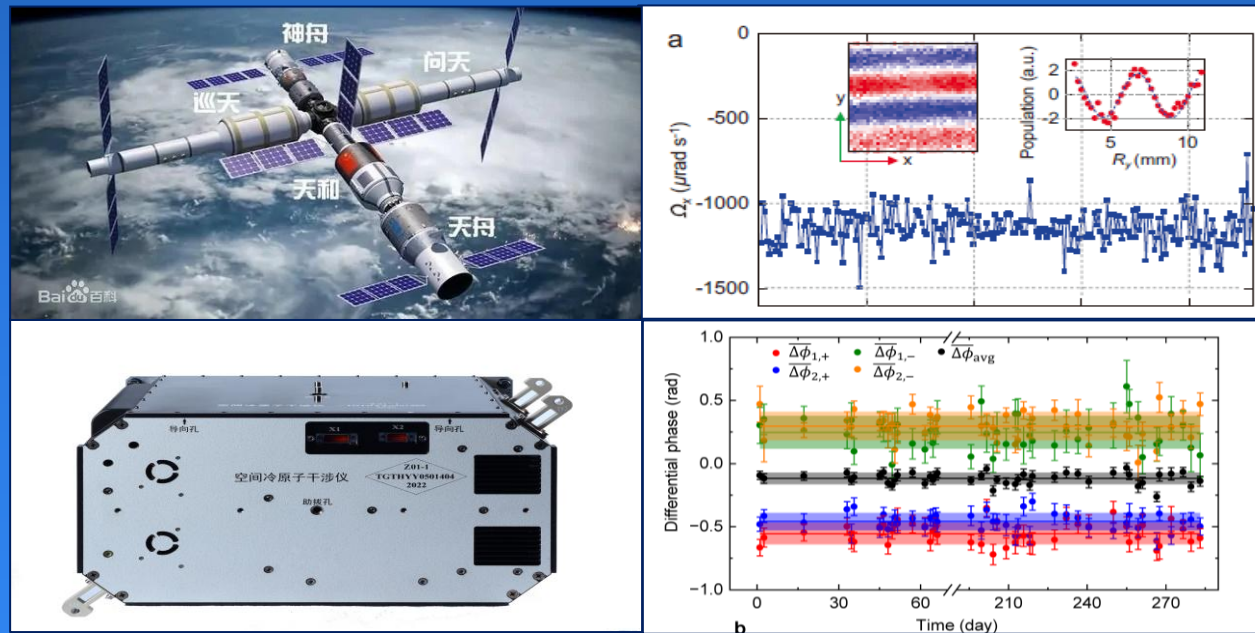


Research progress of cold atom interferometer on China Space Station



Chen Xi

Innovation Academy for Precision Measurement Science and Technology, CAS

2026/06/16

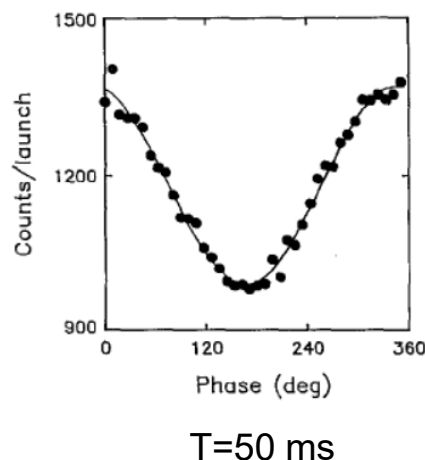
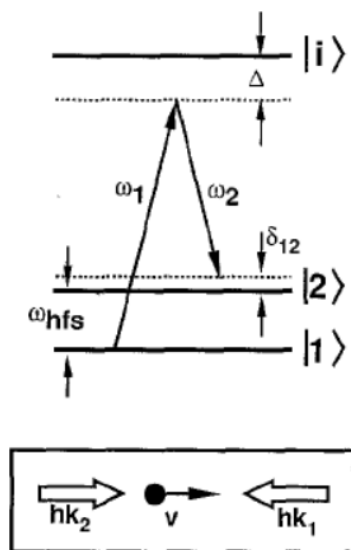
Cold atom interferometer and its application

1. The born of cold atom interferometer

Appl. Phys. B 54, 321–332 (1992)

Measurement of the Gravitational Acceleration of an Atom with a Light-Pulse Atom Interferometer

M. Kasevich and S. Chu



Interference principle

2. Develop of the cold atom interferometer

	First result	Present result
Gravity	30 μGal ^[1] 1992	0.08 μGal ^[2] 2020
Rotation	2×10^{-8} rad/s/ $\sqrt{\text{Hz}}$ ^[3] 1997	3×10^{-10} rad/s ^[4] 2018
Gravity gradient	1 E ^[5] 2002	0.15 E ^[6] 2020
Principle of equivalence	10^{-7} ^[7] 2004	10^{-12} ^[8] 2020
Fine structure constant	100 ppb ^[9] 1994	81ppt ^[10] 2020
Gravitational constant	3150 ppm ^[11] 2008	150ppm ^[12] 2014

More than 30 years development, precision is always the target.

[1]M. Kasevich and S. Chu, Appl. Phys. B **54**, 321 (1992), [2]T. Zhang *et al.*, Phys. Rev. Appl. **20**, 014067 (2023),[3] T. L. Gustavson *et al.*, Phys. Rev. Lett. **78**, 2046 (1997),[4] D. Savoie *et al.*, Sci. Adv. **4**, eaau7948 (2018),[5] J. M. McGuirk *et al.*, Phys. Rev. A **65**, 033608 (2002),[6] C. Janvier *et al.*, Phys. Rev. A **105**, 022801 (2022),[7] S. Fray *et al.*, Phys. Rev. Lett. **93**, 240404 (2004),[8] P. Asenbaum *et al.*, Phys. Rev. Lett. **125**, 191101 (2020),[9] M. Weitz *et al.*, Phys. Rev. Lett. **73**, 2563 (1994),[10] L. Morel *et al.*, Nature **588**, 61 (2020),[11] J. B. Fixler *et al.*, Science **315**, 74 (2007),[12] G. Rosi *et al.*, Nature **510**, 518 (2014)

Why in space

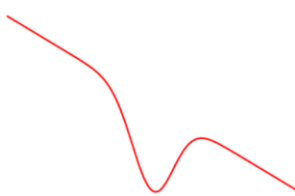

Acceleration resolution

$$a = \frac{\phi}{k_{eff} T^2}$$

space
10⁻¹⁴ m/s²

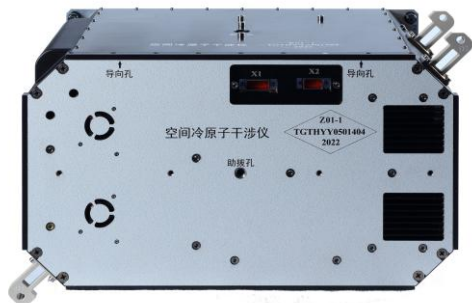
VS

ground
10⁻¹¹ m/s²

	On ground	In space
Interference time	<p>T=1~8 s</p> <p>Fountain: 10 m ~300 m</p> <p>Stanford Wuhan Hanove ...</p>	<p>T=10~100 s</p> <p>Limited by atom temperature</p> <p>Permanent orbit</p> <p>ISS CSS Satellite ...</p>
Residual acceleration	<p>$\sigma_a \sim 10^{-7} \text{m/s}^2 @ 0.3 \text{Hz}$</p> <p>NLNM of the earth</p>	<p>$\sigma_a \sim 10^{-15} \text{m/s}^2 @ 0.01 \text{Hz}$</p> <p>Drag free satellite</p> <p>Lisa path finder</p>
Atom cloud temperature	<p>$T_{tem} \propto h\omega/k_b$</p> <p>$T_{tem} = n\text{K} \sim \text{pK}$</p> <p>modulated by gravity</p> 	<p>$T_{tem} = \text{pK} \sim \text{fK}$</p> <p>Shallow trap in space</p> 

