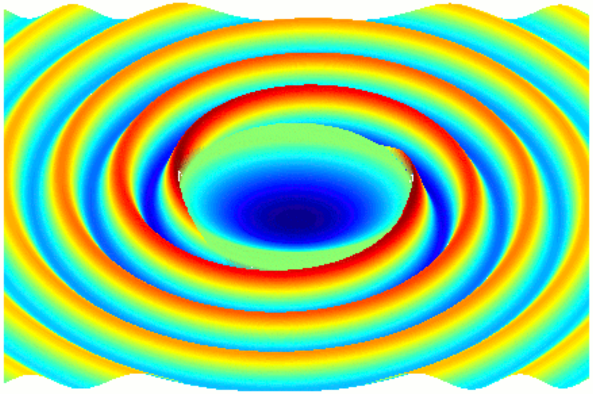
Black Holes And Spacetime

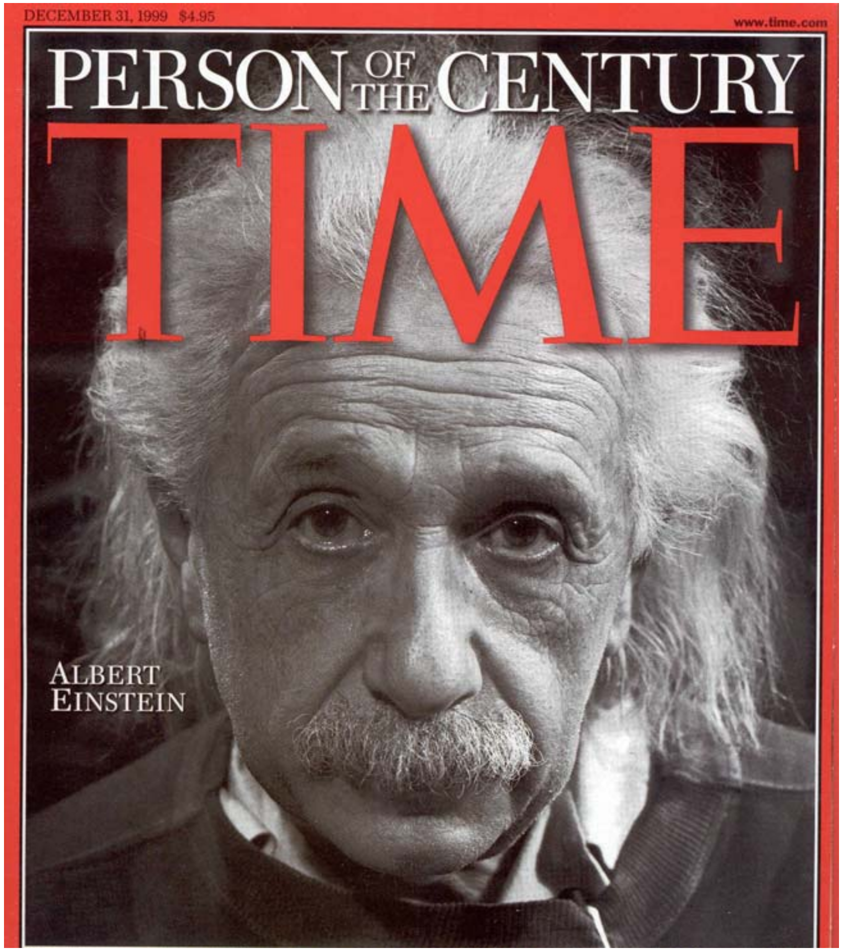


The Laser Interferometer Gravitational-wave Observatory: a Caltech/MIT collaboration supported by the National Science Foundation

Gregory Mendell, LIGO Hanford Observatory,
on behalf of the LIGO Scientific Collaboration

LIGO-G070035-00-W

Einstein

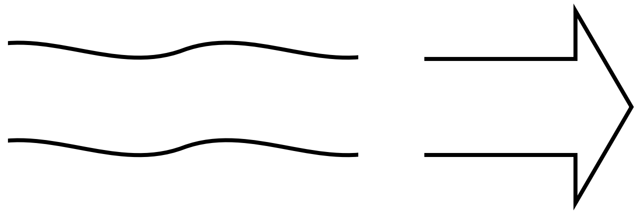


- Einstein, age 26, working at a Swiss Patent Office, published papers in 1905:
  - Sparked the quantum theory of light
  - Showed that atoms were real
  - Introduced a theory of space and time, called Special Relativity
  - Discovered $E=mc^2$.
- Einstein worked 10 years to generalize Special Relativity and Newton's Theory of Gravity, resulting in General Relativity.
- Others contributed: Lorentz, Poincaré, Minkowski, Grossmann, Hilbert, …
- **Einstein revolutionized our concepts of space and time!**

Some Far Out Ideas

- The faster you go the slower time goes.
- Nothing can go faster than light.
- Gravity disappears when you free fall.
- Sources of gravity warp space and time; gravity slows down time.
- Black holes really are like holes in space.
- Worm holes through space and time could exist within our universe or to other universes.
- Gravitational waves are ripples in the fabric of spacetime. LIGO is searching for these waves, with black holes as one possible source.

Einstein Wondered:



Can we catch light?

Mirror

Photo: Albert Einstein at the first Solvay Conference, 1911; Public Domain

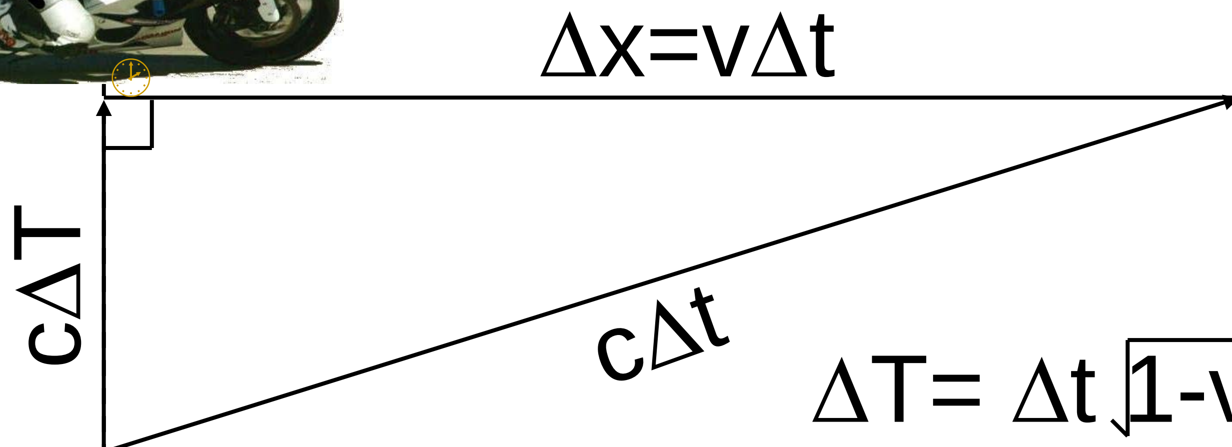
Einstein's Key Idea, 1905

- Galileo & Newton: motion is relative; speeds are additive.
- Newton thought light was made of particles.
- Sound is a wave moving through the air or some material. The speed of sound (741 mph) is fixed to the rest frame of the air. We can catch sound.
- By analogy, in 1905 light was thought to be a wave moving through the "aether". Experiments could not measure the aether or detect changes in the speed of light due to relative motion.
- **Einstein: we cannot catch light; no experiment can detect absolute motion; there is no aether; the speed of light is the same for all observers.**

Niels Bohr

Albert Einstein

Time Dilation



$$\Delta T = \Delta t \sqrt{1 - v^2/c^2}$$

Start

Δ = change in

T = time measured by motercycle riders

t = time measured by observer at “rest”

v = speed of motercycles

c = speed of light

Warning: thought experiment only; do not try this at home.

The Speed of Light

c = 186,000 miles/s = 670,000,000 miles/hr

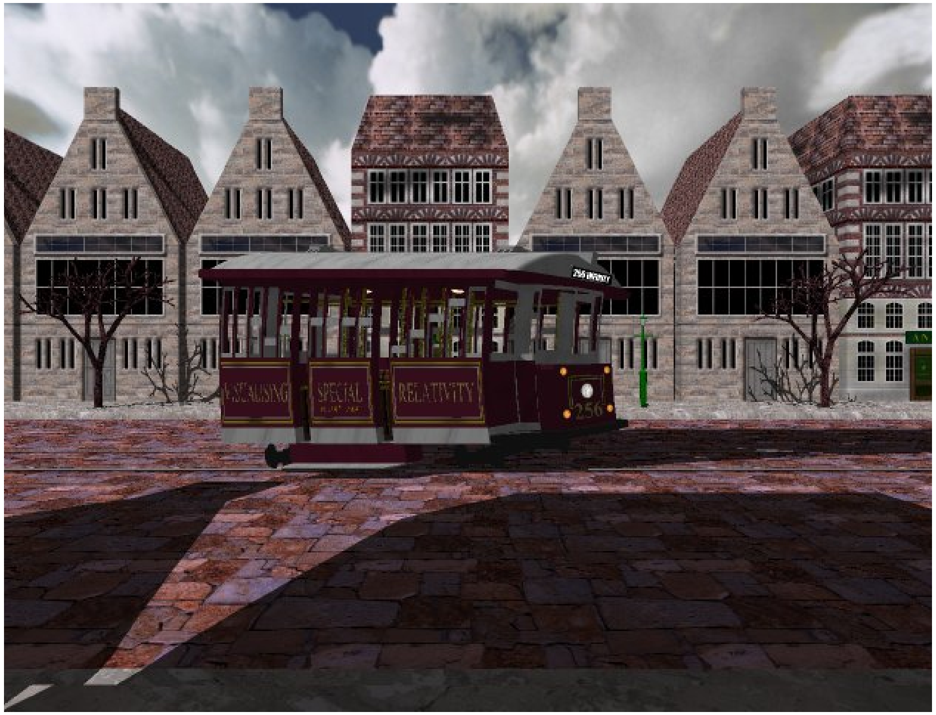
	v	Δt	ΔT
Car	60 mph	1 day	1 day - .35 nanoseconds
Plane	600 mph	1 day	1 day – 35 nanoseconds
Shuttle	17,000 mph	1 day	1 day – 28 microseconds
Voyager	38,000 mph	1 day	1 day – 140 microseconds
Andromeda	300,000 mph	1 day	1 day – 8.7 milliseconds
Electrons	99% c	1 day	3.4 hours

Photo: Stanford Linear Accelerator Center (SLAC); Public Domain

The faster you go the slower time goes!

