UNIVERSITÉ TOULOUSE III PAUL SABATIER

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icb

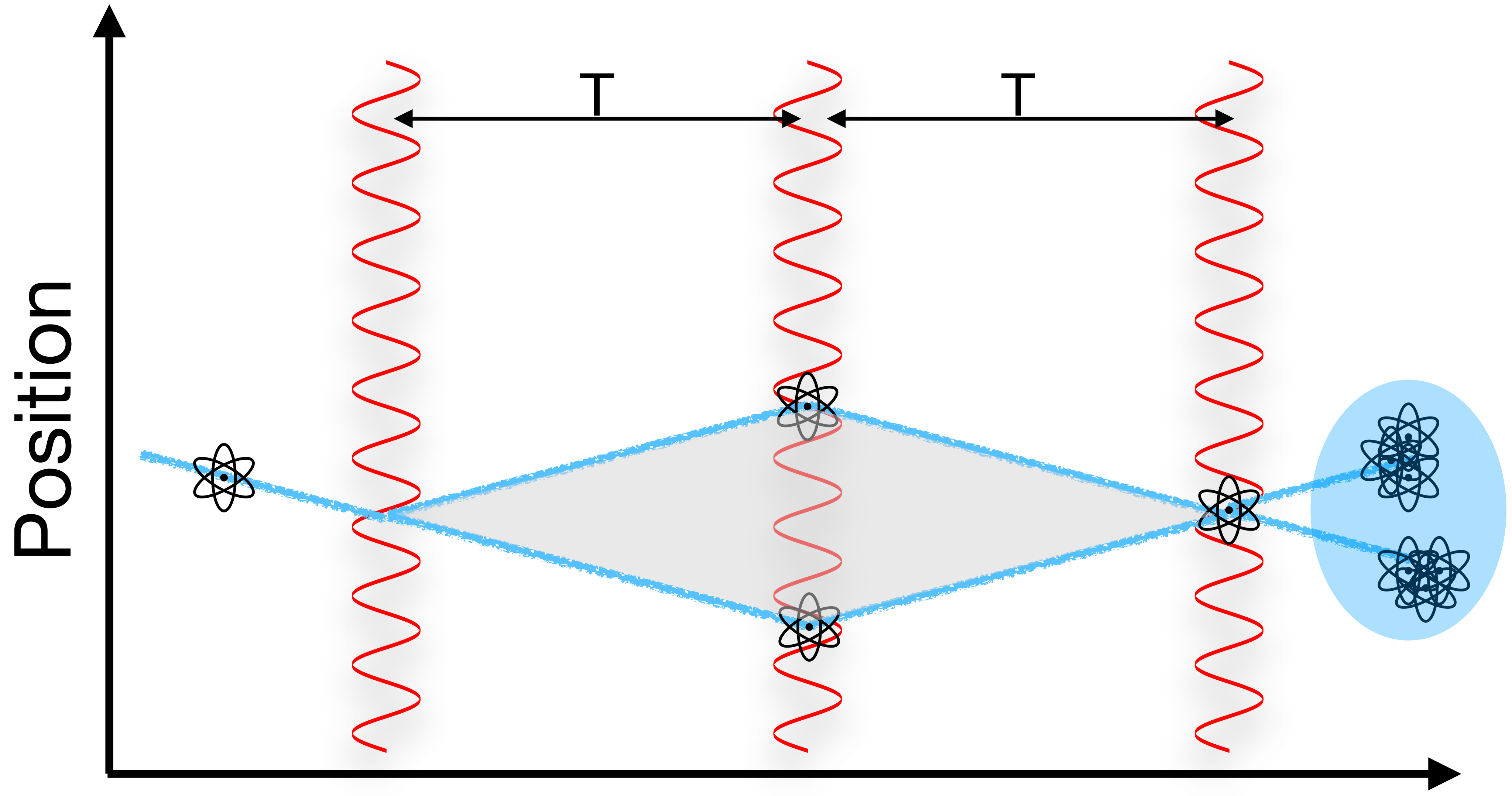
# Optimal Floquet Engineering for Large Scale Interferometer

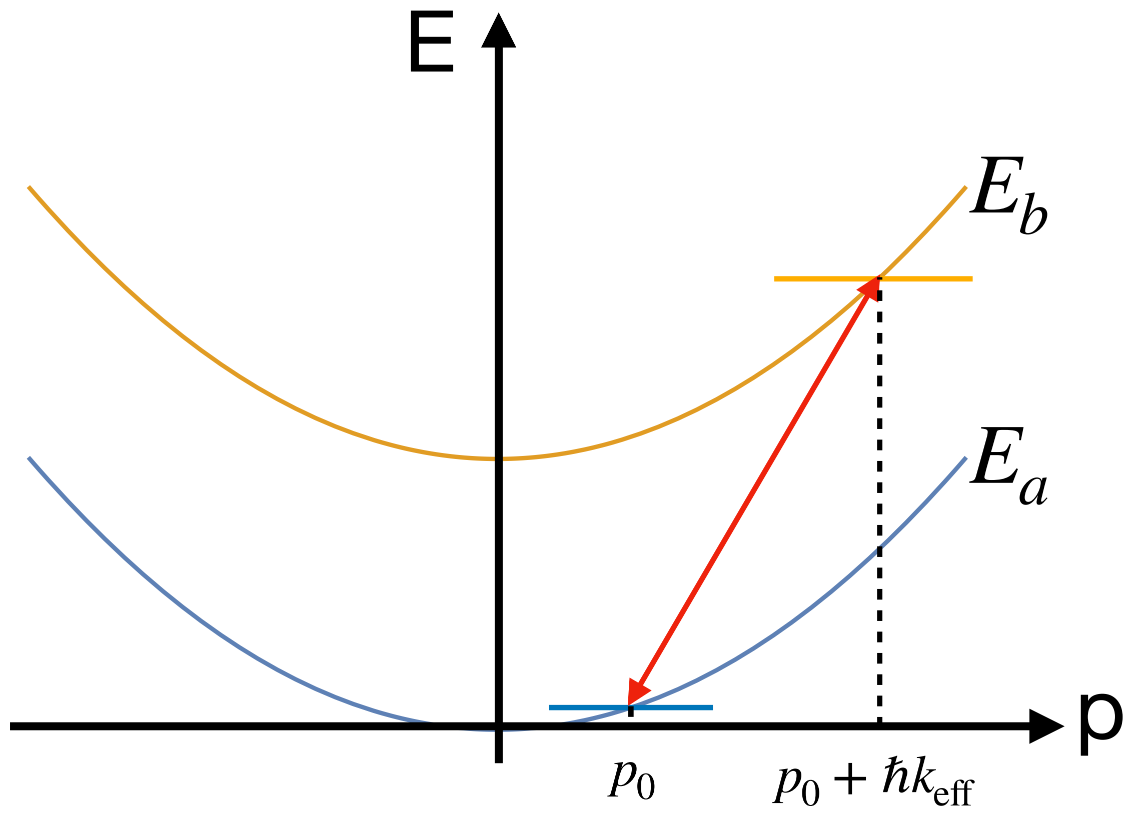
Alexandre Gauguet

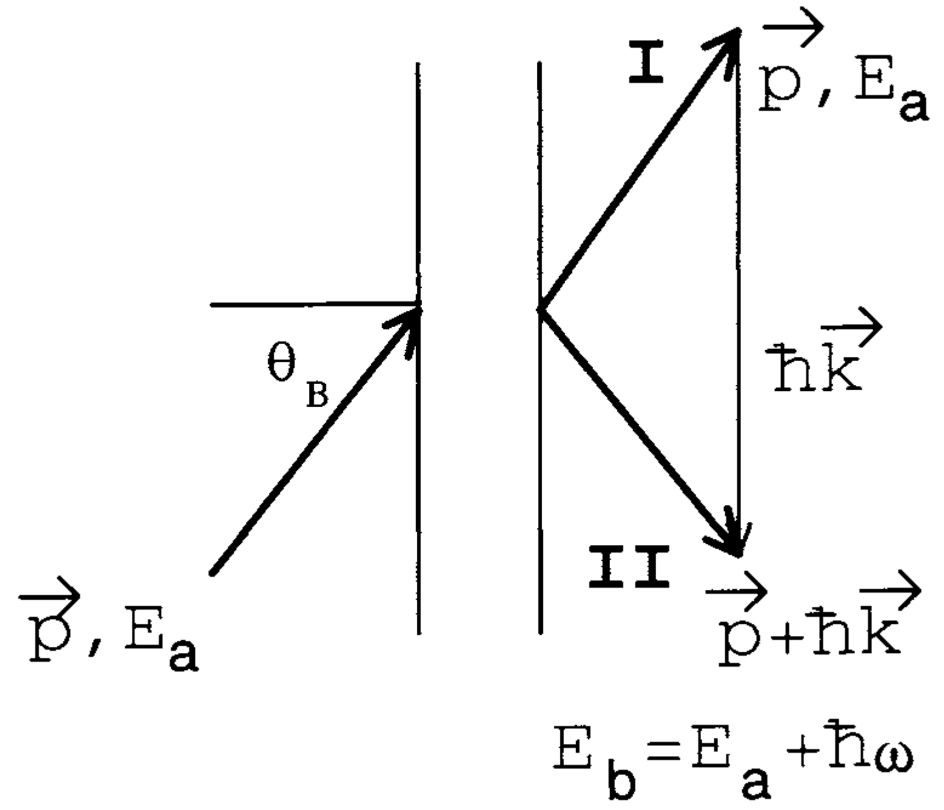
2nd Terrestrial Very-Long-Baseline Atom Interferometry Workshop - April 3,  2024

# Light-pulse Atom Interferometry

## Large Momentum Transfer (LMT)




C.J Bordé, *Matter-Wave Interferometers: a synthetic approach*, (1997)

Coherent transfer of momentum from light-fields $\hbar k_{\text{eff}}$ to the atomic wave function.

# Light-pulse Atom Interferometry

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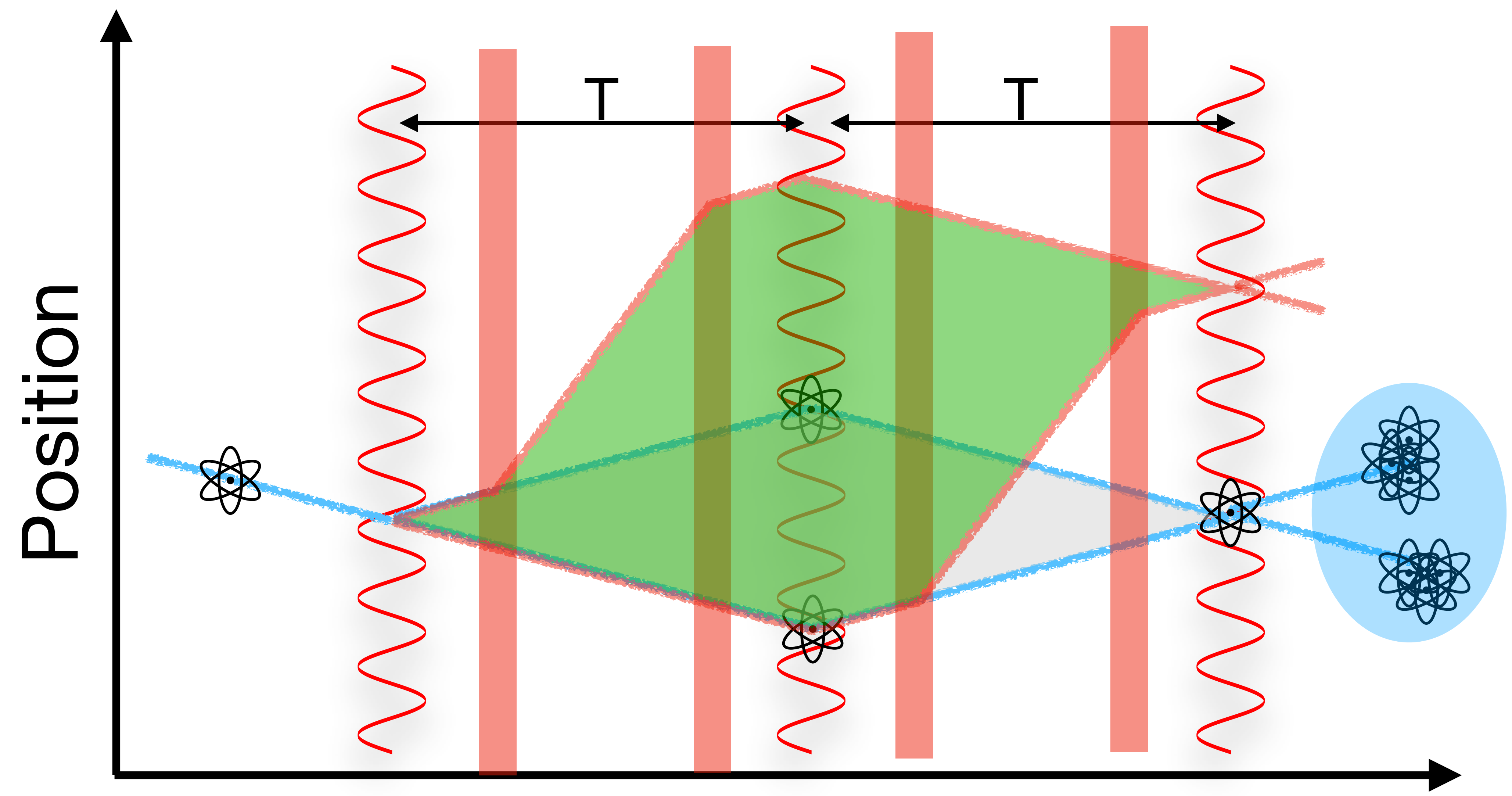
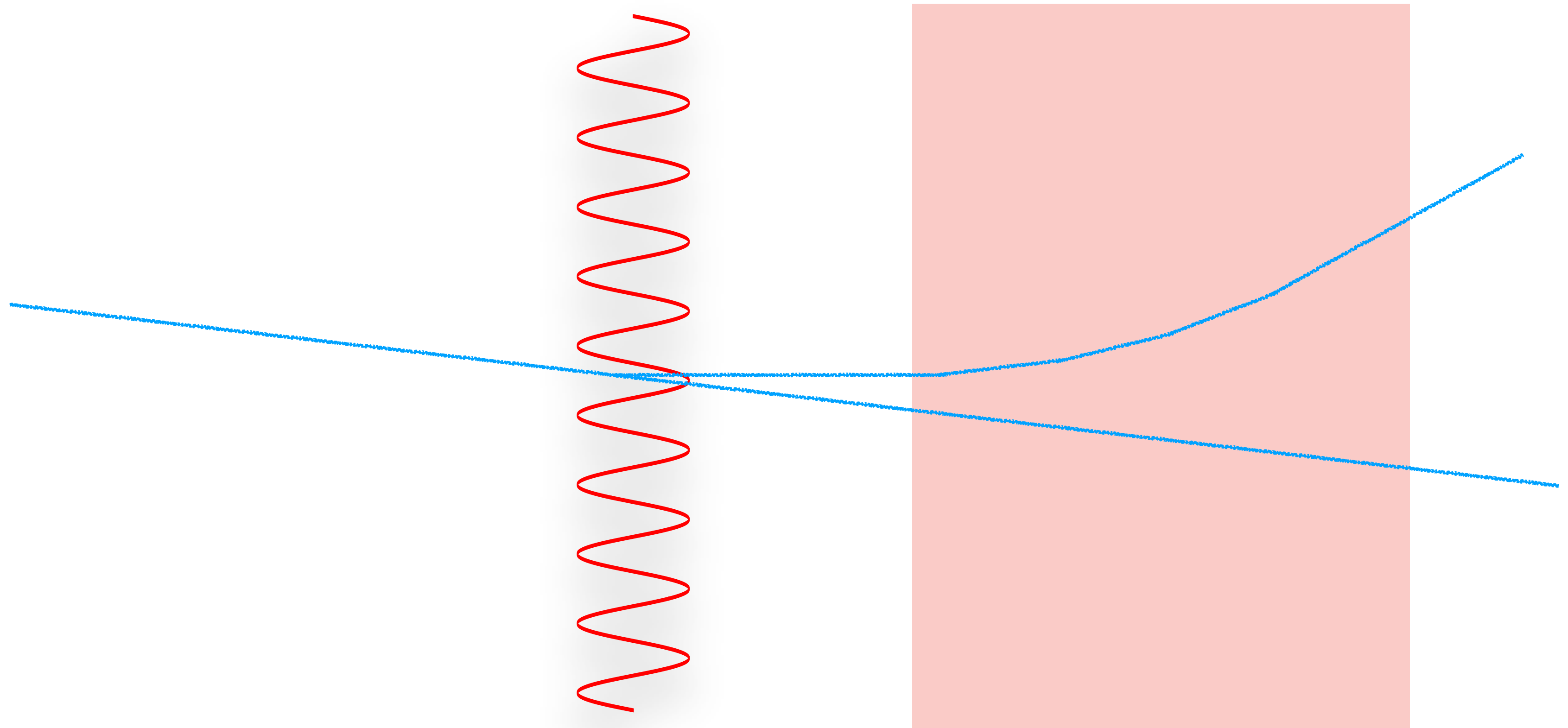



TVLBAI - roadmap:

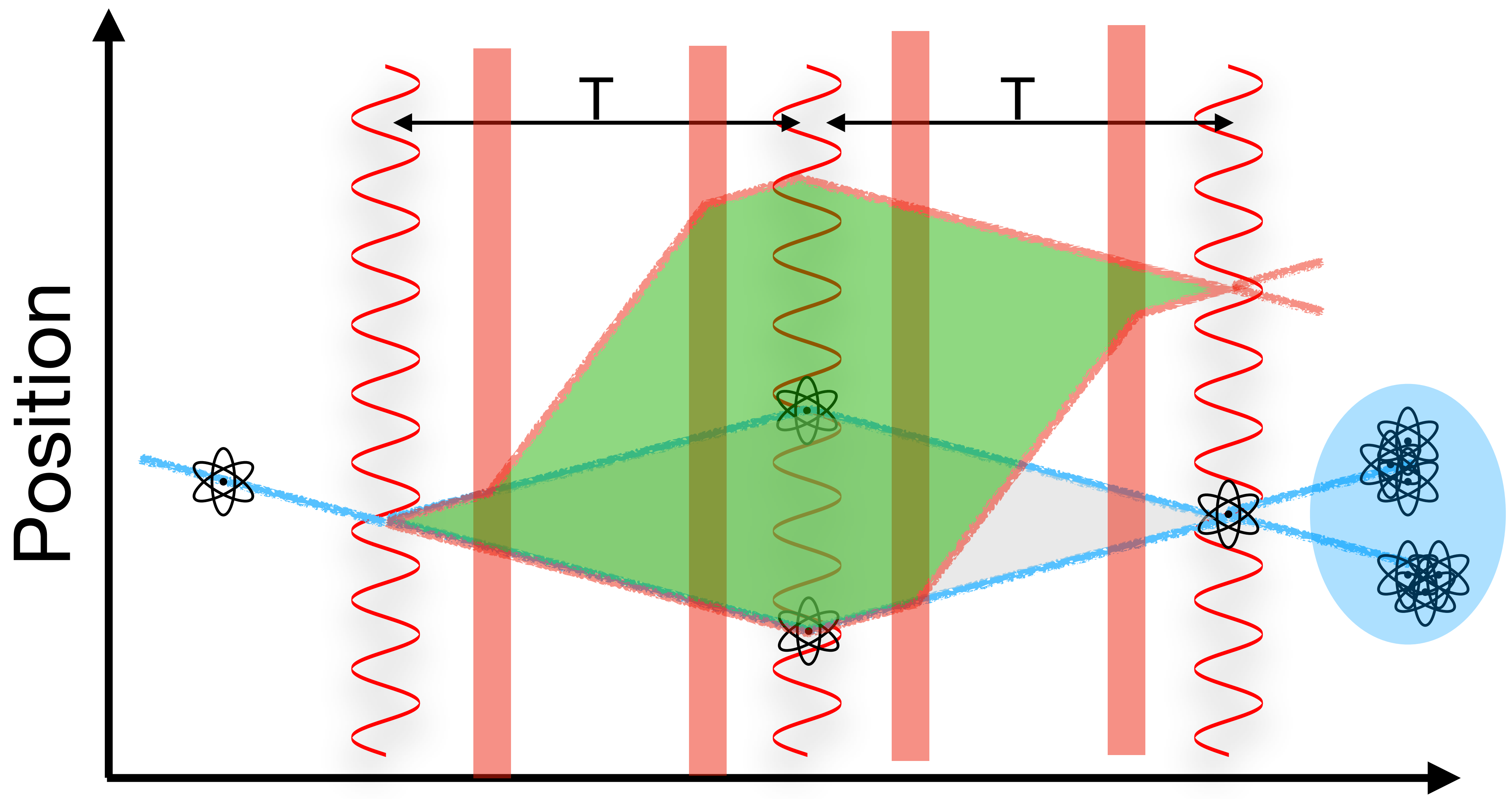
| Sensor Technology | State-of-the-art | Target | Enhancement |
|---|---|---|---|
| LMT atom optics | $10^2\ \hbar k$ | $10^4\ \hbar k$ | 100 |
| *Matter-wave lensing* | 50 pK | 5 pK | – |
| *Laser Power* | 10 W | 100 W | – |
| Spin squeezing | 20 dB (Rb), 0 dB (Sr) | 20 dB (Sr) | 10 |
| Atom flux | $10^5$ atoms/s (Rb) | $10^7$ atoms/s (Sr) | 10 |
| Baseline length | 10 m | 1000 m | 100 |

« We believe that there are no serious barriers to realization of momentum transfers greater than $10\hbar k$. »

J.M. McGuirk et al. Large Area Light-Pulse Atom interferometry PRL (2000)

# A quick tour of LMT beam splitters

## Requirements for Large Scale Interferometers

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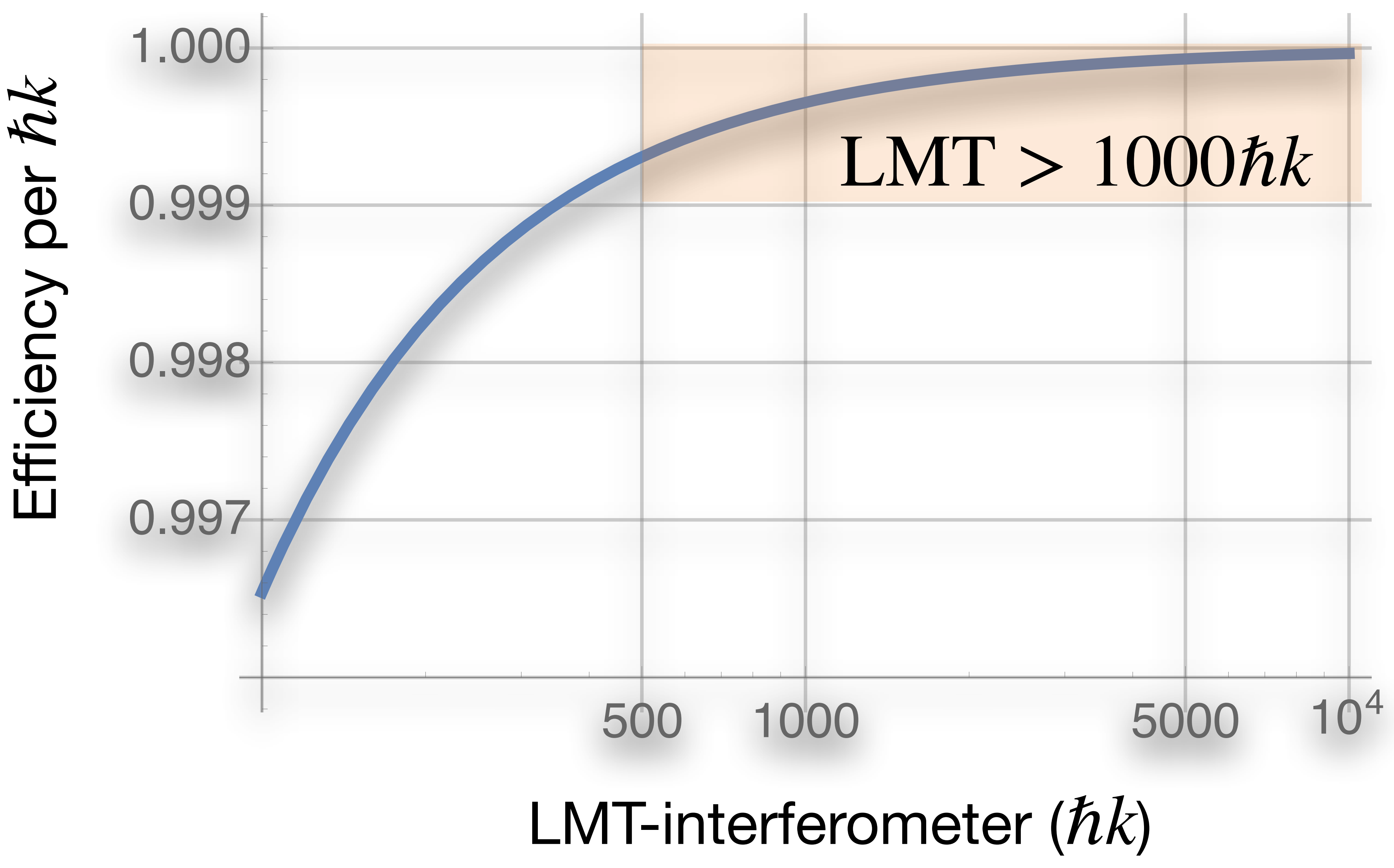
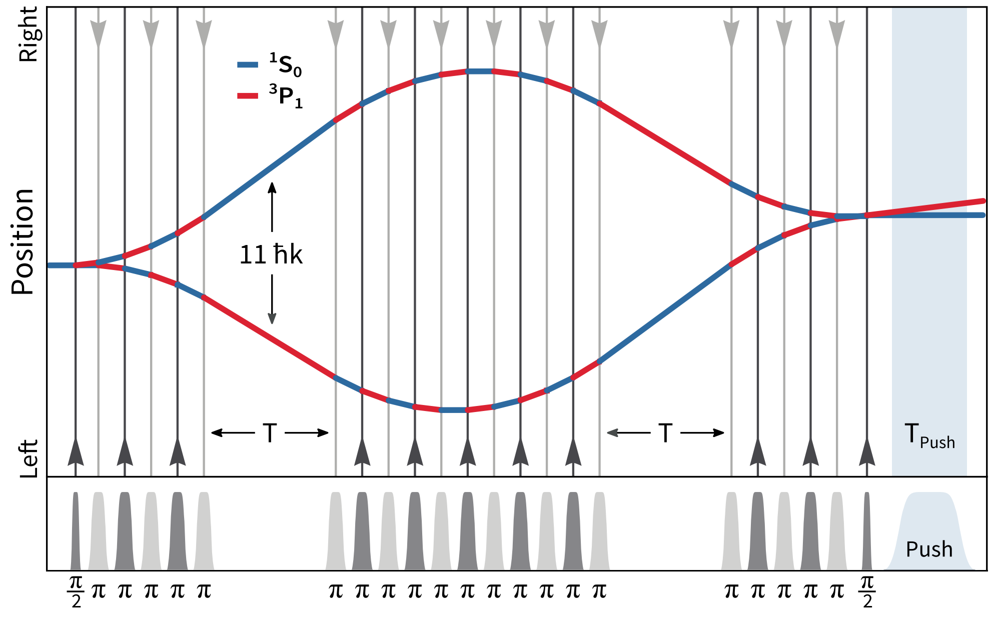



