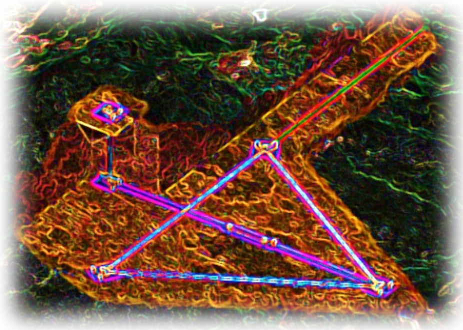

The ZAIGA Project

Mingsheng Zhan

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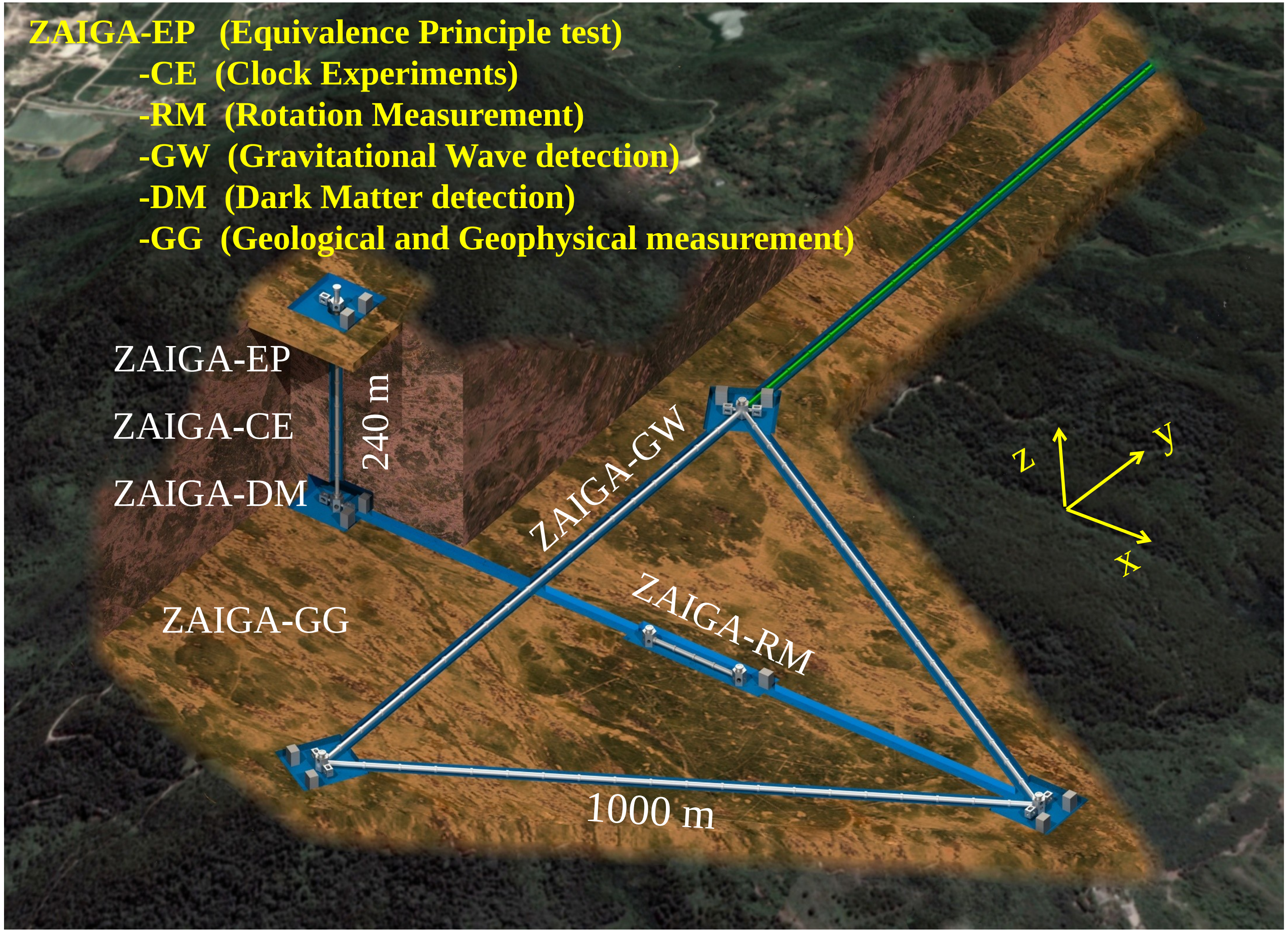
(Former Wuhan Institute of Physics and Mathematics)

2023.6.14 Pisa

ZAIGA: Zhaoshan long-baseline Atom Interferometer Gravitation Antenna

Mingsheng Zhan, Jin Wang, Wei-Tou Ni *et al*., *Intl. J. Mod. Phys. D* **29**,1940005 (2020); arXiv:1903.09288



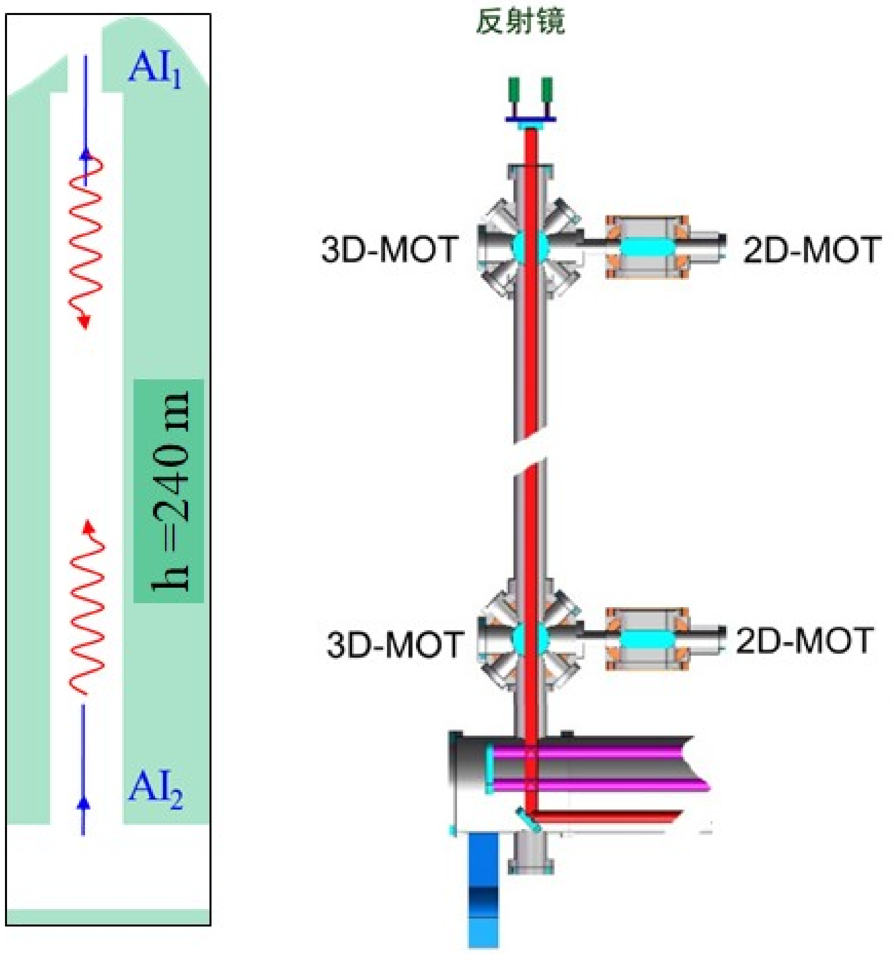
A platform to test gravity theory with large scale atomic interferometers, gyros and optical clocks

- 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

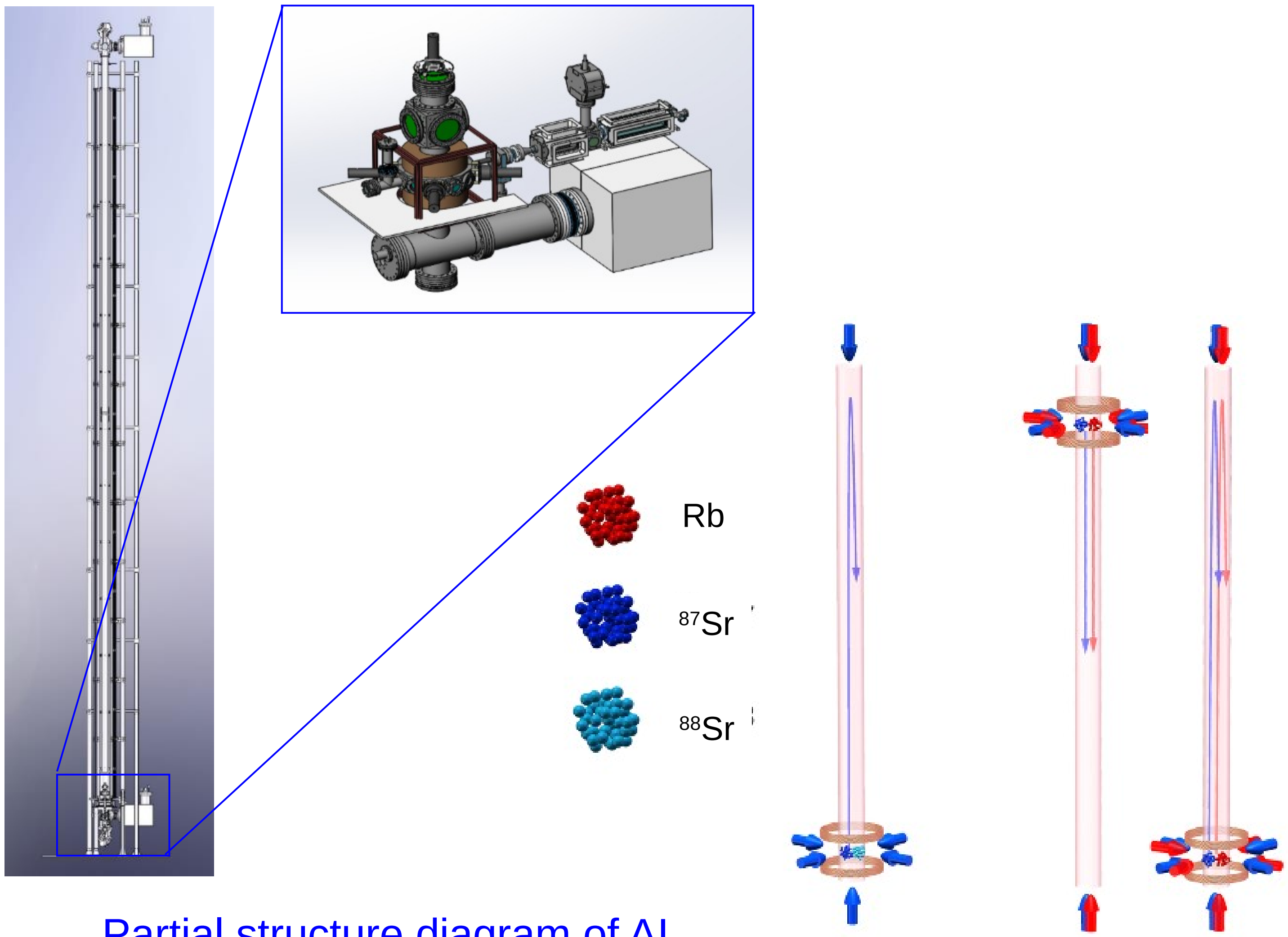
Geological and Geophysical measurement
  — gravimeters, seismometers

The Proposal

ZAIGA-EP



Schematic diagram of long baseline AI

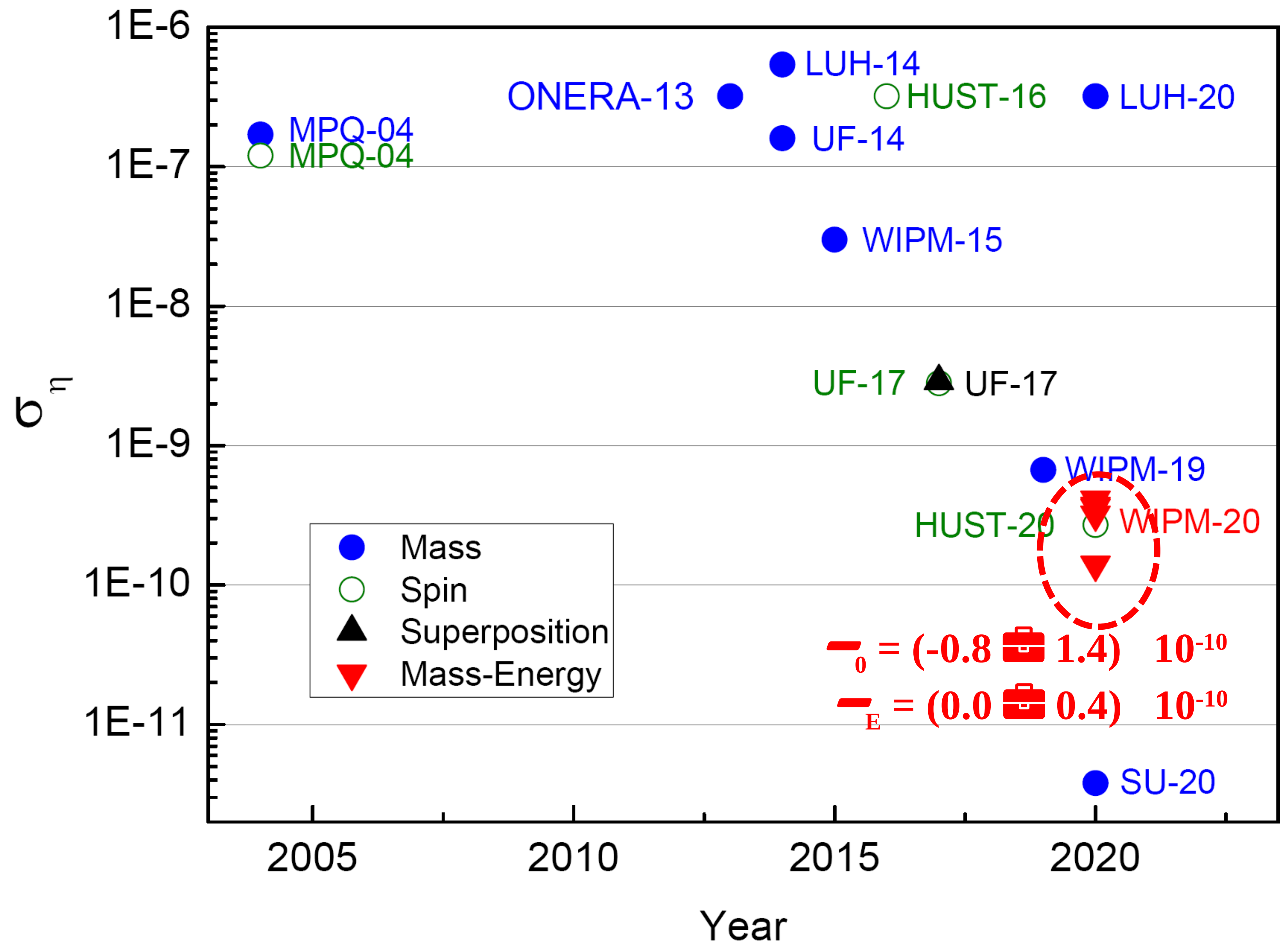


Partial structure diagram of AI

Largest Atomic Pisa Leaning Tower

The Proposal

ZAIGA-EP



EP test with AI

MPQ	(Germany)
ONERA	(France)
LUH	(Germany)
UF	(Italy)
SU	(USA)
WIPM/APM	(China)
HUST	(China)

The Proposal

ZAIGA-EP

ZAIGA

Comparison of EP test experiments with AI

TABLE I. Mass and energy tests of the equivalence principle with atoms. ΔE is the mass-energy difference of the test pair, in units of GeV (for mass) or GHz (for internal energy, 1 GHz = 4.14 μeV). η_i is the measured Eötvös parameter. η_E is the internal energy violation parameter of reduced energy ratio a, where $a = h\nu_0/m_i^{85}c^2$ and $\nu_0 = 1$ GHz.

