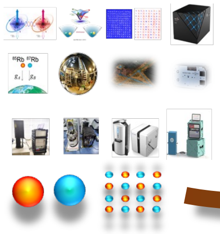
FOMO2024

Atom Interferometry in Space

Mingsheng Zhan (詹明生)

中国科学院精密测量科学与技术创新研究院
Innovation Academy for Precision Measurement Science and Technology, CAS

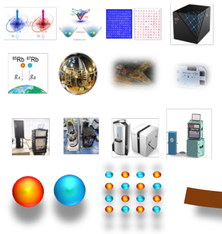
2024.9.10 Crete



OUTLINE

- **Why AI in space**
- **Path of AI to space**
- **CSS-AI: payload**
- **CSS-AI: experiments**

AI: Atom Interferometer
CSS: China Space Station

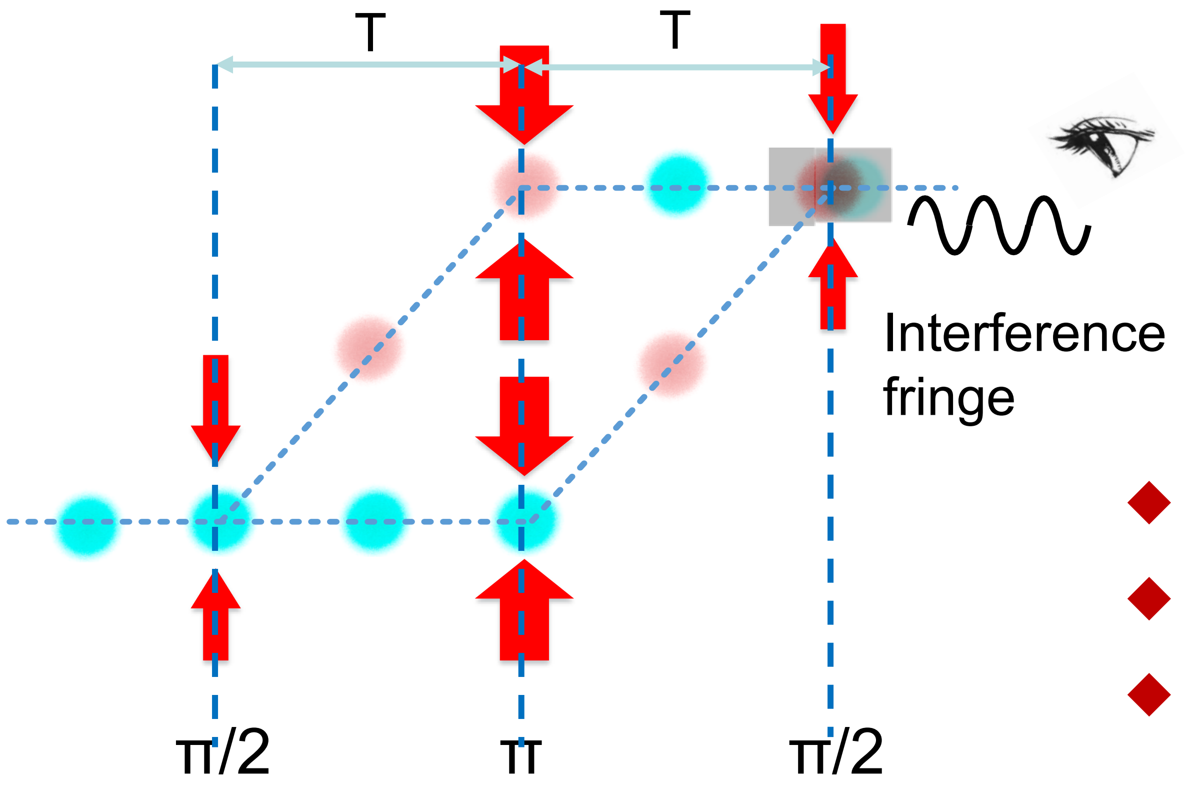


OUTLINE

- **Why AI in space**
- Path of AI to space
- CSS-AI: payload
- CSS-AI: experiments

Atom interferometer and its application

Atom interferometer (AI)



The phase of the fringe

$$\phi = \vec{k}_{eff}(\vec{a} + \vec{\Omega} \times \vec{v})T^2$$

Applications

Applied Physics

- Gravity survey
- Navigation
- Resource exploration

Fundamental physics

- EP test
- Fine structure constant
- Gravitational constant
- Frame dragging effect
- Gravitational wave
- Dark matter