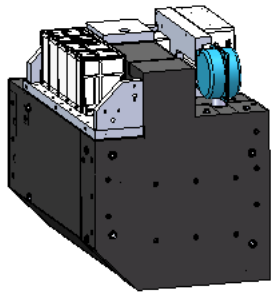
CSSAI-Components and installation

1.CSSAI and its components

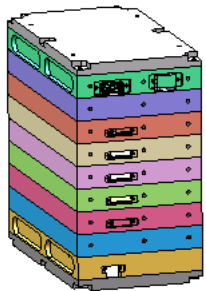


Size: $33 \times 46 \times 26 \text{ cm}^3$
Weight: 37 kg
Power: 70 W

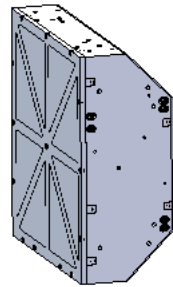
CSSAI



Physical system

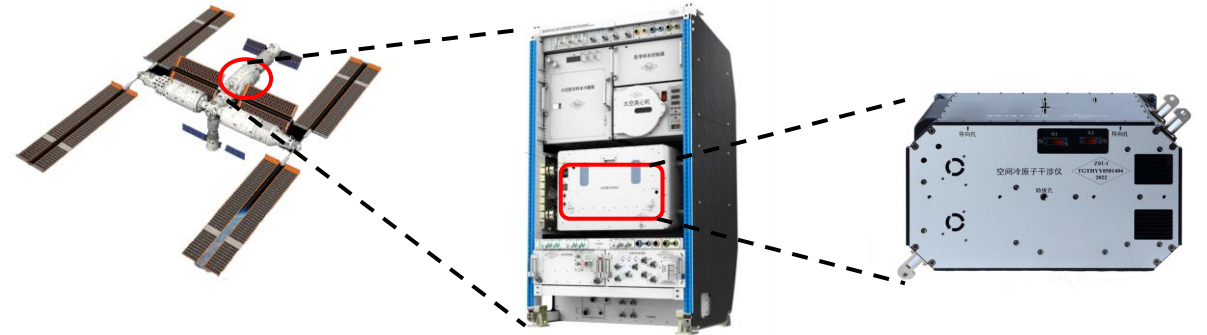


Optical system



Electric system

2.Installation in the CSS

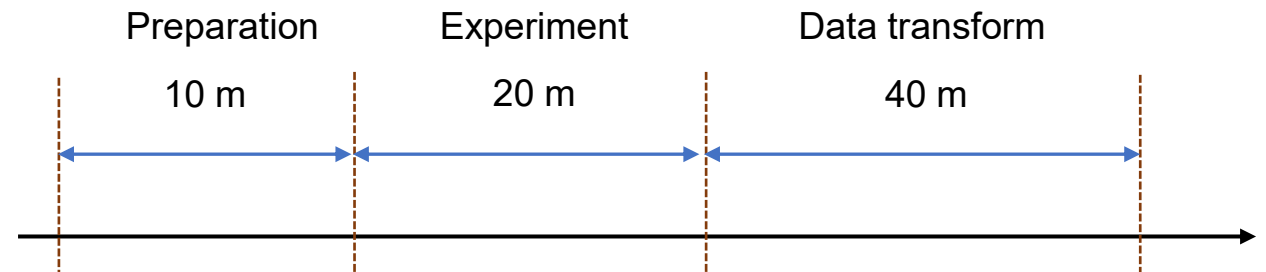


CSS

High Microgravity Level
Research Rack (HMLR)