Nothing can go faster than light!

Length Contraction



http://www.anu.edu.au/Physics/Searle/paper2.html; Web page for "The Physicist" Paper "Visualising special relativity", C.M. Savage and A.C. Searle, The Physicist, vol. 36, pg.141, July/August 1999.

Spacetime Diagram

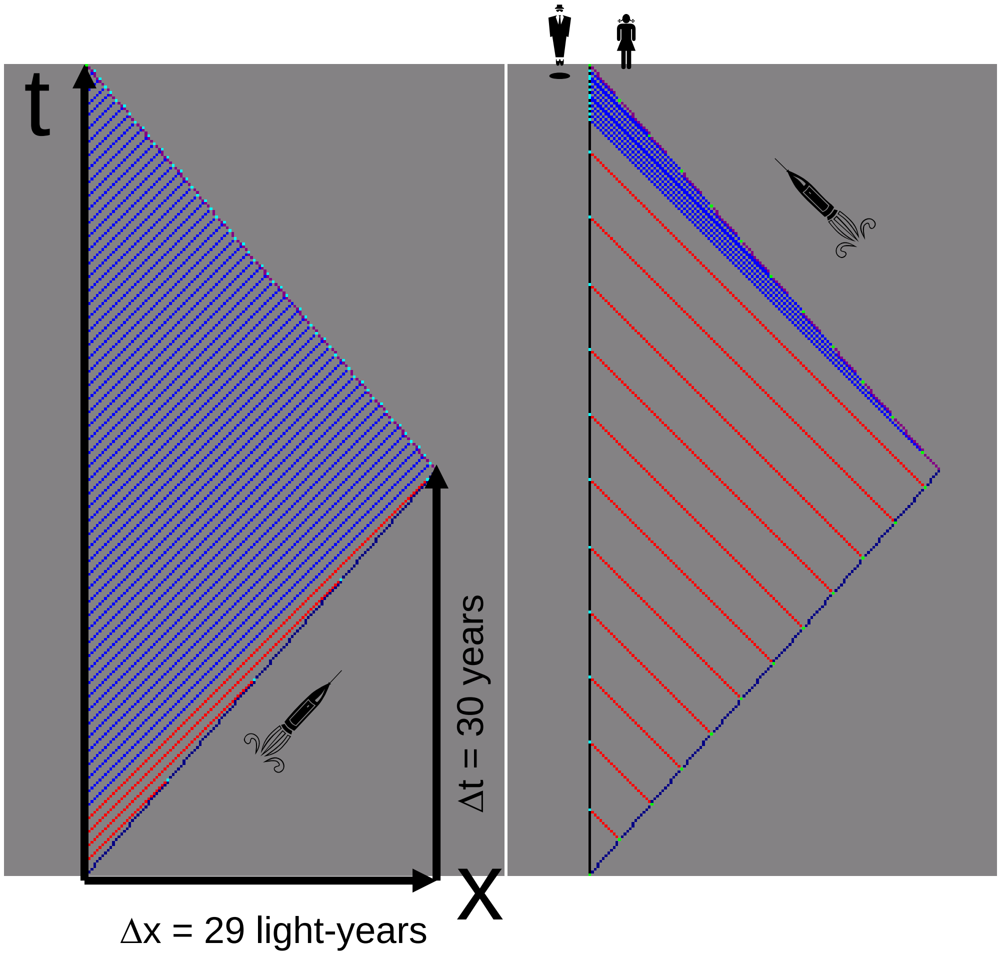
The Twin Paradox

- Imagine twins, Betty and Bob, separated 1 year after birth.

Baby Betty & Bob: ☺ ☺

- Betty takes a rocket traveling at 96.7% the speed of light and travels 29 lt-yrs from Earth and back.

- When Betty returns she is sweet 16, and Bob is 61 years old!!!



$$\Delta T = 30 \text{ yrs} \sqrt{1-(.967)^2} = 7.6 \text{ yrs}$$

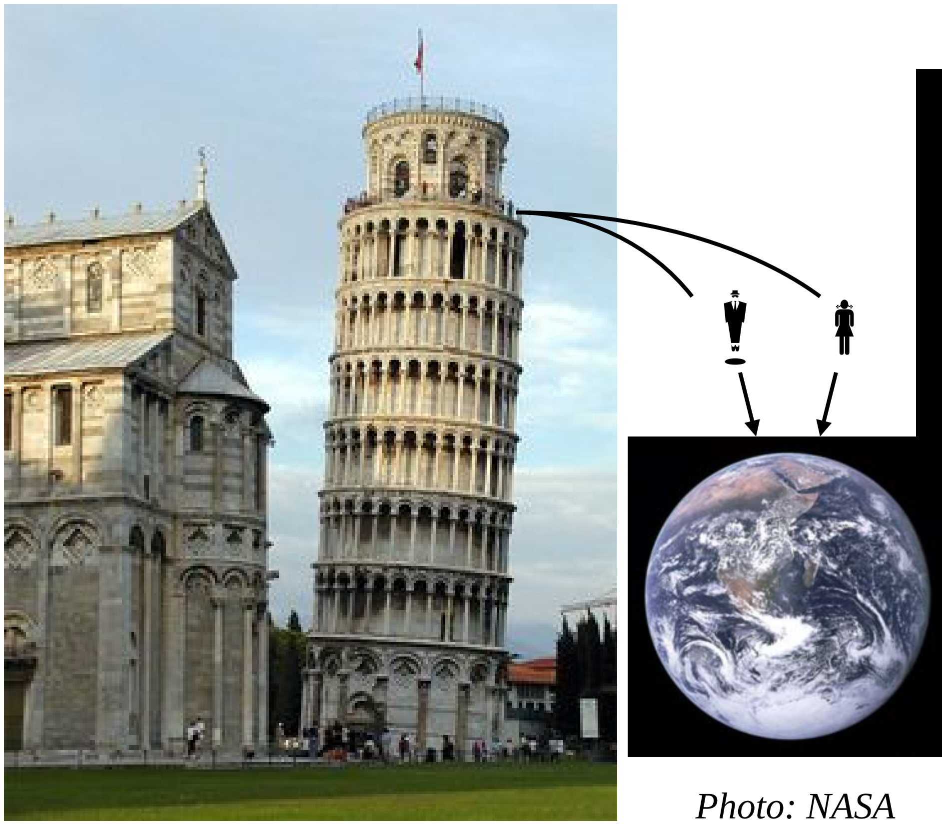
Figure: http://en.wikipedia.org/wiki/Twin_paradox

The Problem With Gravity

Credit: Portrait of Isaac Newton painted in 1689 by Sir Godfrey Kneller (Farleigh House, Farleigh Wallop, Hampshire) *http://www.huntington.org/LibraryDiv/Newton/Newtonexhibit.htm*

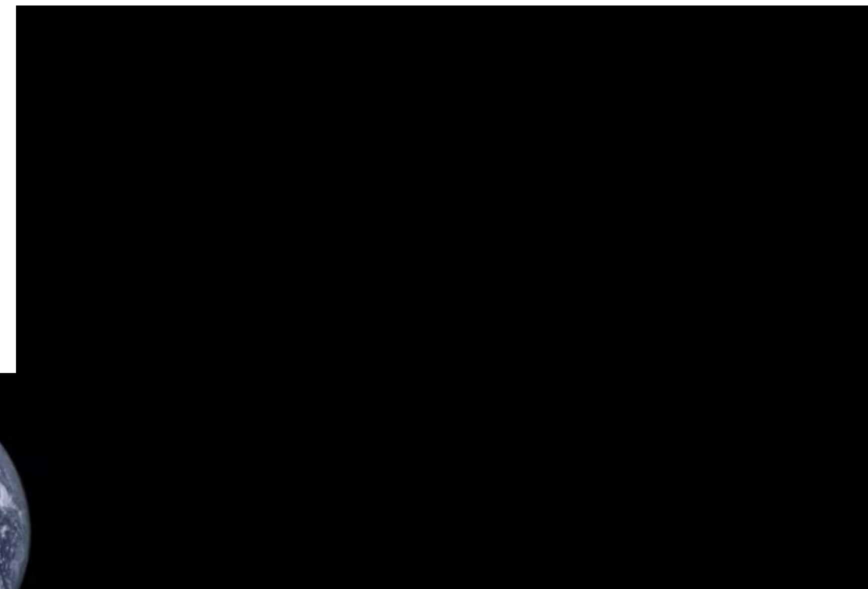
Sir Isaac Newton *invented the theory of gravity and much of the math needed to understand it.*

Einstein's Happiest Thought: Gravity Disappears When You Free Fall



http://en.wikipedia.org/wiki/Leaning_Tower_of_Pisa

Photo: NASA



Video: NASA; http://ksnn.larc.nasa.gov

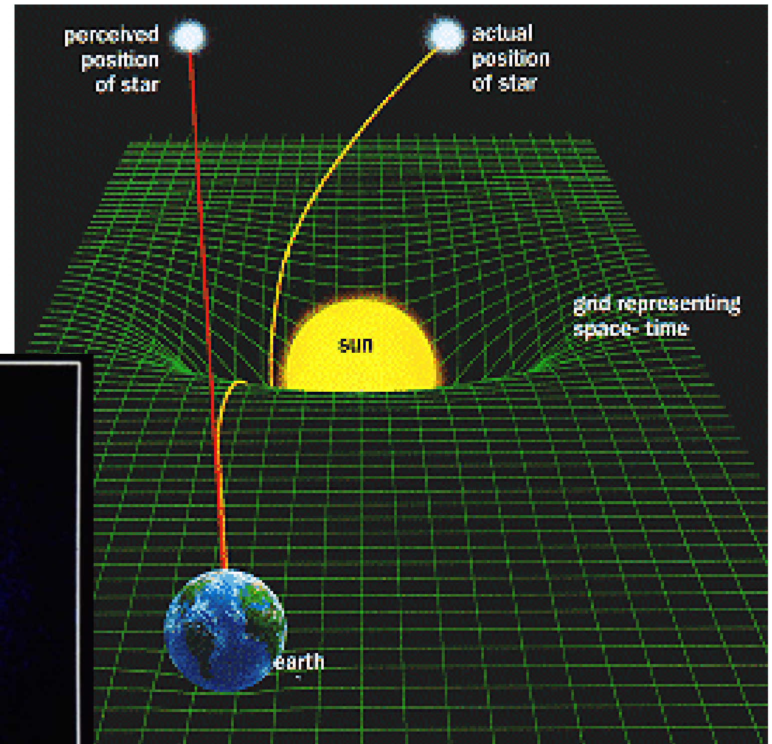
Warning: thought experiment only; do not try this at home.

