Multiple lensing methods of ultracold atomic and molecular ensembles

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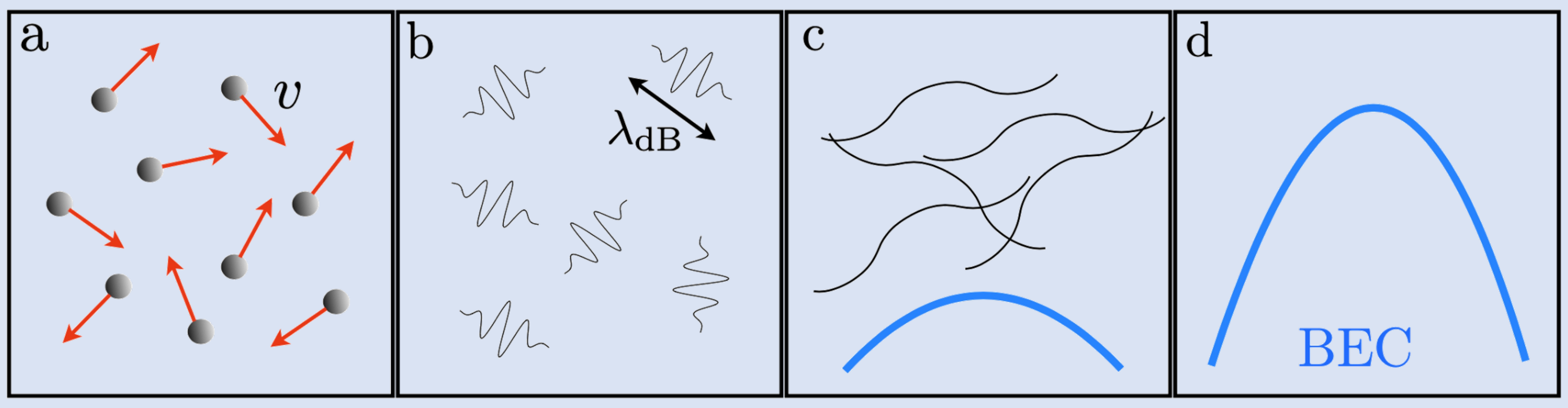
Abstract

We present two different methods to collimate atomic and molecular ultracold ensembles. The idea of both methods is to limit the expansion rate of the considered ensemble while preserving its phase space density [1]. The first method uses time-averaged potentials to form an all-optical matter-wave lens [2]. By using ^{39}K instead of ^{87}Rb in the same apparatus, magnetic Feshbach resonances are implemented to change the atomic scattering length. This procedure allows to even further reduce the final temperature of the ensemble by lowering the mean field energy.

The second method is the Delta-Kick Collimation [1] generalized to molecular ensembles. We consider both the condensed and the thermal regimes. A Delta-Kick Collimation procedure allows us to divide the expansion energy of a released molecular ensemble by at least a factor of 90. In the best case, we can even divide the expansion energy by a factor of 500. Finally, this procedure can also be used to measure the intermolecular scattering length with a high accuracy. This work may provide a useful tool for preparing collimated binary mixtures for atom interferometry.

Quick reminder : BEC



Schematic representation of the creation of a Bose-Einstein Condensate from [3].

