Collective dynamics in RF-dressed quantum gases

How does RF coupling enrich dynamical properties of $^{39}\mathrm{K}$ condensates ?

Alfred Hammond

Quantum gases at LCF (2022)

Tunable three-body interactions in driven two-component Bose-Einstein condensates

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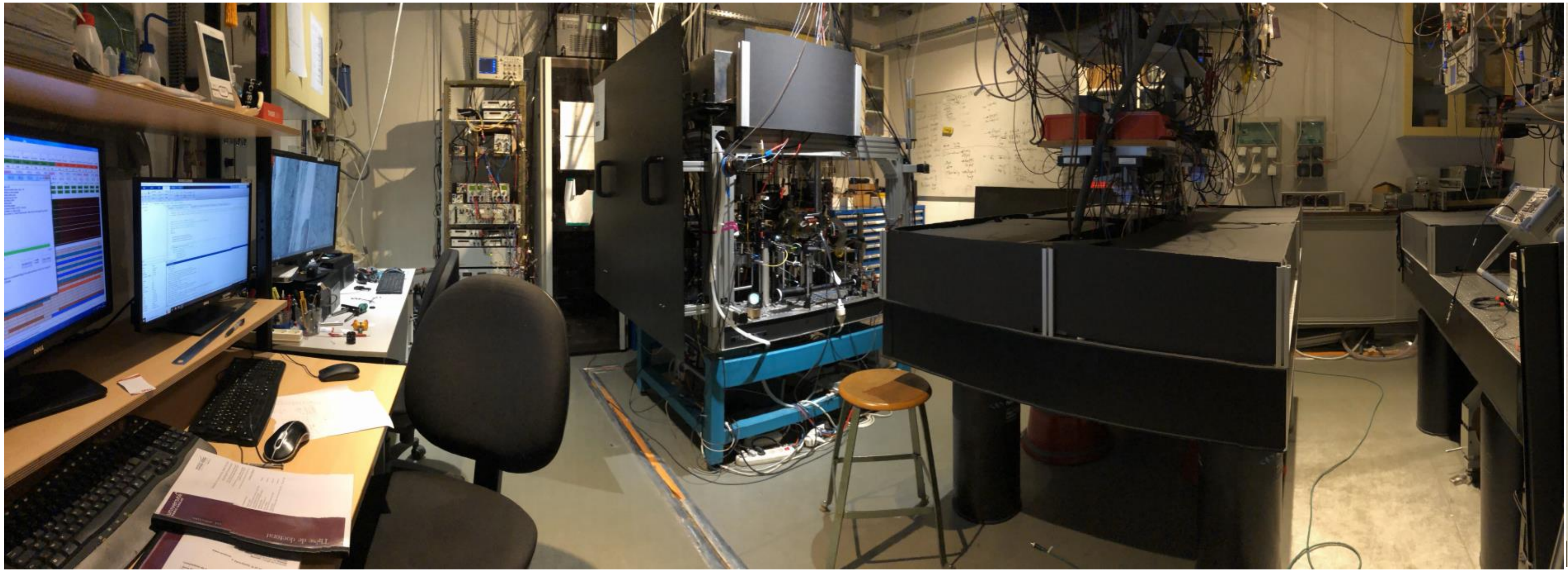
^{39}K team in 2022