**High efficiency & High rate**

# Light-pulse Atom Interferometry

## Large Momentum Transfer

### Single photon transition

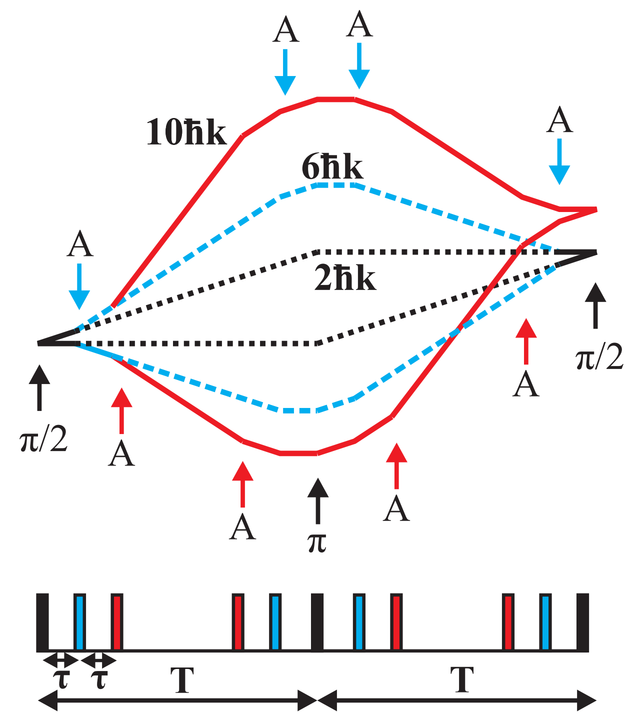


- 2-level system optical transition
- Metastable excited state
- Resonant transition -> Spont. Emission
- Rabi frequency $\Omega \sim$ MHz
- Demonstrated $400\hbar k$
- Very high rate transfer: $\sim 0.1\ \mu s/\hbar k$

Rudolph et al., Phys. Rev. Lett. **124**, 083604 (2020)

Wilkason et al., Phys. Rev. Lett., **129**, 183202 (2022)

### Two-photon Raman transition

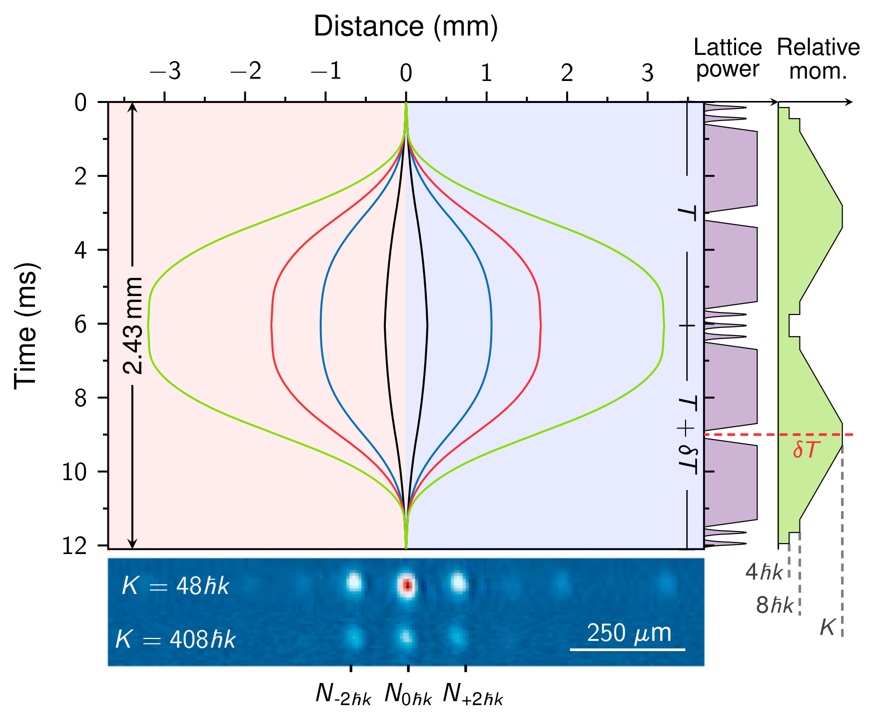


- Effective 2-level system, 2 photons transition
- Ground states
- Rabi frequency $\Omega \sim$ 100kHz
- Demonstrated $30\hbar k$
- High rate transfer: $\sim 2.5\ \mu s/\hbar k$

McGuirk et al., Phys. Rev. Lett., 85,4 4981(2015)

Kotru et al., Phys. Rev. Lett., **115**, 103001(2015)

### Optical lattice Bloch-Type acceleration



Gebbe et al., Nat Commun, **12**, 2544 (2021)

- multi-photon transitions - lattice states
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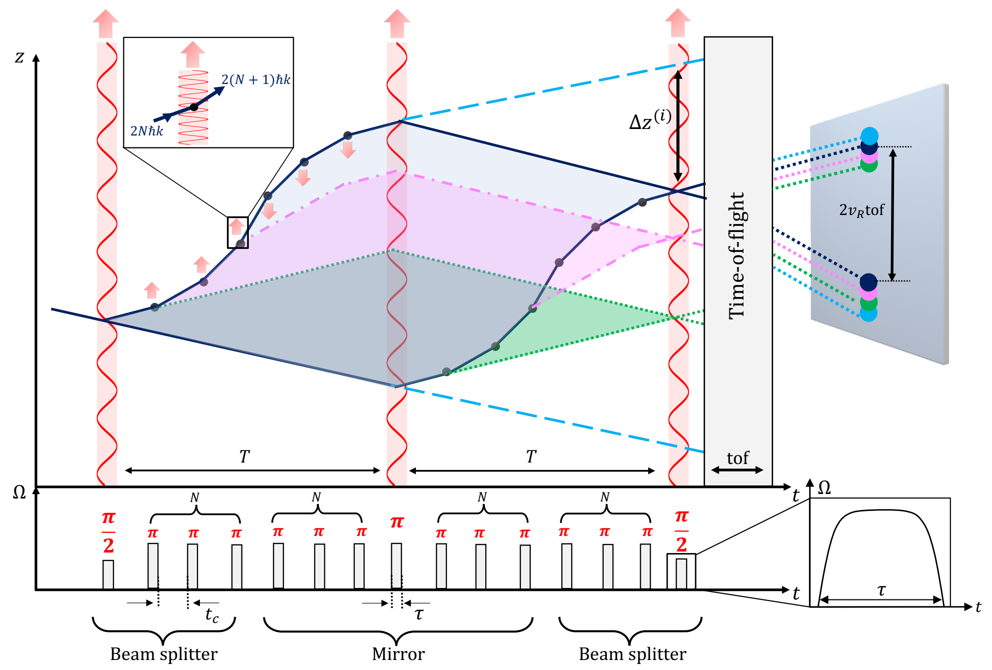
Cladé et al., Phys. Rev. Lett. **102**, 240402 (2009)

McDonald et al., Phys. Rev. A **88**, 053620 (2013)

Pagel et al., Phys. Rev. A **102** 053312 (2020)

### Optical lattice Sequence of Bragg pulses



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Plotkin-Swing et al., Phys. Rev. Lett., **121**, 133201 (2018)

Rodzinka et al . arXiv:2403.14337

# Light-pulse Atom Interferometry

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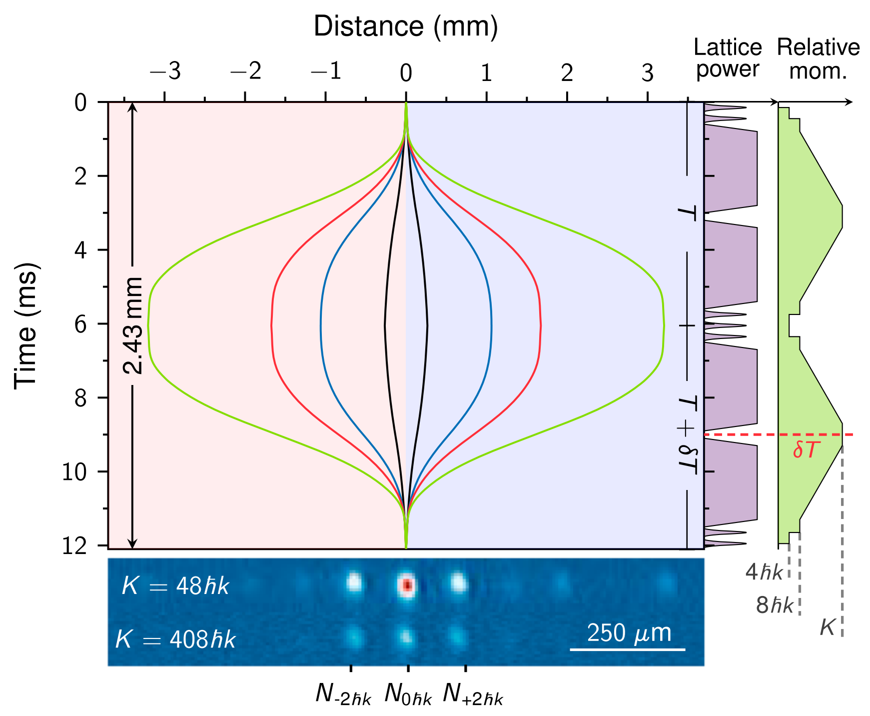


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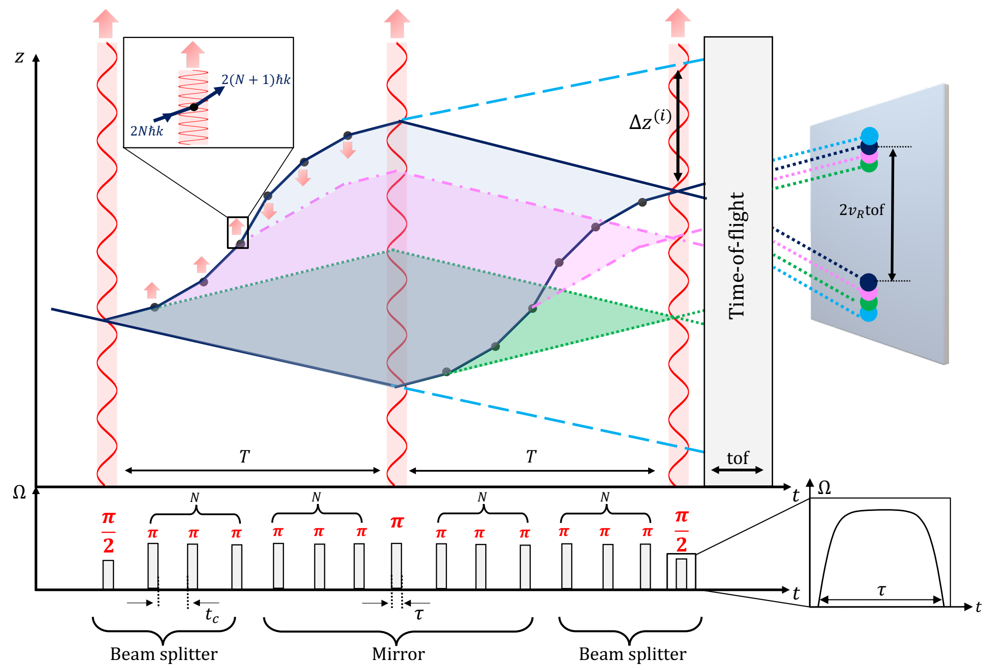


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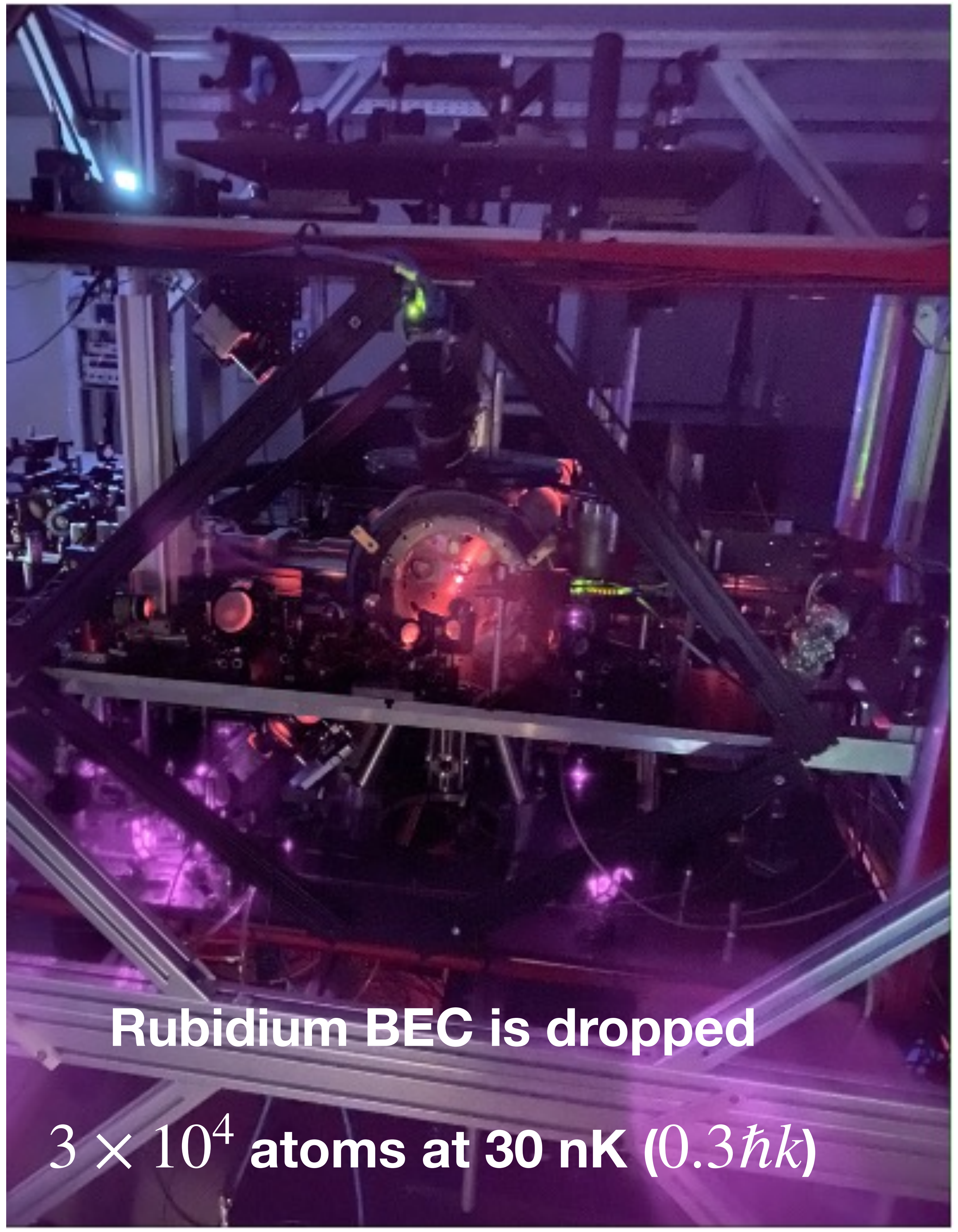
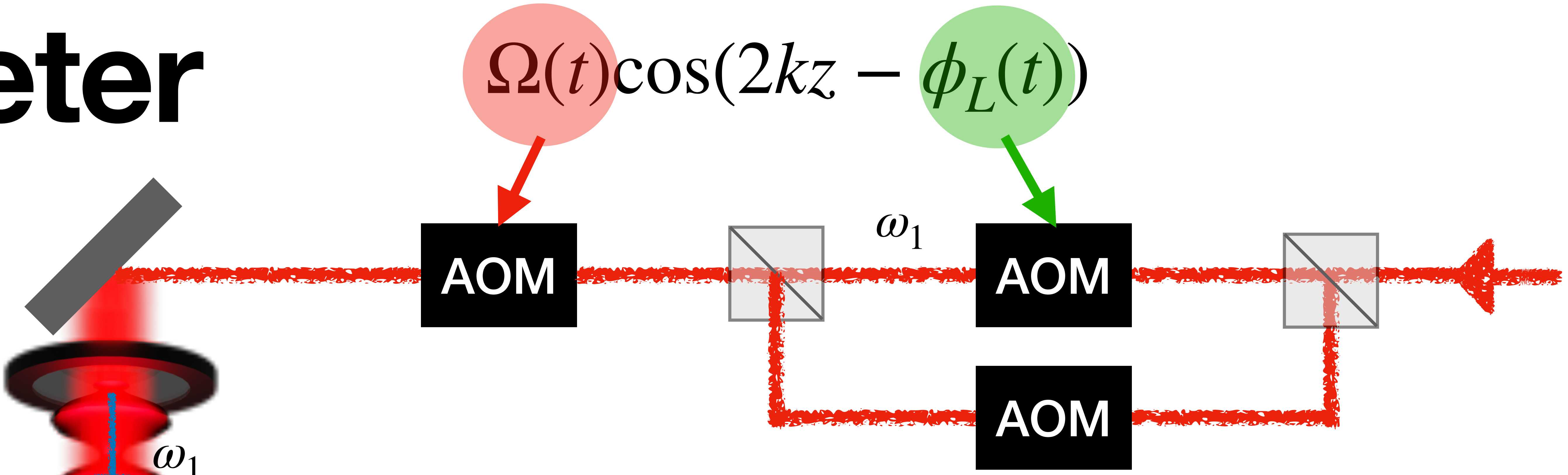
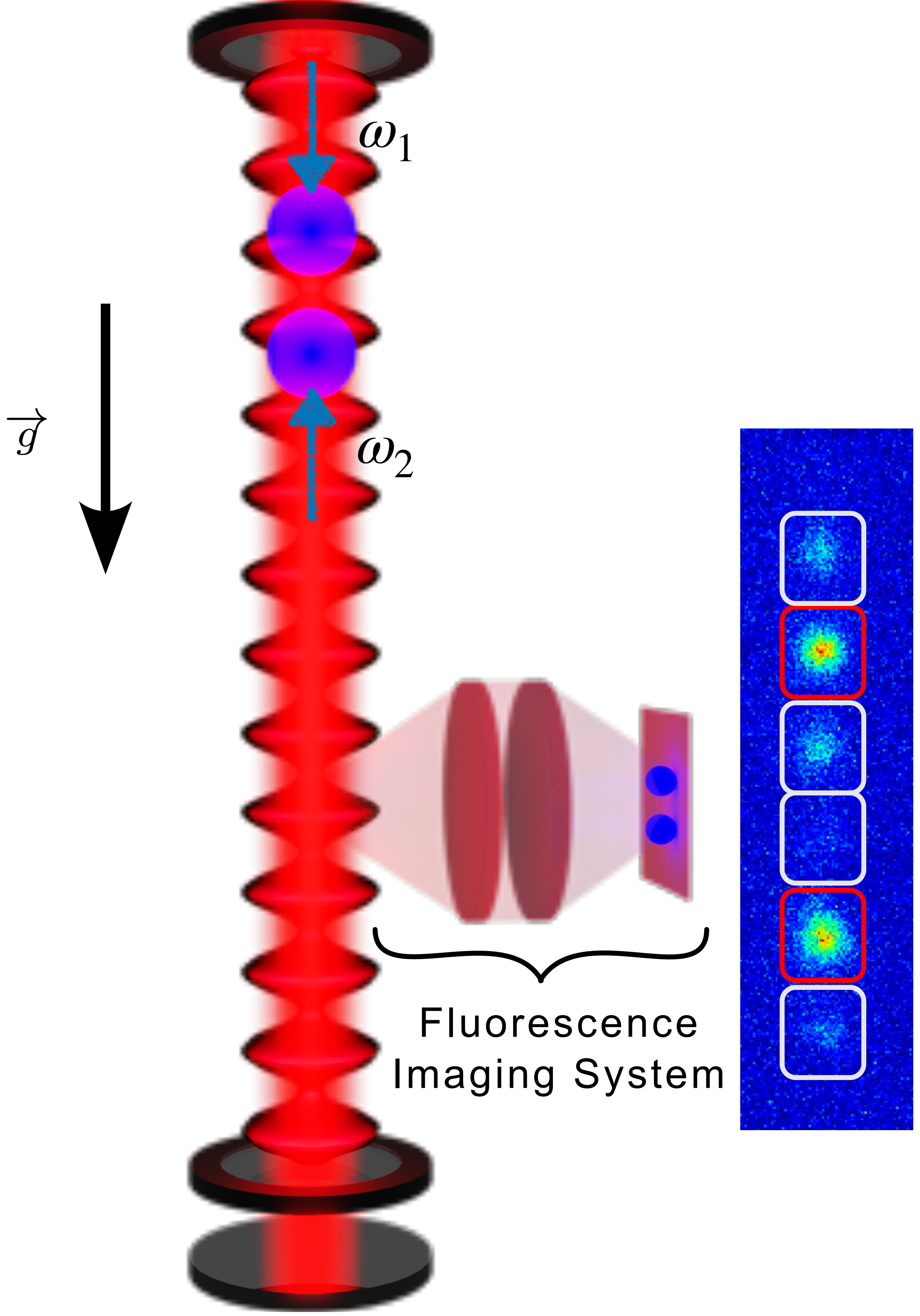
# Atom Interferometer

## Experimental setup




**Vertical optical lattice:**

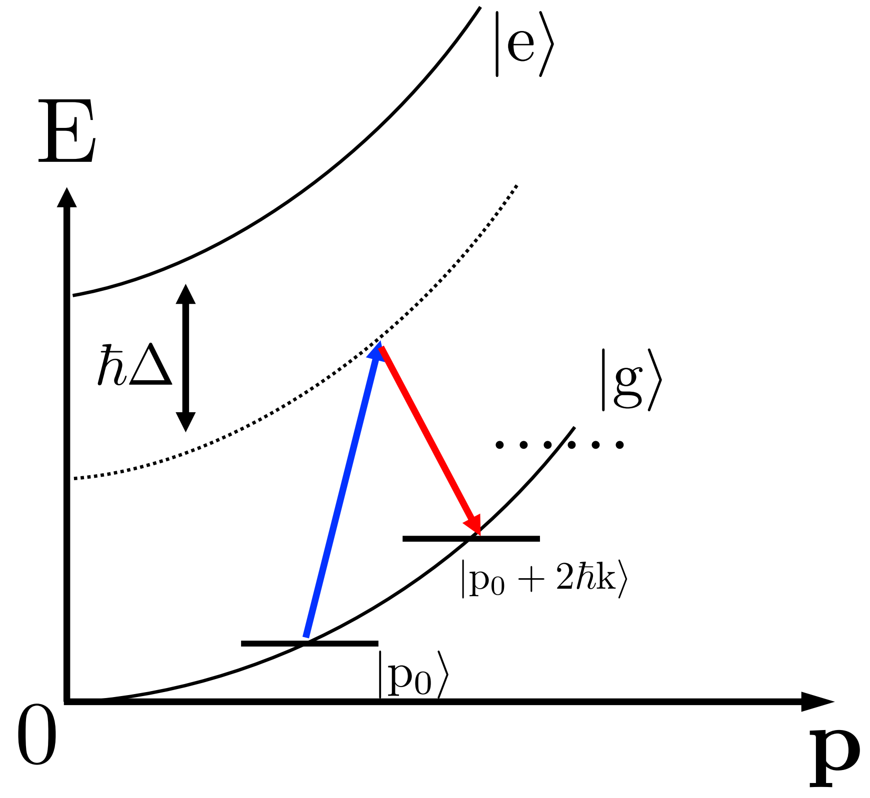
- retroreflected configuration
- lattice depth $\sim 50E_R$
- detuning with excited state $\sim 40$ GHz
- amplitude and phase of the lattice with AOM
- anti-g chirp → free fall frame