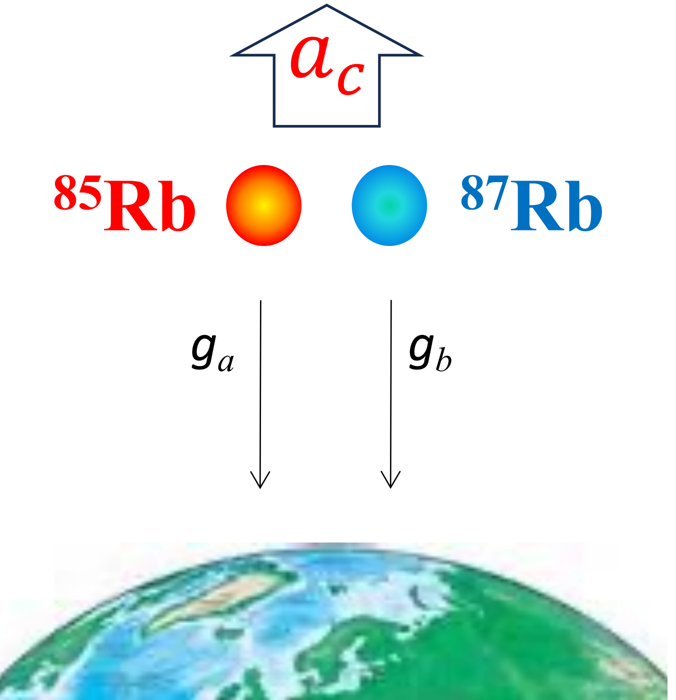
Roadmap of EP test with AI@APM

Equivalence Principle (EP) Test
to check the Eötvös-parameter

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

Sensitivity

T Free evolution time



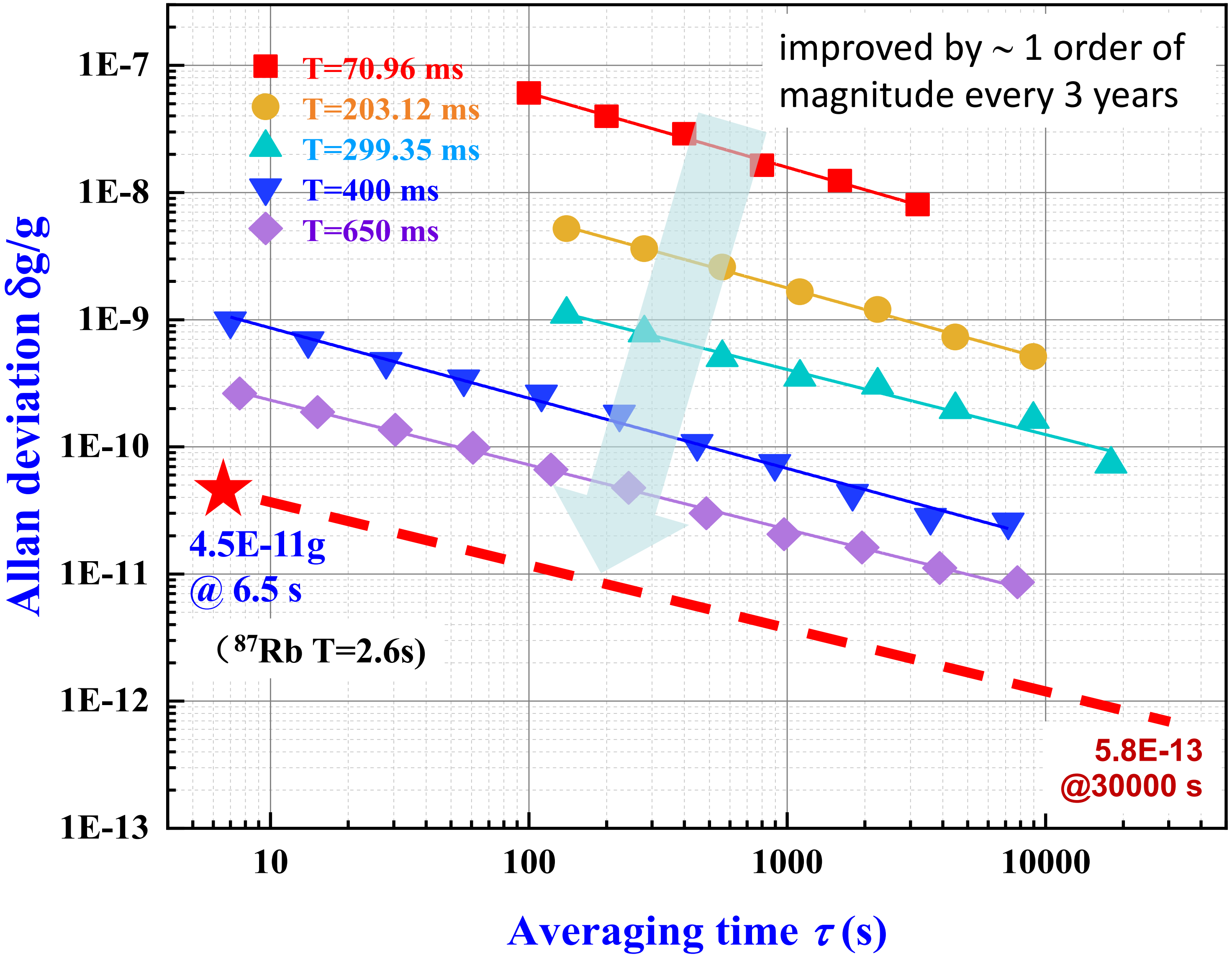
0.2 s

→ 1.3s 10-m Tower

→ 7 s 100-m Tower

→ (2 ~ 100) s Space Satellite

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**

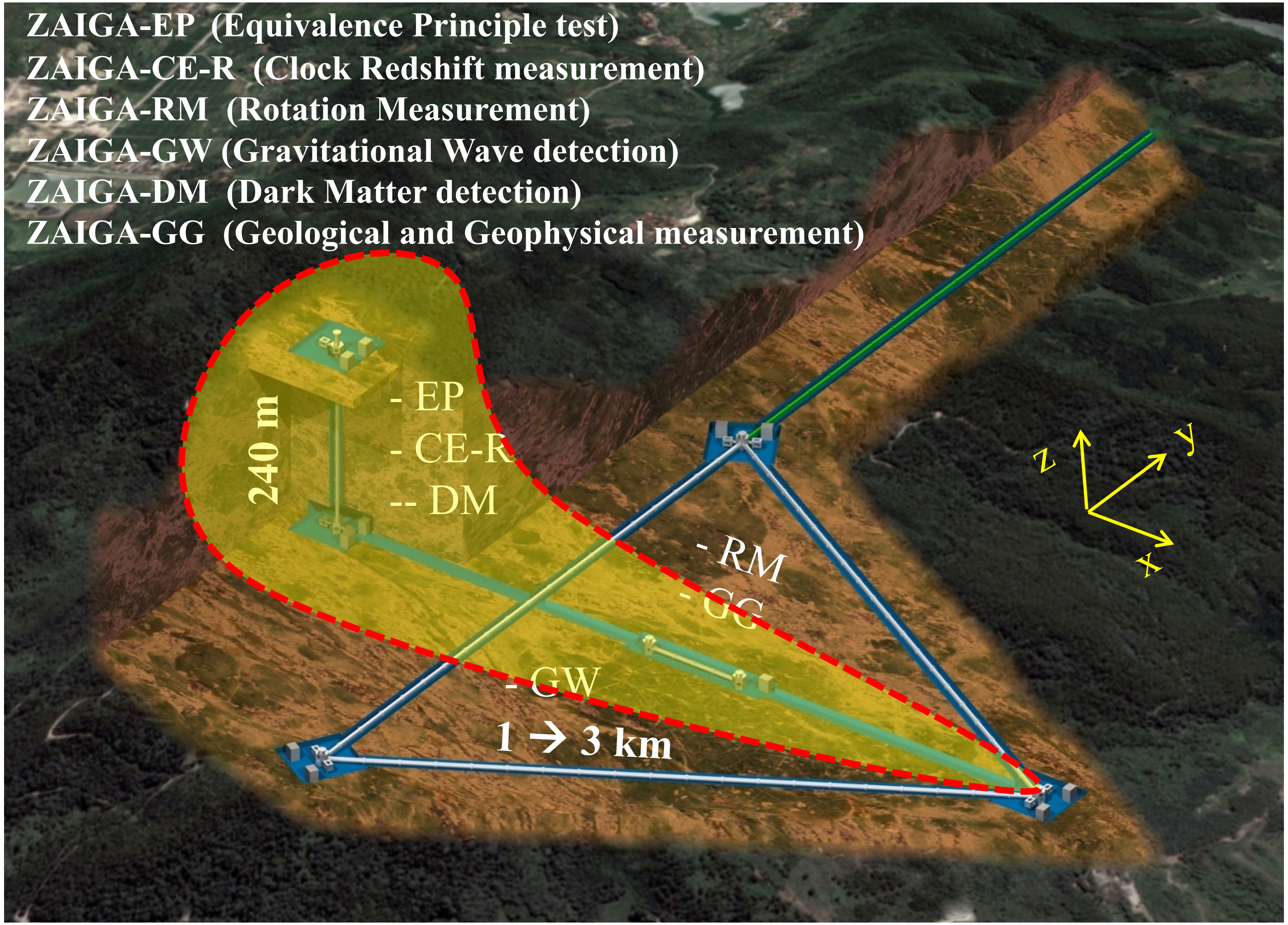
L. Zhou, S. T. Yan et al. *Frot. Phys.* **10**, (2022)

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

2023

Gravity gradient compensation **8.6E-12**

ZAIGA: Zhaoshan long-baseline Atom Interferometer Gravitation Antenna



to test gravity theory by atomic interferometer, atomic optical clock and atomic gyroscope

Ming-Sheng Zhan, Jin Wang, Wei-Tou Ni, *et al.*, *Intl. J. Mod. Phys. D* **29**,1940005 (2020)

Research Roadmap of ZAIGA

Building abilities

Item	Goal
AI baseline (Falling time)	240 m (T ≥ 6 s)
Atom species for AI	^{85}Rb ^{87}Rb ^{87}Sr ^{88}Sr
Gravity measurement	1×10^{-12} g
Rotation measurement	8×10^{-12} rad/s
Stability of Sr/Yb clock	2×10^{-18}
Local gravity monitoring	1 μGal

Scientific Tests

Item	Goal
WEP test	$\eta \sim 10^{-13}$
Redshift test	$\alpha \sim 10^{-5}$
Lense-Thirring effect	$\sim 10^{-14}$ rad/s
Dark matter probe	$d \sim 10^{-4}$ @ 1 Hz
GW detection	$s \sim 10^{-19}$ @ 1 Hz

DM & GW

Item	Goal
Dark matter probe	$d \sim 10^{-6}$@ 1 Hz
GW detection	$s \sim 10^{-21}$ @ 1 Hz

Phase I
2022 - 2027

240 m Vertical AI
20 m Gyros
10 m Dual Rb/Sr AI
2E-18 Optical Clocks

Phase II:
2027 - 2035

240 m Vertical AI array
Δ1000 m Horizontal AI array

Phase III
2035 -

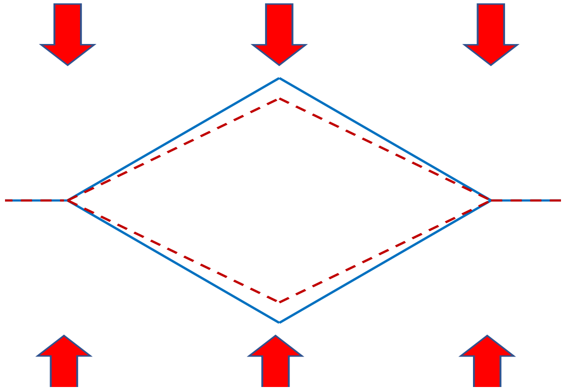
≥ 3000 m Horizontal AI

ZAIGA

AI in space

Advantages in space

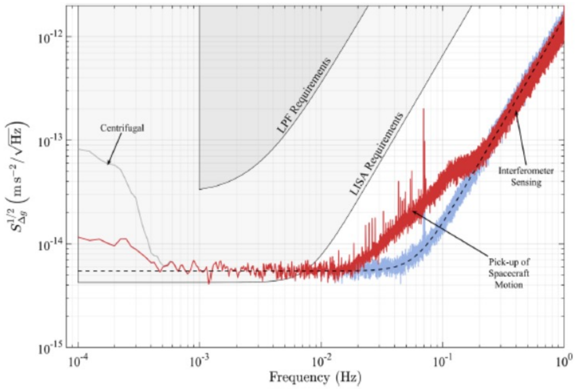
Long Interference time



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

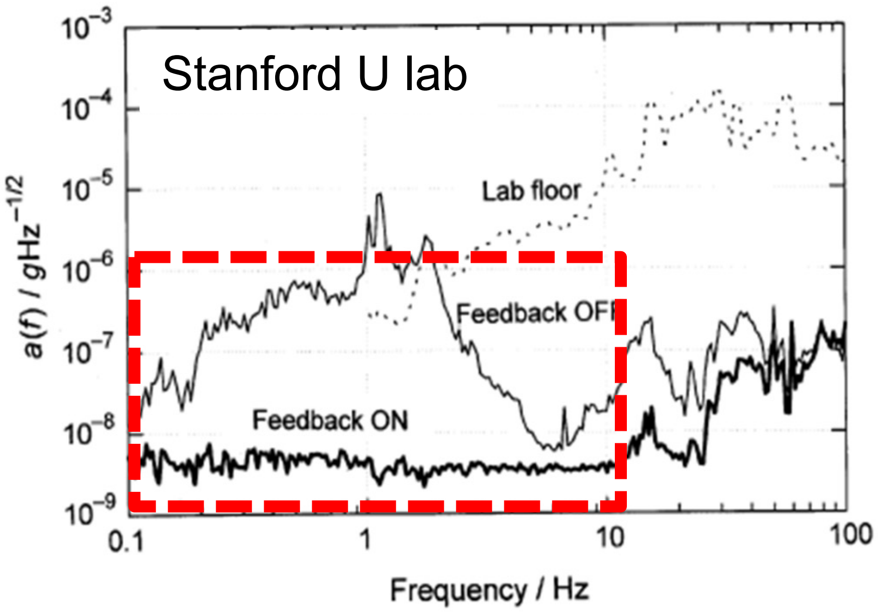
Challenges

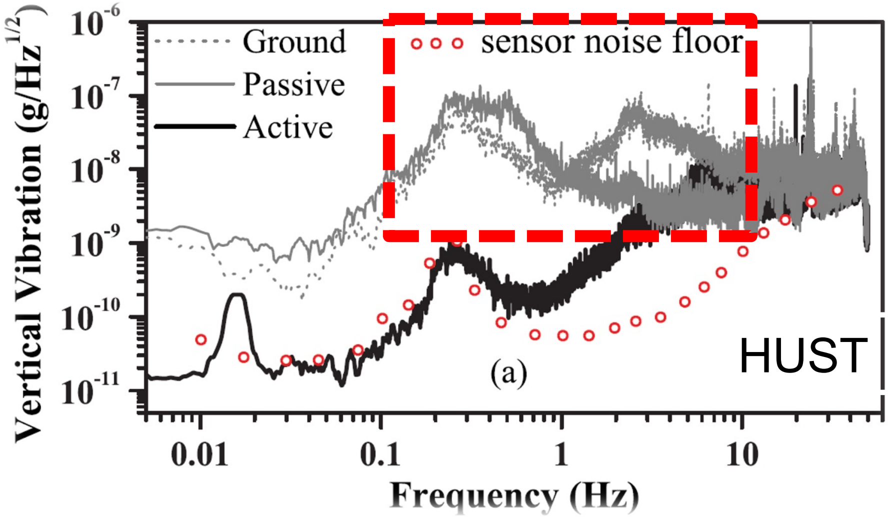
- ◆Requirement for the spacecraft
(Residual acceleration, structural stability, Residual magnetization control)
- ◆Vibration during rocket launch
- ◆Vacuum environment
- ◆Reliability, Long life time
- ◆High-energy particle radiation in space

