Ions in Optical Lattices

Suppression of Ion Transport due to Long-Lived Sub-Wavelength Localization by an Optical Lattice

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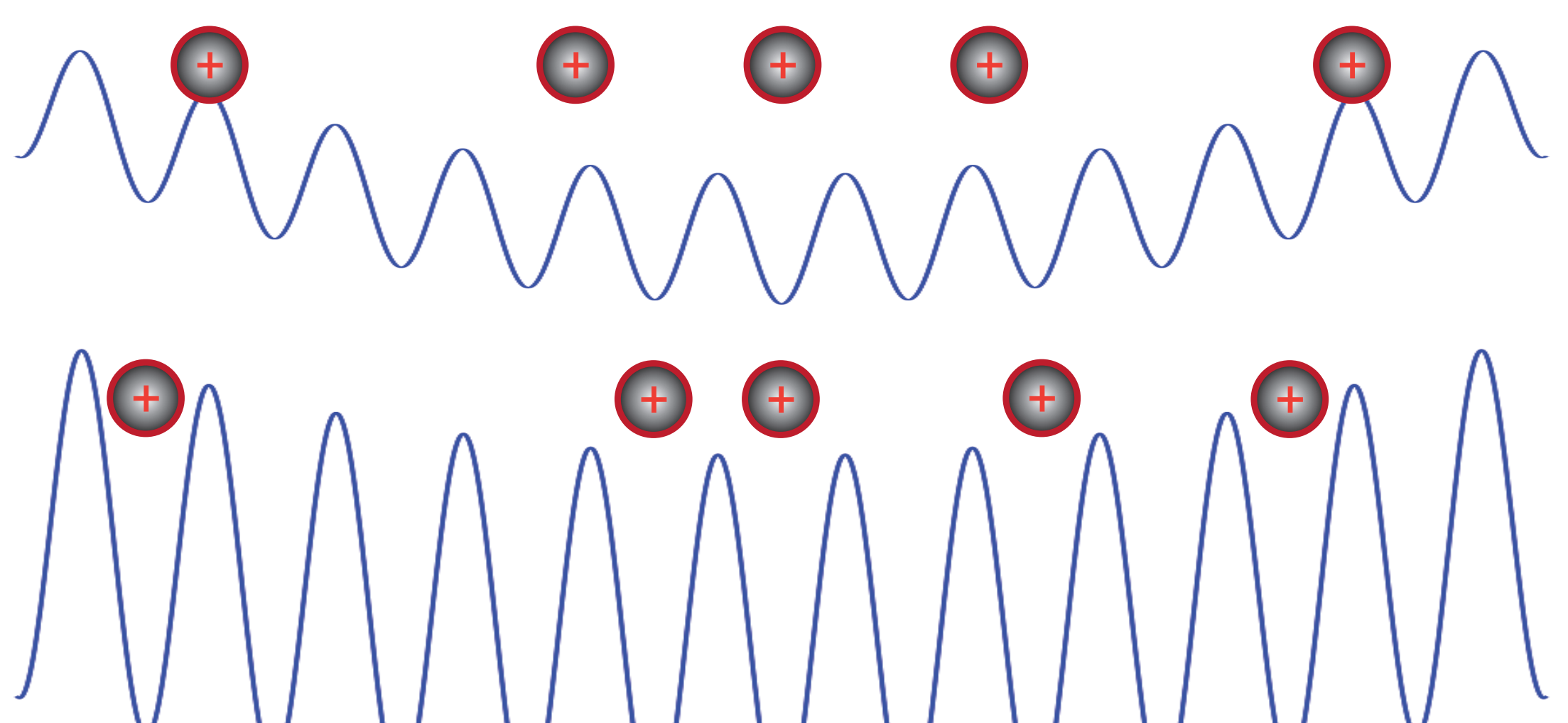
Why: Quantum Nanotribology

