Application for joining Data Analysis Group in KAGRA

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Overall description of Research Unit

- **Unit leader** (Full name, current position, email address)

  Dongfeng Gao, Associate professor, dfgao@wipm.ac.cn

- **Affiliation of unit leader**

  (If the unit leader is not a faculty member (a tenure track assistant professor or above), please write down the reason to submit as a unit leader)

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- **Members** (Full Name, current position, email address, roles)

  1. Dongfeng Gao

     Associate professor, dfgao@wipm.ac.cn, unit leader

  2. Gang Wang

     Postdoc fellow, gwanggw@gmail.com, working on the gravitational-wave parameter estimation

  3. Wei Zhao

     PhD student, zhwzhaow@163.com, working on the gravitational effects in atomic physics

- **Working groups** CBC

- **Research plan:**

Working group: CBC

Project: Test of General Relativity

Description of research: In WIPM, many efforts are put on testing the weak equivalence principle (WEP), which is the foundation of General Relativity. The basic idea is to launch two atomic species in a 10-meter-high atom interferometer, and compare their accelerations due to the Earth's gravity. We are working on to improve the WEP test to the 10^{-10} level.

To push the "Test of General Relativity" in full aspects, it is also important to test the equivalence principle (EP) with other massless microscopic particles, such as photons and gravitons. One of our future research plans at WIPM is to use two atomic clocks at different height, compare the gravitational redshifts of lights, and test the EP.

Then, it is of great value to use data from KAGRA for EP test. Especially, in the era of multi-messenger astronomy, people have done initial test of the EP by comparing the velocities of the light wave and gravitational-wave.

It can be expected that when combining the data from atom interferometer, atomic clock, and KAGRA, a lot of important work on "Test of General Relativity" can be done.

Members: Dongfeng Gao, Gang Wang, Wei Zhao

Collaborators: Mingsheng Zhan, Wei-tou Ni

WEP test with Atom Interferometers (AI) @ WIPM

The weak equivalence principle (WEP)

The statement of WEP is that the trajectory of a freely falling “test” body (one not acted upon by such forces as electromagnetism and too small to be affected by tidal gravitational forces) is independent of its internal structure and composition. In the simplest case of dropping two different bodies in a gravitational field, WEP states that the bodies fall with the same acceleration (this is often termed the Universality of Free Fall, or UFF).

Clifford M. Will, "The Confrontation between General Relativity and Experiment", *Living Rev. Relativity* **17**, (2014), 3.

The Einstein equivalence principle (EEP)

1. WEP is valid.

2. The outcome of any local non-gravitational experiment is independent of the velocity of the freely-falling reference frame in which it is performed. (The local Lorentz invariance (LLI))

3. The outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed. (The local position invariance (LPI))

The strong equivalence principle (SEP)

