EMPIRICAL FOUNDATIONS OF THE RELATIVISTIC GRAVITY

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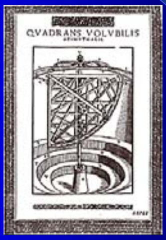
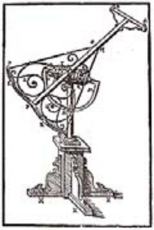
- ***The road map for gravitation is clearly empirical. The current and coming generations are holding such promises.***
- ***As precision is increased by orders of magnitude, we are in a position to explore deeper into the origin of gravitation.***

- In the next 25 years, we envisage a 3-5 order improvement in all directions of tests of relativistic gravity.
- These will give revived interest and development both in experimental and theoretical aspects of gravity, and may lead to answers to some profound questions of gravity and the cosmos.

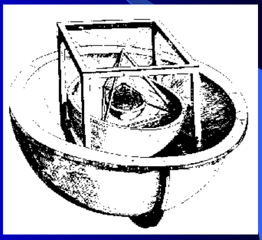
Danish Astronomer Brahe's Observations (1584-1600) (2'-5' accuracy)

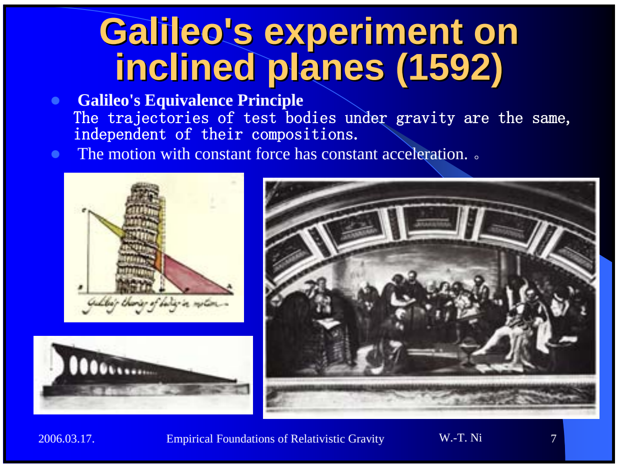
Tycho Brach (1546-1601)





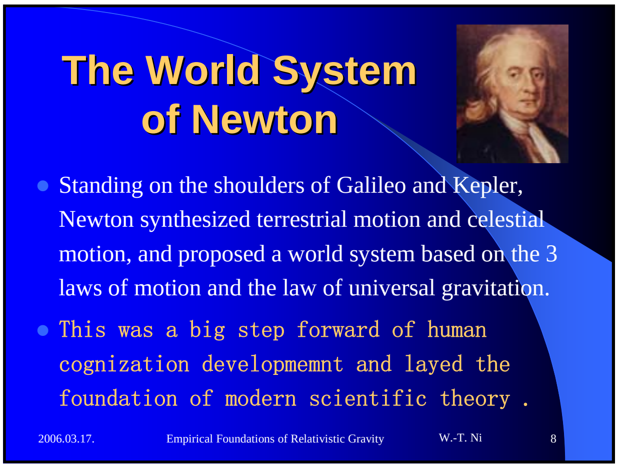
Kepler's Discovery of 3 Laws of Planetary Motion based on Tycho Brahe's Observation





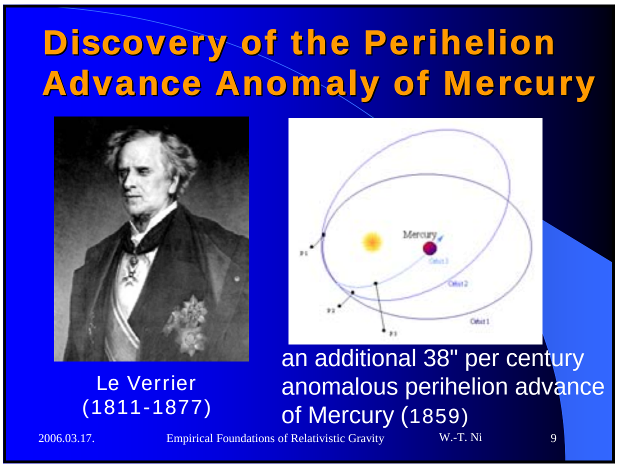
Galileo's experiment on inclined planes (1592)

- **Galileo's Equivalence Principle**
  The trajectories of test bodies under gravity are the same, independent of their compositions.
- The motion with constant force has constant acceleration. 。



The World System of Newton

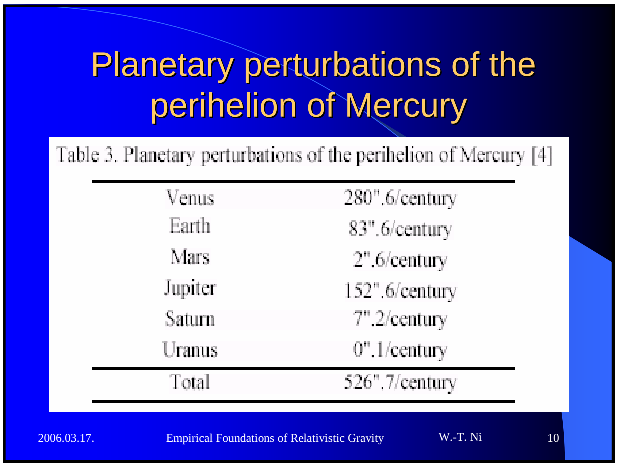
- Standing on the shoulders of Galileo and Kepler, Newton synthesized terrestrial motion and celestial motion, and proposed a world system based on the 3 laws of motion and the law of universal gravitation.
- This was a big step forward of human cognization developmemnt and layed the foundation of modern scientific theory .



Discovery of the Perihelion Advance Anomaly of Mercury

Le Verrier
(1811-1877)

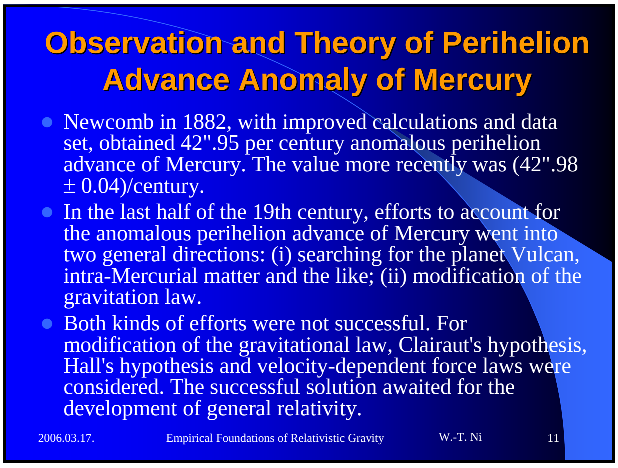
an additional 38" per century anomalous perihelion advance of Mercury (1859)