A new wrinkle on gravity: General Relativity arrives in 1915.

Not only the path of matter, but even the path of light is affected by gravity from massive objects. Gravity is the curvature of space and time!

Figure: Focus Mar95 p30

http://www.geocities.com/Omegaman_UK/relativity.html:



A massive object shifts apparent position of a star

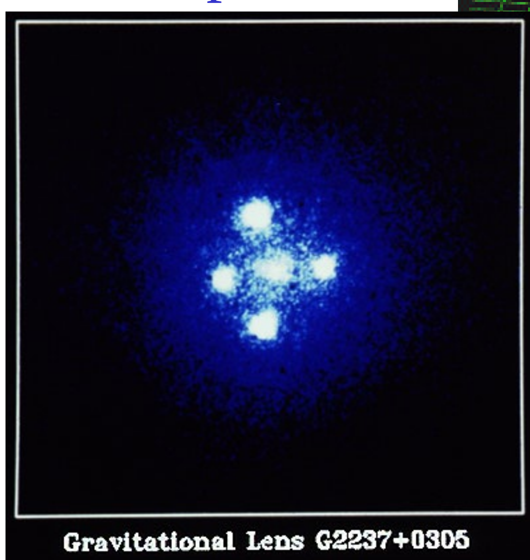
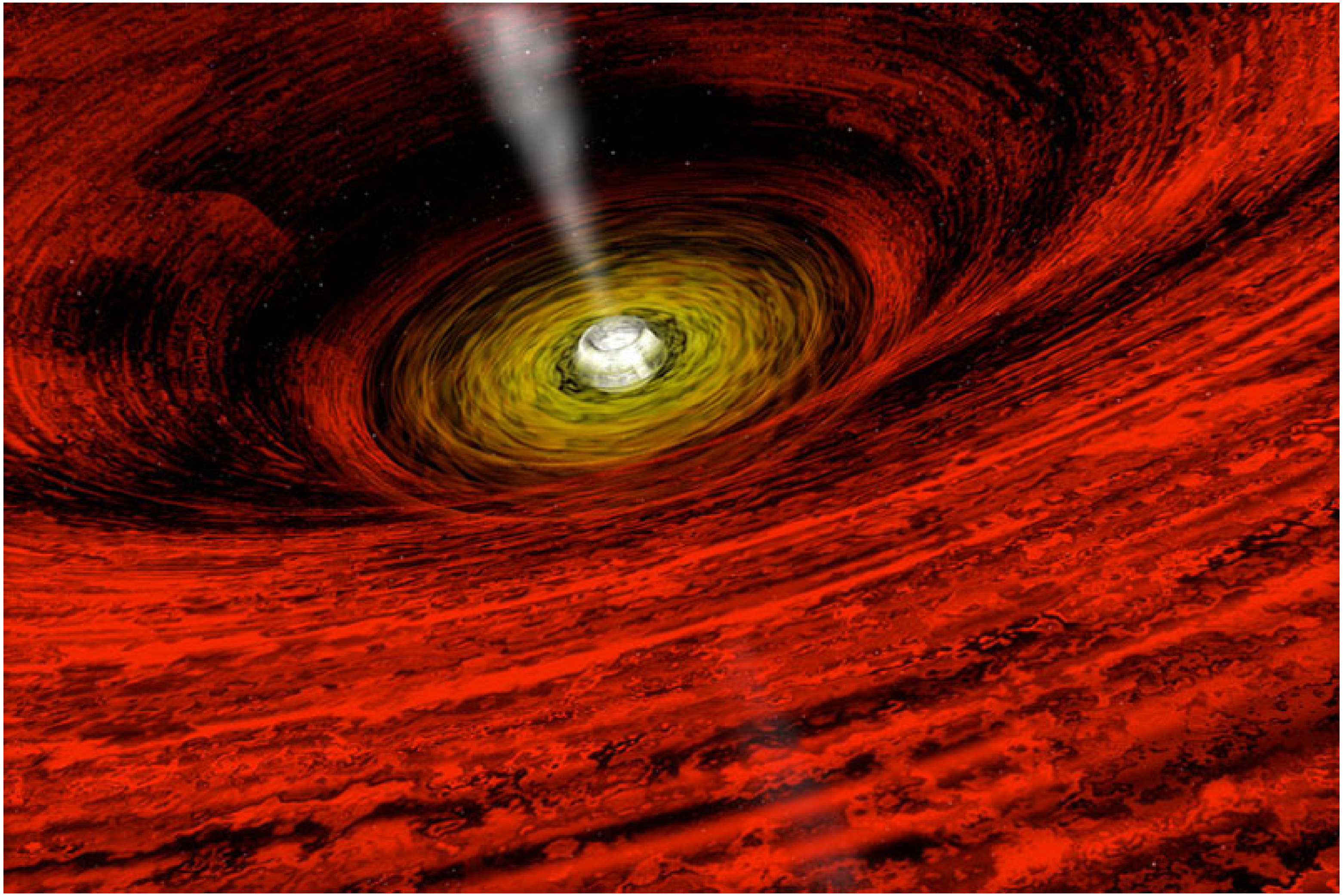


Photo credit: NASA and European Space Agency (ESA)

Black Holes



http://antwrp.gsfc.nasa.gov/apod/ap060528.html; GRO J1655-40: Evidence for a Spinning Black Hole; Drawing Credit: A. Hobart, CXC

Schwarzschild Black Hole

$$dT^2 = \left(1 - \frac{2GM}{rc^2}\right)dt^2 - \frac{1}{\left(1 - \frac{2GM}{rc^2}\right)}dr^2 - r^2 d\theta^2 - r^2 \sin^2 \theta d\phi^2$$

$$dT^2 = \left(1 - \frac{v_{esc}^2}{c^2}\right)dt^2 - \frac{1}{\left(1 - \frac{v_{esc}^2}{c^2}\right)}dr^2 - r^2 d\theta^2 - r^2 \sin^2 \theta d\phi^2$$

Karl Schwarzschild

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

•Escape Velocity

$$R_s = \frac{2GM}{c^2}$$

•Schwarzschild Radius

Object	Schwarzschild Radius
You	1 thousand, million, million, millionth the thickness of a human hair
Earth	1 cm (size of marble)
Sun	3 km (2 miles)
Galaxy	~ trillion miles

Gravitational Time Dilation

$$\Delta T = \sqrt{1 - \frac{2GM}{rc^2}}\Delta t$$

Gravity slows time down!

Photo:http://en.wikipedia.org/wiki/Leaning_Tower_of_Pisa

Clock_Photos:http://en.wikipedia.org/wiki/Cuckoo_clock

Relativity and GPS

• Due to the orbital speed, clocks on the satellite lose 7 microseconds per day

•Due to the weaker gravitational field, clocks on the satellite gain 45 microseconds per day

•Satellite clocks gain a net of 38 microsecond per day

•Distance error = c*38 microseconds; c = 186,000 miles per second.

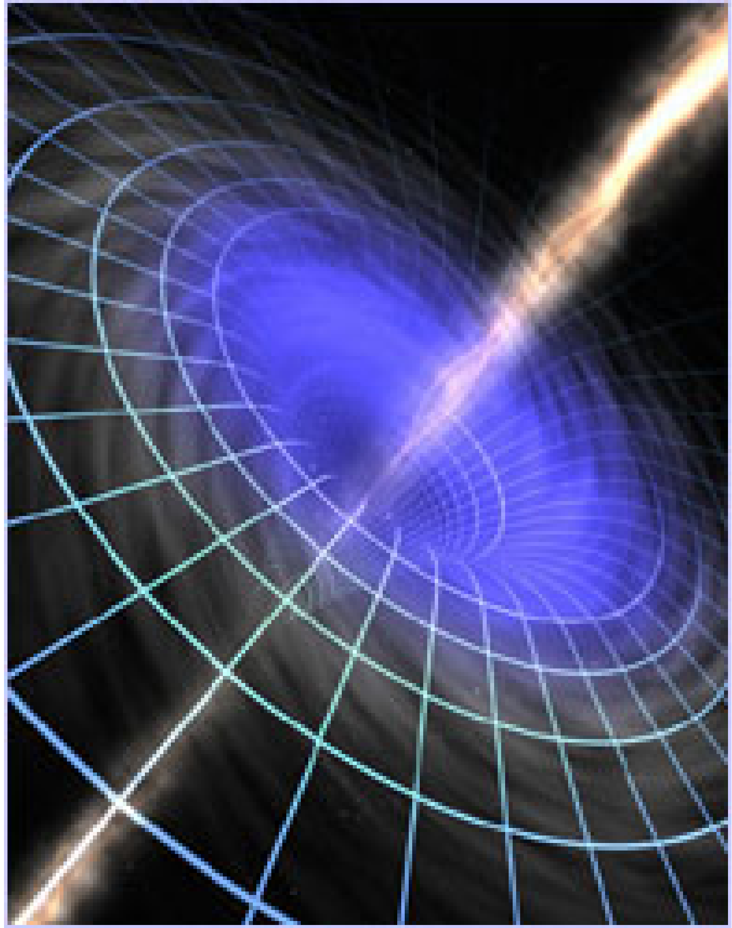
•Without calibrating clocks to account for Relativity, GPS distance would be off by 7 miles after one day!

