Precision Measurement of planetary gravitomagnetic field in general relativity and laser interferometry in space

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The CAS Gravity Consortium

Coordinators:

- National Microgravity Laboratory, Institute of Mechanics (Wenrui Hu)
- University of Chinese Academy of Sciences (Yueliang Wu)

Member Institutes:

- Academy of Mathematics and Systems Science, CAS,
- Huazhong University of Science and Technology,
- Institute of High Energy Physics,Beijing,
- Institute of Physics, Beijing,
- Institute of Theoretical Physics,Beijing,
- Nanjing Institute of Astronomical Optics and Technology,
- National Astronomical Observatories, Beijing,
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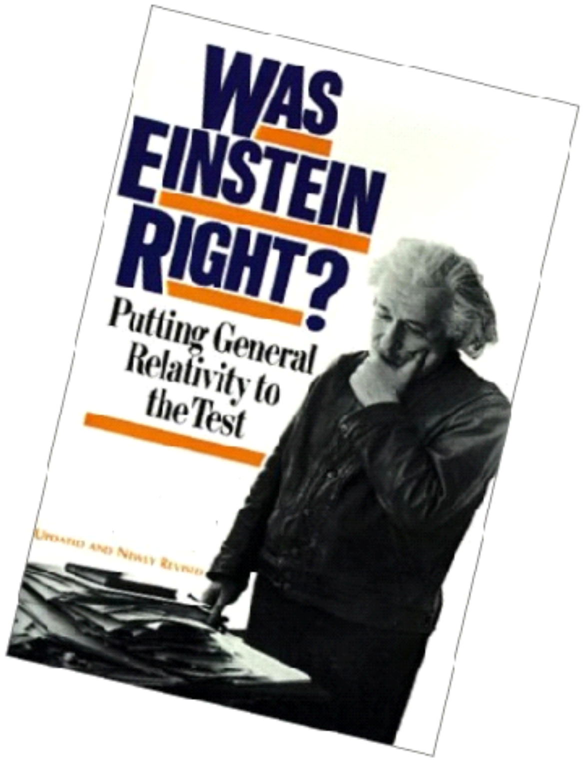
- Main interests: Fundamental physics in space -- general relativity and gravitation
  -- space geodesy.

Scientific Background

- Mercury perihelion
- Shapiro time delay
- Precision measurement of PPN parameters in solar system
- Tests of equivalence principle
- . . . .



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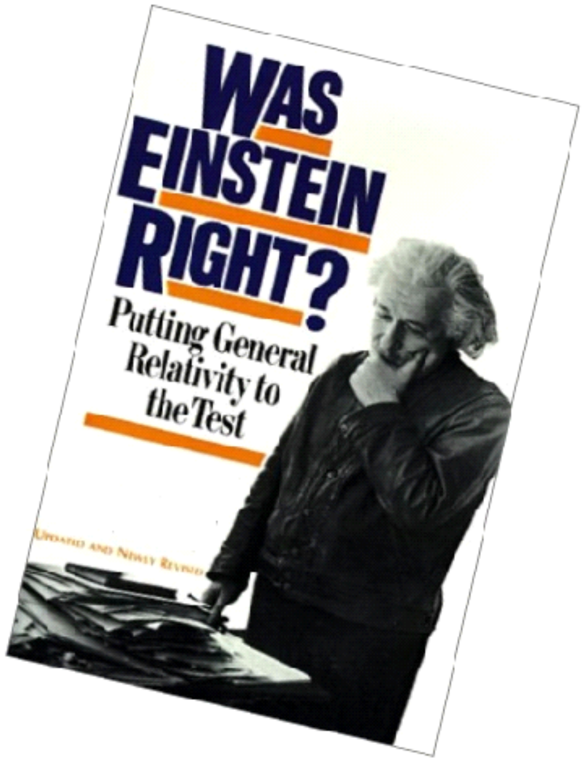

Outstanding tests in 21st century

•Gravitational wave detection ---

galactic and cosmological scale (eLISA, CAS project)

