FEW RESONANT ULTRACOLD BOSONS:

EFFECT OF BACKGROUND SCATTERING

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ABSTRACT

- MOTIVATION: **3 identical bosons near a Feshbach resonance**.

  ☞ **Efimov physics**: taking into account the **background scattering** $\Longrightarrow$ beyond the universal theory.

  ☞ **Quantitative evaluation** of observables with a **'minimal' model**:

  3-body inelastic losses, recombination, atom-dimer resonances...

  ☞ **Interpretation of experiments**:

  $*$ Experiments on ^{133}**Cs at Innsbrück**:

  T. Kraemer, M. Mark, P. Waldburger, J. G. Danzl, C. Chin, B. Engeser, A. D. Lange, K. Pilch, A. Jaakkola, H.-C. Naegerl , R. Grimm, Nature **440**, 315-318.

  S. Knoop, F. Ferlaino, M. Mark, M. Berninger, H. Schoebel, H.-C. Naegerl, R. Grimm, arXiv:0807.3306

  $*$ Experiments on ^{39}**K at Firenze** $\longrightarrow$ c.f. POSTER of the group

- TOOL

  'Realistic' description of a Feshbach resonance $\Leftrightarrow$ use a **2-channel model**.

CONTEXT

- Identical atomic bosons (mass m).

- **Short range** 2-body potential between atoms with a van der Waals tail

$$R_{\rm vdW} = \frac{1}{2}\left(\frac{\mu C_6}{\hbar^2}\right)^{1/4}$$

  ☞ $\exists$ a scattering length $\neq 0$ away a Feshbach resonance:

$$\Longrightarrow \textbf{Background scattering length } a_{\rm bg}.$$

  ☞ Possibility of **shape resonance** (*e.g.* Cs atoms), characterized by

$$|a_{\rm bg}| \gg R_{\rm vdW}.$$

- **Feshbach resonance** in the s-wave channel:

  ☞ $\exists$ a s-wave **molecular state** $\in$ a closed channel coupled with the continuum.

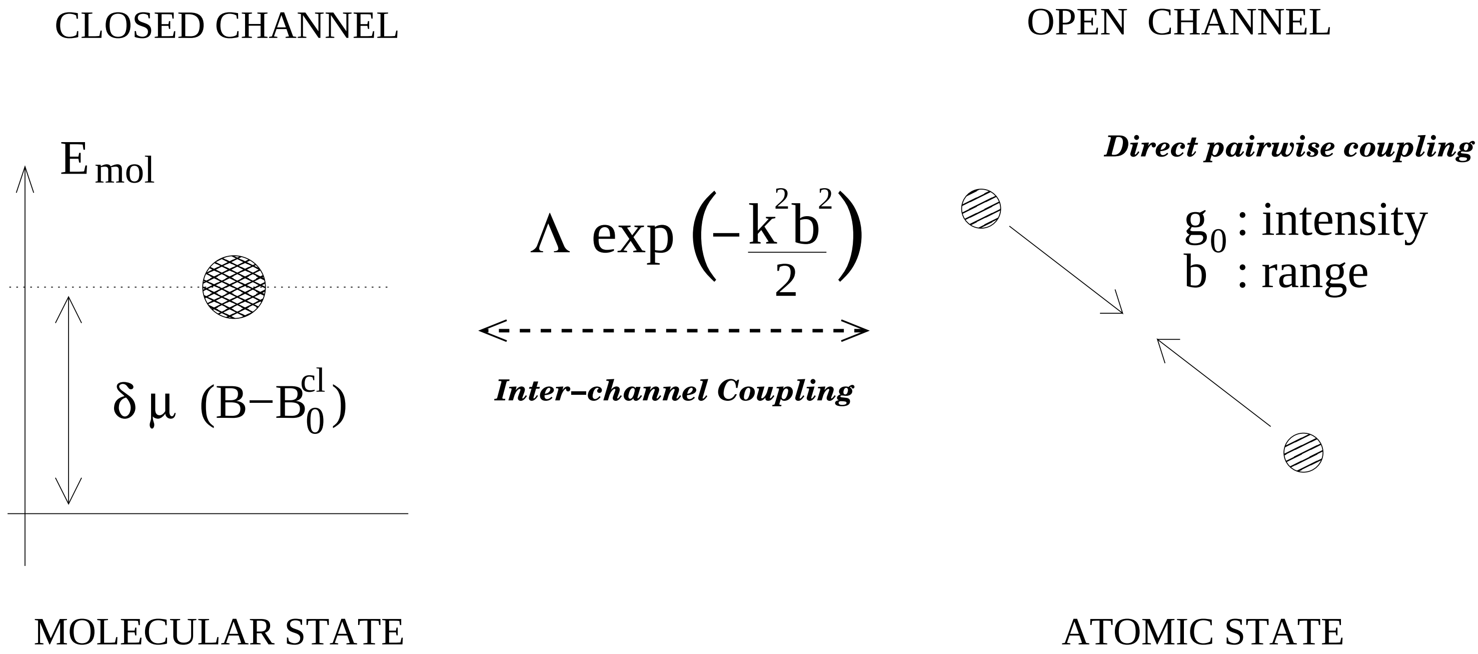
  ☞ Energy of the molecular state tuned by a magnetic field $\mathcal{B}$

