The progress of ZAIGA project

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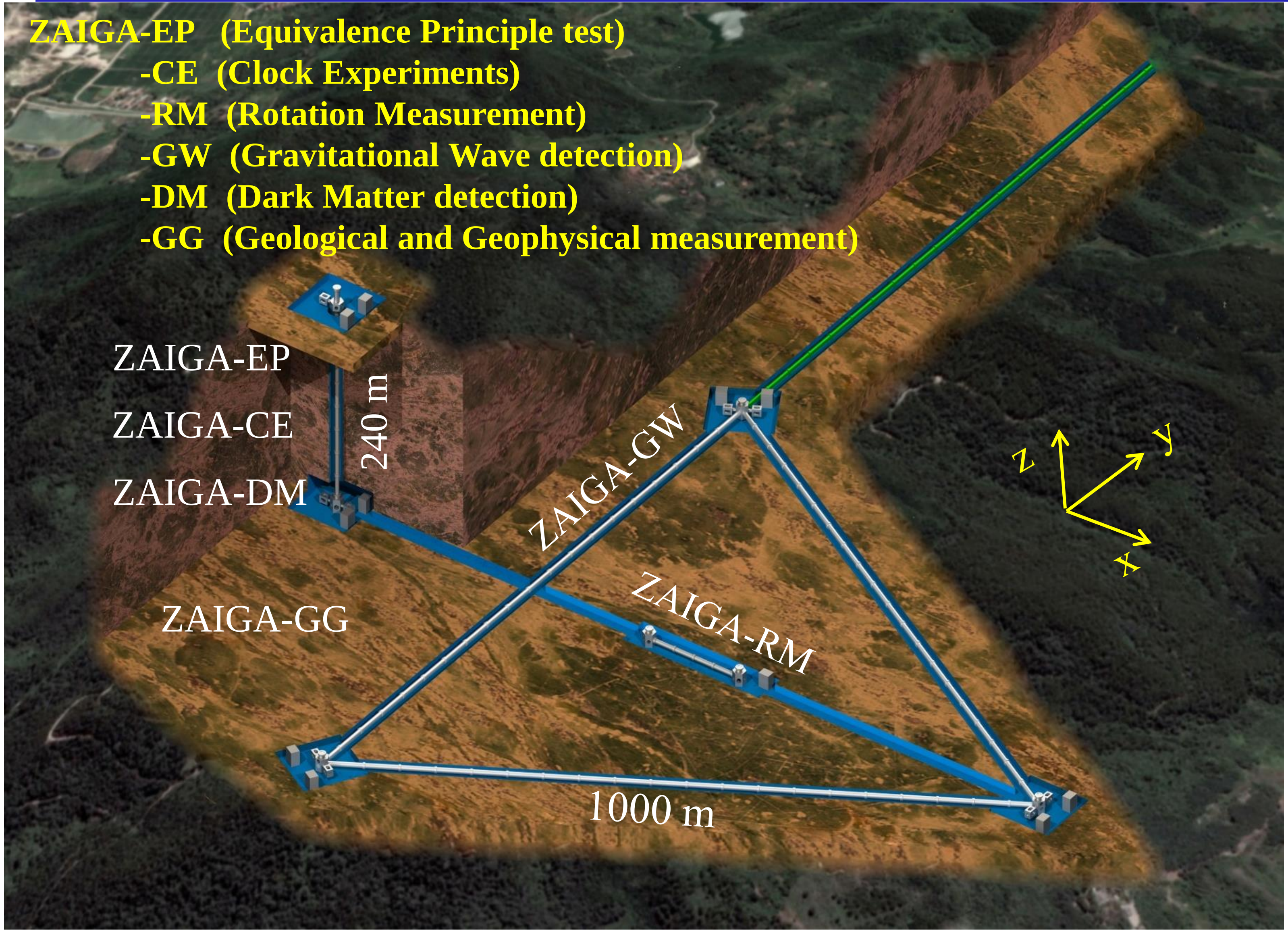
Outline

Overview of ZAIGA

Environment and infrastructure design

Key unit technologies

Plan and Design



A platform to test gravity theory with large scale atomic interferometers, gyros and optical clocks

- Equivalence Principle test
  — 10-m AIs, 240-m AI
- Clock Experiments
  — Sr clocks
- Rotation Measurement
  — 20-m gyros
- Gravitational Wave detection
  — AI array (⊥, //)、clocks
- Dark Matter detection
  — AI array (⊥, //)、clocks
- Geological and Geophysical measurement
  — gravimeters, seismometers

Mingsheng Zhan *et al.*, *Intl. J. Mod. Phys. D* **29**,1940005 (2020); arXiv:1903.09288

Mission assignment

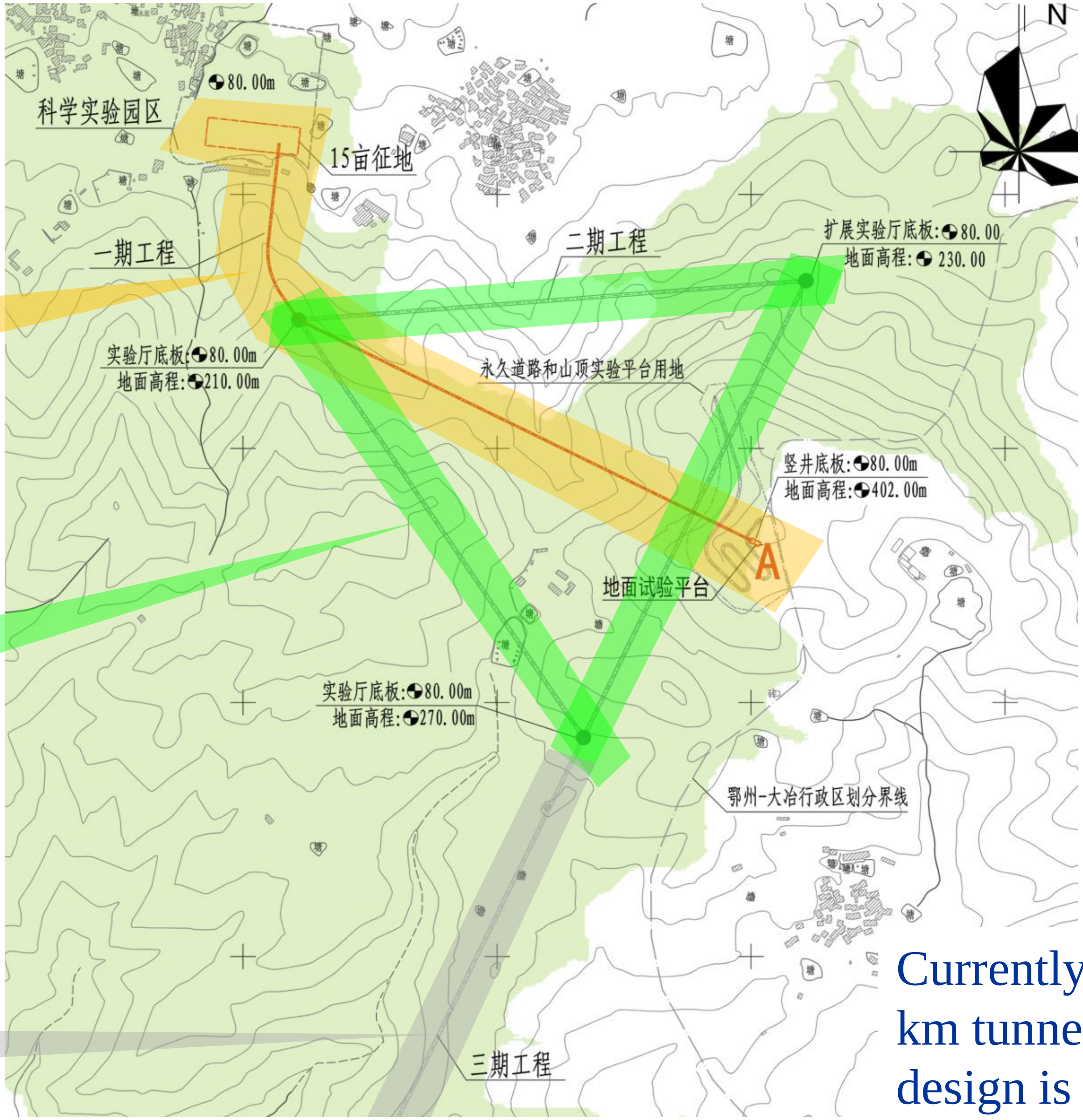
3 Phases

10000 m² Scientific research park on the mountain foot

Phase-I
Funded
¥ 450M (€ 60M)
(2022-2027)

Phase-II
Planned
(2027-2035)

Phase-III
Reserved

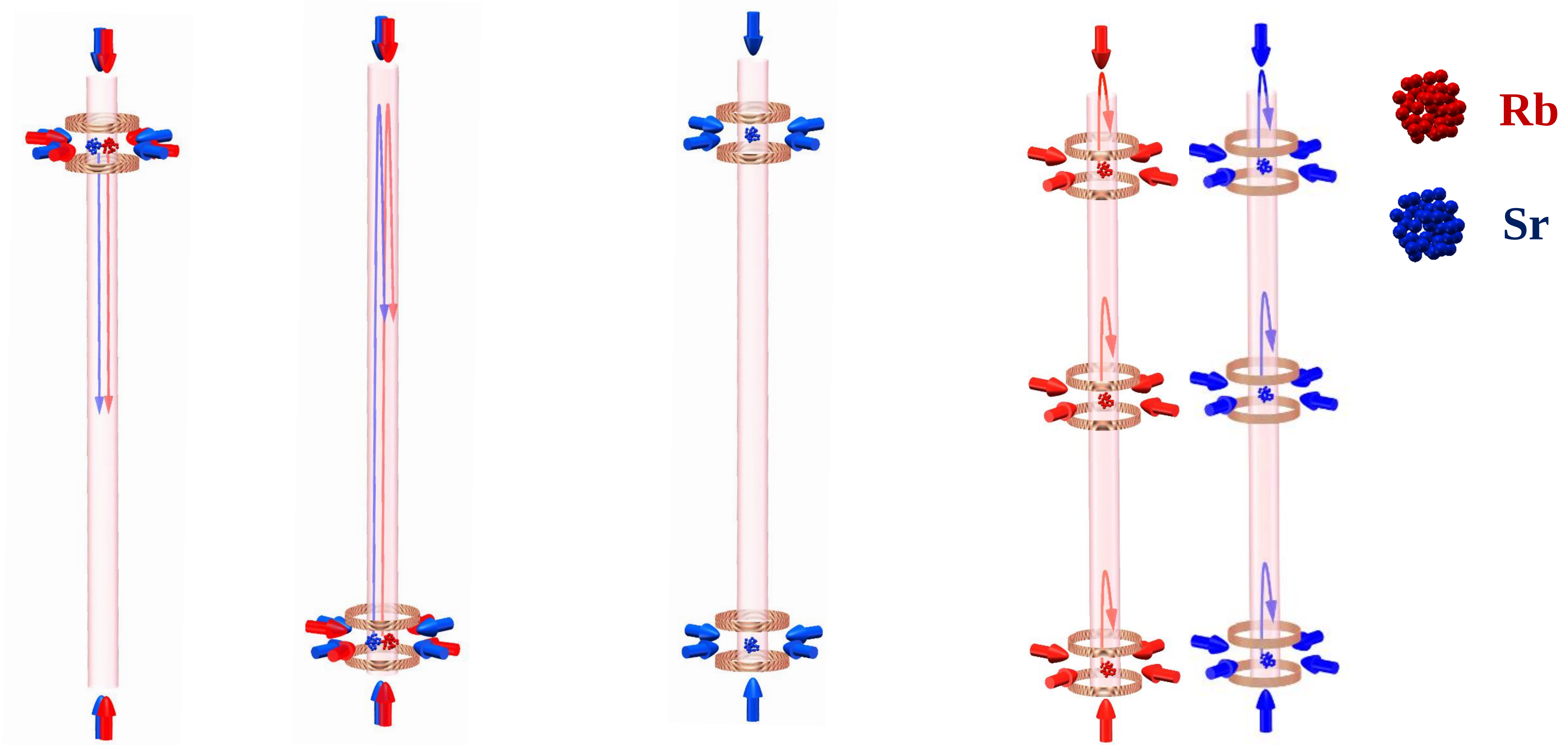


Horizontal tunnel (1.4 km)

Core experimental area inside the mountain: a 240m shaft and an experimental hall

Currently, Phase I（240 m shaft + 1.4 km tunnel）is funded, and preliminary design is under way.