1. WEP is valid for self-gravitating bodies as well as for test bodies.

2. The outcome of any local test experiment is independent of the velocity of the (freely falling) apparatus.

3. The outcome of any local test experiment is independent of where and when in the universe it is performed.

SEP $\supset$ EEP $\supset$ WEP

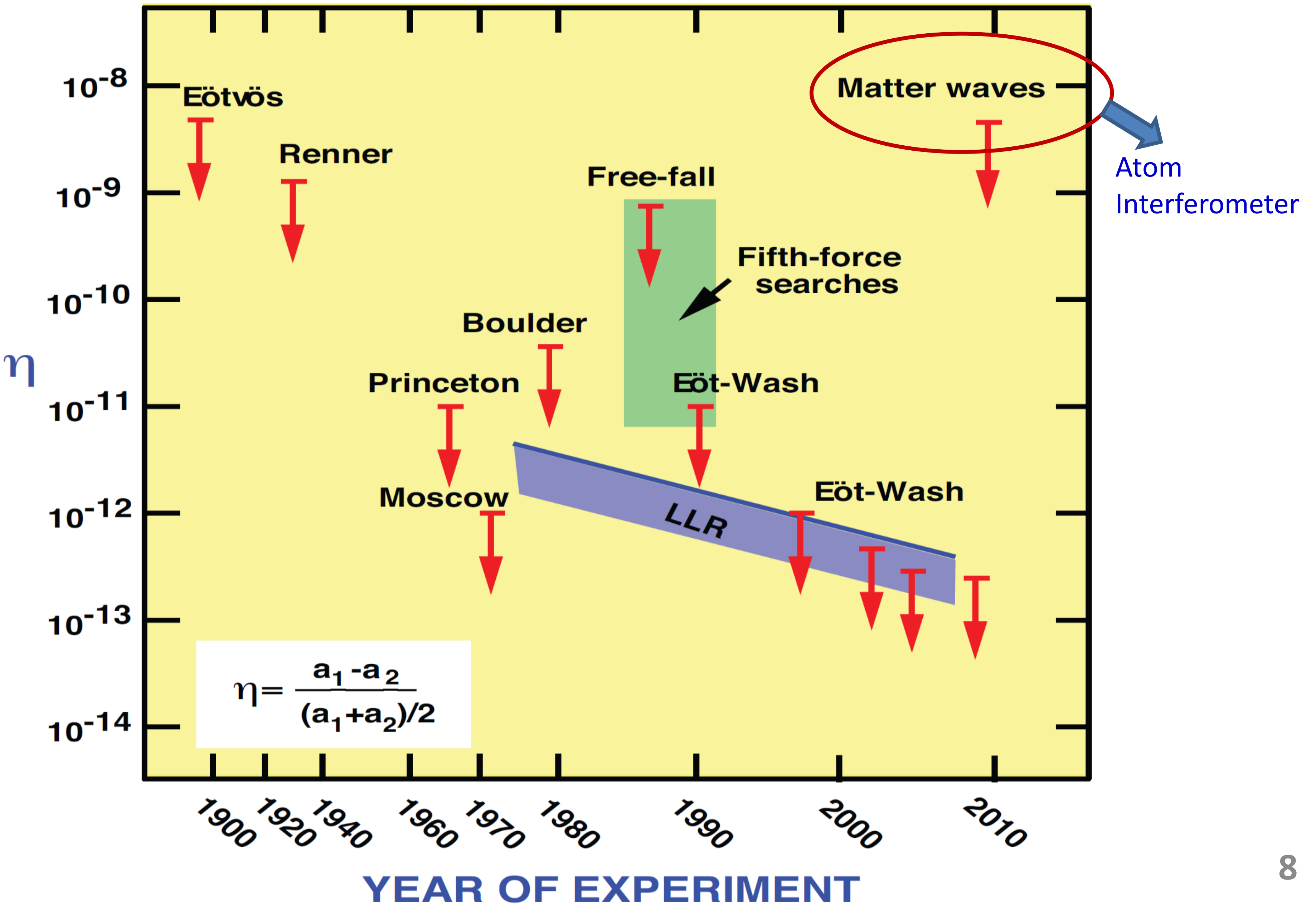
Experimental tests of WEP

A direct test of WEP is the comparison of the acceleration of two laboratory-sized bodies of different composition in an external gravitational field. If the principle were violated, then the accelerations of different bodies would differ.

$$m_{\mathrm{P}} = m_{\mathrm{I}} + \sum_A \frac{\eta^A E^A}{c^2}$$

$$\eta \equiv 2\frac{|a_1 - a_2|}{|a_1 + a_2|} = \sum_A \eta^A \left(\frac{E_1^A}{m_1 c^2} - \frac{E_2^A}{m_2 c^2} \right)$$

TESTS OF THE WEAK EQUIVALENCE PRINCIPLE



Theory of Atom Interferometers (AI)