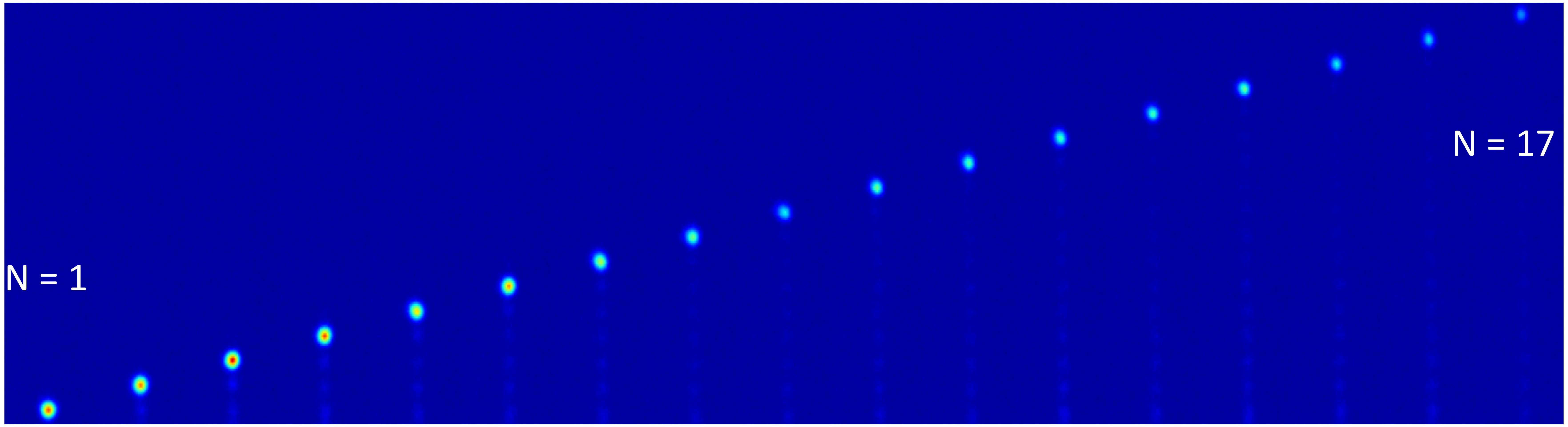
# LMT: Bragg pulse sequence

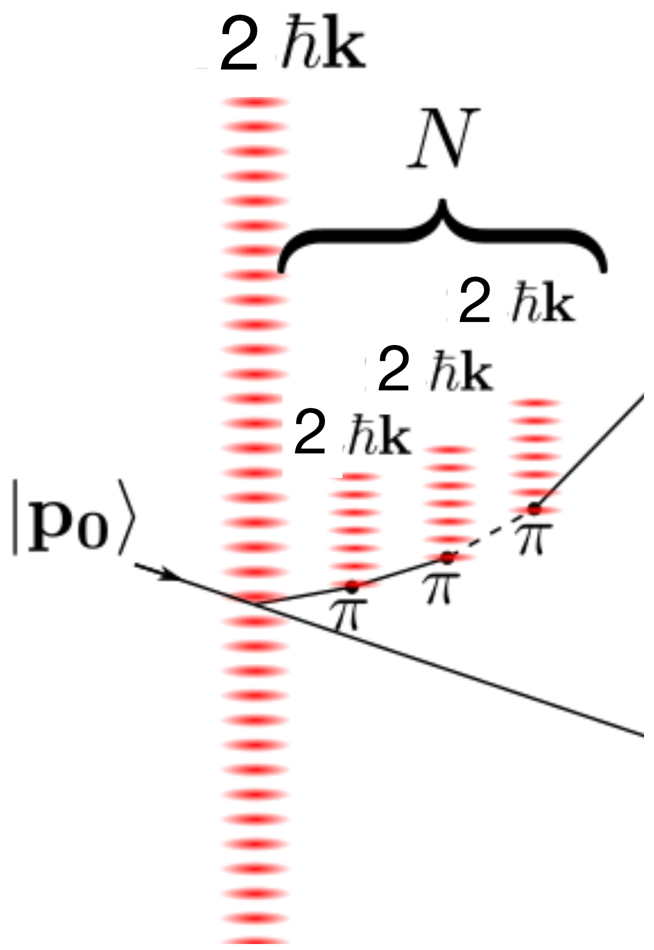
## Independent pulses: gaussian pulse

Beam splitter made with multiple n = 1 accelerating (mirror) pulses.

Chiow et al. Phys. Rev. Lett. 107, 130403 (2011)




- Better control of non-adiabatic losses
- Less spontaneous emission per $\hbar k$

# LMT: Bragg pulse sequence

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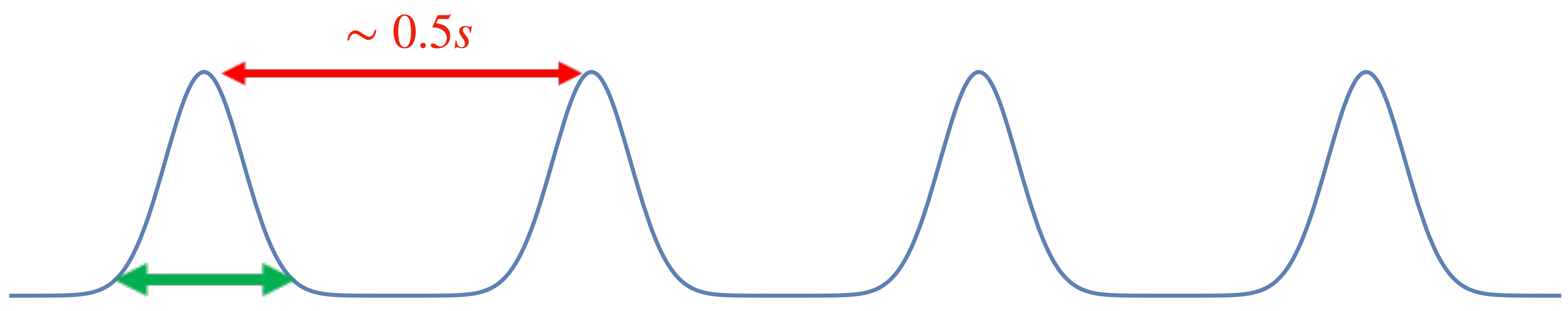
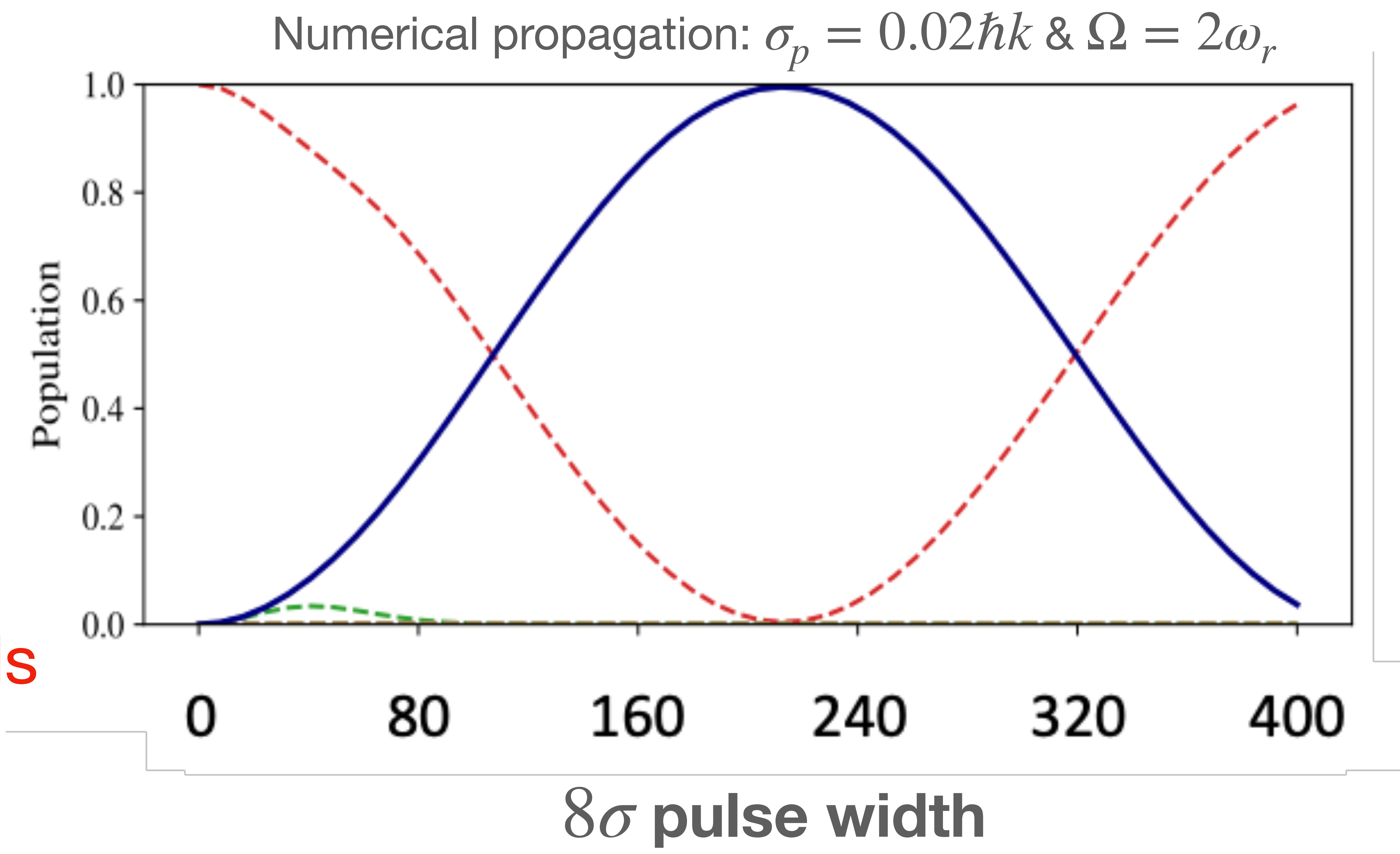
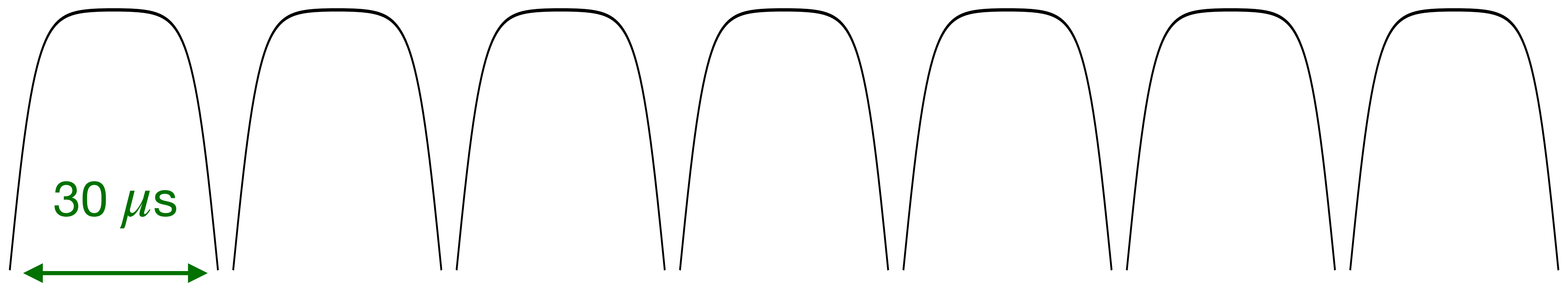



- Adiabatic condition : Long pulses
- Very low temperature < nK
- $> 1000\hbar k$-interferometer needs few seconds



# LMT: Bragg pulse sequence

## Coherent Enhanced pulses

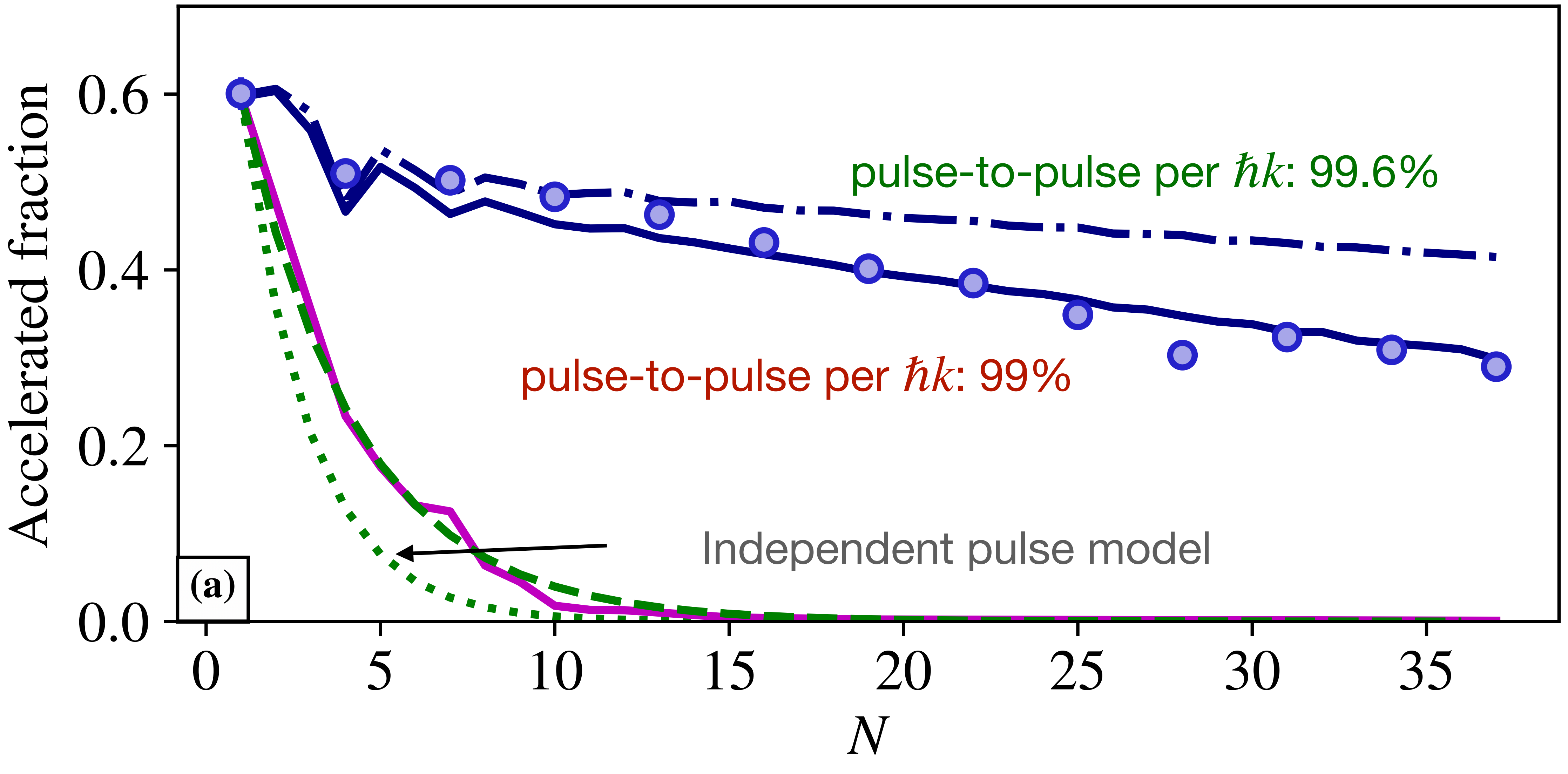


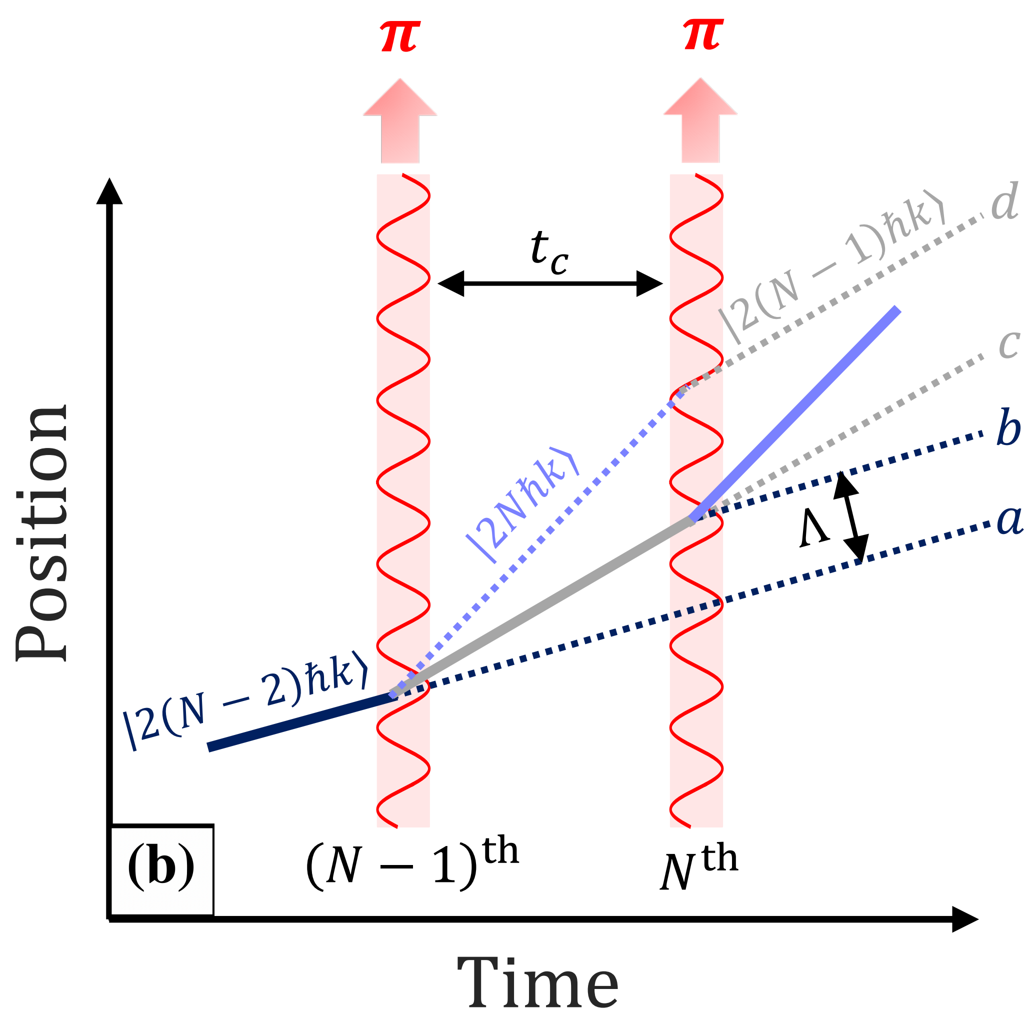

**Short pulses and fast train pulses**

Non-adiabatic losses = coherent losses

Small spatial separation $\Lambda = 2v_R t_c \ll \xi = \dfrac{\hbar}{m\sigma_v}$

Béguin et al. Phys. Rev. Lett., **131**, 143401, (2023)




**Losses interfere destructively:**

$$P_{|N-2\rangle} = 2\epsilon^2\left(1 + cos(\pi + 4\omega_R t_c)\right)$$

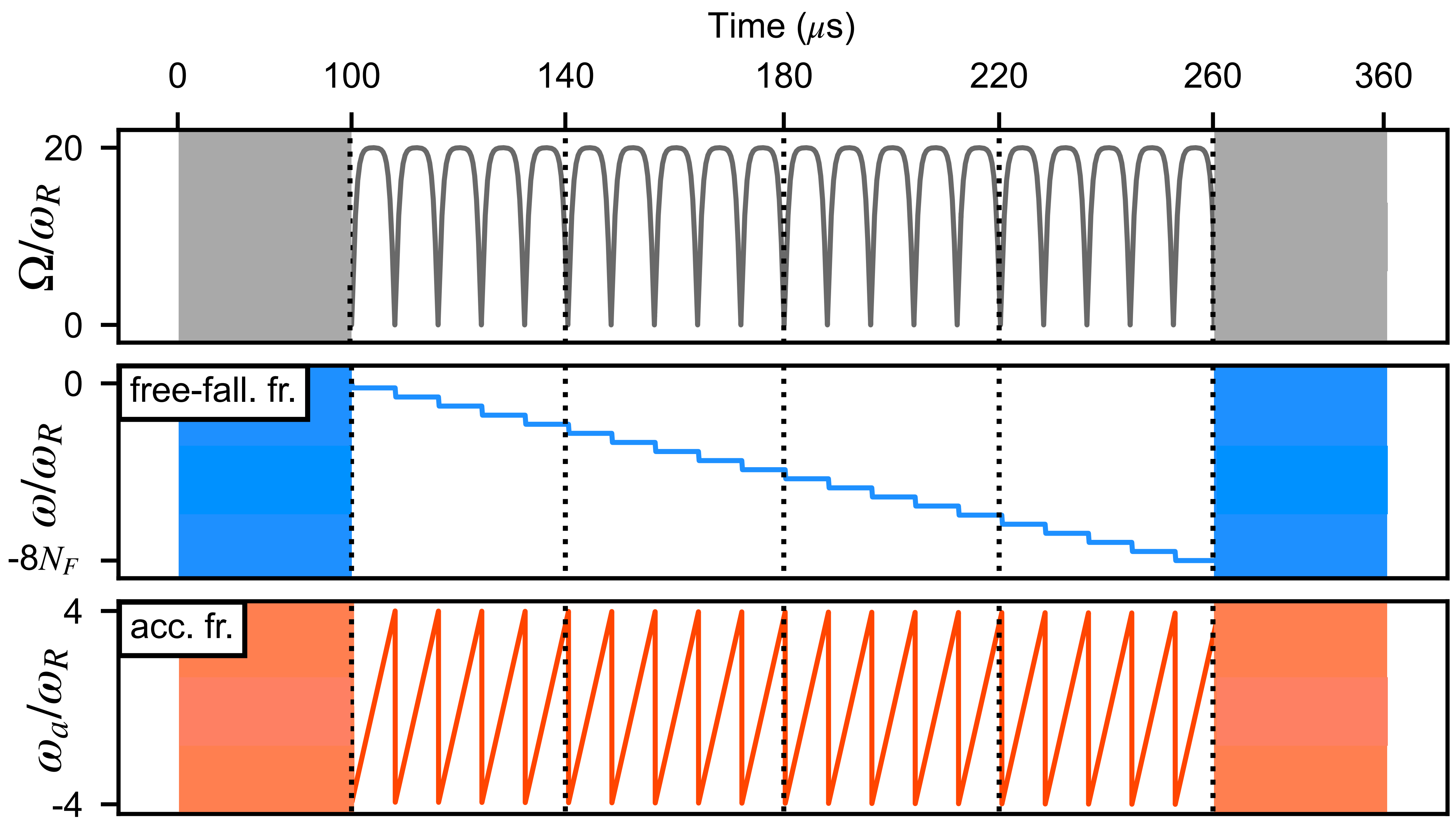
**98% pulse-to-pulse efficiency**

Higher efficiency ?

Faster transfer ?

