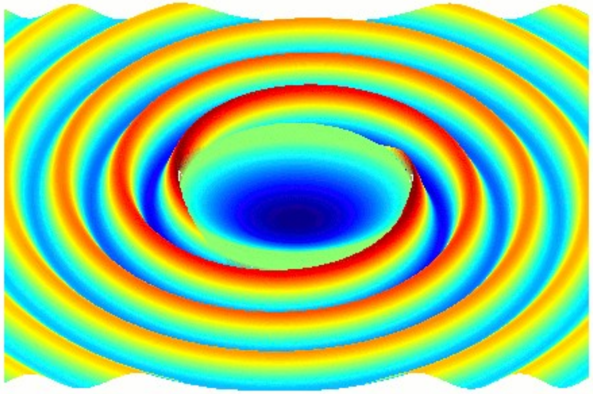
Using LIGO To Listen For Gravitational Waves

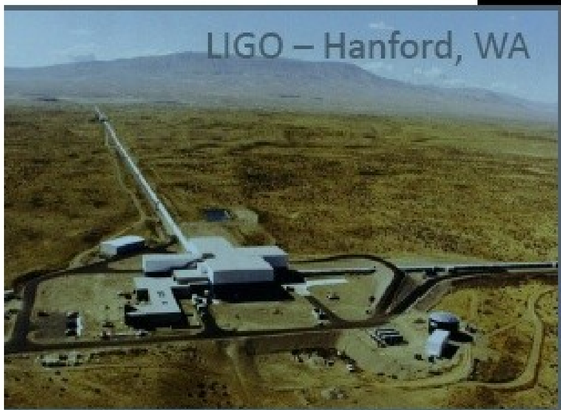


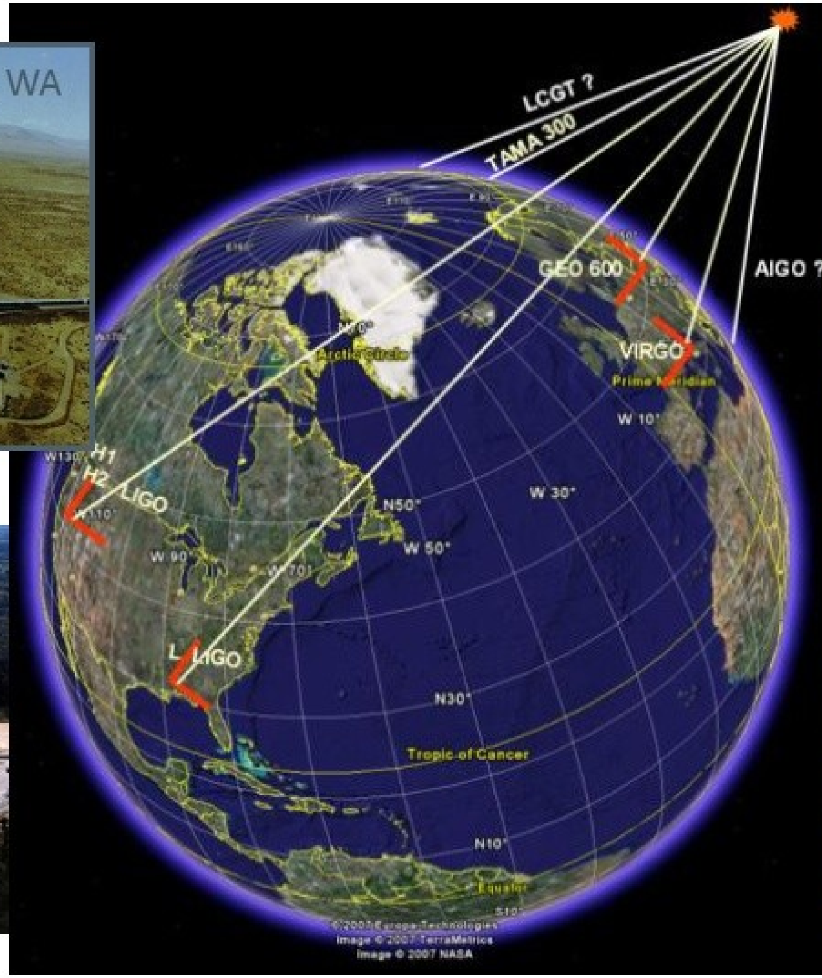
The Laser Interferometer Gravitational-wave Observatory: a Caltech/MIT collaboration supported by the National Science Foundation

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

LIGO-G1000736

The LIGO-Virgo network



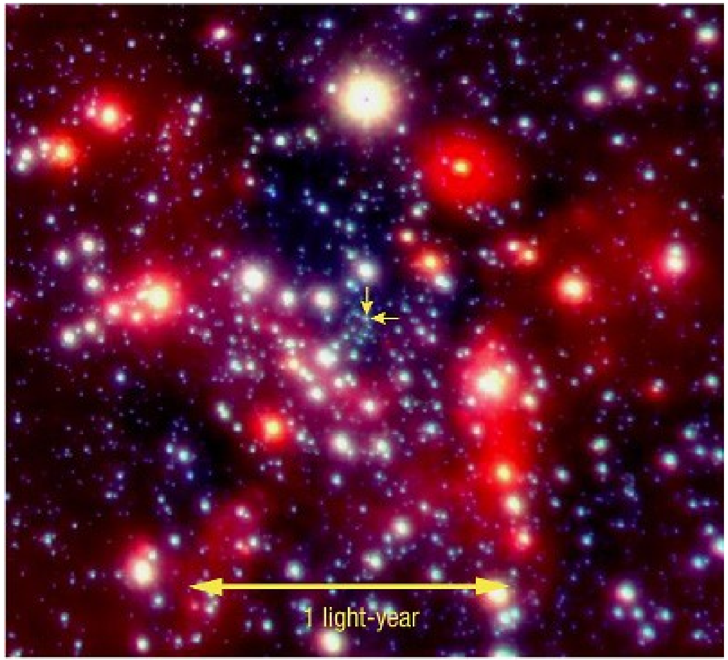


600+ Scientist and Engineers

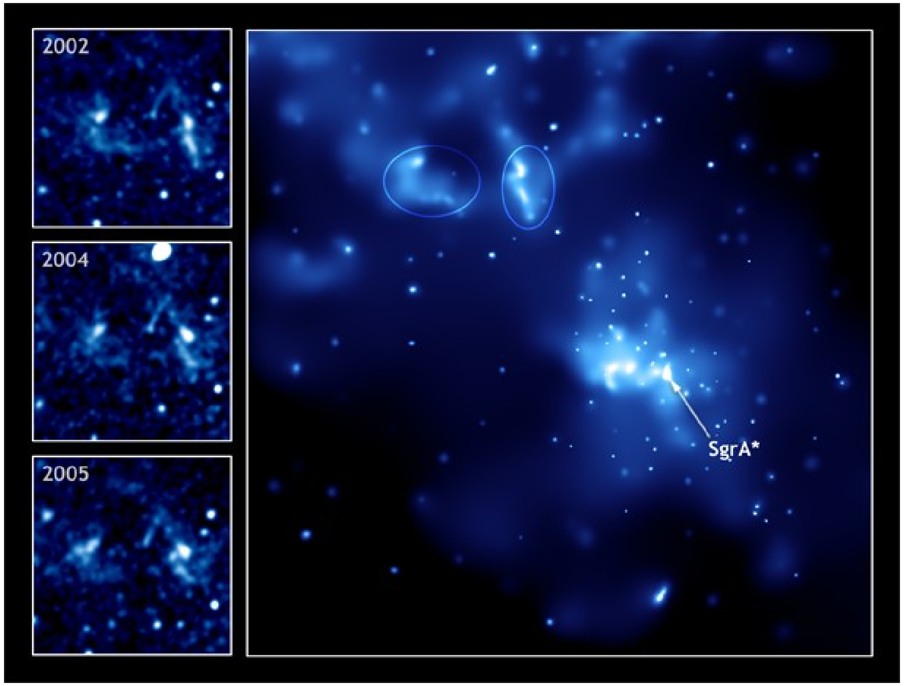
Some Far Out Ideas

- There are crazy things in the universe which we cannot see. Examples are black holes, the interiors of supernovae and dense stars, and the first moments after the big bang.
- Gravity dominates the crazies.
- It all starts with Einstein…
- General Relativity shows that space and time form a fabric that mass and energy can stretch, squeeze, and cause to vibrate; we experience this as gravity.
- Gravitational waves are ripples in the fabric of spacetime.
- LIGO and other detectors are “listening” for these waves.
- The Advanced LIGO Project has started; when completed it and other advanced detectors will increase the odds of discover over a thousand-fold.

What can we see using electromagnetic waves?

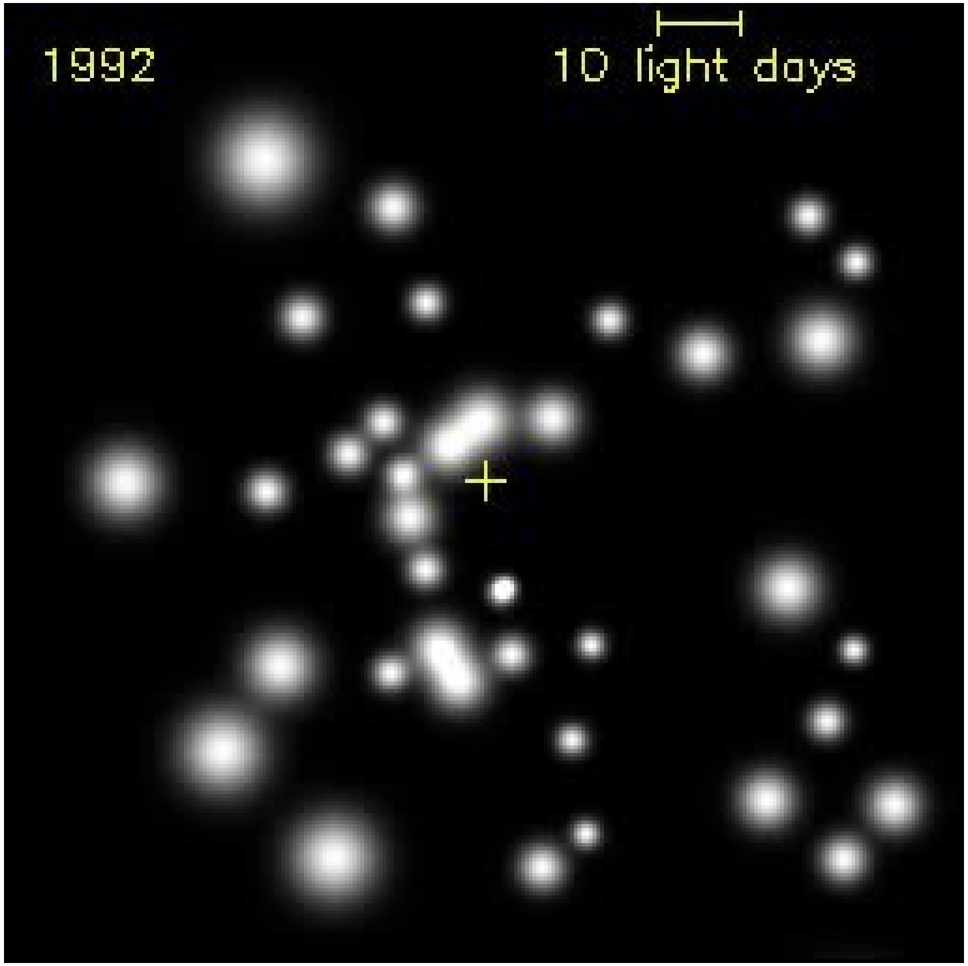


The Centre of the Milky Way
(VLT YEPUN + NACO)
ESO PR Photo 23a/02 (9 October 2002)
©European Southern Observatory



Credit: NASA/Chandra X-Ray Observatory

Zooming in on the galactic center…



Credit: ESO PR Video Clip 02/02; ESO/European Organization for Astronomical Research in the Southern Hemisphere; Press Release 2002

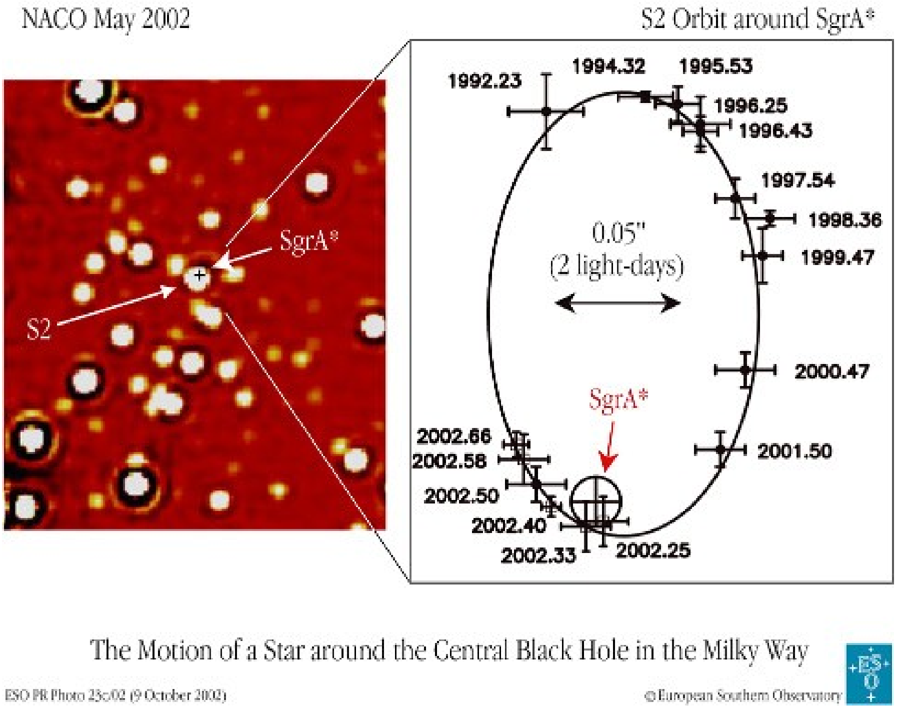
Black Holes

$$M = \frac{4\pi^2 a^3}{GT^2}$$

$$M = \frac{(900AU)^3}{(15yrs)^2}$$

= 3 million Solar Masses

Credit: ESO PR Photo 23c/02; ESO/European Organization for Astronomical Reseach in the Southern Hemisphere; Press Release 2002



Conclusion: there is a Black Hole at the center of our Galaxy that has a mass 3 millions times (or more precisely 3.95 million times) that of the Sun. S2 orbits this Black Hole at a distance of 12000 Schwarzchild Radii.

Supernovae

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

Anglo-Australian Observatory, photo by David Malin.

Pulsars

Play Me

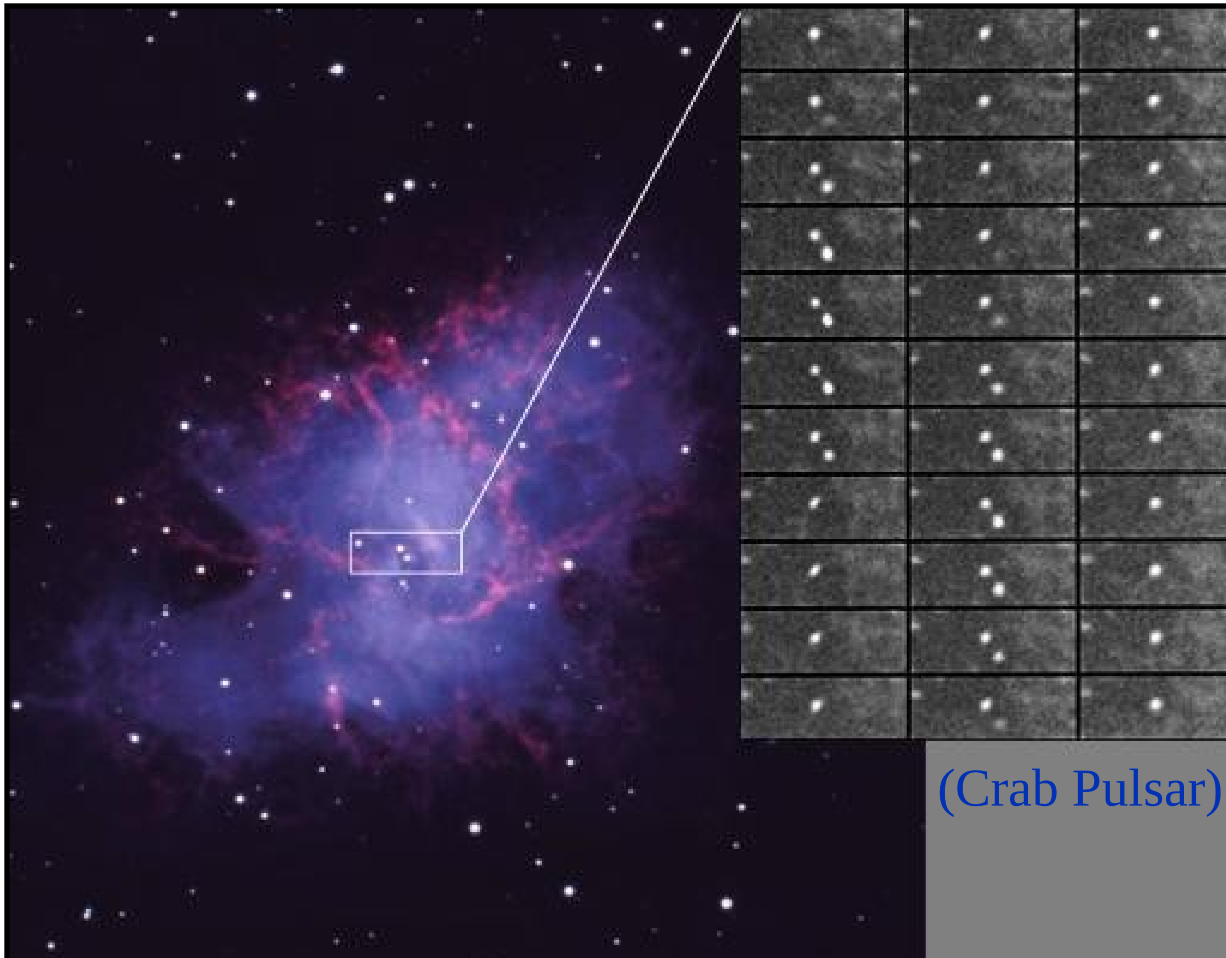
(Vela Pulsar)

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Jodrell Bank Observatory,

Dept. of Physics & Astronomy,

The University of Manchester



(Crab Pulsar)

http://www.noao.edu/image_gallery/html/im0565.html

Crab Pulsar: N.A.Sharp/NOAO/AURA/NSF

The back of the envelope please…

Don't take this the wrong way…

$$\frac{\text{1.4 Solar Masses}}{\text{10 km Sphere}} = \frac{1.4(1.99 \times 10^{33}\text{ g})}{4/3\pi(10^{6}\text{ cm})^{3}}$$

Average density = 6.7×10^{14} g/cm ^{3}

$$\frac{\text{Mass neutron}}{\text{Volume neutron}} = \frac{1.67 \times 10^{-24}\text{ g}}{4/3\,\pi\,(10^{-13}\text{ cm})^{3}}$$

= 4.0×10^{14} g/cm ^{3} (billion tons/teaspoon)

… but parts of you are as dense as a neutron star.

