Motional Spin-Locking Spectroscopy

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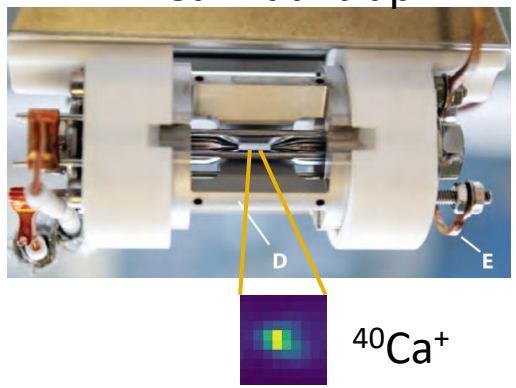
Characterization of noise is important

Linear Paul trap



$^{40}Ca^+$

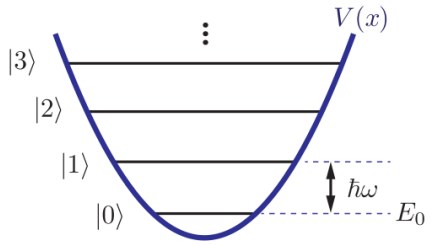
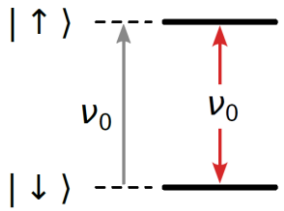


Fig.: C. Hempel, thesis (2014)

Single-qubit gate



Narrow-linewidth laser at 729 nm
$\Delta\nu \approx 10$ Hz

Two-qubit gate

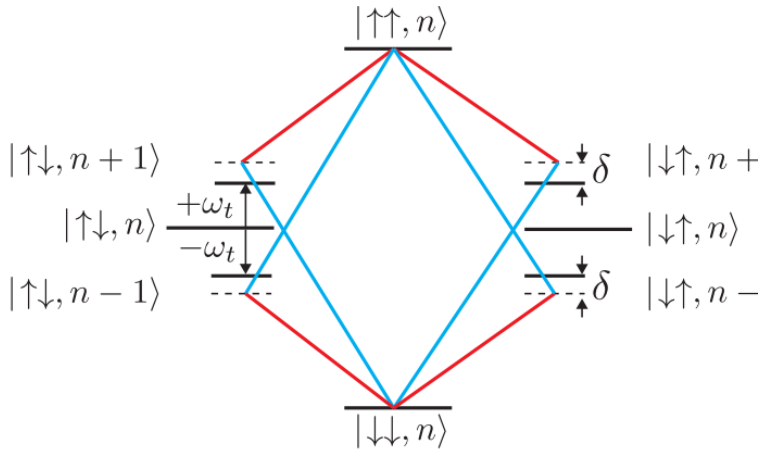


Fig.: C. Hempel, thesis (2014)

Motional modes of the trap become relevant

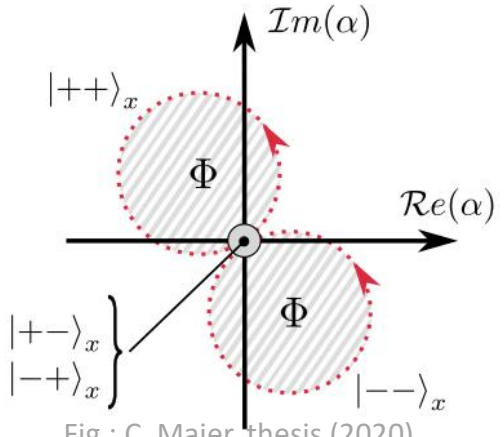
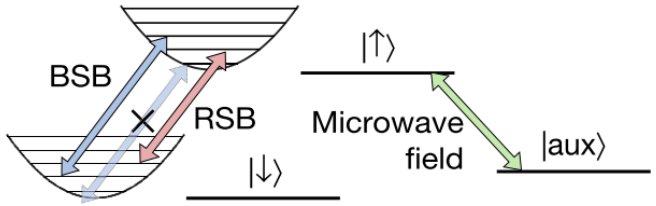


Fig.: C. Maier, thesis (2020)

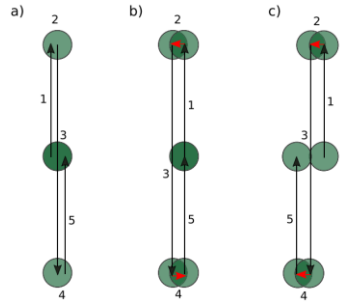
Variety of methods exists

Ramsey experiments on Fock-state superpositions



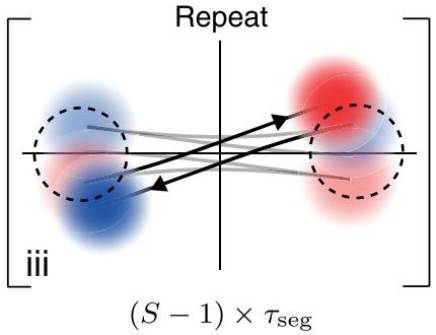
K. C. McCormick et al., Nature **572**, 86 (2019)