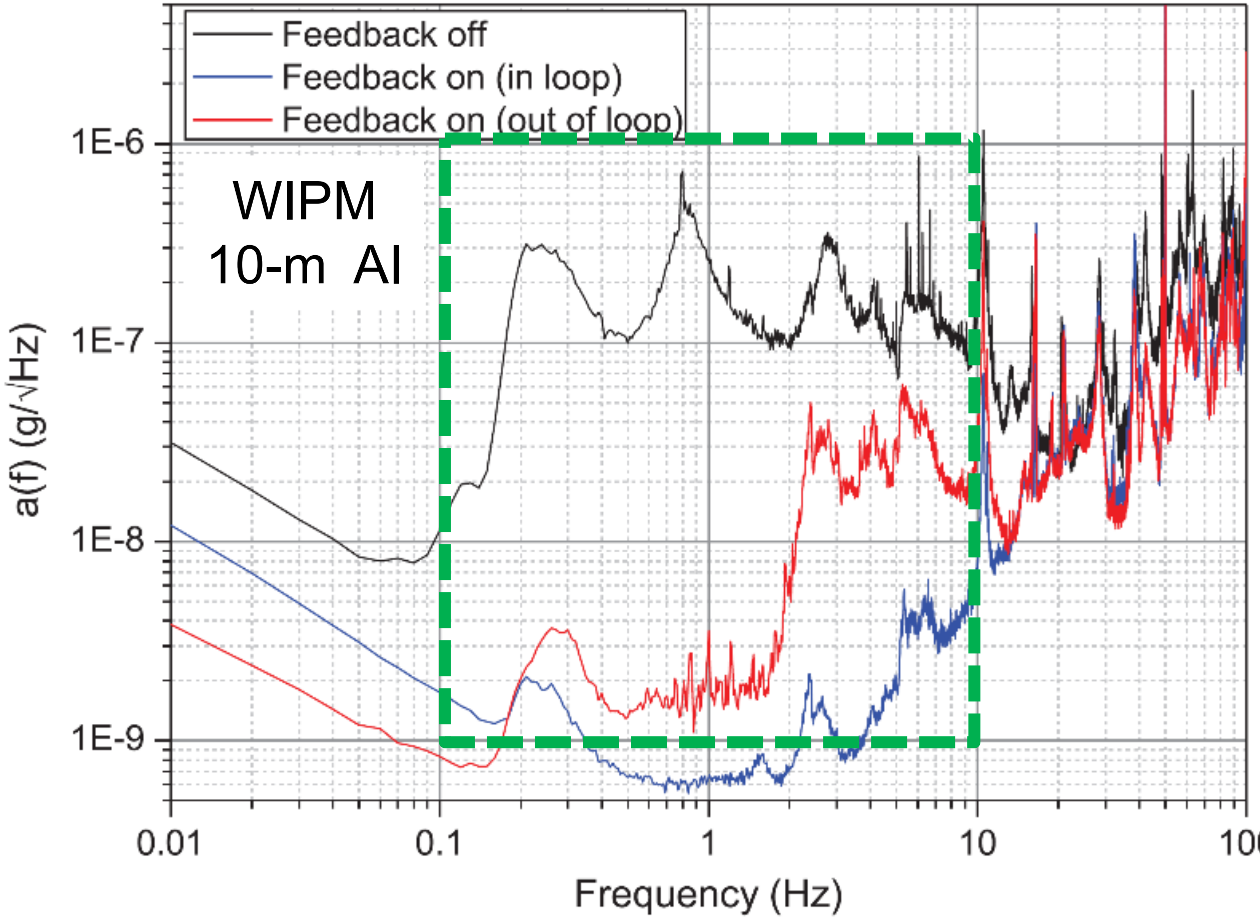
M. Armano et al. (LISA Pathfinder) PRL 116, 231101 (2016)

Vibrational noises on the Ground

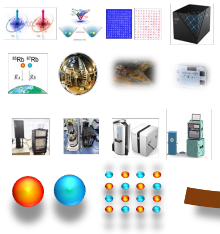
ZMS - AMP







B. Tang *et al., Rev. Sci. Instrum.* **85**, 093109 (2014)



OUTLINE

- Why AI in space
- **Path of AI to space**
- CSS-AI: payload
- CSS-AI: experiments

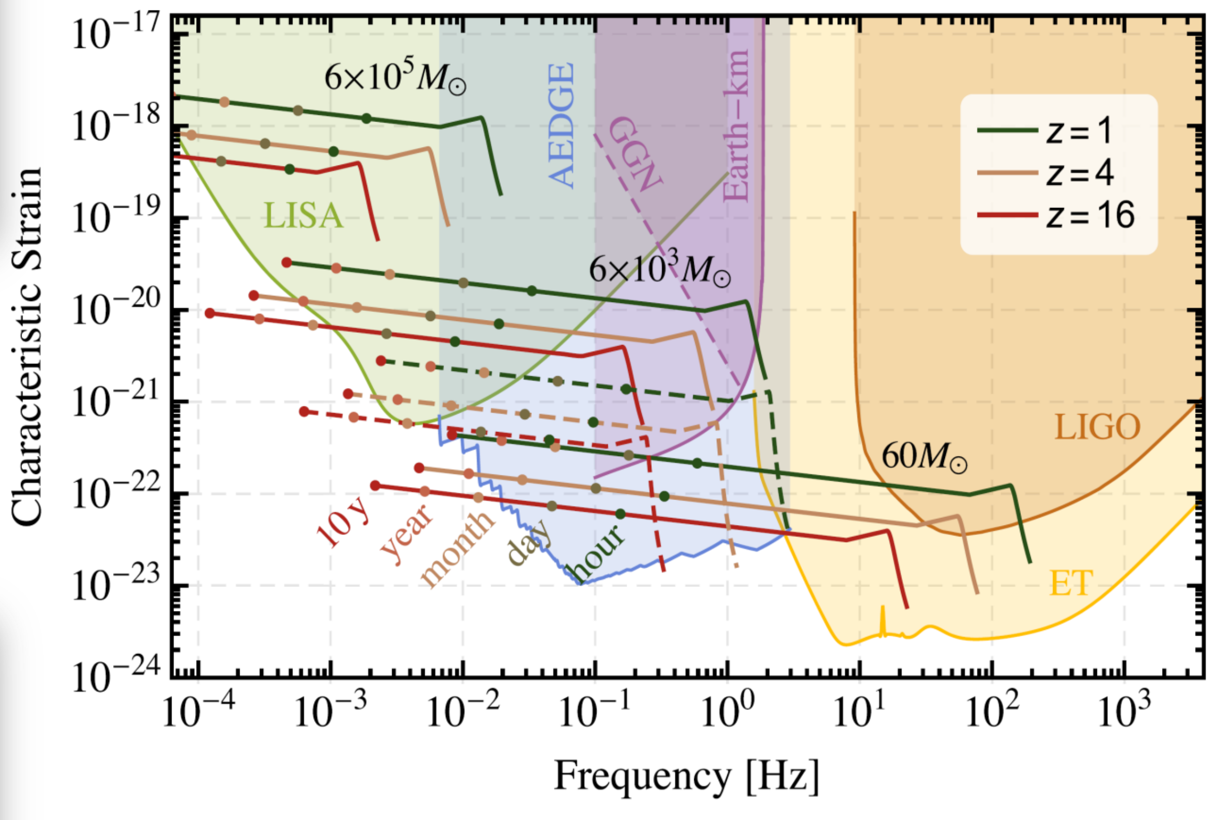
Space AI proposals

El-Neaj et al. *EPJ Quantum Technology* (2020) 7:6
https://doi.org/10.1140/epjqt/s40507-020-0080-0
EPJ.org
EPJ Quantum Technology
a SpringerOpen Journal

RESEARCH **Open Access**

Check for updates

AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space



Alonso et al. *EPJ Quantum Technology* (2022) 9:30
https://doi.org/10.1140/epjqt/s40507-022-00147-w
EPJ.org
EPJ Quantum Technology
a SpringerOpen Journal

REVIEW **Open Access**

Check for updates

Cold atoms in space: community workshop summary and proposed road-map

Space AI proposals

ZMS - AMP

Technology roadmap for cold-atoms based quantum inertial sensor in space

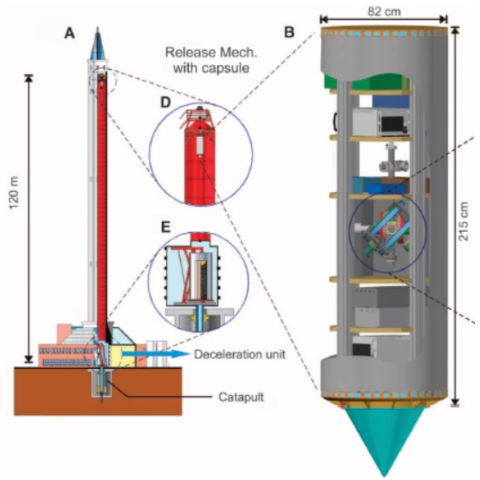
Cite as: AVS Quantum Sci. **5**, 019201 (2023); doi: 10.1116/5.0098119
Submitted: 5 May 2022 · Accepted: 22 November 2022 ·
Published Online: 20 March 2023

View Online Export Citation CrossMark

Sven Abend,[1] Baptiste Allard,[2] Aidan S. Arnold,[3] Ticijana Ban,[4] Liam Barry,[5] Baptiste Battelier,[6] Ahmad Bawamia,[7] Quentin Beaufils,[8] Simon Bernon,[6] Andrea Bertoldi,[6] Alexis Bonnin,[9] Philippe Bouyer,[6,10,11,12,13] Alexandre Bresson,[9] Oliver S. Burrow,[3] Benjamin Canuel,[6] Bruno Desruelle,[13] Giannis Drougakis,[14] René Forsberg,[15] Naceur Gaaloul,[1] Alexandre Gauguet,[2] Matthias Gersemann,[1] Paul F. Griffin,[3] Hendrik Heine,[1] Victoria A. Henderson,[16] Waldemar Herr,[1,17] Simon Kanthak,[18] Markus Krutzik,[7,18] Maike D. Lachmann,[1] Roland Lammegger,[19] Werner Magnes,[20] Gaetano Mileti,[21] Morgan W. Mitchell,[22] Sergio Mottini,[23] Dimitris Papazoglou,[14] Franck Pereira dos Santos,[24] Achim Peters,[16] Ernst Rasel,[1] Erling Riis,[3] Christian Schubert,[1,17] Stephan Tobias Seidel,[25] Guglielmo M. Tino,[26] Mathias Van Den Bossche,[23] Wolf von Klitzing,[14] Andreas Wicht,[7] Marcin Witkowski,[27] Nassim Zahzam,[9] and Michał Zawada[27]

