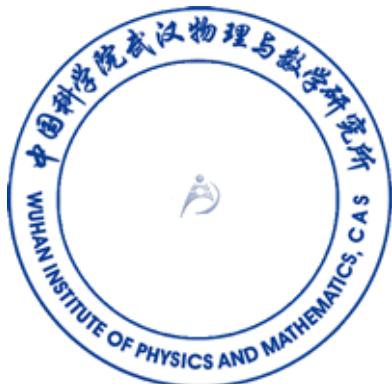


# **ZAIGA: Zhaoshan long-baseline Atom Interferometer Gravitation Antenna**



**Mingsheng ZHAN**

**Wuhan Institute of Physics and Mathematics (WIPM)  
Chinese Academy of Sciences (CAS)**

# OUTLINE

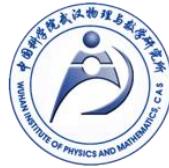
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- Motivation
- ZAIGA: facility and key instruments
- ZAIGA: scientific proposals
- Progress

# OUTLINE

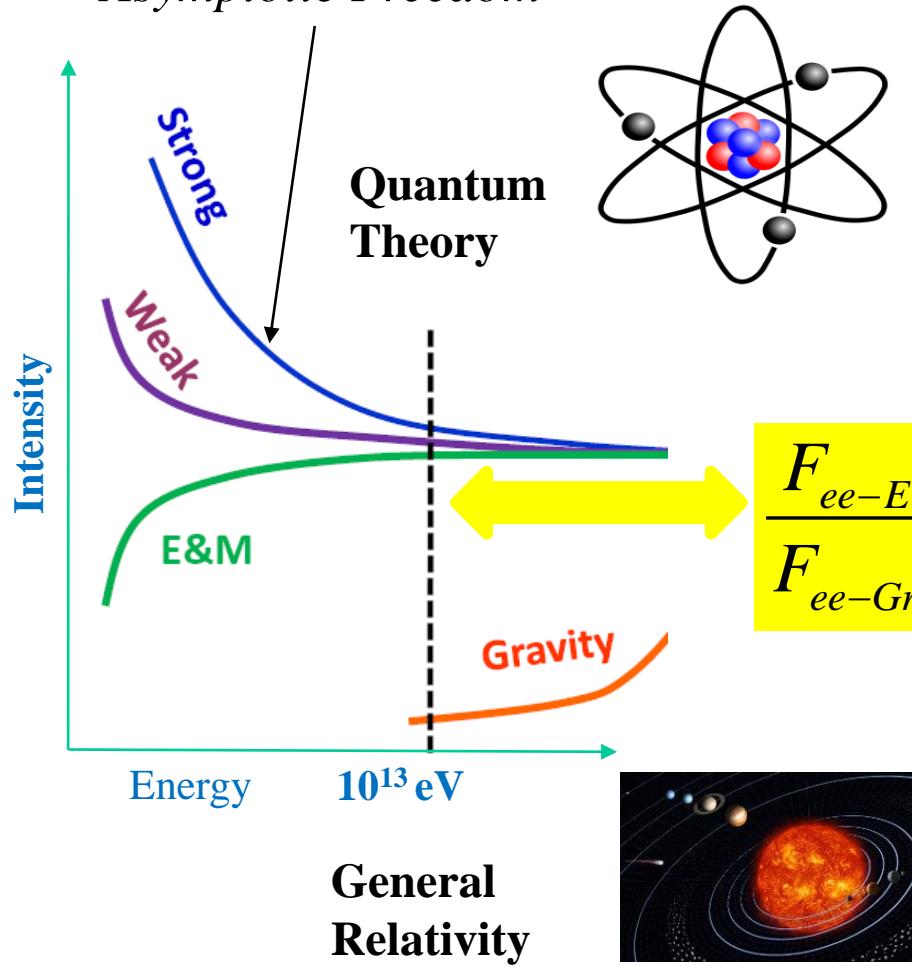
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- Motivation
- ZAIGA: facility and key instruments
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- Progress

# ZAIGA: bridge GR and QT with atomic sensors

*Asymptotic Freedom*



**Gravitational effect  
on micro-systems?**

**Neutron, Atom,  
Ion, Molecule ...**

**Atomic Clock**  
**Atom Interferometer**

$$\frac{F_{ee-E\&M}}{F_{ee-Gravity}} = \left(\frac{e}{m_e}\right)^2 \frac{1}{4\pi\epsilon_0 G} = 4 \times 10^{42}$$

**Quantum effect  
of macro-objects?**

**C<sub>60</sub>, Virus, Bacteria,  
Brain ...**

# Precision Measurement: fighting with noises



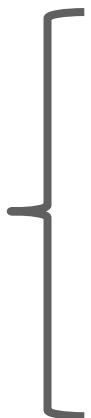
$4 \times 10^{42} : 1$

look for a needle in the sea

**4,000,000,000,000,000,000,000,000,000,000,000,001**

Observables (frequency, phase, energy....): stable

**ZAIGA**



Large scale  
Quantum sensors  
.....

Underground  
Space  
.....

effect, signal: large

**SNR ↑**

noises: small

# Long Base-line Interferometers

VLBI

LIGO

LAIGA



RF

SKA

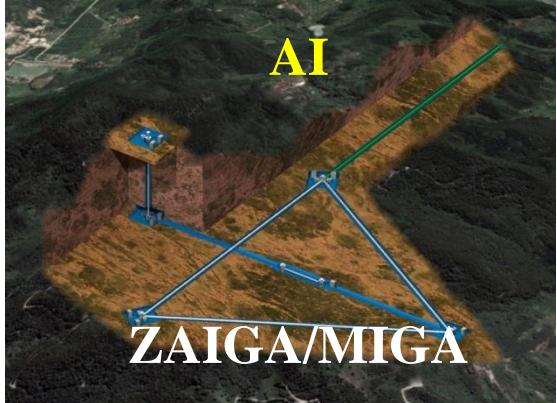
RF/MW



LI

VIRGO/KAGRA/LISA

Laser Light

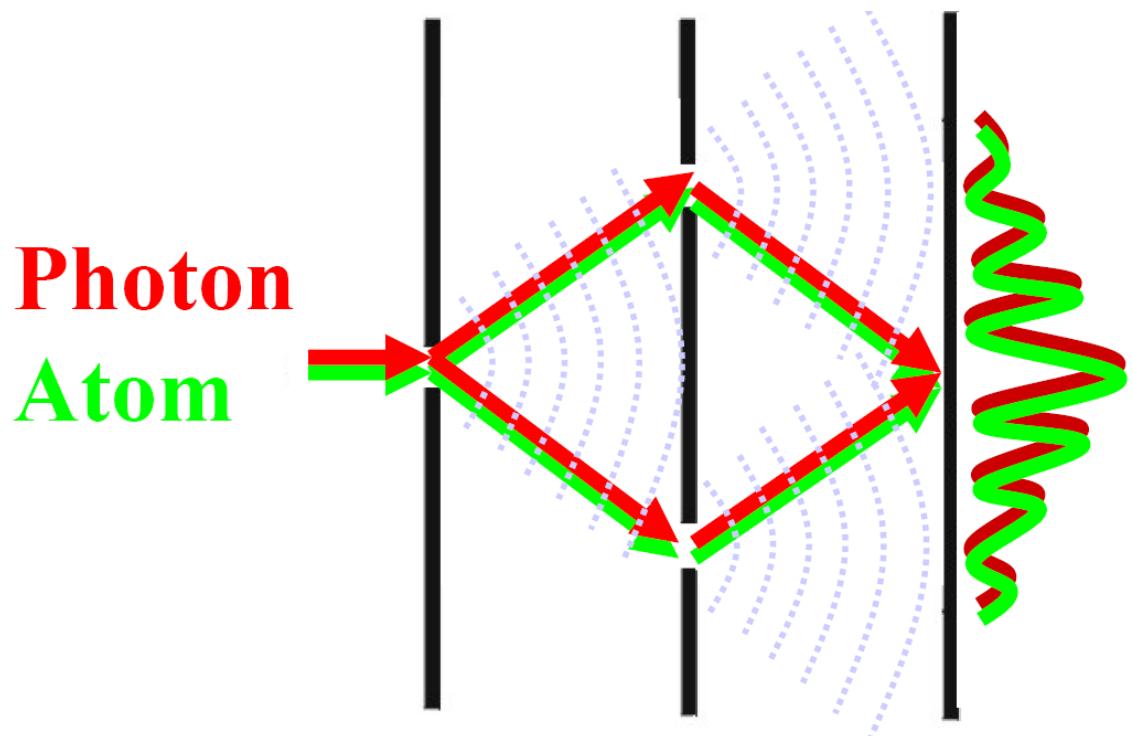
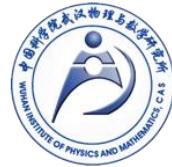


AI

ZAIGA/MIGA

Matter Wave

# Coherence & Interference



Photon  
Atom

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

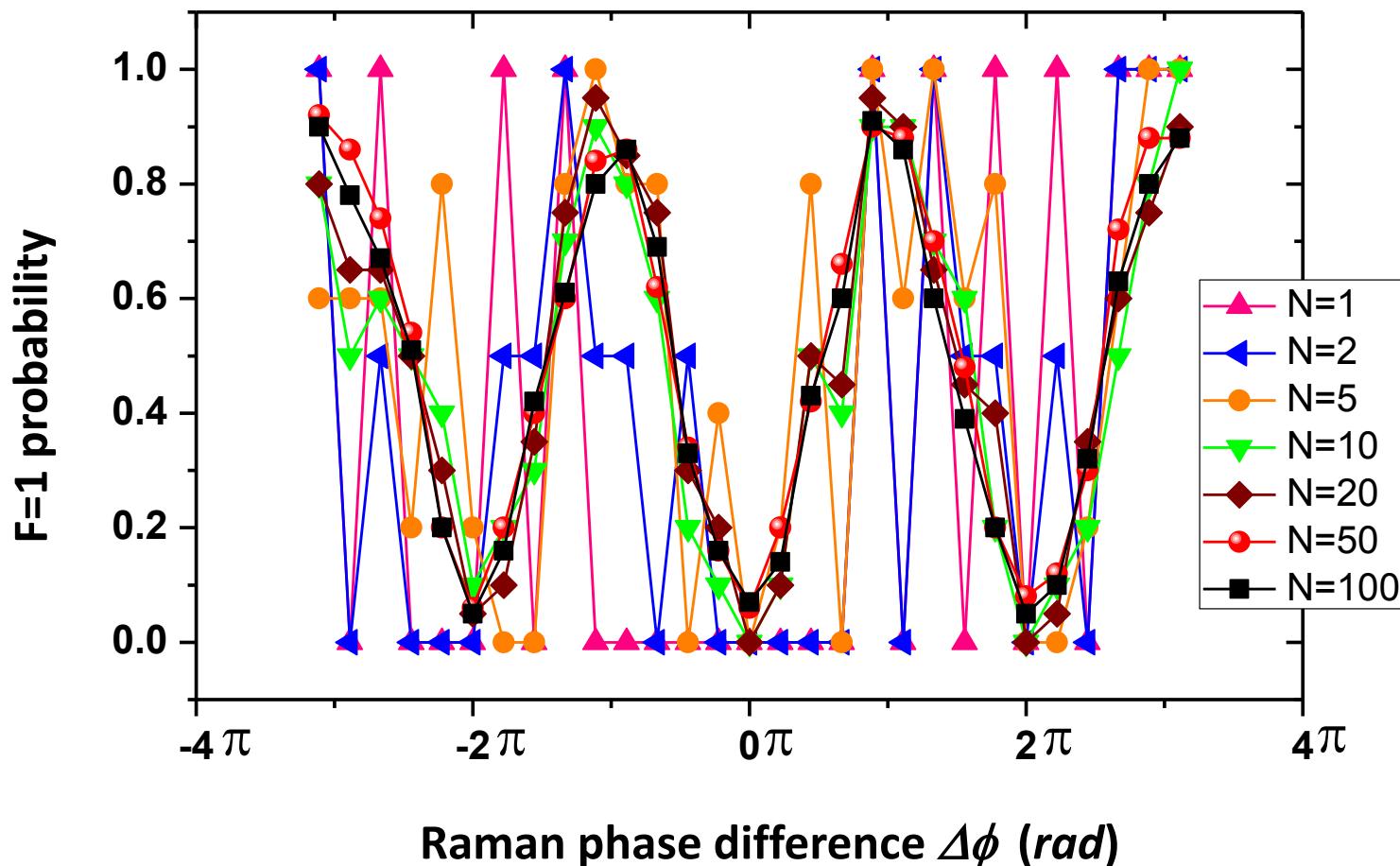
Cold atoms

$v$  small  $\ll c$

$\lambda_{dB}$  larg  $\gg \lambda_L$

# Single atom M-Z interferometer: building up the interference fringe

Each time 1 atom, averaged N times  
**The atom interferes with itself!**



# Laser interferometry vs Atom interferometry

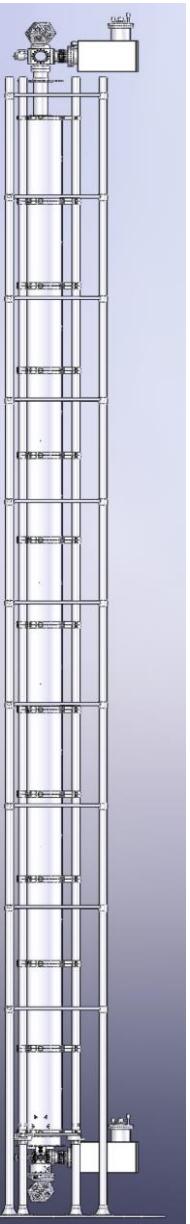
e.g. gyro = interference + Sagnac effect

**Atom gyro**     $\delta_{gyro}(m > 0) = \frac{4\pi m}{h} \Omega \cdot A$

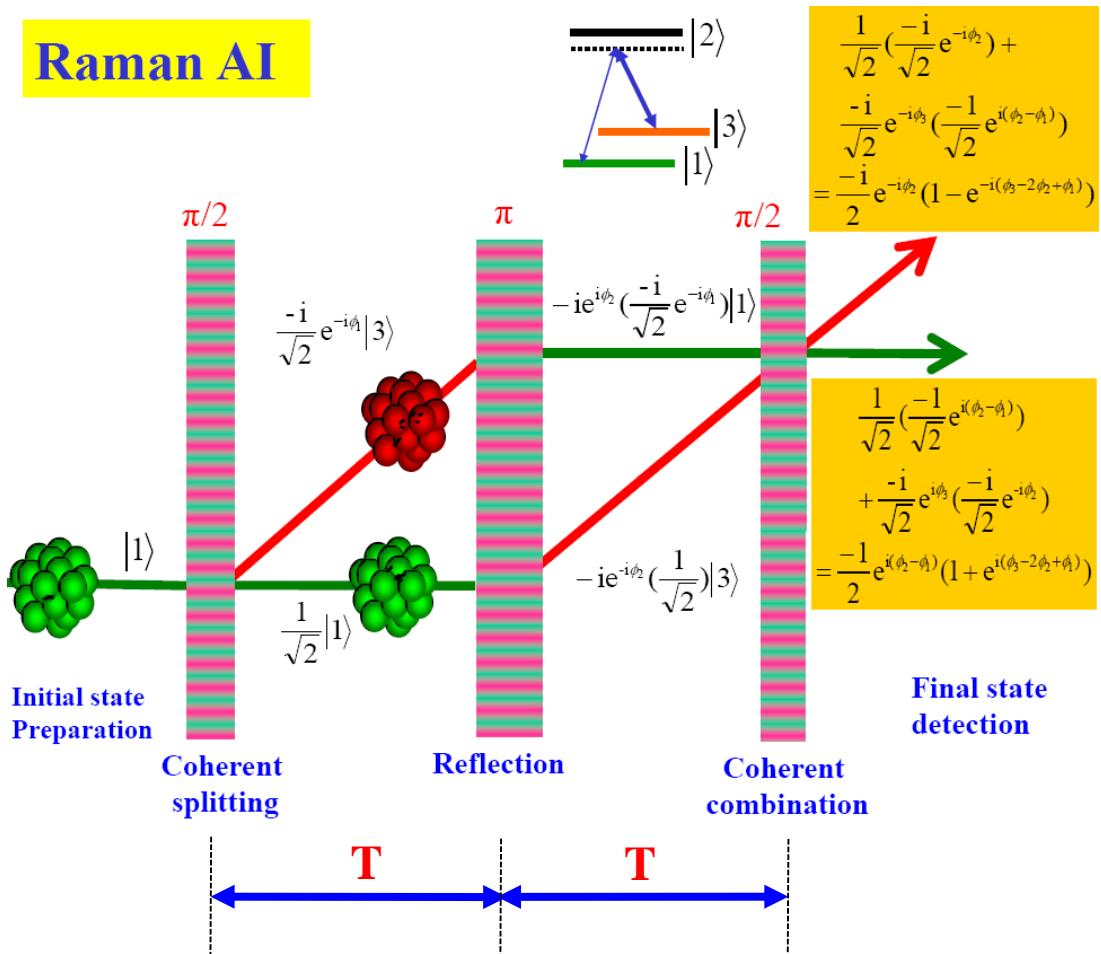
**light gyro**     $\delta_{gyro}(light) = \frac{4\pi}{\lambda c} \Omega \cdot A$

