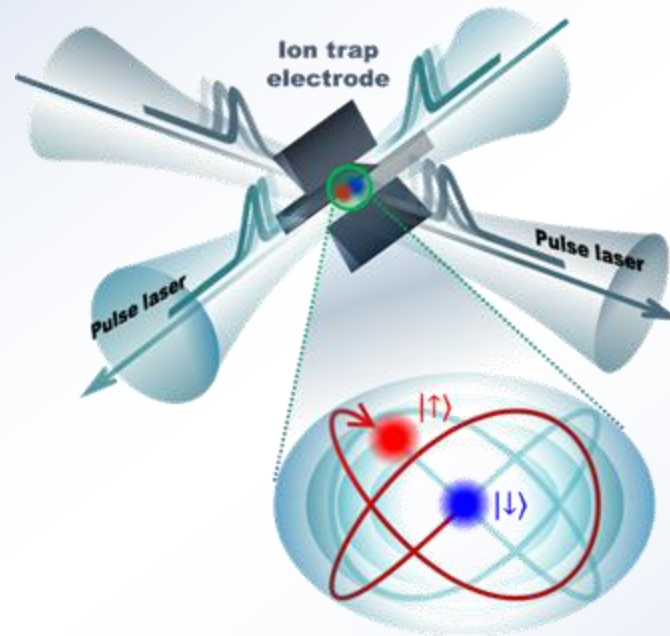
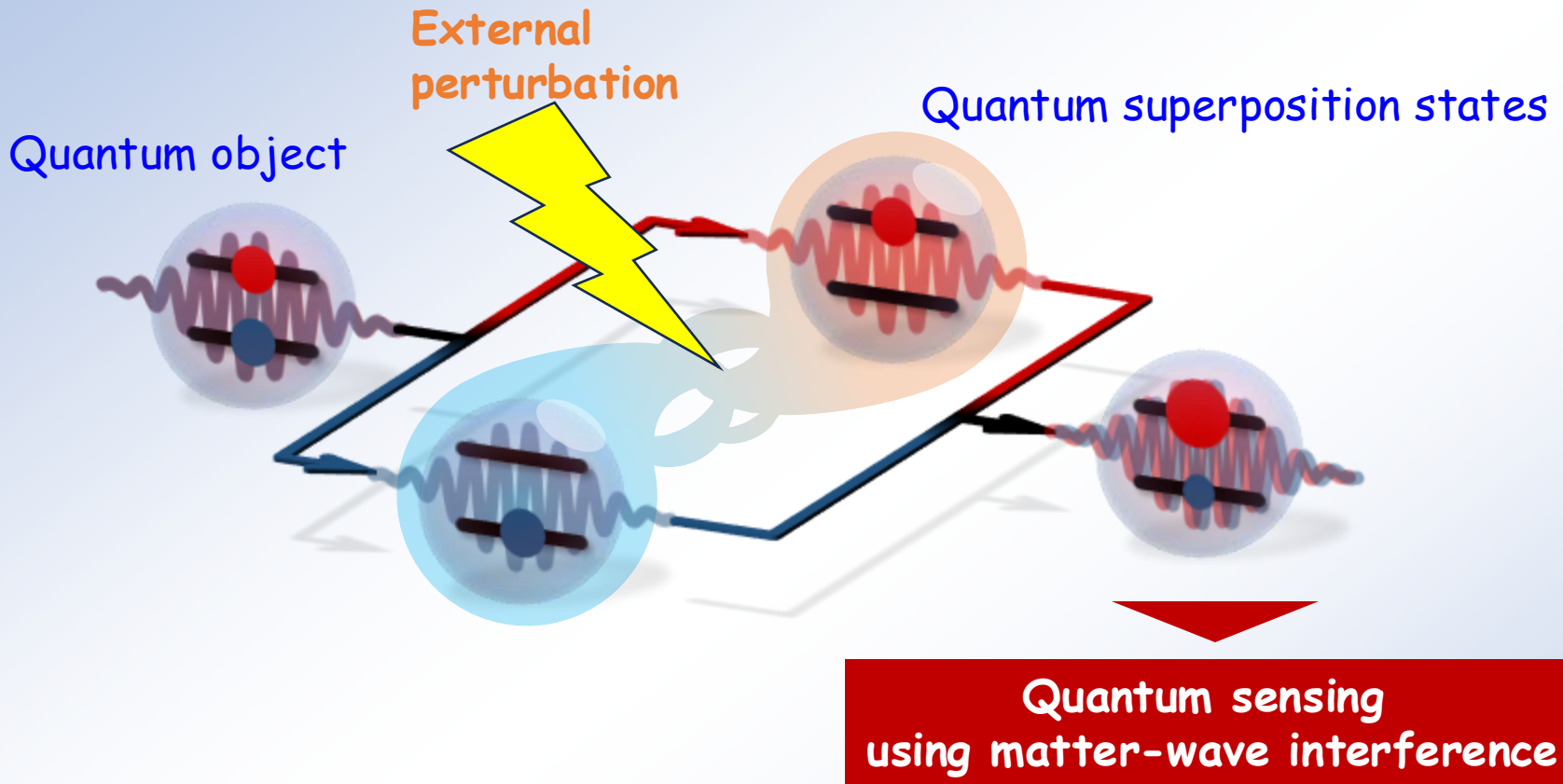


Rotation sensing using an ion trap : a matter-wave interferometer of an ion in three- dimensional motion



Takashi Mukaiyama
Institute of Science Tokyo

Matter-wave interference

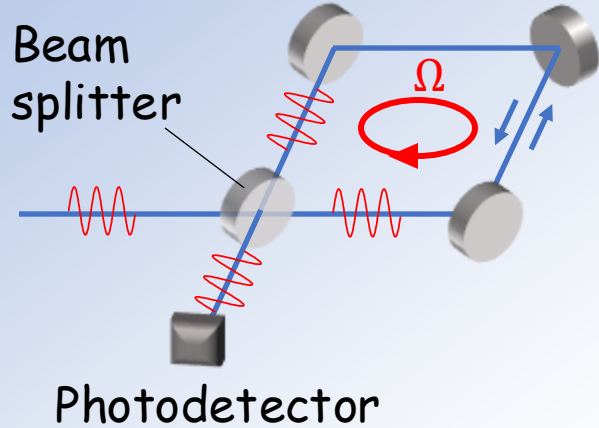


Sensing applications for *acceleration*, *rotation*...

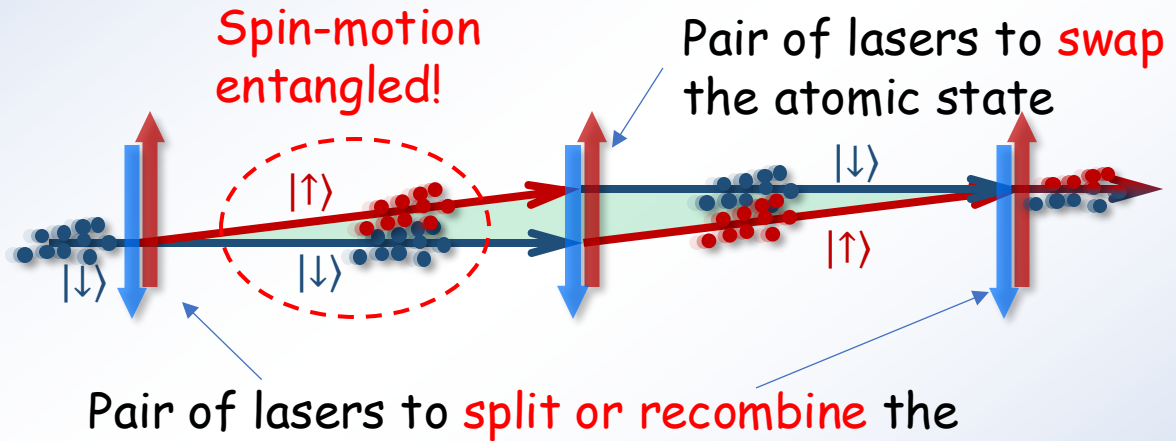
Our target : Rotation sensing using a trapped ion in a spin-motion entangled state

Atomic matter-wave gyroscope

Optical-wave gyroscope



First atomic-beam gyroscope



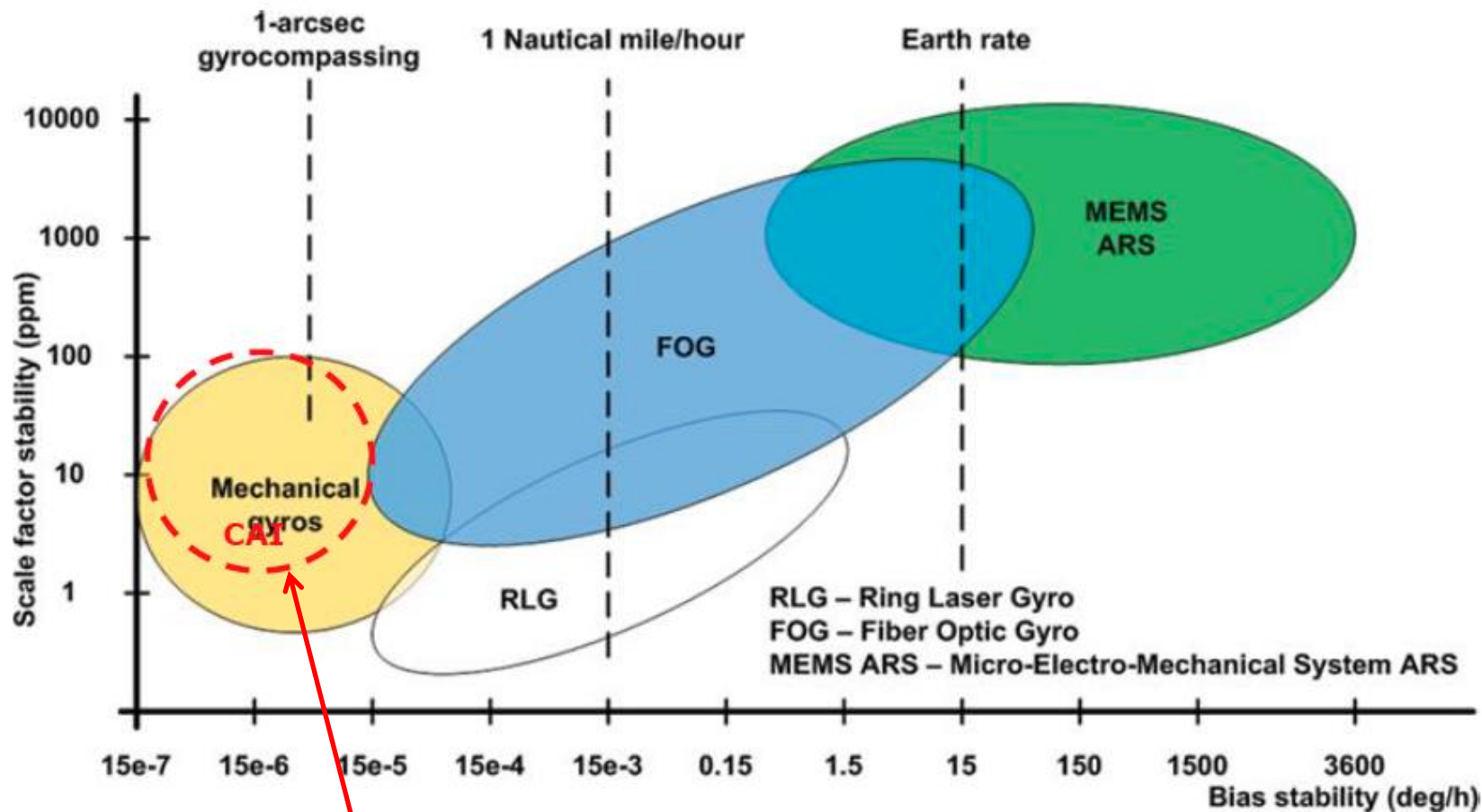
$$\Delta\phi = 4\pi \frac{A}{\lambda v} \Omega$$

