Coherent manipulation of quantum systems with polychromatic driving

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https://github.com/gsinuco/MultimodeFloquet
ArXiv: 1904.12073 (2019)

Non-Equilibrium Phenomena, Newcastle, 12th June 2019

Outline

1. Driven quantum systems
2. Multimode Floquet expansion
3. Polychromatic driving of Rb87 (x 3)
4. Outlook

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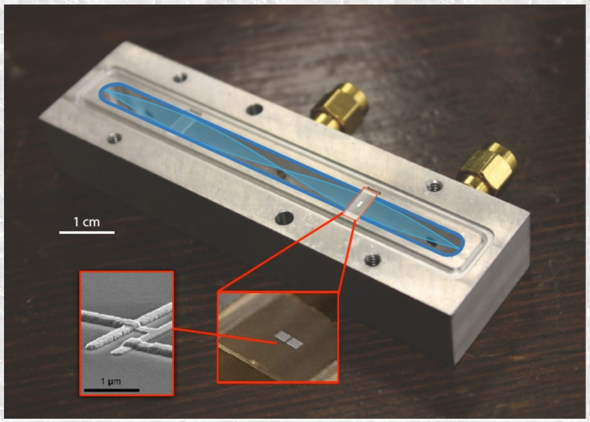
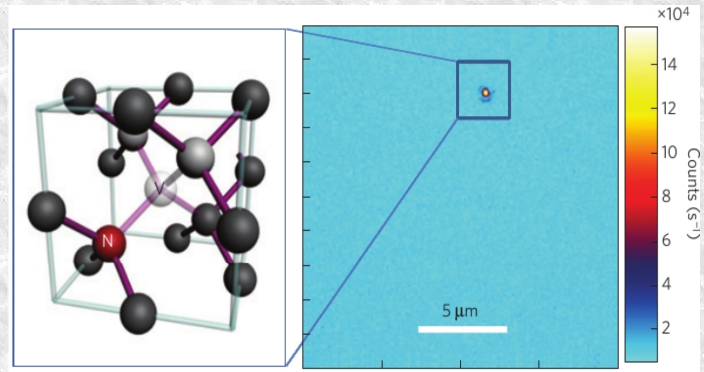
UK National Quantum Technology Hub Sensors and Metrology

UNIVERSITY OF SUSSEX

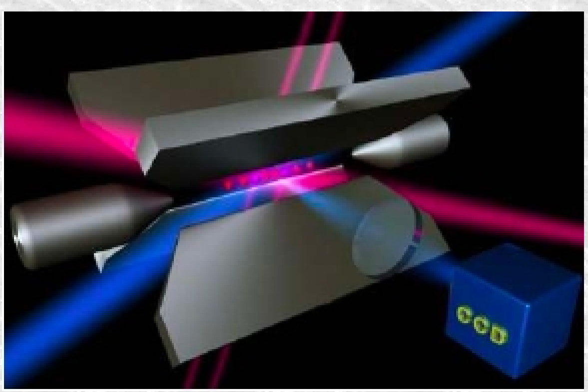
Driven quantum systems



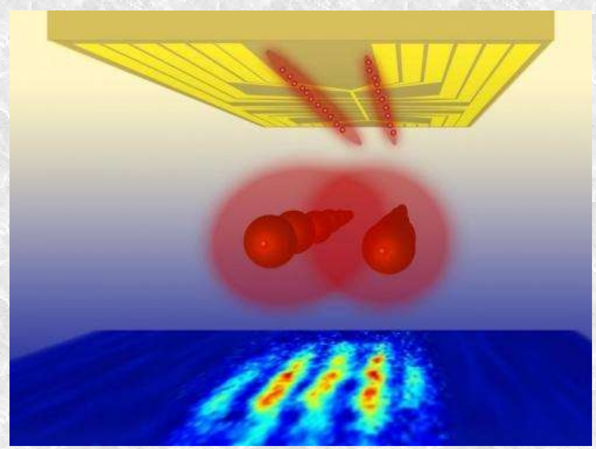
Superconducting circuits



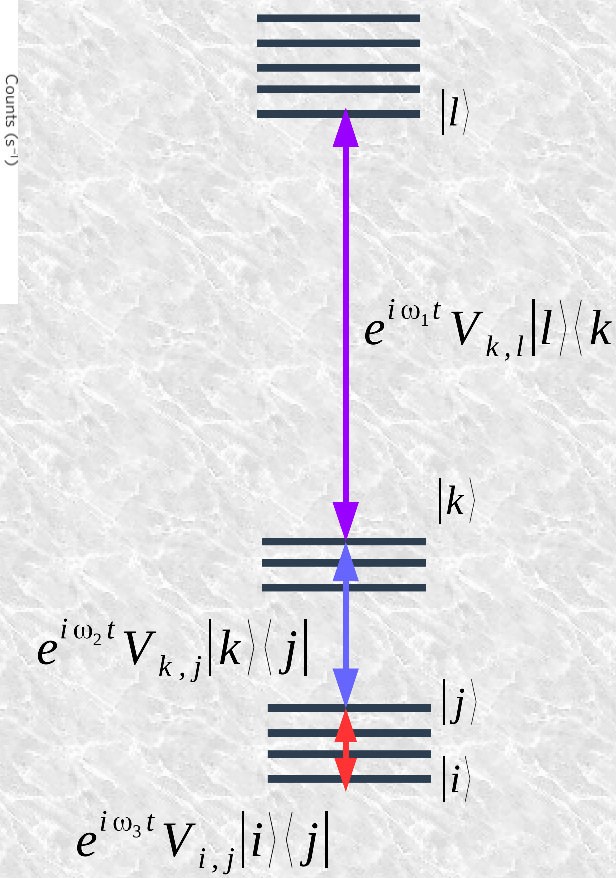
Diamond NV-centres



Trapped ions



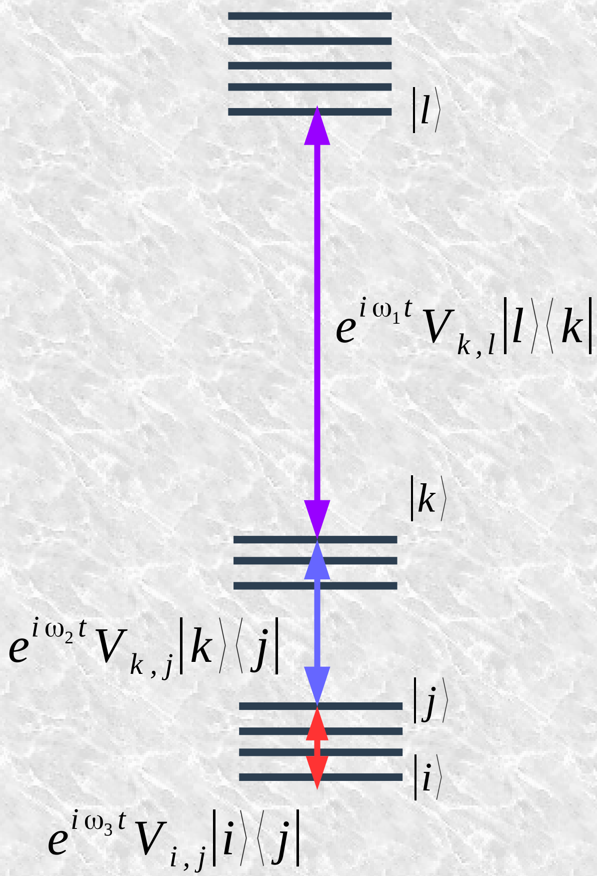
Cold atoms



Electromagnetic Induced Transparency

Multimode Floquet expansion

https://github.com/gsinuco/MultimodeFloquet



$$H = \sum_i E_i |i\rangle\langle i| + \sum_l \sum_n \sum_{i,j} V_{ij} e^{n\omega_l t} |i\rangle\langle j| + h.c.$$

