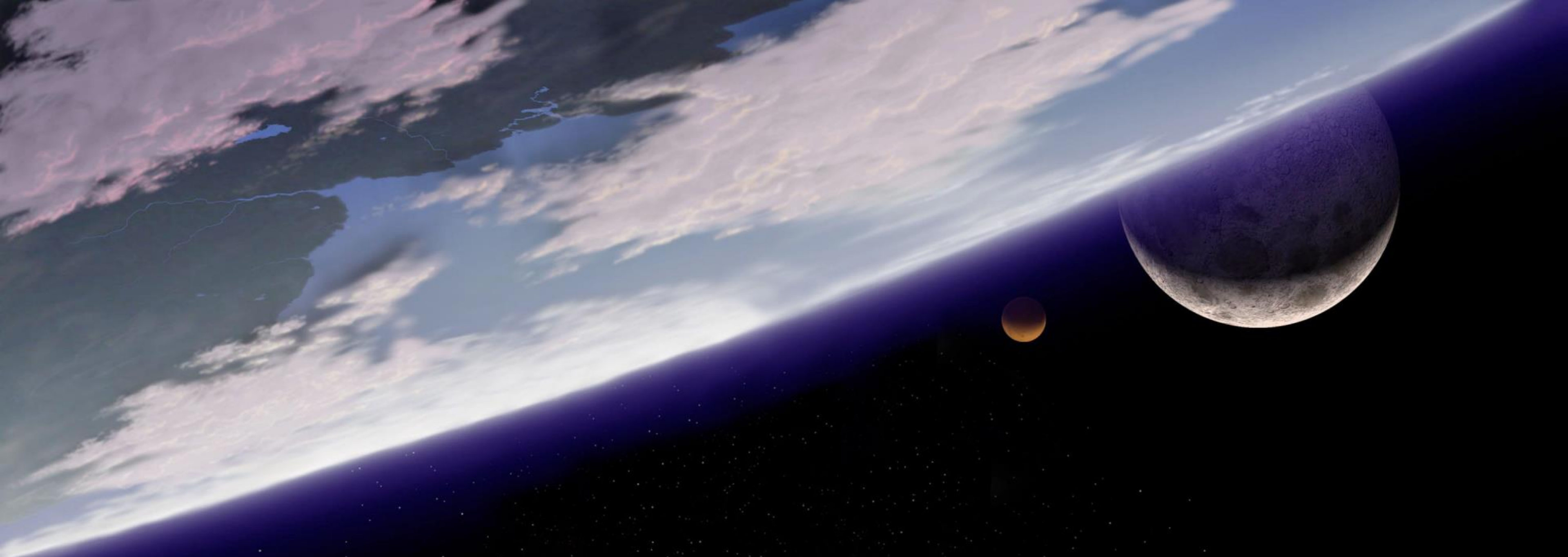
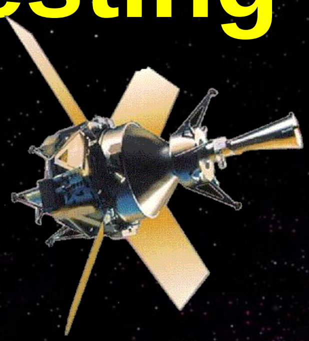


Testing General Relativity and Gravitational Physics



June 28, 2019

Suwen Wang

At Shanghai Jiaotong University

Brief Introduction of Relativity

- Special Relativity

1570年《西游记》：
孙悟空一个跟头十万八千里
天上一日，地上一年

Time Dilation:

$$D = 5.4 \times 10^{7} m$$

$$\Delta t = 0.180125287 \sec$$

$$d\tau = \frac{dt}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

$$c = 299792458 m / \sec$$

$$\Longrightarrow \frac{d\tau}{dt} = 365$$

General Relativity
– A theory of gravity

Einstein's Field Equation (1916)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G T_{\mu\nu}$$

Testing of general relativity falls into two main categories:

- Predictions from the theory
- Testing the assumptions of the theory

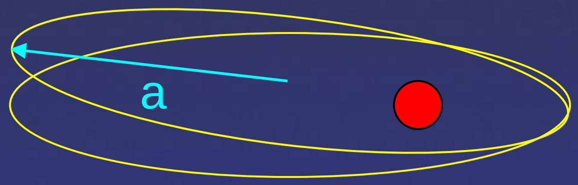
Testing methods involve astronomical observations and physics experiments

Due to the weakness of gravitational interaction,
the experimental test requires extreme precision.

Planet Orbit Precession

Perihelion Precession of Mercury (1943)

- Newton: 5557.62 +/- 0.20 sec/century
- Observation: 5600.73 +/- 0.41 sec/century



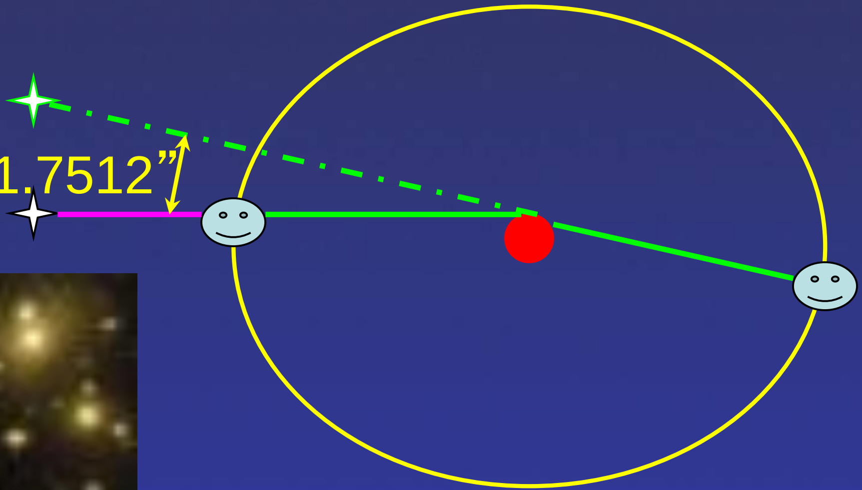
$$\Delta\varphi = 6\pi \frac{MG}{(1-e^2)a} \text{ rad/rev}$$

Other Perihelion Precession Measurements

Planet	Gen. Relativity (sec/century)	Observed (sec/century)
Mercury	43.03	43.11
Venus	8.6	8.4
Earth	3.8	5.0
Icarus	10.3	9.8

Starlight Deflection

- Arthur Eddington with solar eclipse expedition (1919)
- 380 stars measured after Eddington
- Radio signal interferometric measurements yielded more accurate results
- Modern results agree with GR within 1×10^{-4} (VLBI results)

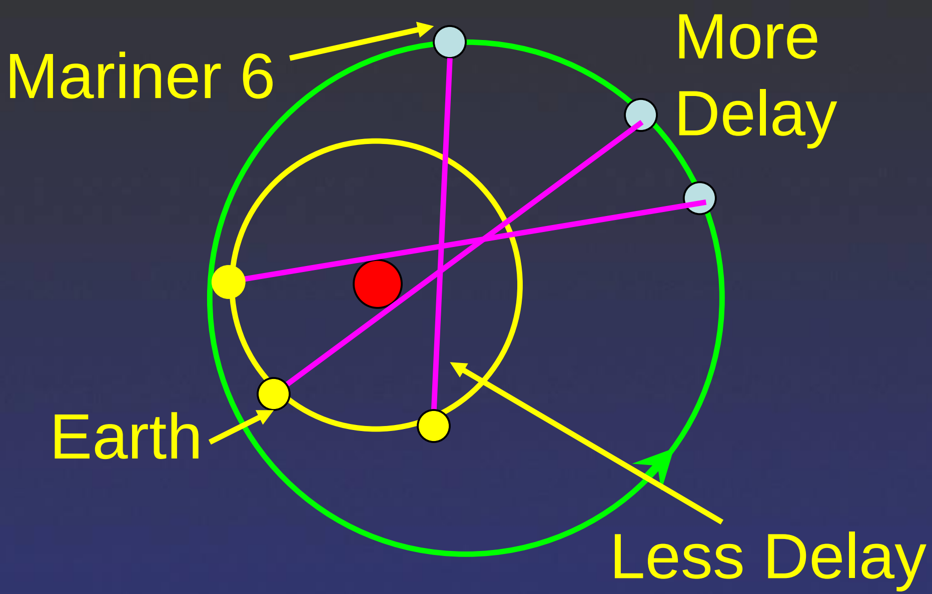


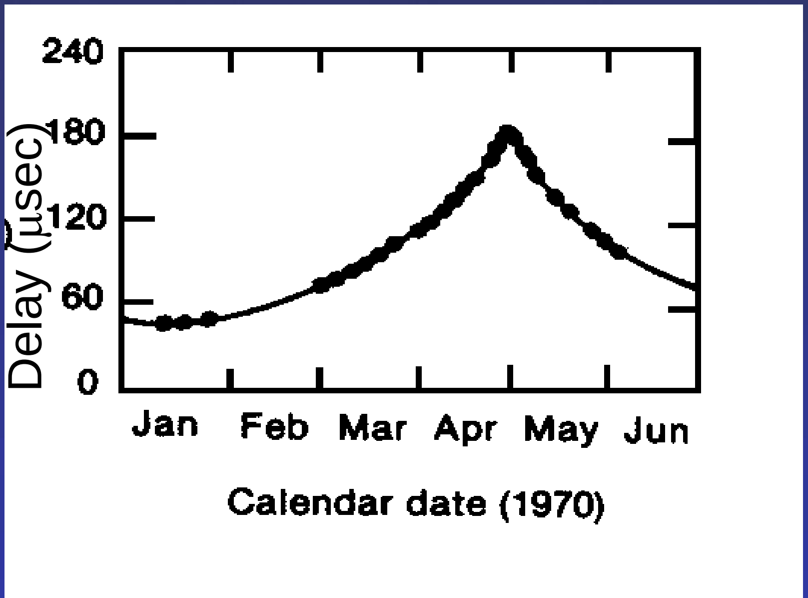
$$q = \frac{4MG}{c^2 R}$$

Shapiro Time-delay

Time delay measured by bouncing radio signals off of:

- Mercury
- Venus
- Mariner 6 spacecraft
- Mariner 7 spacecraft
- Transponder on Mars (0.5%)
- Cassini spacecraft (10 ppm)