A : area
 λ : wavelength
 v : velocity

T. L. Gustavson et al.
 Phys. Rev. Lett. **78**, 2046 (1997).

	Optical gyroscope	Atomic gyroscope
Interference area (m ²)	> 10 ⁻²	~ 10 ⁻⁵
$(\lambda v)^{-1}$ (sec m ⁻²)	10 ⁻³	10 ⁷
Number of particles (sec ⁻¹)	≫ 10 ¹⁰	10 ¹⁰

Gyroscope characteristics

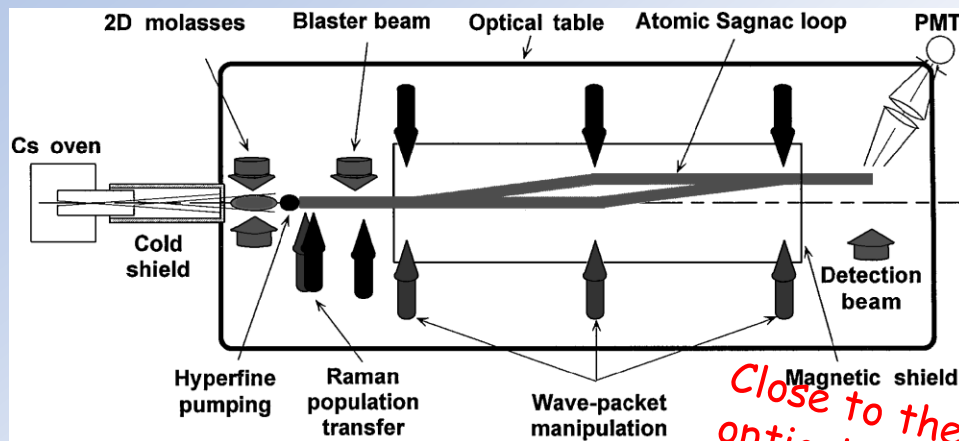


Cold atom interferometer(CAI)

M. Travagnin, Cold atom interferometry for inertial navigation sensors. Technology assessment: space and defense applications, 2020

ISBN 978-92-76-27076-8, doi:10.2760/237221, JRC122785

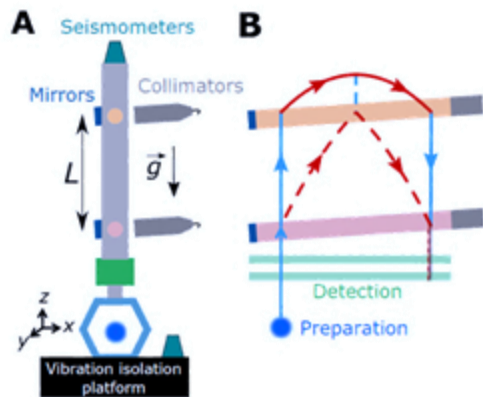
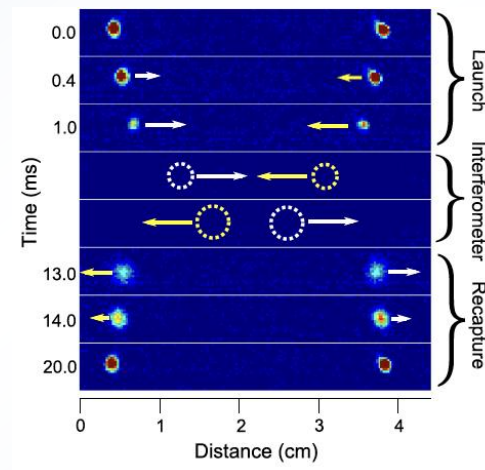
Atomic Interferometer Gyroscope



Rb Atomic beam (Stanford, 2000)

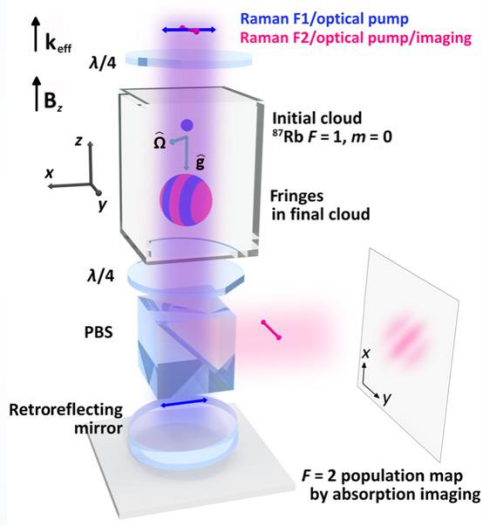
$$S \sim 1 \times 10^{-4} \text{ deg}/\sqrt{\text{h}}$$

Close to the best optical gyroscope



Cs cold atom fountain (SYRTE, 2018)

$$S \sim 6 \times 10^{-5} \text{ deg}/\sqrt{\text{h}}$$

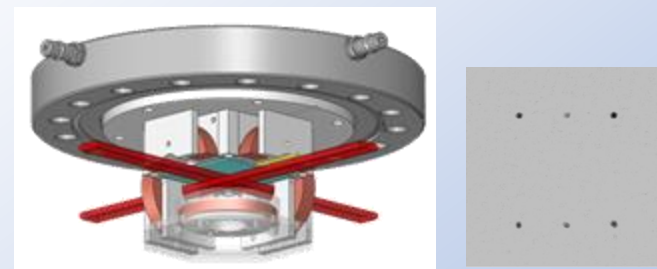


Rb MOT Gyro (NIST, 2019)

$$S \sim 2 \text{ deg}/\sqrt{\text{h}}$$

Rb MOT Gyro (New Mexico, 2014)

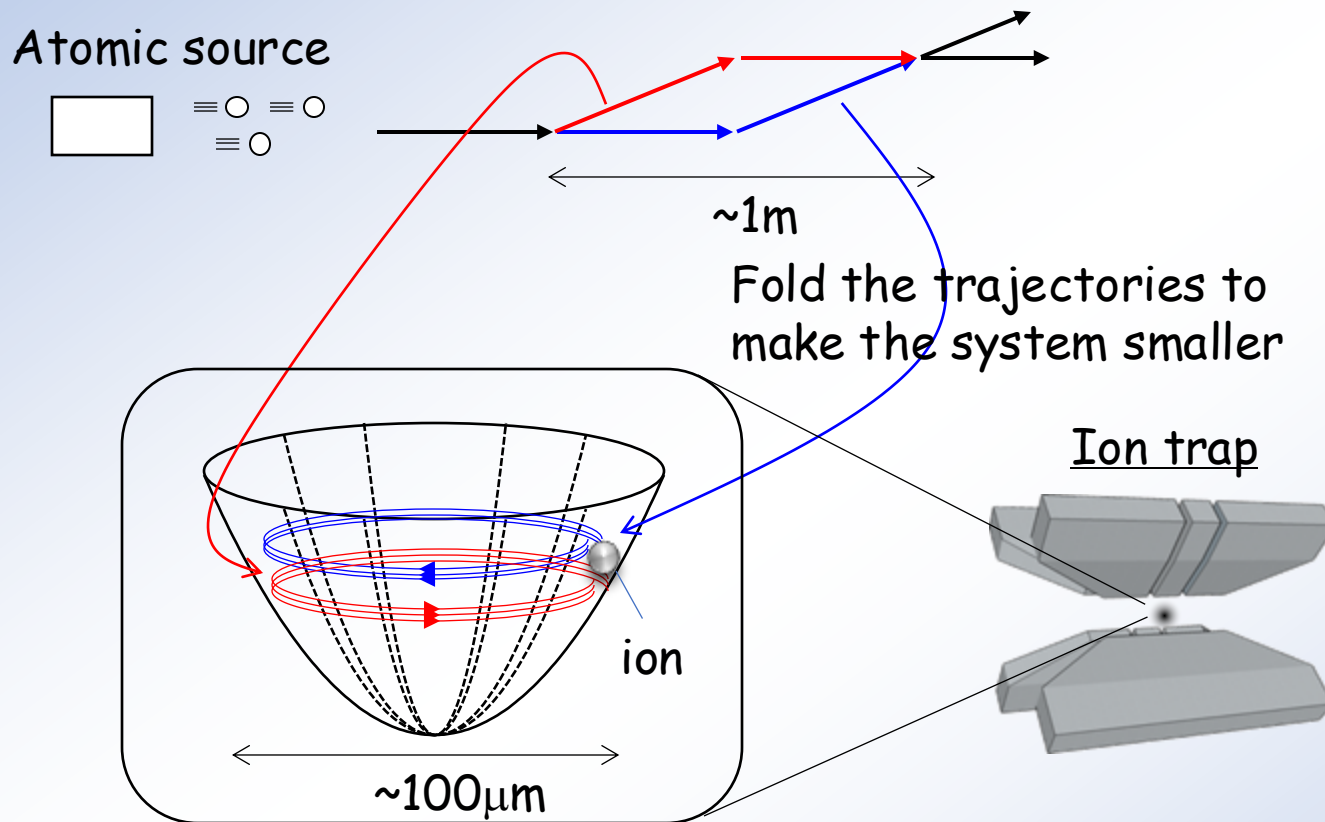
$$S \sim 3 \times 10^{-3} \text{ deg}/\sqrt{\text{h}}$$



Rb BEC in a harmonic trap (Virginia, 2023)

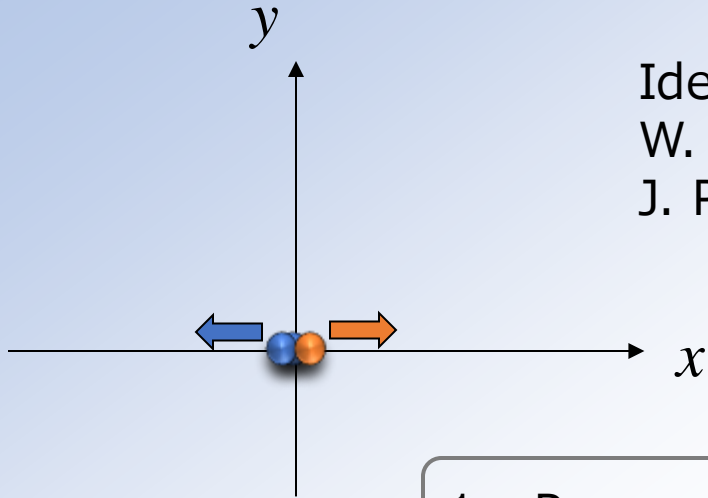
$$S \sim 2 \text{ deg}/\sqrt{\text{h}}$$

Ion trap gyroscope






A single ion trapped in a region on the order of $100\mu\text{m}$ due to electric force can be used as a matter wave to construct a sensitive gyroscope.

