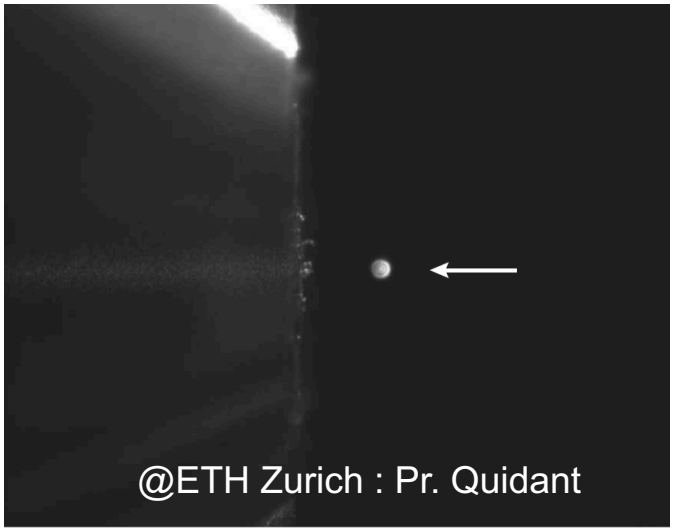
Optimal Cooling of Multiple Levitated Particles



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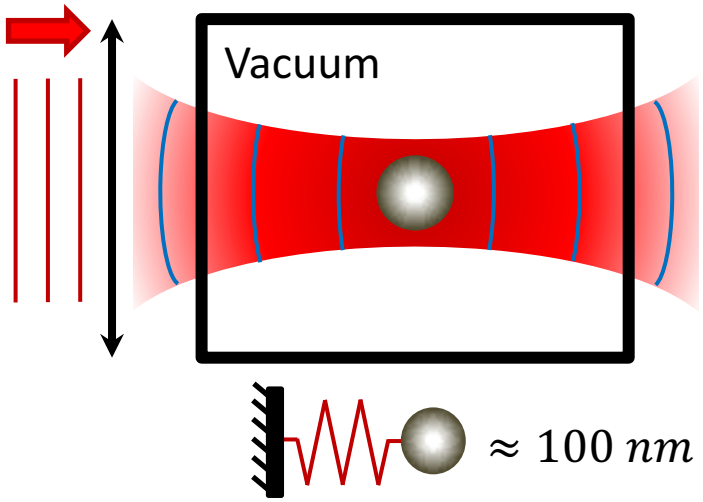
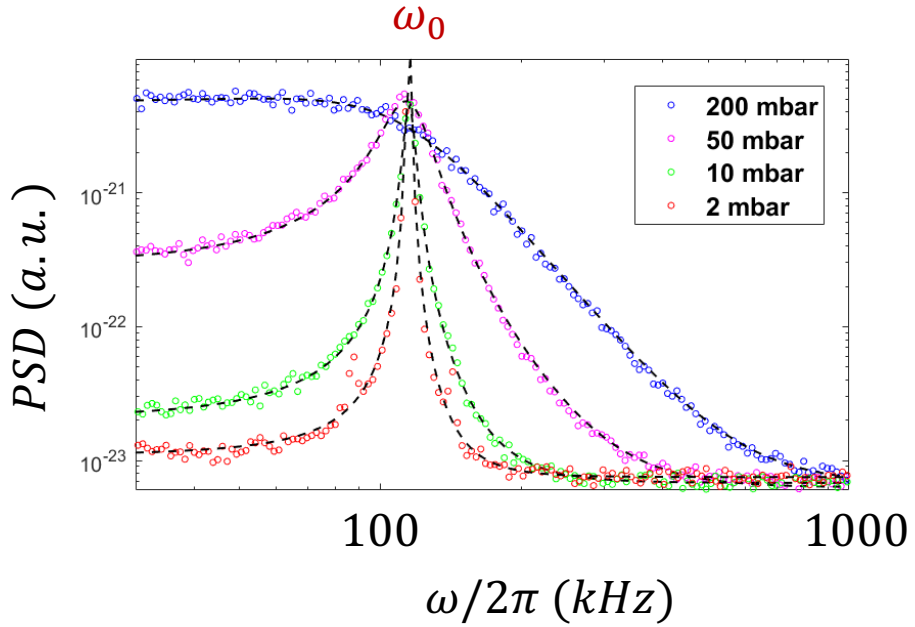
Optical levitation

- Opto-mechanical resonators:





- Quality factors → $Q_{meca} \approx 10^{11}$:

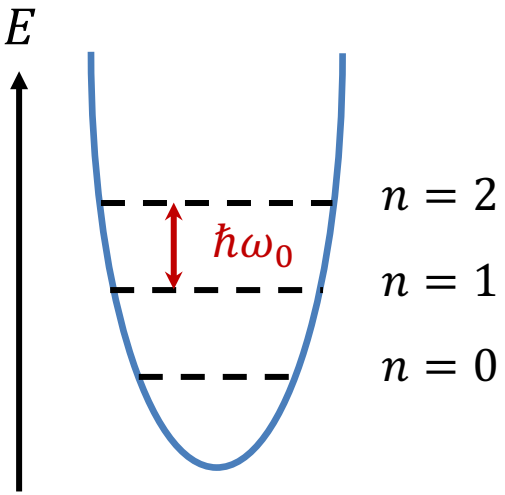
  Statistical physics| Metrology | Quantum mechanics| Gravitational waves …

  ↑

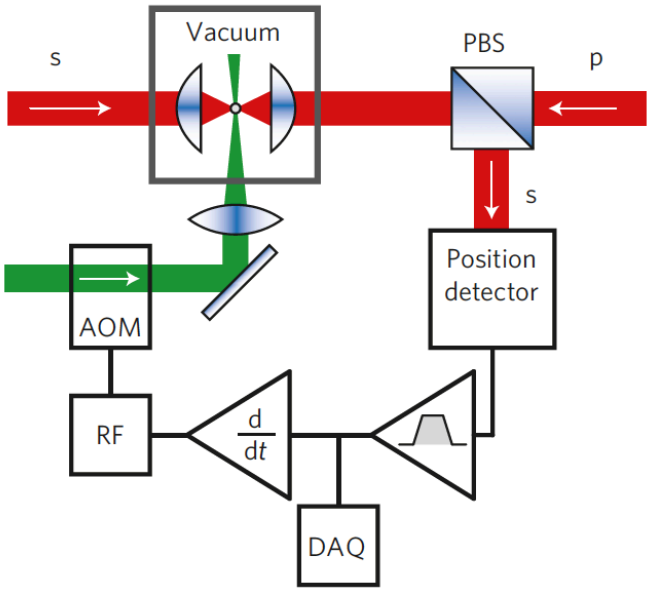
  (Mesoscopic)

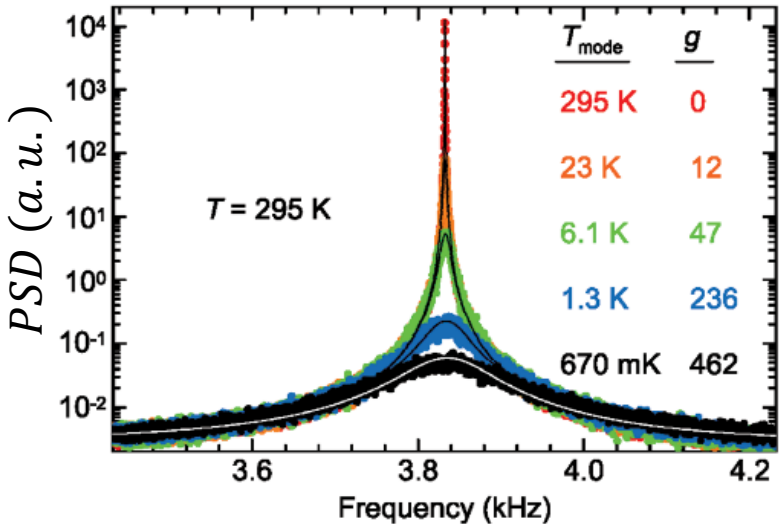
Cooling strategies: Linear cooling or "cold damping"