Gravitational Redshift

- Pound & Rebka (1960)
  - Gamma ray energy shift up the elevator
- Gravity Probe A (1976)
  - Hydrogen maser launched on a rocket to an altitude of 10000 km
- Modern atomic clocks can detect the effect in 1 cm

$$\frac{\Delta\lambda}{\lambda} \approx \frac{MG\Delta R}{c^2 R^2}$$

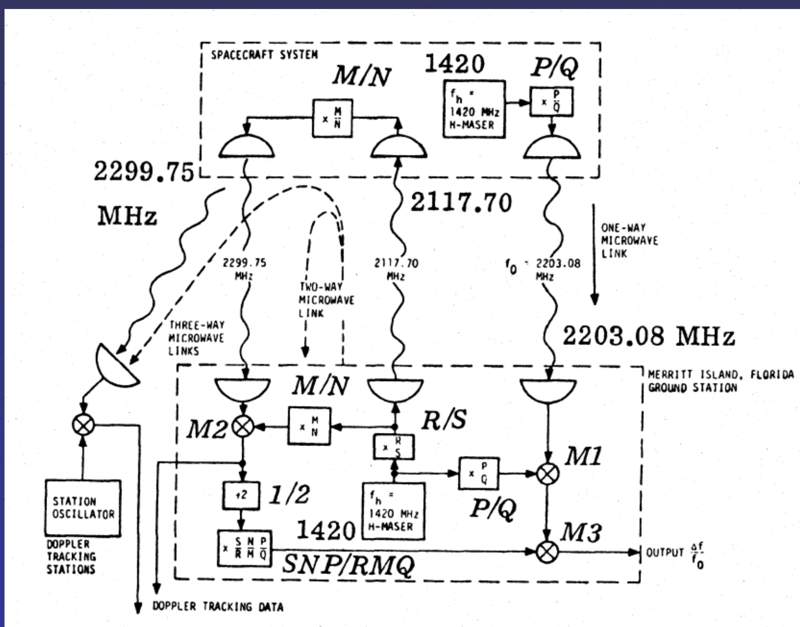
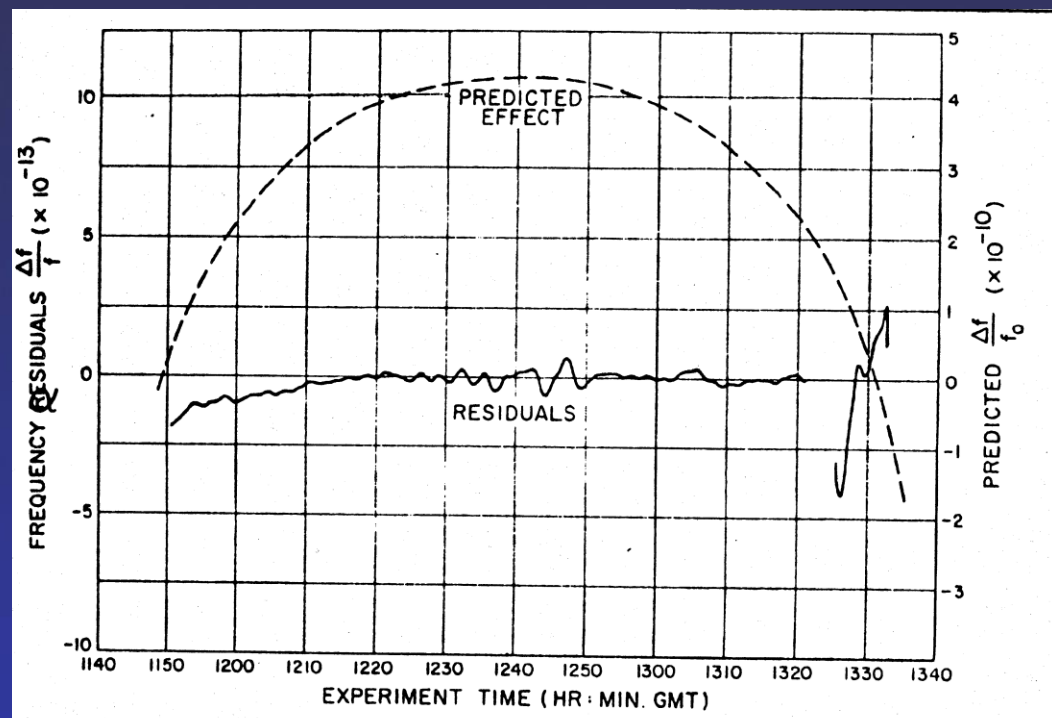


FIG. 1. Doppler cancellation and tracking system.

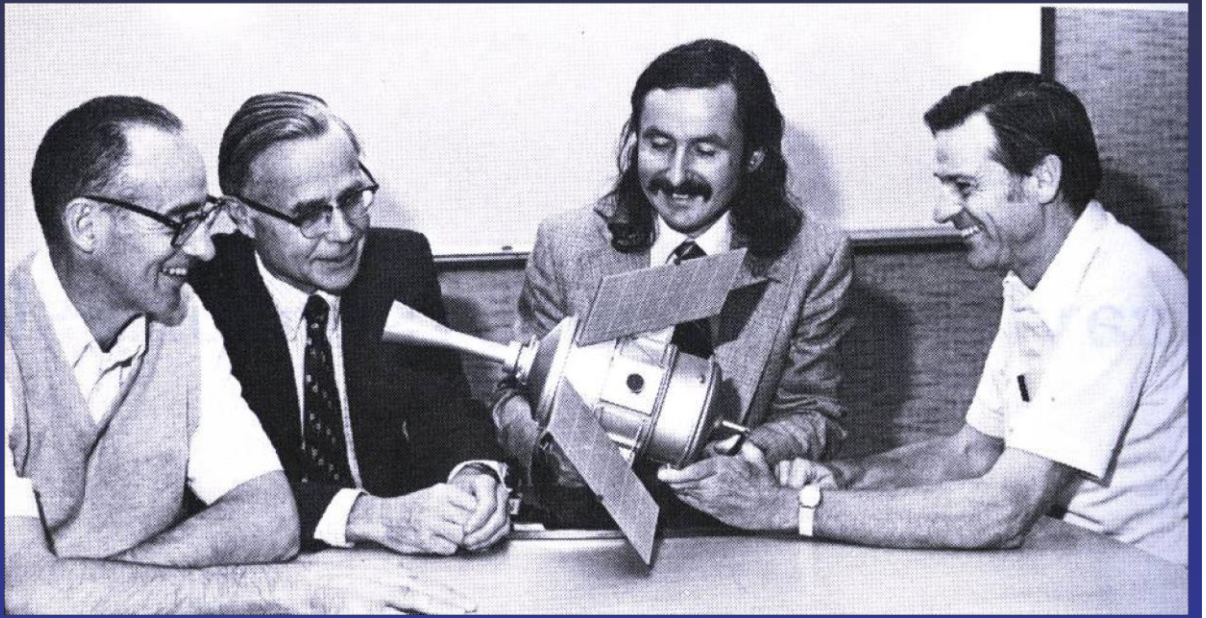


Geodetic and Frame Dragging Effects

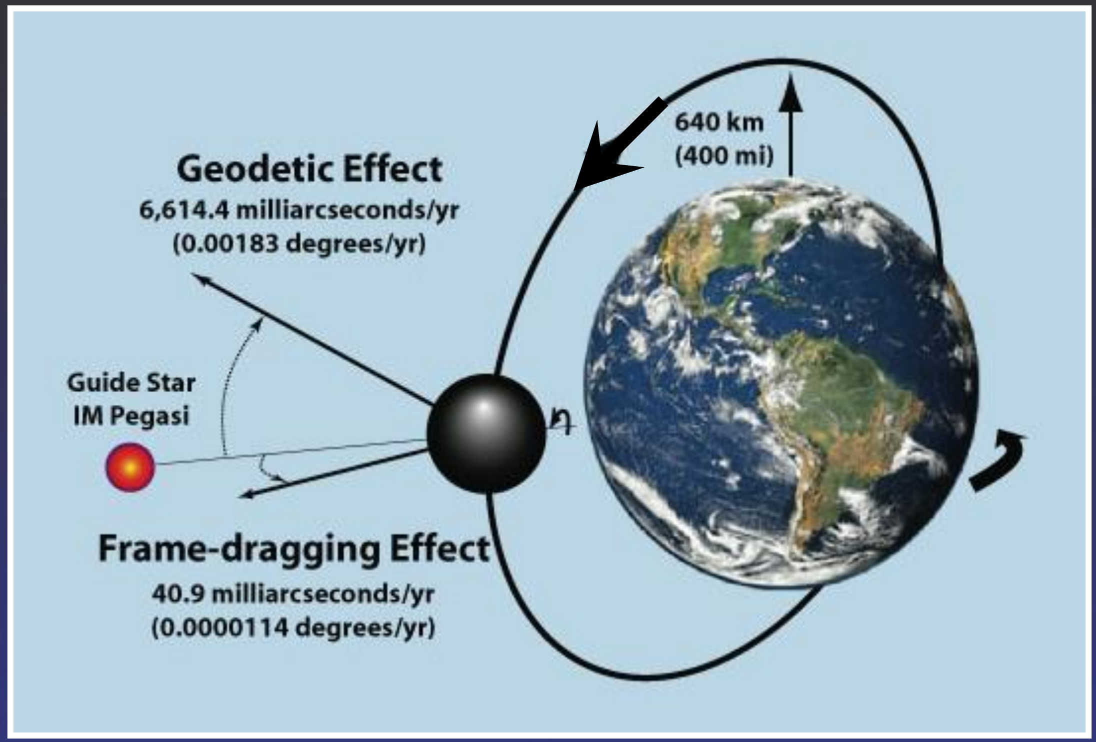
Gravity Probe B

Launched 09:27:54Z April 20, 2004, tech vol published in 2015

Started in 1959



Gravity Probe B Concept



Relativistic precessions:

$$\overline{W}_G = \left(g + \frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\overline{R} \times \overline{v}\right)$$

Geodetic

$$\overline{W}_{FD} = \left(g + 1 + \frac{a_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot\left(\overline{w}_e \cdot \overline{R}\right) - \overline{w}_e\right]$$

Frame Dragging (gravitomagnetic)

