Equivalence Principle Test with Atom Interferometry in Space

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OUTLINE

- WEP test — Introduction
- WEP test near ground
- WEP test in satellite (CSS-AI)

WEP: Weak Equivalence Principle
AI: Atom Interferometer
CSS: China Space Station

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- **WEP test – Introduction**
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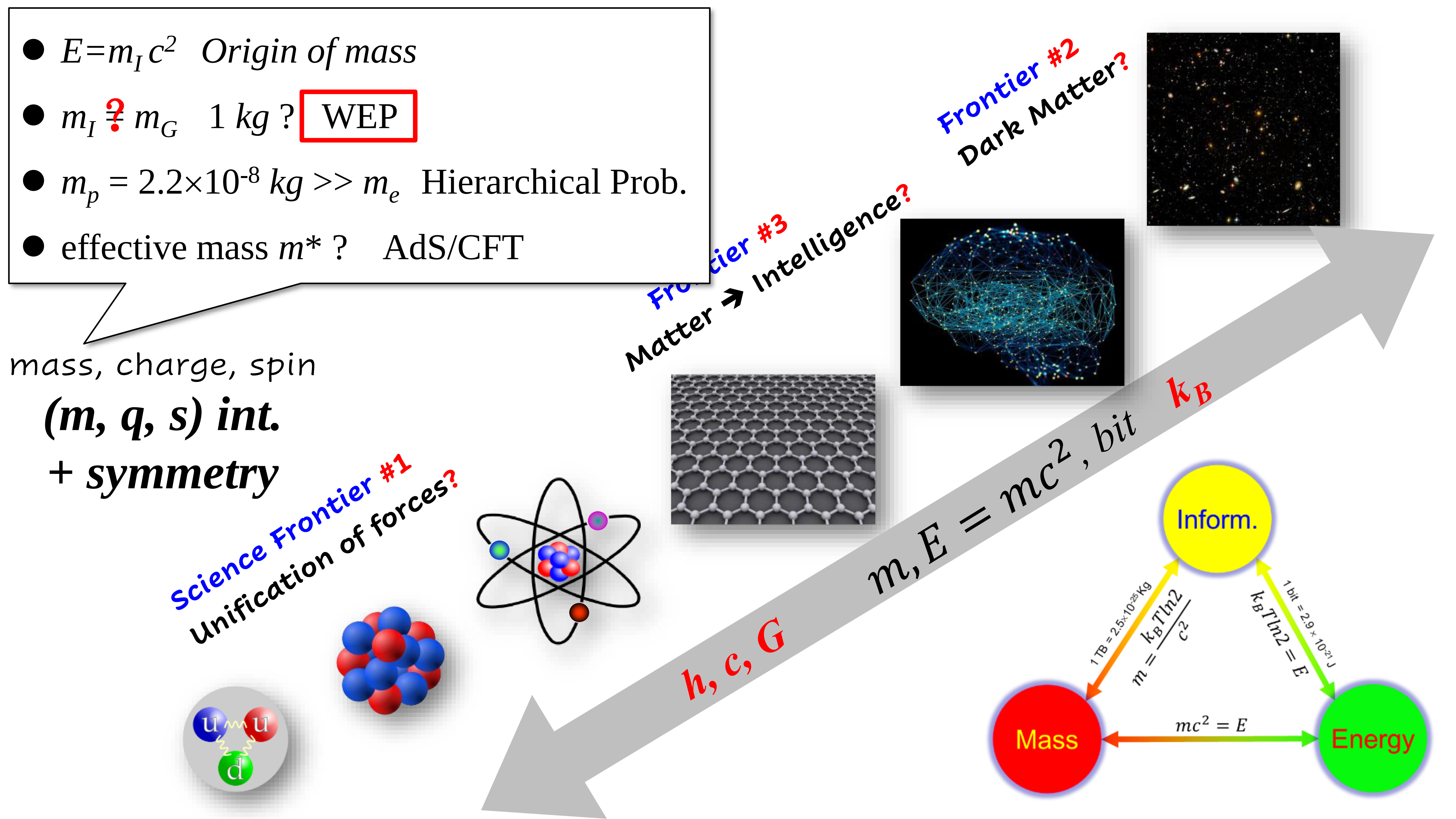


$E = m_I c^2$ Origin of mass
$m_I \overset{?}{=} m_G$ 1 kg ? WEP
$m_p = 2.2\times10^{-8}$ kg >> m_e Hierarchical Prob.
effective mass m^* ? AdS/CFT
mass, charge, spin
(m, q, s) int.
+ symmetry
Science Frontier #1
Unification of forces?
Frontier #3
Matter → Intelligence?
Frontier #2
Dark Matter?
u
u
d
h, c, G
$m, E = mc^2$, bit
k_B
Inform.
Mass
Energy
1 TB = 2.5×10⁻²⁵ Kg
$m = \frac{k_B T \ln 2}{c^2}$
$k_B T \ln 2 = E$
1 bit = 2.9 × 10⁻²¹ J
$mc^2 = E$

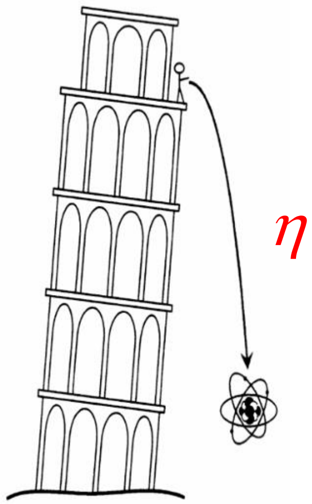
Weak Equivalence Principle (WEP)

Einstein Equivalence Principle (EEP) is organised into three conditions:

WEP + LLI + LPI

1) **Equivalence between the system's inertia and weight – the Weak Equivalence Principle (WEP, η =0);**
2) **Independence of outcomes of local non-gravitational experiments of the velocity of a freely-falling reference frame in which they are performed (or validity of special relativity) – Local Lorentz Invariance (LLI);**
3) **Independence of outcomes of local non-gravitational experiments of their location – Local Position Invariance (LPI).**

Pisa Leaning Tower Experiment



η =0

Eötvös-parameter

$$\eta = \frac{(a_1 - a_2)}{(a_1 + a_2)/2}$$

WEP (η = 0) is the basis of general relativity (GR), but almost all theories linking gravity and standard models (eg, scalar-tensor, gravitational gauge, great unification, high dimension, inflation, etc.) require $\eta \neq 0$.

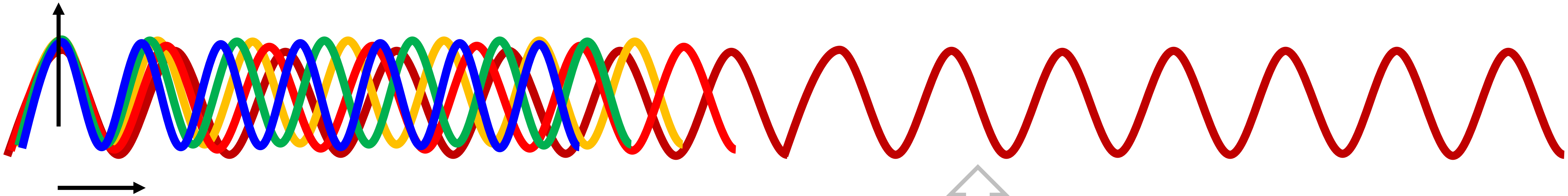
Wave interferometry

- **clock / frequency standard:**
  keep the wave stable, count the cycles
- **interferometer:**
  split a wave to include a path or area, count the fringes

0-order of a comb (***f, t, r***)

e.g. white light interference

N (m, q, s) ***- particle***



φ (f, t; k, r; l, θ) **- wave**

How to determine the **absolute** order of a periodic function:

- bridge to the zero-order *e.g.* optical atomic clock, atomic gravimeter
- scan the scaling factor *e.g.* optical wavelength meter, atomic gyro

Wave-particle duality: wave of particles

Same initial and final states with indistinguishable paths $\xRightarrow{\text{coherence}}$ Interference

Because of coherence there is interference

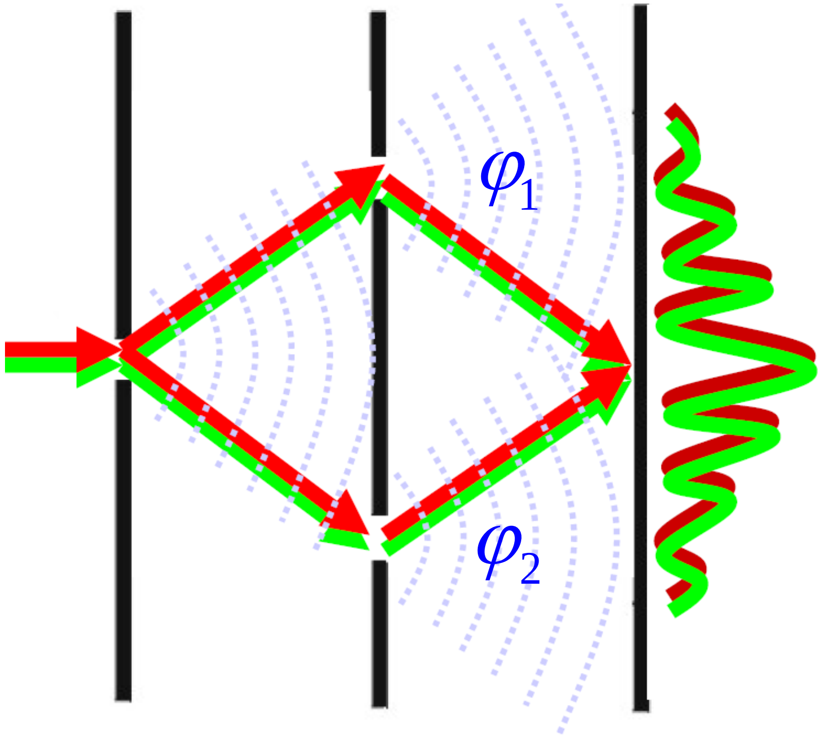
$m \uparrow$

$$\lambda_{dB} = \frac{h}{p} = \frac{h}{mv} \downarrow$$

Compton frequency

$$f_{dB} = \frac{m_0 c^2}{h}$$

photon
electron
neutron
atom
molecule
virus
bacteria
cluster
…

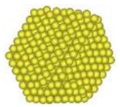


$$\varphi = \varphi_1 + \varphi_2$$

$$P \propto |\varphi|^2$$

$$= |\varphi_1|^2 + |\varphi_2|^2 + 2\varphi_1\varphi_2^*$$

interference term



Current record (2021)
^{23}Na cluster, mass of 1 MDa
containing 43,000 atoms

the Young's double-slit experiment

Quantum Test of WEP

$$\sigma_\eta = \frac{1}{n k_{eff} g T^2} \frac{1}{C N^\delta} \sqrt{\frac{T_c}{\tau}}$$

LMT $n \uparrow$
Ultra cold atom $N \uparrow$
Quantum Tech $\delta = 1/2 \rightarrow 1$

T → 1.3s 10-m Tower
→ 7 s 100-m Tower
→ (2 ~ 100) s Space

Wuhan 10-m Tower

Satellite WEP experiment with atoms

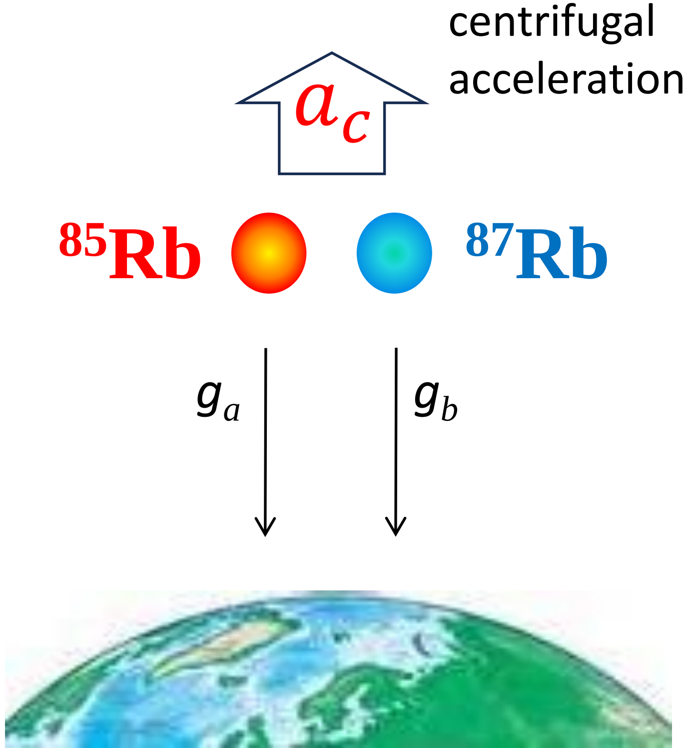
$$\eta \equiv \frac{g_a - g_b}{(g_a + g_b)/2} = \frac{(g_a - a_c) - (g_b - a_c)}{(g_a + g_b)/2} \overset{?}{=} 0$$

g modulation?

400km, $g = 8.7\mathrm{m/s^2}$

Test body attributes:

- mass m
- angular momentum (spin) F
- internal energy E
- superposition / entangled states
- information



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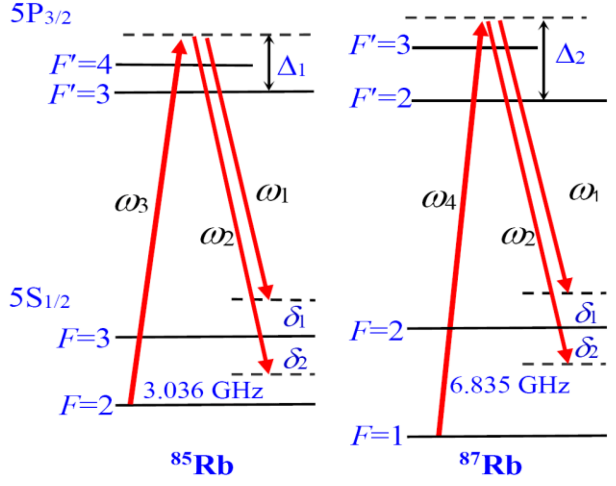
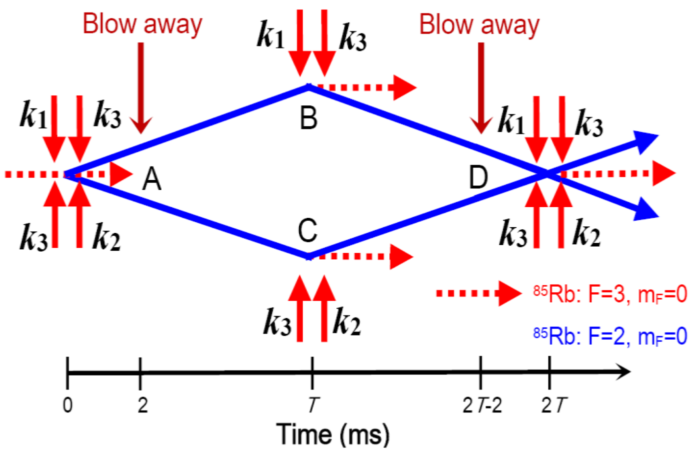
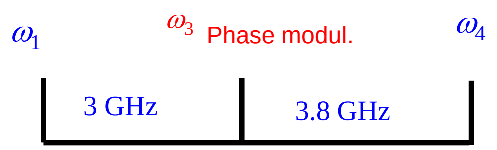
4WDR (Four Wave Double-diffraction Raman Transition) AI