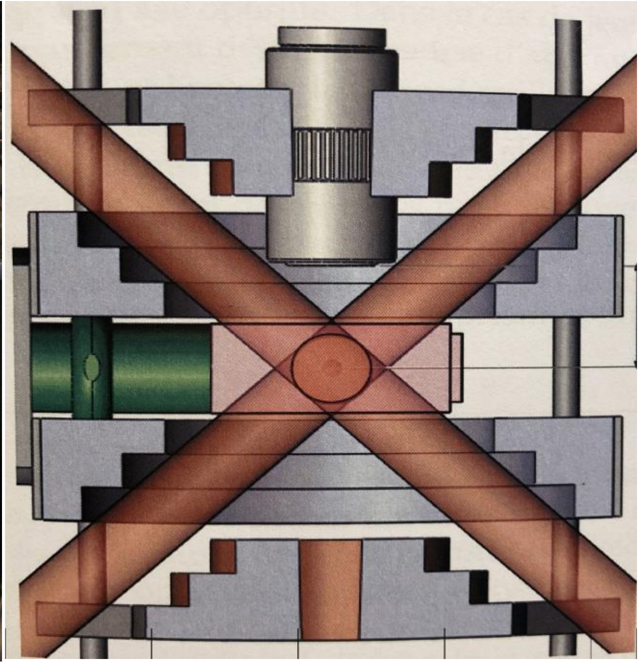
1 Thomas Bourdel

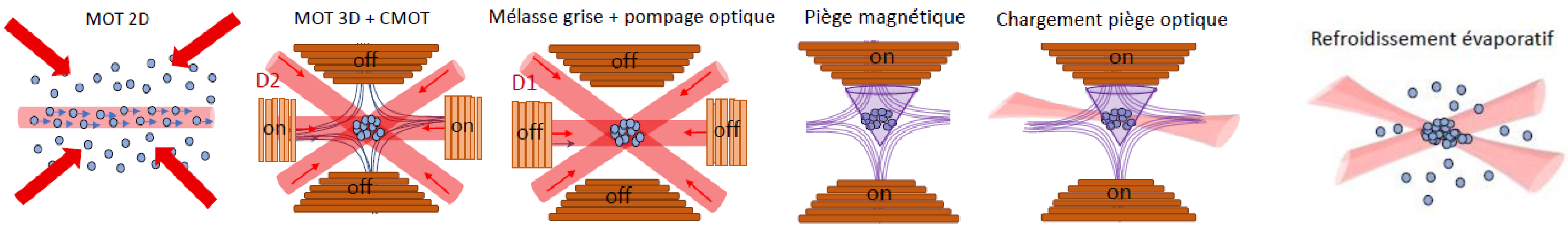
2 Lucas Lavoine

3 Alfred Hammond

The ^{39}K experiment

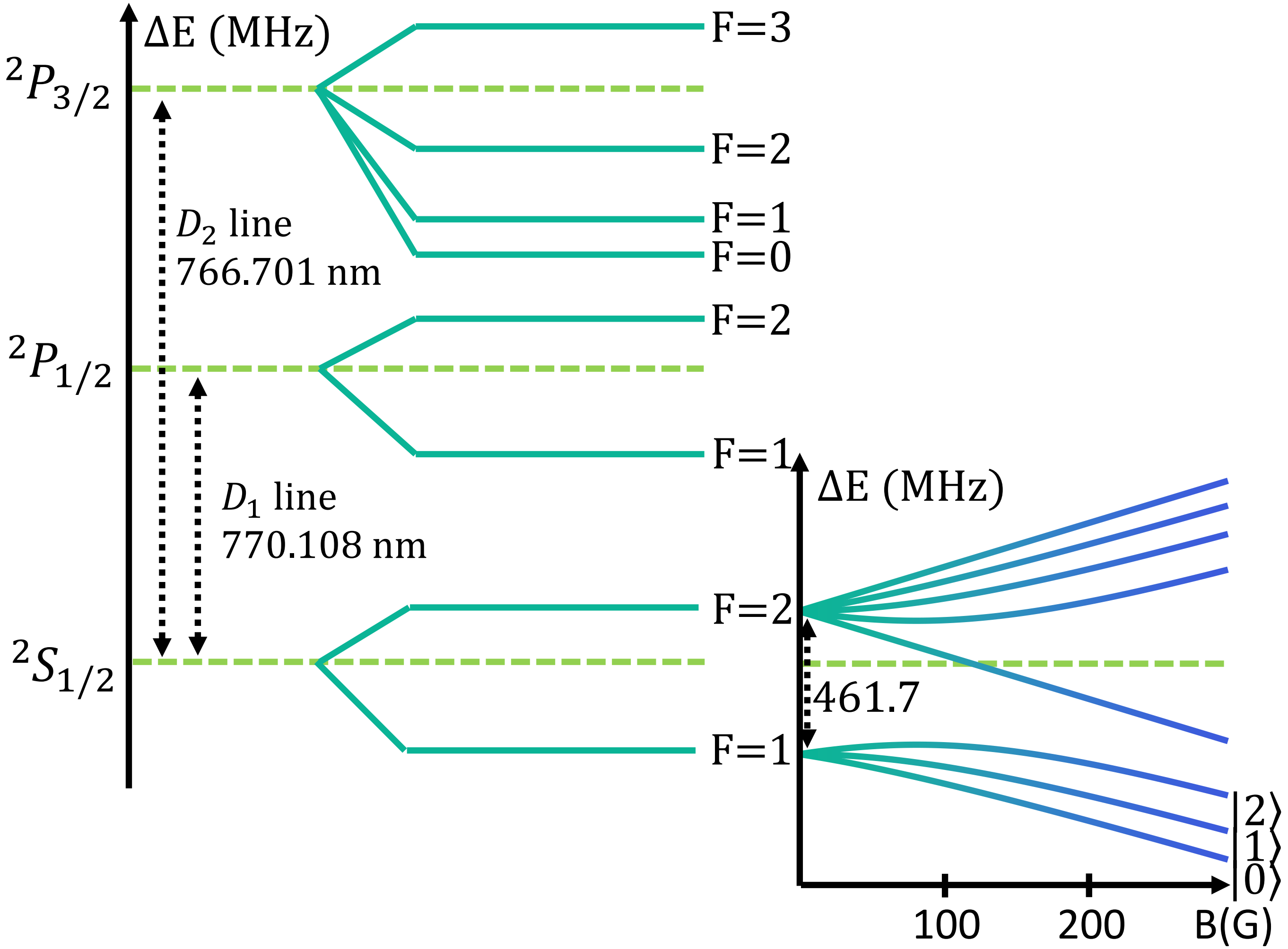


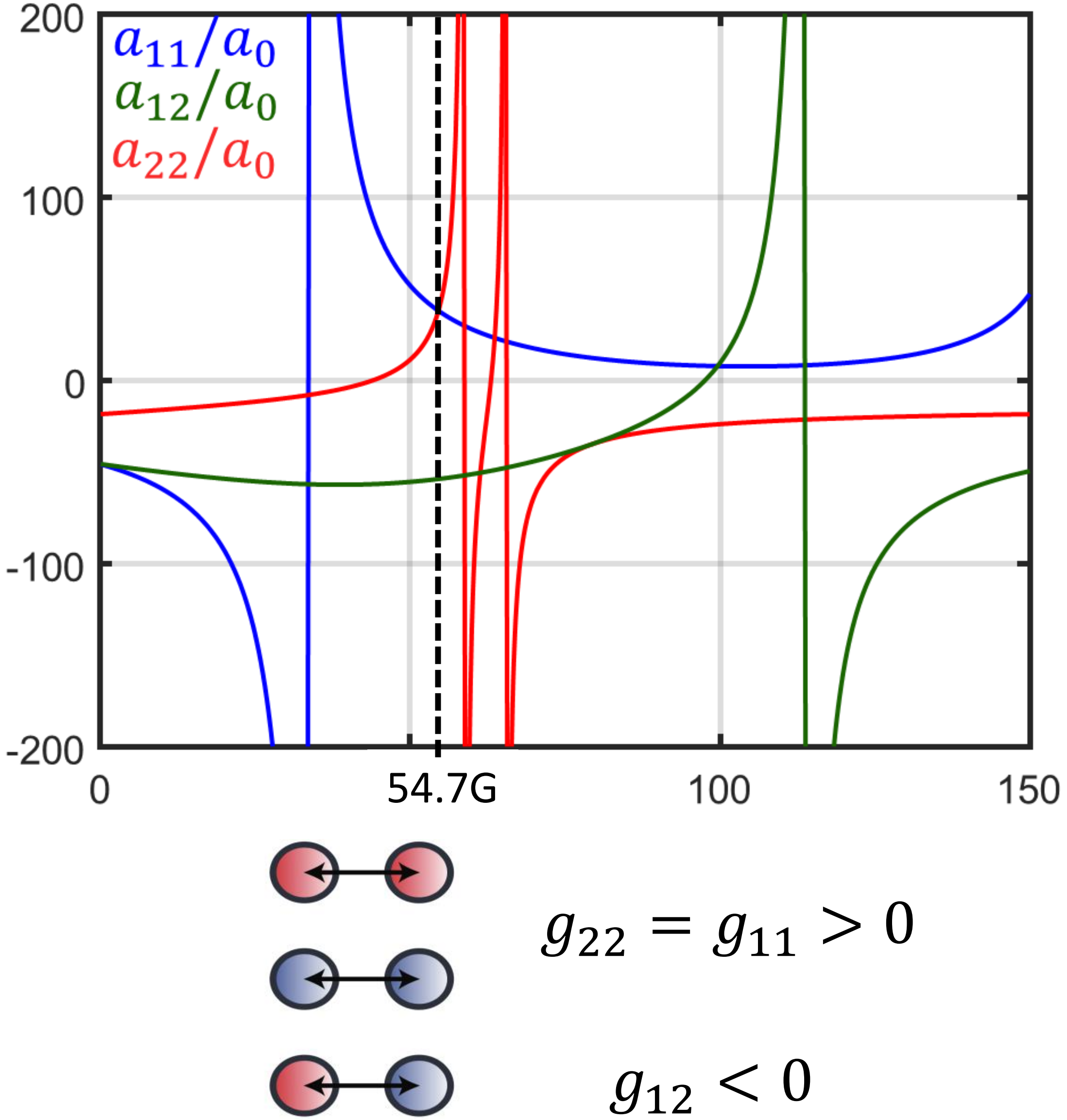




All optical cooling

Internal states of ^{39}K

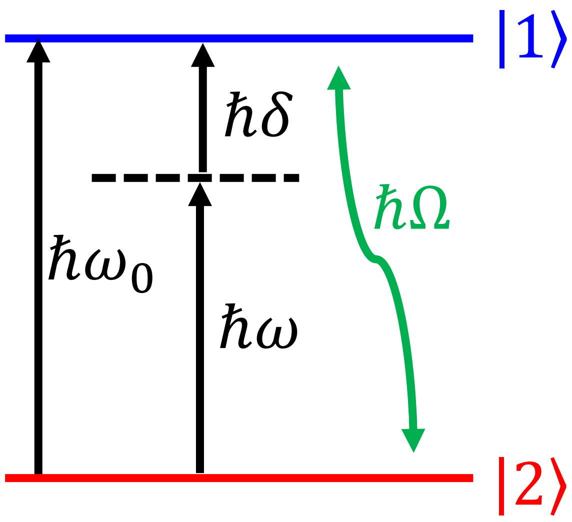




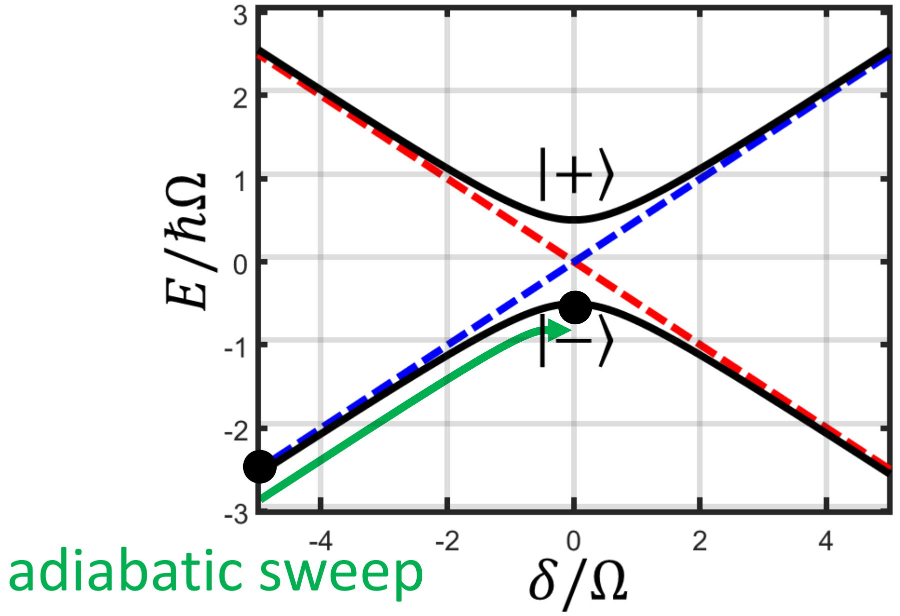
$g_{22} = g_{11} > 0$

$g_{12} < 0$

Coherent-drive & dressed states



At $B = 54.7$ G
$\omega_0 \approx 2\pi \cdot 39.575$ MHz