See Scientific American, Sept. 1994

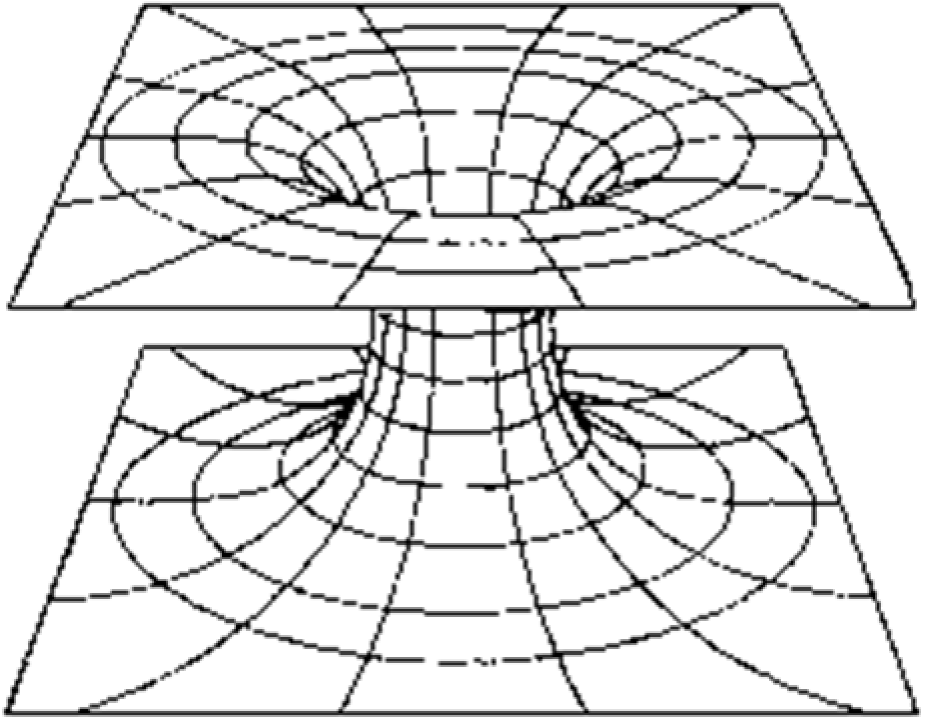
Illustration: NASA

Clock_Photos:http://en.wikipedia.org/wiki/Cuckoo_clock

Black Hole Embedding Diagrams

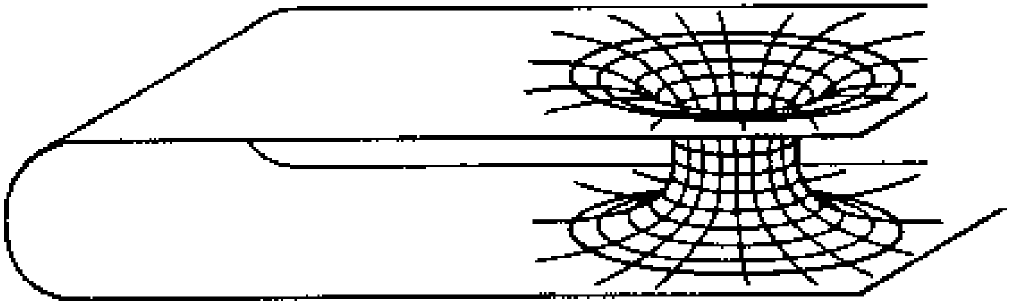


http://www.pbs.org/wgbh/nova/time/times peak.html; Photo: Photodisc Imaging



http://www.astrosociety.org/education/publications/tnl/2 4/24.html http://www.astrosociety.org/education/publications/tnl/24/24.html

Worm Holes
Time Travel & All That



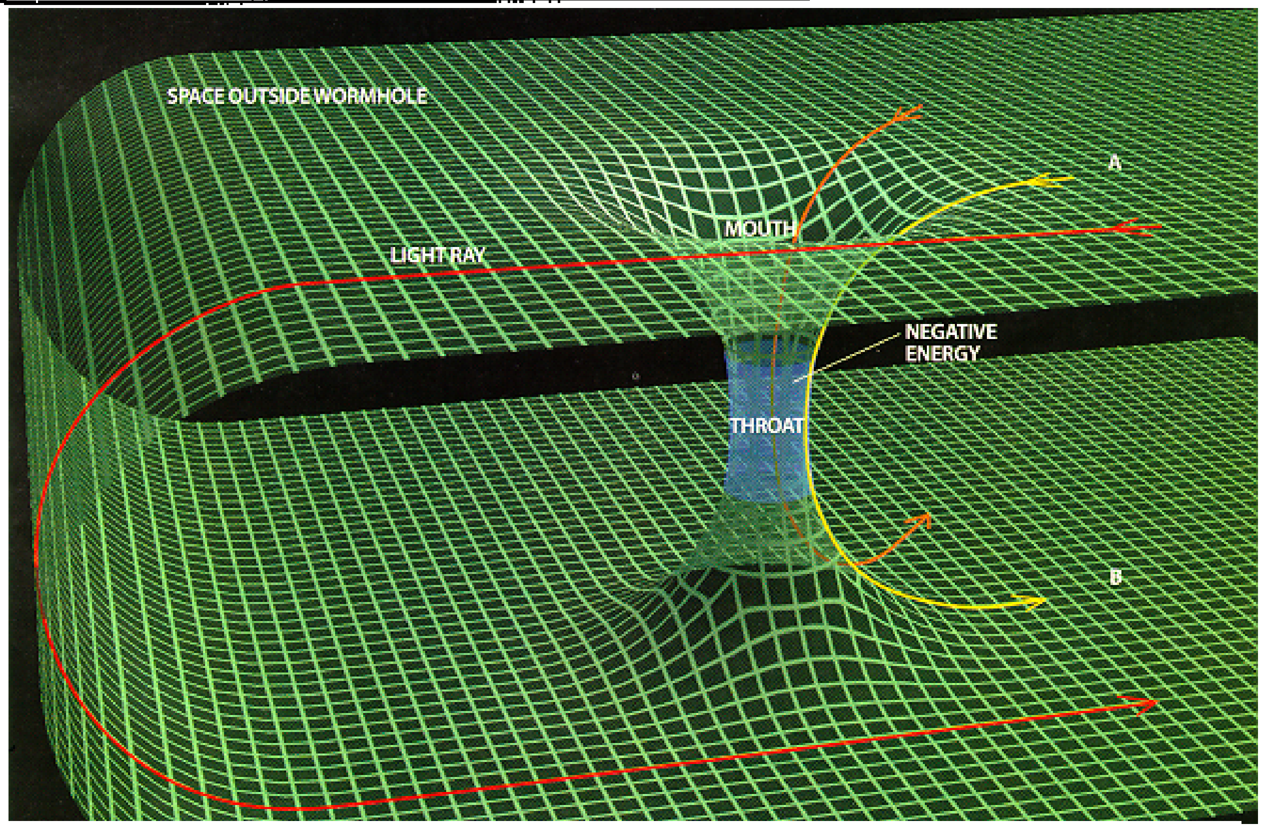
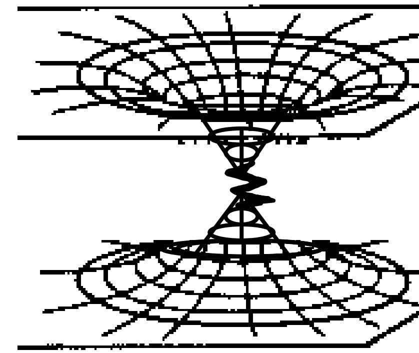
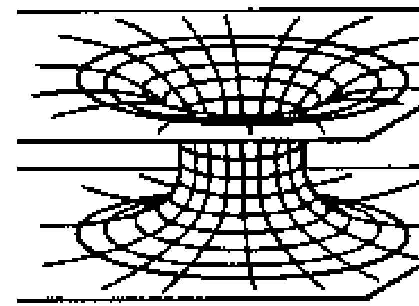
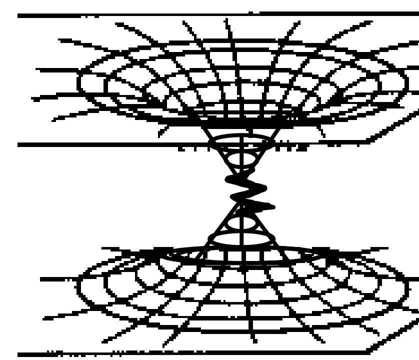


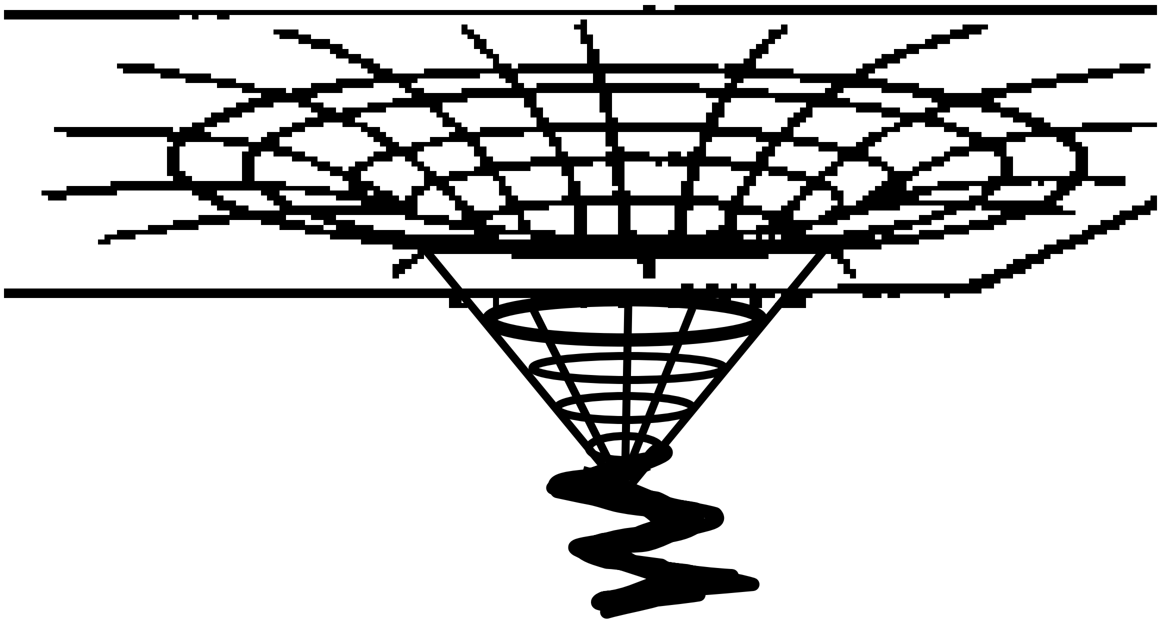
Figure: http://en.wikipedia.org/wiki/Worm_hole. Created by by Benji64 and originally uploaded to English Wikipedia (19:08, 4 March 2006). Made in 3D isis draw. Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License, Version 1.2 or any later version published by the Free Software Foundation; with no Invariant Sections, no Front-Cover Texts, and no Back-Cover Texts.Subject to disclaimers.