To find the time-evolution operator, we build a unitary transformation that takes the Hamiltonian to a time-independent and diagonal form, i.e.:

$$\bar{H} = U_F^\dagger H U_F - i\hbar U_F^\dagger \partial_t U_F = \sum_\lambda \lambda |\lambda\rangle\langle\lambda|$$

The harmonic dependence of the driving let us to find this unitary transformation using the Fourier decomposition:

$$U_F(t) = \sum_{\vec{n},i,\lambda} e^{i\vec{n}\cdot\vec{\omega}t} u_{i\lambda}^{\vec{n}} |i\rangle\langle\lambda|$$

Multimode Floquet expansion

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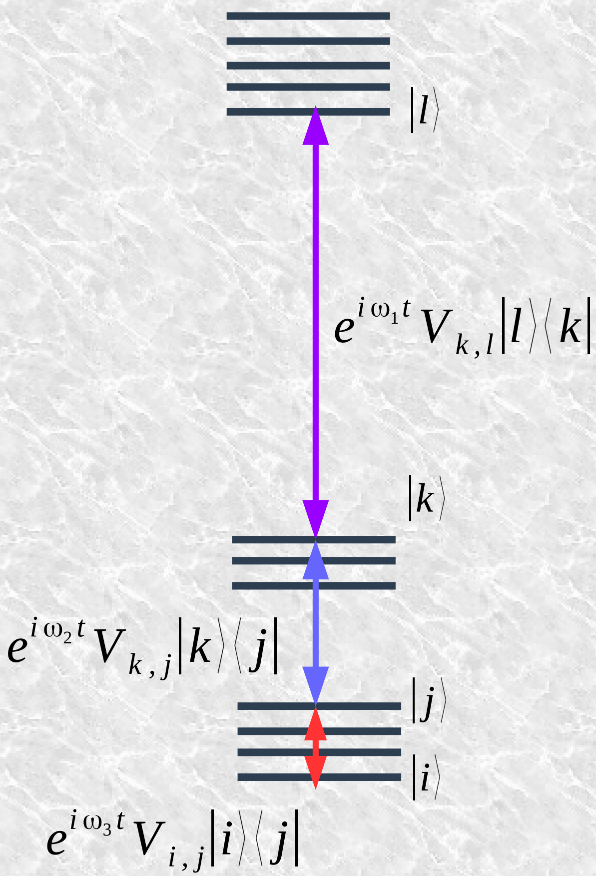


$$\bar{H} = U_F^\dagger H U_F - i\hbar U_F^\dagger \partial_t U_F = \sum_\lambda \lambda |\lambda\rangle\langle\lambda|$$

$$U_F(t) = \sum_{\vec{n},i,\lambda} e^{i\vec{n}\cdot\vec{\omega} t} u_{i\lambda}^{\vec{n}} |i\rangle\langle\lambda|$$

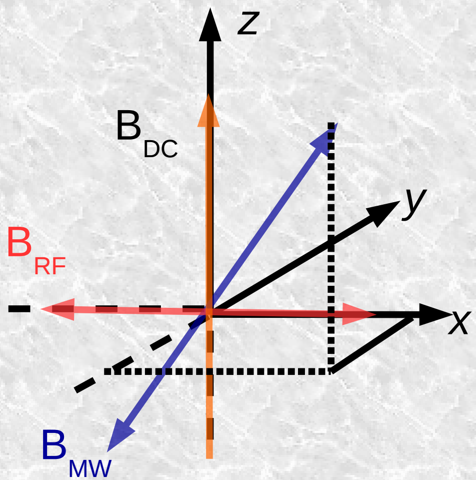
Finally, we can obtain the time-evolution operator in the original static basis using:

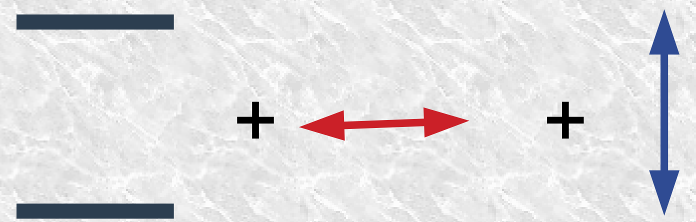
$$U(t',t) = U_F(t') \sum_\lambda e^{-i\lambda(t'-t)} |\lambda\rangle\langle\lambda| U_F^\dagger(t)$$

openMMF: A FORTRAN/C++ library for multimode driven quantum systems

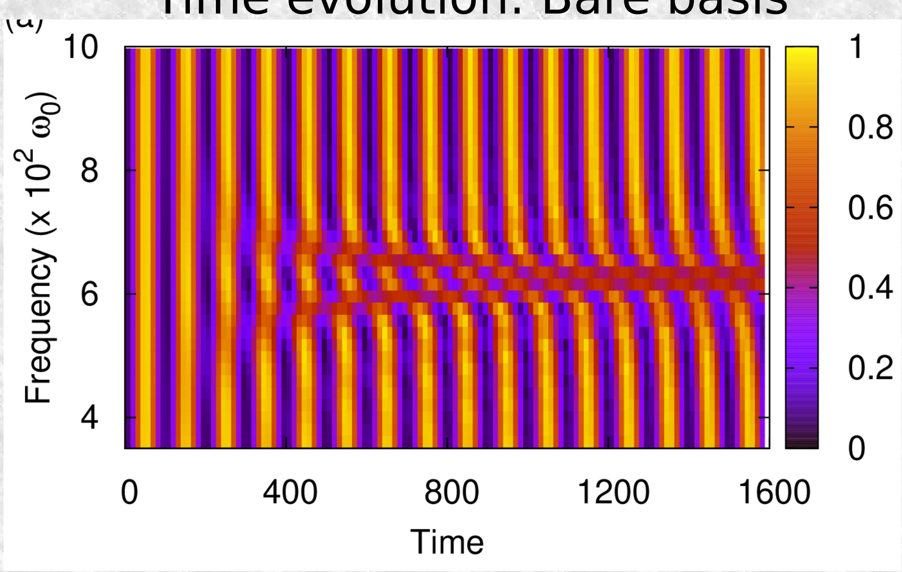
https://github.com/gsinuco/MultimodeFloquet