AI taking off from the ground

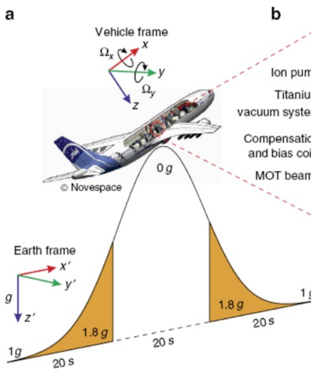
Dropping tower



- 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

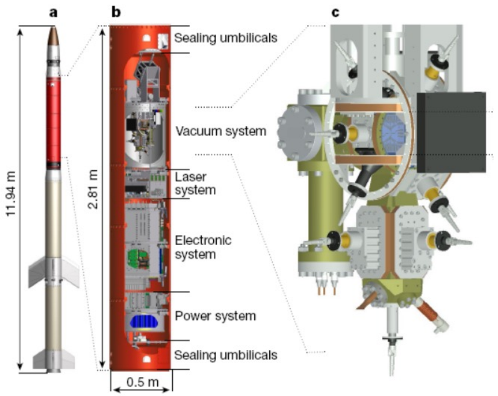
Parabolic flying plane



- 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

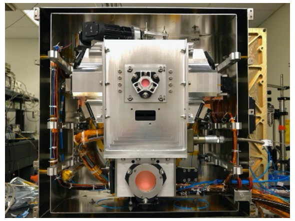
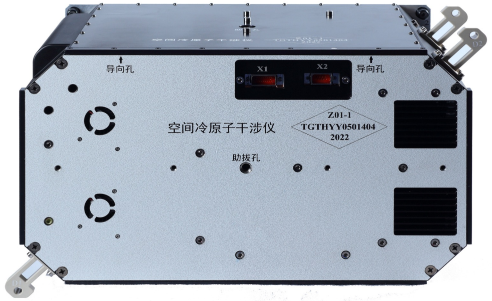
Sounding rocket

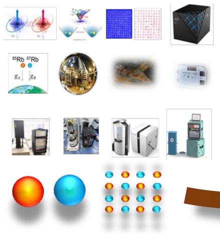


- Space-borne Bose–Einstein condensation for precision interferometry (2018)
- Ultracold atom interferometry in space(2021)

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

ISS-AI *vs* CSS-AI

	ISS-CAL  	**CSS-AI** 
Science objectives	● Ultra cold atom preparation ● Quantum gases research ● Atom interferometry ● EP test	● Atom interferometry ● Rotation measurement ● Gravity measurement ● EP test
Atom species	^{87}Rb, ^{41}K and ^{39}K	^{85}Rb and ^{87}Rb
Atom cooling scheme	Atom chip	2D+3D laser cooling
Cold atom cloud parameters	Number 10^4 Temperature <1 nK	Number $>5\times10^8$ Temperature 2 μK
Interference scheme	Bragg transition	Double diffraction Raman transition
Achieved interference time	150 ms	200 ms
payload parameters	Size about 90 cm× 55 cm× 50cm Power up to 1000 W	Size 46 cm×33 cm×26 cm Power 70 W

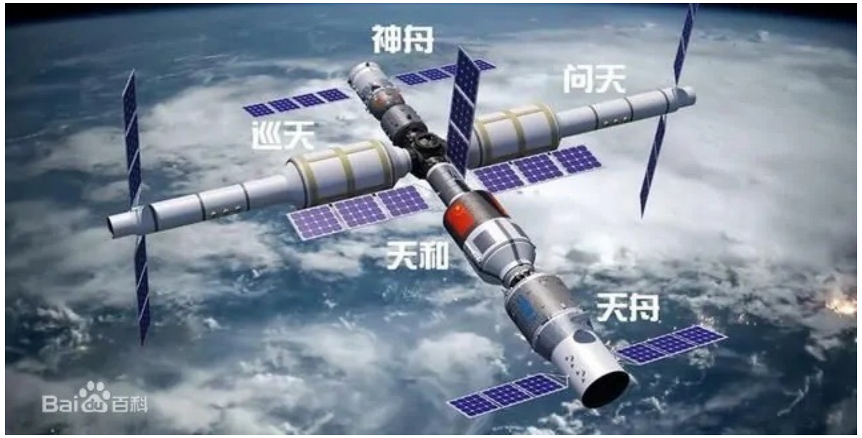


OUTLINE

- Why AI in space
- Path of AI to space
- **CSS-AI: payload**
- CSS-AI: experiments

AI in the China Space Station

The China space station



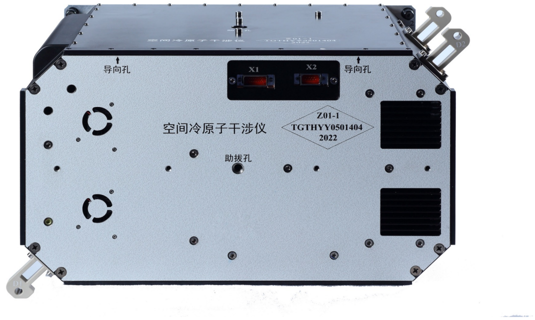
Scientific objectives

Carrying out in-orbit experiments for AI measurements and EP test.

Target accuracy

- Interference time: 0.1~1 s
- Test mass: ^{85}Rb and ^{87}Rb
- EP test precision: ~10^{-10}

High Microgravity Level Research Rack (HMLR)



The China Space Station Atom Interferometer (CSS-AI)

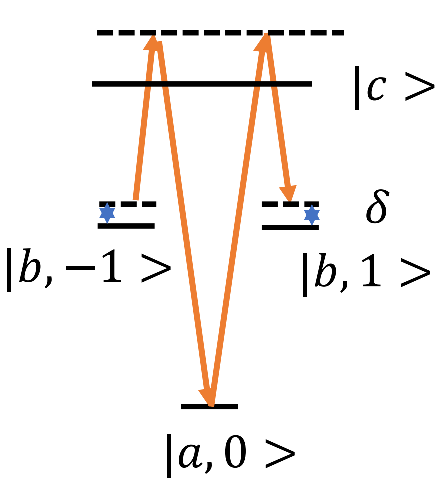
Resources provided by HMLR

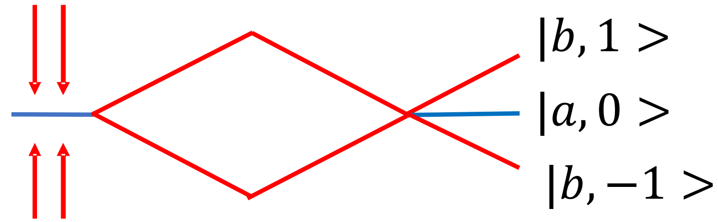
- Micro gravity: 10^{-7}g
- size: 33 cm×46 cm×26 cm
- power: ~70 W
- Installing: levitation, no heat dissipation channel

The interference scheme

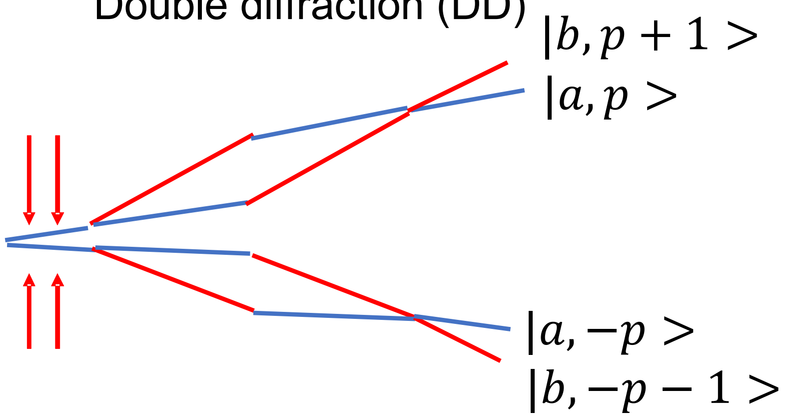
Problem1: lacking initial velocity of the atom cloud

Energy levels of the Raman transition are degenerate





Double diffraction (DD)



Double single diffraction(DSD)

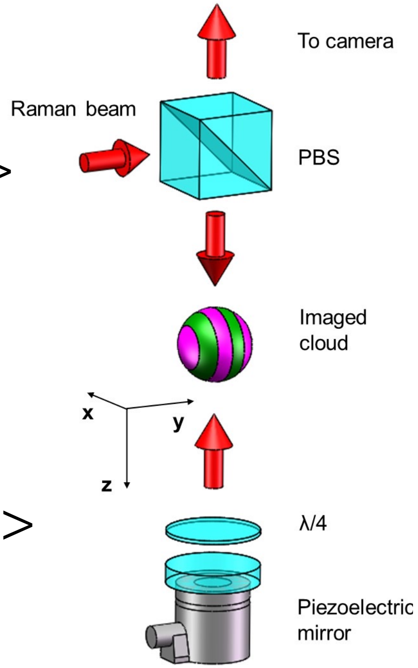
Two interference schemes can be transformed by changing the frequency of the Raman laser.

