Phase-contrast interferometry: Single-shot, phase-insensitive readout of an atom interferometer.

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Atom interferometry is a next-generation technique for precision measurement, mapping information contained in the phase of atoms to an easily measurable output. The sensitivity of atoms to fields such as electromagnetism and gravity allows atom interferometry to examine physics which conventional interferometers cannot. For the probing of fundamental physics such as QED corrections, atoms are an obvious test-bed. Here we describe our experimental setup, which uses atomic Bose-Einstein condensates and coherent light-matter interactions to potentially set new limits on the fine structure constant.

The fine structure constant, α

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137}$$

- Developed to explain fine structure in spectral lines.
- Now known as electromagnetic coupling constant.
- Precision measurement essential for test of QED corrections. [1]
- Current state of the art measurement by Gabrielse group: α^{-1} = 137.035999084(51) [± 0.37 × 10^{-9}] [2].
- Best atom interferometer measurement by Biraben group: α^{-1} = 137.035999037(91) [± 0.66 × 10^{-9}] [3].

Method: Atom interferometry → measure recoil frequency

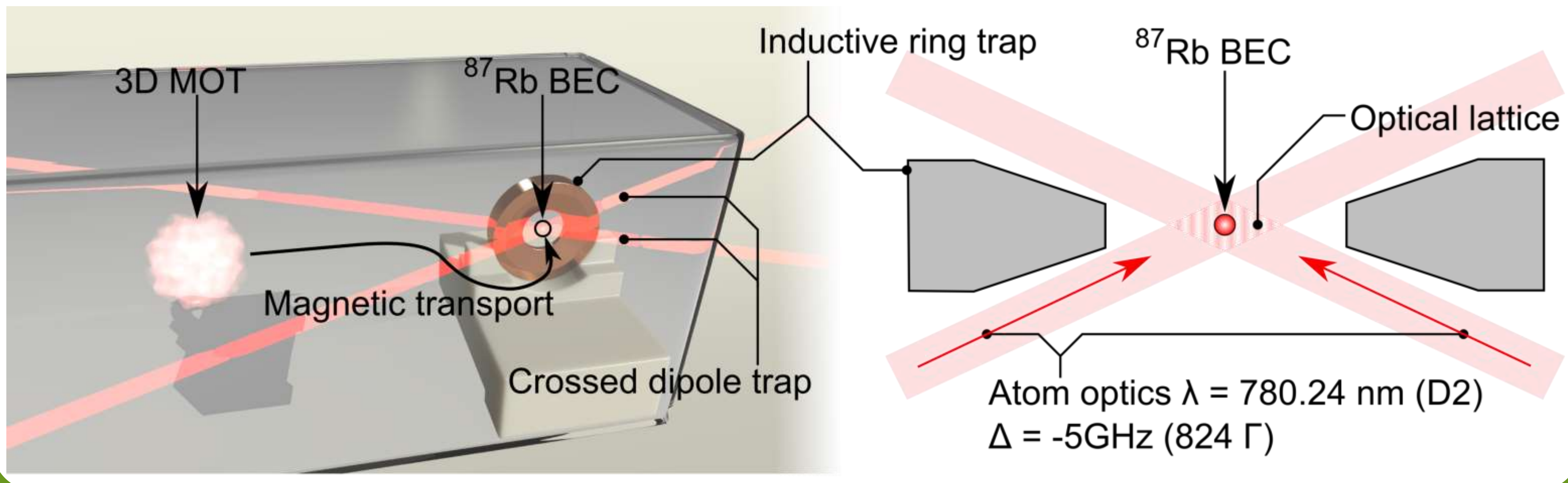
Rydberg constant [uncertainty ± 5.0 × 10^{-12}] [4] — Recoil frequency

$$\alpha^2 = \frac{2R_\infty}{c}\frac{A(Rb)}{A(e)}\frac{h}{m_{Rb}} \longleftrightarrow \frac{\hbar}{m_{Rb}} = 2\frac{\omega_{recoil}}{k^2}$$