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	$(0.4 \pm 1.2) \times 10^{-7}$	$(0.1 \pm 0.4) \times 10^{-7}$	*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	1-1 $\oplus$ 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)
^{85}Rb - ^{87}Rb	2-1	1.86 GeV + 0.00 GHz	$\eta_1 = (1.5 \pm 3.2) \times 10^{-10}$		arXiv: 1904.07096
^{85}Rb - ^{87}Rb	2-2	1.86 GeV + 6.83 GHz	$\eta_2 = (-0.6 \pm 3.7) \times 10^{-10}$		This work
^{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	$\eta_4 = (-2.7 \pm 3.6) \times 10^{-10}$		
			$\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$	$(0.0 \pm 0.4) \times 10^{-10}$	*Phys. Rev. A* (2021)

The mass-energy joint test of EP was realized.

The energy violation parameter η_E value is given.

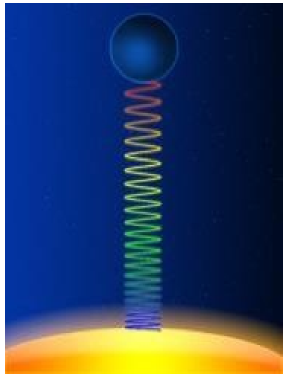
L. Zhou *et al*., *Phys. Rev. A* 104, 022822(2021)

The Proposal

ZAIGA-CE

ZAIGA

ZAIGA - ZMS



Gravitational redshift measurement:

to test the Local Position Invariance (LPI)

-1

0 ✕ ○ ✕

Pound-Rebka Experiment (PRE) with Photon

Mass-energy equivalence: E = mc^2

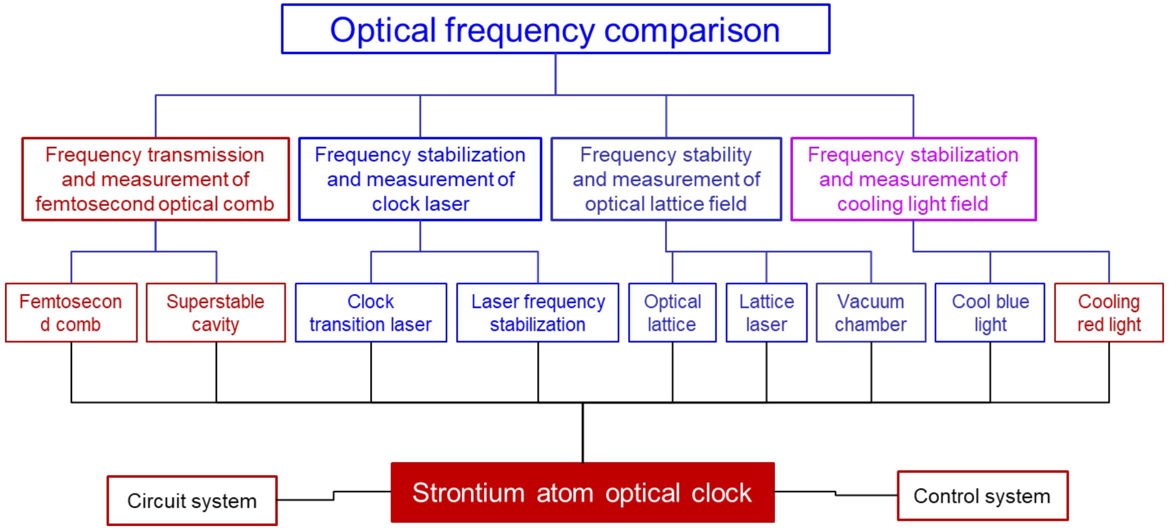
Constant speed of light c

WEP: the Universality of Free Fall （mass,

f ）

Gravitational redshift

$$\frac{\Delta f}{f}=\frac{\Delta U}{c^2}=\frac{g}{c^2}\Delta H=10^{-18}@\Delta H=1cm$$



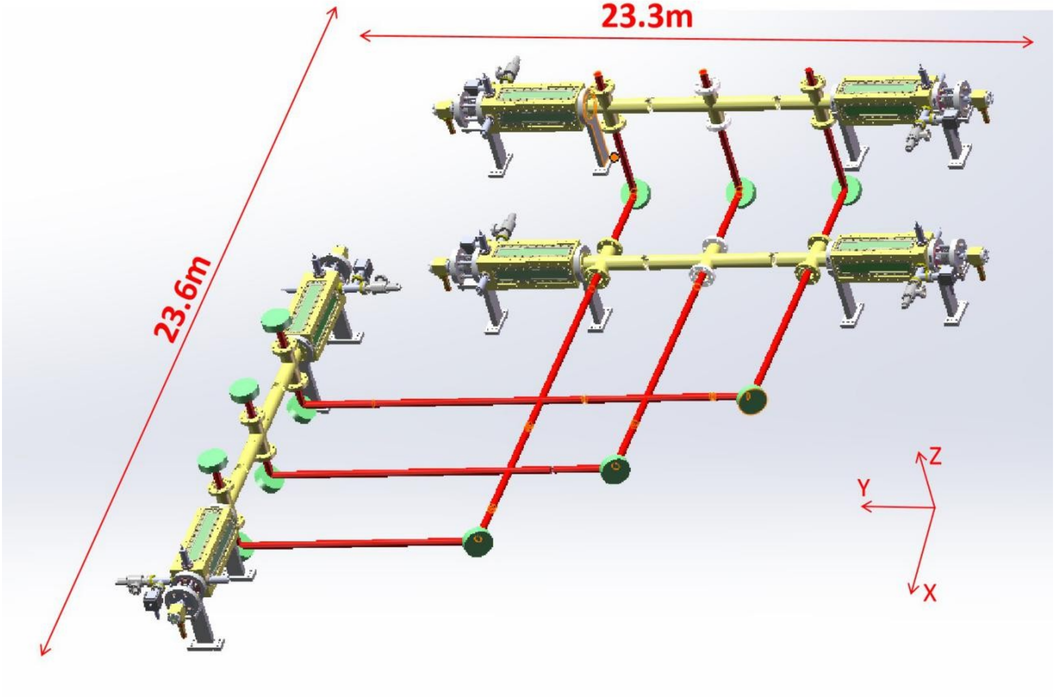
The Proposal

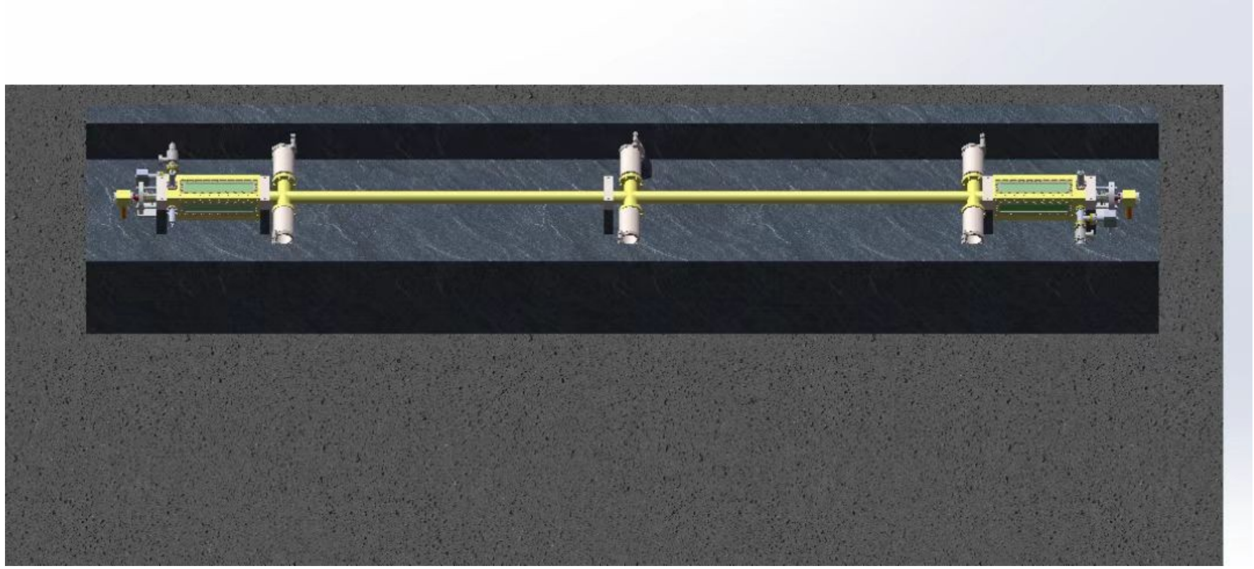
ZAIGA-RM

Rotation Measurement and Calibration

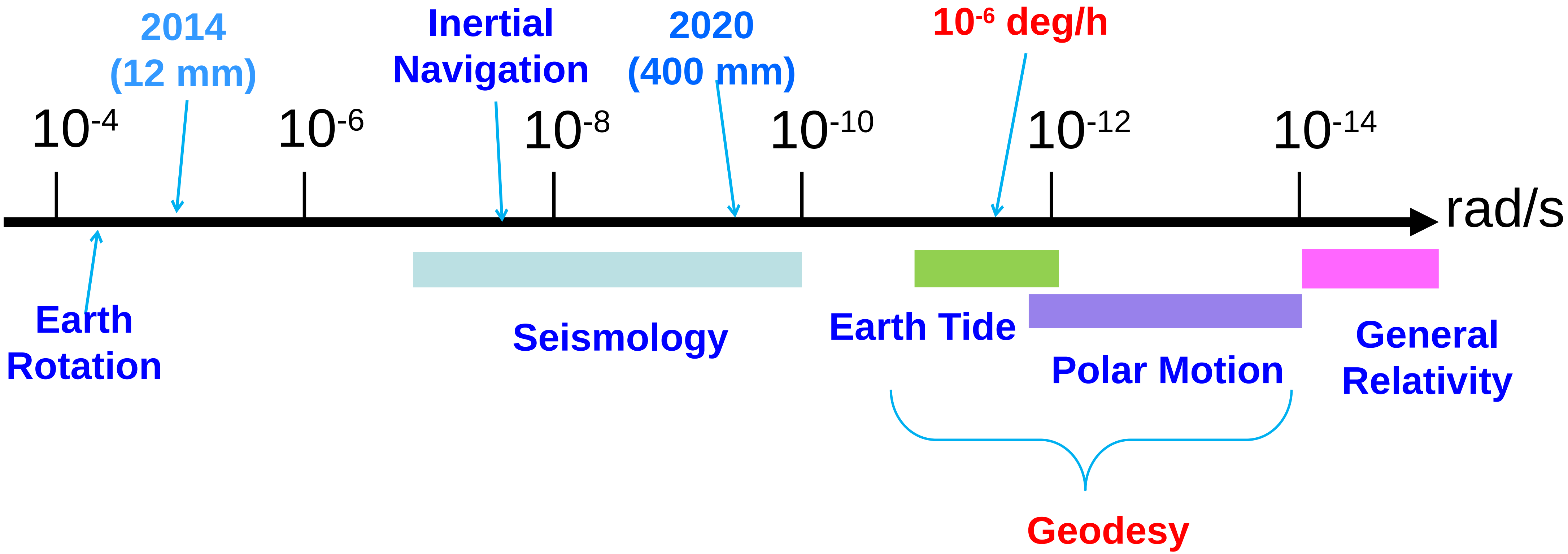
Measurement of Lense-Thirring effect

Test the general relativity





Needs for RM



2014
(12 mm)
Inertial
Navigation
2020
(400 mm)
10-6 deg/h
10-4
10-6
10-8
10-10
10-12
10-14
rad/s
Earth
Rotation
Seismology
Earth Tide
Polar Motion
General
Relativity
Geodesy

High Perf. Gyros

Type	Area	Angle Random Walk (rad/s/$Hz^{1/2}$)	Bias Stability (rad/s)
iXblueFOG	200 m^2	2×10^{-8}	4×10^{-10}
Peking University FOG	2850 m^2	3×10^{-9}	1×10^{-11}
G-Ring Laser	16 m^2	1.2×10^{-11}	7×10^{-13}
LNGS Laser	13 m^2	1.8×10^{-11}	4×10^{-14}
Hannover AIG	41 mm^2	1.2×10^{-7}	2.6×10^{-8}
APM, CAS AIG	1.2 cm^2	1.5×10^{-7}	9.5×10^{-10}
CNRS AIG (4 pulse)	11 cm^2	2×10^{-8}	3×10^{-10}
HUST AIG (4 pulse)	5.92 cm^2	1.2×10^{-7}	2.5×10^{-8}
Yale-Stanford	24 mm^2	6×10^{-10}	4.8×10^{-10}
ZAIGA	**24 cm^2**	**8×10^{-11}**	**8×10^{-12}**

Atom Interferometric Gyros

	CNRS (2018)	**Hannover (2015)**	**Stanford (2006)**	**Stanford (2011)**	**APM,CAS (2021)**
Area(mm^2)	1100	41	24	17	120
Angle Random Walk (rad/s $Hz^{-1/2}$)	3×10^{-8}	1.2×10^{-7}	8.8×10^{-10}	8.5×10^{-8}	1.5×10^{-7}
Bias stability (rad/s)	3×10^{-10}	2.6×10^{-8}	3.2×10^{-10}		9.5×10^{-10}

ZAIGA Gyro: 8E-12 rad/s

How to get a rotation resolution of 8×10^{-12}rad/s

Rotation resolution by AIG

Phase noise

Sampling Rate

Scaling Factor

$$\Delta\Omega=\frac{\delta\phi}{2nk_{eff}vT^2}\sqrt{\frac{T_c}{\tau}}$$

$$\delta\phi=\frac{1}{C\sqrt{N}}$$

	Area	Sampling Rate	Atom Temperature	Atom Number
Cold atoms	11 cm²	2 Hz	10 μK	10^8
Ultra cold atoms	——	0.1 Hz	50 nK	10^5
Atomic beam	24 mm²	500 Hz	120 μK	10^{12}

ZAIGA Gyro: 8E-12 rad/s

Large scale atom interferometer gyroscope

BEC/Atom cloud/Atom beam

Why atom beams?