$p + e \rightleftarrows n + \nu_e$ (inverse beta and beta decay)

$\mu_p + \mu_e = \mu_n$ (beta equilibrium)

$n_p = n_e$ (charge neutrality)

Seen: SN 1987A!

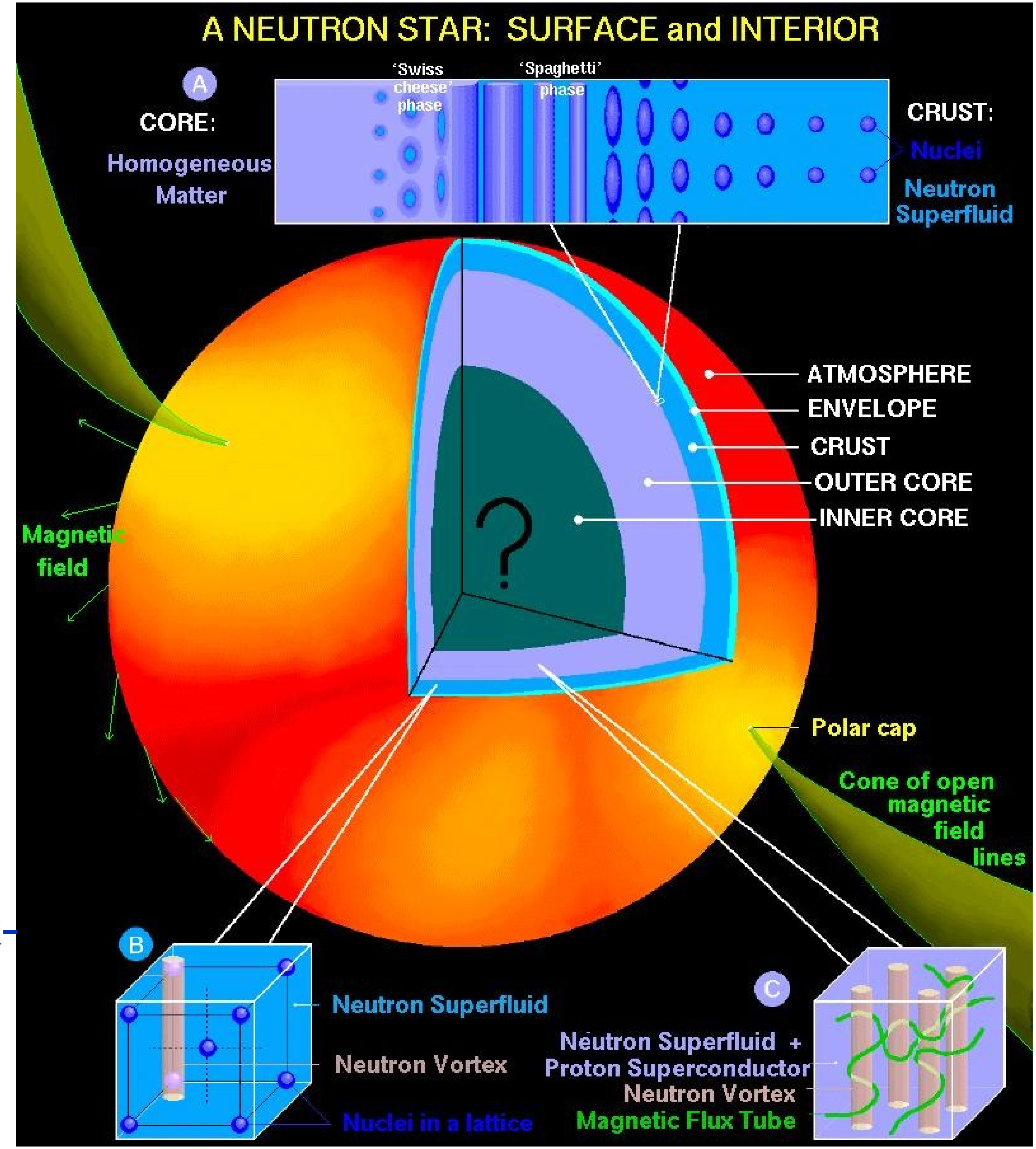
Nuclear density: 95% n, 5% p & e

LIGO

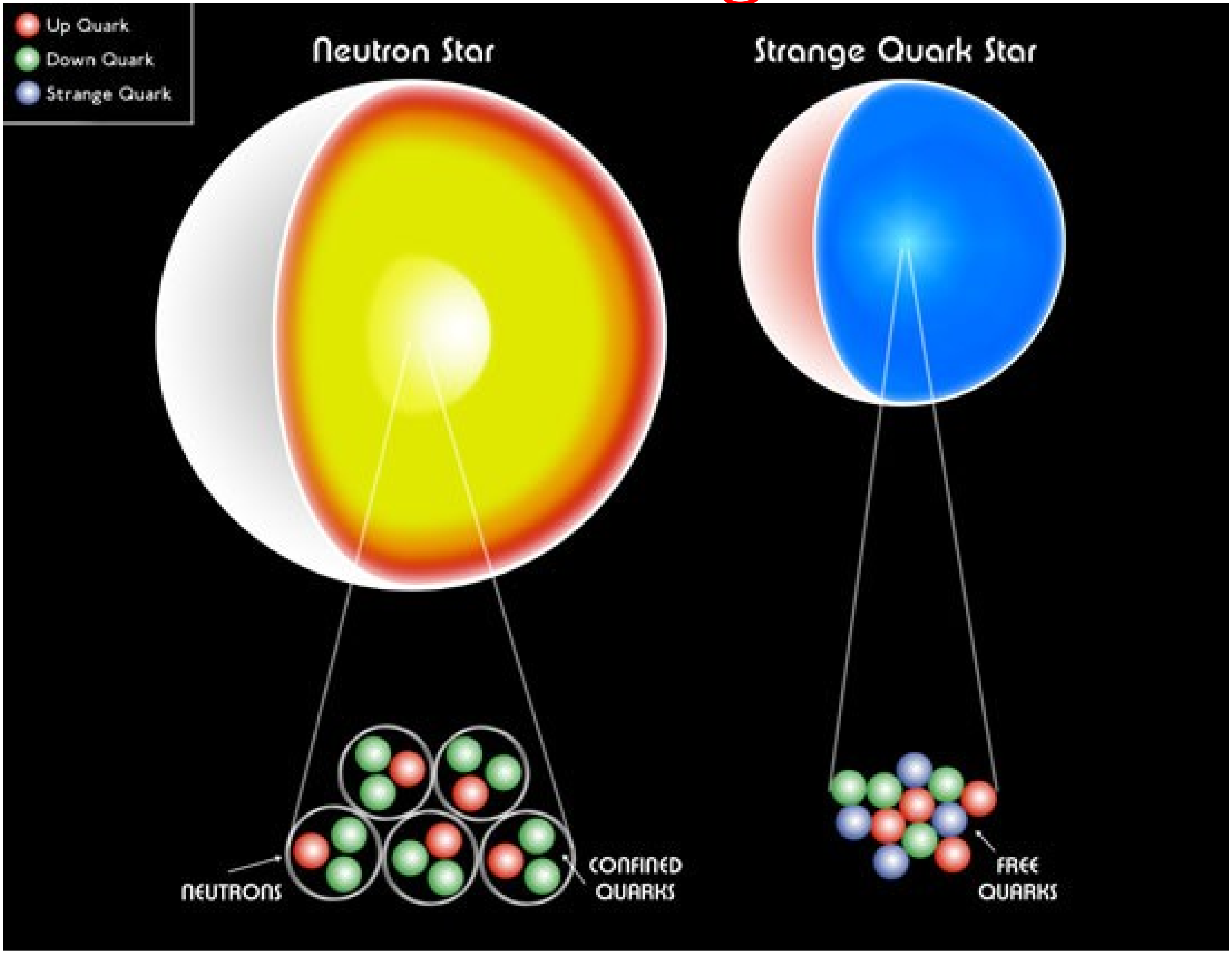
Getting dense…

- Fermi Temp: 10^{12} K.
- NS born at 10^{11} K, cools below 10^{9} K within a year; form superfluid neutrons, superconducting protons .
- Cools to 10^{6} K after 10^{7} yrs; glows with x-rays.

D. Page http://www.astroscu.unam.mx/neutrones/home.html

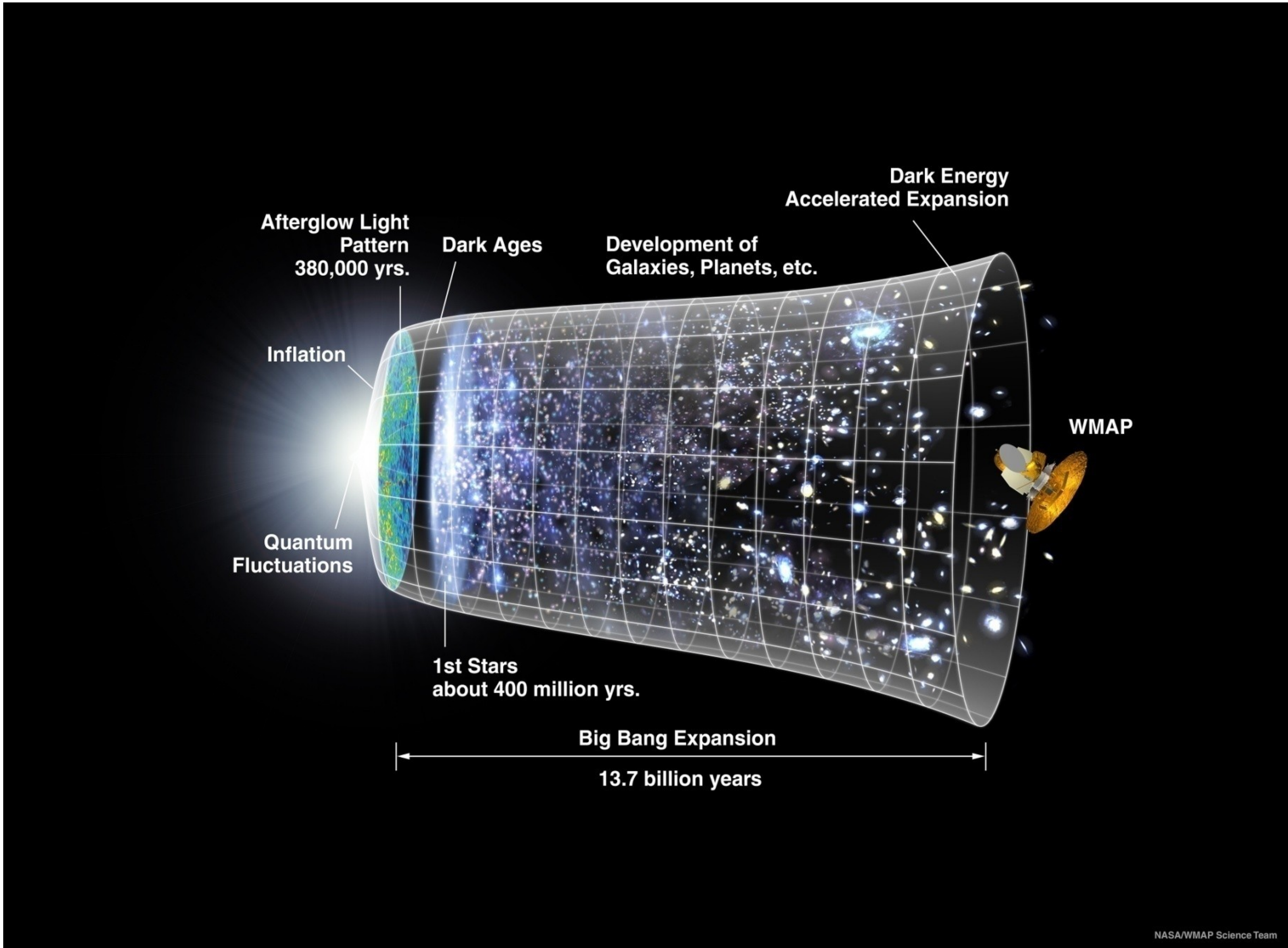


…and strange…



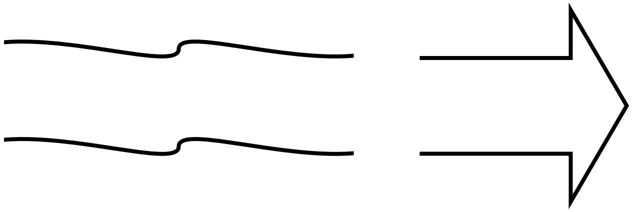
http://chandra.harvard.edu/resources/illustrations/neutronstars_4.html; NASA/CXC/SAO

The Big Bang


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Einstein Wondered:

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



Can we catch light?

Mirror

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

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

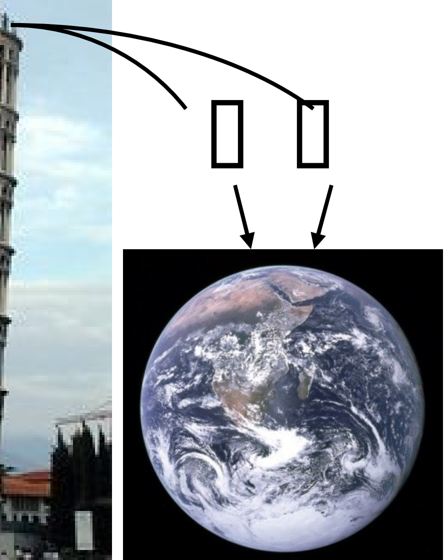
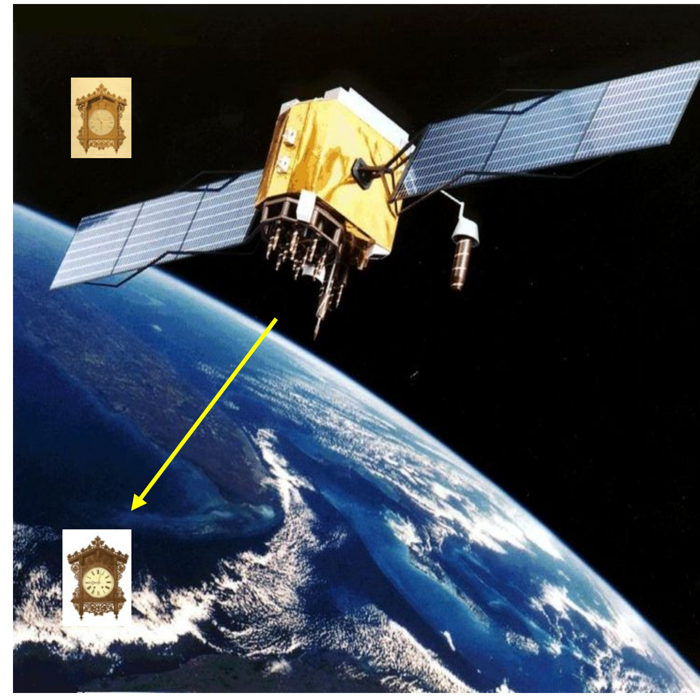