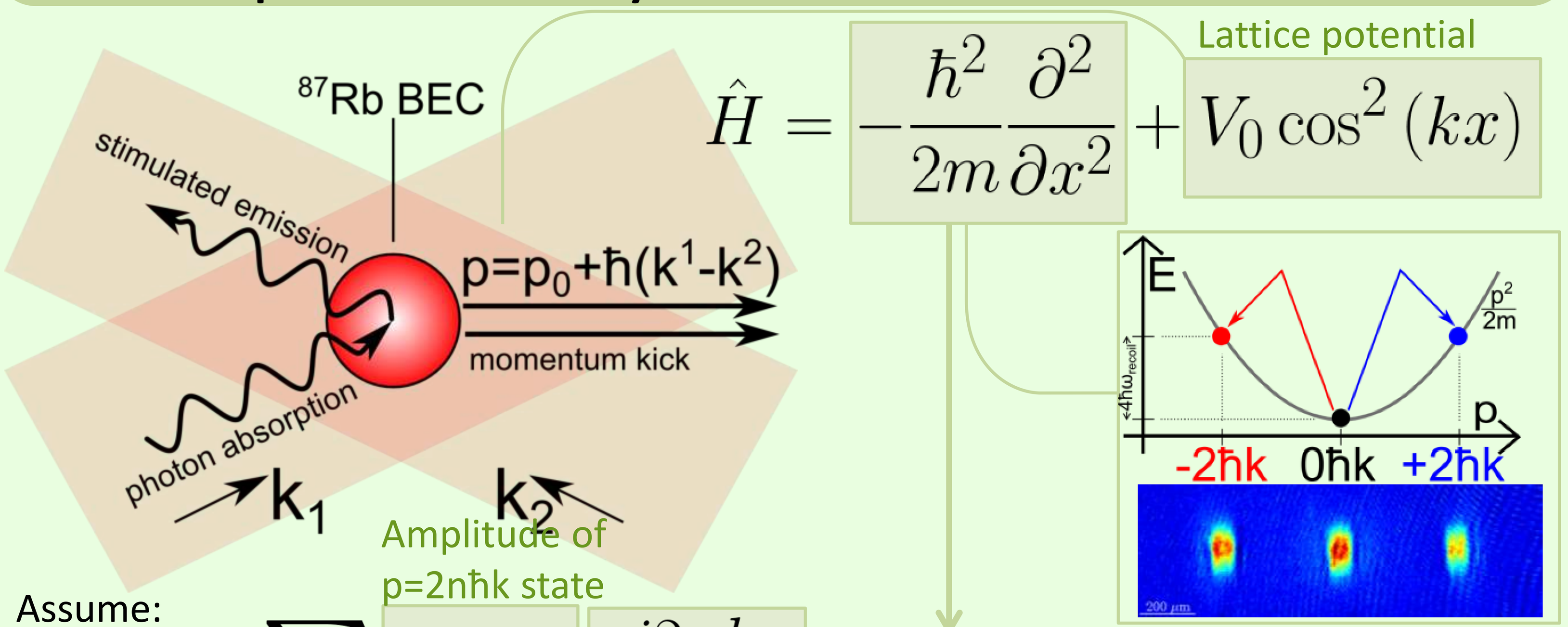
Speed of light — Light wavevector

Rubidium to electron mass ratio [± 0.44 × 10^{-9}] [5,6]

Experimental setup



Atom optics: Theory



$$\hat{H} = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V_0\cos^2(kx)$$

Assume:

$$\psi(t) = \sum_n C_n(t)\, e^{i2nkx}$$

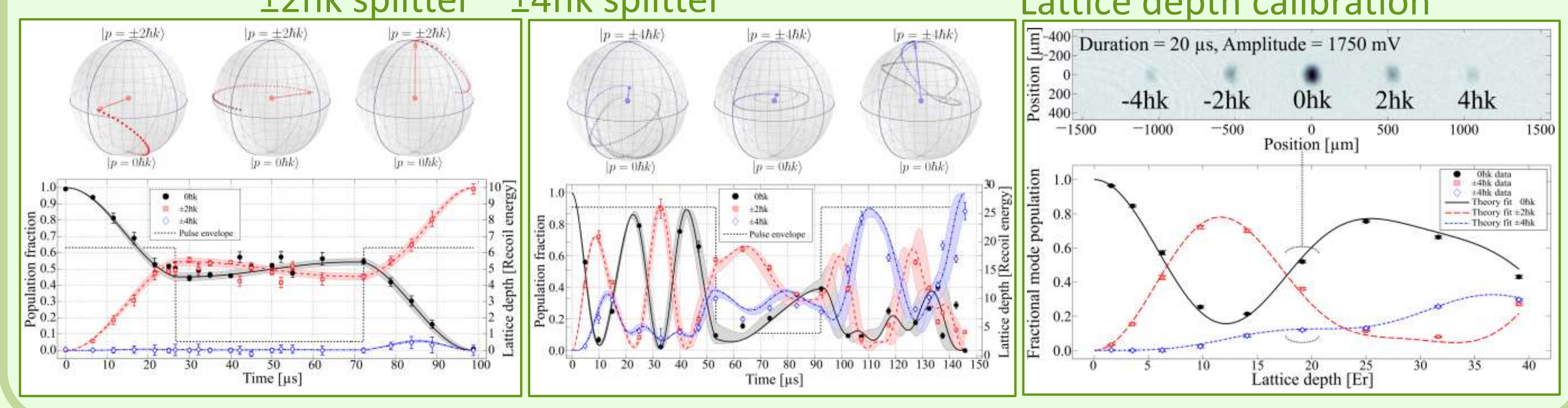
Amplitude of p=2nħk state — Plane waves → Time-dependent Schrödinger Equation

$$\dot{C}_n(t) = -i\left[\frac{Er^{(2)}n^2}{\hbar}C_n(t) + \frac{V_0}{4\hbar}\left(C_{n-1}(t) + 2C_n(t) + C_{n+1}(t)\right)\right]$$

