640-245
Electromagnetism & Special Relativity

General Relativity - Part 2

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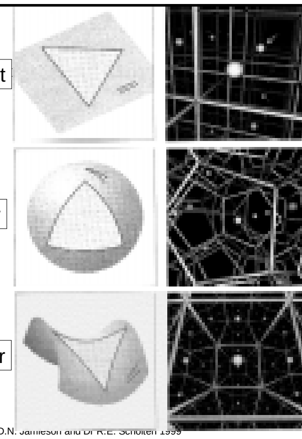
Geometry of Space-time

Flat

C < 2πr

C > 2πr



Apply equivalence principle

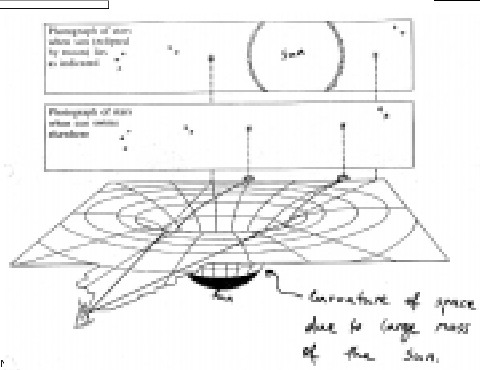
- Conclusion:
- Space is curved (into higher dimensions) by gravity
- How can this effect be tested?
- By drawing circles?
- To difficult!
- Use path of light instead
- Arthur Eddington sent to south seas in 1920 to observe eclipse of the Sun
- Confirmed that the Sun's gravity curves space
- Einstein cannonised!

Examples of Curved Space

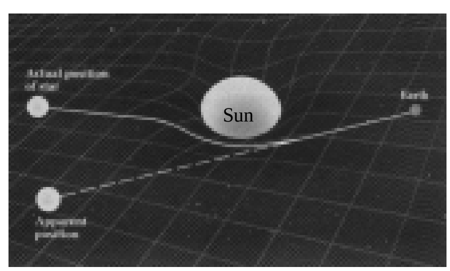
- Space around the Sun
  - Starlight during solar eclipse
  - Radar echo from Venus
  - Radio signals from distant space craft
- Advance in the perihelion of Mercury
- Black Holes
- Gravitational Wave Astronomy

Curved space: Gravity of Sun

- Step1: Observe stars at night, measure separation
- Step 2: Observe stars during eclipse with Sun between, measure separation

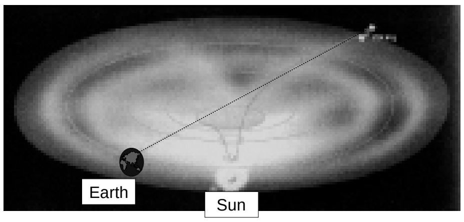


Curved space: Gravity of Sun



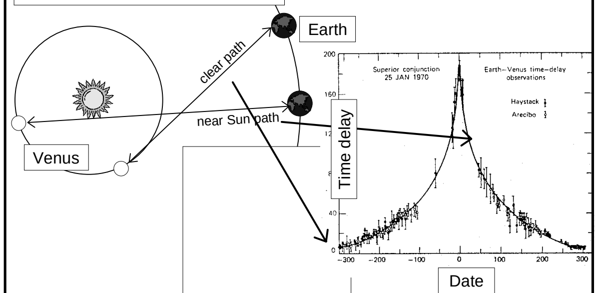
Curved space: Gravity of Sun

- Radio signals from distant space craft are delayed when Sun is near the path
- There is more space in between!



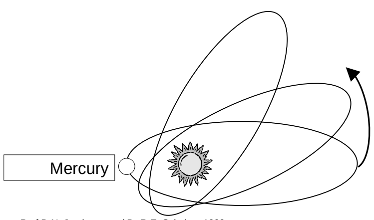
Curved Space: Radar echo from Venus

- Radar echo from Venus takes longer when Sun is nearby



Curved Space: Advance in Perihelion of Mercury

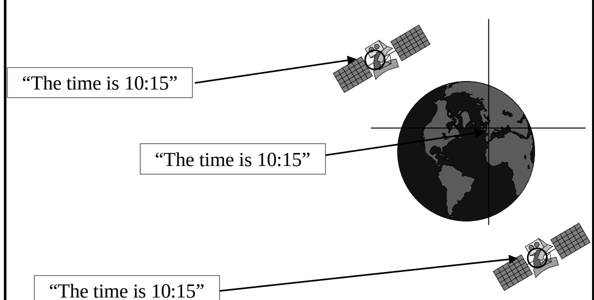
- Perihelion (closest approach to Sun) advances owing to gravitational influence from rest of solar system by 531″ every 100 years
- However this is insufficient to account for the observed advance of 574″ every 100 years
- Residual 574 – 531 = 43″ is due to General Relativity