- Quantum → Cool vibrations



- Cold damping → $\vec{F} = -g\vec{v}$



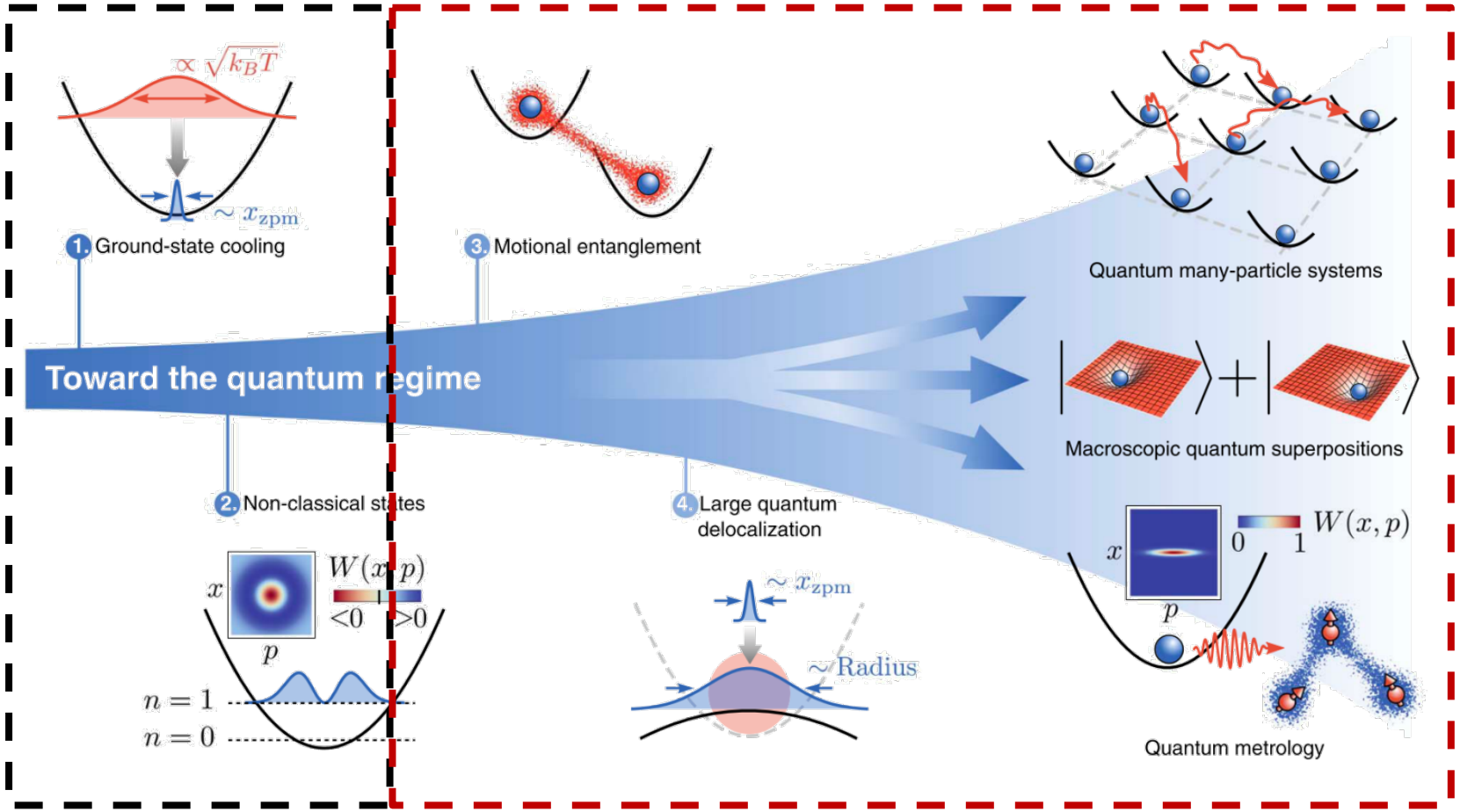


Li *et al.* (2011)

Paggio *et al.* (2007)

State of the art in levitation

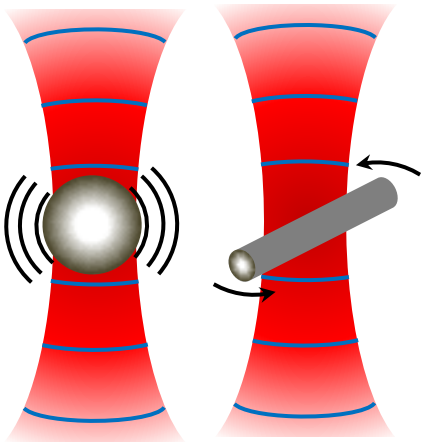
Gonzalez-Ballestero *et al.* (2021)