Phase I： diversity in the 240 m AI



240 m AI FF/Fountain dual-species　　Clock Compar.　　Gravity Gradient

QM、EP test　　Redshift Exp.　　GW、DM

Phase I Goals: building abilities

Item	Project Goal
AI baseline (Free fall time)	240 m ($T \geq$ 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 (2×10^{-6} °/h)
Stability of Sr/Yb optical clock	2×10^{-18}
Local gravity monitoring	1 μGal

Main parameter design

Item	EP	GW	DM
Vacuum pressure	~1×10^{-8}Pa（Collision loss of Rb：1.3%@3s，6%@14s）		
Diameter of vacuum pipe	200mm（Rotation compensation: ±30mm@240m，T=7s）		
Magnetic field fluctuation	<10 nT (Rb)	<10 nT (Rb) ~100 nT（Sr）	<10 nT (Rb) ~100 nT（Sr）
Atom number	10^5~10^6/shot	~10^6/shot	~10^6/shot
Laser power	>10W（780 nm）	>5W（698 nm）	>5W（Sr，698 nm，689nm） >10W（Rb，780 nm）

U. D. Rapol, A. Wasan et al. arXiv:physics/0204022v1
J. Glick, Z. Chen et al. AVS Quantum Sci. 6, 014402 (2023)
Mingsheng Zhan *et al*., *Intl. J. Mod. Phys. D* **29**,1940005 (2020)

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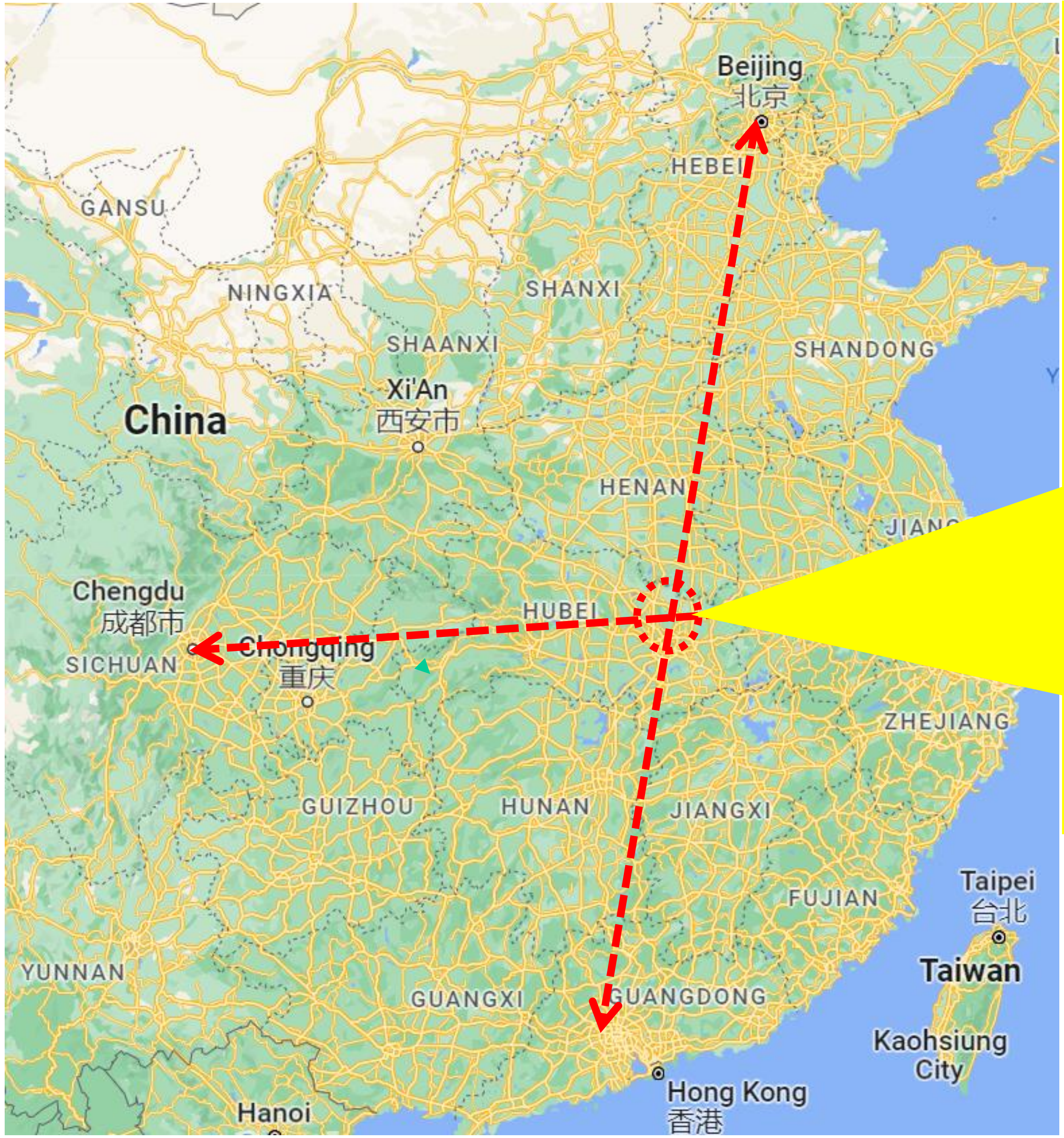
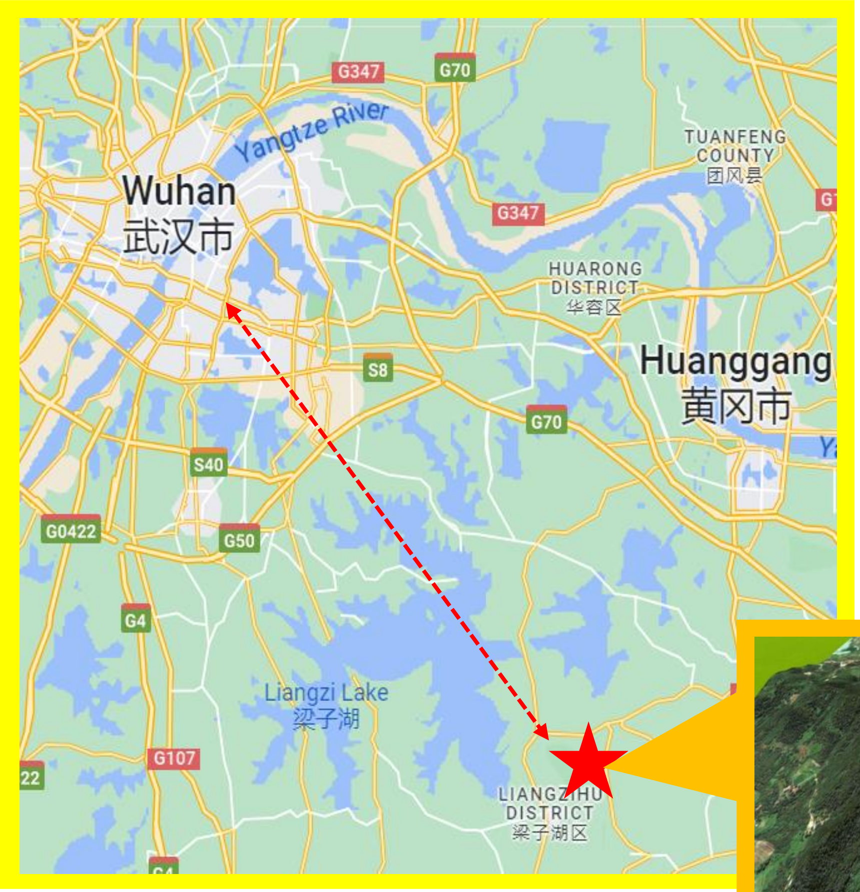
The Site

location





Zhaoshan
(Mountain Zhao)

About mountain Zhao (Zhaoshan)

The weather in Mountain Zhao

Location: E 114.67° and N 30.17°
Mean annual precipitation: 1476.8 mm.
Mean annual evaporation: 1480.7 mm.
Annual average temperature: 17.35 ℃.
Average air temperature in July and August: 29.3 ℃ .
Average air temperature in January: 4 ℃ .
Average annual frost days: 29.8 days.

Underground water

Bedrock fissure water with a general burial depth of 10-80 meters.
A normal water inflow of 1335.3 m^3/d and a maximum water inflow of 2002.90 m^3/d. (water balance method)
A maximum water inflow of 1037.88 m^3/d and a water inflow of the vertical shaft is 130.61 m^3/d. (groundwater dynamics method)

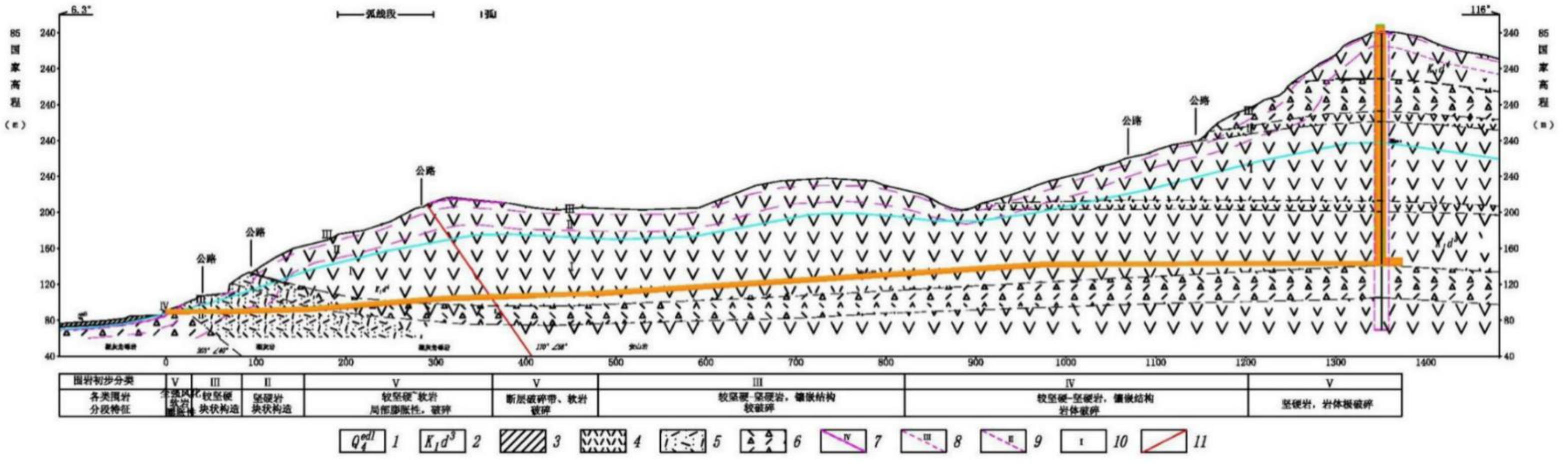
We need to pay attention to underground water.