Rotation sensing using a trapped ion



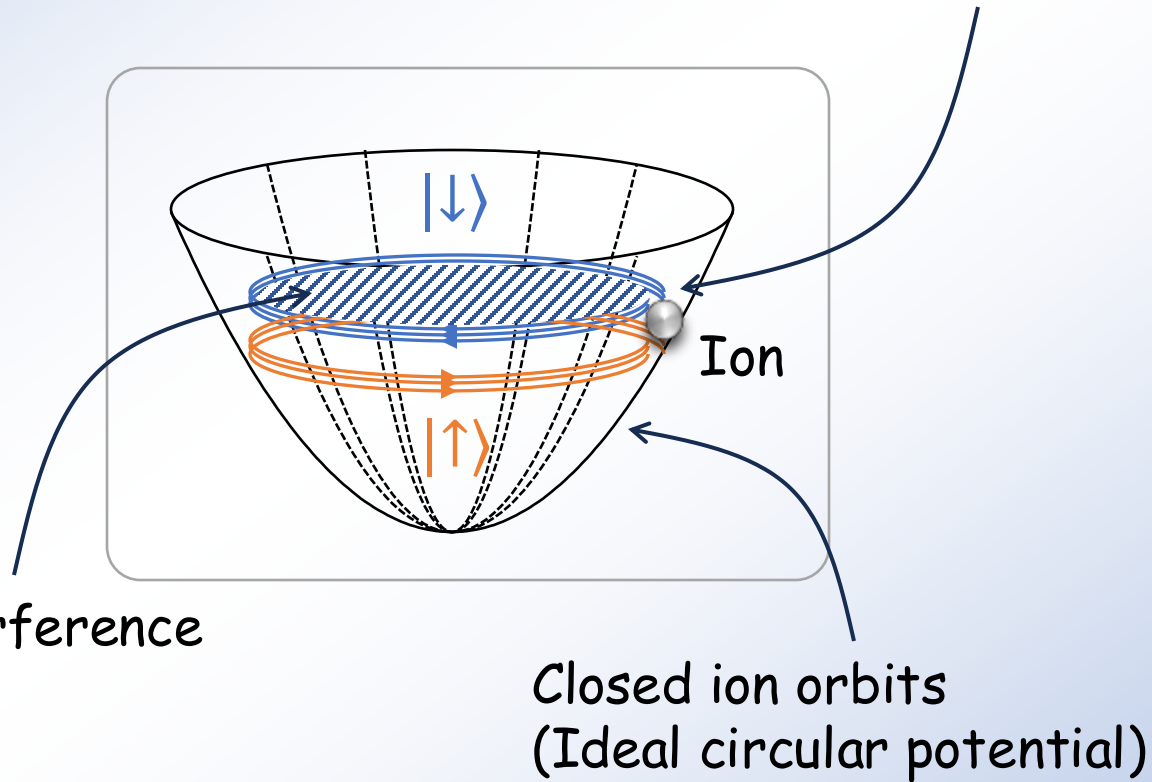
Idea :

W. C. Campbell and P. Hamilton,
J. Phys. B: At. Mol. Opt. Phys. **50**, 064002 (2017).

1. Prepare a spin-state superposition  using RF
2. Apply spin-dependent kick 
3. Displace the trap center along **y** direction
4. Let the ion rotate many times
5. Apply another momentum kick  to close the interferometer
6. Apply RF to detect rotation

Key to the realization of an ion gyroscope

Matter-wave interference of an ion
in a two-dimensional motion



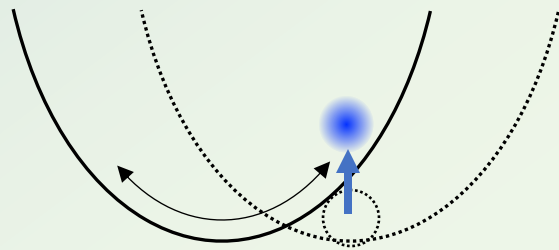
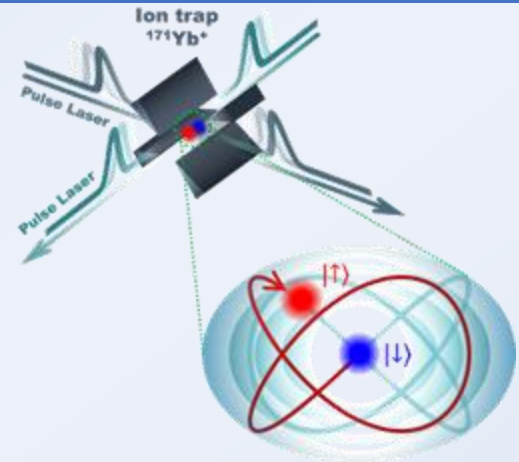
Large interference
area

Closed ion orbits
(Ideal circular potential)

Outline

Matter-wave interference of a trapped single ion in a three-dimensional motion in a harmonic trap.

PRL 2021

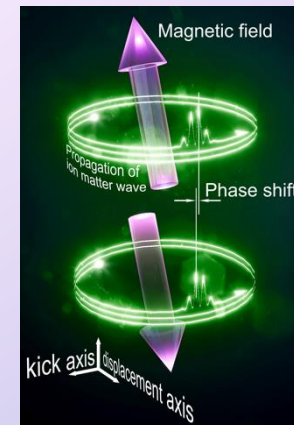


Fast trap-center displacement
(The way to increase an interference area)