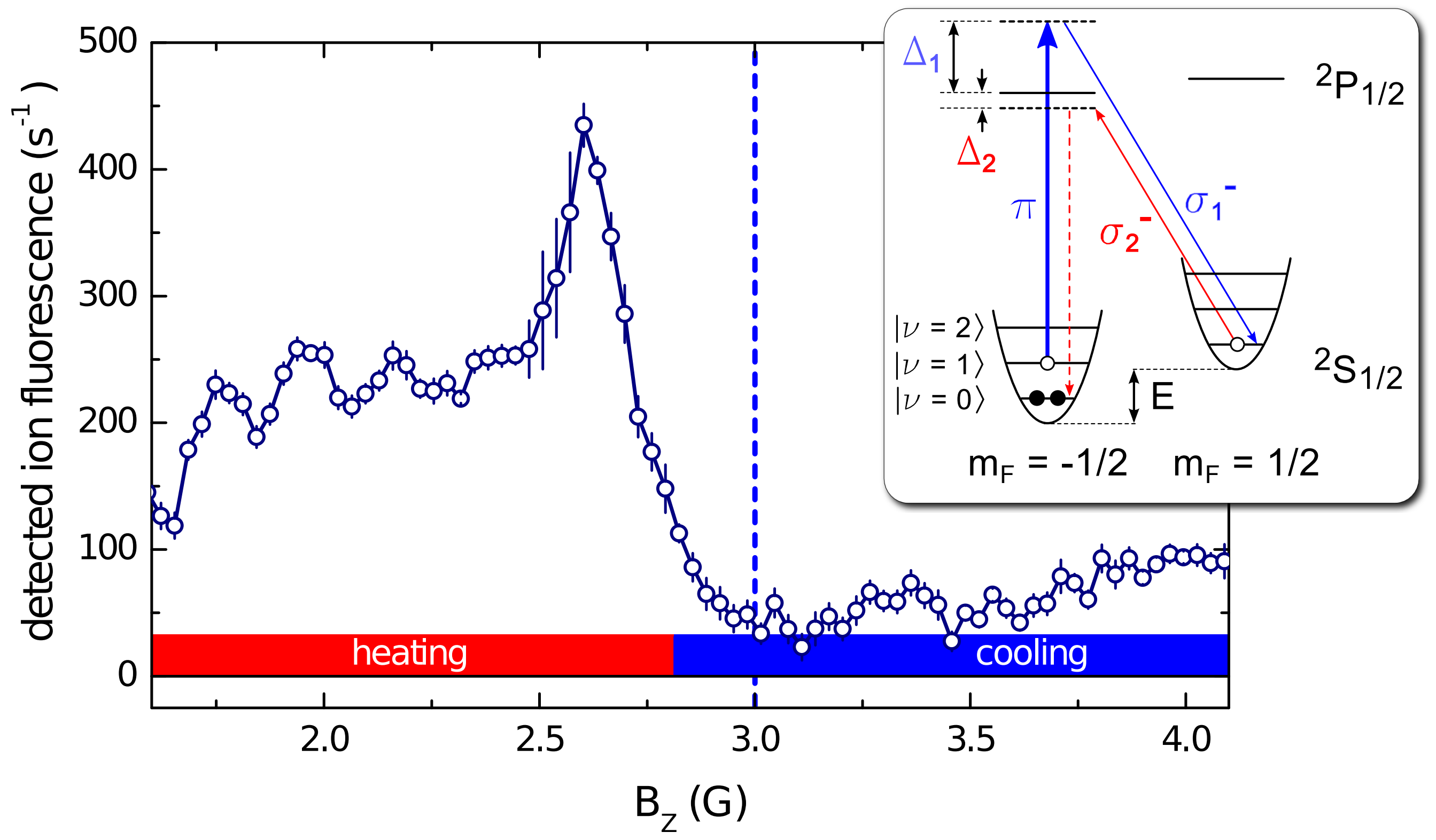
- Quantum Engineering at the nanoscale will require an undestanding of friction forces in the quantum regime. [3]
- What role does quantum mechanics play in describing friction at the mesoscopic scale?
- How does the smearing of the Aubry transition in the quantum regime affect the onset of friction in the Frenkel-Kontorova model? [3]
- Strongly interacting particles, such as ions, in periodic potentials provide a testbed for simulating such behaviour. [1,2,4]



- How do ions re-organize themselves under the competing interactions with neighboring ions and with an optical lattice? [2,4]
- In what regime can we optically trap ions, so as to reach this regime of competing interactions?