Mountain Zhao

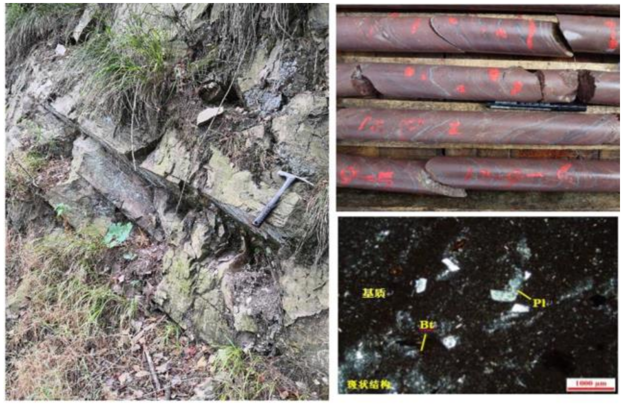
沼山

Area: about 20 km^2
Altitude of main peak: 418.8m

Tunnel engineering geology

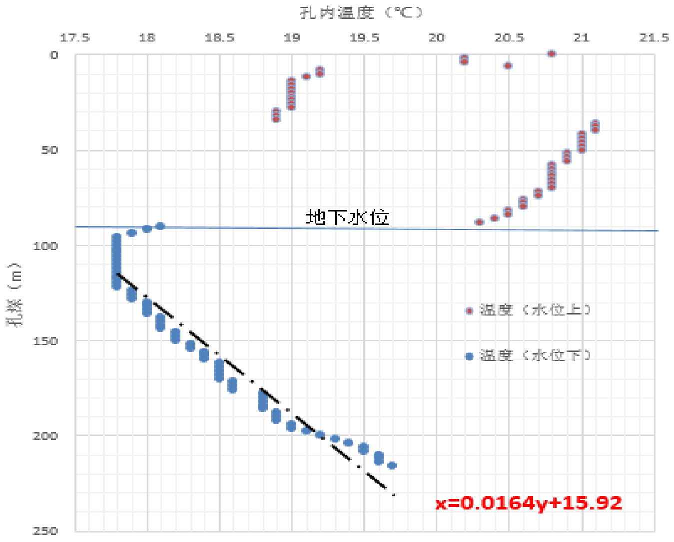


1. Quaternary residual slope deposit; 2. The third section of the Dashi Formation; 3. Loose accumulation layer; 4. Andesite; 5. Tuff; 6. Tuff breccia; 7. Total weathering layer and lower limit; 8. Strong weathering layer and lower limit; 9, medium 10 weathering layer and lower limit; 10. Micro-new rock mass; 11. Faults.

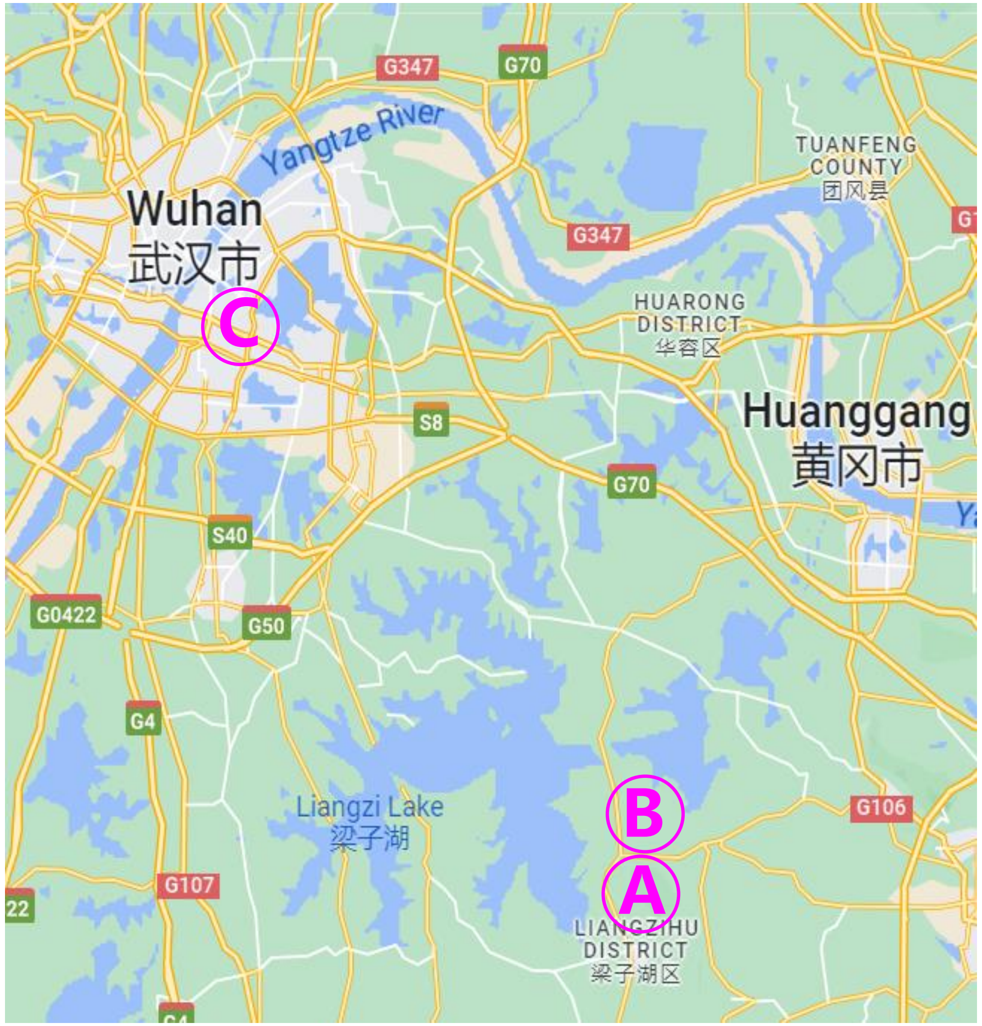


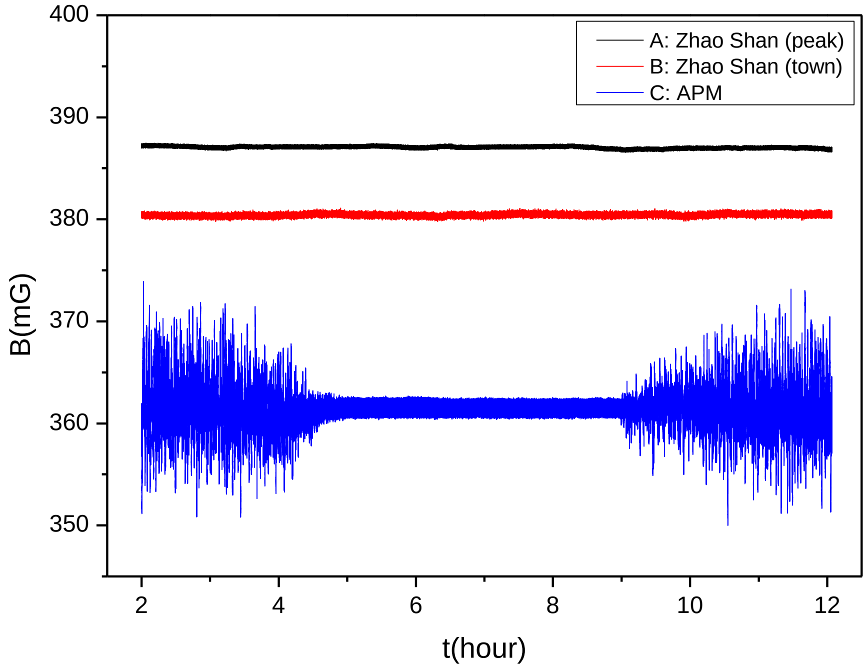
ZAIGA is located in a geologically stable environment，and the engineering geological conditions are favorable.
There are no geologic constraints impeding the construction of the project.

