

The Wuhan 10-meter Atom Interferometer

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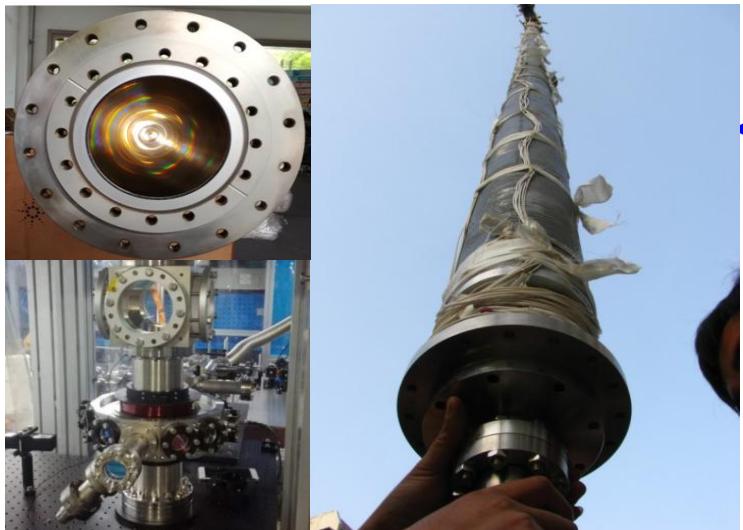
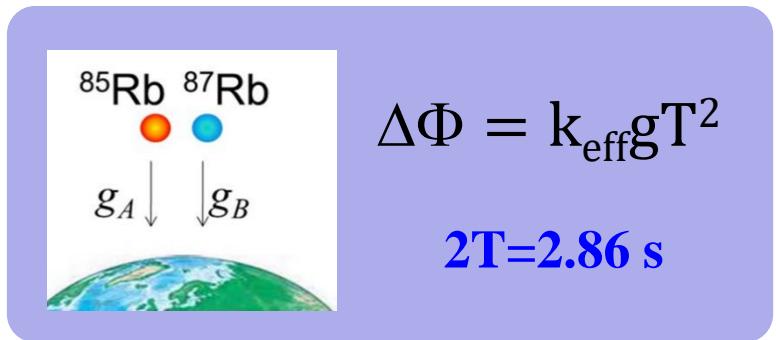
March 13-14, 2023

Outline



- 1. Design and implication of the AI**
- 2. 4WDR method and WEP mass-test**
- 3. 4WDR-e method and WEP jointed test**
- 4. Recent progress**

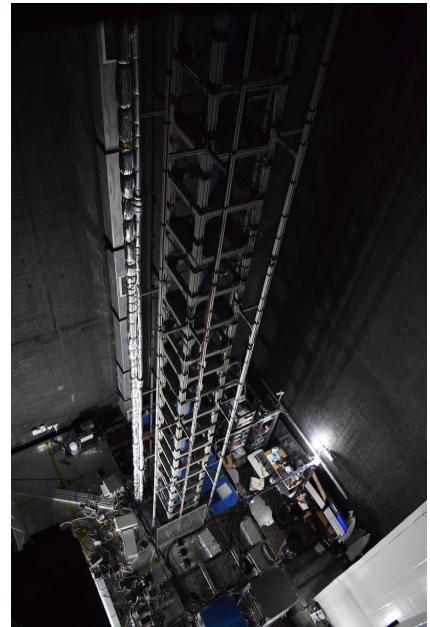
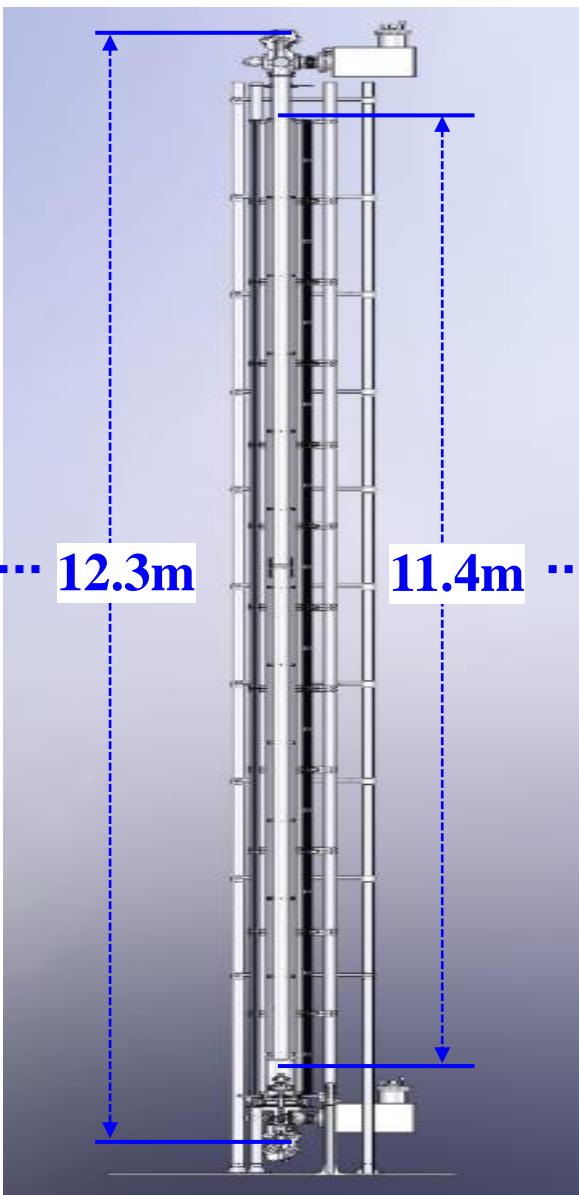
1. Design and implication of the AI



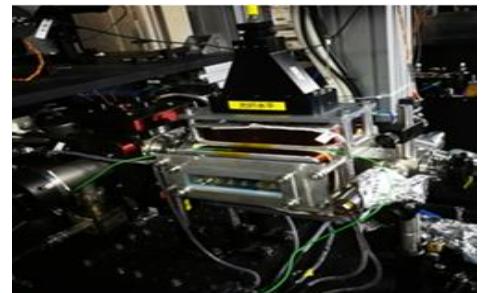
Vacuum chamber

$12.3 \text{ m}, 2 \times 10^{-8} \text{ Pa}$

L. Zhou, et al., Gen. Relat. Gravit. 43, 1931(2011)

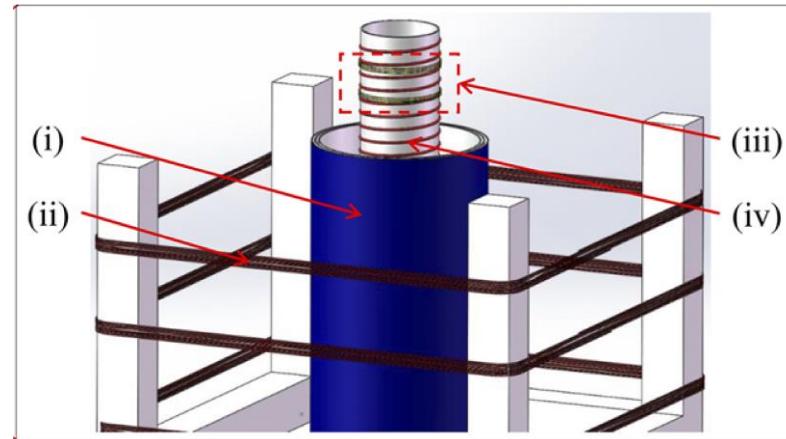


Magnetic shield
 $11.4 \text{ m}, 8 \text{ nT } (10 \text{ m})$



Atom source
 $\sim 10^9, 85\text{Rb} \text{ & } 87\text{Rb}$

Magnetic shield



2010 (The first version)

Welding

max-to-min
~600 nT

2017 (The second version)