CSSAI

3.Operation mode

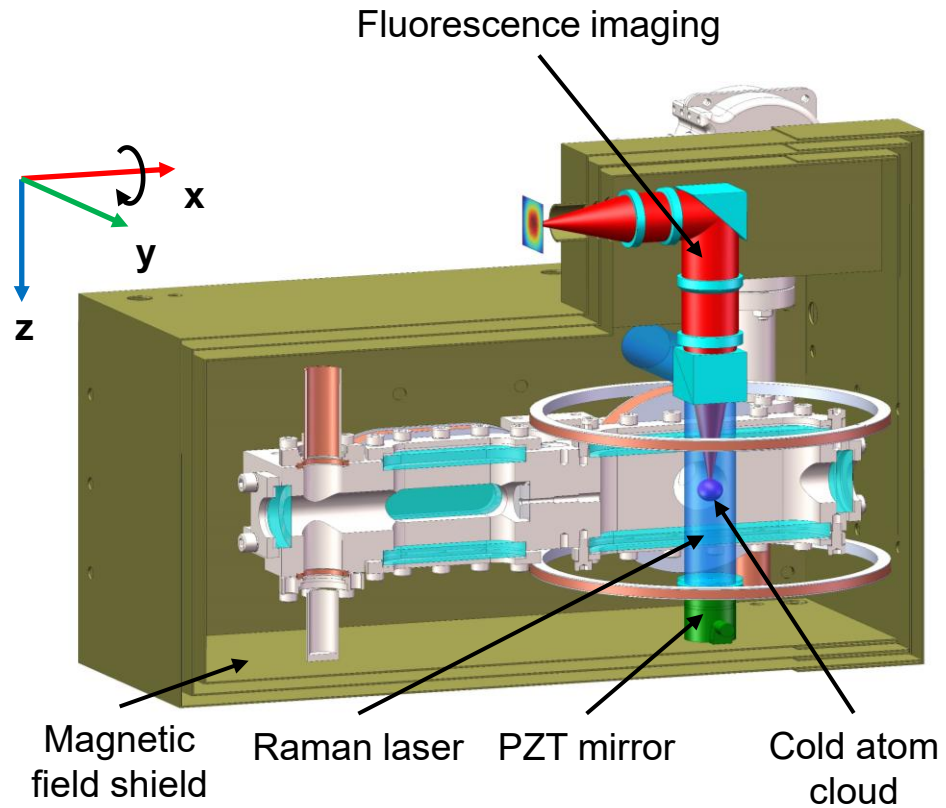


3 experiments for one day

70 minutes for one experiment

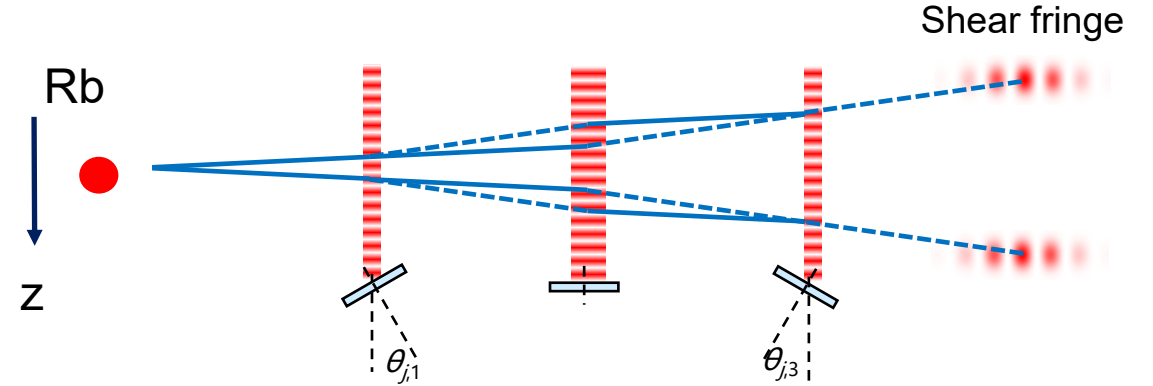
CSSAI-Working principle

1.Components in the physics system



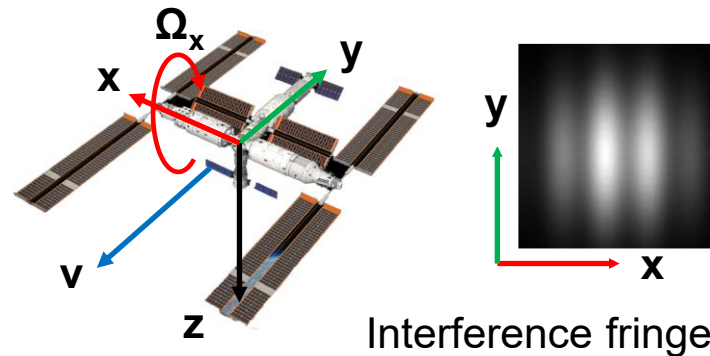
J. T. Li, et al. NSR, 2025, 12(4): nwaf012.

2.Double single diffraction (DSD) interference loop with point source interferometry (PSI) method



Automatic generate symmetric interference loops in microgravity

3.Coordinate relationship



What we can measure

$$\underline{a_z}; \underline{\Omega_x}; \underline{\Omega_y}$$

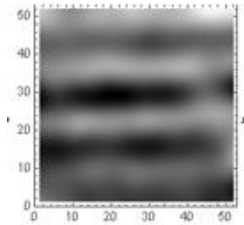
fringe phase

fringe spatial frequency

Interference fringe in orbit

1. Interference fringe in orbit

First interference fringe @2023.08



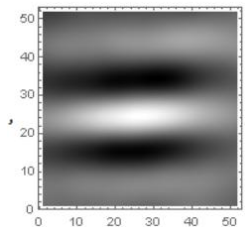
^{85}Rb

$T=50\text{ ms}$



Raman laser frequency/ratio
Detection laser intensity/frequency
...

Optimized interference fringe @2023.11

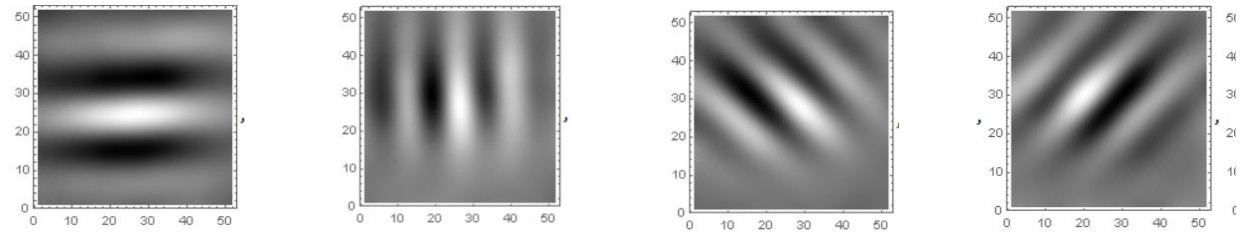


^{85}Rb

$T=50\text{ ms}$

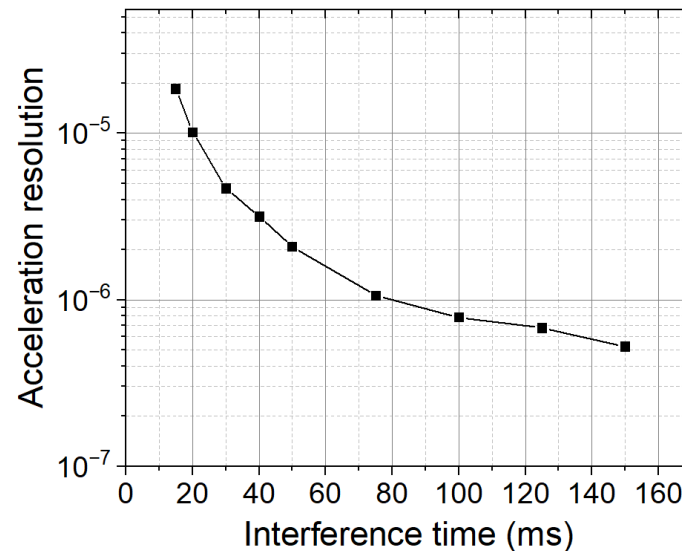
Acceleration resolution:
 $2.8 \times 10^{-6}\text{ m/s}^2$ for one image