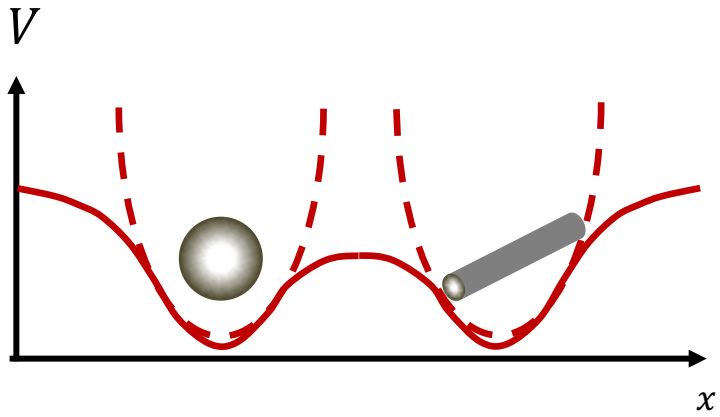


→ Many-body cooling

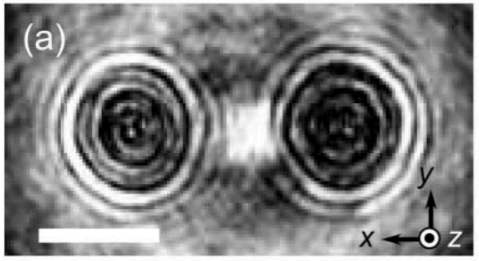
Many-body cooling

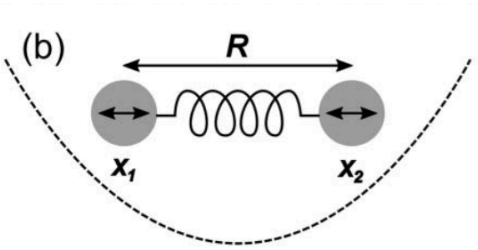
❑ Many-body trapping





❑ Optical binding

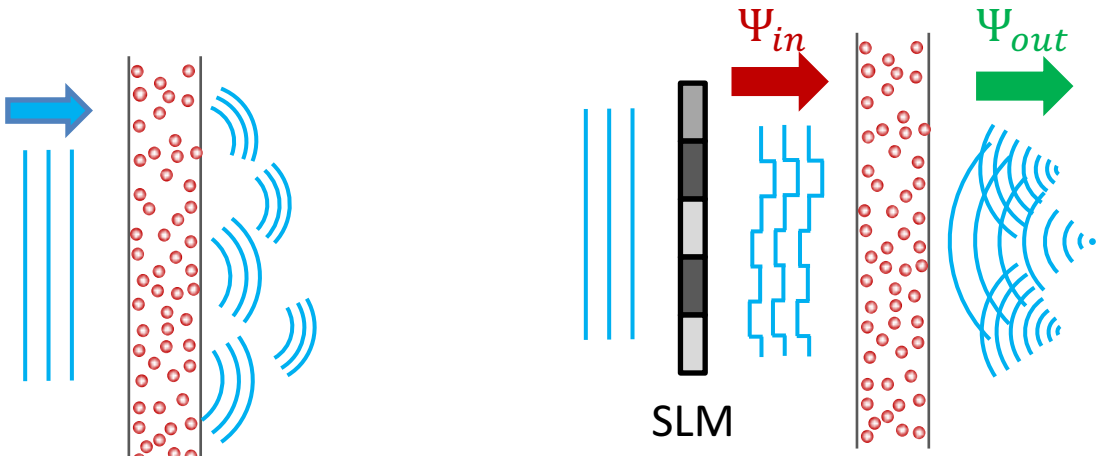




Arita *et al.* (2018)

⟶ Conventional cooling unapplicable

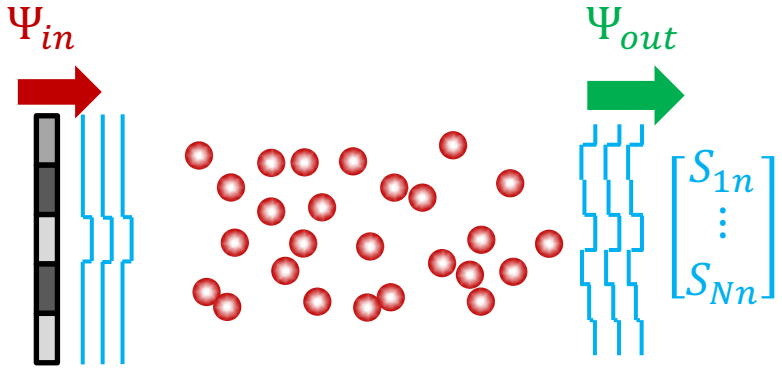
Wavefront shaping



Vellekoop *et al.* (2007)

- Scattering matrix S :

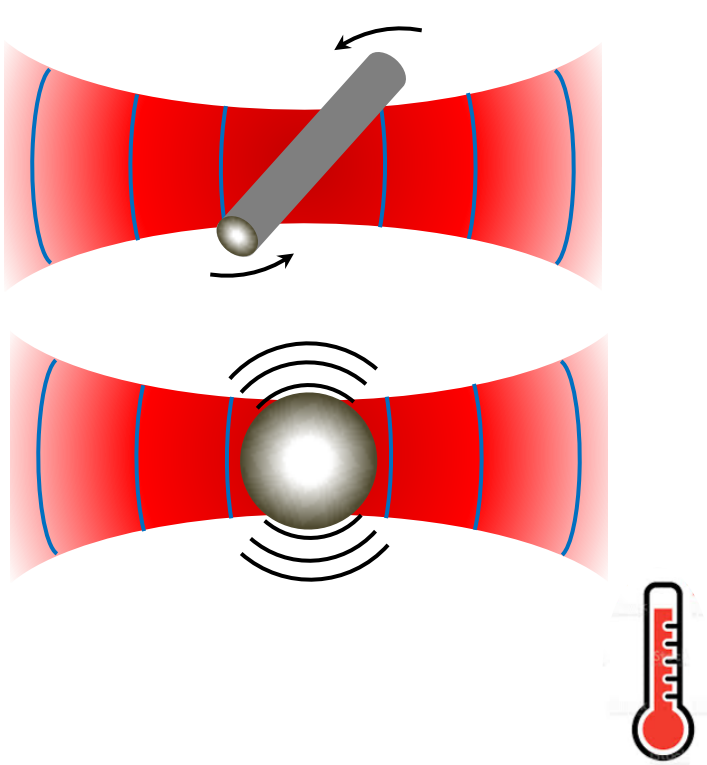
$$\begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \Psi_{in} = \Psi_{out}$$