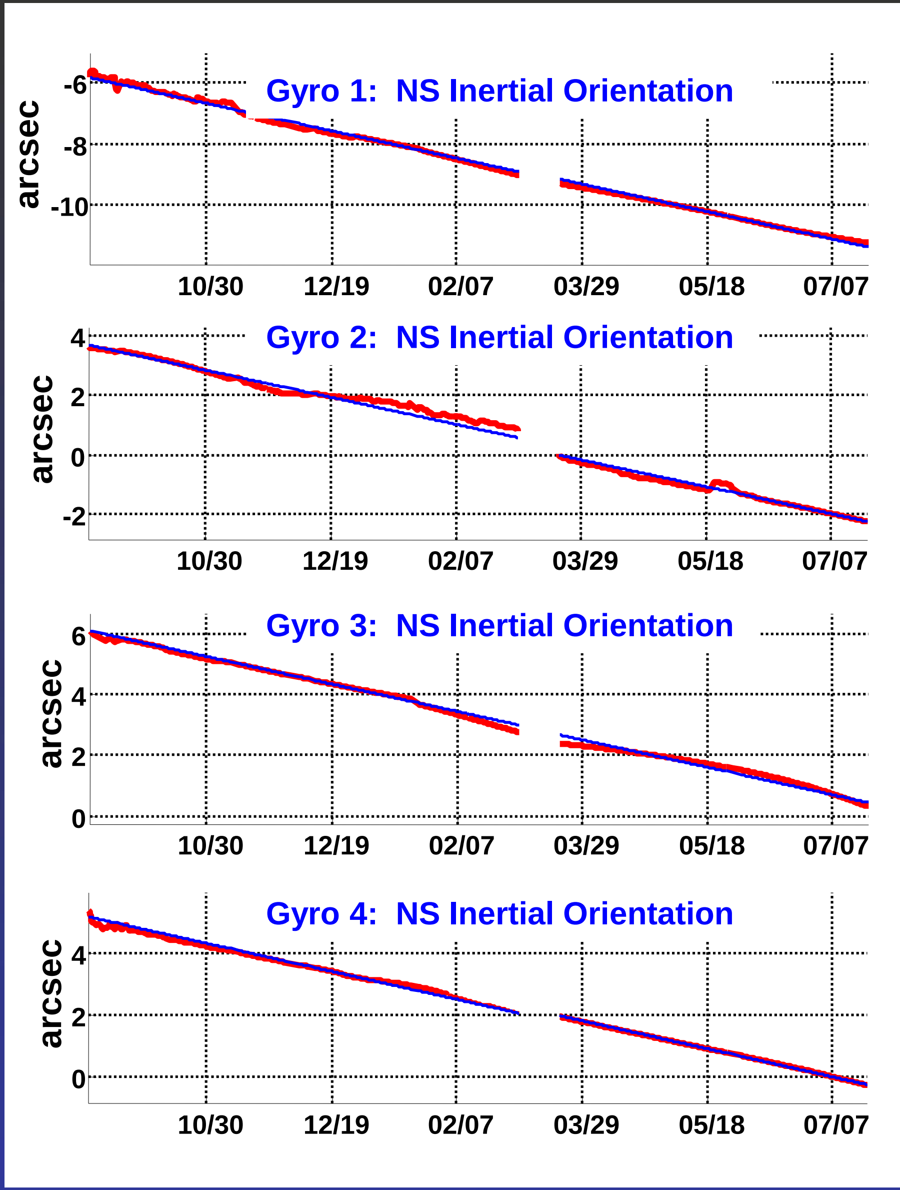
Gravity Probe B Result

Reduced data in NS Inertial Orientation

Two different analysis methods:

- Model with 5 days data in a batch
- Model with Karman filter

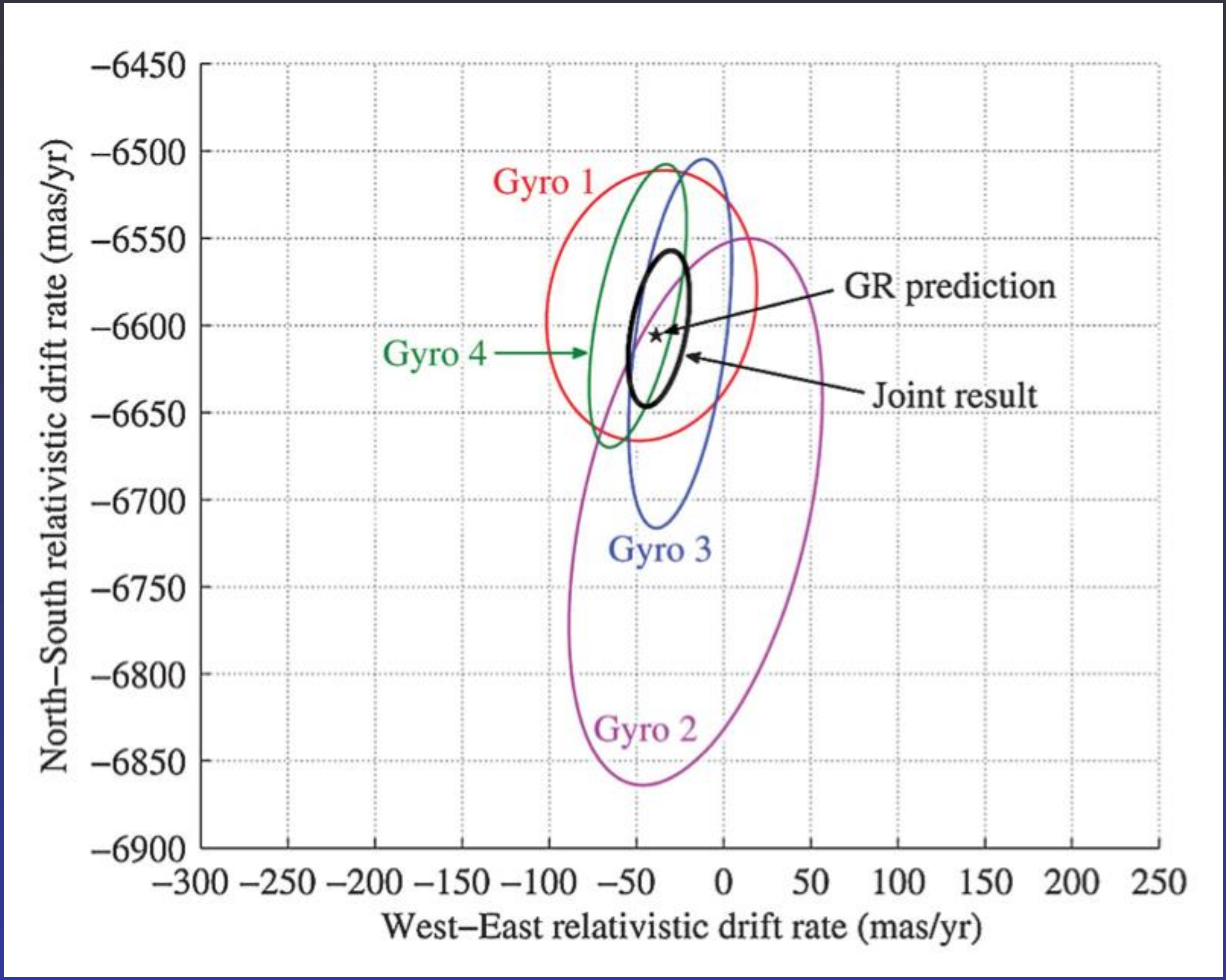
The dominant signal is from geodetic effect!



GR prediction: Earth -6606, solar geodetic +7, proper motion +28 ± 1 net expected -6571 ± 1

Gravity Probe B Result

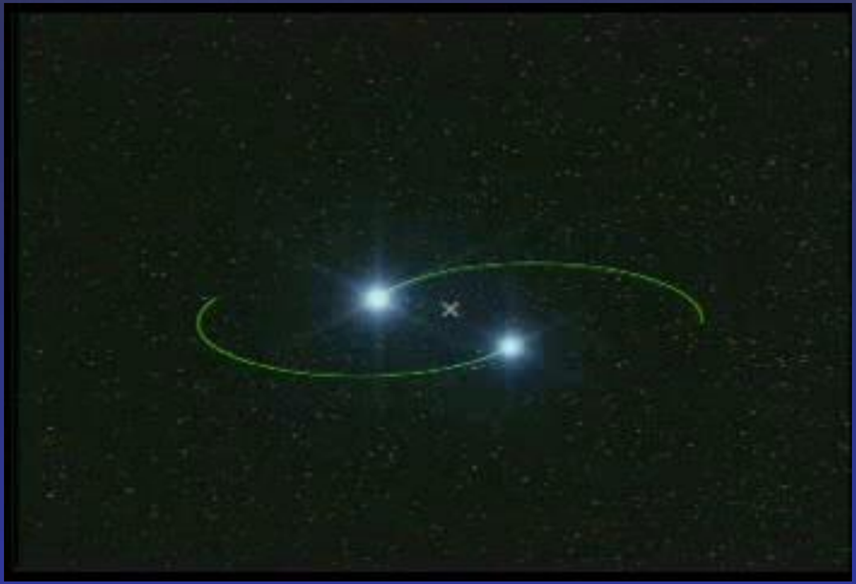
Comprehensive data analysis for all four gyros

