KEY FACTS ABOUT GRAVITY

- THE WEAKEST OF THE FOUR BASIC FORCES
  \[ \frac{F_{\text{grav}}}{F_{\text{EM}}} = \frac{Gm_1^2/r^2}{e^2/r^2} = \frac{Gm_1^2}{e^2} \sim 10^{-40} \]

- UNIVERSAL - COUPLES TO ALL MASS ENERGY.

- LONG-RANGE
  \[ F = \frac{Gm_1m_2}{r^2} \]

- UNSCREENED - NO NEGATIVE GRAVITATIONAL "CHARGE".

GRAVITY GOVERNS THE STRUCTURE OF MATTER ON THE LARGEST SCALES.
RELATIVISTIC GRAVITY
EINSTEIN'S GENERAL RELATIVITY

- GRAVITY IS GEOMETRY.
- MASS CURVES SPACETIME
- FREE MASS MOVES ON THE STRAIGHTTEST PATHS IN CURVED SPACETIME.
Newtonian Gravity (1687)

The Earth travels around the Sun because it is pulled by the gravitational force exerted by the mass of the Sun.
The Earth travels around the Sun because its following the straightest path in the curved spacetime produced by the Sun's mass.
Planck scale

\[ l = \left( \frac{G\hbar c}{c^3} \right)^{\frac{1}{2}} \sim 10^{-33} \text{ cm} \]

Planck energy

\[ E_p = \frac{\hbar c}{l} = \left( \frac{\hbar c^5}{G} \right)^{\frac{1}{2}} \sim 10^{19} \text{ GeV} \]

This is the scale characterizing:

- Unified theories of the four basic forces (e.g. string theory)
- The union of gravity and quantum mechanics (e.g. quantum theory of geometry)
WHERE IN THE UNIVERSE ARE THE HIGHEST ENERGIES REALIZED?

$$E_{pl} = \left( \frac{\hbar c^5}{G} \right)^{\frac{1}{2}} \sim 10^{19} \text{GeV}.$$  

THE BIG BANG:

- EXPLODING BLACK HOLES.

HAWKING EFFECT.
When is relativistic gravity important?

\[ \frac{GM}{c^2R} \sim 1 \]

- **Sun** \[ \frac{GM}{RC^2} \sim 10^{-6} \]
- **Neutron Star** \[ \frac{GM}{RC^2} \sim 0.1 \]
- **Black Hole** \[ \frac{GM}{RC^2} = \frac{1}{2} \text{ (maximum value)} \]
- **Universe** \[ \frac{GM}{RC^2} \sim \frac{1}{2} \]
Gravitational Physics: From Quantum to Cosmos

- Present Universe
- Milky Way
- Sun
- GPS Orbit
- Neutron Star
- Primordial Black Hole Evaporating Today
- Universe at End of Inflation
- The Quantum Gravity Scale
- Probed by Best Accelerators
- Hydrogen Atom
- Strand of DNA
- Human

Mass in Grams vs. Distance in Meters
- The large scales of astrophysics and cosmology are increasingly accessible to observation.

- The smallest scales are increasingly accessible to theoretical speculation.

**Result:**

General relativity is increasingly integrated with neighboring areas.

General relativity is increasingly in contact with experiment & observation.
GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination
SPECIAL RELATIVITY
Moving clocks run slow
\[ \sqrt{1 - \frac{v^2}{c^2}} \to 1 - 0.8 \times 10^{-10} \]

GENERAL RELATIVITY
Clocks higher in a gravitational potential run fast.
\[ 1 + \frac{GM}{r c^2} \to 1 + 8.2 \times 10^{-10} \]
CLASSICAL SOLAR SYSTEM TESTS

- Gravitational Redshift,
- Bending and Time Delay of Light,
- Precession of Perihelion.