Motional spin-echo experiments on displaced coherent states



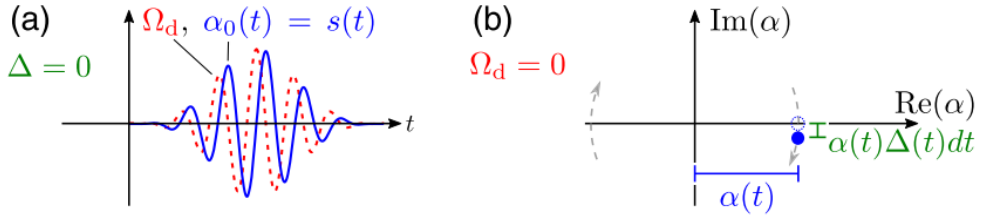
K. C. McCormick et al., Qu. Sc. Tech. **4**, 024010 (2019)

CPMG-type experiments on displaced cat states



A. R. Milne et al., Phys. Rev. Lett. **126**, 250506 (2021)

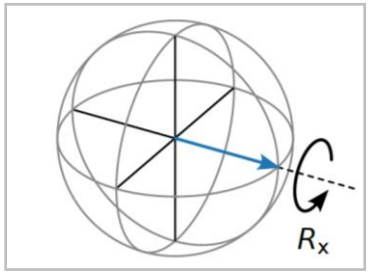
Response measurements to modulated periodic drives