2. Modulation of the spatial frequency



Have the ability to extract a_z , Ω_x and Ω_y at a same time

3. Modulation of the interference time

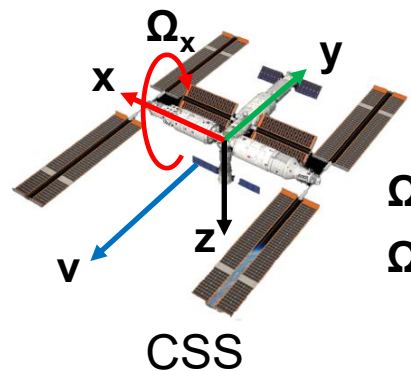


Longest interference time:
150 ms for ^{87}Rb

Acceleration resolution:
 $5 \times 10^{-7}\text{ m/s}^2$ for one image

Measuring the rotation of the CSS

1. Fast rotation of the CSS



Nadir pointing

$$\Omega_x: \sim 1 \times 10^{-3} \text{ rad/s}$$

$$\Omega_y: \sim 0 \text{ rad/s}$$

CSS



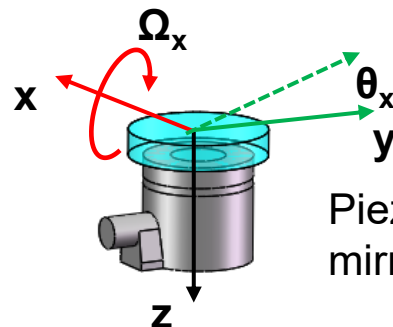
Rotation rate

$$\Omega_{\text{earth}}: \sim 7 \times 10^{-5} \text{ rad/s}$$

Earth

15 times higher than Ω_{earth}

2. Piezoelectric mirror—key component that induce the PSI



Piezoelectric mirror

Inertia induced phase

$$\phi = k_{eff} a_z T^2 + \sum_i k_{eff} [2\Omega_i v_j T^2]$$

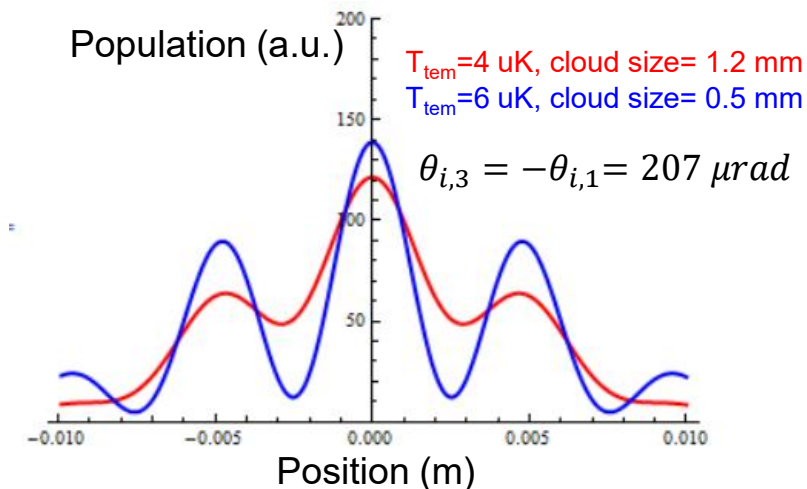
Angle induced phase

$$\phi = \sum_i k_{eff} [\theta_{i,1} r_j + \theta_{i,3} (r_j + 2v_j T)]$$

All phases are related to the distribution of the atom cloud

3 Decoherent effect of the atom cloud's distribution

Same rotation rate and rotation angle but different atom distribution



Spatial frequency difference: 7%

Spatial frequency uncertainty
Reduce for the fringe contrast

Can we avoid it?

The magic angle relationship

The phase $\phi = k_{eff} a_z T^2 + \sum_i k_{eff} [2\Omega_i v_j T^2 + \theta_{i,1} r_j + \theta_{i,3} (r_j + 2v_j T)]$

Submit $r_j = R_j - v_j(2T + t_0)$ and let the coefficient of v_j to be zero

R_j (position at the detection)

The magic angle relationship

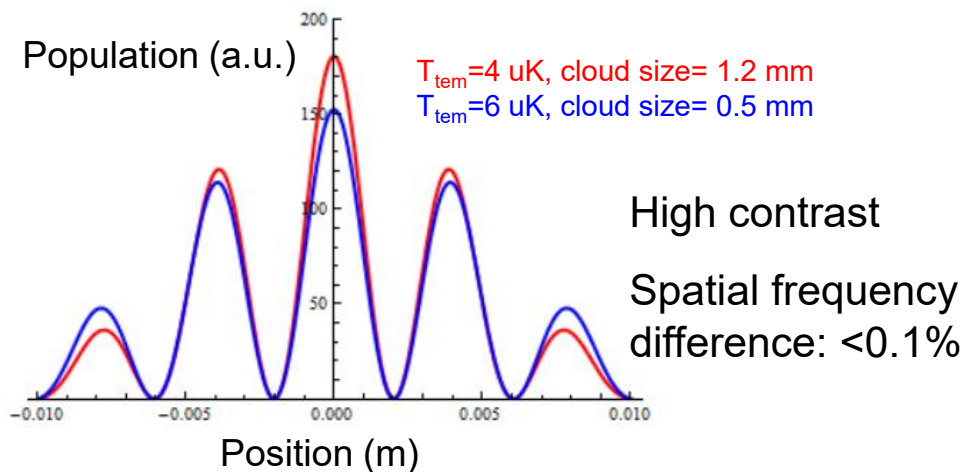
$$\theta_{j,1} = \frac{-t_0 \theta_{j,3} + 2 \Omega_j T^2}{2T + t_0}$$

Reduced phase $\phi_o = k_{eff} a_z T^2 + \sum_{i=x,y} f_i R_i$,
Spatial frequency

$$f_i = \frac{2k_{eff}}{2T + t_0} (\theta_{j,3} T + \Omega_j T^2)$$

Expression to calculate the rotation

ϕ is only related to the position R_j , decoupled to v_j and r_j



What happens if magic angle relationship is not satisfied

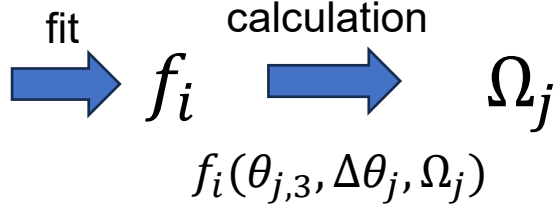
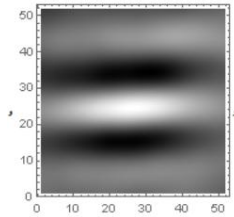
$$\phi_I = \phi_o + \Delta f(\Delta\theta_j) R_i + \Delta\phi(\Delta\theta_j)$$

Spatial frequency correction phase correction

Detailed in J. T. Li, et al. NSR, 2025, 12(4): nwaf012.

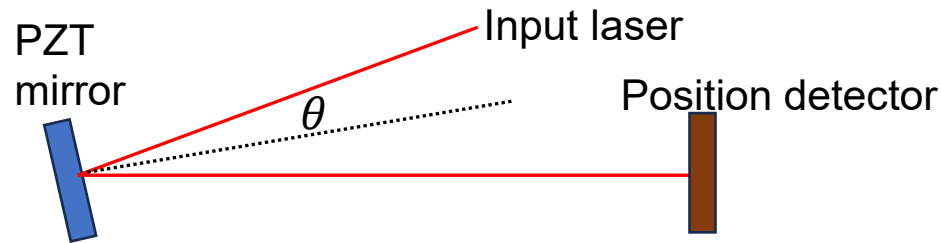
Calibration of the angle

Rotation measurement process



Interference fringe

Assume we know exact value of θ
 θ is calibrate on ground with $\theta = \alpha V$



Calibrated value

$$\alpha_x = 119 \mu\text{rad/V}$$

$$\alpha_y = 121 \mu\text{rad/V}$$

Are these values accurate?