(i) Welding and annealing

(ii) External compensation

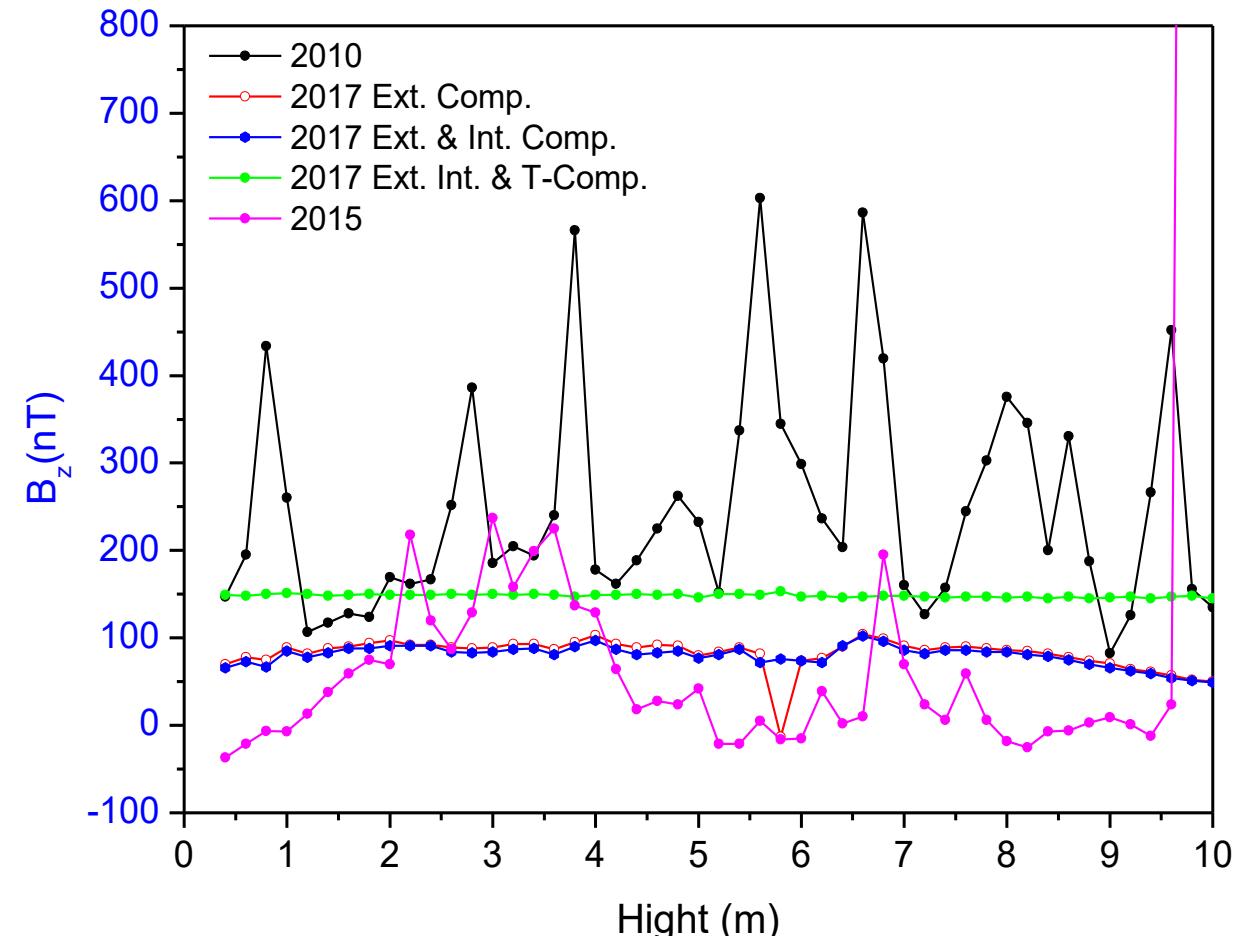
(iii) Internal compensation

(iv) C-field compensation

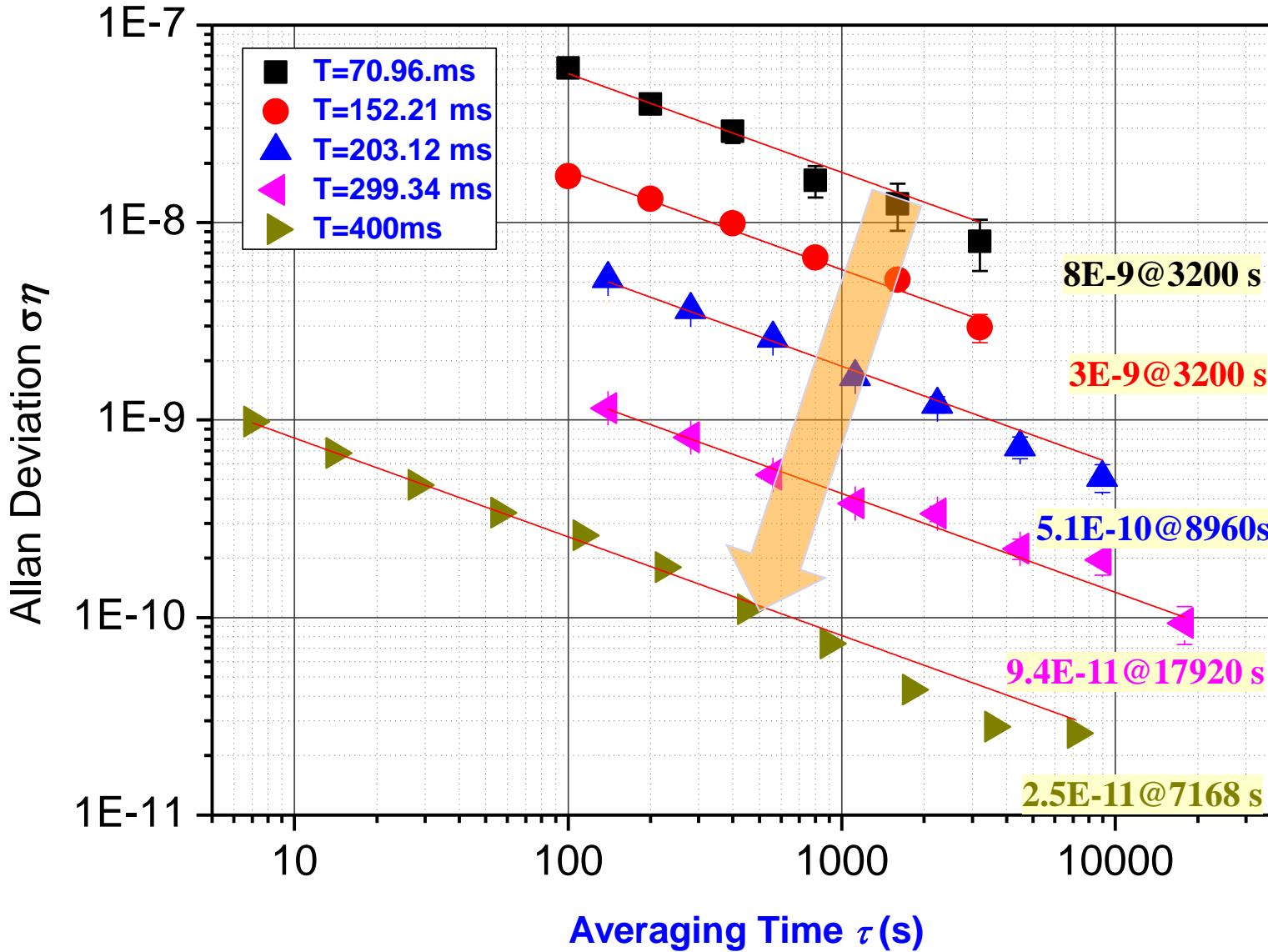
175 nT

55 nT

8 nT



Improvement of the precision



2015 T=70.96ms

2016 T=152.21ms

2018 T=203.16 ms
Optimizing laser system

2018 T=299.34 ms
Coriolis effect compensation

2022 T=400ms
Phase shear readout

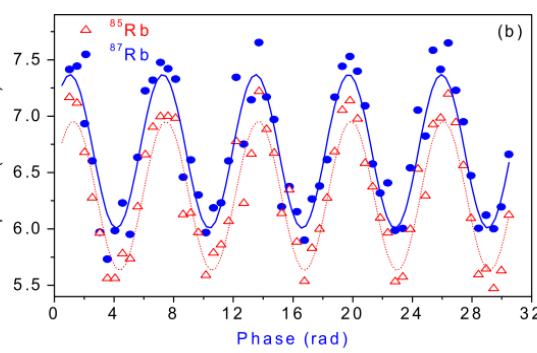
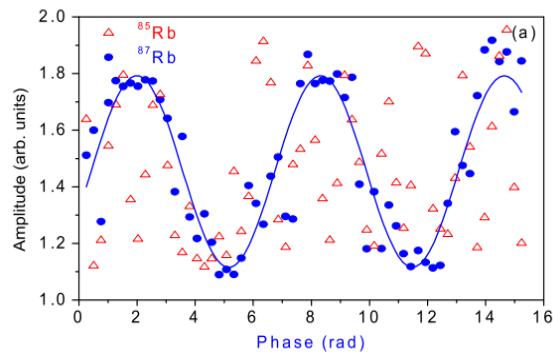
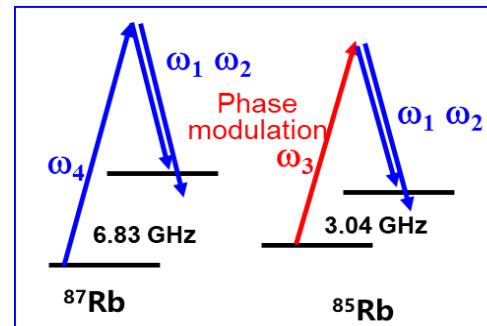
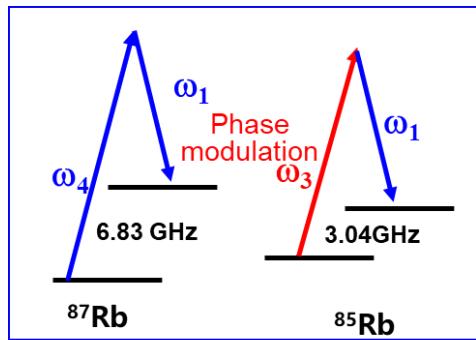
2. 4WDR method and WEP mass-test

Key points for dual species AI scheme

- 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
- Ellipse fitting, $\pi/2$ phase shift difference for minimum fitting error is needed
- State labeled detection, keep high Signal-to-noise ratio detection with cold atoms