**Ratio**     $R_{gyro} = \frac{mc^2}{\hbar\omega} = \frac{\lambda}{\lambda_{deB}} \frac{c}{v}$  ~  $10^{10}$

# Atom Interferometry



## Raman AI



$$1 \text{ m}, T = 0.45 \text{ s}$$

$$10 \text{ m}, T = 1.41 \text{ s}$$

$$300 \text{ m}, T = 7.82 \text{ s}$$

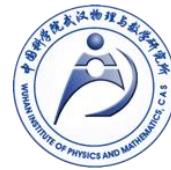
Test mass:

free atoms

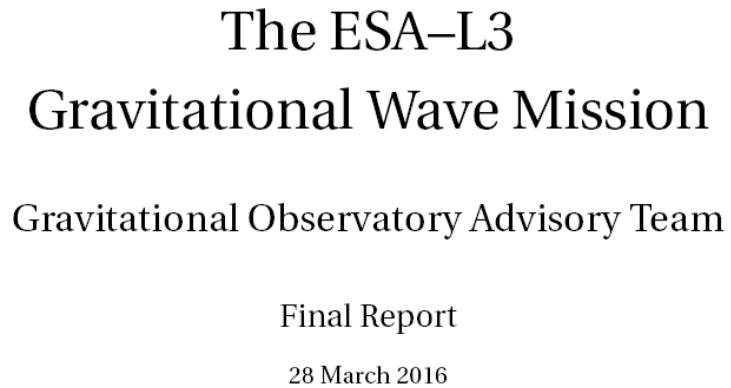
Mirror / Splitter:

light pulse

$$\omega \propto \frac{1}{T} \approx Hz$$

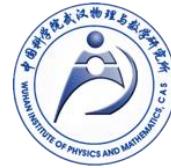


# Laser interferometry vs Atom interferometry



In response to its terms of reference, the Committee's findings are as follows:

1. the Committee has undertaken a review of all known approaches to the measurement of gravitational waves. It has concluded that *laser interferometry* both fully responds to the science goals set out in the 2013 Senior Science Committee report, and is also sufficiently well advanced to offer a highly realistic prospect of implementation according to the L3 schedule. In terms of technology readiness and risk, it is preferred over any alternative;
2. the Committee appreciates that a second approach, based on *atom interferometry*, shows interesting potential. The Committee has encouraged the development of a full mission proposal to assess better its challenges, and its prospects for either a more secure, or a less costly, alternative. With ESA proceeding with plans for small innovative missions, a proof-of-concept atom interferometry experiment could be timely;
3. the Committee has re-evaluated the scientific capabilities of a gravitational wave observatory, quantifying and presenting the expected performance as a function of:



# ZAIGA: why GR test ?

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**General relativity** has held up under extensive experimental scrutiny. The question then arises, why bother to continue to test it? One reason is that gravity is a fundamental interaction of nature, and as such requires the most solid empirical underpinning we can provide. Another is that **all attempts to quantize gravity and to unify it with the other forces suggest that the standard general relativity of Einstein may not be the last word.** Furthermore, the predictions of general relativity are fixed; **the pure theory contains no adjustable constants so nothing can be changed.** Thus **every test of the theory is either a potentially deadly test or a possible probe for new physics.** Although it is remarkable that this theory, born 100 years ago out of almost pure thought, has managed to survive every test, the possibility of finding a discrepancy will continue to drive experiments for years to come. These experiments will search for **new physics beyond Einstein** at many different scales: the large distance scales of the astrophysical, galactic, and cosmological realms; scales of very short distances or high energy; and scales related to strong or dynamical gravity.

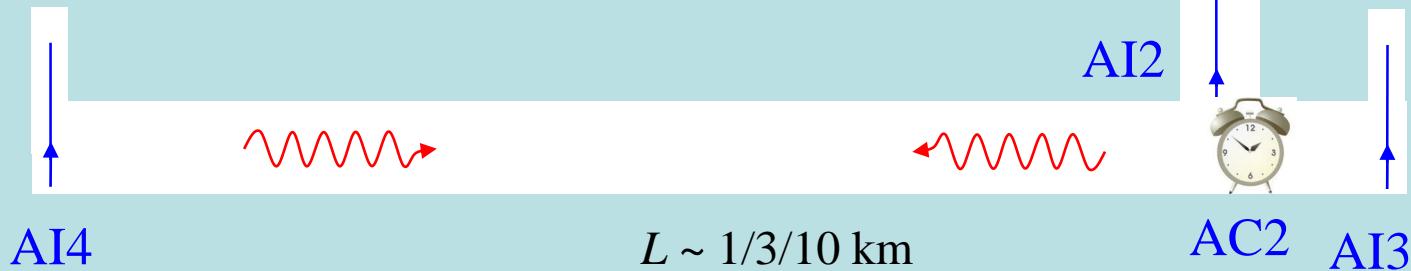


a home for large scale atomic  
interferometers, gyros and clocks

- Underground
- Large scale

AI<sub>i</sub> : i-th Atomic Interferometer

AC<sub>i</sub>: i-th Atomic Clock



Side view

# ZAIGA: announced (arXiv & IJMPD)

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## ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna

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Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*

<sup>2</sup>*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*

<sup>3</sup>*School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China*

(Dated: March 27, 2019)

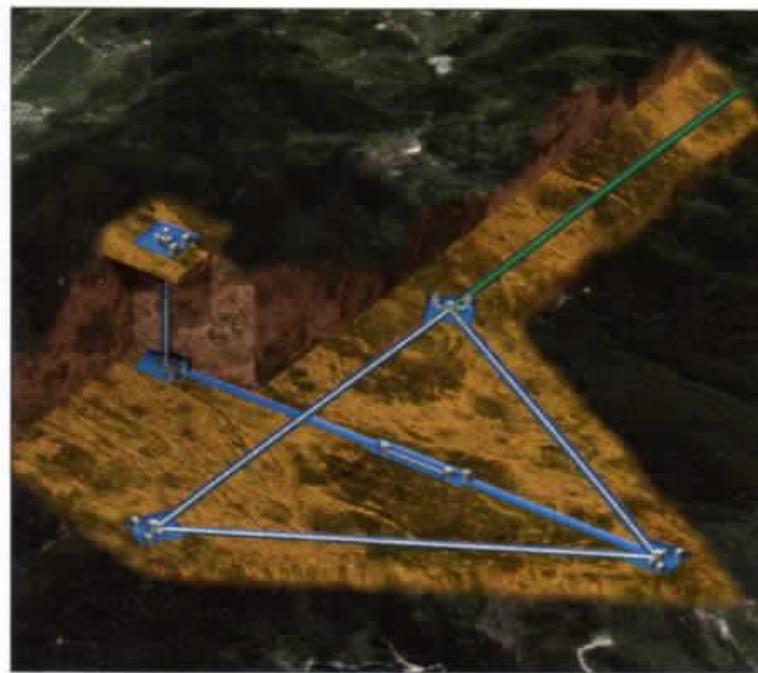
The Zhaoshan long-baseline Atom Interferometer Gravitation Antenna (ZAIGA) is a new type of underground laser-linked interferometer facility, and is currently under construction. It is in the 200-meter-on-average underground of a mountain named Zhaoshan which is about 80 km southeast to Wuhan. ZAIGA will be equipped with long-baseline atom interferometers, high-precision atom clocks, and large-scale gyros. ZAIGA facility will take an equilateral triangle configuration with two 1-km-apart atom interferometers in each arm, a 300-meter vertical tunnel with atom fountain and atom clocks mounted, and a tracking-and-ranging 1-km-arm-length prototype with lattice optical clocks linked by locked lasers. The ZAIGA facility will be used for experimental research on gravitation and related problems including gravitational wave detection, high-precision test of the equivalence principle of micro-particles, clock based gravitational red-shift measurement, rotation measurement and gravito-magnetic effect.

# China unveils plans for giant underground lab

A new facility in central China is designed to study gravitational waves as well as test Einstein's theory of general relativity to unprecedented precision, as **Ling Xin** reports

Physicists in China have revealed plans to build a massive new underground facility in the centre of the country to study gravitational waves and test Einstein's general theory of relativity to an unprecedented precision. The Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (ZAIGA), is to be located in eastern Wuhan and will cost two billion yuan (about £226m). If the project is fully funded, it could be operational by 2025 (arXiv:1903.09288).

The first phase of ZAIGA, which could be complete by the end of 2020, will involve building a 300 m vertical tunnel under the Zhaoshan Mountain – 80 km south-east of Wuhan – to study various predictions resulting from general relativity. It will cost 600 million yuan (£68m) and is fully funded by local governments and the Chinese Academy of Sciences. “We have just completed site exploration, with tunnel excavation starting this



## Tunnel vision

The Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna will be built under the Zhaoshan

optical clocks can be controlled better and are less influenced by outside temperatures.

ZAIGA will also measure the “space–time dragging effect” caused by Earth’s rotation distorting space–time. This will be done to

competence to develop technologies and devices needed for ZAIGA.”

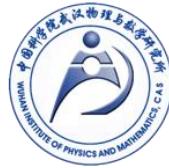
## Bouncing atoms

Once the 300 m vertical tunnel for ZAIGA is complete, physicists then hope to construct a gravitational-wave observatory, which would be under the mountain at an average depth of 200 m to reduce the effect of seismic noise. Rather than detecting gravitational waves by bouncing laser beams off mirrors as used by the LIGO gravitational-wave observatories in the US, ZAIGA-GW would instead use an atom interferometer. This would involve splitting an atom beam in half, and allowing both halves to travel for a certain distance before being recombined to look for differences in their paths. A slightly longer path would result from a tiny curvature in space–time that could be caused by a passing gravitational wave. Atom interferometers can be more sensitive

Thanks !

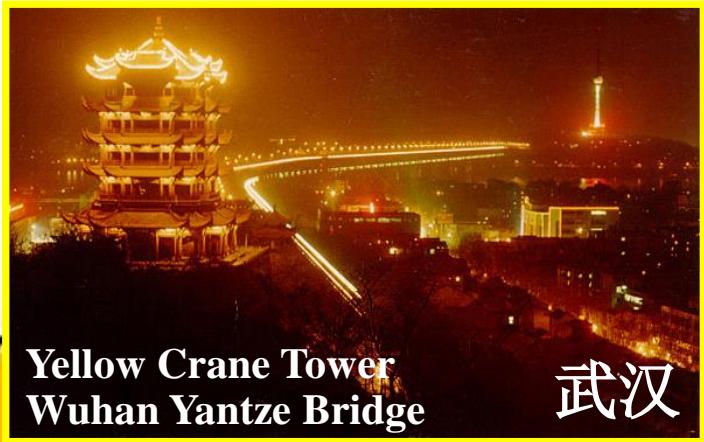
# OUTLINE

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- Motivation
- ZAIGA: facility and key instruments
- ZAIGA: scientific proposals
- Progress

## Three Gorges Dam

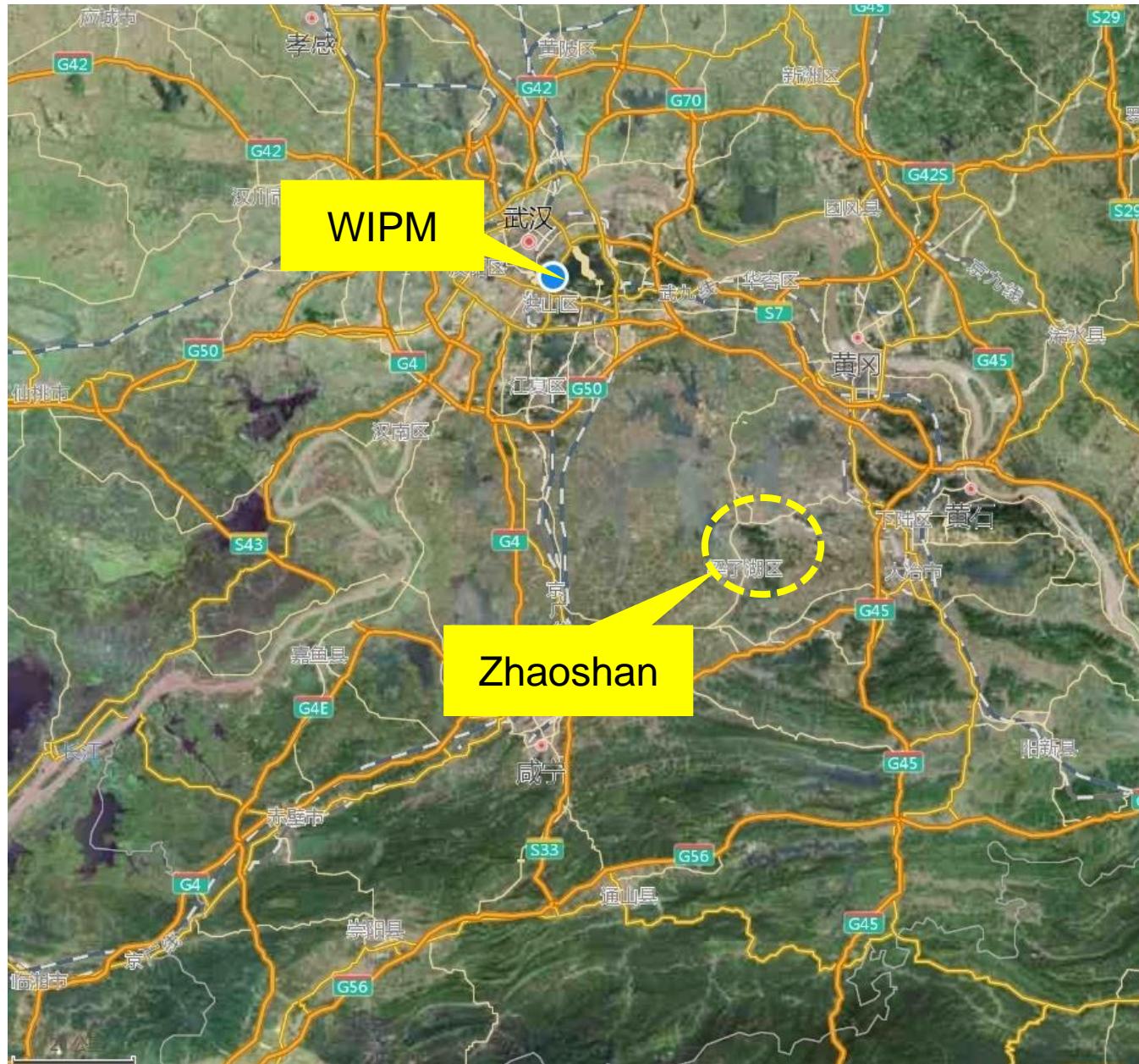


Yellow Crane Tower  
Wuhan Yantze Bridge

武汉



Zhaoshan (沼山) : a mountain about 80 km away from WIPM



# ZAIGA design

ZAIGA-EP (Equivalence Principle test)

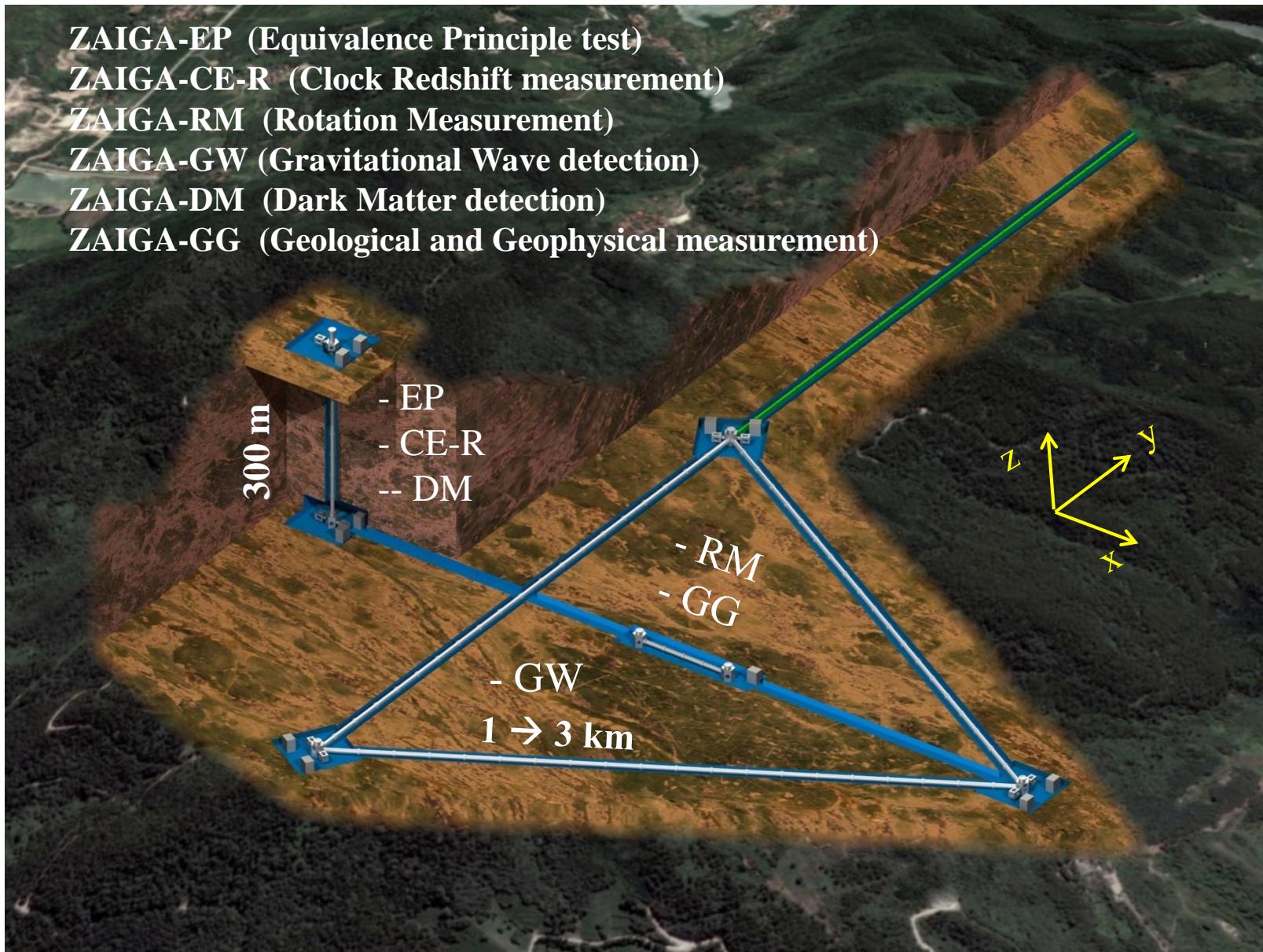
ZAIGA-CE-R (Clock Redshift measurement)