Planetary perturbations of the perihelion of Mercury

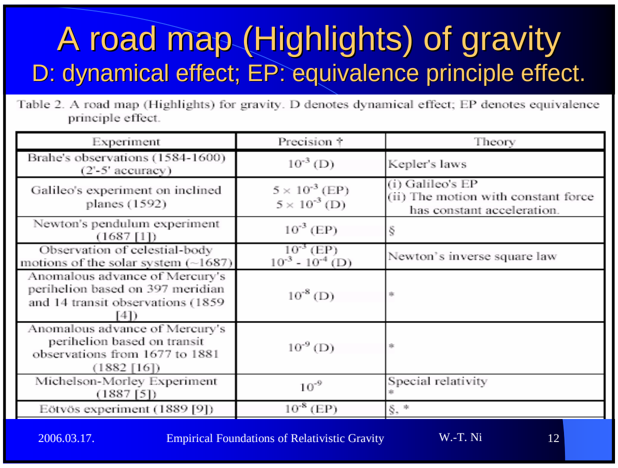
Table 3. Planetary perturbations of the perihelion of Mercury [4]

Venus	280".6/century
Earth	83".6/century
Mars	2".6/century
Jupiter	152".6/century
Saturn	7".2/century
Uranus	0".1/century
Total	526".7/century



Observation and Theory of Perihelion Advance Anomaly of Mercury

- Newcomb in 1882, with improved calculations and data set, obtained 42".95 per century anomalous perihelion advance of Mercury. The value more recently was (42".98 ± 0.04)/century.
- In the last half of the 19th century, efforts to account for the anomalous perihelion advance of Mercury went into two general directions: (i) searching for the planet Vulcan, intra-Mercurial matter and the like; (ii) modification of the gravitation law.
- Both kinds of efforts were not successful. For modification of the gravitational law, Clairaut's hypothesis, Hall's hypothesis and velocity-dependent force laws were considered. The successful solution awaited for the development of general relativity.



A road map (Highlights) of gravity

D: dynamical effect; EP: equivalence principle effect.

Table 2. A road map (Highlights) for gravity. D denotes dynamical effect; EP denotes equivalence principle effect.

Experiment	Precision †	Theory
Brahe's observations (1584-1600) (2'-5' accuracy)	10^{-3} (D)	Kepler's laws
Galileo's experiment on inclined planes (1592)	5×10^{-3} (EP) 5×10^{-3} (D)	(i) Galileo's EP (ii) The motion with constant force has constant acceleration.
Newton's pendulum experiment (1687 [1])	10^{-3} (EP)	§
Observation of celestial-body motions of the solar system (~1687)	10^{-3} (EP) 10^{-3} - 10^{-4} (D)	Newton's inverse square law
Anomalous advance of Mercury's perihelion based on 397 meridian and 14 transit observations (1859 [4])	10^{-8} (D)	*
Anomalous advance of Mercury's perihelion based on transit observations from 1677 to 1881 (1882 [16])	10^{-9} (D)	*
Michelson-Morley Experiment (1887 [5])	10^{-9}	Special relativity *
Eötvös experiment (1889 [9])	10^{-8} (EP)	§, *

The strength of gravity

$$\xi(x, t) = U(x, t) / c^2 = GM / Rc^2$$

Table 1. The strength of gravity for various configurations.

Source	Field Position	Strength of Gravity ξ
Sun	Solar Surface	2.1×10^{-6}
Sun	Mercury Orbit	2.5×10^{-7}
Sun	Earth Orbit	1.0×10^{-8}
Sun	Jupiter Orbit	1.9×10^{-9}
Earth	Earth Surface	0.7×10^{-9}
Earth	Moon's Orbit	1.2×10^{-11}
Galaxy	Solar System	10^{-5} - 10^{-6}
Significant Part of Observed Universe	Our Galaxy	1 - 10^{-2}

The Completion of Special Relativity and Mention of Gravitational Wave

- 1887, Michelson-Morley experiment posed a serious problem to Newtonian mechanics.
- A series of developments [1] led to Poincaré's adding to the five classical principles of Physics the Principle of Relativity [2, 3] in 1904 in World Fair in St. Louis --- "*The laws of physical phenomena must be the same for a fixed observer and for an observer in rectilinear and uniform motion so that we have no possibility of perceiving whether or not we are dragged in such a motion*", and to the seminal works of Poincaré [4] and Einstein [5] to complete Special Relativity in 1905.
- In [3], Poincaré attempted to develop a relativistic theory of gravity and mentioned gravitational-wave propagating with the speed of light based on Lorentz invariance.

The Completion of Special Relativity and Mention of Gravitational Wave：References

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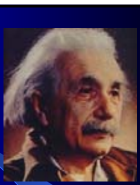
Einstein Equivalence Principle (EEP)



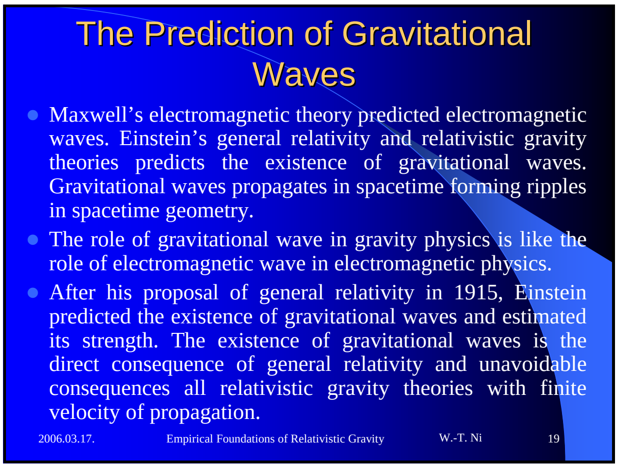
- At any point in spacetime, the local physics is special relativity physics. I.e., in the neighborhood of any point (event), its physics is governed by special relativity.
- EEP could be readily illustrated by Einstein Elevator.
- The Geometrization of Physics

Important Events Leading to Einstein's Proposal of General Relativity in 1915

- The completion of Special Relativity.
- The motivation of using the same theoretical framework to describe electromagnetism and gravitation.
- The elevated accuracy of Eötvös experiment to test the equivalence principle.
- The proposal of Einstein Equivalence Principle.
- The discovery and measurement of the perihelion advance anomaly of Mercury.

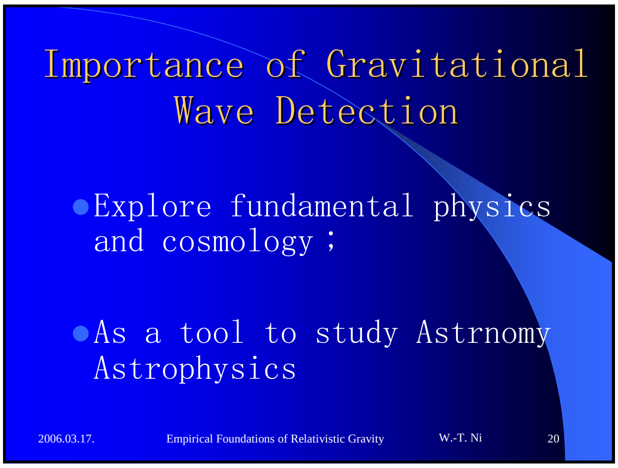
General Relativity

- Started from his proposed EEP, Einstein reached the theory of general relativity in 1915.
- In general relativity, Newton's conception of absolute time and absolute space is not valid, and hence, the main concept is connection and gravitation is 'Tidal Force'.