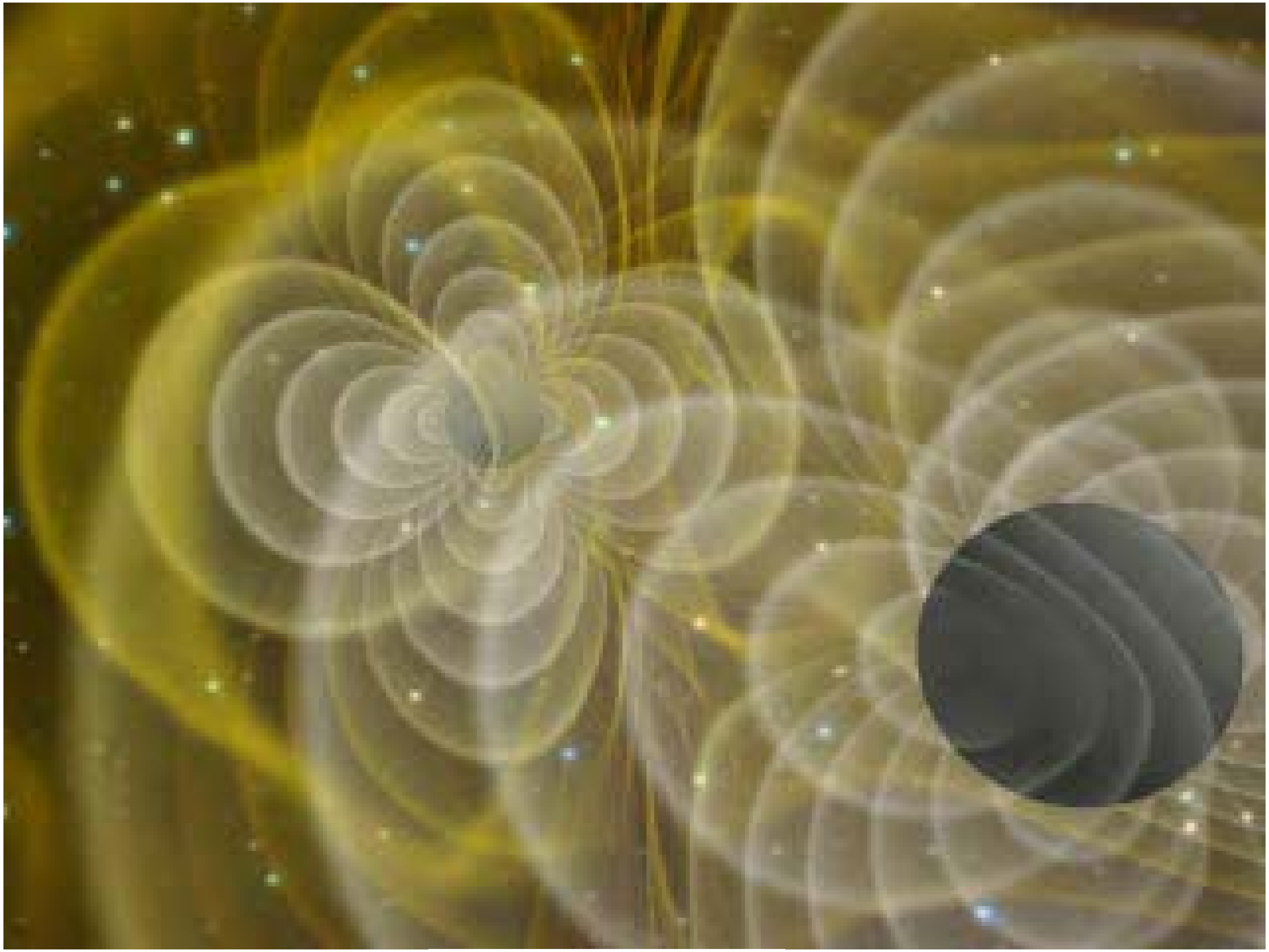
Stellar Collapse To Form A Black Hole



Singularity

Black Holes And LIGO

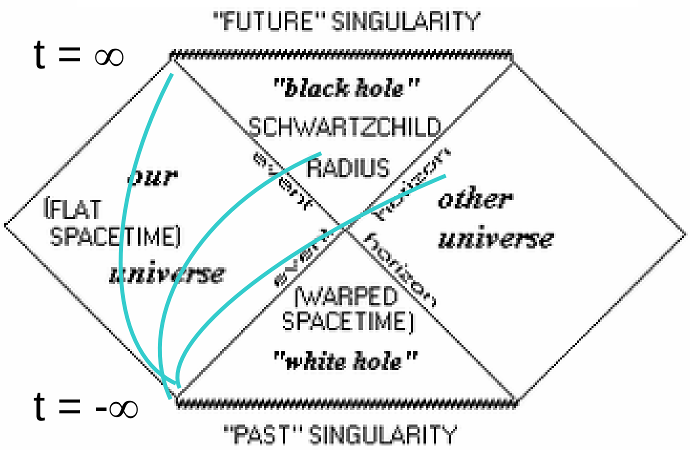
Credit:Henze, NASA; http://www.nasa.gov/vision/universe/starsgalaxies/gwave.html

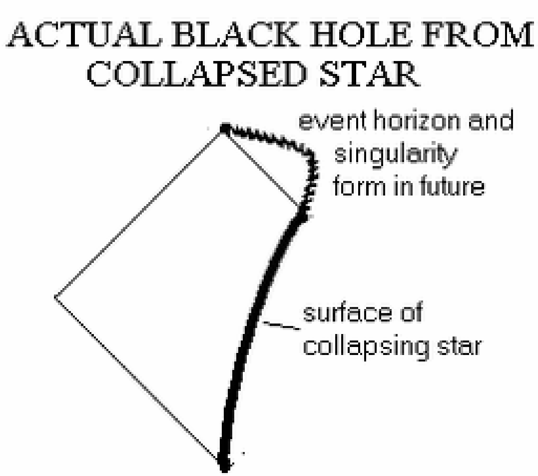


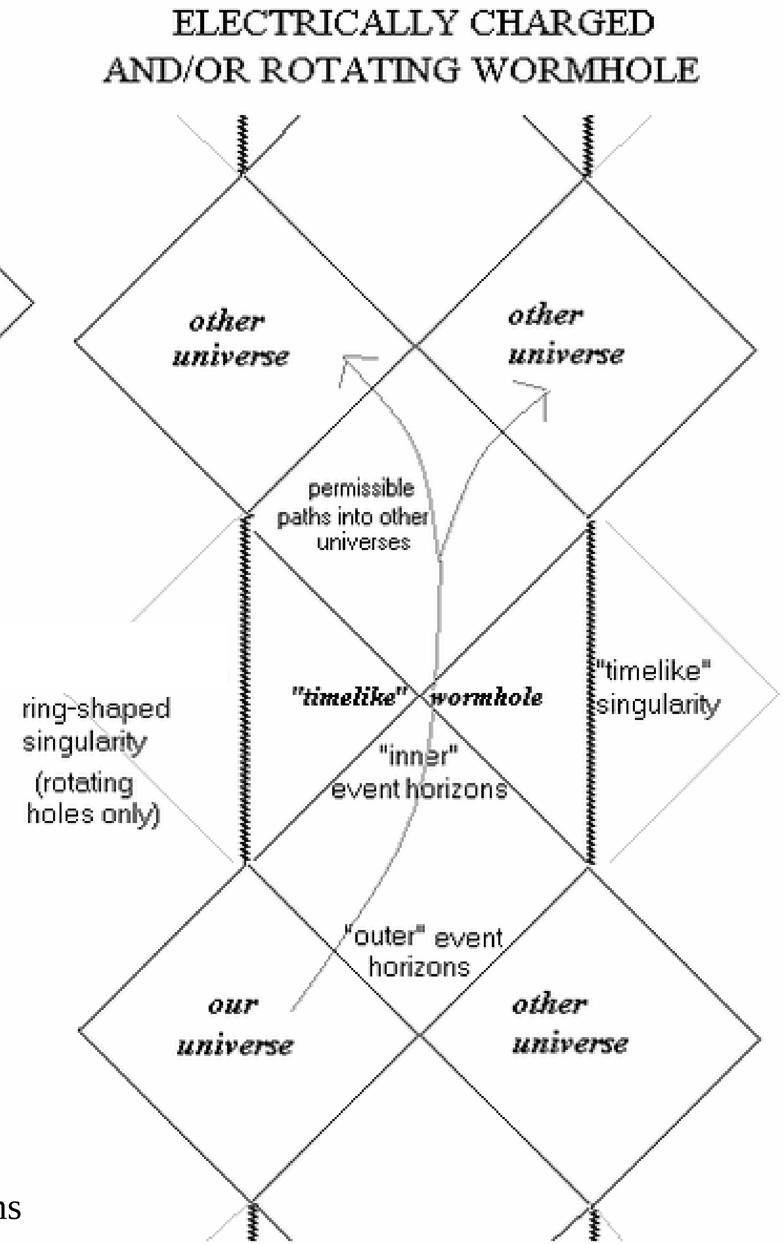
The End

Penrose Diagrams & Black Holes

Schwarzschild Black Hole



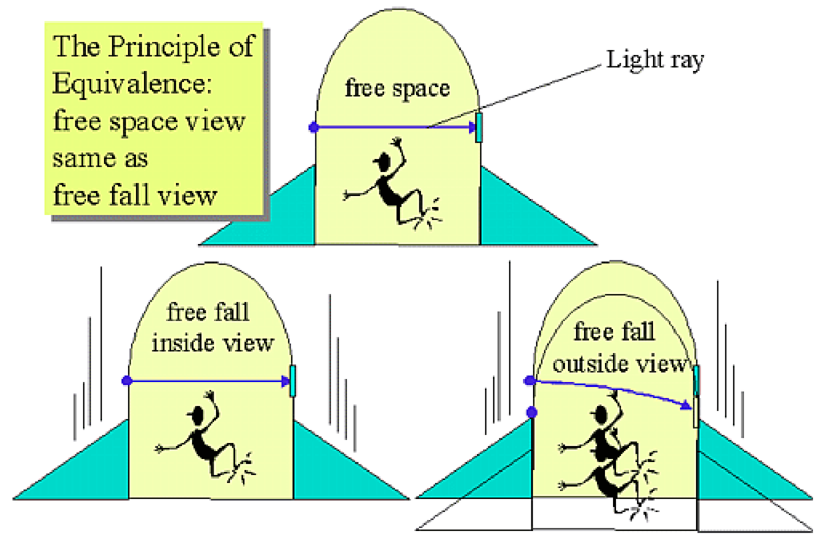




Figures: http://en.wikipedia.org/wiki/Penrose_diagrams

Equivalence Principle: Objects fall with the same acceleration in a gravitational field. There is an equivalence between gravity and acceleration.