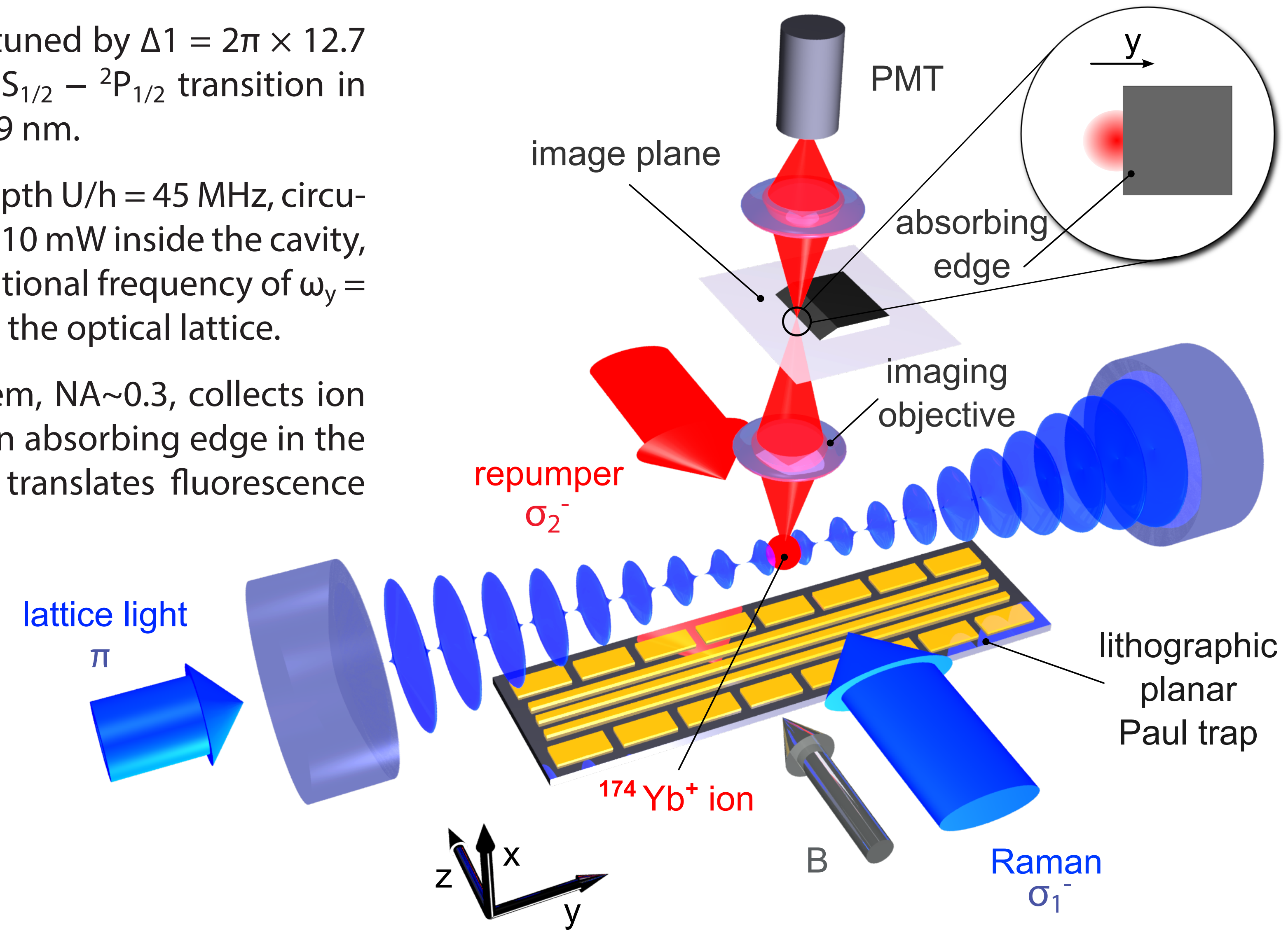
Lattice-assisted Raman Cooling

- Raman sideband cooling, π-polarized trapping light and $\sigma-$ beam used to drive transitions between magnetic sublevels. B field along the z-axis tunes the Raman transition into resonance with the y-axis red vibrational sideband.
- Blue-detuned lattice: atoms are trapped at the nodes where the coupling is exp(kz)sin(ky), there is only cooling to 1st order in the Lamb-Dicke parameter $\eta = (\omega_{rec}/\omega_y)$ along y.
- Fluorescence is a measure of temperature due to increasing AC stark shifts on the pumping beam away from the trap minimum. The low fluorescence on the cooling side of the spectrum is an indication of localization.
- In the 2-photon saturated regime, the residual fluorescence is proportional to the population not in n=0. Under optimized conditions, $\langle n \rangle = 0.1 \pm 0.1$. [5]