# Stroboscopic stabilization in the accelerated frame

## Optical Lattice with periodic driving

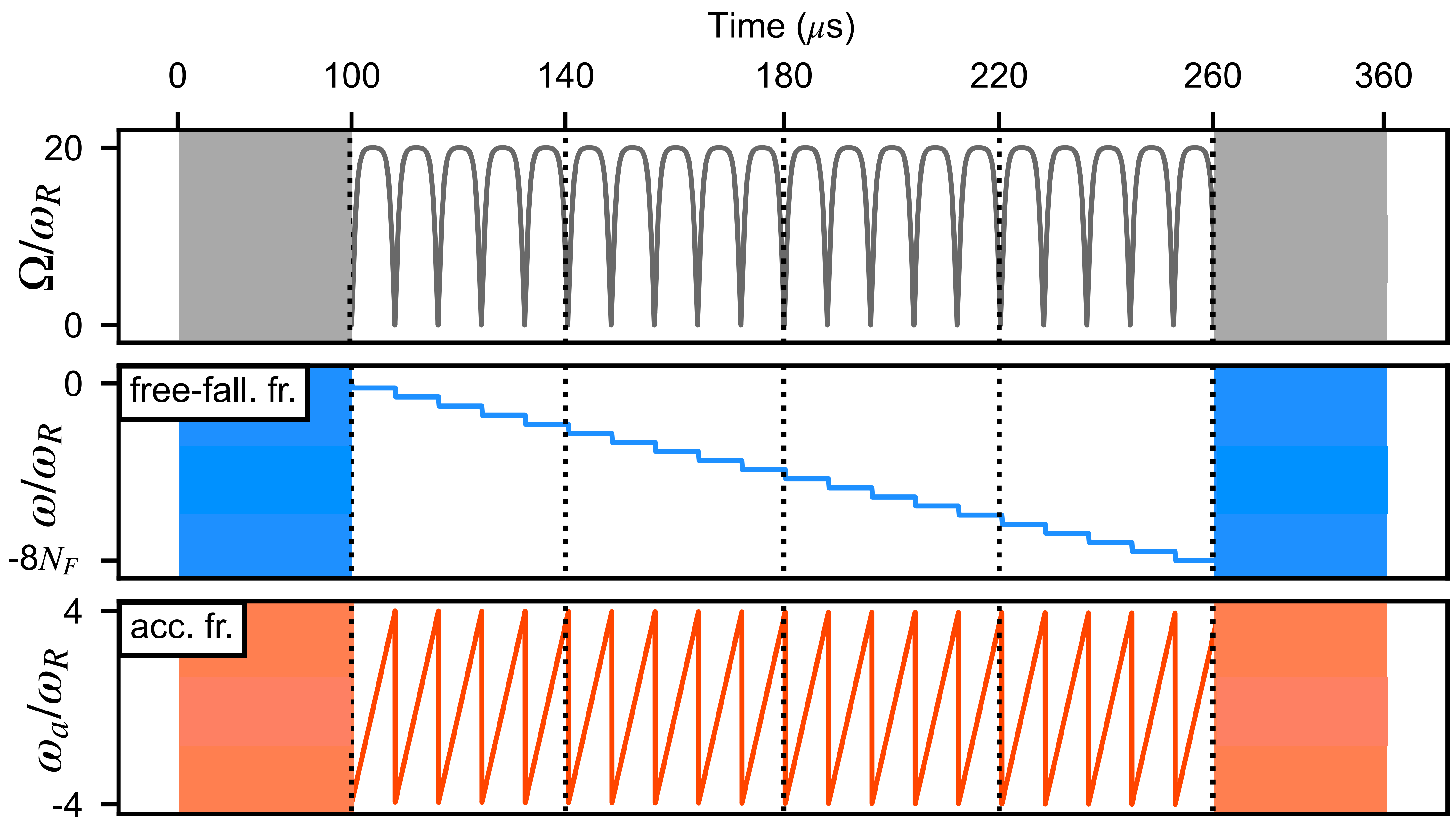



- Periodic driving in the **accelerating frame**
- Periodic hamiltonian $H(t_0) = H(t_0 + \tau)$

Floquet Formalism

# Stroboscopic stabilization in the accelerated frame

## Floquet's formalism




- Periodic driving in the **accelerating frame**
- Periodic hamiltonian $H(t_0) = H(t_0 + \tau)$

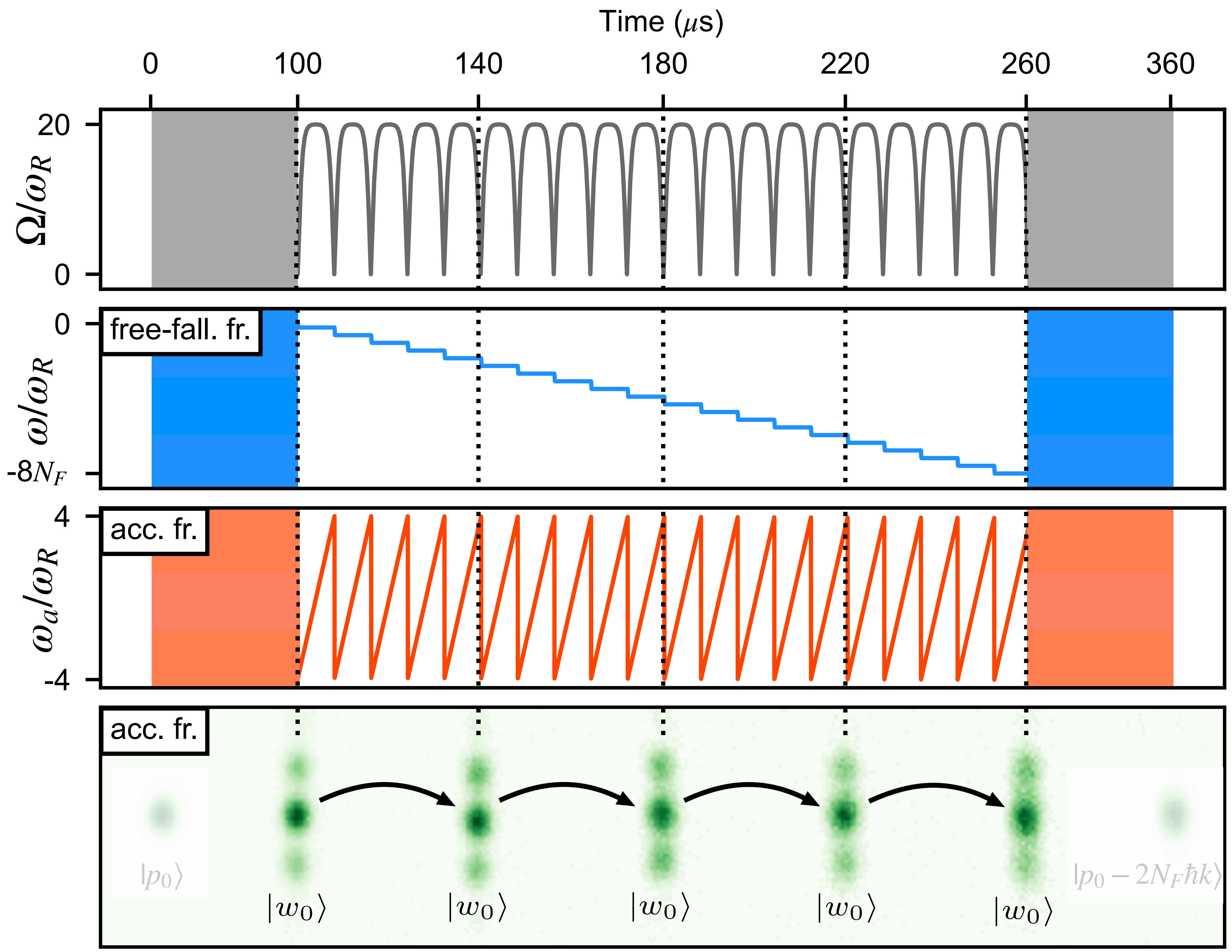
Floquet Formalism

Diagonalization of the one-period propagator = Floquet states $|w_n(t)\rangle = |u_n(t)\rangle e^{i\theta_n}$ with $|u_n(t+\tau)\rangle = |u_n(t)\rangle$

Initial state $|\psi(0)\rangle = \sum_n c_n |u_n\rangle$ → $|\psi(t)\rangle = \sum_n c_n |u_n(t)\rangle e^{i\theta_n}$

# Stroboscopic stabilization in the accelerated frame

## Stabilization in the accelerated frame




Initial state prepared in a Floquet state

$$|\psi(0)\rangle = |w_k\rangle$$

**Stroboscopic stabilization**

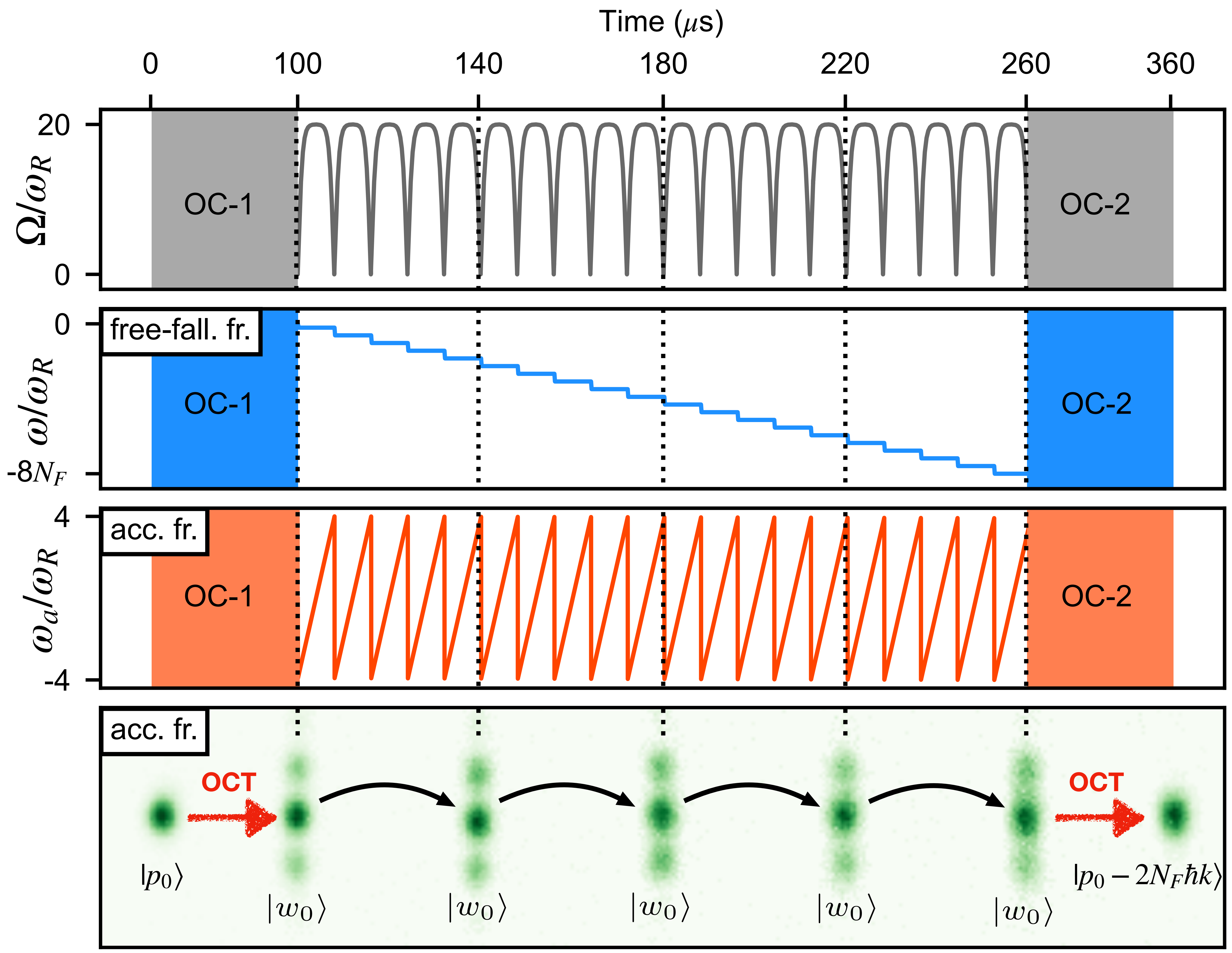
$$|\psi(m\tau)\rangle = |w_k\rangle e^{i\theta_k}$$

**The wave function is ideally transported in the accelerated frame.**

Floquet states can be defined for any periodic sequence

# State preparation $|p_0\rangle \to |w_0\rangle$

## Quantum Optimal Control Theory




We choose the Floquet state $|w_0\rangle$ with the largest projection on $|p_0\rangle$

Hamiltonian with control: amplitude $\Omega(t)$ and frequency $\omega_a(t)$

Find the control fields $\{\Omega(t), \omega_a(t)\}$, maximizing the figure of merit: $|\langle w_0 | \psi(t_f)\rangle|^2$

Optimization procedure with QOCT and implemented with Gradient based method (here GRAPE)

Ansel et al. arXiv: 2403.00532

**The complexity of Optimal Control LMT is encapsulated into the Floquet state**

# Robust preparation

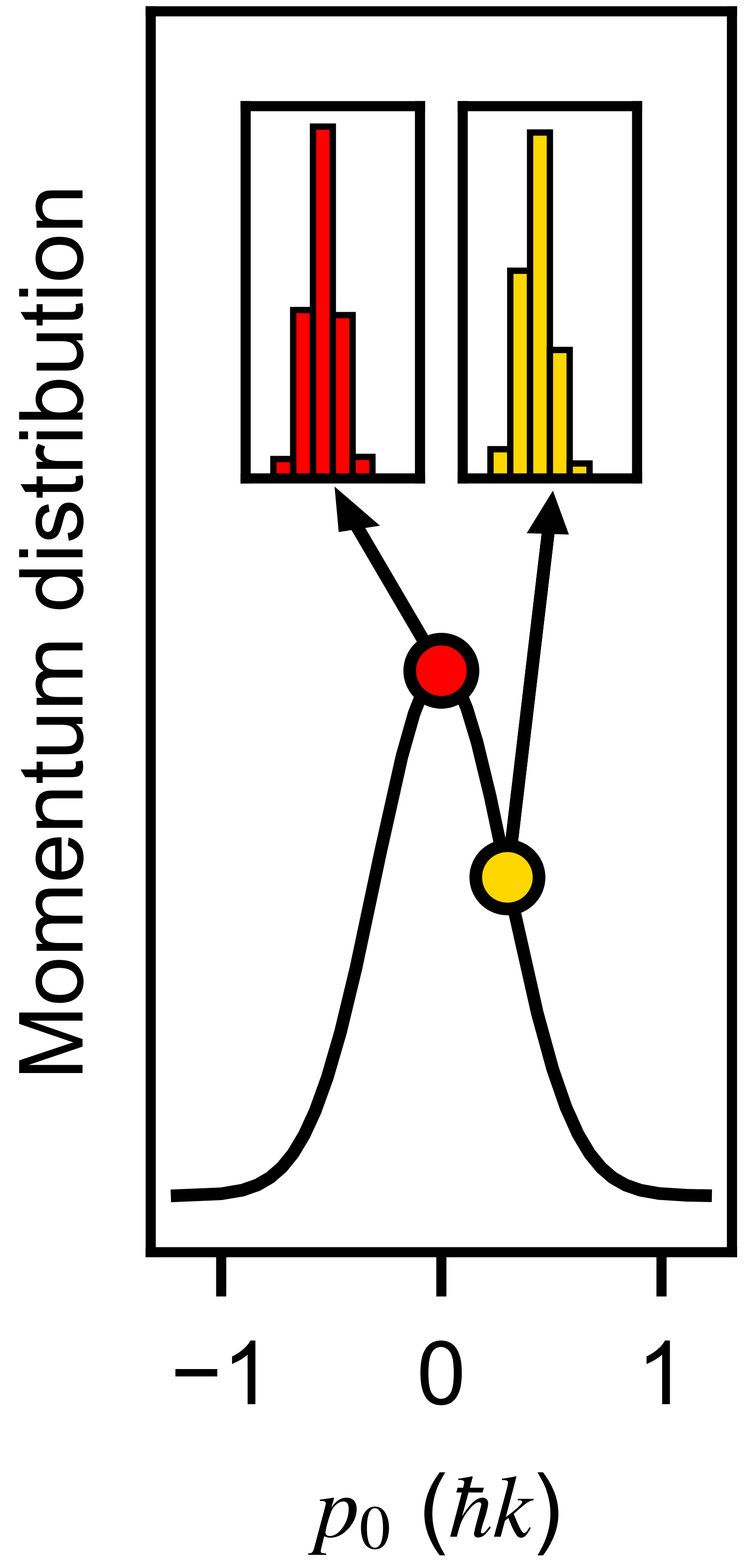
## Initial statistical mixture

A floquet state for each momentum of the distribution

$$|p_0\rangle \rightarrow |w_0(p_0)\rangle$$

Simultaneous control for $|w_0(p_0)\rangle$ = Robust against $p_0$

Rodzinka et al. arXiv:2403.14337



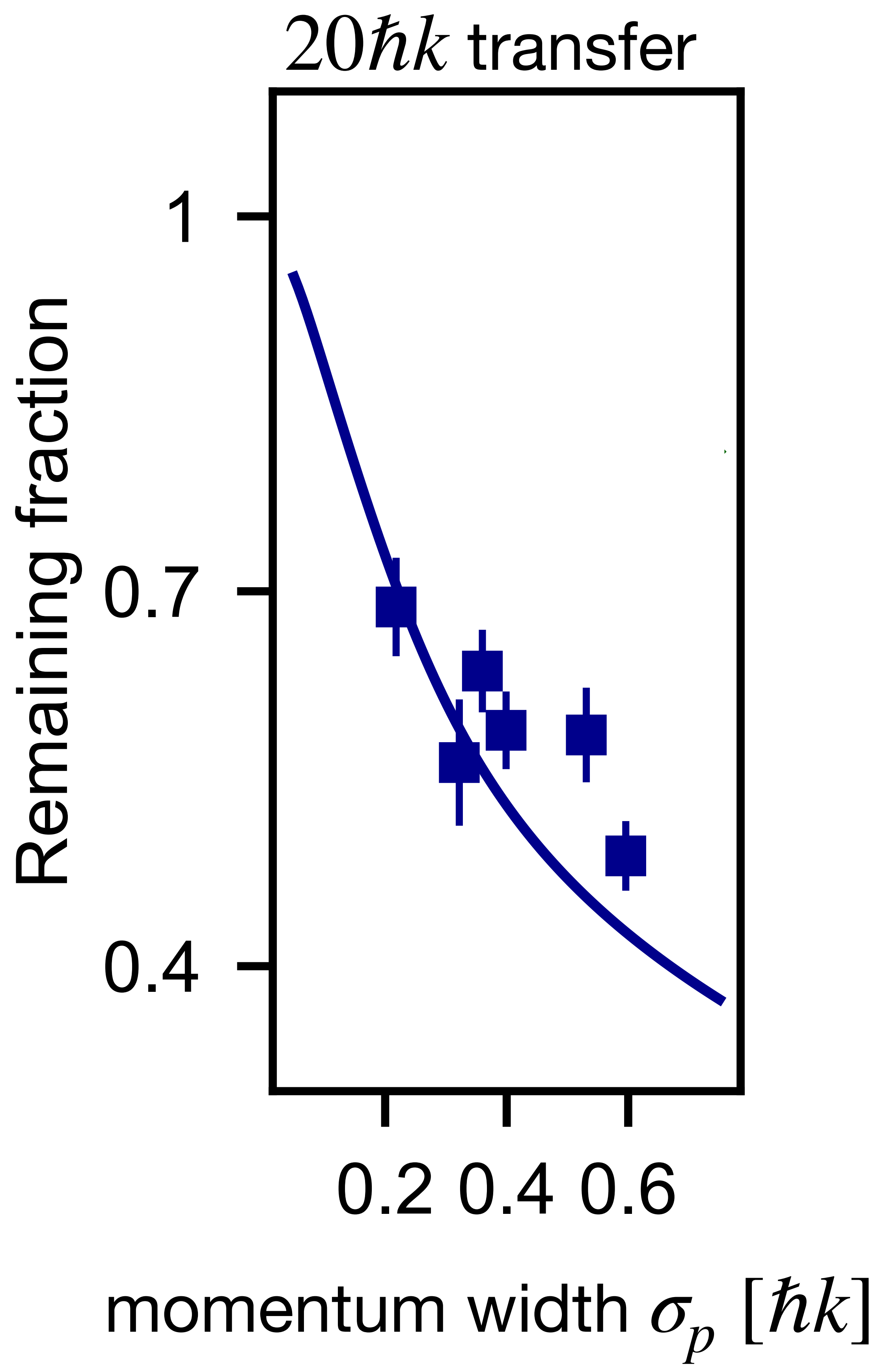



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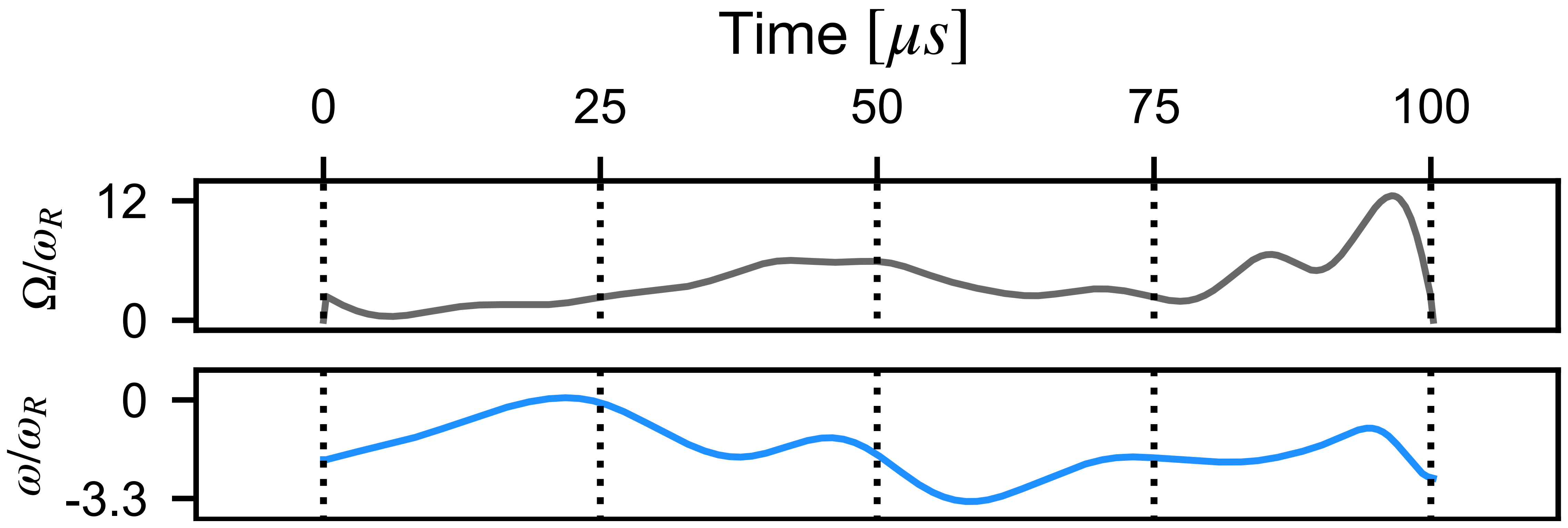
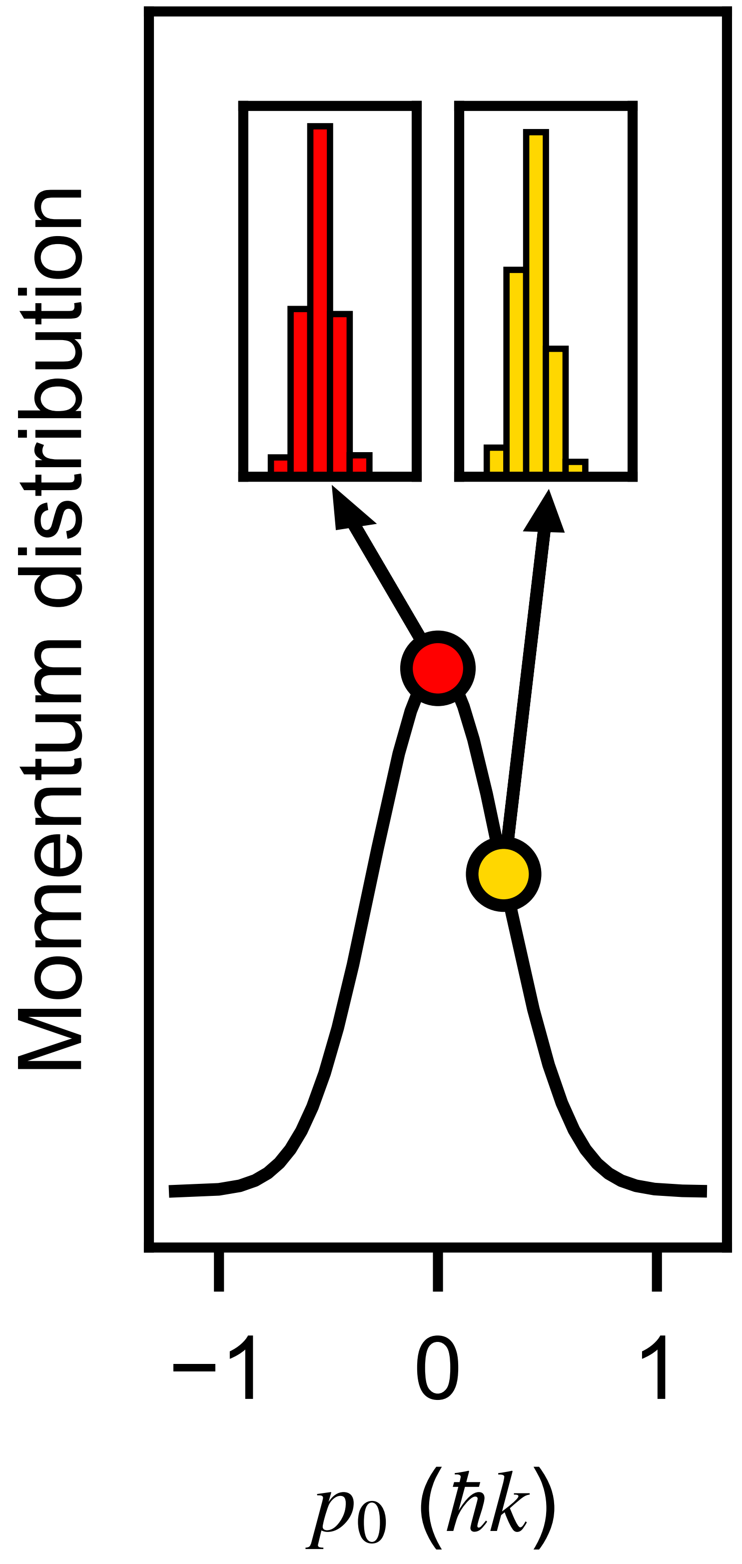
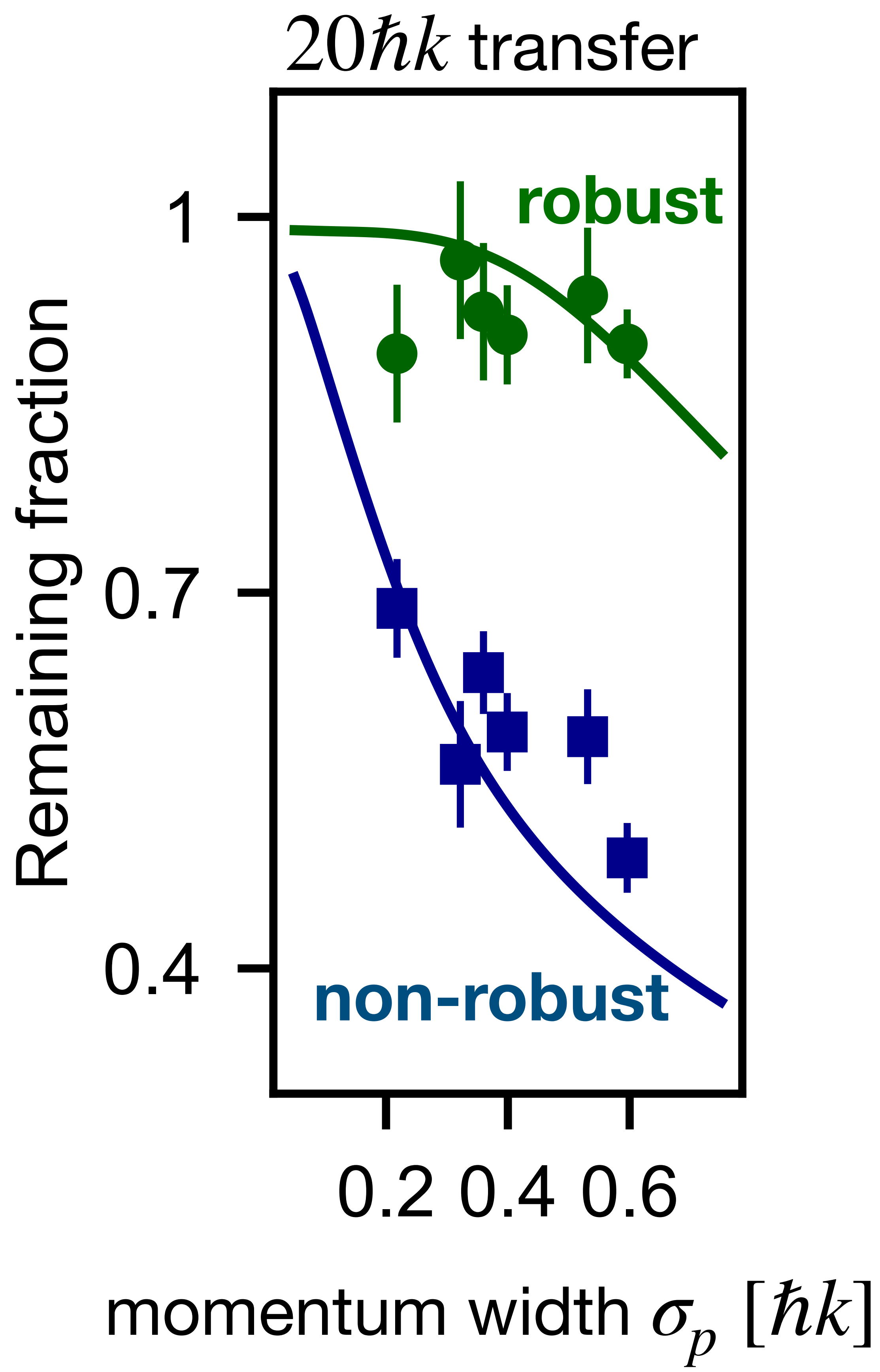
Figure of merit $F_1 = \int_{-\infty}^{+\infty} |\langle \psi(\tau_c) | w_0(p_0) \rangle|^2 f(p_0) dp_0$