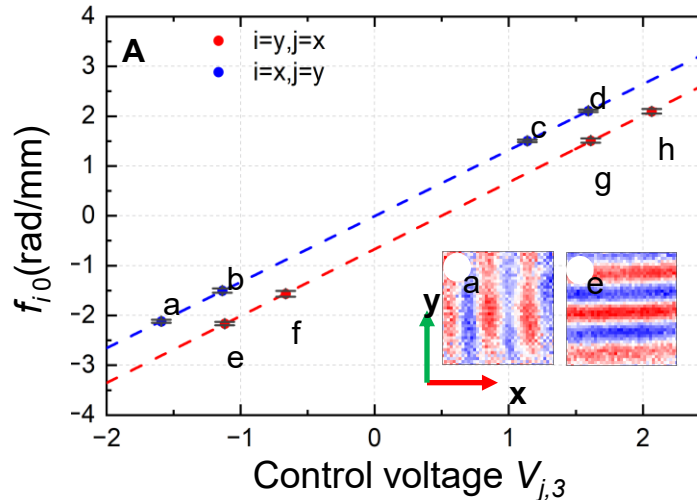
In orbit calibration of θ

Self calibration using the interference fringes themselves

$$f_i = f_{i0}(\alpha_j V_{j,3}, \Omega_j) + \Delta f(\alpha_j \Delta V_j)$$

Spatial frequency is related to parameters α , Ω

Experiment with different values of V could be used to fit the above parameters



Fitting result

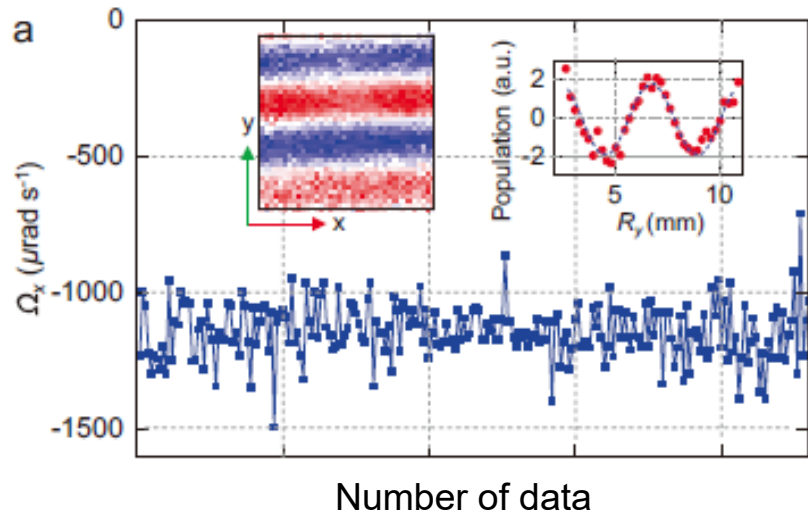
$$\alpha_x = 118.99 \pm 0.50 \mu\text{rad/V}$$

$$\alpha_y = 118.15 \pm 0.23 \mu\text{rad/V}$$

Angle accuracy better than 1 μrad

Rotation measurement result

Rotation measurement process



Resolution

50 $\mu\text{rad/s}$ for a single shot.

17 $\mu\text{rad/s}$ for an averaged number of 32

Error estimation

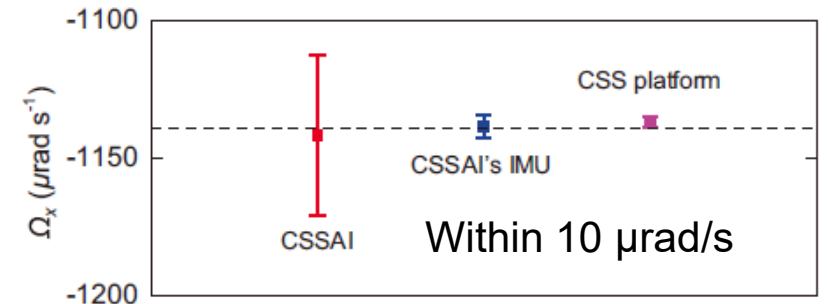
Table 1. Error analysis for the rotation Ω_x with the PSI method in space.

Parameter terms	Parameter values	Evaluated result ($\mu\text{rad/s}$)
Spatial frequency (fitting result)	$f_y = 1.497 \pm 0.013 \text{ rad/mm}$	-1142 ± 17
Magnification factor of the imaging system	$\kappa = 2.22 \pm 0.03$	± 21
Angles of third Raman laser pulses	$\theta_{x,3} = 202.94 \pm 0.72 \mu\text{rad}$	± 10
Difference angle of $\theta_{x,1}$	$\Delta\theta_x = 2.41 \pm 0.41 \mu\text{rad}$	± 1
Interference time	$T = 75137.3 \pm 0.23 \mu\text{s}$	$\pm 3 \times 10^{-3}$
Time before the first Raman pulse	$t_0 = 43245.8 \pm 0.13 \mu\text{s}$	$\pm 2 \times 10^{-5}$
Time after the third Raman laser pulse	$t_1 = 40146 \pm 10 \mu\text{s}$	$\pm 9 \times 10^{-2}$
Width of the Raman π pulse	$\tau = 17 \pm (5 \times 10^{-5}) \mu\text{s}$	$\pm 6 \times 10^{-7}$
Effective wave vector	$k_{\text{eff}} = 16105813.75 \pm 0.09 \text{ m}^{-1}$	$\pm 9 \times 10^{-6}$
Width of the MOT's position	$\sigma_{\rho_i} = 0.427 \pm 0.013 \text{ mm}$	$\pm 3 \times 10^{-2}$
Width of the MOT's velocity	$\sigma_{v_i} = 14.13 \pm 0.18 \text{ mm/s}$	$\pm 1 \times 10^{-2}$
Magnetic field	$B_0 = 504.7 \pm 1.3 \text{ mG}$ $\gamma_{i,2} = \pm 1.3 \text{ G/m}^2$	$\pm 2 \times 10^{-1}$
In total		-1142 ± 29

Main error terms come from the uncertainties of the imaging magnification and the rotation angle.