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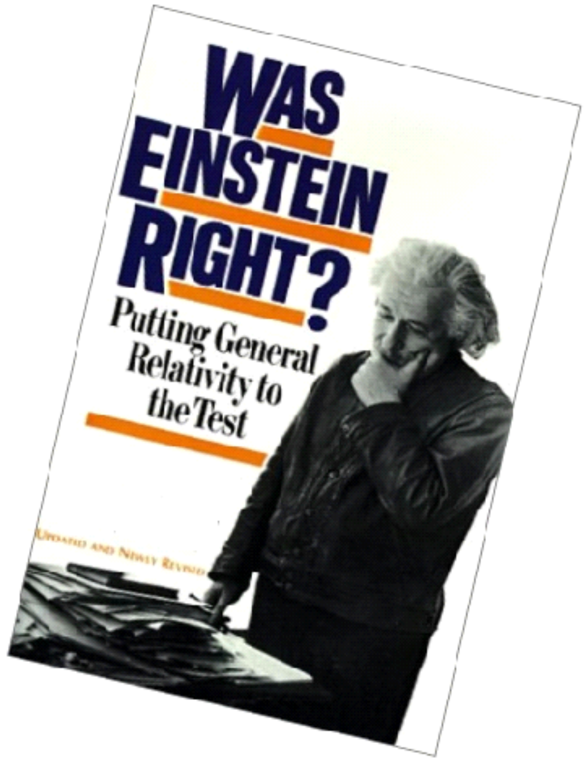


Outstanding tests in 21st century

•Gravitational wave detection ---

galactic and cosmological scale (eLISA, CAS project).

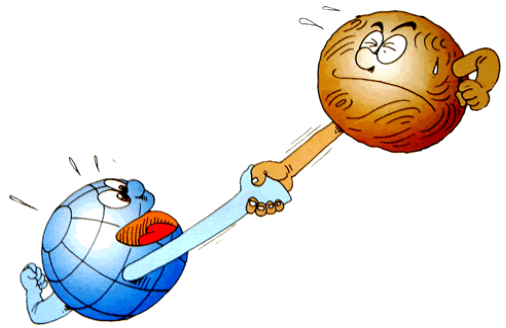
•**Gravitomagnetic field detection** (e.g. Lens Thirring effect)---

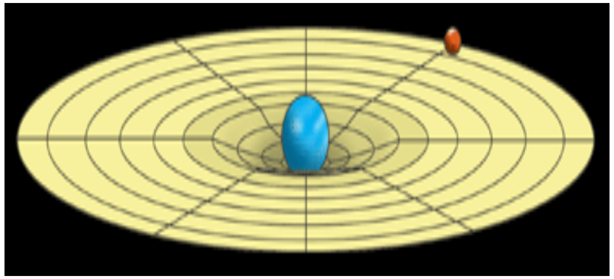
test on the planetary and solar system scale.

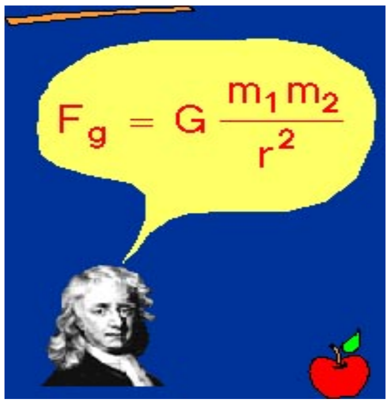
General Relativity —a generalisation of Newtonian theory of gravity

classical mechanics

general relativity







geometry of spacetime

≈universal gravitation

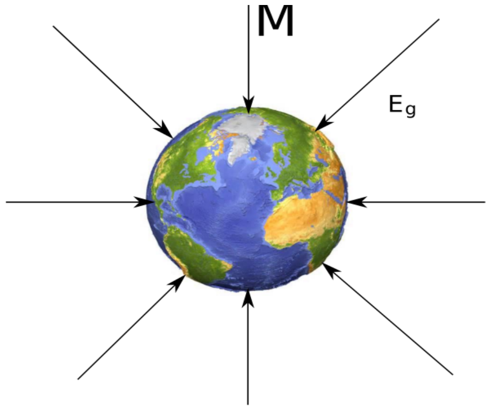
$$g_{ab} = \begin{pmatrix} + & & & \\ & - & & \\ & & - & \\ & & & - \end{pmatrix}$$

Einstein field equations

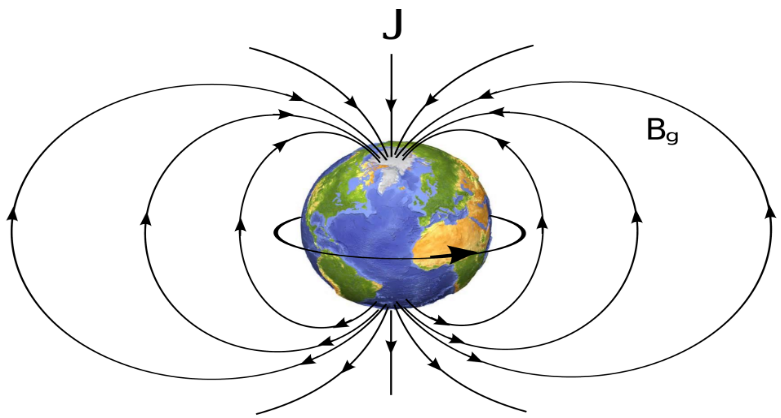
$$R_{ab} - \frac{1}{2} R g_{ab} = 8\pi T_{ab}$$