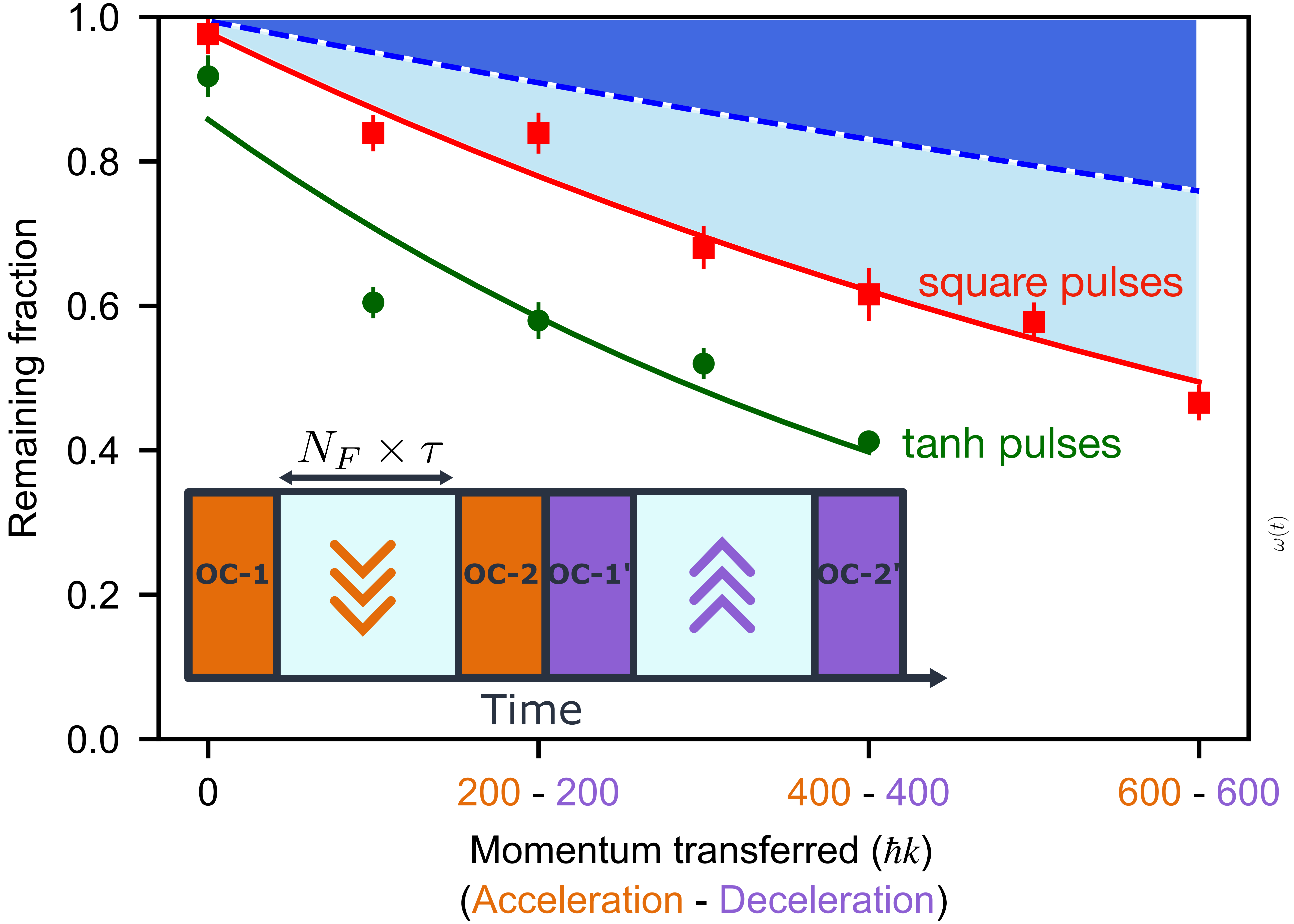



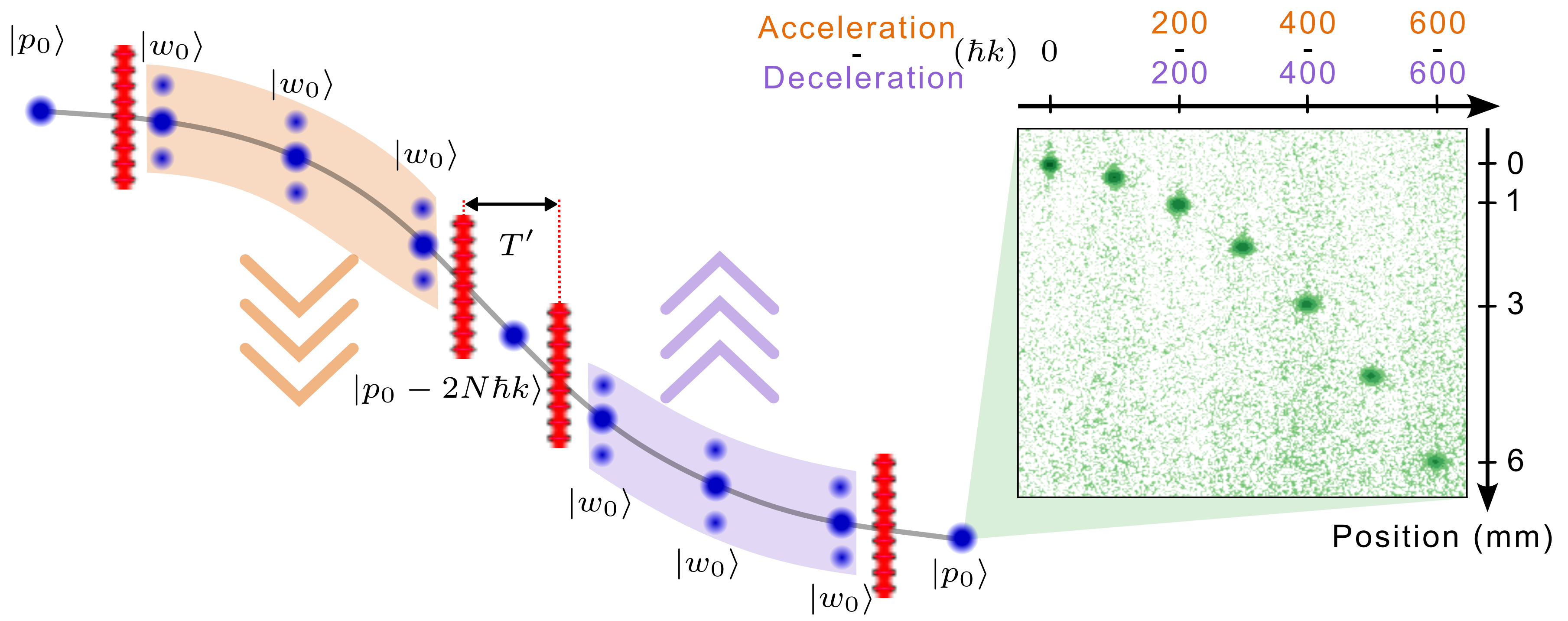

Robust control up to $0.35\hbar k$

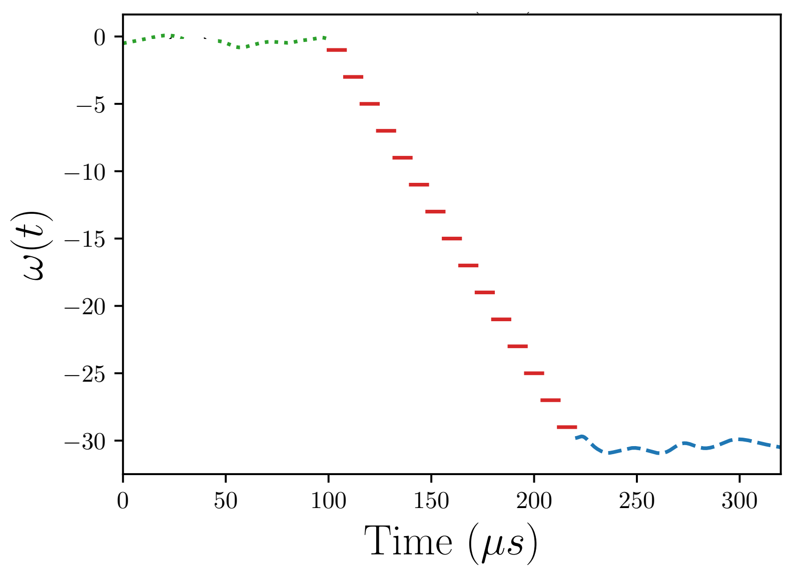
# Floquet acceleration

## Normalized atom number in the fully accelerated state

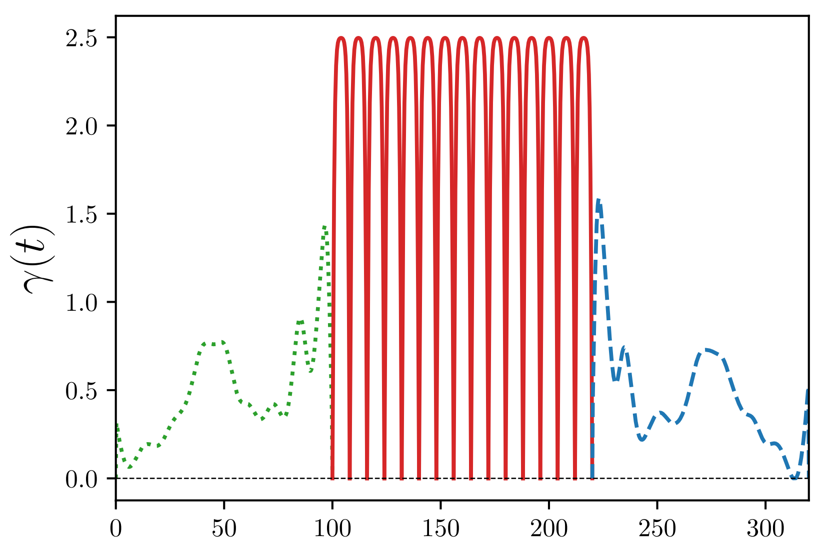
Rodzinka et al. arXiv:2403.14337



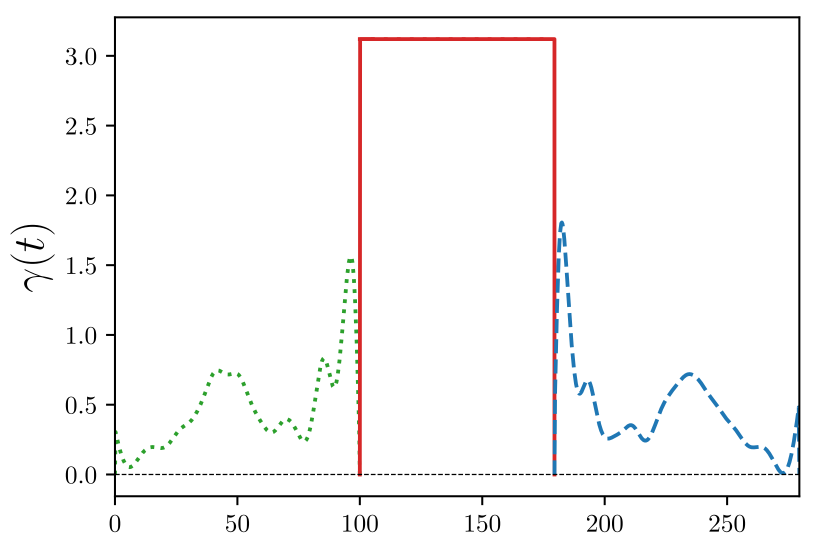




lattice frequency




tanh pulses 8 $\mu s$




square pulses 5 $\mu s$

(≡ continuous)

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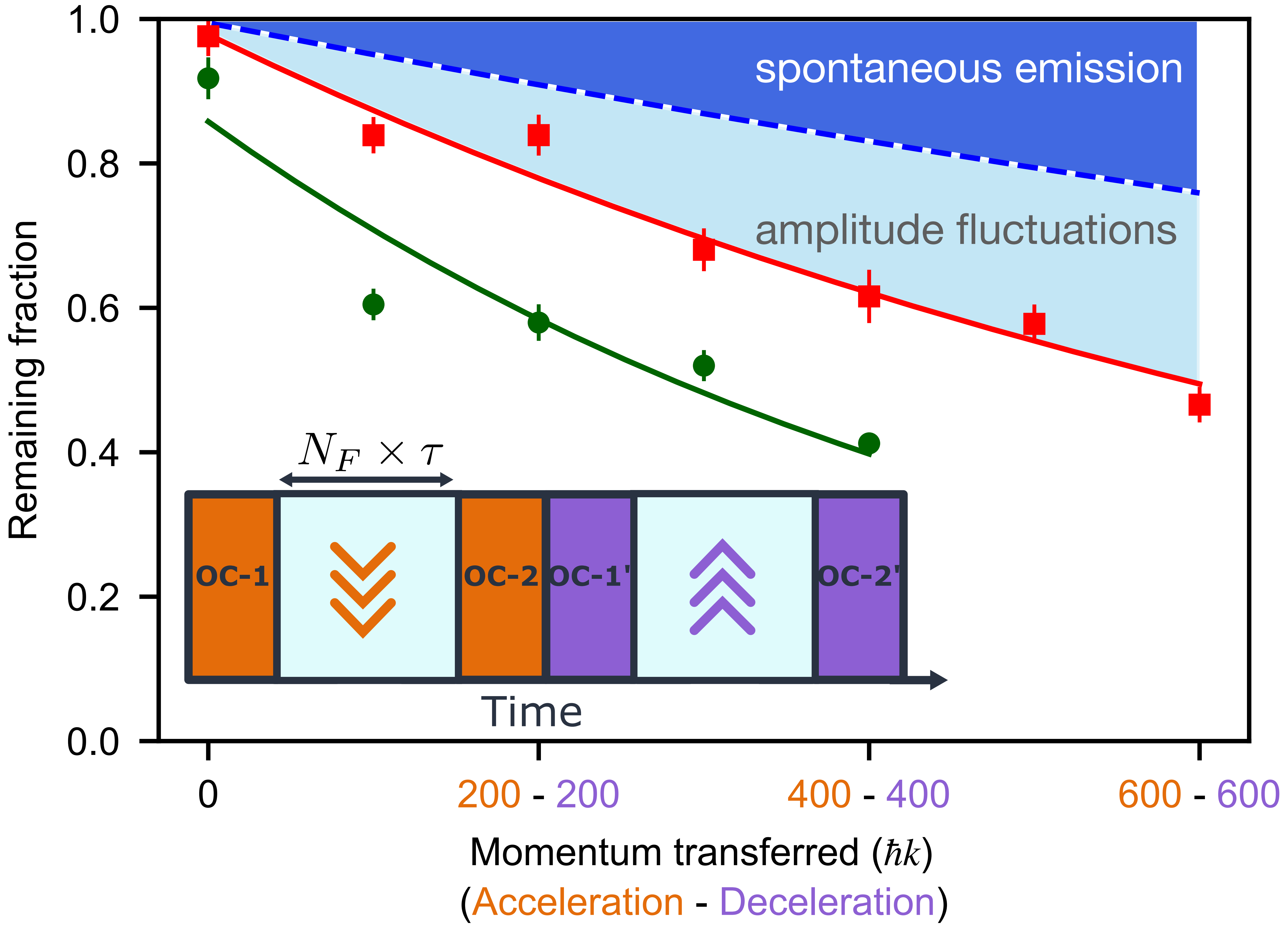
Rodzinka et al. arXiv:2403.14337




Fast LMT peak momentum transfer :

$2.5\ \mu s/\hbar k$

Efficiency per $\hbar k$ : 0.99945(5)

Limitations:

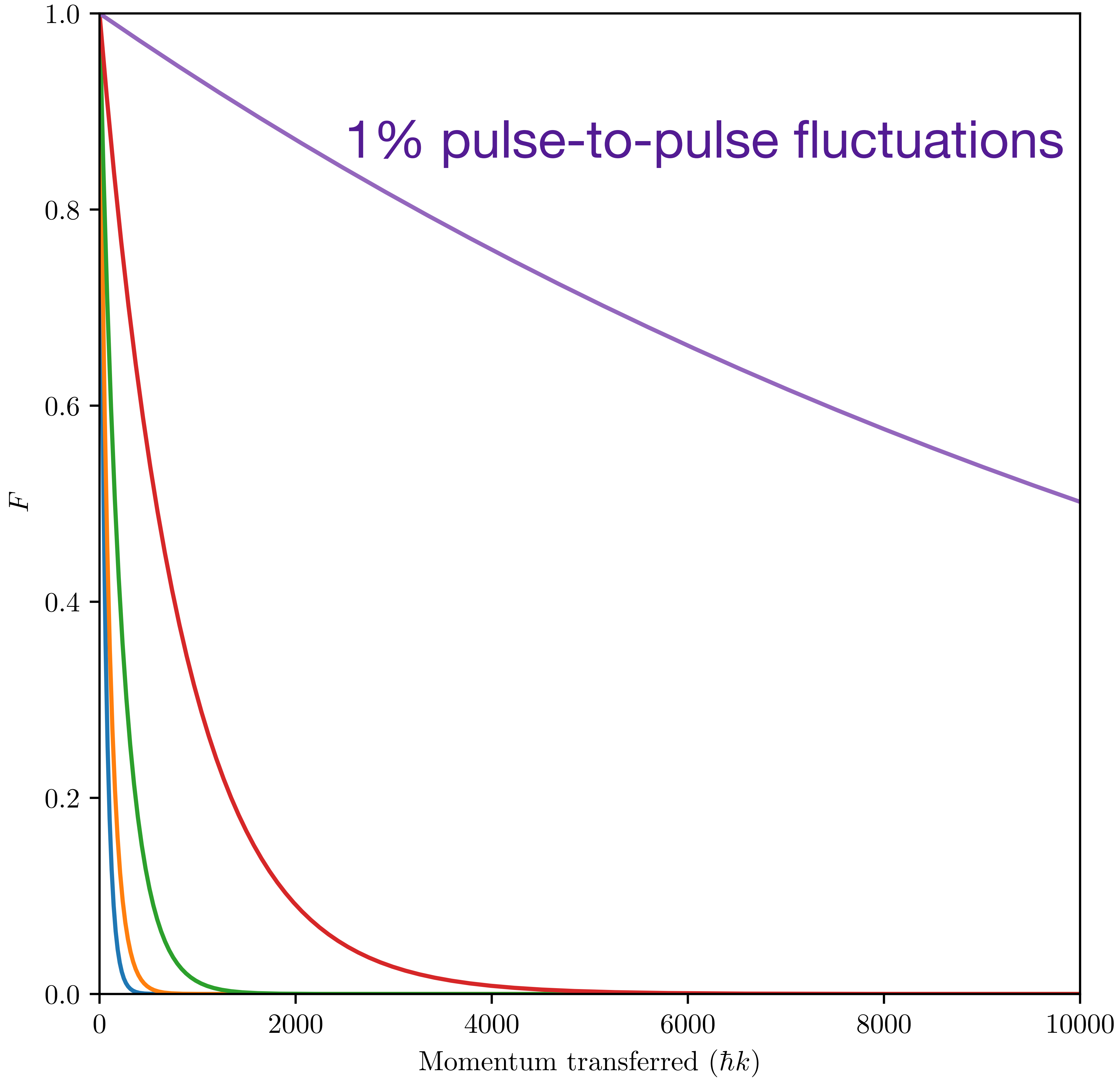
spontaneous emission: $\Delta = 40$ GHz

pulse-to-pulse fluctuations: 4.5 %

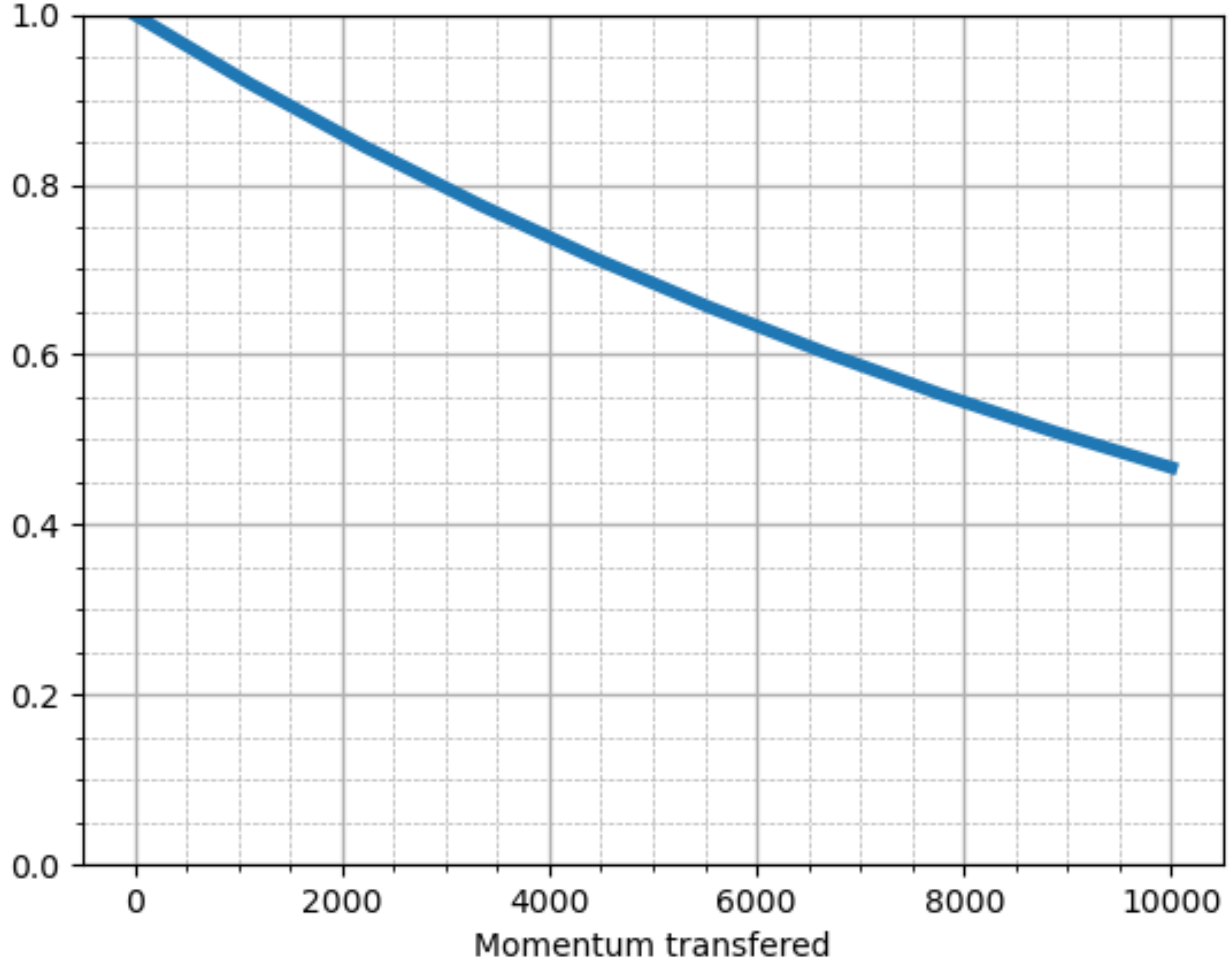
# Floquet acceleration

## Simulation to reach 10000 $\hbar k$

Pulse-to-pulse fluctuations

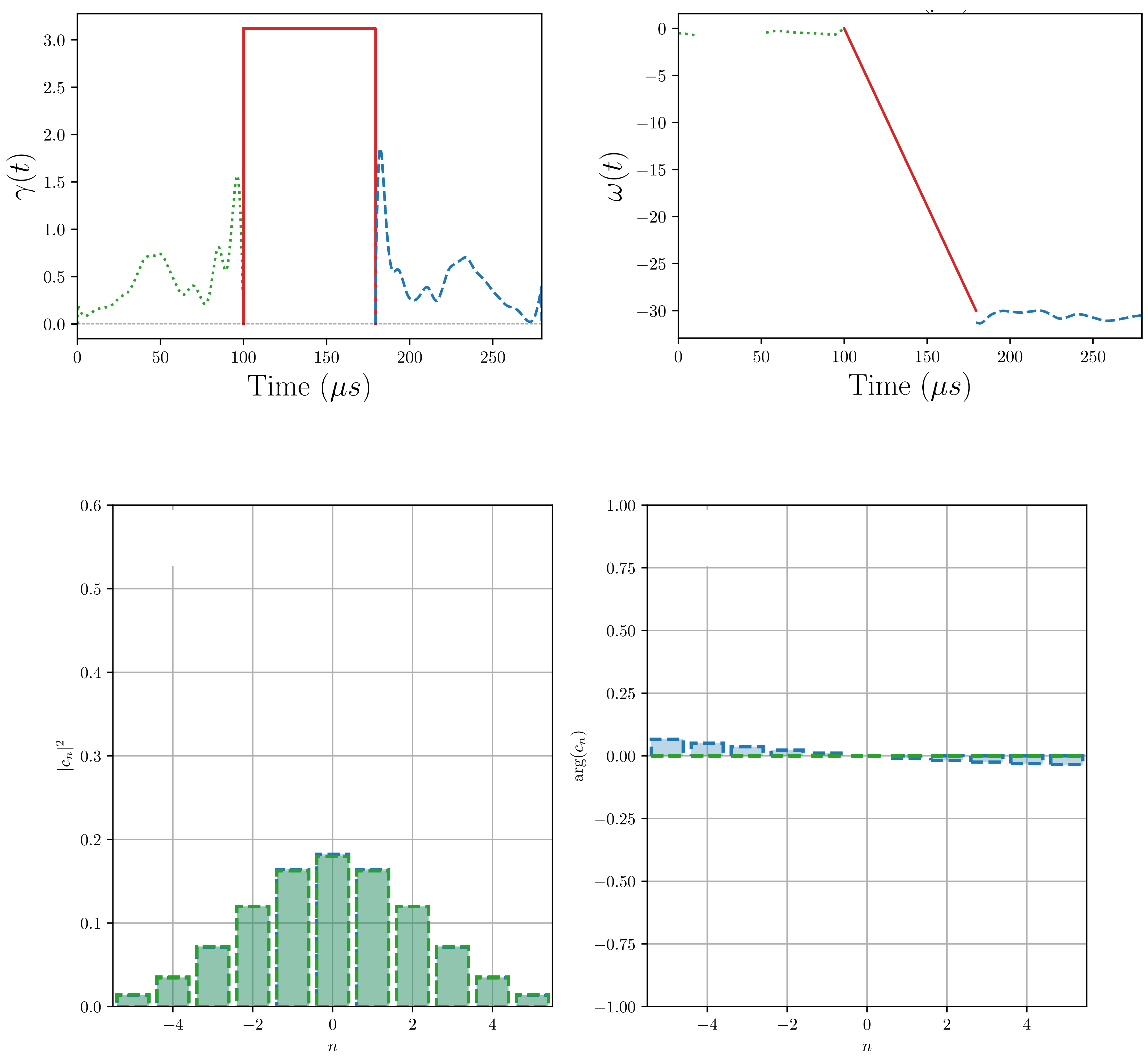



Spontaneous emission 250 GHz



# Bloch-type acceleration

## Constant amplitude and frequency in accelerated frame




Optimal solution results in similar efficiency

For infinitely deep lattices, the Floquet state converges to the lattice ground state.

Comparison with :

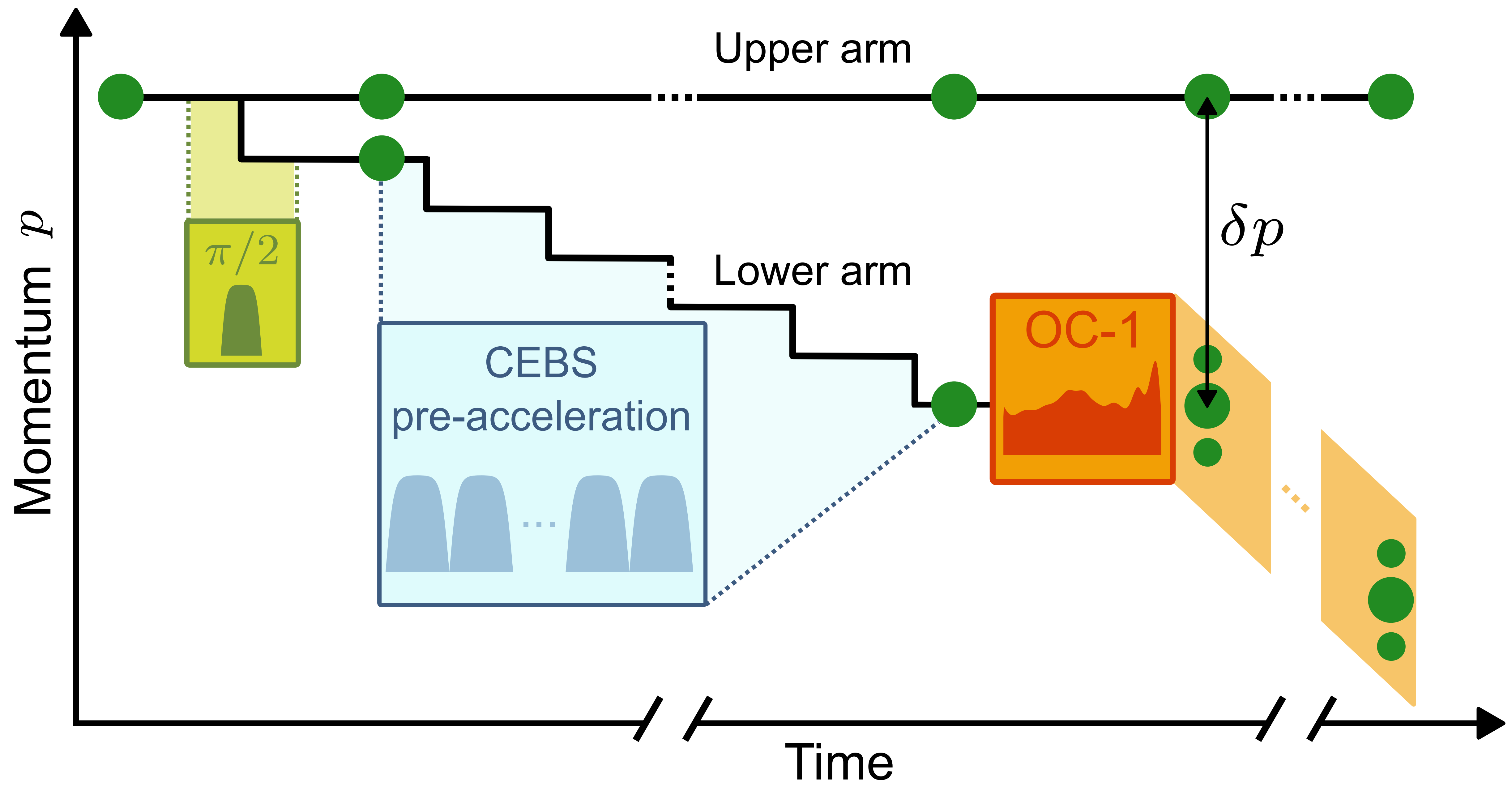
Rahman et al. arXiv:2308.04134

Fitzek et al. arXiv:2306.09399

# LMT-Beam splitters

## Pre-acceleration

Floquet states potentially have a large momentum expansion. This can interfere with the other arm during acceleration. Need for a pre-acceleration step.




$\pi/2$ - pulse quasi-Bragg regime

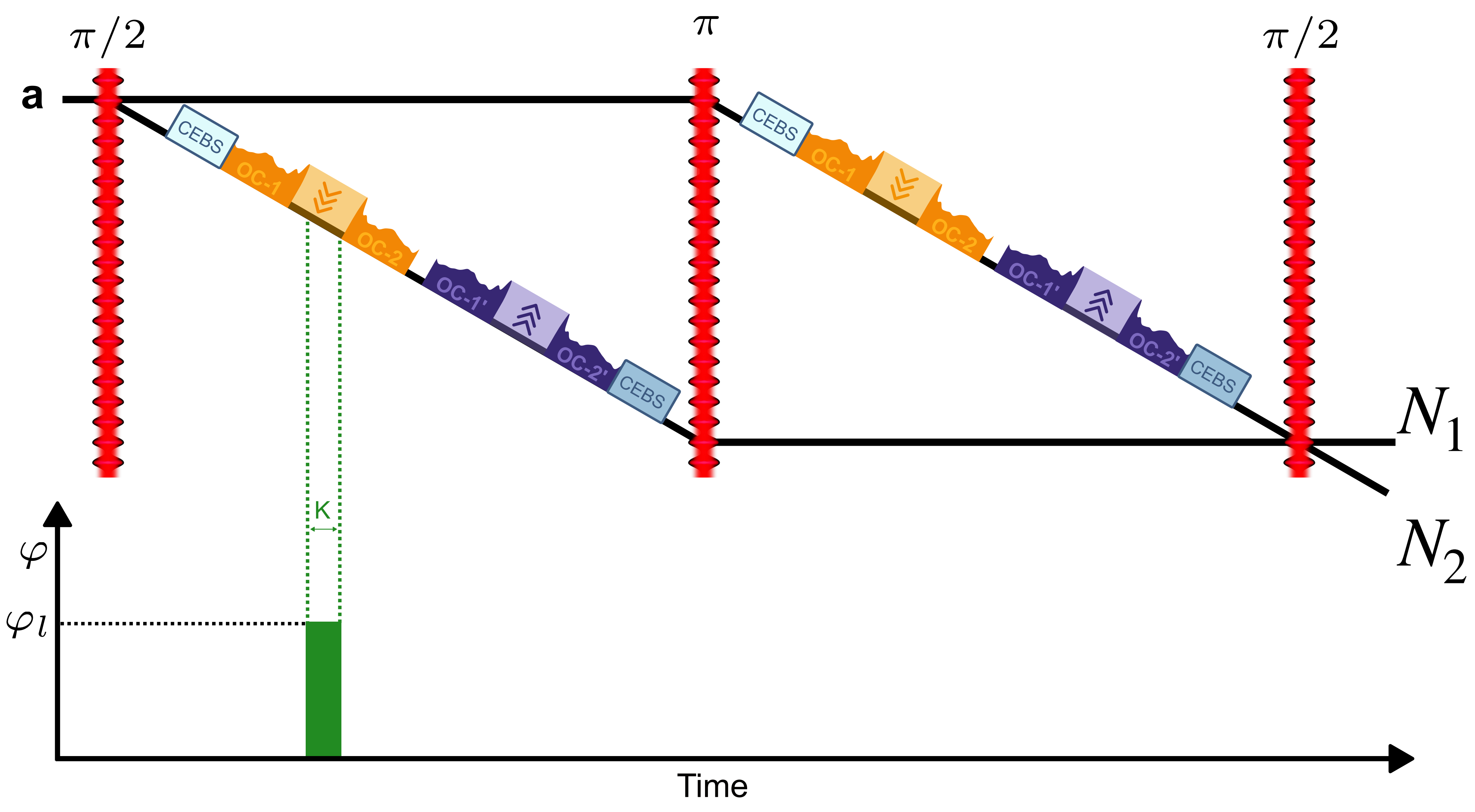
11 CEBS pulses (40 $\mu s$)

Floquet acceleration: N pulses

Total Momentum separation = (1 + 11 + N) $\times 2\hbar k$

# LMT - Interferometer

## $600\hbar k$ - interferometer




Interferometer signal $\frac{N_1}{N_1+N_2} = A\left(1 + V\sin(\Delta\phi)\right)$

Lattice phase imprinted on the atom at each momentum transfer

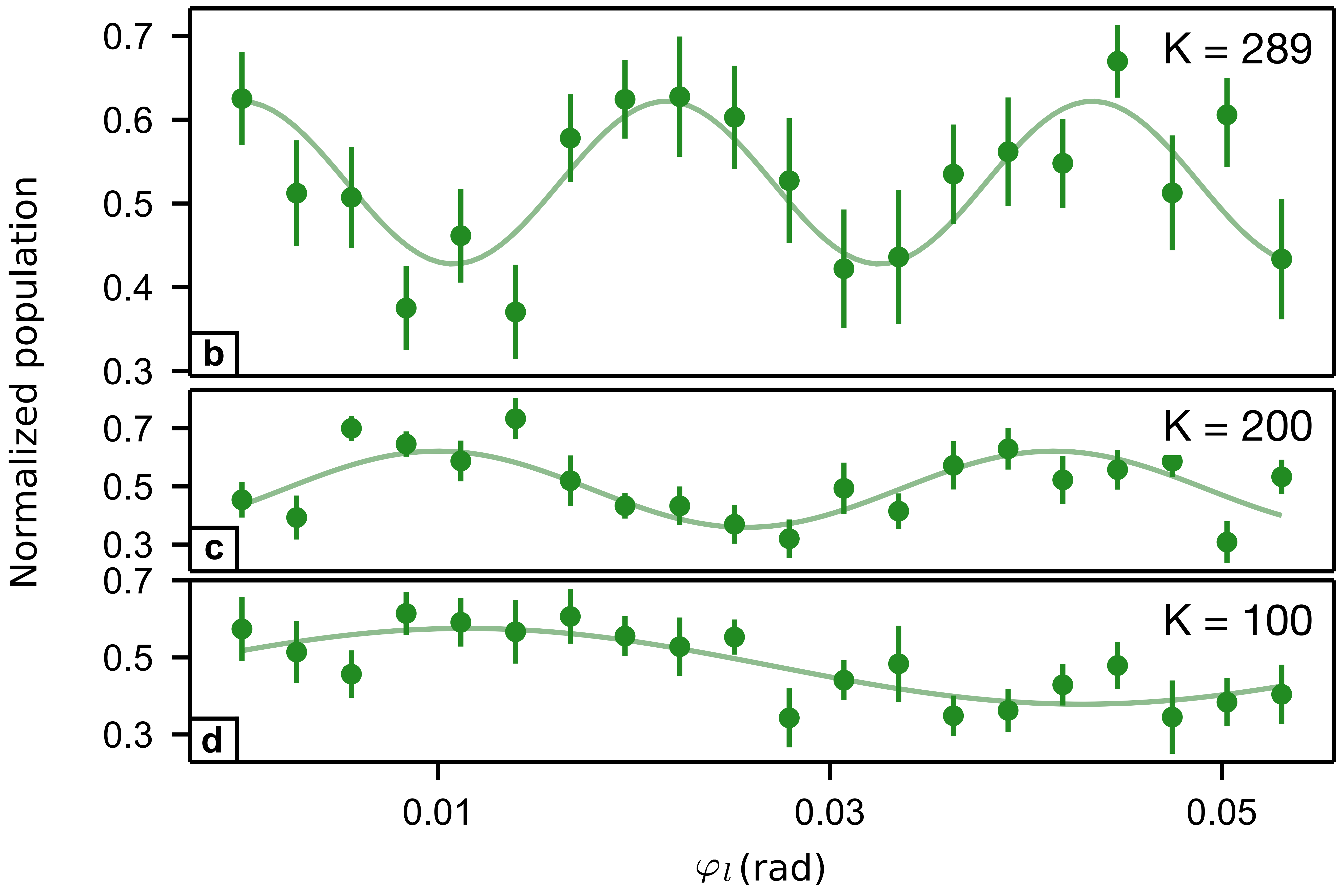
Phase-shift scaling with lattice phase $\Delta\phi = K \times \varphi_l$

Scan the fringes by incrementing $\varphi_l$

# LMT - Interferometer

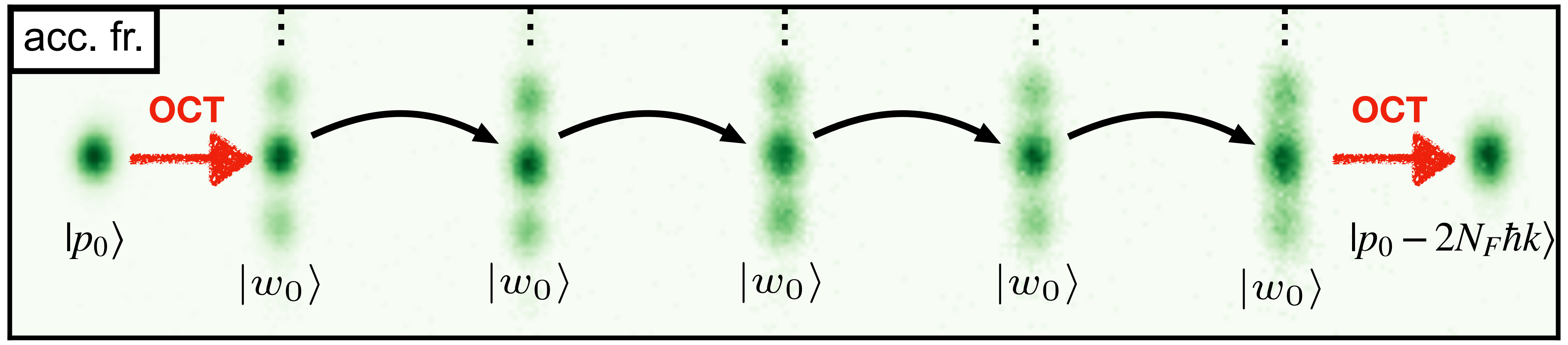
## 600$\hbar k$ - interferometer

Rodzinka et al. [arXiv:2403.14337]

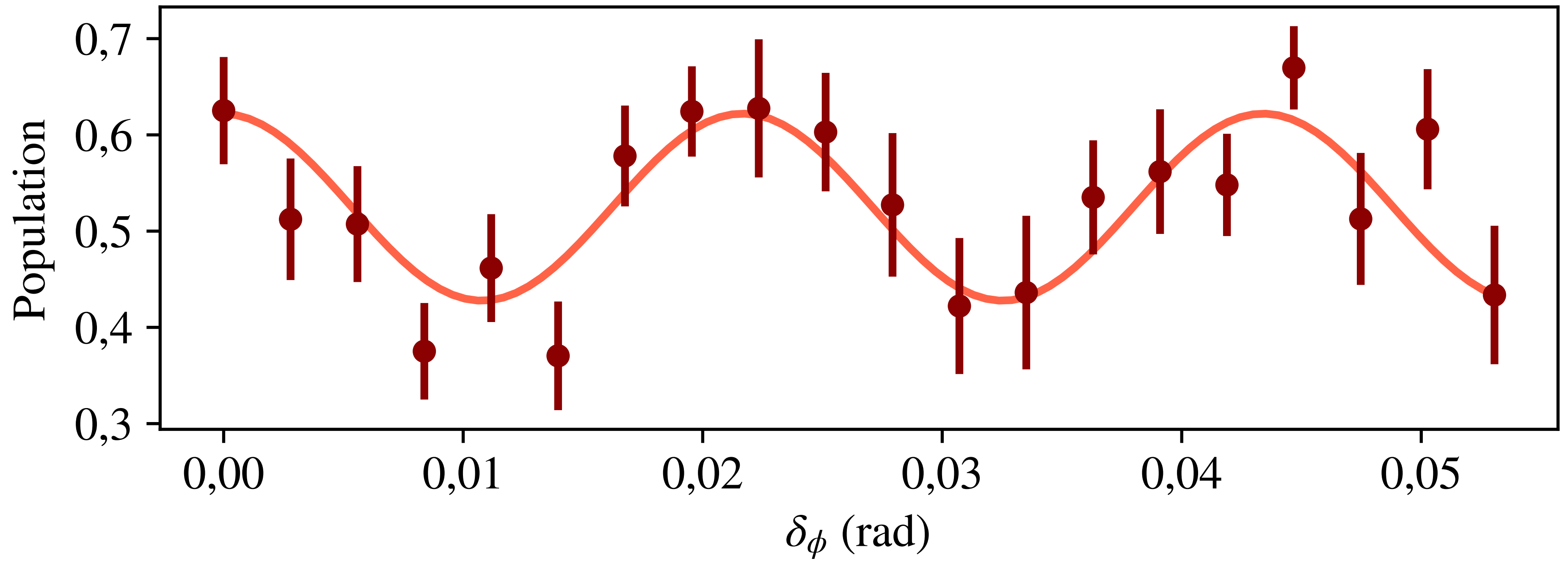



- LMT - Interferometer $600\hbar k$
  - limit = detection volume
- Visibility: $18\% \pm 4\,\%$
  - limit = spontaneous emission & pre-acceleration efficiency

# Conclusion & Discussion



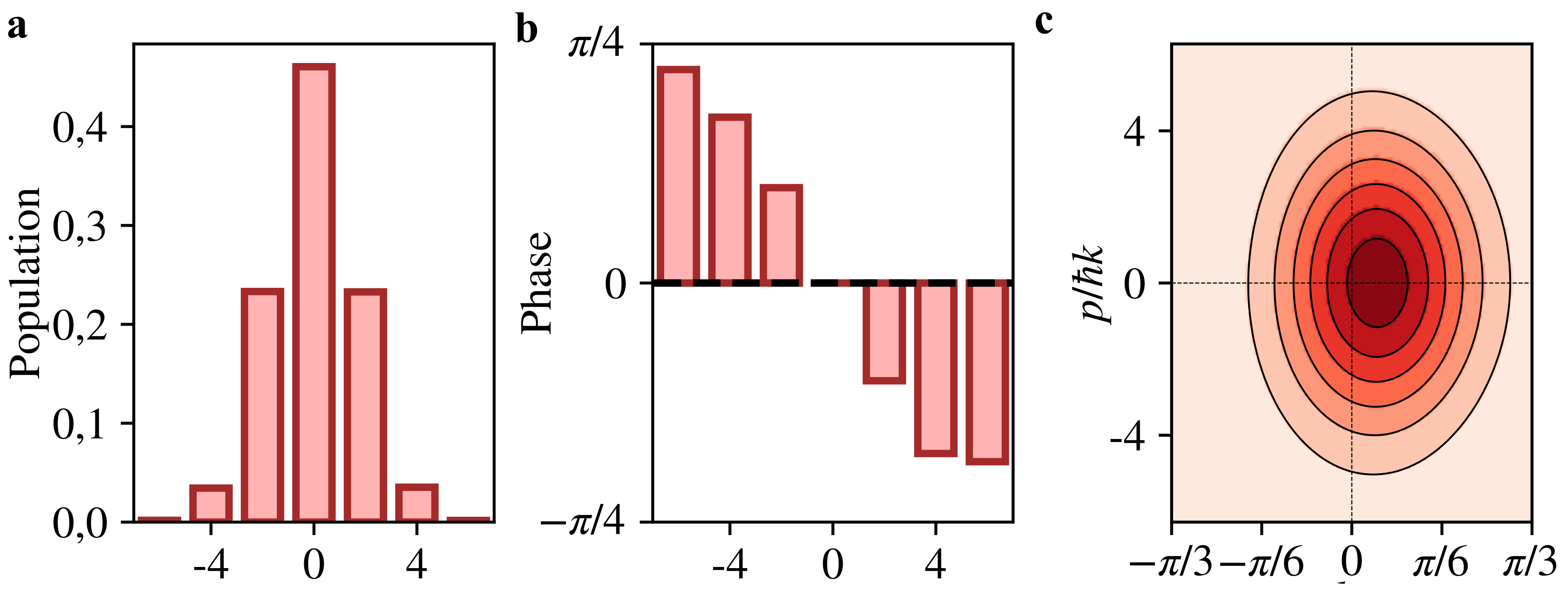

- Floquet approach for sequential and continuous acceleration.
- New QOCT implementation for navigating large Hilbert spaces.
- Fast and very efficient LMT.
- Demonstrates 600 hk atom interferometer.