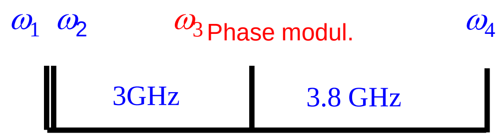
- Using the same laser to reduce phase noise and obtain high common-mode noise rejection ratio
- The Rabi frequencies of different species' AIs are the same, and the ac Stark shift caused by laser beams is zero for both AIs
- Interference with the same internal state to reduce the systematic errors
- Time synchronization and overlap to reduce the systematic errors

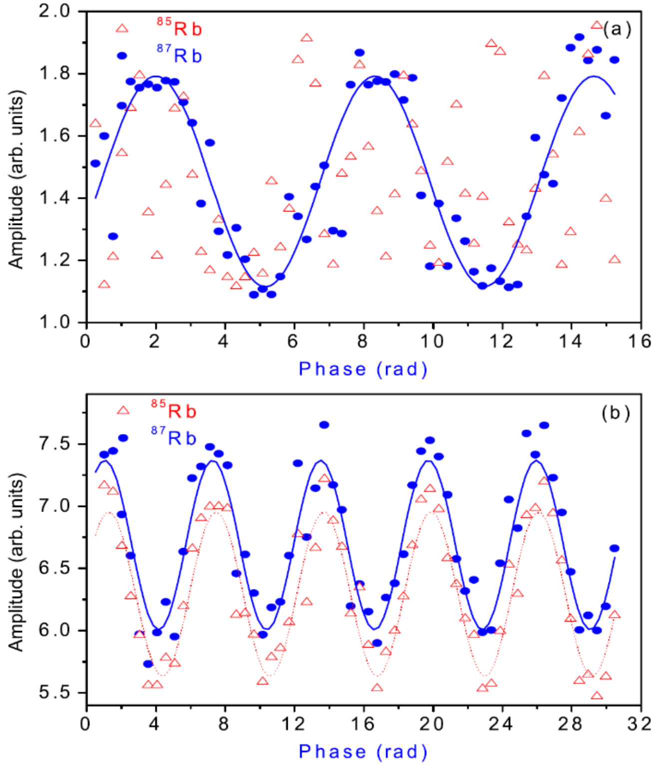


Single Raman



4WDR



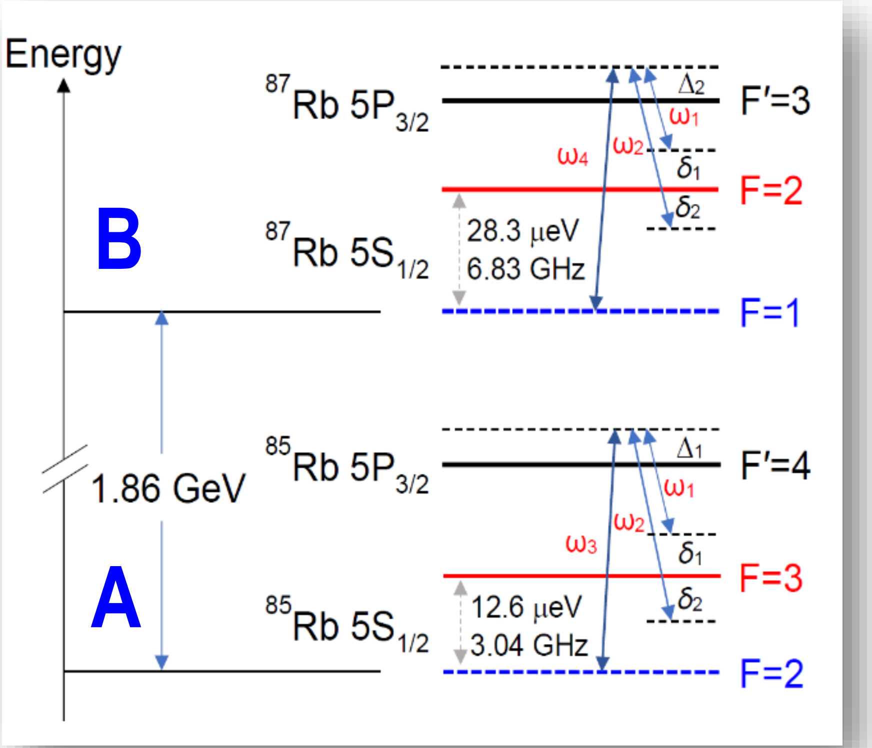


$$\omega_1+\delta_1 = \omega_2-\delta_2 = \omega_3 - 3.036\text{ GHz} = \omega_4 - 6.835\text{ GHz}$$

L. Zhou *et al.*, PRL 115, 013004 (2015)

Joint mass-energy EP test

^{85}Rb – ^{87}Rb Test Pair



$$m_g = (1+\alpha)\frac{E^{LGS}}{c^2} + (1+\beta)\frac{\Delta E}{c^2}$$

$$= (1+\alpha)m_0 + (1+\beta)\frac{\Delta E}{c^2}$$

$$= m_i + \alpha m_0 + \beta\frac{\Delta E}{c^2}$$

$$m_i = \frac{E^{\mathrm{LGS}}}{c^2} + \frac{\Delta E}{c^2}$$

$$m_0 = \frac{E^{\mathrm{LGS}}}{c^2}$$

$$\Delta E = E^{\mathrm{UPS}} - E^{\mathrm{LGS}}$$

(E-7 for sure)

$$E \overset{?}{=} \gamma m_0 c^2$$

α mass violation parameter

β energy violation parameter

1 bit information

rest mass ~ GeV

internal energy ~ μeV (GHz)

Kinetic energy ~ μK (1 μK = 21 kHz)

$$m_i \approx m_0$$

$$m_g^{87} = m_i^{87} + \alpha^{87} m_0^{87} + \beta\frac{\Delta E^{87}}{c^2}$$

$$m_g^{85} = m_i^{85} + \alpha^{85} m_0^{85} + \beta\frac{\Delta E^{85}}{c^2}$$

$$\eta \equiv \frac{g_A - g_B}{(g_A + g_B)/2} \equiv \frac{\frac{m_g^{87}}{m_i^{87}} - \frac{m_g^{85}}{m_i^{85}}}{\frac{1}{2}\left(\frac{m_g^{87}}{m_i^{87}} + \frac{m_g^{85}}{m_i^{85}}\right)}$$

^{85}Rb|F=3⟩ – ^{87}Rb |F=2⟩

^{85}Rb|F=3⟩ – ^{87}Rb |F=1⟩

^{85}Rb|F=2⟩ – ^{87}Rb |F=2⟩

^{85}Rb|F=2⟩ – ^{87}Rb |F=1⟩

Comparison with other results

Mass pair	F-F'	ΔE	η_i	η_E	Ref.
^{85}Rb - ^{87}Rb	2-1	1.86 GeV	$(1.2 \pm 1.7) \times 10^{-7}$		*Phys. Rev. Lett.*(2004)
^{85}Rb - ^{87}Rb	mixed	1.86 GeV	$(1.2 \pm 3.2) \times 10^{-7}$		*Phys. Rev. A* (2013)
^{39}K - ^{87}Rb	mixed	44.66 GeV	$(0.3 \pm 5.4) \times 10^{-7}$		*Phys. Rev. Lett.*(2014)
^{85}Rb - ^{87}Rb	2-1	1.86 GeV	$(2.8 \pm 3.0) \times 10^{-8}$		*Phys. Rev. Lett.*(2015)
^{39}K - ^{87}Rb	mixed @ 0g	44.66 GeV	$(0.9 \pm 3.4) \times 10^{-4}$		*Nat. Commun.* (2016)
^{39}K - ^{87}Rb	mixed	44.66 GeV	$(-1.9 \pm 3.2) \times 10^{-7}$		*Eur. Phys. J. D* (2020)
^{88}Sr - ^{87}Sr	0-9/2	0.93 GeV	$(0.2 \pm 1.6) \times 10^{-7}$		*Phys. Rev. Lett.*(2014)
^{85}Rb - ^{87}Rb	3-2	1.86 GeV	$(1.6 \pm 3.8) \times 10^{-12}$		*Phys. Rev. Lett.*(2020)
^{85}Rb	2-3	3.04 GHz	$(0.4 \pm 1.2) \times 10^{-7}$		*Phys. Rev. Lett.*(2004)
^{87}Rb	$m_F = \pm 1$		$(1.2 \pm 3.2) \times 10^{-7}$		*Phys. Rev. Lett.*(2016)
^{87}Rb	1-2	6.83 GHz	$(1.4 \pm 2.8) \times 10^{-9}$		*Nat. Commun.* (2017)
^{87}Rb	$1\text{-}1 \oplus 2$		$(3.3 \pm 2.9) \times 10^{-9}$		*Nat. Commun.* (2017)
^{87}Rb	1-2	6.83 GHz	$(0.9 \pm 2.7) \times 10^{-10}$		*Chin.Phys.Lett.*(2020)
^{85}Rb - ^{87}Rb	2-1	1.86 GeV + 0.00 GHz	$\eta_1 = (1.5 \pm 3.2) \times 10^{-10}$		This work
^{85}Rb - ^{87}Rb	2-2	1.86 GeV + 6.83 GHz	$\eta_2 = (-0.6 \pm 3.7) \times 10^{-10}$		
^{85}Rb - ^{87}Rb	3-1	1.86 GeV − 3.04 GHz	$\eta_3 = (-2.5 \pm 4.1) \times 10^{-10}$		
^{85}Rb - ^{87}Rb	3-2	1.86 GeV + 3.79 GHz	$\eta_4 = (-2.7 \pm 3.6) \times 10^{-10}$		
			$\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$	$(0.0 \pm 0.4) \times 10^{-10}$	

Mass

Spin（F，m_F）

Superposition

Energy！

Information?

The mass-energy joint test of EP is realized for the first time.
The energy violation parameter η_E value is given for the first time.

L. Zhou *et al.*, *Phys. Rev. A* 104, 022822(2021)

Comparison with other results

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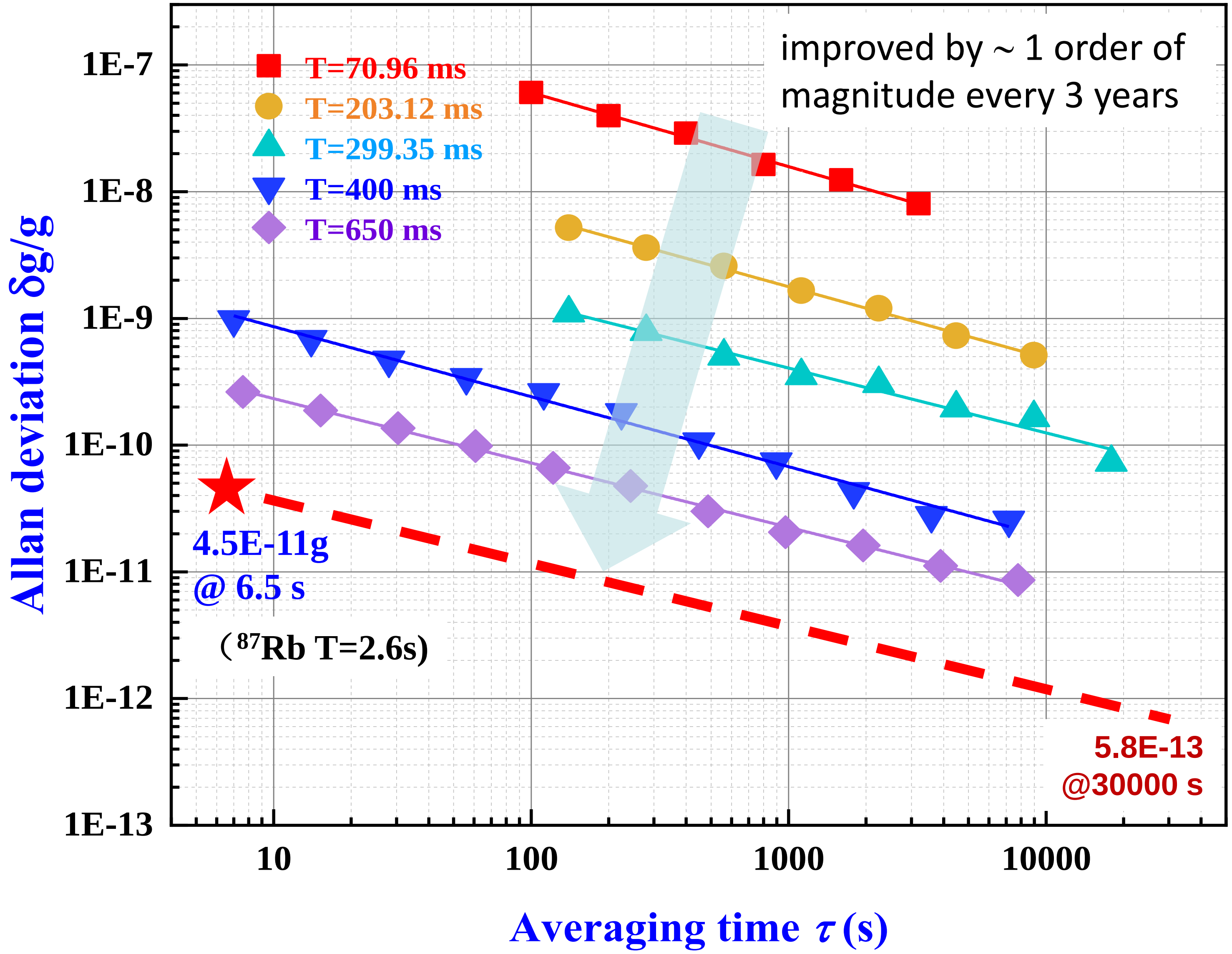
^{39}K-^{87}Rb	mixed		$(0.9 \pm 1.6) \times 10^{-6}$		*AVS Quantum Sci.* (2022)
Rb - Rb	3-2	1.86 GeV	[illegible]		[illegible]
^{85}Rb	2-3	3.04 GHz	$(0.4 \pm 1.2) \times 10^{-7}$	$(0.1 \pm 0.4) \times 10^{-7}$	*Phys. Rev. Lett.*(2004)
^{87}Rb	$m_F = \pm 1$		$(1.2 \pm 3.2) \times 10^{-7}$		*Phys. Rev. Lett.*(2016)
^{87}Rb	1-2	6.83 GHz	$(1.4 \pm 2.8) \times 10^{-9}$	$(0.2 \pm 0.4) \times 10^{-9}$	*Nat. Commun.* (2017)
^{87}Rb	$1\text{-}1 \oplus 2$		$(3.3 \pm 2.9) \times 10^{-9}$		*Nat. Commun.* (2017)
^{87}Rb	1-2	6.83 GHz	$(0.9 \pm 2.7) \times 10^{-10}$	$(0.1 \pm 0.4) \times 10^{-10}$	*Chin.Phys.Lett.*(2020)
^{87}Rb	1-2		$(0.9 \pm 2.9) \times 10^{-11}$		arXiv:2210.08533
^{85}Rb - ^{87}Rb	2-2	1.86 GeV + 6.83 GHz	$\eta_2 = (-0.6 \pm 3.7) \times 10^{-10}$		
^{85}Rb - ^{87}Rb	3-1	1.86 GeV − 3.04 GHz	$\eta_3 = (-2.5 \pm 4.1) \times 10^{-10}$		This work *Phys. Rev. A* (2021)
^{85}Rb - ^{87}Rb	3-2	1.86 GeV + 3.79 GHz	$\eta_4 = (-2.7 \pm 3.6) \times 10^{-10}$		
			$\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$	$(0.0 \pm 0.4) \times 10^{-10}$	

Mass

Spin（F，m_F）

Superposition

Sensitivity Improvement of the Wuhan 10-m AI (2015-)