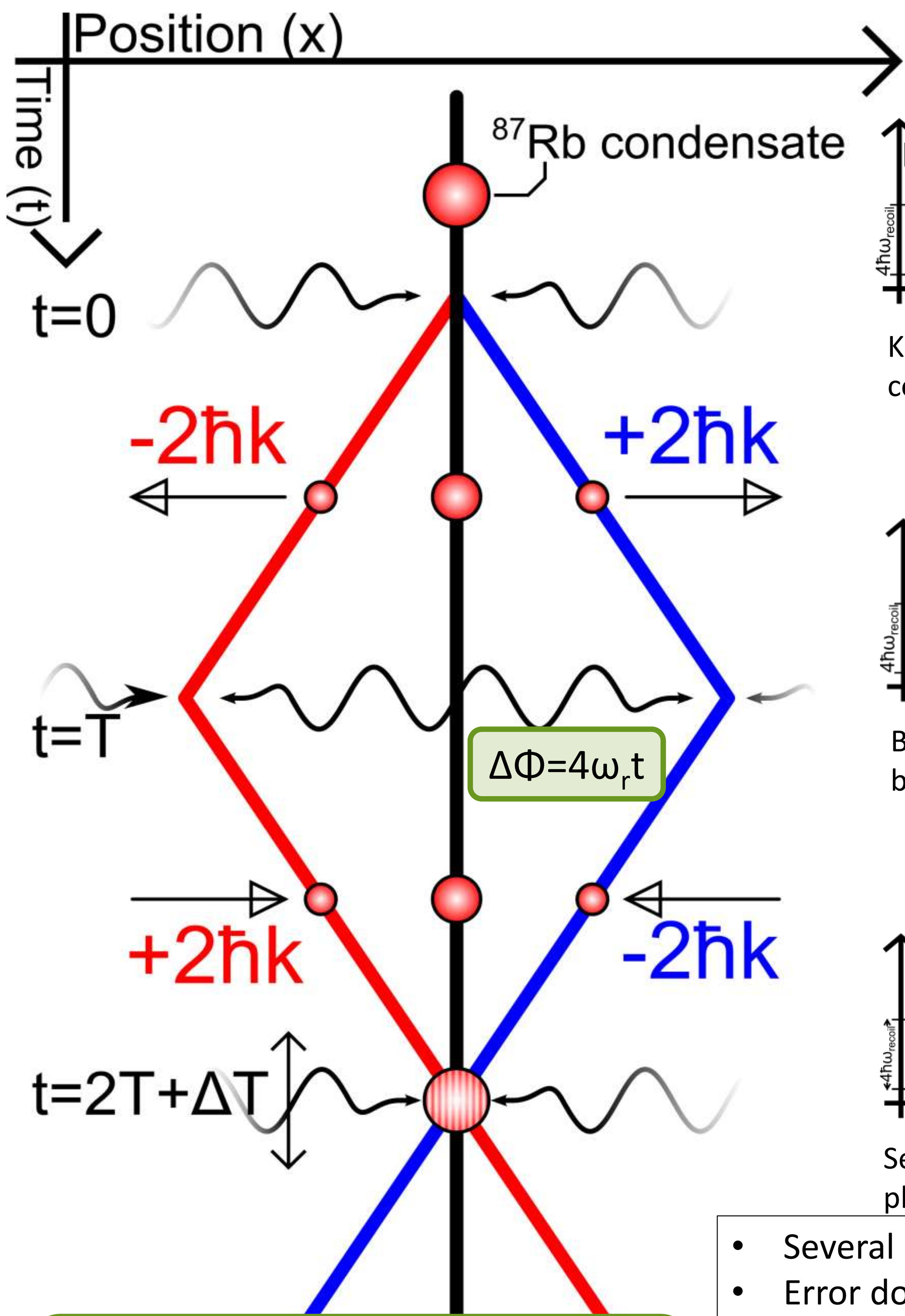
Kinetic energy — Lattice potential

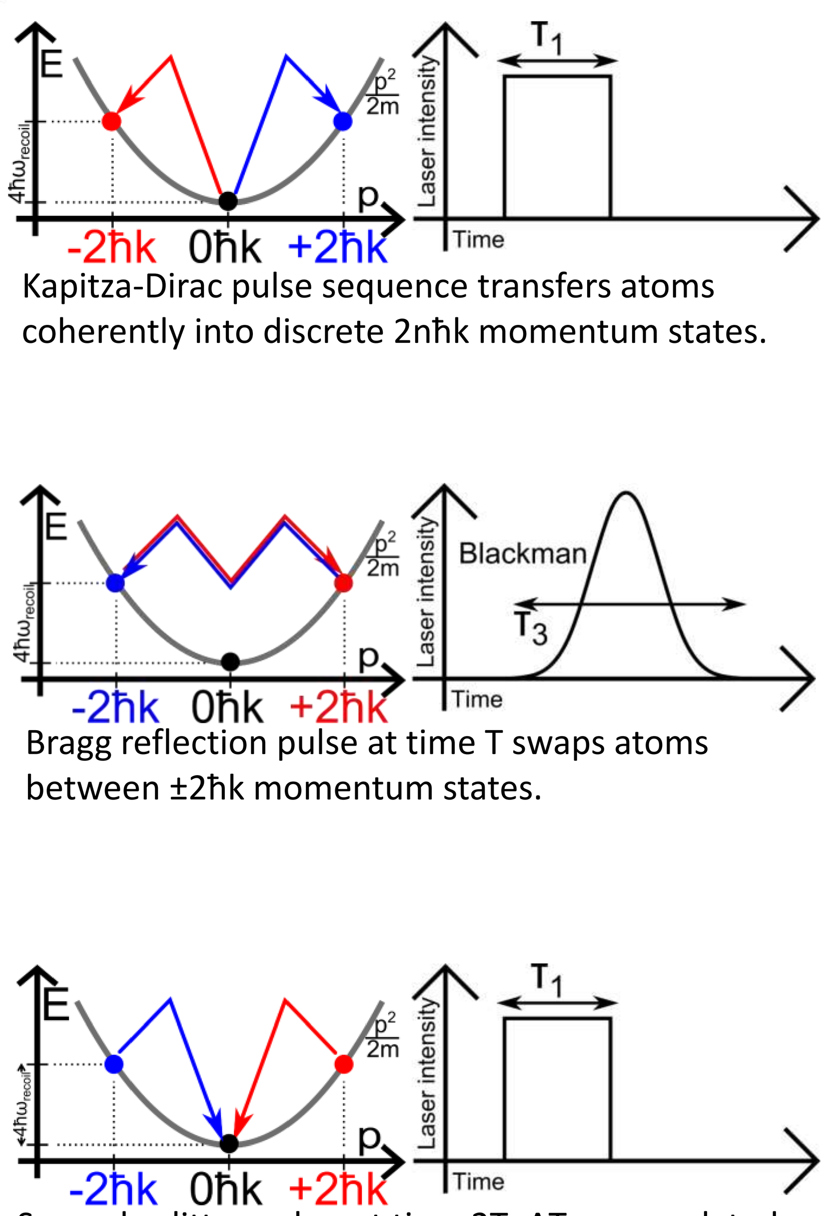
Numerical integration

Design custom atom optics



Atom interferometer





Kapitza-Dirac pulse sequence transfers atoms coherently into discrete 2nħk momentum states.

