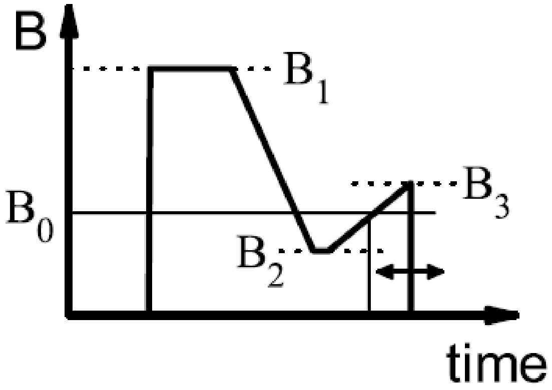


- Conversion efficiency up to 50%, up to 4×10^4 molecules
- 1/e inverse ramp speed 0.3 ms/G
- use in experiment 1ms/G

Feshbach Association / Dissociation

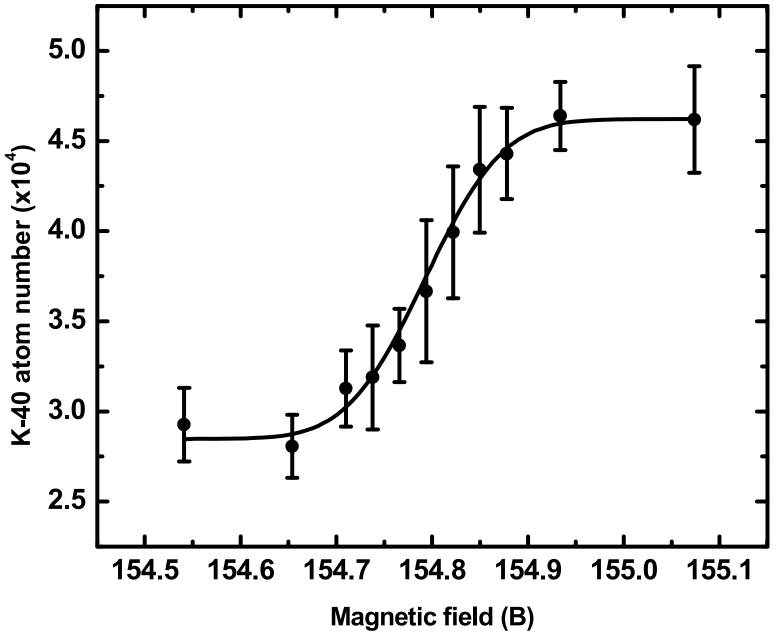
Reversed sweep:

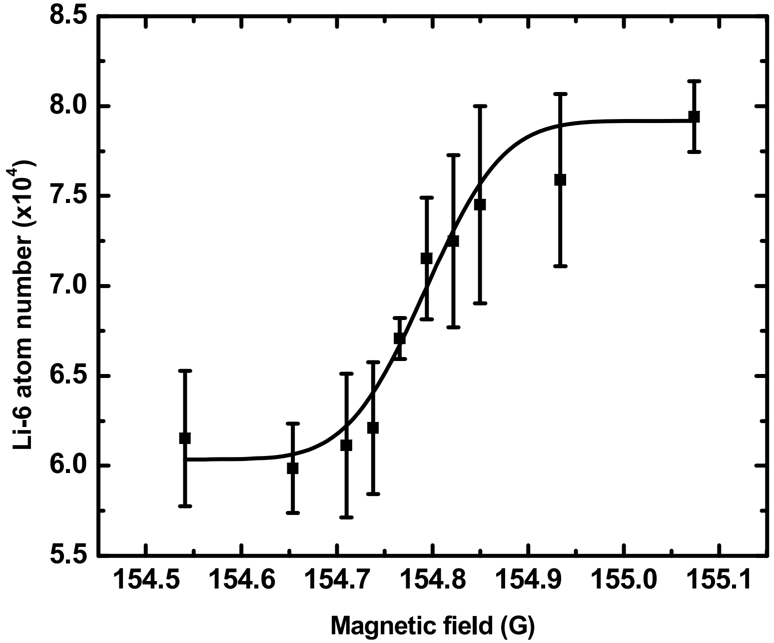




B_2 = 154.54 G

B_1 = 156.90 G

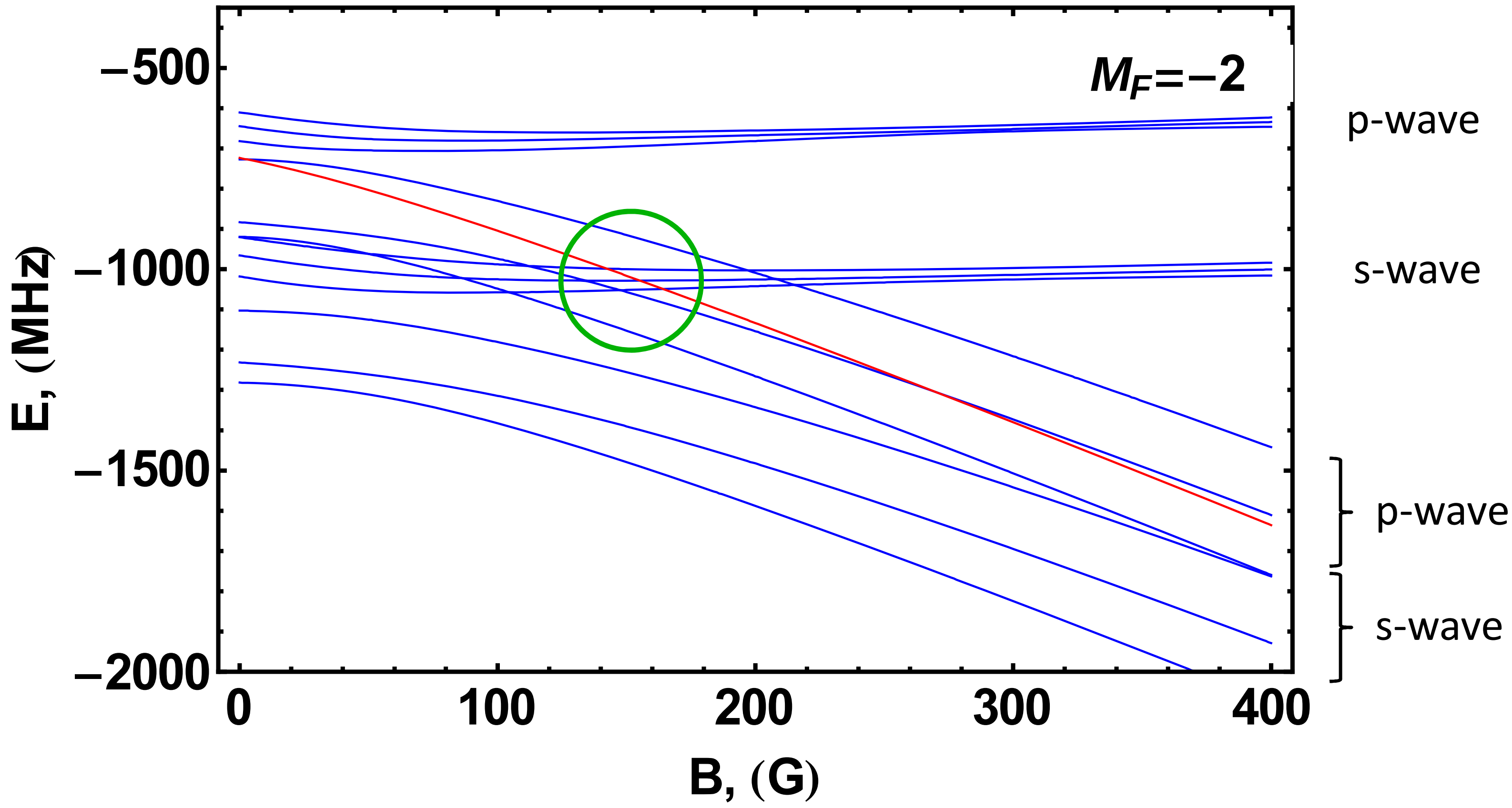




Center at 154.79 (8) G

ABM Model M= -2

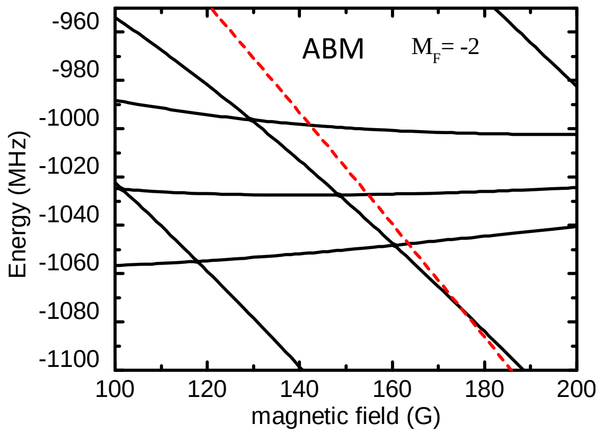
E. Wille et al., PRL 100, 053201 (2008)   T.G. Tiecke, et al., arXiv:1007.0886 (2010)



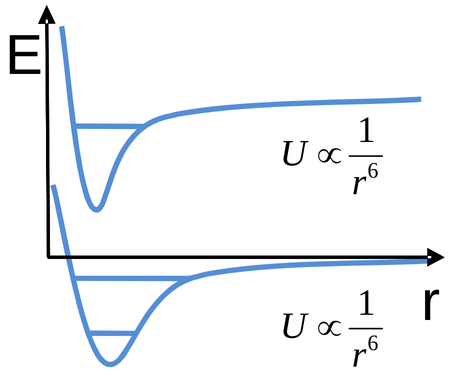
• Magnetic moment of molecular state near zero

Direct Imaging of Heteronuclear Molecules

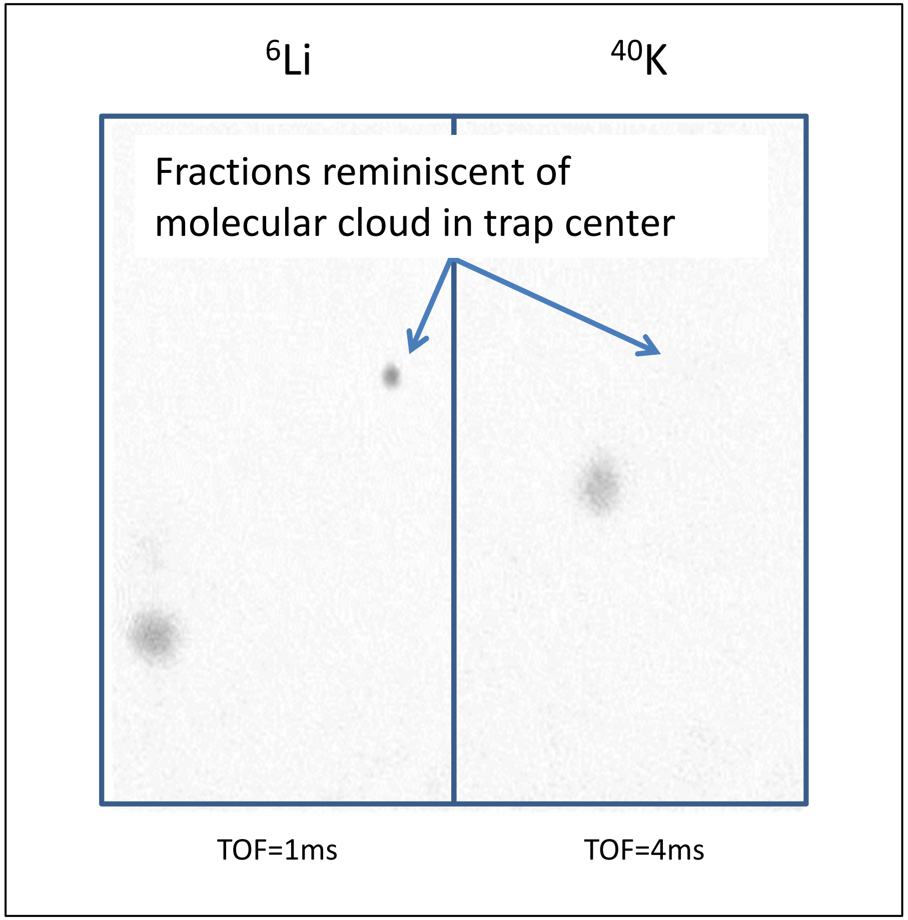
- Stern-Gerlach pulse:
  ~ 570µs at 157 G/cm