Gravitomagnetic field in general relativity

$$\Phi \sim \frac{GM}{r}, \qquad \mathbf{A} \sim \frac{G}{c}\frac{\mathbf{J}\times\mathbf{r}}{r^3}, \qquad \mathbf{E} = -\nabla\Phi - \frac{1}{c}\frac{\partial}{\partial t}\left(\frac{1}{2}\mathbf{A}\right), \qquad \mathbf{B} = \nabla\times\mathbf{A},$$



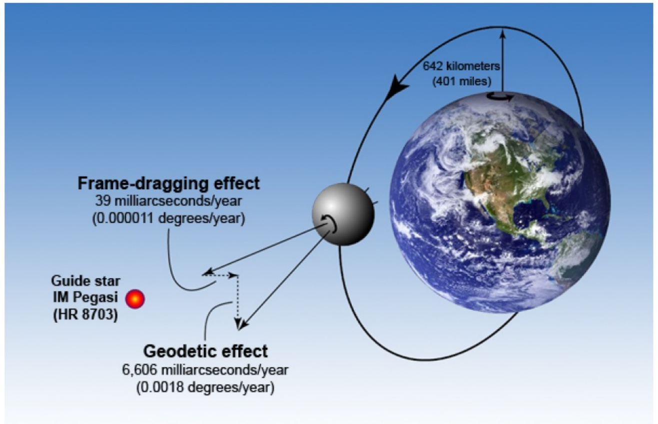
Newtonian gravity field

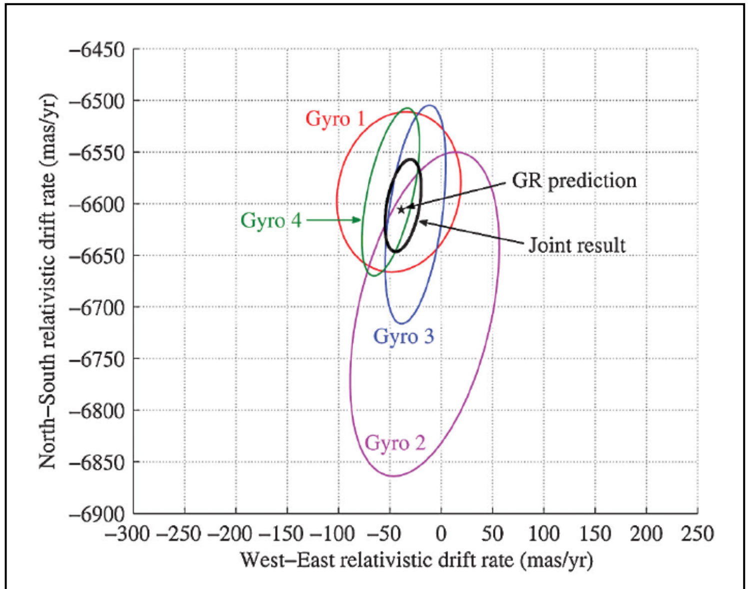


Gravitomagnetic field predicted by Einstein for a spinning body

Einstein field equations ≈ Maxwell equation（1PN）

GPB experiment





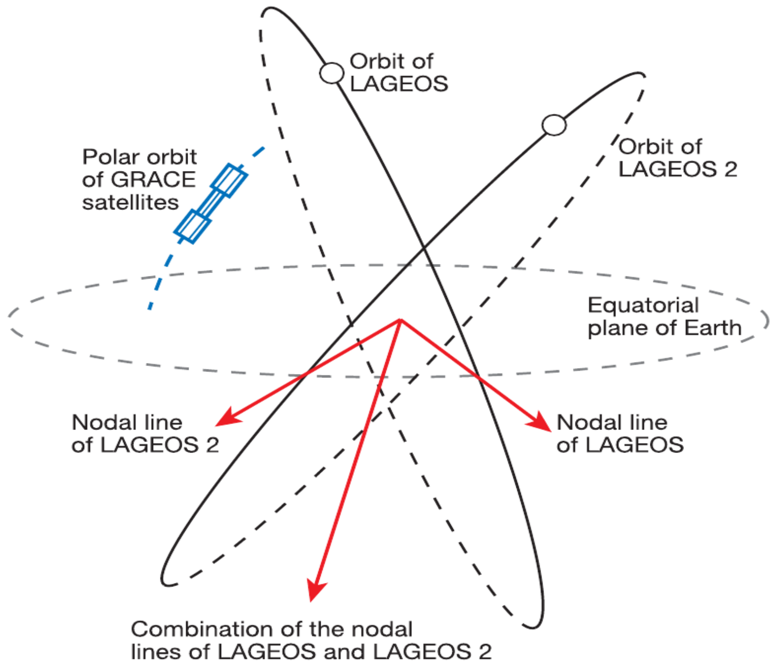
Gravity Probe B – Final Experimental Results		
Gyroscope	$r_{N\text{-}S}$ (Geodetic Measurement)	$r_{W\text{-}E}$ (Frame-Dragging Measurement)
Individual Gyroscope Results		
Gyroscope #1	-6,588.6±31.7 mas/yr	-41.3±24.6 mas/yr
Gyroscope #2	-6,707.0±64.1 mas/ yr	-16.1±29.7 mas/yr
Gyroscope #3	-6,610.5±43.2 mas/yr	-25.0±12.1 mas/yr
Gyroscope #4	-6,588.7±33.2 mas/yr	-49.3±11.4 mas/yr
Weighted-Average Results for All Four Gyroscopes		
All Gyroscopes	-6,601.8±18.3 mas/yr	-37.2±7.2 mas/yr ~19% error
Schiff-Einstein Predicted Theoretical Values		
Theoretical Gyroscope	-6,606.1 mas/yr	-39.2 mas/yr