Example: driven qubit

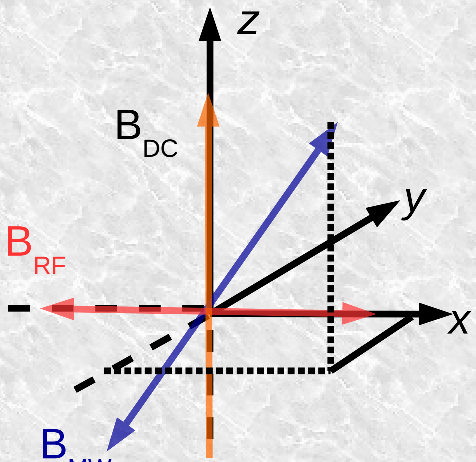


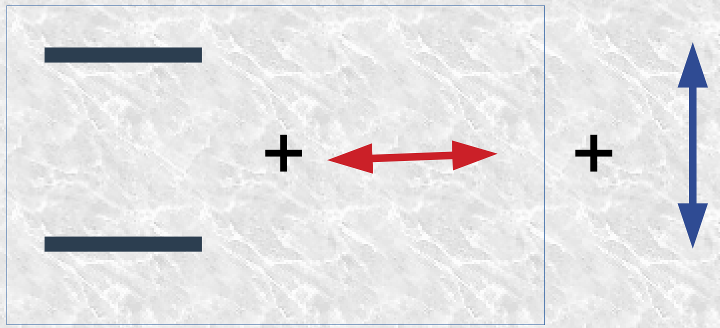


Time evolution: Bare basis

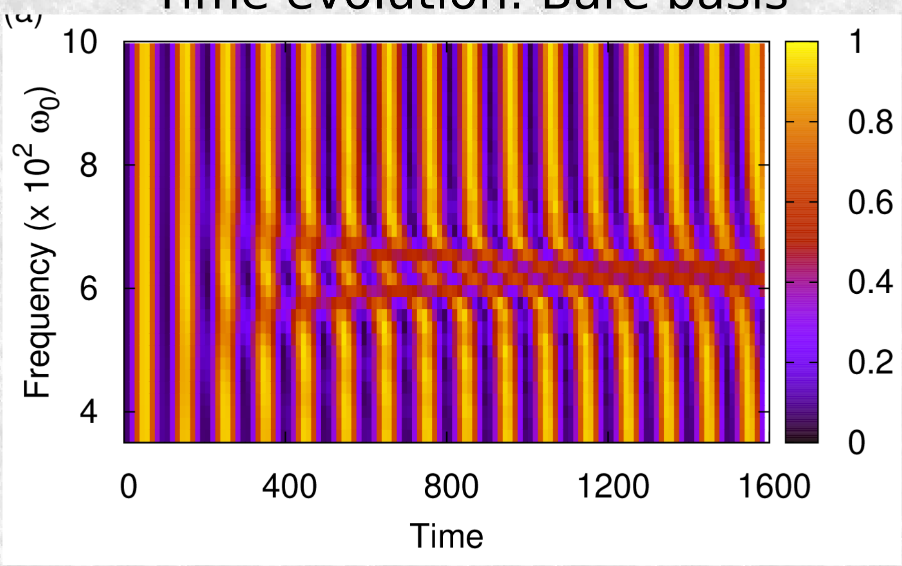


Example: driven qubit

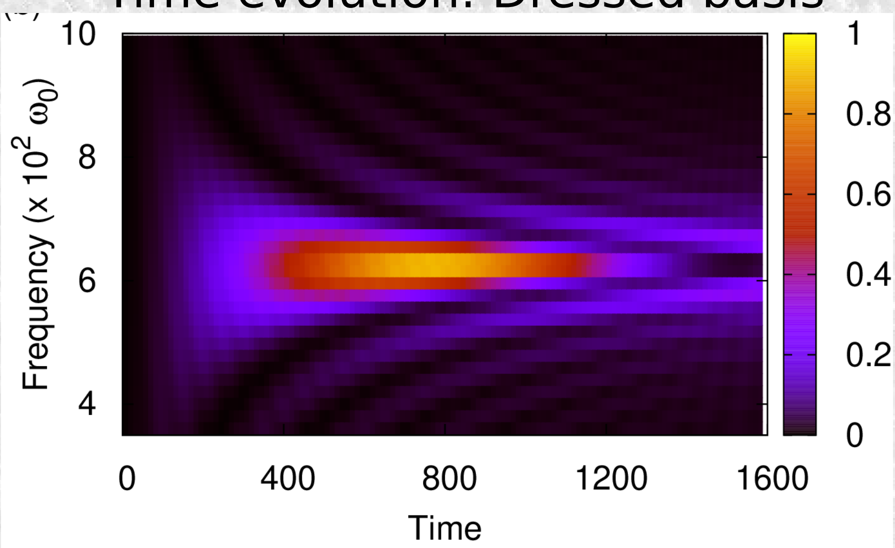




Time evolution: Bare basis

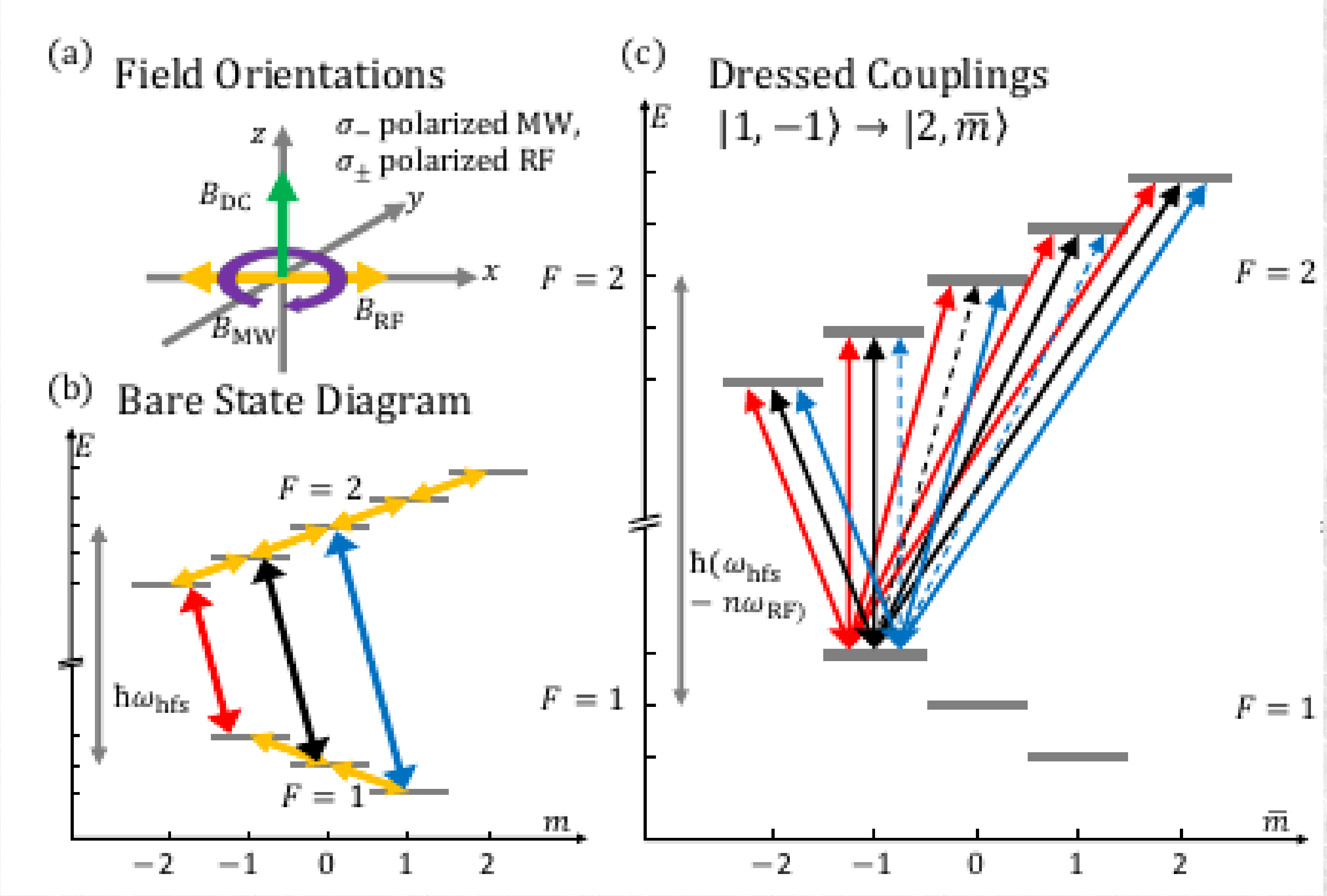


Time evolution: Dressed basis



Driving 87Rb with MW and RF fields: spectroscopy

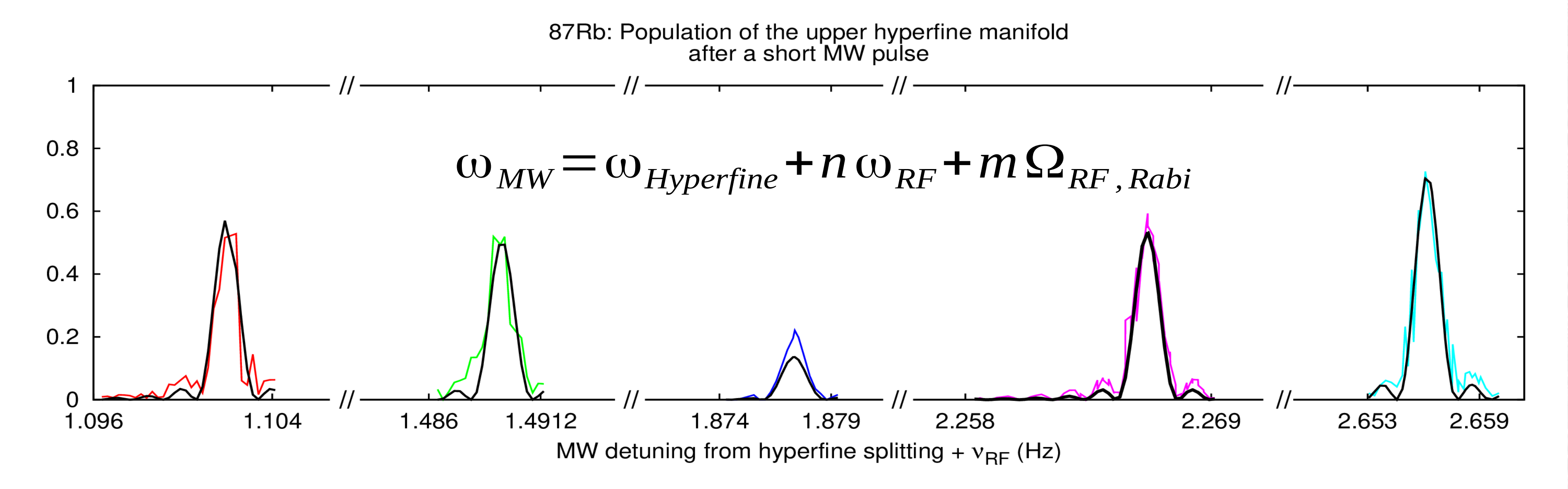
We study the response of 87Rb dressed by a strong radio frequency field and driven by a weak microwave field.



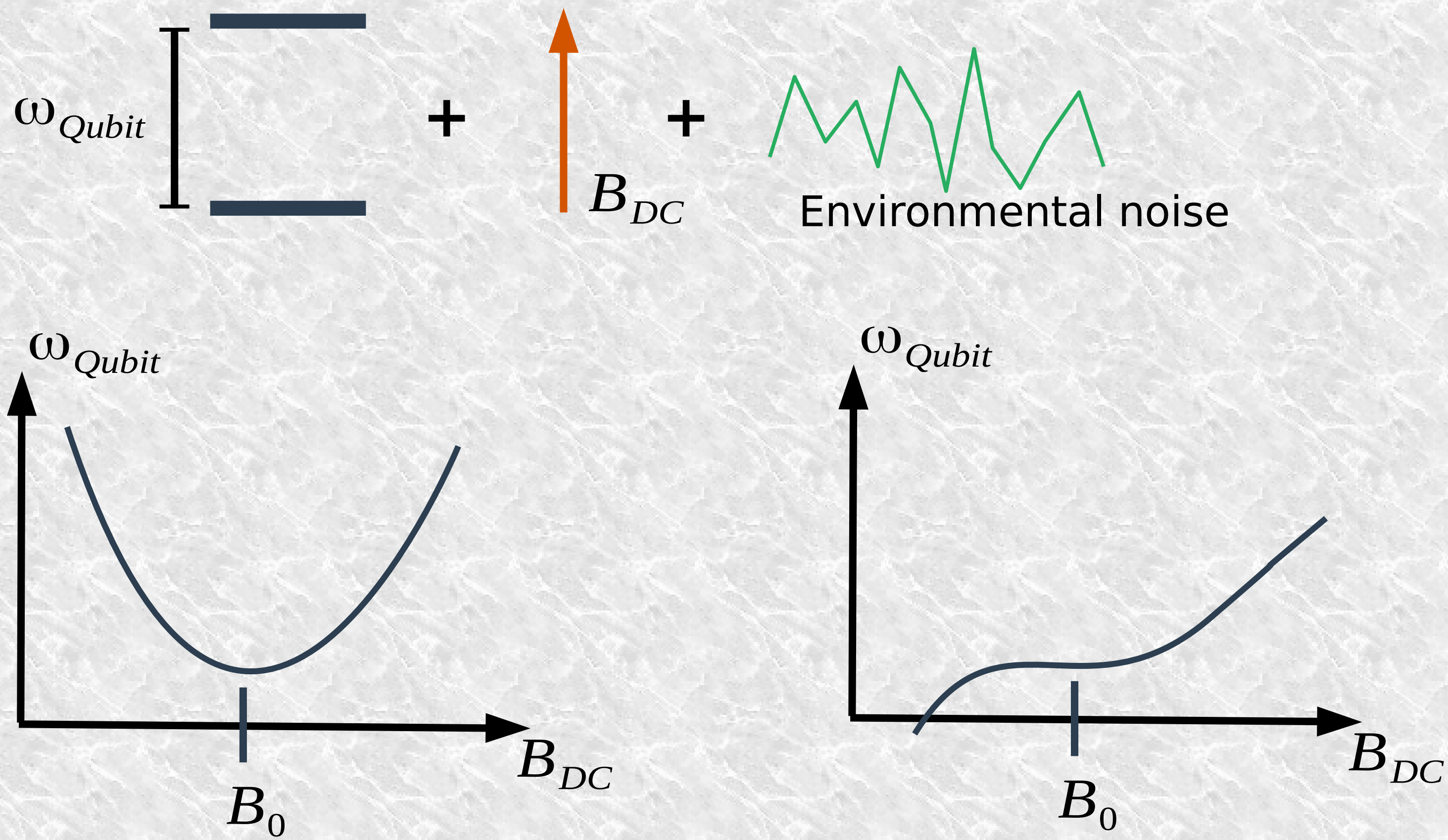
Driving 87Rb with MW and RF fields: spectroscopy

We study the response of 87Rb dressed by a strong radio frequency field and driven by a weak microwave field.

Initially, an ultracold atomic ensemble is prepared in the RF-dressed state |1,-1>. Afterwards, a short MW pulse is applied and we measure the fraction of atoms transferred to the