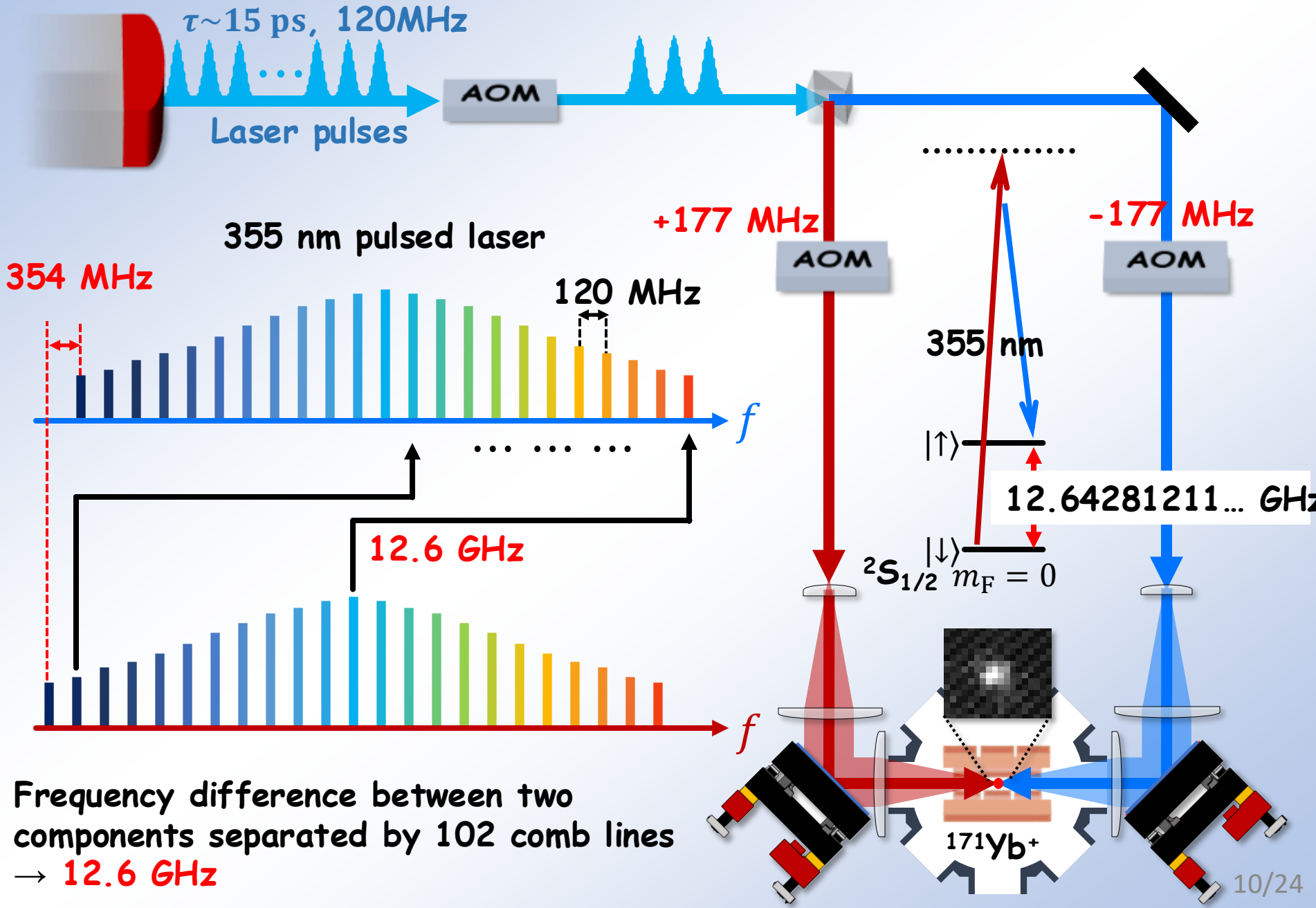
PRA 2021, JAP 2022

Detection of the magnetic-field-induced phases using moving ion wave packets

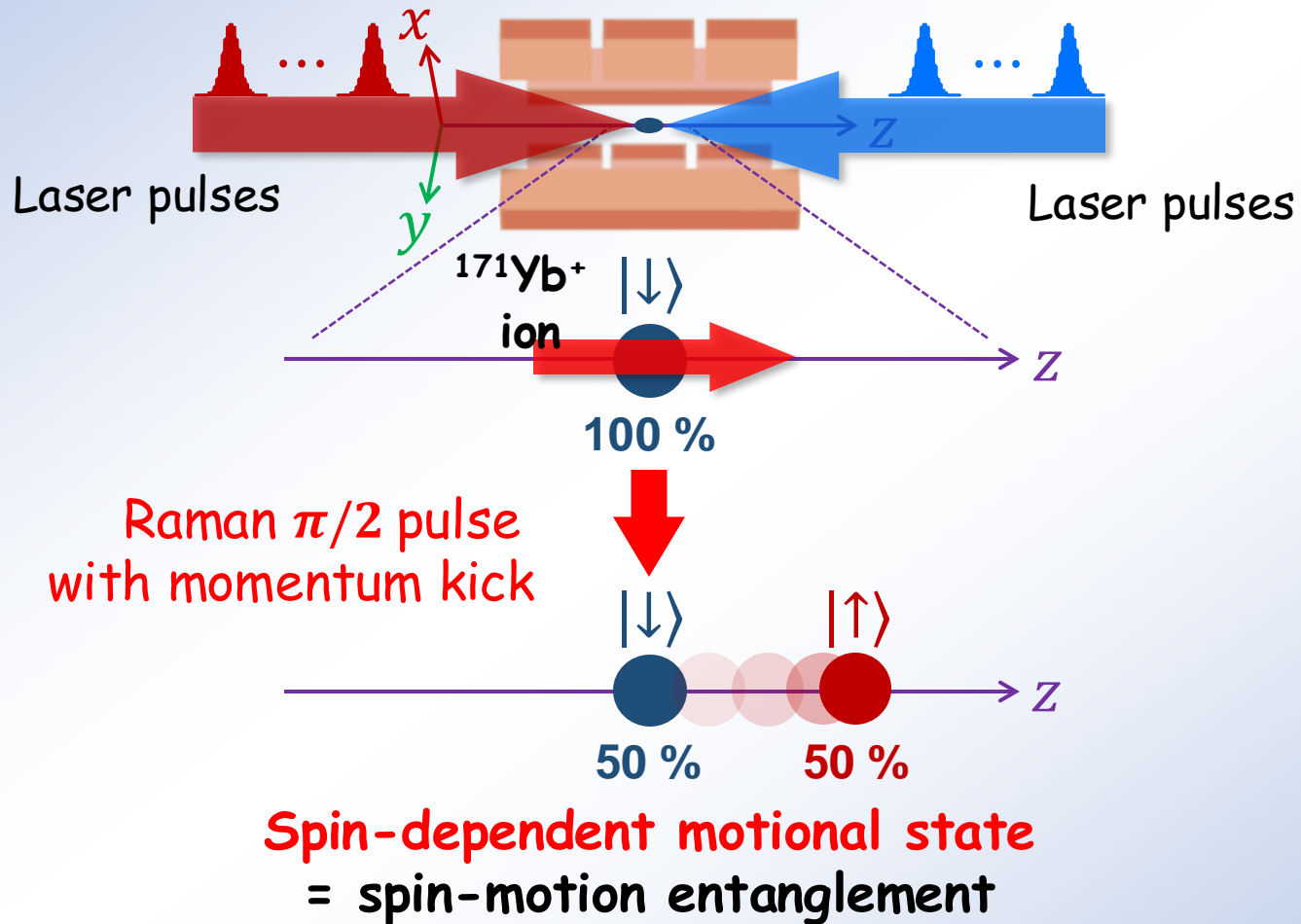
PRL 2024



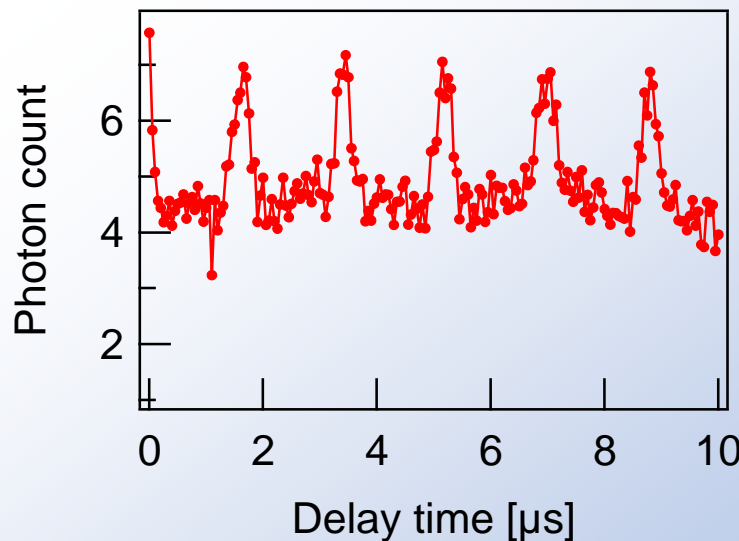
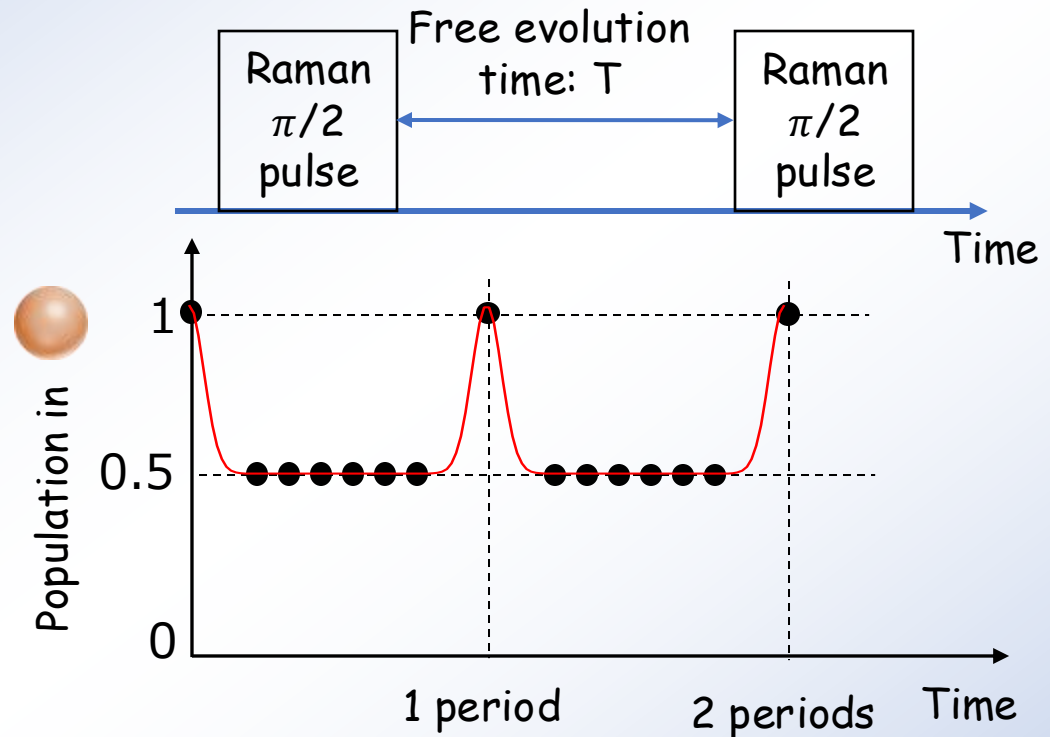
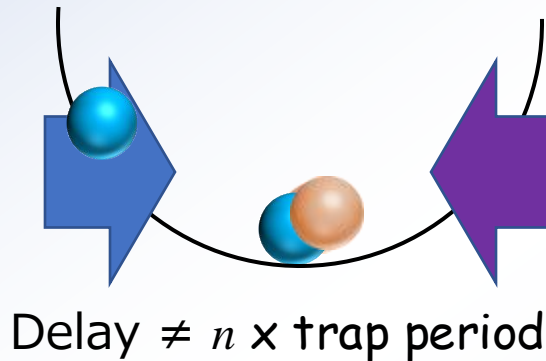
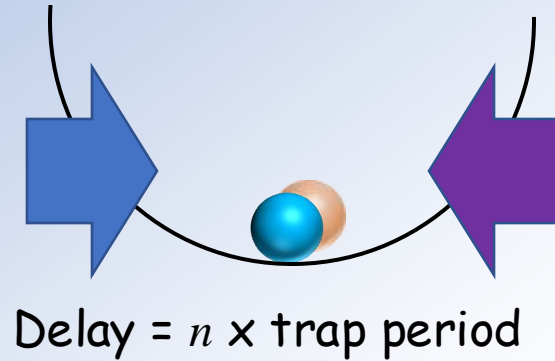
$^{171}\text{Yb}^+$ qubit driven by a pulsed laser



Ion matter-wave interferometer



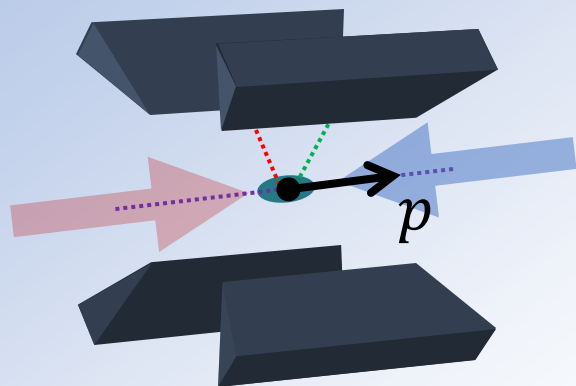
Matter-wave interference of an ion in a linear motion



Constructive interference observed at the integer times the trap period.