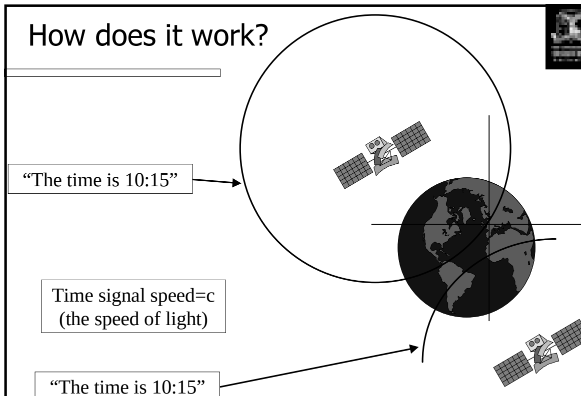
General Relativity: Step-by-step

- Curved space
- Rotating disks
- Stars during eclipse
- Perihelion of Mercury
- The Global Positioning System ← You are here
- Massive objects (Black Holes)
- The Cosmos

How does it work?



How does it work?



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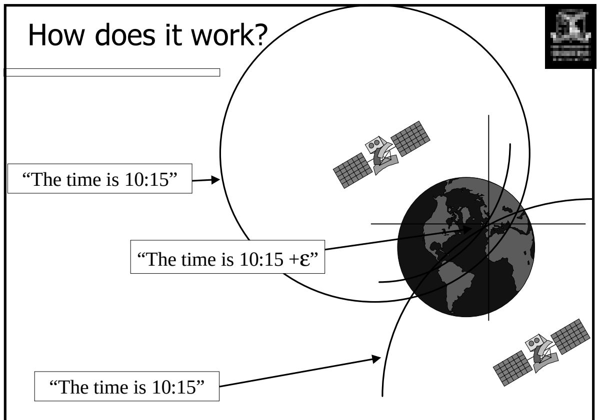
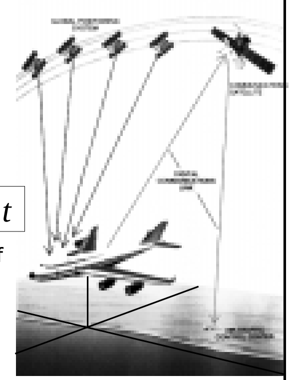


What accuracy?

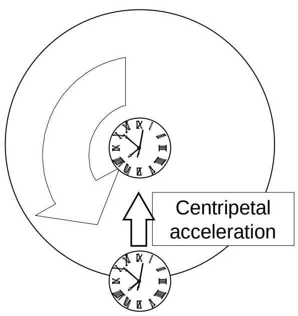
- Need signals from 4 satellites to find:
  - latitude
  - longitude
  - altitude
  - time

$$\delta x = c\delta t$$

- Time Error of 1 millionth of a second leads to
- Position Error of 300 m



Apply Equivalence Principle



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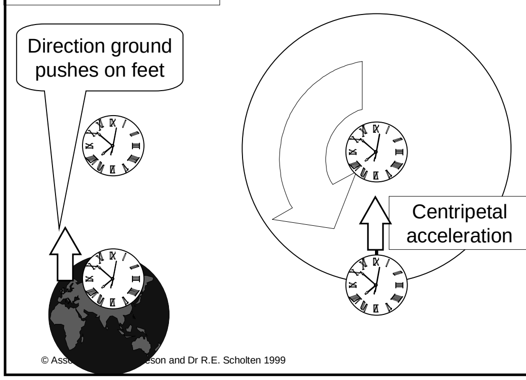
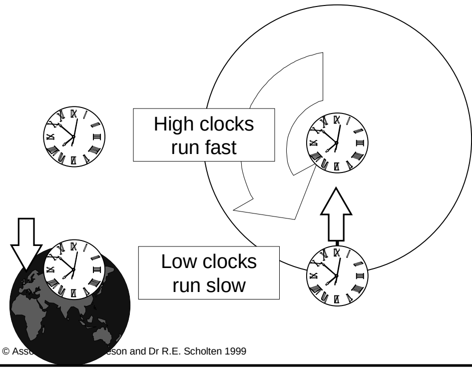
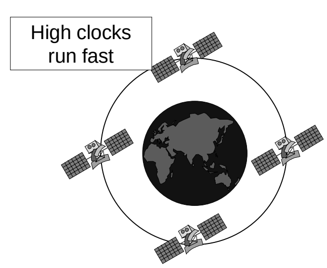