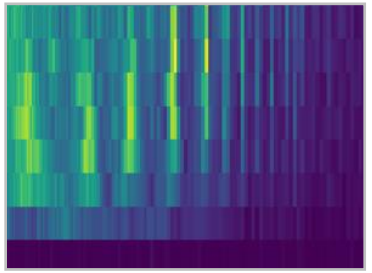


J. Keller et al., Phys. Rev. Lett., **126**, 250507 (2021)

1. Spin locking

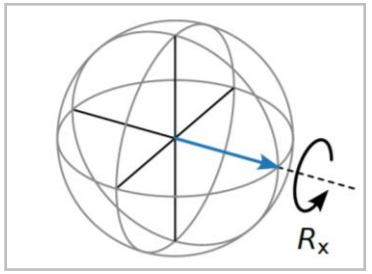
2. Motional spin-locking

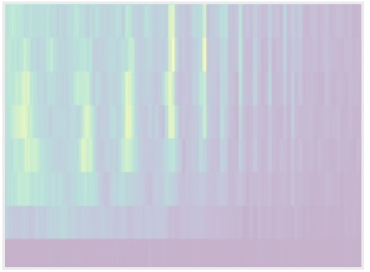




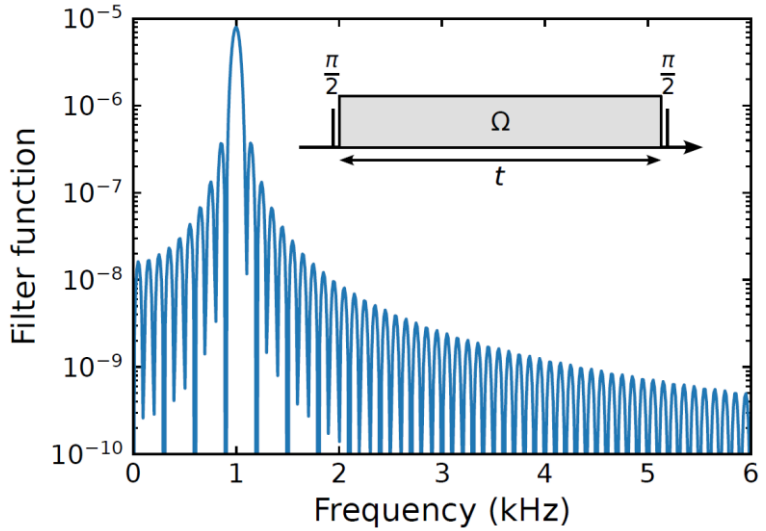
1. Spin locking

2. Motional spin-locking



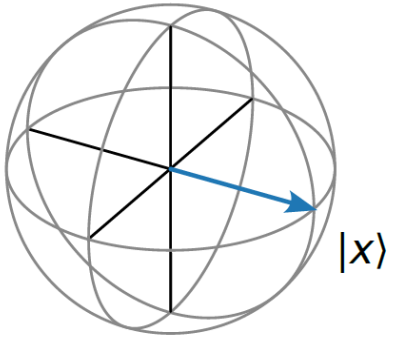


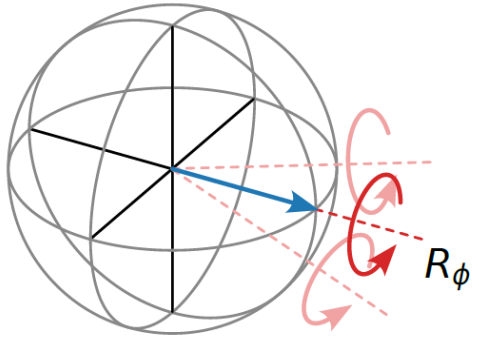
Spin-locking experiment – Basic idea

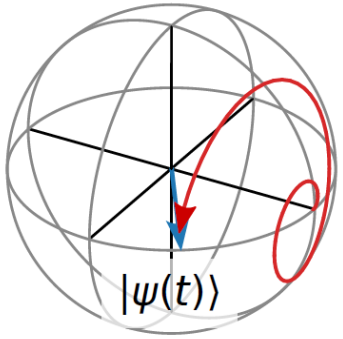


Filter function becomes a simple δ-peak!

Modulated drive evolves the spin







$$\phi(t) = \beta \cos(\omega_m t)$$

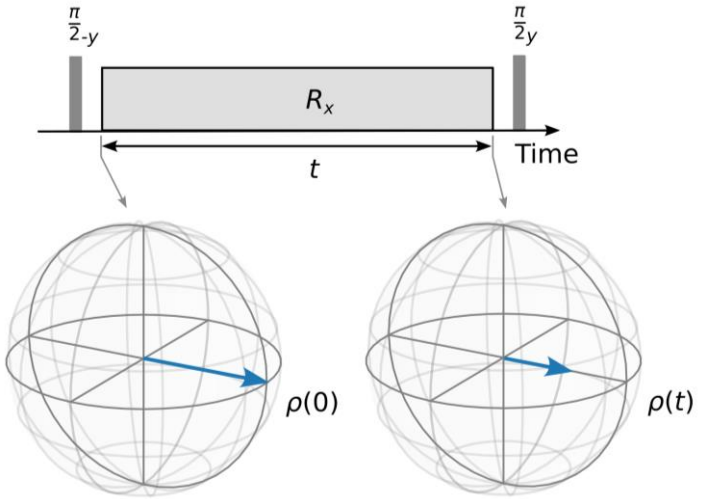
Condition:

$$\Omega = \omega_m$$

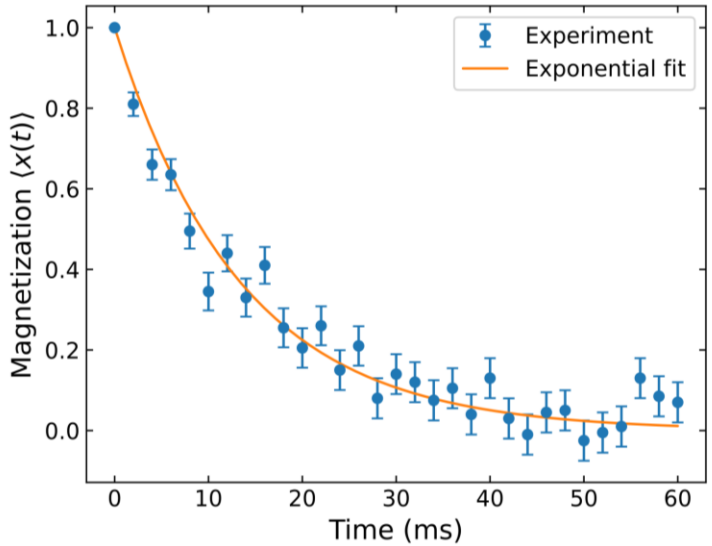
Rabi freq. = mod. freq.

Spin-locking experiment under noise

Experimental sequence

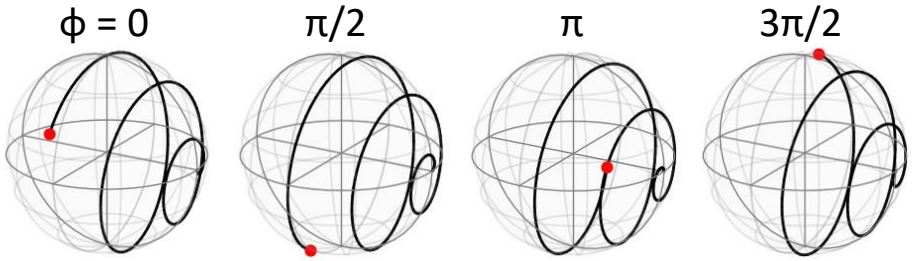


Spectroscopic signal



$$\langle \sigma_x(t) \rangle = \mathrm{e}^{-\frac{1}{2}\Omega^2 S_\phi(\Omega) t} \langle \sigma_x(0) \rangle$$