ZAIGA-RM (Rotation Measurement)

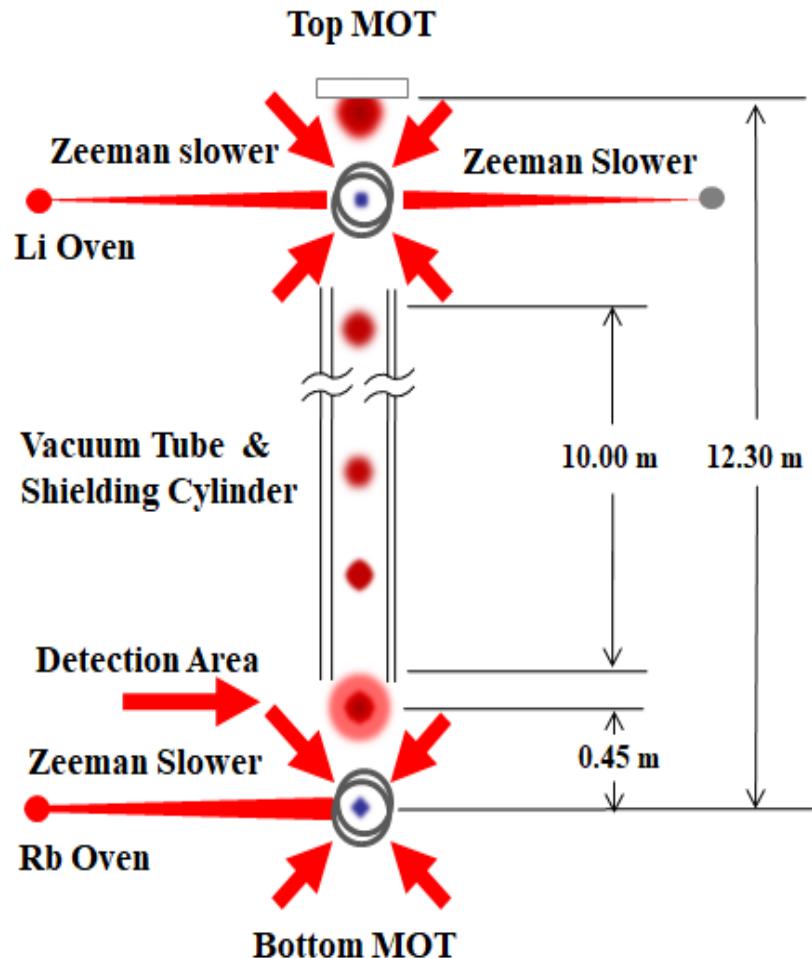
ZAIGA-GW (Gravitational Wave detection)

ZAIGA-DM (Dark Matter detection)

ZAIGA-GG (Geological and Geophysical measurement)



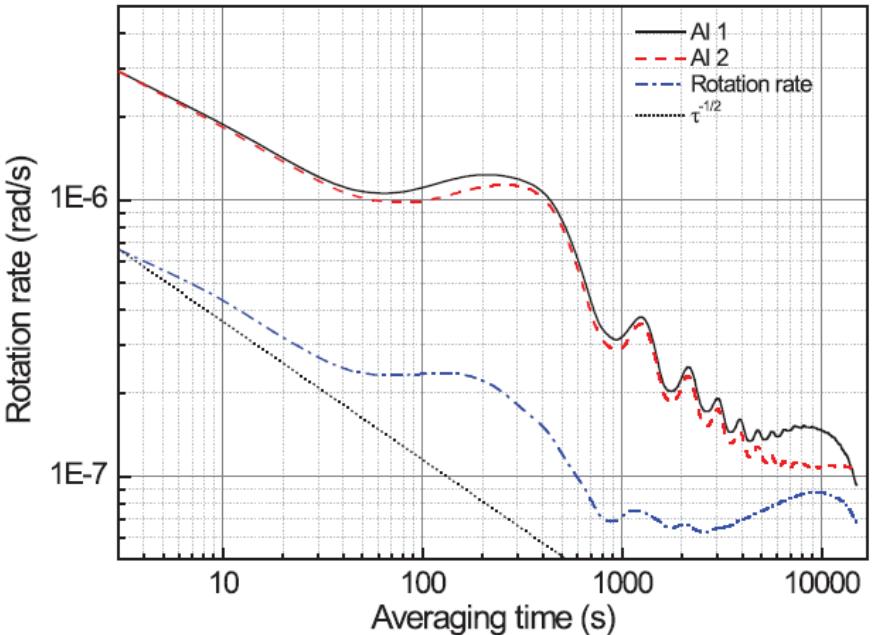
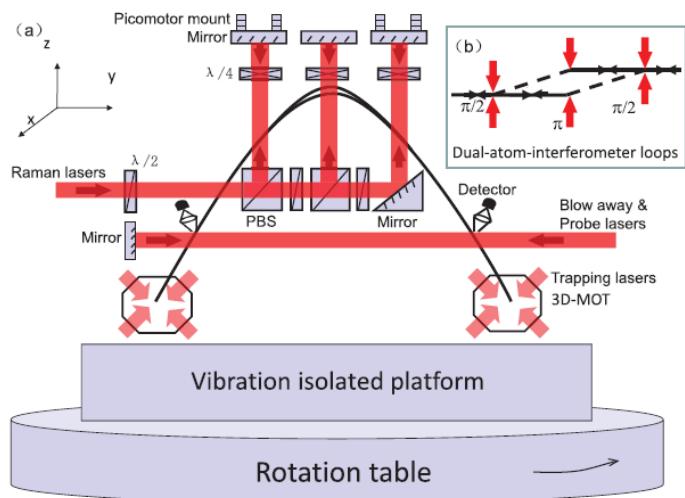
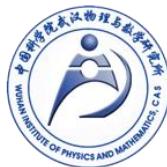
# 10 m AI @ WIPM



Wuhan



# ZAIGA: Atomic gyros

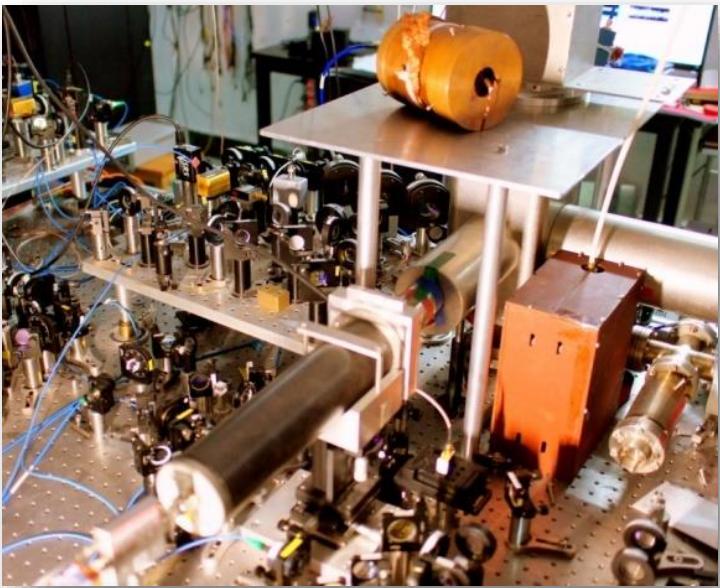


sensitivity  $1.2\text{E-}6 \text{ rad/s} / \sqrt{\text{Hz}}$   
 long term stability  $6.2\text{E-}8 \text{ rad/s} @ 2000\text{s}$

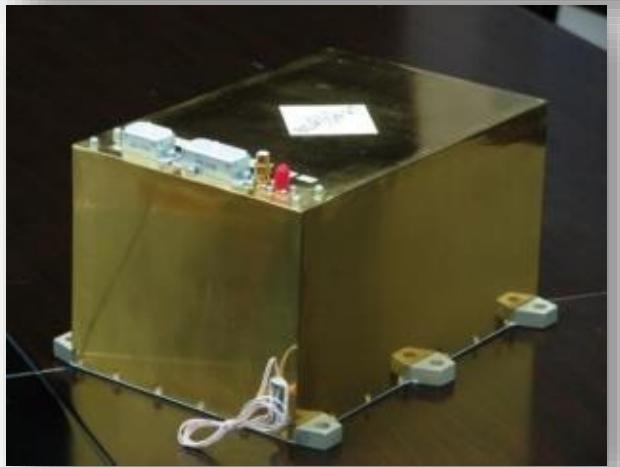
# Atom clocks @ WIPM

(Other groups)

**Ca+**  
**Al+**  
**Yb**

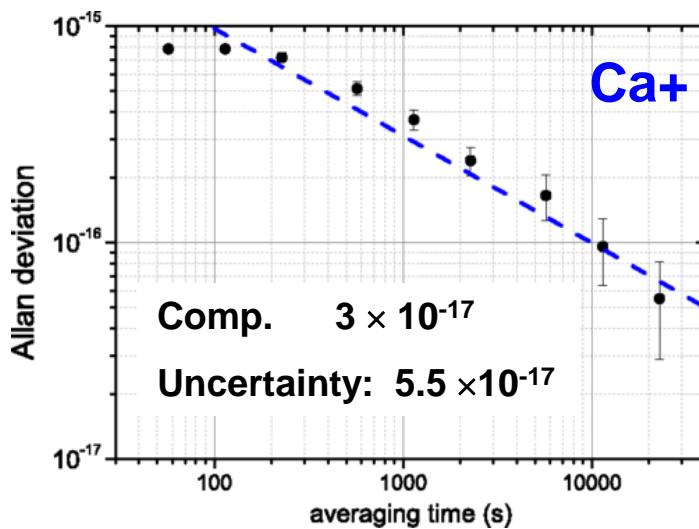


**Rb**  
**Hg+**

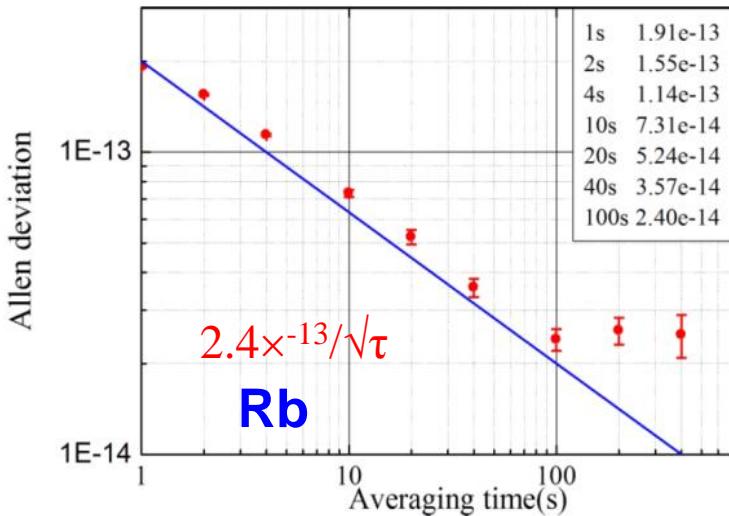


**Hg+**

Short term stability  $6 \times 10^{-13}/\sqrt{\tau}$   
Long term stability  $\sim 10^{-15}$

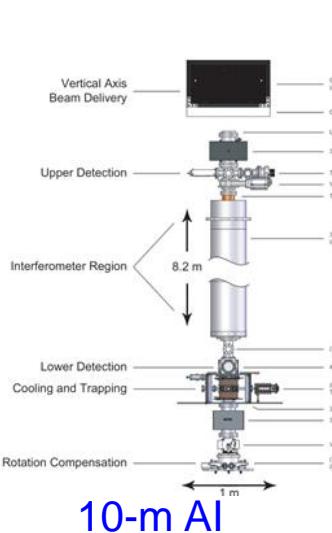


Y. Huang *et al.*, Phys. Rev. Lett. 116, 013001 (2016)

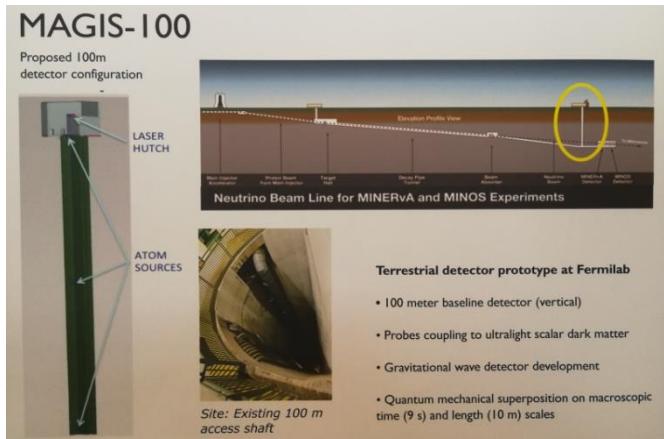


Q. Hao *et al.*, Rev. Sci. Instrum., 87, 123111(2016)

# Similar facilities in the world

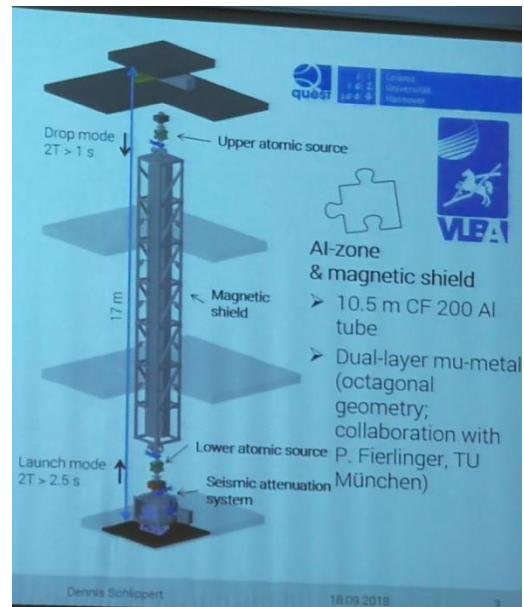


## Stanford



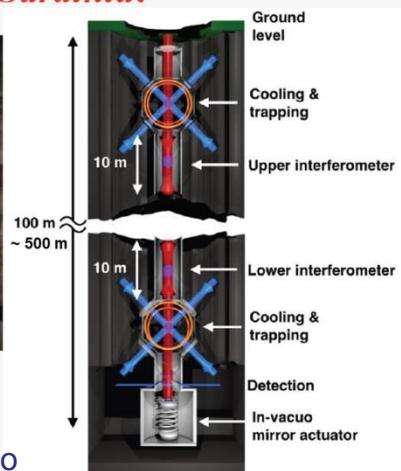
100-m AI proposal  
from Thomas Wilkason's Poster

## Hannover VLBAI



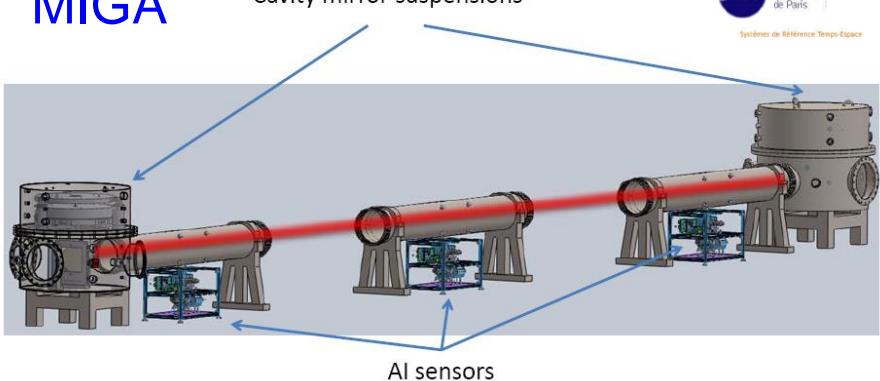
from Dennis Schlipert

## Large-scale atomic fountain → Sardinia?



from Guglielmo M. Tino

## MIGA



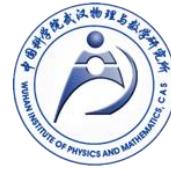
from Philippe Bouyer

# OUTLINE

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- Motivation
- ZAIGA: facility and key instruments
- ZAIGA: scientific proposals
- Progress