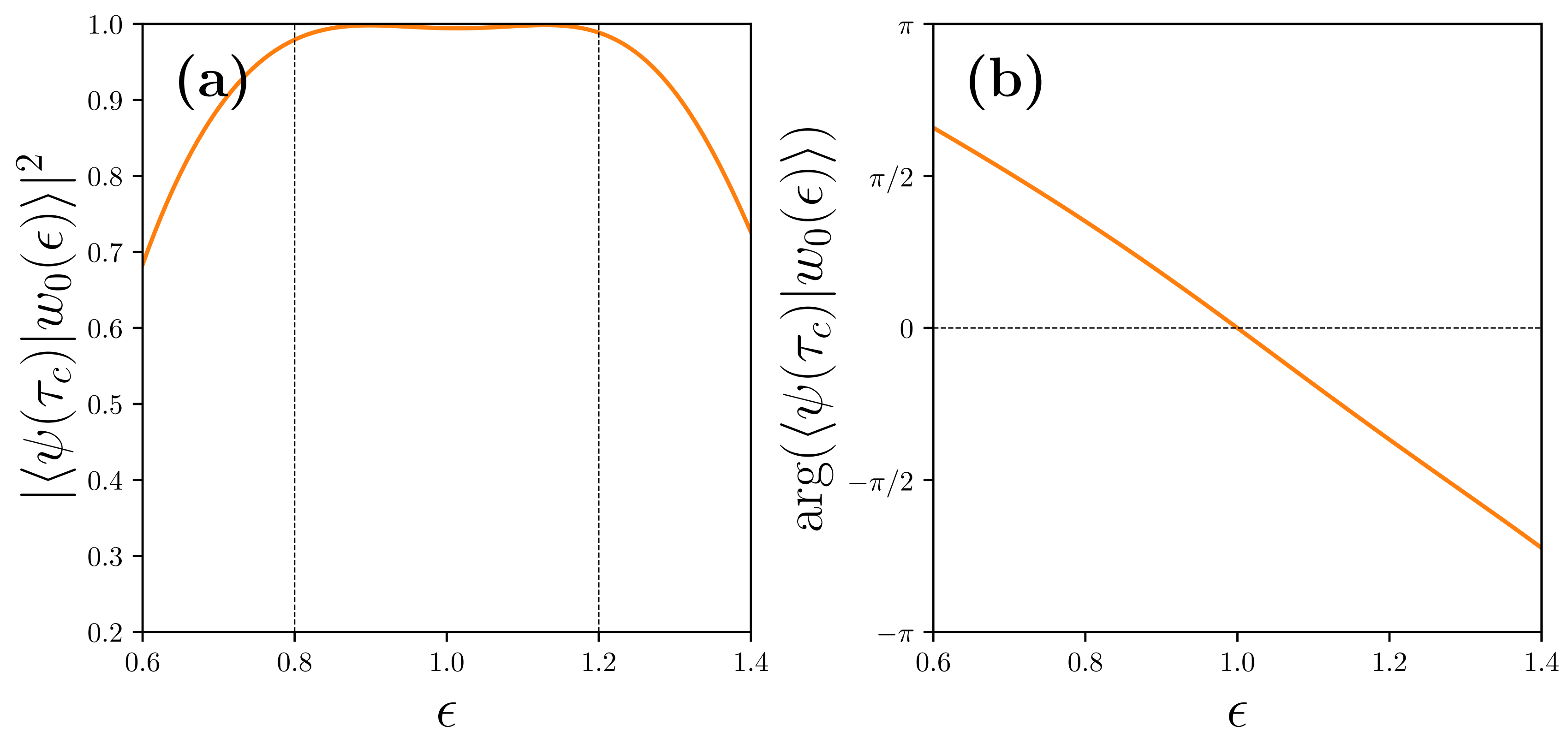



**We believe that there are no serious barriers to realization of momentum transfers greater than $1000\hbar k$.**

# Conclusion & Discussion

- Improving the beam splitting and pre-acc
- Robust against lattice depth fluctuations
    - Pulse Sequence Engineering
    - More powerful and stable laser
- Metrology of LMT interferometer
    - QOCT for Phase shifts robustness
    - Phase shift measurements



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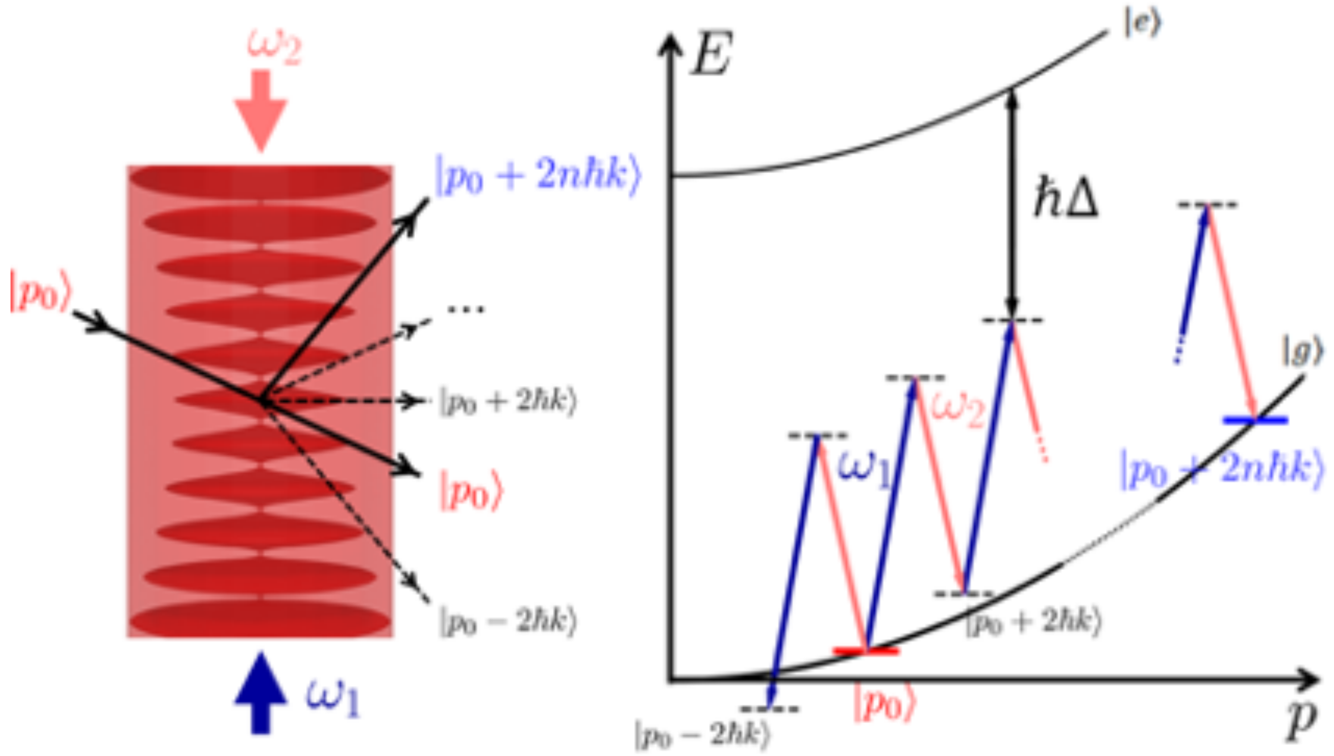
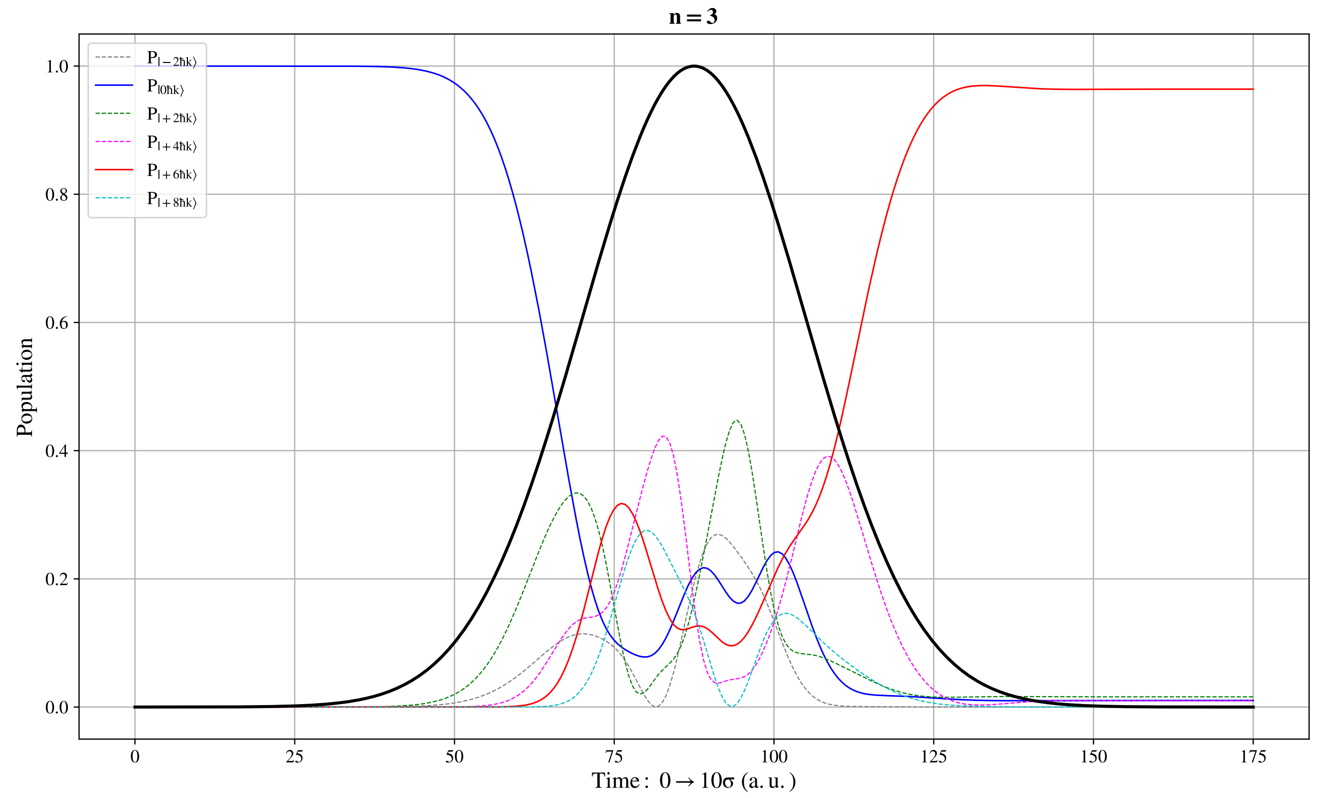
The Machine

# Quasi-Bragg diffraction

## High-order diffraction and Brute-Force Optimal Control

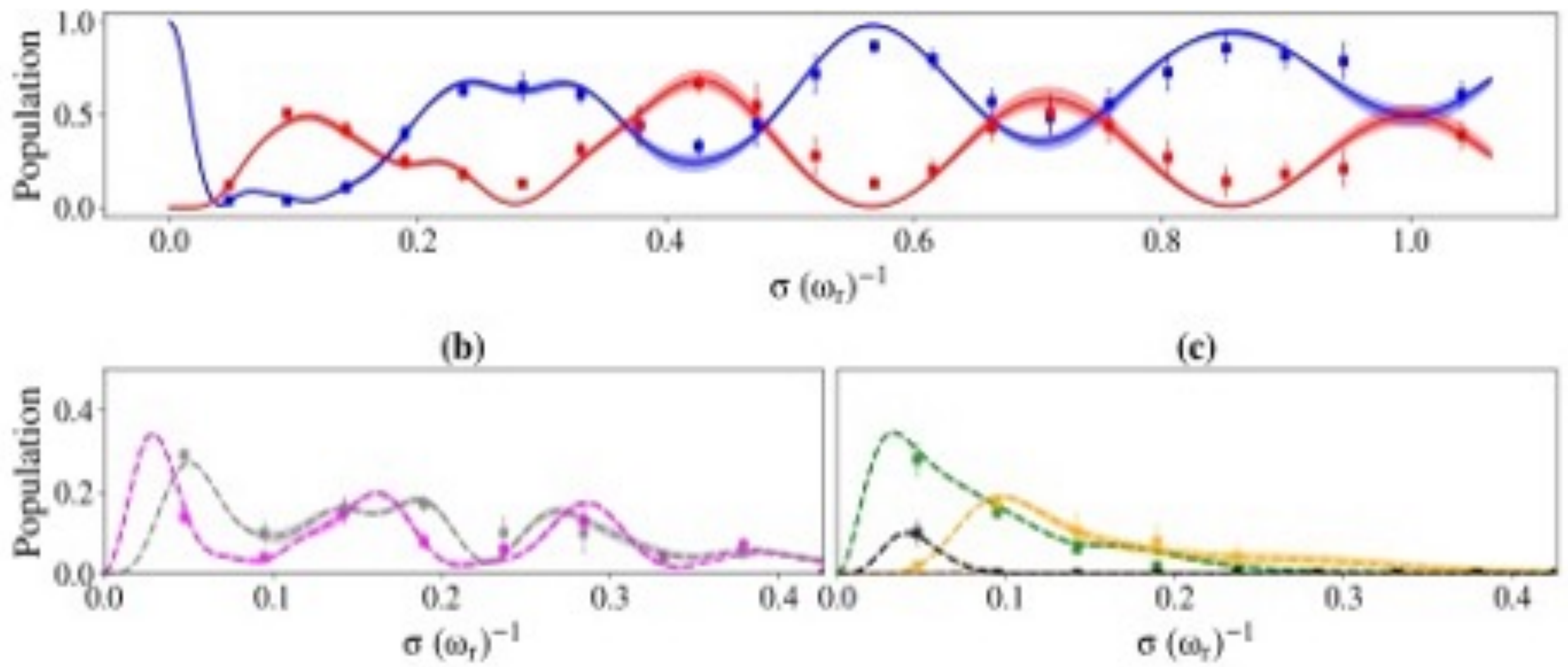



Multiple loss path




Gaussian pulse

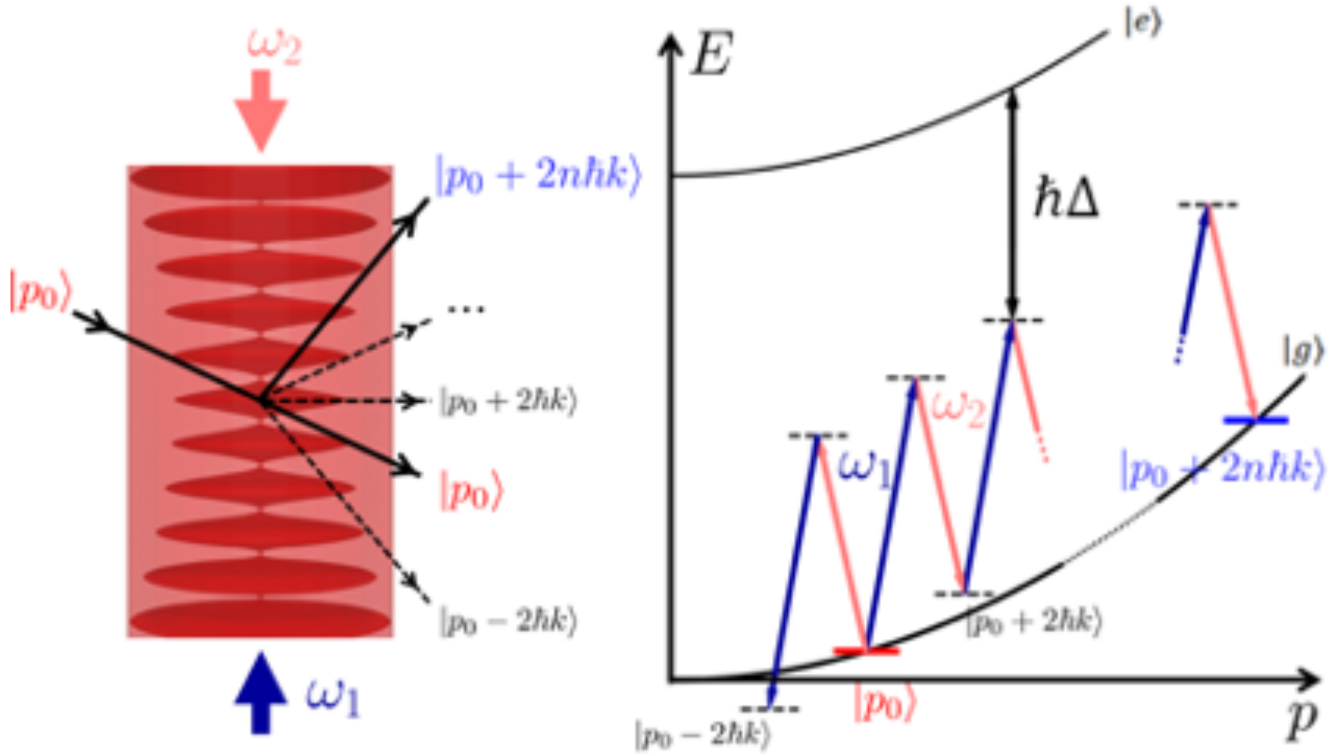
Béguin et al., Phys. Rev. A, **105**, 03302 (2022)



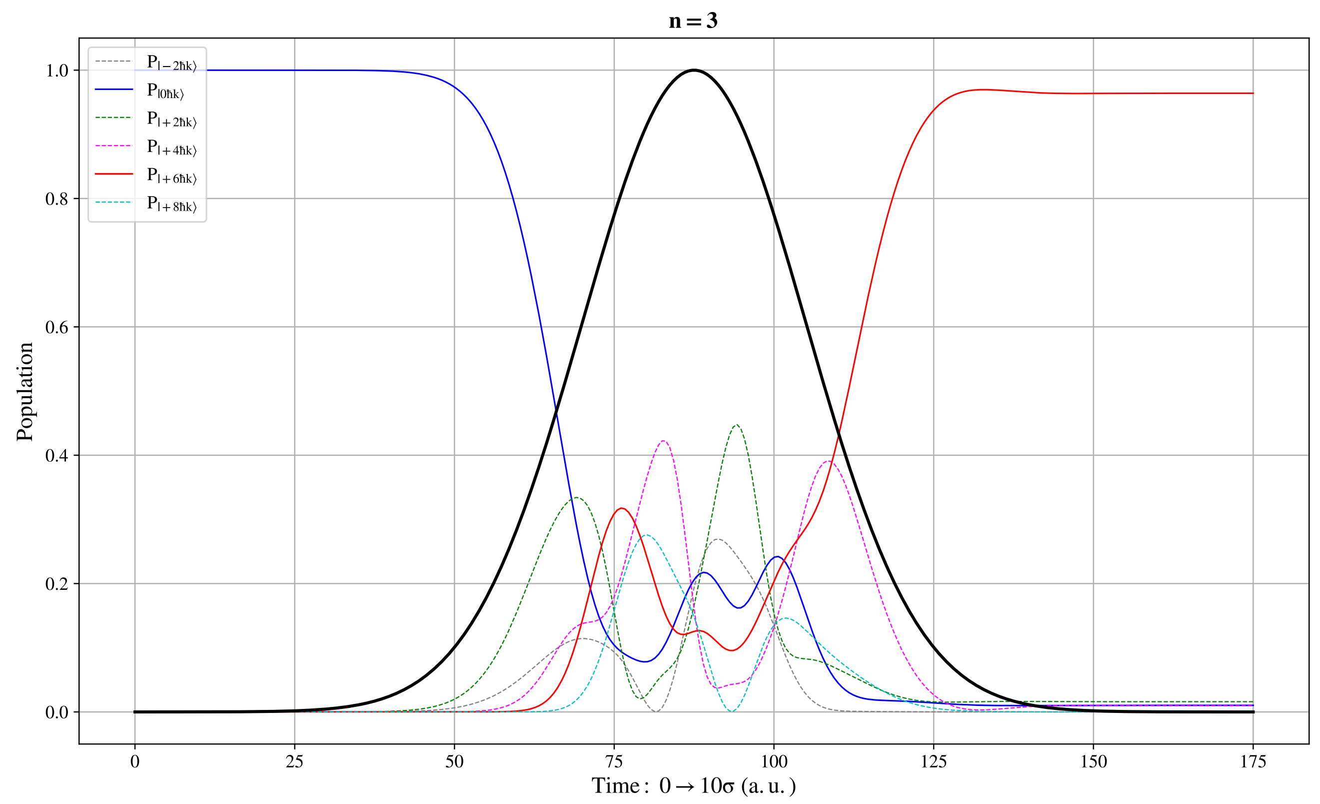

non-adiabatic vs velocity selection

# Quasi-Bragg diffraction

## High-order diffraction and Brute-Force Optimal Control

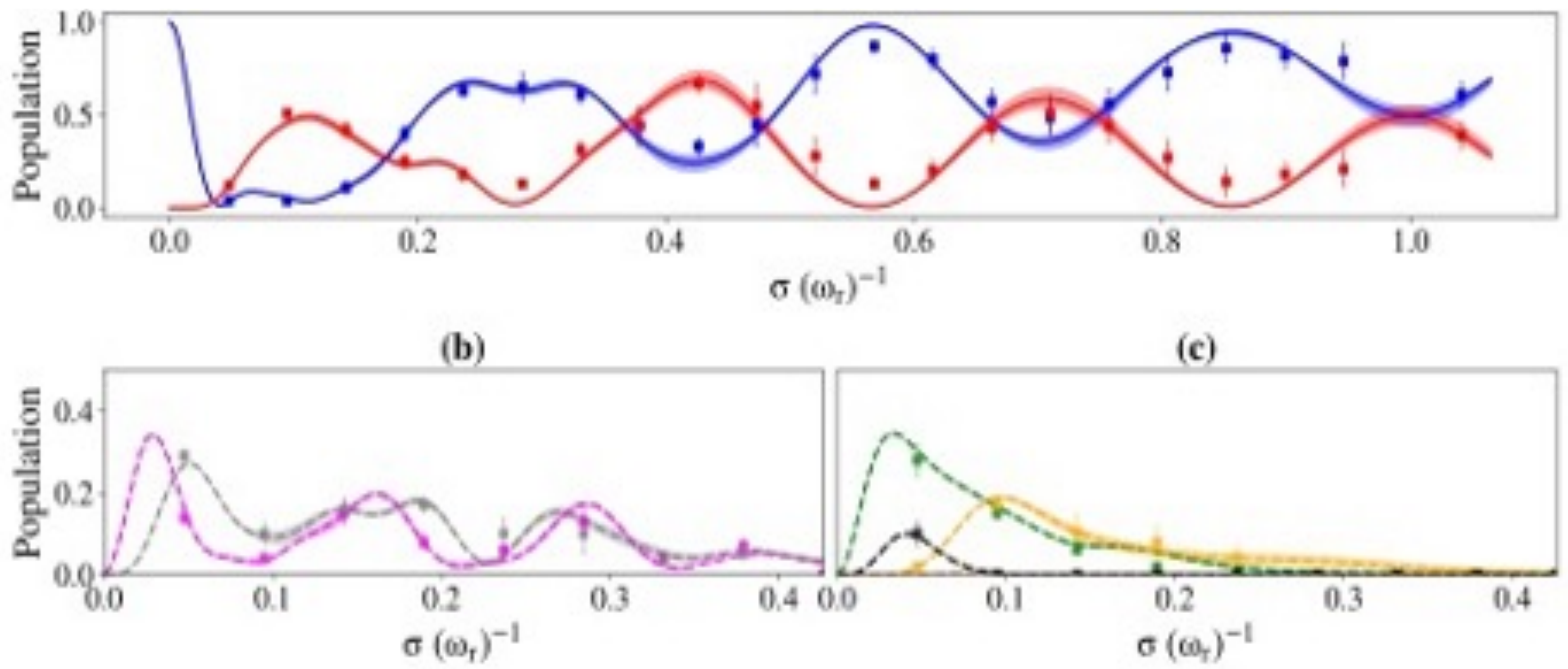



Multiple loss path

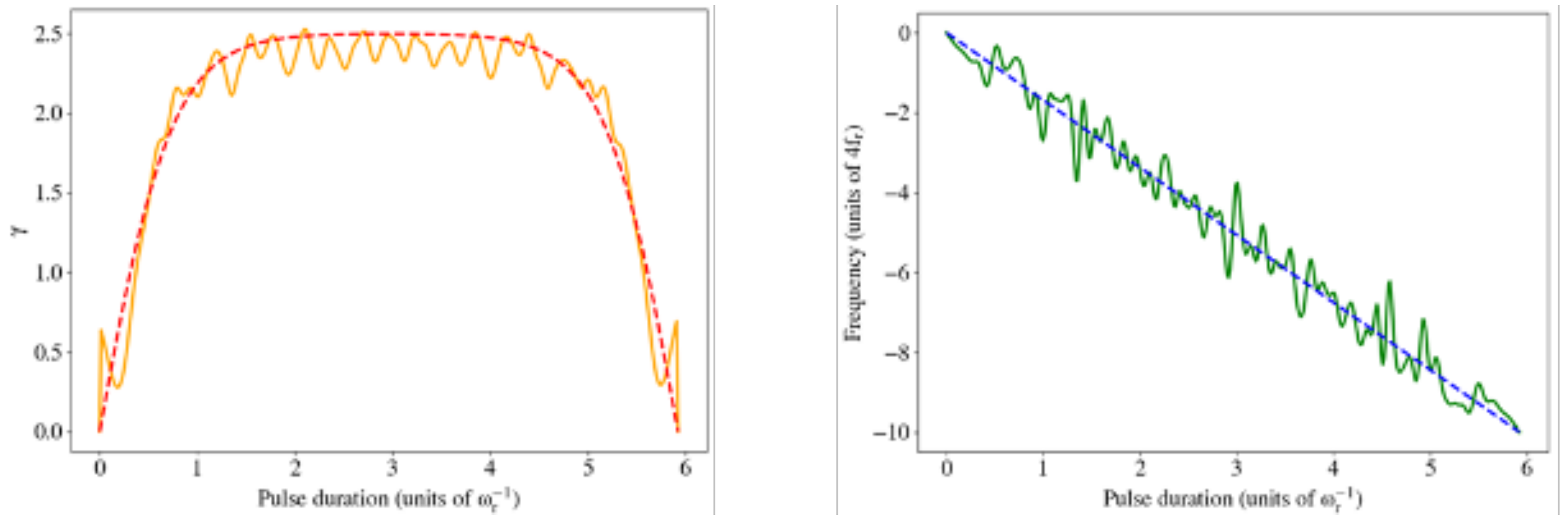



Gaussian pulse

Béguin et al**.**, Phys. Rev. A, **105**, (2022)




non-adiabatic vs velocity selection




Pulse shape based on Optimal Control Theory

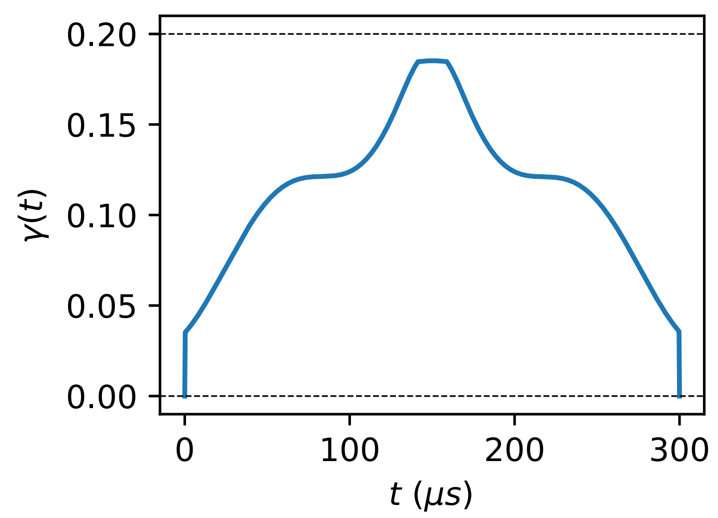
- Can we improve gaussian pulse with OCT ?
- Enhanced robustness to Doppler detuning, lattice depth, etc.
- Very hard to go beyond a few tens of $\hbar k$ with a brute force numerical approach.