Photo: NASA



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

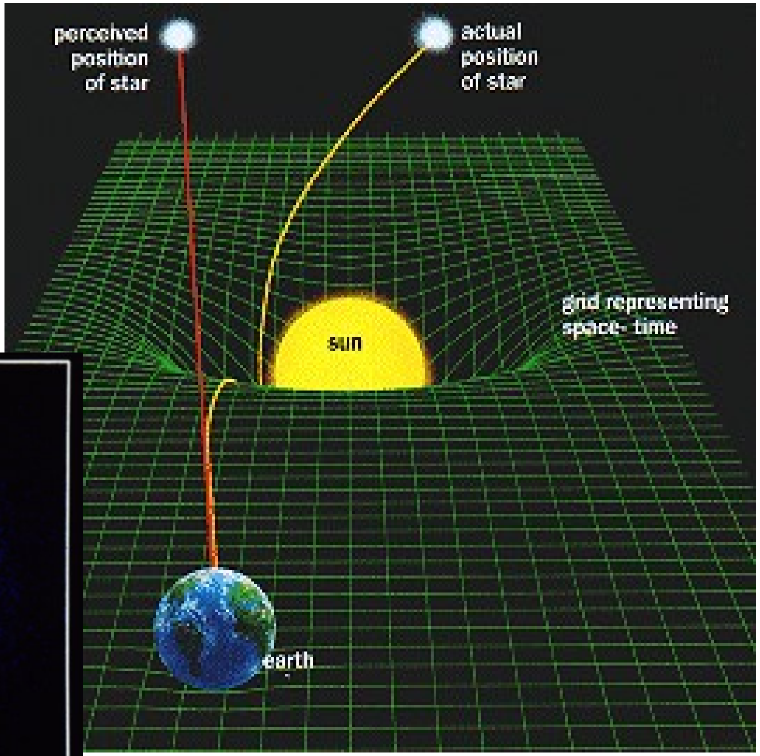
Gravity warps space and time

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

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

Figure: Focus Mar95 p30

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

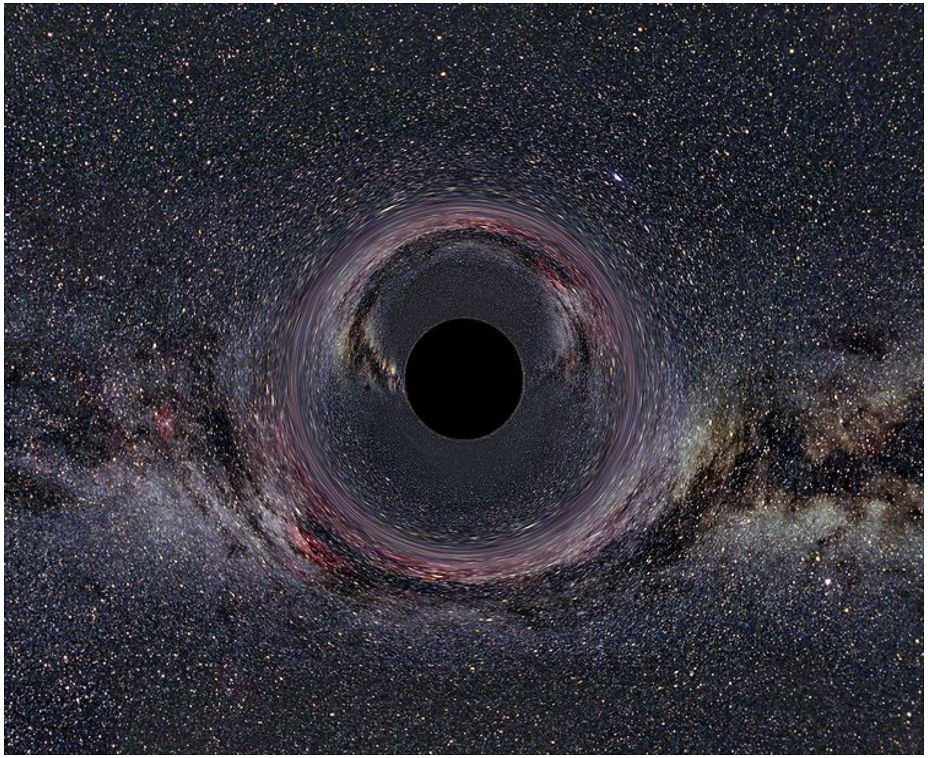


A massive object shifts apparent position of a star

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!

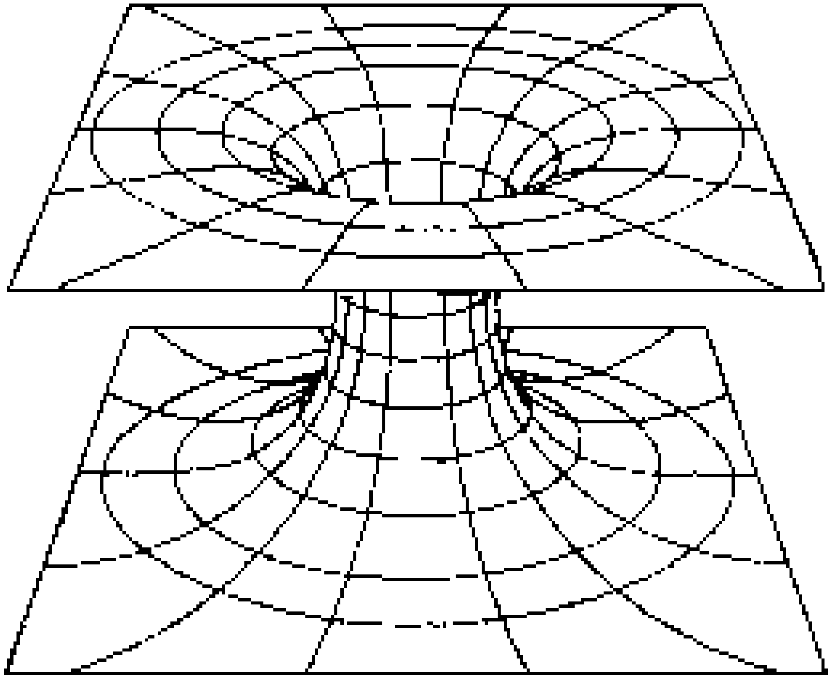
Photo credit: NASA and European Space Agency (ESA)

Black Holes



Simulation of a 10 Solar Mass Black Hole 600 km away, in front of the Milky Way.

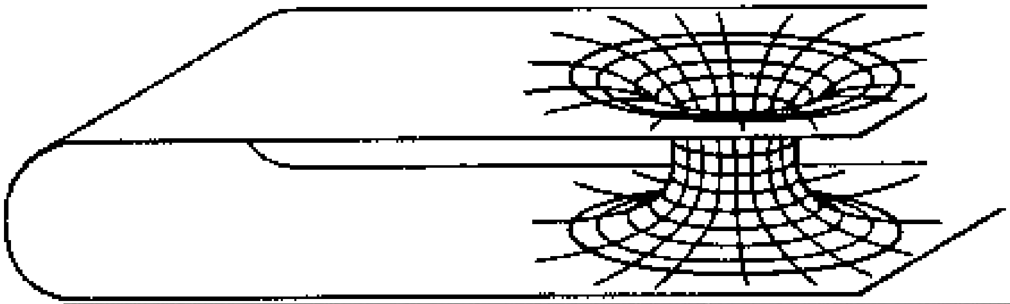
Image: Ute Kraus, physics education group (Kraus), Universität Hildesheim, Space Time Travel (http://www.spacetimetravel.org/)



Two dimensional slice of a Schwarzschild Black Hole embedded in three dimensional space.

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

Worm Holes
Time Travel & All That



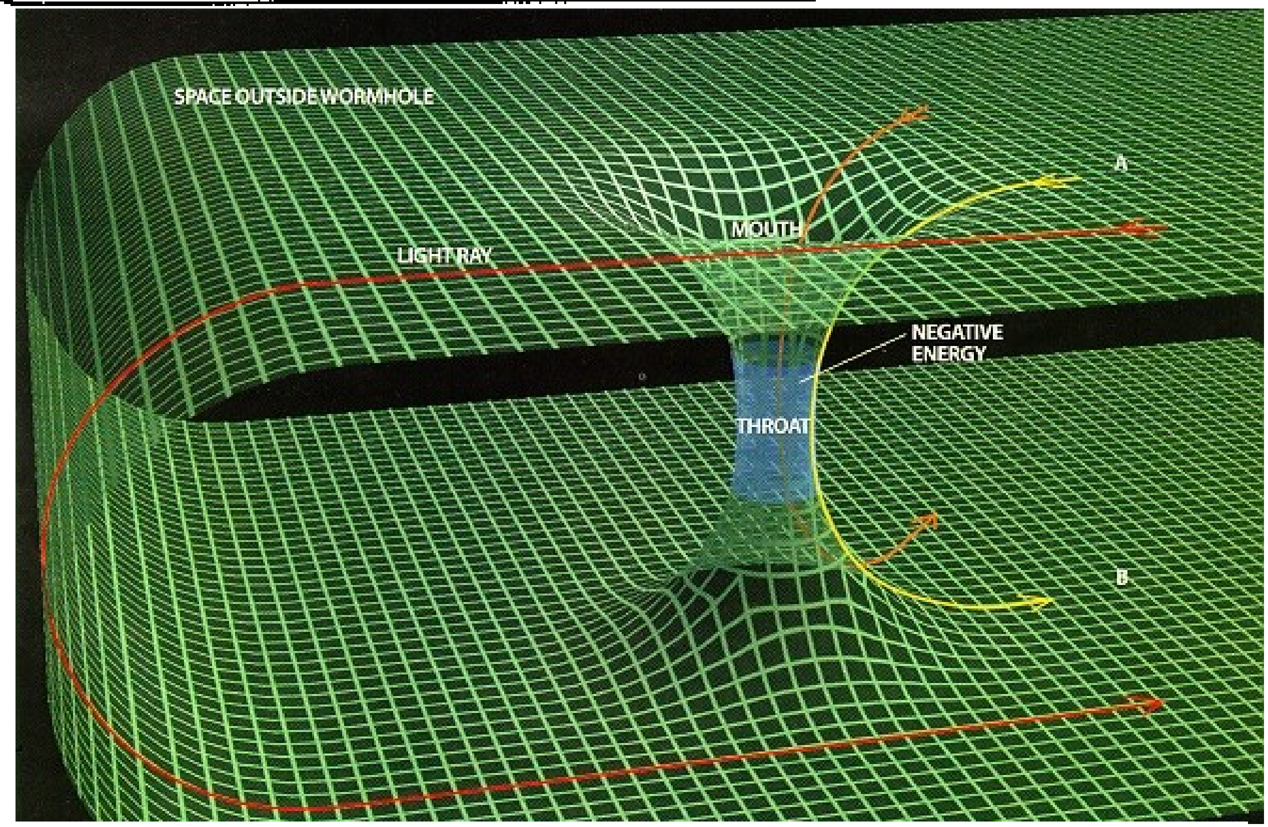
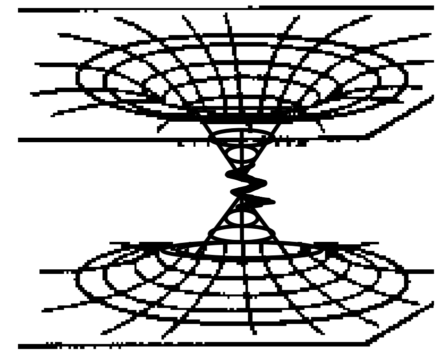
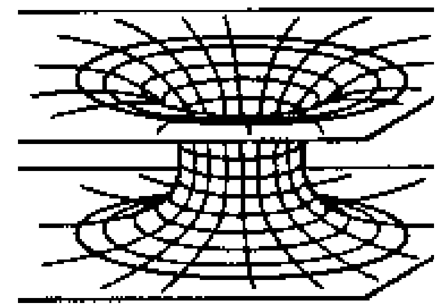
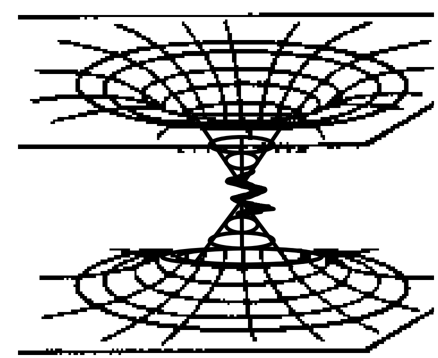


Figure: http://en.wikipedia.org/wiki/Worm_hole. Created by by Benji64 and originally uploaded to English Wikipedia (19:08, 4 March 2006). Made in 3D isis draw. Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License, Version 1.2 or any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