Classical gas

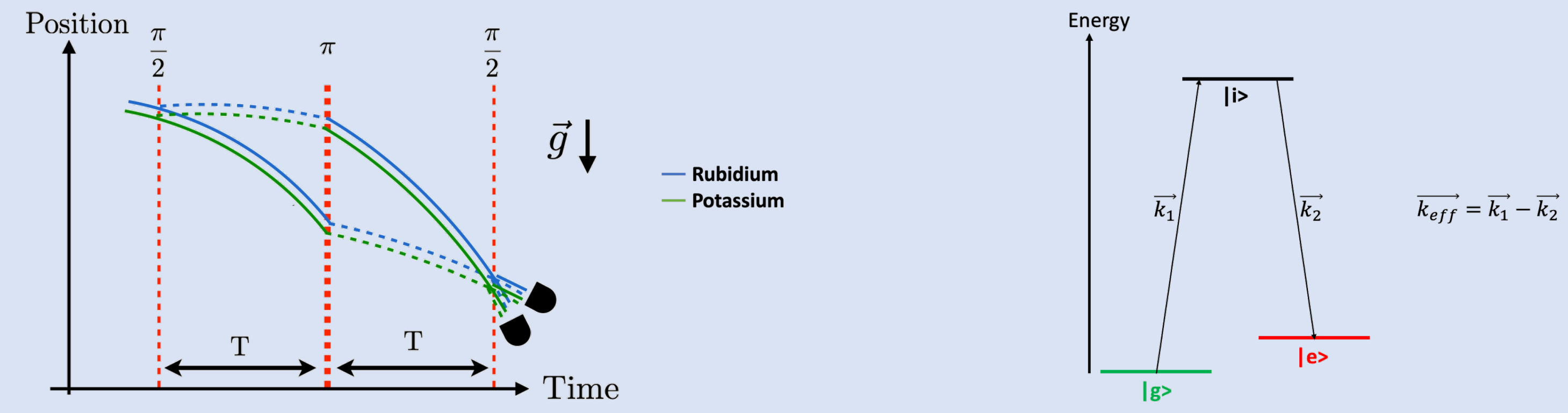
Wave nature of particles

Critical temperature

Bose-Eintein Condensate (BEC)

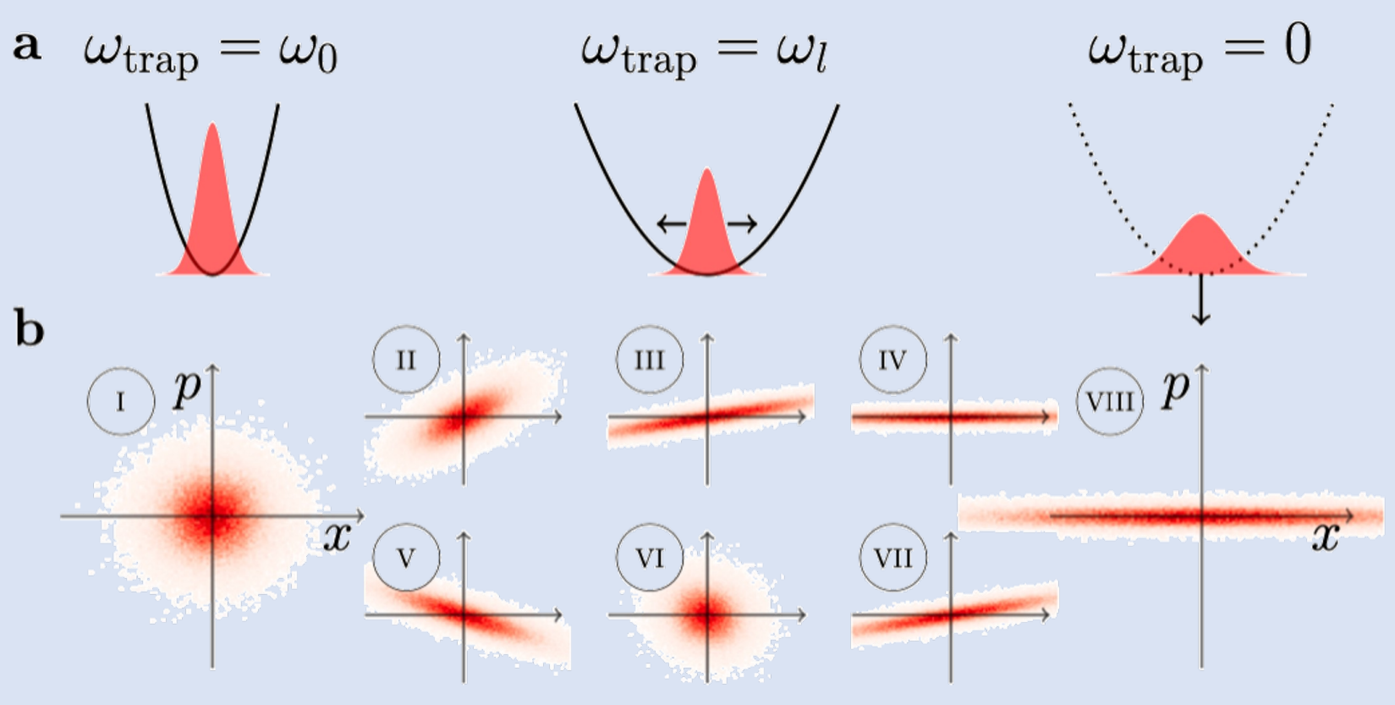
Motivations : Control of ballistic expansion

- Dynamical study of quantum mixtures.
- Dual species atomic interferometry (e.g. Rubidium and Potassium) : $\Delta\phi \propto gT^2$.