The LAGEOS I and II and LARES Missions

Measurement in terms of Keplerian elements of spacecrafts

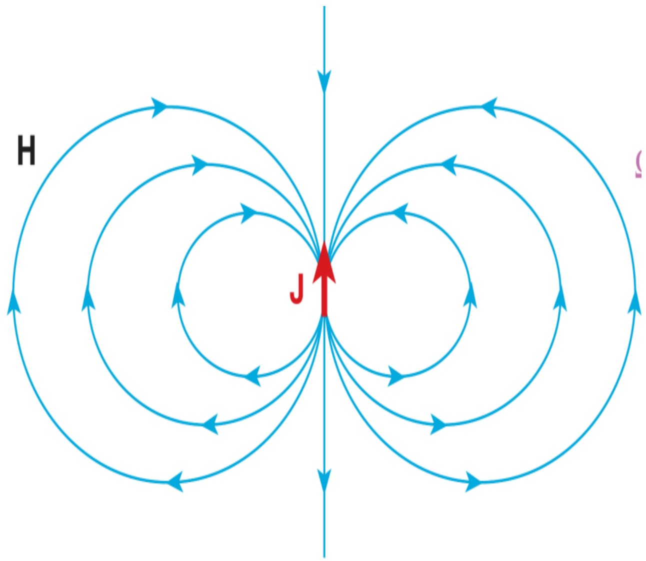
Highly depend on the detailed knowledge of Earth gravity field.

The Gravitomagnetic effect is now confirmed with 10% accuracy, subject to earth gravity field modelling+ non-gravitational force error. .



Other controversial claims of detection: Lunar Laser ranging, Mars orbiter....

Why the interest? 



- Poorly tested, still remain major challenge in experimental relativity

- Impose constraints in post newtonian limit of geometric gravity theories. Provide stringent tests on low energy effective theory coming from string theory and loop quantum gravity.

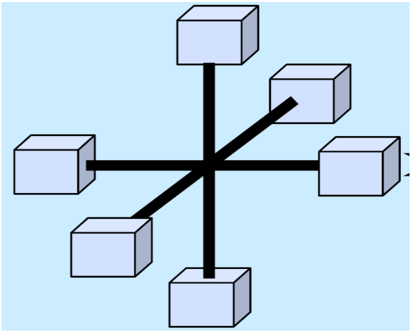
- Applications in future space science such as ClockSync in space and etc....

The scientific objectives of the proposed mission

- Direct, precision measurement of earth's gravitomagnetic field predicted by Einstein's theory of general relativity to unprecedented accuracy better than 0.1%.
- Improve the accuracy in the measurement of some post-Newtonian parameters in our solar system.
- New tests and constraints on alternative theories of gravity, low energy effective theory related to string theory and quantum gravity.
- Track global climate through the temporal variation of the Earth gravity field with geoid accuracy better than 1cm and order of earth multipoles up to order 120……..