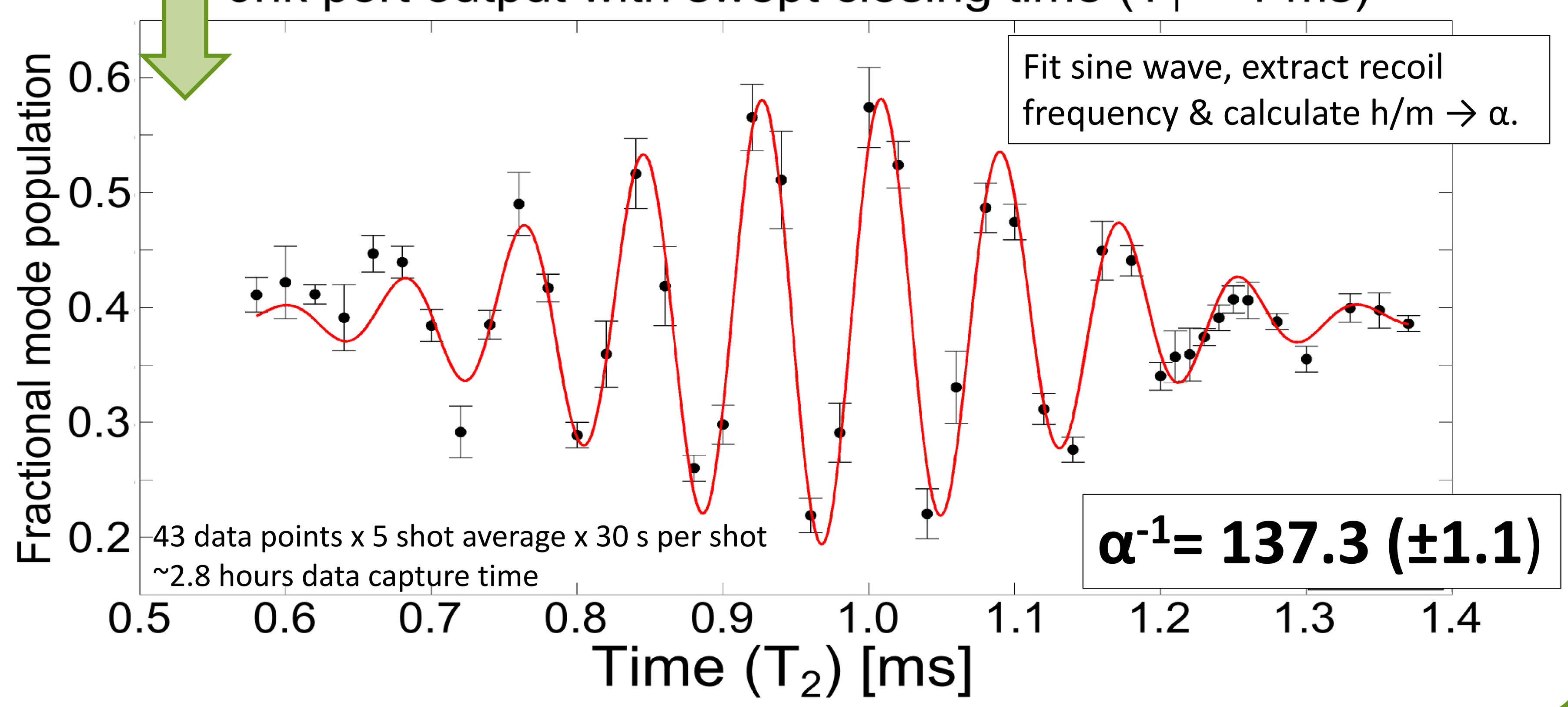
Bragg reflection pulse at time T swaps atoms between ±2ħk momentum states.