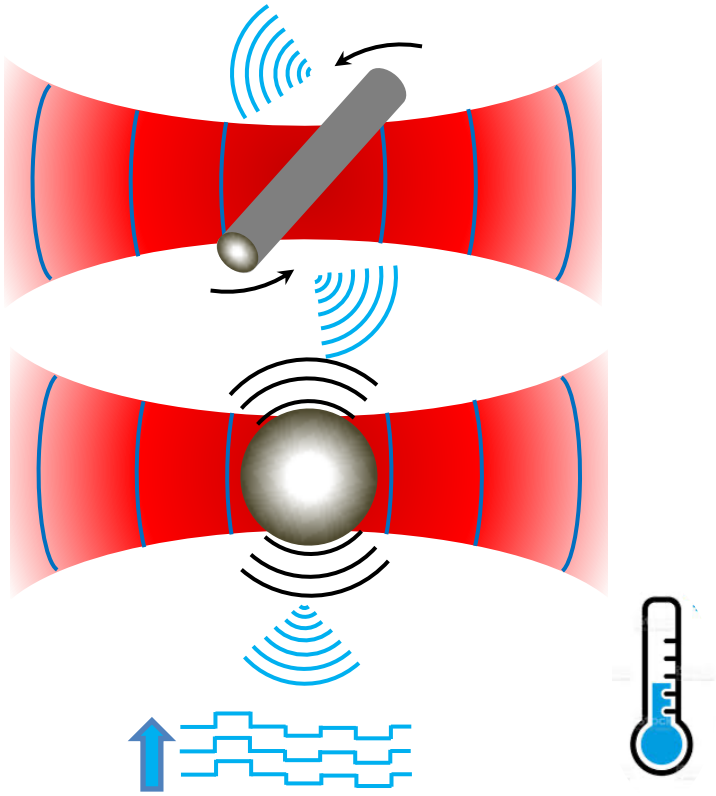


Popoff *et al.* (2010)

Concept

⟶ Wavefront shaping: Focus on particles regardless of binding

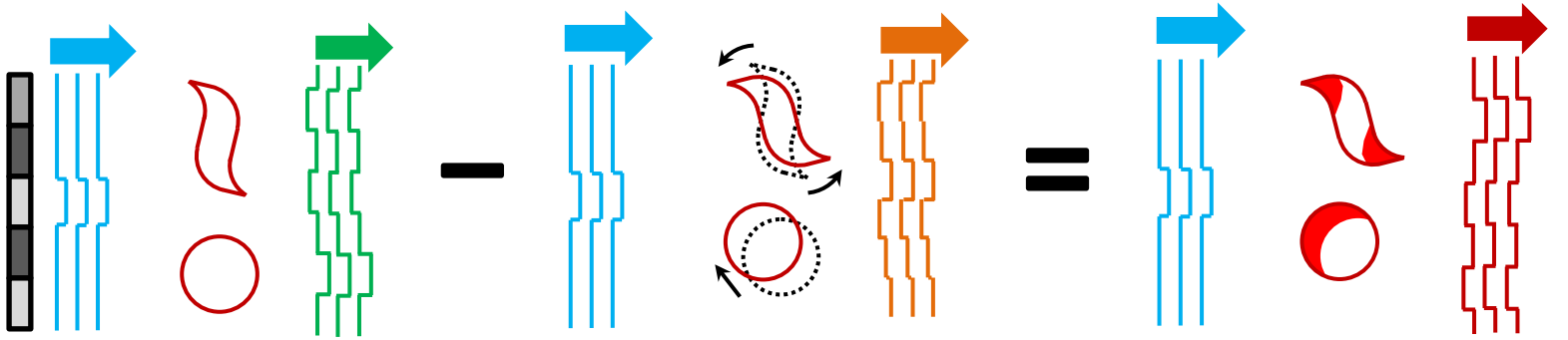




Implementation

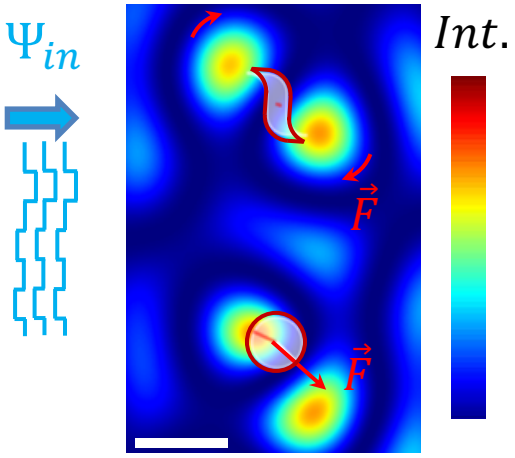
❑ Analysis → S to isolate the scattering of moving parts