Gradiometric measurement of gravitomagnetic field

Braginsky, Polnarev(1981), Mashhoon, Paik, Will (1989) and others



3 axis gradiometer

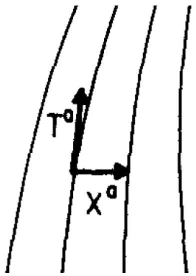
readout →

$$\begin{pmatrix} \frac{\partial^2 V}{\partial x^2} & \frac{\partial^2 V}{\partial x \partial y} & \frac{\partial^2 V}{\partial x \partial z} \\ \frac{\partial^2 V}{\partial y \partial x} & \frac{\partial^2 V}{\partial y^2} & \frac{\partial^2 V}{\partial y \partial z} \\ \frac{\partial^2 V}{\partial z \partial x} & \frac{\partial^2 V}{\partial z \partial y} & \frac{\partial^2 V}{\partial z^2} \end{pmatrix}$$

force gradient tensor

Geodesic deviation (Jacobi) equation

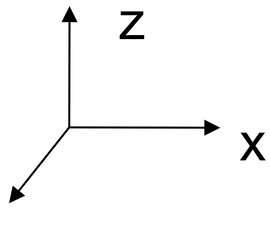
$$\frac{D^2 X^a}{D\tau^2} = -R_{bcd}{}^{a} T^b T^d X^a$$



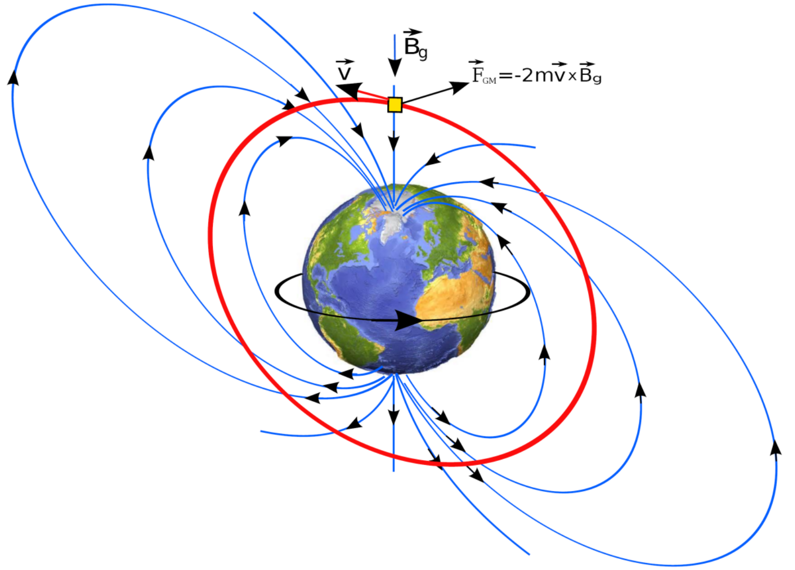
Analytic solution of the geodesic deviation equation at the 1PN level

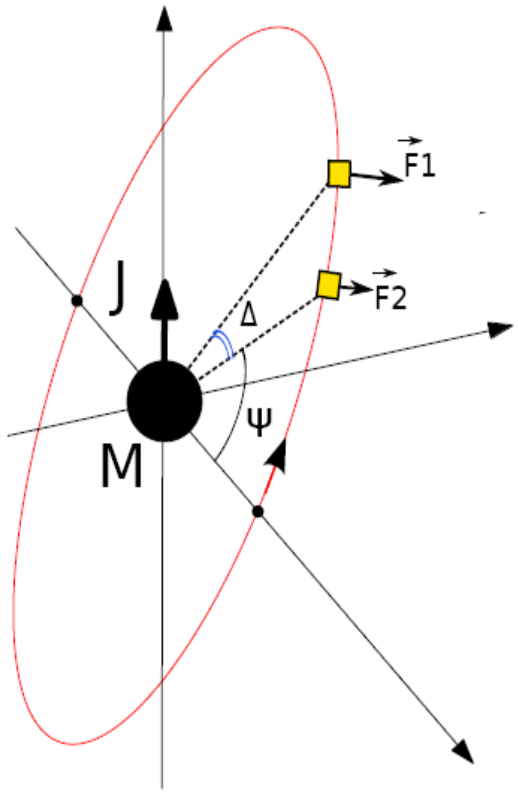
$$x(\tau) \approx \frac{(1+\gamma+\frac{1}{4}\alpha_1) J d \sin I \sin(\omega\tau)}{r^3}\tau,$$