$\Omega \in 2\pi \cdot [5, 40] kHz$



$$\hat{H}_{int} = \frac{\hbar}{2}\begin{pmatrix} \delta & -\Omega \\ -\Omega & -\delta \end{pmatrix}$$

$$|+\rangle = \cos(\theta_0/2)\,|1\rangle - \sin(\theta_0/2)\,|2\rangle$$
$$|-\rangle = \sin(\theta_0/2)\,|1\rangle + \cos(\theta_0/2)\,|2\rangle$$

$$\text{cotan}(\theta_0) = \delta/\Omega$$

Interaction energy in RF-dressed BEC

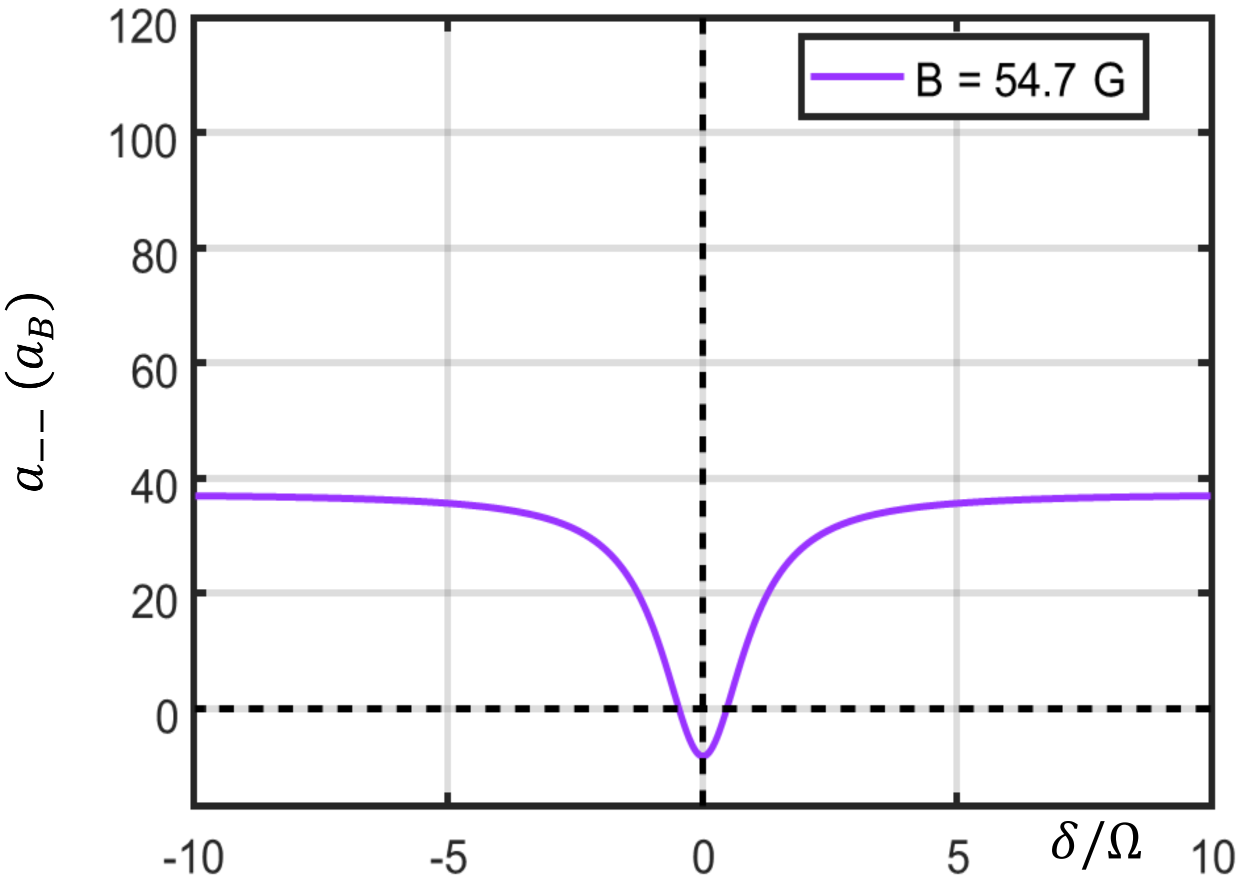
Mean-field ansatz $$|\psi\rangle = \frac{1}{\sqrt{V}}\frac{1}{\sqrt{N!}}\left(\hat{a}_{-}^{\dagger}\right)^{N}|0\rangle$$