Trap period $\sim 1.8 \mu$ sec

Matter-wave interference of an ion in a three-dimensional motion

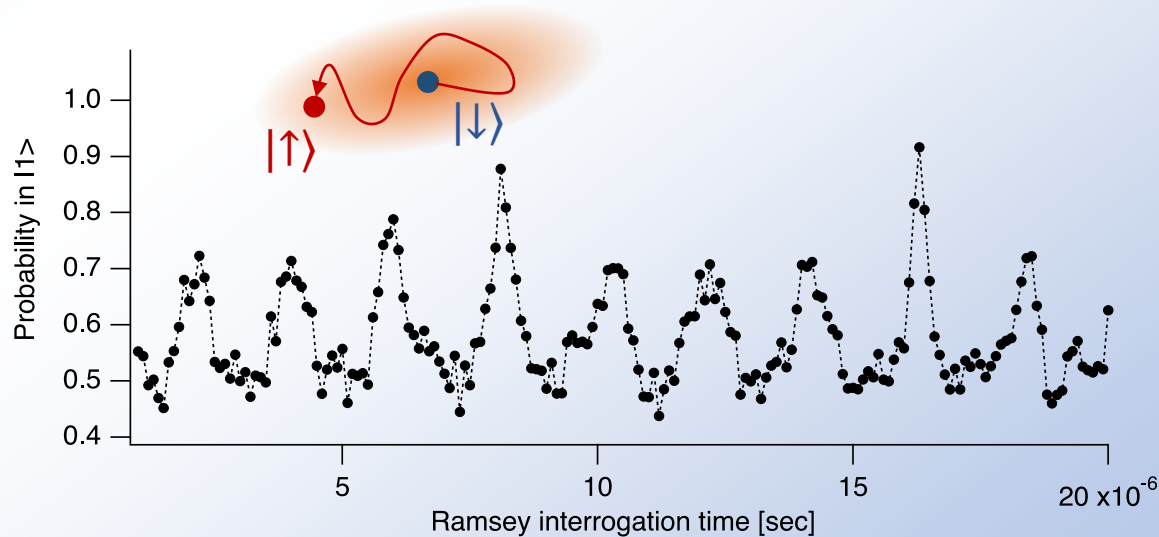
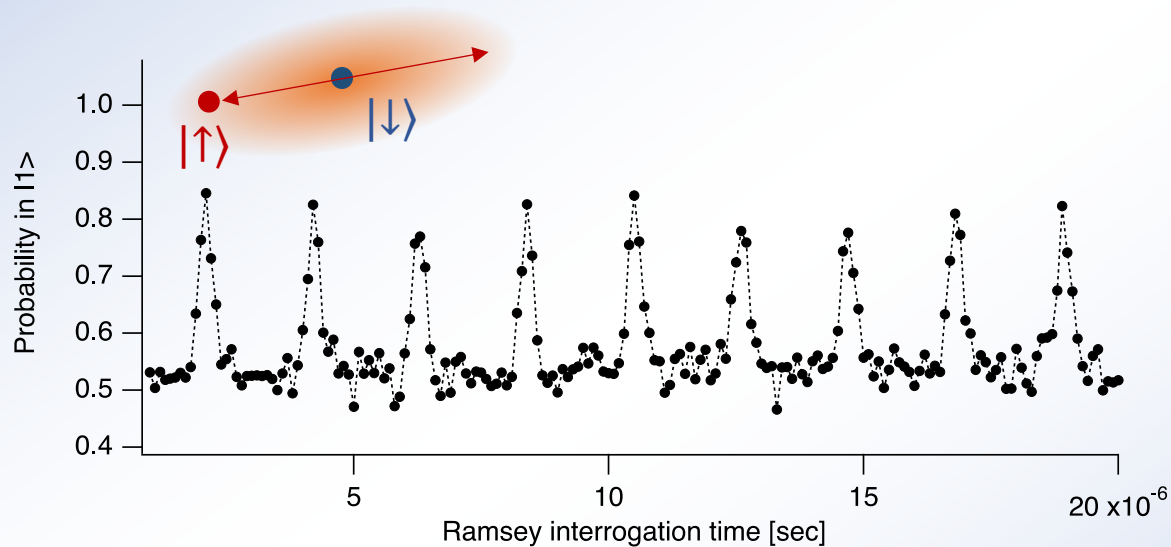
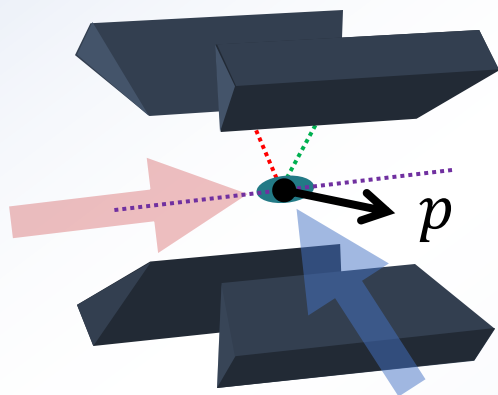
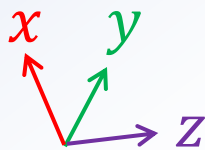


Trap periods

$$\tau_x \sim 0.819 \mu\text{s}$$

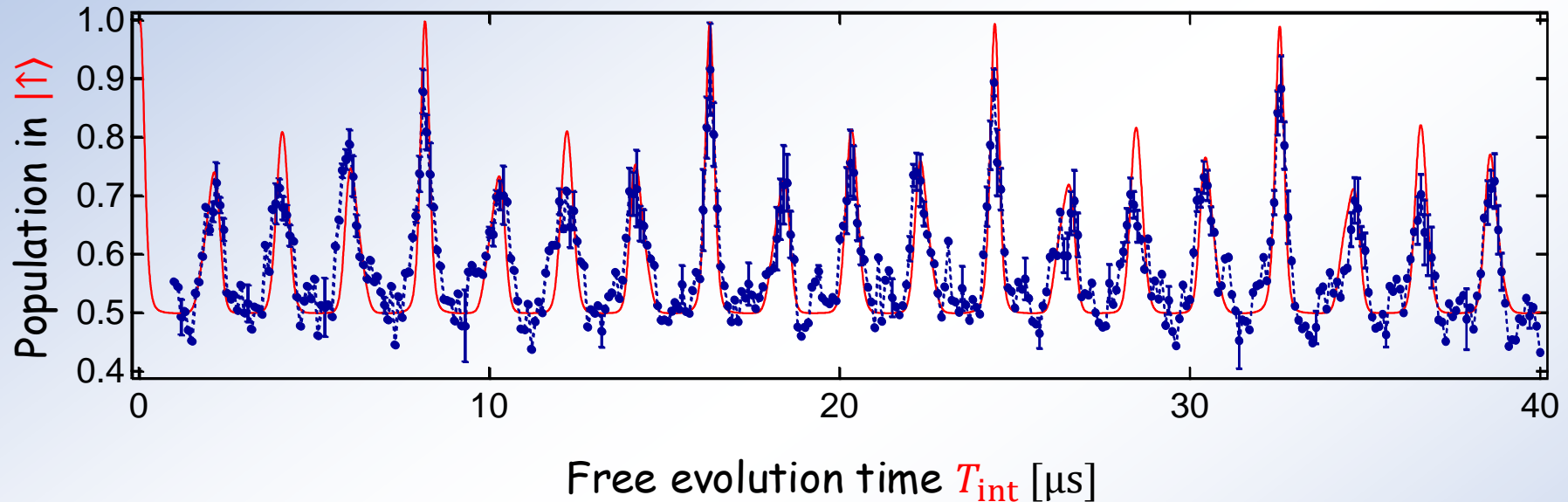
$$\tau_y \sim 0.761 \mu\text{s}$$

$$\tau_z \sim 2.04 \mu\text{s}$$



Matter-wave interference of an ion in a three-dimensional motion

A. Shinjo, M. Baba, K. Higashiyama, R. Saito, and T. Mukaiyama,
Phys. Rev. Lett. **126**, 153604 (2021).

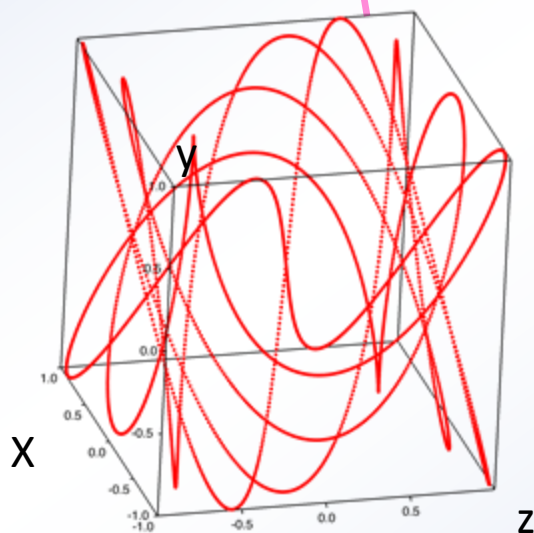
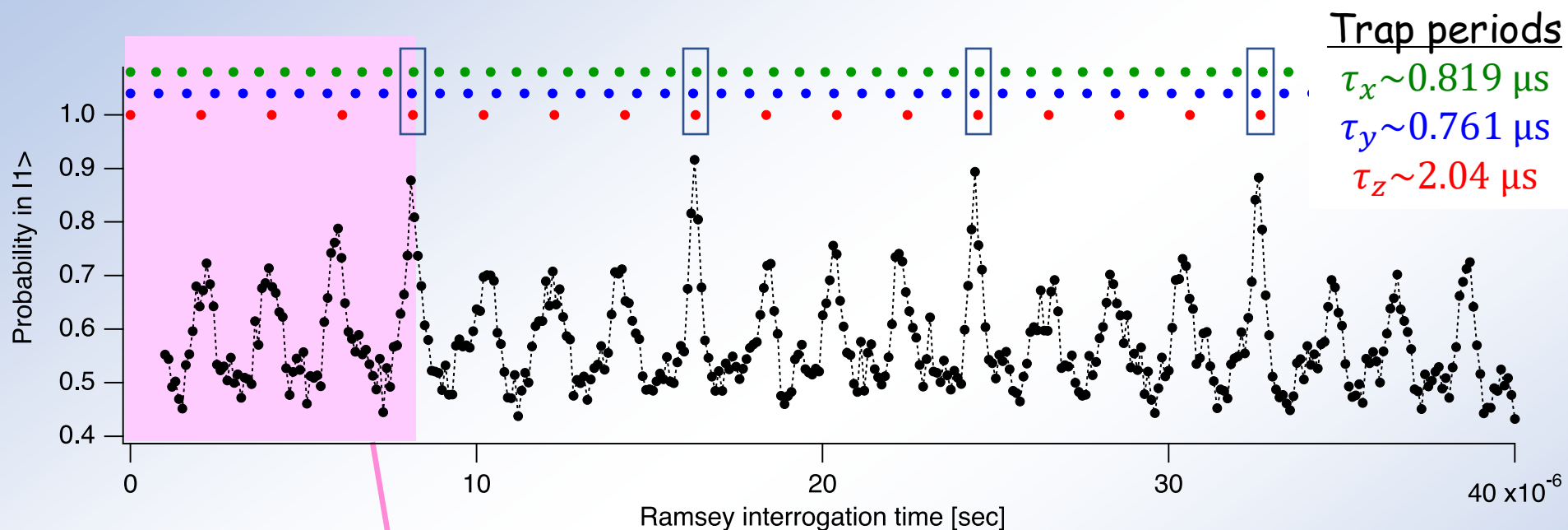


From the equation on the time evolution of the ion motional state (as a superposition of coherent states), we get

$$\begin{aligned} \mathcal{P}(T_{\text{int}}) = & \frac{1}{2} + \frac{1}{2} e^{-p_x^2(2k_B T/\hbar\omega_x+1)\{1-\cos(\omega_x T_{\text{int}})\}} \cos\{p_x^2 \sin(\omega_x T_{\text{int}})\} && \text{Motion in } x \\ & \times e^{-p_y^2(2k_B T/\hbar\omega_y+1)\{1-\cos(\omega_y T_{\text{int}})\}} \cos\{p_y^2 \sin(\omega_y T_{\text{int}})\} && \text{Motion in } y \\ & \times e^{-p_z^2(2k_B T/\hbar\omega_z+1)\{1-\cos(\omega_z T_{\text{int}})\}} \cos\{p_z^2 \sin(\omega_z T_{\text{int}})\} && \text{Motion in } z \end{aligned}$$

Matter-wave interference of an ion in a three-dimensional motion

A. Shinjo, M. Baba, K. Higashiyama, R. Saito, and T. Mukaiyama,
Phys. Rev. Lett. 126, 153604 (2021).



10 periods in x
11 periods in y
4 periods in z
directions

Successful observation of a Multi-dimensional matter-wave interference

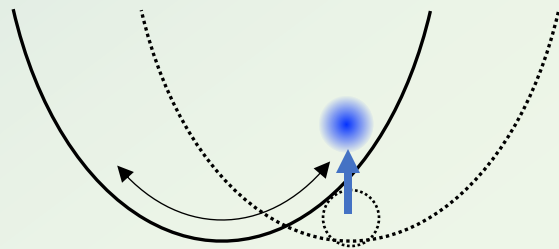
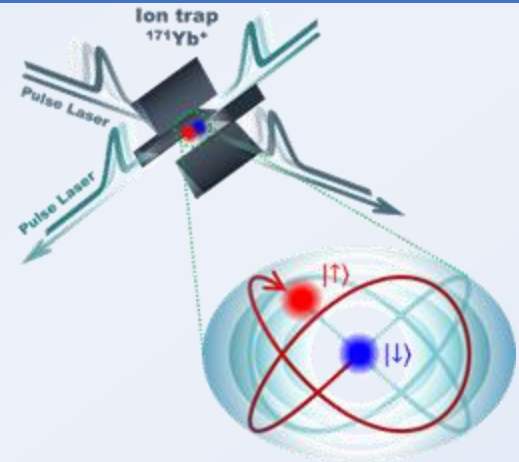


An important key technique to realize an ion Sagnac interferometer

Outline

Matter-wave interference of a trapped single ion in a three-dimensional motion in a harmonic trap.