- Test of the universality of free fall in experiments such as the Cold Atoms Laboratory (CAL) in the ISS or Quantus in the drop tower in Bremen.

In-trap lensing



Schematic representation of the in-trap lensing from [2].

- Time dependant Gross-Pitaevskii equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(\vec{r},t) = \left[-\frac{\hbar^2}{2m}\Delta + V(\vec{r},t) + N g_{int}|\Psi(\vec{r},t)|^2\right]\Psi(\vec{r},t).$$

- Scaling law: $\sigma_j(t) = \sigma_j(0)\lambda_j(t),\ \ j \in \{x,y,z\}$.
- Thomas-Fermi model [4,5] ($T_0 = 0$ K):

$$\ddot{\lambda}_j + \omega_j^2(t)\lambda_j = \frac{\omega_j^2(0)}{\lambda_j\,\lambda_x\lambda_y\lambda_z}.$$

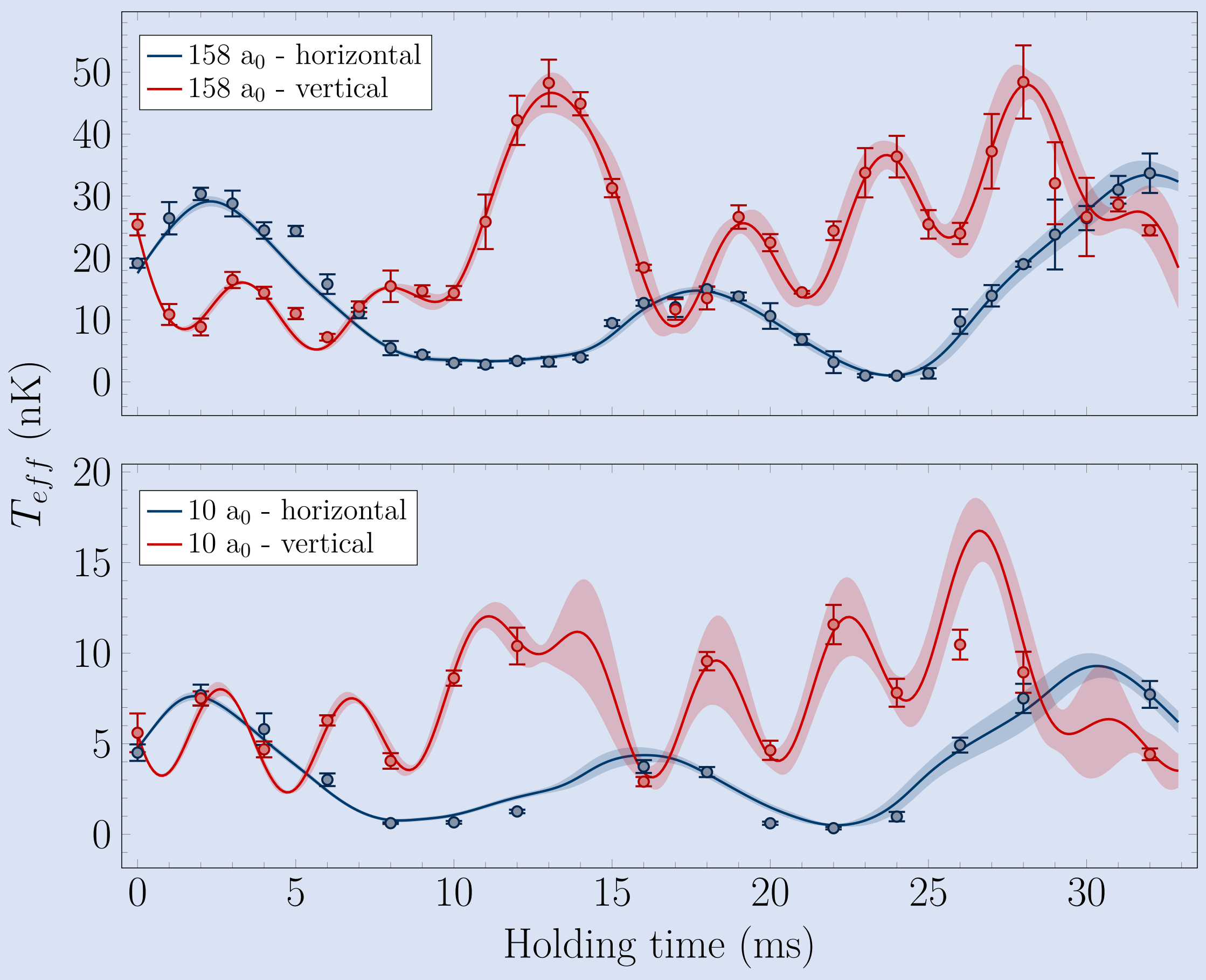
- Variational approach [6] ($T_0 = 0$ K):