  ☞ Resonance between the scattering states and the molecule at $\mathcal{B} = \mathcal{B}_0$

$$a = a_{\rm bg}\left(1 - \frac{\Delta\mathcal{B}}{\mathcal{B} - \mathcal{B}_0}\right)$$

a: scattering length
$\Delta\mathcal{B}$: resonance width
$\nu = \delta\mu(\mathcal{B} - \mathcal{B}_0)$: energy detuning

MODEL



- Λ: intensity of the (atomic pair)$\leftrightarrow$(molecule) coupling.

- g_0: intensity of the direct coupling between two-atoms.

- b: of the order of the range of the interaction $\Longrightarrow b \equiv O(R_{\rm vdW})$.

- $E_{\rm mol} = \delta\mu(\mathcal{B} - \mathcal{B}_0^{\rm cl})$: energy of the molecular state
  ($\delta\mu$: difference of magnetic moment between the 2 channels).

$\Longrightarrow$ 4 parameters adjusted on $\{R_{\rm vdW}, a_{\rm bg}, \nu, \delta\mu\Delta\mathcal{B}\}$

2-BODY PHYSICS: $\exists \neq$ type of Feshbach resonances

2 characteristic scales: $R^\star = \dfrac{\hbar^2}{m a_{bg} \delta\mu \Delta\mathcal{B}}$ & $E_{bg} = \dfrac{\hbar^2}{m a_{bg}^2}$

- BROAD FESHBACH RESONANCE $\quad |\delta\mu\Delta\mathcal{B}| \gg E_{bg}$

☞ Large coupling between the 2 channels $\Leftrightarrow R^\star \ll |a_{bg}|$

☞ Shallow dimer $a > 0$ & $\frac{|\mathcal{B}_0 - \mathcal{B}|}{|\Delta\mathcal{B}|} \ll 1$: $E_{dim} \simeq \dfrac{\hbar^2}{ma^2}$ (threshold law).

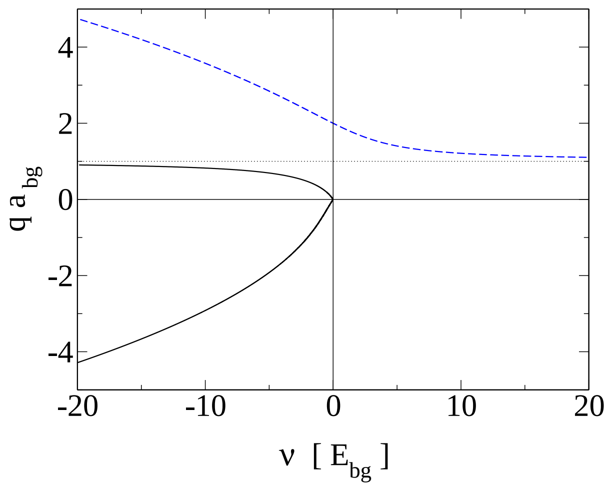
- NARROW FESHBACH RESONANCE $\quad |\delta\mu\Delta\mathcal{B}| \ll E_{bg}$

☞ Small coupling between the 2 channels and $\Leftrightarrow R^\star \gg |a_{bg}|$

☞ Shallow dimer $E_{dim} = \dfrac{\hbar^2 q^2}{m}$ where $q \simeq \dfrac{-a + \sqrt{a^2 + 4R^\star(a - a_{bg})}}{2R^\star(a - a_{bg})}$.

- NEARBY A SHAPE RESONANCE $\quad |a_{bg}| \gg R_{vdW}$

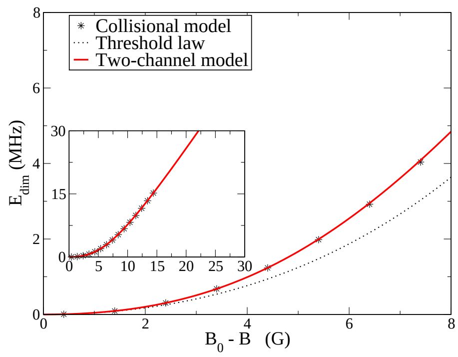
☞ For $a_{bg>0}$, interplay (Feshbach dimer) $\leftrightarrow$ ('Background' dimer)



☞ Effective range approach unable to describe the interplay.