Underground temperature



Background magnetic field noise





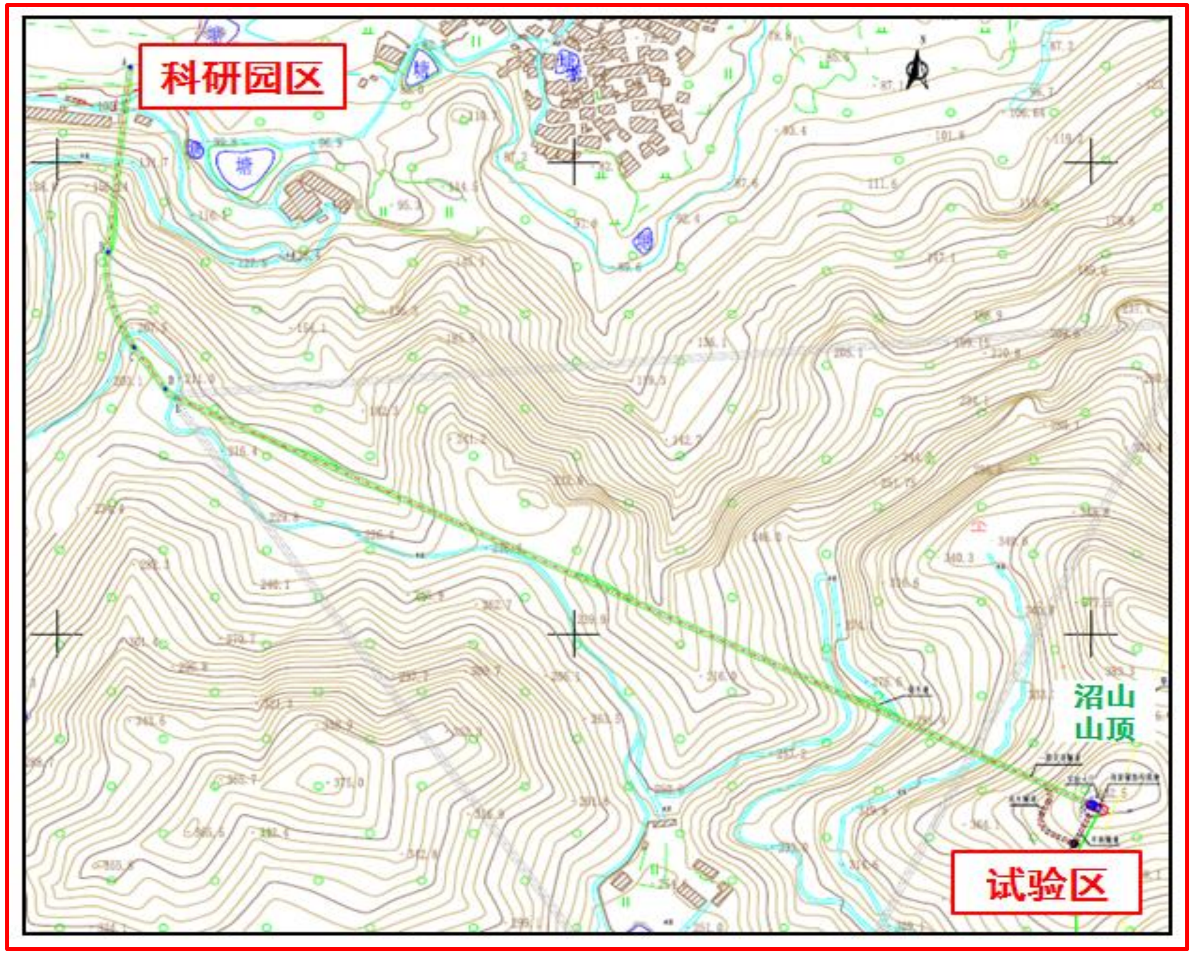
A: Zhao Shan (peak)
~50 nT

B: Zhao Shan (in the town)
~100 nT

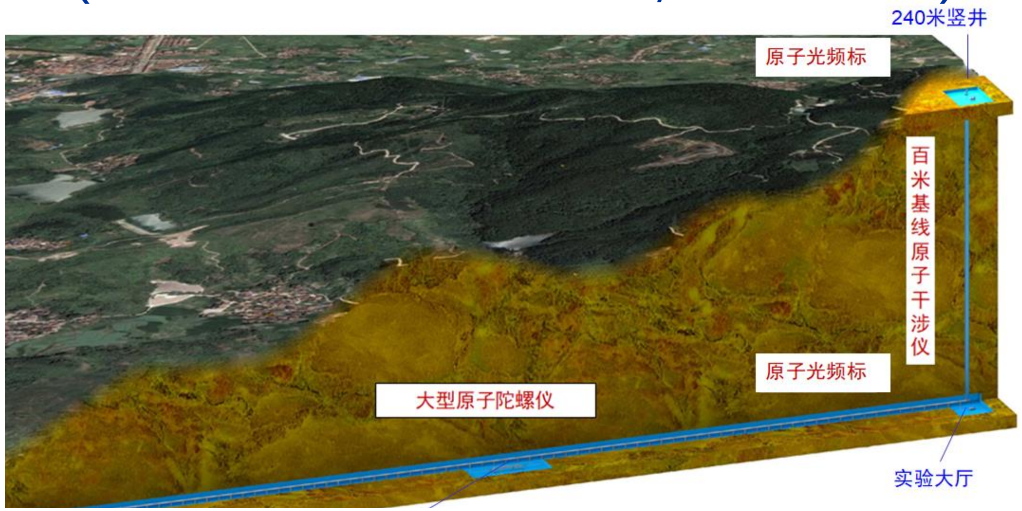
C: APM (in the city)
~2500 nT (Subway in operation)
~300 nT (Subway shut down)

The ZAIGA facility is situated within an ecological conservation zone, ensuring the long-term stability of its surrounding environment.

Phase I: design and sketch

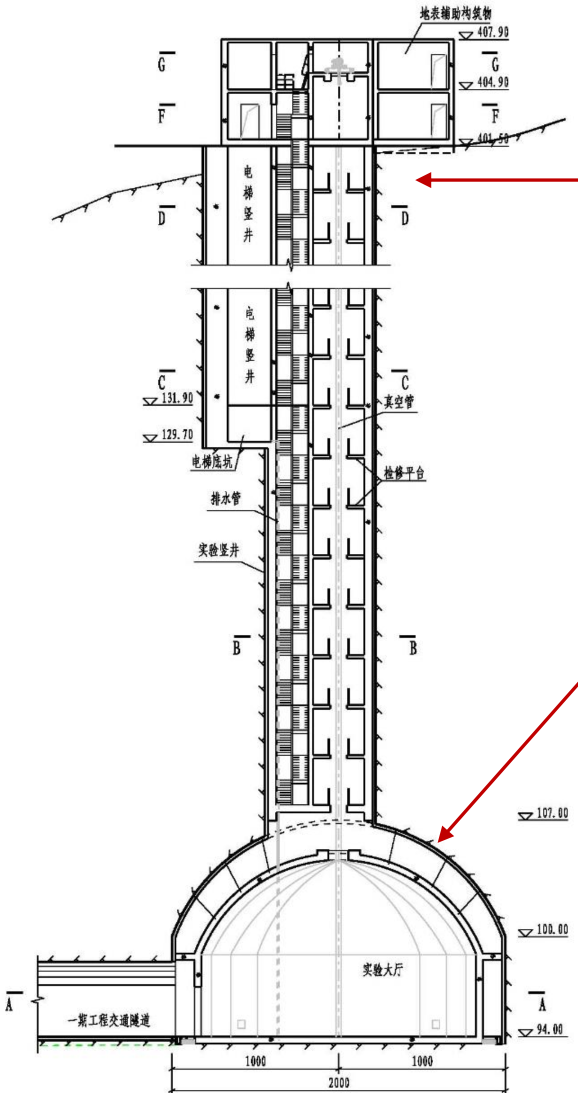


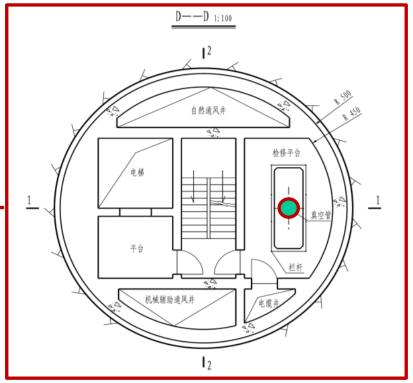
The scientific research park
(on the mountain foot, 10000 m^2)



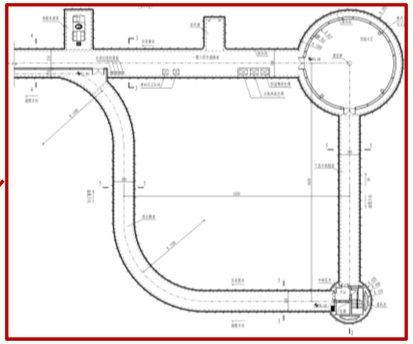
The Shaft and the tunnel
(inside the mountain, 240 m+1400 m)

Phase I: The shaft and the Experimental hall





Shaft of ZAIGA
Height: 228m
Diameter: 9m
Floor height: 3m
Number of floors:76



Experimental hall
Height: 13 m
Area : 200 m^2

To provide more space for future experimental system upgrade and research content expansion, the shaft adopts multi-story design. This kind of design is also convenient for the installation, maintenance of the long baseline atom interferometer.