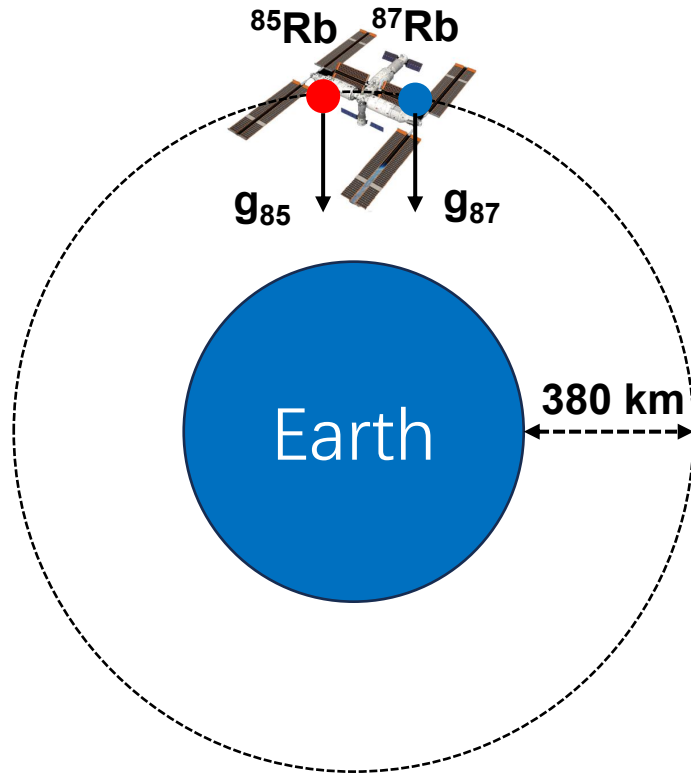
$-1142 \pm 29 \mu\text{rad/s}$

Comparison



Weak equivalence principle test

In orbit test of the WEP

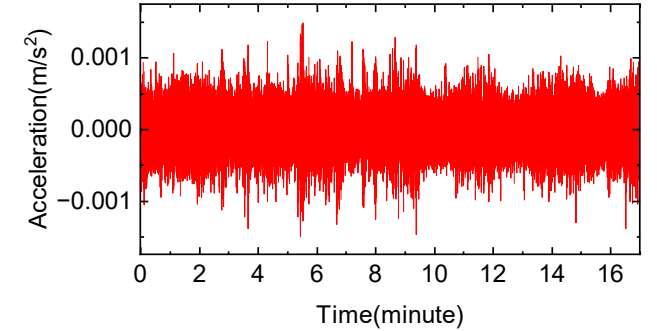


The Eotvos parameter

$$\eta_{\text{Rb85,Rb87}} = \frac{a_{z,\text{Rb85}} - a_{z,\text{Rb87}}}{g_z}$$

$$g_z = 8.72 \text{ m/s}^2$$

Vibration of the CSS

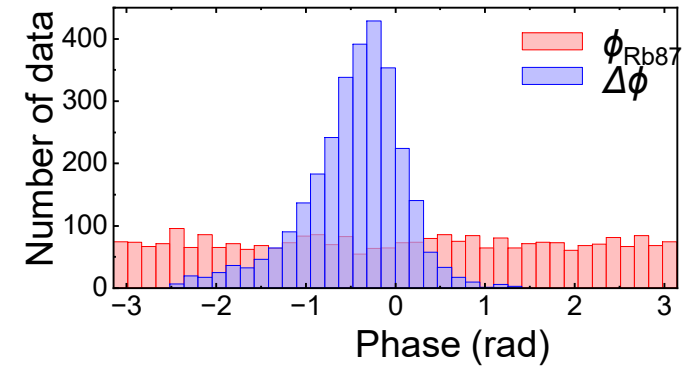
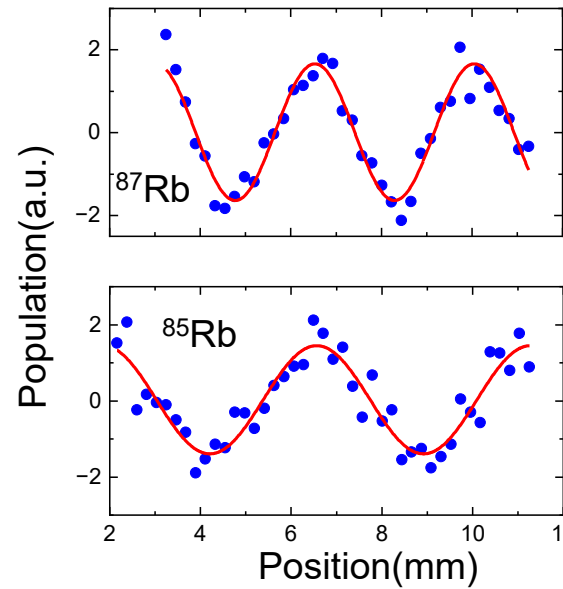


$$\sigma_a = 2.5 \times 10^{-4} \text{ m/s}^2$$



$$\sigma_\phi = 7.84 \text{ rad}$$

Dua-species Interference fringe and vibration suppression

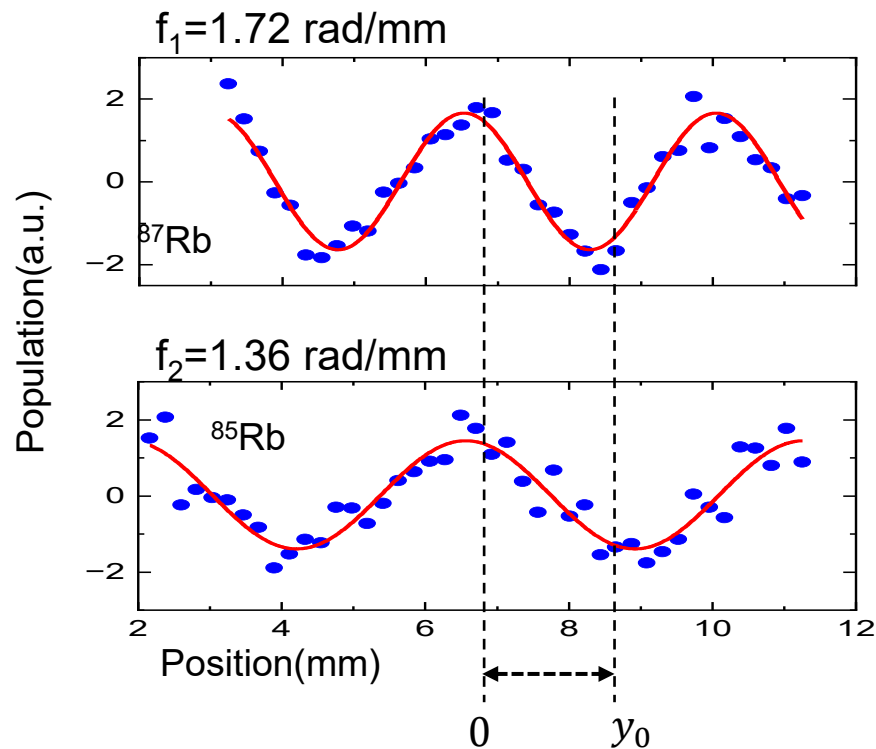


$$\sigma_{\Delta\phi} = 0.55 \text{ rad}$$

$$\eta_{\text{Rb85,Rb87}} = \frac{\Delta\phi}{k_{\text{eff}} g_z T^2}$$

Spatial frequency induced phase

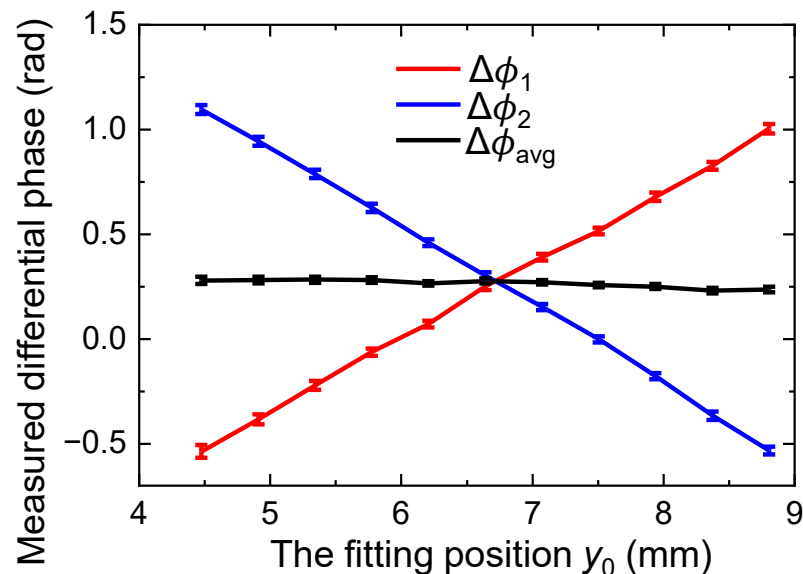
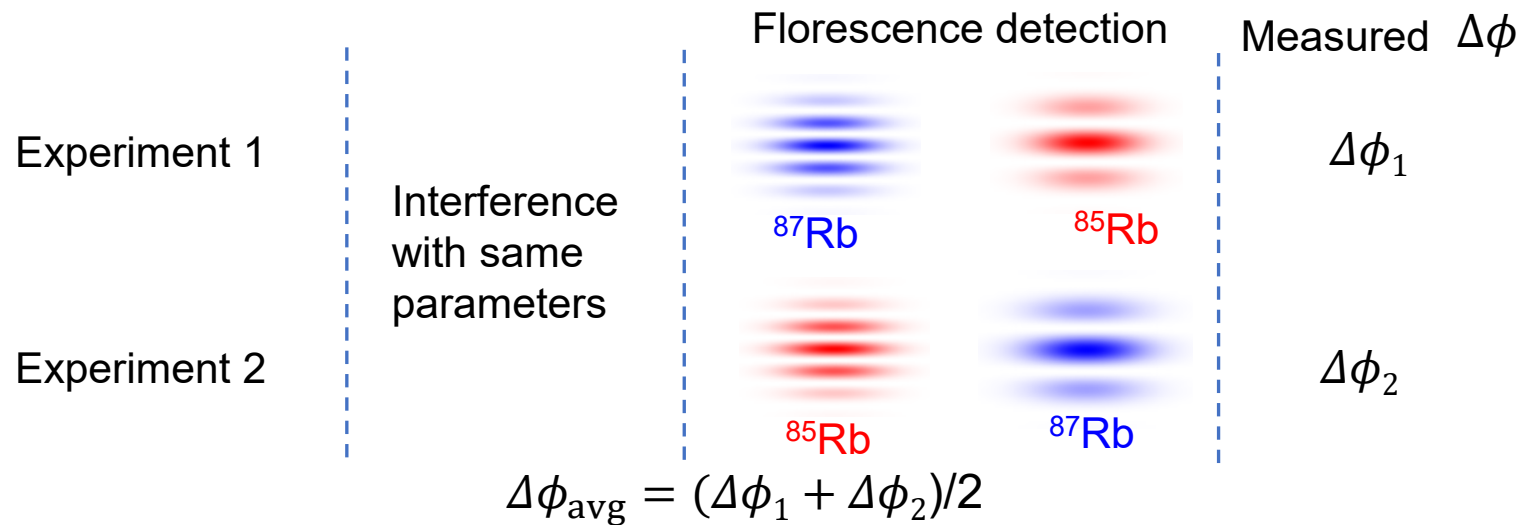
Spatial frequencies difference