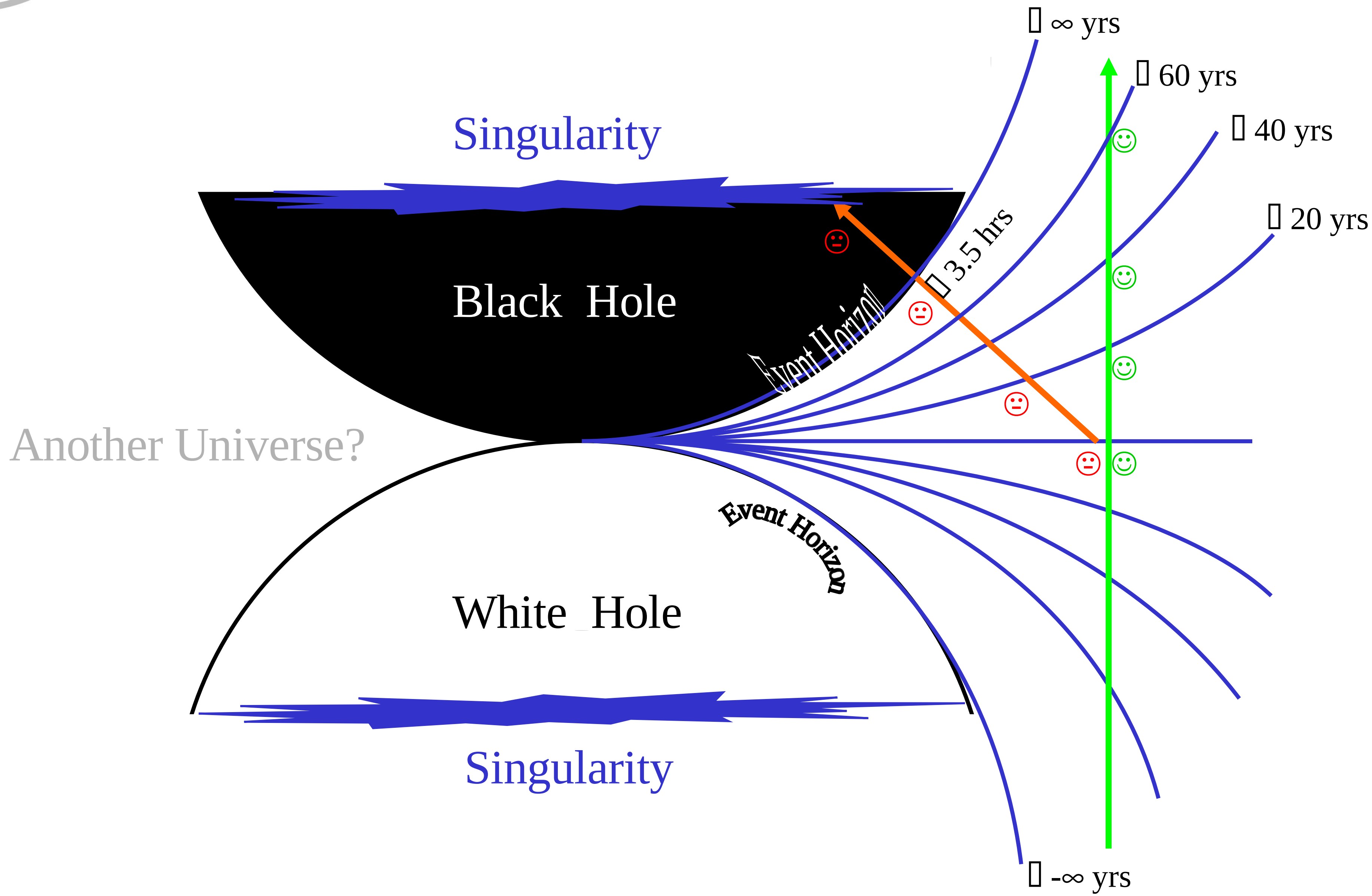




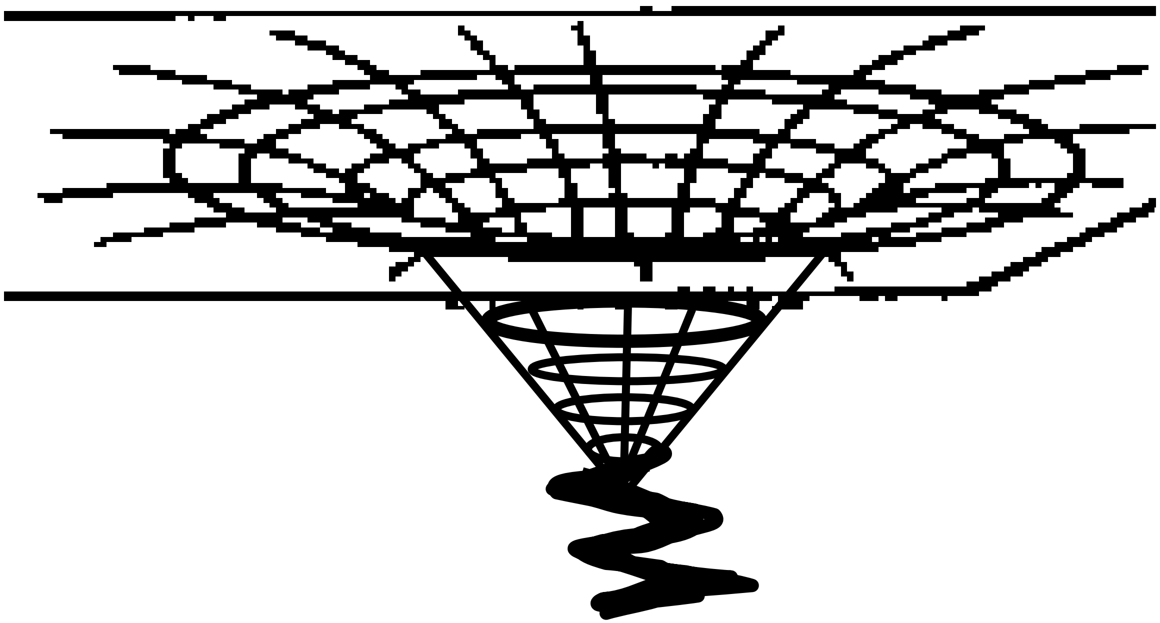


LIGO

Falling Into A Black Hole



Stellar Collapse To Form A Black Hole

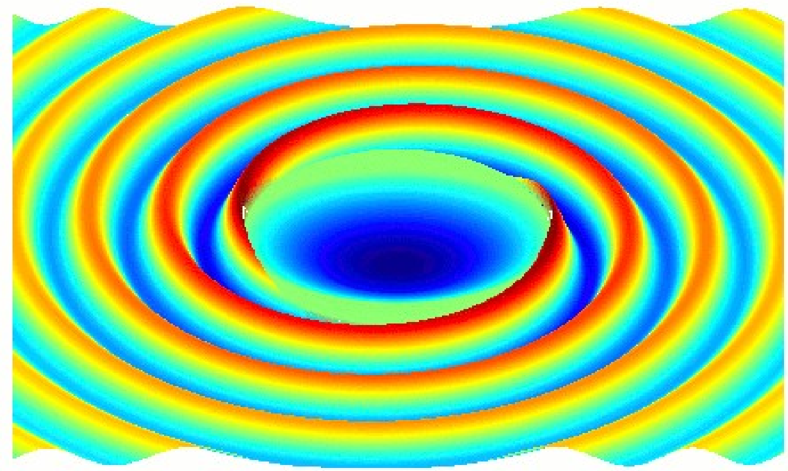


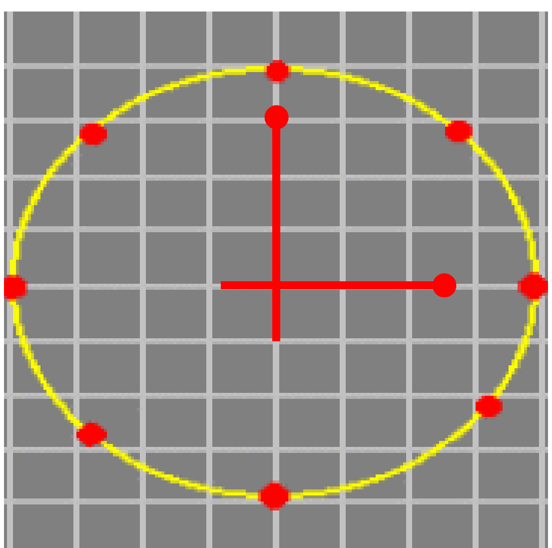
Singularity

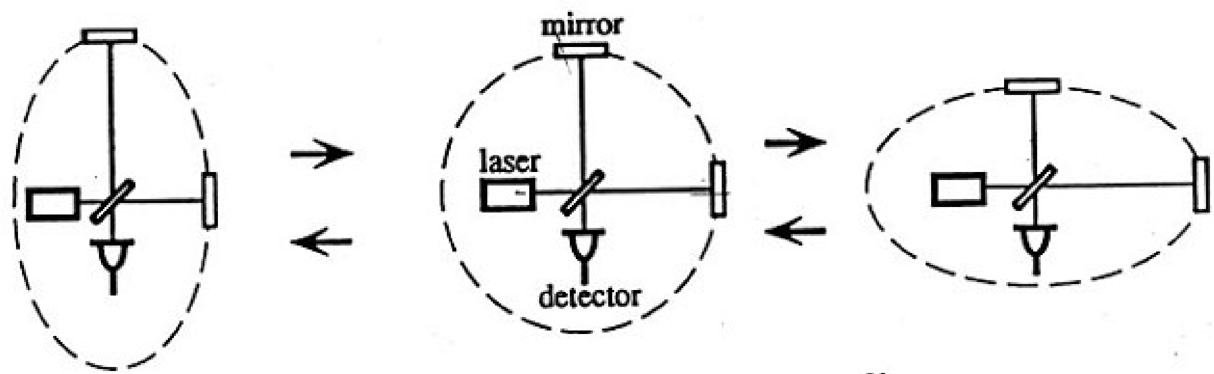
Gravitational Waves

Gravitational waves are ripples in spacetime when it is stirred up by rapidly changing motions of large concentrations of matter or energy. **The waves are extremely weak by the times they reach Earth.**

Illustration of Gravitational Waves:







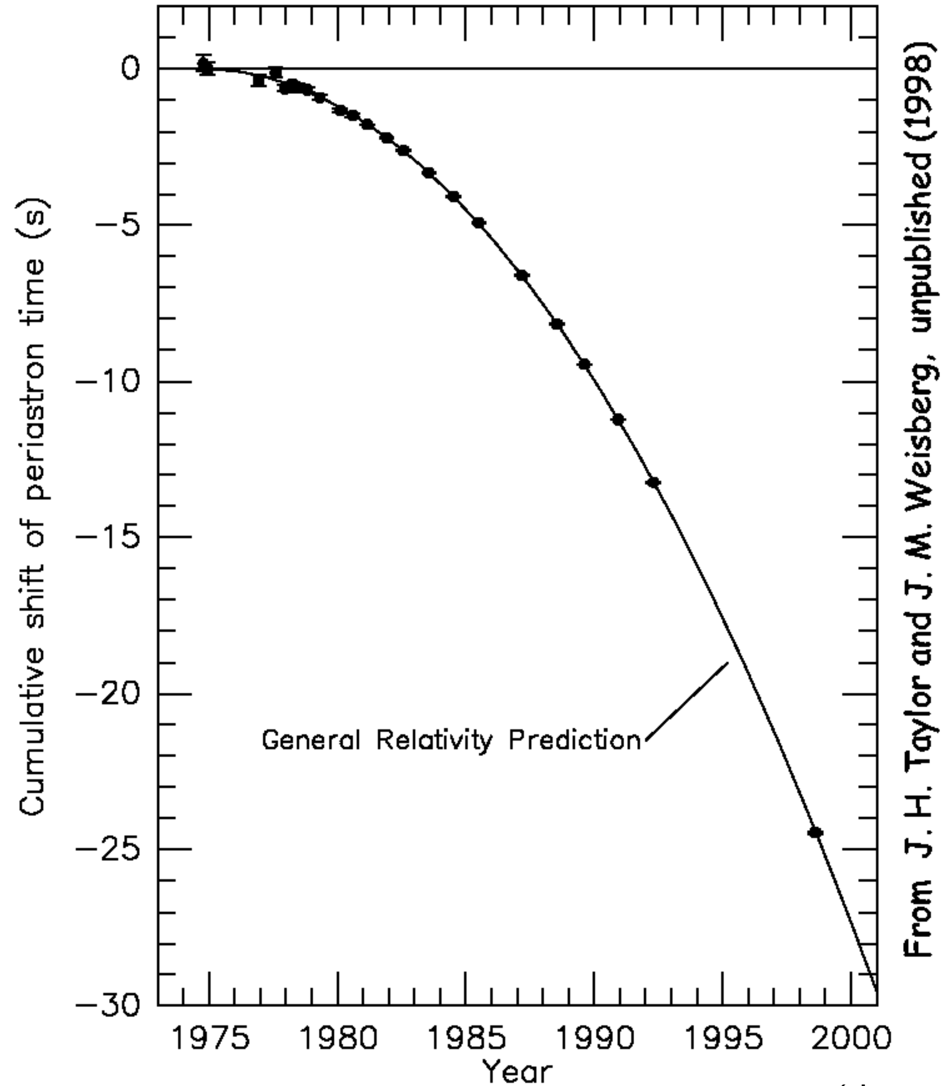
Do Gravitational Waves Exist?

Radio pulsar B1913+16, discovered in 1974 by Hulse and Taylor, is in a close orbit around an unseen companion

Long-term radio observations have yielded neutron star masses (1.44 and 1.39 $M_{\odot}$) and orbital parameters

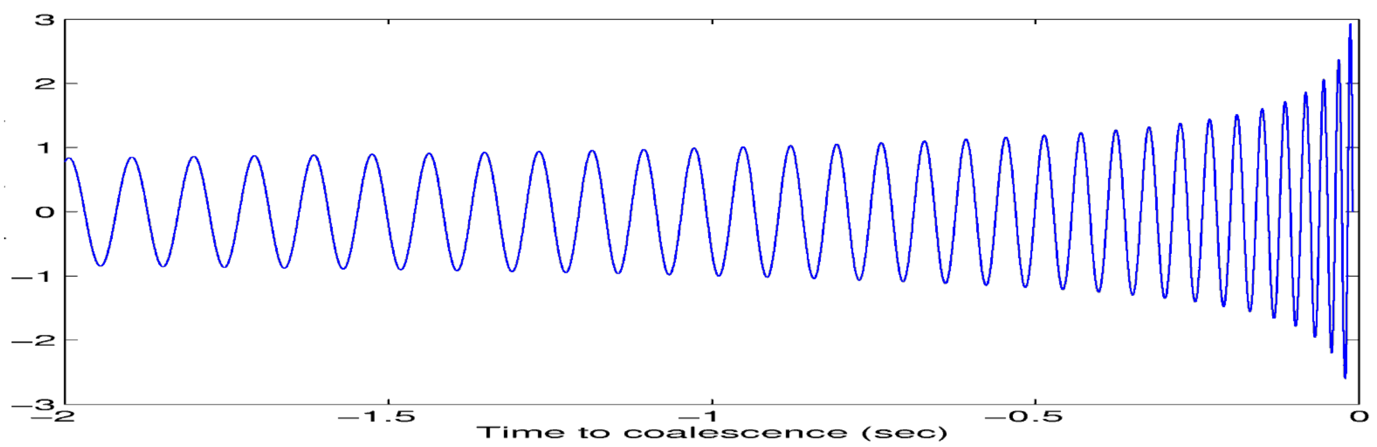
System shows very gradual orbital decay – just as general relativity predicts!

⇒ Very strong indirect evidence for gravitational radiation



The Fate of B1913+16

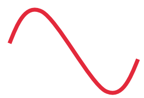
- Gravitational waves carry away energy and angular momentum
- Orbit will continue to decay over the next ~300 million years, until…

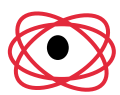


How weak are they?

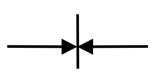
One meter, about 40 inches

÷10,000  *Human hair, about 100 microns*

÷100  *Wavelength of light, about 1 micron*

÷10,000  *Atomic diameter, 10^{-10} meter*

÷100,000  *Nuclear diameter, 10^{-15} meter*

÷1,000  *LIGO sensitivity, 10^{-18} meter*

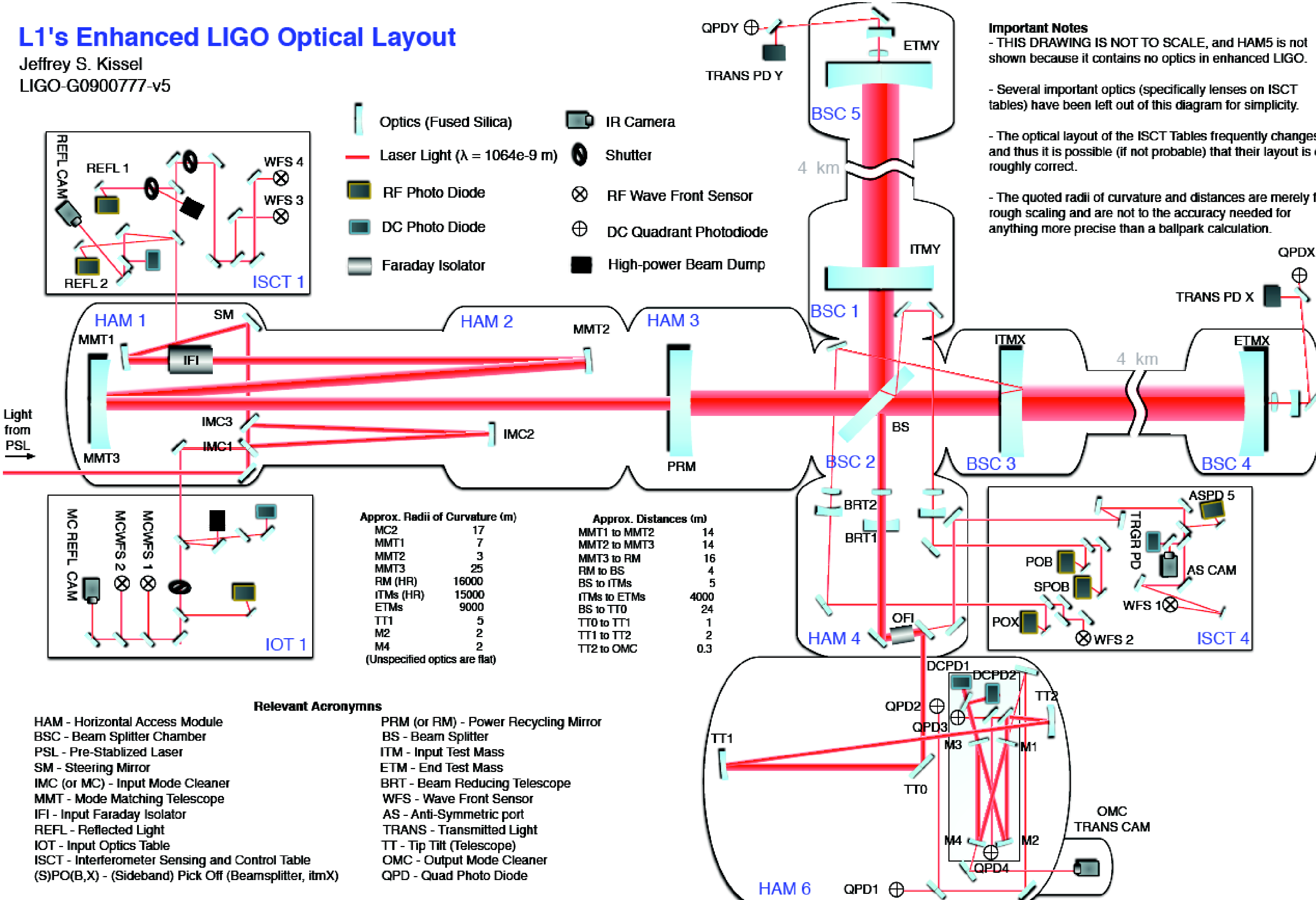
L1's Enhanced LIGO Optical Layout

Jeffrey S. Kissel

LIGO-G0900777-v5

Important Notes

- THIS DRAWING IS NOT TO SCALE, and HAM5 is not shown because it contains no optics in enhanced LIGO.
- Several important optics (specifically lenses on ISCT tables) have been left out of this diagram for simplicity.
- The optical layout of the ISCT Tables frequently changes and thus it is possible (if not probable) that their layout is only roughly correct.
- The quoted radii of curvature and distances are merely for rough scaling and are not to the accuracy needed for anything more precise than a ballpark calculation.



Approx. Radii of Curvature (m)

MC2	17
MMT1	7
MMT2	3
MMT3	25
RM (HR)	16000
ITMs (HR)	15000
ETMs	9000
TT1	5
M2	2
M4	2

(Unspecified optics are flat)

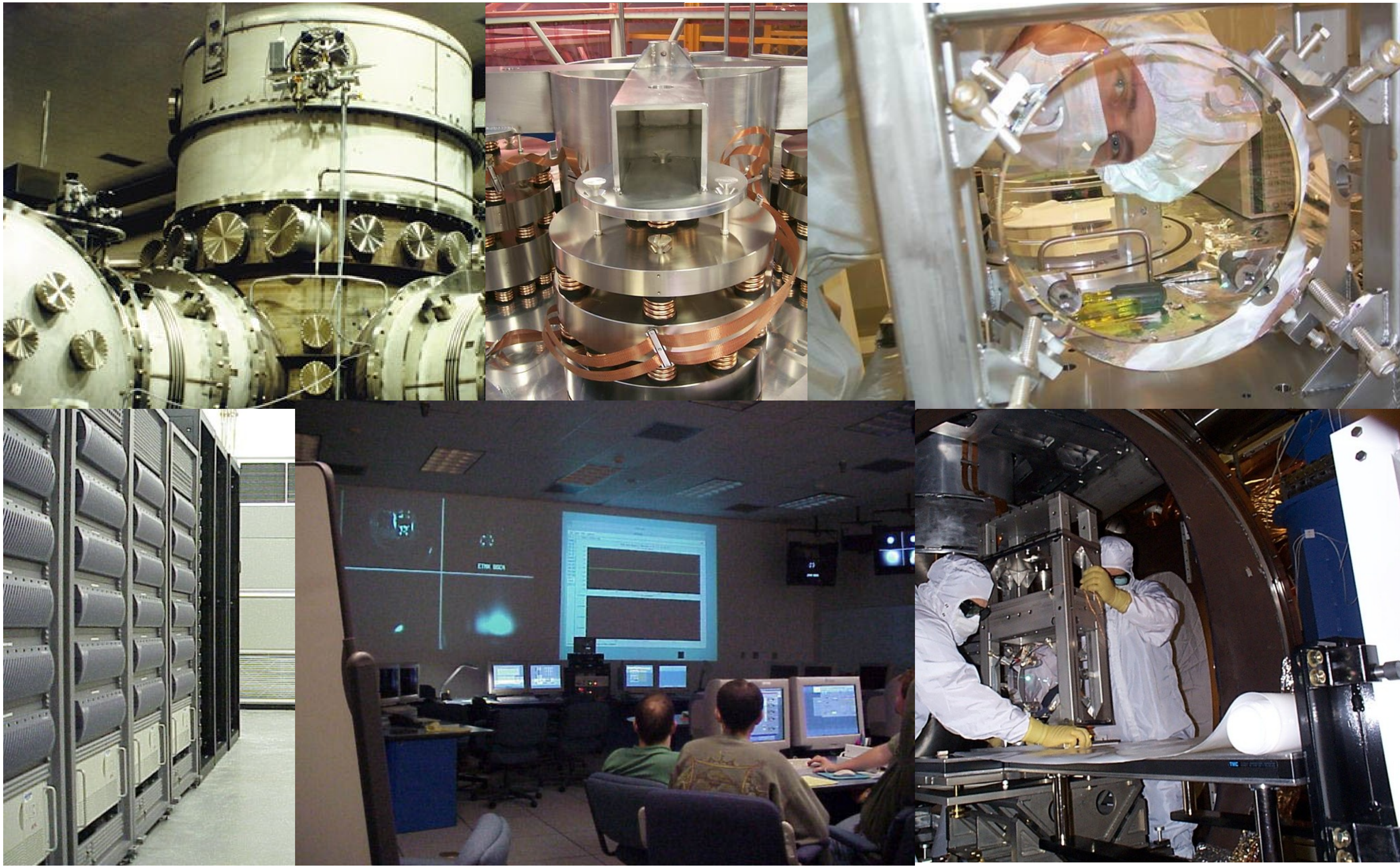
Approx. Distances (m)

MMT1 to MMT2	14
MMT2 to MMT3	14
MMT3 to RM	16
RM to BS	4
BS to ITMs	5
ITMs to ETMs	4000
BS to TT0	24
TT0 to TT1	1
TT1 to TT2	2
TT2 to OMC	0.3

Relevant Acronyms

HAM - Horizontal Access Module
BSC - Beam Splitter Chamber
PSL - Pre-Stablized Laser
SM - Steering Mirror
IMC (or MC) - Input Mode Cleaner
MMT - Mode Matching Telescope
IFI - Input Faraday Isolator
REFL - Reflected Light
IOT - Input Optics Table
ISCT - Interferometer Sensing and Control Table
(S)PO(B,X) - (Sideband) Pick Off (Beamsplitter, itmX)
PRM (or RM) - Power Recycling Mirror
BS - Beam Splitter
ITM - Input Test Mass
ETM - End Test Mass
BRT - Beam Reducing Telescope
WFS - Wave Front Sensor
AS - Anti-Symmetric port
TRANS - Transmitted Light
TT - Tip Tilt (Telescope)
OMC - Output Mode Cleaner
QPD - Quad Photo Diode

Inside Initial LIGO



There has been no direct detection of gravitational waves so far.