$S(t)\Psi_{in} = \Psi_{out}$ $\quad S(t+\Delta t)$ $\quad Q_t \propto S(t+\Delta t) - S(t)$



❑ Wavefront shaping → Focusing

Simulation

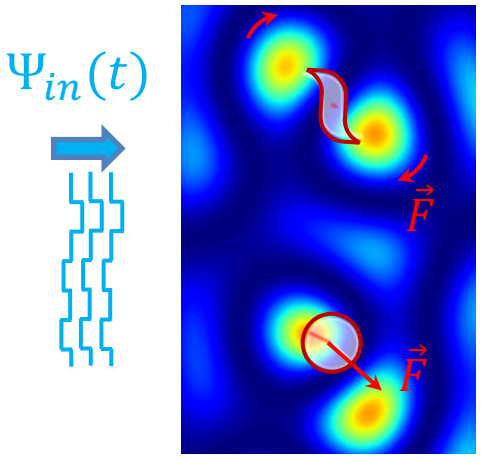


Hüpfl and Bachelard *et al.* (Arxiv)

Implementation: Scattering-matrix operator

- Energy-shift operator:

$$Q_t(t) = -i\, S(t)^{\dagger} \partial_t S(t)$$



- Energy-shift relation:

$$\langle \Psi | Q_t(t) | \Psi \rangle \approx \partial_t E_{tot}$$

Rotation and Translation of all particles

- Smallest EV (i.e., most negative):

$$Q_t(t)|\Psi_{in}\rangle = -|\alpha||\Psi_{in}\rangle \;\Rightarrow\; \text{Optimal reduction of } E_{tot}$$

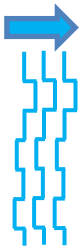
Implementation: Iterative process

- Time t:

$$Q_t(t) = -i\, S(t)^{\dagger}[S(t) - S(t - \Delta t)]$$

Smallest EV: $Q_t(t)|\Psi_{in}(t)\rangle = -|\alpha||\Psi_{in}(t)\rangle$

$\Psi_{in}(t)$



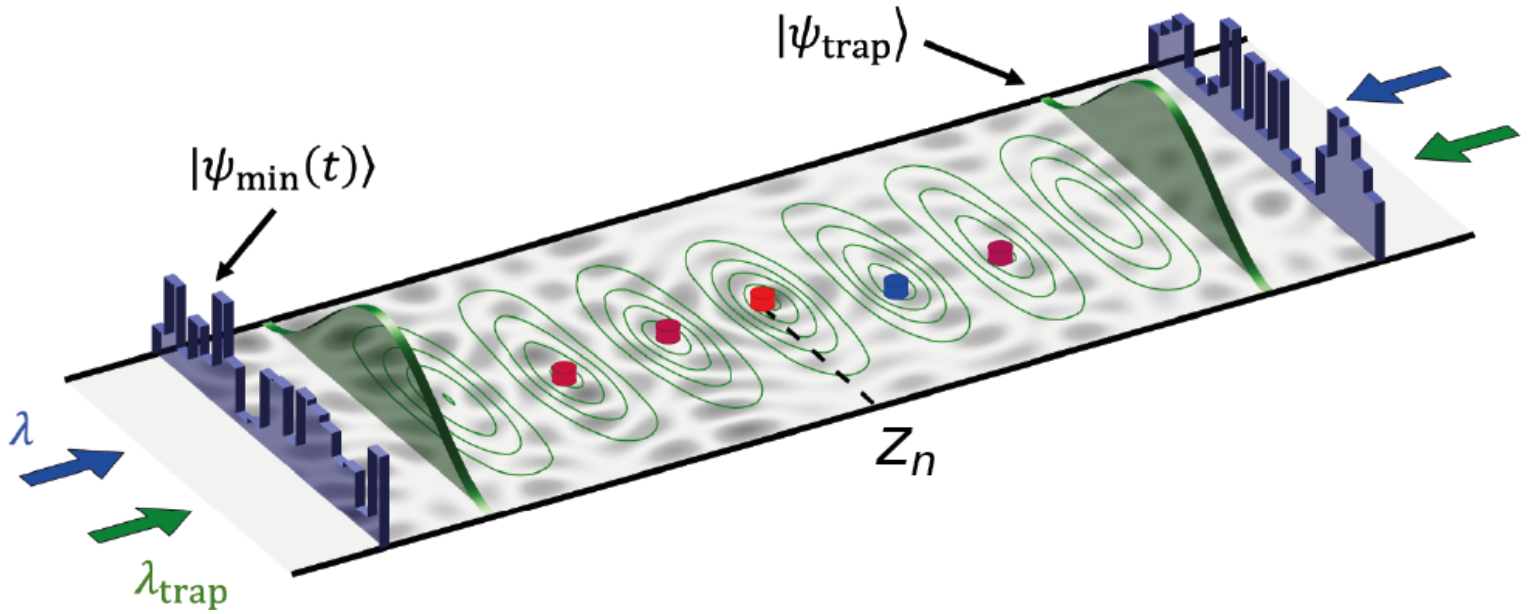
- Time $t + \Delta t$:

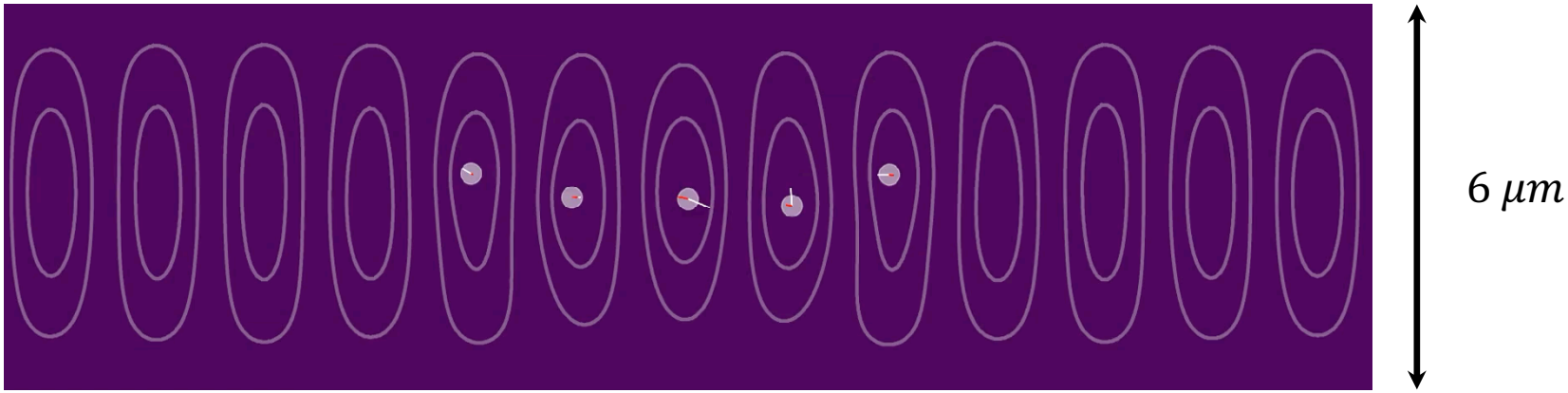
$$Q_t(t + \Delta t) = -i\, S(t + \Delta t)^{\dagger}[S(t + \Delta t) - S(t)]$$

Smallest EV: $Q_t(t + \Delta t)|\Psi_{in}(t + \Delta t)\rangle = -|\beta||\Psi_{in}(t + \Delta t)\rangle$