Induced differential phase

$$\Delta\phi = \Delta f y_0$$

Fluorescence detection switching method



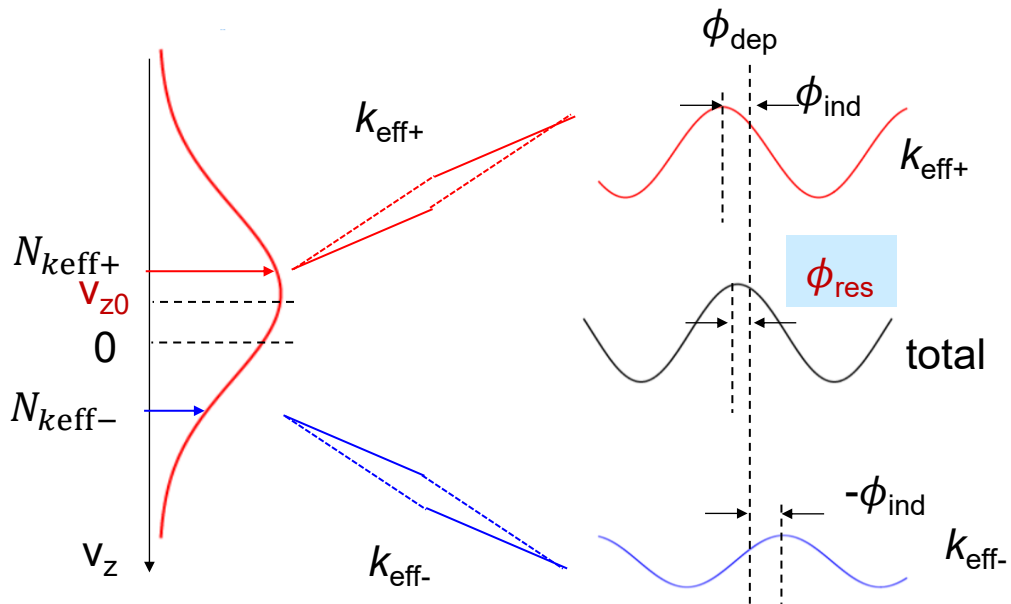
$\Delta\phi_i$ change by 1.6 rad

$\Delta\phi_{\text{avg}}$ changes by 0.044 rad

keff-independent phase

Residual phase for the DSD interference fringe

Asymmetric DSD interference loop

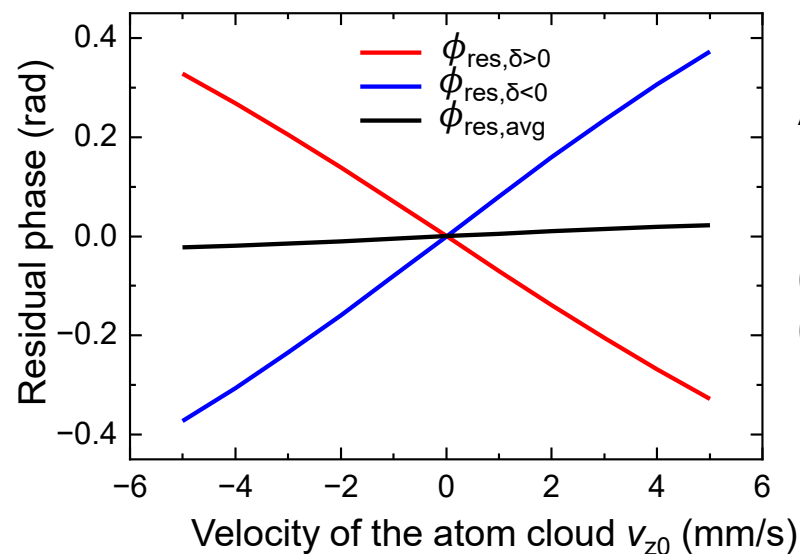
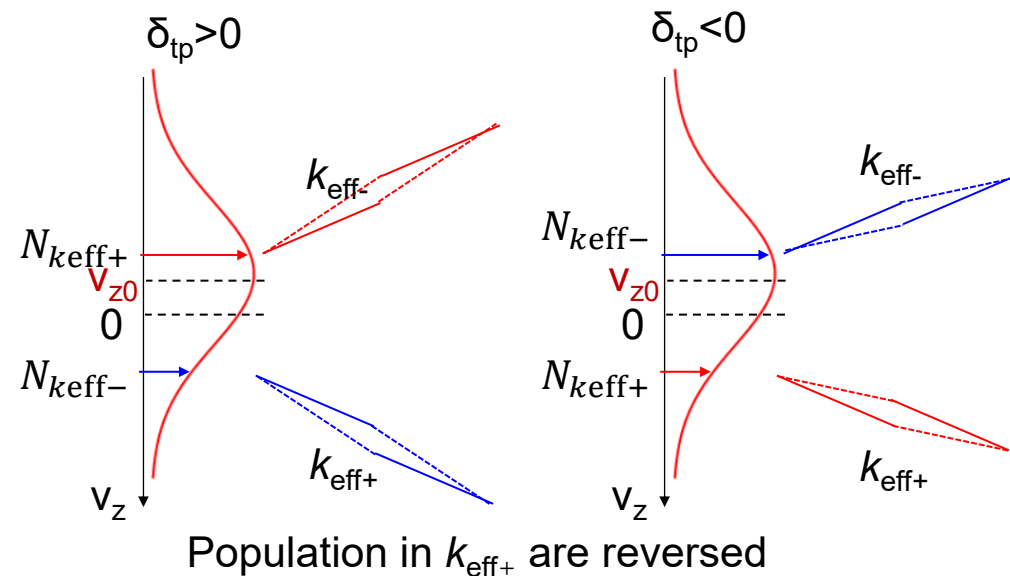