# ZAIGA: GR test proposals

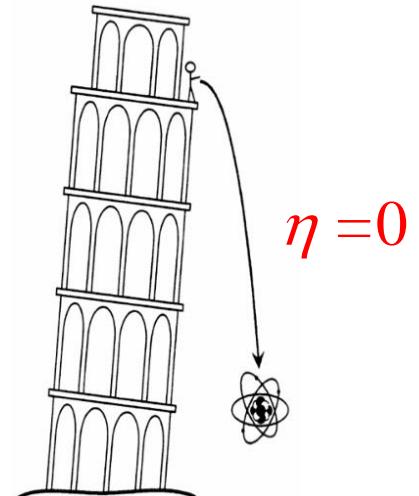
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- ZAIGA-EP: Test of the Weak Equivalence Principle (WEP)  
by free falling atom interferometers
- ZAIGA-CR: Test of the Local Position Invariance (LPI)  
by clock red shift measurement
- ZAIGA-GW: Detection of mid-frequency Gravitational Waves  
by Atomic Interferometers
- ZAIGA-RM: Gravito-magnetic Effect by Large Scale Gyros
- ZAIGA-DM: Detection of Dark Matter by Atomic Interferometers  
and Clocks

# ZAIGA: GR test — WEP (fund. assumpt.)

**Weak Equivalence Principle (WEP)**  
**or Universality of Free Fall (UFF)**  
**Einstein Equivalence Principle (EEP)**

Pisa Leaning Tower Experiment



**EEP** is organised into three conditions:

**WEP + LLI + LPI**

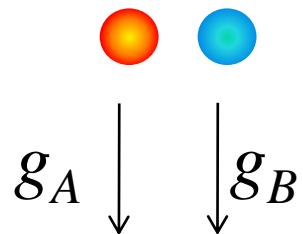
- 1) Equivalence between the system's inertia and weight – the Weak Equivalence Principle (**WEP**,  $\eta = 0$ );
- 2) Independence of outcomes of local non-gravitational experiments of the velocity of a freely-falling reference frame in which they are performed (or validity of special relativity) –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

**Eötvös-parameter**

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

# EEP: classical test formulation

$^{85}\text{Rb}$      $^{87}\text{Rb}$



Eötvös ratio:

$$\eta \equiv \frac{g_A - g_B}{(g_A + g_B)/2}$$

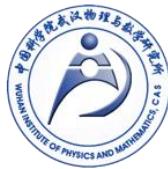
Physical Regime	WEP	$\eta^\alpha$
Newtonian	$m_i = m_g$	$m_g / m_i - 1$
Newtonian & m-E equivalence	$m_i c^2 + E_i = m_g c^2 + E_g$	$(m_g + \frac{E_g - E_i}{c^2}) / m_i - 1$

For atoms, internal energy can be changed.

$$m_g = m_i + \sum_{\alpha} \frac{\eta^{\alpha} E^{\alpha}}{c^2}, \quad \eta = \sum_{\alpha} \eta^{\alpha} \left( \frac{E_A^{\alpha}}{m_A c^2} - \frac{E_B^{\alpha}}{m_B c^2} \right)$$

# EEP: quantum test formulation

M. Zych and C.Brukner



$$\hat{H} = mc^2 + \frac{\hat{P}^2}{2m} + m\phi(\hat{Q}) + \hat{H}_{\text{int}}(1 - \frac{\hat{P}^2}{2m^2c^2} + \frac{\phi(\hat{Q})}{c^2})$$

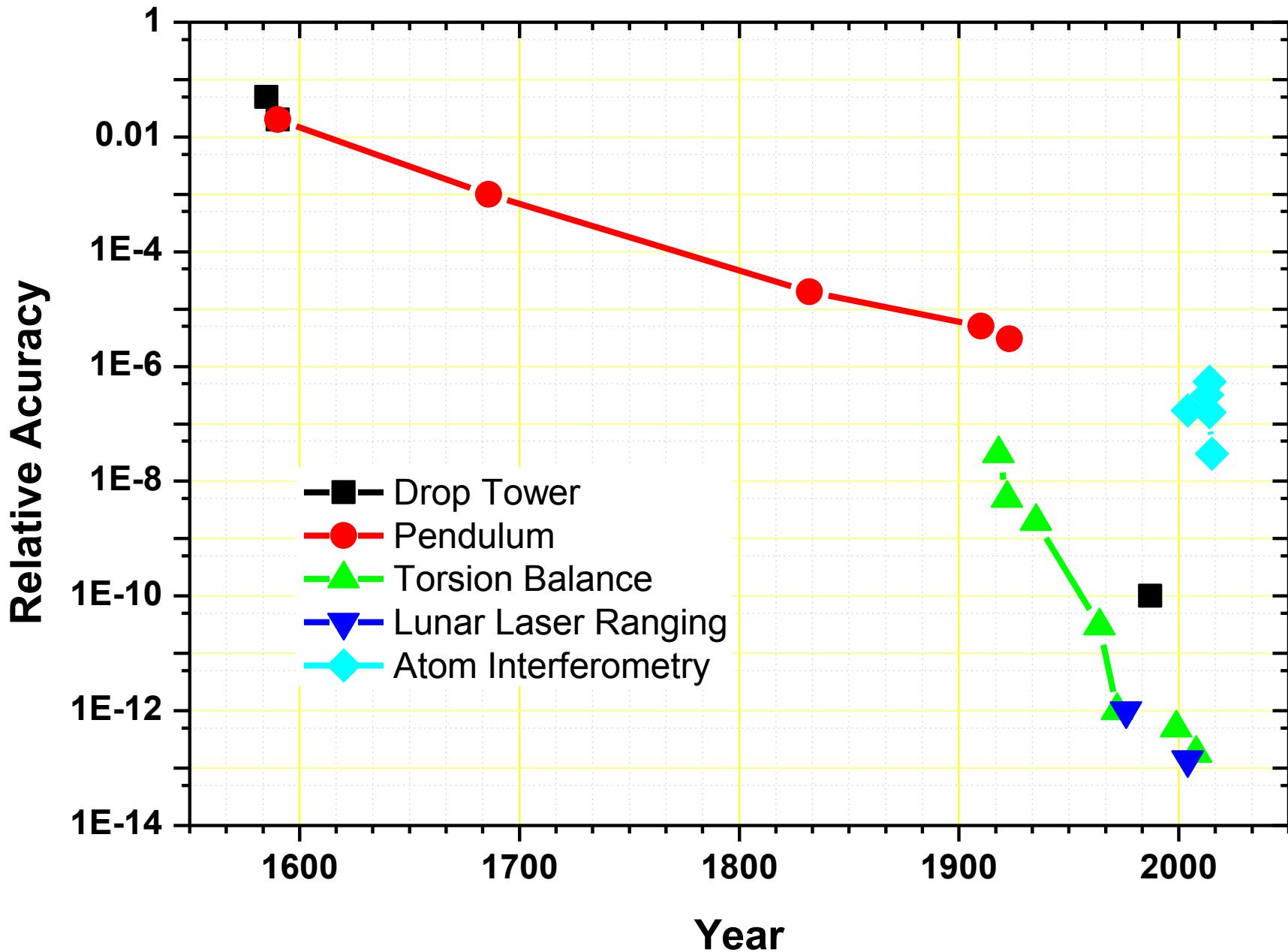
$$\hat{M} = m\hat{I}_{\text{int}} + \frac{\hat{H}_{\text{int}}}{c^2} \quad \hat{\eta} := \hat{I}_{\text{int}} - \hat{M}_g / \hat{M}_i$$

Physical Regime	Classical / Quantum	WEP	Number of parameters
Newtonian	C & Q	$m_i = m_g$	1
Newtonian & m-E equivalence	C	$m_i c^2 + E_i = m_g c^2 + E_g$	2n-1
	Q	$m_i c^2 I + H_i = m_g c^2 I + H_g$	2n <sup>2</sup> -1

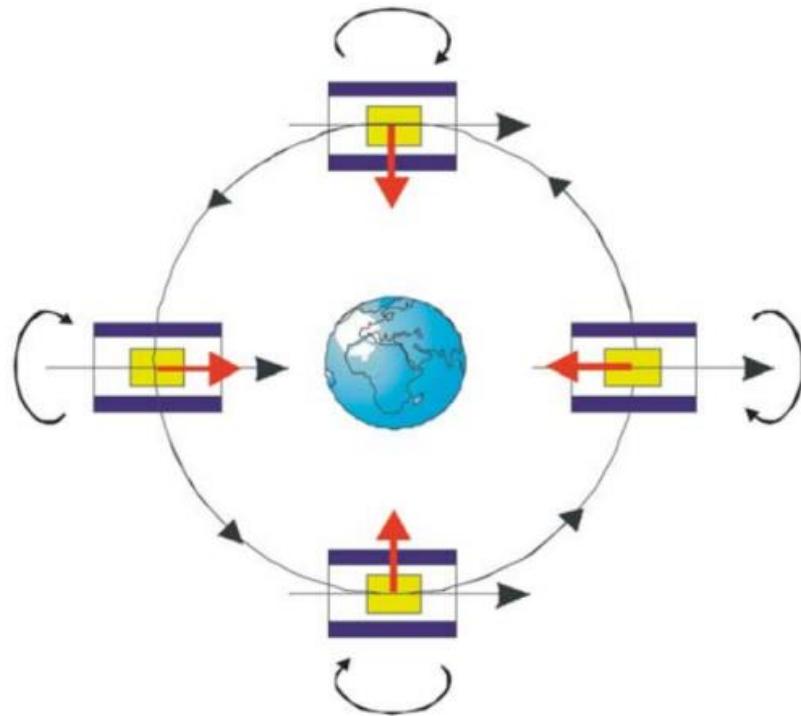
$$H_{\text{test}}^C = m_r c^2 + E_r + \frac{\hat{P}^2}{2m_i} + m_g \phi(\hat{Q}) - E_i \frac{\hat{P}^2}{2m_i^2 c^2} + E_g \frac{\phi(\hat{Q})}{c^2}$$

$$\boxed{\hat{H}_{\text{test}}^Q = m_r c^2 + \hat{H}_{\text{int},r} + \frac{\hat{P}^2}{2m_i} + m_g \phi(\hat{Q}) - \hat{H}_{\text{int},i} \frac{\hat{P}^2}{2m_i^2 c^2} + \hat{H}_{\text{int},g} \frac{\phi(\hat{Q})}{c^2}}$$

# 400 years of WEP test (massive body)



# MICROSCOPE (MICROSatellite pour l'Observation du Principe d'Equivalence)



**Figure 1.** The MICROSCOPE experiment: shielded by the satellite, the two masses, made of different materials, fall around the Earth; they are submitted to the same gravity field and controlled along the same orbit; in case of EP violation, the electrostatic force (in red) is accurately measured towards the Earth while the instrument frame (in black) rotates.

Measuring the force required to maintain two test masses (of titanium and platinum alloys) exactly in the same orbit.

P. Touboul, M. Rodrigues, G. Métris, and B. Tatry, [C. R. Acad. Sci. Paris Ser. IV 2, 1271 \(2001\)](#).

TABLE III. Evaluation of systematic errors in the differential acceleration measurement for SUEP at  $f_{EP} = 3.1113 \times 10^{-3}$  Hz.

Term in the Eq. (1) projected on $\vec{x}$	Amplitude or upper bound	Method of estimation
$(T_{xx}\Delta x; T_{xy}\Delta y; T_{xz}\Delta z)$	Gravity gradient effect $[T]\vec{\Delta}$ along X @ $f_{EP}$ (in phase with $g_x$ ) $<(10^{-18}; 10^{-19}; 10^{-17}) \text{ m s}^{-2}$	Earth's gravity model and in flight calibration
$\dot{\Omega}_y\Delta_z - \dot{\Omega}_z\Delta_y$	Gradient of inertia matrix [In] effect along X at $f_{EP}$ $10^{-18} \text{ m s}^{-2}$	DFACS performances and calibration
$\Omega_x\Omega_y\Delta_y - \Omega_x\Omega_z\Delta_z - (\Omega_y^2 + \Omega_z^2)\Delta_x$	$1.3 \times 10^{-17} \text{ m s}^{-2}$	DFACS performances and calibration
$([M_d]\vec{\Gamma}_c^{\text{app}}) \cdot \vec{x}$	Drag-free control $1.7 \times 10^{-15} \text{ m s}^{-2}$	DFACS performances and calibration
$(\vec{\Gamma}_d^{\text{quad}}) \cdot \vec{x}$	Instrument systematics and defects $5 \times 10^{-17} \text{ m s}^{-2}$	DFACS performances and calibration
$([\text{Coulpl}_d]\dot{\vec{\Omega}}) \cdot \vec{x}$	$<2 \times 10^{-15} \text{ ms}^{-2}$	Couplings observed during commissioning phase
Thermal systematics	$<67 \times 10^{-15} \text{ m s}^{-2}$	Thermal sensitivity in-orbit evaluation
Magnetic systematics	$<2.5 \times 10^{-16} \text{ m s}^{-2}$	Finite-element calculation
Total of systematics in $\Gamma_{dx}^{\text{meas}}$	$<71 \times 10^{-15} \text{ m s}^{-2}$	
Total of systematics in $\delta$	$<9 \times 10^{-15}$	

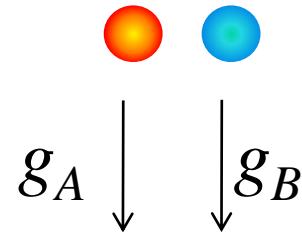
According to the weak equivalence principle, all bodies should fall at the same rate in a gravitational field. The *MICROSCOPE* satellite, launched in April 2016, aims to test its validity at the  $10^{-15}$  precision level, by measuring the force required to maintain two test masses (of titanium and platinum alloys) exactly in the same orbit. A nonvanishing result would correspond to a violation of the equivalence principle, or to the discovery of a new long-range force. Analysis of the first data gives  $\delta(\text{Ti}, \text{Pt}) = [-1 \pm 9(\text{stat}) \pm 9(\text{syst})] \times 10^{-15}$  ( $1\sigma$  statistical uncertainty) for the titanium-platinum Eötvös parameter characterizing the relative difference in their free-fall accelerations.

# WEP Test with Atoms

Year	Inst.	Test Pairs	$\eta$	Remark
2004	MPQ	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$(1.2 \pm 1.7) \times 10^{-7}$	
2013	ONERA	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$(1.2 \pm 3.2) \times 10^{-7}$	
2014	Hannover	$^{87}\text{Rb}$ - $^{39}\text{K}$	$(0.3 \pm 5.4) \times 10^{-7}$	
2014	Florence	$^{88}\text{Sr}$ - $^{87}\text{Sr}$	$(0.2 \pm 1.6) \times 10^{-7}$	
2015	WIPM	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$(2.8 \pm 3.0) \times 10^{-8}$	
2016	Bordeaux	$^{87}\text{Rb}$ - $^{39}\text{K}$	$(0.9 \pm 3.0) \times 10^{-4}$	0-g
2016	HUST	$^{87}\text{Rb}$ ( $m_F = \pm 1$ )	$(0.2 \pm 1.2) \times 10^{-7}$	Spin
2017	Florence	$^{87}\text{Rb}$ ( $F=1,2, s$ )	$(1.4 \pm 2.8) \times 10^{-9}$ $(3.3 \pm 2.9) \times 10^{-9}$	State Superposition

# WEP Test with A(<sup>85</sup>Rb,F=2/3) – B(<sup>87</sup>Rb,F'=1/2) pairs

<sup>85</sup>Rb    <sup>87</sup>Rb



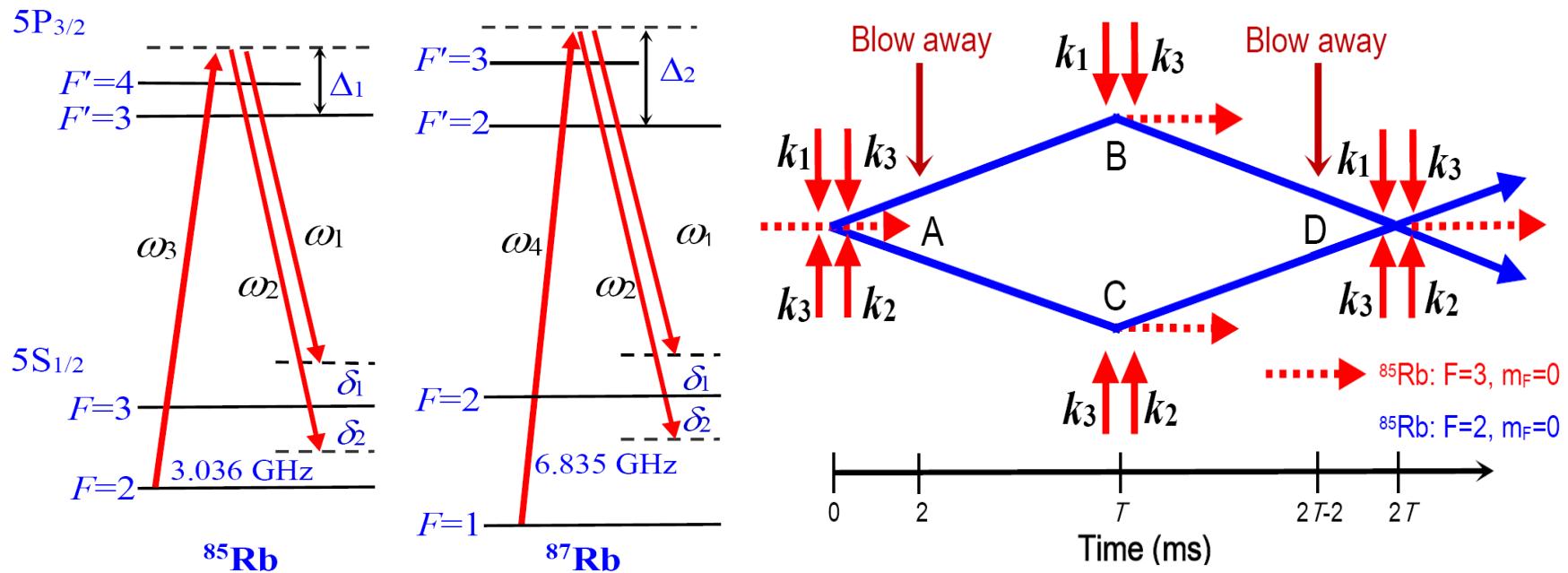
Eötvös ratio:

$$\eta \equiv \frac{g_A - g_B}{(g_A + g_B)/2}$$

Physical Regime	Classical / Quantum	WEP	Number of parameters
Newtonian	C & Q	$m_i = m_g$	1
Newtonian & m-E equivalence	C	$m_i c^2 + E_i = m_g c^2 + E_g$	3
	Q	$m_i c^2 I + H_i = m_g c^2 I + H_g$	7