Small Effect
Difficult to Detect

Precision Measurement ≤ 1%

Annoying Correction
In Other Precision Measurements

New Tool
BENDING OF LIGHT BY THE SUN

ACTUAL POSITION

* APPARENT POSITION
Solar Eclipse 1922

Campbell & Trumpler
1975 LBI Bending of Light by the Sun

\[ x = 1.007 \pm 0.009 \]

Fomalont & Swavek
VLBI Measurements of Bending of Light

\[ \chi = 0.99983 \pm 0.00045 \]

S. Shapiro, et al. (2004)
M. Eubanks, et al. (unpub)
CASSINI DETERMINATION OF $y'$

Measure frequency shift of two-way radio signal

$$y' = \frac{v_{\text{rec'd}} - v_{\text{trans}}}{v_{\text{trans}}}$$

$$y_{gr} = 4(1+y') \frac{GM_0}{bc^3} \frac{db}{dt}$$

Three different up-downlink pairs (XX, KK, XK) allow for correction by solar corona

$$y' = 1 \pm (2.1 \pm 2.3) \times 10^{-6}$$
USING THE SUN AS A LENS

OBSERVATORY IN THE KUIPER BELT.
SOME NEXT STEPS IN PRECISION TESTS

- GRAVITOMAGNETIC EFFECTS ($\sim 1/c^3$)
  - GP-B (April 20, 2004)
  - Sept 29, 2005

- NEW TESTS OF THE PRINCIPLE OF EQUIVALENCE
  - STEP ($\sim ?$)
Geodetic Effect
6,614.4 milliarcseconds/yr
(0.00183 degrees/yr)

Guide Star IM Pegasi

Frame-dragging Effect
40.9 milliarcseconds/yr
(0.0000114 degrees/yr)

640 km (400 mi)
PRINCIPLE OF EQUIVALENCE

- $g$'s equal to $1.5 \times 10^{-13}$

- Central to a geometric theory of gravity.

- Violations would signal breakdown of our notions of spacetime.

- New forces
Lunar Laser Ranging

POSITION OF THE MOON TO ~Few CM.
Time, Space Obsolete in New View of Universe

Many physicists are embracing a revolutionary, still mysterious idea called string theory. The concept rejects several familiar notions and includes the existence of 11 dimensions.

Now, some physicists are taking this revolutionary line of thinking one step further: If their theories are right, in the words of Edward Witten of the Institute for Advanced Study in Princeton, space and time may be "doomed."

Concedes physicist Nathan Seiberg, also of the institute: "I am almost certain that space and time are illusions. These are primitive notions that will be replaced by something more sophisticated."

Theory: Bizarre Concept Could Explain Universe
\[ \frac{\Delta g}{g} \sim 10^{-18} \]
MAJOR THEME
OF THE THIS DECADE:
THE EXPLORATION OF
STRONG
GRAVITATIONAL FIELDS
STRONG GRAVITY

- Gravitational Waves
- Black Holes
- Cosmology
GRAVITATIONAL WAVES
EINSTEIN'S THEORY PREDICTS
PROPAGATING RIPPLES IN
SPACETIME CURVATURE.
GRAVITATIONAL WAVES
PROPAGATING RIPPLES IN CURVATURE

- SPEED C
- TWO POLARIZATIONS
Mass in Motion
The Source of Gravitational Waves

- **Binary Stars**
  \[ L_{GW} \sim L_{EM} \left( \frac{M}{M_0} \right)^{10/3} \]

  Explosive collapse is much brighter

  Binary stars mass \( M \), period \( P \).

- Once produced, little is absorbed.
  We could potentially see to the surface of black holes, and to the earliest times of the Big Bang with gravitational waves.
\[ P_{\text{rot}} = 0.059029997929613 \pm 0.0000000000000073 \text{s} \]

(July 7, 1984 ~ 6h GMT)

\[ P_{\text{orbit}} = 7.75 \text{h} \]

(DECREASE DUE TO GRAV. RAD) \approx 10 \mu s/\text{yr.}
DETECTION OF GRAVITATIONAL WAVES

LASER INTERFEROMETER

BIG INTERFEROMETERS CAN DETECT DIFFERENCES IN LENGTH OF A FRACTION OF THE SIZE OF THE NUCLEUS OF AN ATOM!
Gravitational Wave Detectors