$$\hat{H}_{int} = \frac{1}{2V}\sum g_{ij}\hat{a}_i^{\dagger}\hat{a}_j^{\dagger}\hat{a}_j\,\hat{a}_i$$

$$E_{int} = \langle\psi|\hat{H}_{int}|\psi\rangle$$

$$E_{int} = g_{--}\frac{N(N-1)}{2V}$$

$$g_{--}(\theta_0) = \sin^4(\theta_0/2)\,g_{11} + \cos^4(\theta_0/2)\,g_{22} + \\ +2\sin^2(\theta_0/2)\cos^2(\theta_0/2)\,g_{12}$$

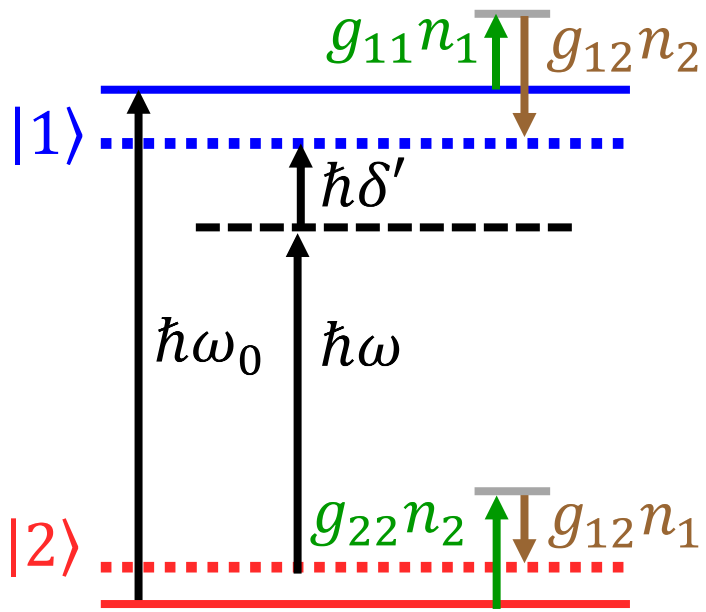


Mean-field competition between Rabi coupling and interactions

Gross-Pitaevskii equation :

$$i\hbar\frac{\partial}{\partial t}\left[\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}e^{-i\mu t/\hbar}\right]=\left[\frac{-\hbar^2}{2m}\Delta+\frac{m}{2}\left(\omega_x^2x^2+\omega_y^2y^2+\omega_z^2z^2\right)+\frac{\hbar}{2}\begin{pmatrix}\delta & -\Omega\\ -\Omega & -\delta\end{pmatrix}+\begin{pmatrix}g_{11}n_1+g_{12}n_2 & 0\\ 0 & g_{22}n_2+g_{12}n_1\end{pmatrix}\right]\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}e^{-i\mu t/\hbar}$$

Kinetic | Harmonic traping | Rabi | Interaction



$$\delta'=\delta+\frac{g_{11}n_1+g_{12}n_2-g_{22}n_2-g_{12}n_1}{2\hbar}$$

$$|-\rangle=\begin{pmatrix}\sin(\theta/2)\\ \cos(\theta/2)\end{pmatrix}$$

$$\mathrm{cotan}(\theta)=\frac{\delta}{\Omega}+\frac{2\overline{g}n}{\hbar\Omega}\cos(\theta)$$

$$\overline{g}=\frac{g_{11}+g_{22}-2g_{12}}{4}$$

Low density limit : tunable 3-body attractive interactions

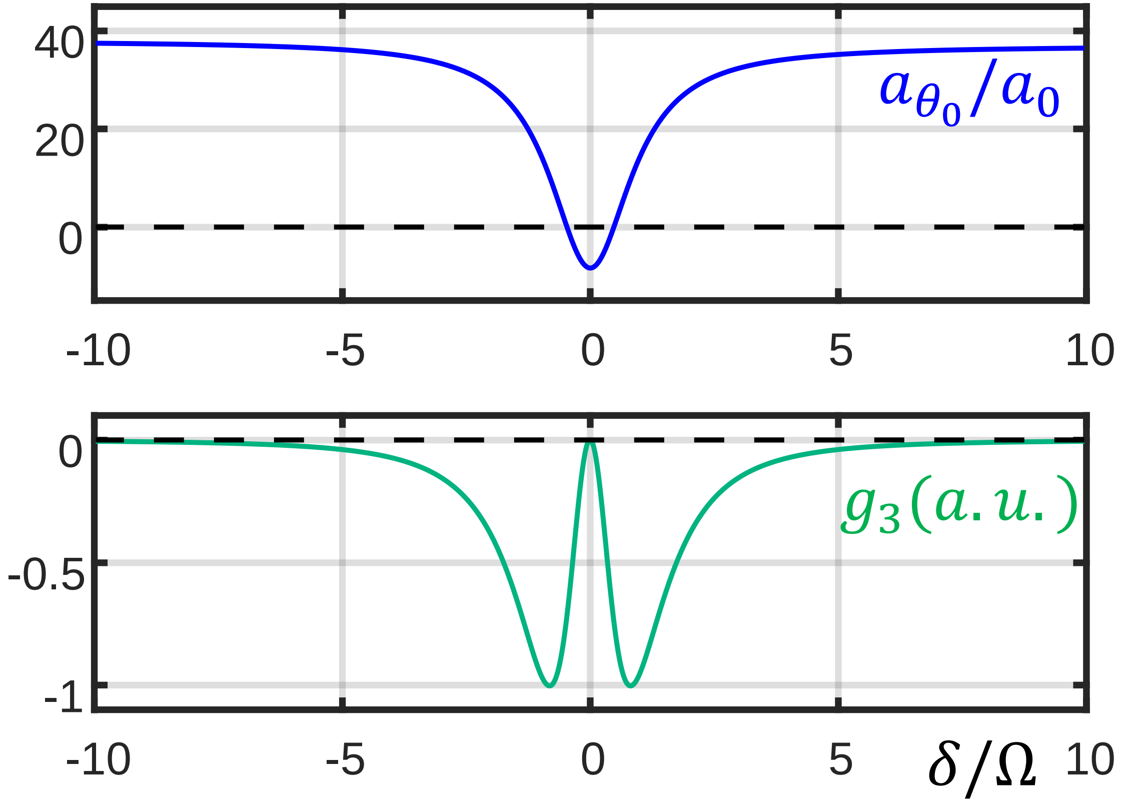
$$\frac{2\bar{g}n}{\hbar\Omega} \ll 1 \Rightarrow \theta - \theta_0 \propto n$$