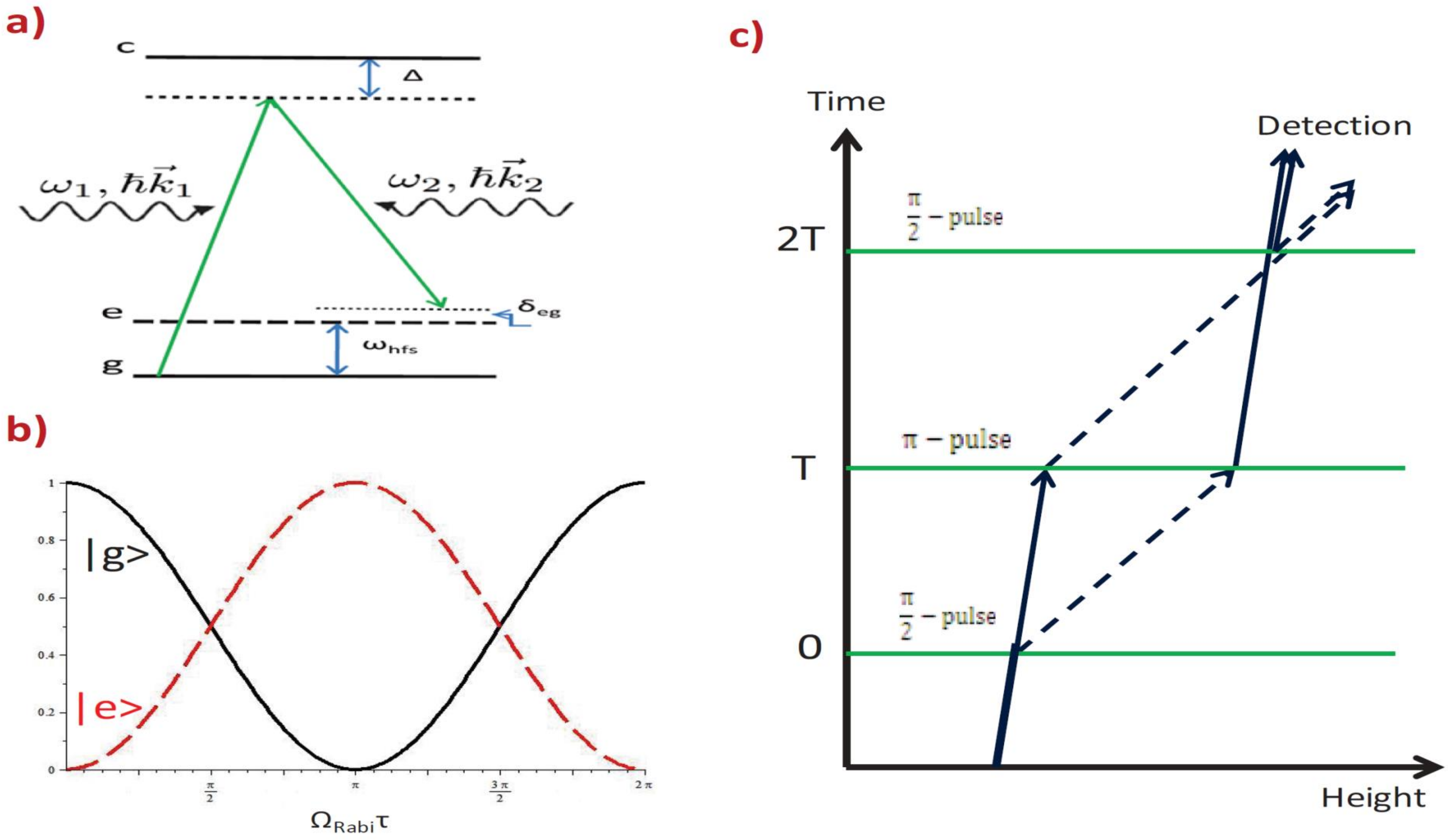
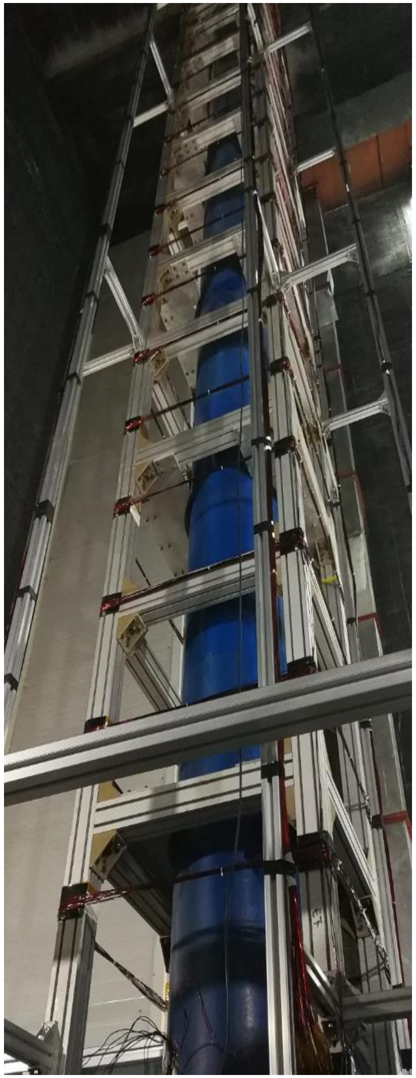