Apply Equivalence Principle

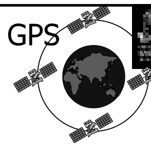


Problem for the GPS

- GPS satellites run fast compared to surface clocks



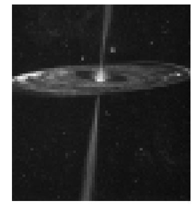
Summary of Problems for the GPS



- 1. GPS satellites clocks run slow by 6 millionths of a second per day (SR - time dilation)
- 2. Cannot synchronise by exchange of signals
- 3. GPS satellite clocks run fast by 45 millionths of a second per day (GR - gravitational blue shift)
- Net effect: Run fast by 39 millionths of a second per day (=error of 12 kilometres)!
- SOLUTION: Make the clocks run slow to compensate!

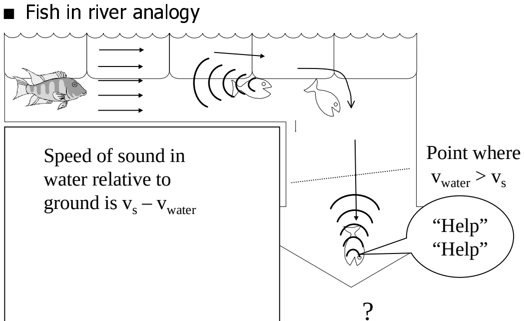
Curved Space: Massive Objects

- Gravity - Revision
- Massive objects
  - What determines their size?
- Black holes and the event horizon
- Gravitational red shift
- Detecting black holes



Massive objects and light

- Fish in river analogy



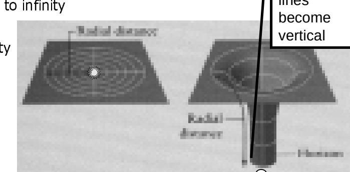
Applications

- Global positioning system
  - Satellite clocks run fast by 45 μs/day
- Black Holes

Black Holes: Summary

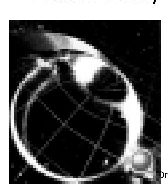
- No force can prevent gravitational collapse of an object greater than about 3 solar masses
- Object will collapse to a "singularity" (infinitely small)
- Gravity is very strong near the singularity, but otherwise unchanged by the collapse
- Gravity causes light to orbit at the radius of the photosphere
- At the radius of the "event horizon":
  - Volume of space goes to infinity
  - Clocks stop
  - Redshift goes to infinity
  - Radius of event horizon is $2GM/c^2$ "The Schwatzchild radius"

Horizon is point where lines become vertical



Size of Event Horizon

Object	Event Horizon Radius*
Asteroid	10^{-15} m (diam of nucleus)
Earth	1 cm
Sun	3 km
Globular Cluster (10^5) stars	300,000 km
Entire Galaxy	10^{12} km



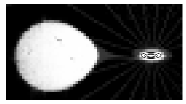
*Size object would have to be compressed to become a black hole

Detecting Black Holes

- From observation of orbit of "normal" star can deduce mass of unseen companion

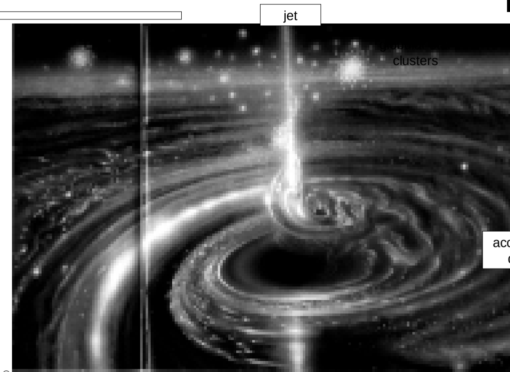
Best candidates:

Object	Mass (solar masses)
Cygnus X-1	9.5
LMC X-1	2.6
AN 620-00	3.2
LMC X-3	7.0
SS433	4.3
Sagittarius A	3.5×10^6
Quasar Engines	10^8 - 10^{12}



NB: Mass less than 3 solar masses implies neutron star (too light to be a black hole)

Massive Galactic Centre Black Hole



From Sky & Telescope June 1996

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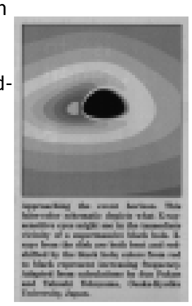
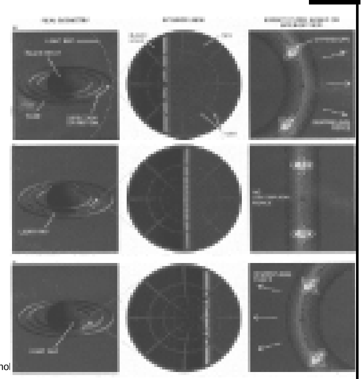
Black Hole in X-rays

- See intense x-rays from accretion disk
- Huge gravitational field distorts view and introduces massive red-shift of light



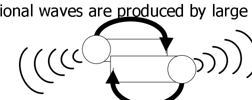
Life around a Black Hole

- Strange perspective in a space station constructed around a Black Hole

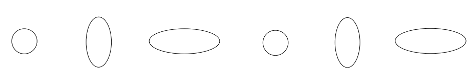


Gravitational Wave Astronomy

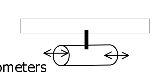
- Gravitational waves are produced by large masses moving about



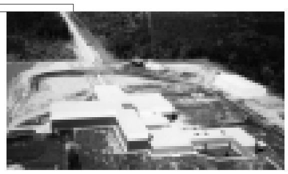
- Effect of gravitational wave on a sphere



- Gravity wave antennas
  - (1) Super cooled bars oscillations in length: diameter of nucleus in 1 m
  - (2) Super accurate interferometers



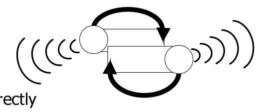
LIGO

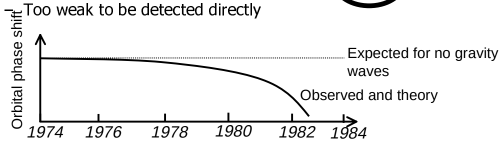


- A giant Michelson-Morely interferometer!
- Massive engineering to detect subtle warps in space-time caused by passing gravity waves

Source of gravity waves

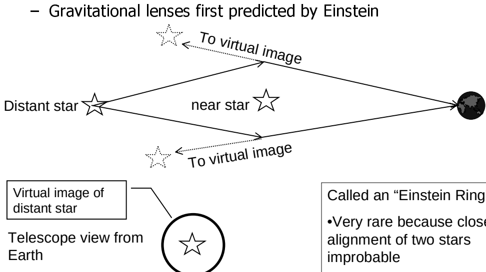
- Pulsar PSR 1913+16 is slowing down
  - consists of a neutron star and a white dwarf in close orbit
  - orbital speed is about 400 km/s = 1/750 speed of light
  - located 16,000 l.y. from Earth
  - orbital period 8 hours
  - as energy is radiated in the form of gravity waves the period shortens
  - Too weak to be detected directly





Gravitational Lensing: Introduction

- Gravity can bend light
  - so strong gravitational fields can form images
  - Gravitational lenses first predicted by Einstein

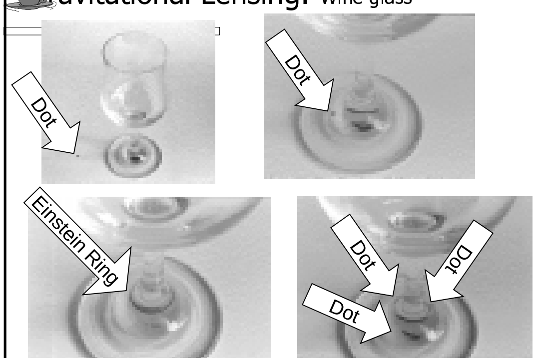


Called an "Einstein Ring"

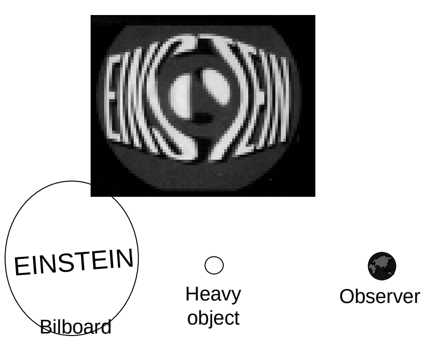
•Very rare because close alignment of two stars improbable

•Observed instead with galaxies!