- shorter interrogation time : vibration noise, shorter launch height
- High data rate: continuous
- High signal noise ratio: lock-in amplifier

Challenge

- High flux atom source
- Narrow transverse velocity distribution
- Alignment of laser beams

Proposal

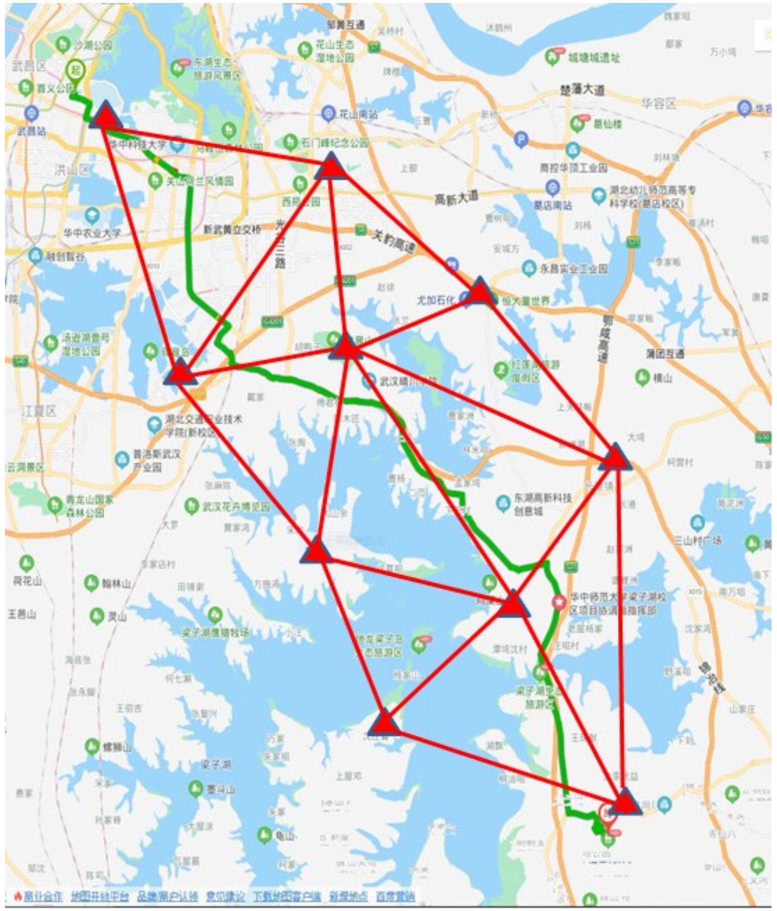
- Interference length 2L=20 m
- Atom flux 10^{12} atoms/s
- Transverse atom temperature 100 μK(0.1 m/s)
- Hybrid interferometer

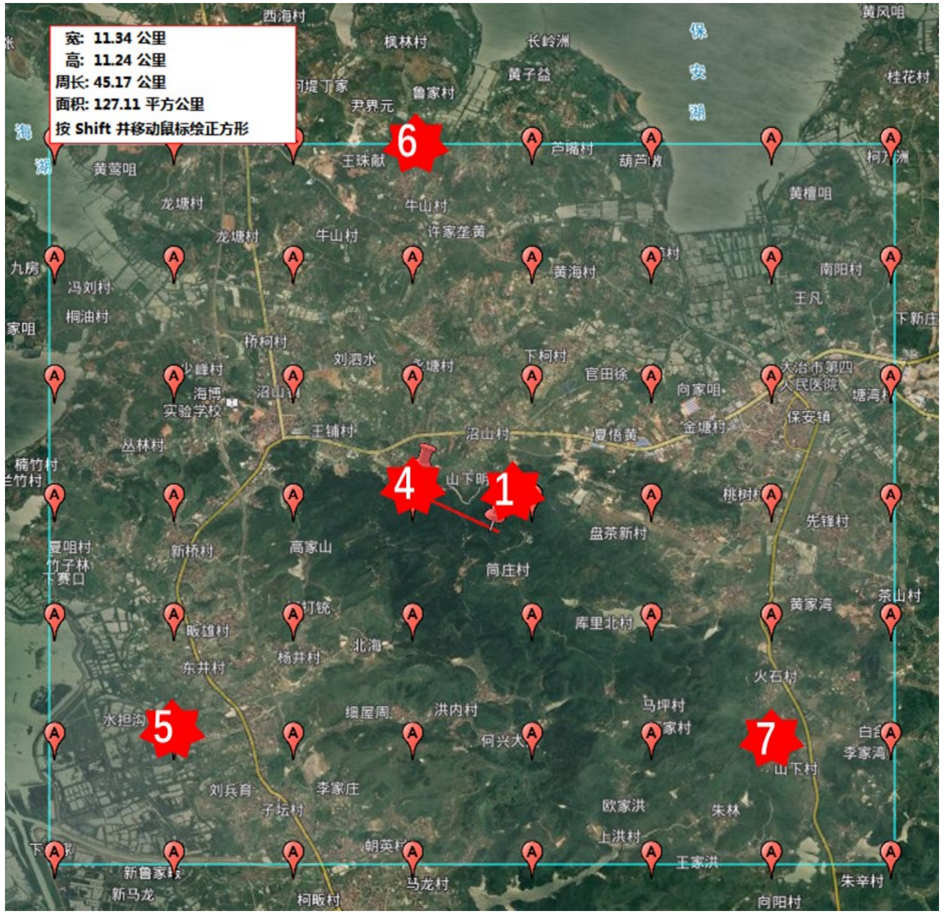
The Proposal

ZAIGA-GG

Environmental monitoring

GNSS, Earthquake, Rotation, Ground Water, Meteorological, Geogravity, Relativistic Geodesy, Dynamic Coordinate Reference Frame

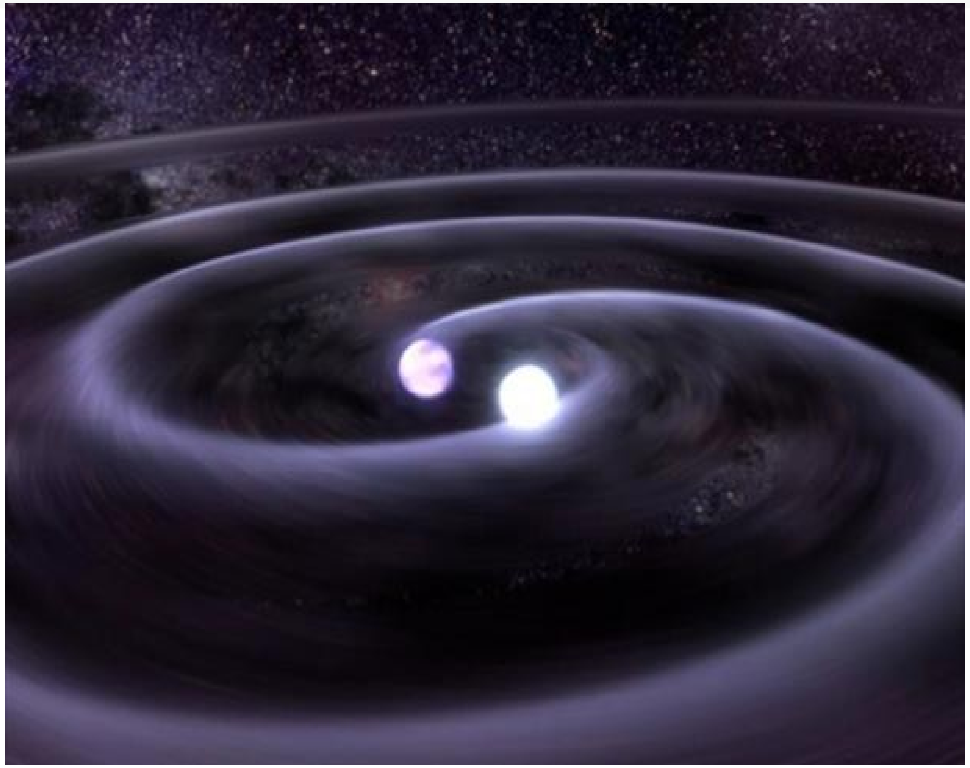


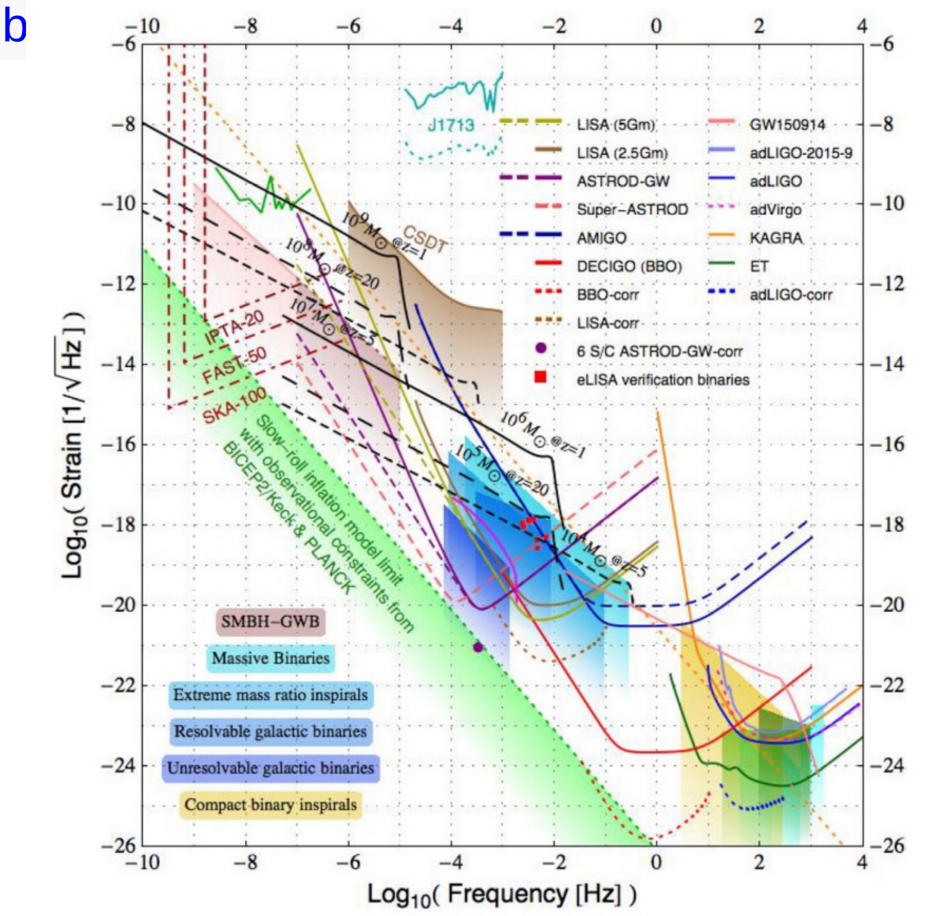


The Proposal

ZAIGA-GW

Ultralow frequency band （10^{-18}-10^{-15} Hz）： Ground or space detector(BICEP3, Ali)
Very low frequency band （10^{-9}-10^{-7} Hz）： Millisecond pulsar timing array (EPTA, NANOGrav, PPTA)
Low frequency band （10^{-4}-10^{-1} Hz）： Space-based laser interferometer(LISA, Taiji/Tianqin)
High frequency band （10 -10^{4} Hz）： Ground-b RGO,KAGRA)





Wei-Tou Ni， EPJ Web of Conferences **168**, 01004 (2018)

The Proposal

ZAIGA-GW

ZAIGA

Parameters:

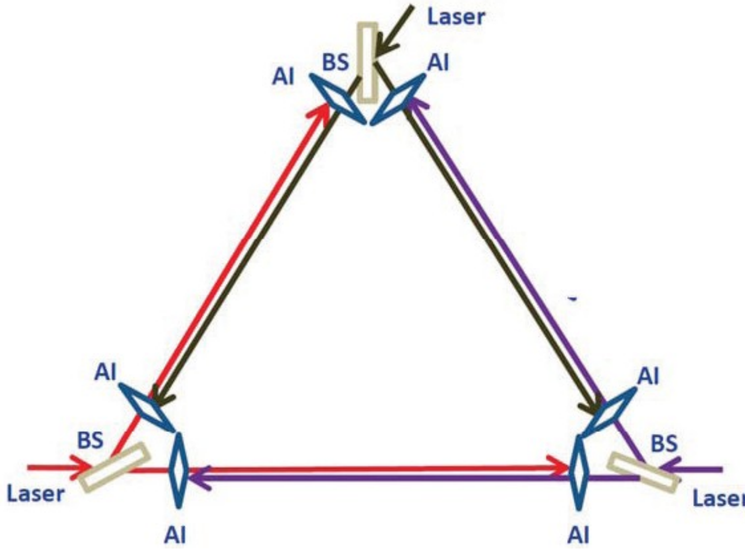
Laser wavelength: 780 nm $k_l = 8.5\times10^6$ m^{-1}

Height of atom interferometers: 5 m, T=1 s

Flux intensity: R=10^{14} atoms/s

Photon momentum transfer: N=1000

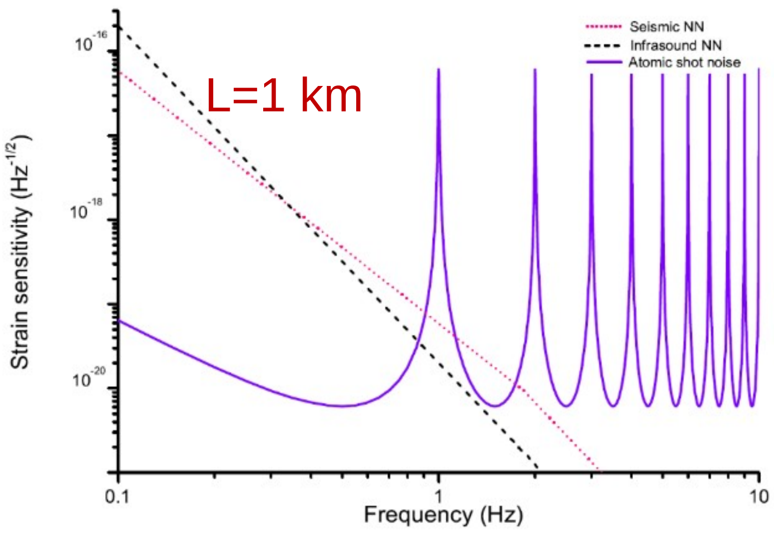
Arm length: L= 1000 m /3000 m.