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

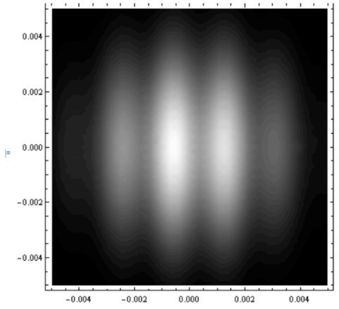
Brynle Barrett, et al. NATURE COMMUNICATIONS, 7:13786, 2016

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:

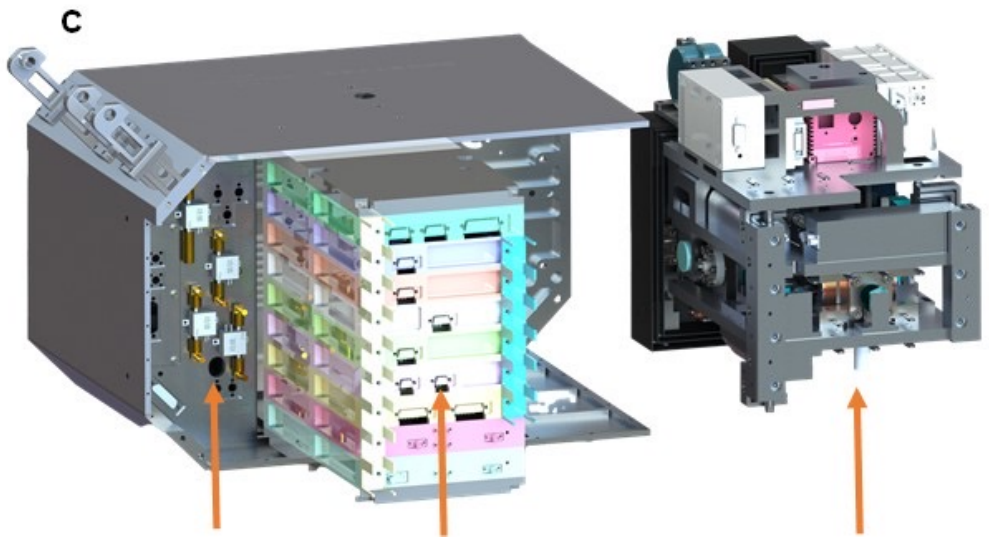
The direction of the Raman laser is consistent with the direction of imaging to avoid reducing the fringe's contrast

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

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

Design of the payload

System configuration

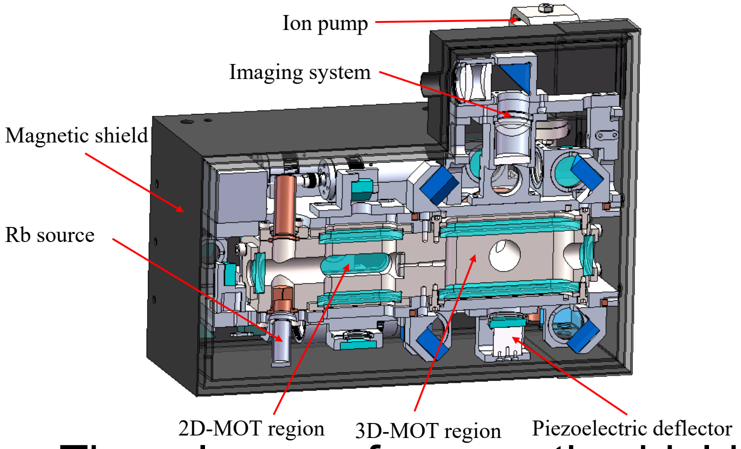


Optical system Electric system Physical system

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

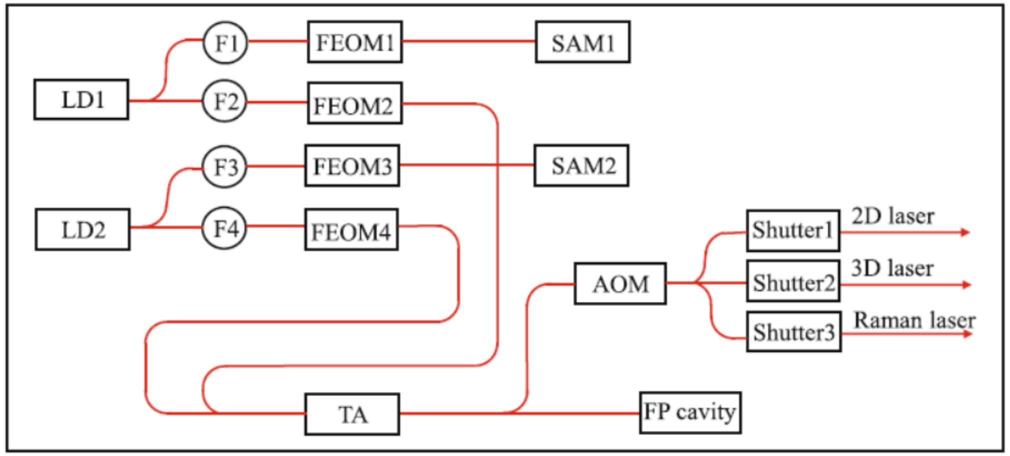
M. He, et al. npj Microgravity 9, 58 2023

Physical system



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

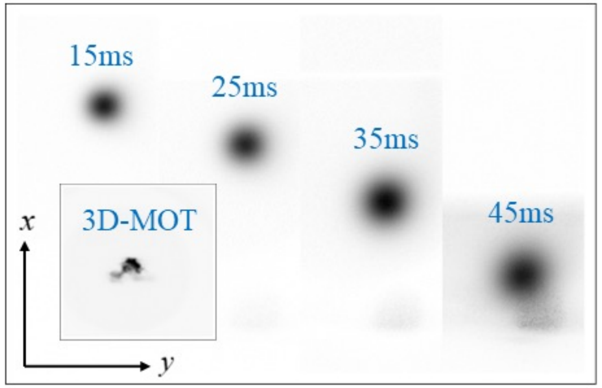
Optical system



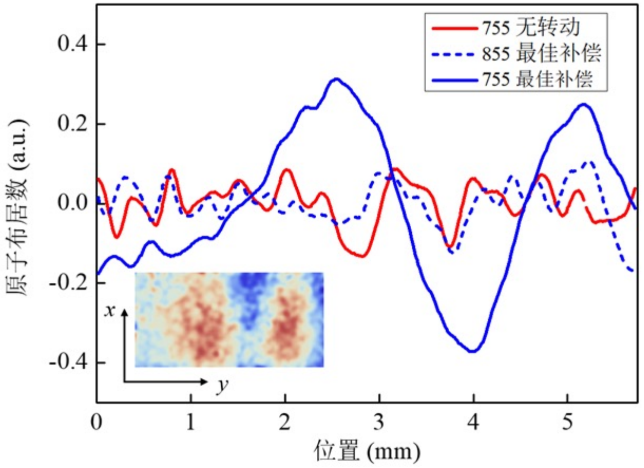
Sideband frequency stabilization, sidebands modulation, Fused silica optical bench

Ground test

Function test



Cold atom preparing: 10^8, 5 μK

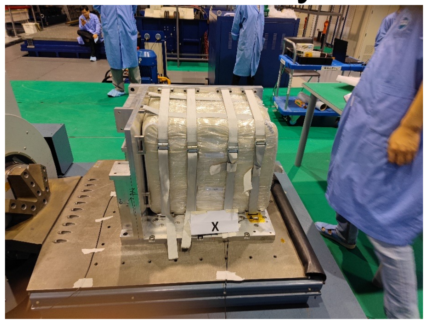


Atom interference： 5 ms

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

Environmental test

Thermal Cycle



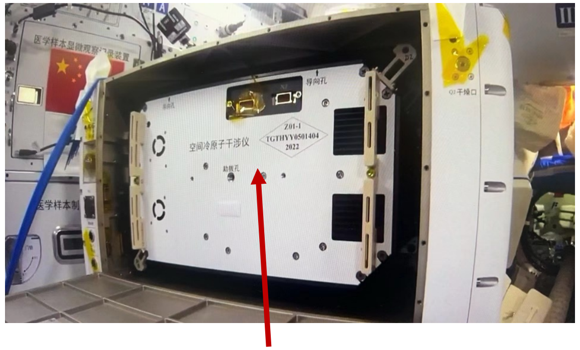
Vibration test

Other tests

- electromagnetic compatibility
- Medical Science
- Ergonomics

Launch and install

Launched by Tianzhou-5 cargo spacecraft (2022/9)



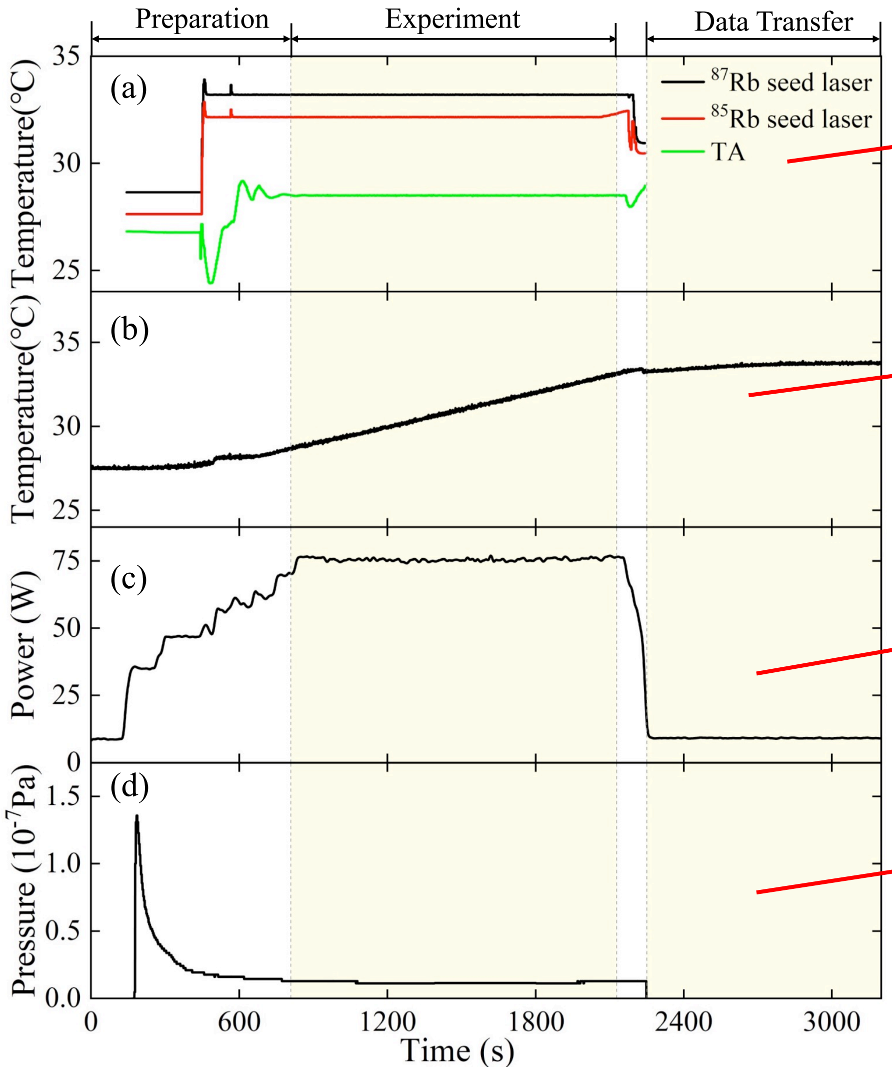
The Space AI in the HMLR (2022/12)