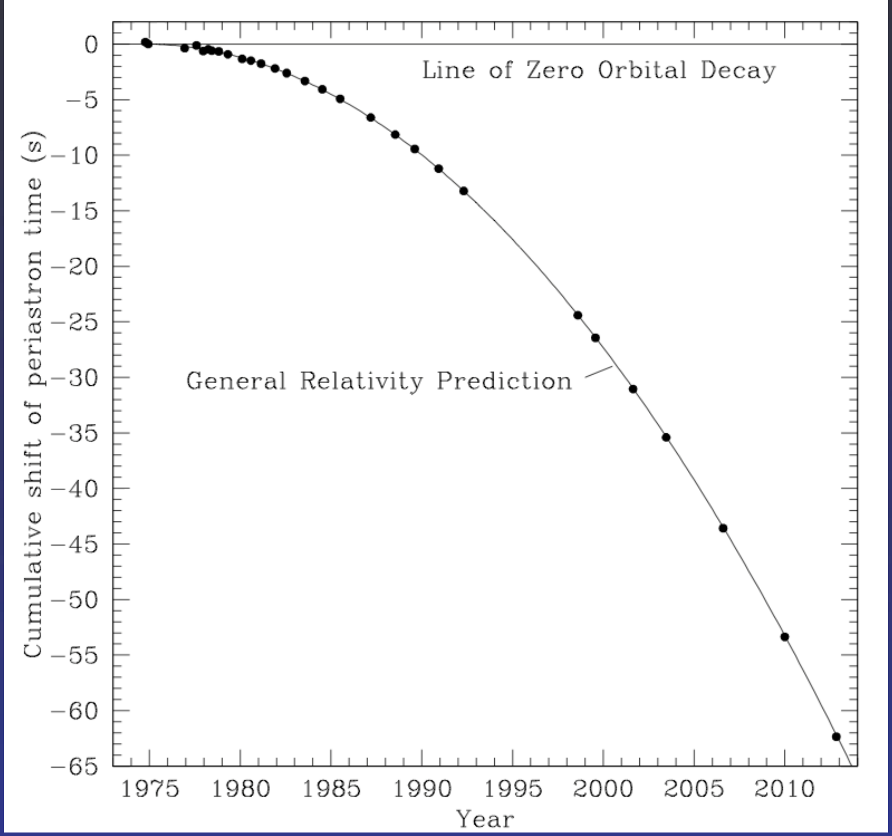


Gravity Waves

Indirect measurement

Hulse and Taylor. Energy loss by the eclipsing binary pulsars. (1993 Nobel Prize)





PSR 1913 + 16

Gravity Waves

Direct measurements

$$h \approx \frac{4G}{c^2}\frac{m_1 m_2}{m_1+m_2}\left(\frac{G\left(m_1+m_2\right)}{c^3}2pf\right)^{2/3}$$

Baton Rouge, Louisiana

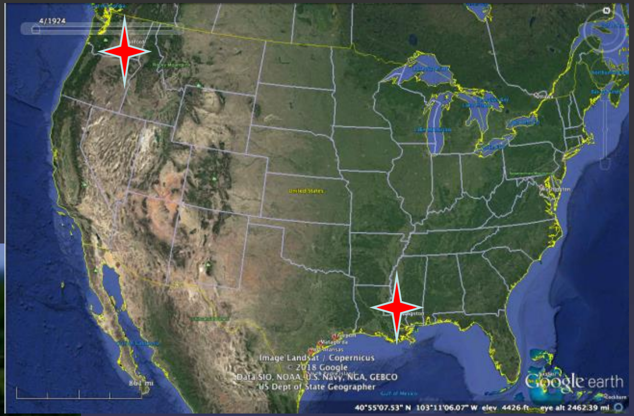
Al bar & sphere antennae

MiniGRAIL, Kamerlingh Onnes Laboratory

Gravity Waves

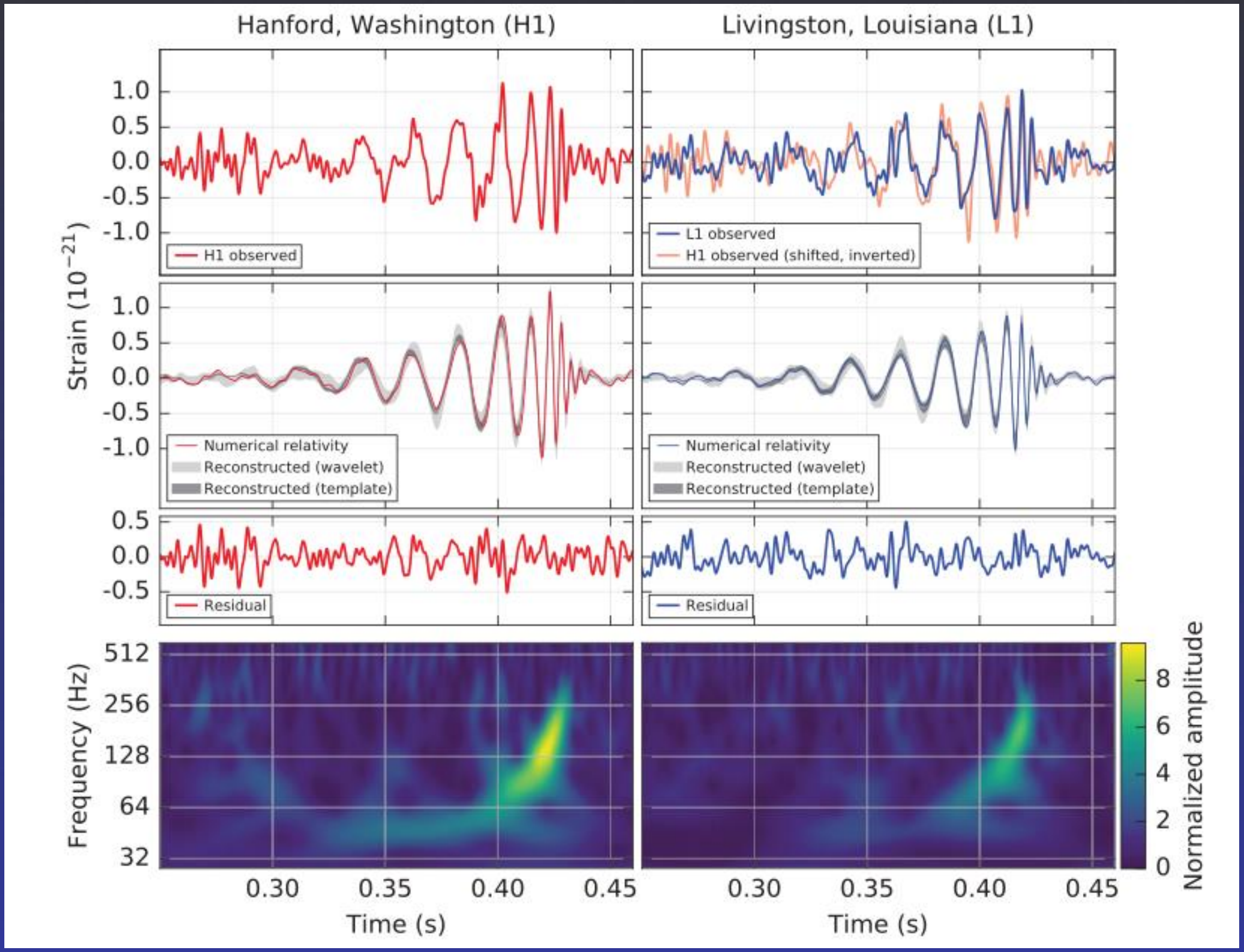
Direct measurements – LIGO/VIRGO

- Initial Concept in 1960's
- Construction in 1990's

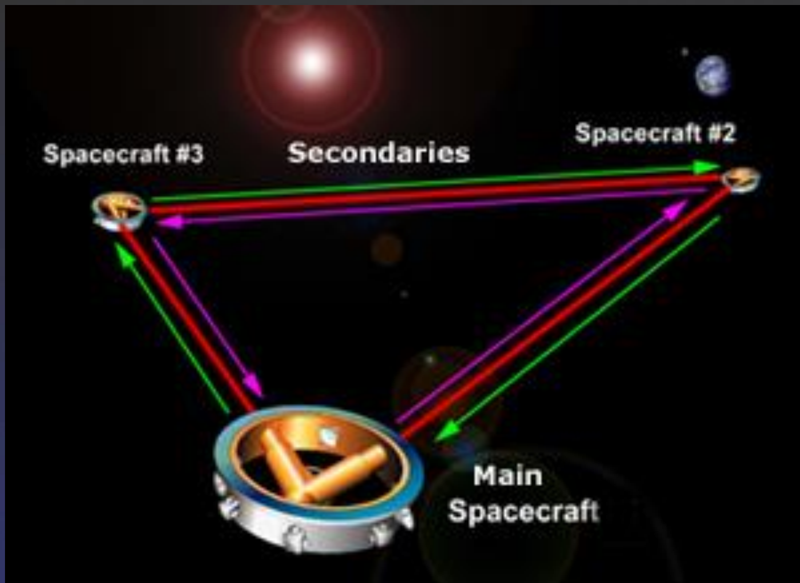


Gravity Waves

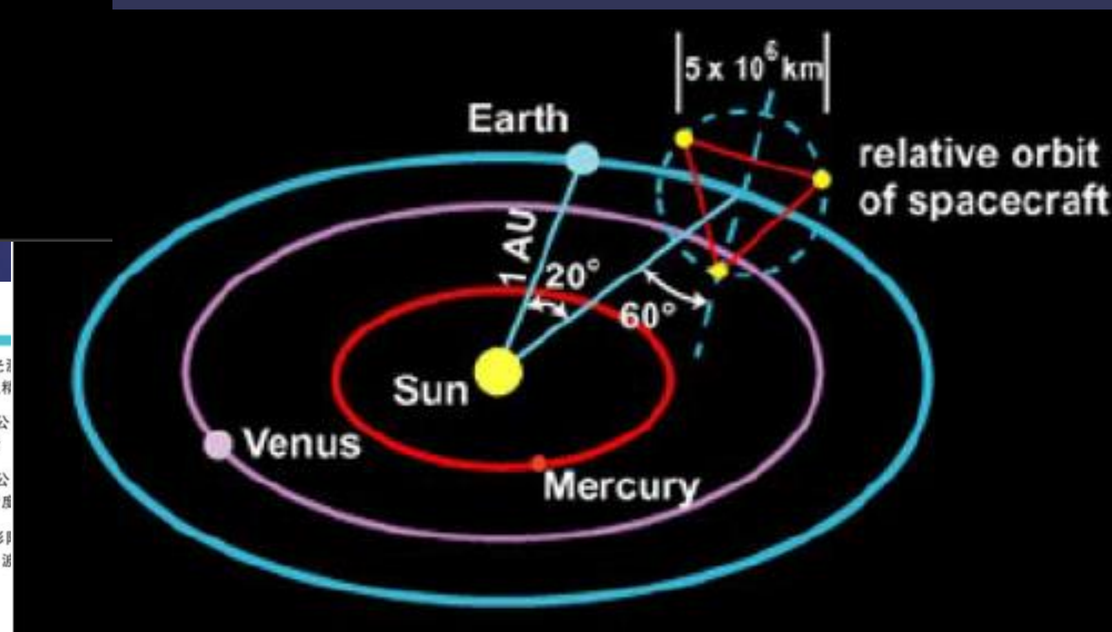
First detection in 2015, Nobel Prize in 2017