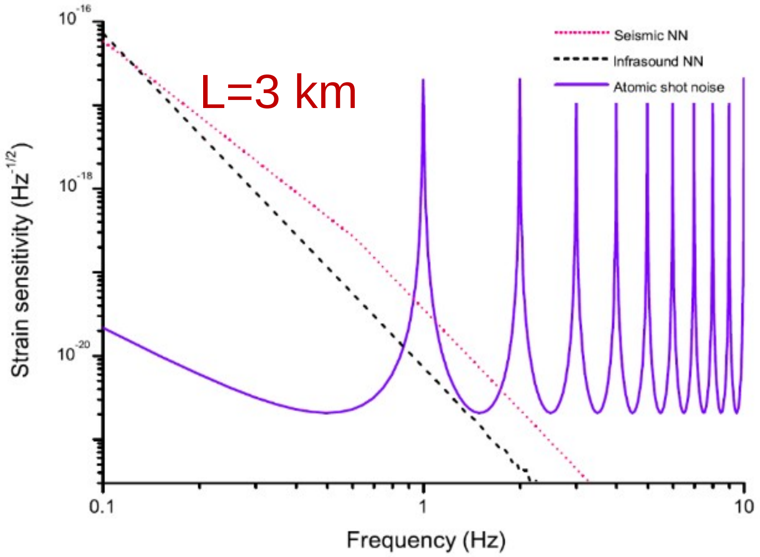
$$\Delta\phi_{\mathrm{tot}} = 2k_{\mathrm{eff}} hL \sin^2\left(\frac{\omega T}{2}\right)\sin(\phi_0)$$

$$k_{\mathrm{eff}} = 2Nk_l$$

L=1 km



L=3 km



- Atomic shot noise
- Seismic Newtonian Noise (Seismic NN)
- Infrasound Newtonian Noise (Infrasound NN)

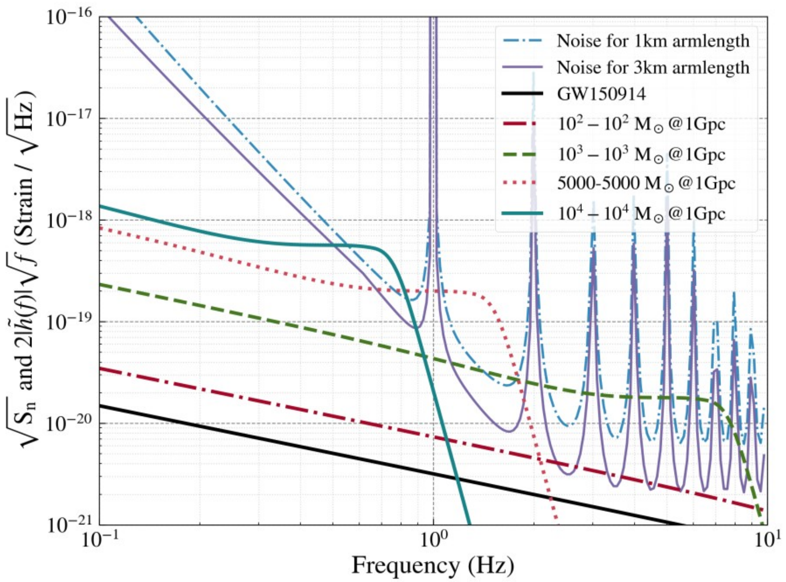
M. S. Zhan, J. Wang, W. -T. Ni, *et al.*, *Intl. J. Mod. Phys. D* **29**, 1940005(2020)

The Proposal

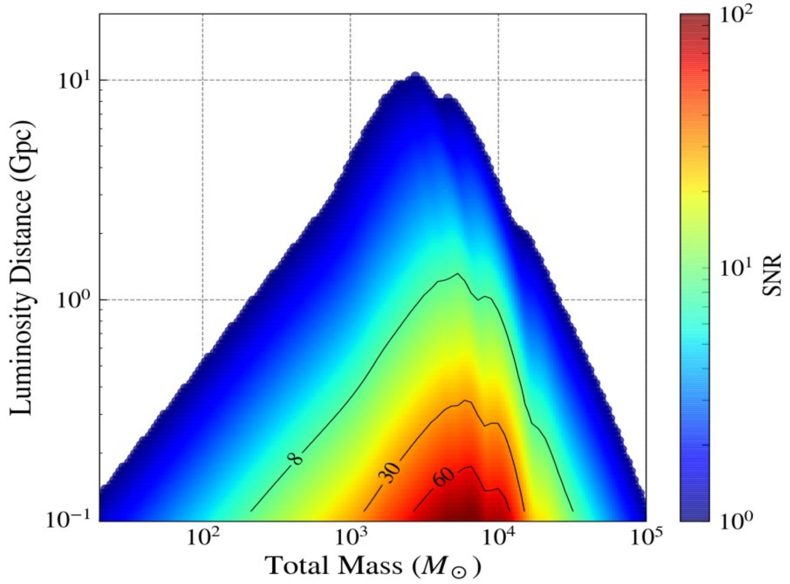
ZAIGA-GW

ZAIGA

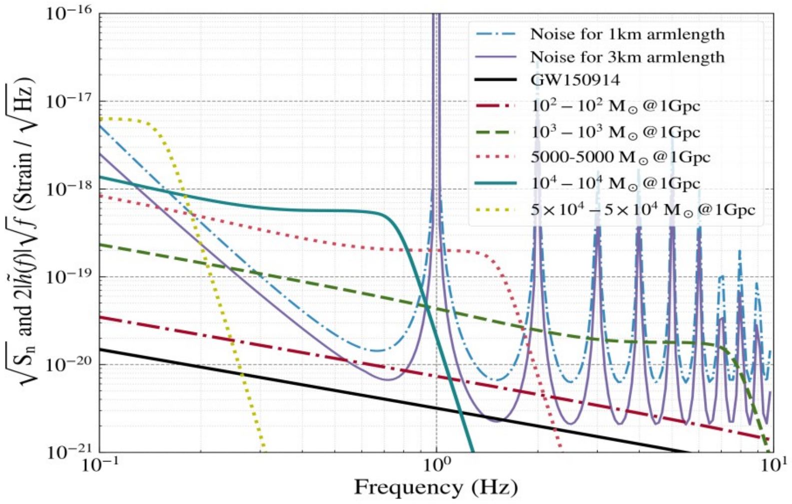
ZAIGA - ZMS



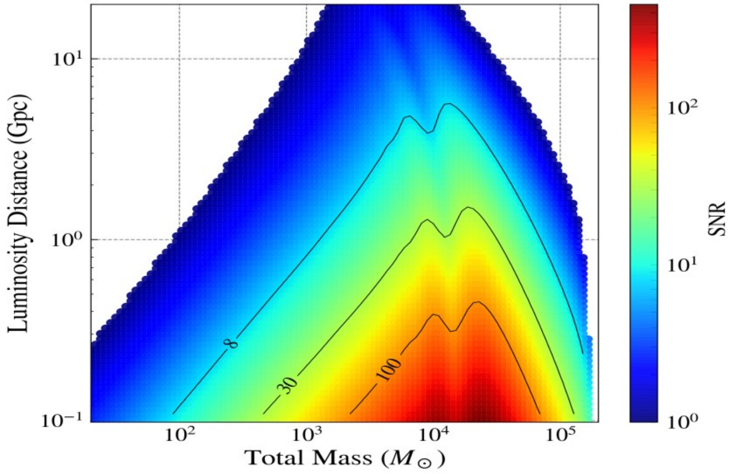
Detection performance without Newtonian Noise reduction



Signal to noise ratio vs. detectable distance



Detection performance with 50 times NN reduction assumed



Signal to noise ratio vs. detectable distance

Event estimation

Medium-frequency GW source:
Medium mass Black Hole binary system (10^2-10^4 times the solar mass)

Medium-band GW detector：
is possible to solve the problem of whether there are medium mass Black Holes

Atomic interferometer:
can detect the GW source in the blank frequency band (0.1~10 Hz) between LIGO and LISA

Theoretical model of ultralight dark matter

$$S = \int d^4x\sqrt{|g|}\left\{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + L_{SM} + L_\phi\right\}$$

L_{sm} Lagrangian in the standard model of particle physics

$$L_\phi = \kappa\phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_m m_e\bar{e}e - \sum_{i=u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

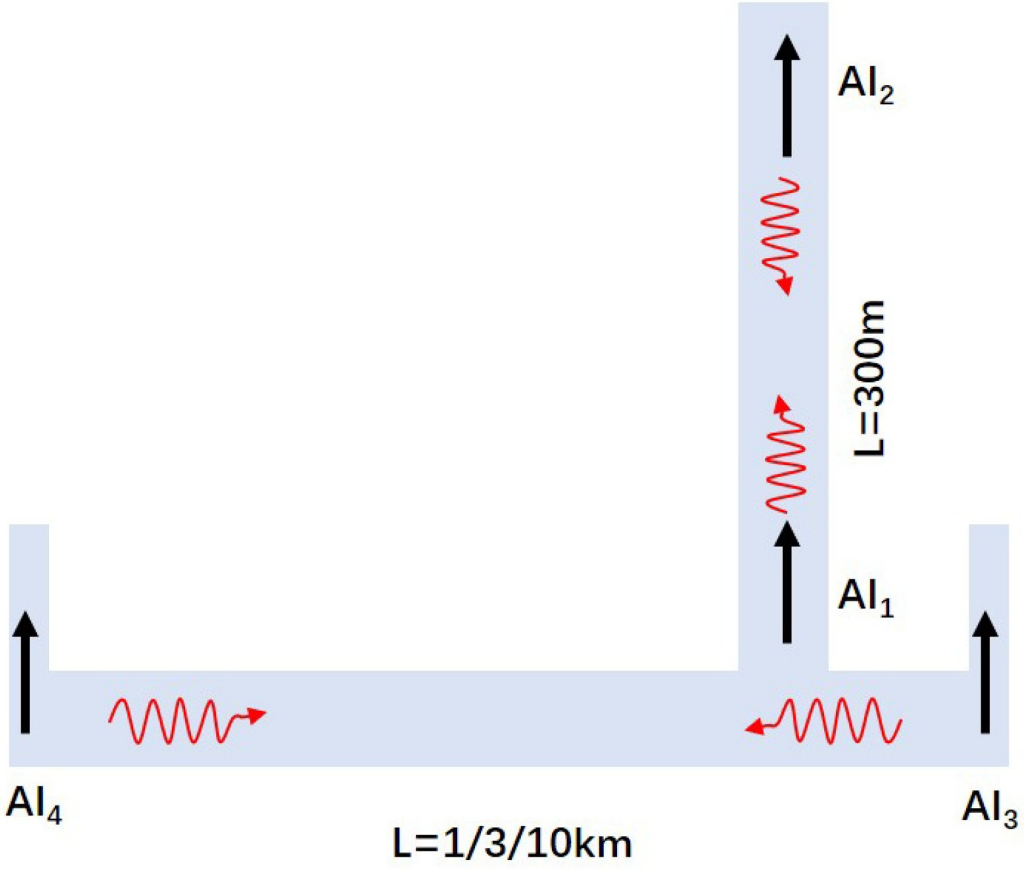
coupling coefficients: $d_e, d_g, d_{m_e}, d_{m_u}, d_{m_d}$

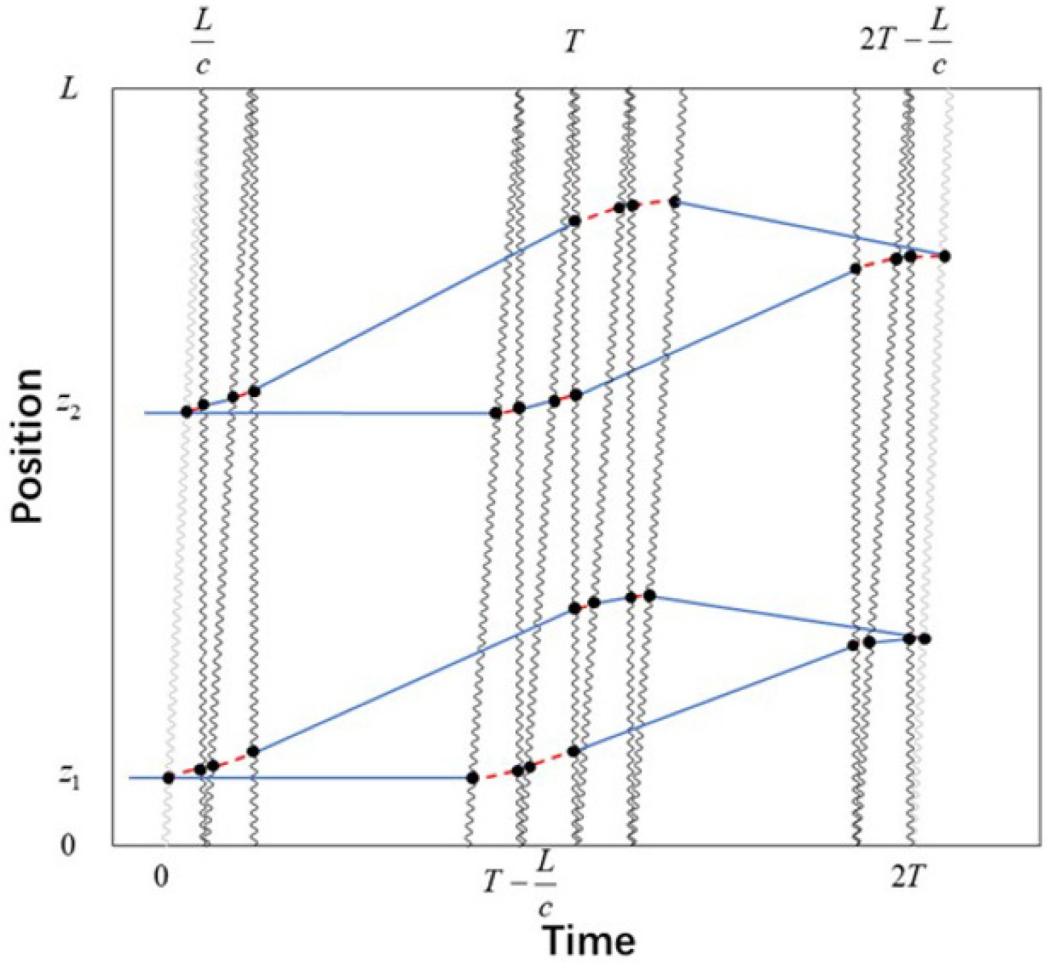
It is necessary to determine whether they are zero through experiments.

Self-interaction between dark matter

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{3}a_\phi\phi^3 + \frac{1}{4}\lambda_\phi\phi^4$$

Detect ultralight dark matter by ZAIGA-DM





W. Zhao, X. T. Mei, D. F. Gao, J. Wang, and M. S. Zhan, *Int. J. Mod. Phys. D* **31**, 2250037 (2022)

The Proposal

ZAIGA-DM

ZAIGA

Constraints on the DM coupling parameters

For the horizontal AI pair

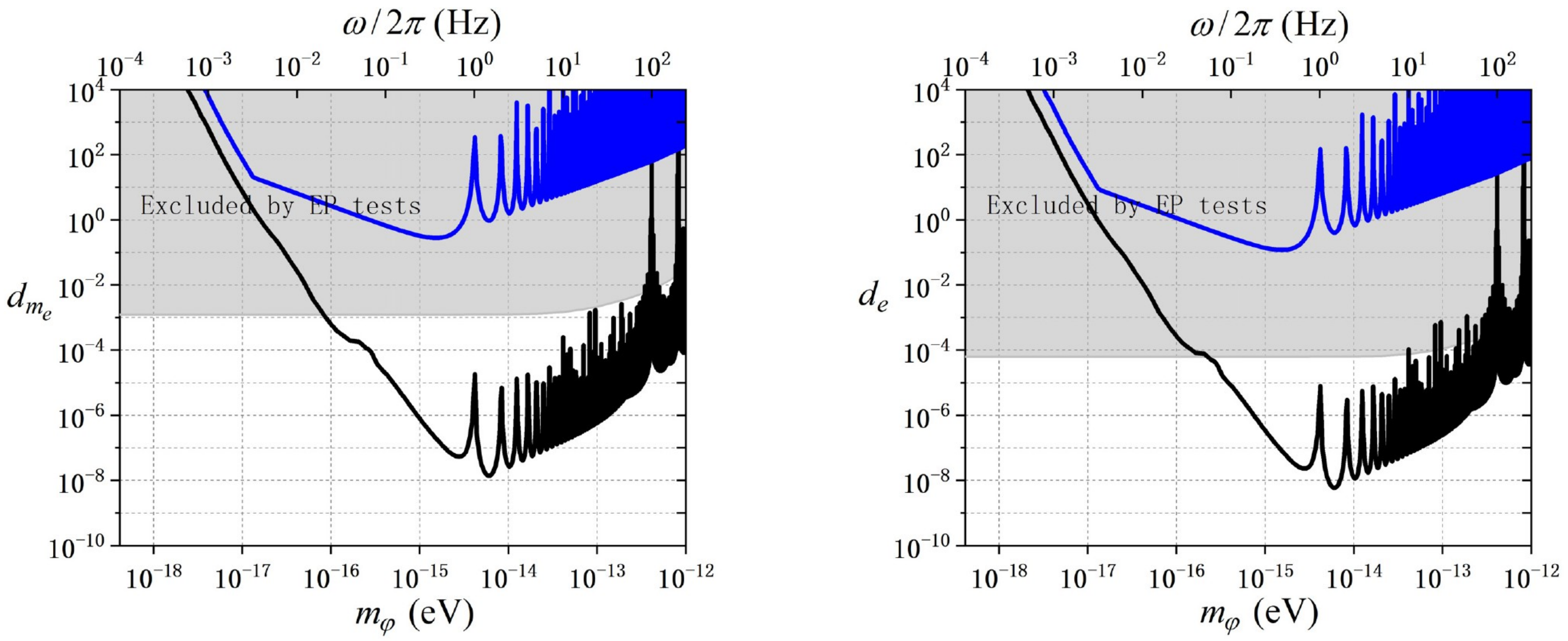


Table 2. The technical parameters for a pair of horizontally separated AIs.