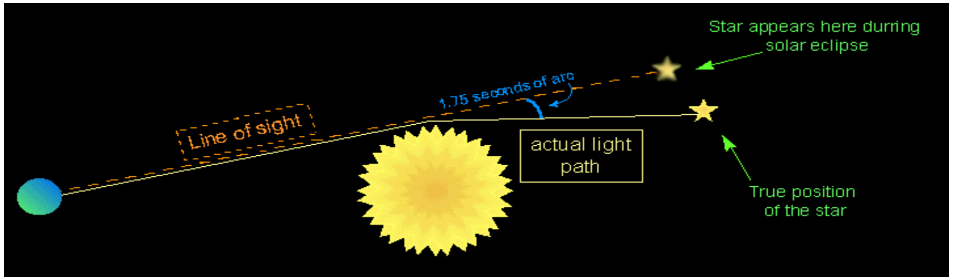
http://en.wikipedia.org/wiki/Leaning_Tower_of_Pisa



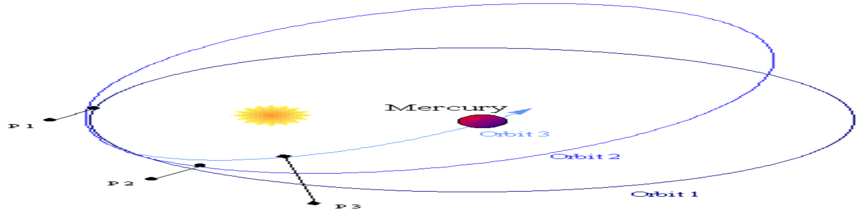
http://www.physics.fsu.edu/Courses/Spring98/AST3033/Relativity/GeneralRelativity.htm

Tests Of General Relativity

1. Bending of starlight by the Sun



2. Shift of Mercury's Perihelion by 43'' per century



Sun and Mercury Figures: http://www.astro.cornell.edu/academics/courses/astro201/astro201.html; http://www.astro.cornell.edu/academics/courses/astro201/topics.html; pages designed by Martha Haynes and Stirling Churchman

http://en.wikipedia.org/wiki/Leaning_Tower_of_Pisa

Gravitational Redshift of Light

Penrose Diagrams & Spacetime

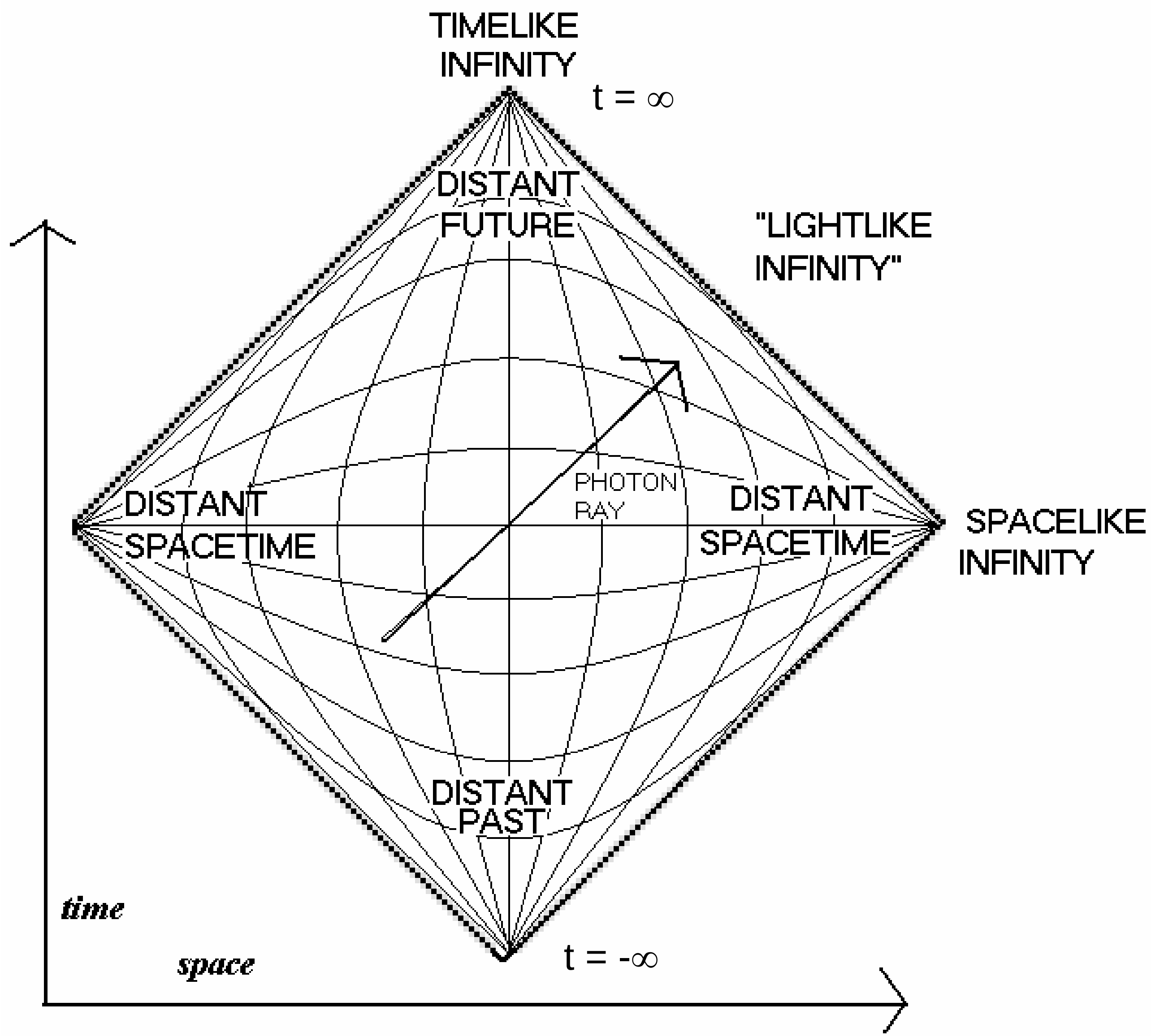
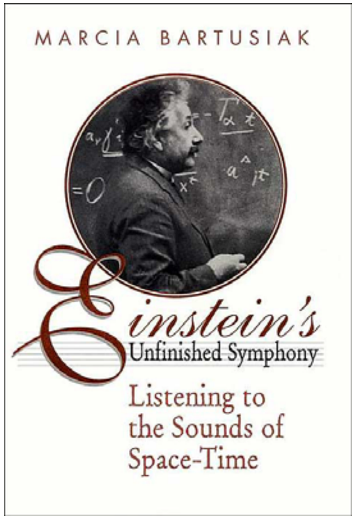
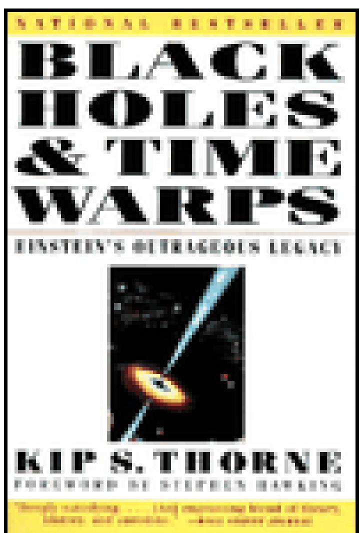


Figure: http://en.wikipedia.org/wiki/Penrose_diagrams

Further Reading

Popular:





Example LIGO Scientific Collaboration Papers:

arXiv.org Search Results

Back to Search form | Next 21 results

The URL for this search is http://xxx.lanl.gov/find/grp_physics/1/au:+LIGO/0/1/0/all/0/1

Showing results 1 through 25 (of 46 total) for au:ligo

1. gr-qc/0605028 [abs, ps, pdf, other] :
Title: **Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1:**
Authors: **The LIGO Scientific Collaboration**
Comments: 35 pages, 30 figures

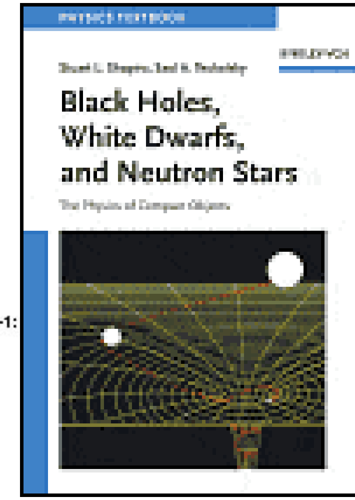
2. gr-qc/0512078 [abs, ps, pdf, other] :
Title: **Joint LIGO and TAMA300 Search for Gravitational Waves from Inspiralling Neutron Star Binaries**
Authors: **LIGO Scientific Collaboration, TAMA Collaboration**
Comments: 8 pages, 5 figures

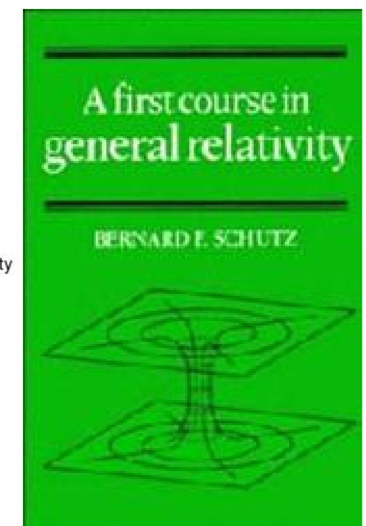
3. gr-qc/0511152 [abs, ps, pdf, other] :
Title: **Recent results on the search for continuous sources with LIGO and GEO600**
Authors: **Alicia M Sintes (for the LIGO Scientific Collaboration)**
Comments: TAUP2005 Proceedings to be published in Journal of Physics: Conference Series

4. gr-qc/0511146 [abs, ps, pdf, other] :
Title: **Search for gravitational wave bursts in LIGO's third science run**
Authors: **LIGO Scientific Collaboration**
Comments: 12 pages, 6 figures. Amaldi-6 conference proceedings to be published in Classical and Quantum Gravity
Journal-ref: Class.Quant.Grav. 23 (2006) S29-S39

5. gr-qc/0509129 [abs, ps, pdf, other] :
Title: **Search for gravitational waves from binary black hole inspirals in LIGO data**
Authors: **LIGO Scientific Collaboration: B. Abbott et. al**
Comments: 18 pages, 8 figures
Journal-ref: Phys.Rev. D73 (2006) 062001

Textbooks:





LIGO & Gravitational Waves

Gravitational waves carry information about the spacetime around black holes & other sources.