$$g_\theta - g_{\theta_0} \propto n$$

$$\langle E_{int} \rangle = \int g_\theta \frac{n^2}{2} dV \simeq \int g_{\theta_0} \frac{n^2}{2} + g_3 \frac{n^3}{3} dV$$

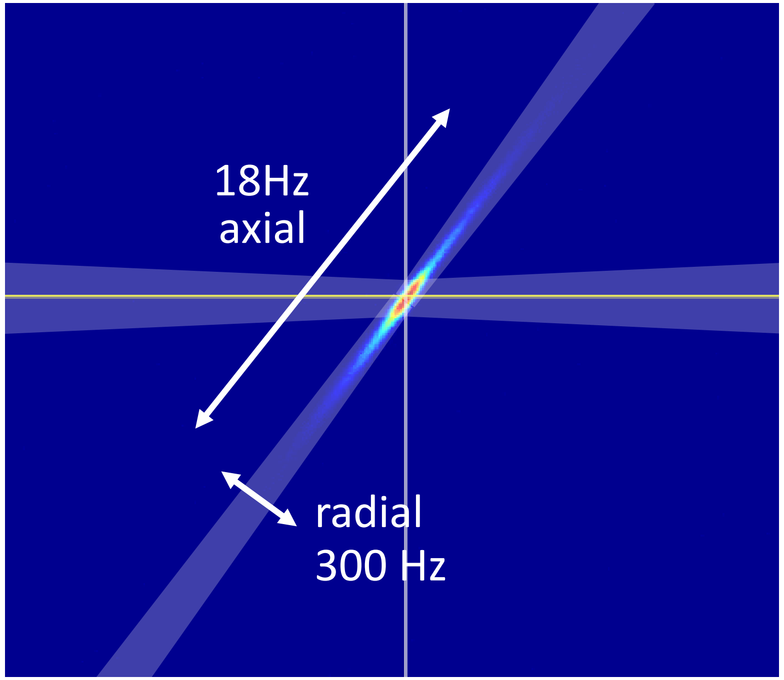
$$g_3 = -\frac{3\bar{g}^2}{\hbar\Omega} \frac{\delta^2/\Omega^2}{(1+\delta^2/\Omega^2)^{5/2}} < 0$$

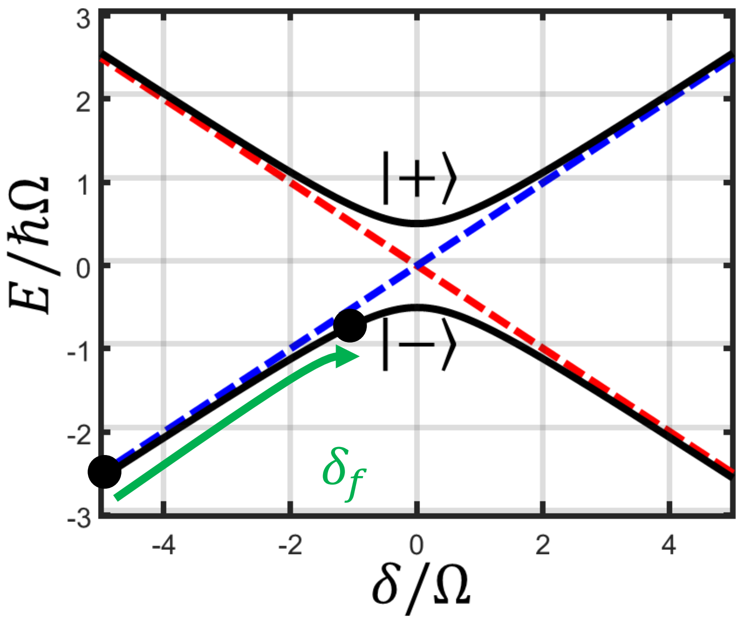
$$g_{\theta_0} = g_{min} + \frac{\bar{g}}{2} \frac{1}{1+\delta^2/\Omega^2}$$

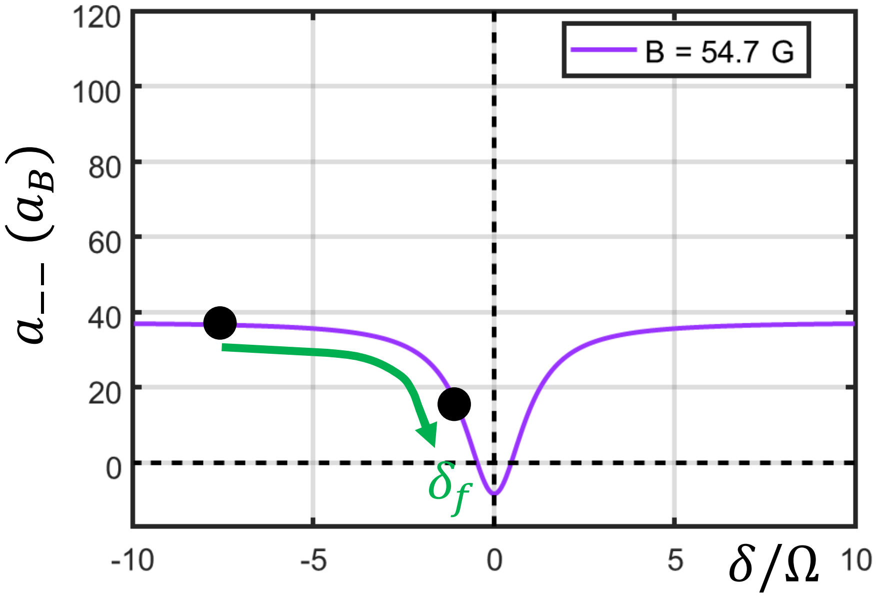


Experimental proof : breathing frequency in a cigar trap

- ^{39}K BEC with $150\ 000$ atoms, all in state $|1\rangle$, cigar trap
- Choosing RF power fixes Ω in $[5, 40]kHz$.
- RF sweep (0.4ms) from $\delta = -7\ \Omega$ to δ_f