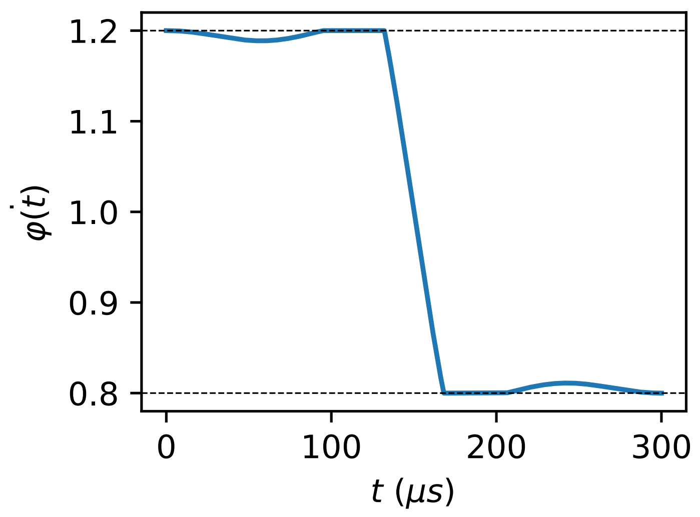
Louie et al 2023 New J. Phys. **25** 083017

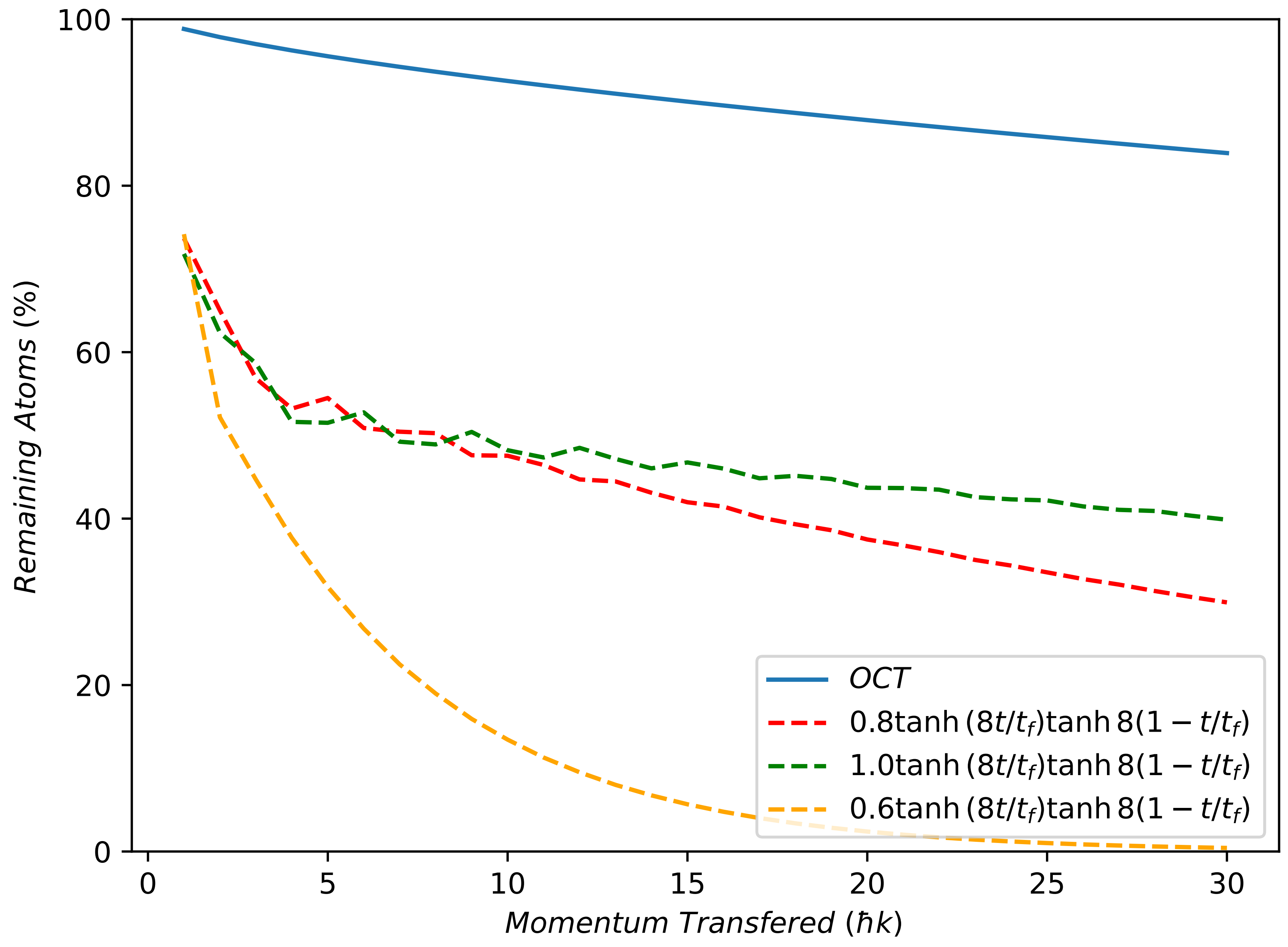
Saywell *et al. Nat Commun* **14**, 7626 (2023).

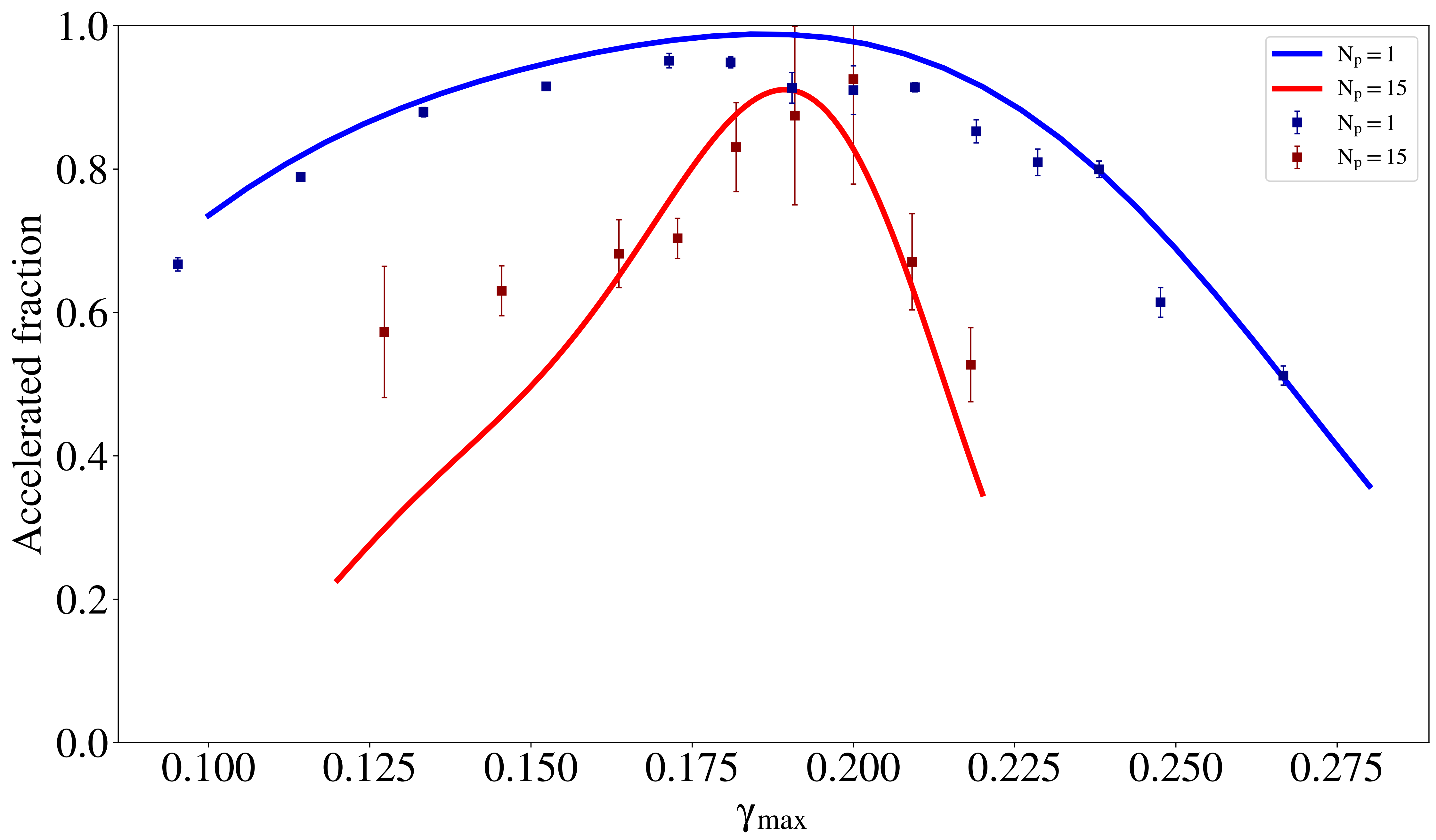
# LMT: Bragg pulse sequence

## Independent pulses: OCT pulses



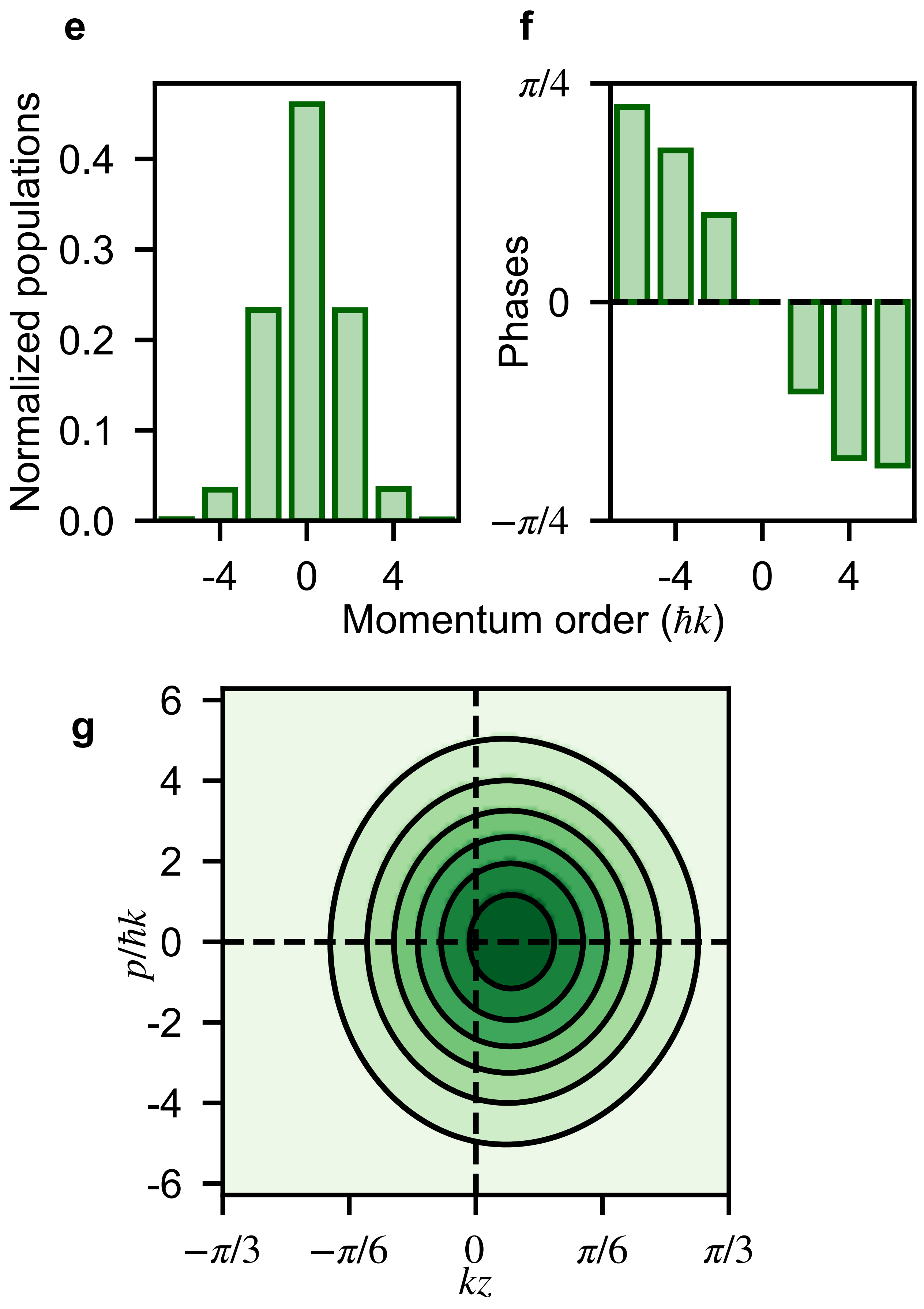



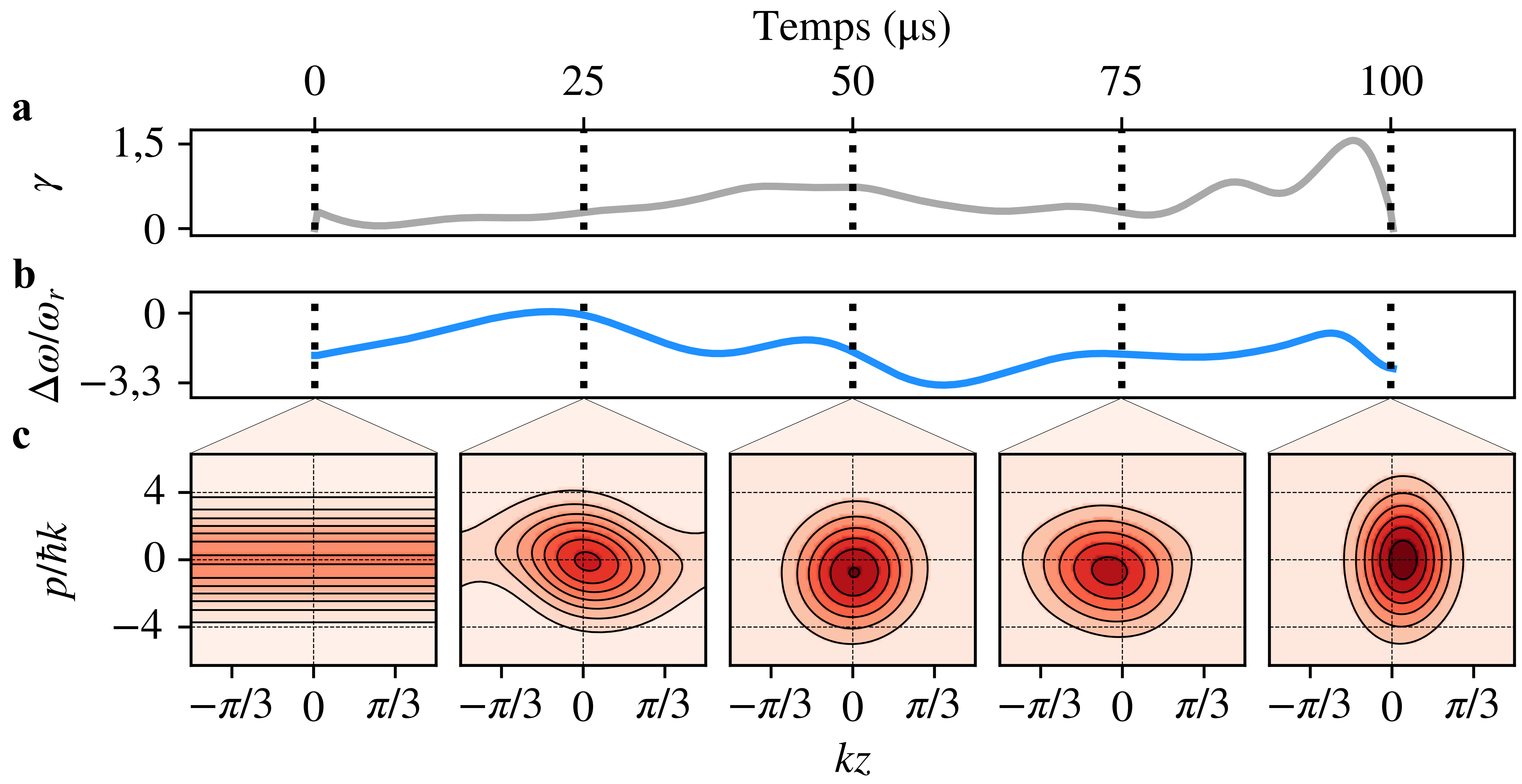




- Experimental efficiency limited by detection
- **Testing robustness ?**
- Comparison with gaussian pulse $8\sigma = 300\ \mu s$

# Floquet state in phase space

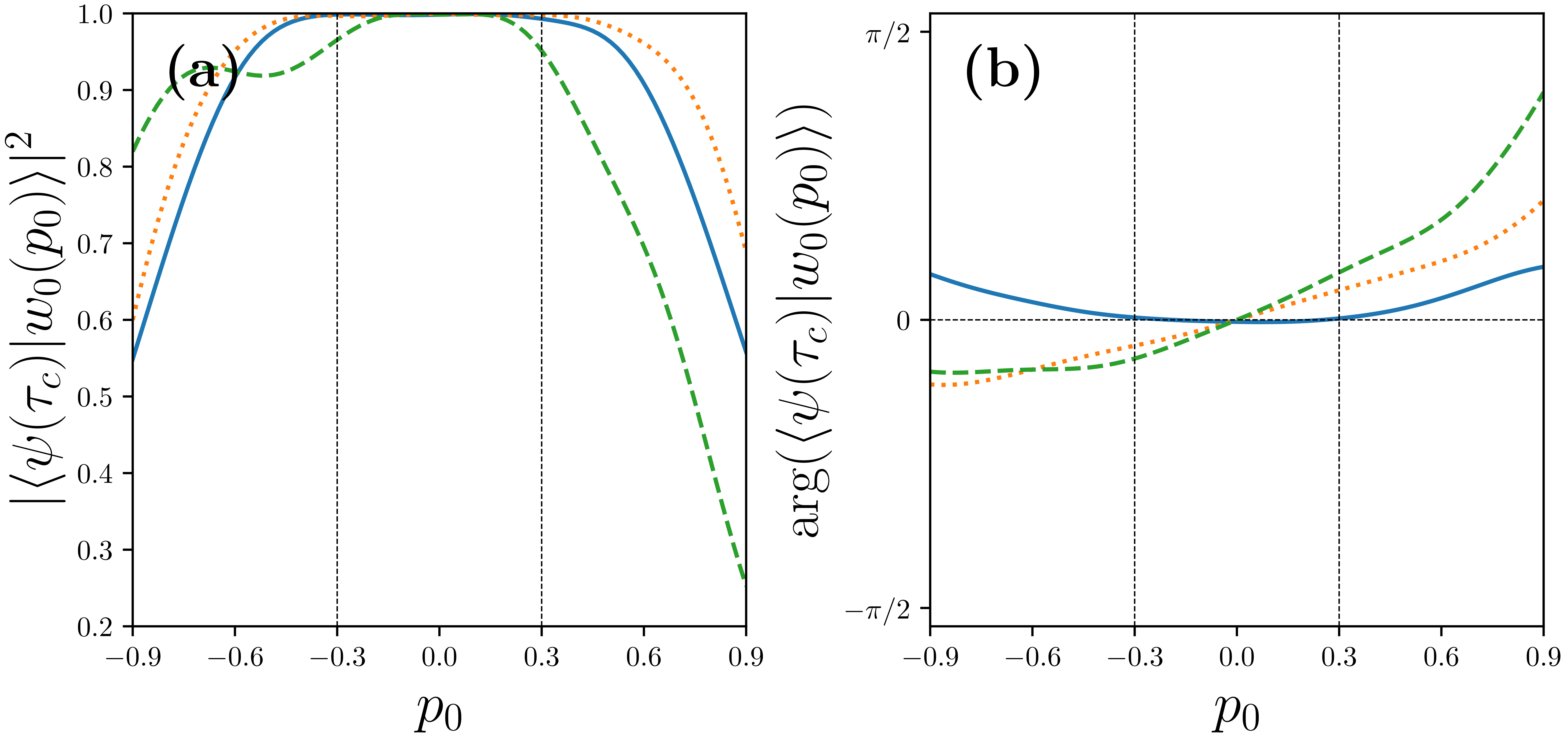
## A simple parameterization of $|w_0\rangle$



# Phase dispersion

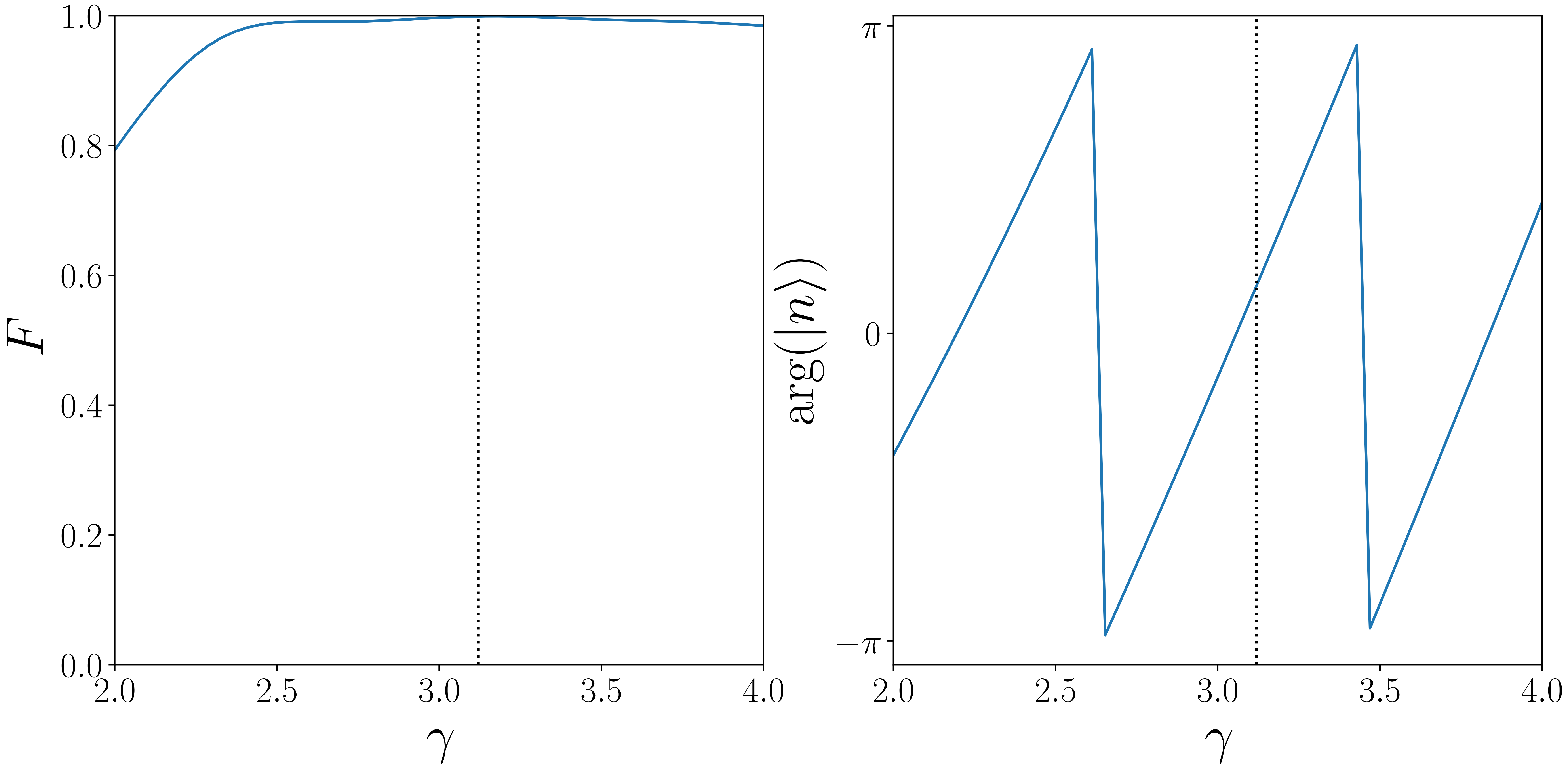
## QOCT allows non-dispersive phase



# Phase shift vs Lattice depth

## Fidelity and phase of the accelerated state

$20\hbar k$ momentum transfer:




$$\frac{\Delta\gamma}{\gamma} = 10^{-6} \to \sim 1 \text{ mrad}/1000\hbar k$$

Can be improved with sequence engineering