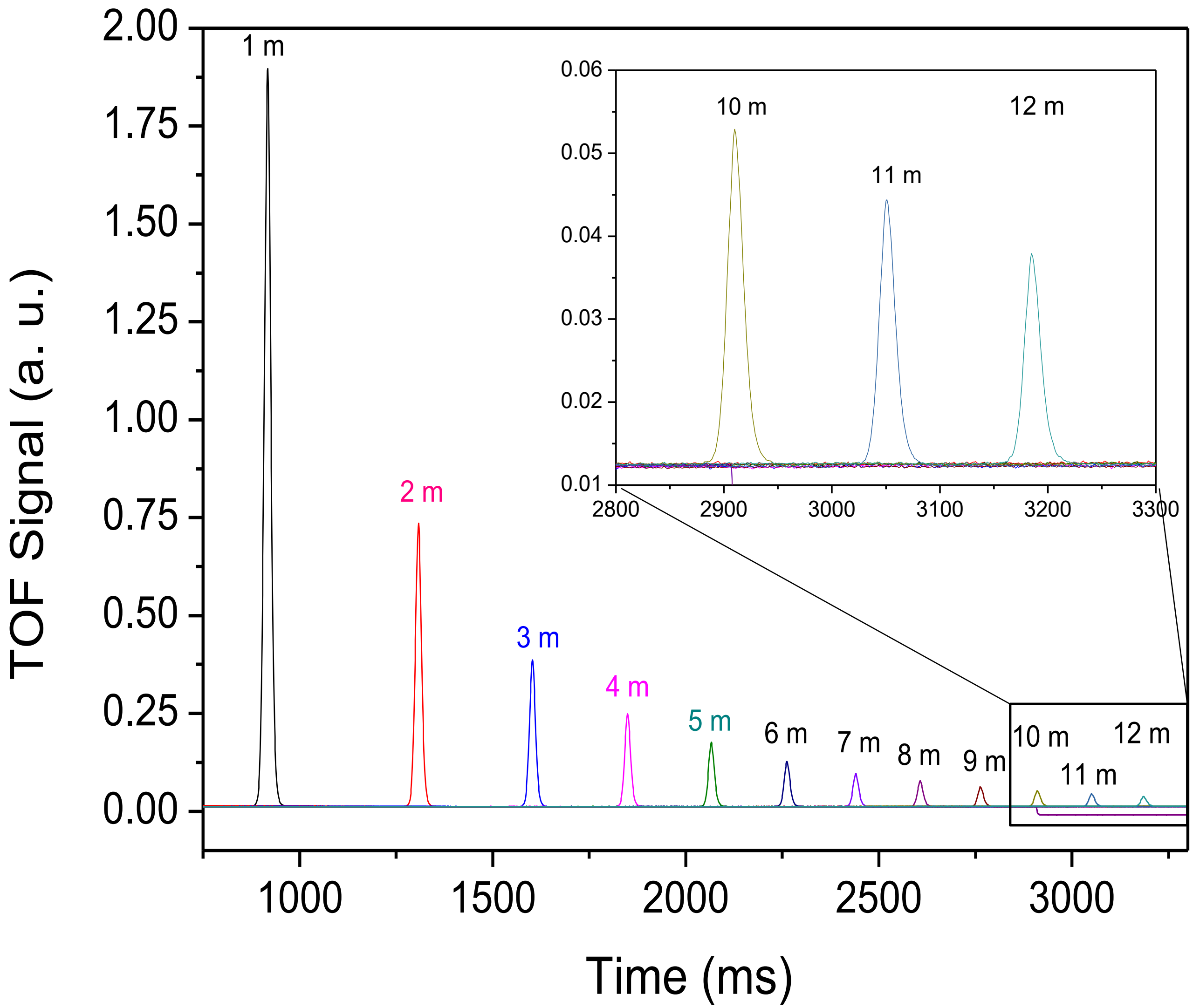


