IHP 2006

Experimental Tests of General Relativity

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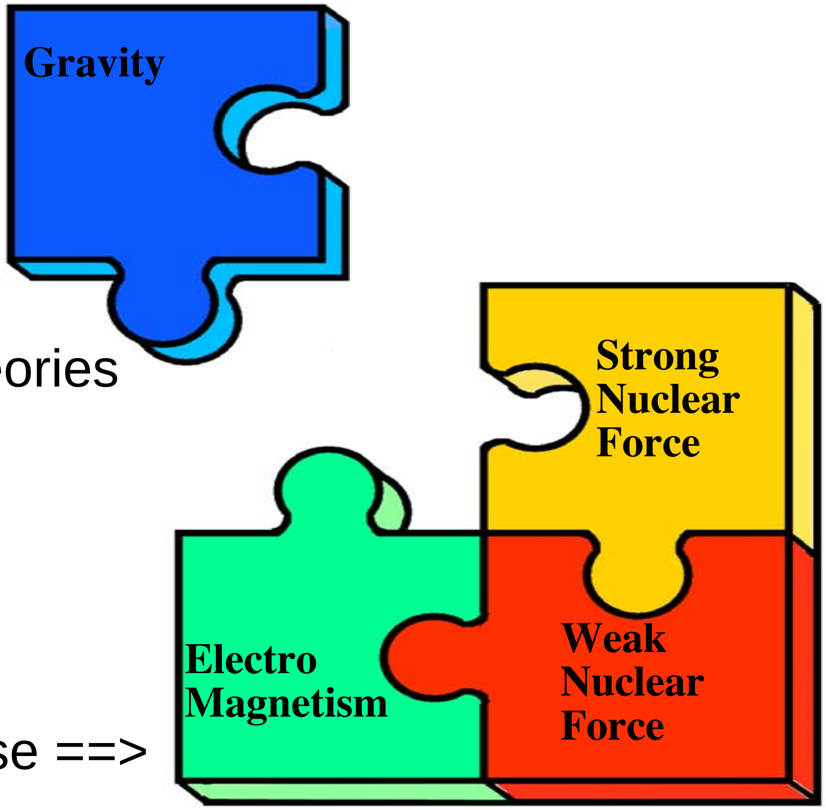
Why Measure Gravity?

- General Relativity = Present Theory of Gravity
  - Mathematically Consistent
  - Agrees with Observation (so far)



- Unified Physics ?
  - Standard Model: Quantum Gauge Theories
  - GR cannot be quantized
- Partial steps toward Grand Unification
  - Strings/supersymmetry in early Universe ==> scalar-tensor theory, not Einstein's
  - Damour - Polyakov ==> long range, equivalence-violating dilaton

Tests of General Relativity: Background

Einstein Equivalence Principle (EEP)

Weak EP – Universality of Free Fall

Local Lorentz Invariance

Local Position Invariance

Gravitational energy Gravitates

EEP ==> metric theory of Gravity

events in spacetime separated by invariant line element

$ds^2 = g_{\mu\nu}dx^{\mu}dx^{\nu}$

objects in free fall follow geodesics of the metric

Weak Field Limit $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $\eta_{\mu\nu}$ is the Minkowski metric

Tests of General Relativity: Background 2

Einstein Field Equation $G_{\mu\nu} = R_{\mu\nu} - 1/2\, g_{\mu\nu}R = (8\pi G/C^4)T_{\mu\nu}$

"matter tells spacetime how to curve, and curved space tells matter how to move"

No adjustable parameters

– G directly measurable Newtonian gravitational constant

Schwarzschild solution: static, spherically symmetric field of a point mass

– weak field expansion to first order

$ds^2 = (1–2GM/C^2R)C^2dt^2 – (1+2GM/C^2R)dr^2$

$g_{00} = -(1–2\,\Phi/C^2)$

Tests of General Relativity: Background 3

For laboratory tests and even solar system tests spacetime distortions due to gravity are small

$\Phi/C^2 = GM/RC^2$

At surface of	a proton	$\Phi/C^2 = 10^{-39}$
	1m diam Tungsten sphere	$\Phi/C^2 = 10^{-23}$
	earth	$\Phi/C^2 = 7 \text{x} 10^{-10}$
	sun	$\Phi/C^2 = 2 \text{x} 10^{-6}$
	neutron star	$\Phi/C^2 = 0.15$
	black hole	$\Phi/C^2 = 1$