$$\ddot{\lambda}_j + \omega_j^2(t)\lambda_j = \frac{\omega_j^2(0)}{\lambda_j\,\lambda_x\lambda_y\lambda_z} + \alpha_j\frac{\omega_j^2(0)}{\lambda_j^3}.$$

- Simulated annealing [7] to fit the free parameters.
- Effective temperature :

$$\frac{3}{2}k_B T_{eff}^{3D} = \frac{1}{2}\sum_j m\,v_j^2.$$

- In the vertical plane, at 2D :
  - 1.2 nK at 158 a_0.
  - 500 pK at 9.9 a_0.



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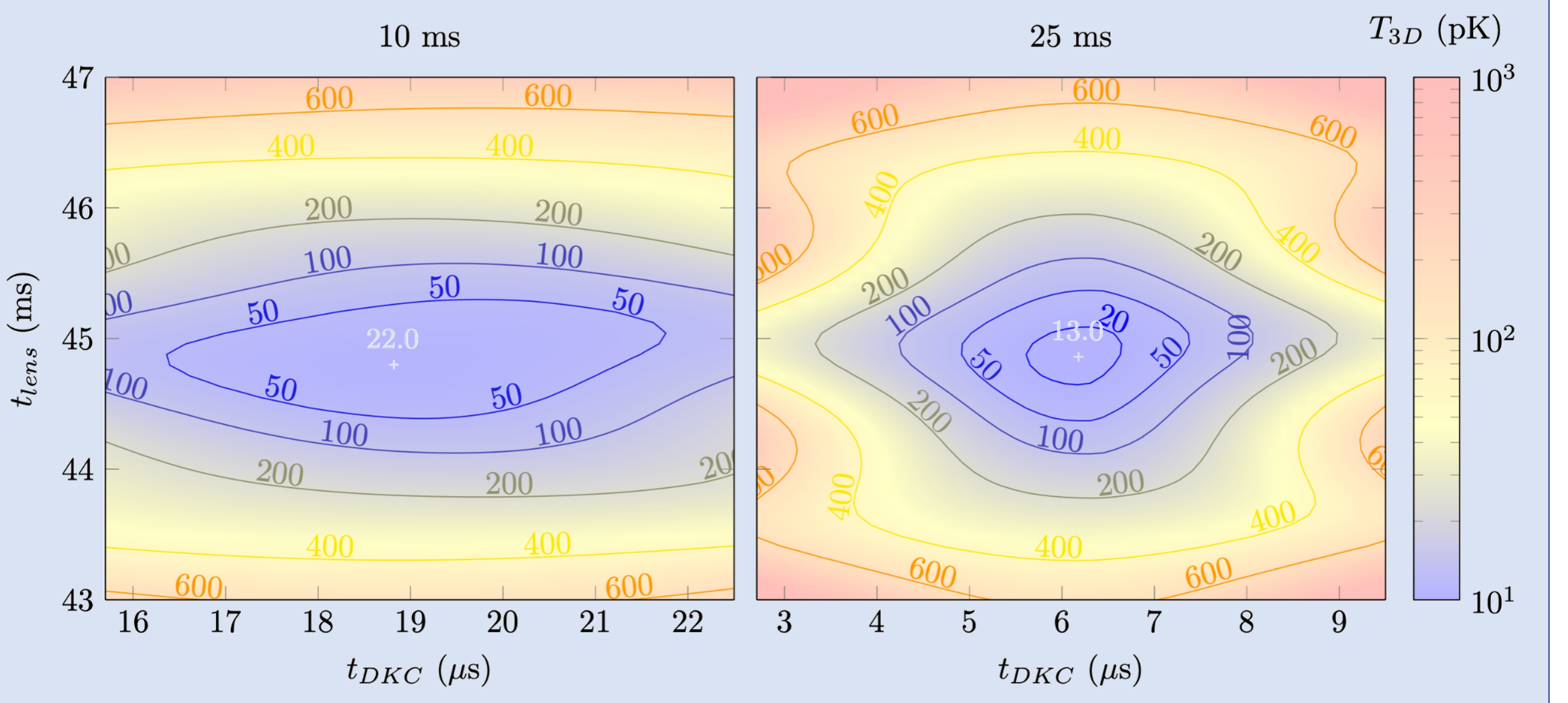
Outlook : Combination of both methods