2-BODY PHYSICS: example of known resonances

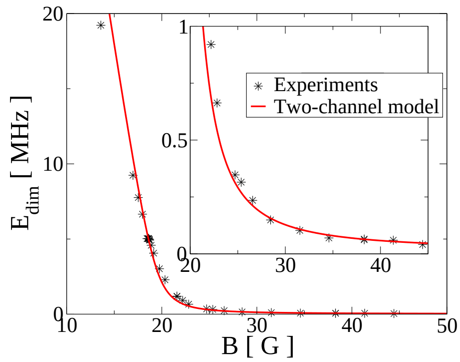
- Broad resonance of ^{39}K ($\mathcal{B}_0 \sim 402$ G, $\Delta\mathcal{B} = -52$ G)



(data of the collisional model from A. Simoni)

- Resonance of of ^{133}Cs ($B_0 \sim -11.8$ G, $a_{\rm bg} \simeq 16.9 R_{\rm vdW}$)

$\Longrightarrow$ nearby a shape resonance



(data obtained in the experiments at Innsbrück)

- Narrow resonance of ^{39}K ($B_0 \sim 752$ G $\Delta\mathcal{B} = -0.4$ G)

Black line: exact solution of the 2-channel model

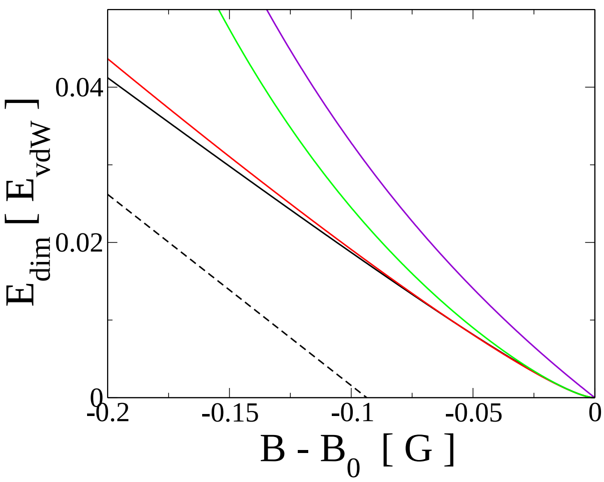
Red line: $q = \frac{-a+\sqrt{a^2+4R^\star(a-a_{\rm bg})}}{2R^\star(a-a_{\rm bg})}$

Green line: effective range approach

$q = \frac{-a+\sqrt{a^2+4R^\star a}}{2R^\star a}$

Violet line: $q = 1/\sqrt{R^\star a}$

Dashed line : $E_{\rm mol}$



3-BODY PHYSICS: BOUND STATES

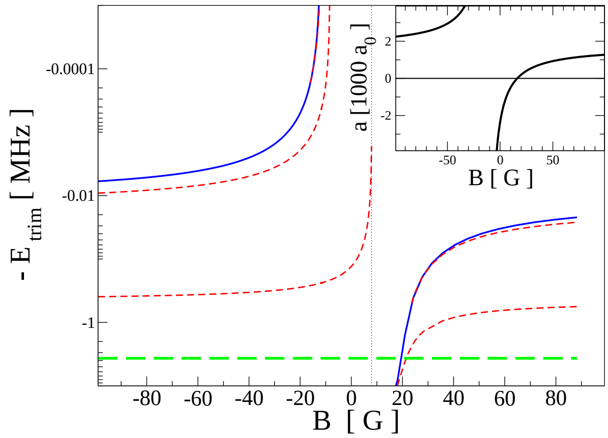
- Trimers of ^{133}Cs atoms for the resonance at $B_0 = -11.8$ G

Blue line: Dimers binding energy.