Second splitter pulse at time 2T+ΔT, accumulated phase maps to population of momentum states.

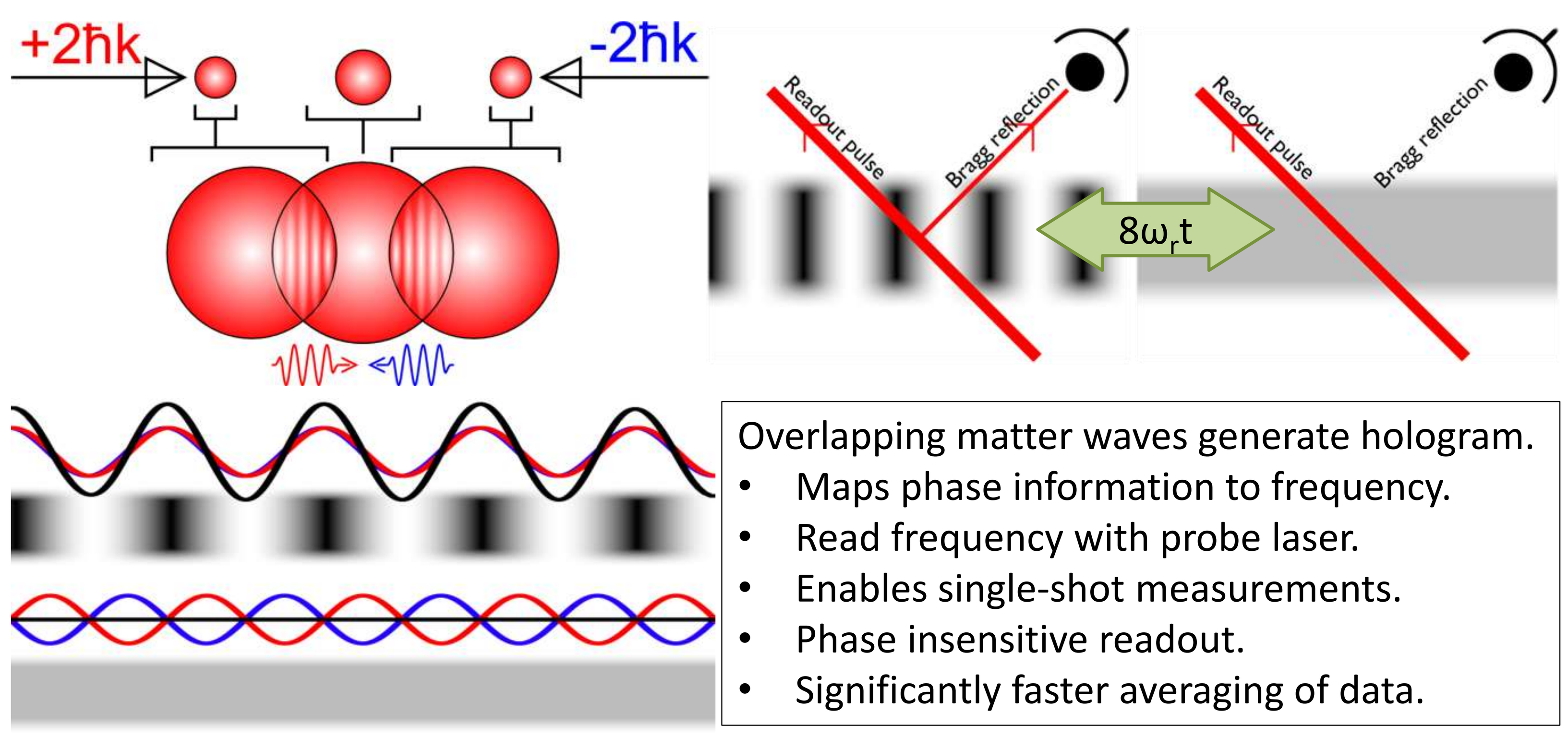
- Several hours data capture, no data averaging.
- Error dominated by uncertainty in beam angles.
- Interferometer precision scales with increasing N recoil events as N^2.
- Can further improve precision with repeated M measurements; precision scales as √M.