2015

4WDR method **8E-9**

L. Zhou, S.T. Long et al. *Phys. Rev. Lett.* **115**, 013004 (2015)

2018

Coriolis effect compensation **5.1E-10**

W. T. Duan, C. He et al. *Chin. Phys. B* **29**, 070305(2020)

2020

AC Stark shift Optimization **7.3E-11**

L. Zhou, C. He et al. *Phys. Rev. A* **104**, 022822 (2021)

2022

Shear phase readout **2.5E-11**

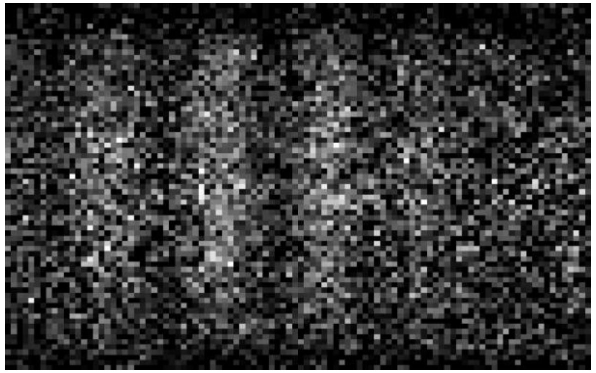
L. Zhou, S. T. Yan et al. *Frot. Phys.* **10**, (2022)

S. T. Yan et al. *Phys. Rev. A* **108**, 063313 (2023)

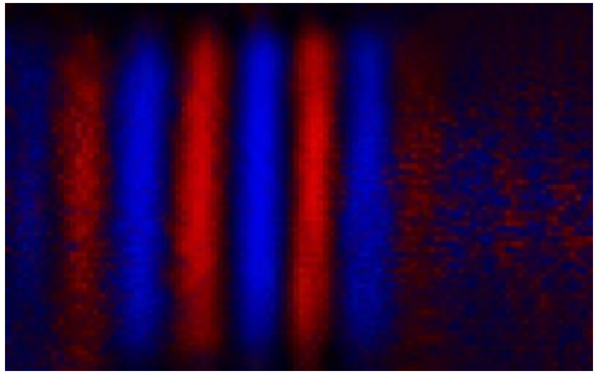
2023

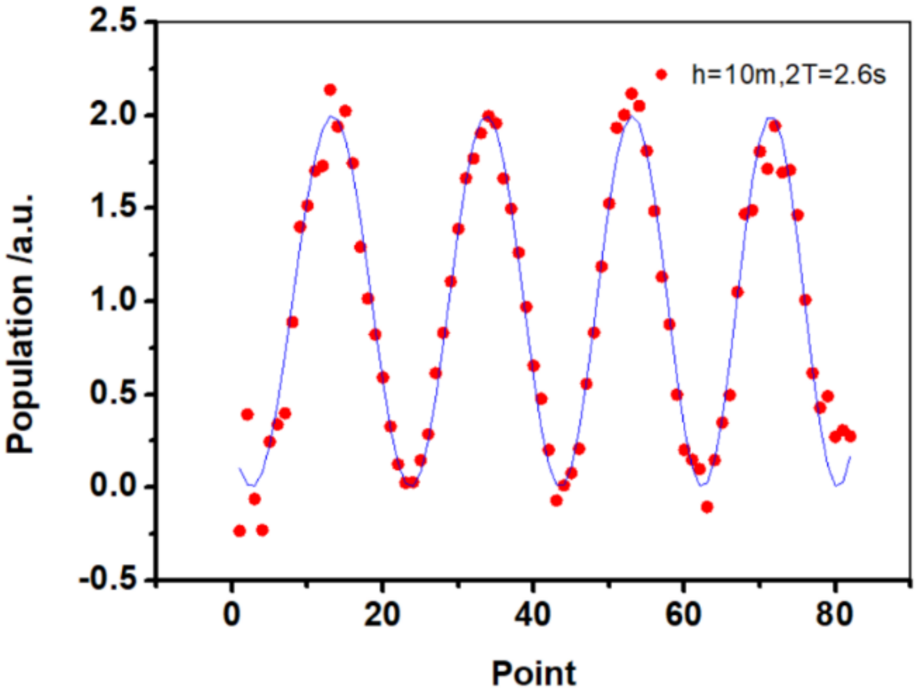
Gravity gradient compensation **8.6E-12**

Fringe observed in the 10-m AI



Shear Interference Detection





Interference fringe
with T=1300 ms

$$\frac{\delta g}{g} = \frac{\delta \phi}{kgT^2} = 4.5\times10^{-11} \,/\,\text{shot}$$

AI height	Evolution time	WEP test precision
10 m	2T = 2.6 s	~ 10^{-13} (expected)

L. Zhou *et al.*
Front. Phys. **10**, 01 (2022)

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CAP – AMP – CAS

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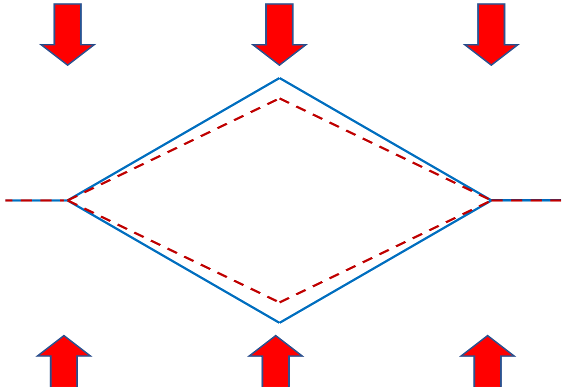
AI in space

Advantages in space

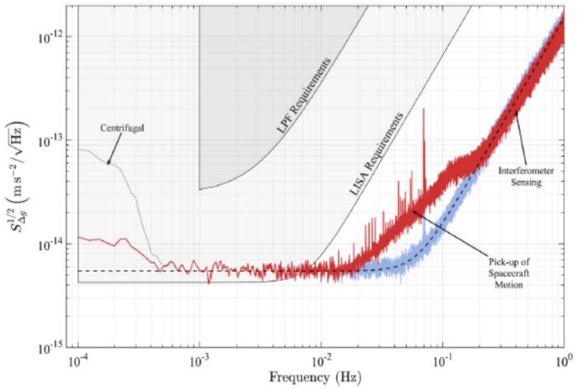
Long Interference time



1.2 m Separation of the wave packet for T=50 s

Mainly limited by the temperature of the atom cloud

Extremely quiet vibration environment



Residual acceleration
10^{-11}~10^{-15} m/s^2
(Drag free control)

Much better than ground

Challenges

- ◆Requirement for the spacecraft

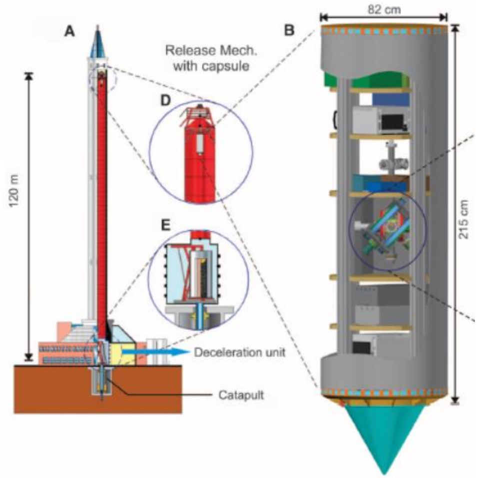
(Residual acceleration, structural stability, Residual magnetization control)

- ◆Vibration during rocket launch
- ◆Vacuum environment
- ◆Reliability, Long lifetime
- ◆High-energy particle radiation in space

M. Armano et al. (LISA Pathfinder) PRL 116, 231101 (2016)

AI taking off from the ground

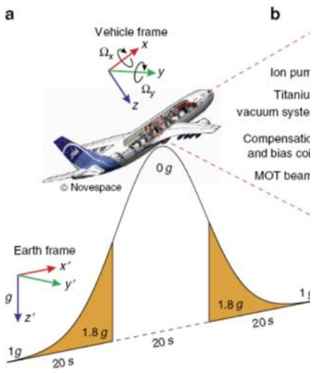
Dropping tower



- Bose-Einstein Condensation in Microgravity(2010)
- Interferometry with Bose-Einstein Condensates in Microgravity(2013)

T. van Zoest, et al. Science 328, 1540,2010
H. Muntinga, et al. PRL 110, 093602,2013

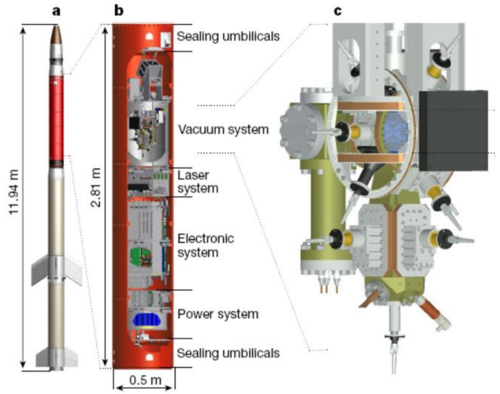
Parabolic flying plane



- Detecting inertial effects with airborne matter-wave interferometry(2011)
- Dual matter-wave inertial sensors in weightlessness(2016)

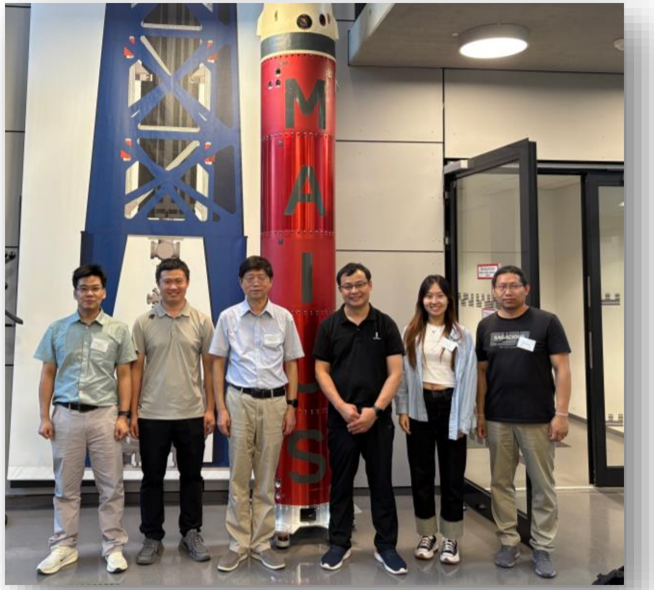
R. Geiger, et al. NATURE COMMUNICATIONS, 2:474, 2011
Brynle Barrett, et al. NATURE COMMUNICATIONS, 7:13786, 2016

Sounding rocket



- Space-borne Bose–Einstein condensation for precision interferometry (2018)
- Ultracold atom interferometry in space(2021)

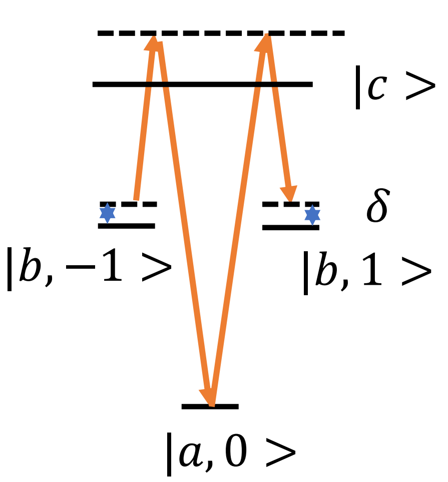
Dennis Becker, et al. NATURE, 562, 18, 2018
Maike D. Lachmann, et al. NATURE COMMUNICATIONS, 12:1317,2021

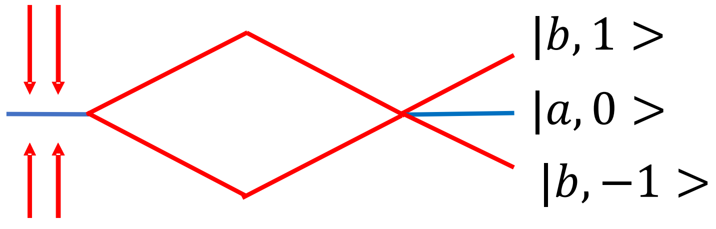


The interference scheme

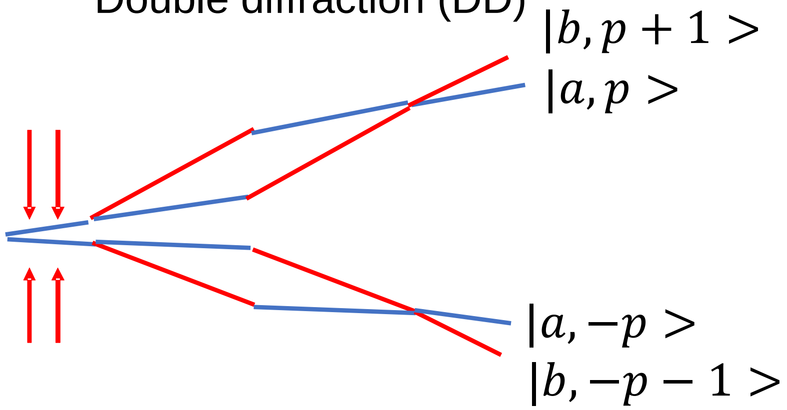
Problem1: lacking initial velocity of the atom cloud

Energy levels of the Raman transition are degenerate





Double diffraction (DD)



Double single diffraction(DSD)

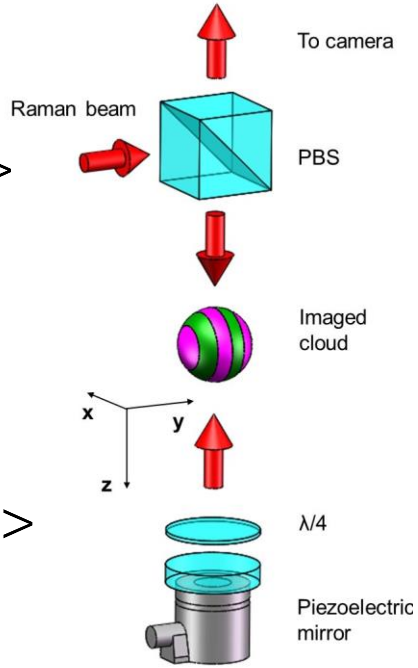
Two interference schemes can be transformed by changing the frequency of the Raman laser.

N. Malossi, et al. PRA 81, 013617 (2010)

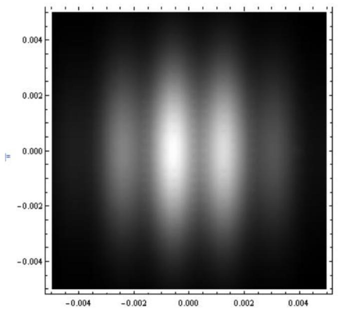
Brynle Barrett, et al. NATURE COMMUNICATIONS, 7:13786, 2016

Problem2: Both DD and DSD are immune to the phase of the Raman laser in space

One can not obtain the interference fringe by scanning the phase of the Raman laser.