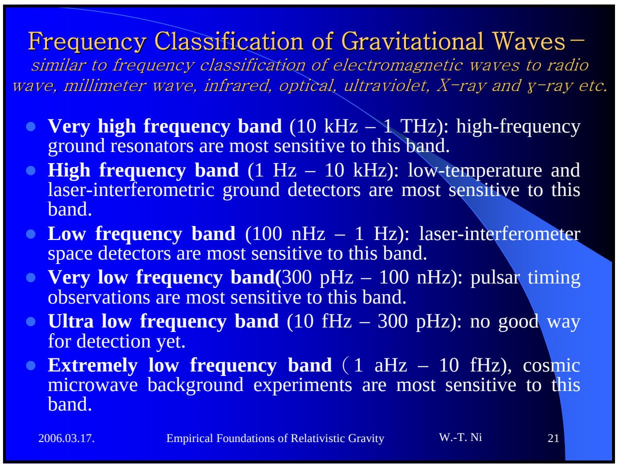
The Prediction of Gravitational Waves

- Maxwell's electromagnetic theory predicted electromagnetic waves. Einstein's general relativity and relativistic gravity theories predicts the existence of gravitational waves. Gravitational waves propagates in spacetime forming ripples in spacetime geometry.
- The role of gravitational wave in gravity physics is like the role of electromagnetic wave in electromagnetic physics.
- After his proposal of general relativity in 1915, Einstein predicted the existence of gravitational waves and estimated its strength. The existence of gravitational waves is the direct consequence of general relativity and unavoidable consequences all relativistic gravity theories with finite velocity of propagation.



Importance of Gravitational Wave Detection

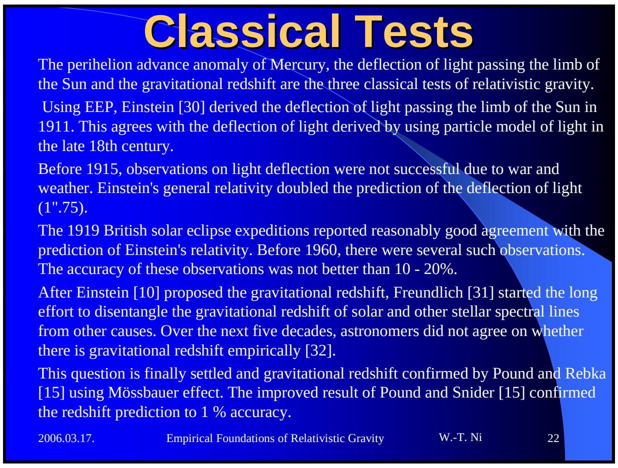
- Explore fundamental physics and cosmology；
- As a tool to study Astrnomy Astrophysics



Frequency Classification of Gravitational Waves –

similar to frequency classification of electromagnetic waves to radio wave, millimeter wave, infrared, optical, ultraviolet, X-ray and γ-ray etc.

- **Very high frequency band** (10 kHz – 1 THz): high-frequency ground resonators are most sensitive to this band.
- **High frequency band** (1 Hz – 10 kHz): low-temperature and laser-interferometric ground detectors are most sensitive to this band.
- **Low frequency band** (100 nHz – 1 Hz): laser-interferometer space detectors are most sensitive to this band.
- **Very low frequency band**(300 pHz – 100 nHz): pulsar timing observations are most sensitive to this band.
- **Ultra low frequency band** (10 fHz – 300 pHz): no good way for detection yet.
- **Extremely low frequency band** (1 aHz – 10 fHz), cosmic microwave background experiments are most sensitive to this band.



Classical Tests

The perihelion advance anomaly of Mercury, the deflection of light passing the limb of the Sun and the gravitational redshift are the three classical tests of relativistic gravity.

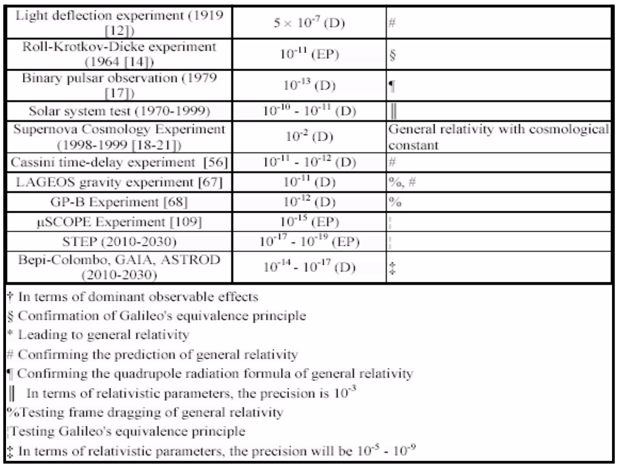
Using EEP, Einstein [30] derived the deflection of light passing the limb of the Sun in 1911. This agrees with the deflection of light derived by using particle model of light in the late 18th century.

Before 1915, observations on light deflection were not successful due to war and weather. Einstein's general relativity doubled the prediction of the deflection of light (1".75).

The 1919 British solar eclipse expeditions reported reasonably good agreement with the prediction of Einstein's relativity. Before 1960, there were several such observations. The accuracy of these observations was not better than 10 - 20%.

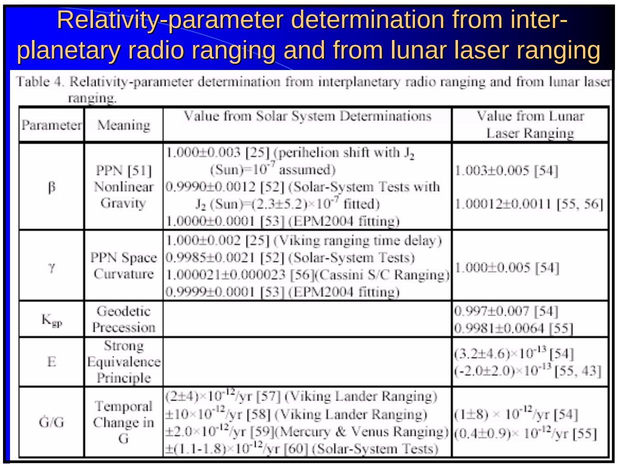
After Einstein [10] proposed the gravitational redshift, Freundlich [31] started the long effort to disentangle the gravitational redshift of solar and other stellar spectral lines from other causes. Over the next five decades, astronomers did not agree on whether there is gravitational redshift empirically [32].