$$\sqrt{2\pi}\ t_{DKC}\,\omega^2\,T_{TOF} \simeq 1$$

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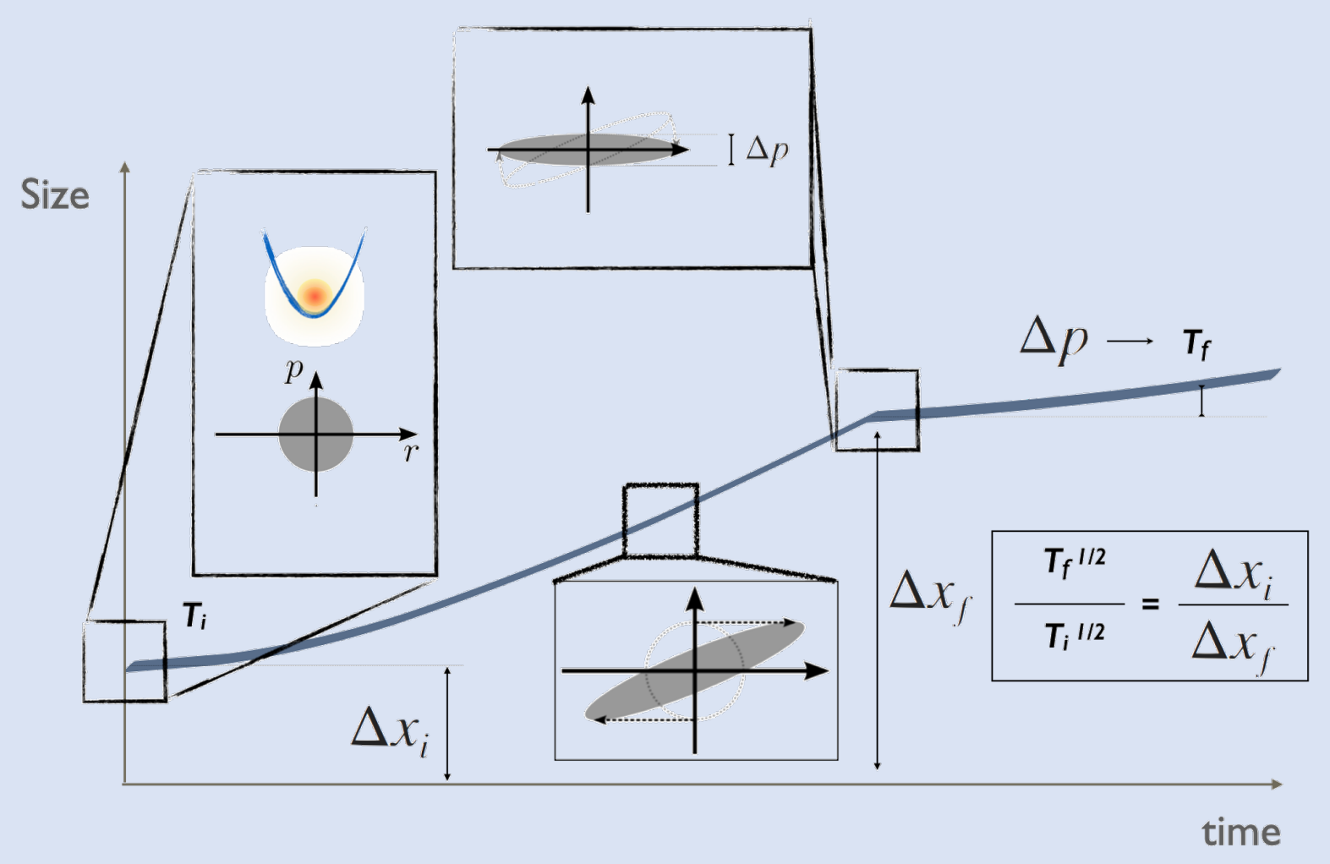
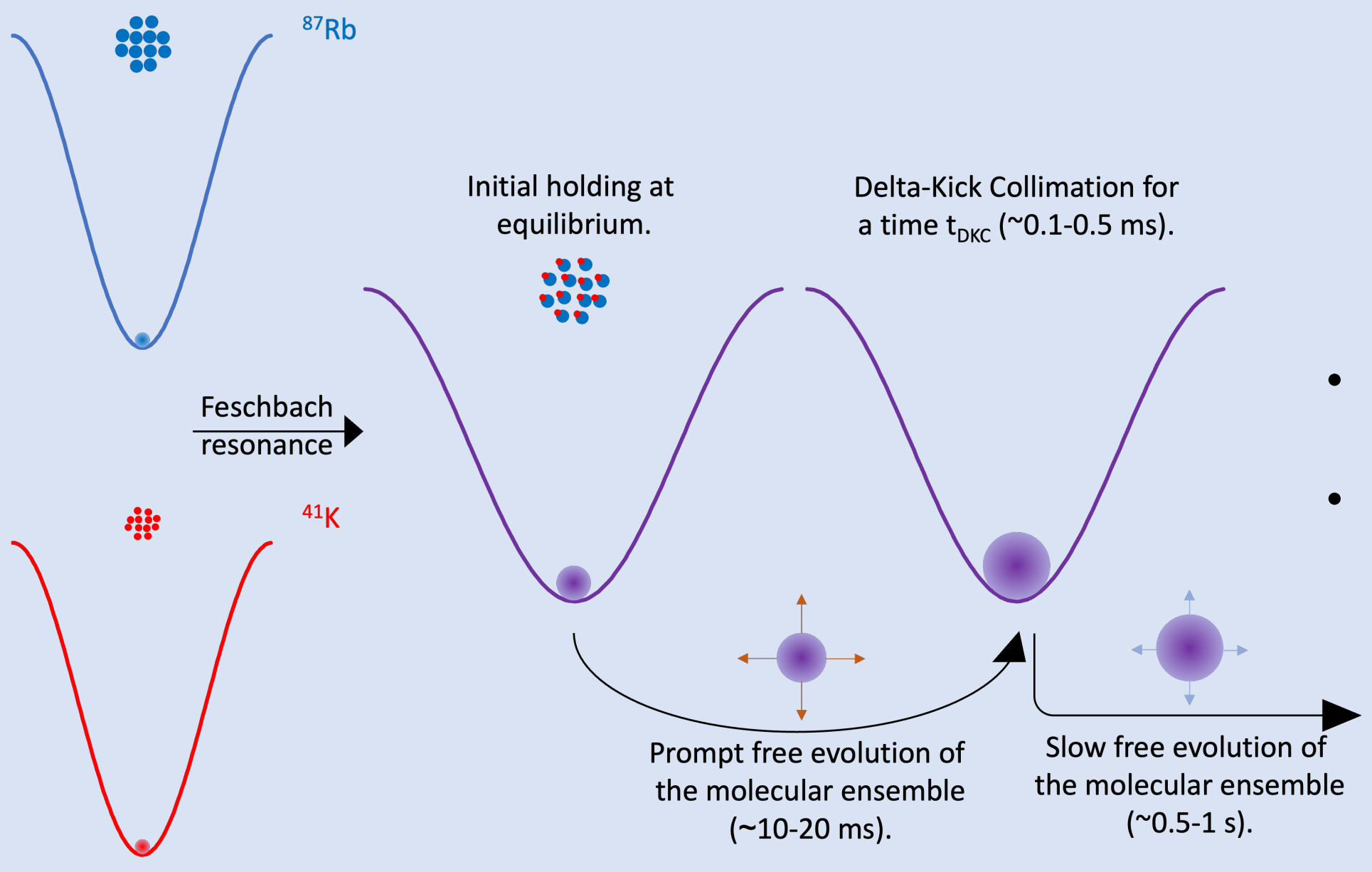
Molecular Delta-Kick Collimation