Initial LIGO has reported interesting upper limits and the Advanced LIGO project has started.

Gamma Ray Burst (GRB) 070201

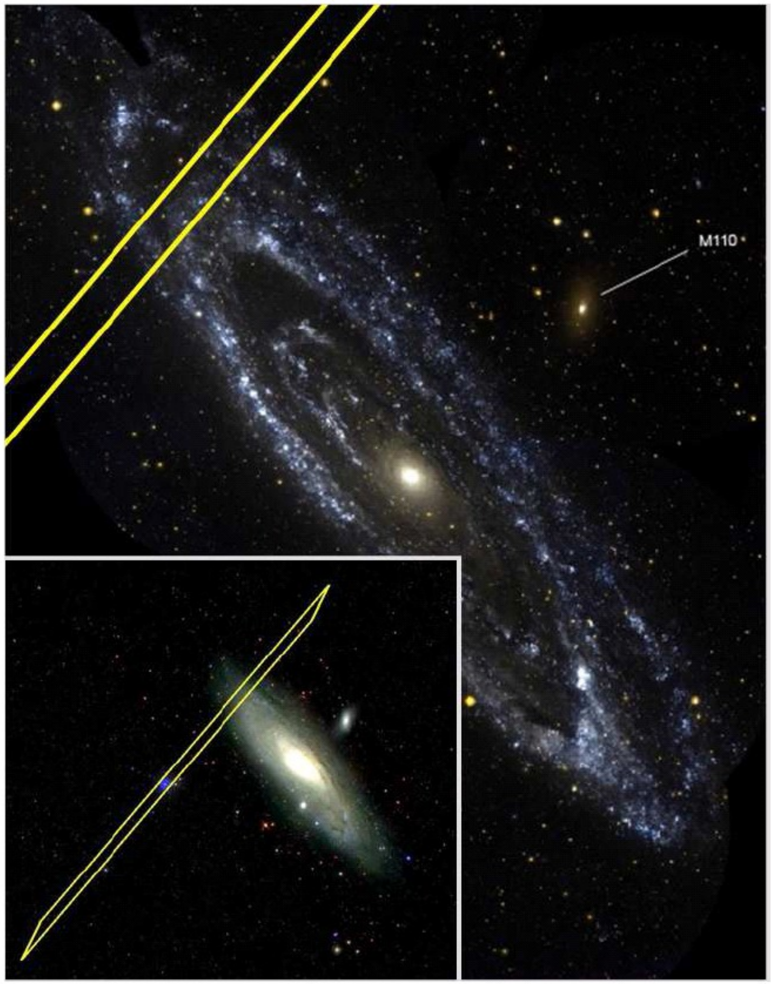
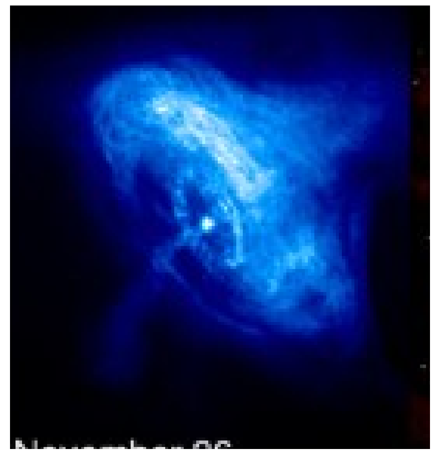


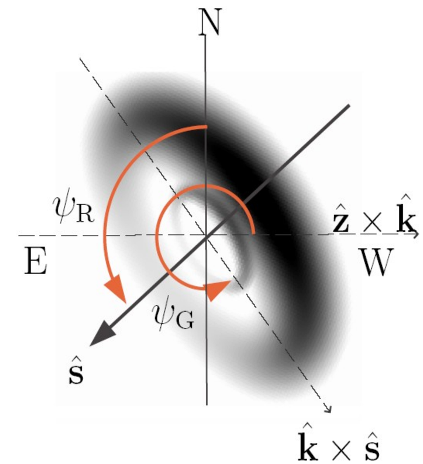
FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

- Short, hard gamma-ray burst
  - Leading model for short GRBs: binary merger involving a neutron star
- Position (from gamma-ray satellite data) is consistent with being in M31
- Both LIGO Hanford detectors were operating
  - Searched for inspiral & burst signals
- Result from LIGO data analysis: No plausible GW signal found; therefore very unlikely to be from a binary merger in M31

Crab Search Results

- Two different Bayesian priors for neutron star spin orientation
  - ▶ Uniform
  - ▶ Restricted using X-ray observations





No GW signal detected

Upper limits on GW strain amplitude *h_0*

Single-template, uniform prior: **3.4×10^{-25}**

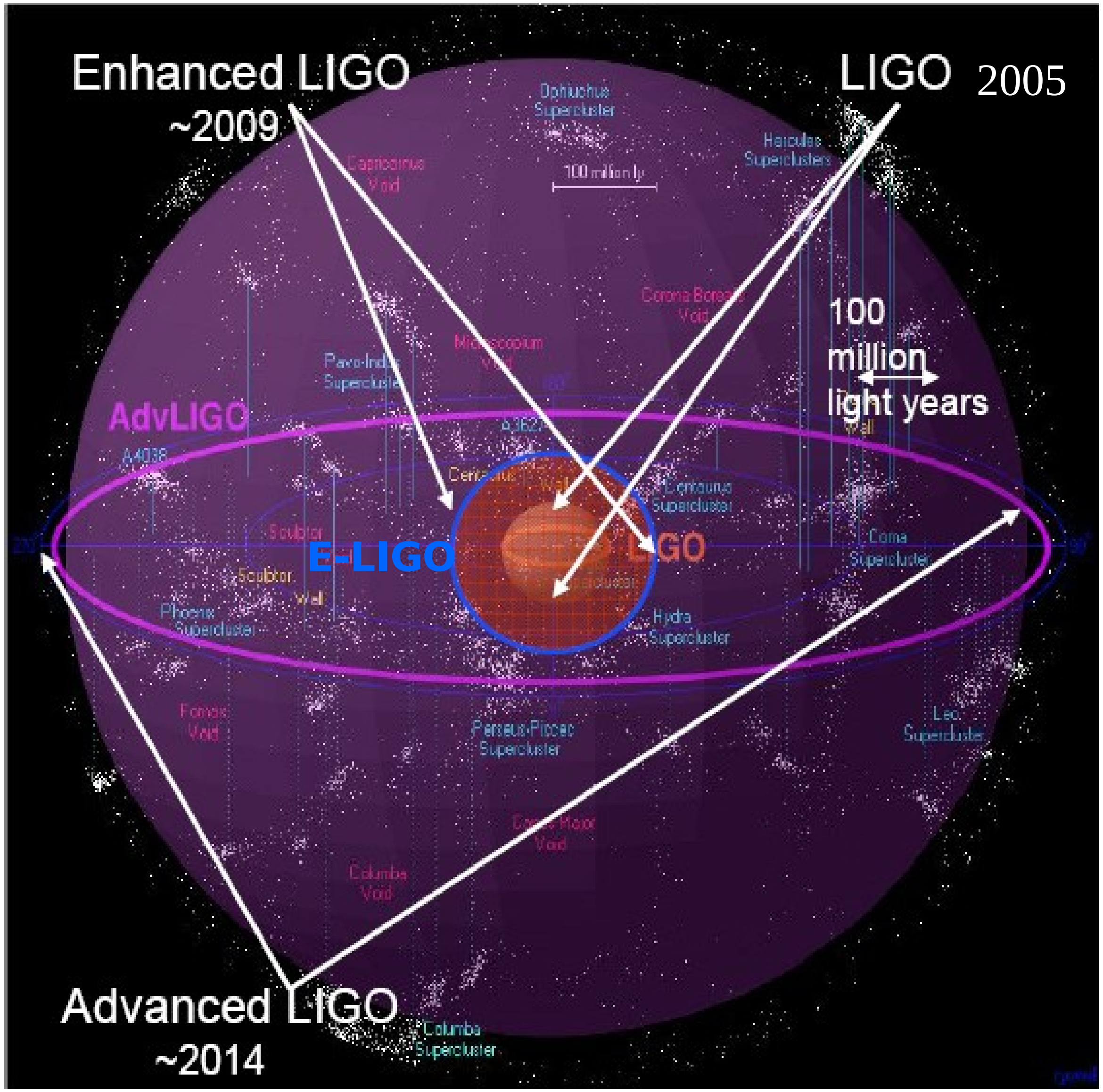
Single-template, restricted prior: **2.7×10^{-25}**

Multi-template, uniform prior: **1.7×10^{-24}**

Multi-template, restricted prior: **1.2×10^{-24}**

← **Implies that GW emission accounts for ≤ 4% of total spin-down power**

Reaching farther with Advance LIGO



Likely event rates per year:

~20 binary NS mergers

~5 NS-BH ?

~15 BH-BH ??

Other plausible signals:

Intermediate-mass-ratio inspiral into IMBH

CW signals from pulsars, LMXBs, or unseen NSs

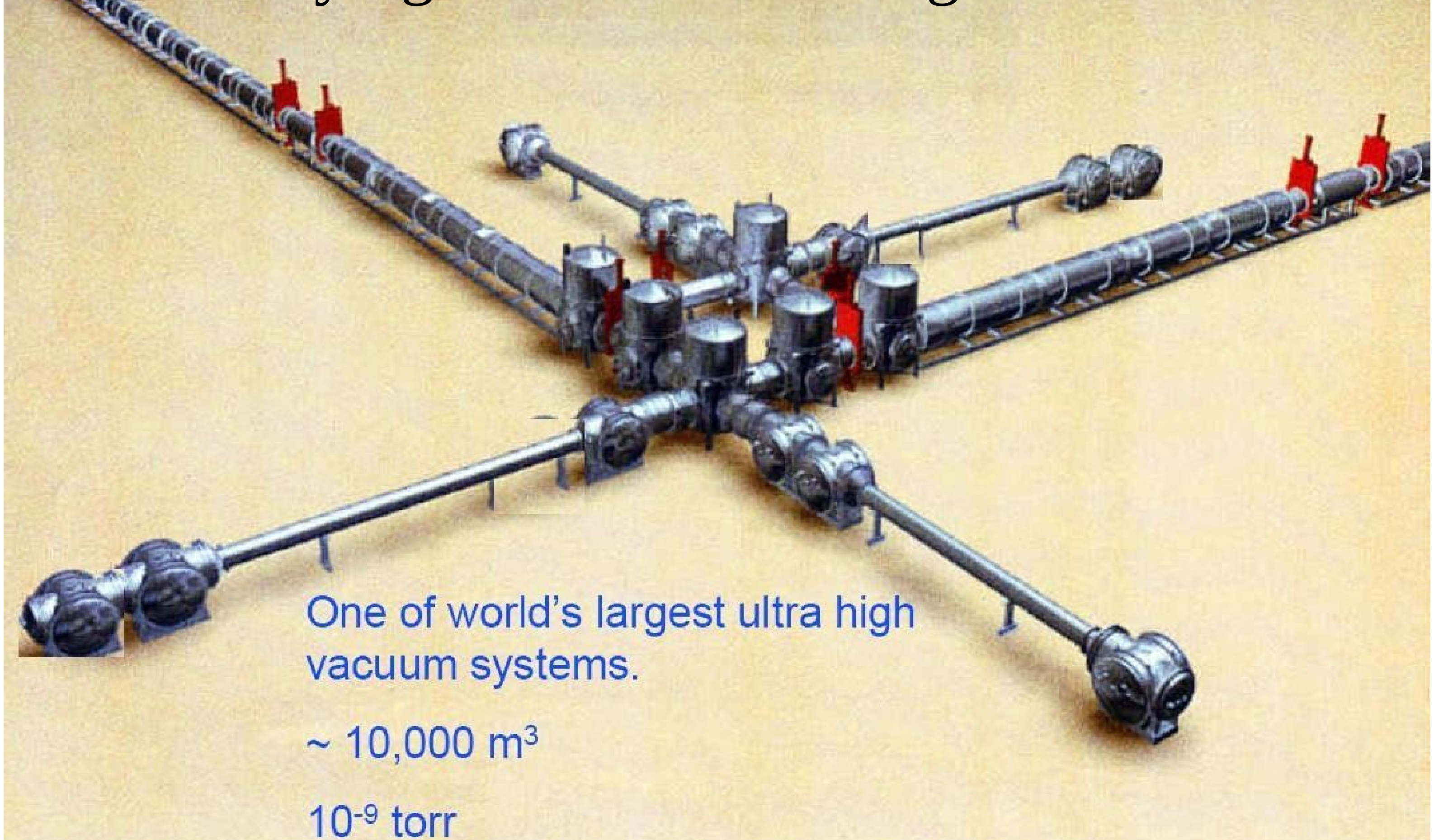
Stellar core collapse

Transient or stochastic signal from cosmic strings

etc…

LIGO

LIGO is in some ways like a space mission flying a few feet off the ground

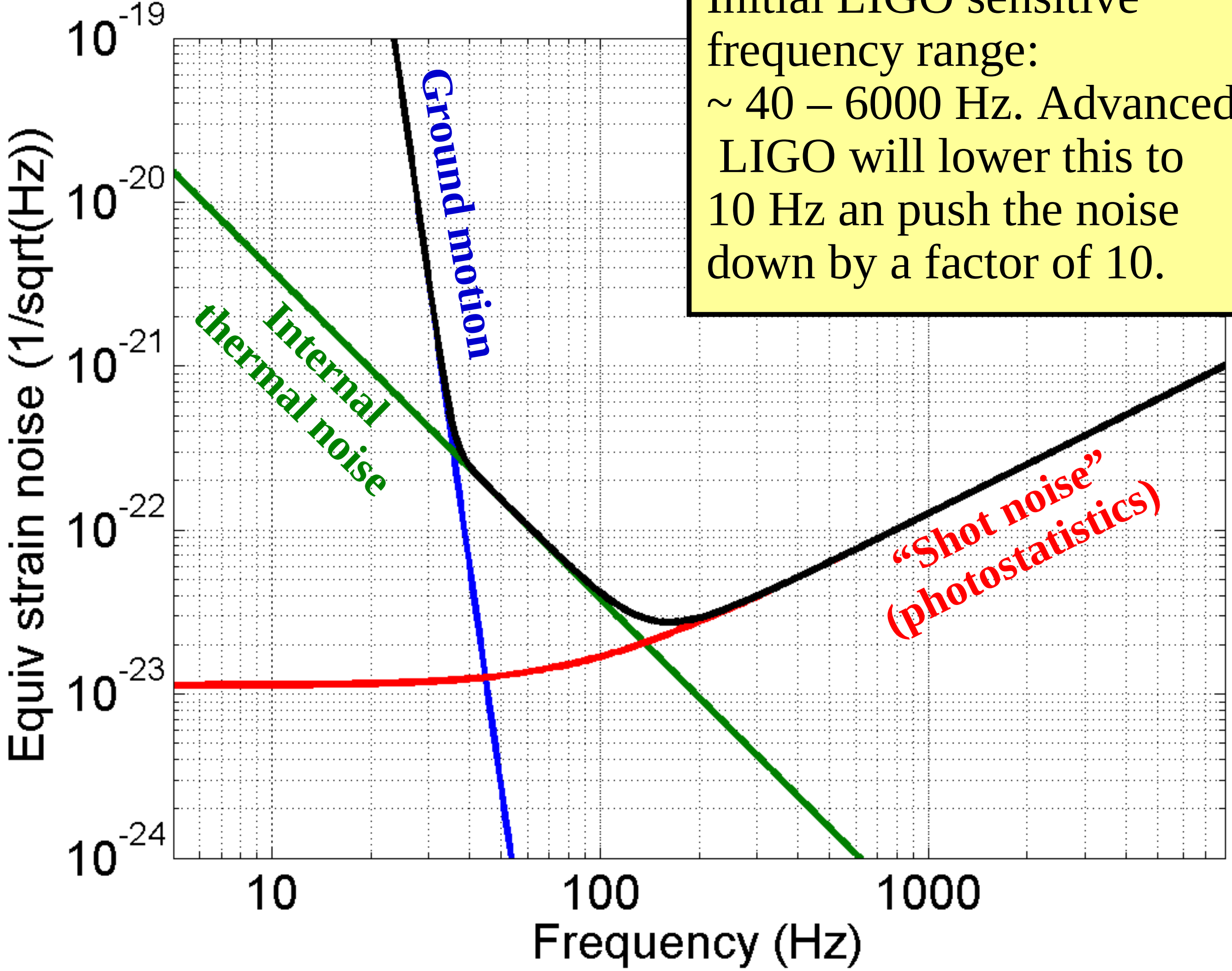


One of world's largest ultra high vacuum systems.