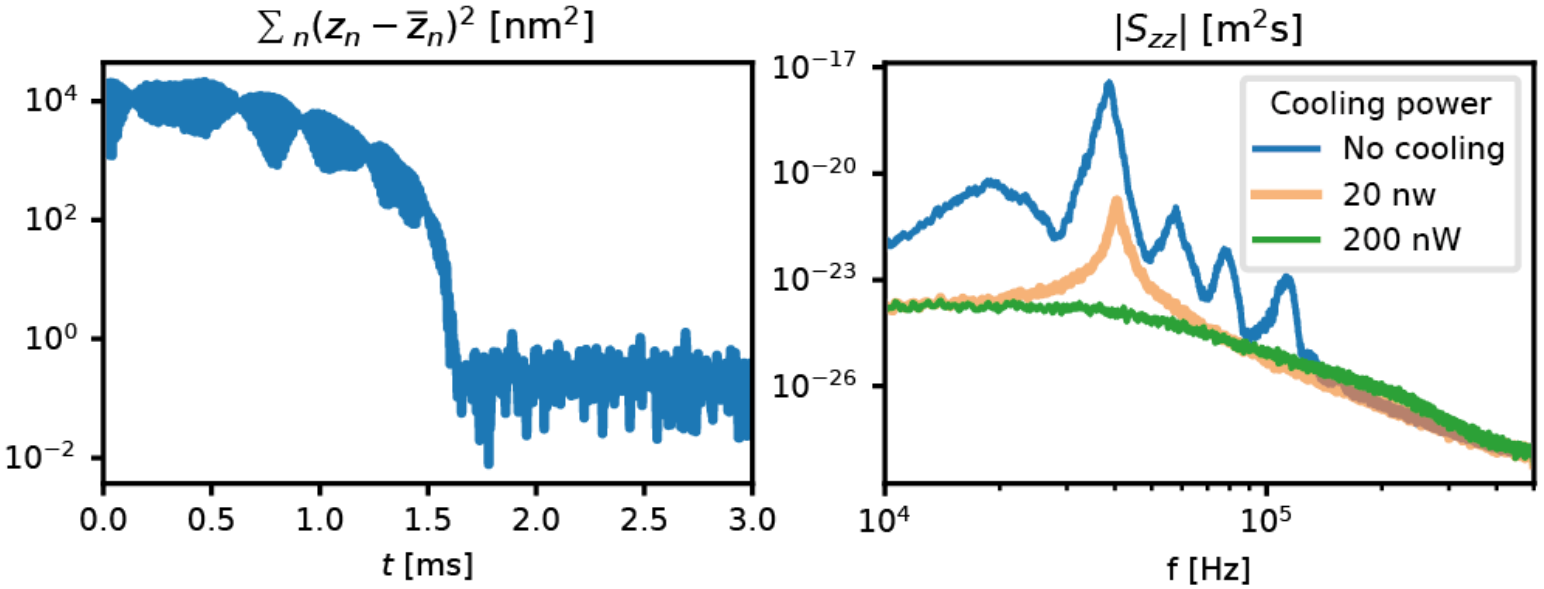
$\Psi_{in}(t + \Delta t)$

Numerical simulations: Scheme





Numerical simulations: Results



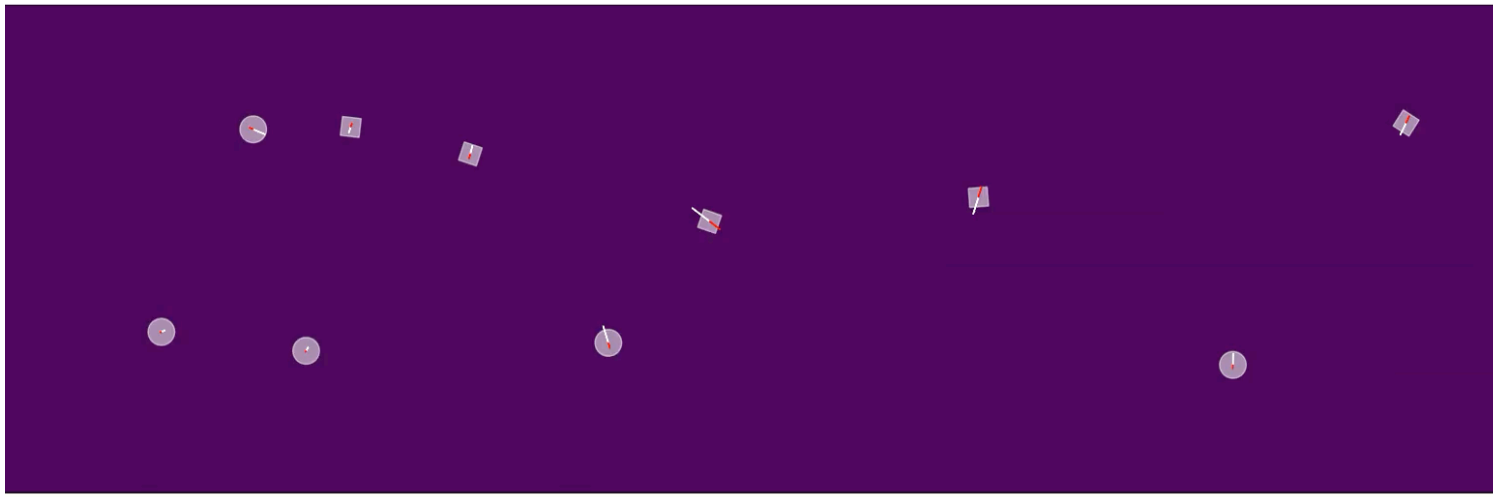
$\longrightarrow$ Cooling from $295\ K$ down to $10\ mK$

Hüpfl and Bachelard *et al.* (Arxiv)

Hüpfl *et al.* (Arxiv)

Numerical simulations: Different degrees of freedom

- Mixture of translation and rotations



Hüpfl and Bachelard *et al.* (Arxiv)

Hüpfl *et al.* (Arxiv)

Conclusion

- ❑ First many-body cooling of coupled elements
- ❑ Any degree of freedom (rotation + translation)
- ❑ Robustness to partial reconstruction of S
- ❑ Ongoing experimental implementation