Gravitational Lensing: Wine glass

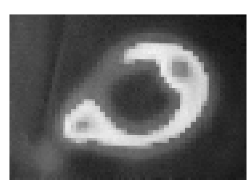


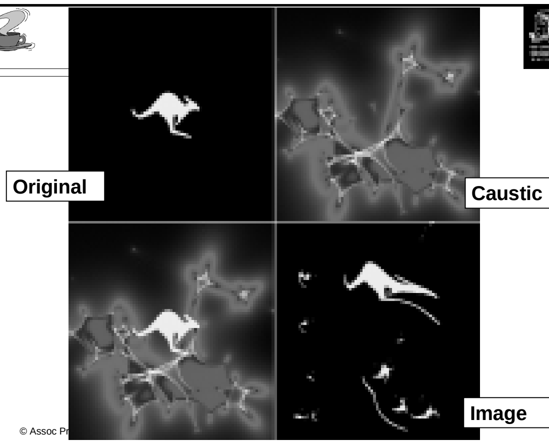
Gravitational Lensing: Einstein Bilboard



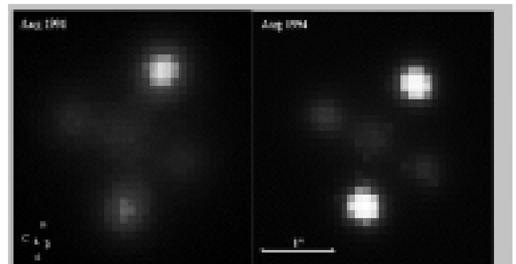
Gravitational Lensing: Einstein Ring

- Seen here in radio wavelegths
- Distant galaxy imaged by intermediate galaxy
- Alignment is not perfect



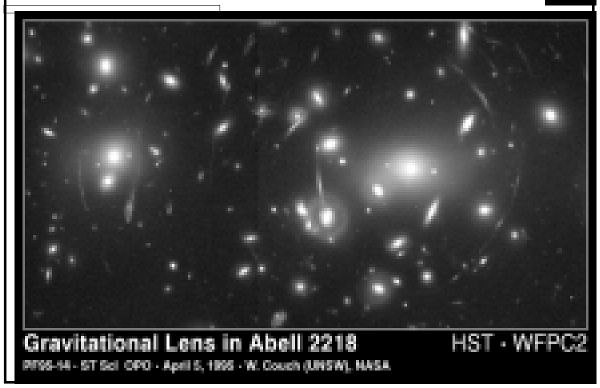


Einstein Cross



The Einstein Cross, 2237+0305. This frame presents two images of the quadruple lensing system 2237+0305. Both were taken on the William Herschel telescope, the first by Geraint Lewis in 1991. The second was obtained by Mike Irwin in 1994 as part of a follow-up program into the study of the effect of microlensing on quasar emission lines. Image A has brightened by 0.5 magnitudes over the three year period. Image courtesy of Geraint Lewis.

Lensing by galaxy cluster



Predictions of General Relativity

- Gravitational red shift
  - Tested on Earth with the Mössbauer effect over a 20m tall tower
- Bending of starlight by the Sun
  - Tested by obervations of stars during a solar eclipse
- Advance in the perihelion of Mercury
  - Tested by observation
- Gravity waves
  - Tested by observations of pulsars in binary systems
  - Other experiments soon to come on line
- Many others
- Status: All ok!

References

- *Gravity's fatal attraction - Black holes and the universe*, M. Begelman and M. Rees, Scientific Amercian Library, 1996, Freeman.
- *Gravity and spacetime*, J.A. Wheeler, Scientific Amercian Library, 1990, Freeman.
- *Scouting black holes: Exploring general relativity with calculus*, E.F. Taylor & J.A. Wheeler, Freeman, 1995