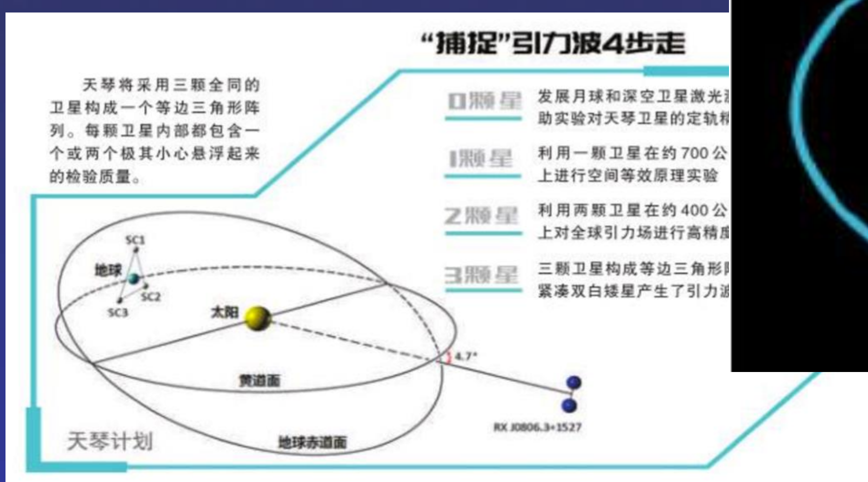


Gravity Waves, Next Step



LISA – ESA/NASA
Taiji – CAS
Tianqin – Zhongshan Univ

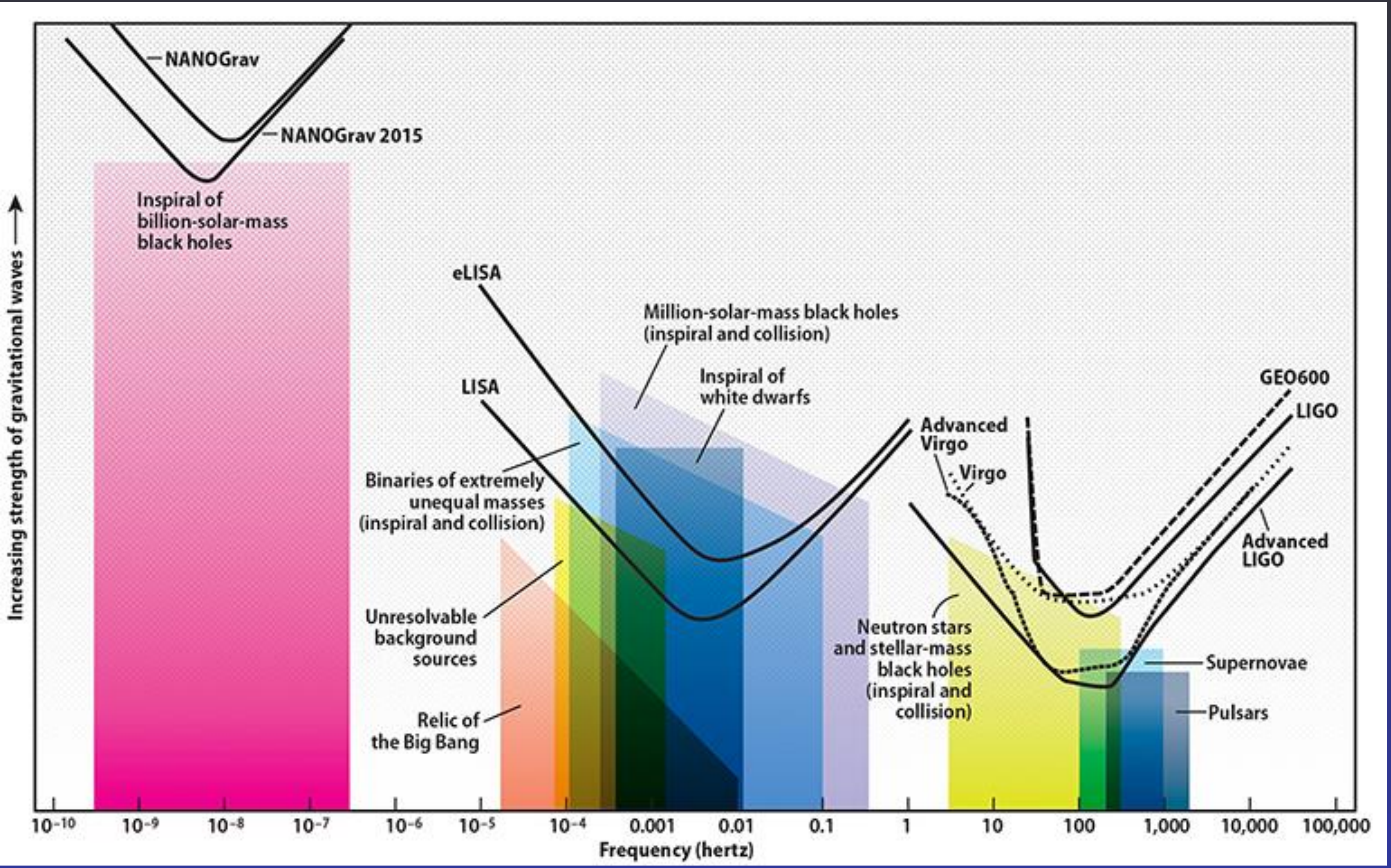




First proposed in early 1990. Estimated launch 2034

Gravity Waves, Next Step

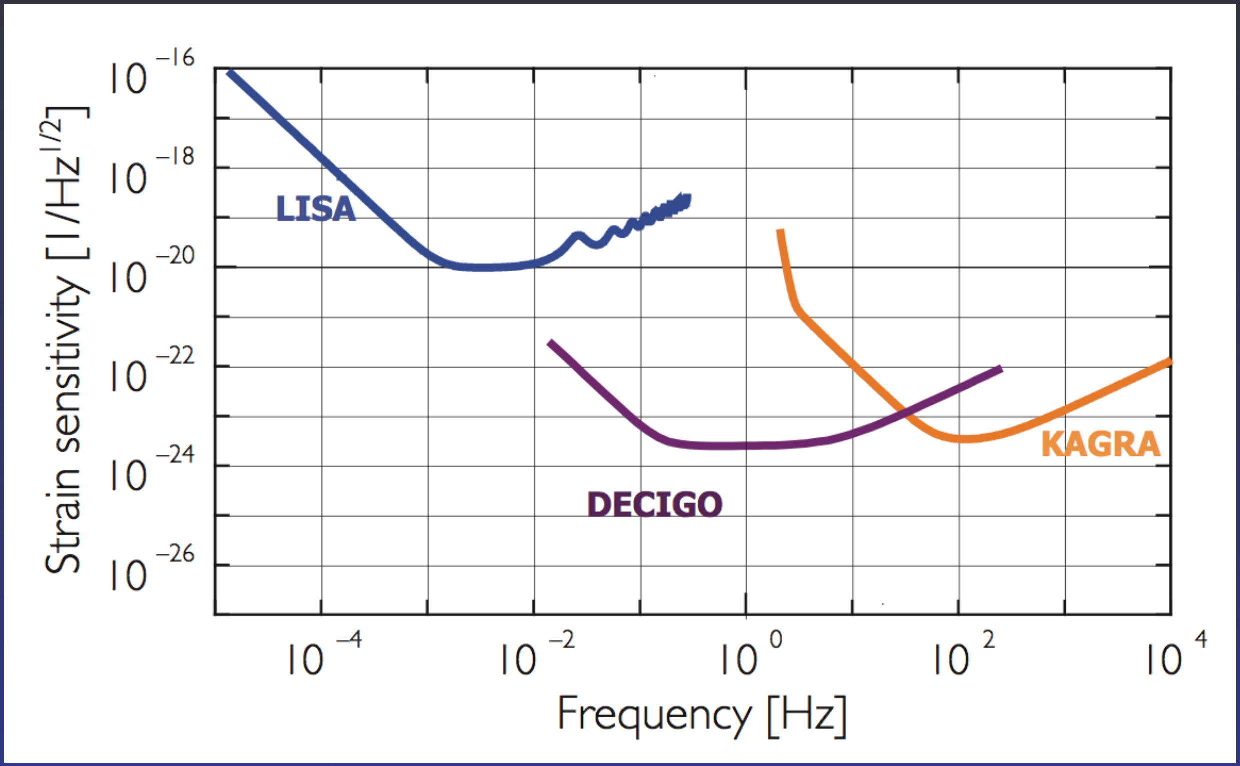
Rational for space based antennas



Gravity Waves, Next Step

DECIGO – Japanese Mission

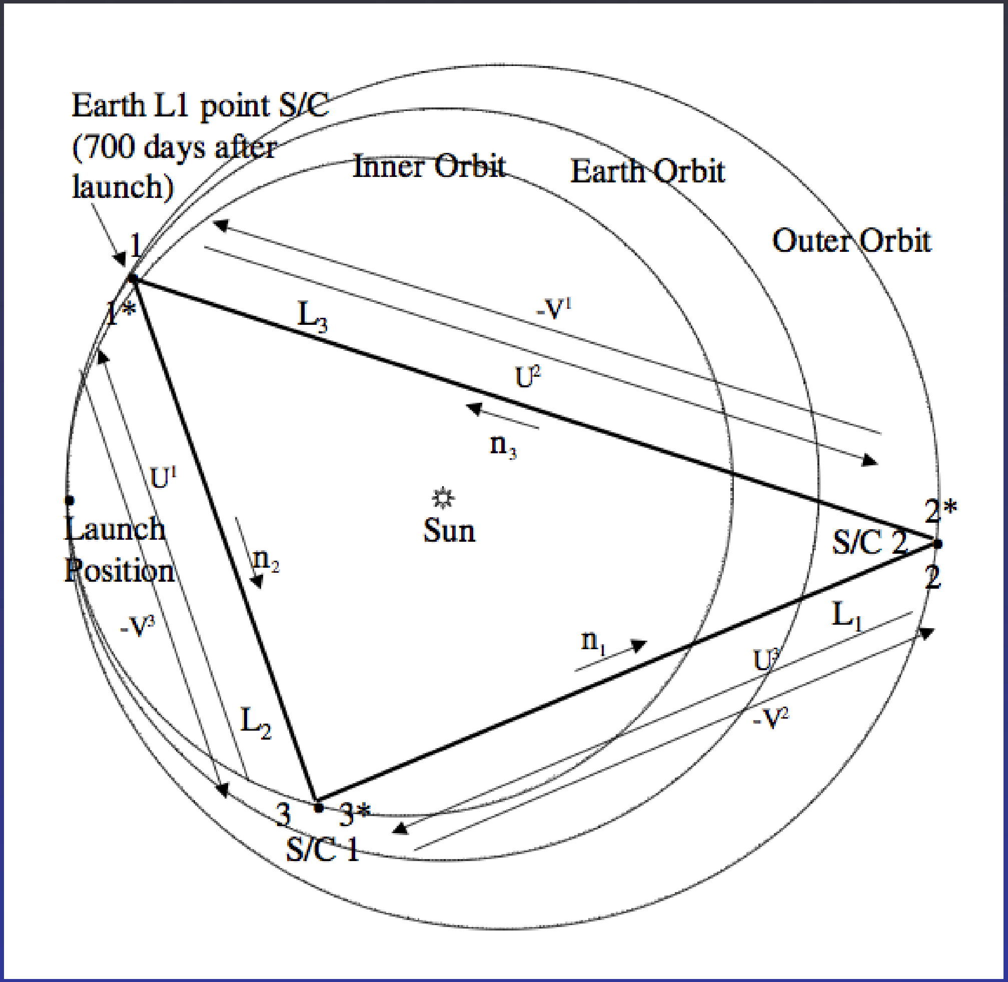
Features:
•Deci-Hz optimal freq band
•1000 km interferometry arm
•Solar orbit
•10 W laser
•Launch in 2030's
•B-DECIGO 2020's
•Precursor detections
•NS-NS GW for universe accl study



Gravity Waves, Next Step

ASTROD – Prof. Ni