~ 10,000 m^3

10^{-9} torr

Limiting Sources of Noise



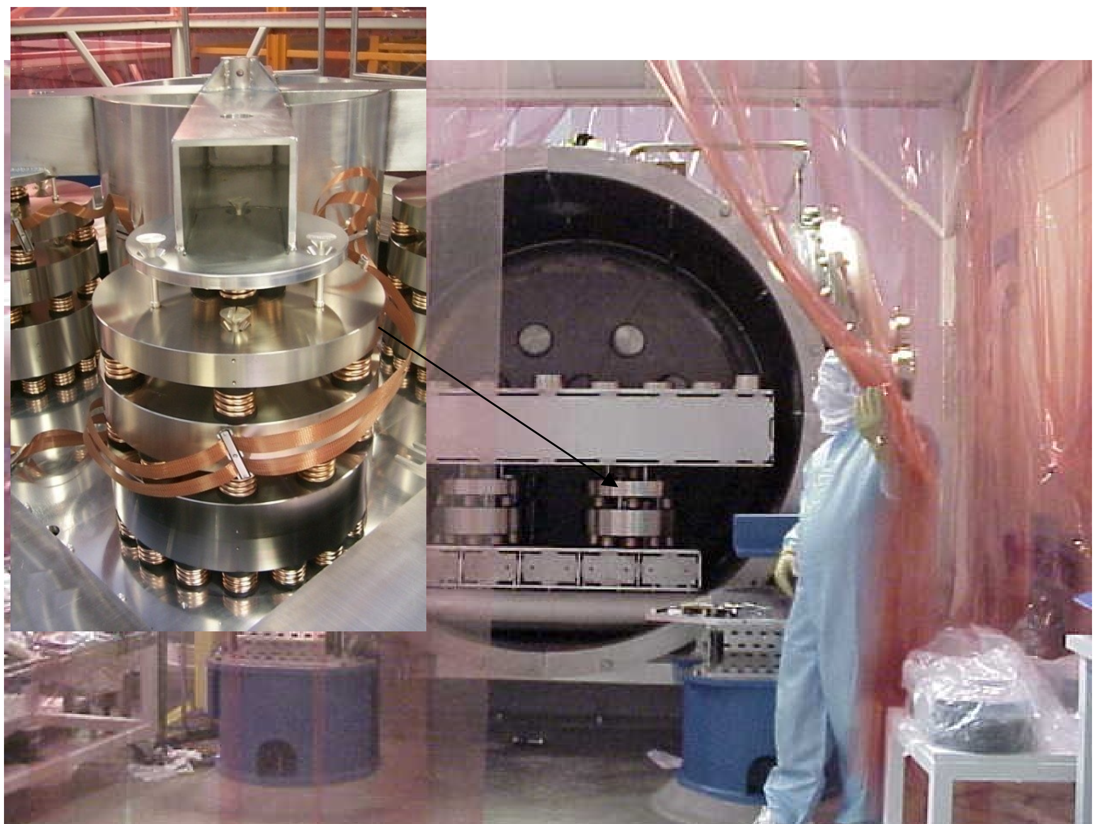
Initial LIGO sensitive frequency range: ~ 40 – 6000 Hz. Advanced LIGO will lower this to 10 Hz an push the noise down by a factor of 10.

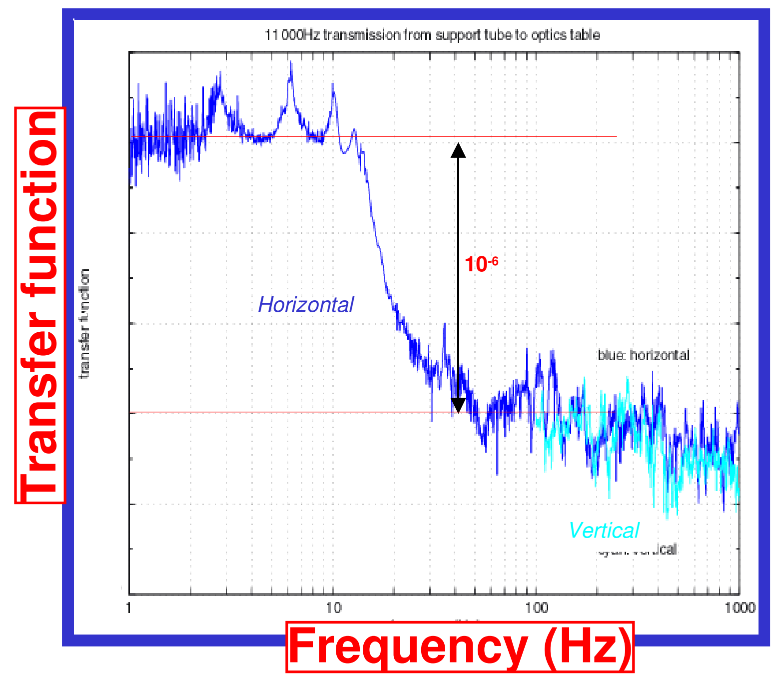
Advanced LIGO Assembly Space

Initial LIGO Seismic Isolation

Seismic Isolation

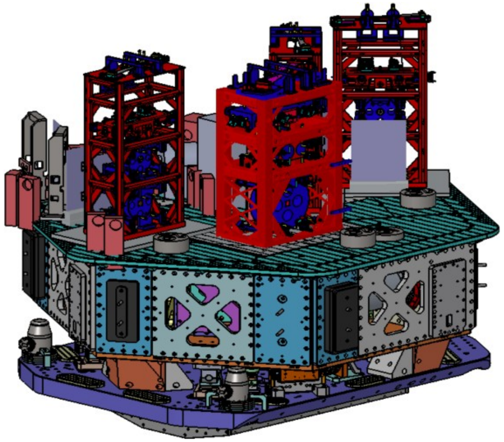
- Multi-stage (mass, springs, and viton) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz

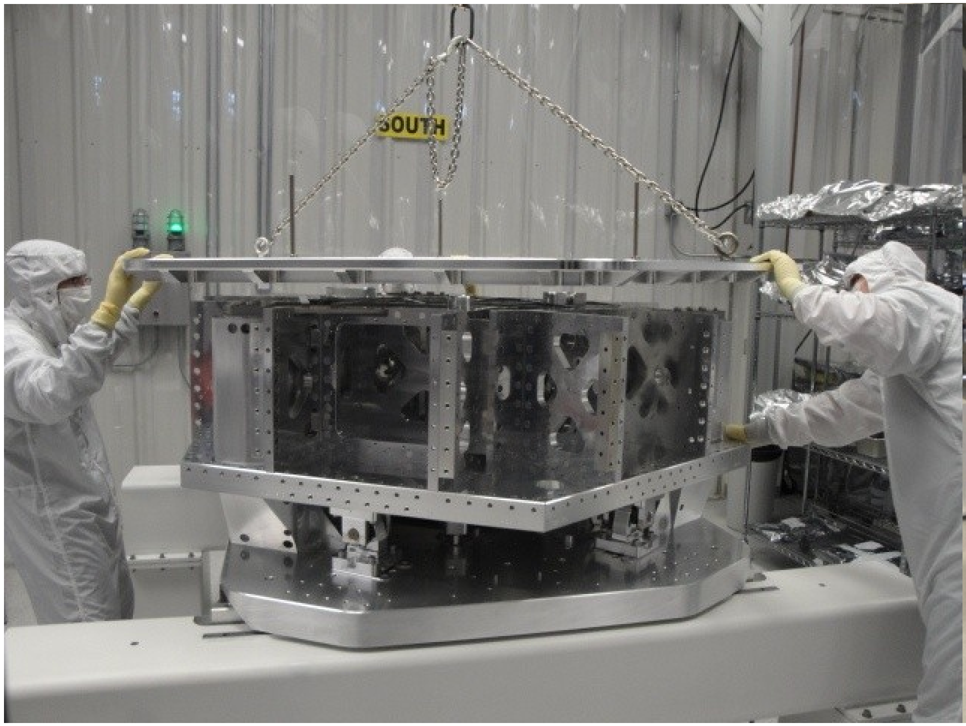


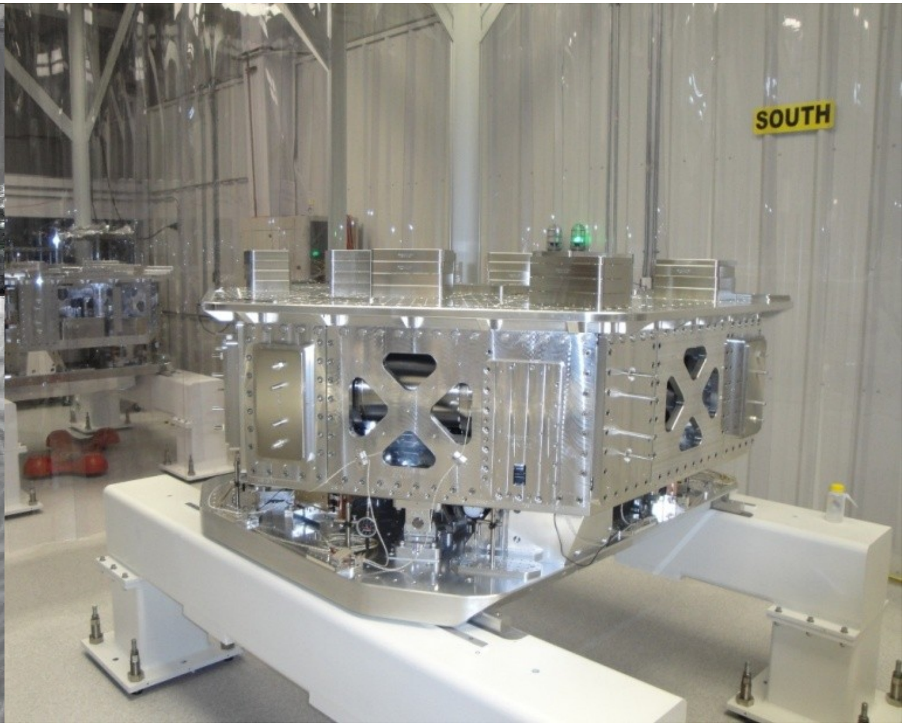


Advanced LIGO Seismic Isolation

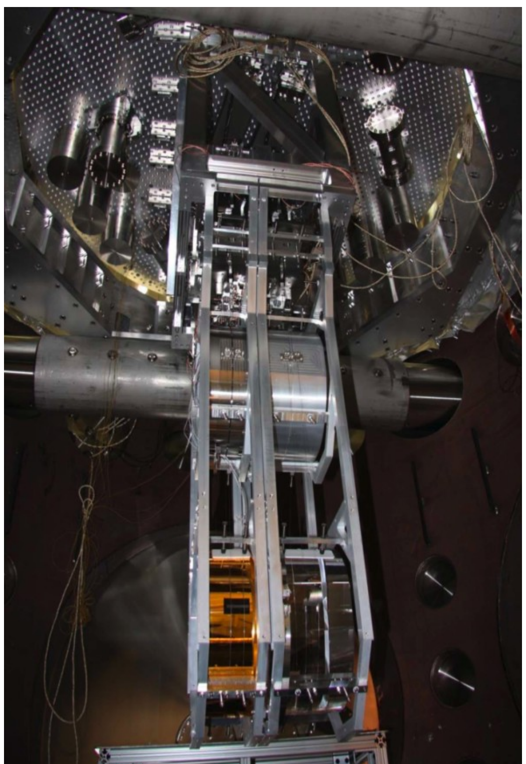
- Assembly of the Horizontal Access Module stacks is in full swing at both observatories.
- Active feedback control will be used.
- One assembly already used in current Enhanced LIGO configuration.

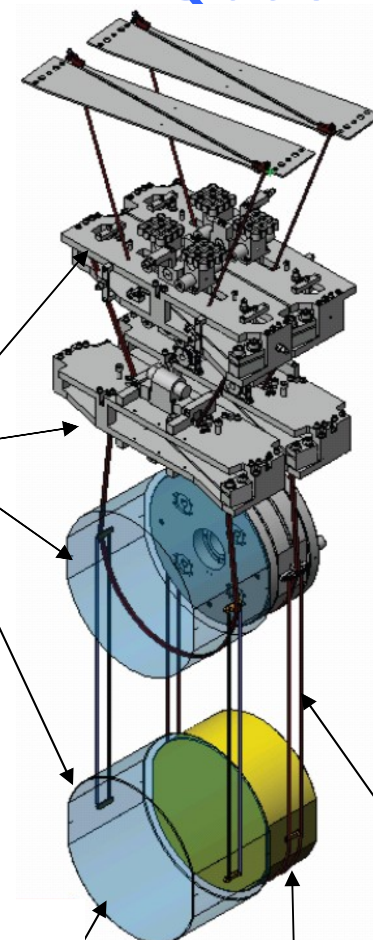






Suspension Systems
Initial Single vs. Advanced Quad Pendulum





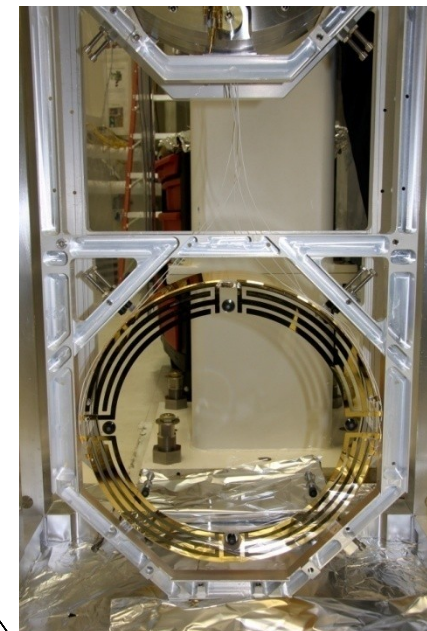
four stages

40kg silica masses

parallel reaction chain for control

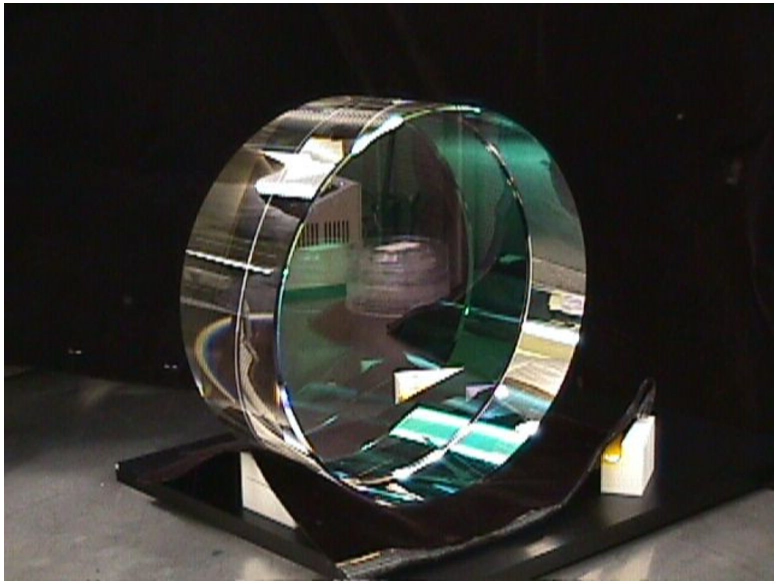
silica fibers

Electro Static Drive (ESD) on last stage: Reduces noise from electromagnets



Initial LIGO Core Optics

- Substrates: SiO_2
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5 x 10^{-7}
  - Internal mode Q's > 2 x 10^{6}
- Polishing
  - Surface uniformity < 1 nm rms
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity <10^{-3}
- Production involved 6 companies, NIST, and LIGO

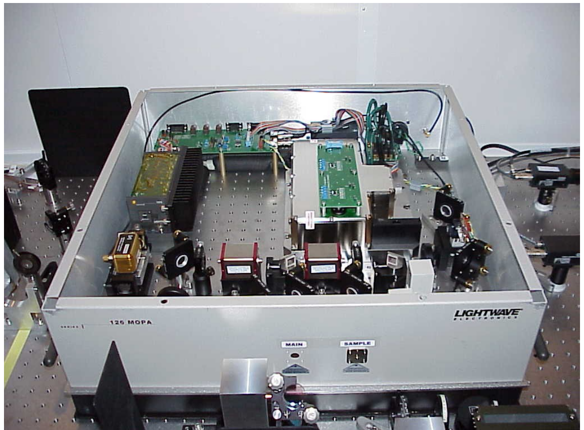


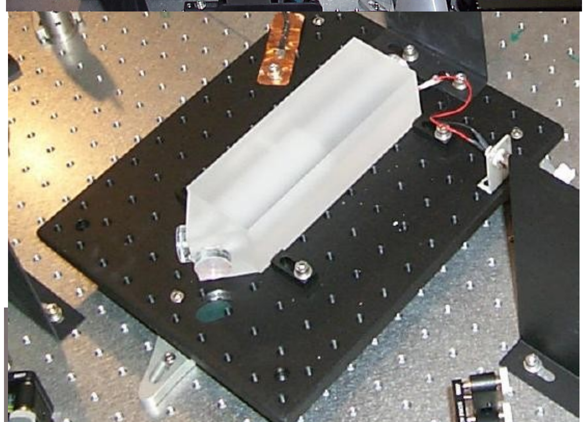
LIGO Advanced LIGO Core Optics

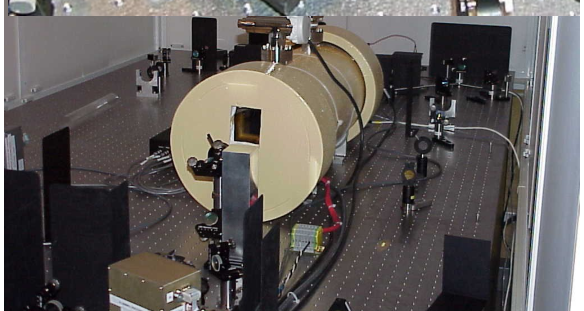
- 40 kg, 34 cm diam, 20 cm thick
(Initial LIGO masses are 11 kg, 25cm diam, 10 cm thick)