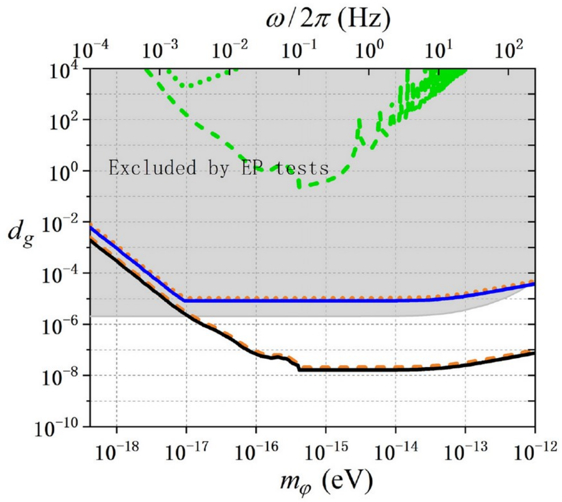
	Free evolution time (T)	Phase sensitivity	Momentum transfer (n)	Integration time (t_{int})	Arm-length (L)
Near term	1 s	$10^{-3}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$	4	10^4 s	1 km
Future	1 s	$10^{-7}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$	10^3	10^6 s	3 km

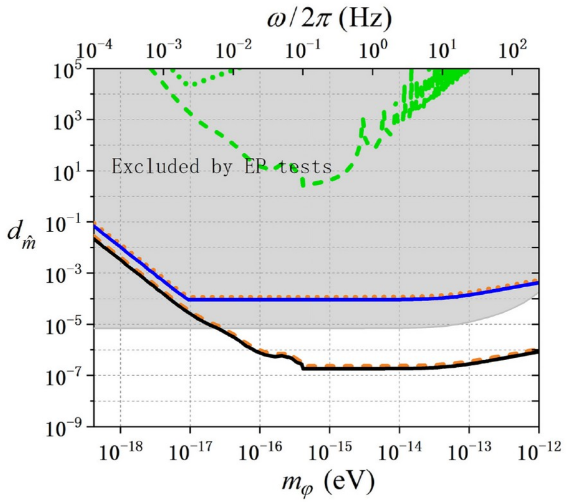
The Proposal

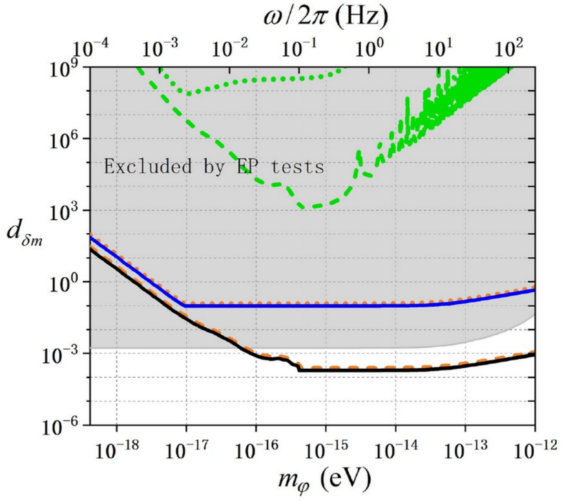
ZAIGA-DM

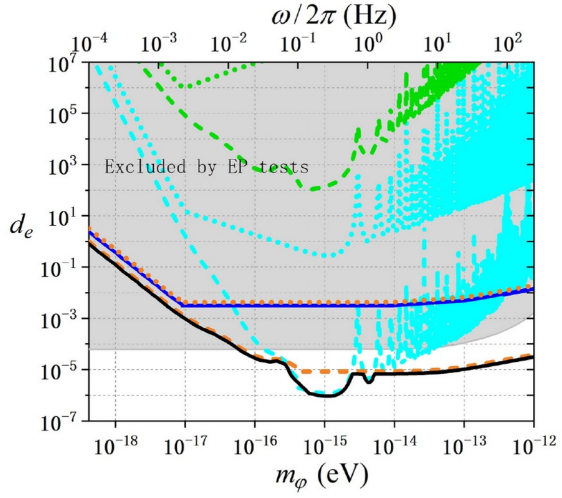
Constraints on the DM coupling parameters

For the vertical AI pair









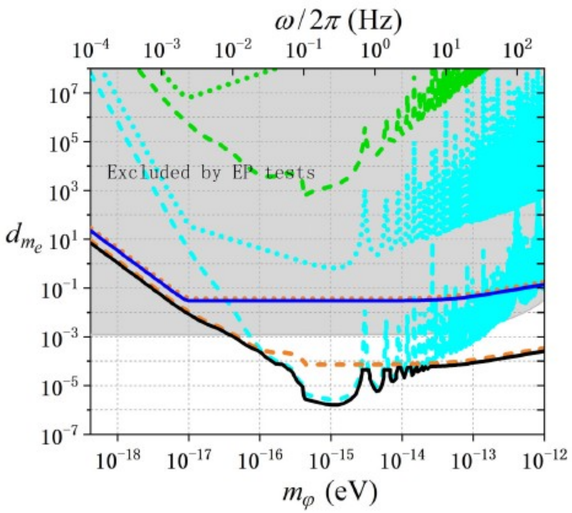


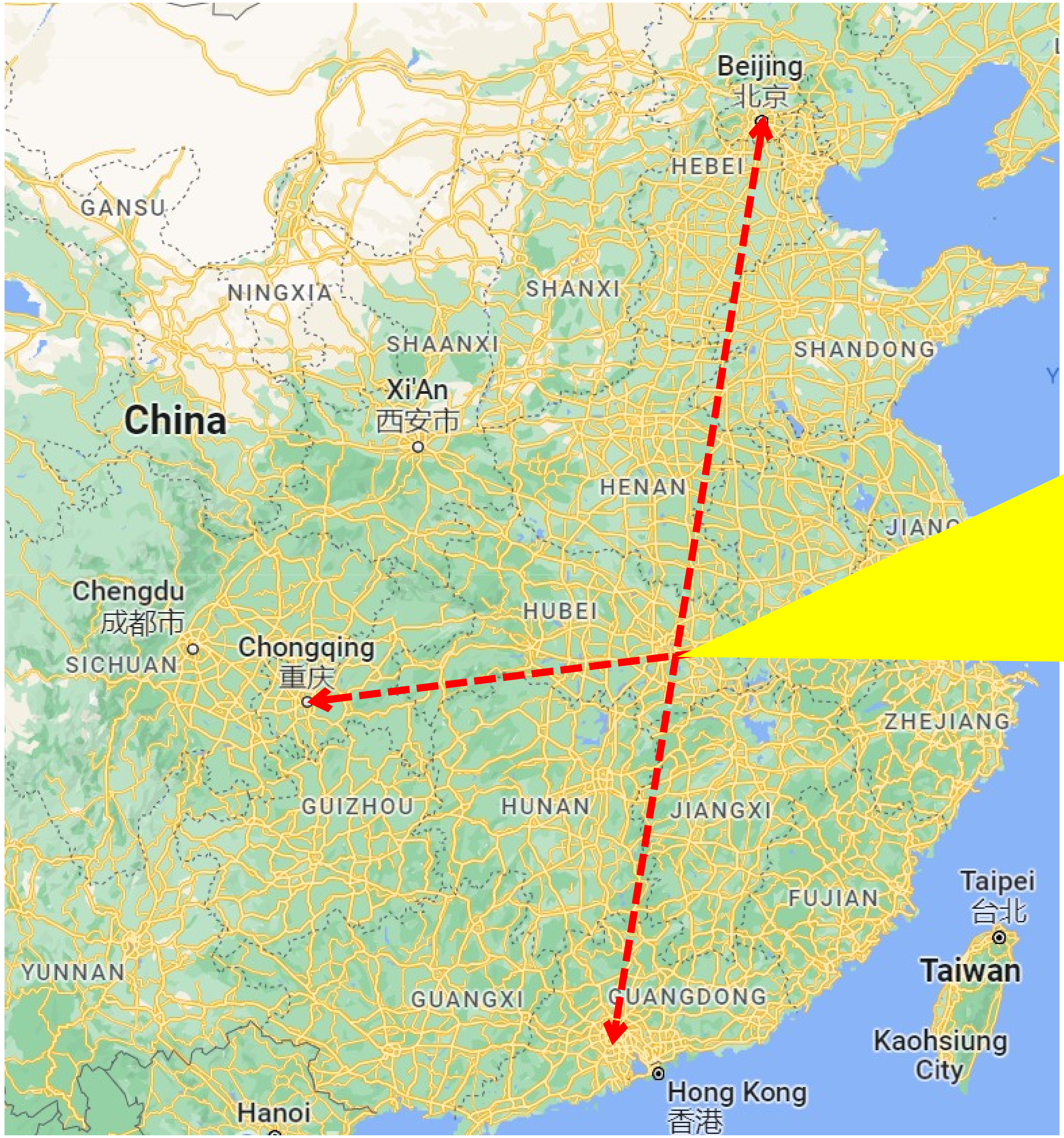
Table 1. The technical parameters for a pair of vertically separated AIs.

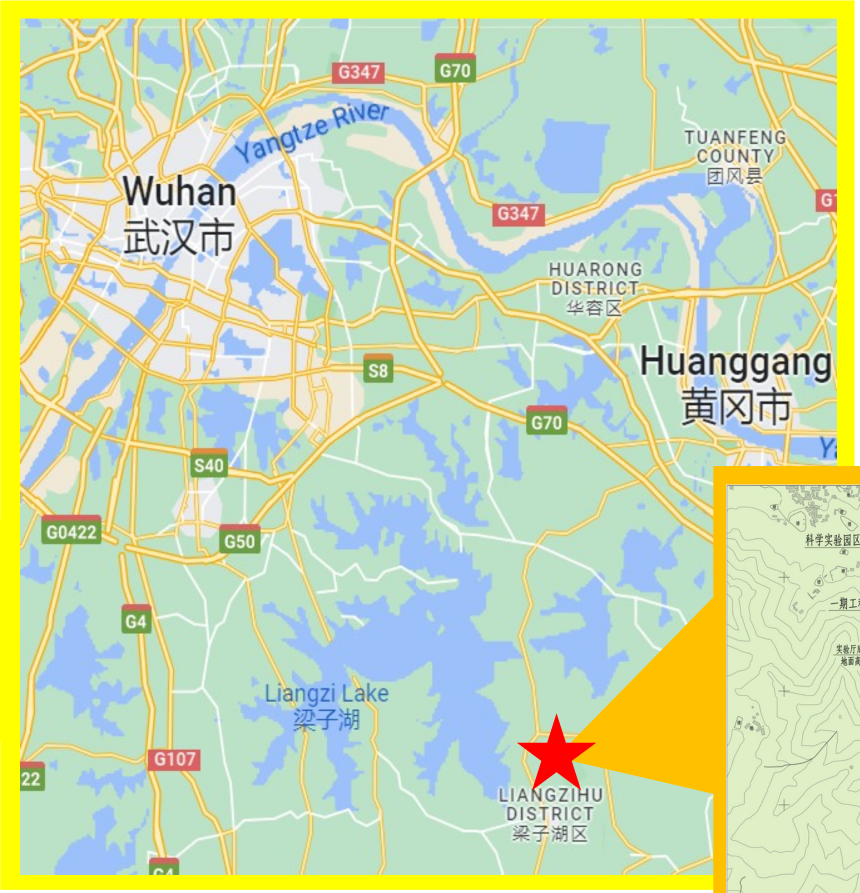
	Free evolution time (T)	Phase sensitivity	Momentum transfer (n)	Integration time ($t_{\rm int}$)	Arm-length (L)
Near term	1.4 s	10^{-3} rad/$\sqrt{\rm Hz}$	4	10^4 s	300 m
Future	1.4 s	10^{-4} rad/$\sqrt{\rm Hz}$	10^4	10^6 s	300 m