Features:
- •Use L1 as one reference point
- •Drag free flight
- •Use 3 spacecraft ranging for gravity mapping around solar orbit
- •Varying solar orbit
- •1-2 W laser
- •Timing accuracy 1 ps
- •Range precision ~ 3µm
- •Inter-spacecraft distance ~ 260 million km
- •Measure GW, Shapiro time delay, etc.

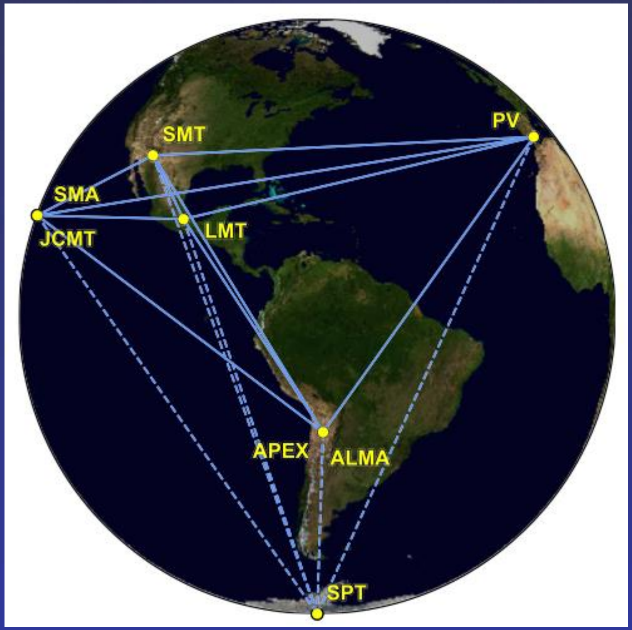


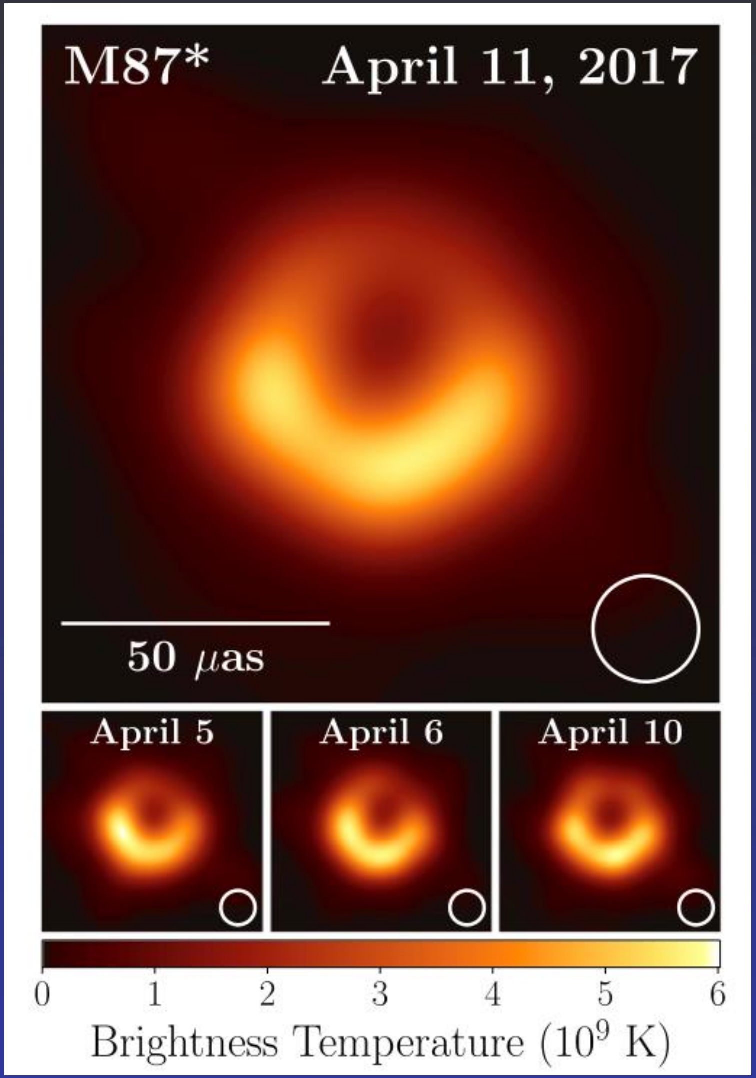
Black hole imaging

Event Horizon Telescope (EHT)

Features:

- VLBI mm wave imaging
- Telescopes in Arizona, Mexico, Chili, South Pole, Spain and Hawaii
- Observe M87 and central blackhole in Milkyway





Testing foundations of relativity

Two basic assumptions of GR:

- Equivalence Principle
- Constancy of speed of light

Testing foundations of relativity

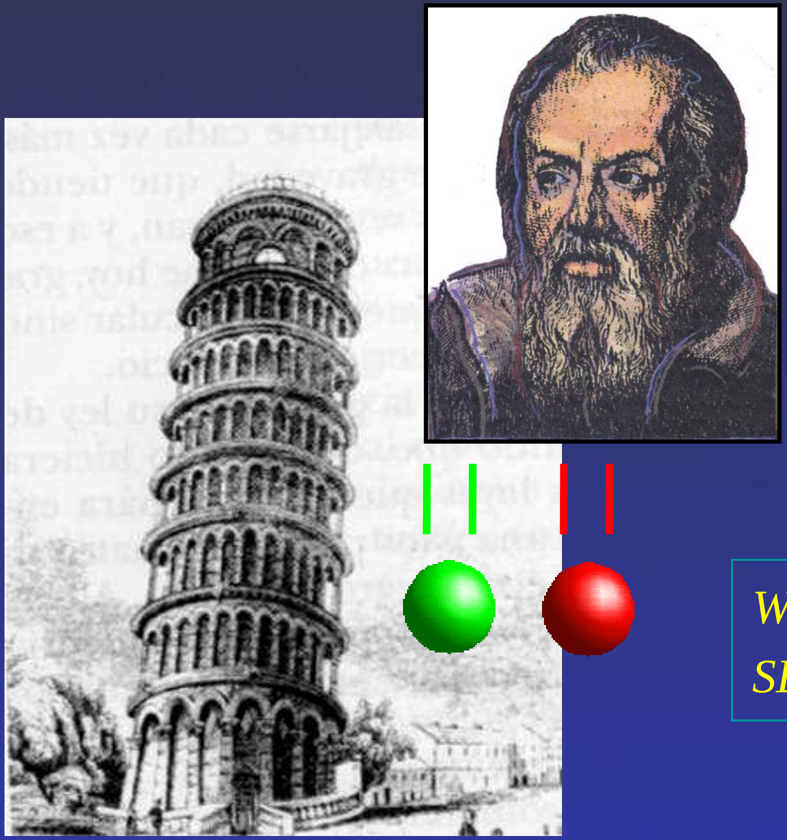
Equivalence Principle Test

$$F_i = m_i a$$

$$F_G = G\frac{m_G M}{r^2}$$

$$m_i \stackrel{?}{=} m_G$$

→ *Equivalence Principle*

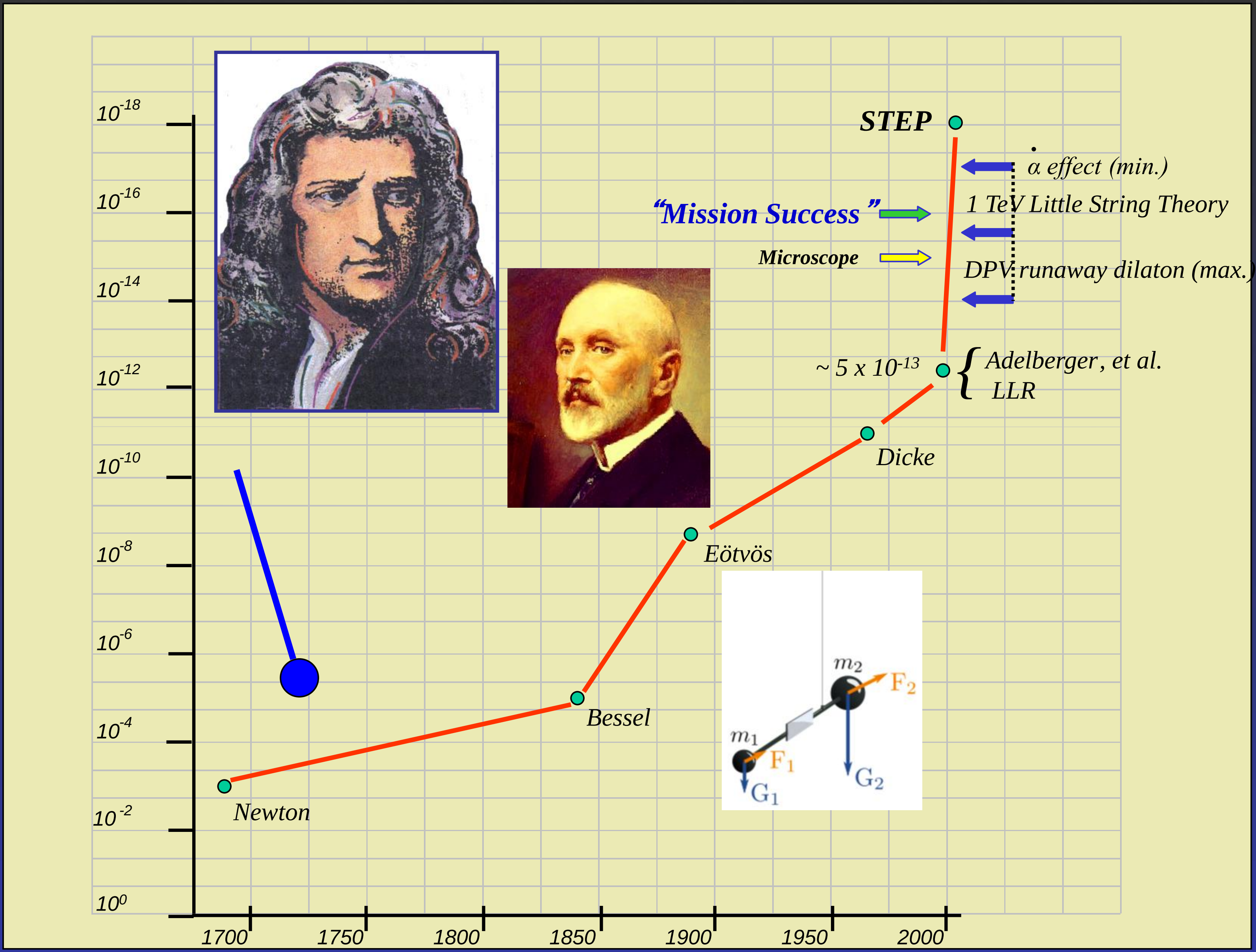


$$\frac{M_G}{M_I} = 1 + SEP + WEP = 1 + \omega\frac{E_G}{mc^2} + \eta$$

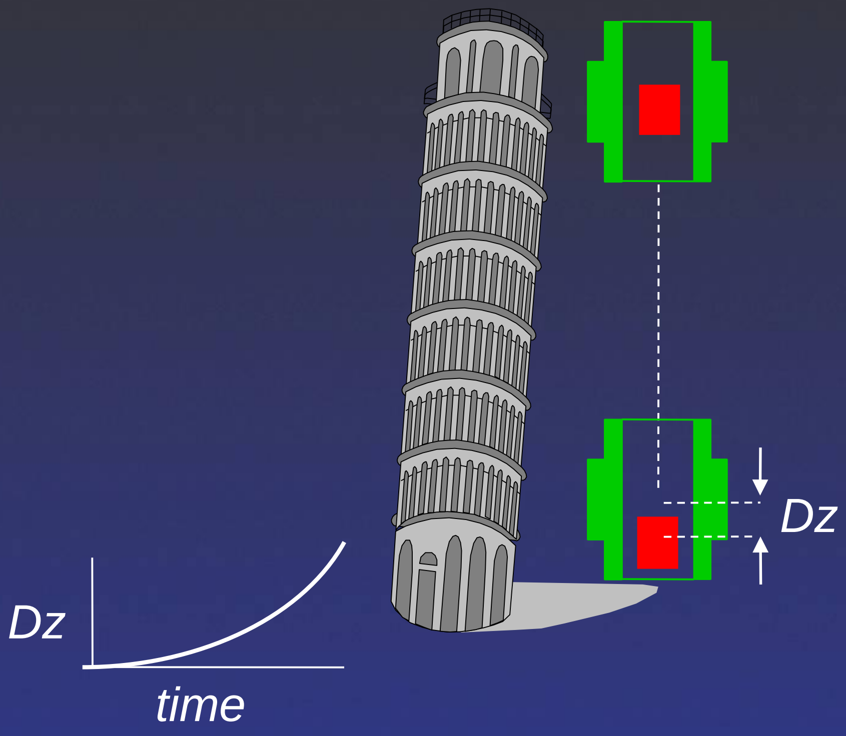
WEP : Effect of matter composition on free fall motion

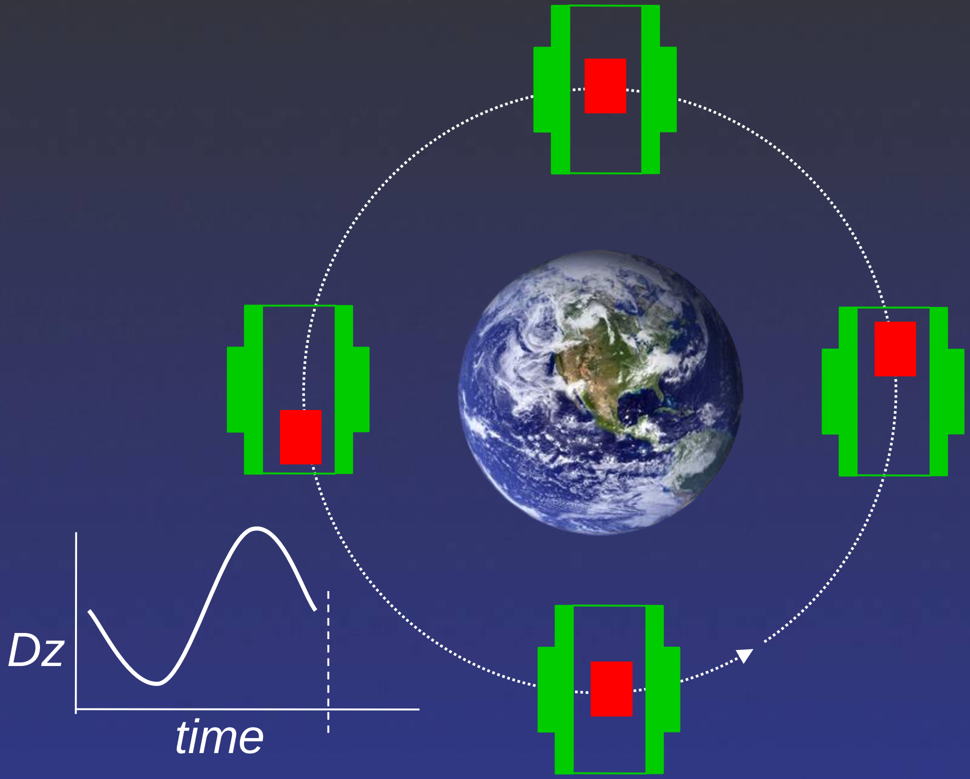
SEP : Coupling between gravity and intern energy

Historical tests of EP



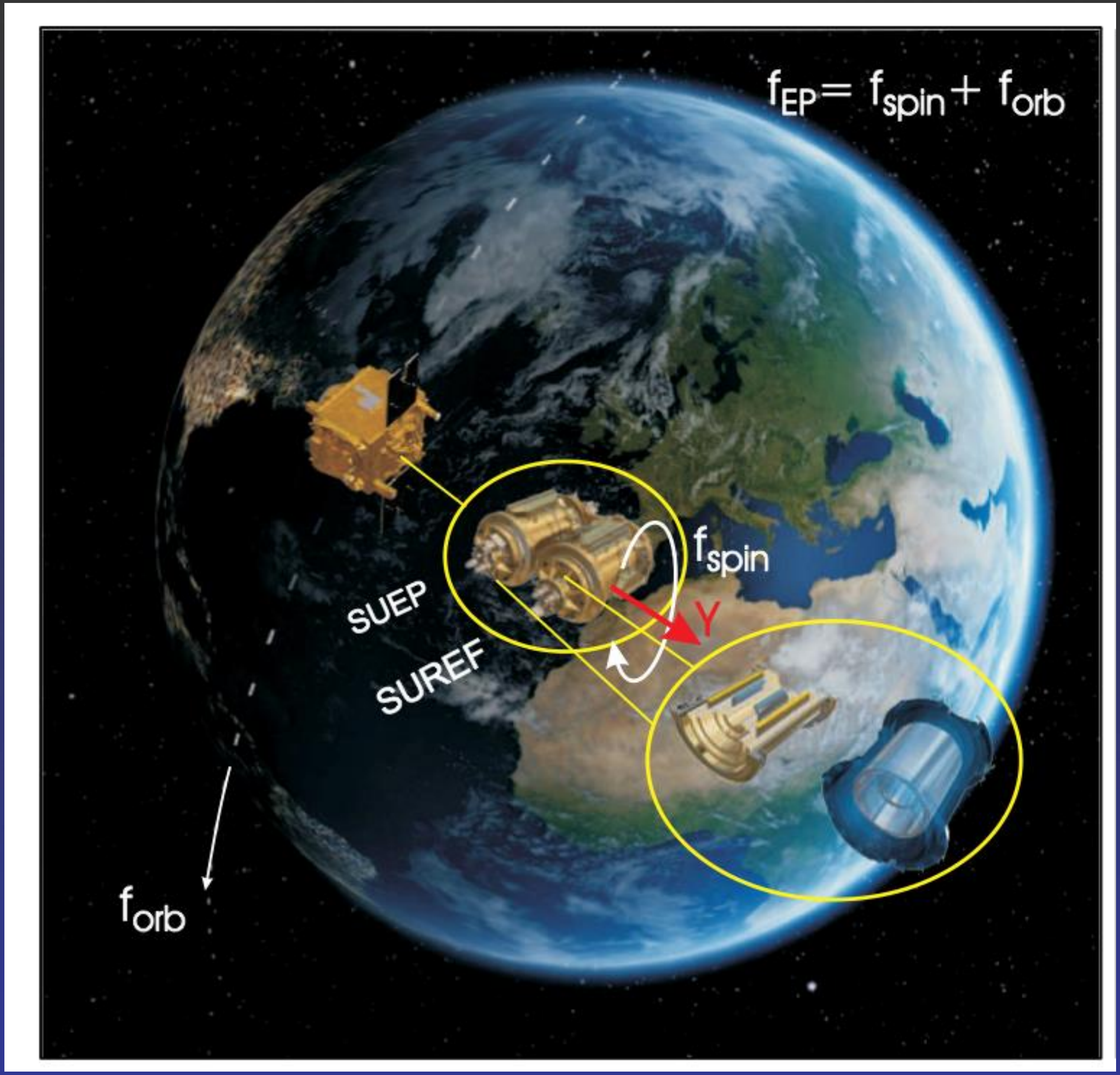
Basic Principle of Space Test





Orbiting drop tower experiment { * *More time for separation to build*
* *Periodic signal*