OUTLINE

- Why AI in space
- Path of AI to space
- CSS-AI: payload
- **CSS-AI: experiments**

In orbit test

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



Temperature control: Stabilized in 5 minute

Temperature: 0.2 ˚C /min

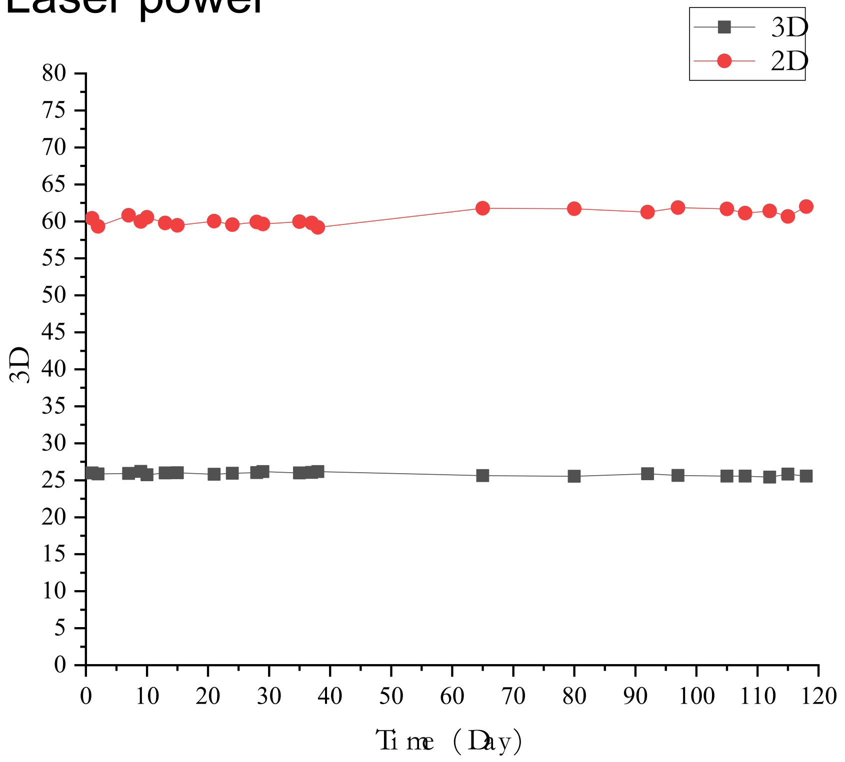
Power: Peak power 75 W

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



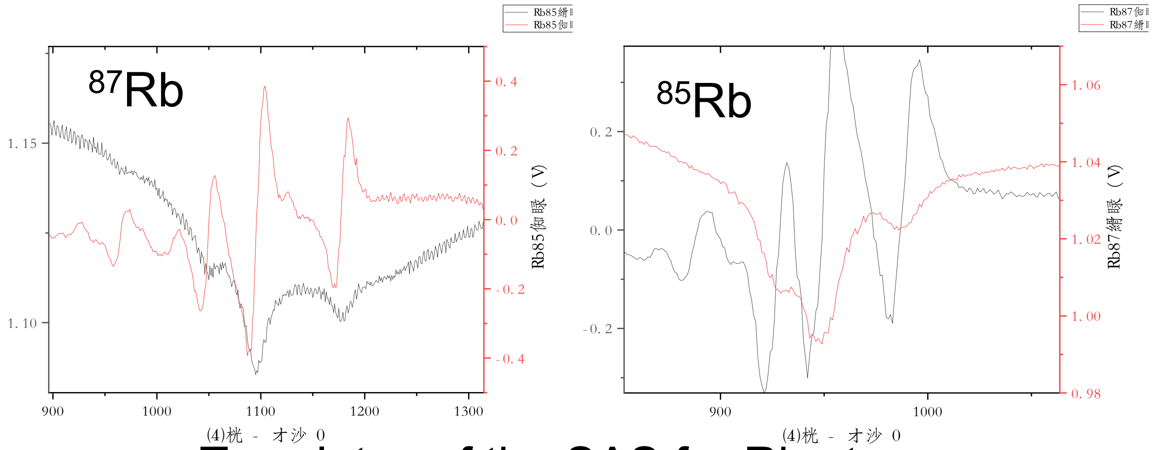
Fluctuation: <1.5% for more than 100 days

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



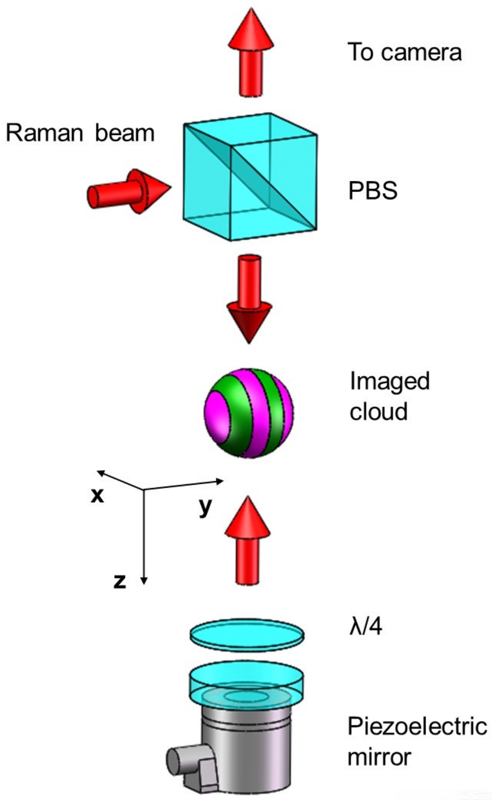
Templates of the SAS for Rb atom

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

Interference phase of the PSI

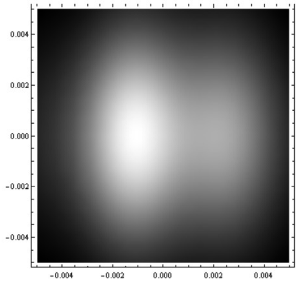


piezoelectric Mirror from coremorrow

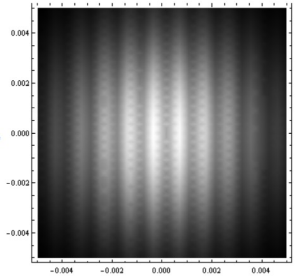
Spatial phase of PSI without rotation the angle of the Raman laser

$$\phi = k_{eff} a_z T^2 + \sum_i k_{eff} 2\Omega_i v_j T^2 \qquad i=(x,y), j=(y,x)$$

Problem: For a fix rotation rate (~1mrad/s for the CSS) the spatial frequency is related to the interference time



Frequency too low



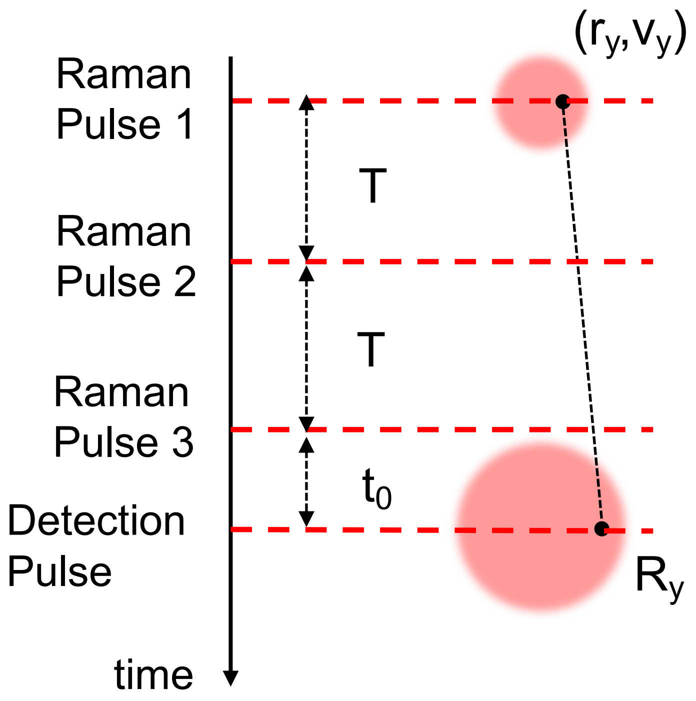
Frequency too high

Introduce a Piezoelectric mirror, the phase of the Spatial fringe is

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

Can adjust the spatial frequency and its direction

Optimizing the Raman laser's angle

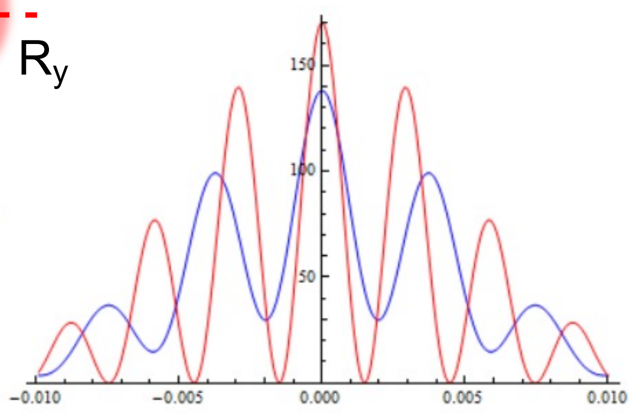


Problem: what we measured is the position of atom at the detection time, but the phase is related to the position and velocity of atom at the time of the first Raman pulse

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

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

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)

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

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

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

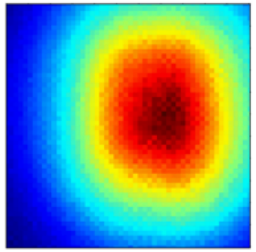
Eliminate the offset and distributions of the position and velocity of the atom cloud and maximize the fringe's contrast.