Trajectory depends on initial light phase and power:



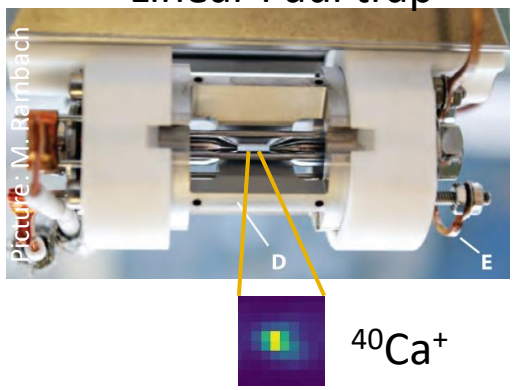
Noise averages over trajectories

Rate of decay depends on noise power spectral density $S_\phi(\Omega)$

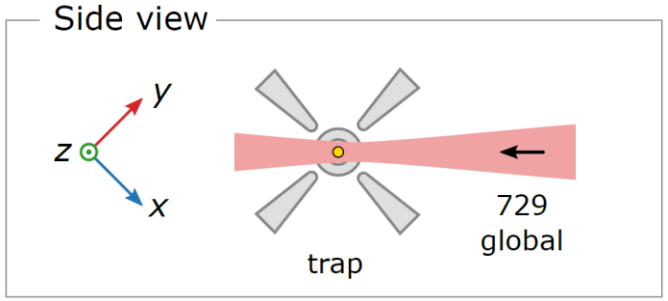
R. Kubo, J. Math. Phys. **4**, 174 (1963)

Laser noise spectrum

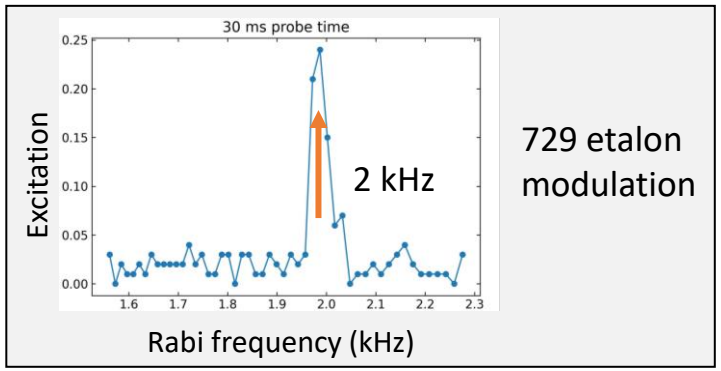
Linear Paul trap



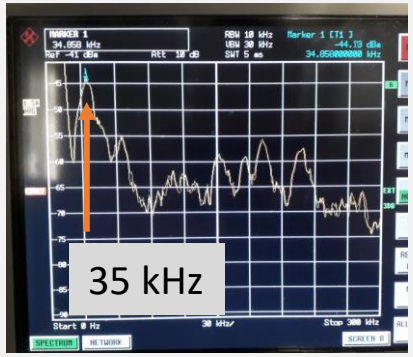
$^{40}Ca^+$



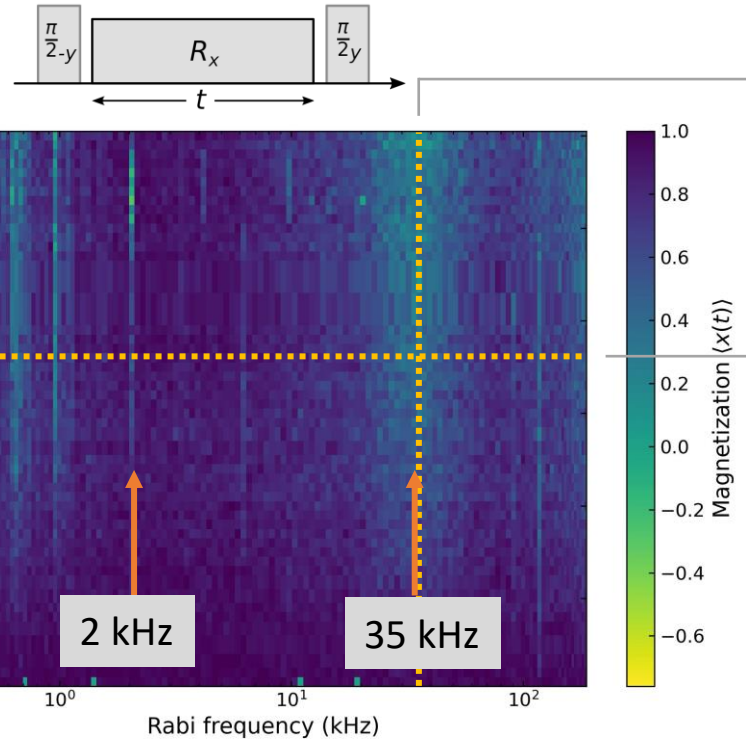
$$\nu_x = 2\pi \times 3.167\,\mathrm{MHz}$$
$$\nu_y = 2\pi \times 2.909\,\mathrm{MHz}$$