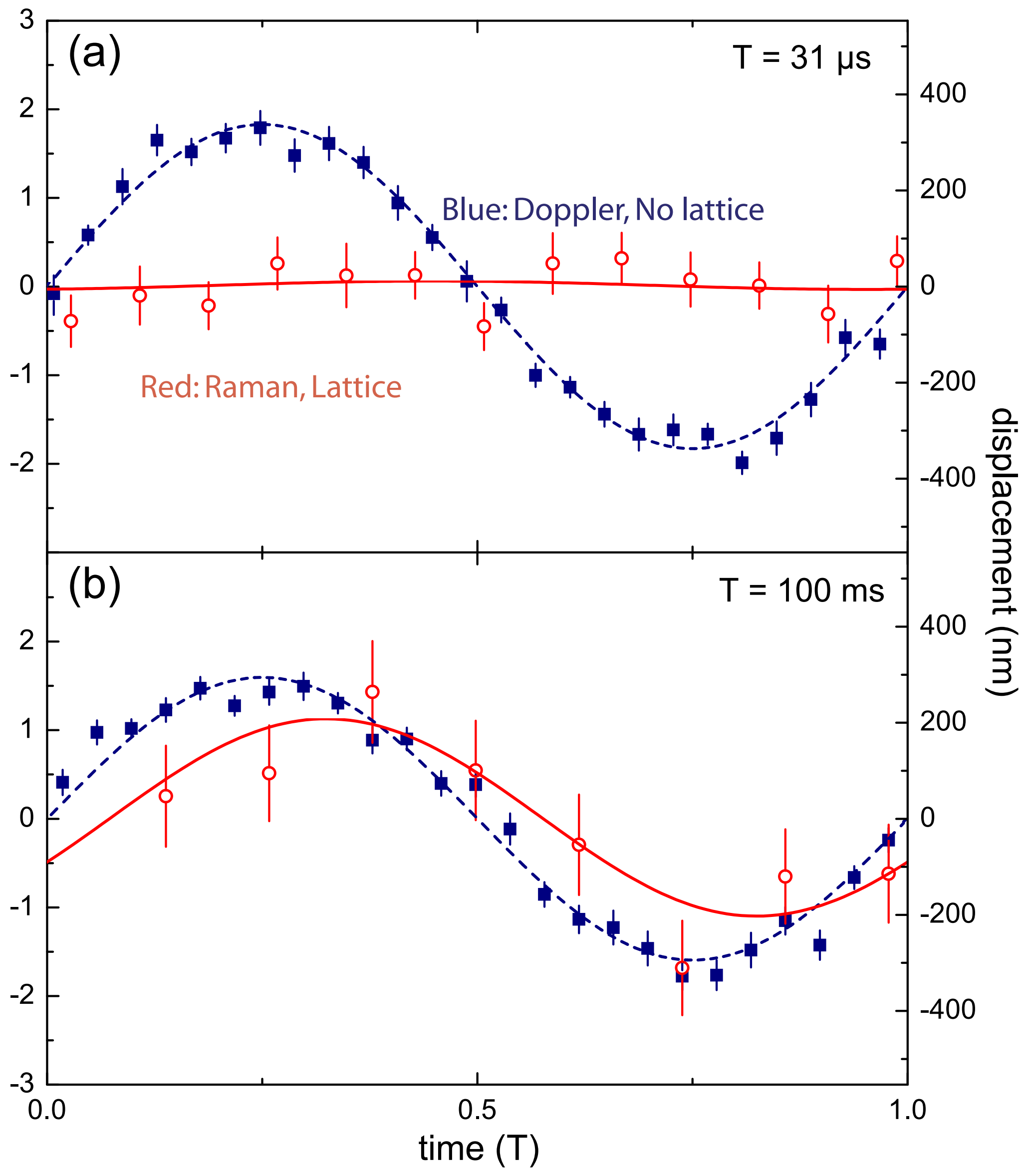
Cavity Mode as a 1D Optical Lattice

- Lithographic planar Paul trap with radial confinement $\omega_z \approx \omega_x \approx 2\pi \times 1.1$ MHz and weak y-axis electrostatic confinement, $\omega_y = 2\pi \times 130$ kHz (and superimposed optical lattice).
- Optical lattice trap, from cavity ($F \approx 1500$), aligned with linear rf quadrupole trap; TEM_{00} mode of the cavity has a waist size of 38 µm.