This question is finally settled and gravitational redshift confirmed by Pound and Rebka [15] using Mössbauer effect. The improved result of Pound and Snider [15] confirmed the redshift prediction to 1 % accuracy.



Light deflection experiment (1919 [12])	5×10^{-7} (D)	#
Roll-Krotkov-Dicke experiment (1964 [14])	10^{-11} (EP)	§
Binary pulsar observation (1979 [17])	10^{-13} (D)	¶
Solar system test (1970-1999)	10^{-10} - 10^{-11} (D)	‖
Supernova Cosmology Experiment (1998-1999 [18-21])	10^{-2} (D)	General relativity with cosmological constant
Cassini time-delay experiment [56]	10^{-11} - 10^{-12} (D)	#
LAGEOS gravity experiment [67]	10^{-11} (D)	%, #
GP-B Experiment [68]	10^{-12} (D)	%
μSCOPE Experiment [109]	10^{-15} (EP)	¦
STEP (2010-2030)	10^{-17} - 10^{-19} (EP)	¦
Bepi-Colombo, GAIA, ASTROD (2010-2030)	10^{-14} - 10^{-17} (D)	‡

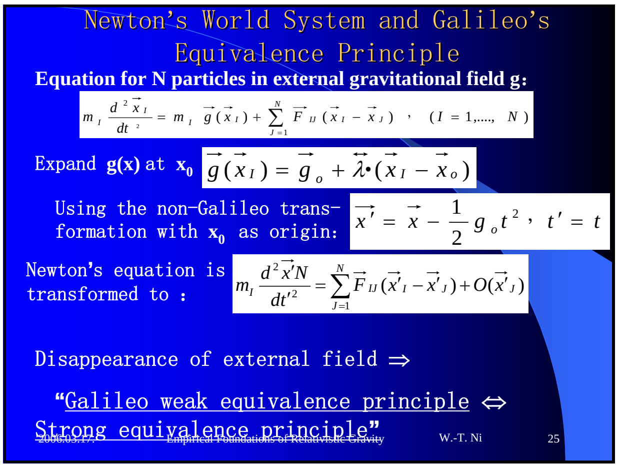
† In terms of dominant observable effects
§ Confirmation of Galileo's equivalence principle
* Leading to general relativity
# Confirming the prediction of general relativity
¶ Confirming the quadrupole radiation formula of general relativity
‖ In terms of relativistic parameters, the precision is 10^{-3}
%Testing frame dragging of general relativity
¦Testing Galileo's equivalence principle
‡ In terms of relativistic parameters, the precision will be 10^{-5} - 10^{-9}



Relativity-parameter determination from inter-planetary radio ranging and from lunar laser ranging

Table 4. Relativity-parameter determination from interplanetary radio ranging and from lunar laser ranging.

Parameter	Meaning	Value from Solar System Determinations	Value from Lunar Laser Ranging
β	PPN [51] Nonlinear Gravity	1.000 ± 0.003 [25] (perihelion shift with J_2 (Sun)$=10^{-7}$ assumed) 0.9990 ± 0.0012 [52] (Solar-System Tests with J_2 (Sun)$=(2.3 \pm 5.2) \times 10^{-7}$ fitted) 1.0000 ± 0.0001 [53] (EPM2004 fitting)	1.003 ± 0.005 [54] 1.00012 ± 0.0011 [55, 56]
γ	PPN Space Curvature	1.000 ± 0.002 [25] (Viking ranging time delay) 0.9985 ± 0.0021 [52] (Solar-System Tests) 1.000021 ± 0.000023 [56](Cassini S/C Ranging) 0.9999 ± 0.0001 [53] (EPM2004 fitting)	1.000 ± 0.005 [54]
K_{gp}	Geodetic Precession		0.997 ± 0.007 [54] 0.9981 ± 0.0064 [55]
E	Strong Equivalence Principle		$(3.2 \pm 4.6) \times 10^{-13}$ [54] $(-2.0 \pm 2.0) \times 10^{-13}$ [55, 43]
$\dot{G}/G$	Temporal Change in G	$(2 \pm 4) \times 10^{-12}$/yr [57] (Viking Lander Ranging) $\pm 10 \times 10^{-12}$/yr [58] (Viking Lander Ranging) $\pm 2.0 \times 10^{-12}$/yr [59](Mercury & Venus Ranging) $\pm(1.1\text{-}1.8) \times 10^{-12}$/yr [60] (Solar-System Tests)	$(1 \pm 8) \times 10^{-12}$/yr [54] $(0.4 \pm 0.9) \times 10^{-12}$/yr [55]



Newton's World System and Galileo's Equivalence Principle

Equation for N particles in external gravitational field g:

$$m_I \frac{d^2 \vec{x}_I}{dt^2} = m_I \vec{g}(\vec{x}_I) + \sum_{J=1}^{N} \vec{F}_{IJ}(\vec{x}_I - \vec{x}_J), \quad (I = 1, \ldots, N)$$

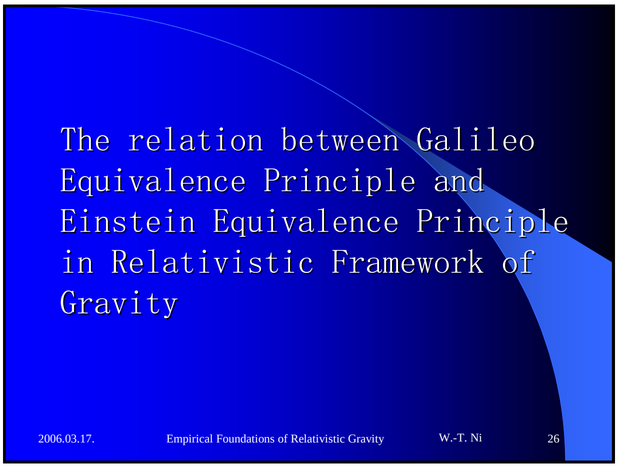
Expand **g(x)** at **x_0** $\vec{g}(\vec{x}_I) = \vec{g}_o + \overleftrightarrow{\lambda} \cdot (\vec{x}_I - \vec{x}_o)$

Using the non-Galileo transformation with **x_0** as origin: $\vec{x}' = \vec{x} - \frac{1}{2} g_o t^2, \quad t' = t$