Red dashed line: Trimers binding energy

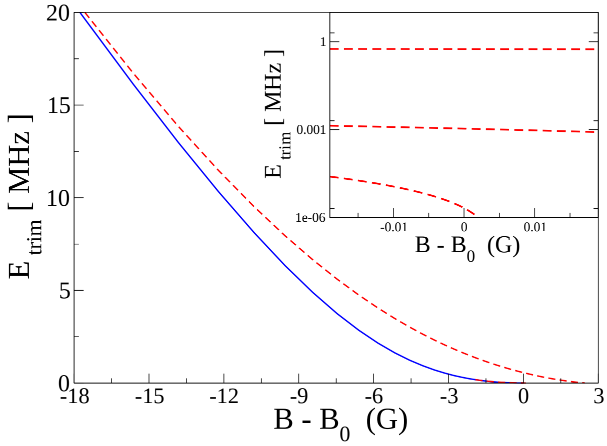
Green dashed line: Energy $\frac{\hbar^2}{mR_{\rm vdW}^2}$

Insert: scattering length as a function of $\mathcal{B}$



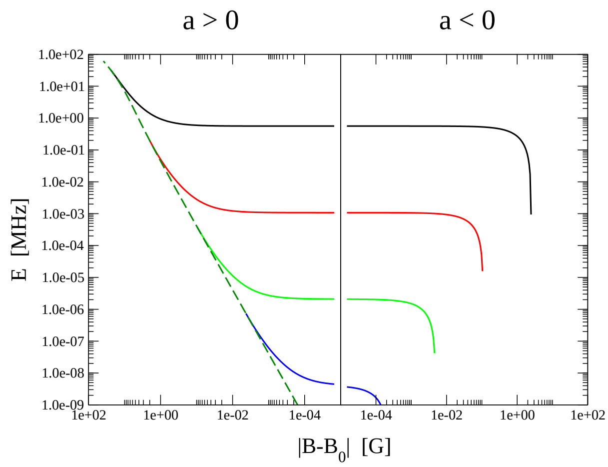
- Trimers of ^{39}K atoms for the resonance at $B_0 = 402$ G

☞ Efimov spectrum (log scale for the energy, linear scale for the detuning)



☞ Efimov spectrum in log-log scale

→ The first four Efimov states as a function of the detuning
→ Dashed green line: dimer threshold.



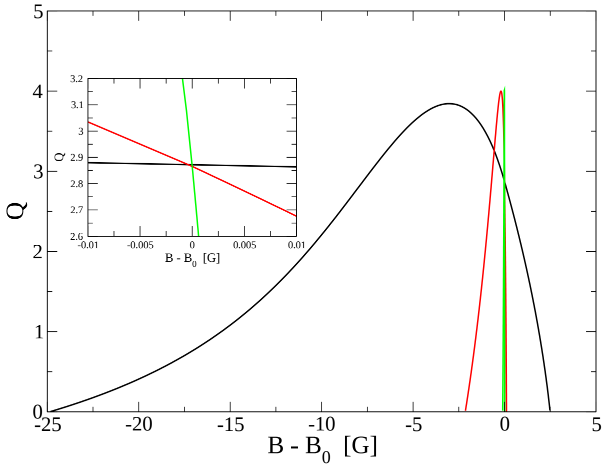
☞ Desintegration of trimers into deep-bound states & **Quality factor**

→ Probability $\mathcal{P}^{<b}$ that 3 atoms $\in$ Volume $\sim b^3$

→ Loss rate $\Gamma_{\rm loss} = \frac{\hbar}{mb^2}\mathcal{P}^{<b}$

→ Lifetime $\sim 1/\Gamma_{\rm loss}$

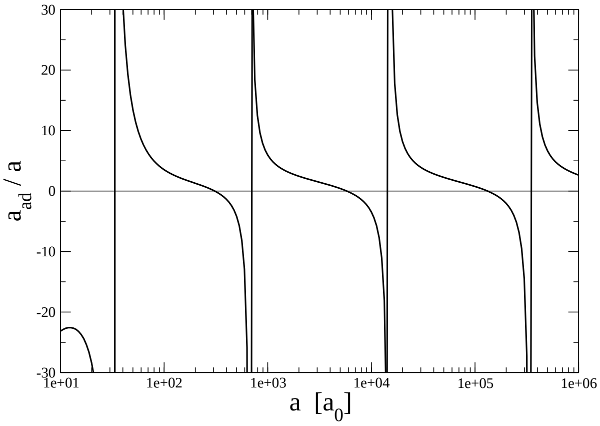
→ Quality factor $\mathcal{Q} = \frac{E^{\rm trim} - E_{\rm dim}}{\hbar\Gamma_{\rm loss}}$



3-BODY PHYSICS: Atom-dimer scattering

- s-wave atom-dimer scattering length as a function of the external magnetic field for the ^{39}K resonance at $B_0 = 402$ Gauss

→ Appearance of first four Efimov states



CONCLUSIONS AND PERSPECTIVES

- A simple two channel model interprets and reproduces the features observed in present experiments on two- and three- body physics (^{39}K and ^{133}Cs).
- The background scattering is found to play an important role in realistic situations.
- Universal physics beyond the effective range model.
- Extension of the model to mixtures and also to Fermionic statistics.