PRL 2021

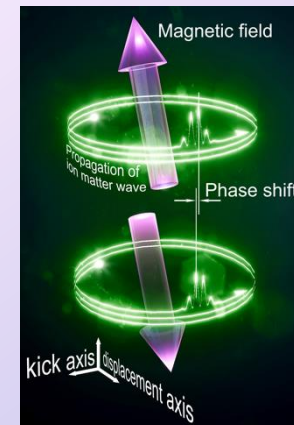


Fast trap-center displacement
(The way to increase an interference area)

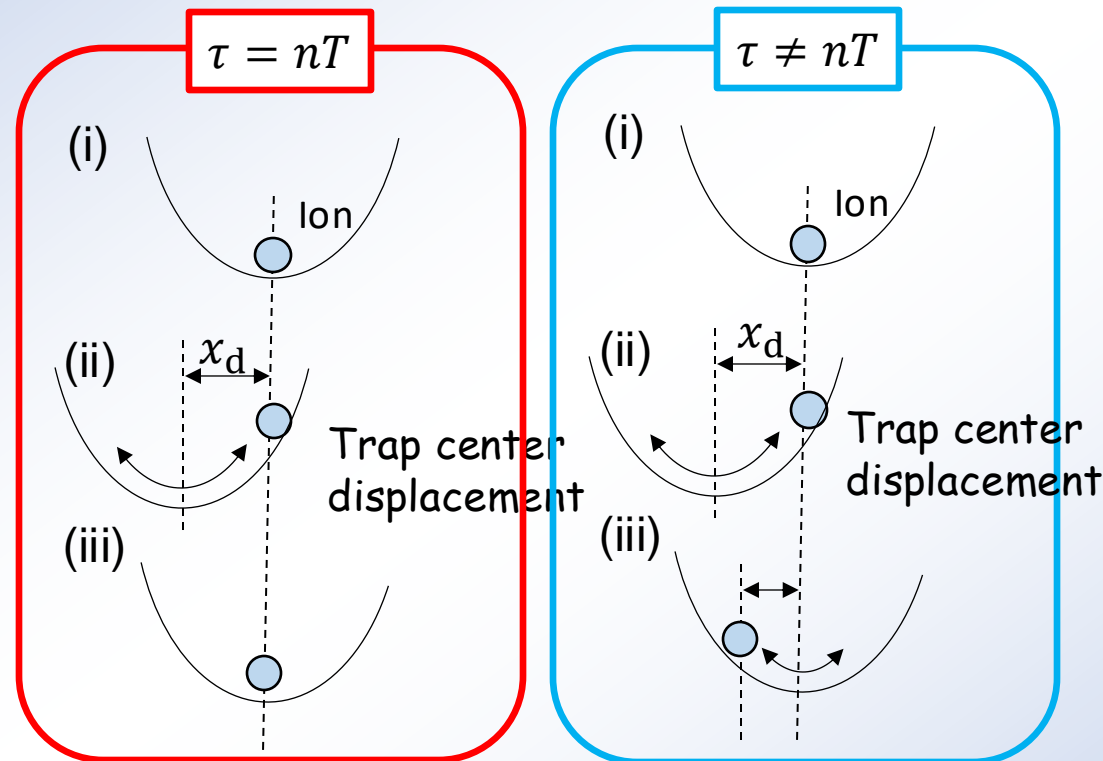
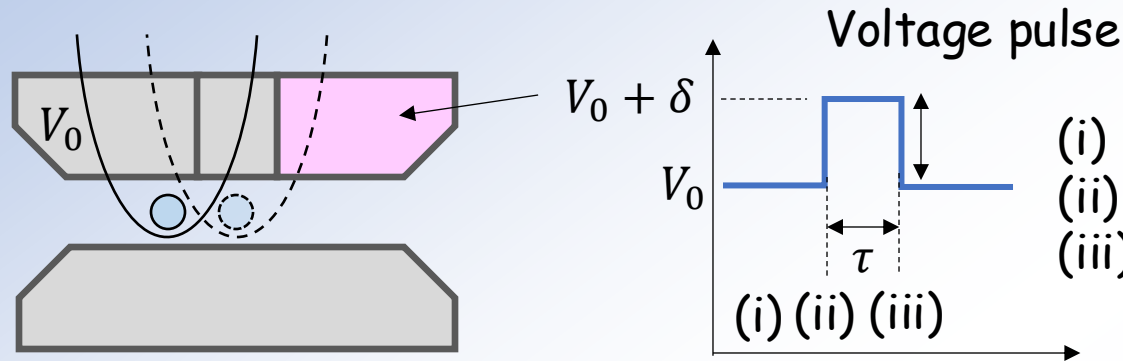
PRA 2021, JAP 2022

Detection of the magnetic-field-induced phases using moving ion wave packets

Opt. Expr. 2024, PRL 2024



Non-adiabatic trap-center displacement



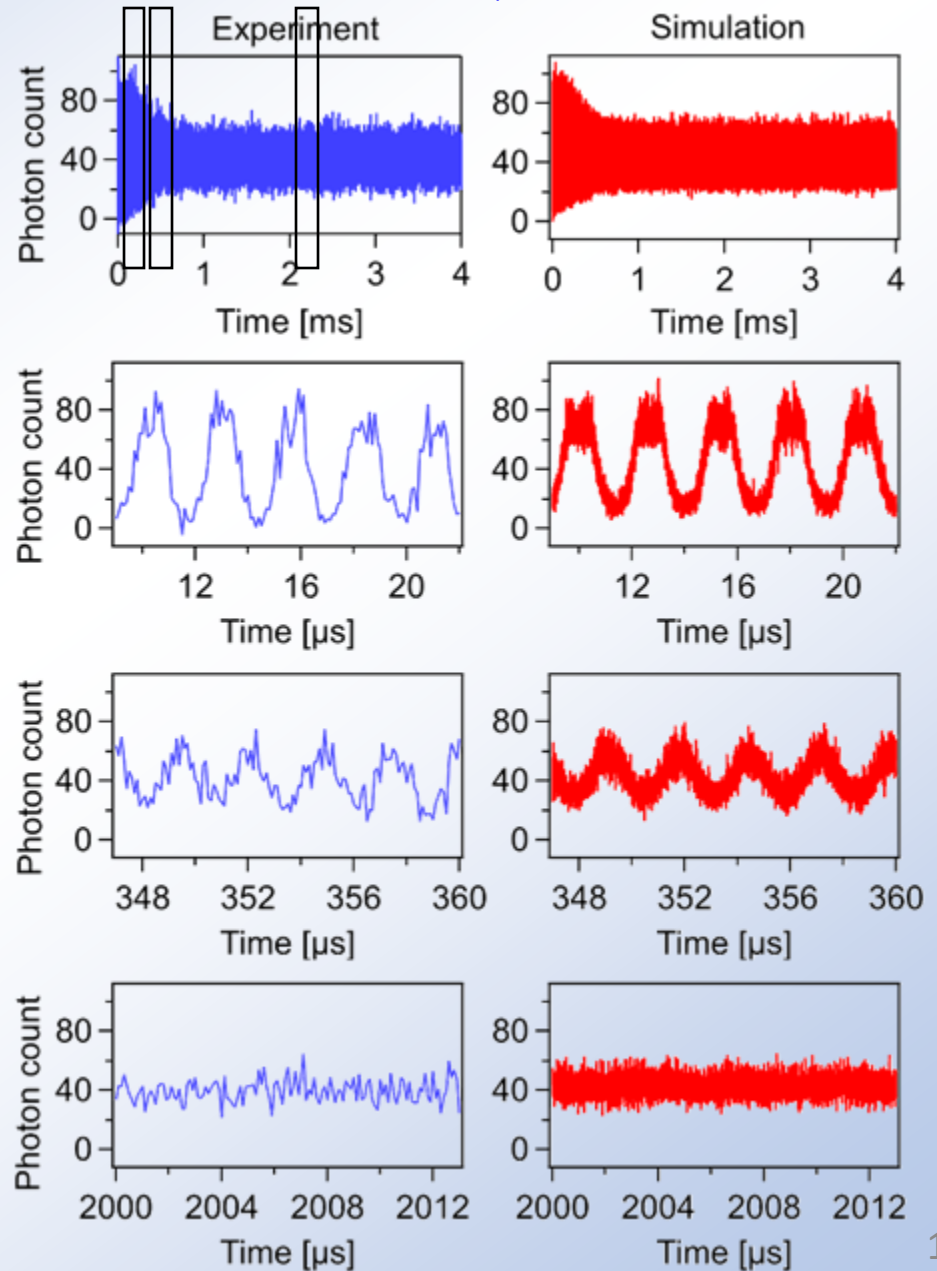
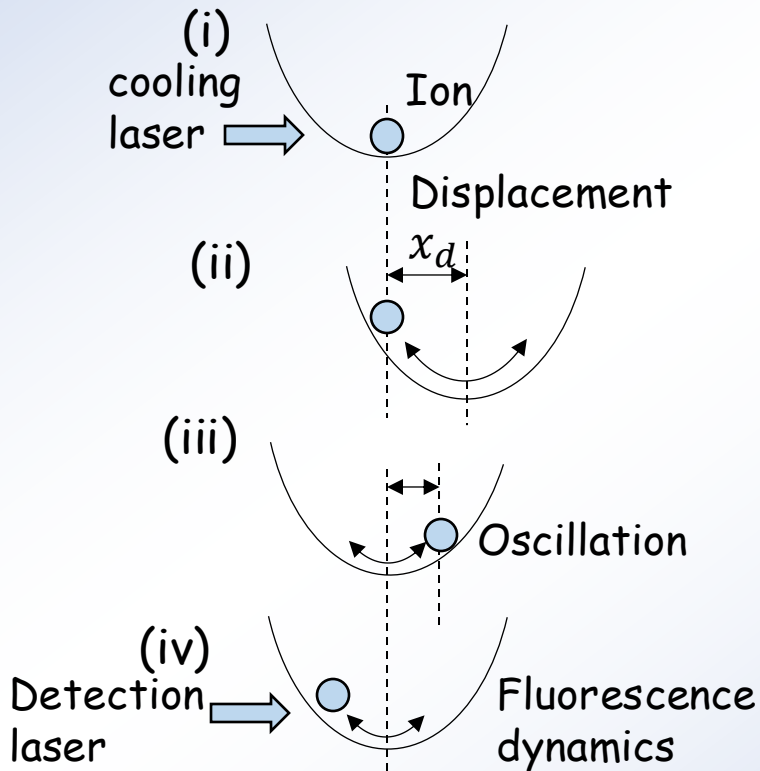
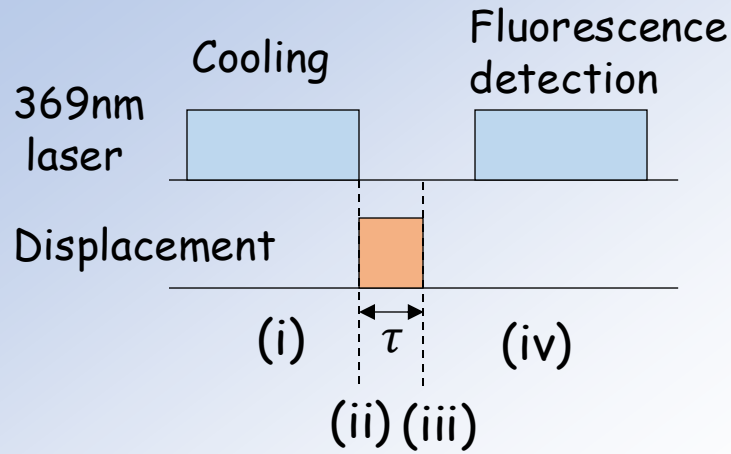
$\tau = nT \rightarrow$ Oscillatory motion vanishes
 $\tau \neq nT \rightarrow$ Oscillatory motion remains