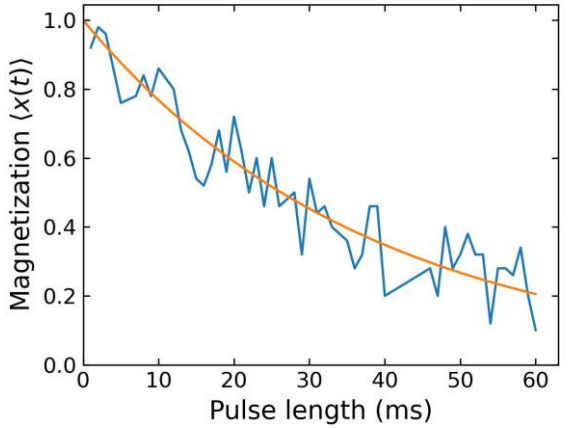
729 etalon modulation



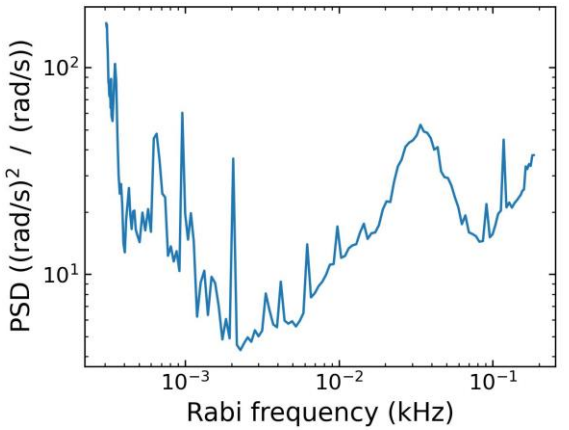
729 servo bump Error signal



Time evolution



Frequency power spectral density (PSD)



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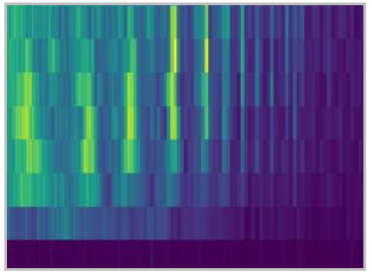
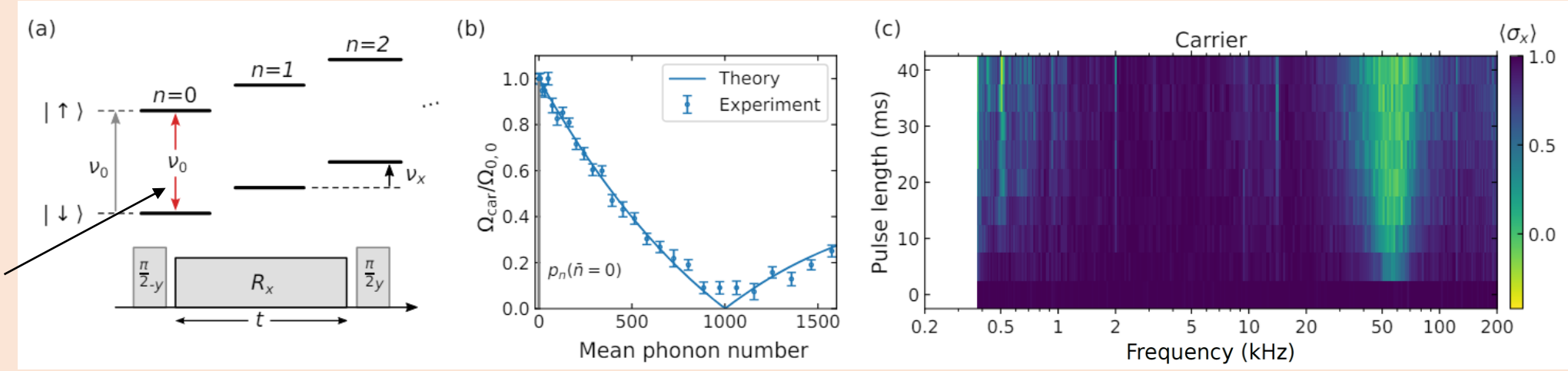
2. Motional spin-locking