2-level system  
 $n = 2$

# FWDR (Four Wave Double-diffraction Raman Transition)



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

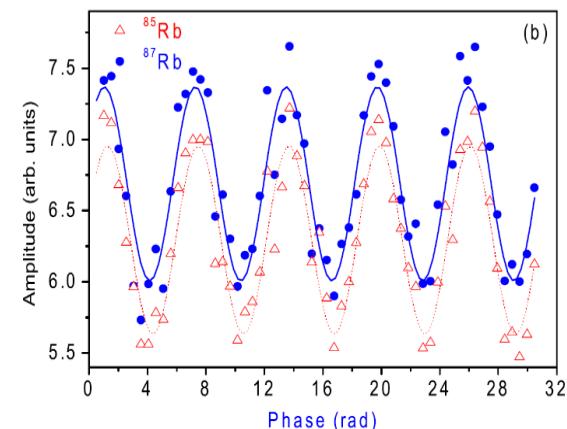
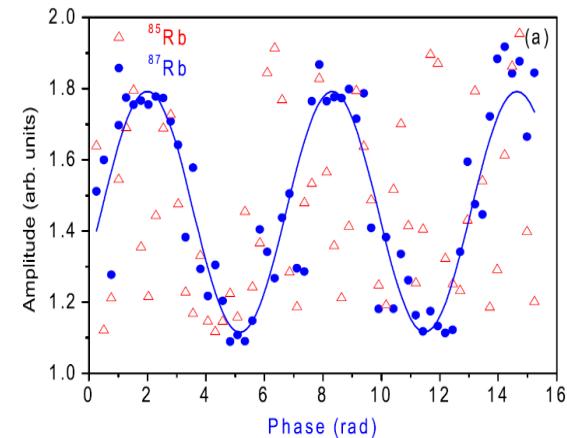
F specified AI:  $m_{87} F=1 \leftrightarrow m_{85} F=2$

mode phase noise of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  AIs caused by shared  $\omega_1$  and  $\omega_2$  can be rejected. The phase noise of  $\omega_3$  and  $\omega_4$  are suppressed by double-diffraction Raman transition. The crosstalk among different Raman beams are minimized by optimizing the frequencies and intensity ratio of Raman beams.

### 单衍射拉曼跃迁

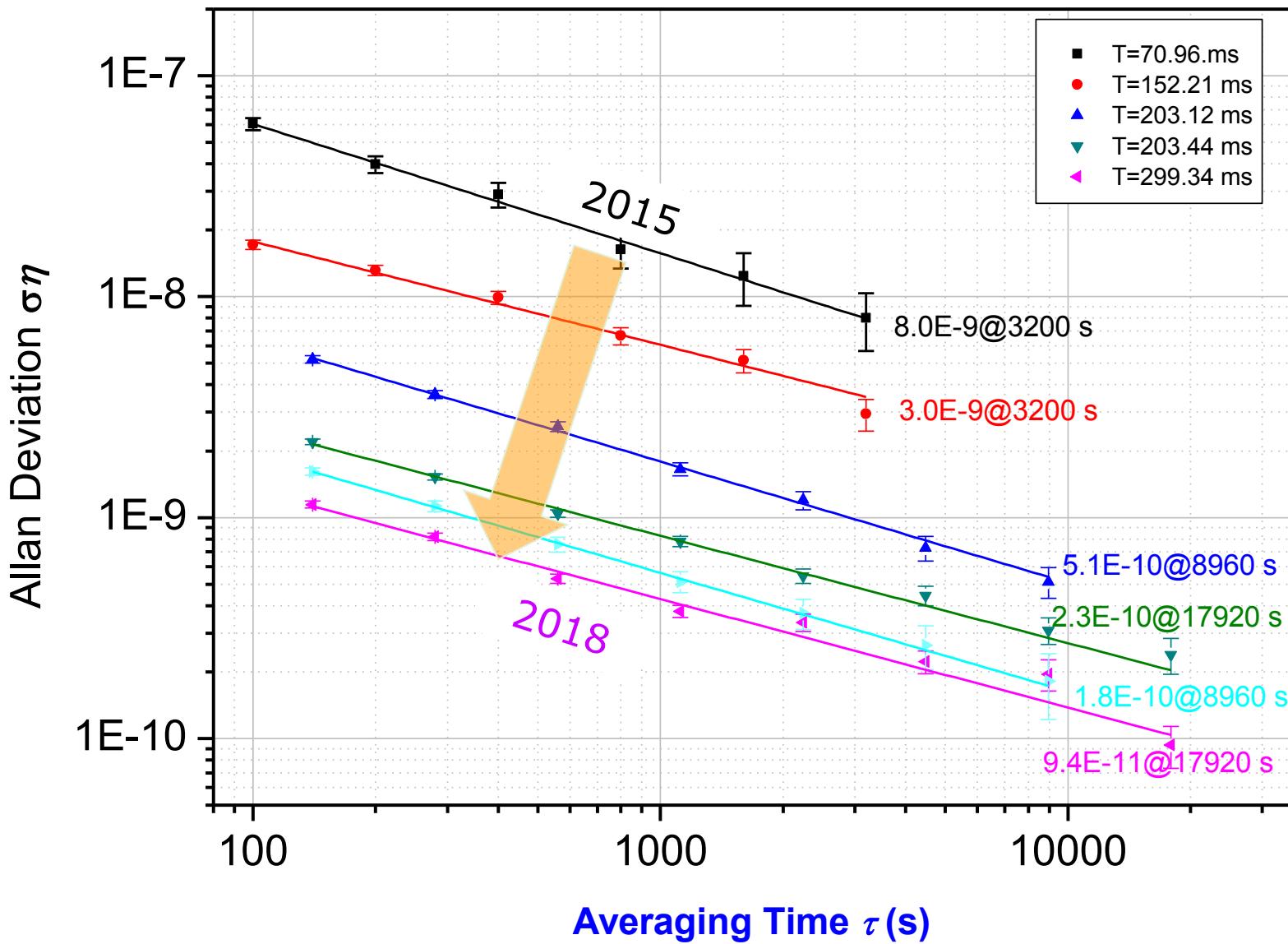


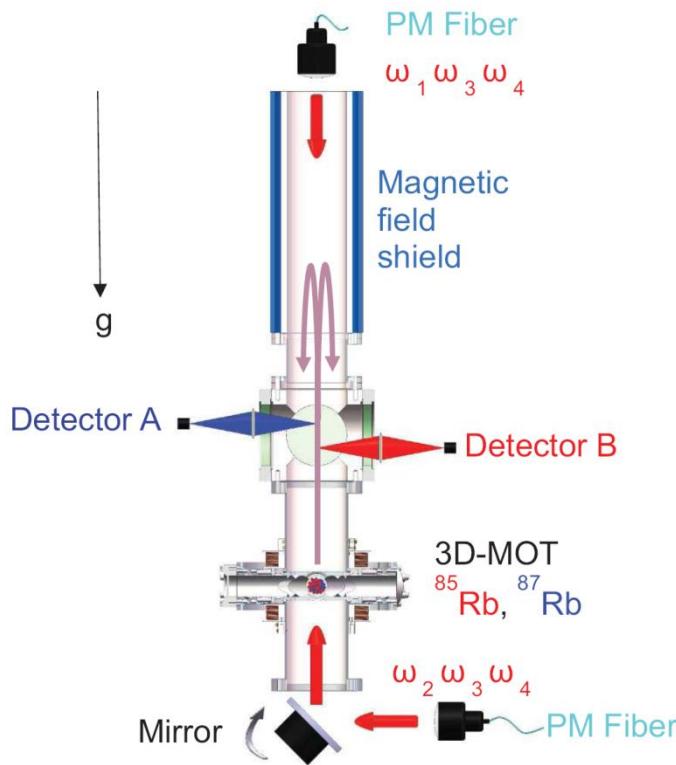
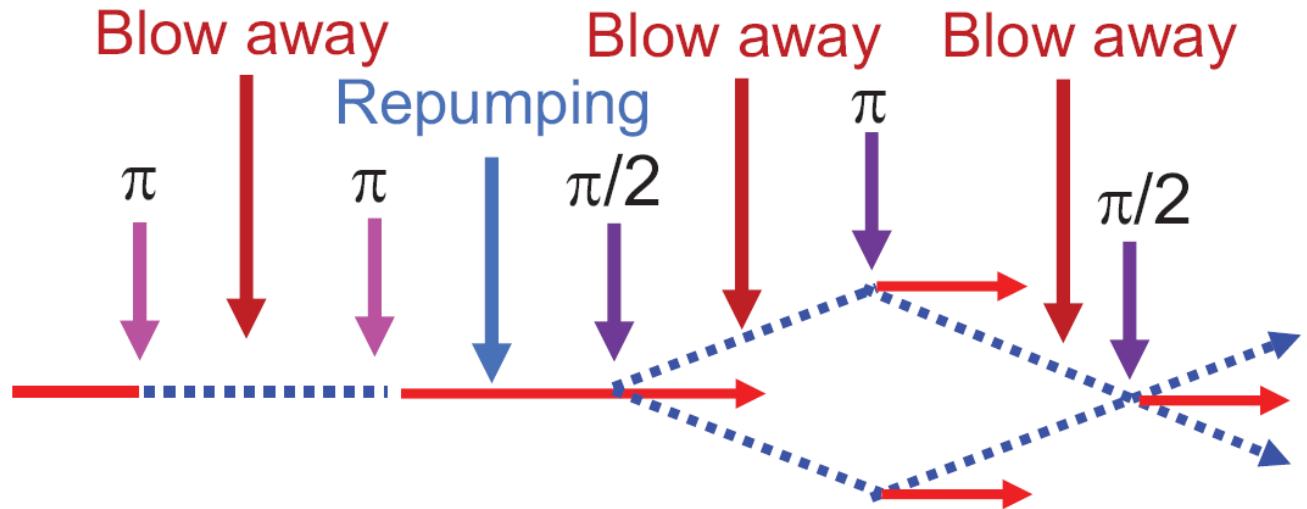
### 四波双衍射拉曼跃迁



Year	Group	Element pair	$\eta$	Note
2004	MPQ	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$(1.2 \pm 1.7) \times 10^{-7}$	
2013	ONERA	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$(1.2 \pm 3.2) \times 10^{-7}$	
2014	Hannover	$^{87}\text{Rb}$ - $^{39}\text{K}$	$(0.3 \pm 5.4) \times 10^{-7}$	1 g
2014	Florence	$^{88}\text{Sr}$ - $^{87}\text{Sr}$	$(0.2 \pm 1.6) \times 10^{-7}$	
2015	WIPM	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$(2.8 \pm 3.0) \times 10^{-8}$	
2016	Bordeaux	$^{87}\text{Rb}$ - $^{39}\text{K}$	$(0.9 \pm 3.0) \times 10^{-4}$	0 g

	$\eta$ ( $\times 10^{-8}$ )	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





Legend:

- .....  $^{87}\text{Rb}|F=1> \quad ^{85}\text{Rb}|F=2>$
- $^{87}\text{Rb}|F=2> \quad ^{85}\text{Rb}|F=3>$

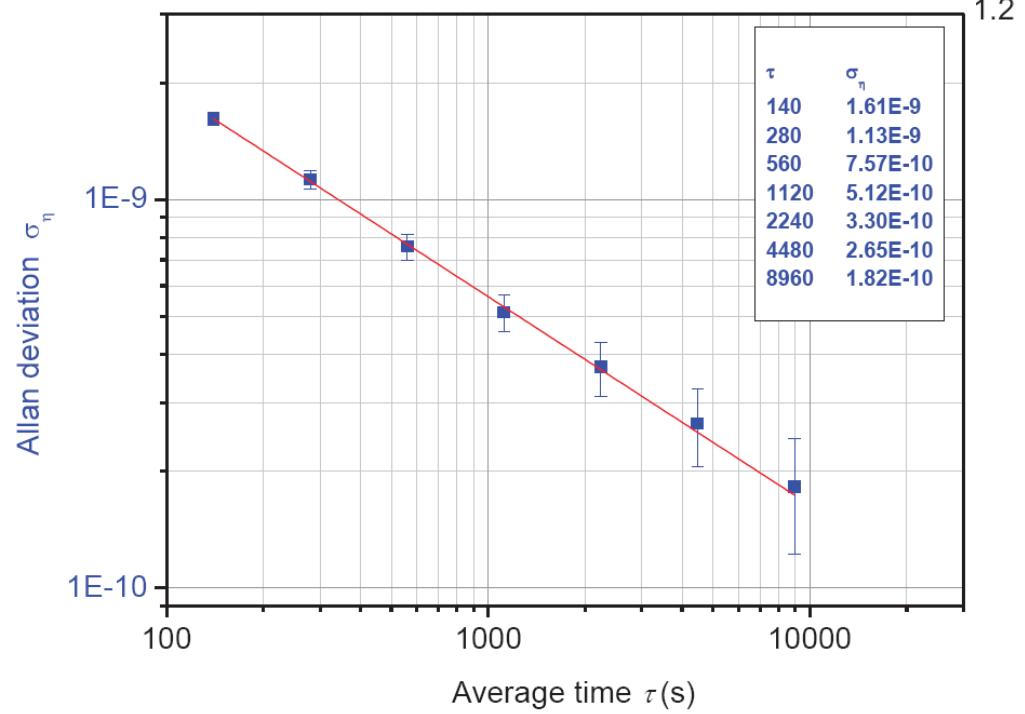
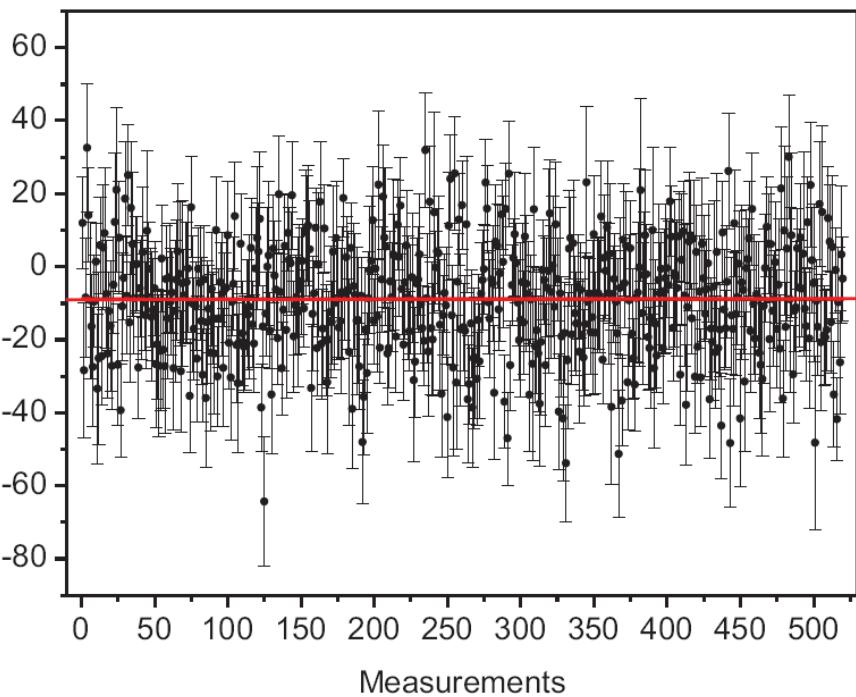
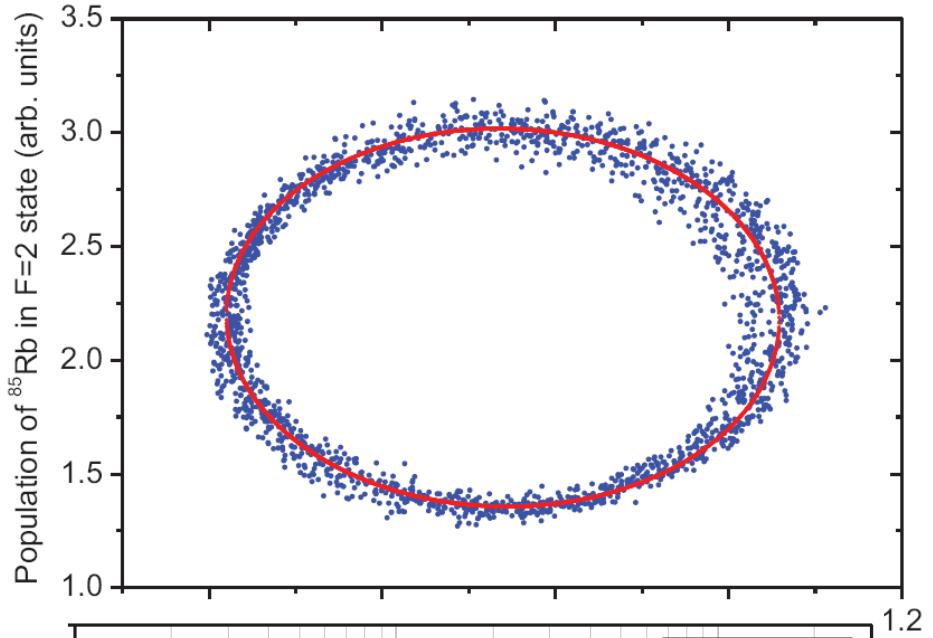