Four-wave double-diffraction Raman transition (4WDR) method

Phase noise suppression

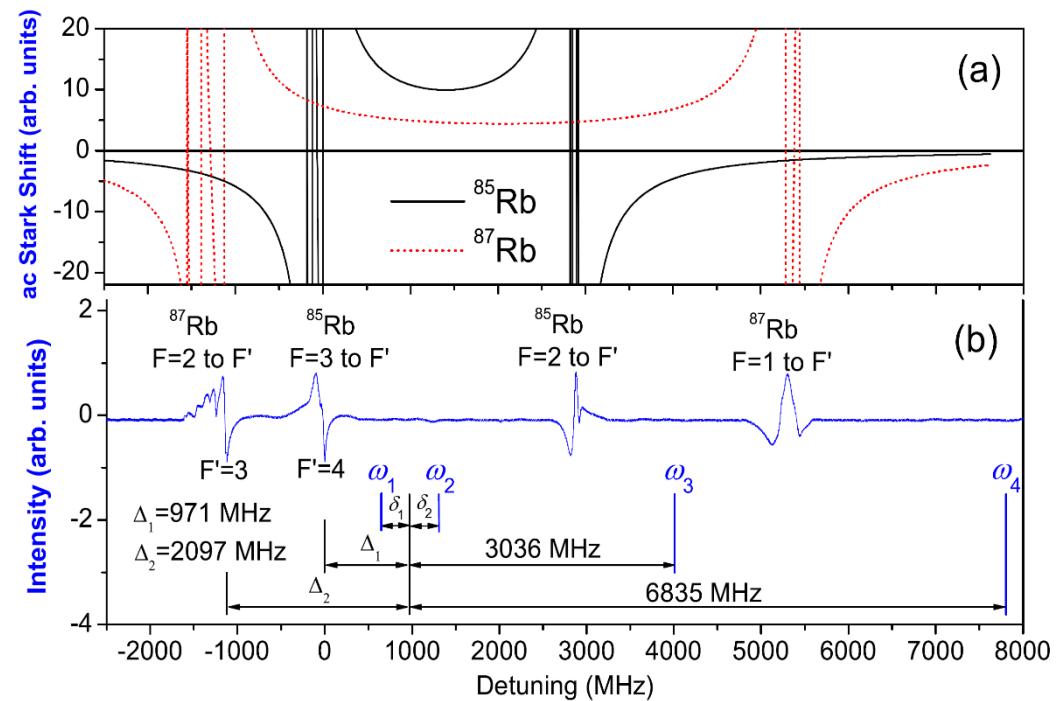


Single diffraction

Double diffraction

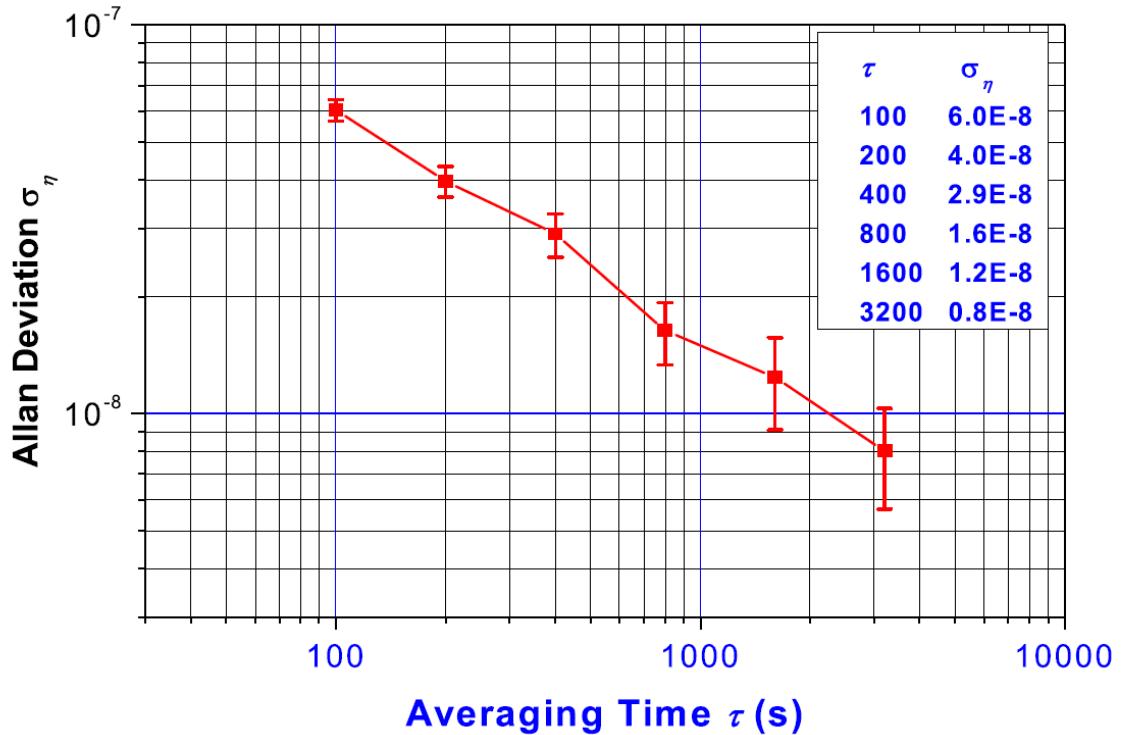
4WDR scheme

^{85}Rb : $\omega_1/\omega_2/\omega_3$
 ^{87}Rb : $\omega_1/\omega_2/\omega_4$



$$\omega_1:\omega_2:\omega_3:\omega_4 = 1.0:1.0:3.1:14$$

Mass test of WEP in 2015

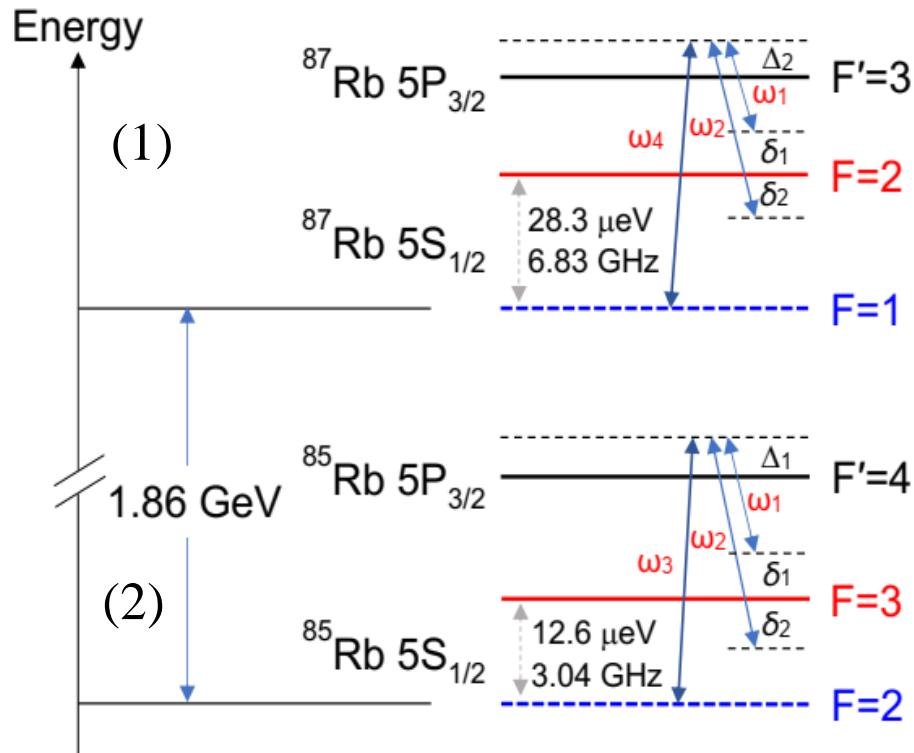


Allan deviation

Error budget

	η ($\times 10^{-8}$)	Uncertainty ($\times 10^{-8}$)
Experimental data	-491.6	0.8
Effective wave vector error	-494.4	0.0
Second order Zeeman shift	0	0.01
Gravity gradient	0.01	0.03
Coriolis effect	0	2.9
ac Stark shift	0	0.2
Total	2.8	3.0

3. 4WDR-e method and WEP jointed test



Relevant sub-levels of ^{85}Rb and ^{87}Rb

$$m_g \approx (1+\alpha')m_i + \beta' \frac{\Delta E}{c^2} \quad \text{Gravitational mass}$$