Outline

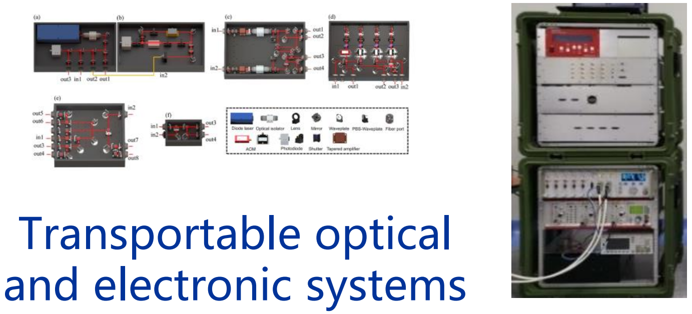
Overview of ZAIGA

Environment and infrastructure design

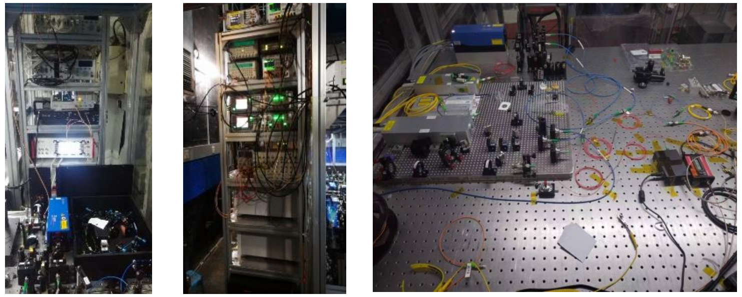
Key unit technologies

Planning of the shaft and the experimental hall

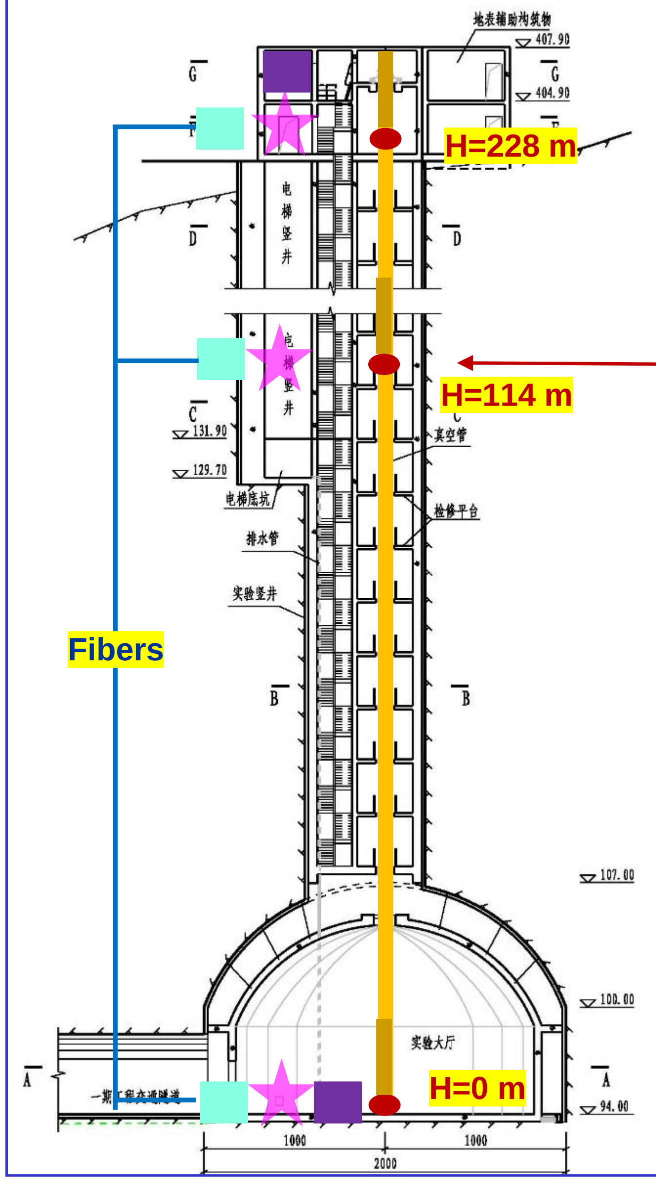
Background environment monitoring

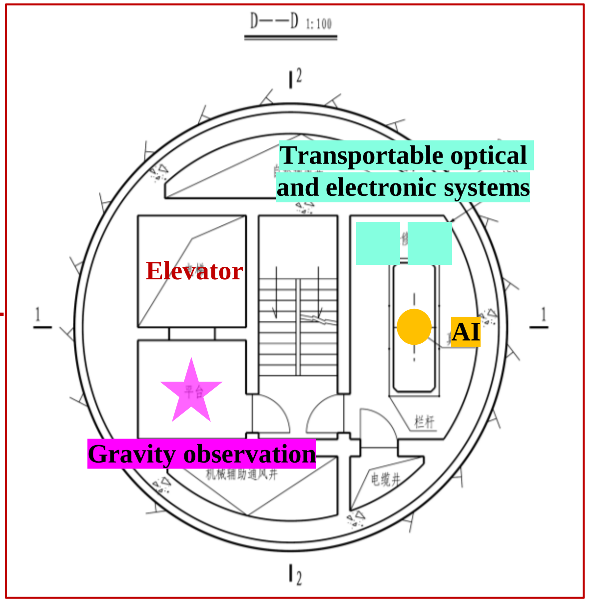


Transportable optical
and electronic systems



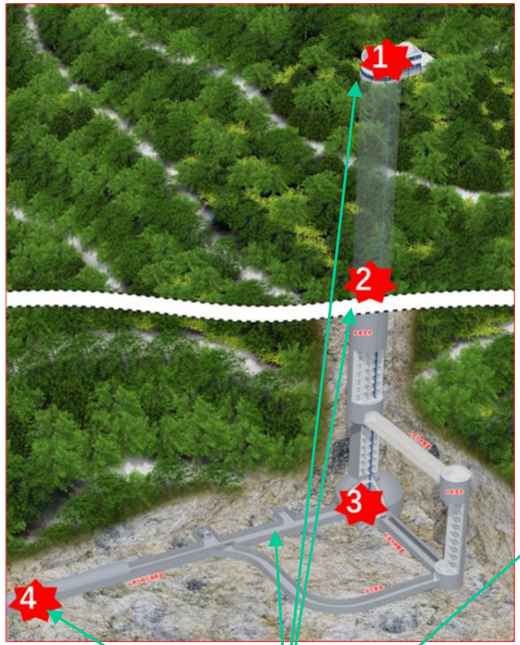
Platform optical and electronic systems

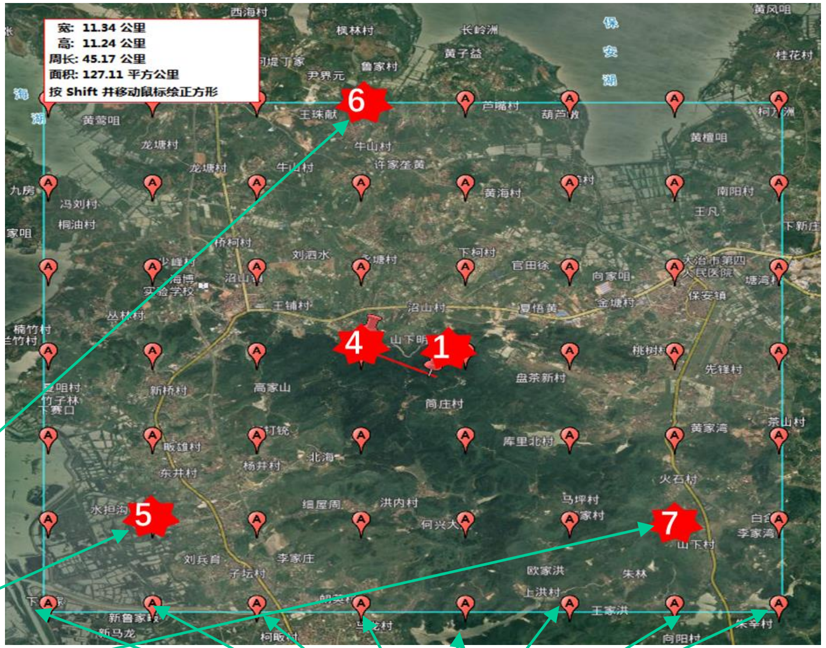


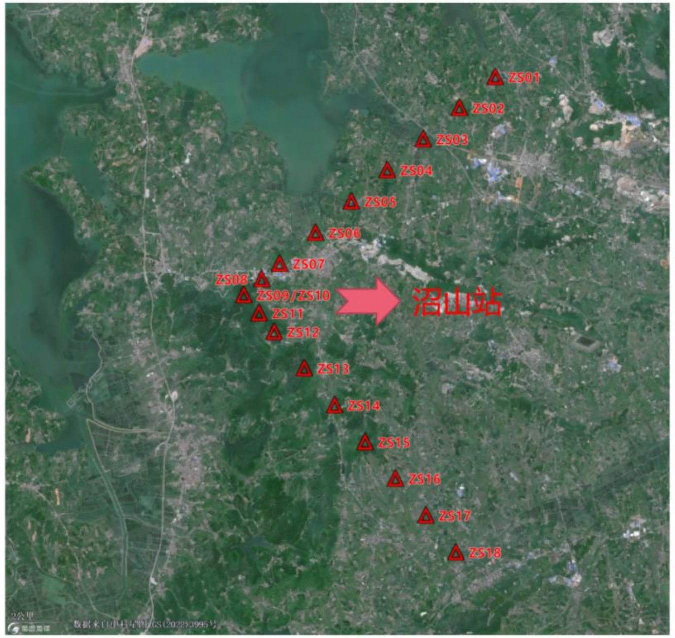


Rb AI × 3 + Sr AI × 3
Sr Clock × 2
Atom Gravimeter× 3
Superconducting gravimeter ×2
Other sensors

Gravity observation networks and platforms





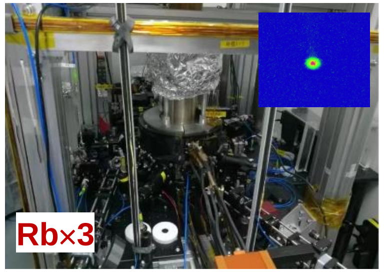


Absolute gravity observation

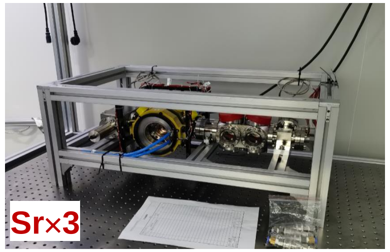
Relative gravity observation

Design of seismometer array

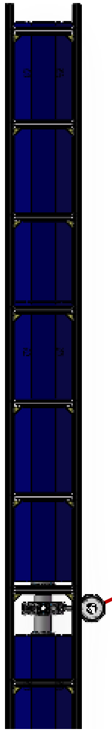
240-m atom interferometer



Rb Source

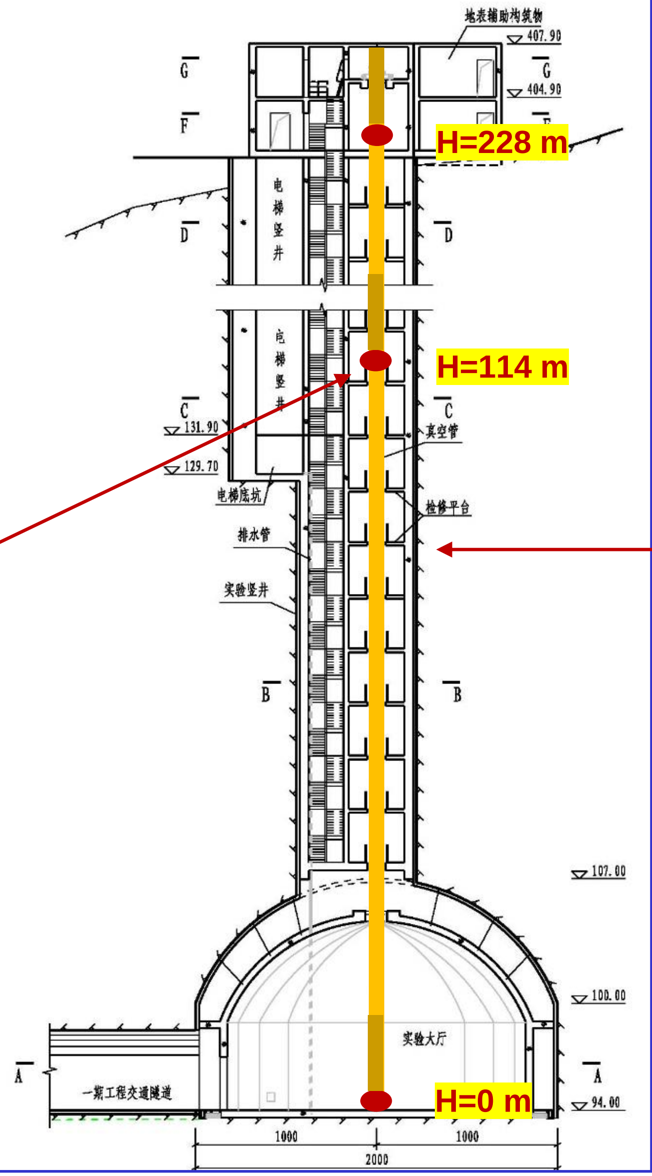


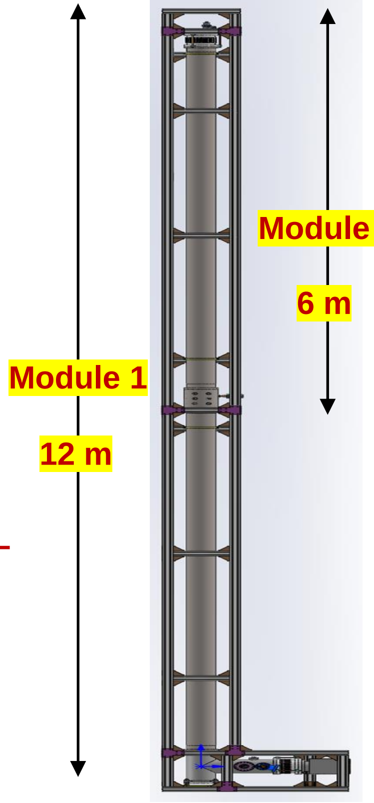
Sr Source

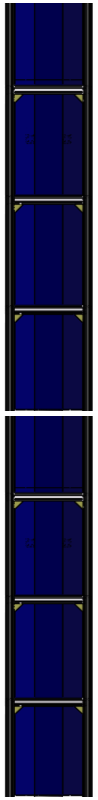


10 m AI：12m ×3 (0 m,114m,228m)
Atom source：Rb & Sr
Vacuum chamber pressure：~1×10^{-8} Pa
Residual field fluctuation： <10 nT