Probing motional noise

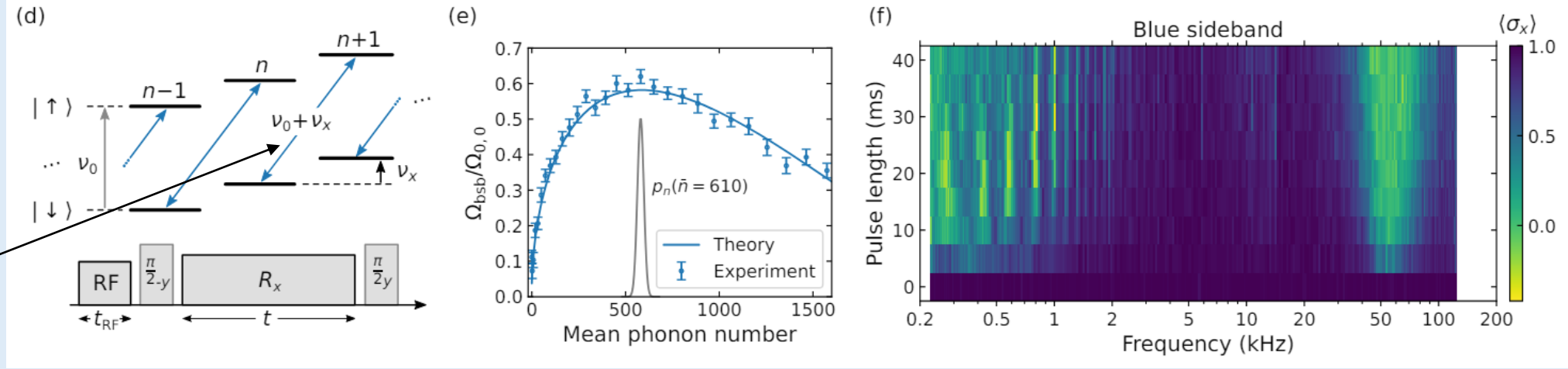
So far:
Probing noise on **carrier**

Depends on
- laser noise
- qubit noise

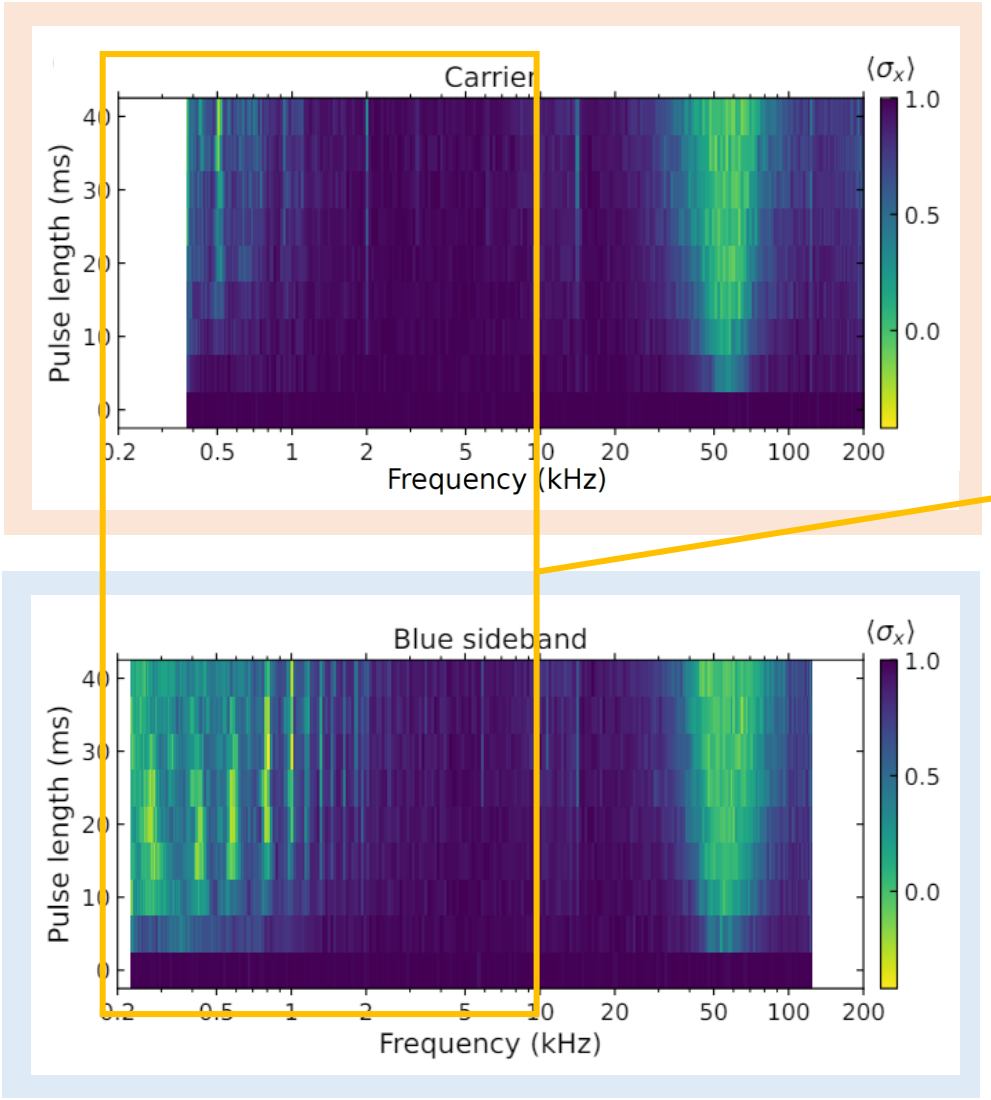


Motional noise shows up on **blue sideband**