$$m_i = \frac{E^{\text{LGS}}}{c^2} + \frac{\Delta E}{c^2} \quad \text{Inertial mass}$$

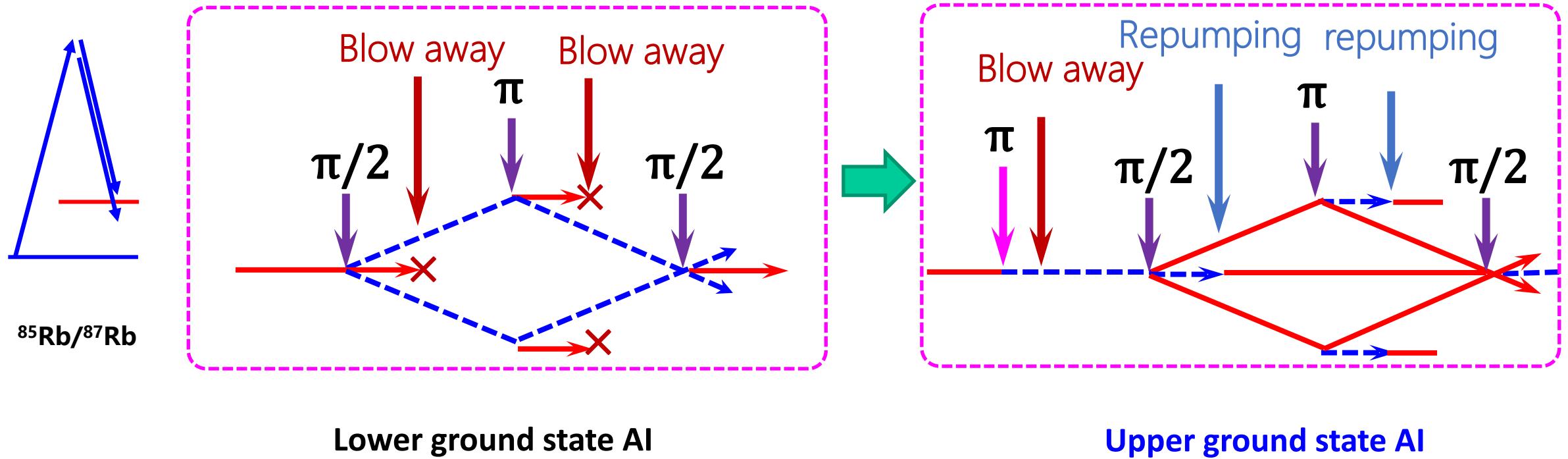
$$m_0 = \frac{E^{\text{LGS}}}{c^2} \quad \text{Rest mass of lower ground state}$$

$$\begin{cases} \eta_1 = \eta_0 \\ \eta_2 = \eta_0 - \beta \varepsilon^{85} \\ \eta_3 = \eta_0 + \beta \varepsilon^{87} \\ \eta_4 = \eta_0 + \beta (\varepsilon^{87} - \varepsilon^{85}) \end{cases}$$

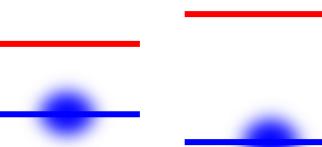
- $\eta_1: {}^{85}\text{Rb } |F=2\rangle - {}^{87}\text{Rb } |F=1\rangle$
- $\eta_2: {}^{85}\text{Rb } |F=2\rangle - {}^{87}\text{Rb } |F=2\rangle$
- $\eta_3: {}^{85}\text{Rb } |F=3\rangle - {}^{87}\text{Rb } |F=1\rangle$
- $\eta_4: {}^{85}\text{Rb } |F=3\rangle - {}^{87}\text{Rb } |F=2\rangle$

4WDR-e method

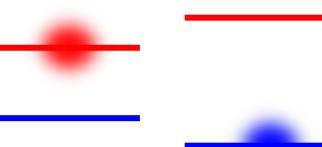
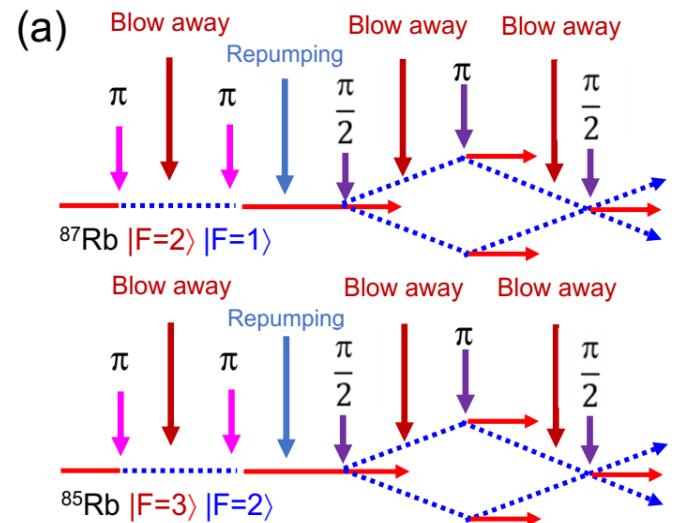
4WDR-e method: Lower ground state AI+ Upper ground state AI