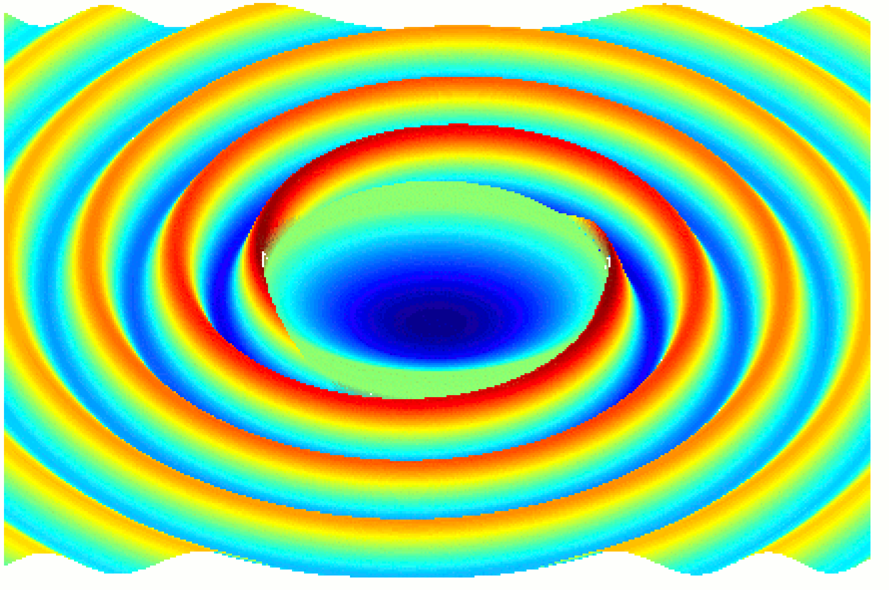
$$dT^2 = g_{\mu\nu} dx^{\mu} dx^{\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \bar{h}^{\mu\nu} = 0$$

$$h^{TT}_{\hat{\theta}\hat{\theta}} (\theta = \pi / 2) \propto \frac{1}{r} \cos[2\pi f (t - r / c) + 2\phi]$$

$$h^{TT}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} e^{2\pi i f (t - z/c)}$$



The Pythagorean Theorem Of Spacetime

$$c^2\Delta T^2 + v^2\Delta t^2 = c^2\Delta t^2$$

$$c^2\Delta T^2 = c^2\Delta t^2 - v^2\Delta t^2$$

$$c^2\Delta T^2 = c^2\Delta t^2 - \Delta x^2$$

c = 1 light-year/year

$$\boxed{\Delta T^2 = \Delta t^2 - \Delta x^2}$$

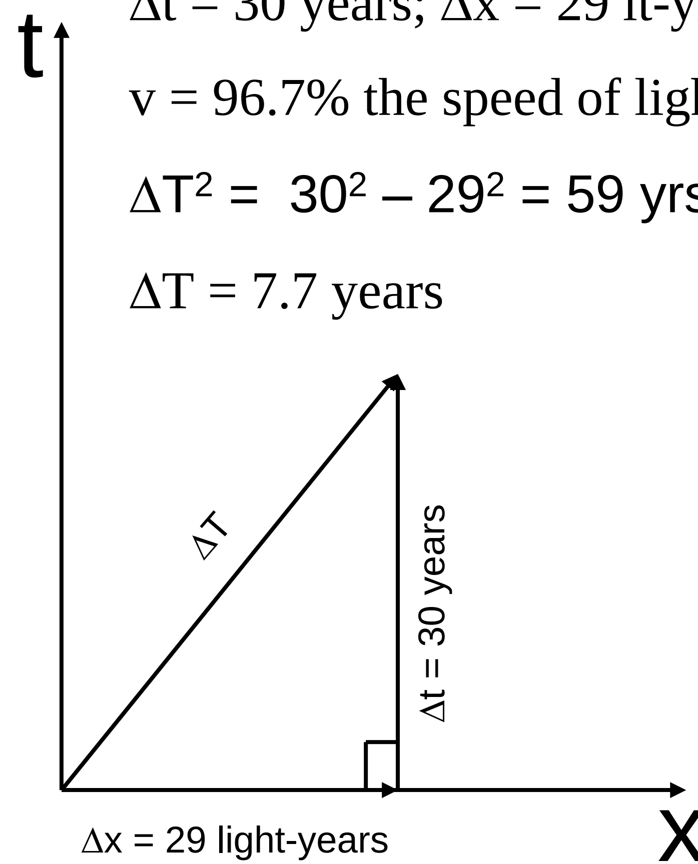
Pythagorean Thm. of Spacetime

Δt = 30 years; Δx = 29 lt-yrs.

v = 96.7% the speed of light

$\Delta T^2 = 30^2 - 29^2 = 59$ yrs^2

ΔT = 7.7 years



Spacetime

$E=mc^2$

$$c^2\Delta t^2 = c^2\Delta T^2 + v^2\Delta t^2$$

$$m^2c^4\Delta t^2 = m^2c^4\Delta T^2 + m^2c^2v^2\Delta t^2$$

$$m^2c^4\Delta t^2/\Delta T^2 = m^2c^4 + m^2c^2v^2\Delta t^2/\Delta T^2$$

$$[mc^2/(1-v^2/c^2)^{1/2}]^2 = [mc^2]^2 + [mv/(1-v^2/c^2)^{1/2}]^2c^2$$

$$[mc^2 + 1/2mv^2]^2 = E^2 = [mc^2]^2 + p^2c^2$$

For $v = 0$: $E = mc^2$

Newtonian Momentum

Approximate to order v^2/c^2 == Newtonian Kinetic Energy

Pythagorean Theorem and Einstein's General Theory of Relativity

$\Delta \rightarrow$ d = infinitesimal change

$dT^2 = g_{tt}dt^2 + g_{xx}dx^2$

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

In GR the components of a 4x4 symmetric matrix called the metric tensor define the curvature of spacetime.

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$$

$$R_{\mu\nu} = R^{\alpha}{}_{\mu\alpha\nu}; R = g^{\mu\nu} R_{\mu\nu}$$

$$R^{\alpha}{}_{\mu\beta\nu} = \partial_\beta \Gamma^{\alpha}{}_{\mu\nu} - \partial_\nu \Gamma^{\alpha}{}_{\mu\beta} + \Gamma^{\alpha}{}_{\beta\gamma}\Gamma^{\gamma}{}_{\mu\nu} - \Gamma^{\alpha}{}_{\gamma\nu}\Gamma^{\gamma}{}_{\mu\beta}$$

$$\Gamma^{\alpha}{}_{\mu\nu} = \frac{1}{2} g^{\alpha\beta} (\partial_\nu g_{\mu\beta} + \partial_\mu g_{\beta\nu} - \partial_\beta g_{\mu\nu})$$

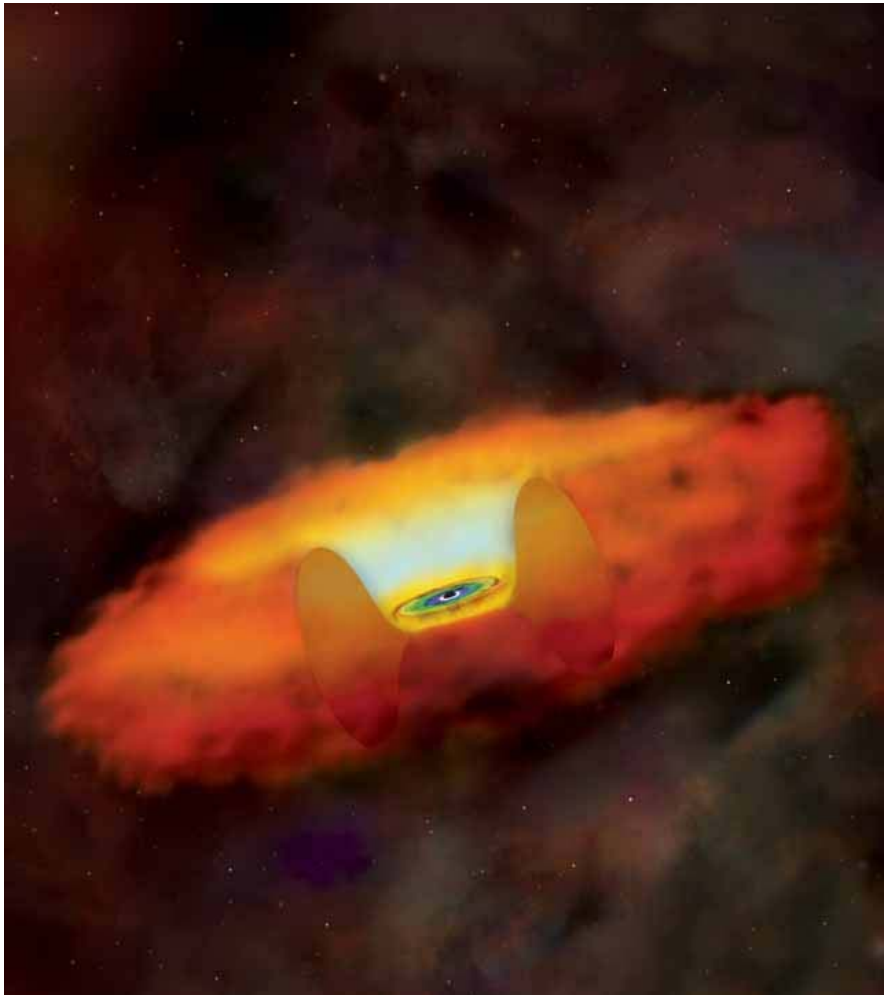
Einstein's Field Equations

Black Hole Formation: Supernovae

Photo: Supernova 1987A
http://www.aao.gov.au/images/captions/aat050.html

Anglo-Australian Observatory, photo by David Malin.