FIG. 2. (a) The diagram for a stimulated Raman transition between two atomic hyperfine ground states $|g\rangle$ and $|e\rangle$. Laser beams are detuned by Δ from the optical state $|c\rangle$. The atomic population is resonantly transferred between $|g\rangle$ and $|e\rangle$ if the frequency difference $\omega_1 - \omega_2$ is close to $\omega_{\rm hfs}$. (b) A $\frac{\pi}{2}$-pulse is a beam splitter since the atom beam prepared in one state is transferred into a superposition of states $|g\rangle$ and $|e\rangle$. A π-pulse is a beam reflecter since the atomic state is reversed completely. (c) The light pulse sequence for a $\frac{\pi}{2}$-π-$\frac{\pi}{2}$ Mach-Zender atom interferometer.

12-meter AI @ WIPM



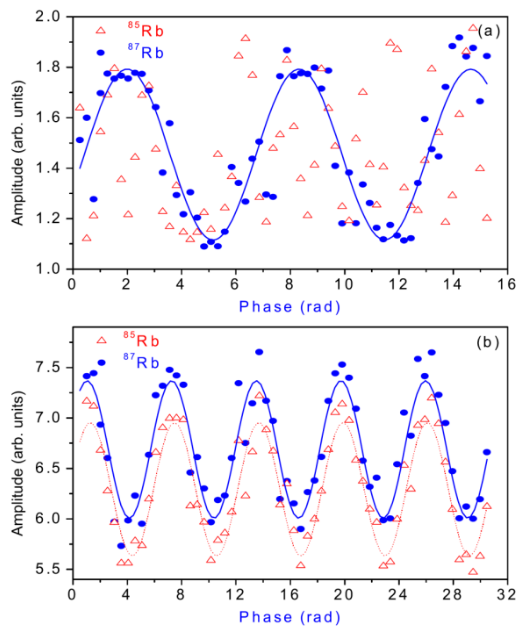


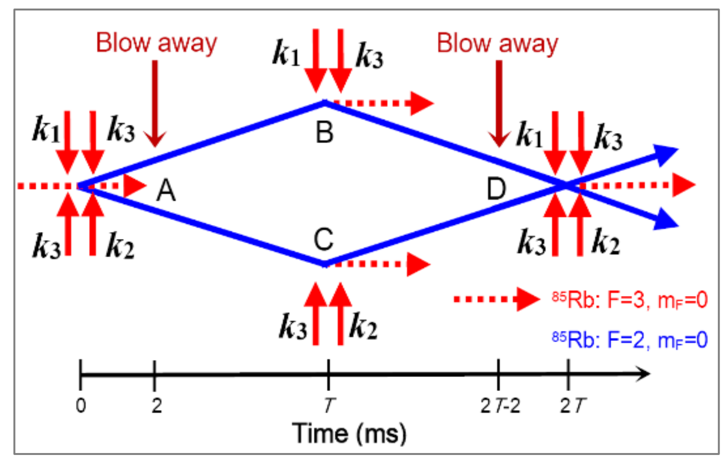
WEP test to the 10^{-8} –level @ WIPM

Signal: $\phi = k_{eff}\, g\, T^2$

Acceleration Sensitivity: $\delta\phi / \phi = \delta a / a = 1 / (\sqrt{N}\ k\ T^2\ g)$

$N=10^6$, $T = 0.1$ s , $k_{eff} = 4\pi/\lambda = 1.6\times10^7\ m^{-1}$ → $d\phi / \phi = 10^{-8}$



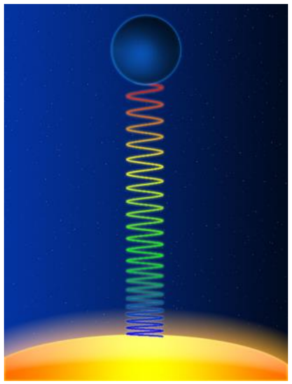


$\eta=(2.8\pm3.0)\times10^{-8}$

10^{-10} -level in the near future

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

Planned EP test with Atomic Clocks (AC) @ WIPM



Redshift measurement: test the local Lorentz invariance (LLI)

In a gravitational potential field:

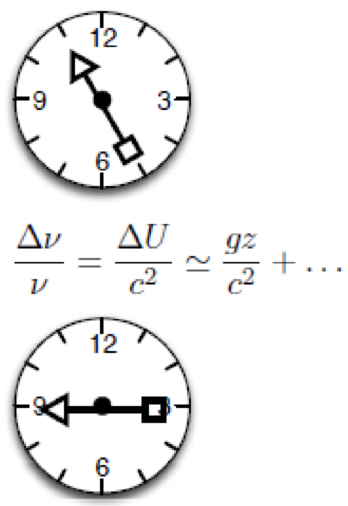
$$\frac{\omega_1 - \omega_2}{\omega_0} = \frac{\Delta u}{c^2} \qquad \frac{\omega_1 - \omega_2}{\omega_0} = (1+\beta)\frac{\Delta u}{c^2}$$