The point source interferometry (PSI) is an ideal method to create spatial fringe in space.



spatial fringe

Special design:

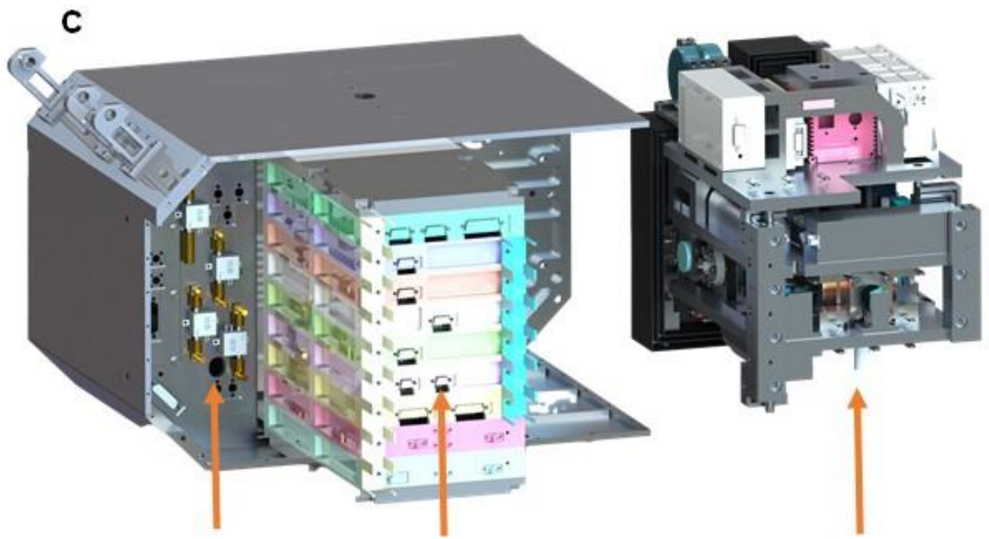
The direction of the Raman laser is consistent with the direction of imaging to avoid reducing the fringe's contrast

Susannah M. Dickerson, et al. PRL 111, 083001 (2013)

Gregory W. Hoth, et al. APL 109, 071113 (2016)

Design of the payload

System configuration

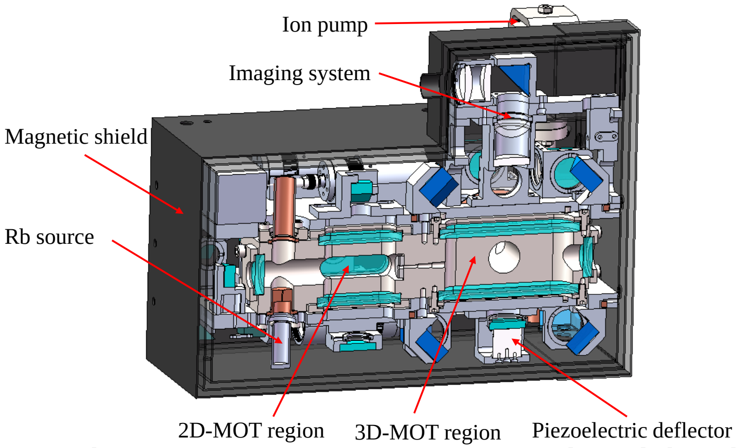


Optical system Electric system Physical system

Physical system： 31 cm×20cm×25 cm
Optical system： 24 cm×10cm×25 cm
electric system： 24 cm×14cm×25 cm
Total： 33 cm×46 cm×26 cm
Weight： 37 kg

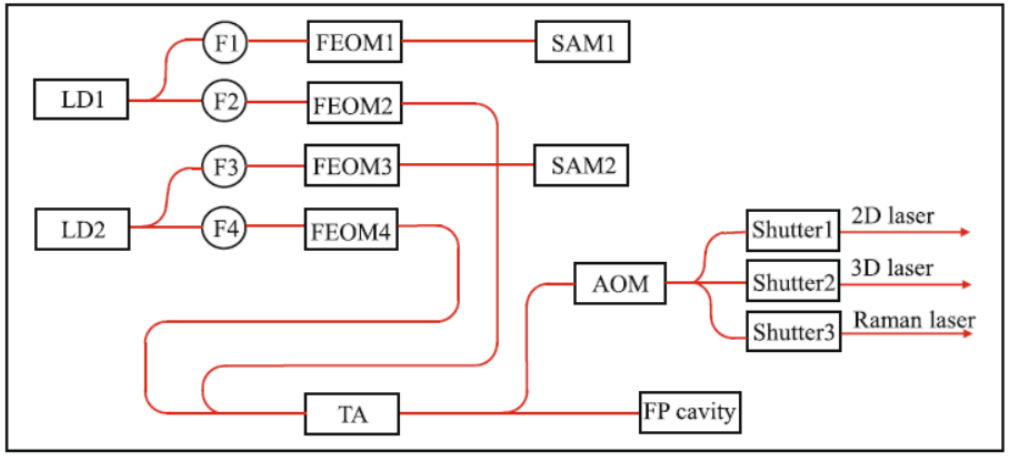
M. He, et al. npj Microgravity 9, 58 2023

Physical system



2D+3D chamber， Three layers of magnetic shielding ，
Integrated IMU

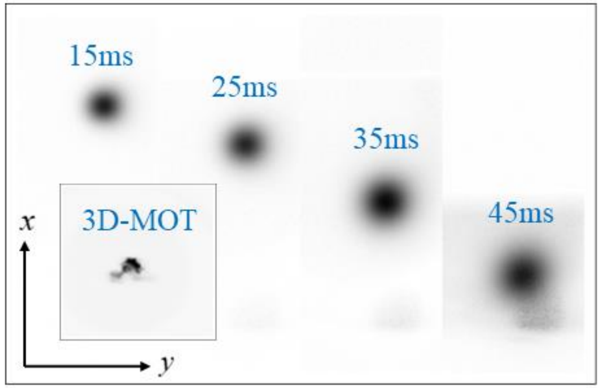
Optical system



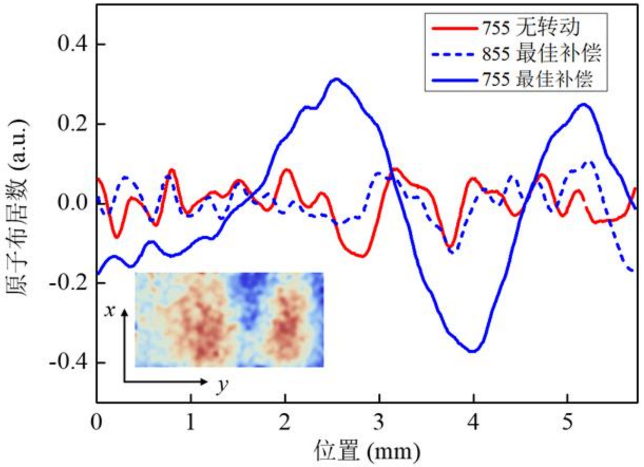
Sideband frequency stabilization, sidebands modulation,
Fused silica optical bench

Ground test

Function test



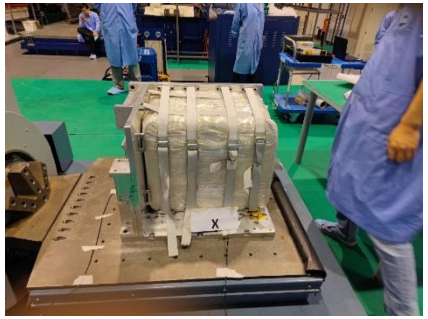
Cold atom preparing: 10^8, 5 μK



Atom interference： 5 ms

Environmental test

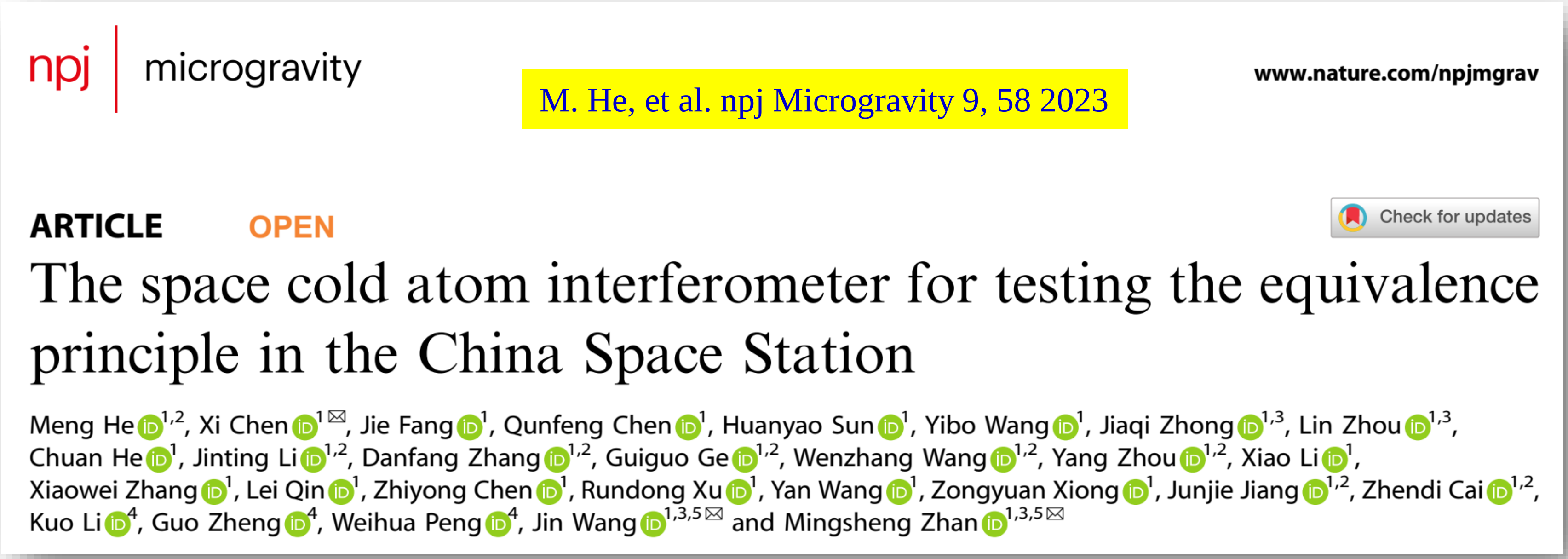
Thermal Cycle



Vibration test

Other tests

- electromagnetic compatibility
- Medical Science
- Ergonomics



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ARTICLE OPEN

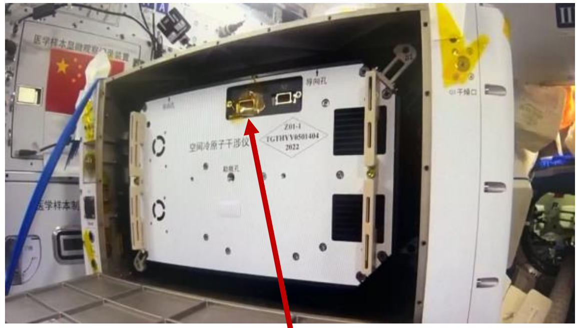
Check for updates

The space cold atom interferometer for testing the equivalence principle in the China Space Station

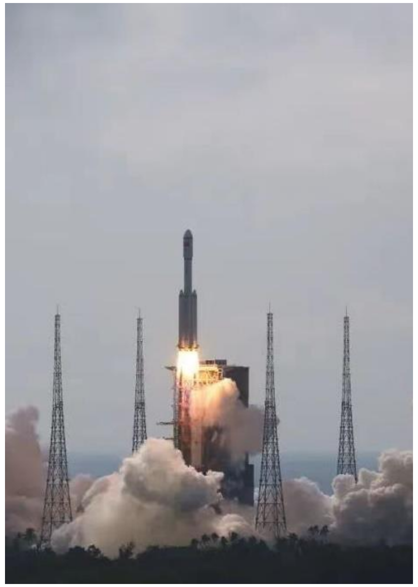
Meng He[1,2], Xi Chen[1]✉, Jie Fang[1], Qunfeng Chen[1], Huanyao Sun[1], Yibo Wang[1], Jiaqi Zhong[1,3], Lin Zhou[1,3], Chuan He[1], Jinting Li[1,2], Danfang Zhang[1,2], Guiguo Ge[1,2], Wenzhang Wang[1,2], Yang Zhou[1,2], Xiao Li[1], Xiaowei Zhang[1], Lei Qin[1], Zhiyong Chen[1], Rundong Xu[1], Yan Wang[1], Zongyuan Xiong[1], Junjie Jiang[1,2], Zhendi Cai[1,2], Kuo Li[4], Guo Zheng[4], Weihua Peng[4], Jin Wang[1,3,5]✉ and Mingsheng Zhan[1,3,5]✉