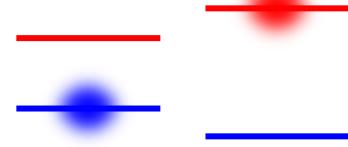
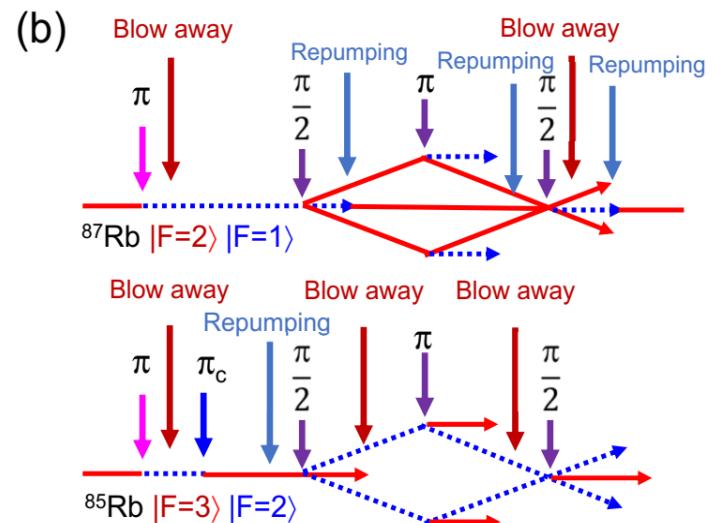
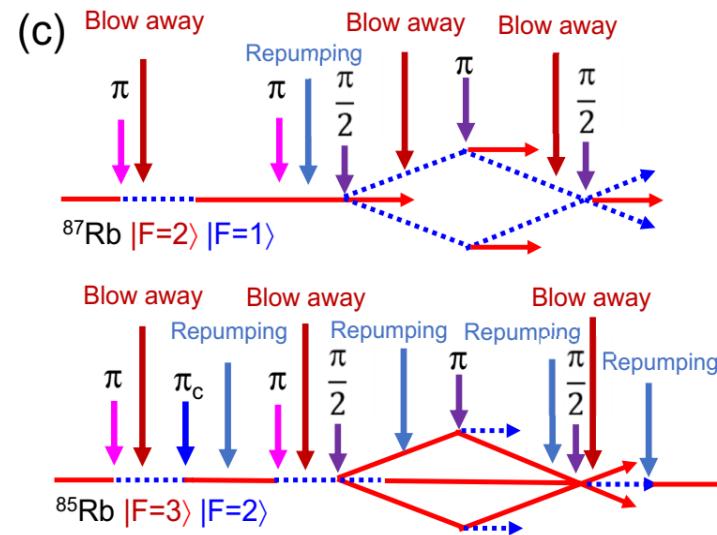
4WDR-E dual-species Als



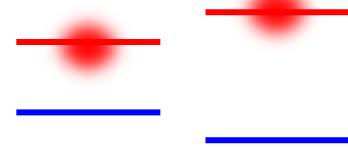
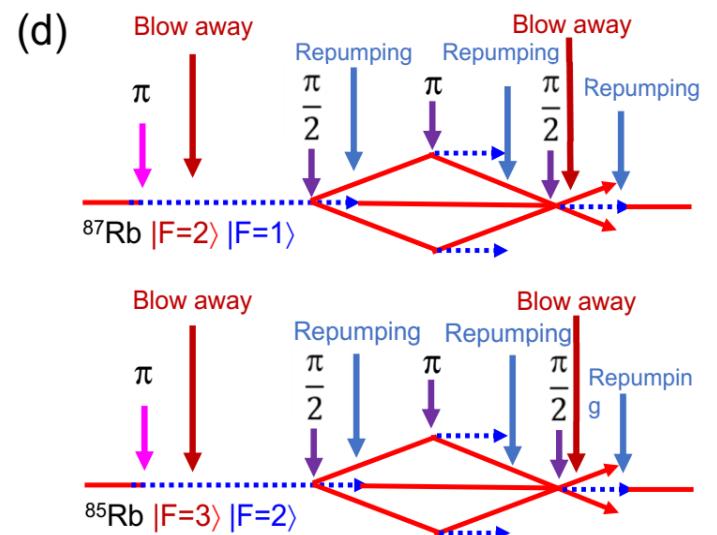
^{85}Rb ^{87}Rb



^{85}Rb ^{87}Rb

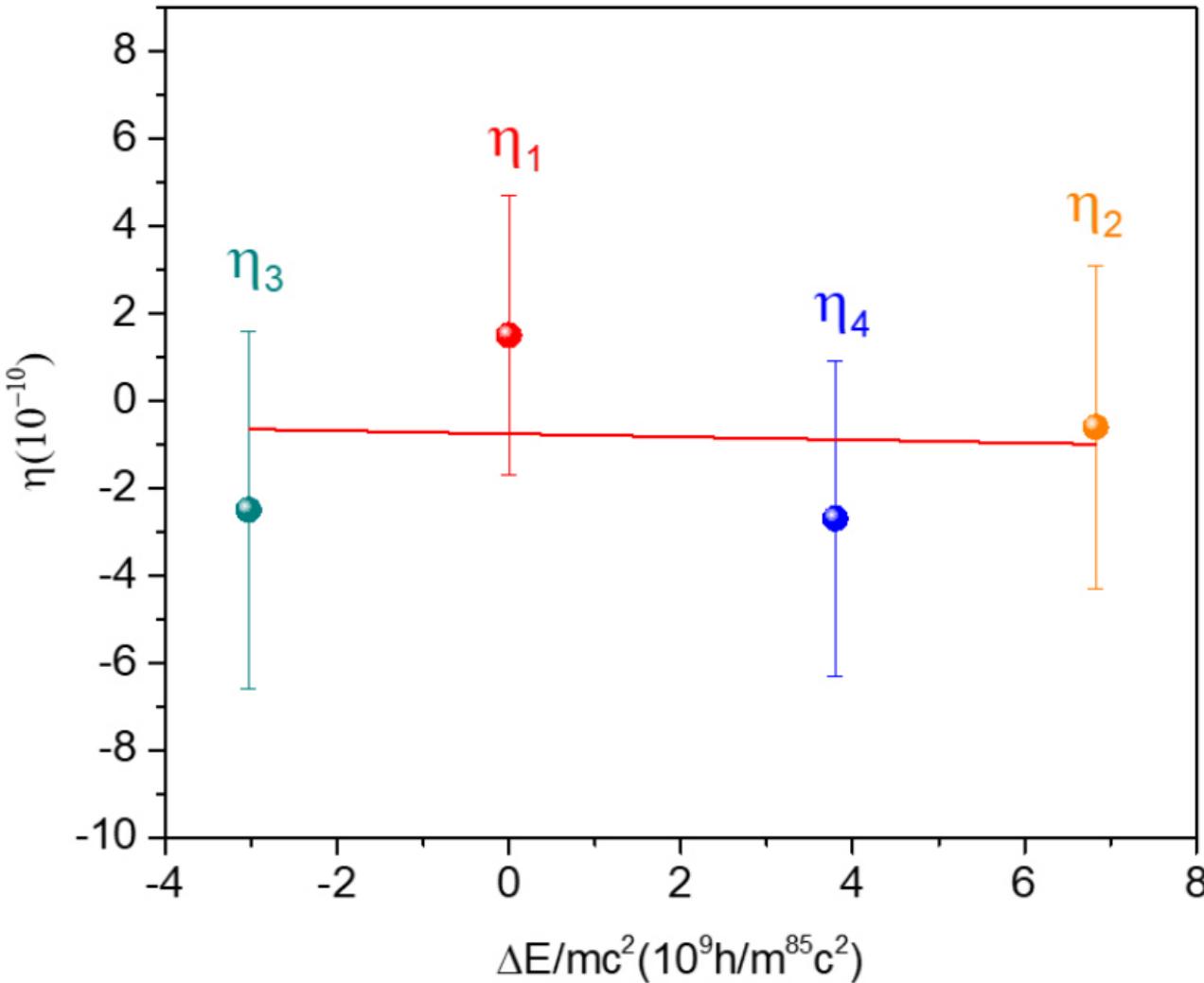


^{85}Rb ^{87}Rb



^{85}Rb ^{87}Rb

Violation parameter of jointed WEP tests



$$\begin{array}{ll} {}^{85}\text{Rb } |F=2\rangle - {}^{87}\text{Rb } |F=1\rangle: & \eta_1 = (1.5 \pm 3.2) \times 10^{-10} \\ {}^{85}\text{Rb } |F=2\rangle - {}^{87}\text{Rb } |F=2\rangle: & \eta_2 = (-0.6 \pm 3.7) \times 10^{-10} \\ {}^{85}\text{Rb } |F=3\rangle - {}^{87}\text{Rb } |F=1\rangle: & \eta_3 = (-2.5 \pm 4.1) \times 10^{-10} \\ {}^{85}\text{Rb } |F=3\rangle - {}^{87}\text{Rb } |F=2\rangle: & \eta_4 = (-2.7 \pm 3.6) \times 10^{-10} \end{array}$$