Additionally:
- motional mode noise

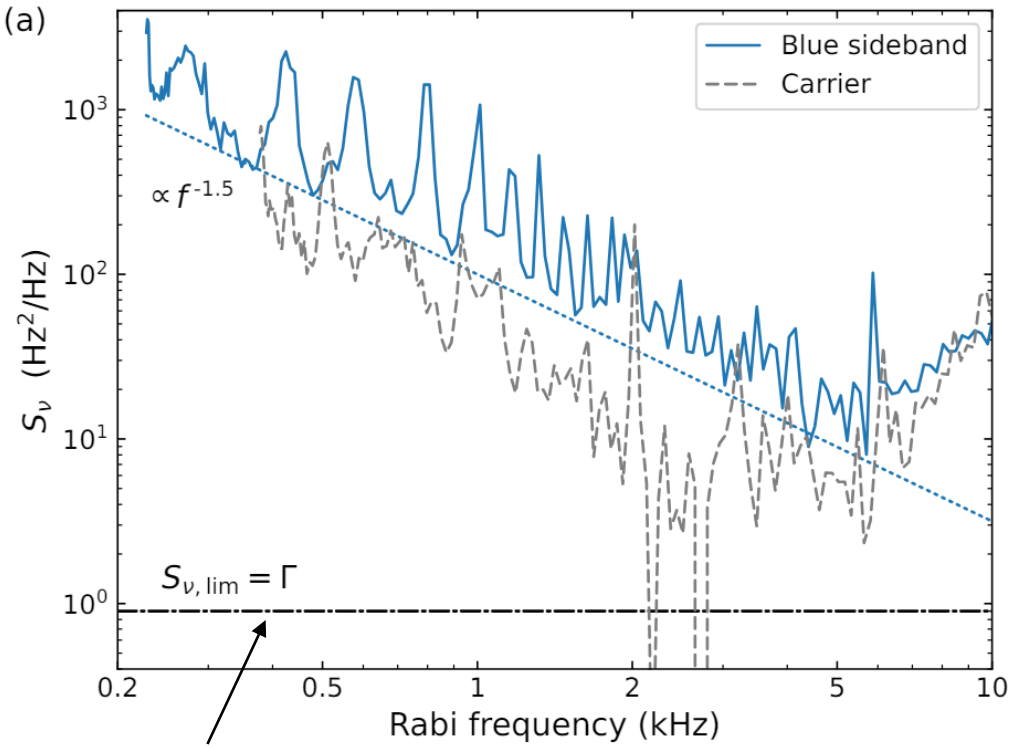


Probing motional noise



Spectroscopic signal: $\langle \sigma_x(t) \rangle = \mathrm{e}^{-\frac{1}{2}\Omega^2 S_\phi(\Omega) t} \langle \sigma_x(0) \rangle$