$y(\tau), z(\tau) << x(\tau)$



Lorentz force of gravitomagnetic field



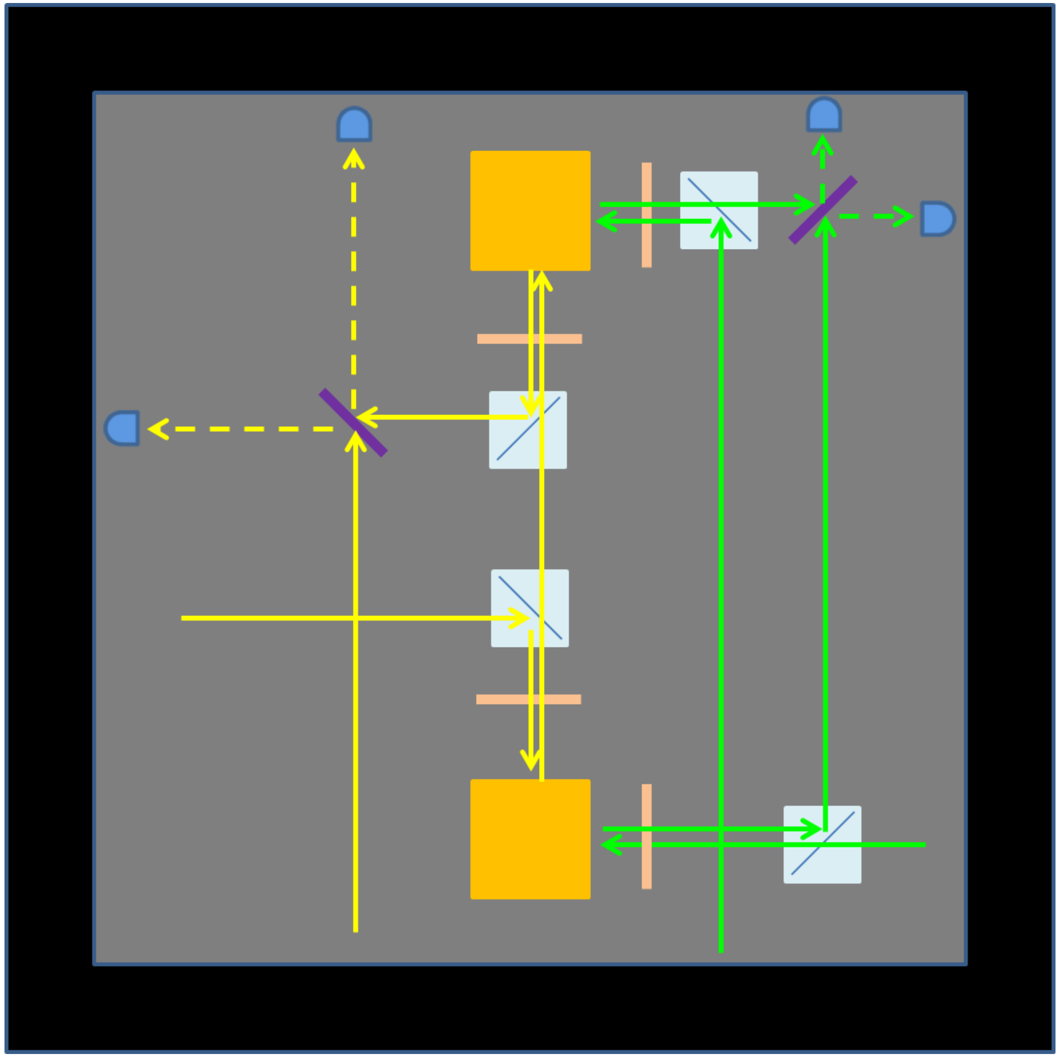


$$\vec{F} = 2m\vec{v} \times \vec{B}_g$$

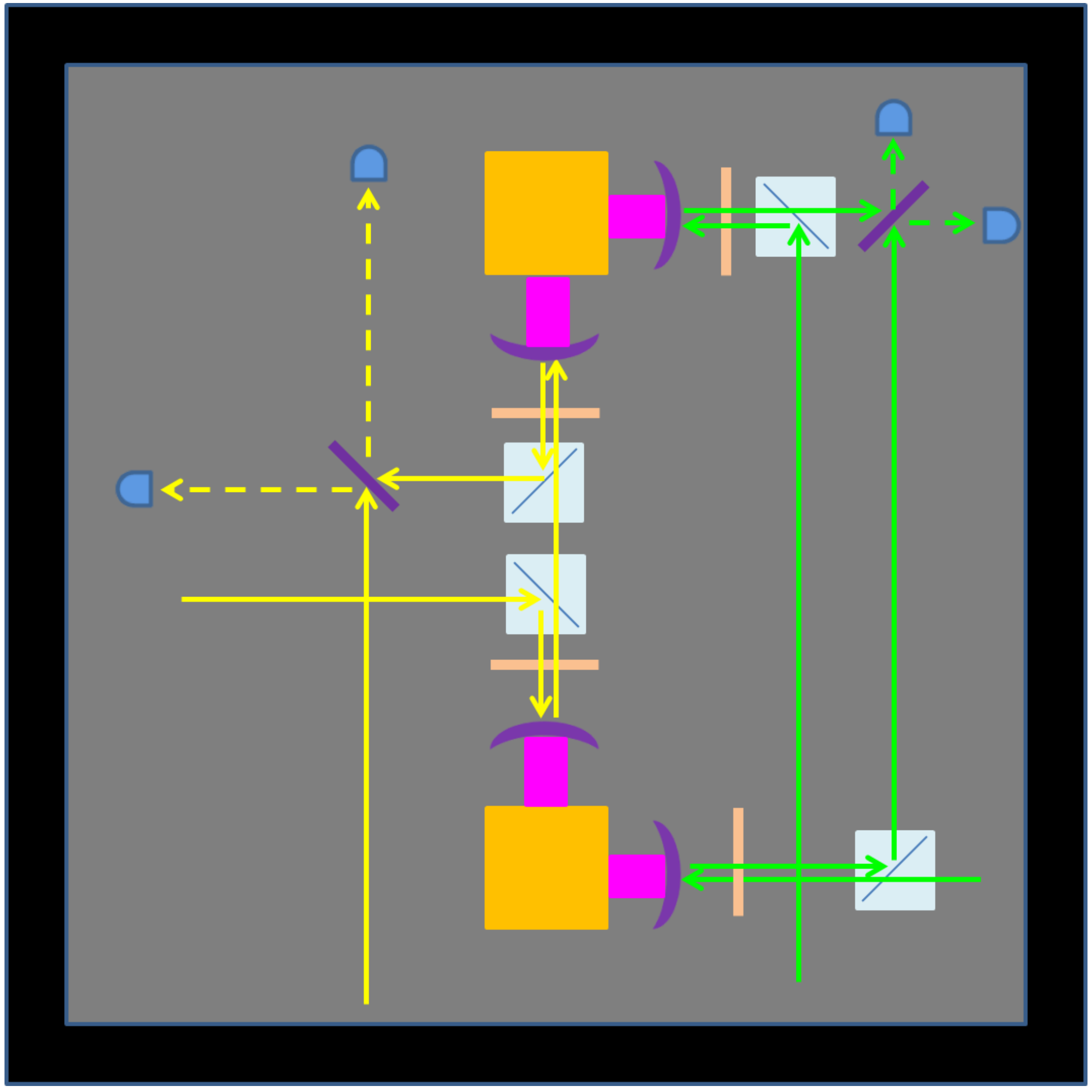
$$|\vec{F}| = 2m|\vec{v}||\vec{B}_g| \cos \Psi$$

$$|\vec{F}_1 - \vec{F}_2| \sim 2m|\vec{v}||\vec{B}_g|(\sin \Psi)\Delta$$