Dual-species Space Atom Interferometer

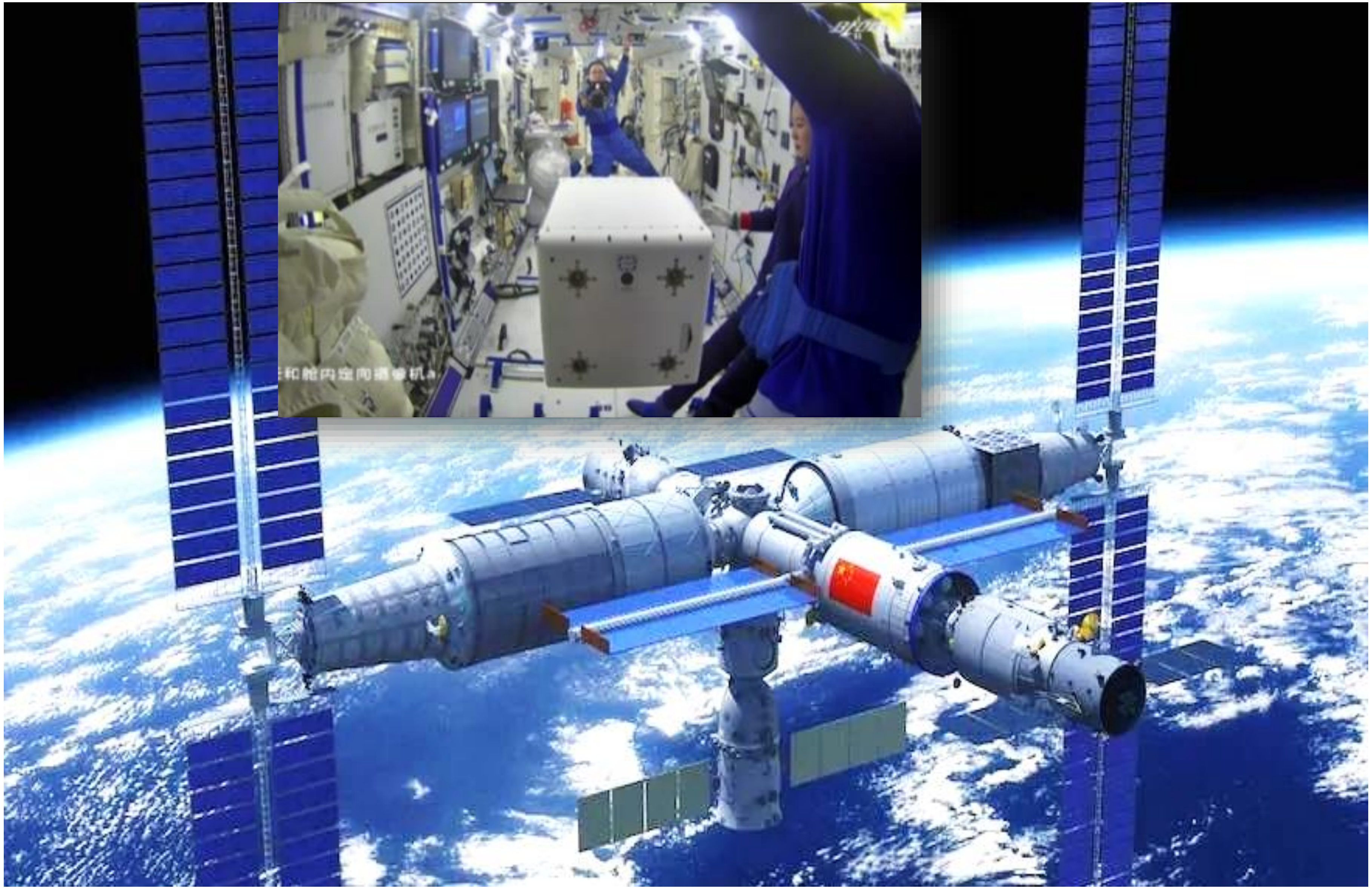
WEP test in China Space Station



The Space AI in the HMLR

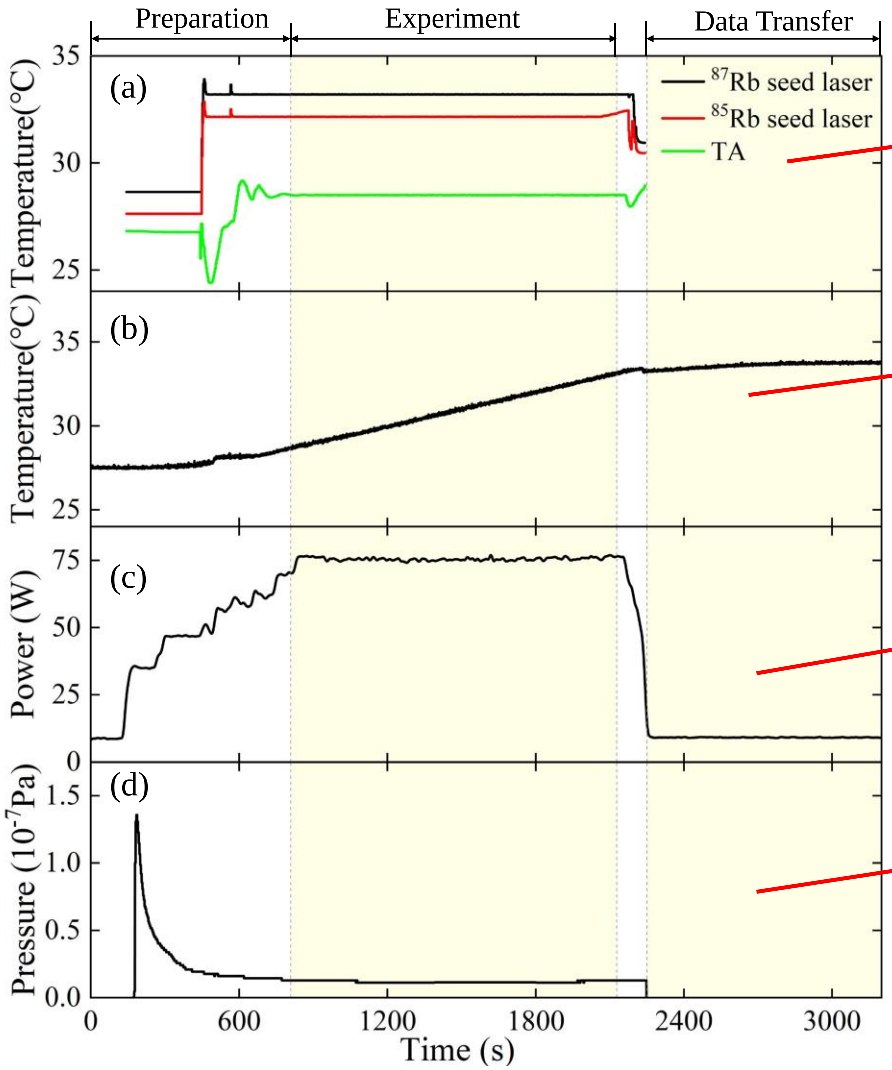


Tianzhou-5 cargo spacecraft
Launched: Nov. 12, 2022



In orbit test

Intermittent operation mode, each experiment lasts for 50-70 min



Temperature control: Stabilized in 5 minute

Temperature: 0.2 ˚C /min

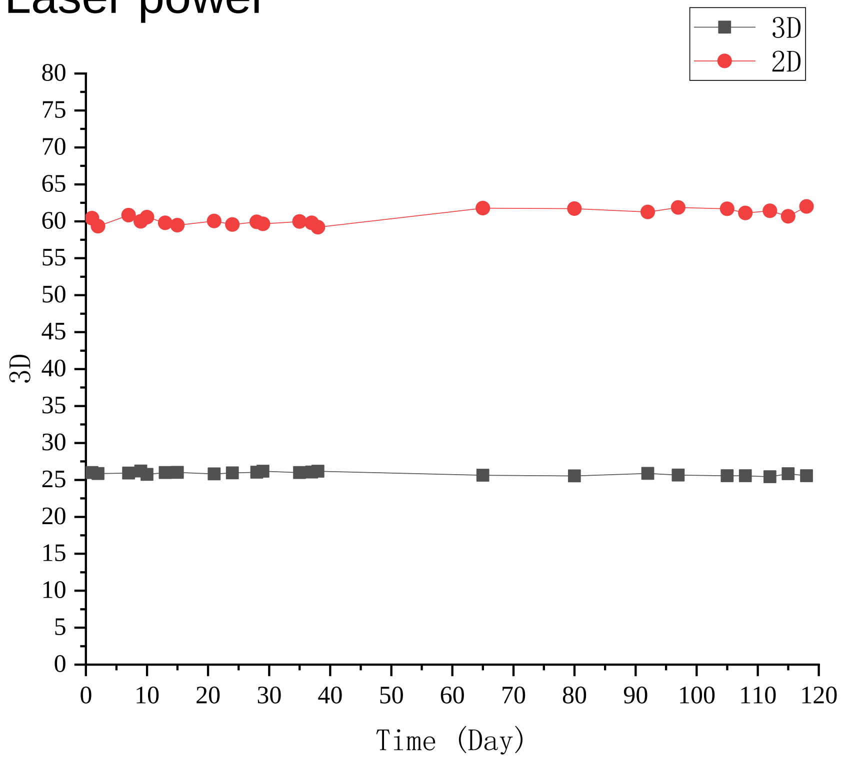
Power: Peak power 75 W

Vacuum: Stabilized in 10 minute, to 10^{-8}Pa

In orbit test

Laser power stability

In orbit monitor the power of the 2D and 3D Laser power



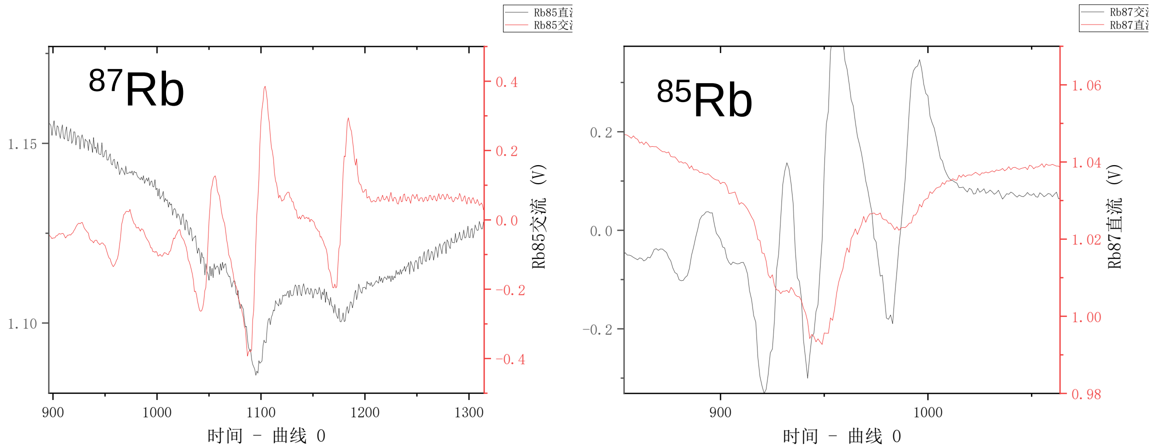
Fluctuation: <1.5% for more than 100 days

Laser frequency locking

In orbit realization of the auto frequency lock of the two seed lasers

$$Corr(m) = \sum_n \frac{x(n)y(n-m)}{\sqrt{\sum_k x^2(k) \sum_k y^2(k)}}$$

Qi-Xue Li, et al. Optics and Lasers in Engineering 126 (2020) 105881



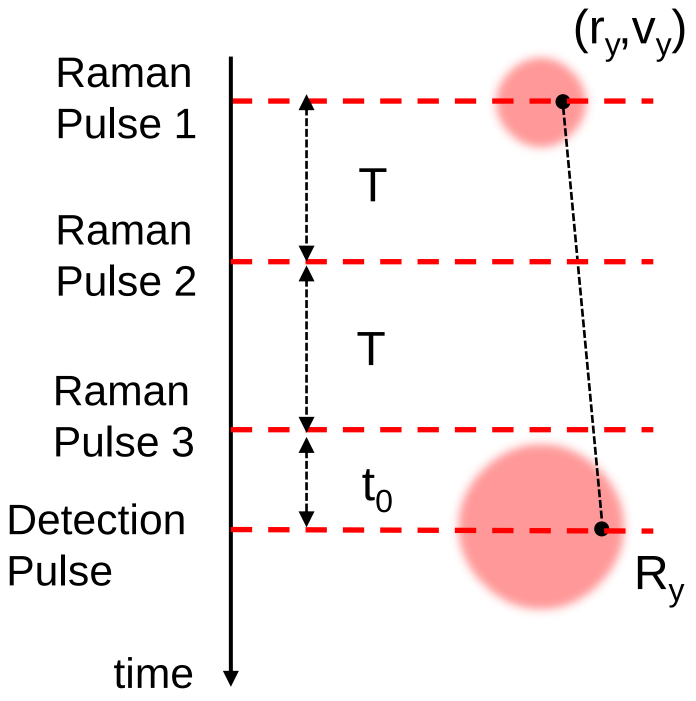
Templates of the SAS for Rb atom

success rate： 100% for Rb^{85} 95% for Rb^{87}

Frequency fluctuation after locking

0.94 MHz for Rb^{85} 0.80 MHz for ^{87}Rb

Optimizing the Raman laser's angle

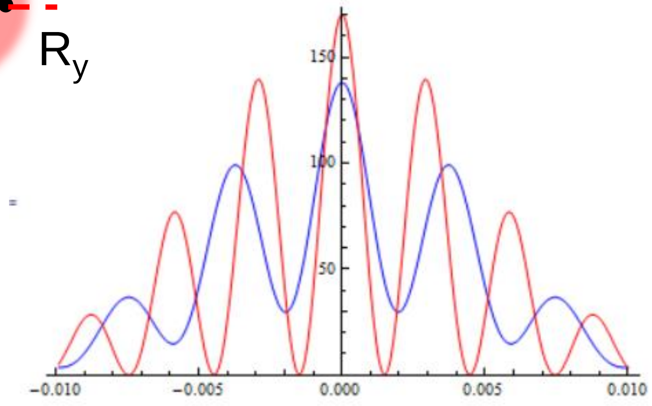


Problem: what we measured is the position of atom at the detection time, but the phase is related to the position and velocity of atom at the time of the first Raman pulse

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

$$R_j = r_j + v_j(2T + t_0)$$

The distribution of the atom will influence the spatial frequency of the fringe and lower its contrast.



Blue: rotation with a fix rate $\theta_{i,3} = -\theta_{i,1}$

Red: rotation according to Eq. (1)

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

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

$$f_{i0} = \frac{2k_{eff}}{2T + t_0}(\theta_{j,3} T + \Omega_j T^2),$$

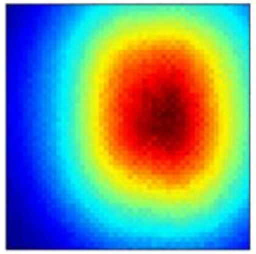
Eliminate the offset and distributions of the position and velocity of the atom cloud and maximize the fringe's contrast.

Extracting the spatial fringe from the background

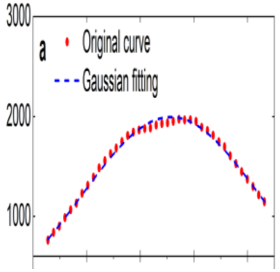
Problem: the contrast of the fringe is low, and the expression of the envelop is unknow.

Design a scheme to extract the fringe

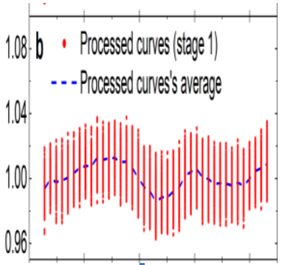
1.Origin PSI image



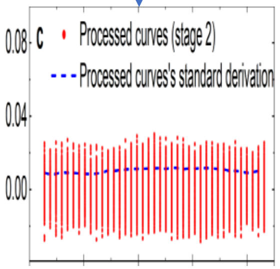
2.Averaged to 1D



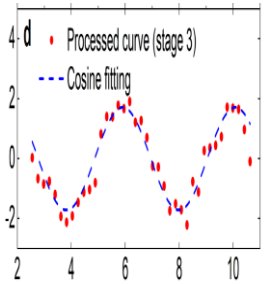
3.Divided by Gaussian fitting



4.divided by the curves' average



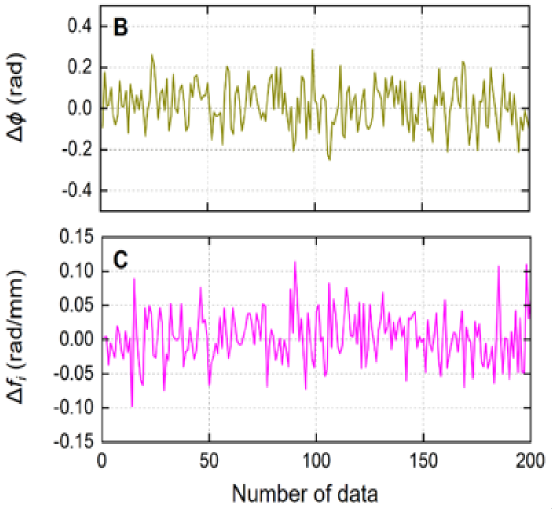
5.divided by the curves' standard derivation



Check this scheme by numeral simulation

$$R_j = amp_{noise} + f(x)A \cdot Exp[(-x - x0)^2 / \sigma x^2]*$$
$$(1 + g(x)C \cdot Cos[\omega(x - x0) + pha_{noise}])$$

f(x) represents the offset and g(x) represents the amplitude



set value VS fitted value

phase difference: $\Delta\phi$=16±109 mrad

spatial frequency difference: Δf_i=3±38 mrad/mm.

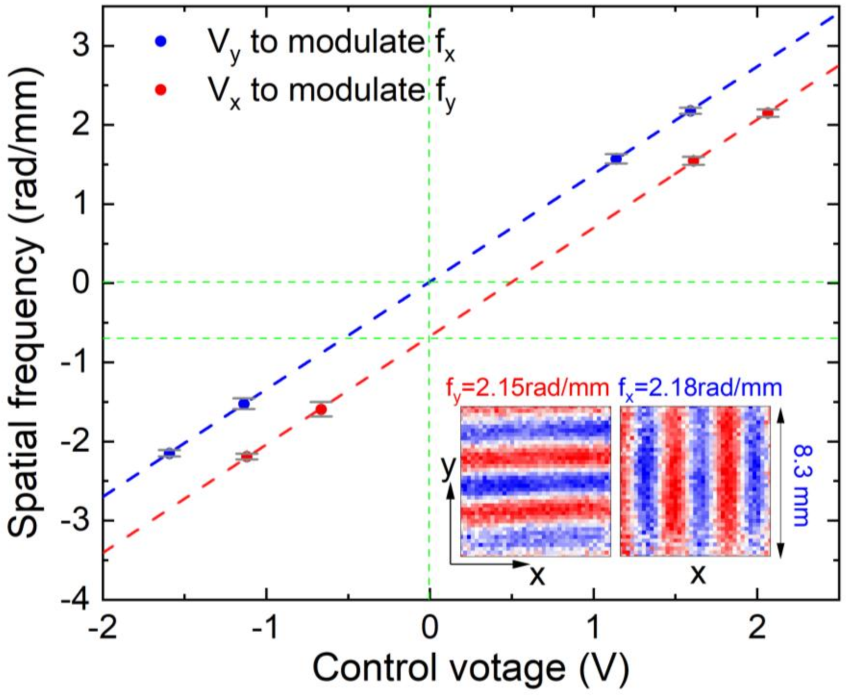
The method has no bias and near optimal

Calibration the angle of the Raman laser in orbit

Problem: The rotation is extract from the PSI fringe's spatial frequency, the spatial frequency is closely relative to angle of the mirror

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

How to calibrate the angle of the mirror in orbit?