TABLE I. The error budget

Parameters	$\eta$ ( $\times 10^{-10}$ )	Uncertainty( $\times 10^{-10}$ )
Experimental data	49426.6	1.8
Effective wave vector	49435.5	0.5
Detector difference	1.0	2.5
Coriolis effect	0	2.0
Wave-front aberration	0	5.0
ac Stark shift	0	0.6
Quadratic Zeeman shift	0	2.0
Gravity gradient	-5.5	1.2
Others	0	1.0
Total	-4.4	6.7

# United test of the equivalence principle at $10^{-10}$ level using mass and internal energy specified atoms

Lin Zhou,<sup>1,2</sup> Chuan He,<sup>1,3</sup> Si-Tong Yan,<sup>1,3</sup> Xi Chen,<sup>1,2</sup> Wei-Tao Duan,<sup>1,3</sup> Run-Dong Xu,<sup>1,3</sup> Chao Zhou,<sup>1</sup> Yu-Hang Ji,<sup>1</sup> Sachin Barthwal,<sup>1</sup> Qi Wang,<sup>1,3</sup> Zhuo Hou,<sup>1,3</sup> Zong-Yuan Xiong,<sup>1,2</sup> Dong-Feng Gao,<sup>1,2</sup> Yuan-Zhong Zhang,<sup>4</sup> Wei-Tou Ni,<sup>1</sup> Jin Wang,<sup>1,2,\*</sup> and Ming-Sheng Zhan<sup>1,2,†</sup>

<sup>1</sup>*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics,  
Wuhan Institute of Physics and Mathematics, Chinese Academy of  
Sciences-Wuhan National Laboratory for Optoelectronics, Wuhan 430071, China*

<sup>2</sup>*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*

<sup>3</sup>*School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China*

<sup>4</sup>*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

(Dated: April 24, 2019)

We use both mass and internal energy specified rubidium atoms to jointly test the weak equivalence principle (WEP). We improve the four-wave double-diffraction Raman transition method (FWDR) we proposed before to select atoms with certain mass and angular momentum state, and perform dual-species atom interferometer. By combining  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$  atoms with different angular momenta, we compare the differential gravitational acceleration of them, and determine the value of Eötvös parameter,  $\eta$ , which measures the strength of the violation of WEP. For one case ( $^{87}\text{Rb}|F=1\rangle - ^{85}\text{Rb}|F=2\rangle$ ), the statistical uncertainty of  $\eta$  is  $1.8 \times 10^{-10}$  at integration time of 8960 s. With various systematic errors correction, the final value is  $\eta = (-4.4 \pm 6.7) \times 10^{-10}$ . Comparing with the previous WEP test experiments using atoms, this work gives a new upper limit of WEP violation for  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$  atom pairs.

PACS numbers: 03.75.Dg, 04.80.Cc, 37.25.+k

$$m_1 m_2 \otimes |F_1 F_2\rangle$$

arXiv:1904.07096v2 [quant-ph] 23 Apr 2019

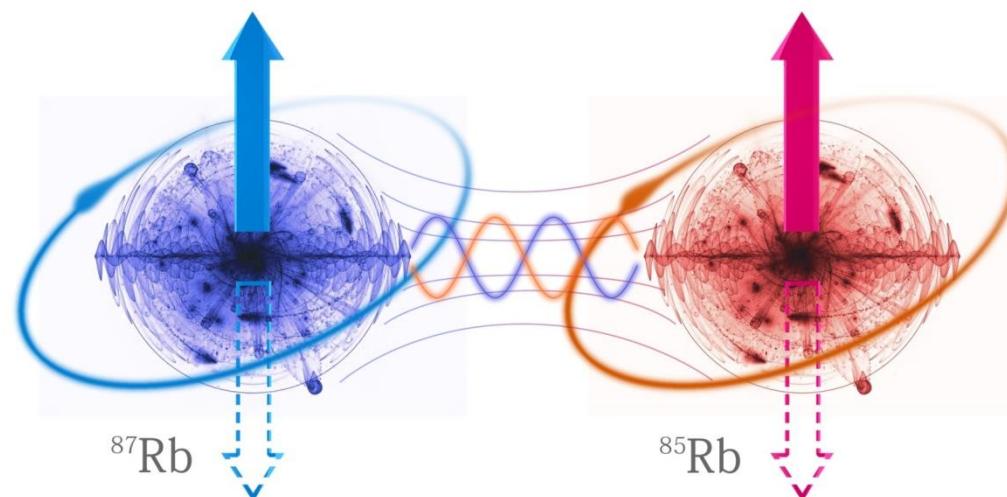
## Entangling Two Individual Atoms of Different Isotopes via Rydberg Blockade

Yong Zeng,<sup>1,2,3</sup> Peng Xu,<sup>1,2,\*</sup> Xiaodong He,<sup>1,2</sup> Yangyang Liu,<sup>1,2,3</sup> Min Liu,<sup>1,2</sup> Jin Wang,<sup>1,2</sup>  
D. J. Papouras,<sup>4</sup> G. V. Shlyapnikov,<sup>5,6,7,8</sup> and Mingsheng Zhan<sup>1,2,†</sup>

(Received 12 March 2017; published 18 October 2017)

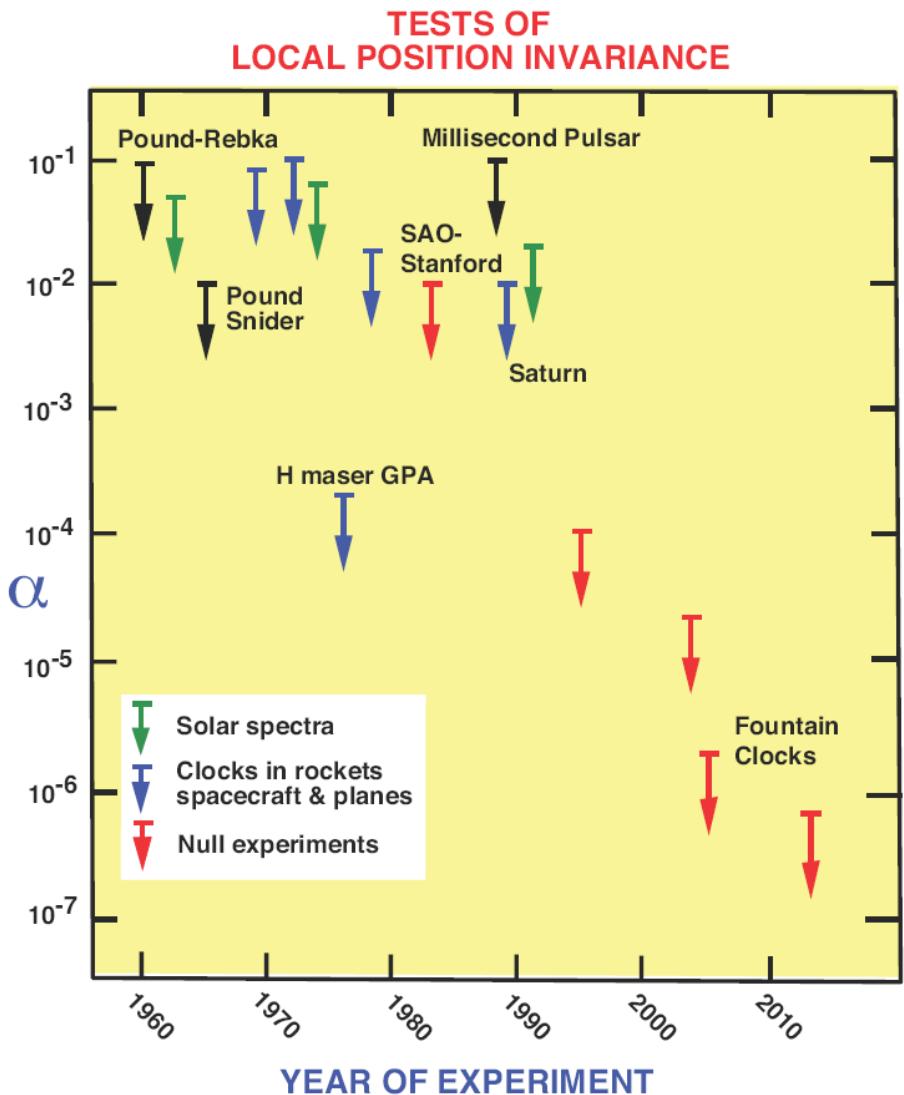
We report on the first experimental realization of the controlled-NOT (CNOT) quantum gate and entanglement for two individual atoms of different isotopes and demonstrate a negligible cross talk between two atom qubits. The experiment is based on a strong Rydberg blockade for  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$  atoms confined in two single-atom optical traps separated by  $3.8 \mu\text{m}$ . The raw fidelities of the CNOT gate and entanglement are  $0.73 \pm 0.01$  and  $0.59 \pm 0.03$ , respectively, without any corrections for atom loss or trace loss. Our work has applications for simulations of many-body systems with multispecies interactions, for quantum computing, and for quantum metrology.

DOI: 10.1103/PhysRevLett.119.160502



# ZAIGA: GR test — LPI

## LPI test、PR、cosmological gravitation



$$\frac{\Delta\omega^{(1)}}{\omega} - \frac{\Delta\omega^{(2)}}{\omega} = (\alpha_1 - \alpha_2) \frac{\Delta\varphi}{c^2}$$

The main idea of null redshift experiments: if the experiments show that  $(\alpha_1 - \alpha_2) \rightarrow 0$ , then  $\alpha_{1,2} \rightarrow 0$  that is, the principle of local invariance is not violated. However, as shown above, the presence of  $\alpha \neq 0$  can be associated with cosmological gravitation, where  $\alpha$  is universal and does not depend on the type of atomic clock.

# Limits on gravitational Einstein equivalence principle violation from monitoring atomic clock frequencies during a year

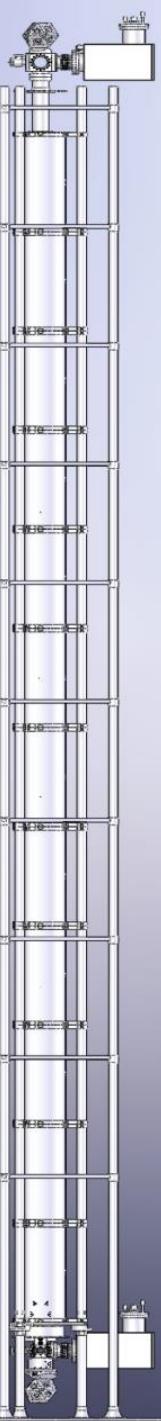
V. A. Dzuba<sup>1</sup> and V. V. Flambaum<sup>1,2</sup>

TABLE III. Limits on the EEP violating parameter  $c_{00}$  from different experiments.

Clocks	Ref.	$c_{00}$
Al <sup>+</sup> /Hg <sup>+</sup>	[22]	$(-3.0 \pm 5.7) \times 10^{-7}$
Dy/Cs	[23]	$(6.4 \pm 6.0) \times 10^{-7}$
Hg <sup>+</sup> /Cs	SME for EEP	$(1.8 \pm 3.2) \times 10^{-6}$
Sr/Cs	$\delta H = c_{00} \frac{2}{3} \frac{U}{c^2} \frac{p^2}{2m}$	$(1.4 \pm 2.0) \times 10^{-6}$
Rb/Cs		$(4.8 \pm 4.2) \times 10^{-7}$
H/Cs	[34]	$(0.4 \pm 5.4) \times 10^{-6}$

**$\neq 0 !$**

$$c_{00} = \frac{3}{2} \frac{\Delta\omega_1/\omega_1 - \Delta\omega_2/\omega_2}{(R_2 - R_1)\Delta U/c^2}. \quad \Delta U/c^2 \approx 3.3 \times 10^{-10}$$



## Pound-Rebka Experiment (PRE) with Photon

Mass-energy equivalence:  $E = mc^2$

Constant speed of light  $c$

WEP: the Universality of Free Fall (mass, freq.)

→ **Gravitational redshift**

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

$$\frac{\omega_1 - \omega_2}{\omega_0} = (1+\beta) \frac{\Delta u}{c^2}$$

If clock  $\delta\omega/\omega$  of  $10^{-19}$  and distance  $\delta h$  is 1 mm, then

$\beta \sim 10^{-5}$  for  $h=300\text{ m}$

**1976, GP-A experiment, 10000 km, E-14 H clock,  
 $|\beta| \leq 7 \times 10^{-5}$  (*Phys.Rev.Lett. 45, 2081(1980)*)**

**2018, Galileo satellite clock comparison  
 $|\beta| \leq 3 \times 10^{-5}$  (*Phys.Rev.Lett. 121, 231101/2(2018)*),**

# Precision Measurement:

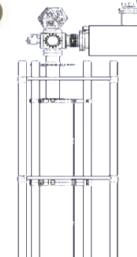
e.g. gravitational redshift

$$\frac{\Delta f}{f} = (1 + \beta) \frac{\Delta u}{c^2}$$

$$c = 299792458 \text{ m/s}$$

$$g = 9.8011\textcolor{red}{11} \text{ m/s}^2$$

$$h = 300.11\textcolor{red}{11} \text{ m}$$



$$gh/c^2 = 0.000,000,000,000,032,727,\textcolor{blue}{73}$$

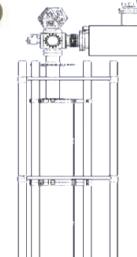
$$\Delta f/f = 0.000,000,000,000,032,727,\textcolor{blue}{x}$$

$$\beta = 0.0\ 000\ \textcolor{blue}{x}$$

Satellite,  $\beta$  limited by  $g$  or  $h$   
 Terrestrial, by  $\Delta f/f$  (clock)

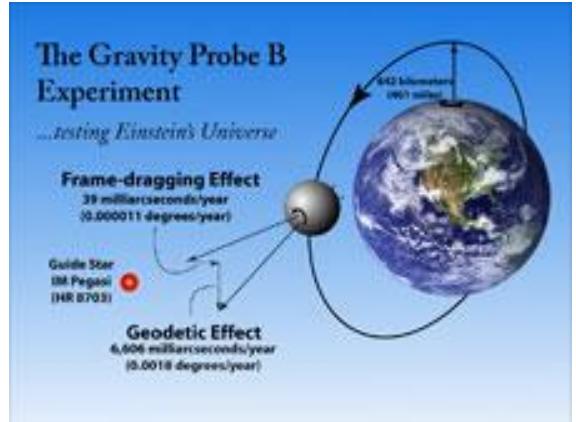
If clock uncertainty  $\Delta f/f$  of  $1\times 10^{-19}$  and distance  $\delta h$  is 1 mm, then

$$\beta = 3 \times 10^{-6} \text{ for } h=300 \text{ m}$$



# ZAIGA: GR test — GM

Lense-Thirring effect (the effect of frame dragging), Gravitomagnetism



$$\Omega_{LT} = \frac{2}{5} \frac{GM\omega}{c^2 R} \cos \theta$$

$$\Omega_{LT} = 2.8E - 10 \Omega_E$$

$$\Omega_E = \frac{360^\circ}{24h} = 15^\circ/h$$

$$1^\circ/h = 4.85 \times 10^{-6} \text{ rad/s}$$



GP-B  $-37.2 \pm 7.2 \text{ mas/yr}$ ,  $15 \rightarrow 0.5\% \text{ (?)}$

GINGER , G-Ring, ROMY :  $\Omega_E \pm 5 \cdot 10^{-9}$

Atomic Gyros

Atomic gyroscope  $10^{-9} \text{ rad/s} \rightarrow 10^{-13} \text{ rad/s}$

# ZAIGA: GR test — GW

## Parameters:

Laser wavelength: 780 nm       $k = 8.5 \times 10^6 \text{ m}^{-1}$

Height of atom interferometers: 5 m,  $T=1 \text{ s}$

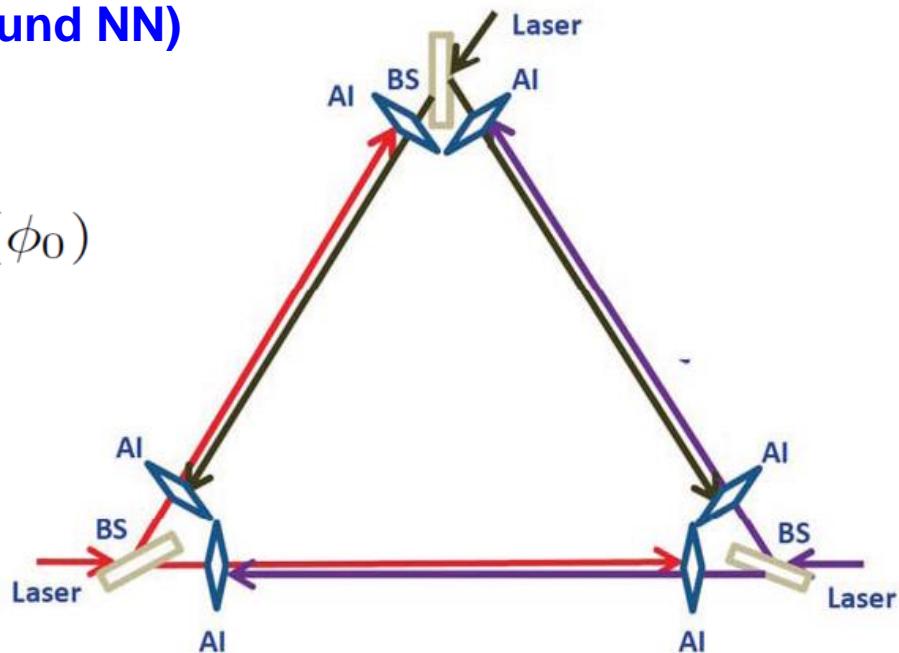
Flux intensity:  $R=10^{14} \text{ atoms/s}$