upper hyperfine manifold. This procedure is repeated scanning the MW frequency and we compare numerical against experimental data. *arXiv:1904.12073*



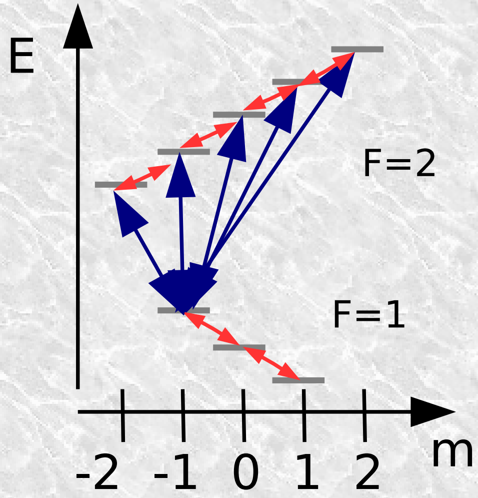
Driving 87Rb with two RF fields: Protected microwave q*d*its



L. Sárkány, P. Weiss, H. Hattermann, and J. Fortágh, PRA **90**, 053416 (2014). (MW dressing)
G. A. Kazakov and T. Schumm, PRA **91**, 023404 (2015). (RF dressing)

Driving 87Rb with two RF fields: Protected microwave q*d*its

Can we reduce the sensitivity of more than one transition?



$$\omega_{\sigma_P} = \mu_B g_2 B_{DC}$$
$$\omega_{\sigma_M} = \mu_B |g_1| B_{DC}$$

RWA →

$$\alpha_{m,m'} := \frac{\partial \Delta E_{m,m'}}{\partial B_{DC}} = 0$$

$$\frac{B_{RF}^{\sigma_P}}{B_{RF}^{\sigma_M}} = \frac{m' \, sign(g_2)}{m \, sign(g_1)} \left| \frac{g_2}{g_1} \right|$$

RWA →

$$\alpha_{m,m'}^{(2)} := \frac{\partial^2 \Delta E_{m,m'}}{\partial B_{DC}^2} = 0$$

but...