By changing the rotation angle and measure the spatial frequency, one the separate the rotation angle (slope) and the rotation rate(offset).

$$\alpha_x = 116.75 \pm 0.41\ \mu\text{rad/V}$$
$$\alpha_y = 115.21 \pm 0.20\ \mu\text{rad/V}.$$

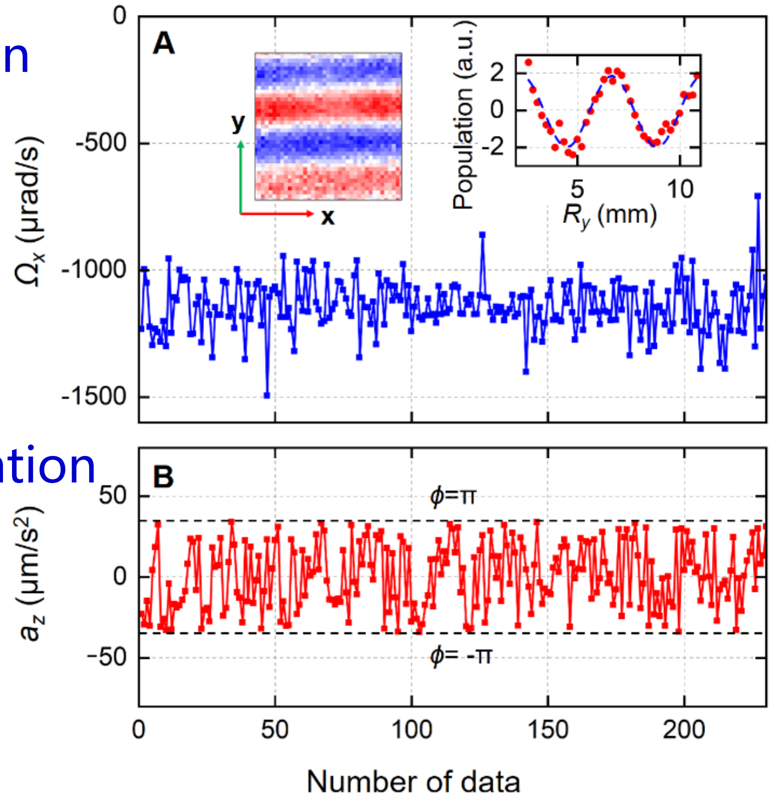
$$\Omega_x = (-115.3 \pm 1.2) \times 10^{-5}\ \text{rad/s},$$
$$\Omega_y = (-0.37 \pm 0.57) \times 10^{-5}\ \text{rad/s}.$$

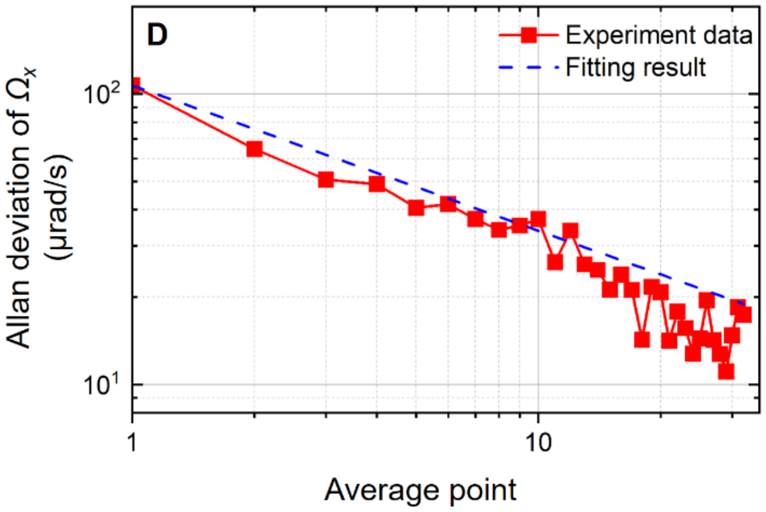
Rotation and acceleration measurement

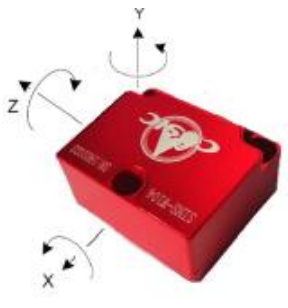
Rotation and acceleration measurement with T=75 ms

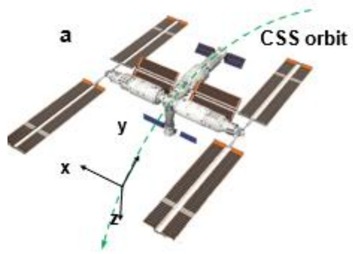
Rotation

Acceleration





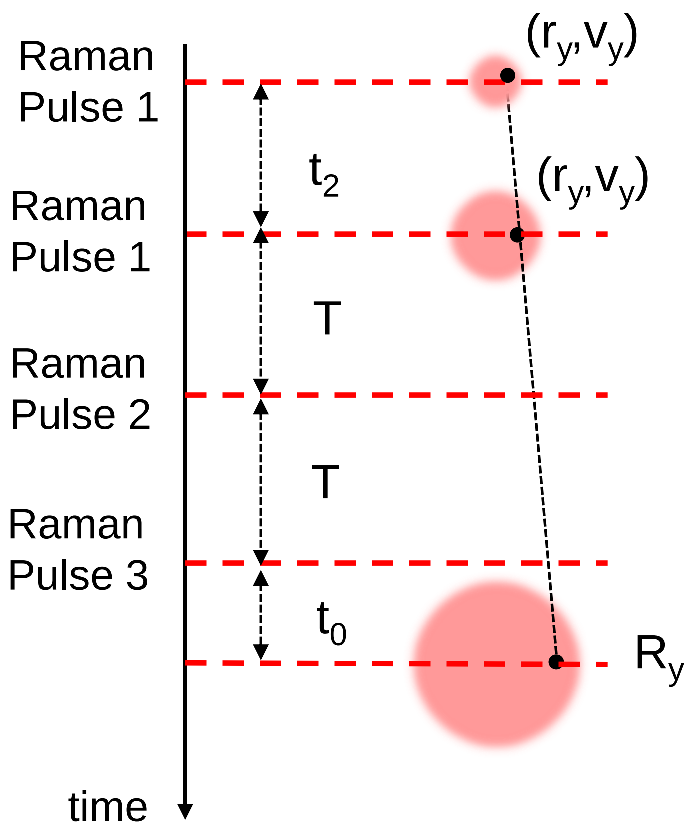




Resolution for rotation: 1.7 $\times 10^{-5}$ rad/s for 32 PSI measurements

Resolution for acceleration: 1.0$\times 10^{-6}$ m/s^2 for one PSI measurement

Systemic effect estimation



Exact formulars of the phase and spatial frequency of PSI

$$\begin{cases} \phi = k_{eff} a_z T^2 + \sum_i k_{eff} [2\Omega_i v_j T^2 + \theta_{i,1} r_j + \theta_{i,3}(r_j + 2v_j T)] \\ R_j = r_j + v_j (2T + t_0) \end{cases}$$

↓ Integrated over the atom cloud's distributions

$$\phi_I = \phi_o + k_{eff} \sum_i \delta_i \left(\frac{t_0}{t} + \frac{t - t_0}{t} \frac{{\sigma_{\rho i}}^2}{{\sigma_{vi}}^2 t^2 + {\sigma_{\rho i}}^2} \right) R_i \Delta\theta_j + k_{eff} \sum_i \delta_i \frac{t - t_0}{t} \cdot \frac{{\sigma_{vi}}^2 t^2 \rho_{i0} - {\sigma_{\rho i}}^2 v_{i0} t}{{\sigma_{vi}}^2 t^2 + {\sigma_{\rho i}}^2} \Delta\theta_j$$

$$f_i = f_{io} + \Delta f_i$$

$$f_i + k_{eff} \left(\frac{t_0}{t} + \frac{t - t_0}{t} \frac{{\sigma_{\rho i}}^2}{{\sigma_{vi}}^2 t^2 + {\sigma_{\rho i}}^2} \right) \Delta\theta_j.$$

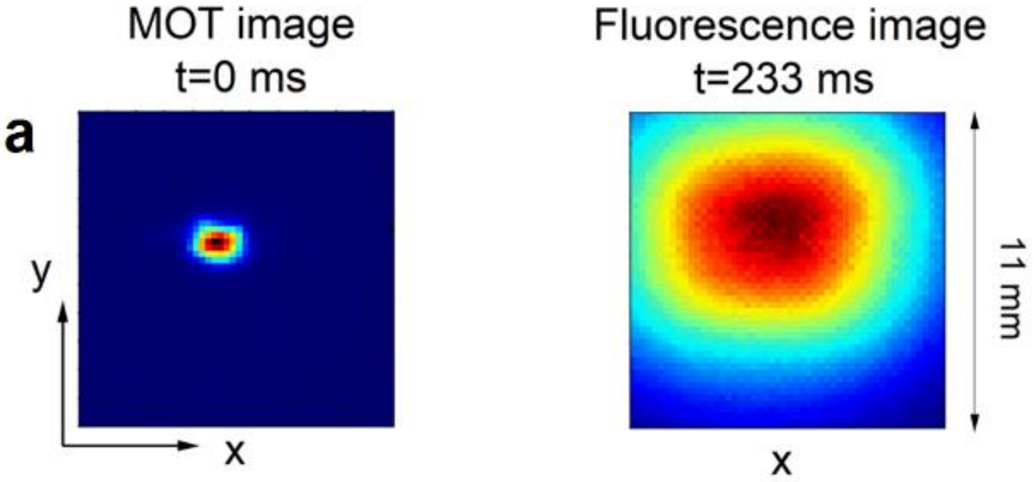
Acceleration and rotation can be accuracy extracted through the above two equations.

Systemic effect estimation

One should measure or estimate all parameters and their uncertainty to estimate the value of rotation.

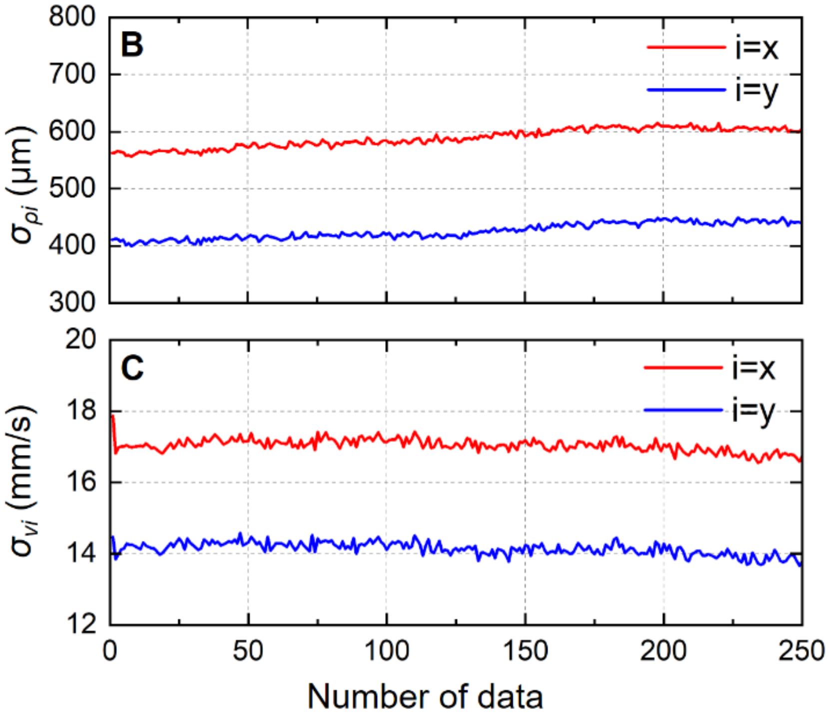
One example: velocity and position distributions of the atom cloud.

$$F(\rho_i, v_i) = N_1 e^{-\frac{(\rho_i-\rho_{i0})^2}{2\sigma_{\rho i}^2}} e^{-\frac{(v_i-v_{i0})^2}{2\sigma_{vi}^2}}$$



Position and velocity distributions are measured by the TOF method.

Tx=2.94±0.06 μK
Ty=2.02±0.05 μK.



Position distribution

x: 0.590 mm
y: 0.427 mm

Velocity distribution

x: 17.04 mm/s
y: 14.13 mm/s

Systemic effect estimation

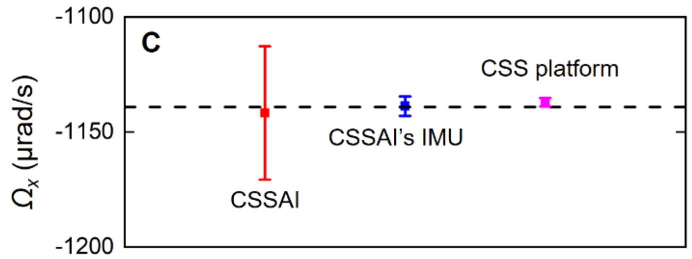
Rotation measurement error estimation

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

CSSAI (-114.2±2.9)$\times 10^{-5}$ rad/s

CSSAI's IMU (-113.87±0.41)$\times 10^{-5}$ rad/s

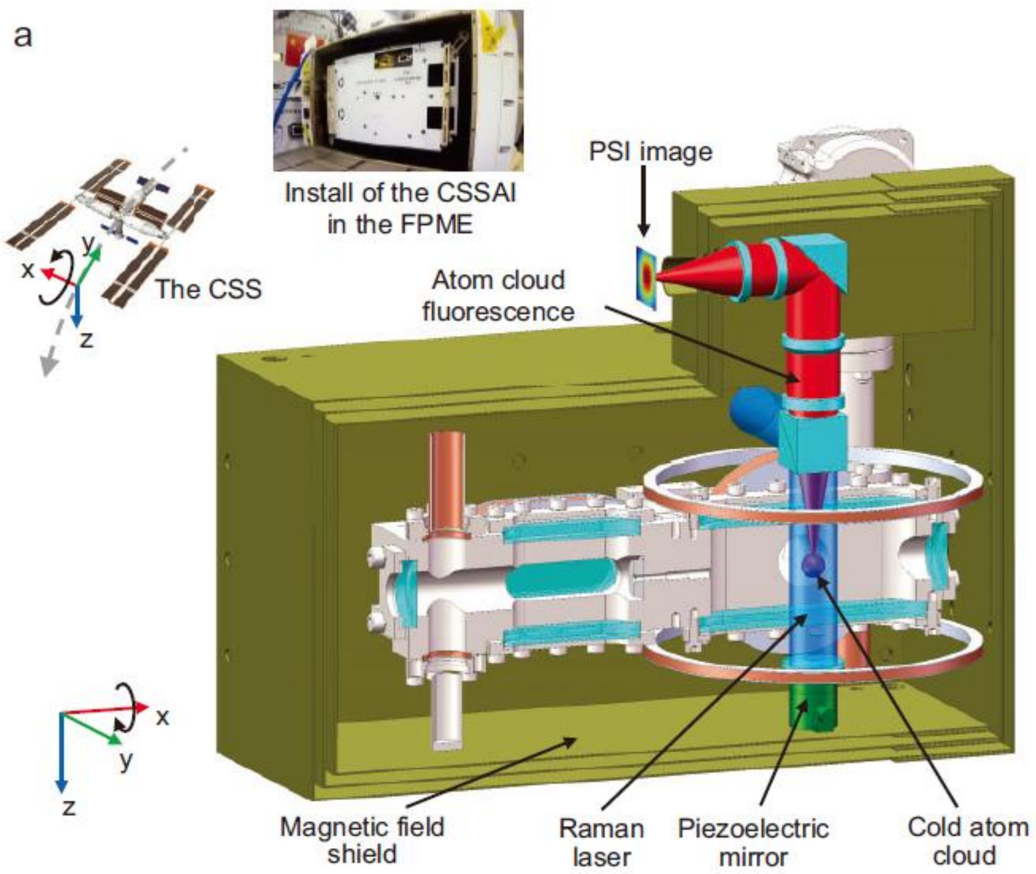
CSS platform (-113.70±0.18)$\times 10^{-5}$ rad/s