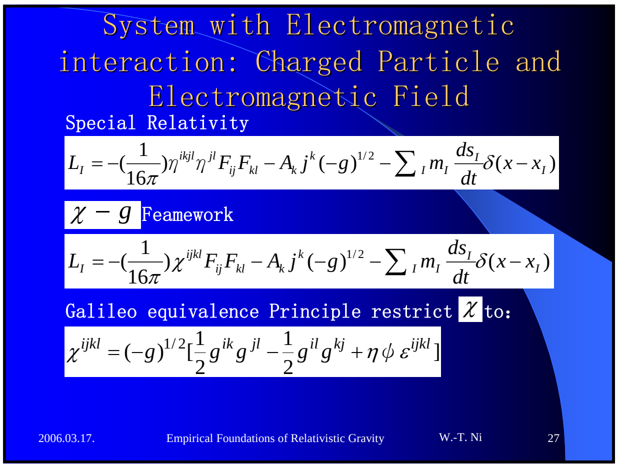
Newton's equation is transformed to : $m_I \frac{d^2 \vec{x}' N}{dt'^2} = \sum_{J=1}^{N} \vec{F}_{IJ}(\vec{x}'_I - \vec{x}'_J) + O(\vec{x}'_J)$

Disappearance of external field ⇒

"Galileo weak equivalence principle ⇔ Strong equivalence principle"



The relation between Galileo Equivalence Principle and Einstein Equivalence Principle in Relativistic Framework of Gravity



System with Electromagnetic interaction: Charged Particle and Electromagnetic Field

Special Relativity

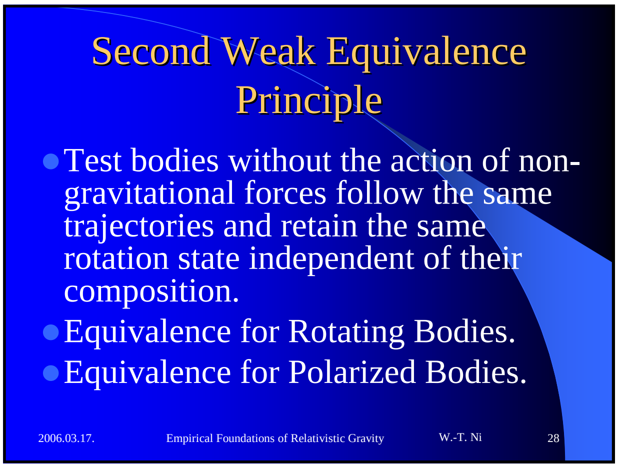
$$L_I = -\left(\frac{1}{16\pi}\right) \eta^{ikjl} \eta^{jl} F_{ij} F_{kl} - A_k j^k (-g)^{1/2} - \sum_I m_I \frac{ds_I}{dt} \delta(x - x_I)$$

$\chi - g$ Feamework

$$L_I = -\left(\frac{1}{16\pi}\right) \chi^{ijkl} F_{ij} F_{kl} - A_k j^k (-g)^{1/2} - \sum_I m_I \frac{ds_I}{dt} \delta(x - x_I)$$

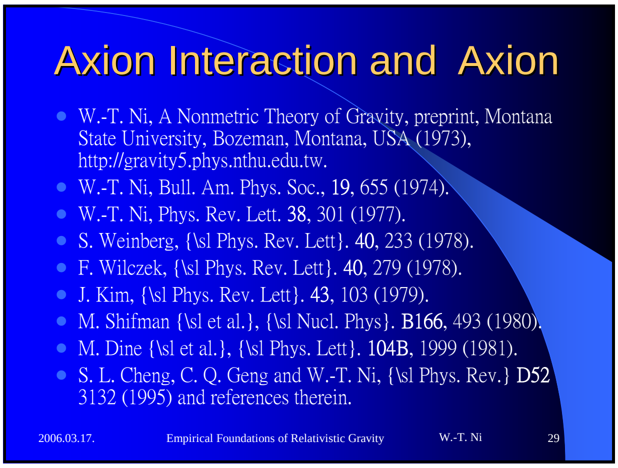
Galileo equivalence Principle restrict χ to:

$$\chi^{ijkl} = (-g)^{1/2} \left[\frac{1}{2} g^{ik} g^{jl} - \frac{1}{2} g^{il} g^{kj} + \eta \phi \, \varepsilon^{ijkl}\right]$$



Second Weak Equivalence Principle

- Test bodies without the action of non-gravitational forces follow the same trajectories and retain the same rotation state independent of their composition.
- Equivalence for Rotating Bodies.
- Equivalence for Polarized Bodies.



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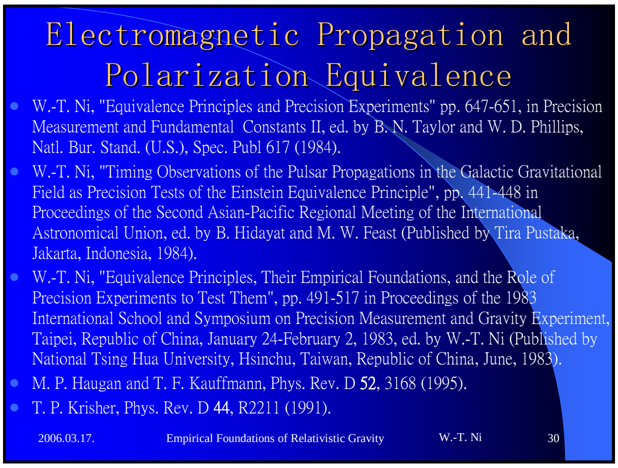

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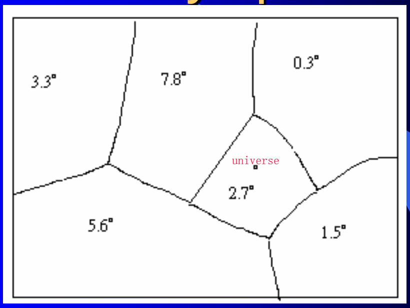
- Accelerated Universe
- The evolution of Cosmological Models
- Inflationary Cosmology
- Vacuum Energy, Dark Energy and Quintessence

Inflationary Spacetime



10^{22} light year(?) The present observed universe is a fractional part of inflationary spacetime

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Spacetime – the last frontier

Scale(trillion)	state	illustration
＞ 10^{33} l. y. (?)	Linde spacetime, landscape	Spacetime with different physical laws & dim.
10^{22} l. y. (?)	Inflationary spacetime	The present observed univ-erse could be a small part of it
10^{9} l. y. (10^{22} km)	Largest cluster s.	Great Walls, Great Attractors
10^{10} km	Interplanary world	Solar system
10 m	Ordinary world	House, trees, human
10^{-9} cm	Atomic world	atoms
10^{-21} cm	Deep in physical vacuum	Vacuum in standard model, full of virtual part's
10^{-33} cm	Spacetime quantum structrure	Twistors、gravitons, super-strings, foams

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Cosmology and Electromagnetic Polarization

- Cosmology is becoming a precision science
- DASY and WMAP have detected the polarization and the polarization-temperature correlation of CMR, and hence could probe the axion interaction to the cosmological propagation of the electromagnetic waves. PLANCK SURVEYOR will have much better precision.