- A bigger mass (and larger beam size) means less thermal noise amd radiation pressure, which means

Nd:YAG Lasers: Initial LIGO 10W; Enhanced LIGO 35W; Advanced LIGO 150W

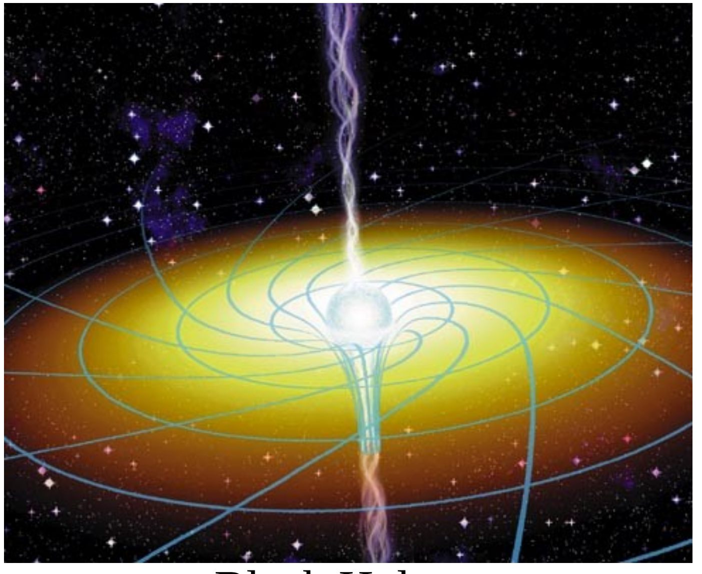




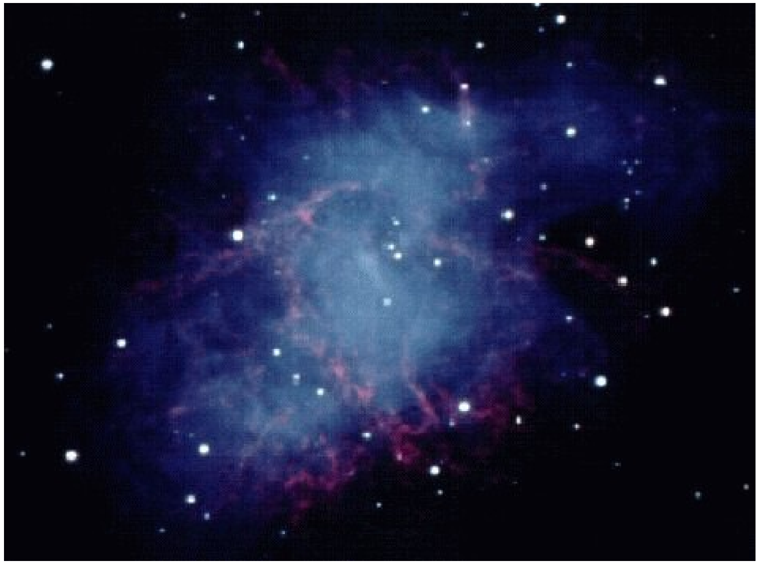


- Nd: YAG Neodymium-doped yttrium aluminum garnet.
- 1064 nanometers = infrared
- Stable to 1 part per million at 100 Hz.

Astrophysical Sources

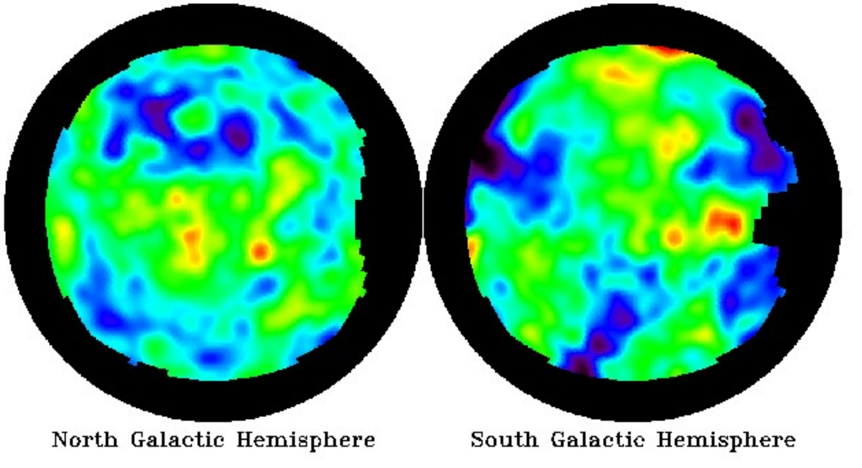


Black Holes



Dense Stars

Supernovae

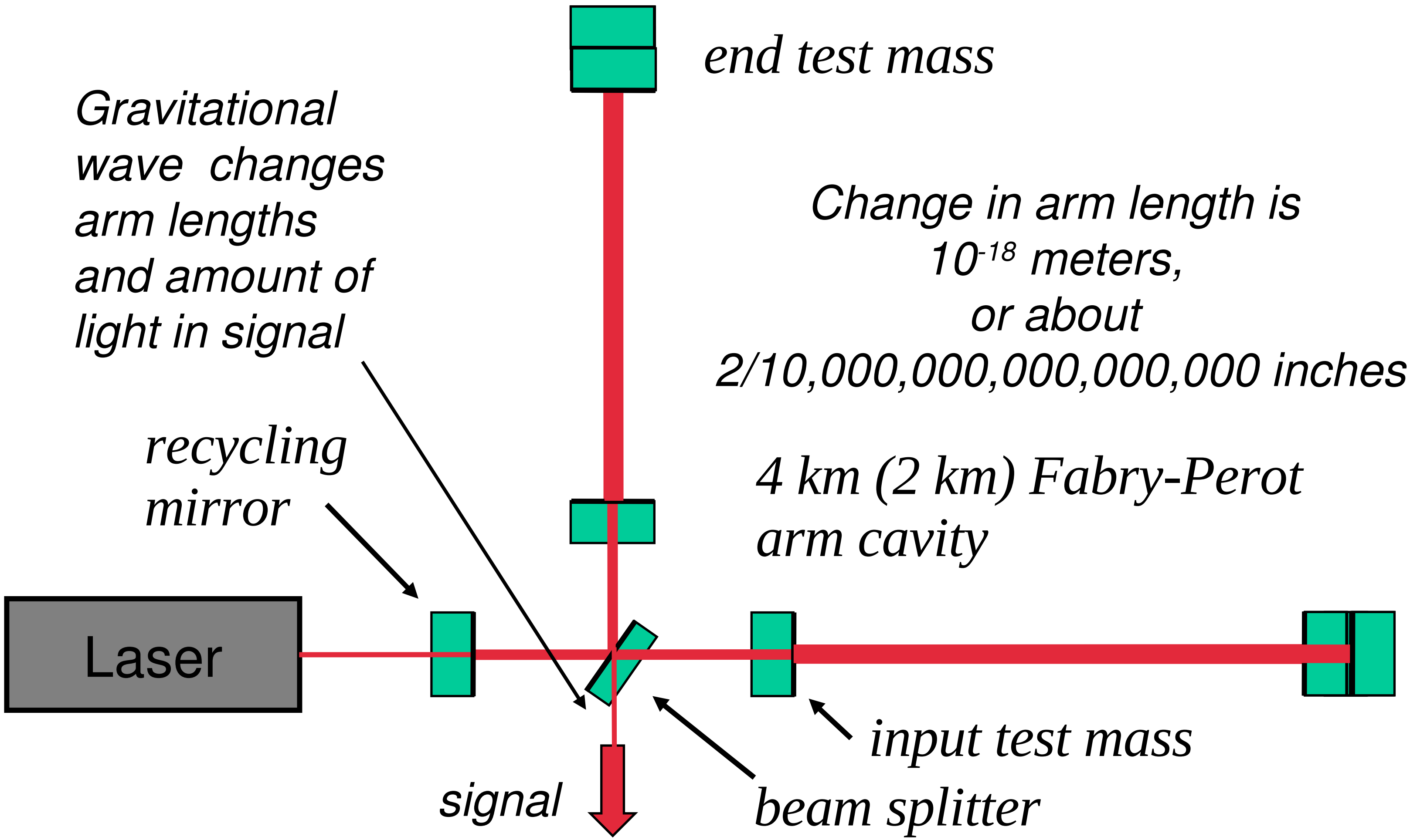


Stochastic Background

Photos: http://antwrp.gsfc.nasa.gov; http://imagine.gsfc.nasa.gov

The End

Sensing the Effect of a Gravitational Wave



LIGO

Niels Bohr

Time Dilation

Albert Einstein

$\Delta x = v\Delta t$

$c\Delta T$

$c\Delta t$

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

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.

LIGO

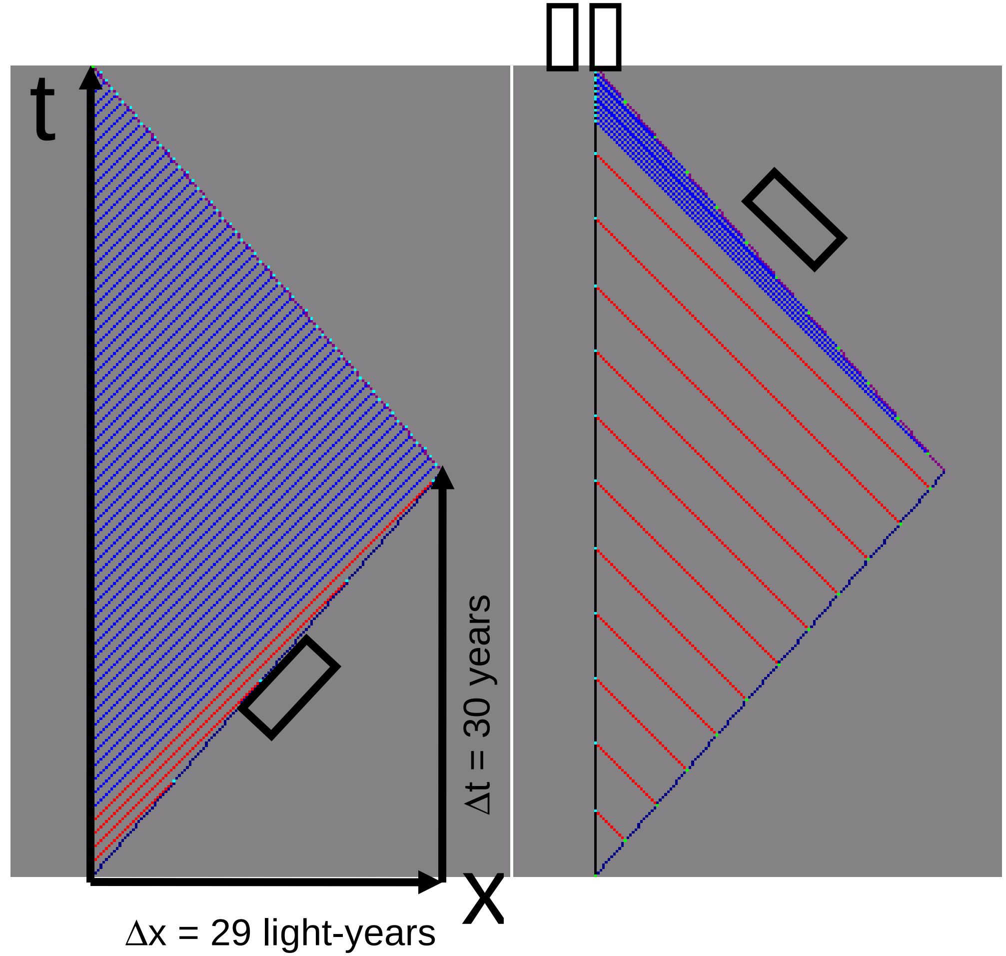
Spacetime Diagram

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!!!



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

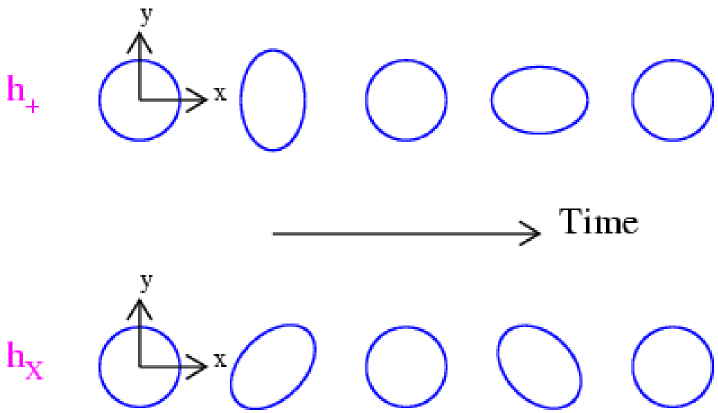
Figure: http://en.wikipedia.org/wiki/Twin_paradox

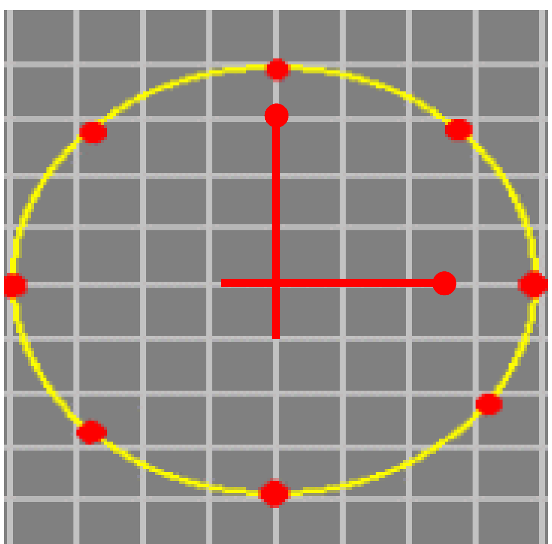
LIGO

What is the observable effect?

Example:

Ring of test masses responding to wave propagating along z





Amplitude parameterized by (tiny) dimensionless strain h:

$$h(t) = \frac{\delta L(t)}{L}$$

LIGO & Gravitational Waves

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

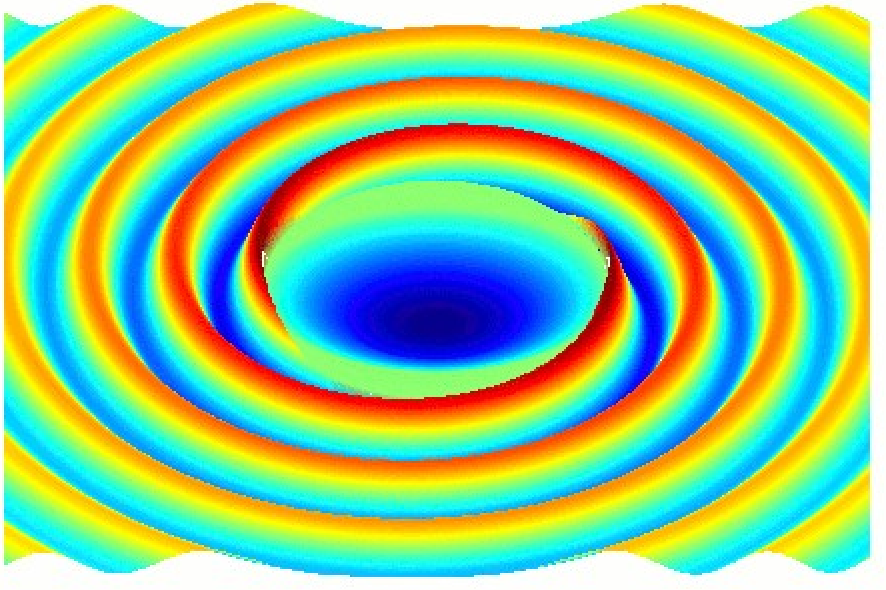
$$dT^2 = g_{\mu\nu} dx^\mu dx^\nu$$

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

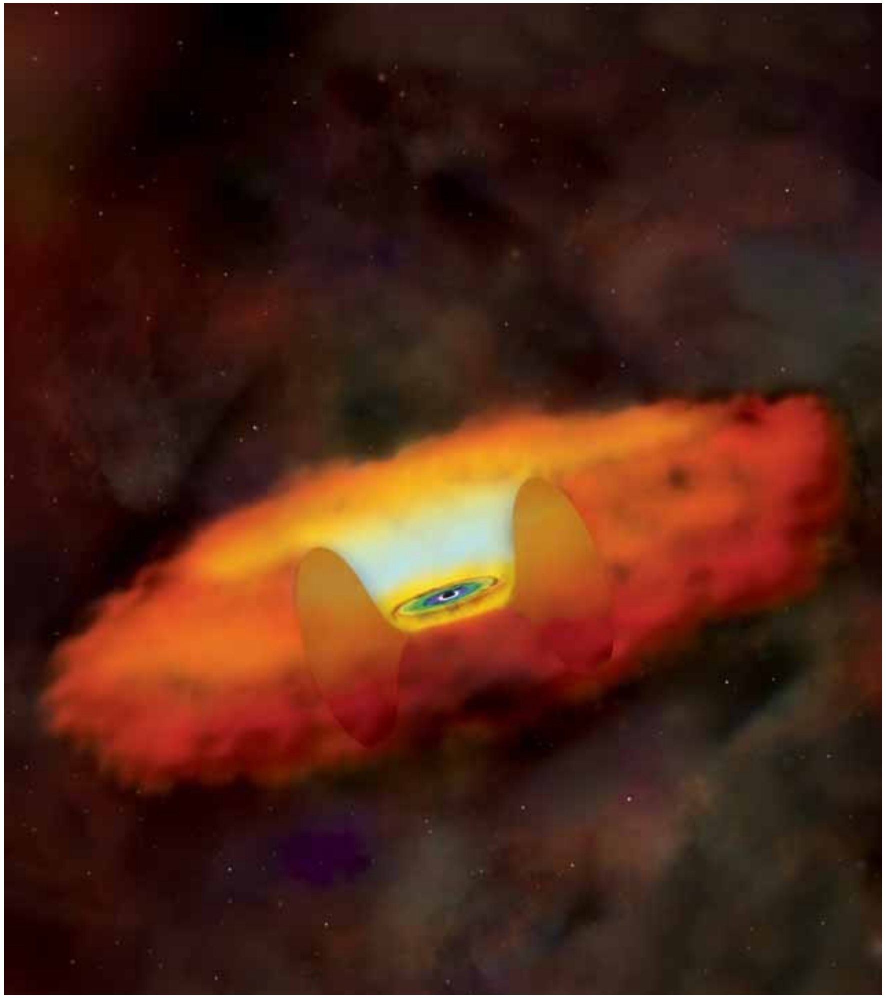
$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} \right) \bar{h}^{\mu\nu} = 0$$