Violation parameter of mass :

$$\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$$

Violation parameter of internal energy :

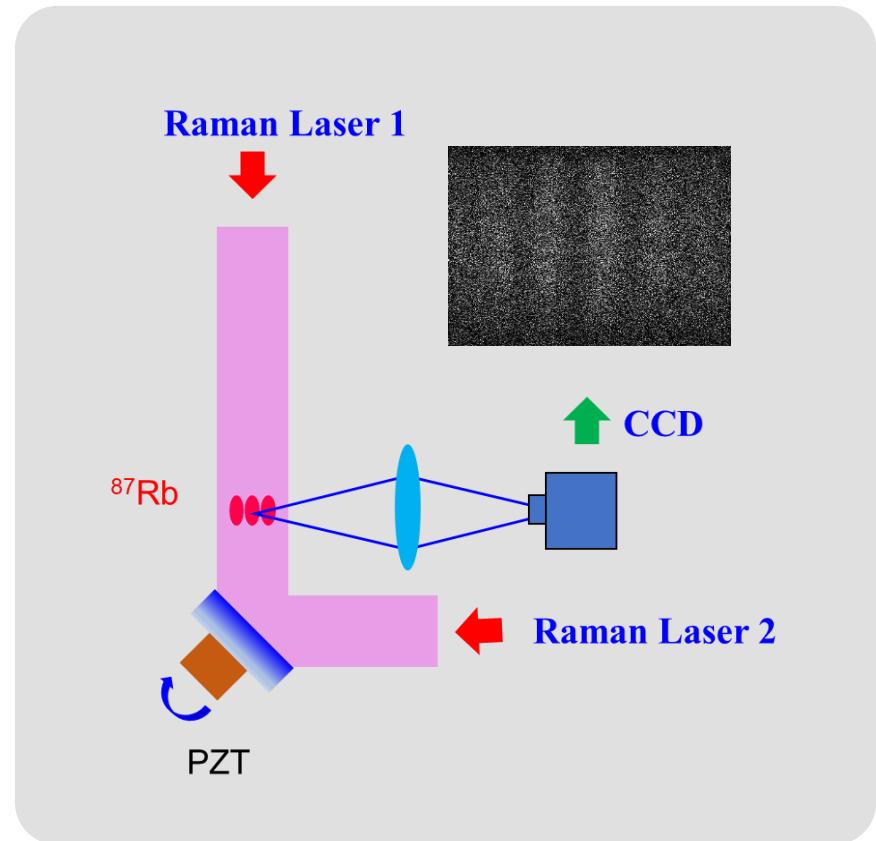
$$\eta_E = (0.0 \pm 0.4) \times 10^{-10} \quad (\text{per } 10^9 h/m_i^{85}c^2)$$

WEP tests with AI

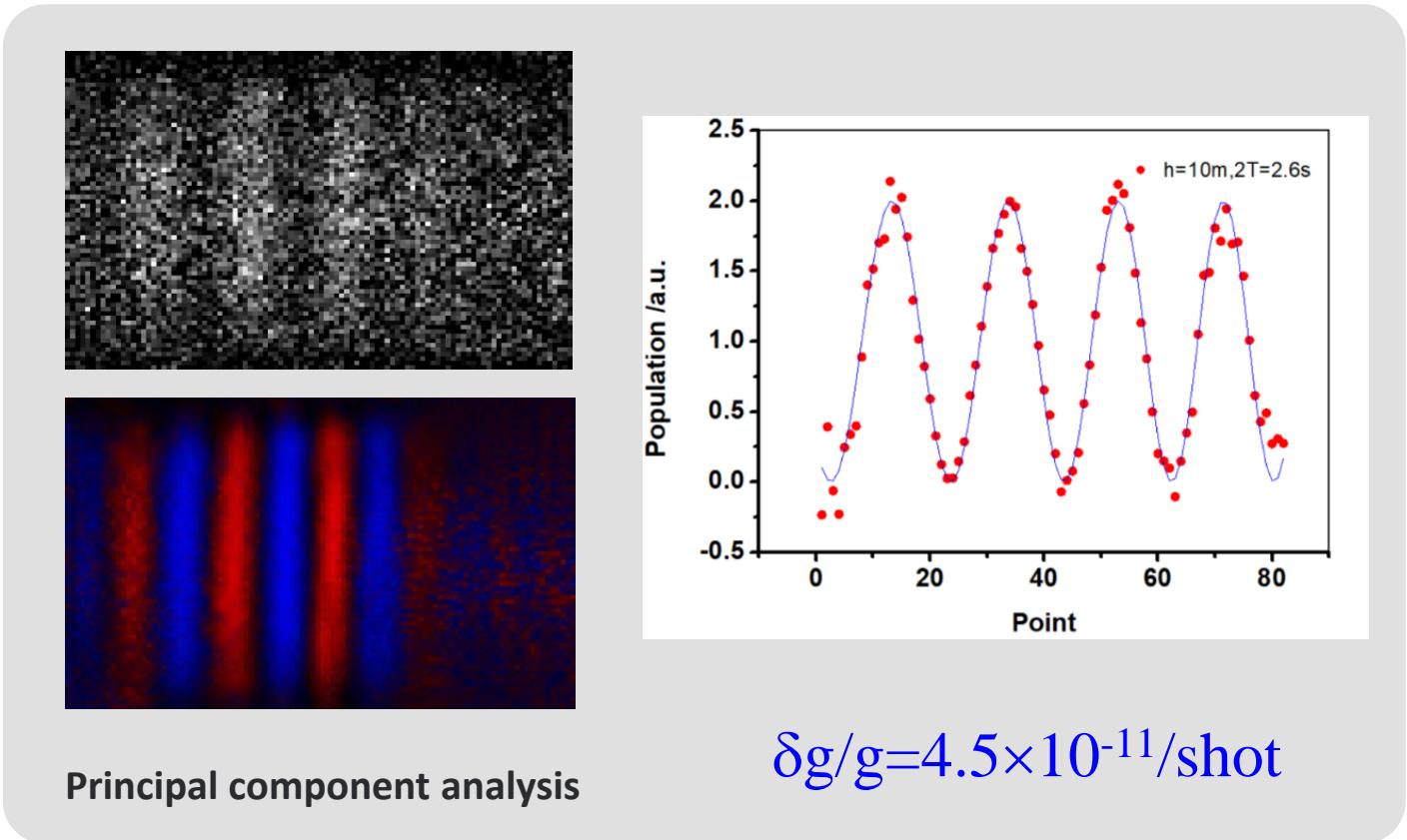
Mass pair	$F-F'$	ΔE	η_i	η_E	Ref.
^{85}Rb - ^{87}Rb	2-1	1.86 GeV	$(1.2 \pm 1.7) \times 10^{-7}$		<i>Phys. Rev. Lett.</i> (2004)
^{85}Rb - ^{87}Rb	mixed	1.86 GeV	$(1.2 \pm 3.2) \times 10^{-7}$		<i>Phys. Rev. A</i> (2013)
^{39}K - ^{87}Rb	mixed	44.66 GeV	$(0.3 \pm 5.4) \times 10^{-7}$		<i>Phys. Rev. Lett.</i> (2014)
^{85}Rb - ^{87}Rb	2-1	1.86 GeV	$(2.8 \pm 3.0) \times 10^{-8}$		<i>Phys. Rev. Lett.</i> (2015)
^{39}K - ^{87}Rb	mixed @ 0g	44.66 GeV	$(0.9 \pm 3.4) \times 10^{-4}$		<i>Nat. Commun.</i> (2016)
^{39}K - ^{87}Rb	mixed	44.66 GeV	$(-1.9 \pm 3.2) \times 10^{-7}$		<i>Eur. Phys. J. D</i> (2020)
^{88}Sr - ^{87}Sr	0-9/2	0.93 GeV	$(0.2 \pm 1.6) \times 10^{-7}$		<i>Phys. Rev. Lett.</i> (2014)
^{85}Rb - ^{87}Rb	3-2	1.86 GeV	$(1.6 \pm 3.8) \times 10^{-12}$		<i>Phys. Rev. Lett.</i> (2020)
^{85}Rb	2-3	3.04 GHz	$(0.4 \pm 1.2) \times 10^{-7}$	$(0.1 \pm 0.4) \times 10^{-7}$	<i>Phys. Rev. Lett.</i> (2004)
^{87}Rb	$m_F = \pm 1$		$(1.2 \pm 3.2) \times 10^{-7}$		<i>Phys. Rev. Lett.</i> (2016)
^{87}Rb	1-2	6.83 GHz	$(1.4 \pm 2.8) \times 10^{-9}$	$(0.2 \pm 0.4) \times 10^{-9}$	<i>Nat. Commun.</i> (2017)
^{87}Rb	1-1 \oplus 2		$(3.3 \pm 2.9) \times 10^{-9}$		<i>Nat. Commun.</i> (2017)
^{87}Rb	1-2	6.83 GHz	$(0.9 \pm 2.7) \times 10^{-10}$	$(0.1 \pm 0.4) \times 10^{-10}$	<i>Chin.Phys.Lett.</i> (2020)
^{85}Rb - ^{87}Rb	2-1	1.86 GeV + 0.00 GHz	$\eta_1 = (1.5 \pm 3.2) \times 10^{-10}$		
^{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	$\eta_3 = (-2.5 \pm 4.1) \times 10^{-10}$		<i>Phys. Rev. A</i> (2021)
^{85}Rb - ^{87}Rb	3-2	1.86 GeV + 3.79 GHz	$\eta_4 = (-2.7 \pm 3.6) \times 10^{-10}$		
			$\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$	$(0.0 \pm 0.4) \times 10^{-10}$	