CMB Polarization Observation

- In 2002, DASY microwave interferometer observed the polarization of the cosmic background.
- With the axial interaction (2), the polarization anisotropy is shifted relative to the temperature anisotropy.
- In 2003, WMAP found that the polarization and temperature are correlated. This gives a constraint of 10^{-1} of $\Delta\varphi$.
- Planck Surveyor will be launched in 2007 with better polarization-temperature measurement and will give a sensitivity to $\Delta\varphi$ of 10^{-2}-10^{-3}.

Limits on No Birefringence

- In weak field, the no-birefringence (no polarization-dependent delay toin astrophysical propagation gives 10 constraints χ^{ijkl}.
- With this 10 conditions， χ^{ijkl} can be written as：

$\chi^{ijkl} = (-H)^{1/2}[(1/2)H^{ik}H^{jl} - (1/2)H^{il}H^{kj}]\ \psi + \phi e^{ijkl}$, (4)

where $H = \det(H^{ij})$， e^{ijkl} *is the completely antisymmetric symbol* ($e^{0123}=1$) .

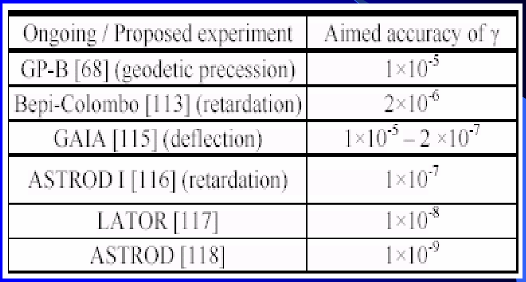
Recently， Lämmerzahl and Hehl proved this statement in strong field too.

Limits on No Birefringence

- From pulsar timing observation and radio galaxy polarization observation, the above formula has been observed to high precision.
- Haugan and Kauffmann [75] used the polarization observation data of extra-galactic radio sources to infer that no gravitational birefringence is observed to a high precision, for 5 GHz signal, the limit is 0.02 cycle. This gives a time resolution of 4×10^{-12} s. More detailed analysis would give（4）to 10^{-28}-10^{-29} in cosmological distance.
- In 2002, Kostelecky and Mews [76] used polarization measurements of light from cosmologically distant astrophysical sources to yield stringent constraints down to 2×10^{-32}.

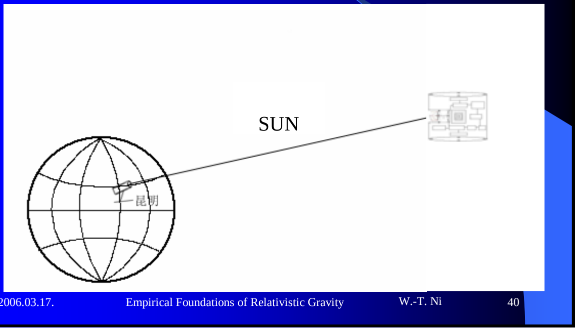
Aimed accuracy of PPN space parameter γ for various ongoing / proposed experiments.

The types of experiments are given inthe parentheses.



Ongoing / Proposed experiment	Aimed accuracy of γ
GP-B [68] (geodetic precession)	1×10^{-5}
Bepi-Colombo [113] (retardation)	2×10^{-6}
GAIA [115] (deflection)	$1\times10^{-5} - 2\times10^{-7}$
ASTROD I [116] (retardation)	1×10^{-7}
LATOR [117]	1×10^{-8}
ASTROD [118]	1×10^{-9}

ASTROD I: Two-Way Interferometric and Pulse Laser Ranging between Spacecraft and Ground Laser Station



OBJECTIVE

ASTROD I

- Testing relativistic gravity and the fundamental laws of spacetime with three-order-of-magnitude improvment in sensitivity;
- Initiating the revolution of astrodynamics with laser ranging in the solar system, increasing the sensitivity of solar, planetary and asteroid parameter determination by 1-3 orders of magnitude;
- Improving the sensitivity in the 5 μHz - 5 mHz low frequency gravitational-wave detection by several times (Auxiliary goal).

Orbit Simulation Assumptions

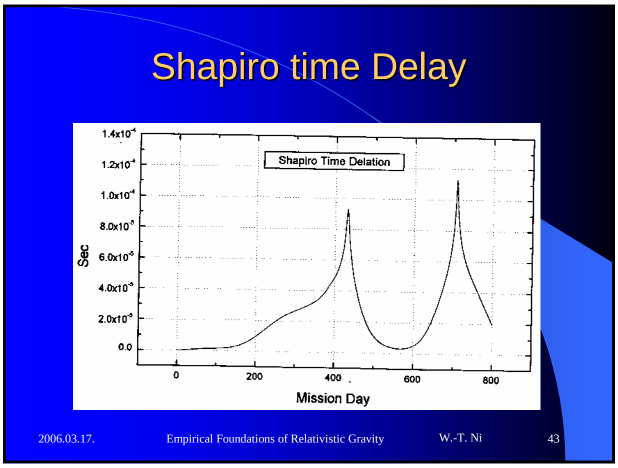
- (1) The uncertainty due to the imprecision of the ranging devices:

  10 ps one way (Gaussian)

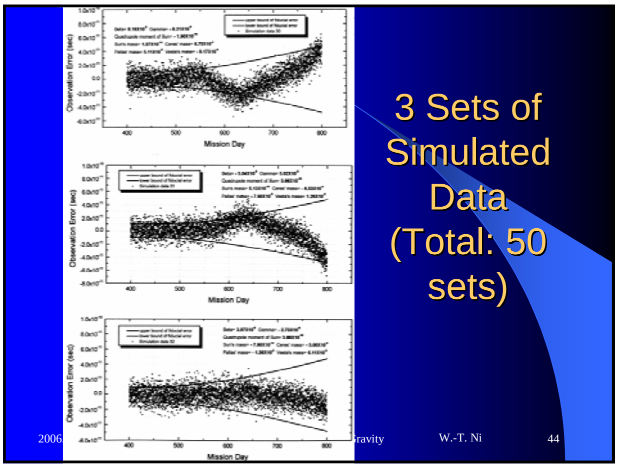
- (2) Unknown acceleration due to the imperfections of the spacecraft drag-free system:

  10^{-15}m/s^2 & change direction randomly every 4 hr (~10^4s)

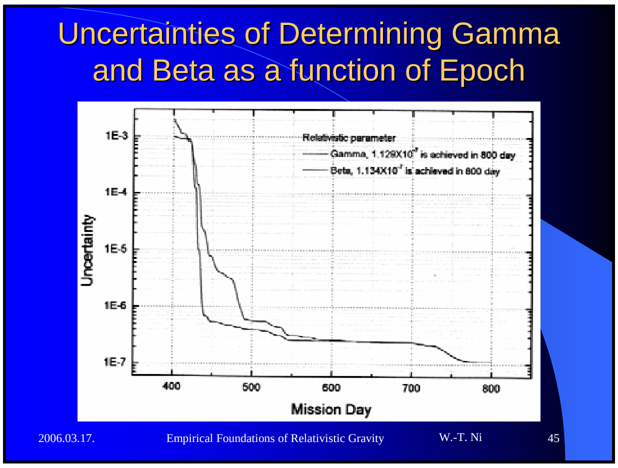
  [This is equivalent to $(10^{-15}\text{m/s}^2) \times (10^4\text{s})^{1/2} = 10^{-13}\text{m/s}^2(\text{Hz})^{1/2}$ at 10^{-4}Hz]