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

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



Black Holes & Accretion Disks



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

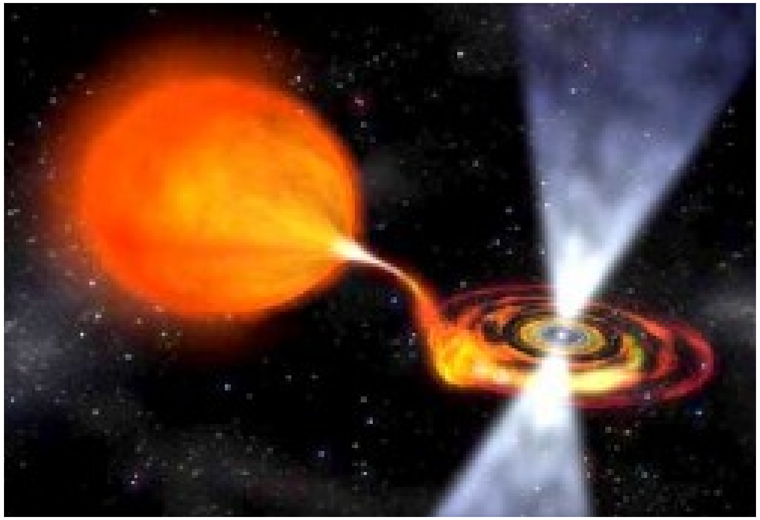
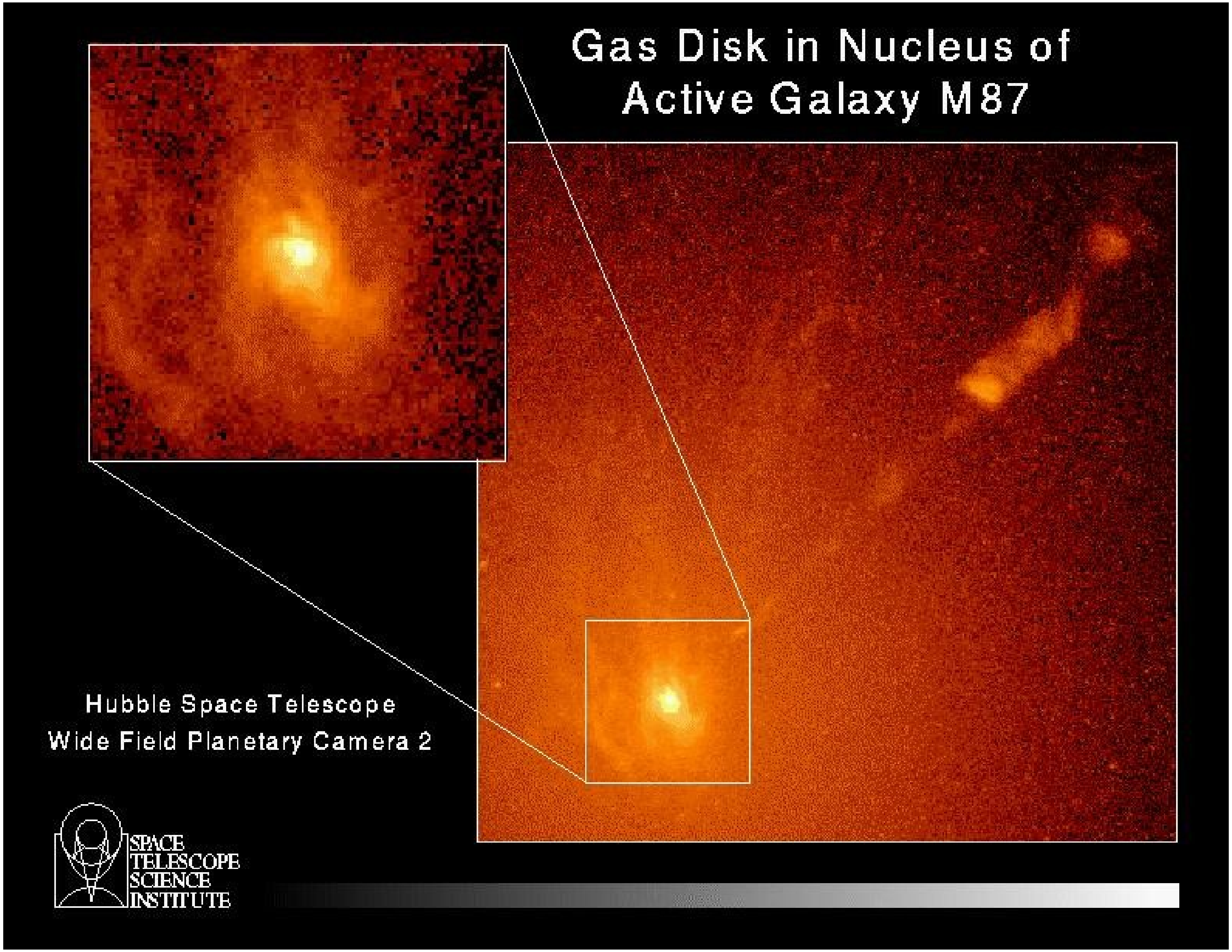
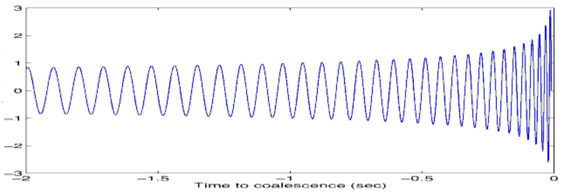


image by Dana Berry/NASA; NASA News Release posted July 2, 2003 on Spaceflight Now.

Black Hole Detection



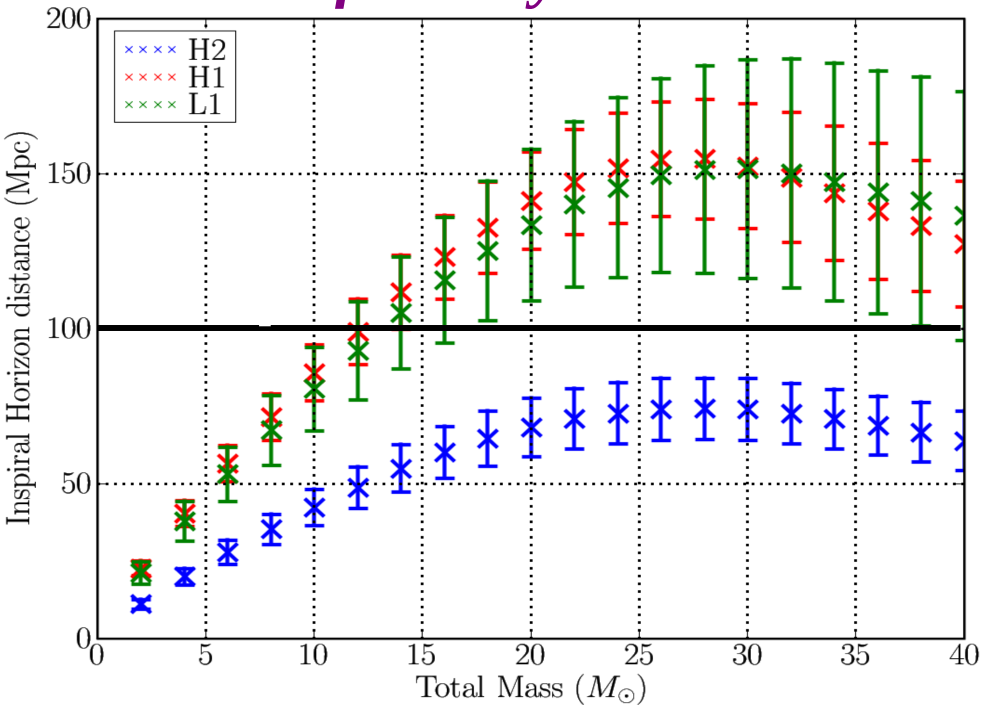
Binary Inspiral Searches



[arXiv:0901.0302]

- Recently released result from first year of S5 data
- No inspiral signals detected
- Using population models, calculated 90% confidence limits on coalescence rates:
- For binary neutron stars:
  3.8×10^{-2} per year per L_{10}
- For 5+5 $M_{\odot}$ binary black holes:
  2.8×10^{-3}
- For BH-NS systems:
  1.9×10^{-2}

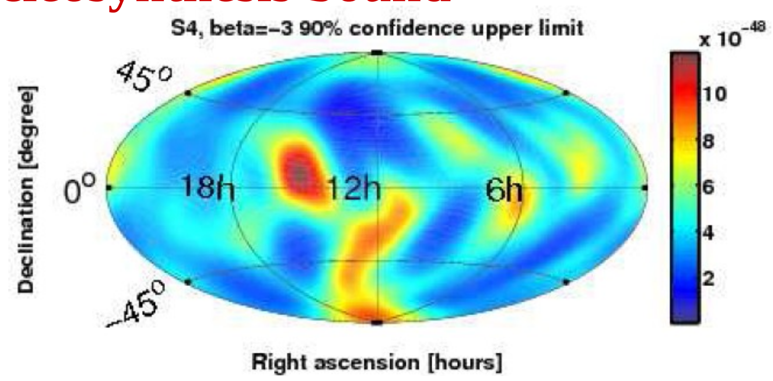
How far away can we hear?



- (Slightly tighter limits if BHs are assumed to have no spin)

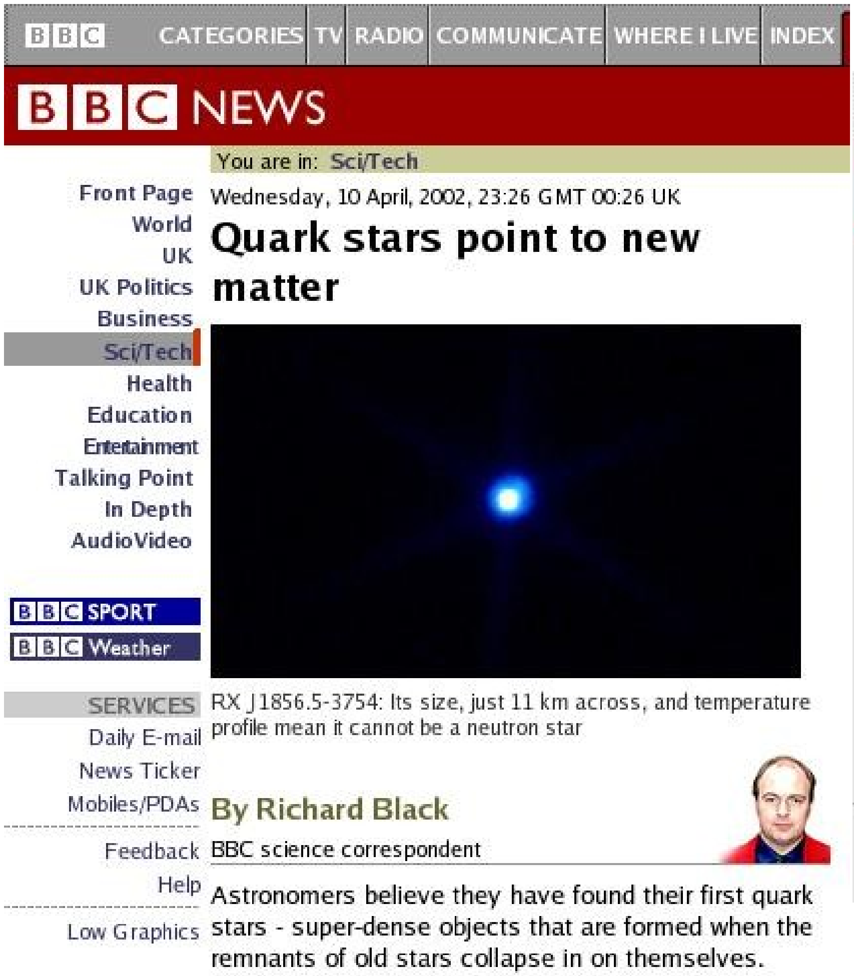
Searches for a Stochastic Background of Gravitational Waves

- Weak, random gravitational waves should be bathing the Earth
  - Left over from the early universe, analogous to CMBR ;
    or from overlapping signals from many astrophysical objects / events
- Results from S5 data analysis
  - Searched for isotropic stochastic signal with power-law spectrum
  - For flat spectrum, set upper limit on energy density in gravitational waves:
  - *Preliminary* result from ~half of S5 data: $\Omega_0 < 1.3 \times 10^{-5}$
  - Starts to constrain cosmic (super)string and "pre-Big-Bang" models
  - Final S5 result to be released soon, with factor of ~2 better sensitivity – **will dip below Big Bang Nucleosynthesis bound**
- Or look for anisotropic signal:



LIGO

Strange Stars in the News



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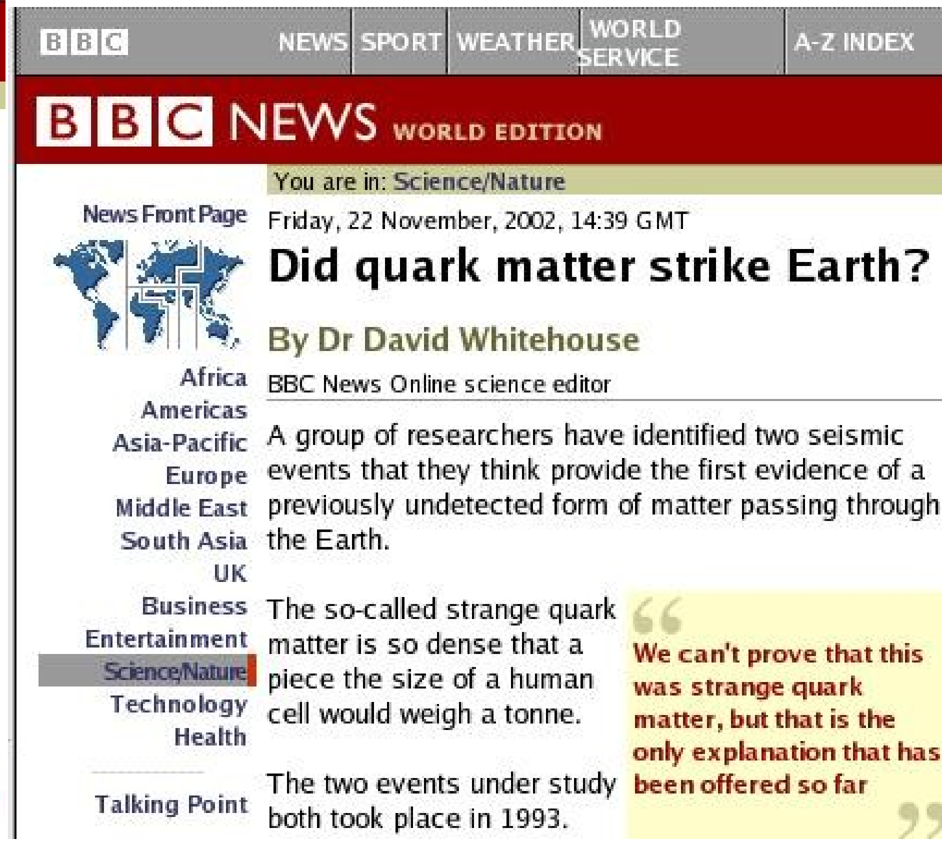
Wednesday, 10 April, 2002, 23:26 GMT 00:26 UK

Quark stars point to new matter

RX J1856.5-3754: Its size, just 11 km across, and temperature profile mean it cannot be a neutron star

By Richard Black
BBC science correspondent

Astronomers believe they have found their first quark stars - super-dense objects that are formed when the remnants of old stars collapse in on themselves.



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Friday, 22 November, 2002, 14:39 GMT

Did quark matter strike Earth?

By Dr David Whitehouse
BBC News Online science editor

A group of researchers have identified two seismic events that they think provide the first evidence of a previously undetected form of matter passing through the Earth.

The so-called strange quark matter is so dense that a piece the size of a human cell would weigh a tonne.

"We can't prove that this was strange quark matter, but that is the only explanation that has been offered so far"

The two events under study both took place in 1993.

Black Holes And LIGO

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