Generality Relativity: $\beta = 0$

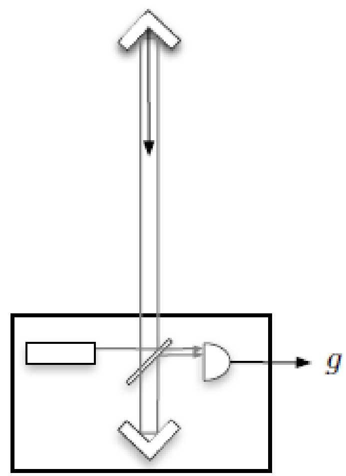
Year		Methods	Parameters	References
1976	Smithsonian	$\Delta h \sim 10000$ km Gravity Probe A	$\beta < 7 \times 10^{-5}$	*Phys. Rev. Lett.* **45**, 2081(1980）
2008	JILA , LNE-SYRTE，The University of Tokyo	Sr-clock, H maser, $^{199}Hg^{+}$	$\beta < 3.5 \times 10^{-6}$	*Phys. Rev. Lett.* **100**, 140801 (2008)
2010	UC Berkeley Müller	Atom Interferometer	$\beta < 7 \times 10^{-9}$?	*Nature*, **467**, E2(2010) *Nature*, **463**, 926(2010)
2010	JILA Wineland	Al+-clock $\Delta h \sim 30$ cm	$\Delta\omega = 0.5 \times 10^{-16}$ β ?	*Science* **329**,1630(2010)
2011	UC Berkeley Müller	Atom Interferometer	$\beta \sim 10^{-6}$	*Phys. Rev. Lett.* **106**, 151102(2011)