- Laser blue detuned by $\Delta 1 = 2\pi \times 12.7$ GHz from the $^2S_{1/2} - {}^2P_{1/2}$ transition in $^{174}Yb^+$ at $\lambda = 369$ nm.
- Typical trap depth $U/h = 45$ MHz, circulating power of 10 mW inside the cavity, and a trap vibrational frequency of $\omega_y = 2\pi \times 1.2$ MHz in the optical lattice.
- Imaging System, NA~0.3, collects ion fluorescence. An absorbing edge in the imaging plane translates fluorescence into position.



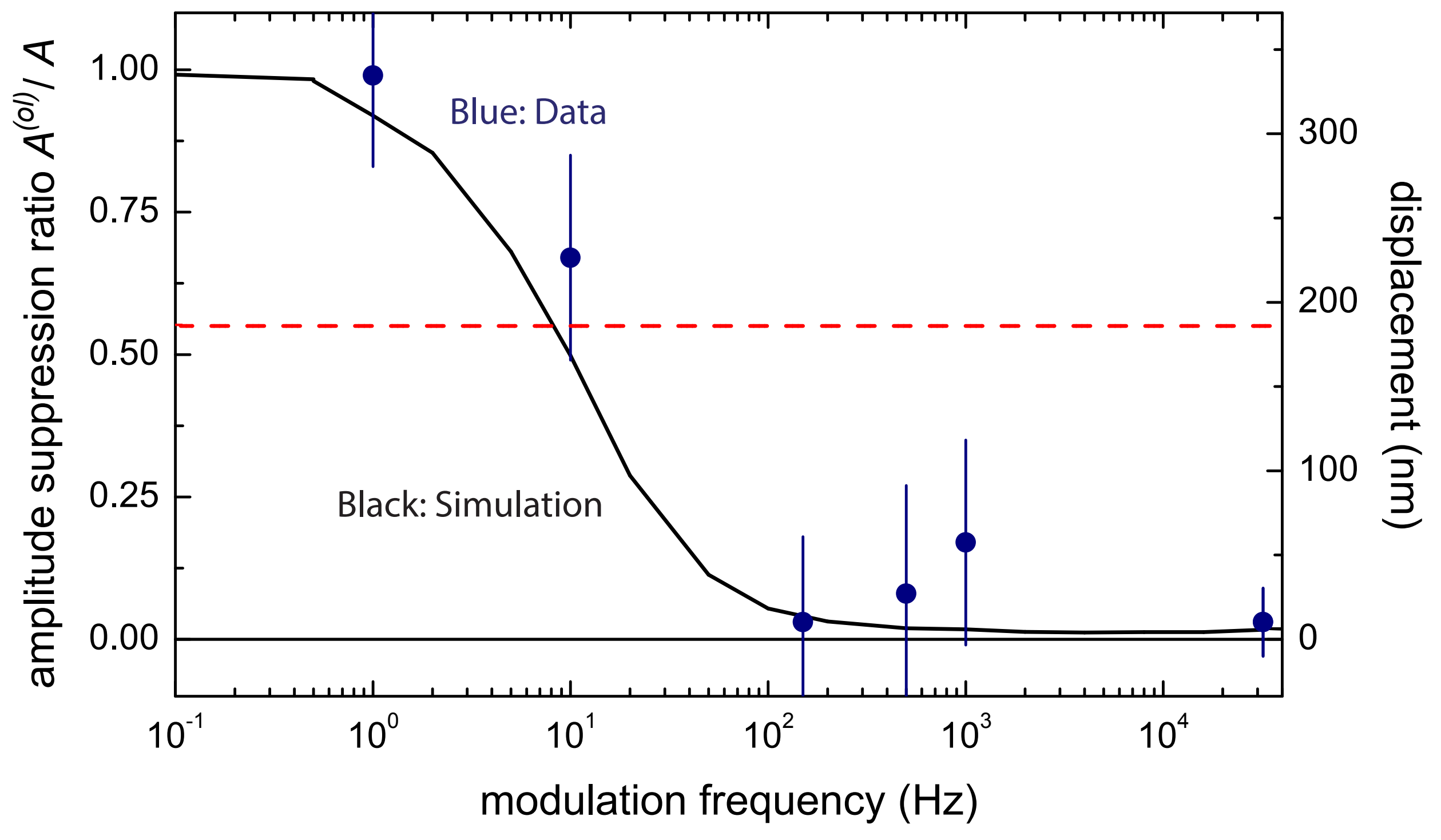
Sub-Wavelength Position Detection & Localization