Driving 87Rb with two RF fields: Protected microwave q*d*its

Can we reduce the sensitivity of more than one transition?

$B_{RF}^{\sigma_P}, \omega_{\sigma_P}$ → Off-resonant energy shift of the F=1 manifold

+

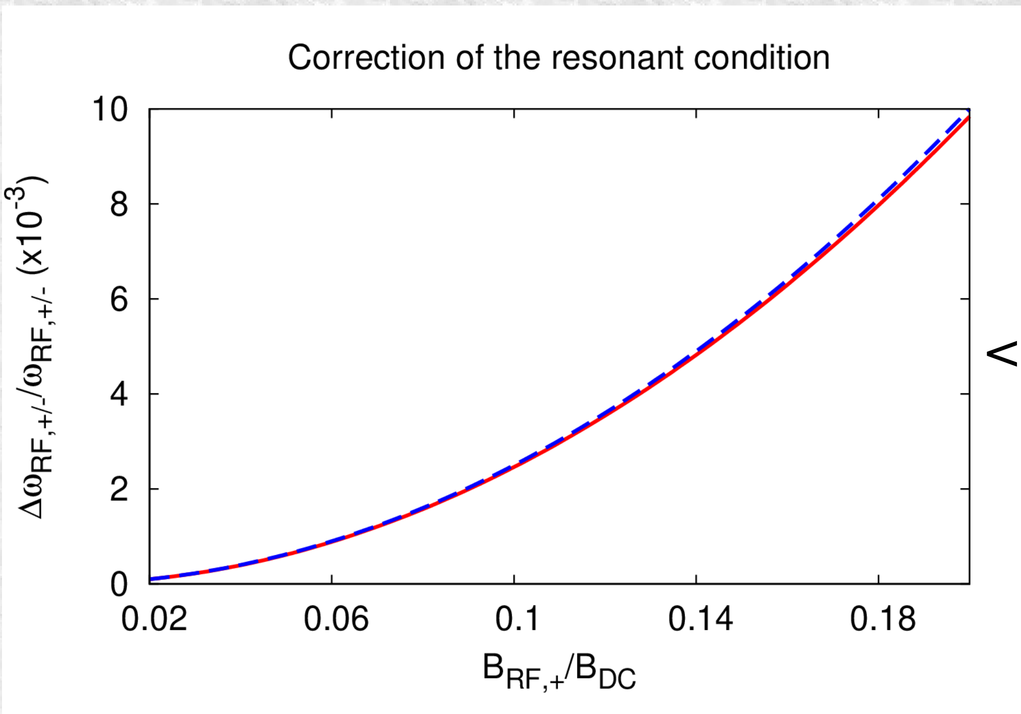
$B_{RF}^{\sigma_M}, \omega_{\sigma_M}$ → Off-resonant energy shift of the F=2 manifold

+

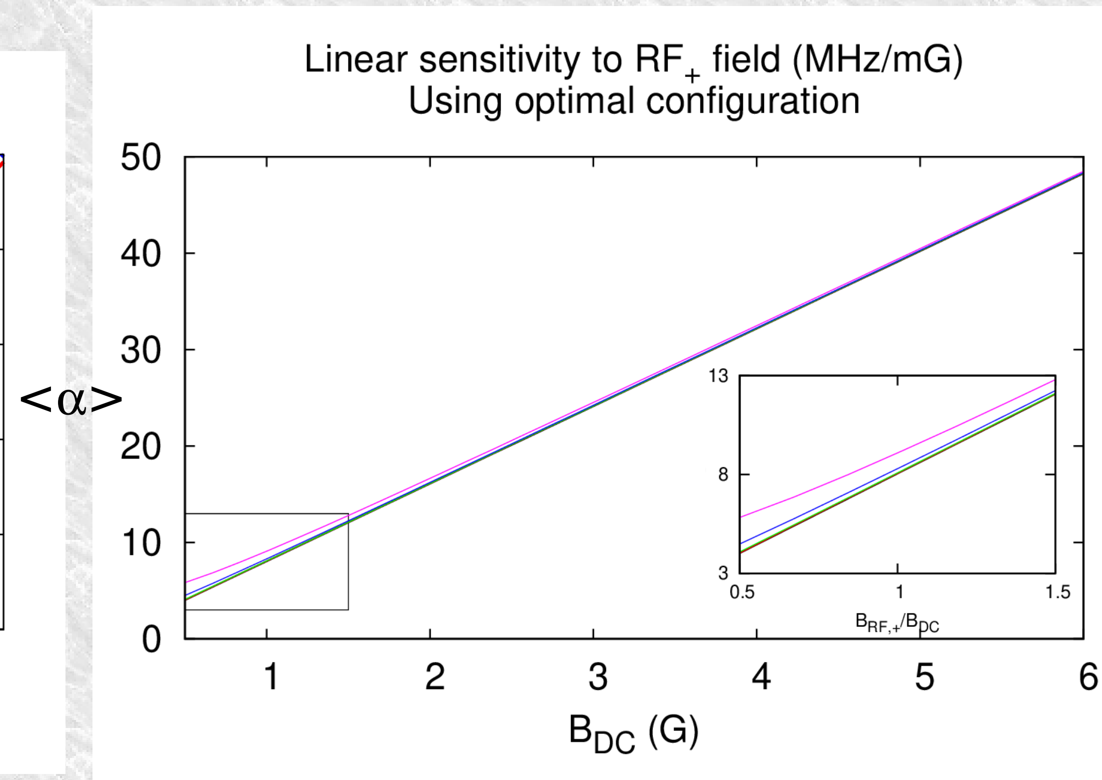
Non-Linear Zeeman Shift

Driving 87Rb with two RF fields: Protected microwave q*d*its

Can we reduce the sensitivity of more than one transition?



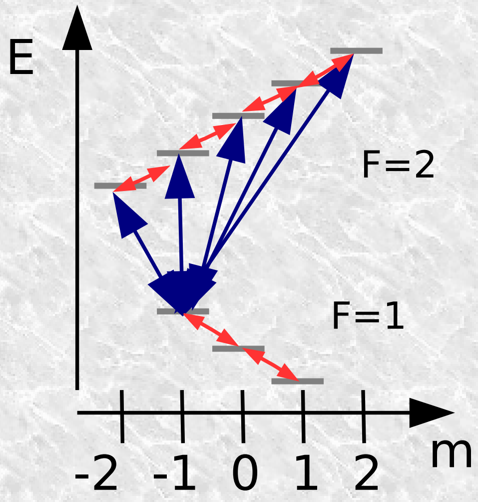
$$\omega_{\sigma_P} \rightarrow \mu_B g_2 B_{DC} + \Delta\omega_{\sigma_P}$$



Driving 87Rb with two RF fields: Protected microwave q*d*its

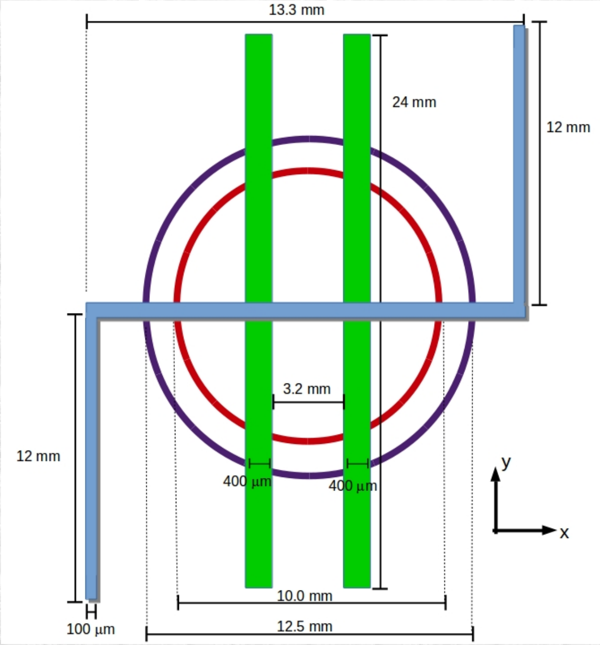
Can we reduce the sensitivity of more than one transition?