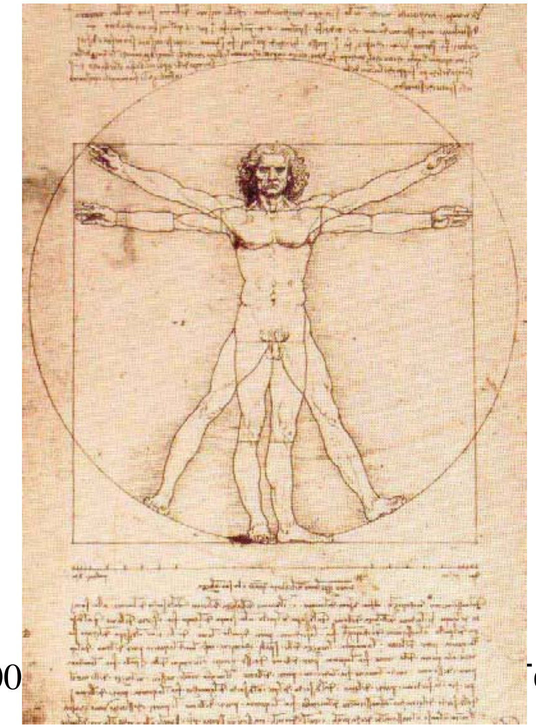
Tests of General Relativity: Background 4

Solar system space-time distortions are small =>

both earth bound and space based experimental tests require high precision

and often cancellation or complex "fitting out" of Newtonian and perturbing effects

Theory



Experiment

Tests of General Relativity: Scope of Lectures

Will not give general survey of state GR tests (this is covered by the lectures of Cliff Will)

Will not discuss gravitational radiation (this is covered by lectures of Jean-Yves Vinet)

Will give some background on areas of tests to motivate specific experiments

Will concentrate on the unique experimental techniques required by testing GR, and

Will cover several key experiments in detail

Will give a general description special advantages the space affords precision experiments in fundamental physics

Syllabus

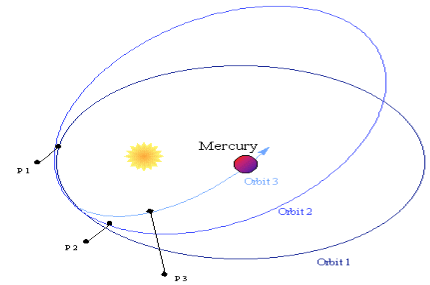
- Overview of Experimental tests of General Relativity
- Pound-Rebka Experiment, Gravity Probe A, ACES
- Ranging to Remote benchmarks
    - LLR
    - Shapiro time delay to Viking Lander
    - Shapiro time delay to Cassini Spacecraft
- Ground Based Tests of the Equivalence Principle and
    - Short Range Tests of Newton's Inverse-Square Law
    - Space Based Tests of the Equivalence Principle
- Space Based Tests of the Equivalence Principle
- Gravity Probe B
    - Derivation of General Relativity Prediction-
    - Geodetic and Frame Dragging Effects
    - Experiment Design, Integration, Launch, and Operations

- Technology for future Fundamental physics missions in space

3 Classical Tests of GR

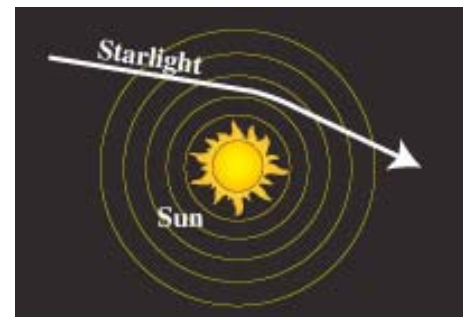
Einstein's 2 1/2 Tests

Perihelion Shift of Mercury



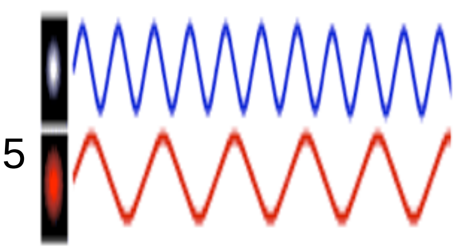
GR resolved 43 arcsec/century discrepancy

Deflection of light by the sun



GR correctly predicted 1919 eclipse data
1.75 arcsec deflection

Gravitational Redshift -- Test of EP



1960 Pound-Rebka experiment, $\Delta\nu/\nu = 2.5\text{x}10^{-15}$
1976 Vessot-Levine GP-A

Testing GR requires high precision, even the sun is a weak source

Recent Tests of GR

1968 – Through present

Shapiro Time Delay Viking

Recent Result - Cassini Spacecraft: 3-5 X10^{-5}

1969 – Through present

Lunar Laser Ranging

EP, Nordtvedt Effect, Geodetic Effect

1974 – Through present

Taylor Hulse Binary Pulsar- Evidence for Gravitational radiation

2004 – GP-B Launch