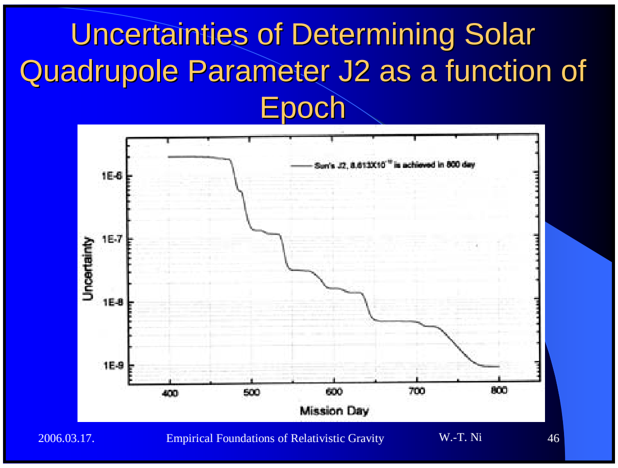
Shapiro time Delay



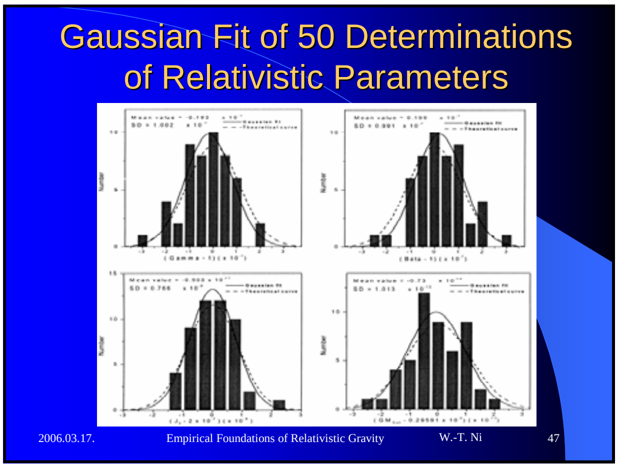
3 Sets of Simulated Data (Total: 50 sets)



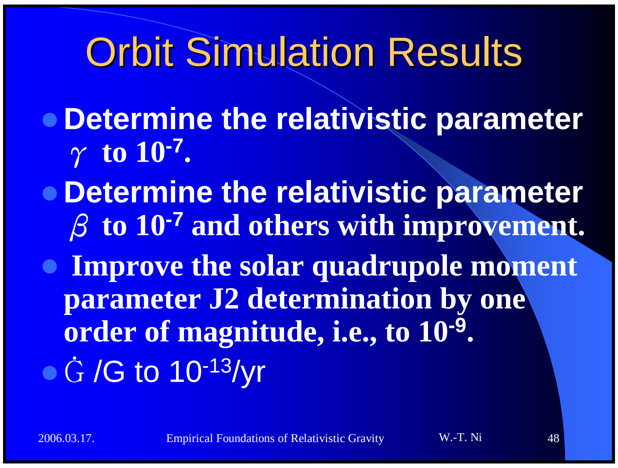
Uncertainties of Determining Gamma and Beta as a function of Epoch



Uncertainties of Determining Solar Quadrupole Parameter J2 as a function of Epoch

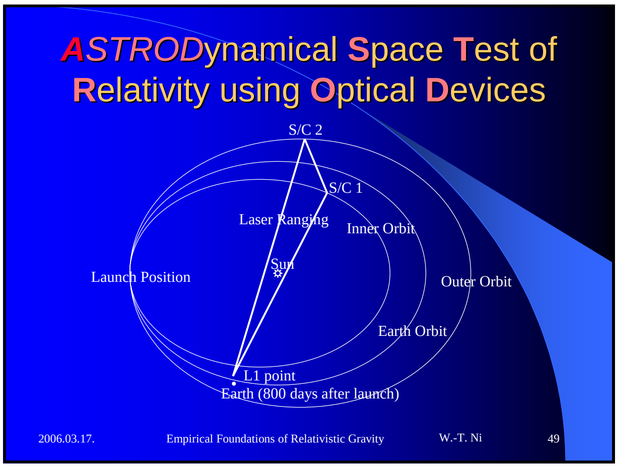


Gaussian Fit of 50 Determinations of Relativistic Parameters

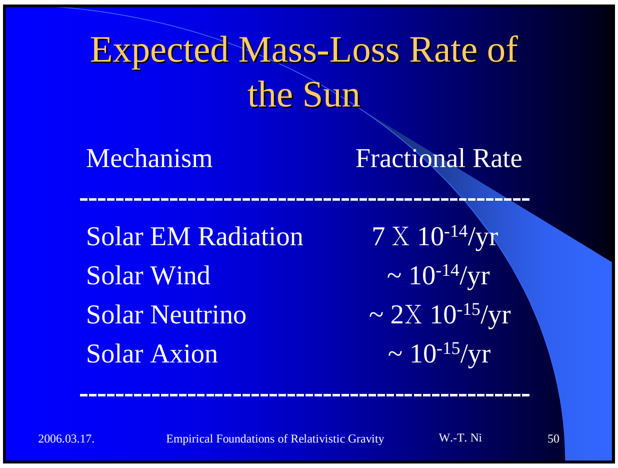


Orbit Simulation Results

- **Determine the relativistic parameter γ to 10^{-7}.**
- **Determine the relativistic parameter β to 10^{-7} and others with improvement.**
- **Improve the solar quadrupole moment parameter J2 determination by one order of magnitude, i.e., to 10^{-9}.**
- $\dot{G}/G$ to 10^{-13}/yr