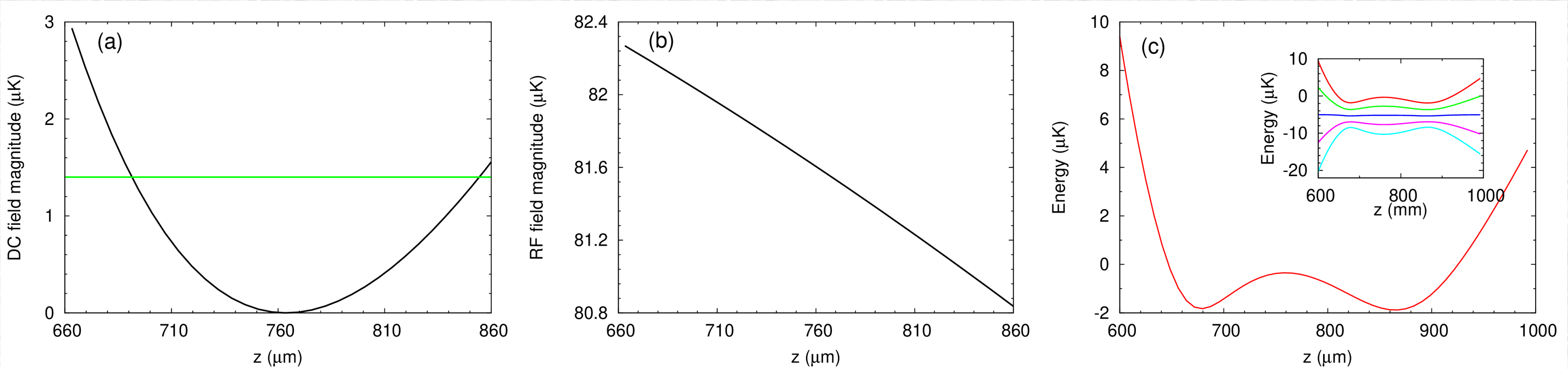
Fractional fluctuations of the transition frequency from the state |1,-1> to the F=2 manifold, assuming DC and RF fields with noise of amplitude 0.1mG.



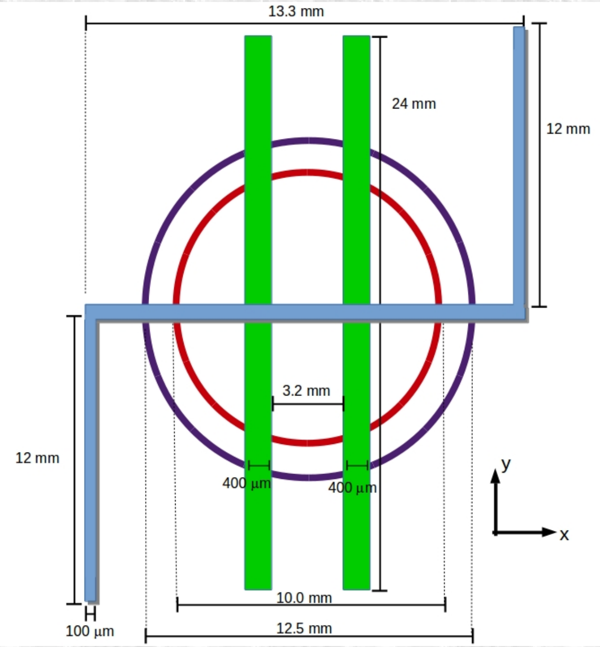
B_{DC}	$F=2$ state	Bare	RF	RF x 2	Opt. RFx2
3.2 (G)	$\|2,-2\rangle$	3×10^{-7}	5×10^{-9}	7×10^{-9}	2×10^{-10}
	$\|2,-1\rangle$	2×10^{-7}	4×10^{-9}	4×10^{-9}	4×10^{-10}
	$\|2,0\rangle$	9×10^{-8}	4×10^{-9}	2×10^{-9}	4×10^{-10}
	$\|2,1\rangle$	4×10^{-12}	3×10^{-9}	3×10^{-10}	4×10^{-10}
	$\|2,2\rangle$	9×10^{-8}	3×10^{-9}	2×10^{-9}	2×10^{-10}