10 m AI



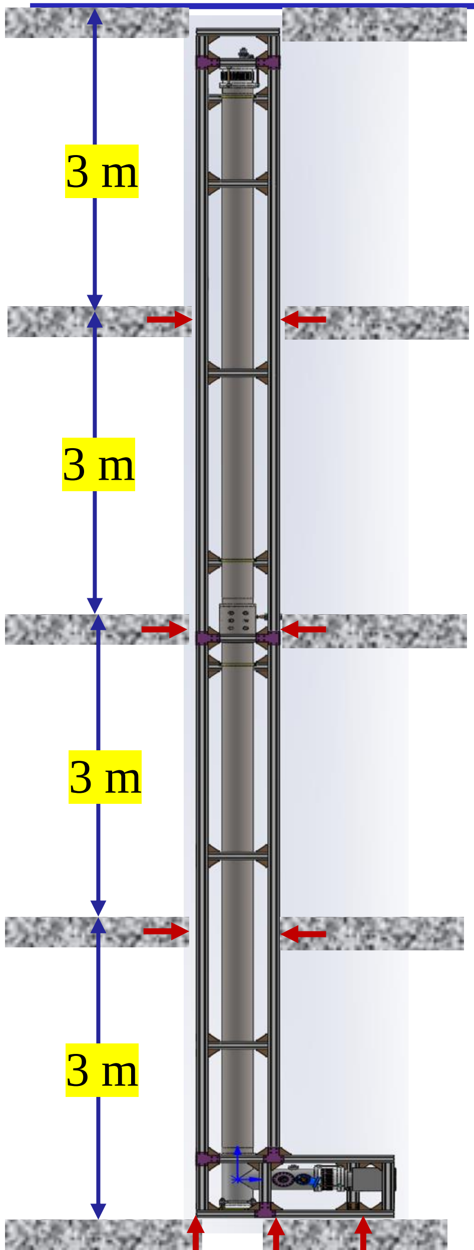


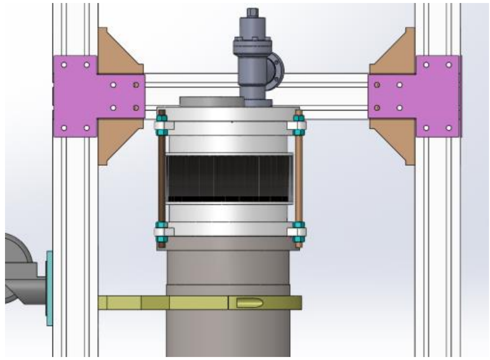


Module 1：12 m×16
Module 2：6 m×2
Vacuum chamber pressure：~1×10^{-8} Pa
Residual field fluctuation： <500 nT (now), <100nT (future)
All-metal gate valves： × 6

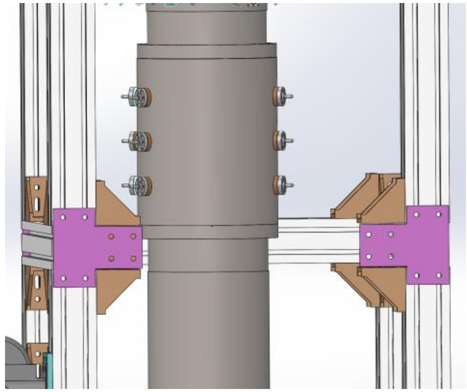
Vacuum Chamber + magnetic shield

Vacuum chamber module

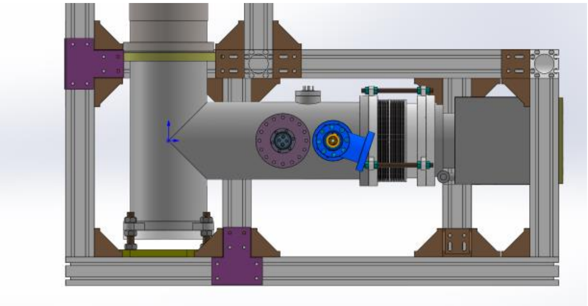




Bellows



Titanium sublimation pump (TSP)



Support cage
Ion pump
sublimation pump
getter pump(Getter)
vacuum gauge
vacuum valve

Module 1:

length: 12 m (5.7m+0.6m+5.7m)
diameter: 200 mm
thermal expansion: 5cm
vacuum pump: TSP、Getter、Ion

Module 2:

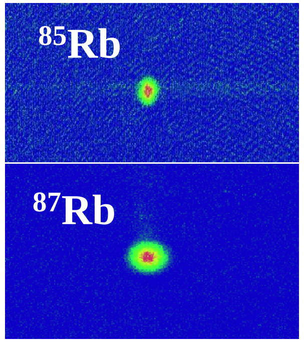
length: 6m
diameter: 200 mm

Materials	Bottom	Middle	Pressure
Ti	300 L Ion 1000 L Getter 1000 L TSP	0	1.1E-8Pa
Ti	300 L Ion 1000 L Getter 2000 L TSP	2000 L TSP	2E-9Pa

By Limit Vacuum Technology (Beijing) Co. Ltd

Ultracold atom source

Rb

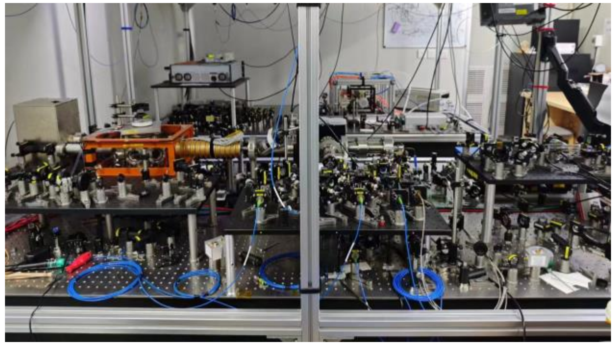


~100nK
~10^5 atoms

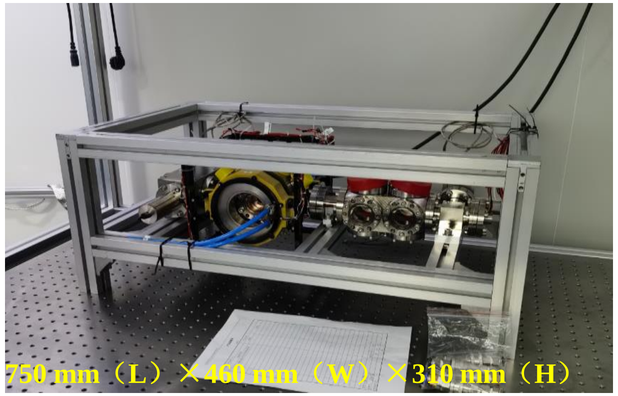
Next step：
~10^6 atoms, atom clouds transfer,
large momentum transfer

By Dr. Rundong Xu

Sr



Yb clock:
5.4E-18

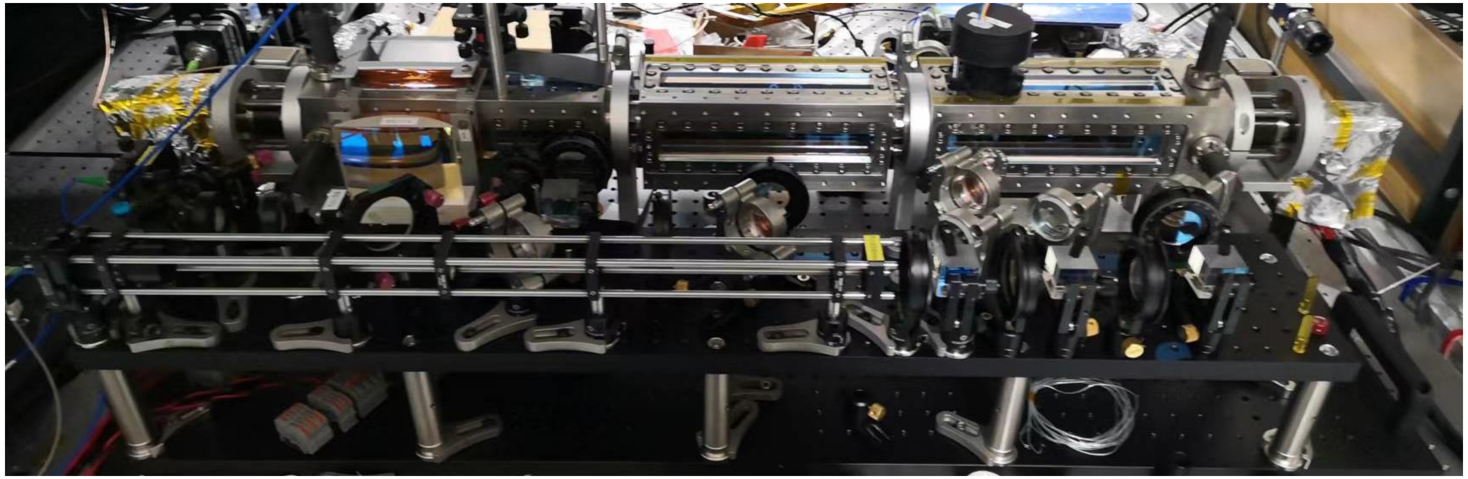


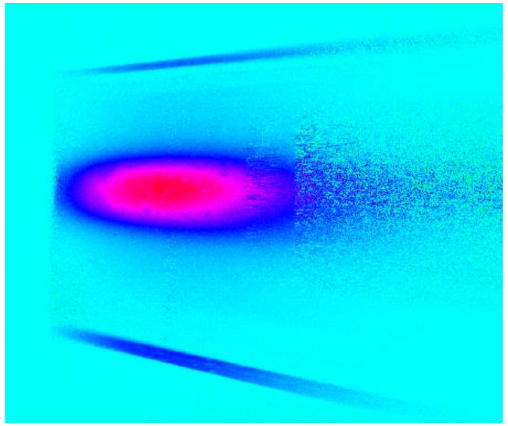
Sr Vacuum Chamber

Next step:
Sr clock and interferometer

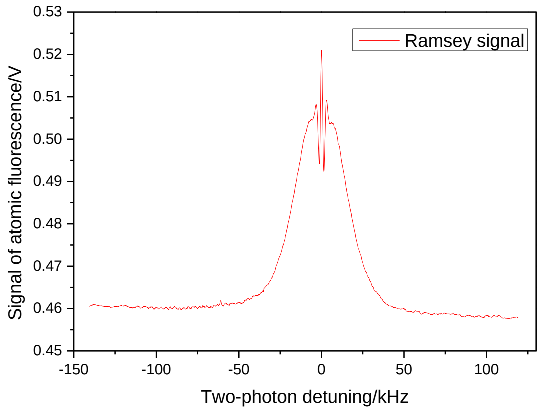
By Prof. Linxiang He

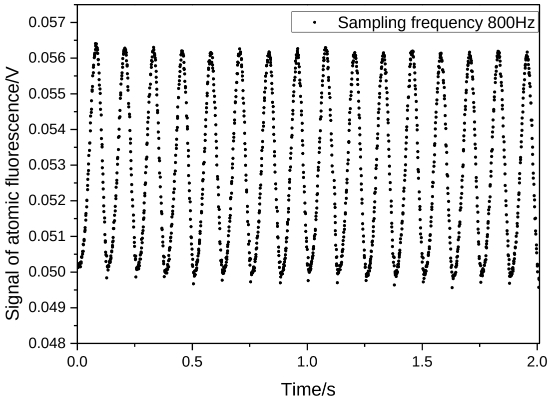
Large atomic beam source



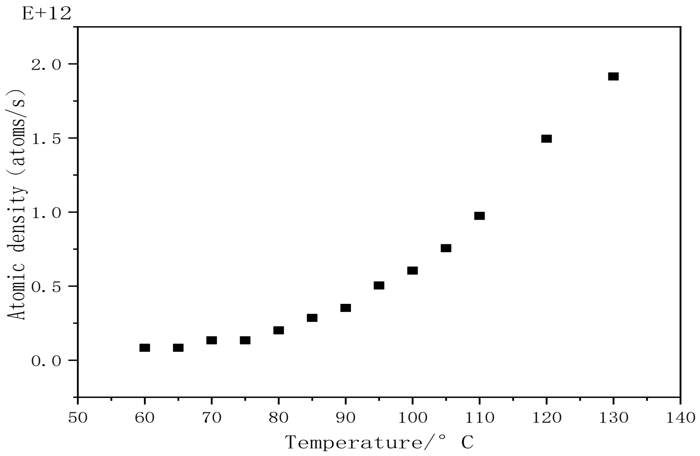


Atom temperature: 100 μK
(Sub-Doppler Cooling)