- Interferometric
- Resonant-Mass

Locations:
- LIGO
- ALLEGRO
- EXPLORER
- AURIGA
- VIRGO
- GEO
- NAUTILUS
- LISA
- TAMA
- NIOBE

Gravitational wave research
LIGO

HANFORD, WA.
HANFORD 4 km

Strain Sensitivities for the LIGO Interferometers

$H(f) \propto \sqrt{1/f} [Hz]$ vs. Frequency [Hz]

- September 2002
- August 2005

H1 Performance adapted from LIGO-G050483-01-Z
DANCING BLACK HOLES

(P. Diener)

EVENT HORIZON OF TWO MERGING BLACK HOLES
MASS IN MOTION PRODUCES GRAVITATIONAL WAVES.
MERGING BLACK HOLES Emit

$$E \sim (\text{fraction}) \, M c^2$$

IN A TIME

$$t \sim (\text{few}) \times \frac{GM}{c^3}$$

$$L_{GW} \sim \frac{Mc^2}{GM/c^3} \sim \frac{c^5}{G} \sim 10^{59} \text{ erg/sec}$$

$$L_{\gamma \text{ burst}} \sim 10^{52} \text{ erg/sec}$$

MAXIMUM PHYSICAL LUMINOSITY.
Analysis of LIGO data for gravitational waves from binary neutron stars


LIGO Scientific Collaboration

(1) Albert-Einstein Institute, Max-Planck-Institut fur Gravitationsphysik, D-14476 Golm, Germany
(2) Albert-Einstein Institute, Max-Planck-Institut fur Gravitationsphysik, D-30167 Hannover, Germany
(3) Australian National University, Canberra, 2600, Australia
(4) California Institute of Technology, Pasadena, California 91125, USA
(5) California Institute of Technology, Pasadena, California 91125, USA
(6) Cardiff University, Cardiff, CF2 3YB, United Kingdom
(7) Carnegie College, Northfield, Minnesota 55057, USA
(8) 2004 The American Physical Society

© 2004 The American Physical Society
**CONTINUOUS WAVE (PULSAR) SEARCHES.**

**60,000 USERS (w. CREDIT)**

**25 T-flops CONTINUOUSLY ($7k/DAY ELECTRIC BILL)**

**NUMBERS 3 IN BOINC BEHIND SETI @ HOME CLIMATE PREDICTION: NET**

http://einstein.phys.uwm.edu
BLACK Holes

Einstein's theory predicts that when mass is compressed to a small enough volume, the gravitational force is so strong nothing can escape.
BLACK HOLES

General relativity predicts that the geometry of astrophysical black holes is characterized by just two parameters:

- $M$ – Mass
- $J$ – Angular momentum

Black holes provide the cleanest connection between astrophysics and fundamental physics.
WEIGHING THE SUN

THE MASS OF THE SUN CAN BE DETERMINED FROM THE SPEED OF THE EARTH AND THE SIZE OF ITS ORBIT.

THE EARTH WOULD GO AROUND TWICE AS FAST IF THE SUN WERE FOUR TIMES MORE MASSIVE.
THE BLACK HOLE IN OUR GALAXY

Keck/UCLA Galactic Center Group

1995-2004

(A. Ghez, et al. 2004)
Black holes power some of the most energetic phenomena in the universe.

- **X-ray sources**
  \[ L_x \sim 10^{38} \text{ ergs/sec} \]
  \[ L_\odot \sim 10^{33} \text{ ergs/sec} \]

- **Active galactic nuclei**
  \[ L \sim 10^{42} - 10^{48} \text{ ergs/sec} \]
  \[ L_{\text{galaxy}} \sim 10^{44} \text{ ergs/sec} \]
ACTIVE GALACTIC NUCLEI
\[ \frac{1}{100} \] - 10,000 TIMES BRIGHTER THAN ALL THE STARS IN THE GALAXY.