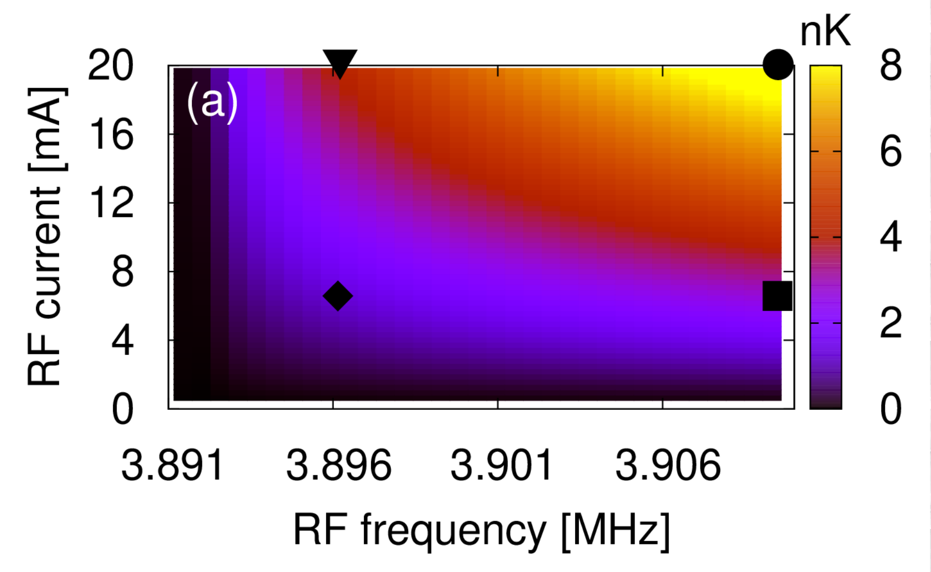
MW +RF dressed adiabatic landscapes

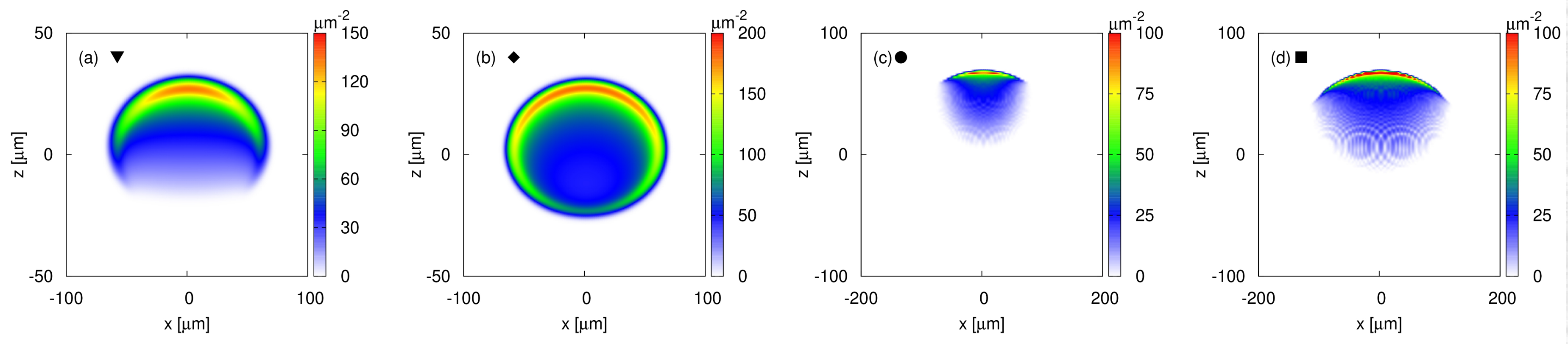




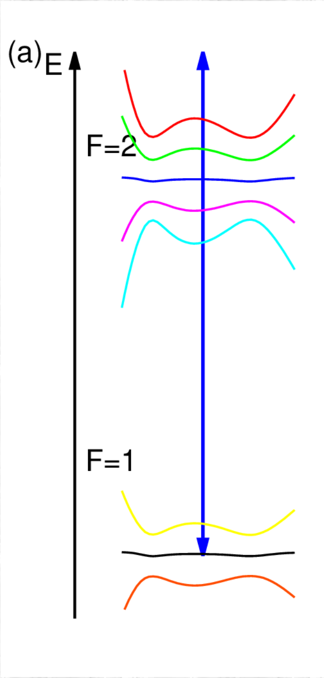
MW +RF dressed adiabatic landscapes

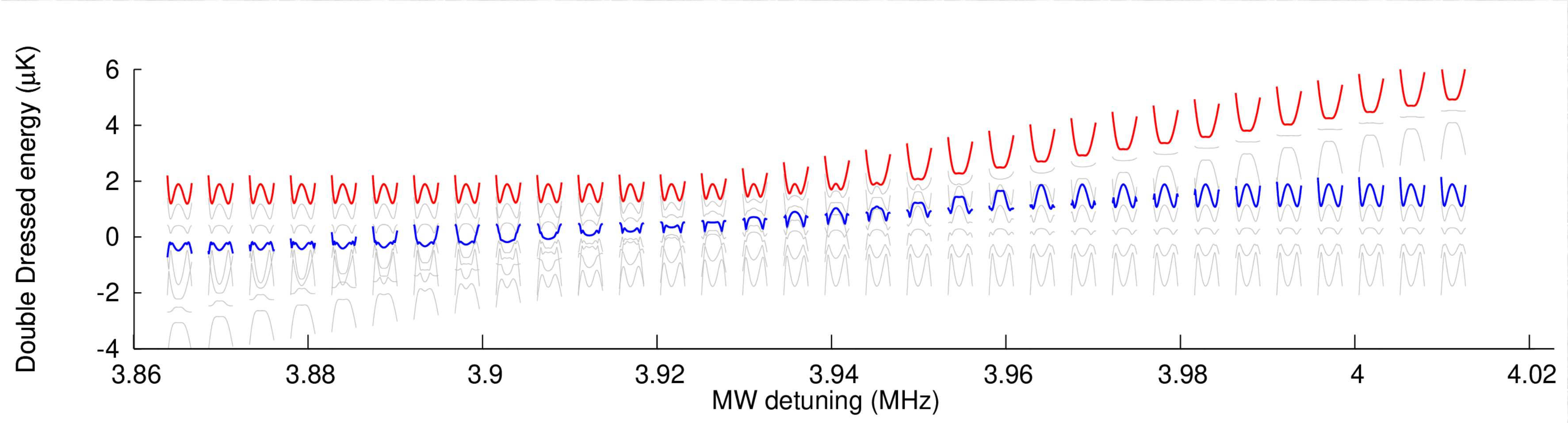




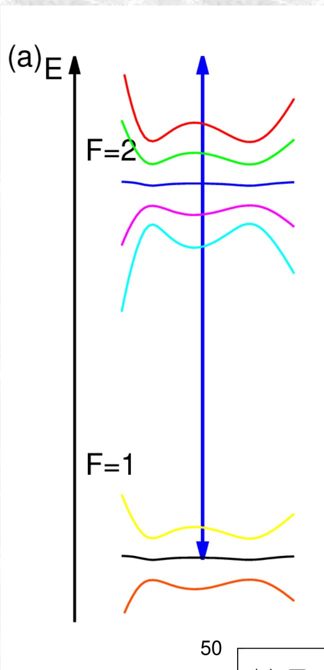


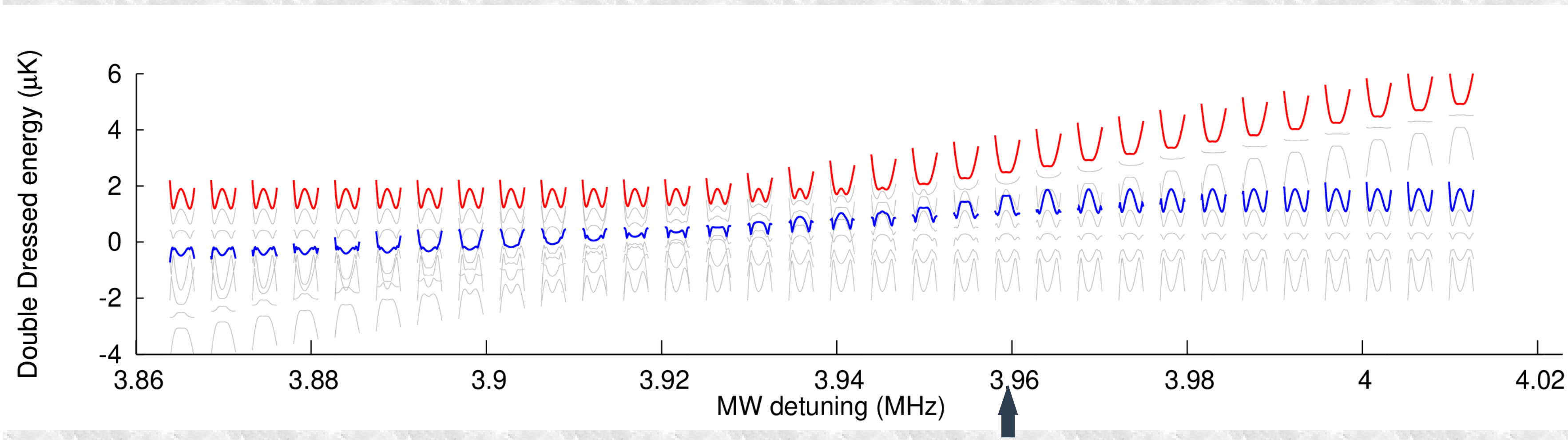
MW +RF dressed adiabatic landscapes

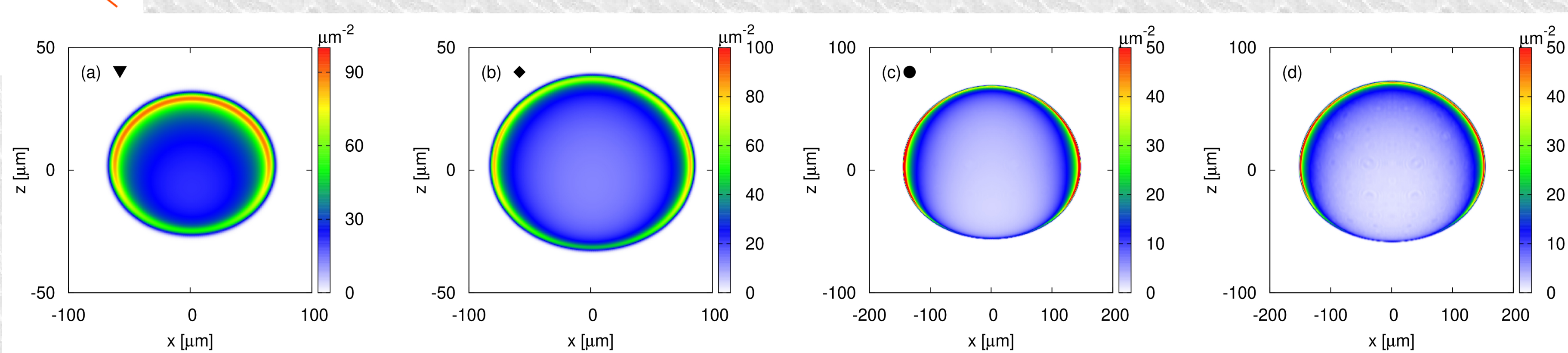




MW +RF dressed adiabatic landscapes

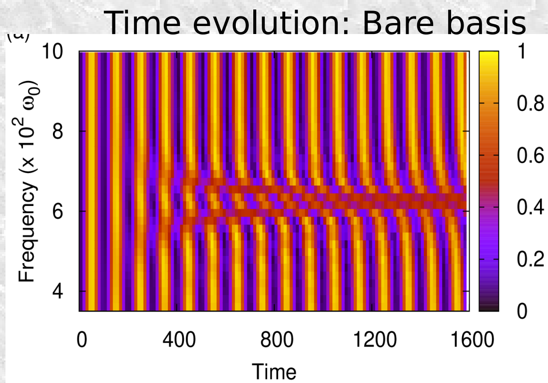




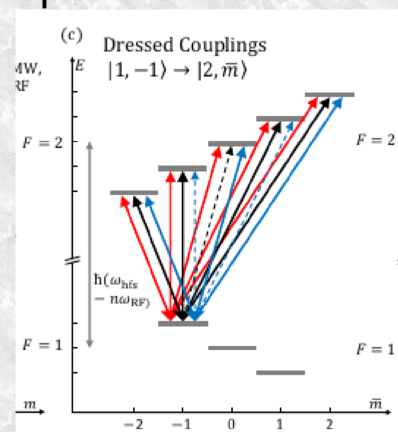


Outlook

Multimode expansion of the time evolution



Microwave spectrum of RF dressed 87Rb



Bichromatic RF dressing to define qudits