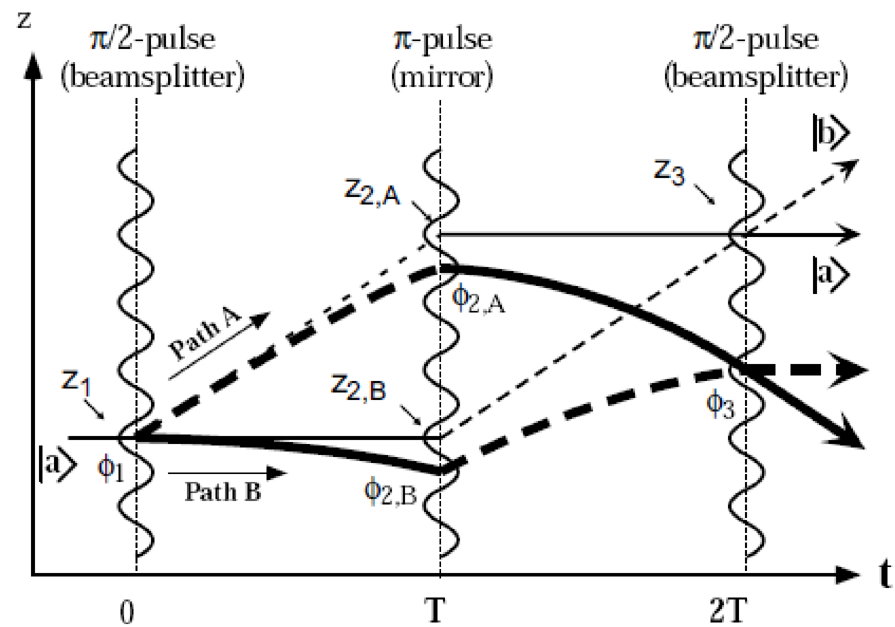
AI + AC to measure Redshift of photons

Proper time difference



Gravity





Atomic clocks

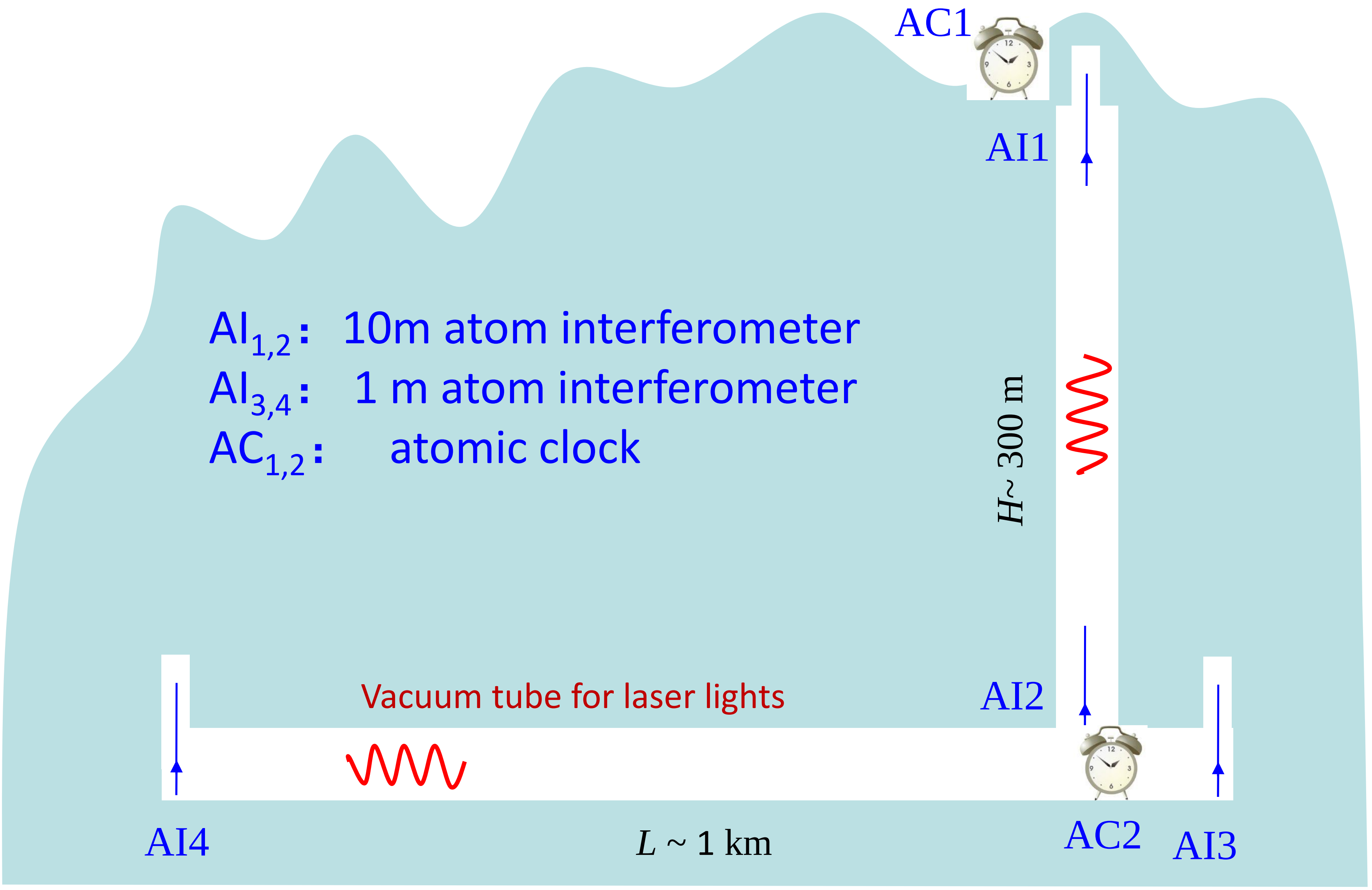
$$\frac{\Delta\omega}{\omega_0} = (1+\beta)\frac{\mathrm{gh}}{c^2}$$

$$1+\beta = \frac{\Delta\omega\, c^2}{\omega_0\, \mathrm{gh}}$$

$$\partial\beta = -c^2\left(\frac{\Delta\omega}{\omega_0}\right)\frac{(g\partial h + h\partial g)}{(\mathrm{gh})^2}$$

Atom Interferometers

Planned underground lab at Mountain Zhao



EP test with gravitational-wave detection

4.3. Test of the Equivalence Principle

Probing whether EM radiation and GWs are affected by background gravitational potentials in the same way is a test of the equivalence principle (Will 2014). One way to achieve this is to use the Shapiro effect (Shapiro 1964), which predicts that the propagation time of massless particles in curved spacetime, i.e., through gravitational fields, is slightly increased with respect to the flat spacetime case. We will consider the

$$-2.6 \times 10^{-7} \leqslant \gamma_{\rm GW} - \gamma_{\rm EM} \leqslant 1.2 \times 10^{-6}.$$

LIGO Scientific Collaboration and Virgo Collaboration, Fermi Gamma-ray Burst Monitor, and INTEGRAL, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A, Astrophys. J. Lett. **848**, L13 (2017).

Summary

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