Photon momentum transfer:  $n=1000$

Arm length:  $L= 1000 \text{ m} / 3000 \text{ m.}$

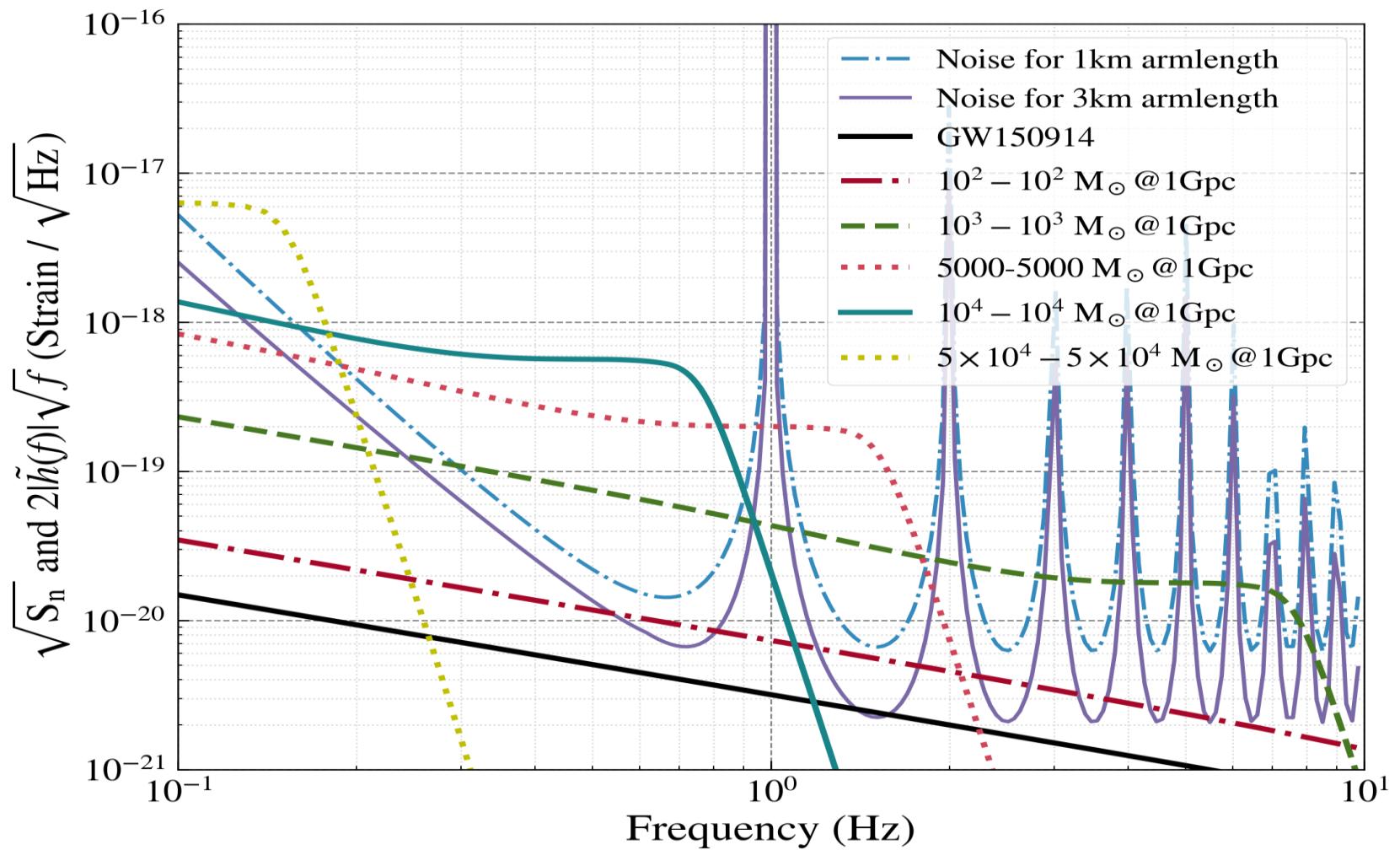
- **Atomic shot noise**
- **Seismic Newtonian Noise (Seismic NN)**
- **Infrasound Newtonian Noise (Infrasound NN)**

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



# ZAIGA: GR test — GW

GW detection with the NN subtraction factor of 50



# Challenges : Full AI for GW

- Seismic noise: Vibrational isolation
- Uniform gravity gradient
- Atom optics: high flux atom source and ultracold atoms  
large photon momentum transfer  
quantum enhanced measurement:

$$1/\sqrt{N} \Rightarrow 1/N$$

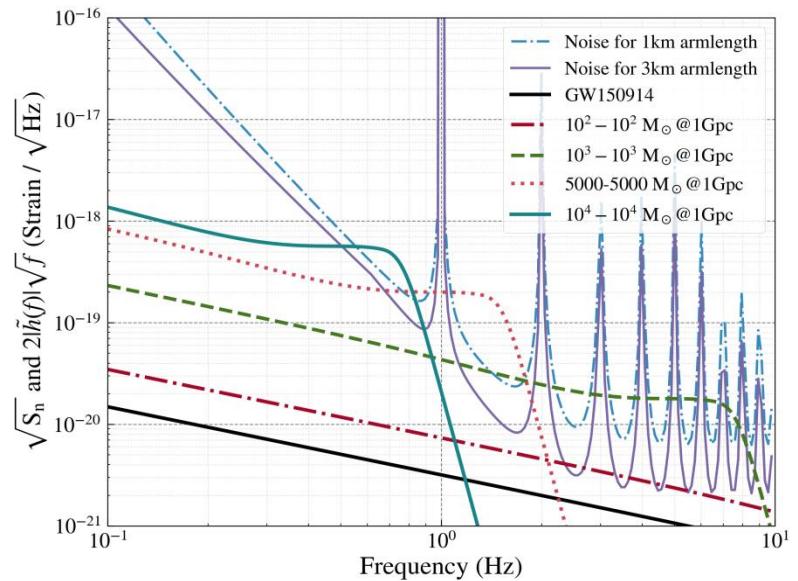
$$h \propto \frac{1}{nkL} \frac{1}{\sqrt{N}} = \frac{\lambda}{2\pi} \frac{1}{nL} \frac{1}{\sqrt{N}}$$

Now only

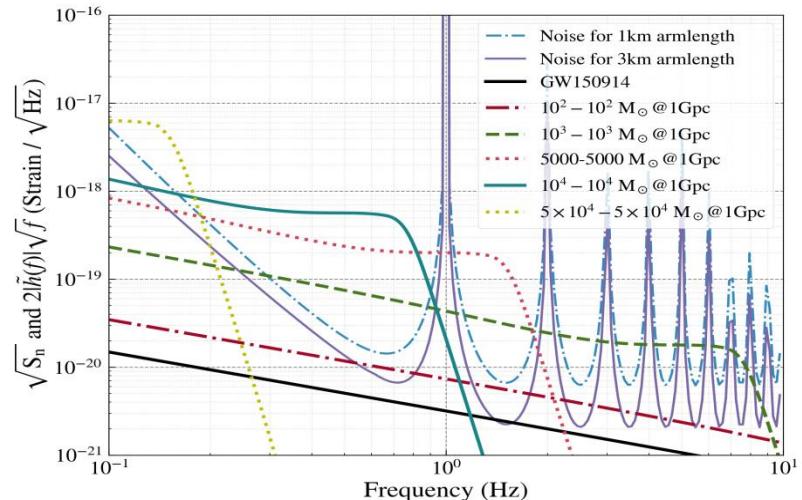
$$h \propto 1 \mu\text{m}/10\text{m}/100/\sqrt{10^6} = 10^{-12}$$

AI with laser link

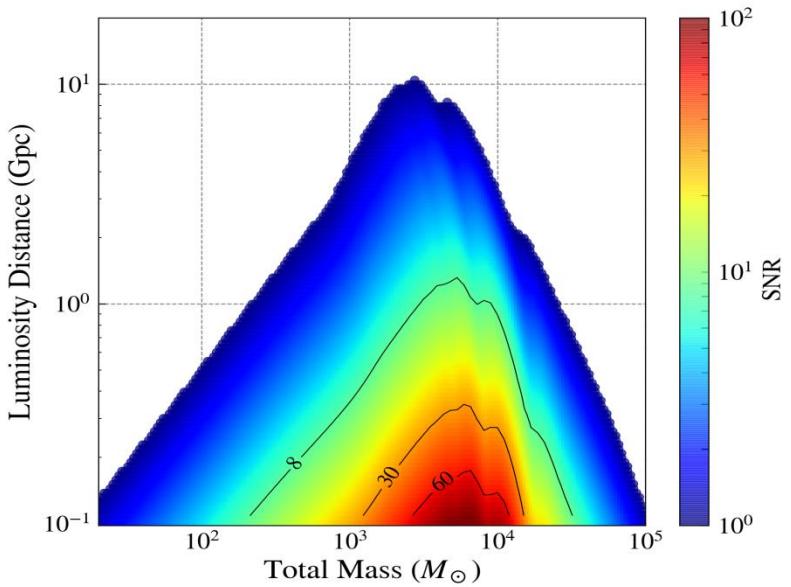
## Event estimating



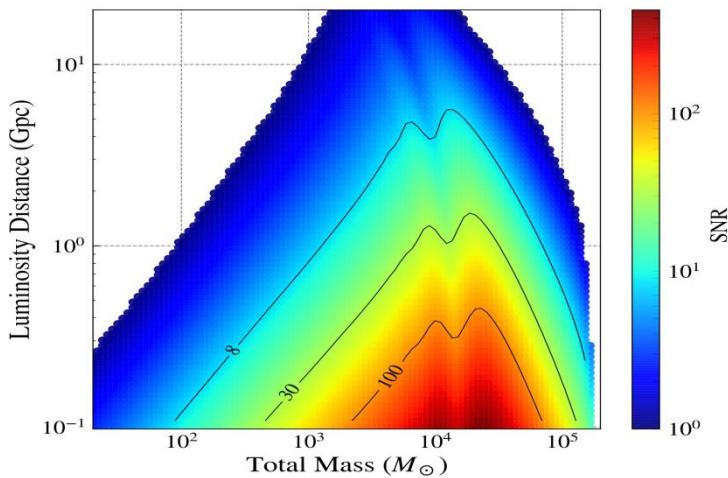
Detection performance without Newtonian Noise reduction



Detection performance with Newtonian Noise reduction

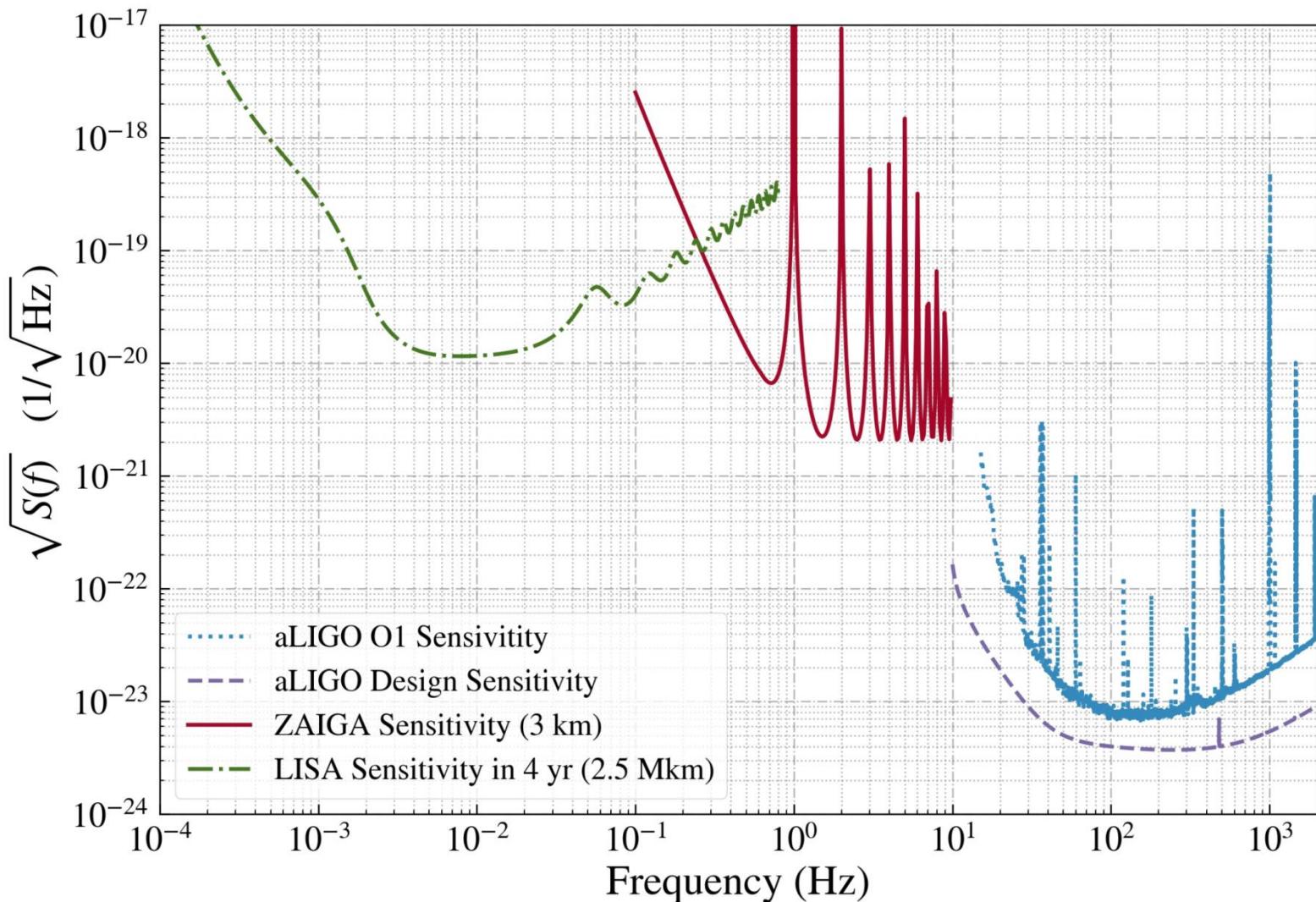


Signal to noise ratio vs. detectable distance



Signal to noise ratio vs. detectable distance

## Comparison of ZAIGA-GW with LIGO and LISA



ZAIGA-GW will fill the gap between LIGO and LISA

# ZAIGA: GR test — DM

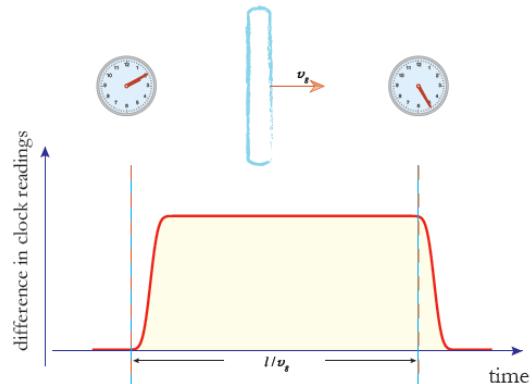
(Andrei Derevianko)



Non-baryonic	Baryonic
Axions	$(10^{-5} \text{ eV})$
Neutrinos	$(\sim 10 \text{ eV})$
WIMPs	$(1\text{--}10^3 \text{ GeV})$
Monopoles	$(10^{16} \text{ GeV})$
Planck relics	$(10^{19} \text{ GeV})$
Primordial black holes	$(> 10^{15} \text{ g})$
Quark nuggets	$(< 10^{20} \text{ g})$
Shadow matter	?
Cosmic strings	?
	Snowballs
	Brown dwarfs
	M-dwarfs
	White dwarfs
	Neutron stars
	Stellar black holes
	Very Massive Objects
	Super Massive Objects
	Cold diffuse gas