Output populations modulated by phase as closing pulse applied

0ħk port output with swept closing time (T_1 = 1 ms)

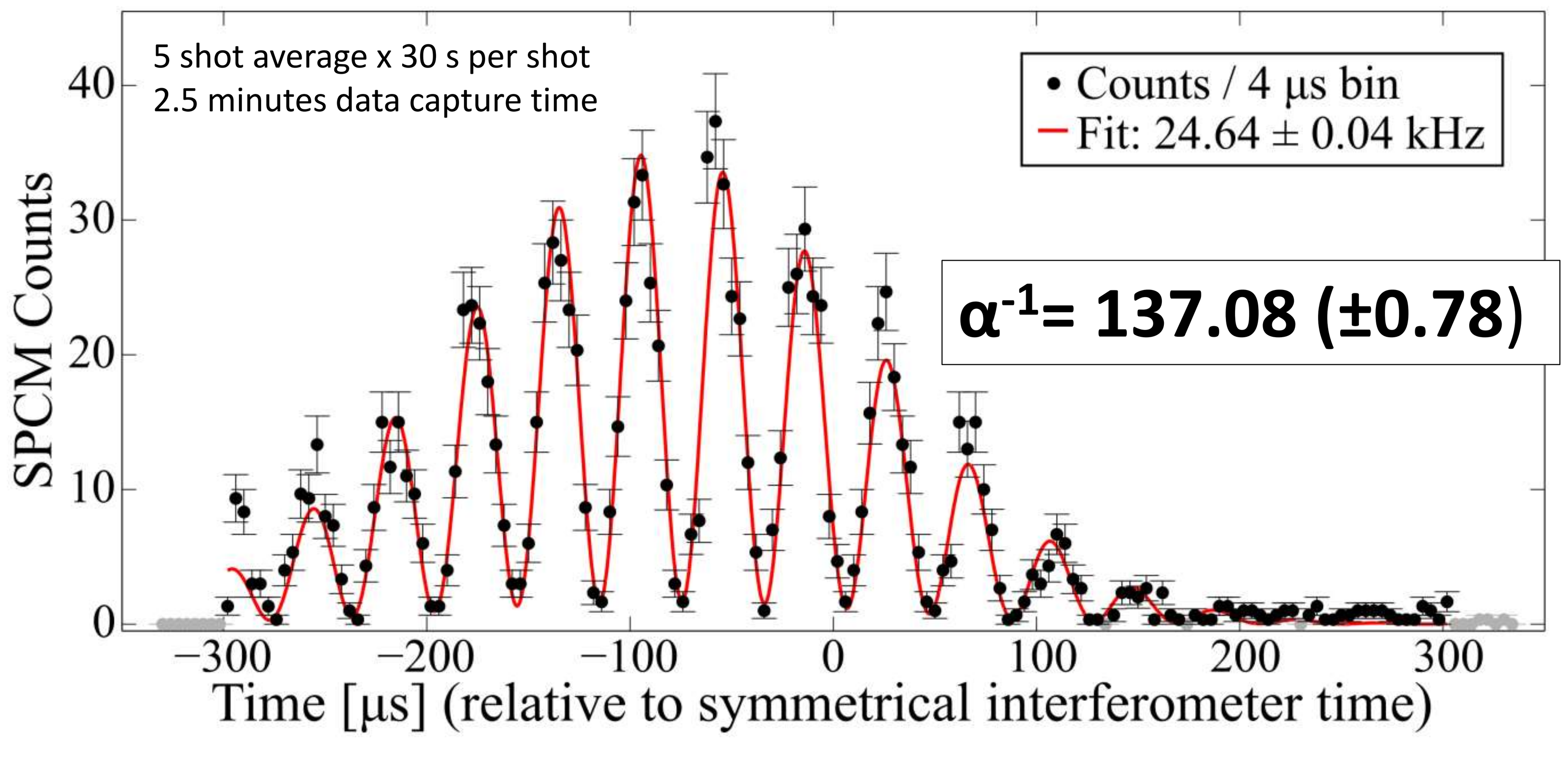


Phase contrast interferometry



Overlapping matter waves generate hologram.

- Maps phase information to frequency.
- Read frequency with probe laser.
- Enables single-shot measurements.
- Phase insensitive readout.
- Significantly faster averaging of data.



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