Amplitude of remaining oscillatory motion reflects the displacement of the trap center.

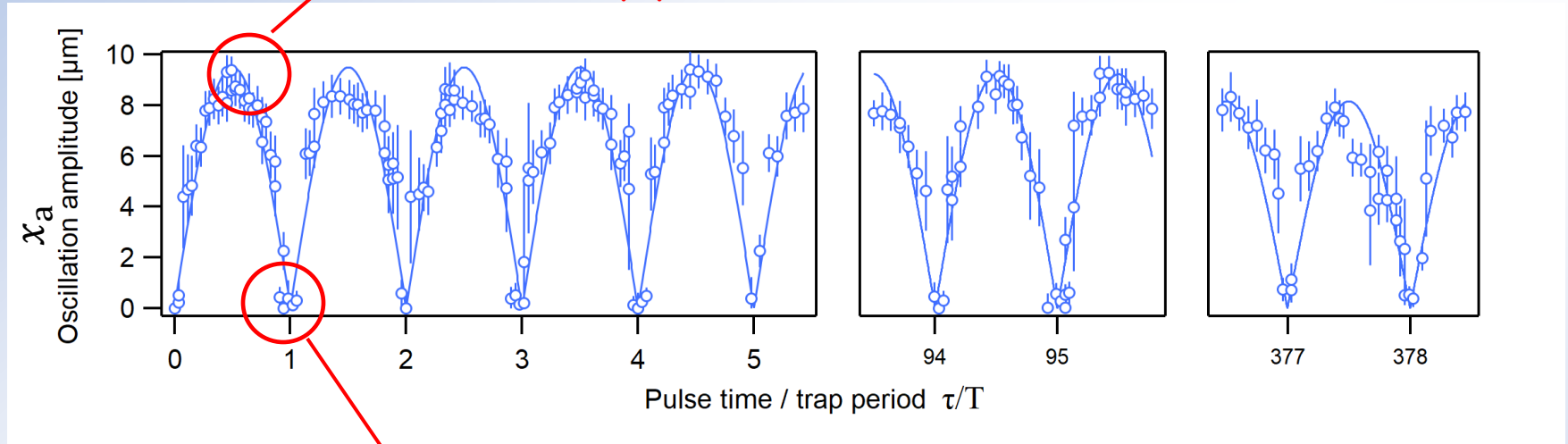
Fluorescence dynamics

R. Saito and T. Mukaiyama,
Phys. Rev. A 104, 053114 (2021).



Oscillation amplitude

Maximum remaining oscillation is observed at the half integer times the trap period.



Oscillation vanishes at the integer multiple of the trap period.

R. Saito and T. Mukaiyama,
Phys. Rev. A 104, 053114 (2021).

$$\text{Fitting function : } x_a = x_d \sqrt{2 \left\{ 1 - \cos \left(\frac{2\pi\tau}{T} \right) \right\}}$$



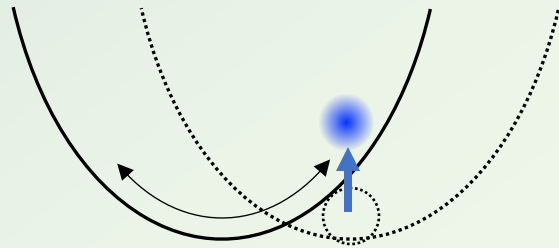
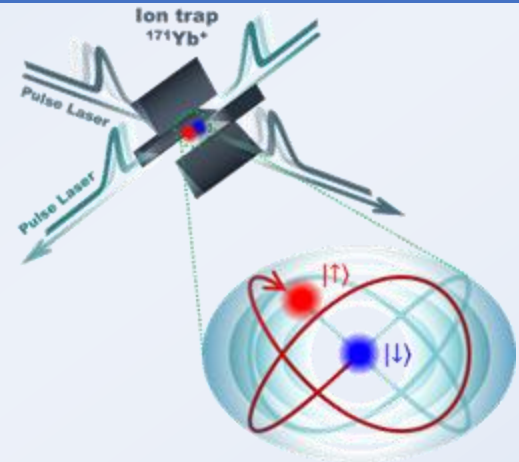
$$x_d = 4.7 \pm 0.1 \mu\text{m}$$

Maximum displacement of $10.5 \mu\text{m}$ has been realized in our experiment.

Outline

Matter-wave interference of a trapped single ion in a three-dimensional motion in a harmonic trap.

PRL 2021

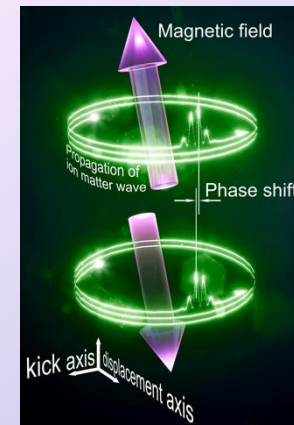


Fast trap-center displacement
(The way to increase an interference area)

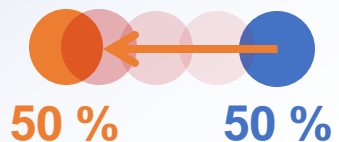
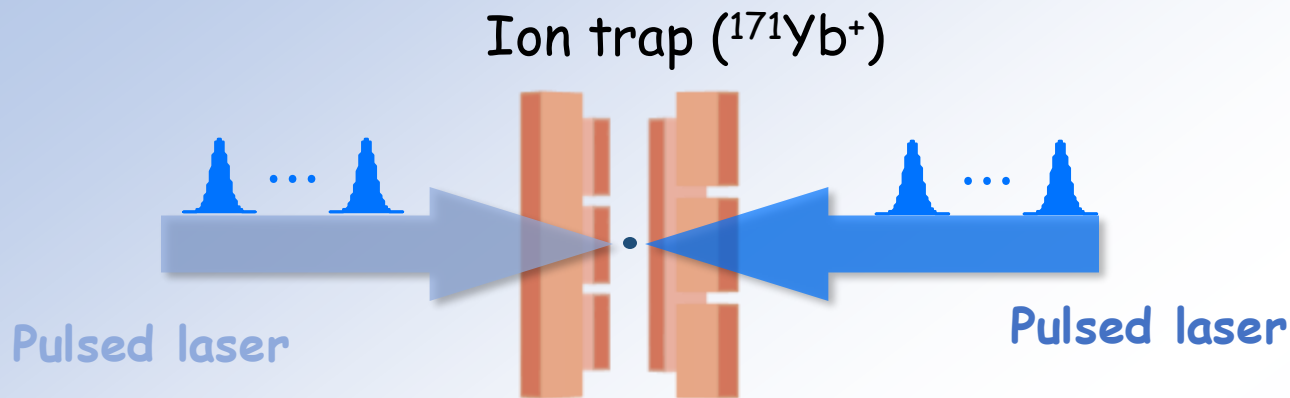
PRA 2021, JAP 2022