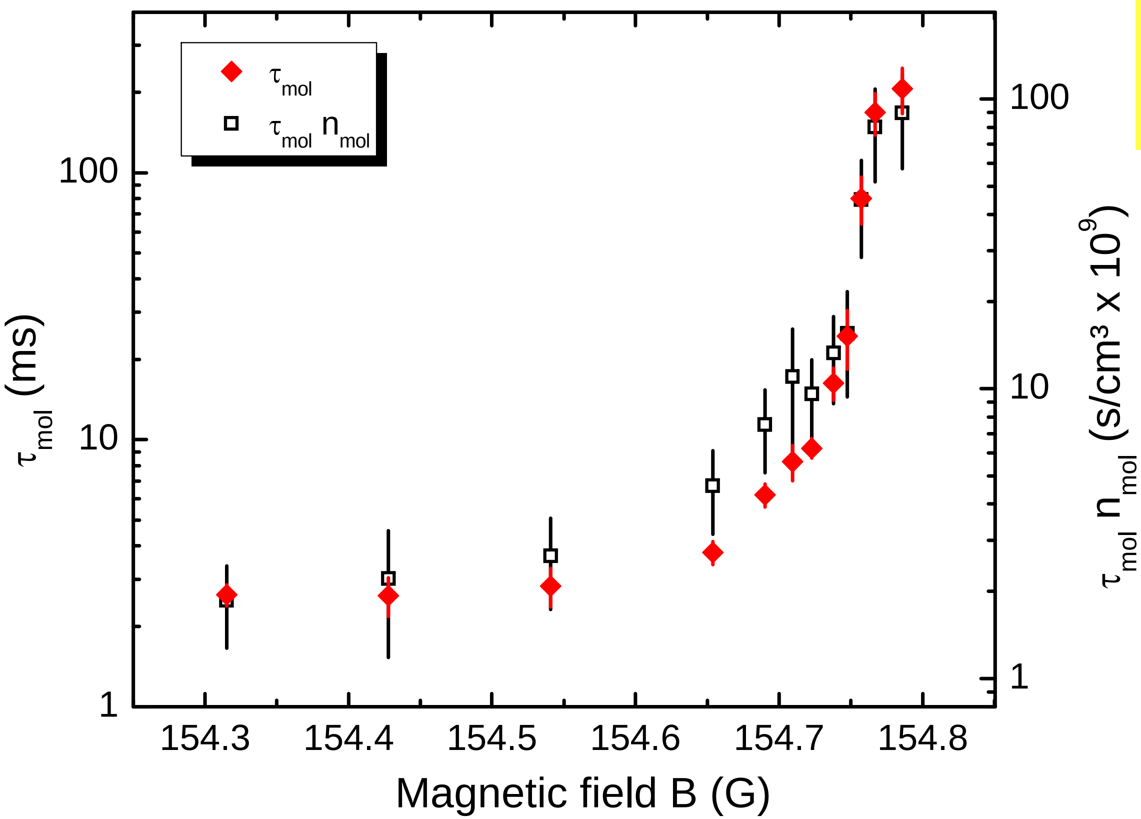
- Simultaneous high field imaging of
  atoms and molecules



J. J. Zirbel et al., PRL, 100, 143201 (2008).



Lifetimes



- Suppression of losses close to resonance observed

- Proposed decay mechanisms:
  - Spontaneous molecular spin relaxation

    *T. Köhler et al., PRL **94**, 020402 (2005)*

    *J.L. Roberts et al., PRL **85**, 728 (2000)*
  - Vibrational relaxation

    *D. Petrov et al., J. Phys. B: At. Mol. Opt. Phys. **38** 645 (2005)*

- Size of closed channel?

$$g_0 \approx E_F \approx k_B \cdot 1\,\mu K$$

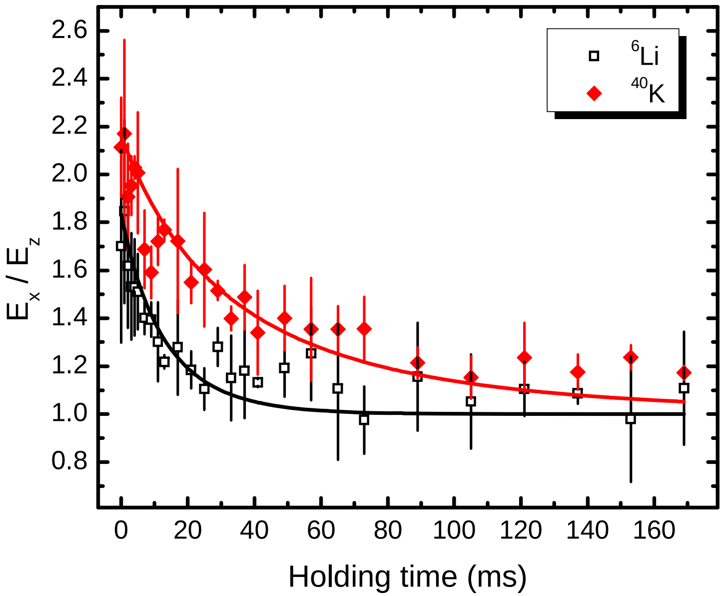
- study strongly interacting regime (width ≈ 40 mG)
- Where is the resonance?