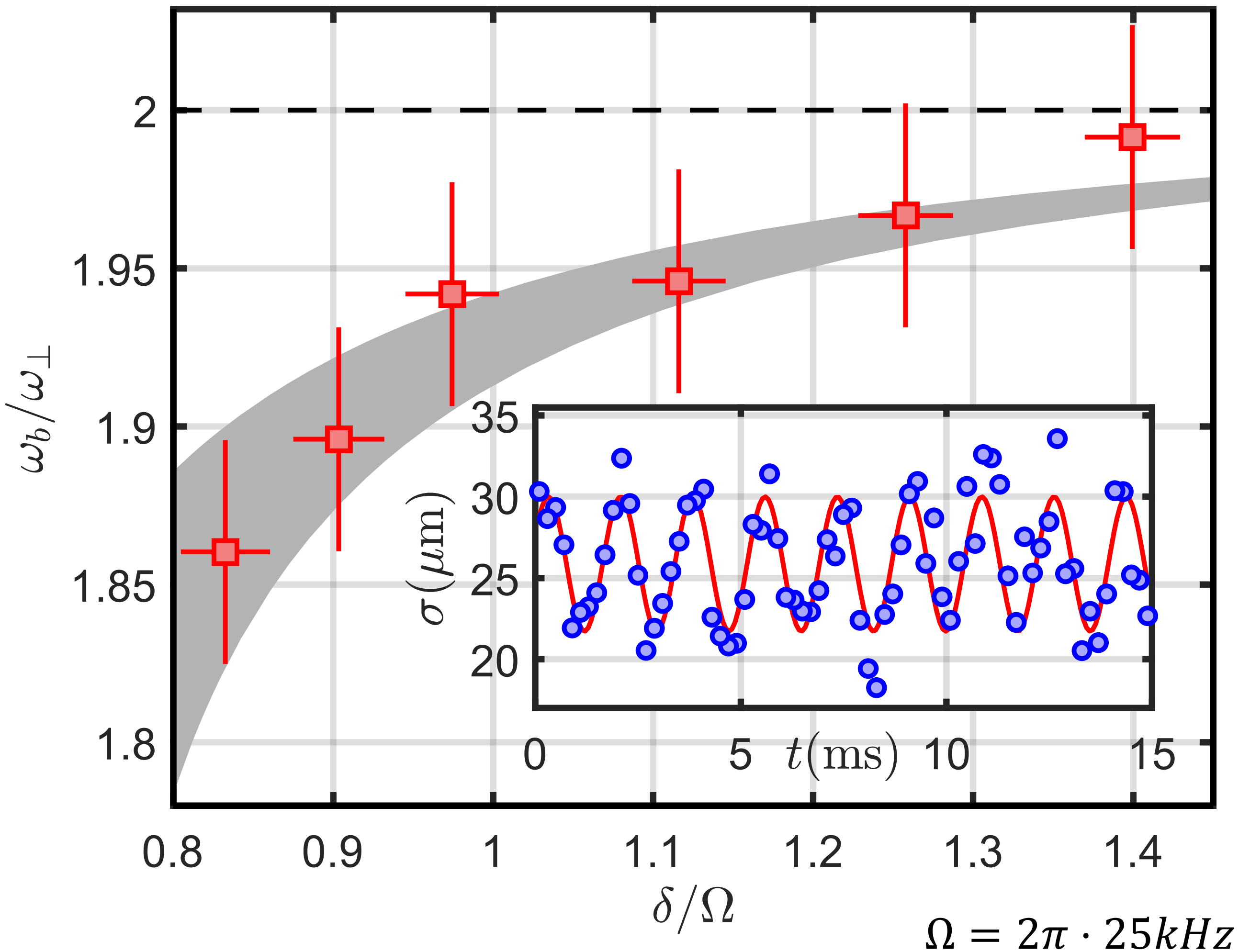






- Quasi-quench of interaction strength $\Longrightarrow$ radial breathing oscillations ($T \approx 1.7ms$)
- No axial dynamics observed at short times