Laser interferometric readout



Fabry-Perot cavity design



The Mission Concept

- Near polar orbits.

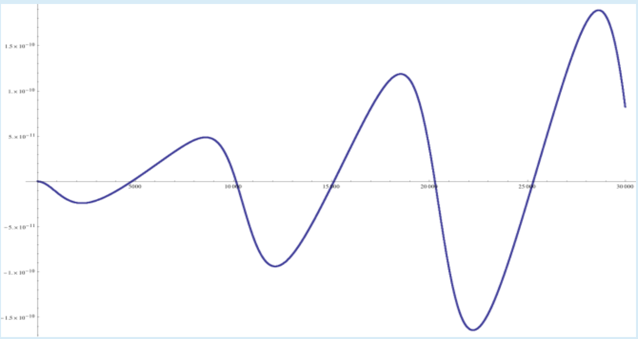
To increase the GM signal while suppress the noises from gravitoelectric field.

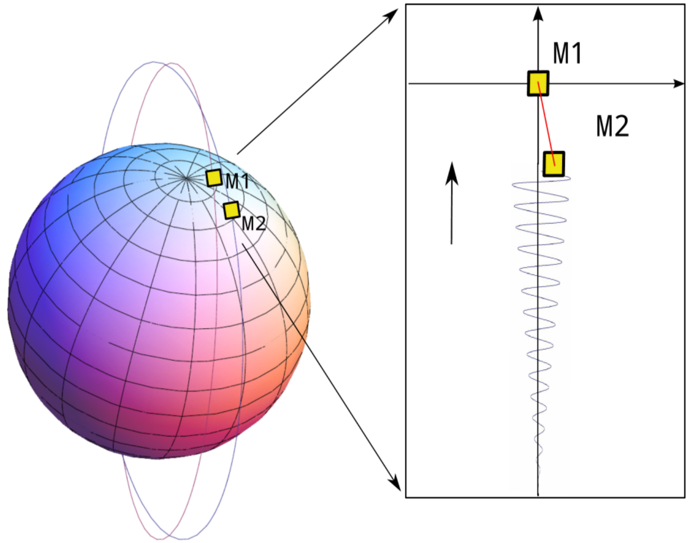
- Altitude options: 3000km to 6000km (even to 10000km).