- The collected ion fluorescence is linearly dependent on the ion position. By sufficiently long integration we find the ion average position to much better than the resolution D = 2.9µm or even the optical wavelength λ.
- A lock-in technique enables resolving relative ion motion on time scales much shorter than the signal integration time. A slowly varying electric force with period T displaces the ion along the y-axis, we measure the time-resolved ion fluorescence synchronously with the applied force, and integrate the signal. Under Doppler cooling conditions (blue solid squares), with an integration time of 150s, we can resolve the ion's average response to the applied force down to 10 nm ≈ λ/40.
- We then turn on the optical lattice and switch to Raman cooling. If the modulation is not too slow, we observe a strong suppression of the ion's driven motion, to an amplitude consistent with zero, $A^{(ol)} = 10 \pm 20$ nm, and much smaller than the lattice spacing $\lambda/2 = 185$ nm or the amplitude $A^{(ref)} = 340 \pm 10$ nm in the pure Paul trap under the same conditions. [5]



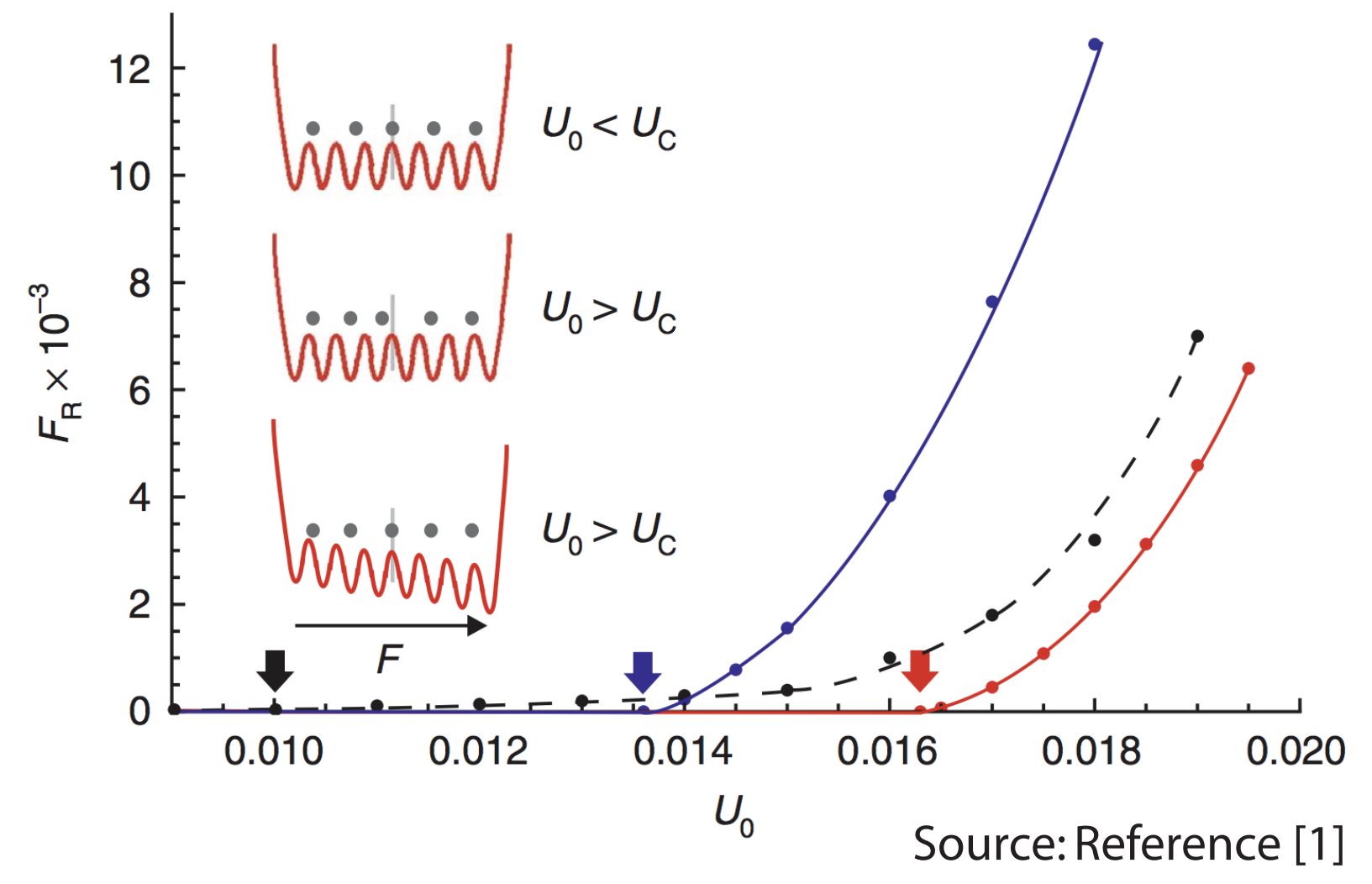
Trapping Time & Thermal Diffusion

- From best repeatedly observed amplitude suppression for a set of frequencies of the applied force, we infer an approximate trapping time on the order of 0.1s, corresponding to an amplitude suppression of the driven motion by 30%. This is 10^4 longer than the optical trap period of 1µs [5]
- Ion transport dynamics in the lattice: probabilistic model of the ion's energy; on a time scale set by the cooling rate, energy randomly samples the thermal distribution (fixed T). At the cooling rate, the energy changes by a motional quantum (up or down), weighted by the ratio of Boltzmann factors. If the energy is smaller than the lattice depth it stays localized at that site. Otherwise the ion follows the external displacement in the shallow electric potential, until its recapture occurs in one of the optical lattice sites (distributed thermally) [5]