- Scaling law: $\sigma_j(t) = \sigma_j(0)\lambda_j(t),\ \ j \in \{x,y,z\}$.
- Thomas-Fermi model, variational approach: $T_0 = 0$ K.
- Hydrodynamical approach at 1D [8] ($T_0 \neq 0$ K):

$$\ddot{\lambda} + \omega_{Mol}^2(t)\lambda = \frac{\omega_{Mol}^2(0)}{\lambda^3} - \omega_{Mol}^2(0)\,\xi\left(\frac{1}{\lambda^3} - \frac{1}{\lambda^4}\right),$$

$$\xi = \frac{E_{mf}}{E_{mf} + k_B T_0}.$$





Initial holding at equilibrium.

Delta-Kick Collimation for a time t_{DKC} (~0.1-0.5 ms).

Prompt free evolution of the molecular ensemble (~10-20 ms).

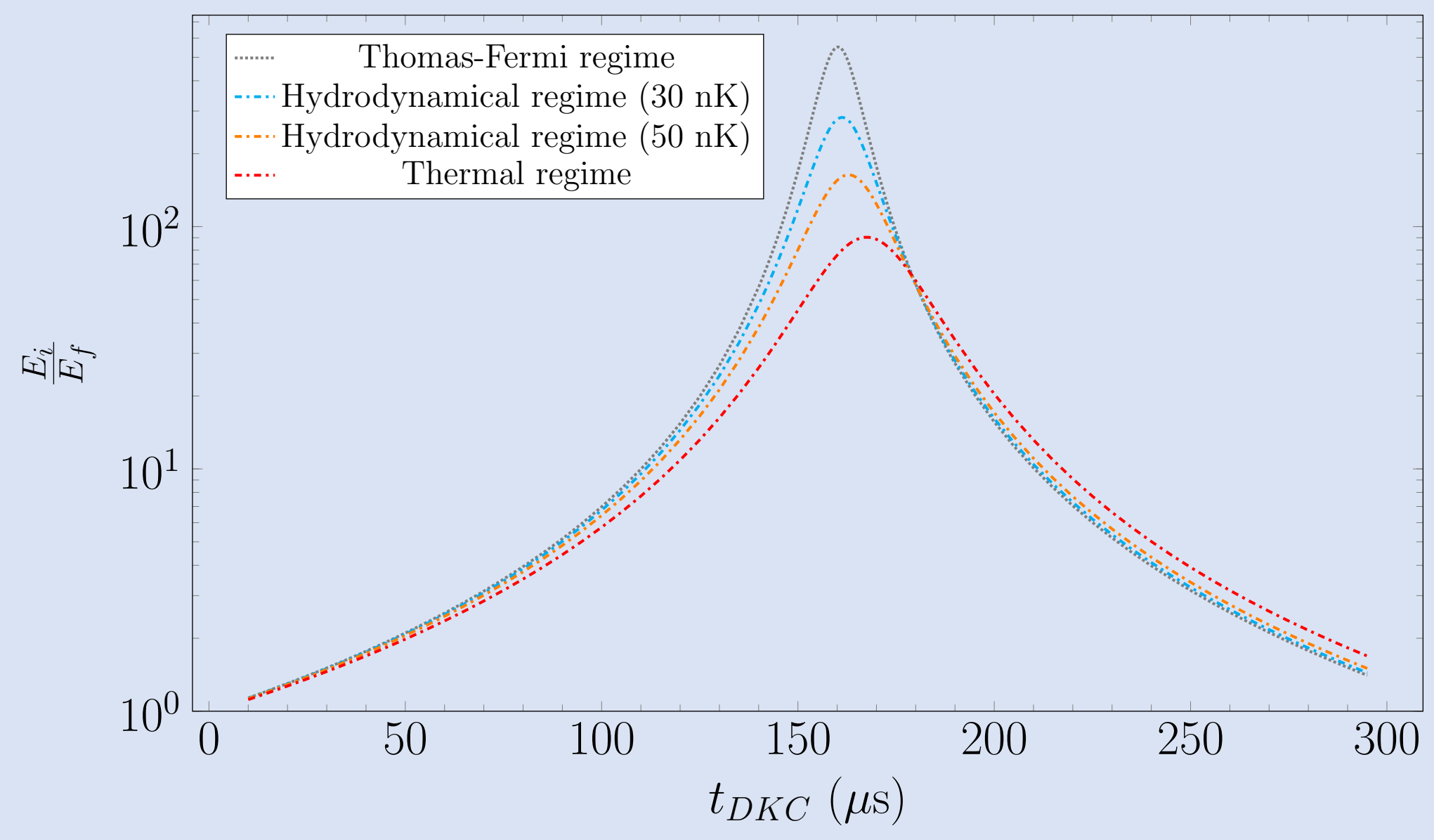
Slow free evolution of the molecular ensemble (~0.5-1 s).