4. Recent progress

Phase shear readout

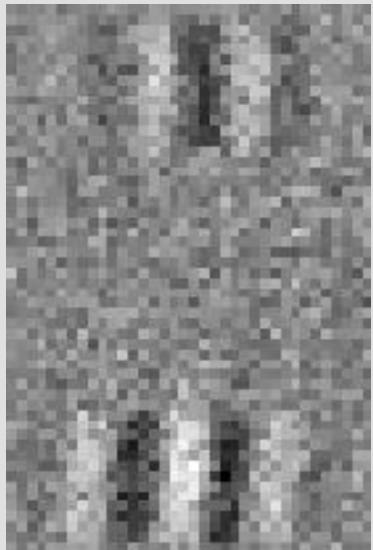


Interference fringe with T=1300 ms

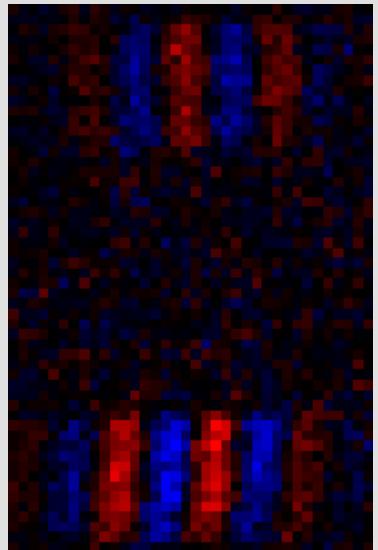


Dual-species atom interferometer

Interference fringe

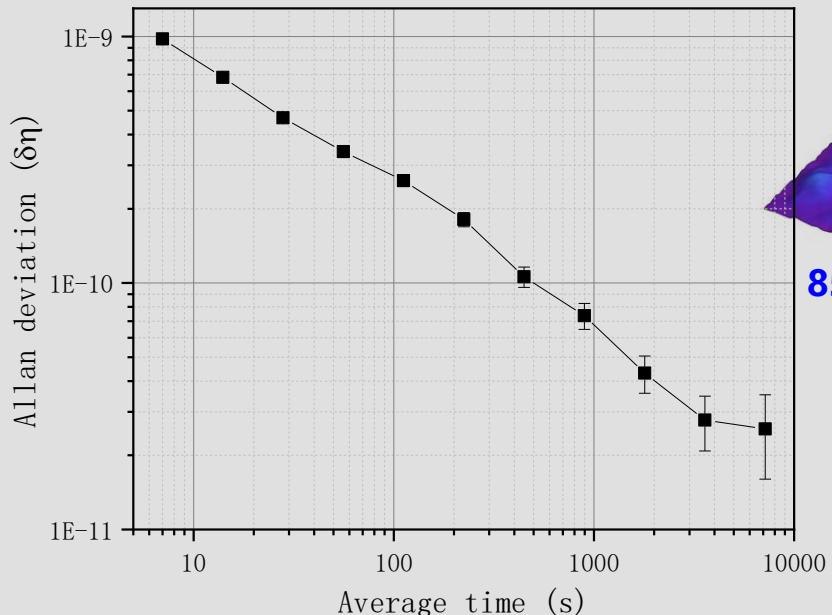


^{87}Rb



^{85}Rb

Allan deviation



$T=2000$ ms

$\Delta\eta=5 \text{ E-}10 / \text{shot}$

(Detected by a horizontal laser)