Possible dark matter

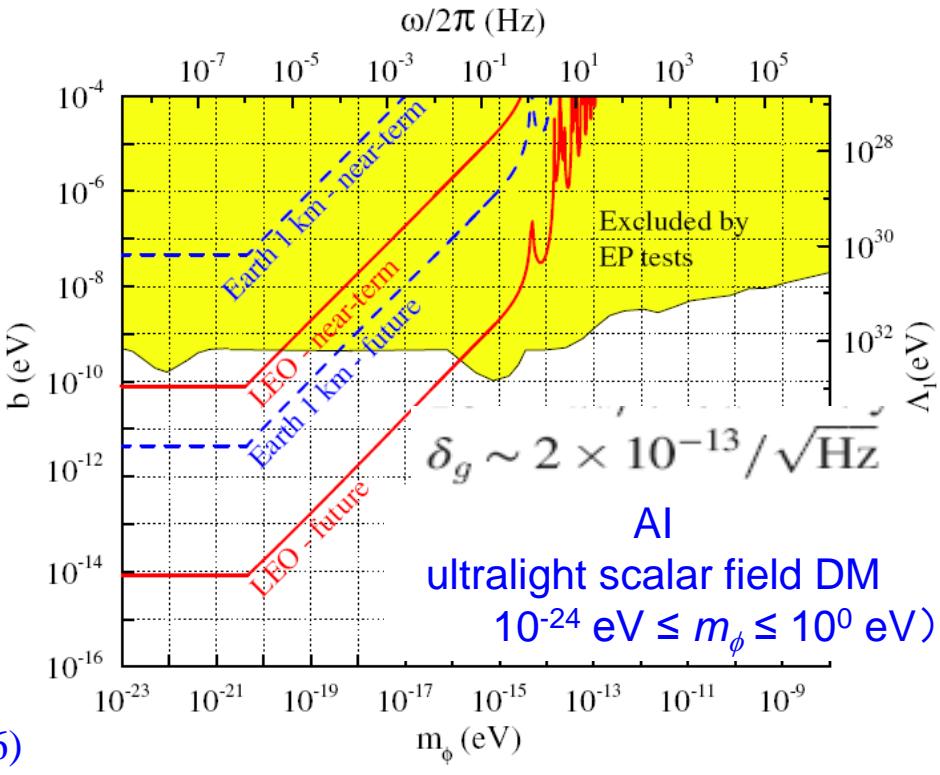
Recent Nature 2018 shows  $m_\chi < 4.3 \text{ GeV}$

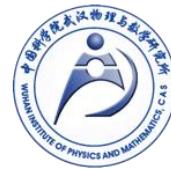


Derevianko and Pospelov, Nature Phys. 10, 933 (2014)

A.A.Geraci and A.Derevianko, PRL 117, 261301(2016)

A.A.Geraci et.al., PRL 123, 031304 (2019)





# ZAIGA: GR test — summery

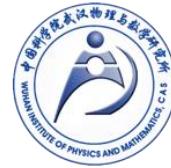
Tests	Current Limits	Expected Improvement
WEP	$\eta \sim 10^{-8}$	$\eta < 10^{-8} \sim 10^{-13}$
LPI	$\beta \sim 10^{-5}$	$\beta < 10^{-5}$
GM	$10^{-9}$ rad/s	$< 10^{-13}$ rad/s
GW	$10 \sim 10^4$ Hz	$10^{-1} \sim 10$ Hz
DM	$m_x < 4.3$ GeV	$10^{-24} \text{ eV} \leq m_x \leq 10^0 \text{ eV}$

# OUTLINE

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- Motivation
- ZAIGA: facility and key instruments
- ZAIGA: scientific proposals
- Progress



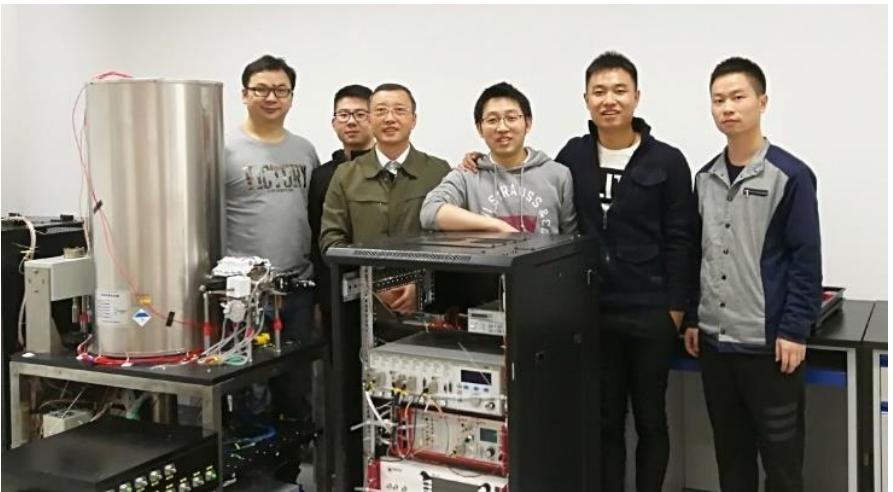
# ZAIGA budget and plans

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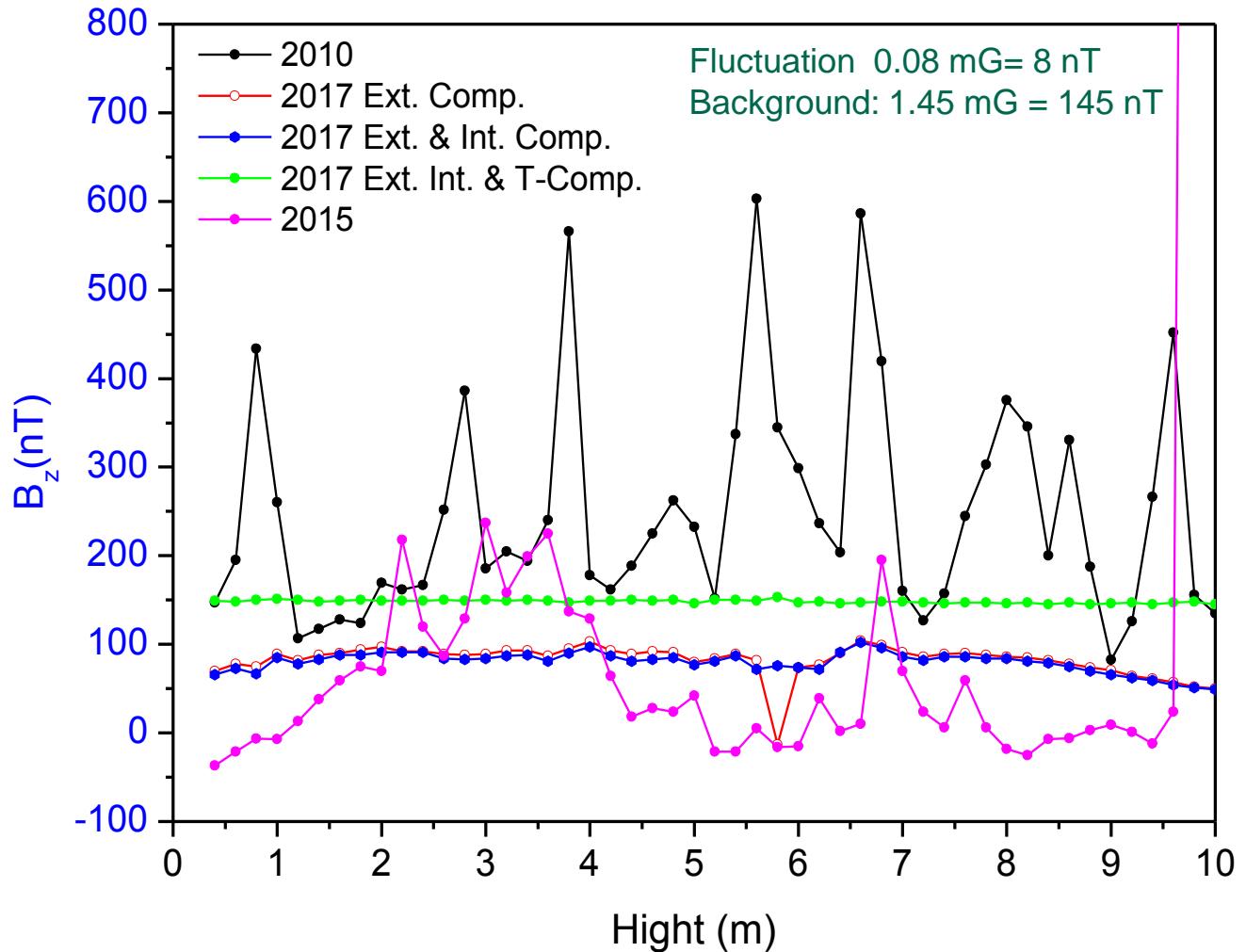
- ✓ site exploration started
- ✓ initial fund 70M RMB granted
- ✓ 2019-2021 V300m + H1.7km + Lab  
**-EP -CE –RM -GG**
- ✓ 2022-2025 Δ1km  
**-GW**

The 10<sup>th</sup> International Comparison of Absolute Gravimeters, 16 Oct.-11 Nov, 2017, Beijing, China

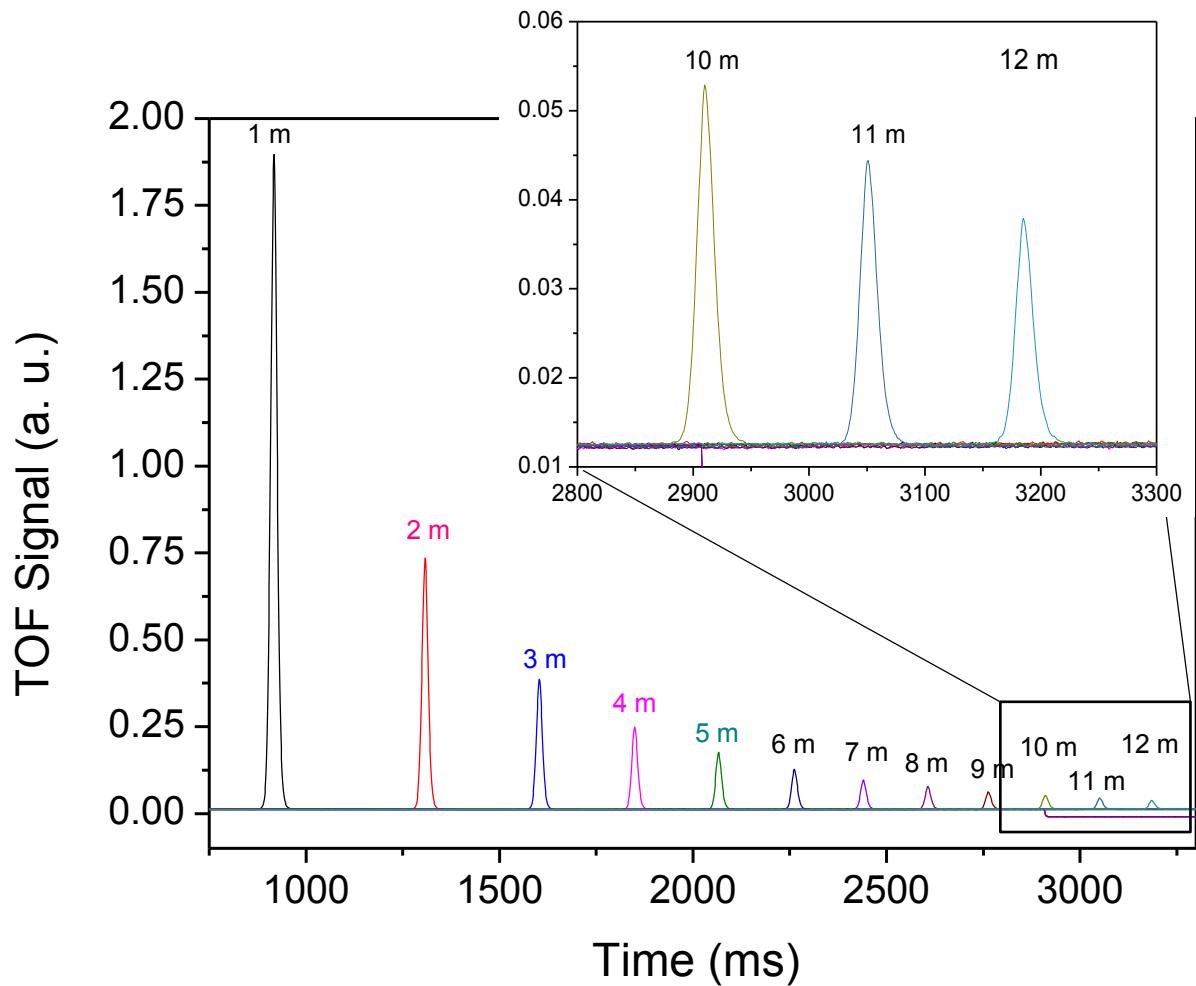
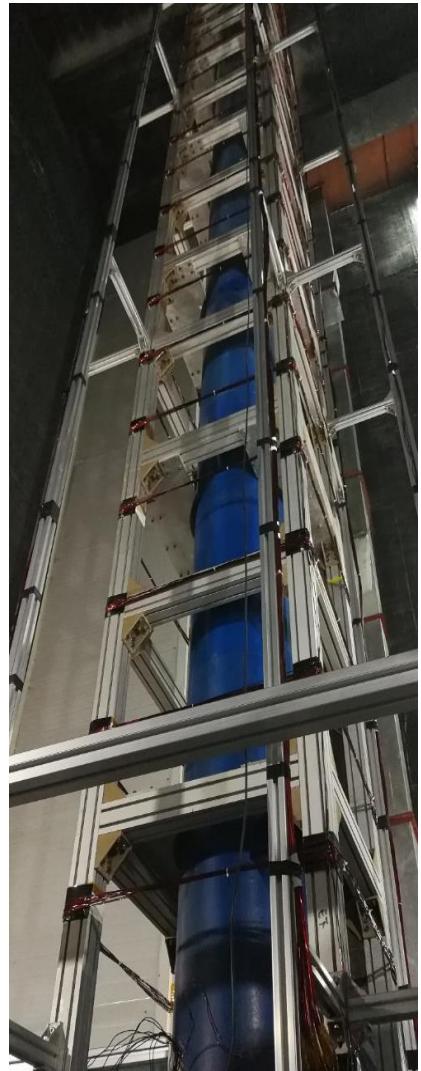
- 17 countries
- 29 FG-5 gravimeters
- 6 atomic gravimeters
- Active vibration isolation
- Rotation compensation
- Long distance handling
- $^{85}\text{Rb}$  atoms



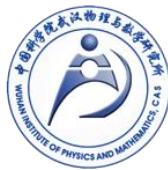
# Large scale (10 m) sub-10nT magnetic field shielding



# TOF of the 12-m atomic fountain ( $2T = 3.13$ s)

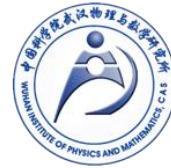


# LVK-Z (?)



**ZAIGA-GW hopes to join the Ligo-Virgo-Kagra family for GW astronomy in 6 years**





# Future: AIGA in space

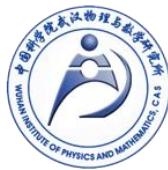
## SAGE: A Proposal for a Space Atomic Gravity Explorer

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arXiv:1907.03867v1 [astro-ph.IM]

- [23] Dongfeng Gao, Jin Wang, and Mingsheng Zhan. Atomic Interferometric Gravitational-wave Space Observatory (AIGSO). *Commun. Theor. Phys.*, 69:37–42, 2018.
- [24] Gang Wang, Dongfeng Gao, Wei-Tou Ni, Jin Wang, and Mingsheng Zhan. Orbit Design for Space Atom-Interferometer AIGSO. *Int. J. Mod. Phys. D*, 28:1940004, 2019.

# WEP test in China Space Station (-2022)

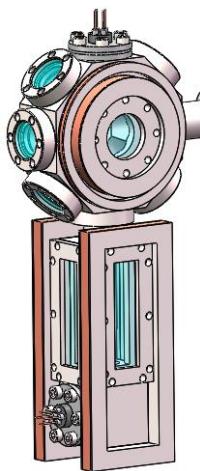
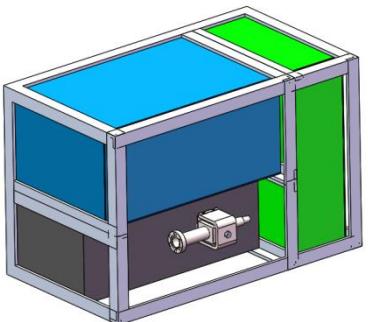
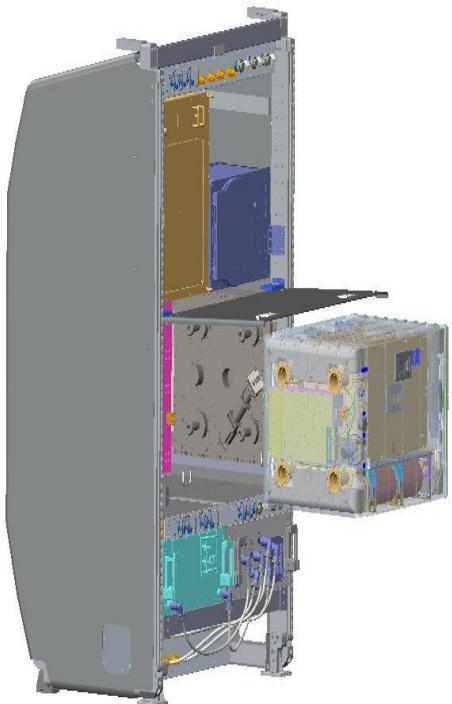


Heavenly Palace



$$\eta = 10^{-10} \sim 10^{-12}$$

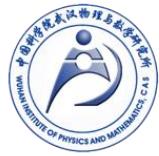
$^{85}\text{Rb} - ^{87}\text{Rb}$



@ 2022

$\leq 1 \times 10^{-7}\text{g RMS}$   
 $46 \times 30 \times 26\text{ cm}^3$   
30 kg  
30 W





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(王谨)



Wei-Tou Ni  
(倪维斗)

**ZAIGA-GW  
-DM**

**ZAIGA-EP**

**ZAIGA-CE**

**ZAIGA-RM**



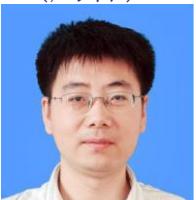
**MOST  
CAS  
NSFC**



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(贺凌翔)



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G. V. Shlyapnikov  
A. Derevianko**

**Students / Postdocs**

**Thank you for  
your attention !**