Cross Dimensional Relaxation

Applying CDR method to FBR at 154.7 G:

$$\omega_x \to \omega_x' \ , \ \omega_y = \omega_y' \ , \ \omega_z = \omega_z' \qquad \dot{\omega}_x \ll \omega_x^2, \qquad \Delta t \cdot \Gamma_{el} \ll 1$$

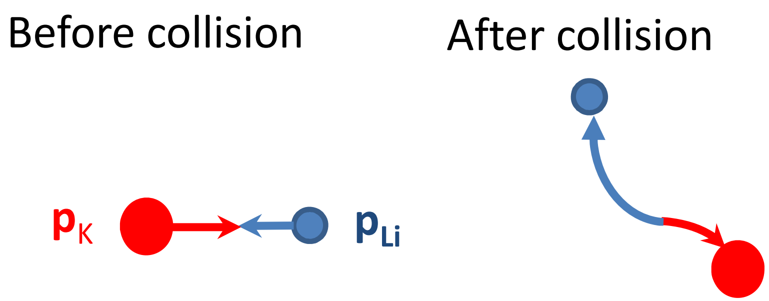
$$\langle E_x \rangle \neq \langle E_y \rangle \ , \ \langle E_z \rangle$$



$$\Gamma_{12} \equiv \frac{1}{\beta_{12}} n_{12} \cdot v_{\mathrm{rel}} \cdot \sigma_{12}$$

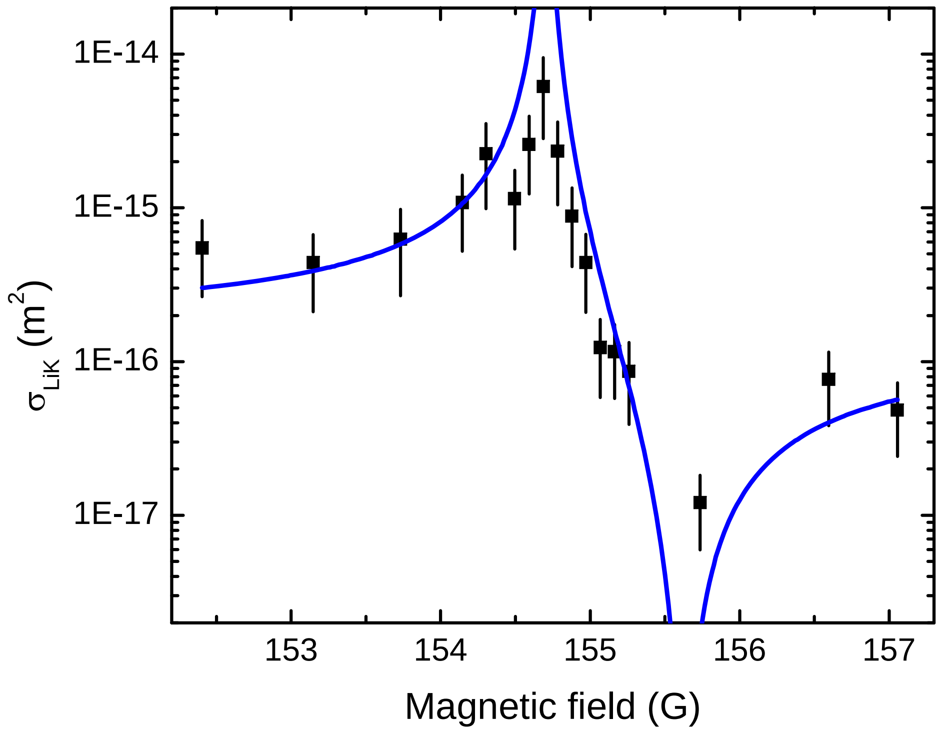
β_{12}: "mean number of collisions of species 1 to thermalize with species 2"

$$\beta_{\mathrm{Li,K}} = 2.0 \neq \beta_{\mathrm{K,Li}} = 7.3$$



S-Wave collisions at FBR

Applying CDR method to FBR at 154.7 G:



Magnetic field scans with constant holding time:

B_0 = 154.71(5) G
B_{Zero} = 155.73(4) G
Δ=1.02(7)

Ab-initio curve:

$$\sigma = 4\pi \, | \, f(k) \, |^2$$

$$f(k) = \frac{1}{-\frac{1}{a} + \frac{1}{2} R^* k^2 - ik}$$

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

$$R^* = \frac{\hbar^2}{m_r a_{bg} \mu_{rel} \Delta}$$

$$B_0 = 154.71 \text{ G}$$

$$\Delta = 0.81 \text{ G}$$

$$a_{bg} = 63.5 \, a_0$$

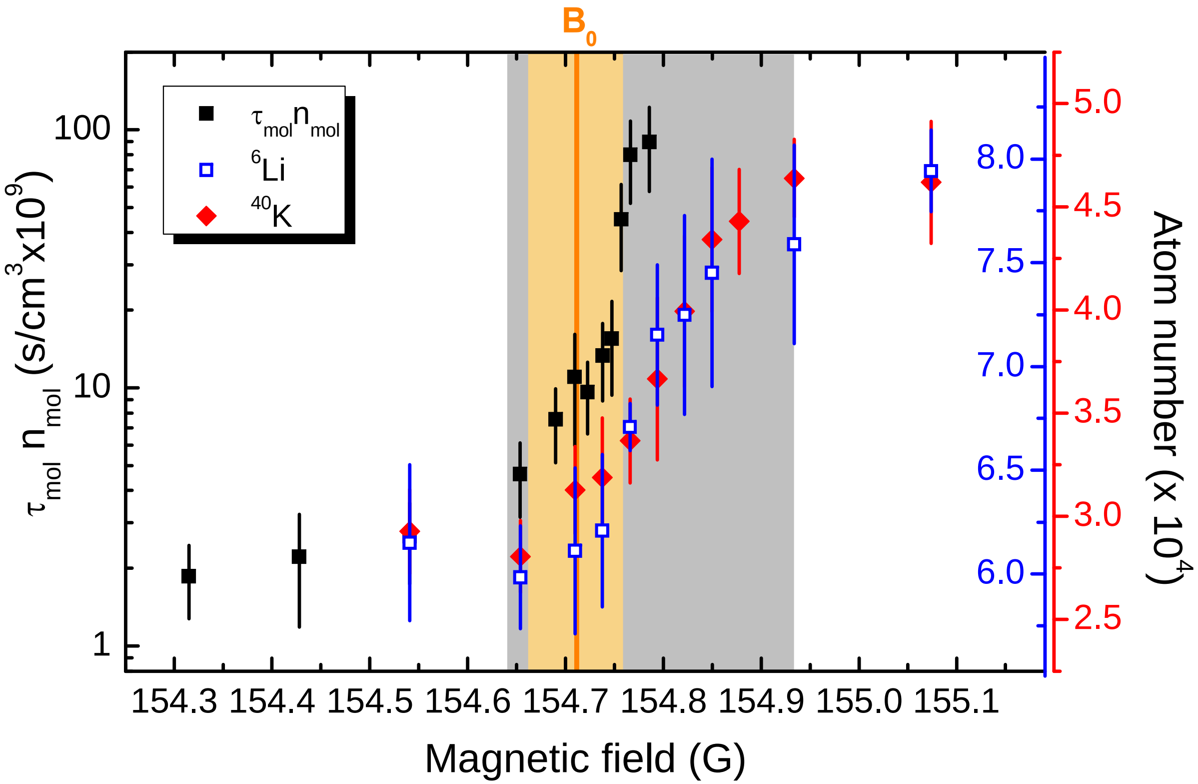
$$\mu_{rel} = 1.67 \, \mu_B$$

$$k = k_F$$

D. S. Petrov et al., PRL, 93, 143201, (2004)
E. Wille et al., PRL 100, 053201 (2008)

Crossover at a Narrow FBR I

Narrow Feshbach resonance: molecules above resonance



Observed shift ⟹ **many body effect at a narrow FBR**

Further broadening due to finite T and Feshbach coupling

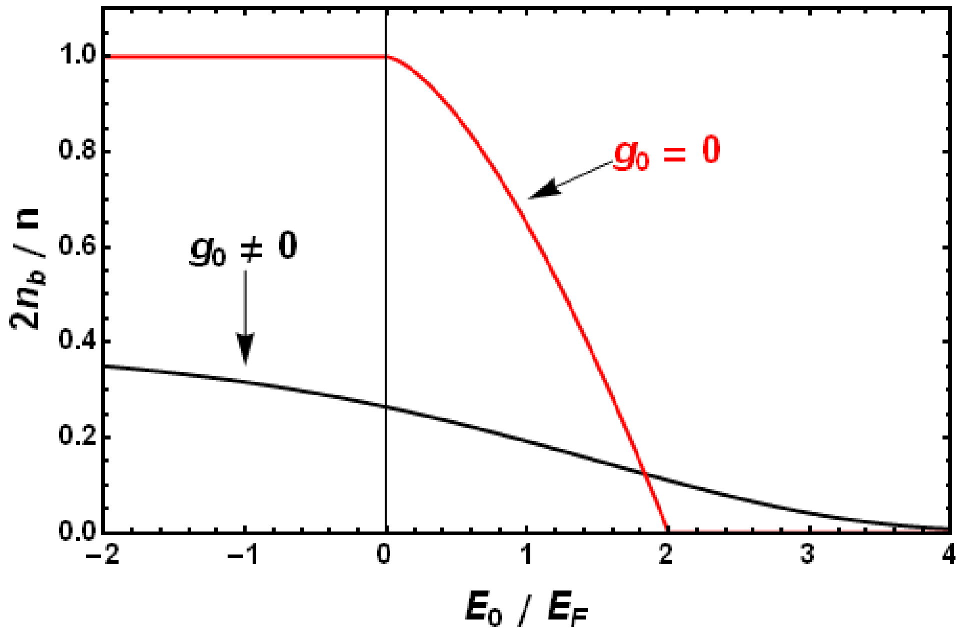
$$\Delta B = \frac{E_{F,\mathrm{Li}} + E_{F,\mathrm{K}}}{\mu_{\mathrm{rel}}\mu_{\mathrm{B}}} = 70\ \mathrm{mG}$$

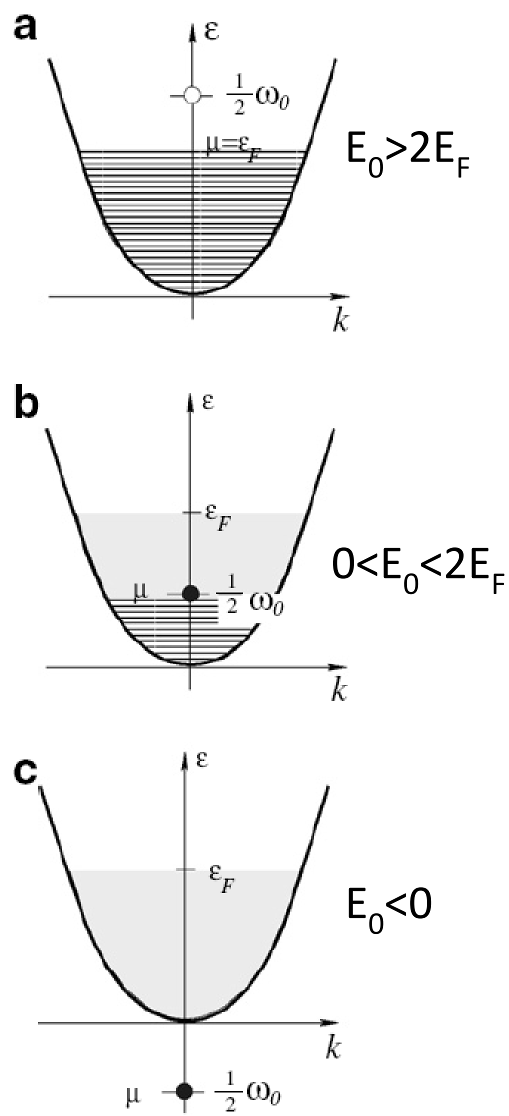
- V. Gurarie, and L. Radzihovsky, Annals of Physics 322, 2-119 (2007).
  L. M. Jensen et al., PRA 74, 043608, (2006)

Crossover at a Narrow FBR II

T=0 molecular condensate fraction:

V. Gurarie, and L. Radzihovsky, Annals of Physics 322, 2-119 (2007).





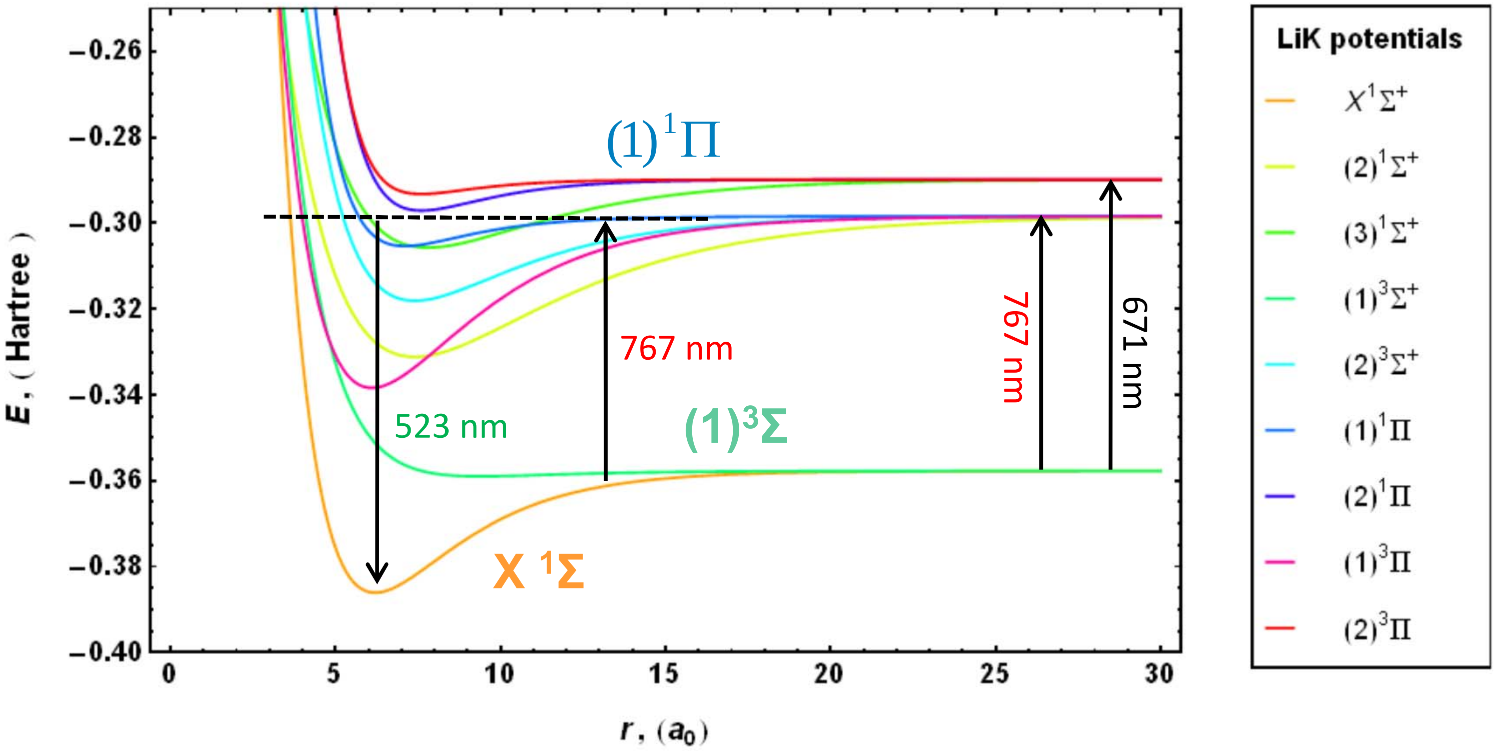
Extension on atomic side
g_0 = 0 and T = 0 limit:

$$\Delta B = \frac{E_{F,\mathrm{Li}} + E_{F,\mathrm{K}}}{\mu_{\mathrm{rel}}\mu_{\mathrm{B}}} = 70\ \mathrm{mG}$$

Towards Dipolar Molecules (in Singapore)