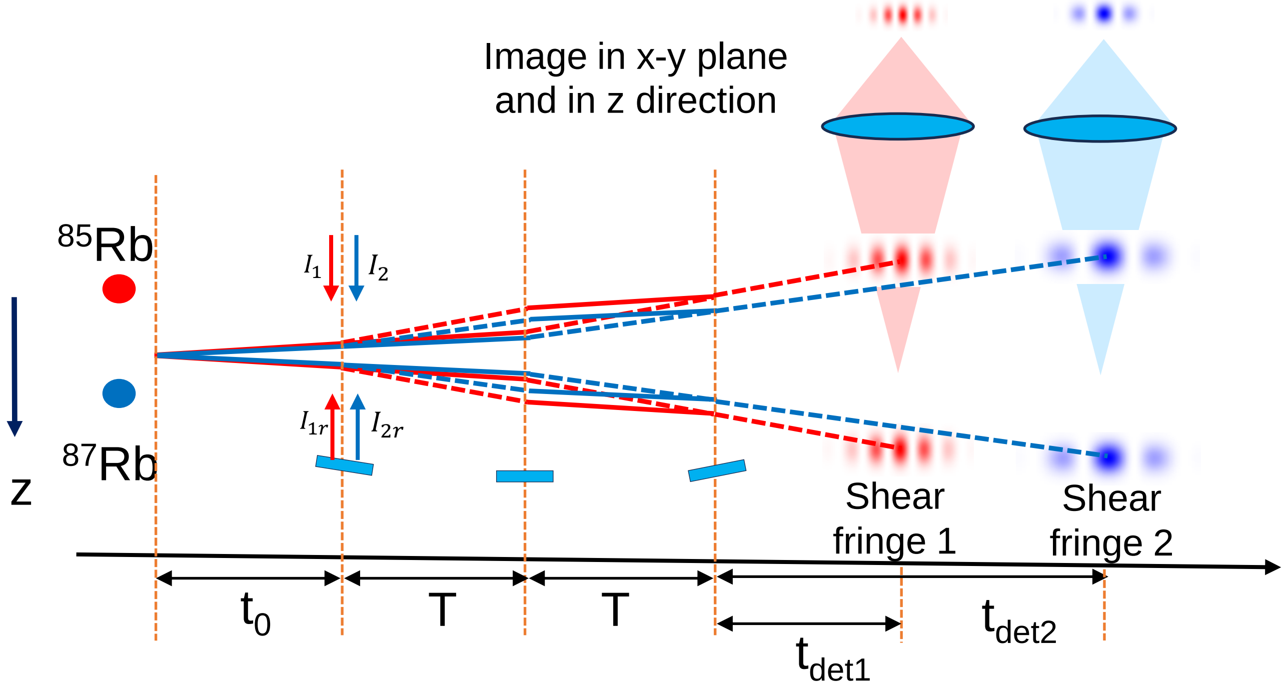
J.T. Li, et al, Realization of a cold atom gyroscope in space. *Nat. Sci. Rev.* 12(4), nwaf012 (2025)【arXiv:2405.20659】

The CSSAI and the dual-species atom interference configuration

CSS and its coordinate



Dual-species atom interference with ^{85}Rb and ^{87}Rb



Interference scheme:

Double single diffraction(DSD)[1] & point source interferometry (PSI)[2]

1. Brynle Barrett, et al. NATURE OCMMUNICATIONS, 7:13786, 2016

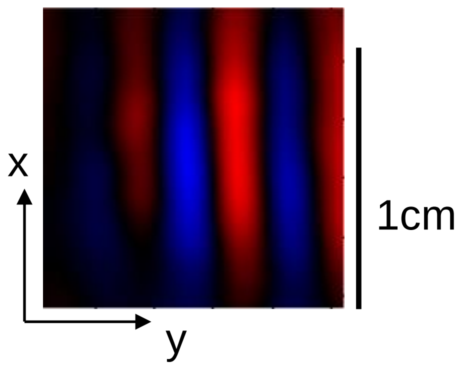
2. Susannah M. Dickerson, et al. PRL 111, 083001 (2013)

Synchronous operation of the dual-species CAIs in space

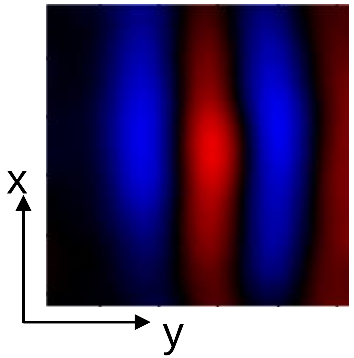
- Synchronously obtain interference fringes for Interference Time: T=50 ms

Principal component analysis (PCA) of the 2D shear interference image

^{85}Rb



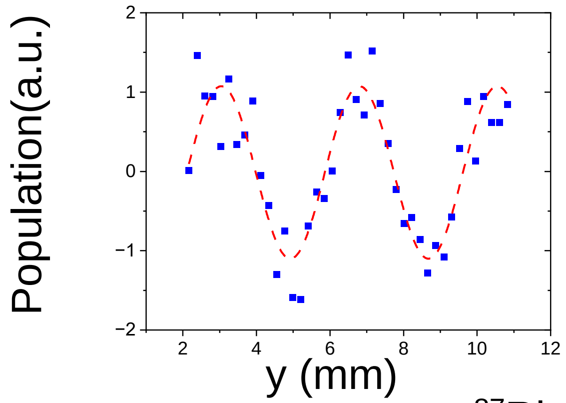
^{87}Rb



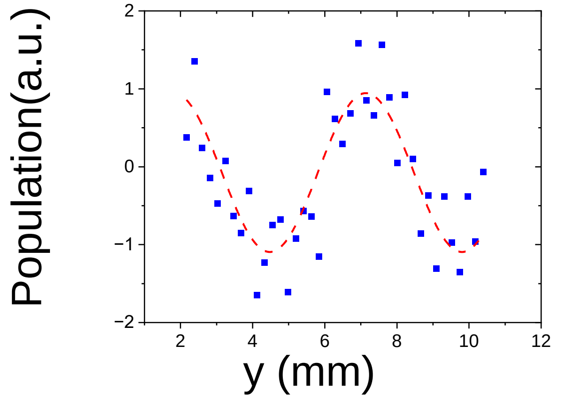
Each for about 400 images

Averaged and normalized to 1D interference fringe

^{85}Rb



^{87}Rb



Each fringe for 1 image

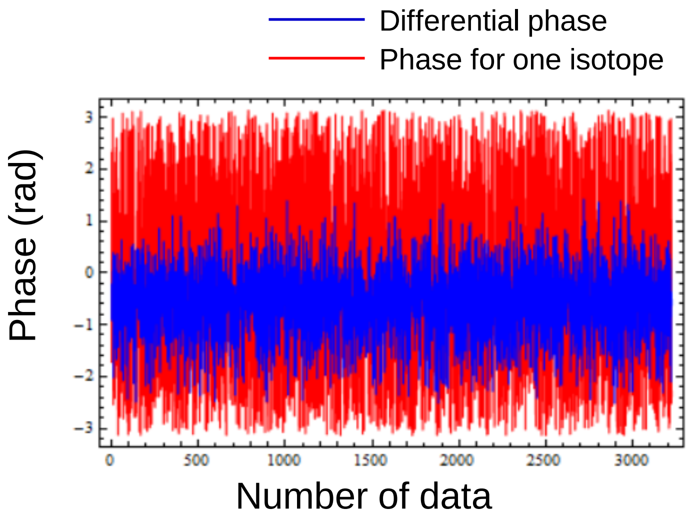
Extracting the phases and spatial frequencies of the fringes

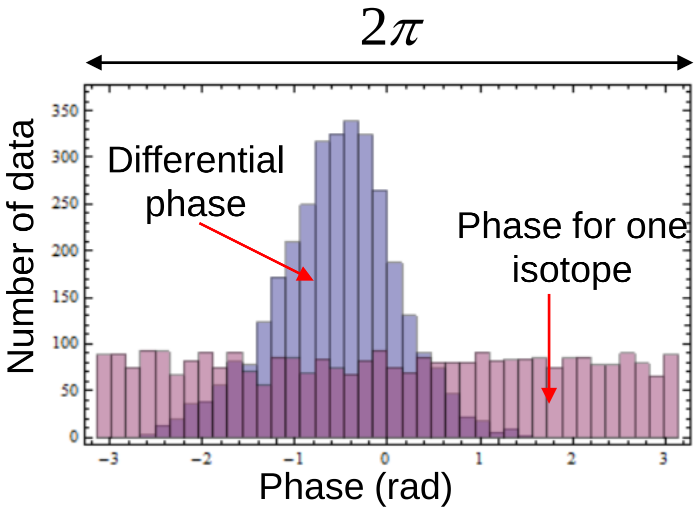
- Phase resolution: 0.23 rad for 1 image
- Equivalent acceleration measurement resolution: 5.7×10^{-6} m/s^2

Differential phase extraction and vibration noise suppression

- Differential phase measurement for over 3000 images pairs.

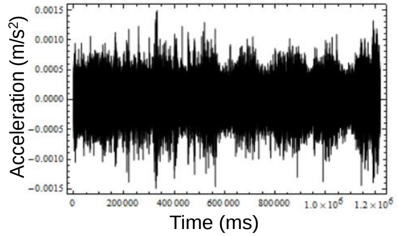
Measurement phase & differential phase



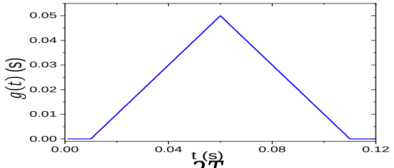


Differential phase standard deviation: 0.65 rad

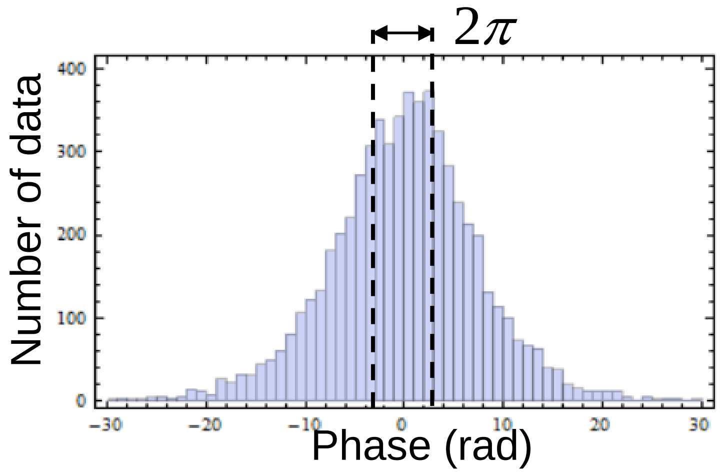
Recorded acceleration a(t) by classical accelerator



Acceleration sensify function g(t)



$$\phi = k_{eff}\int_0^{2T} a(t)g(t)dt$$

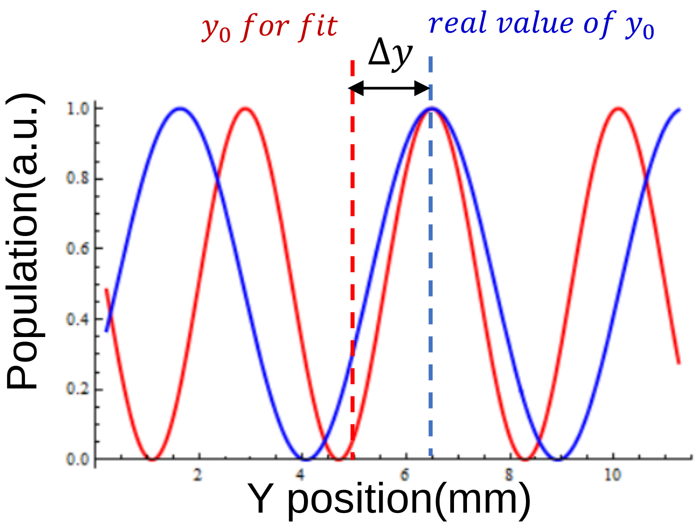


Phase standard deviation: 8.4 rad

Vibration noise is suppressed by at least 13 times

Switching method for the fluorescence detection time sequence

- The spatial frequencies of the two interference fringes are different. An offset of the Sine fitting position will cause an offset of the differential phase.



$$P_1 = 1 + cos\,[\omega_1(y - y_0) + \phi_{01}]$$

$$P_2 = 1 + cos\,[\omega_2(y - y_0) + \phi_{02}]$$

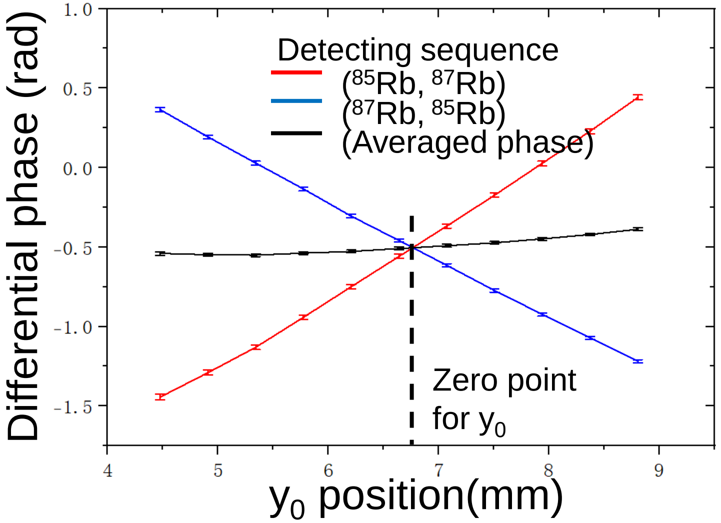
$$\Delta\phi = (\omega_1 - \omega_2)\Delta y$$

Problem: The real value of y_0 is the position of tilt mirror's rotation axis, but we do not know where it is exactly.