Extracting the spatial fringe from the background

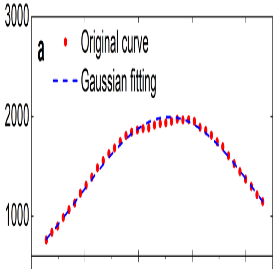
Problem: the contrast of the fringe is low, and the expression of the envelop is unknow.

Design a scheme to extract the fringe

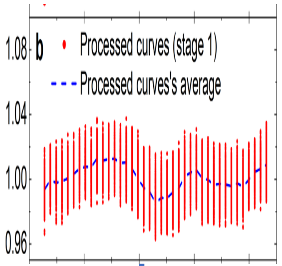
1.Origin PSI image



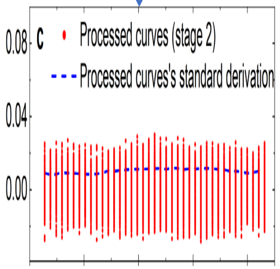
2.Averaged to 1D



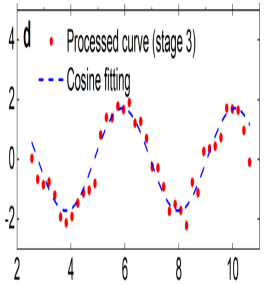
3.Divided by Gaussian fitting



4.divided by the curves' average



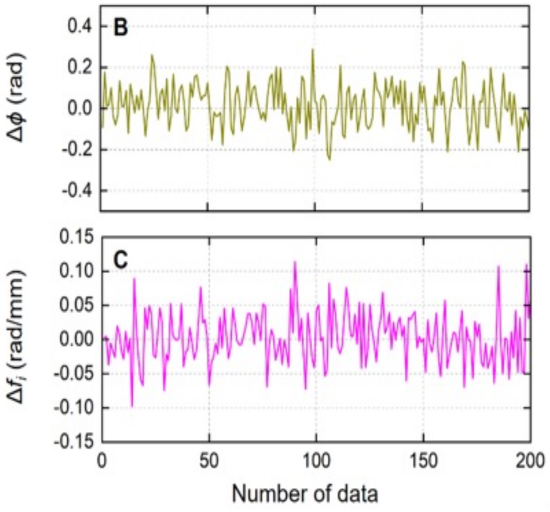
5.divided by the curves' standard derivation



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.

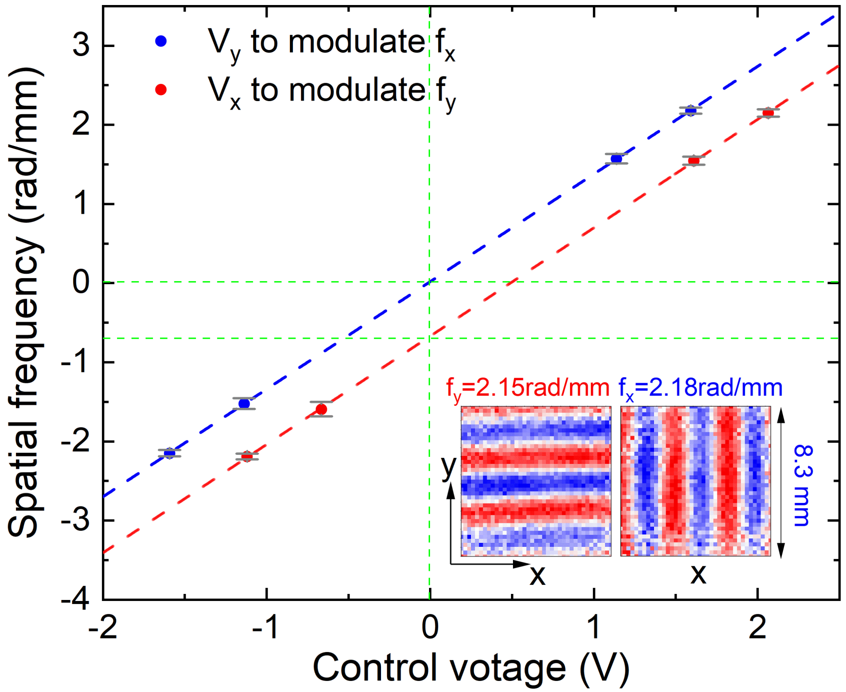
The method has no bias and near optimal

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).

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

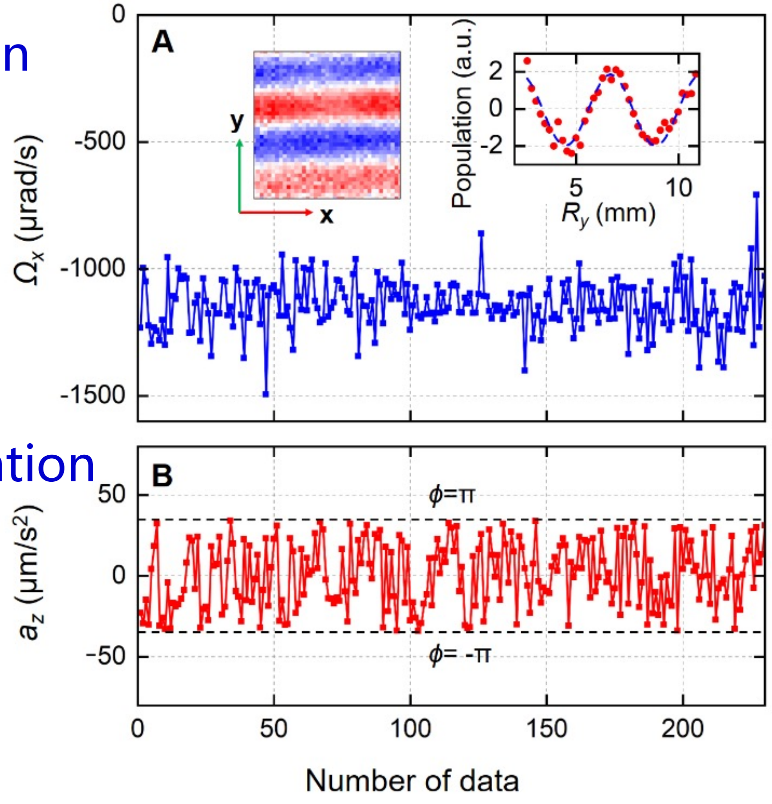
$$\Omega_x = (-115.3 \pm 1.2) \times 10^{-5}\ \text{rad/s},$$
$$\Omega_y = (-0.37 \pm 0.57) \times 10^{-5}\ \text{rad/s}.$$

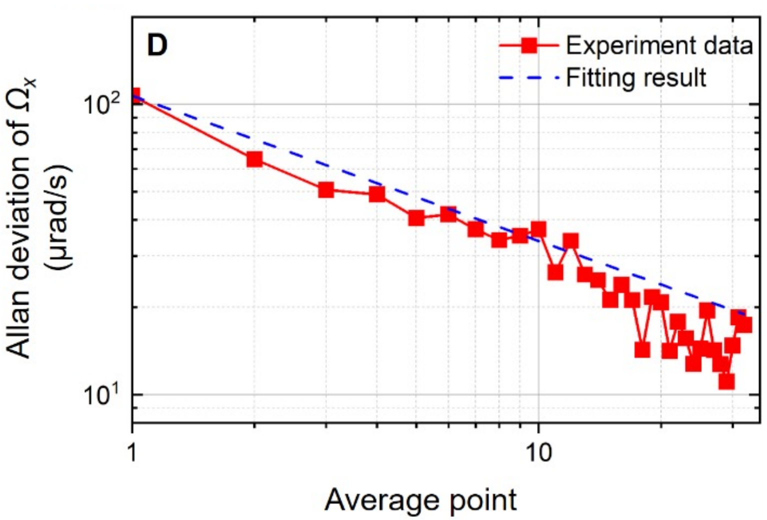
Rotation and acceleration measurement

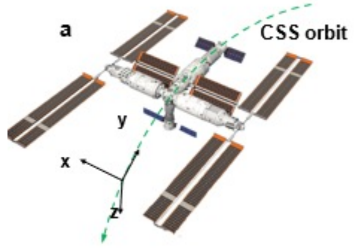
Rotation and acceleration measurement with T=75 ms