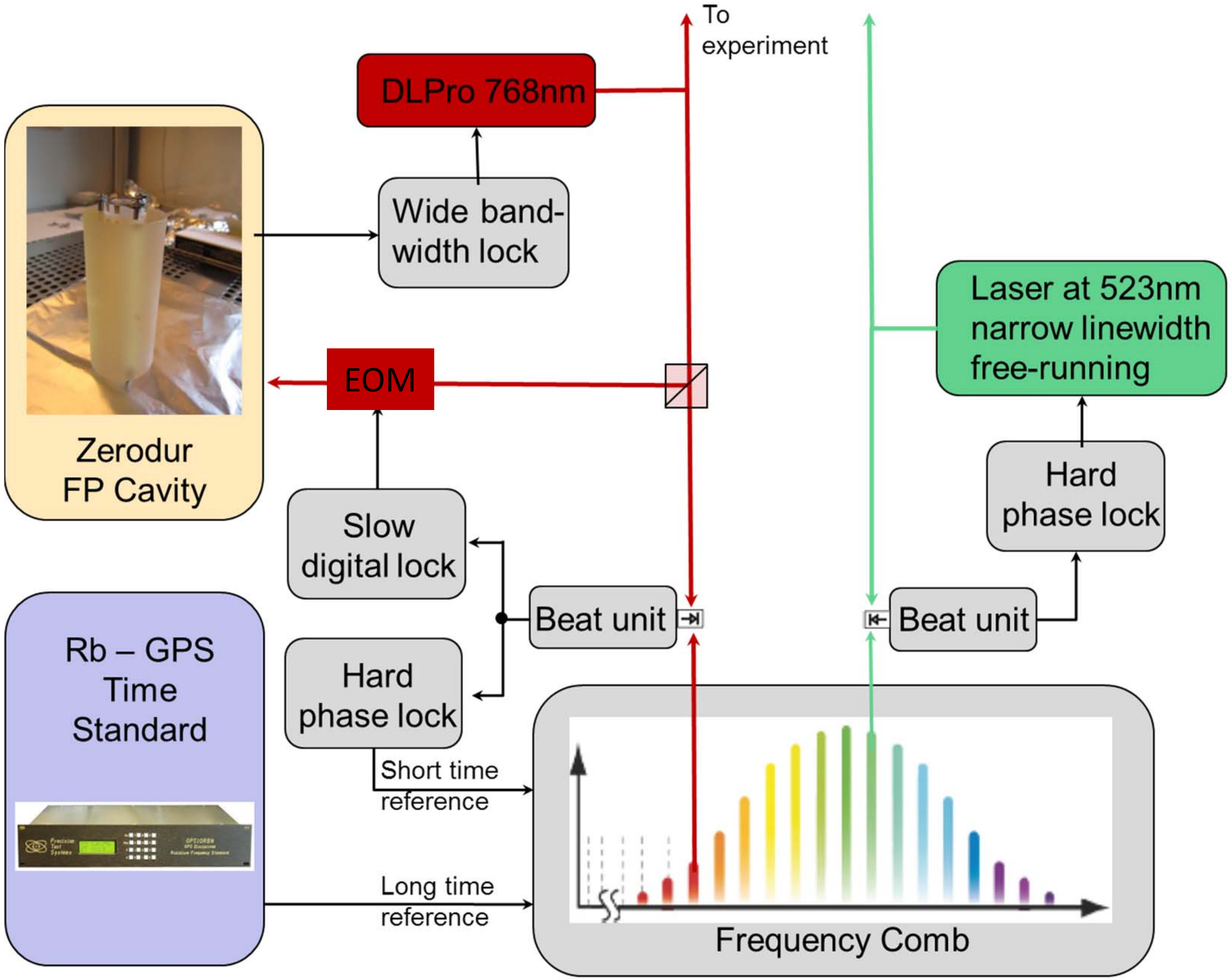
Transfer to Ground State

Transitions by Stimulated Raman Adiabatic Passage (STIRAP):

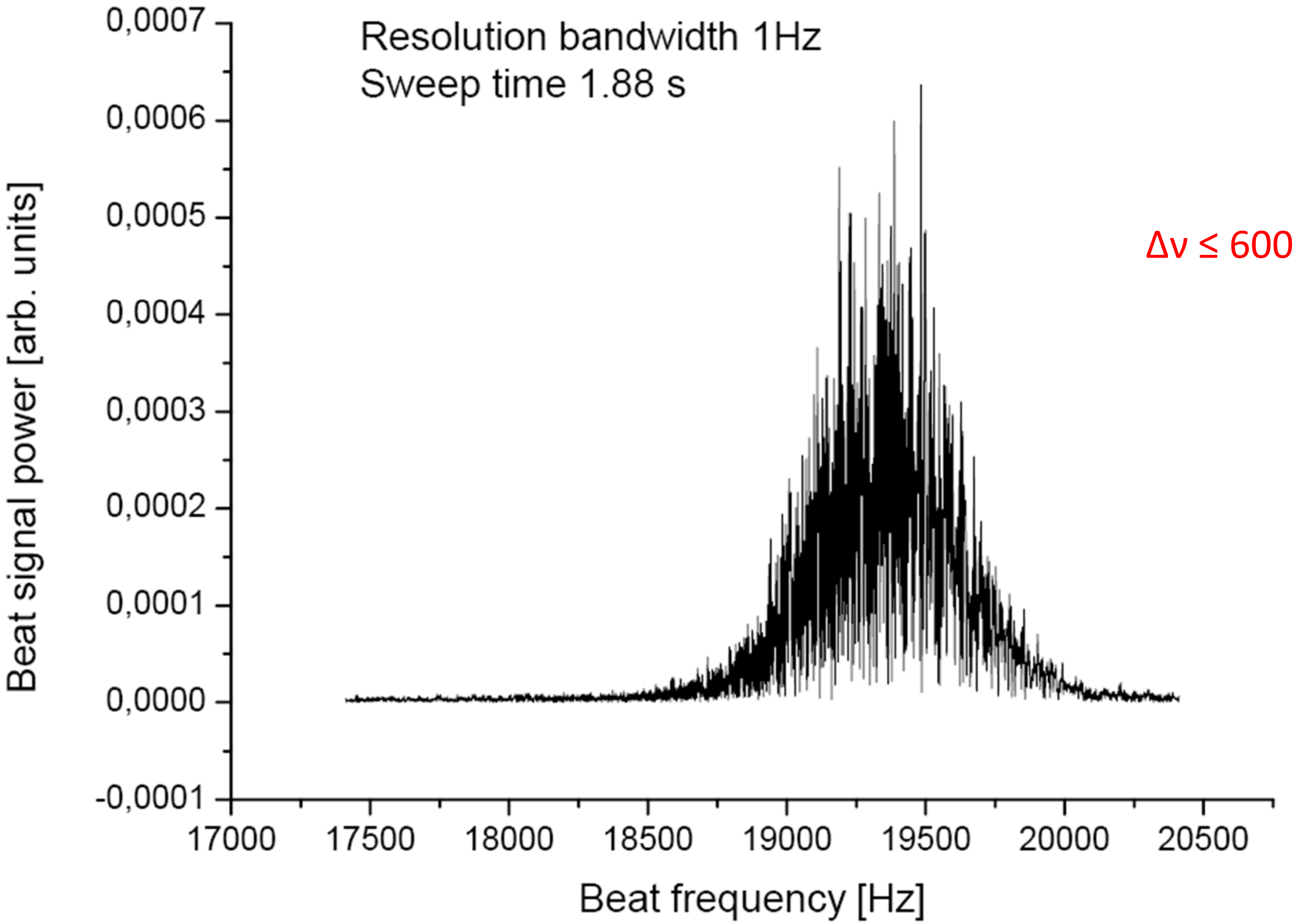


- KRb: mixing of $(2)^3\Sigma$ and $(1)^1\Pi$ states
- LiK: mixed singlet triplet character of initial state
- Repulsive C_6 for potentials connecting to Li asymptote