Cygnus A
**GRAVITATIONAL BINDING VS THERMONUCLEAR FUSION**

- **FUSION** \(4 \text{H}^1 \rightarrow \text{H}_2^4 + \) (ENERGY OUT)

\[
\frac{(\text{ENERGY OUT})}{(\text{REST ENERGY IN})} \approx 17\%.
\]

- **GRAVITATIONAL BINDING**

NEUTRON STAR:

\[
\frac{(\text{ENERGY OUT})}{(\text{REST ENERGY IN})} \sim 6\%.
\]

EXTREME ROTATING BLACK HOLE:

\[
\frac{(\text{ENERGY OUT})}{(\text{REST ENERGY IN})} \sim 80\%.
\]
THE BLACK HOLES OF GENERAL RELATIVITY (1915) ARE THE MOST EFFICIENT WAY OF REALIZING $E = mc^2$ OF SPECIAL RELATIVITY (1905)
FUTURE OF BLACK HOLE PHYSICS

• TODAY: IDENTIFIED PLACES WHERE THERE IS MUCH MASS IN A SMALL VOLUME.

• FUTURE: CHECK THE DETAILED PREDICTION OF EINSTEIN’S THEORY FOR THE GEOMETRY AROUND BLACK HOLES.

X-Ray

Gravitational Waves
NEWTONIAN

SPECIAL RELATIVITY

GENERAL RELATIVITY

BROAD, SKewed LINE
Fe line in MCG-6-30-15
COSMOLOGY

EINSTEIN'S THEORY PREDICTS

THE EXPANSION OF
THE UNIVERSE
FROM A BIG BANG.
Gravitational Issues in Cosmology

- What is the geometry of the universe?
- What is the source of curvature?
  - Dark Matter
  - Vacuum Energy (Cosmological Constant)
- Does the universe obey the Einstein equation?
COSMOLOGY TODAY

- HOMOGENEOUS, ISOTROPIC \( (\delta \leq 100 \text{ Mpc}) \)
- INITIAL MATTER THERMAL EQUILIBRIUM

FRW MODELS

\[ H_0 = 71 \text{ (km/s)/Mpc} \]
\[ \Omega_{\text{vacuum}} = 0.73 \]
\[ \Omega_{\text{radiation}} = 8 \times 10^{-5} \]
\[ \Omega_{\text{baryon}} = 0.04 \]
\[ \Omega_{\text{dark matter}} = 0.23 \]

COSMOLOGICAL PARAMETERS.
\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \]

Is Einstein's gravitational theory correct on the scales of cosmology?

\[ \Omega_V = 0.73 \]
\[ \Omega_R = 8 \times 10^{-5} \]
\[ \Omega_b = 0.04 \]
\[ \Omega_{DM} = 0.23 \]

96% of uncertain character
COSMOLOGY AND QUANTUM GRAVITY

- AT THE BIG BANG, PLANCK ENERGIES ARE REACHED, CHARACTERISTIC OF QUANTUM FLUCTUATIONS IN GEOMETRY AND THE CONJECTURED SCALE OF THE UNIFICATION OF ALL FORCES.

\[ E_p = \left( \frac{c^5}{\hbar G} \right)^{\frac{1}{2}} \]

- AT THE BIG BANG, WE ARE CLOSEST TO THE QUANTUM INITIAL CONDITION OF THE UNIVERSE.

- AT THE BIG BANG, LARGE AND SMALL ARE ONE.
THE DIRECT DETECTION OF GRAVITATIONAL WAVES AND THEIR APPLICATION TO PROBE REGIONS OF STRONG GRAVITY

VERIFICATION OF THE DETAILED PREDICTIONS OF GR FOR THE GEOMETRY OUTSIDE BLACK HOLES.

TESTS OF GENERAL RELATIVITY ON COSMOLOGICAL SCALES

EXPLORATION OF THE LIMITS OF GENERAL RELATIVITY AND NEW PRECISION TESTS.

OBSERVATIONAL SIGNATURES OF QUANTUM GRAVITY.
A theory is more impressive the greater the simplicity of its premises, the more different kinds of things it relates, and the more extended its area of applicability.

A. Einstein