A residual velocity of 4 mm/s



16% change in the population

Two-photon detuning switching method



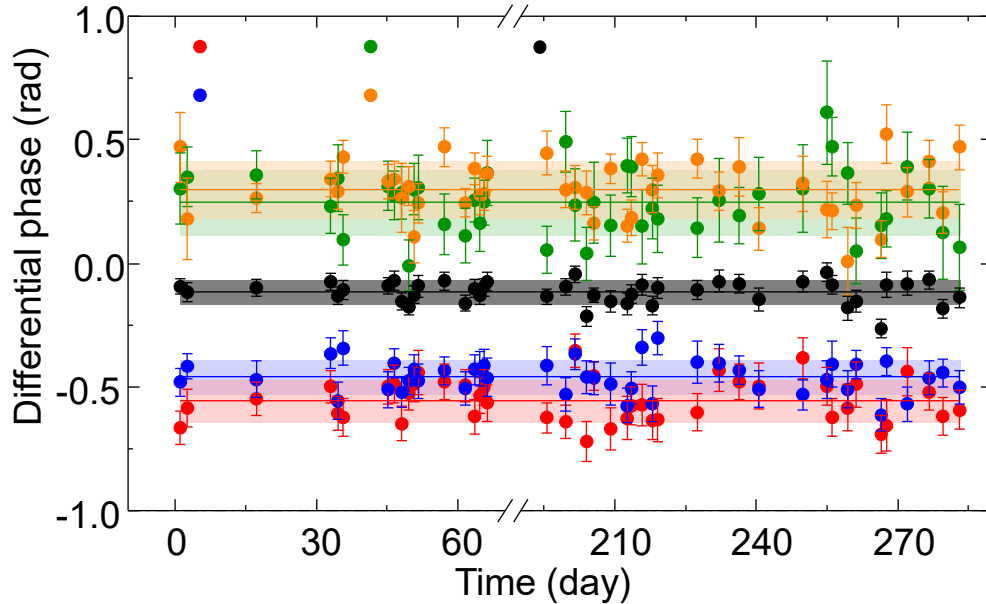
Assuming ϕ_{ind} to be 0.92 rad

0.65 rad for single case

0.04 rad for the averaged case

WEP test result

Long term differential phase measurement result



Last for more than 280 days
 Effective of the switching methods (from -0.556 rad to -0.117 rad)
 Allen deviation down to 0.01 rad for 64-day average

Error estimation

Table 1. Error budget for the differential phase.

Terms		Differential phase(rad)
Measurement result		-0.12 ± 0.01
Systematic effects	Residual acceleration	$(-2.1 \pm 8.0) \times 10^{-5}$
	Centrifugal force	$(0.0 \pm 7.4) \times 10^{-5}$
	Gravity gradient	$(0.0 \pm 1.5) \times 10^{-4}$
	Imaging angle offset	0.01 ± 0.16
	Shearing fringe frequency mismatch	$(-1.5 \pm 3.7) \times 10^{-4}$
	Single-photon ac Stark shift	$(0.0 \pm 1.0) \times 10^{-2}$
	Two-photon ac Stark shift	$(0.0 \pm 2.3) \times 10^{-3}$
	Multiple-sideband effect	$(0.0 \pm 2.2) \times 10^{-5}$
	Magnetic field	$(0.0 \pm 3.8) \times 10^{-4}$
	Wavefront distortion	$(0.0 \pm 1.2) \times 10^{-2}$
Uncertainty of k_{eff} and T		$< 10^{-6}$
EP violation induced phase		-0.11 ± 0.16

Newly discovered imaging angle offset term (special for PSI)
 Phase shifts related to acceleration are greatly suppressed (multiple-sideband effect, uncertainties of k_{eff} and T)

$$\eta_{\text{Rb85,Rb87}} = (-3.1 \pm 4.6) \times 10^{-7}$$

Comparing with other WEP test experiment

	Platform	Result	Parameters
Macroscopic object record	Drag free satellite	10^{-15} [1] MICROSCOPE 2022	Pt and Ti
Ground record (quantum)	On ground	10^{-12} [2] 2020	^{85}Rb and ^{87}Rb T= 1 s
Microgravity record (quantum)	Zero-g plane	10^{-4} [3] 2016	Rb and K T= 2 ms
This work	Space station	10^{-7} [4] 2026	^{85}Rb and ^{87}Rb T=50 ms
Future proposal (quantum)	Drag free satellite	10^{-17} [5] STE-QUEST	Rb and K T= 25 s

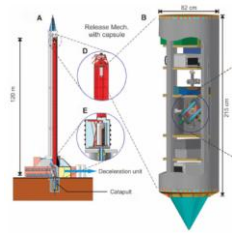
Best in space (quantum), but still far below the requirement to find new physics

Summary

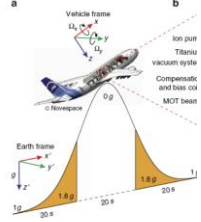
- **Method:** Eliminate Dephasing of PSI, Self calibration of Raman laser's angle, Eliminate phase error of PSI and DSD
- **Scientific result:** First rotation measurement and highest WEP test result in orbit with atom interferometer
- **Engineering:** Atom interferometer meeting space requirements, integrated design, Long on-orbit lifetime

Roadmap for quantum testing of WEP in space

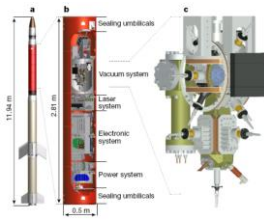
QUANTUS
2004



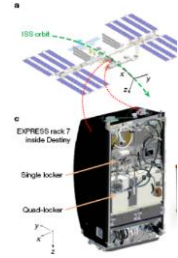
I.C.E.
2008



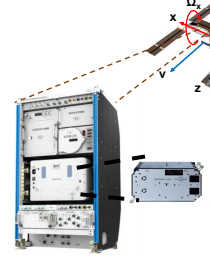
MAIUS
2017



CAL
2018



CSSAI
2022



CAPR
2022



- Ultra cold atom under microgravity
- Atom interferometry under microgravity
- Ultra-quiet and ultra-stable platform
- Quantum-enhanced atom interferometry in space
- High TRL

Space WEP test using atom interferometry with competitive precision

For science

Probing physics beyond SM and GR

- String theory
- Loop quantum gravity

Search for ultralight dark matter

Test of spin-gravity coupling and spacetime torsion

Acknowledgments

Cold atom group



Team for CSSAI



Other supporter

CSS

Hongen Zhong, CSU,CAS
Xihe Yu, CSU,CAS
Yao tian, CSU,CAS
Shuquan Wang, CSU,CAS
Zongfeng Li, CSU,CAS
Shan Jin, CSU,CAS
Chencheng zhang, CSU,CAS

...

Interference mechanism

Lin Zhou, APM, CAS
Dongfeng Gao, APM, CAS
Weidou Ni, University of CAS

...

Electronics and optics

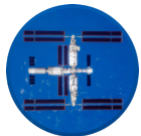
Qunfeng Chen, APM, CAS
Huanyao Sun, APM, CAS
Yan Wang, APM, CAS
Fang Yu, APM, CAS
Lei Qin, APM, CAS
Zhiyong Chen, APM, CAS
Li Wang, APM, CAS

...

Software

Kuo Li, Zmvision Technology
Guo Zheng, Zmvision Technology
Weihua Peng, Zmvision Technology
Ke Ma, CAS Cold Atom Technology

...



Space Science and application Project of CSS



**Innovation Academy for Precision
Measurement Science and Technology,
CAS**

Thank you for your attention