Higher altitude will suppress the noises from higher order gravity multipoles.

- Eccentric orbits.

Distinguish gravitomagnetic field signal from J_2 signal of earth gravity





Precision measurement of PPN parameter

Parameter	Effect	Limit	Remarks
$\gamma - 1$	(i) Time delay	2.3×10^{-5}	Cassini tracking
	(ii) Light deflection	4×10^{-4}	VLBI
$\beta - 1$	(i) Perihelion shift	3×10^{-3}	$J_2 = 10^{-7}$ from helioseismology
	(ii) Nordtvedt effect	2.3×10^{-4}	$\eta = 4\beta - \gamma - 3$ assumed
ξ	Earth tides	10^{-3}	Gravimeter data
α_1	Orbital polarization	10^{-4}	Lunar laser ranging
			PSR J2317 + 1439
α_2	Solar spin precession	4×10^{-7}	Alignment of Sun and ecliptic
α_3	Pulsar acceleration	2×10^{-20}	Pulsar $\dot{P}$ statistics
η^{a}	Nordtvedt effect	9×10^{-4}	Lunar laser ranging
ζ_1	–	2×10^{-2}	Combined PPN bounds
ζ_2	Binary motion	4×10^{-5}	$\ddot{P}_p$ for PSR 1913 + 16
ζ_3	Newton's 3rd law	10^{-8}	Lunar acceleration
ζ_4	–	–	Not independent

(Will, Theory and experiiments in general relativity)

- Improve the accuracy in the measurement of α_1 to 10^{-5}!
- α_1--- a measure of local Lorentz invariance of gravity theories.
- A test of quantum gravity violation of Loretnz invariance!

Possible Tests and Constraints for the Predictions from Quantum Gravity

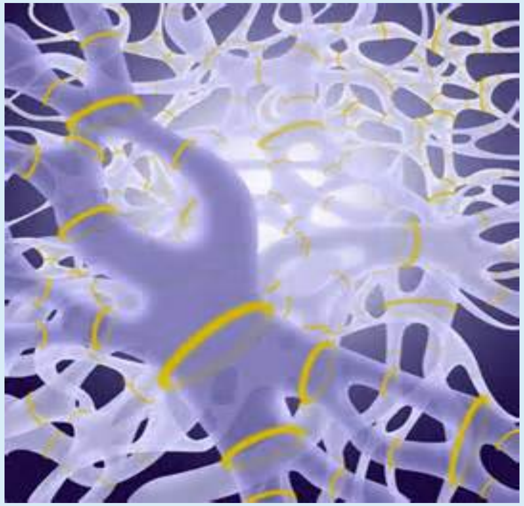
Chern-Simons modified gravity serves as a representative phenomenological model predicted by string theory and loop quantum gravity

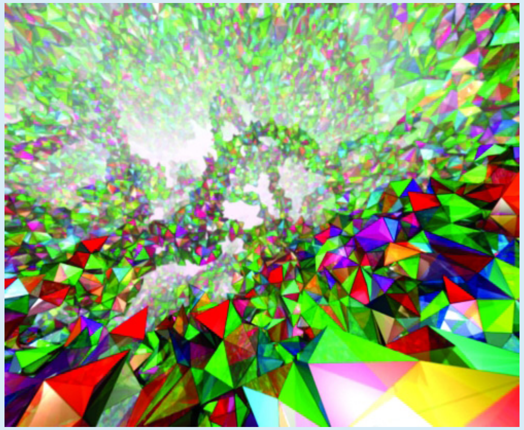
$$S_{CS} = \frac{1}{16\pi G}\int d^4x \frac{1}{4} f R^{\star} R,$$

A characteristic and rather large signal in the in-line direction in our experiment.

$$-\frac{dJ\chi \sin I(\tau\omega \sin(\tau\omega) + \cos(\tau\omega))}{2r^3\omega}$$

The dimensionless parameter $\chi = 2\frac{\dot{f}}{r}$ describes the magnitude of the Chern-Simons action, which can be precisely measured or constrained to 10^{-15} !





Bases for Joint Mission

eLISA consortium

- Accelerometer

  micro-newton ion thrusters

  (under development)
- Optics in space

  (development completed for LPF)
- Charge management (UV LED)

  (not started yet)
- satellite platform
- launcher

CAS gravity consortium

- Accelerometer
- micro-newton ion thrusters

  (just started)
- Optics in space

  laser interferometry (100pm/√Hz),

  phase meter (in progress)
- Charge management (UV LED)

  (not started yet)
- satellite platform
- launcher

Thanks!!