B_{DC}	$F = 2$ state	Bare	RF	RF x 2	Opt. RFx2
	$\|2,-2\rangle$	3×10^{-7}	5×10^{-9}	7×10^{-9}	2×10^{-10}
	$\|2,-1\rangle$	2×10^{-7}	4×10^{-9}	4×10^{-9}	4×10^{-10}
3.2	$\|2,0\rangle$	9×10^{-8}	4×10^{-9}	2×10^{-9}	4×10^{-10}
(G)	$\|2,1\rangle$	4×10^{-12}	3×10^{-9}	3×10^{-10}	4×10^{-10}
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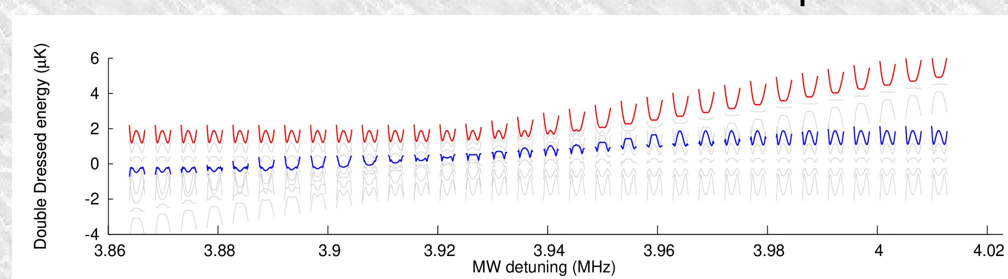
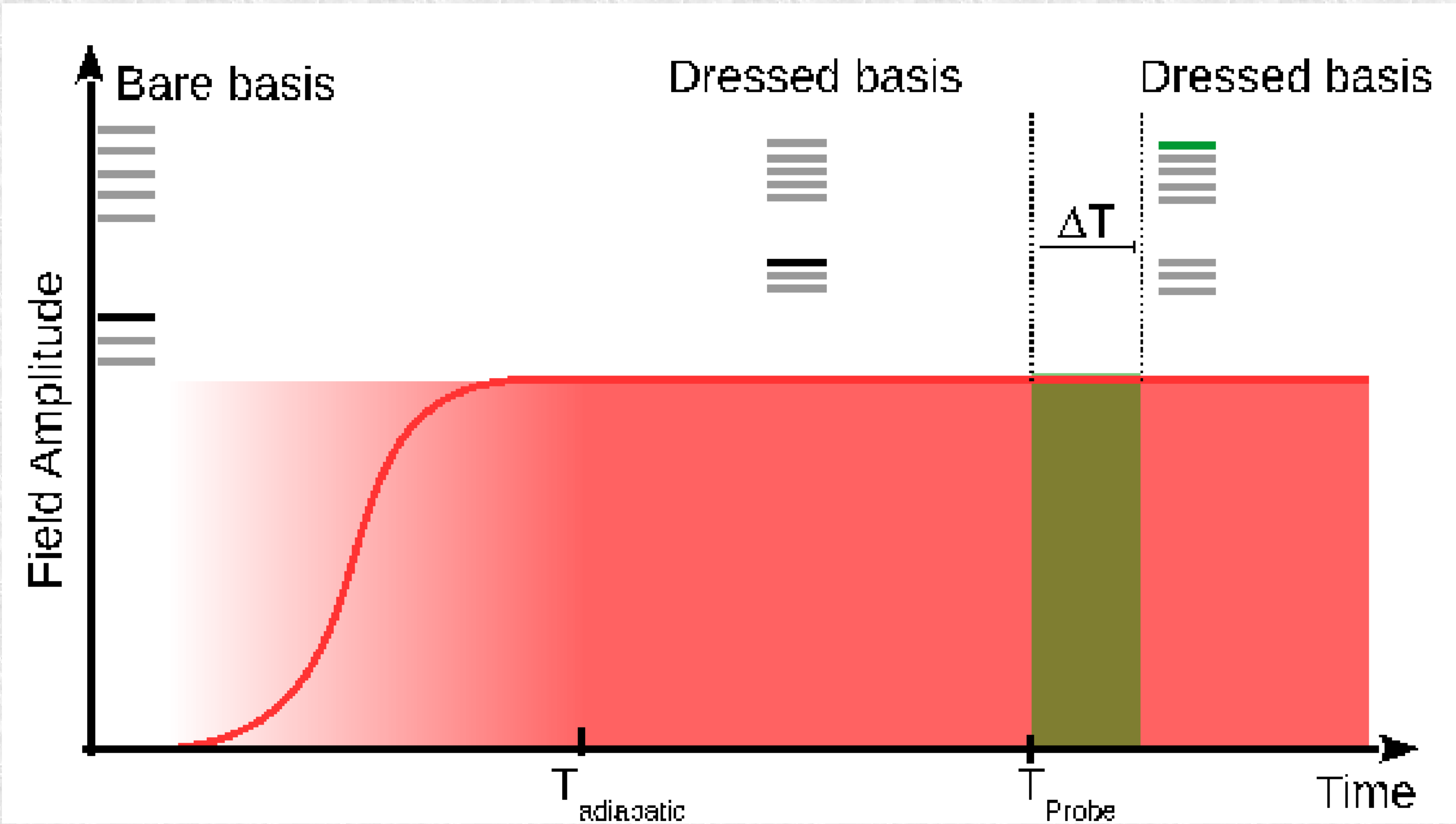
RF+MW dressed adiabatic landscapes



Multimode dressed states



Typical time sequence to prepare and probe dressed states. The dressing modes are adiabatically switched on and kept constant during the probing period.