- Use of Feshbach resonances to associate both species.
- Treatment of the molecules as point mass particles :

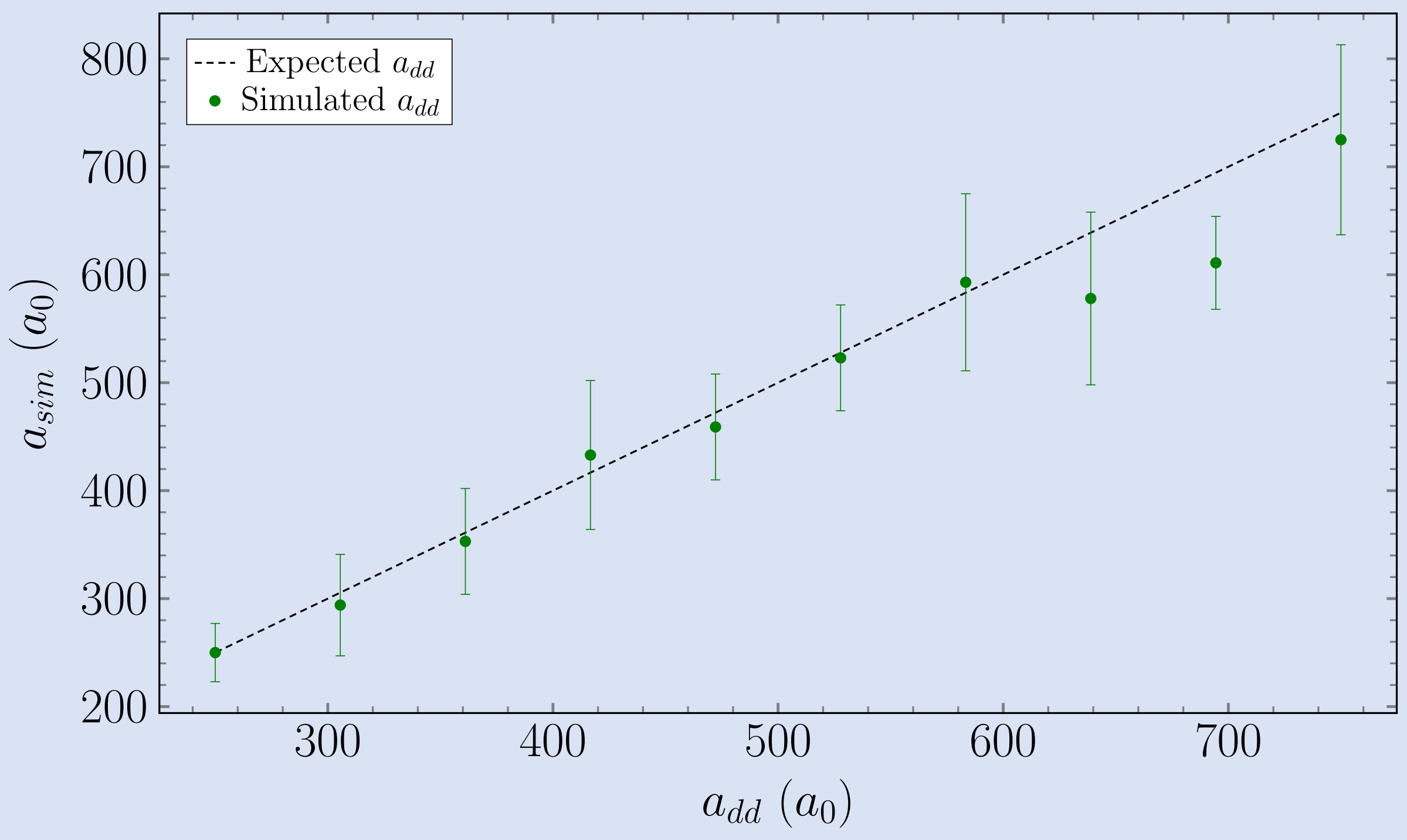
$$\alpha_{Mol} = \alpha_K + \alpha_{Rb}$$

$$\Longrightarrow \omega_{Mol}^2 = \frac{m_K\omega_K^2 + m_{Rb}\omega_{Rb}^2}{m_{Mol}}.$$

- Gain: $\frac{E_i}{E_f}$.
- 100 Hz at 1D: gain between 90 and 550.
- Higher frequencies (4 kHz) : 3.5×10^4.



- Using the different regimes this process can offer (under, well and over collimated), it can also be used to measure an unknown scattering length.



To be published : **T. Estrampes** *et al.* (2023).

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