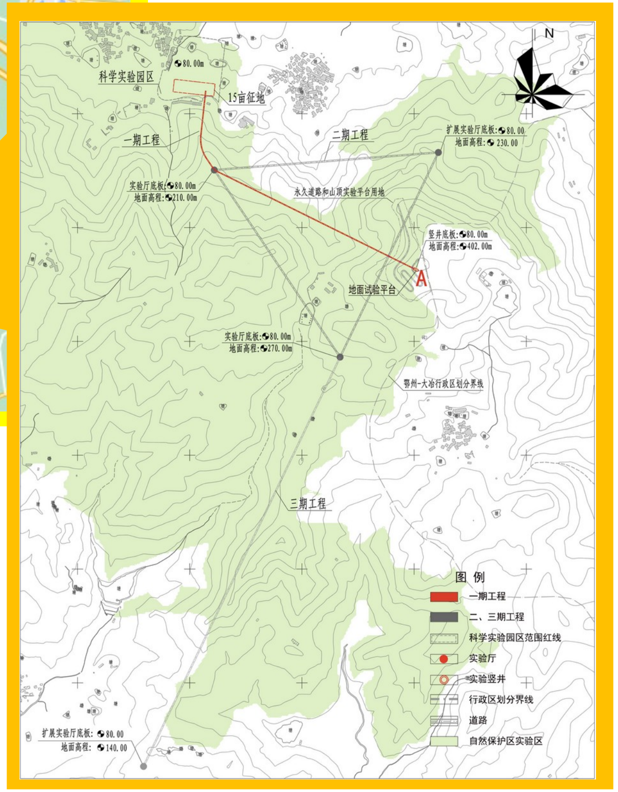
The Site

location

ZAIGA







Zhaoshan
沼山

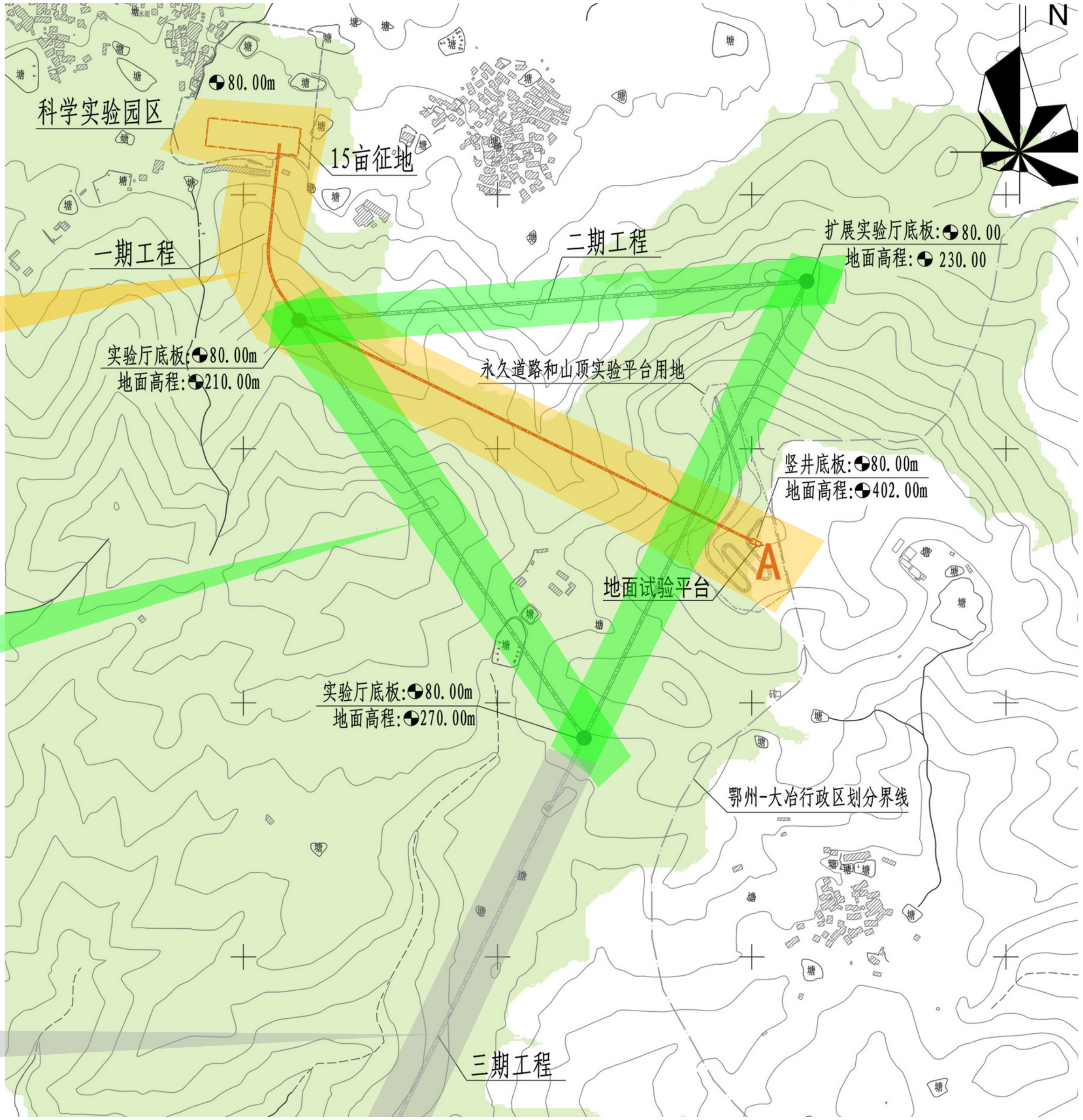
Mission assignment

3 Phases

ZAIGA

ZAIGA - ZMS

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

Phase I Goals: building abilities

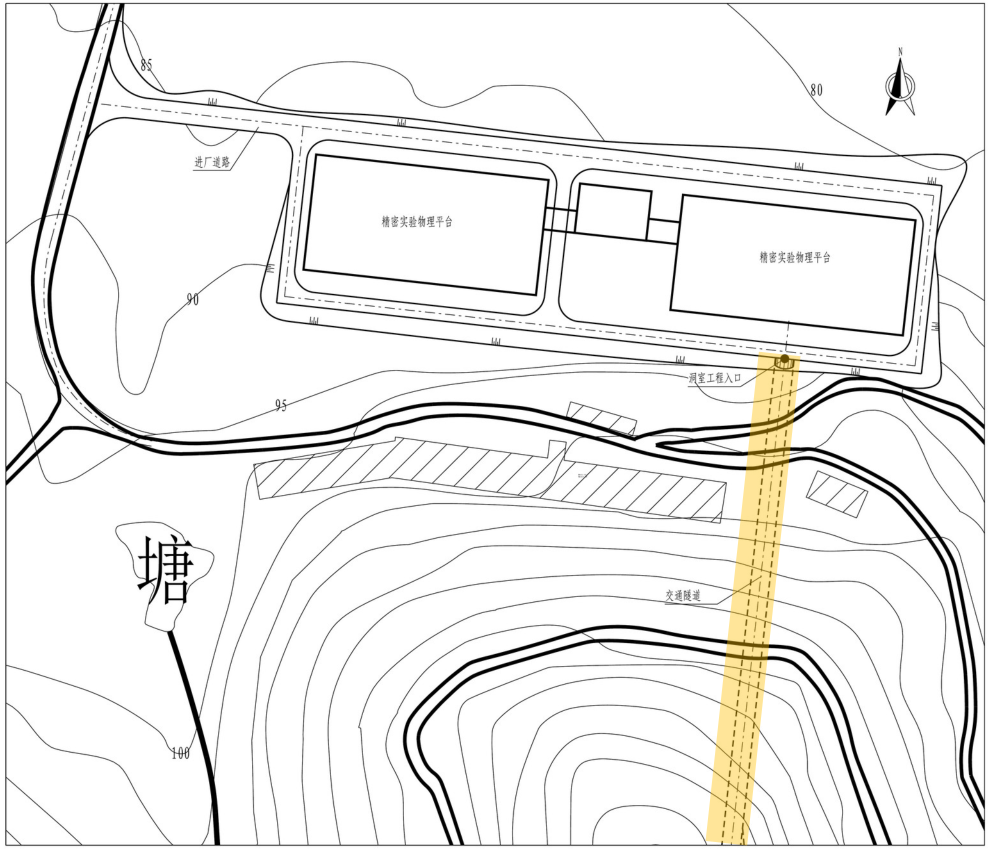
Item	Project Goal
AI baseline (Free fall time)	240 m (T 6 s)
Atom species for AI	^{85}Rb ^{87}Rb ^{87}Sr ^{88}Sr
Gravity measurement	1 10^{-12} g
Rotation measurement	8 10^{-12} rad/s (2 10^{-6} °/h)
Stability of Sr/Yb optical clock	2 10^{-18}
Local gravity monitoring	1 μGal

Phase I

design and sketch

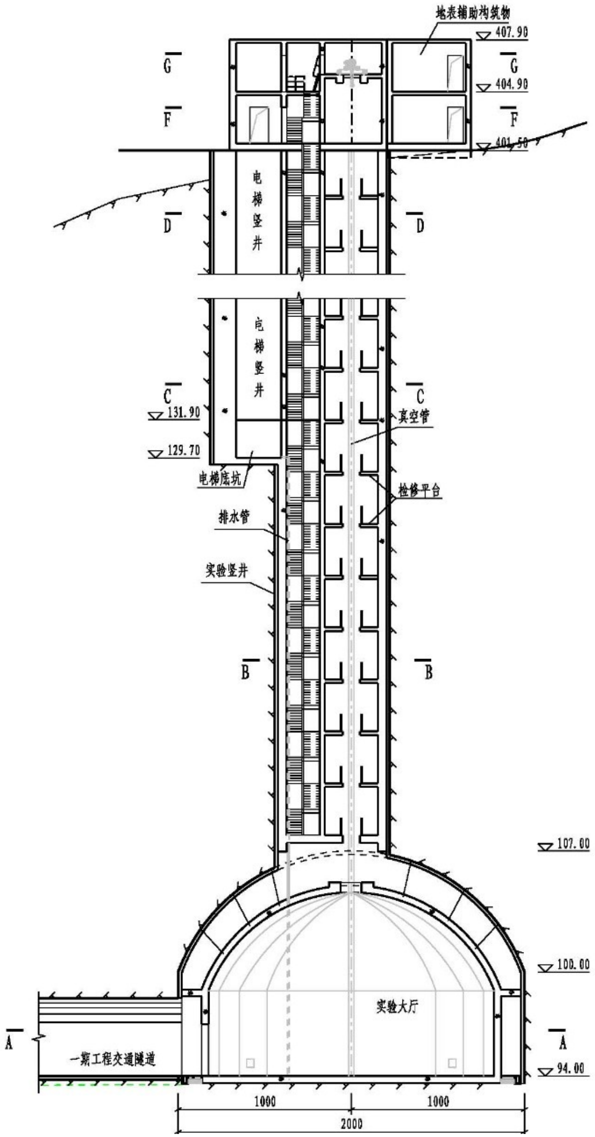
ZAIGA

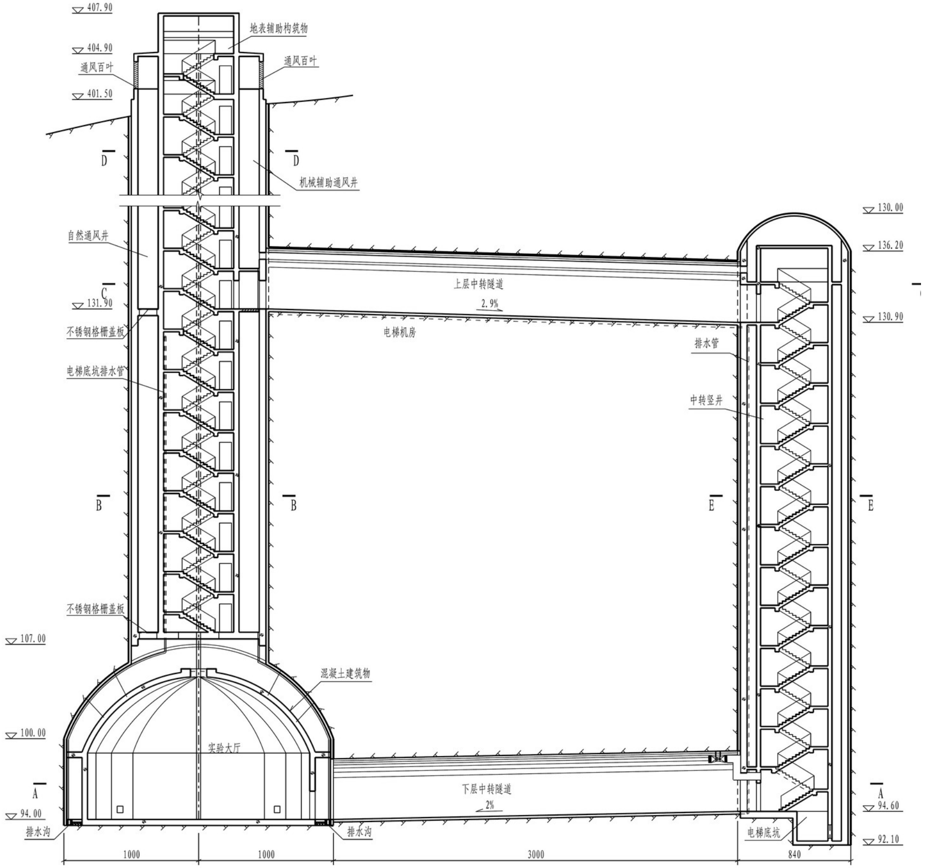
The scientific research park
(on the mountain foot, 10000 m^2)



Phase I design and sketch

The shaft and the Experimental hall (1)