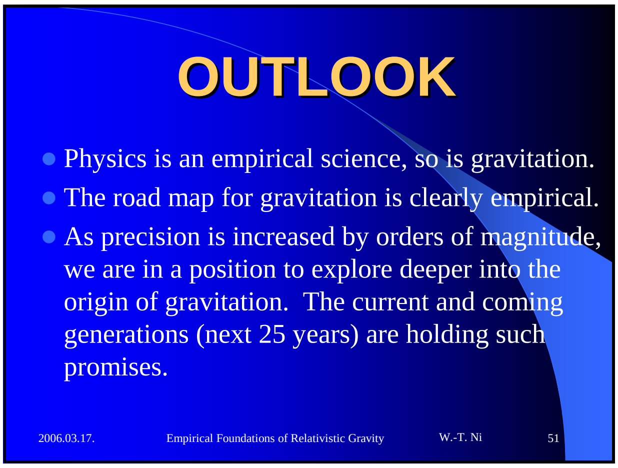


ASTRODynamical Space Test of Relativity using Optical Devices



Expected Mass-Loss Rate of the Sun

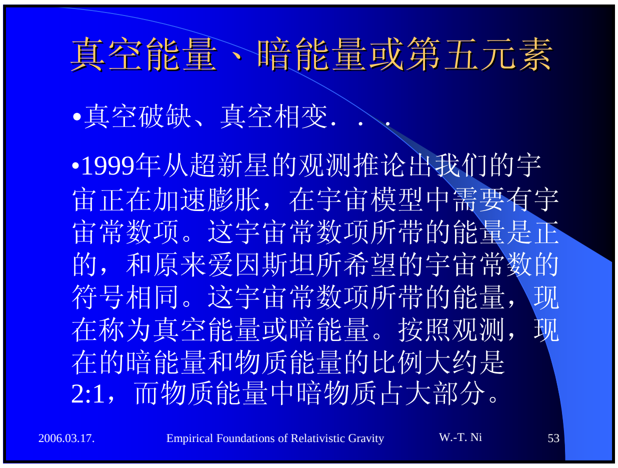
Mechanism	Fractional Rate
Solar EM Radiation	7 X 10^{-14}/yr
Solar Wind	~ 10^{-14}/yr
Solar Neutrino	~ 2X 10^{-15}/yr
Solar Axion	~ 10^{-15}/yr



OUTLOOK

- Physics is an empirical science, so is gravitation.
- The road map for gravitation is clearly empirical.
- As precision is increased by orders of magnitude, we are in a position to explore deeper into the origin of gravitation. The current and coming generations (next 25 years) are holding such promises.

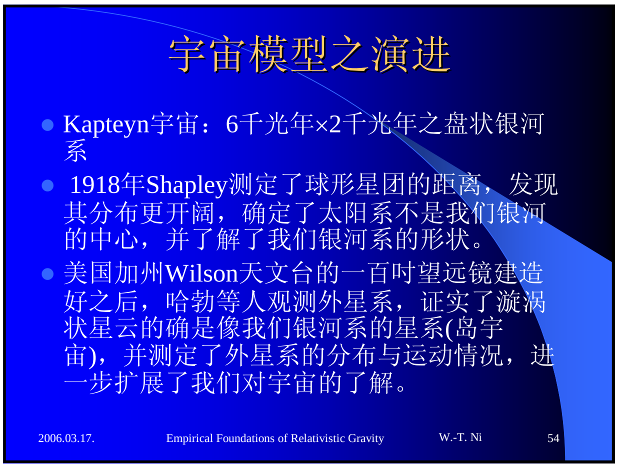
Thank You!



真空能量、暗能量或第五元素

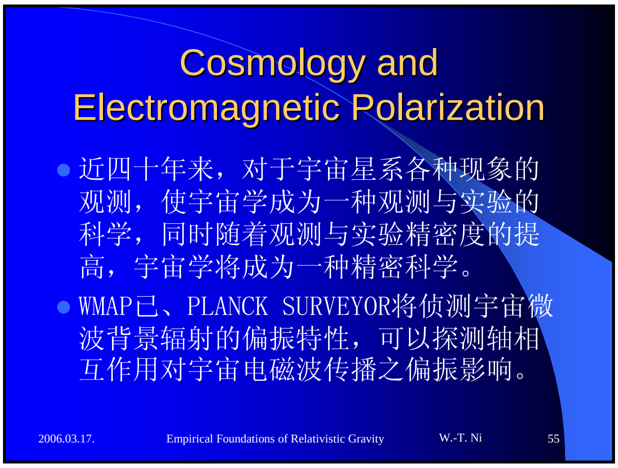
•真空破缺、真空相变. . .

•1999年从超新星的观测推论出我们的宇宙正在加速膨胀，在宇宙模型中需要有宇宙常数项。这宇宙常数项所带的能量是正的，和原来爱因斯坦所希望的宇宙常数的符号相同。这宇宙常数项所带的能量，现在称为真空能量或暗能量。按照观测，现在的暗能量和物质能量的比例大约是2:1，而物质能量中暗物质占大部分。



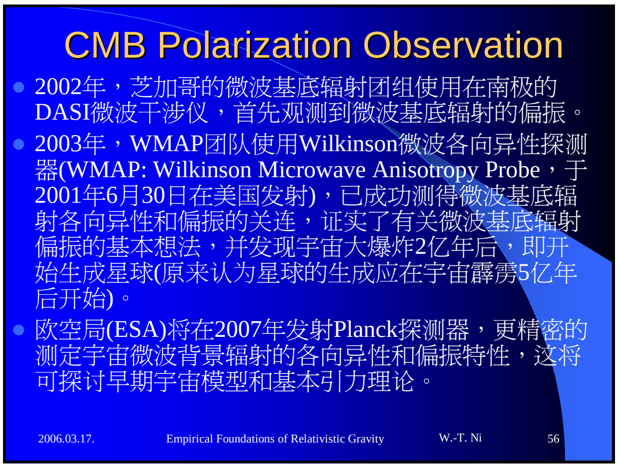
宇宙模型之演进

- Kapteyn宇宙：6千光年×2千光年之盘状银河系
- 1918年Shapley测定了球形星团的距离，发现其分布更开阔，确定了太阳系不是我们银河的中心，并了解了我们银河系的形状。
- 美国加州Wilson天文台的一百吋望远镜建造好之后，哈勃等人观测外星系，证实了漩涡状星云的确是像我们银河系的星系(岛宇宙)，并测定了外星系的分布与运动情况，进一步扩展了我们对宇宙的了解。



Cosmology and Electromagnetic Polarization

- 近四十年来，对于宇宙星系各种现象的观测，使宇宙学成为一种观测与实验的科学，同时随着观测与实验精密度的提高，宇宙学将成为一种精密科学。
- WMAP已、PLANCK SURVEYOR将侦测宇宙微波背景辐射的偏振特性，可以探测轴相互作用对宇宙电磁波传播之偏振影响。



CMB Polarization Observation

- 2002年，芝加哥的微波基底辐射团组使用在南极的DASI微波干涉仪，首先观测到微波基底辐射的偏振。
- 2003年，WMAP团队使用Wilkinson微波各向异性探测器(WMAP: Wilkinson Microwave Anisotropy Probe，于2001年6月30日在美国发射)，已成功测得微波基底辐射各向异性和偏振的关连，证实了有关微波基底辐射偏振的基本想法，并发现宇宙大爆炸2亿年后，即开始生成星球(原来认为星球的生成应在宇宙霹雳5亿年后开始)。
- 欧空局(ESA)将在2007年发射Planck探测器，更精密的测定宇宙微波背景辐射的各向异性和偏振特性，这将可探讨早期宇宙模型和基本引力理论。