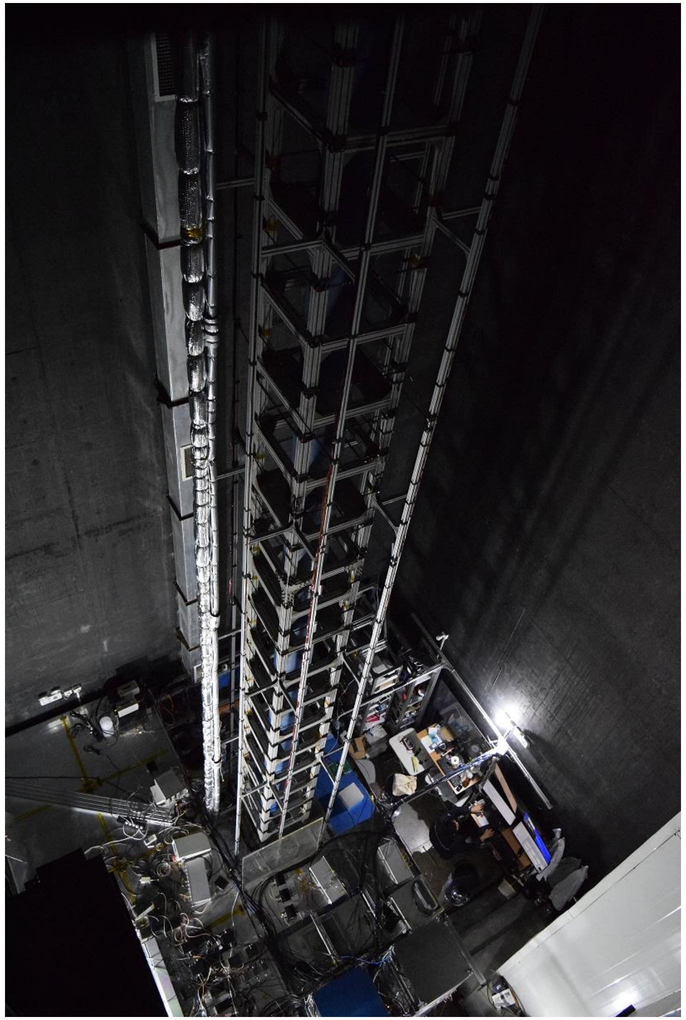


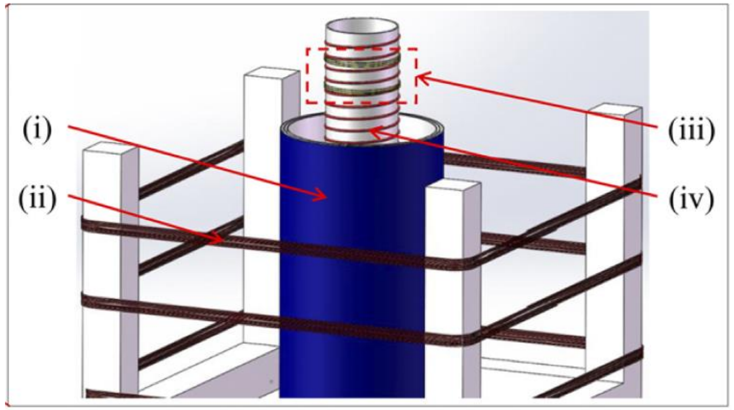
Ramsey fringes with the sampling rate is 800Hz

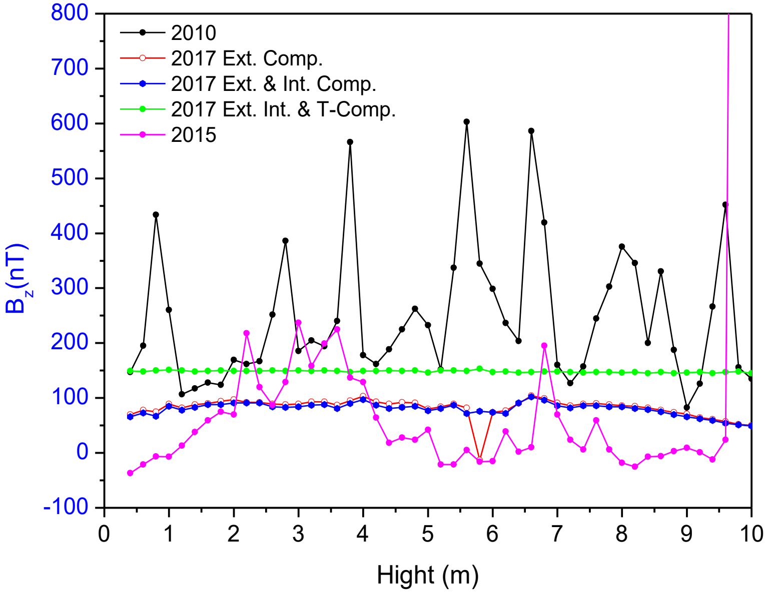


Atom number: 10^{12}atoms/s(capillaries)

Magnetic shield







(i): Welding+annealing
(ii)(iii)(iV): compensation

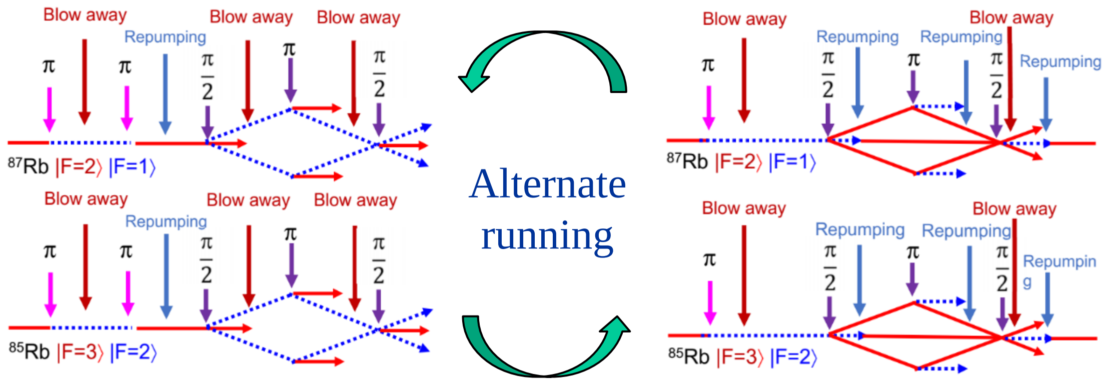
10-m AI
11.4 m， ~8 nT

Y. H. Ji, et al., Rev. Sci. Instrum. 92, 083201 (2021).

HGSE method for magnetic field measurement

Hyperfine ground state exchange (**HGSE**)
Real-time magnetic field measurement method

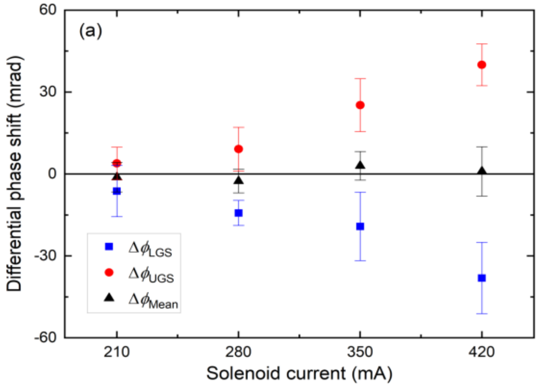
Upper ground state AI | Lower ground state AI



^{85}Rb |F=2⟩ and ^{87}Rb |F=1⟩ | ^{85}Rb |F=3⟩ and ^{87}Rb |F=2⟩

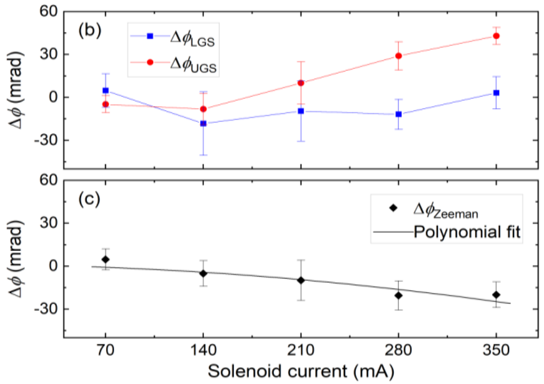
$$\Delta\phi_{i\text{-}F} = 2\pi\alpha_{i\text{-}F}\int_0^{2T}\{B^2[z^{(u)}(t)] - B^2[z^{(d)}(t)]\}dt$$

$\alpha_{85\text{-}2} = -646.99$ Hz/G^2 $\alpha_{87\text{-}1} = -287.57$ Hz/G^2
$\alpha_{85\text{-}3} = 646.99$ Hz/G^2 $\alpha_{87\text{-}2} = 287.57$ Hz/G^2



$\Delta\phi_{Mean} = (\Delta\phi_{LGS} + \Delta\phi_{LGS})/2$

The differential phase shifts respond to magnetic field variations

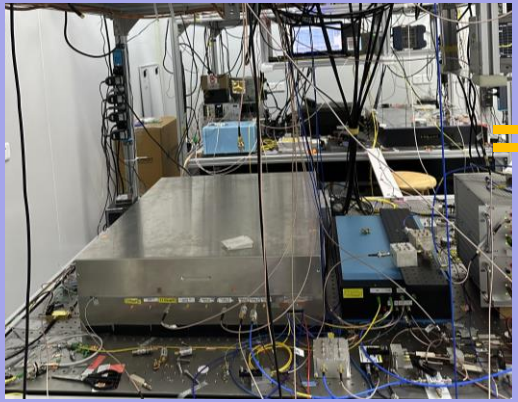


$\Delta\phi_{Zeeman} = (\Delta\phi_{LGS} - \Delta\phi_{LGS})/2$

The HGSE method is still valid in the presence of other sysmatic drifts

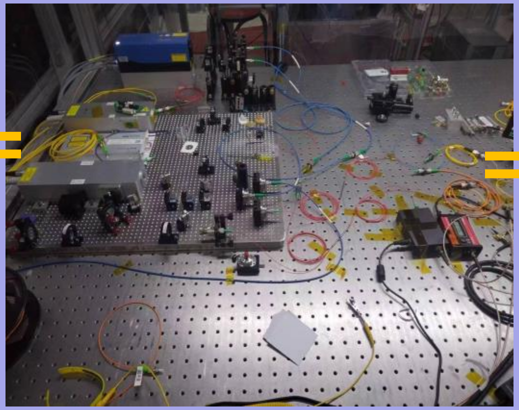
Arxiv

Optical and electronic system



Fibers

30 m



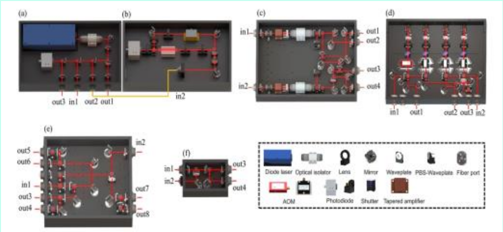
Fibers

50 m

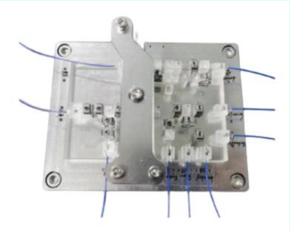
Optical frequency comb

780 nm：2~10W, <100Hz @1s

Platform optical system



Modular laser system



Portable optical & electrical system

Working temperature: 15-25 °C

Lasers for cooling and traping:

461nm: >1 W, 780 nm: > 3 W

1064nm: ~50 W

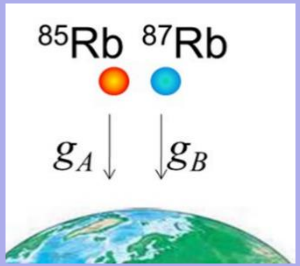
461nm: 2~5 W, 1064nm: ~160 W

780 nm: 2~25 W, 698 nm: ~8 W

689 nm: ~8 W

High power laser source

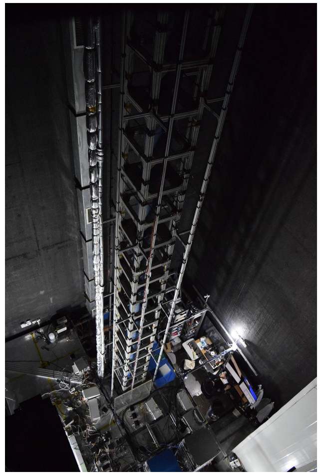
The Wuhan 10-m AI



$$\Delta\Phi = k_{eff} g T^2$$

2T=2.86 s

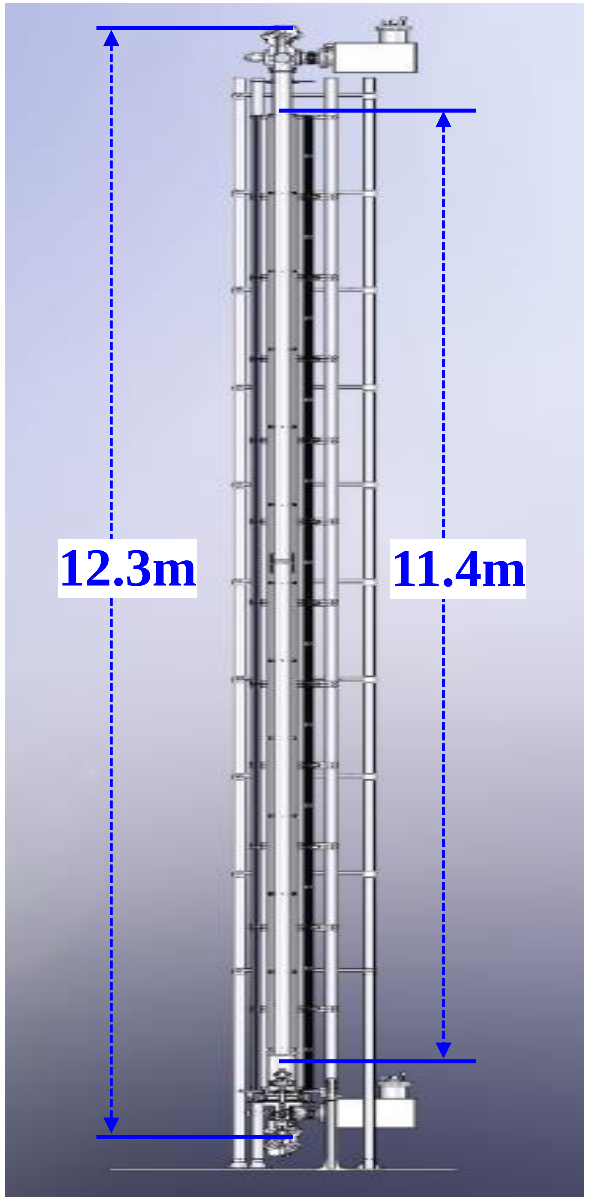
Weak equivalence principle test

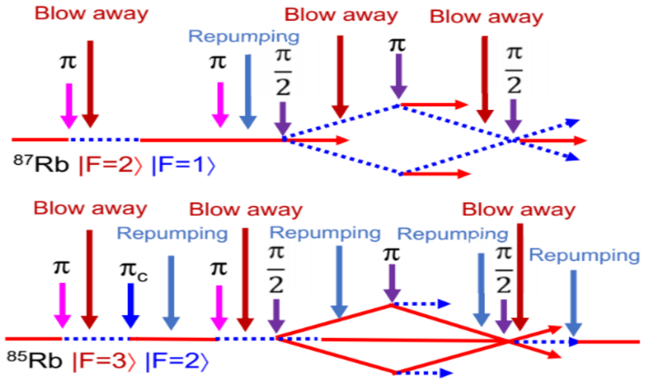


Vacuum chamber
12.3 m, 2×10^{-8} Pa

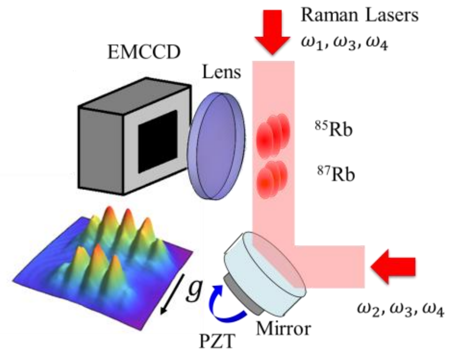
Magnetic shield
11.4m, 8 nT (10 m)

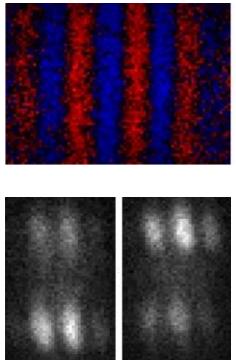
L. Zhou, et al., *Gen. Relat. Gravit.* **43**, 1931(2011)





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



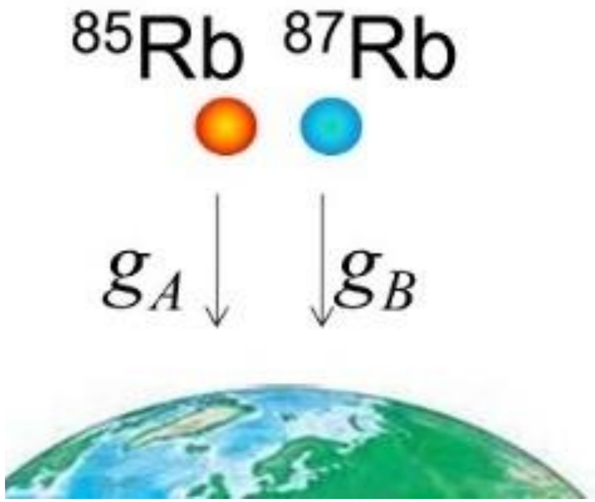


Phase shear readout

^{87}Rb: T=1.3s, 4.5×10^{-11}/shot

^{85}Rb & ^{87}Rb : T=1s, 8.6×10^{-12}@7168s

Equivalence principle test



EP test 4WDR

2015, mass test 3.0×10^{-8}

Lin Zhou, *et al.*, *Phys. Rev. Lett.* **115**,013004(2015)

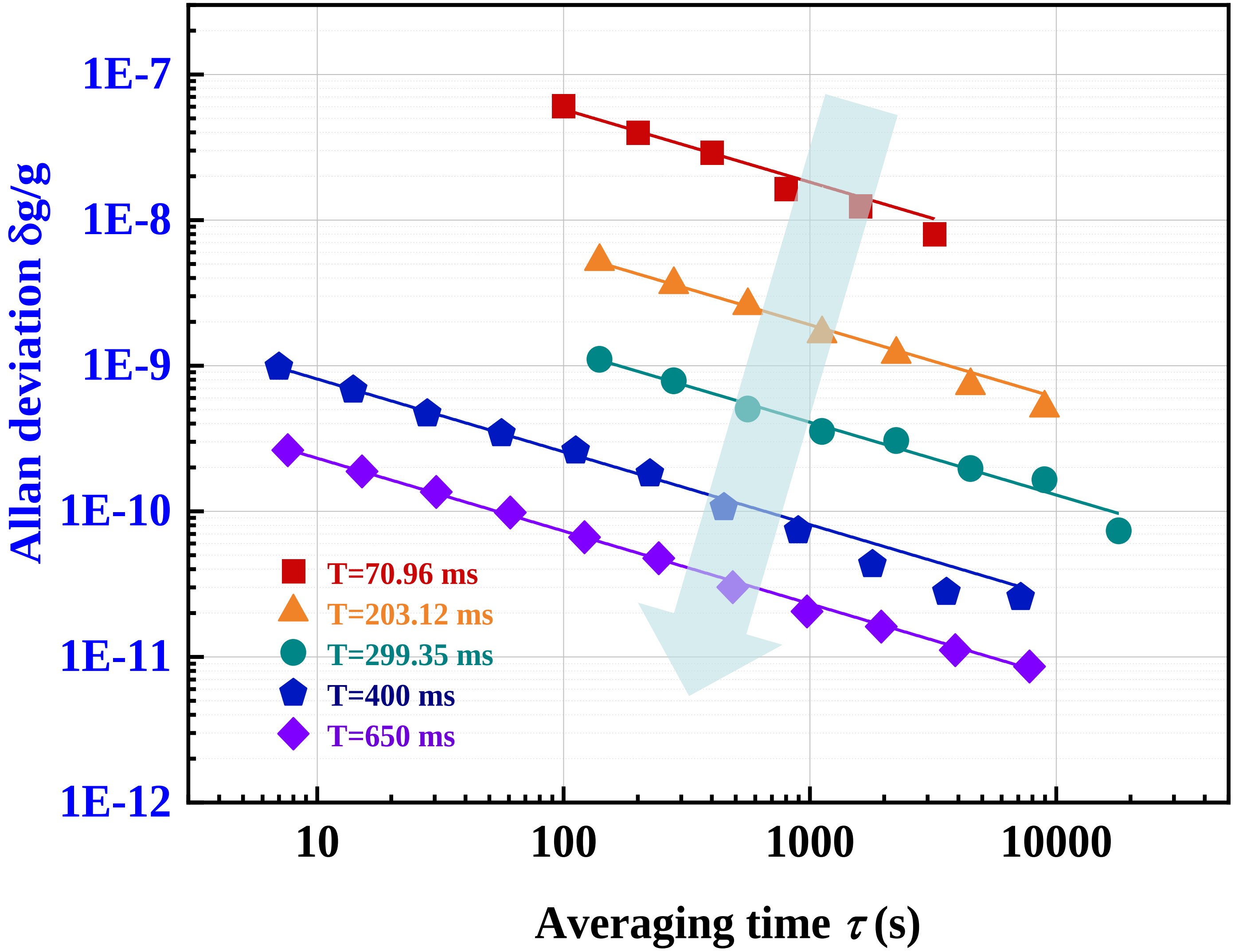
2019, mass test 6.7×10^{-10}

Lin Zhou, *et al.*, *arXiv:1904.07096 [quant-ph]* (2019)

2021, mass-energy joint test 1.4×10^{-10} 0.4×10^{-10}

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

Sensitivity Improvement of the Wuhan 10-m AI



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**

Research Roadmap

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

Phase II:
2027 - 2035

Phase III
2035 -

ZAIGA

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

240 m Vertical AI array
1000 m Horizontal AI array

≥ 3000 m Horizontal AI

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Graduate students： Yu-Hang Ji, Zhuo Hou, Jun-Jie Jiang, Jia-Qi Lei, Zhixin Li, Lu Zhou, Yuxuan Pan, Youmeng Hu.

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Thank you for your attention!