Rotation

Acceleration



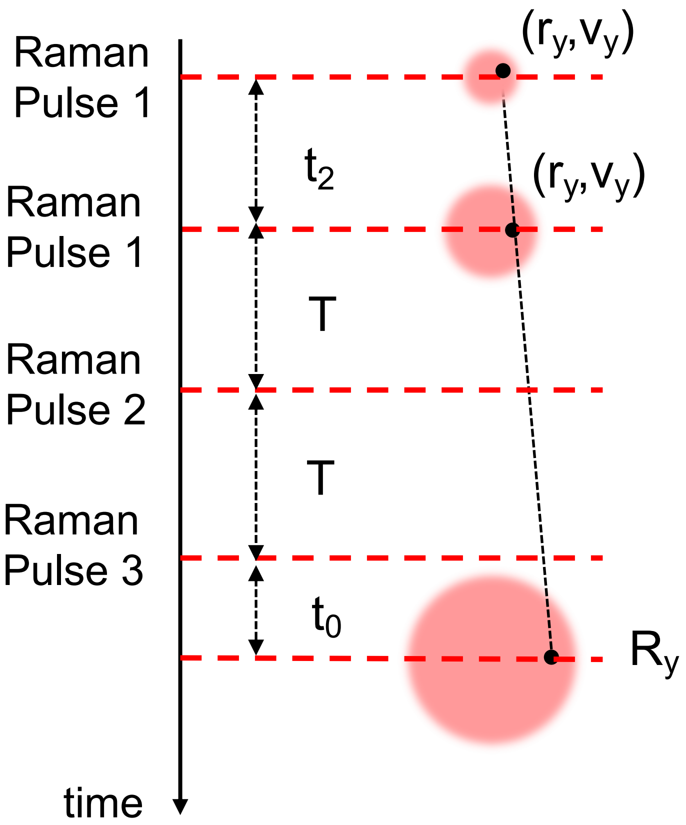




Resolution for rotation: 1.7 $\times 10^{-5}$ rad/s for 32 PSI measurements

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

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

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

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

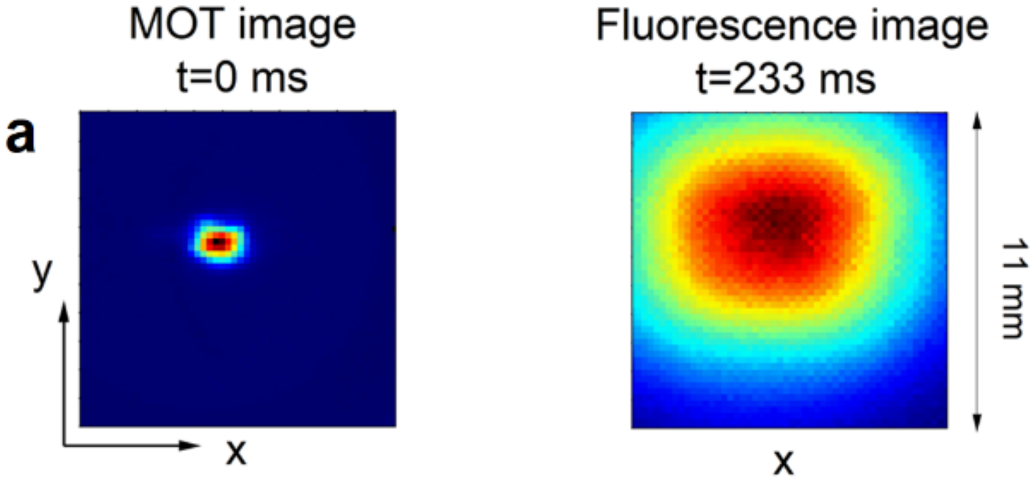
Acceleration and rotation can be accuracy extracted through the above two equations.

Systemic effect estimation

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

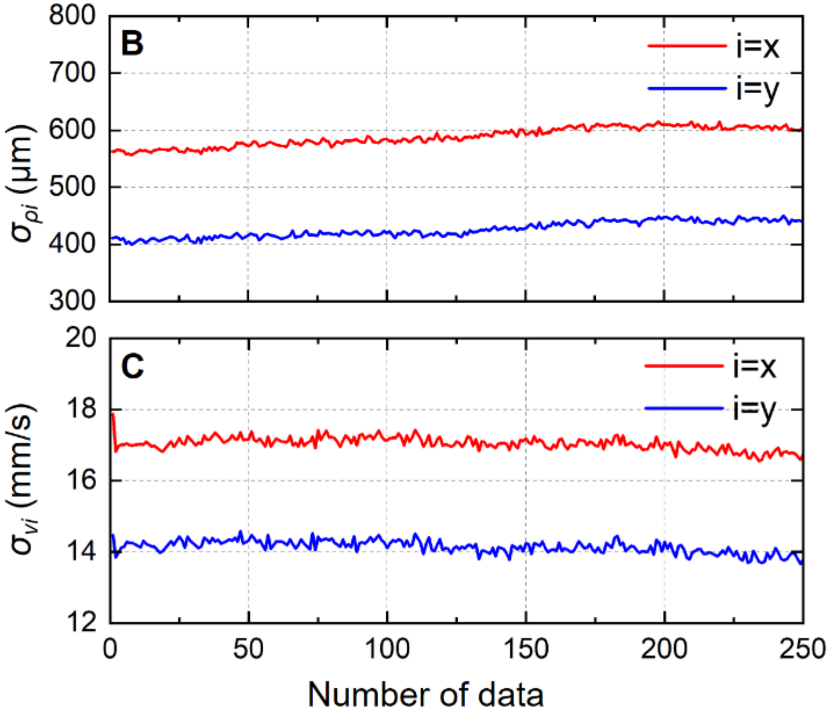
One example: velocity and position distributions of the atom cloud.

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



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

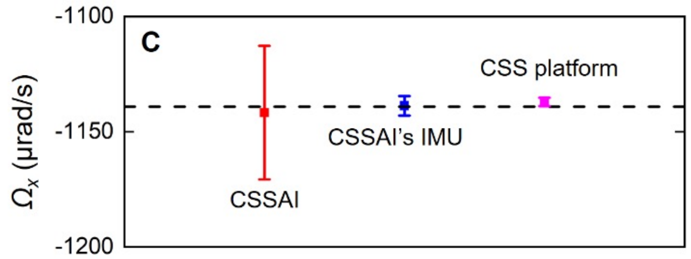
Rotation measurement error estimation

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	$\pm 3\times10^{-3}$
Time before the 1st Raman pulse (μs)	t_0=43245.8±0.13	$\pm 2\times10^{-5}$
Time after the 3rd Raman laser pulse (μs)	t_1=40146±10	$\pm 9\times10^{-2}$
Width of the Raman π pulse (μs)	$\tau=17\pm(5\times10^{-5})$	$\pm 6\times10^{-7}$
Effective wave vector (m^{-1})	k_{eff}=16105813.75±0.09	$\pm 9\times10^{-6}$
Width of the MOT's position (mm)	$\sigma_{\rho i}$=0.427±0.013	$\pm 3\times10^{-2}$
Width of the MOT's velocity (mm/s)	σ_{vi}=14.13±0.18	$\pm 1\times10^{-2}$
Magnetic field	B_0=504.7±1.3 mG $\gamma_{i,2}=\pm1.3\ G/m^2$	$\pm 2\times10^{-1}$
In total		-1142±29

CSSAI (-114.2±2.9)×10^{-5} rad/s

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

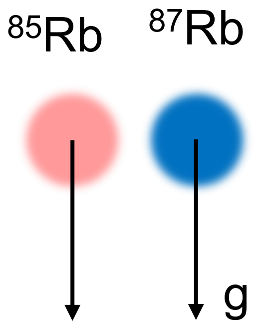
CSS platform (-113.70±0.18)×10^{-5} rad/s



J.T. Li, et al, Realization of a cold atom gyroscope in space. arXiv:2405.20659

What we can do next

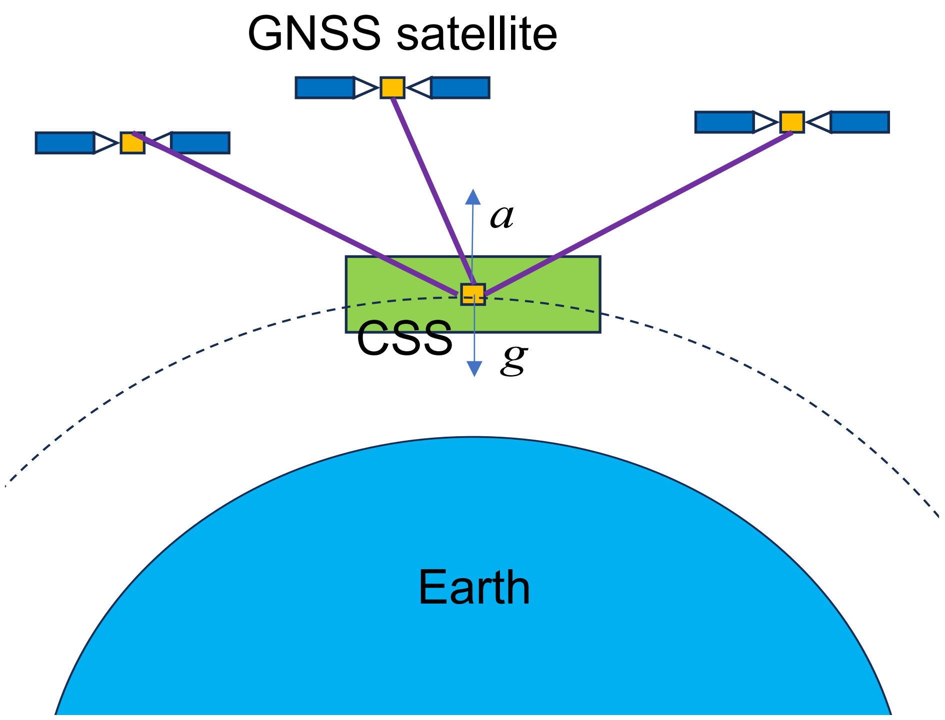
EP test



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

$\sim 10^{-9}$

Gravity field mapping



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

$\sim 10^{-6}$ g

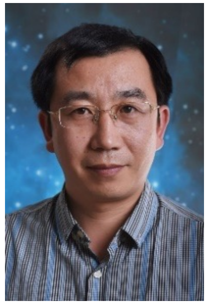
Acknowledgments

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

ZMS - AMP


Mingsheng Zhan
詹明生


Jin Wang
王谨


Runbing Li
李润兵


Peng Xu
许鹏


Xiaodong He
何晓东

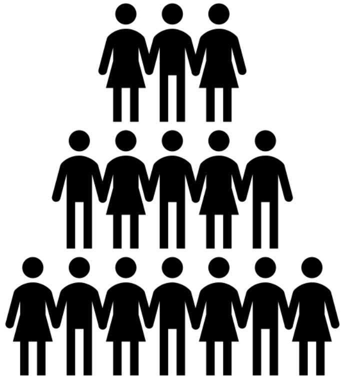

Xi Chen
陈曦


Feng Zhou
周锋


Min Liu
刘敏

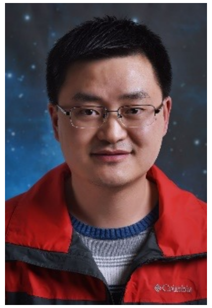

Wei-Tou Ni
倪维斗

Assistants
Postdocs
Students

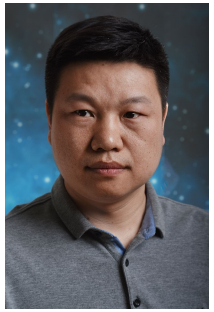


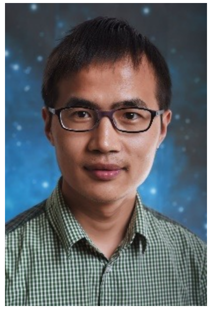

Dongfeng Gao
高东峰


Lin Zhou
周林


Jiaqi Zhong
仲嘉琪


Zongyuan Xiong
熊宗元


Min Ke
柯敏


Zhanwei Yao
姚战伟


Biao Tang
汤彪


Yibo Wang
王一波

¥

Ministry of Sci & Tech of China (MOST)
Natural Science Foundation of China (NSFC)
Chinese Academy of Sciences (CAS)

All of you,
for your attention!