Method: we propose a switching methods for the fluorescence detection

	detection1	detection2	Measured differential phase
Experiment 1	 ^{85}Rb	 ^{87}Rb	$\Delta\phi_1$
Experiment 2	 ^{87}Rb	 ^{85}Rb	$\Delta\phi_2$

$$\Delta\phi = (\Delta\phi_1 + \Delta\phi_2)/2$$

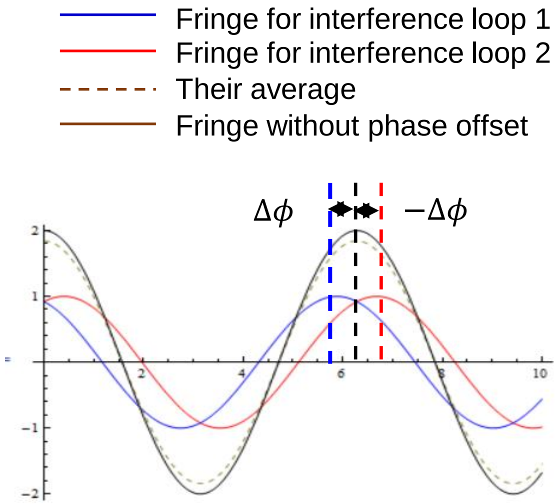


By using this switching and averaging method, the differential phase is not related to the offset of y_0. And we can calibrate the real value of y_0.

Switching method for the two-photon detuning

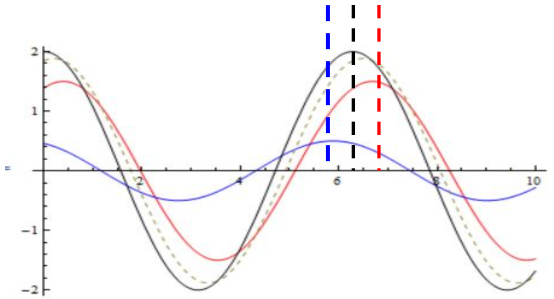
- The double single diffraction (DSD) interference method can eliminate the wavevector-independent phase, but a breaking of the symmetry of the interference loops will cause residual phase offset.

Case 1: symmetric



No phase offset

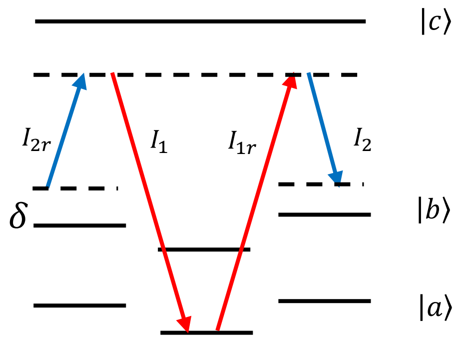
Case 2: asymmetric

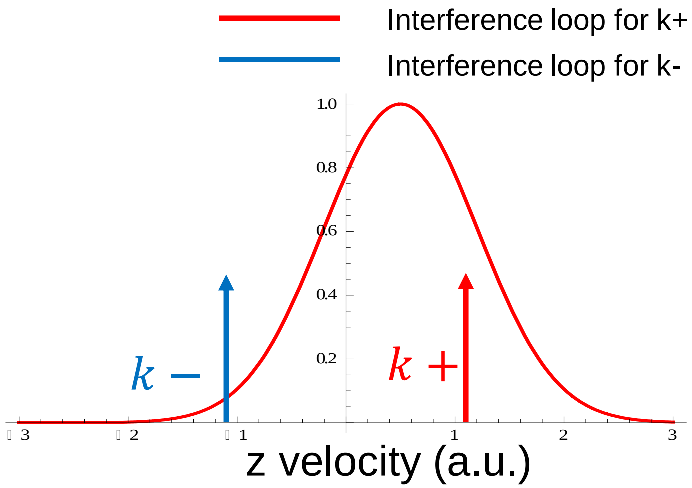


Residual phase offset exist

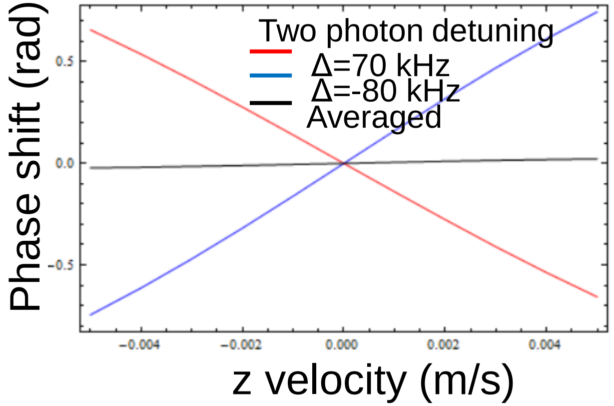
Problem: If the atom cloud has certain velocity along the z direction. it will break the symmetry of the two interference loops.

Method: Switching the signal of the two-photon detuning δ





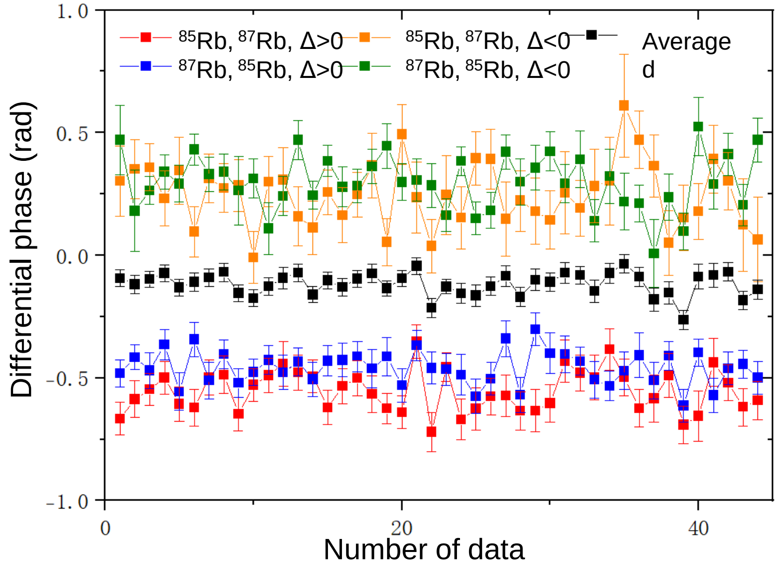
Simulated calculation result (assuming a wavevector-independent phase of 1rad)



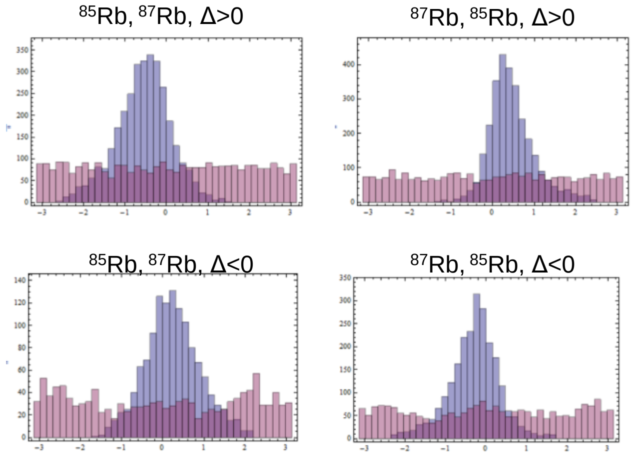
suppress phase offset by a factor of 30

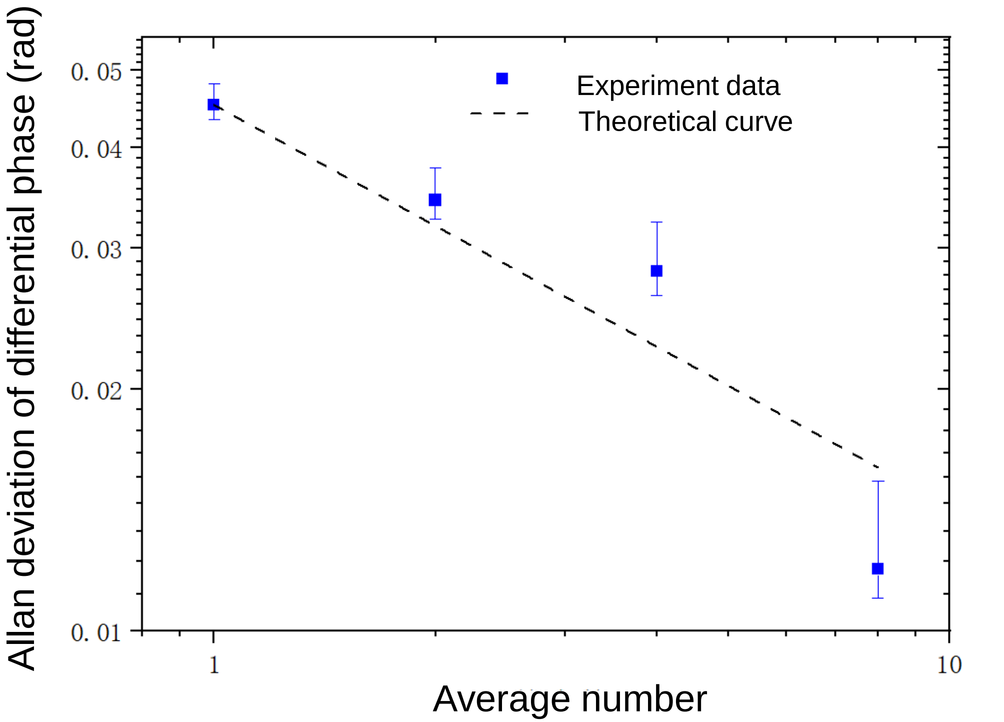
Long-term differential phase measurements with T=50 ms

- We carried out long-term differential phase measurements with T=50 ms. The data is collected from August 2024 to June 2025. Four kinds of experiments are carried out and then averaged.



Phase distribution





The averaged differential phases have a mean value of -0.117 rad and a standard deviation of 0.046 rad. The Allan deviation of the averaged differential phase is 0.012 rad for an average number of 8 (about 80 minutes in time), which corresponds to an EP test resolution of 3.40×10^{-8}.

Error estimation of the differential phase

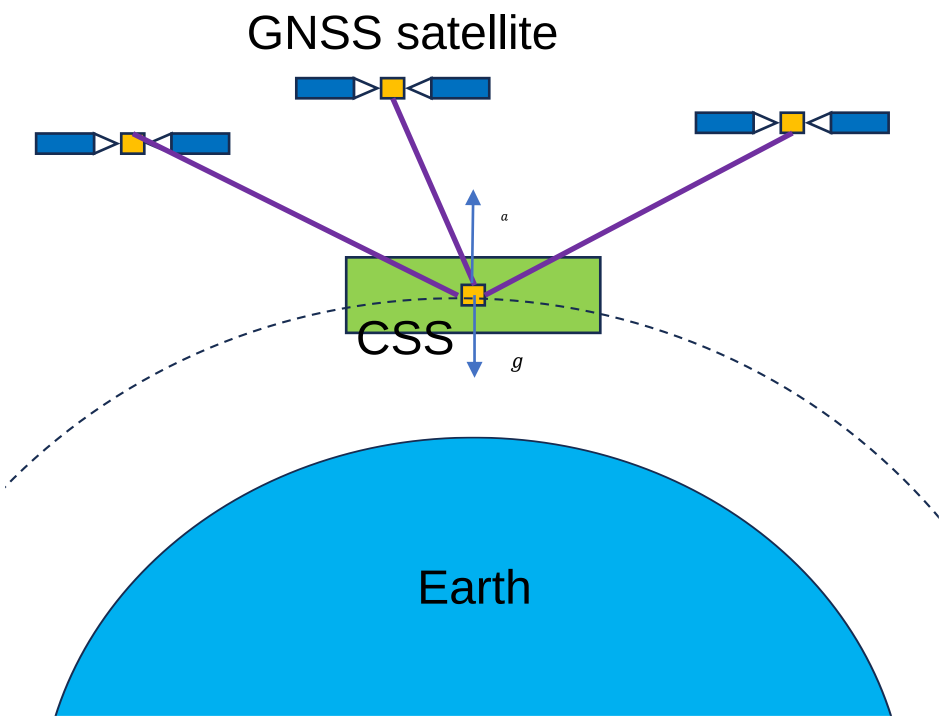
name	related to wave vector direction	symbol	Measurement/correction phase(rad)
Measured differential phase		$\Delta\phi_{AVE}$	-0.117±0.012
Residual acceleration	related	$\Delta\phi_{acc}$	$(3.5\pm2.3)\times10^{-5}$
Atom distribution	related	$\Delta\phi_{rot\ ad}$	$(-2.4\pm5.1)\times10^{-4}$
centrifugal force	related	$\Delta\phi_{rot\_cf}$	$(0\pm4.0)\times10^{-3}$
Single-photon ac Stark shift	not related	$\Delta\phi_{Ram-sp}$	$(0\pm2.0)\times10^{-3}$
Two-photon ac Stark shift	not related	$\Delta\phi_{Ram-dp}$	$(0\pm2.0)\times10^{-5}$
Multiple-sideband effect	related	$\Delta\phi_{Ram-ms}$	$(-0.6\pm0.2)\times10^{-4}$
wavefront distortion	related	$\Delta\phi_{Ram-wd}$	$(0\pm6)\times10^{-3}$
Magnetic field	not related	$\Delta\phi_{mag}$	$(-4.1\pm1.9)\times10^{-4}$
Gravity gradient	related	$\Delta\phi_{gg}$	$(0\pm2.1)\times10^{-5}$
Raman wave vector uncertainty	related	$\Delta\phi_{wv}$	$\ll10^{-4}$
Interference time sequence Uncertainty	related	$\Delta\phi_{ts}$	$\ll10^{-4}$
Other effect			
EP induced phase		$\Delta\phi_{\eta}$	a ± b

-0.117 rad represent to an EP test breaking coefficient of -3.31×10^{-7}

$$\eta = (A \pm B)\times10^{-7}$$

What we can do next

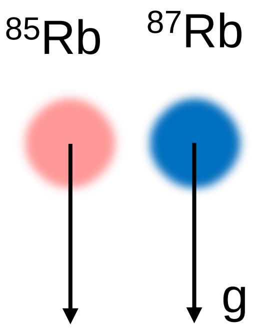
Gravity field mapping



$$g = a_{\text{Residual}} + a_{Motion}$$

~ 10^{-6} g

EP test



$$\eta = \frac{\Delta\phi}{k_{eff} g T^2}$$

~ 10^{-9}

~ 10^{-15}

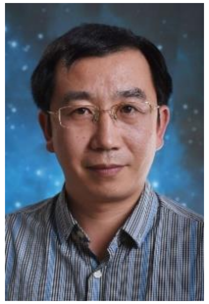
Acknowledgments

http://cap.apm.ac.cn/

ZMS - AMP

Mingsheng Zhan 詹明生

Jin Wang 王谨



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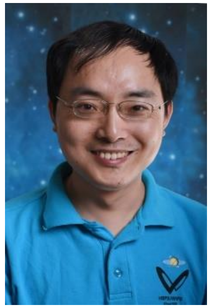

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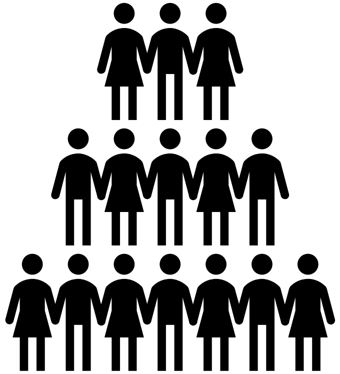

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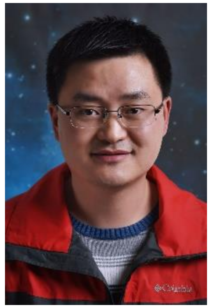

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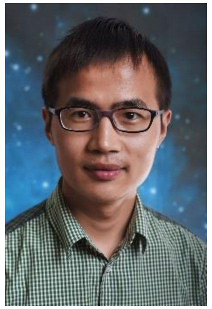

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All of you,
for your attention!