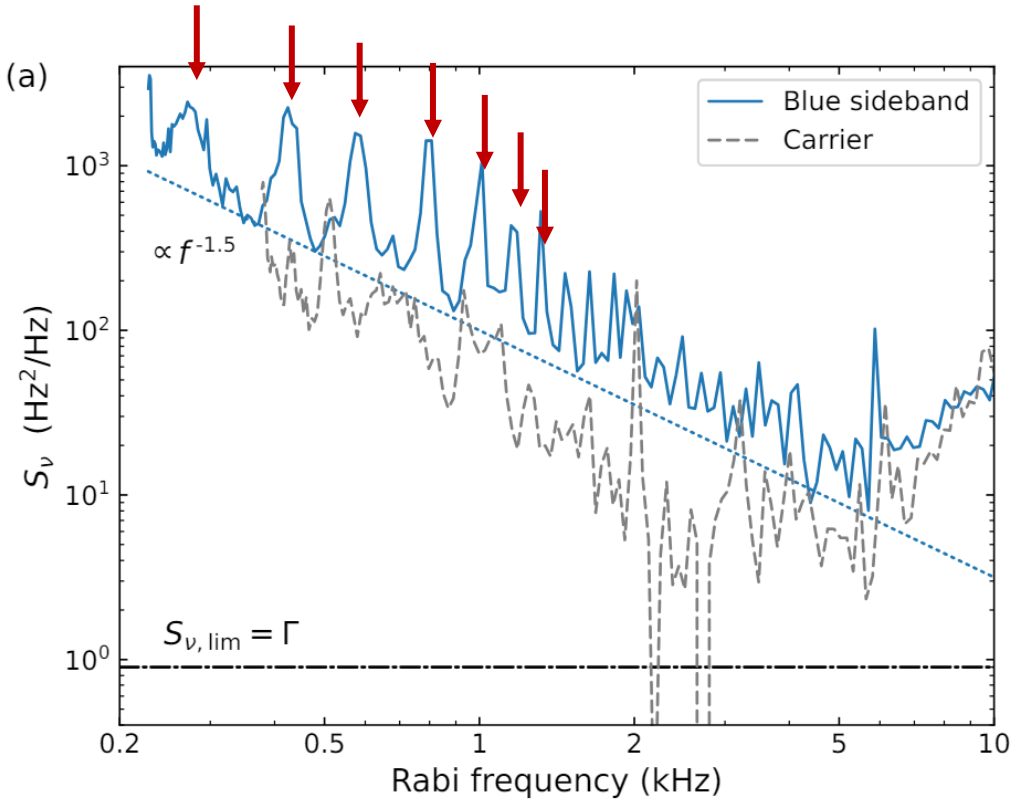
Frequency noise ↔ phase noise: $S_\nu(\omega) = \omega^2 S_\phi(\omega)$



Lower limit of sensitivity is given by spontaneous decay of the excited state ($^{40}Ca^+$: $\Gamma \approx 0.9\ s^{-1}$)

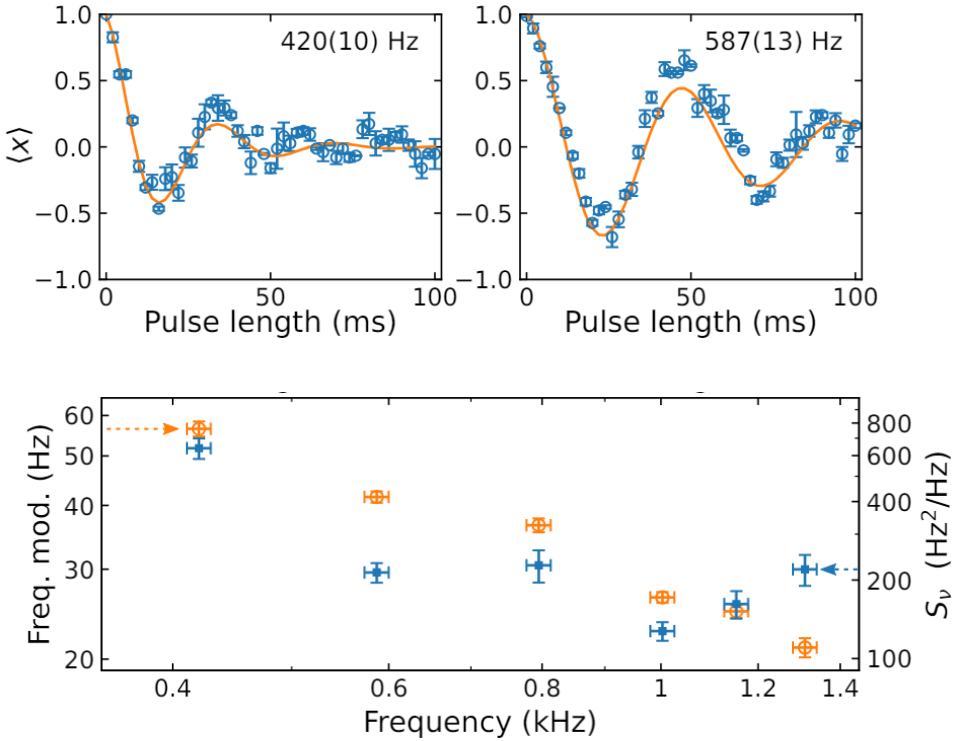
Motional noise spectrum

Partially coherent features



Spectroscopic signal with partial coherence:

$$\langle \sigma_x(t) \rangle = \cos\left(\frac{1}{2}\beta\Omega t\right) \mathrm{e}^{-\frac{1}{2}S_\nu(\Omega)t}$$



Summary

- Spin-locking spectroscopy for probing motional noise
- Uses ion directly as probe
- Direct access to noise spectrum

Acknowledgments

Quantum Simulation Experiment


M. Joshi

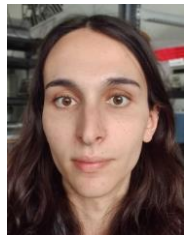

F. Kranzl


J. Franke


C. Roos


R. Blatt

École Normale Supérieure
de Lyon


A. Rospars

Blatt group