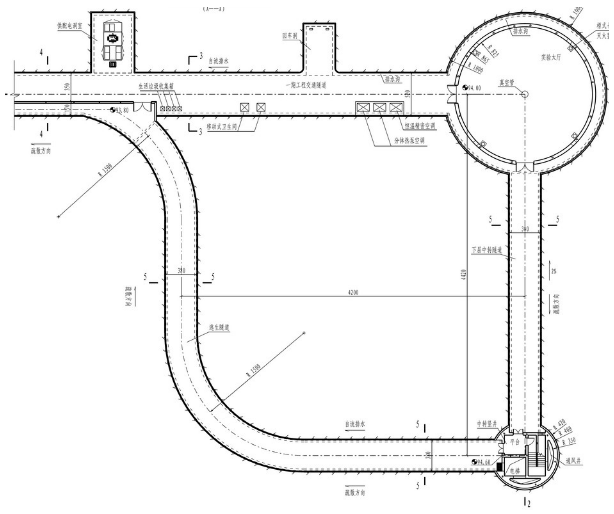




Phase I

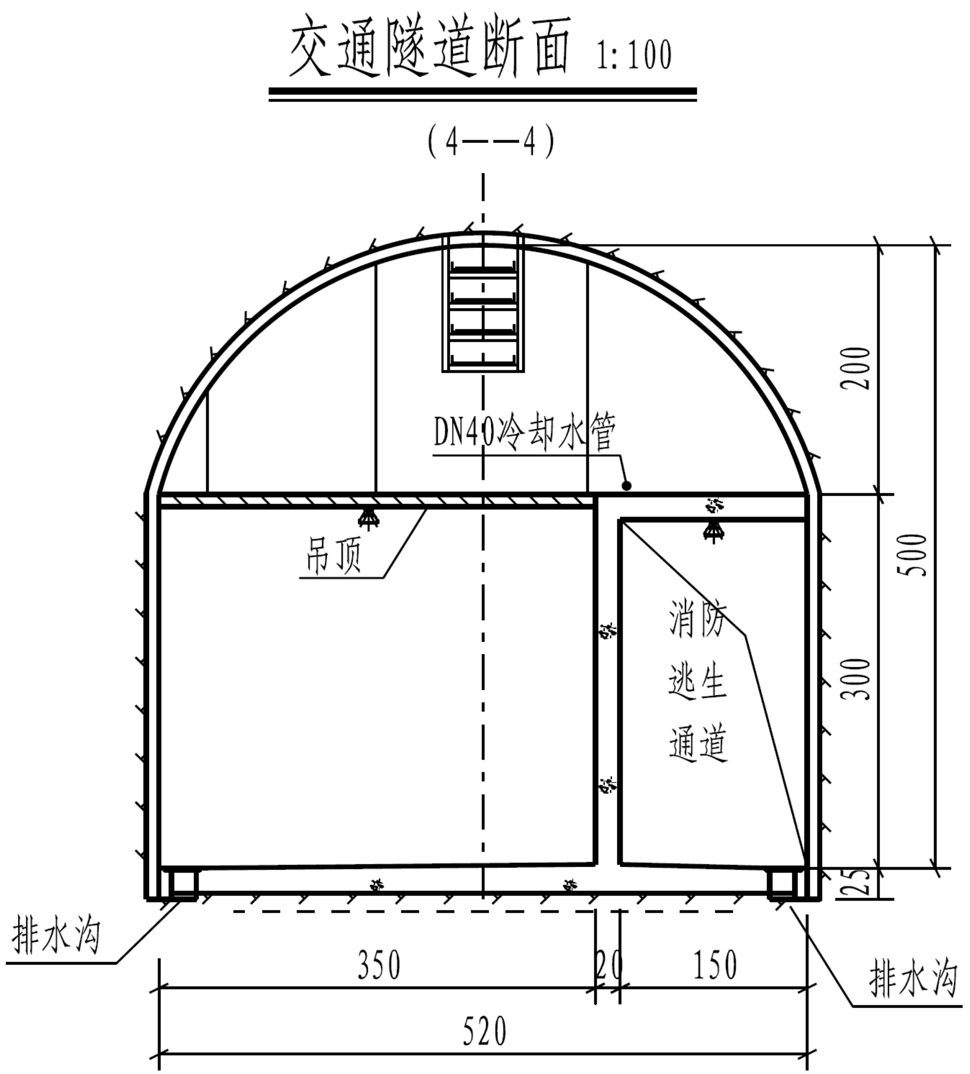
design and sketch

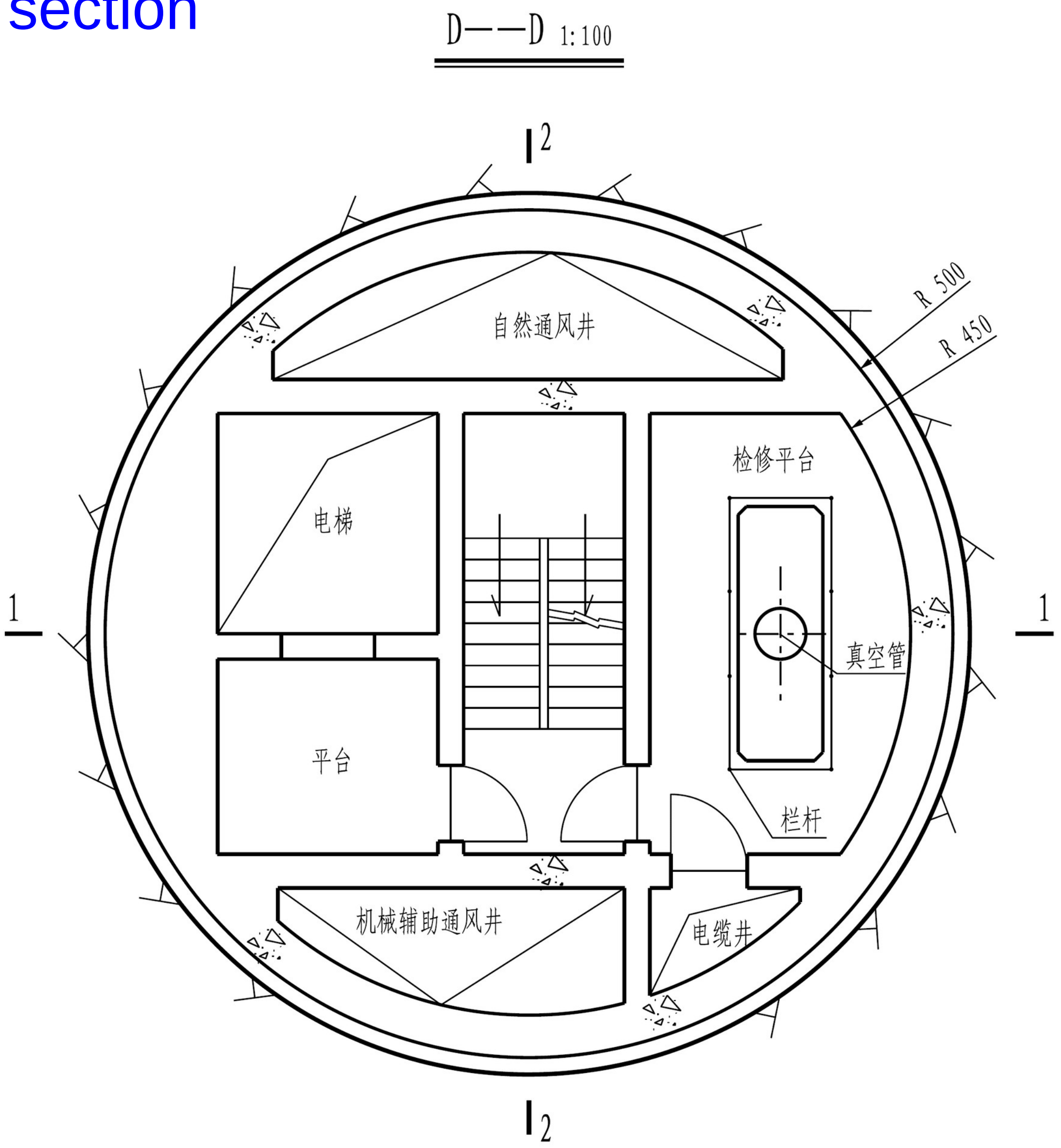
The shaft and the Experimental hall （2）



design and sketch

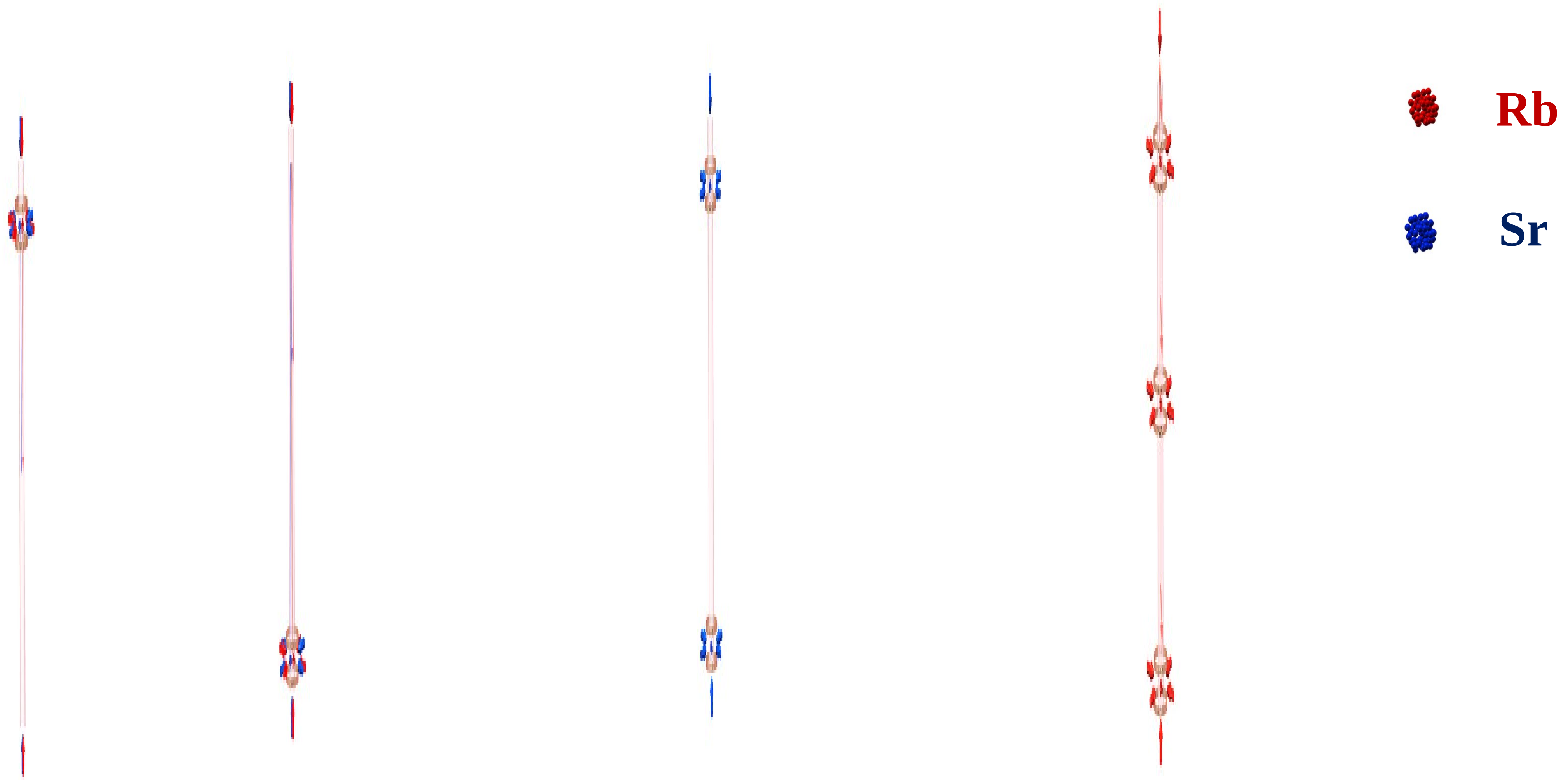
Shaft and tunnel section





Phase I

diversity in the 240 m AI



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

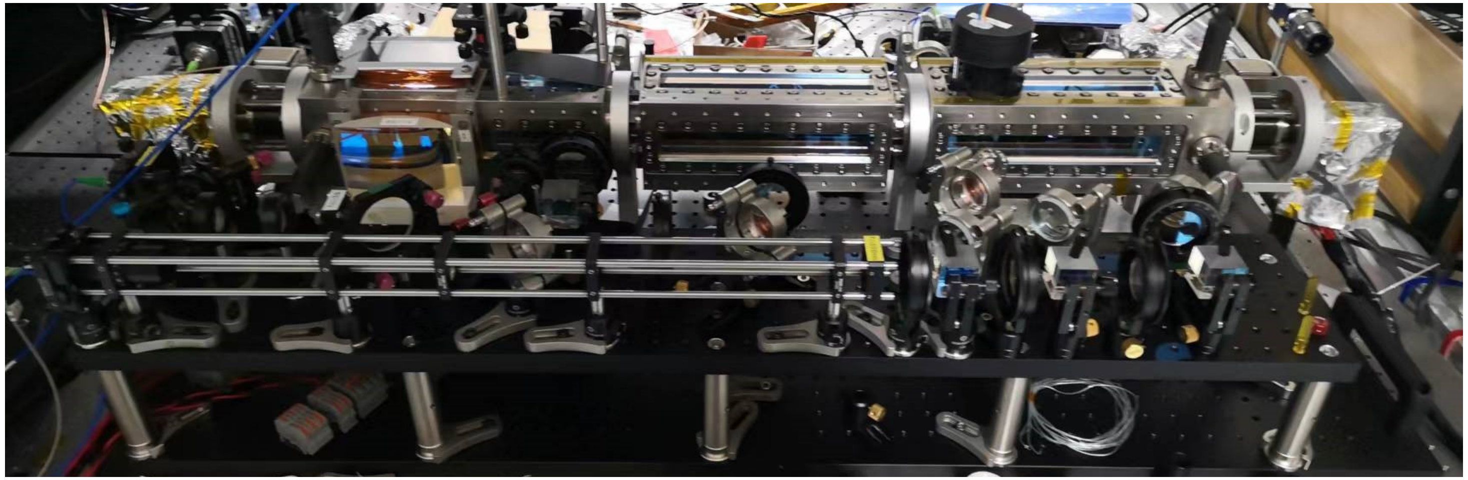
QM 、 EP test | Redshift Exp. | GW 、 DM

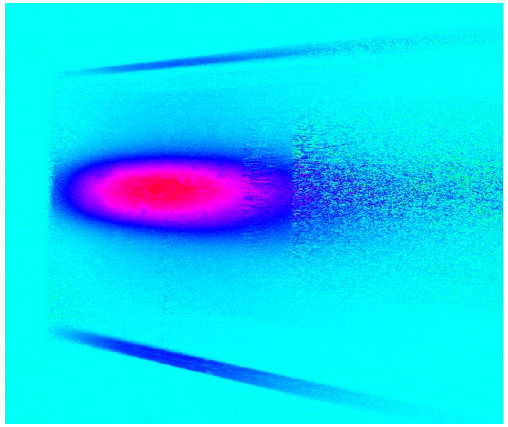
Recent Progress

1 m Atomic Beam Test Setup

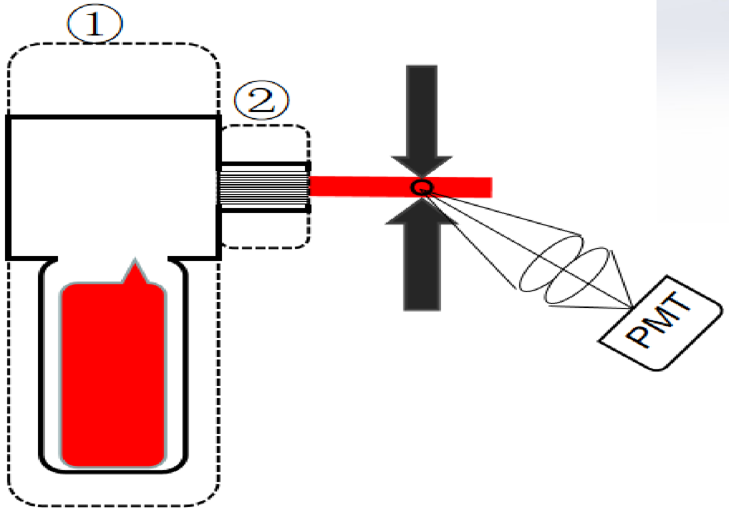
ZAIGA

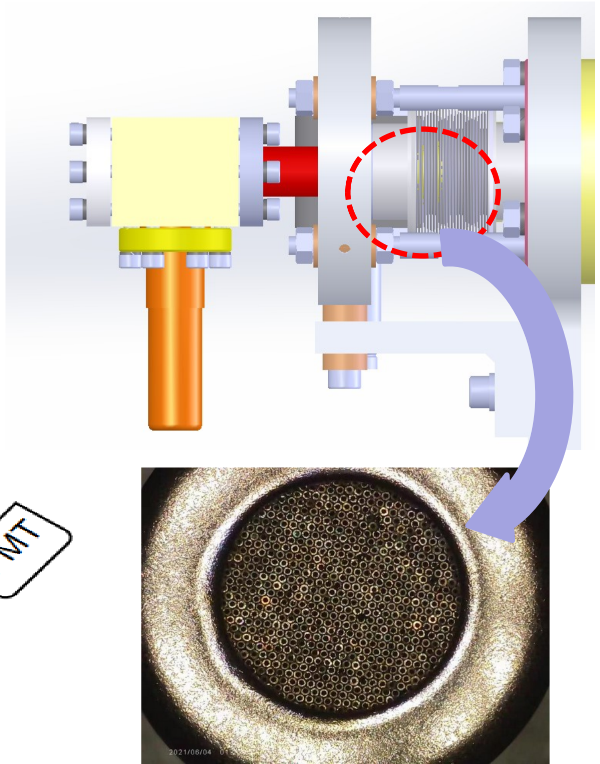
ZAIGA - ZMS

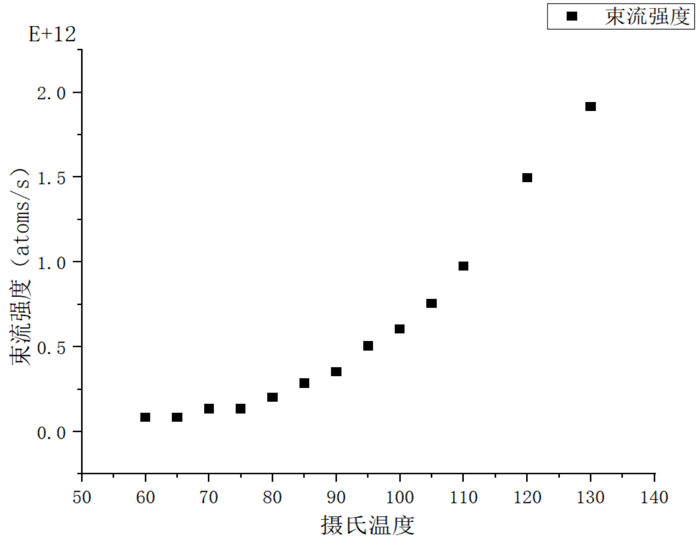




Atom Temperature: 100 μK
(Sub-Doppler Cooling)