Detection of the magnetic-field-induced phases using moving ion wave packets

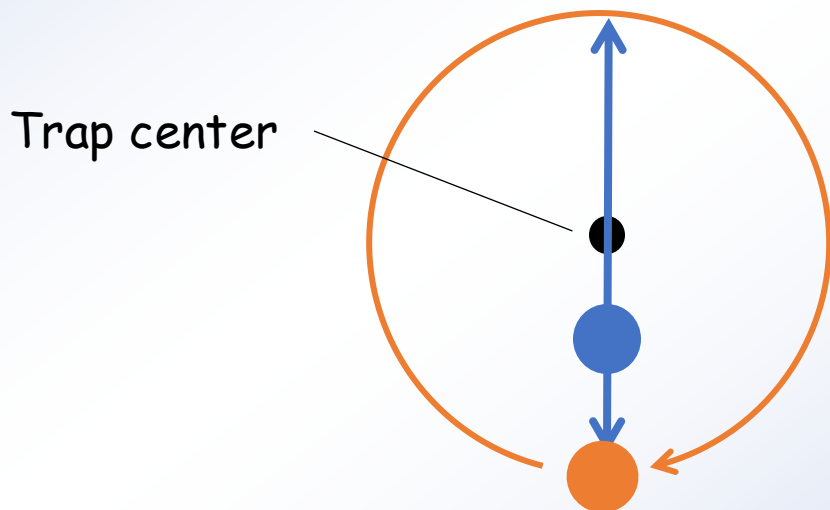
PRL 2024



Experimental procedure



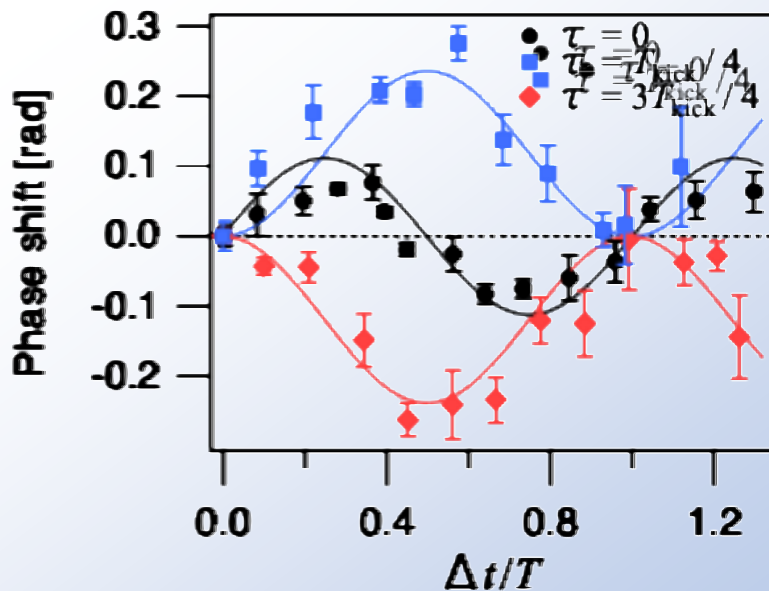
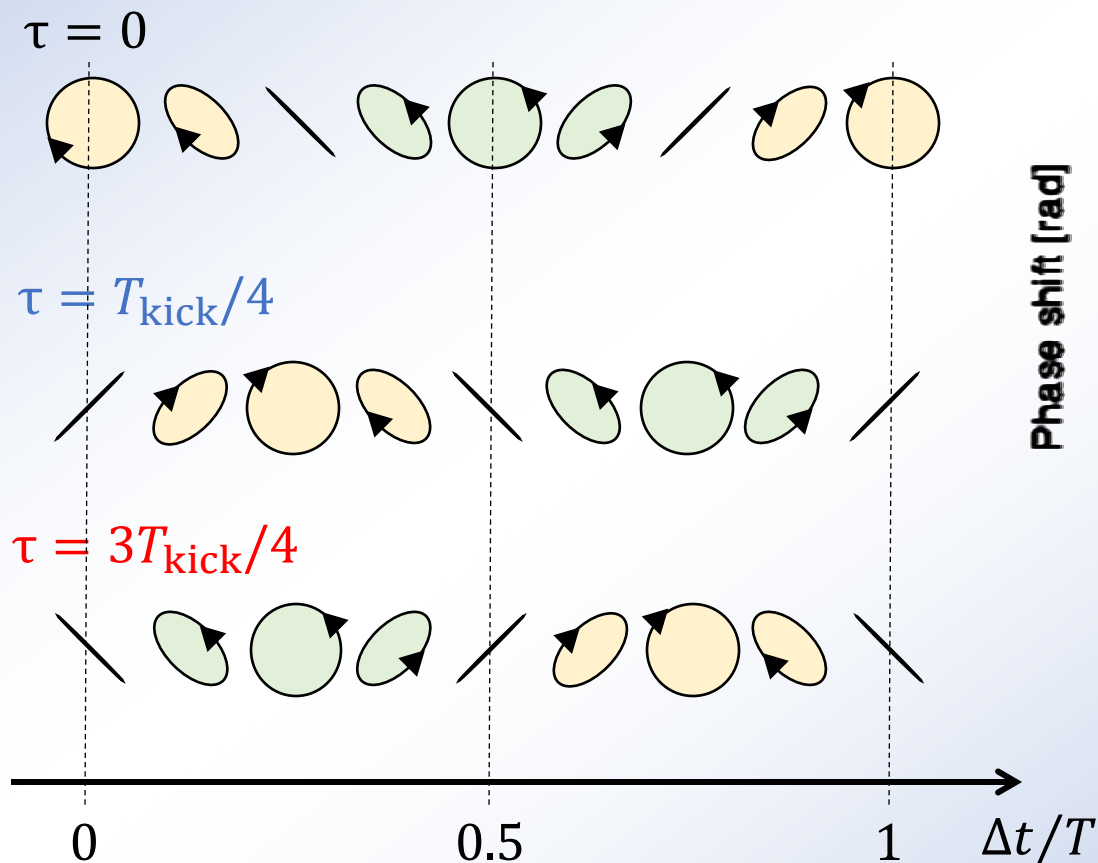
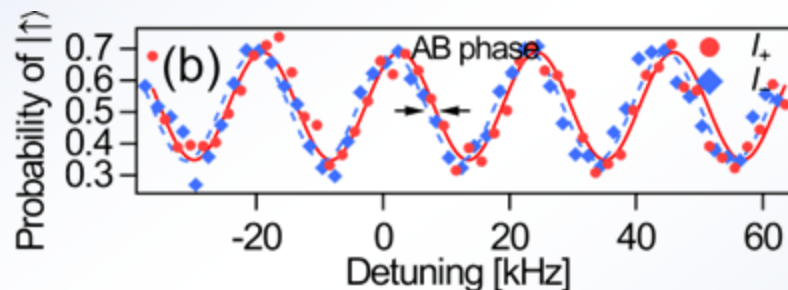
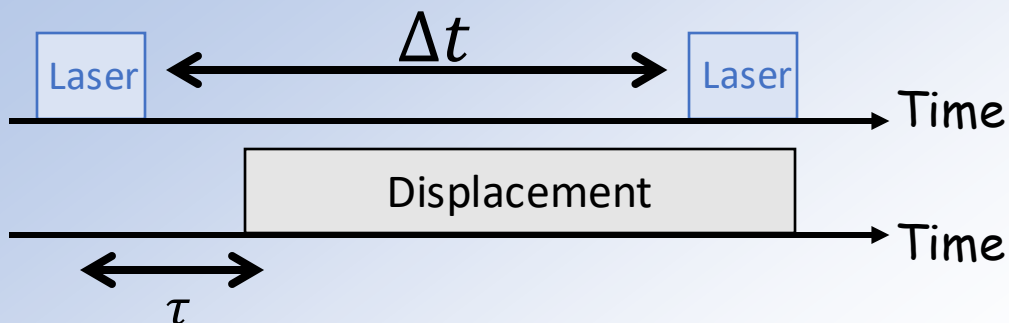
$\pi/2$ -pulse condition



Rotational direction flips because of an elliptic (not perfectly circular) potential



Detection of the Magnetic-field induced phase

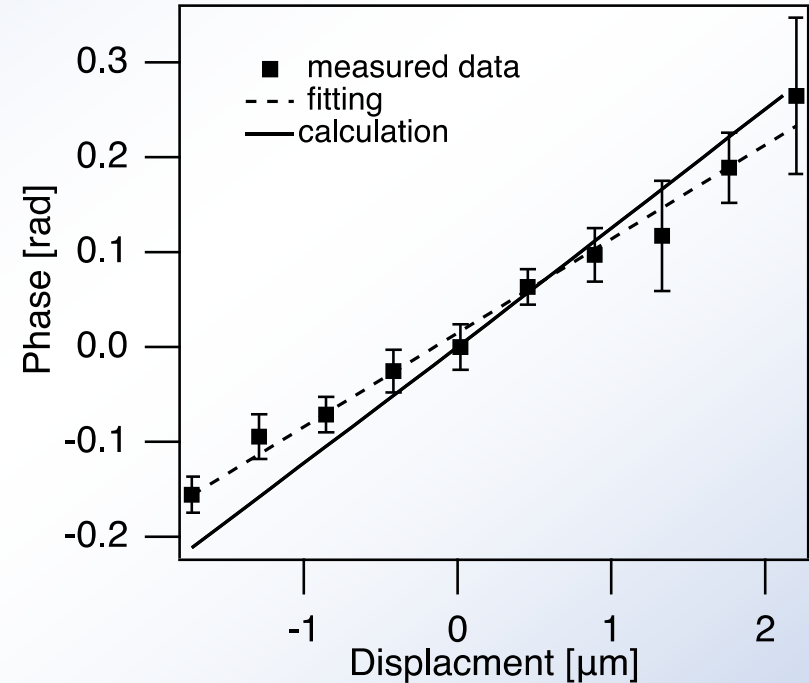
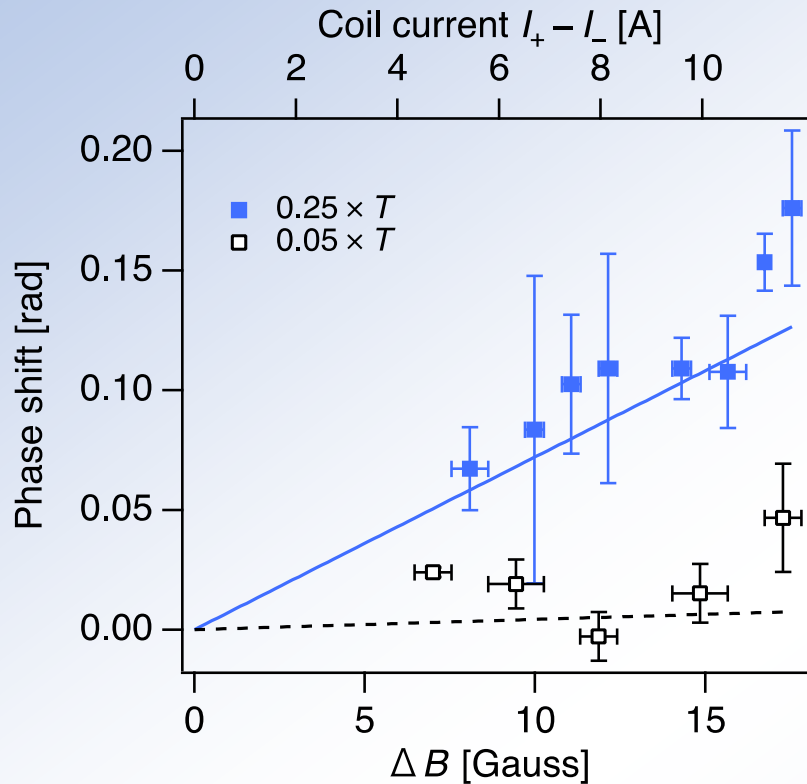


Solid curves:

$$\phi(\Delta t) = \frac{e\omega}{2\pi} B_{\perp} \int_0^{\Delta t} S(t) dt$$

Phase shift vs B-field strength and displacement

R. Saito and T. Mukaiyama,
Phys. Rev. Lett., accepted.



Phase shift increases with the magnetic field strength and the interrogation time

Phase shift increases with the displacement size

Summary

- Matter-wave interference of a trapped single ion in a three-dimensional motion
- Quick trap-center displacement demonstrated.
- Detection of the magnetic-field-induced phases using moving ion wave packets