Experimental proof : breaking of scale invariance

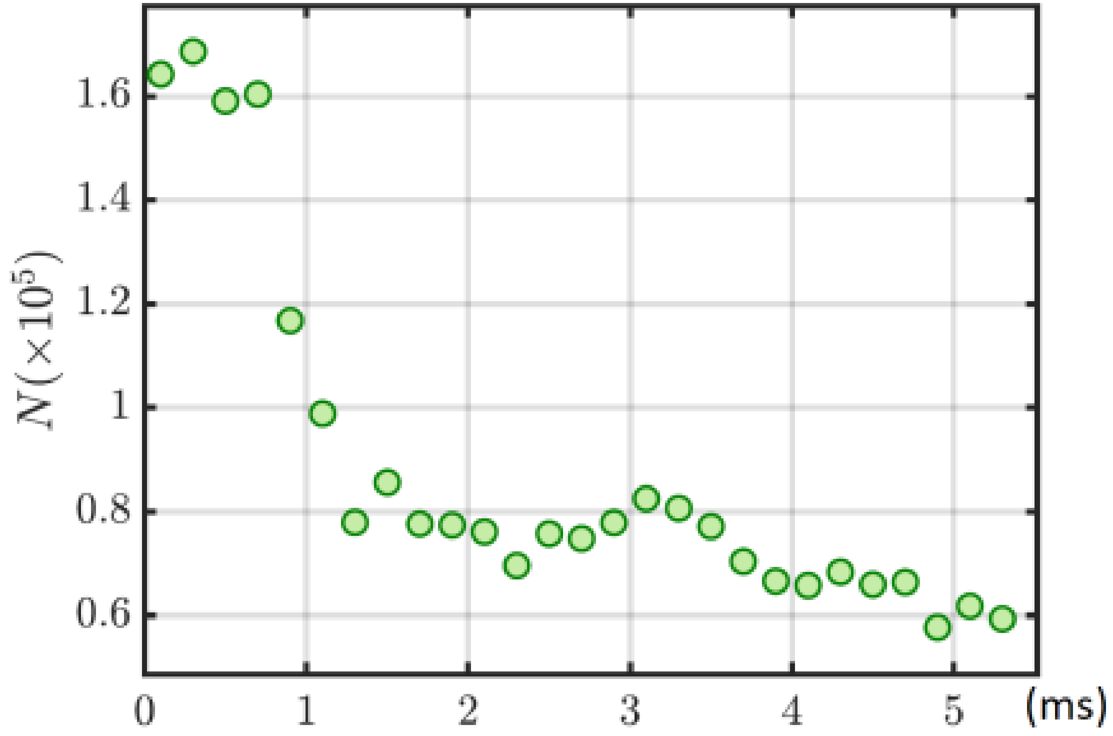


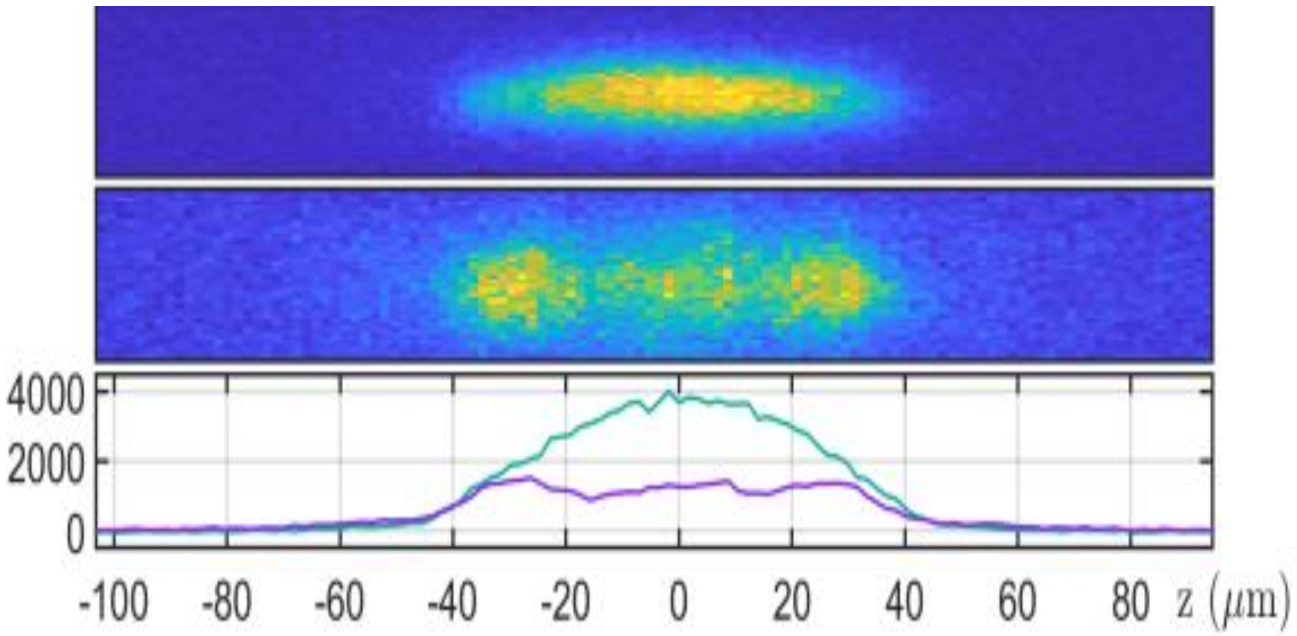
$\Omega = 2\pi \cdot 25kHz$

- If only 2-body interaction in 2D geometry : hidden scale invariance $\Longrightarrow \omega_b = 2\omega_\perp$
- 3-body interactions break the scale invariance, variational approach gives :

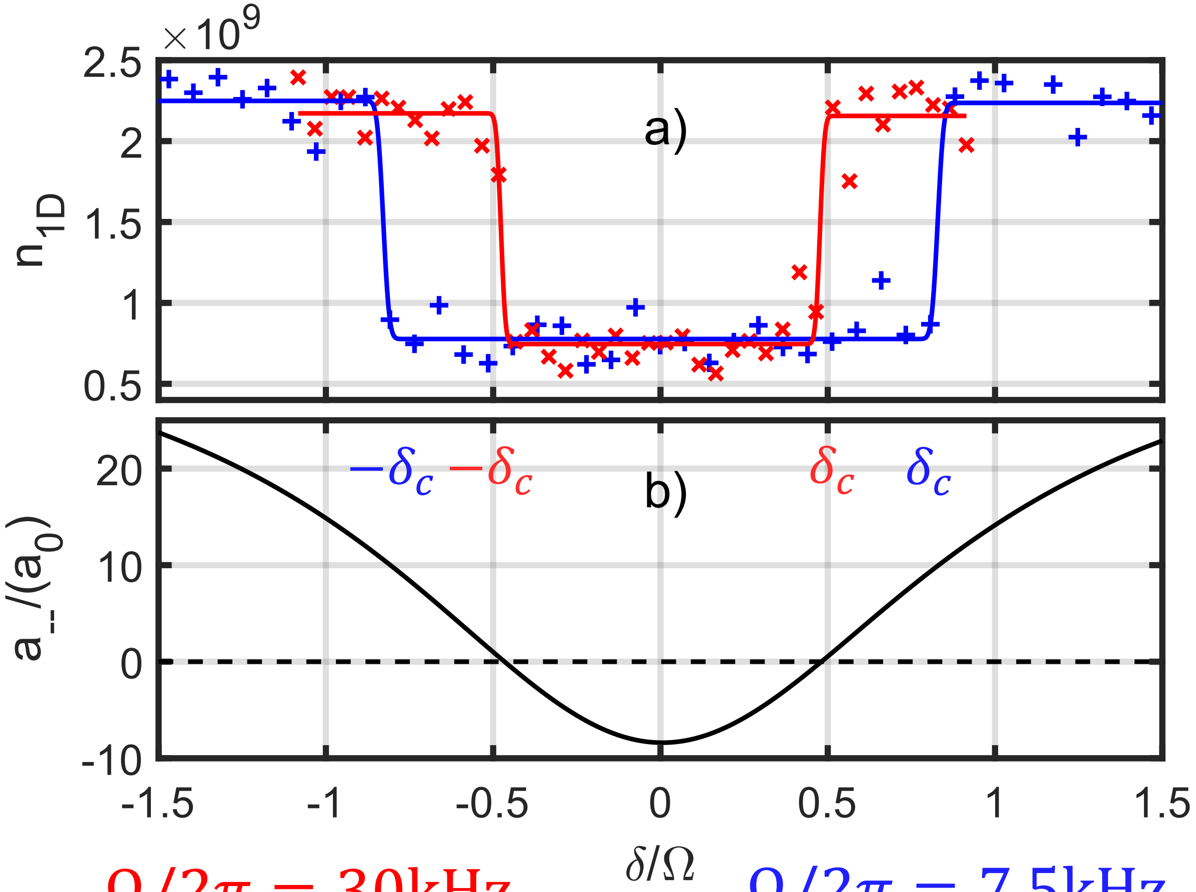
$$\omega_b = 2\omega_\perp \sqrt{1 + \frac{\int g_3 n(r)^3/3 d^2 r}{\int m\omega_\perp^2 n(r) d^2 r}}$$