Black Holes & Accretion Disks



http://researchnews.osu.edu/archive/fuzzballpic.htm
(Illustration: CXC/M.Weiss)

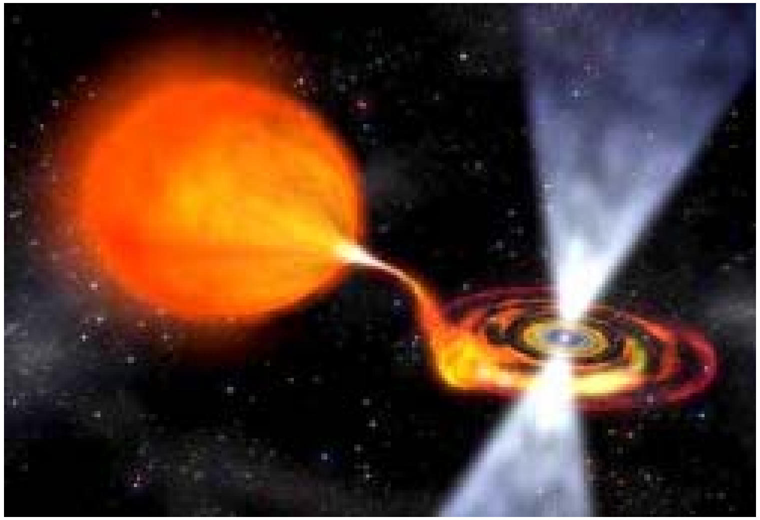
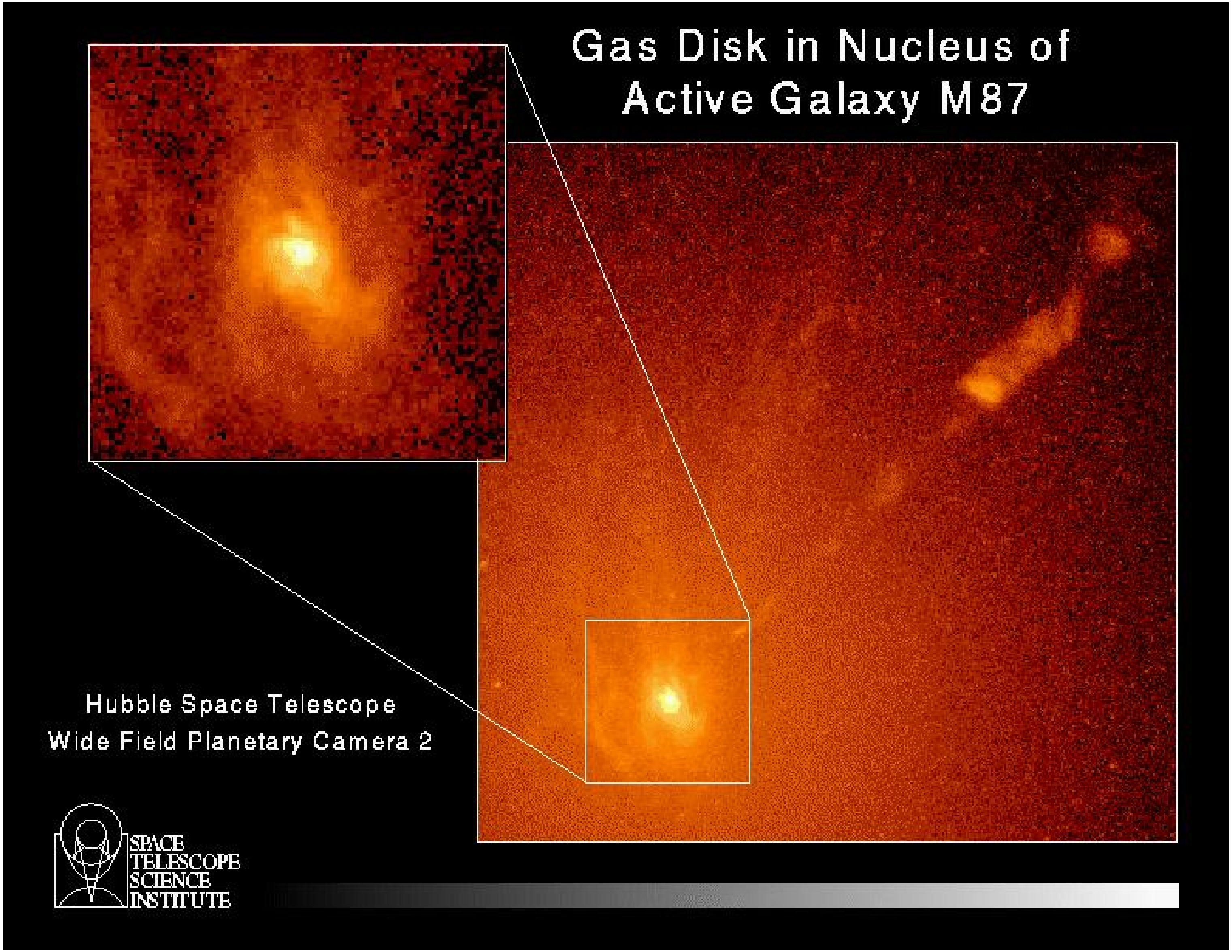
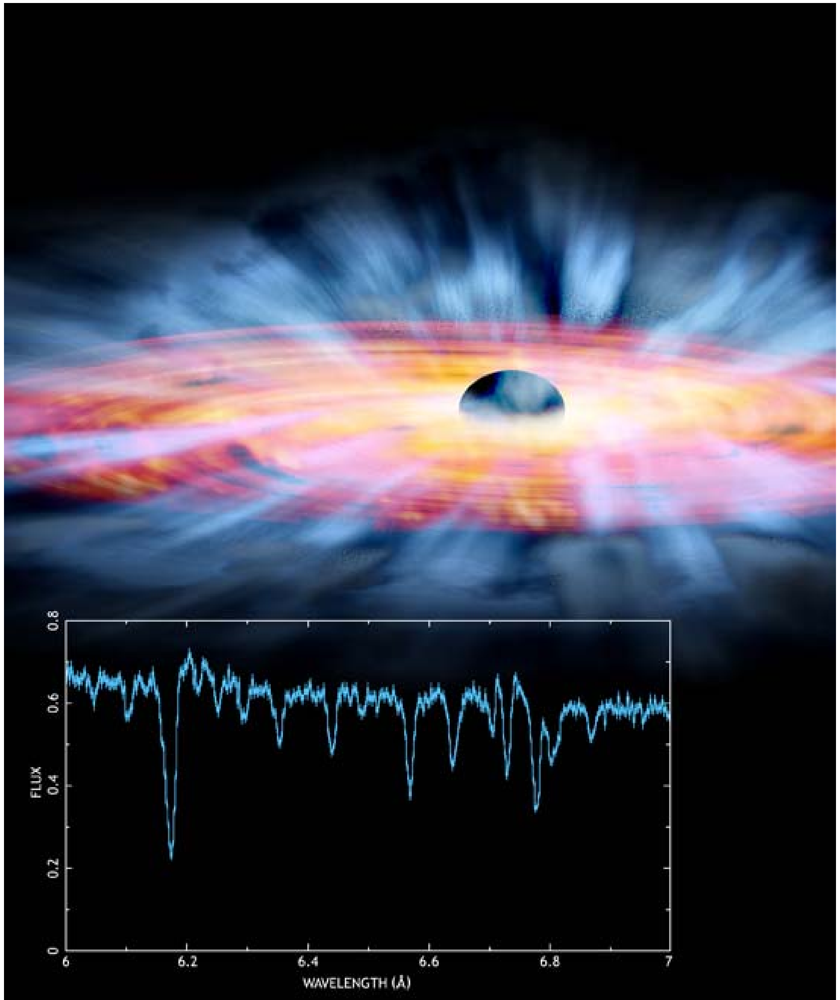


image by Dana Berry/NASA; NASA News Release posted July 2, 2003 on Spaceflight Now.

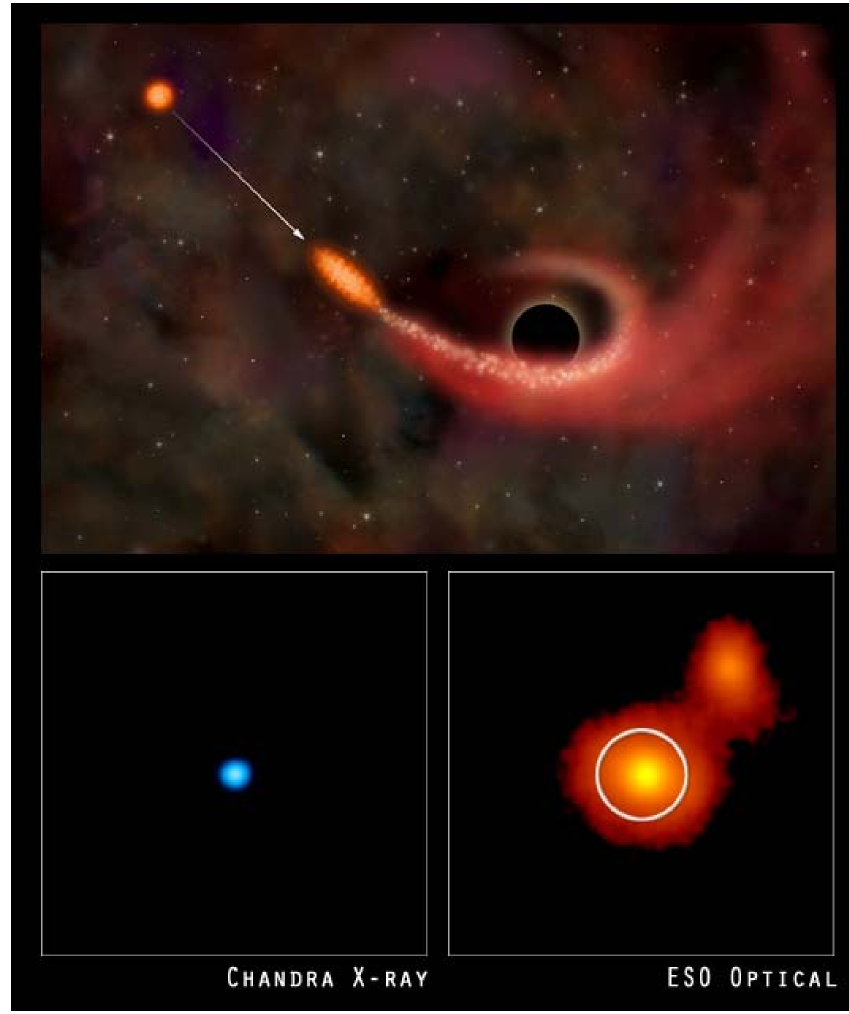
Black Hole Detection



Black Hole Detection



http://chandra.harvard.edu/photo/2006/j1655/; Credit: Illustration: NASA/CXC/M.Weiss; X-ray Spectrum: NASA/CXC/U.Michigan/J.Miller et al.



http://chandra.harvard.edu/photo/2004/rxj1242/index.html; Credit: Illustration: NASA/CXC/M.Weiss; X-ray: NASA/CXC/MPE/S.Komossa et al.; Optical: ESO/MPE/S.Komossa