MICROSCOPE



Features:

- PtRb and TiAl test masses
- Room T readout
- Launched Apr 2016
- Decommissioned Dec 2018
- Results ~ 1 x 10^{-14}

Other EP test methods:

•Atom interferometers: marred by noise forever.
•Projected limit: $10^{-13} – 10^{-15}$
•10m well at Stanford
•300m well for ZAIGA, near Wuhan

Lorentz Invariance Test

Kinematic approach to Lorentz invariance violations:

Assumptions:

- ***Considers only rods, clocks and light beams:***
- ***Assumes a 'preferred' inertial frame in which there are no Lorentz violations***
- ***Considers a moving frame in which violations can occur***

Experiment:

If a laboratory is moving at a velocity v relative to a preferred frame, the speed of light as a function of the angle q relative to the velocity vector is

$$c(\theta)/c = 1 + (1/2 - \beta + \delta)(v/c)^2 \sin^2\theta + (\beta - \alpha - 1)(v/c)^2$$

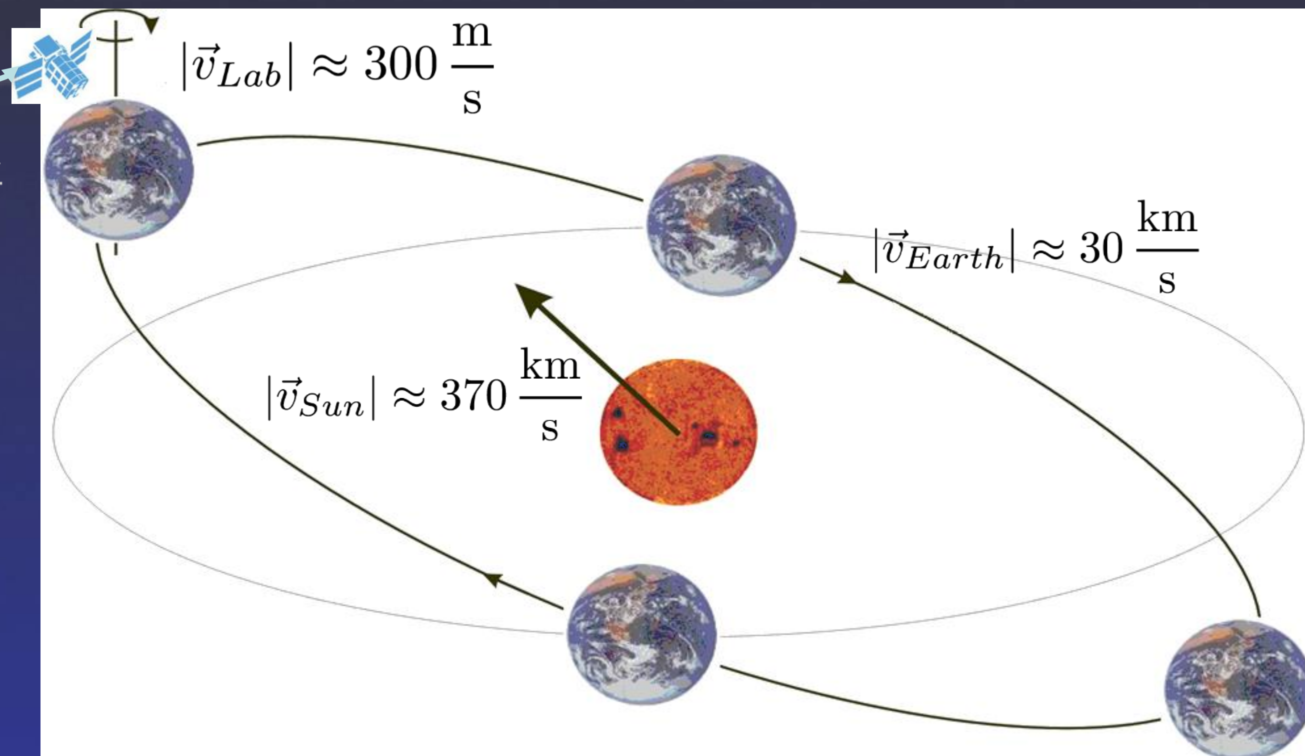
where a is the time dilation parameter, b is the length contraction parameter, and d tests for transverse contraction. (SR: a = -1/2; b = 1/2; d = 0)

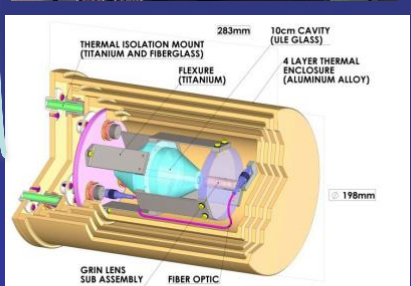
Analysis:

- ***Michelson-Morley : q-dependent term***
- ***Kennedy-Thorndike : q-independent term***

Lorentz Invariance Test

laboratory moving with velocity $\vec{v}$ relative to a preferred rest frame (e.g. CMB)

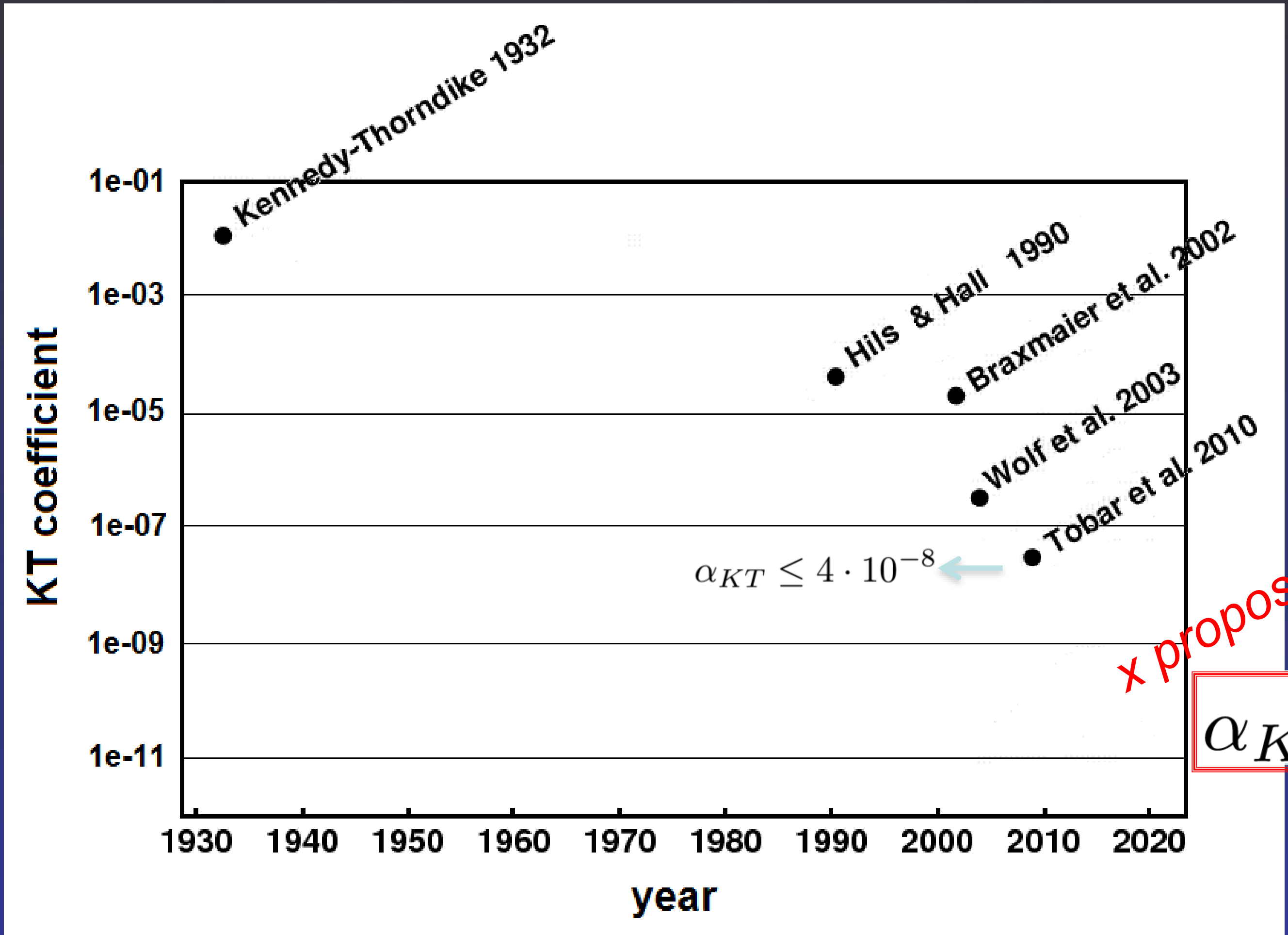




Circular, sun-synchronous orbit: 650 km

Lorentz Invariance Test

Planned accuracy



x proposed

$$\alpha_{KT} = 4 \cdot 10^{-10}$$

Summary

- *GR theory has been successful up to this point (no violations among robust numerical tests)*
- *Field has been active in the last twenty years due to fast technology development, especially in time, position and angle measurements*
- *New physics call for possible violations of EP, one of the fundamental pillars of GR*
- *Tests are still very limited compared to what has been done to E&M and quantum mechanics.*

THANK YOU!!!