3-Body induced collapses

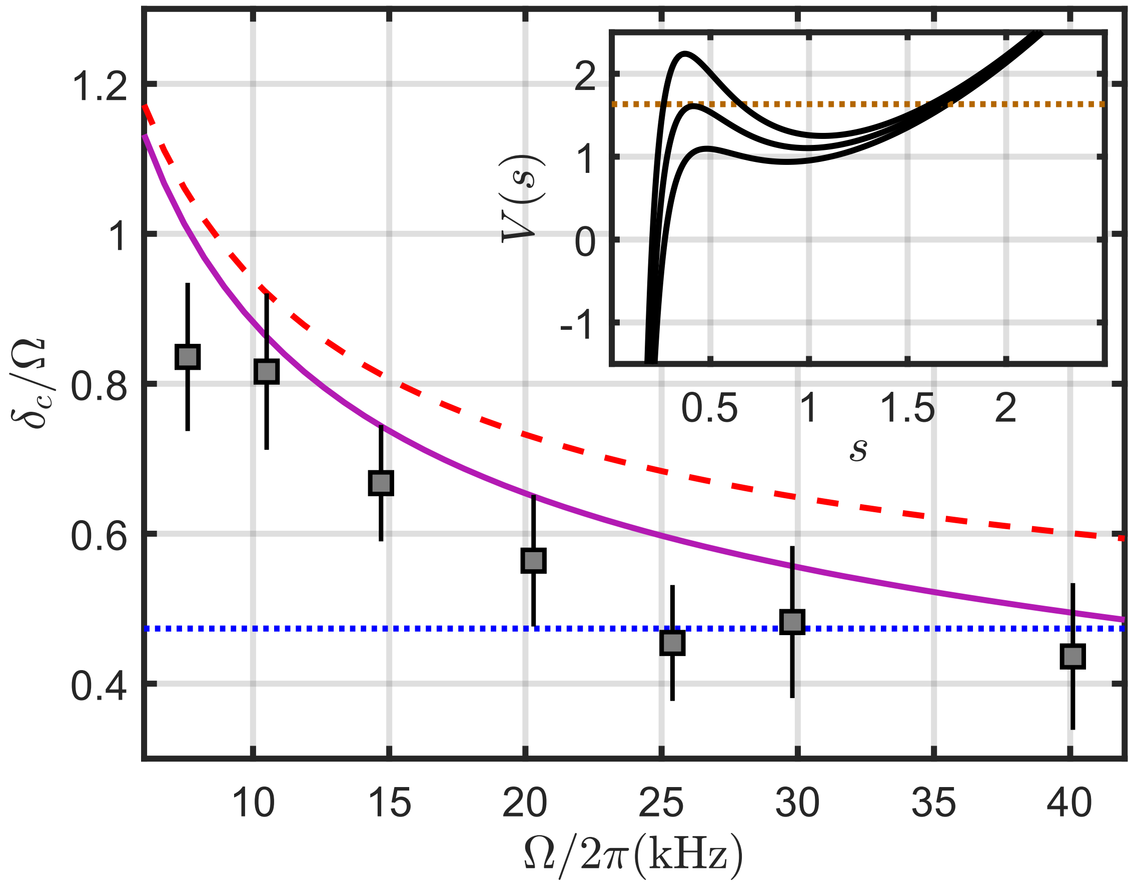




3-Body induced collapses



$\Omega/2\pi = 30\text{kHz}$ $\Omega/2\pi = 7{,}5\text{kHz}$



Conclusion :

Universality ?

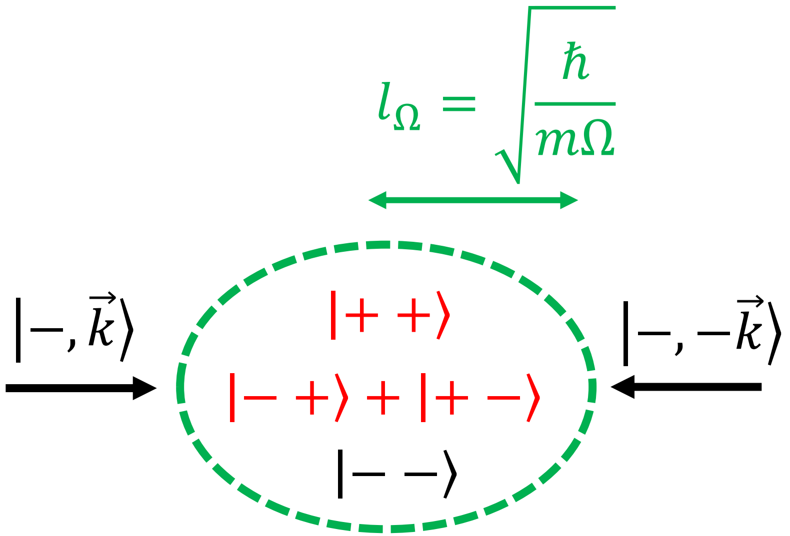
- $\gamma = \frac{2\overline{g}n}{\hbar\Omega}$
- $g_{min} \ll \overline{g}$

$$\overline{g} = \frac{g_{11} + g_{22} - 2g_{12}}{4} \qquad g_{min} = \frac{g_{11}g_{22} - g_{12}^2}{4\overline{g}}$$

Other interesting regimes ?

- $\gamma \gg 1$ incoherent mixture
- $\gamma \sim 1$?

Renormalisation of two-body interactions



$$a_{--} = a_{--}^{(0)} + a_{--}^{(1)}$$

$$a_{--}^{(1)} \propto \overline{a}^2 \sqrt{m\Omega/\hbar}$$

Beyond-mean-field effects in Rabi-coupled two-component Bose-Einstein condensate

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