STIRAP Laser System

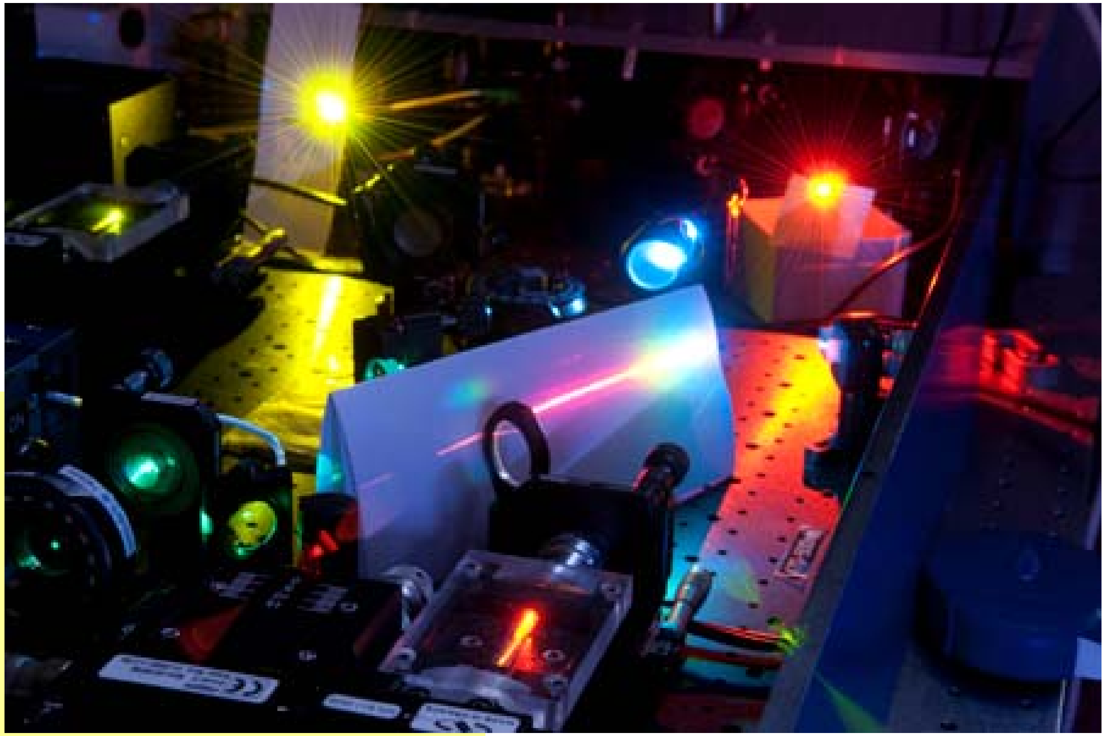


Narrow Laser at 767 nm



$\Delta\nu \leq 600$ Hz

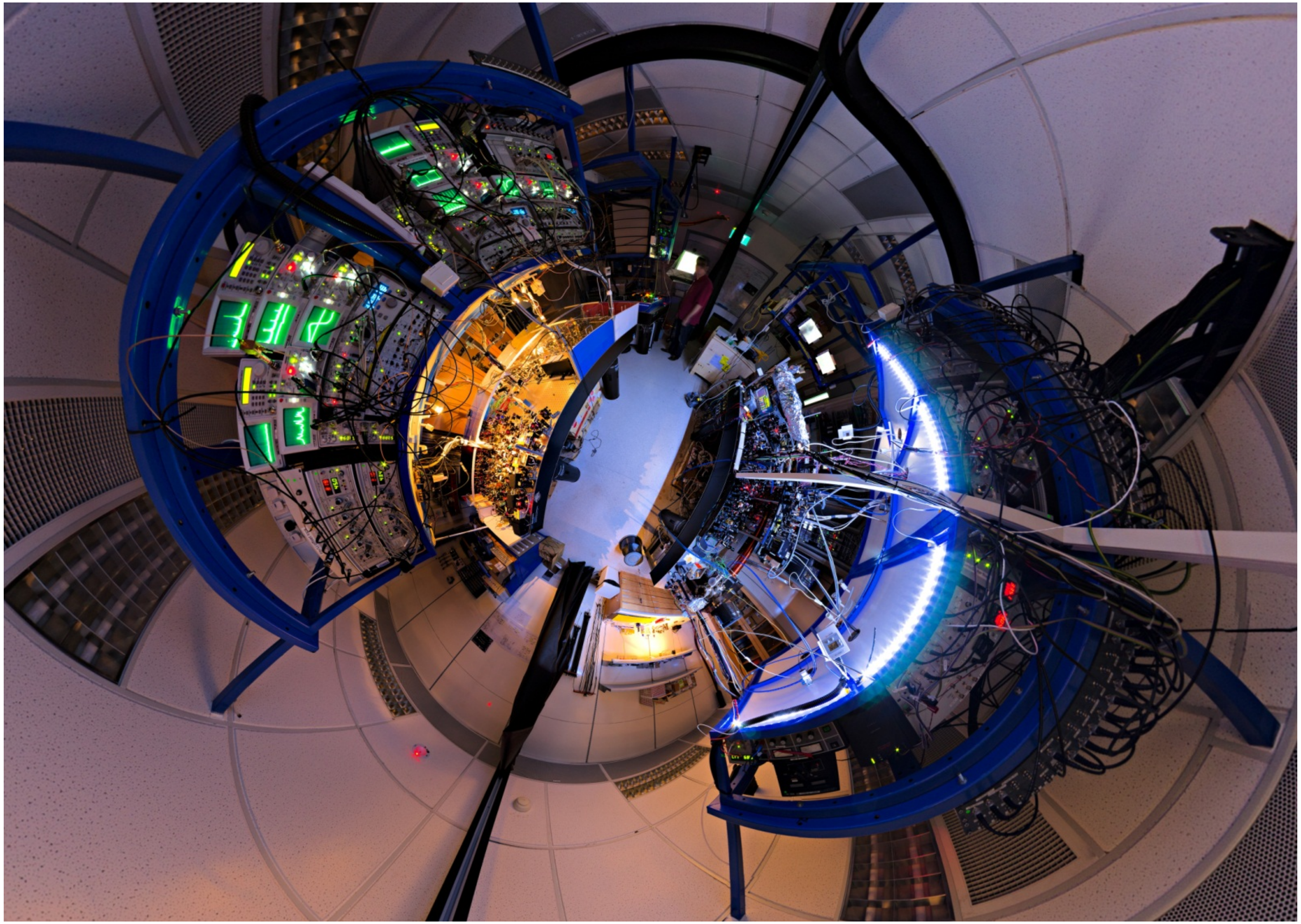
Cold Fermions at CQT



Quantum Matter Group

- New project with fermionic lithium in a optical lattice
- Postdoc openings
- http://qmatter.quantumlah.org/

Cold Fermions at CQT



Thank you…