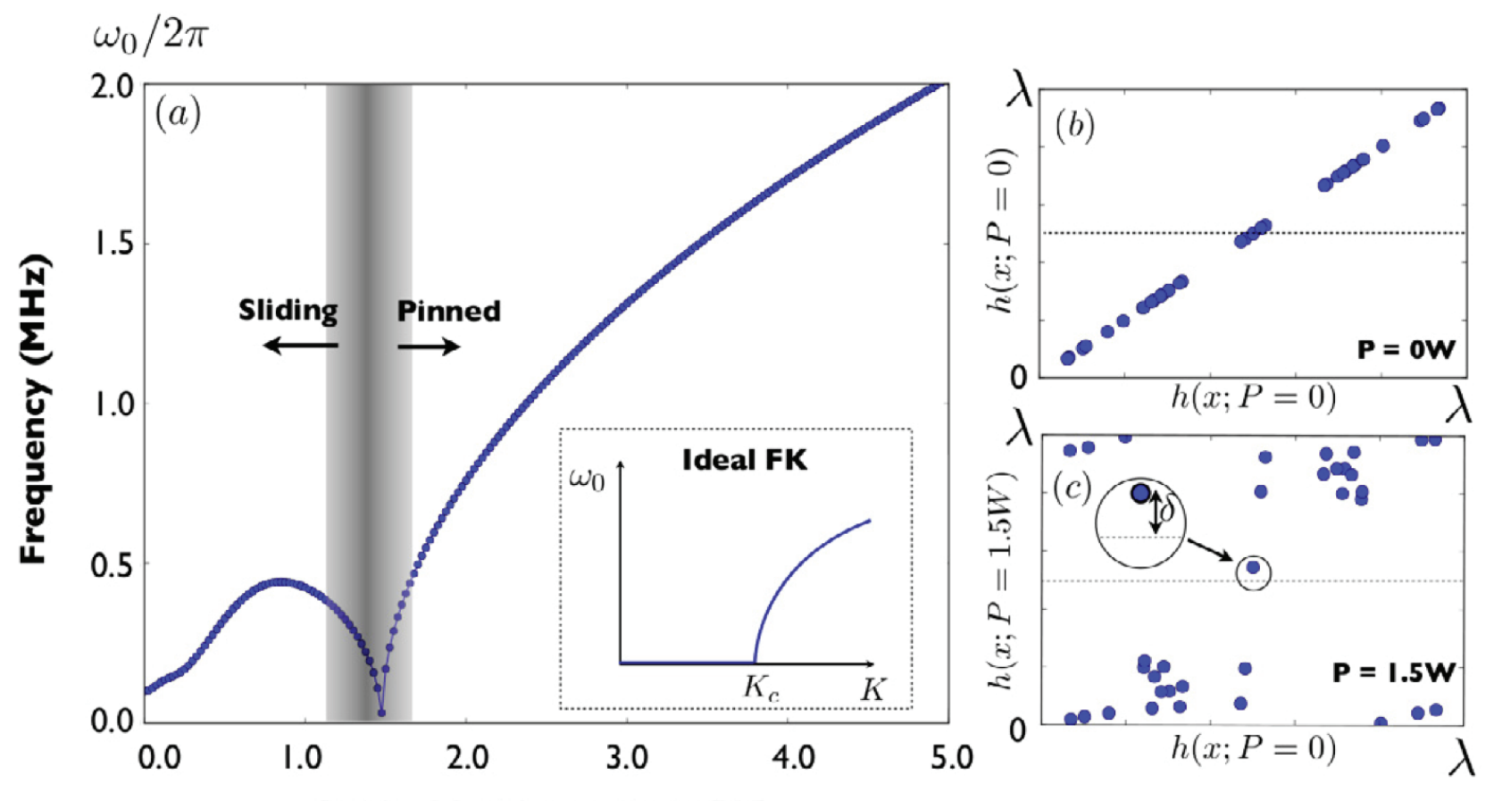


Short-Term Outlook: Classical Friction

- Study friction of ion chains in the lattice across the sliding–pinned phase transition, using transport measurements on time scales shorter than thermal. Two regimes: static (weak perturbation < λ/2), dynamic (strong perturbation >> λ/2)



Source: Reference [1]



Source: Reference [2]

- Study phase transition via sub-λ position detection and motional spectroscopy

References:

[1] Benassi, a, Vanossi, a, & Tosatti, E. (2011). Nanofriction in cold ion traps. Nature communications, 2, 236.
[2] Pruttivarasin, T., Ramm, M., Talukdar, I., Kreuter, A., & Häffner, H. (2011). Trapped ions in optical lattices for probing oscillator chain models. New Journal of Physics, 13(7), 075012.
[3] Hu, B., & Li, B. (2000). Quantum Frenkel-Kontorova Model. Physica A: Stat. Mech. and its Applications, 1–20.
[4] I. Garcia-Mata, et al. *Frenkel-Kontorova model with cold trapped ions*. The European Physical Journal D, 41(2):325–330, September 2006.
[5] Karpa, L., Bylinskii, A., Gangloff, D., Cetina, M., & Vuletić, V. (2013). Suppression of Ion Transport due to Long-Lived Sub-Wavelength Localization by an Optical Lattice,, http://arxiv.org/abs/1304.0049