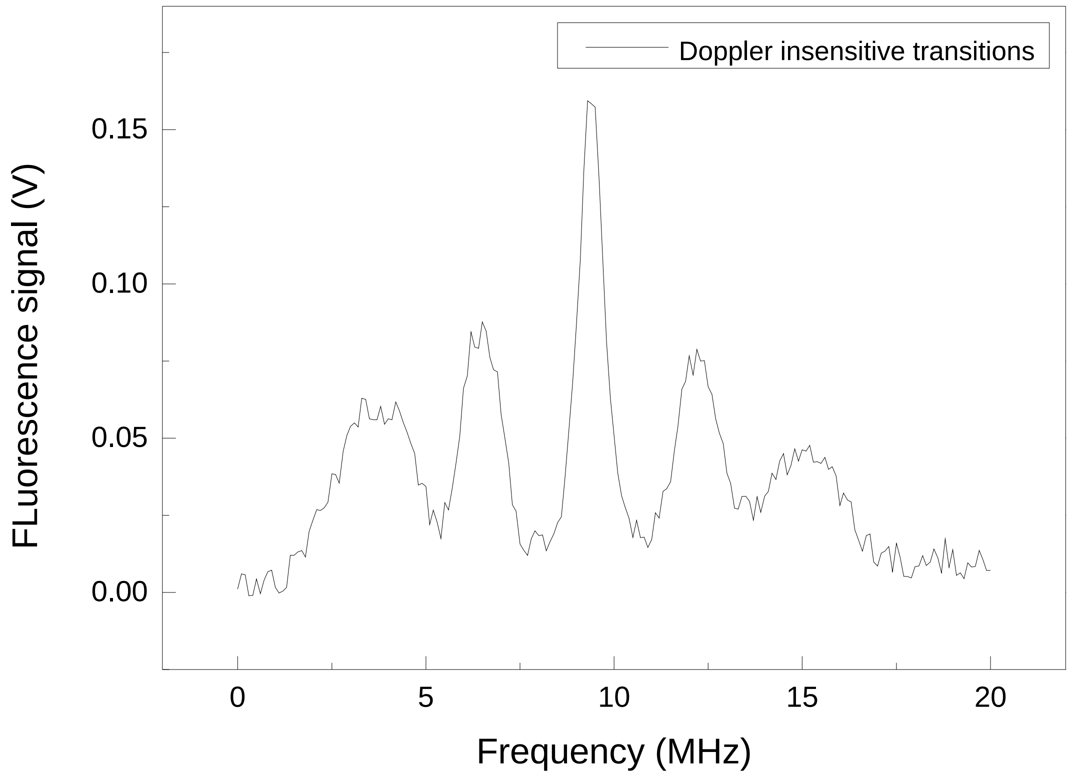


Atom number:
10^{12}atoms/s(capillaries)

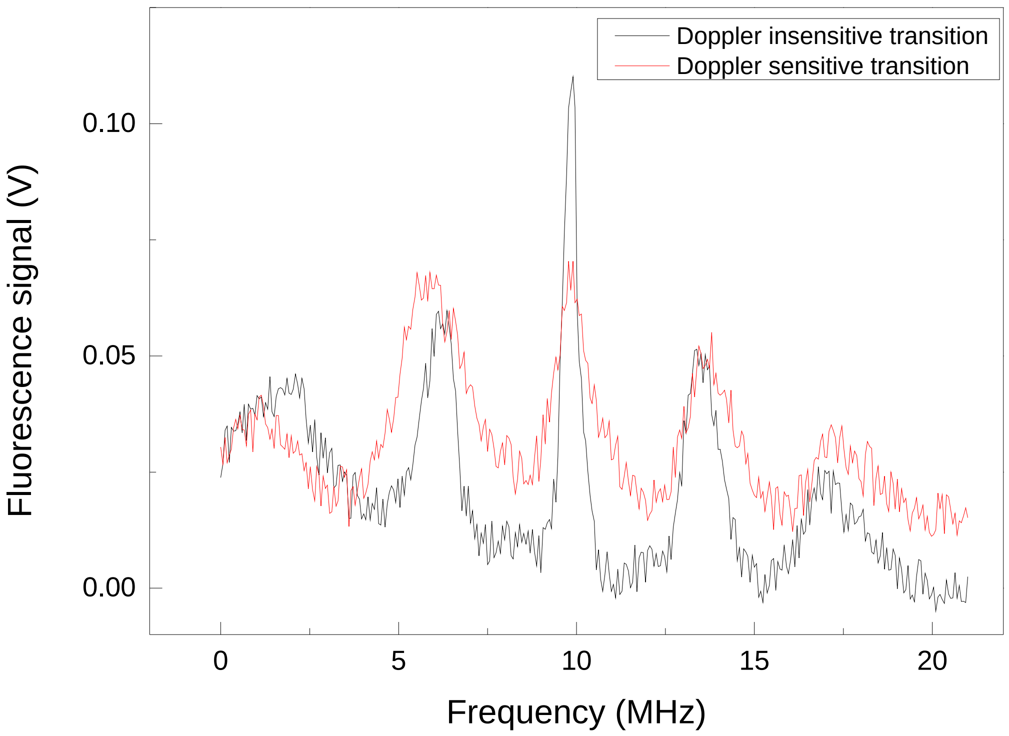
Recent Progress

1 m Atomic Beam Test Setup

ZAIGA



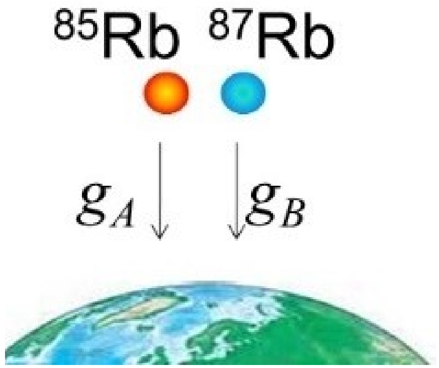
Raman transitions in the co-propagating



Comparison between the counter-propagating and co-propagating transitions

EP test at the 10-m AI

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)

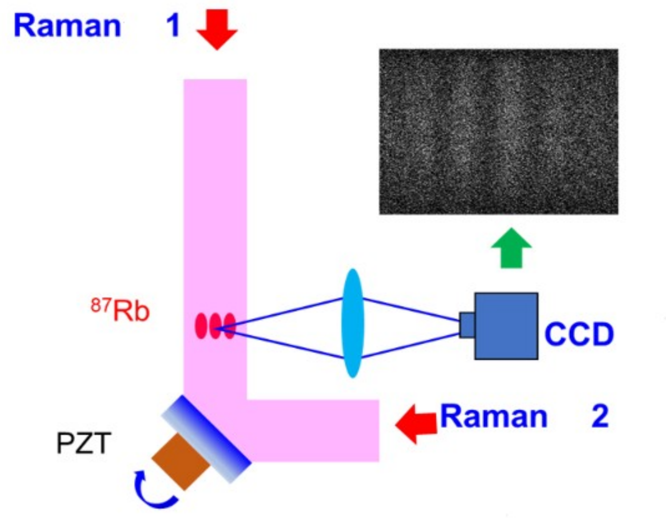
^{85}Rb-^{87}Rb dual-species AI

Mass-energy joint test of EP

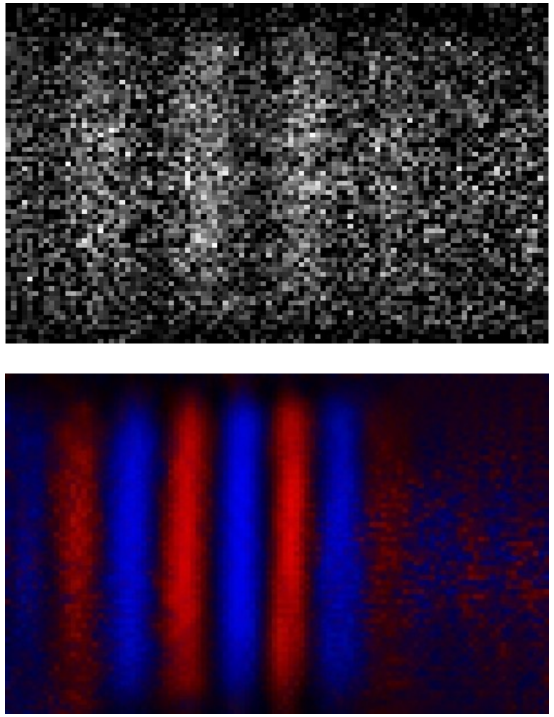
First time: energy violation parameters for EP

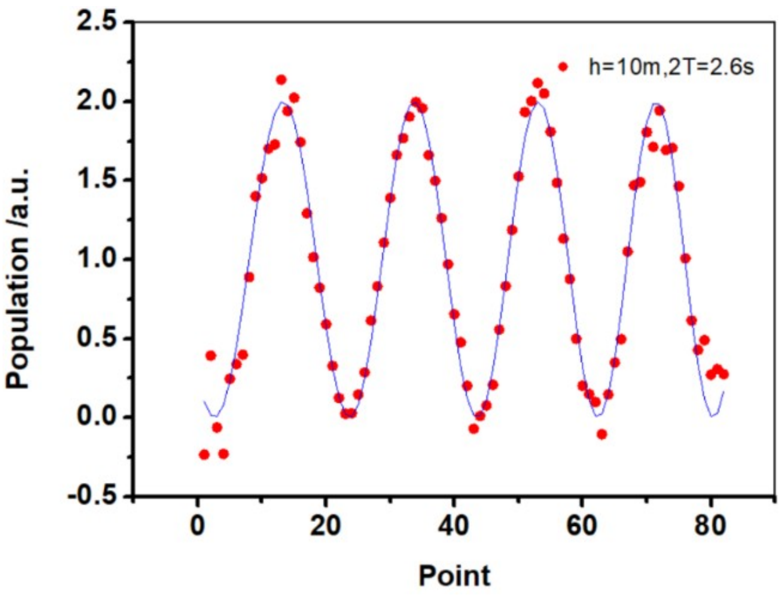
Opens a new way: mass-energy joint quantum test of EP

Atom interference fringes @ launch up 10 m



Shear Interference Detection





$$\frac{\delta g}{g} = \frac{\delta \phi}{k g T^2} = 4.5 \times 10^{-11} \text{ / shot}$$

Launch height	Free falling time	EPT precision
10 m	2T=2.6 s	Expected 10^{-13}

Roadmap of WEP test with AI@APM

Violation Signal

- isotope ✉ element — **Rb - Sr**
- MW ✉ visible (optical clock transition)
  - eV ✉ eV

Detection Sensitivity

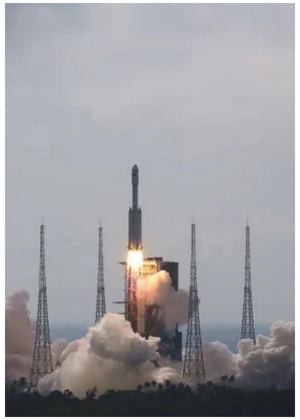
T

0.2 s ✉ 1.3s ✉ 7 s ✉ (2 ⟷ 100) s

Recent Progress

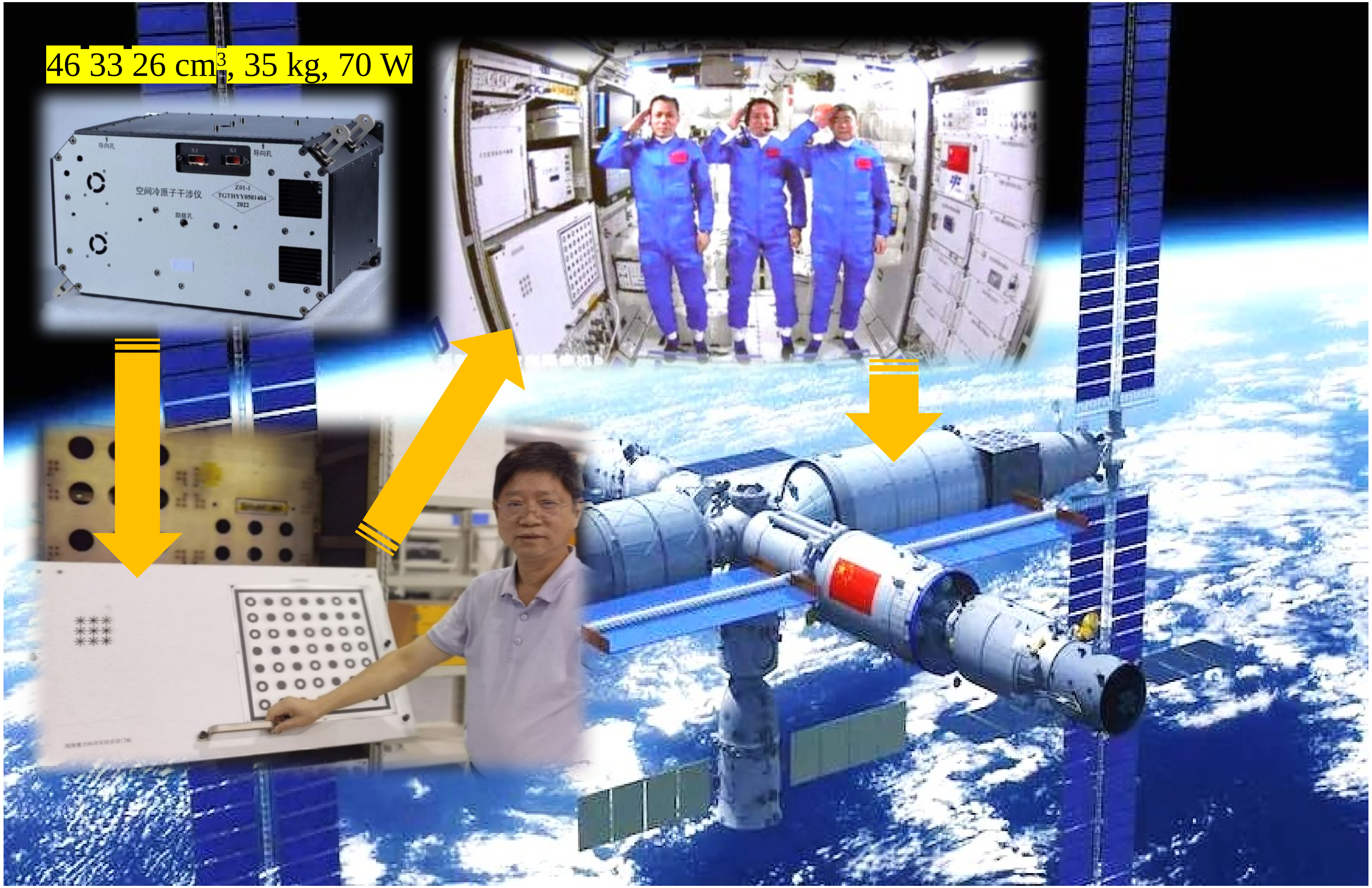
WEP test in China Space Station

Dual-species
Space AI



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

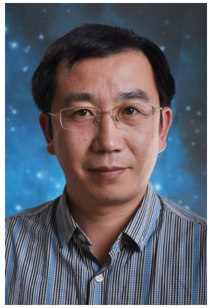
Now working well,
optimizing,
collecting data

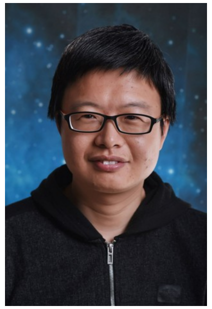


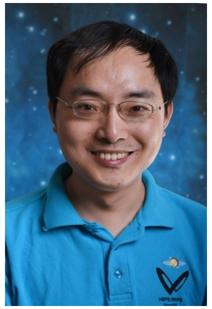
Acknowledgments

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


Jin Wang


Runbing Li


Peng Xu

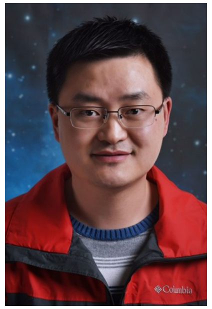

Xiaodong He

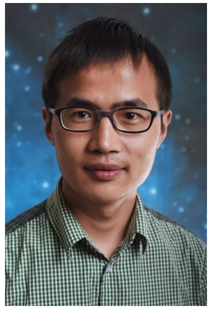

Lin Zhou


Min Liu


Wei-Tou Ni


Xi Chen


Jiaqi Zhong


Zhanwei Yao


Biao Tang


Dongfeng Gao


Zhongyuan Xiong


Min Ke

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

All of you, for your attention!