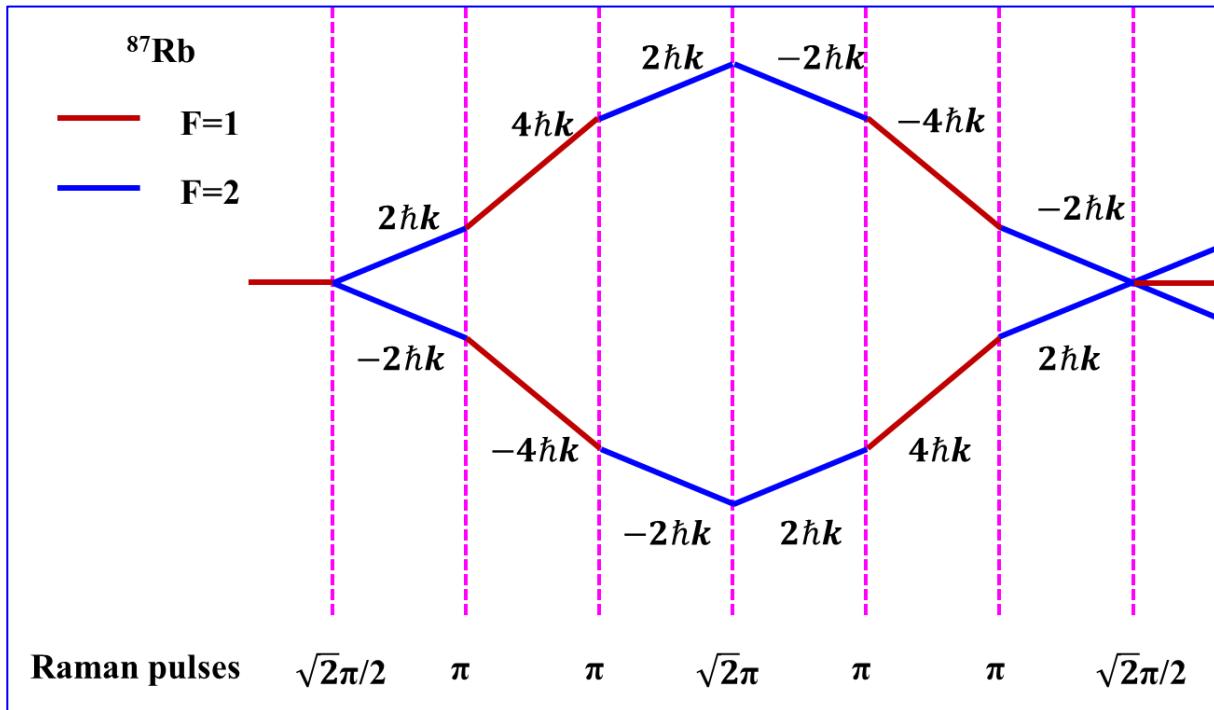
$T=400$ ms

$\Delta\eta=2.5 \text{ E-}11 @ 7168 \text{s}$

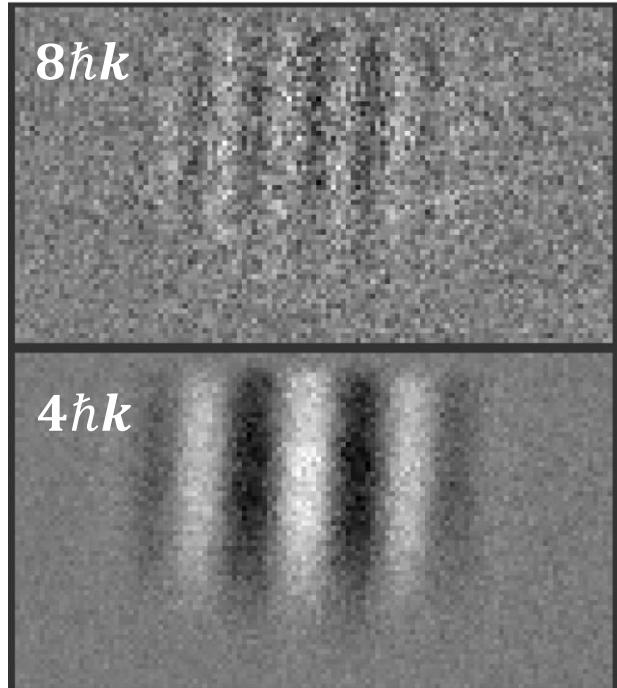
(Detected by a vertical laser)

Large Momentum Transfer (LMT) with 4WDR

LMT with $8\hbar k$



Interference fringes



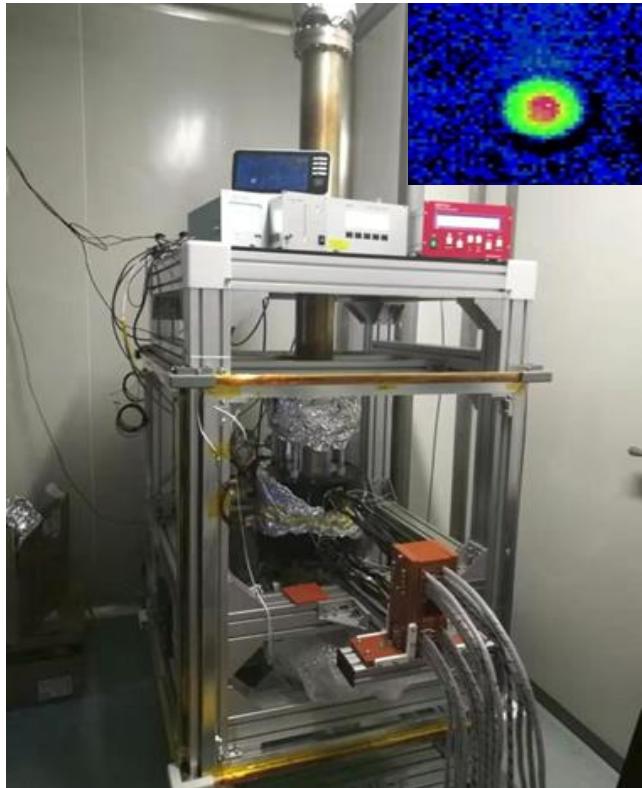
4WDR-E scheme

⁸⁵Rb: $\omega_1/\omega_2/\omega_3$
⁸⁷Rb: $\omega_1/\omega_2/\omega_4$

Independent frequency shift compensation for photon recoils
 $(^{85}\text{Rb}:\omega_3, ^{87}\text{Rb}:\omega_4)$

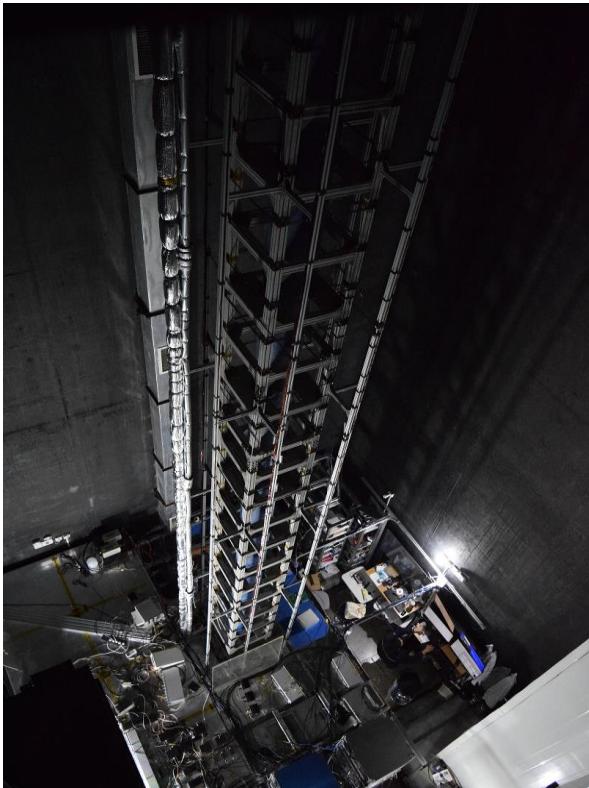
Future plan: Jointed test of WEP @ E-12~E-13

Ultracold atom source



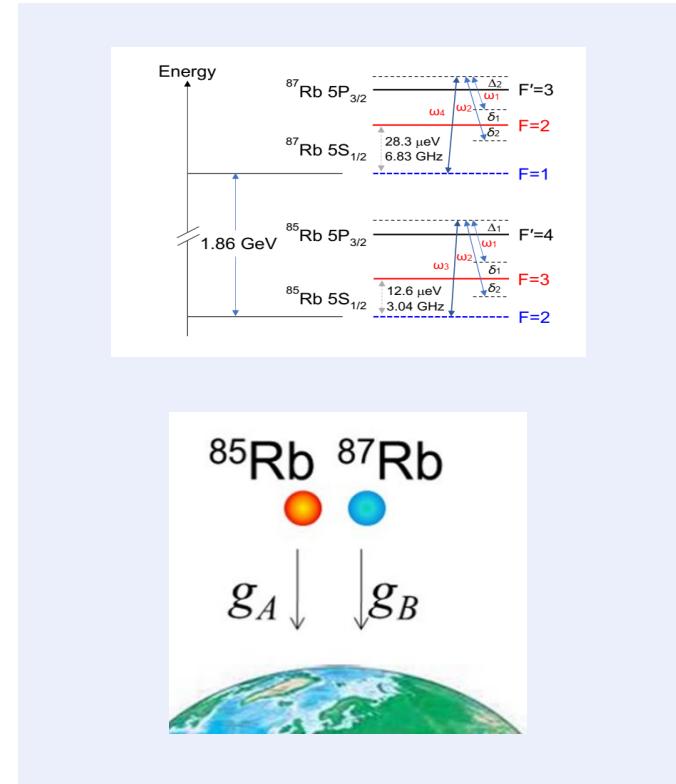
$^{85}\text{Rb}/^{87}\text{Rb}$ ultra-cold atom source
100nK, 10^5 atoms

Long baseline AI



4WDR AI
 $T \sim 1.43\text{s}$, 4-20 $\hbar k$

Jointed test



Mass, internal energy test
 $\eta: 10^{-12} \sim 10^{-13}$

Acknowledgments

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Graduate students: Si-Tong Yan, Yu-Hang Ji, Chao Zhou, Qi Wang, Zhuo Hou, Jun-Jie Jiang, Jia-Qi, Lei



Thank you for your attention!