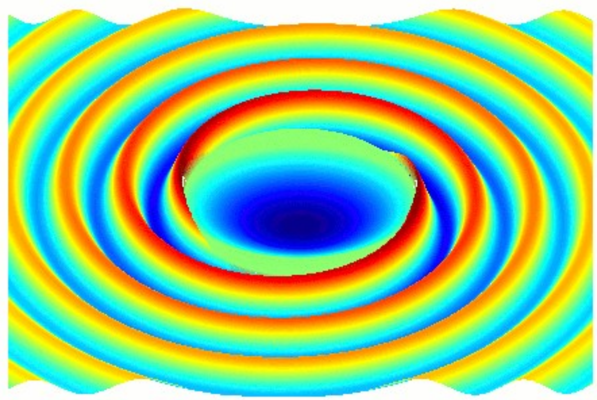
Using LIGO To Search For Gravitational Waves: Sources, Detectors, and Computing.



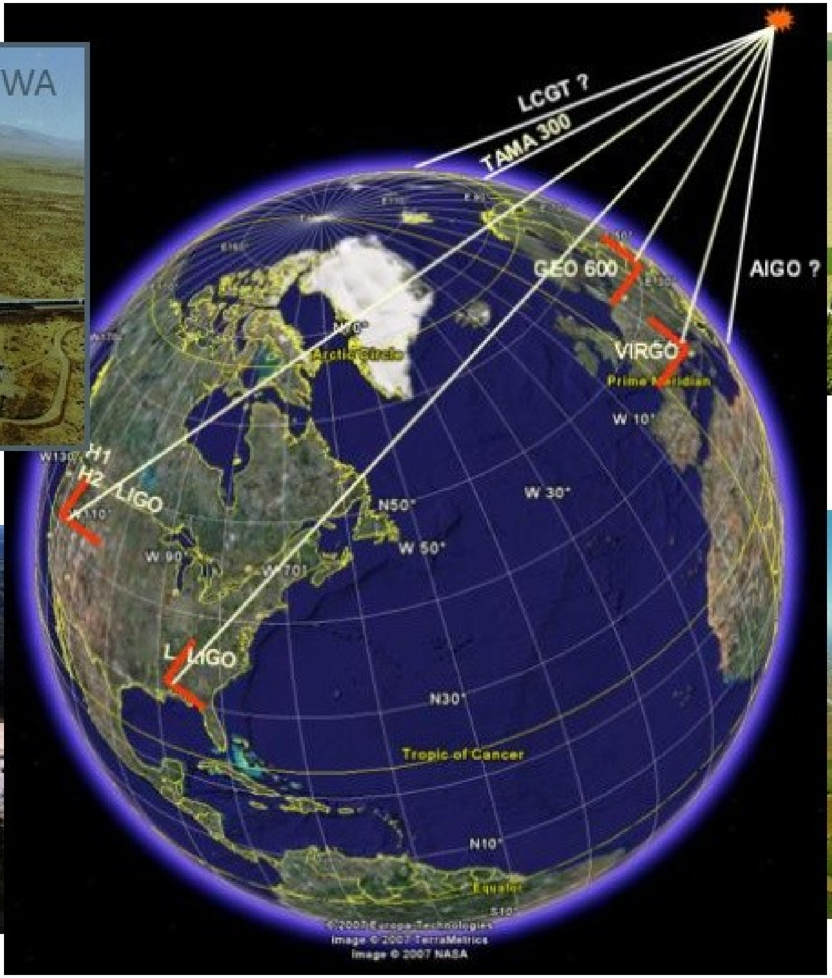
The Laser Interferometer Gravitational-wave Observatory: a Caltech/MIT collaboration supported by the National Science Foundation

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

Welcome CCSC

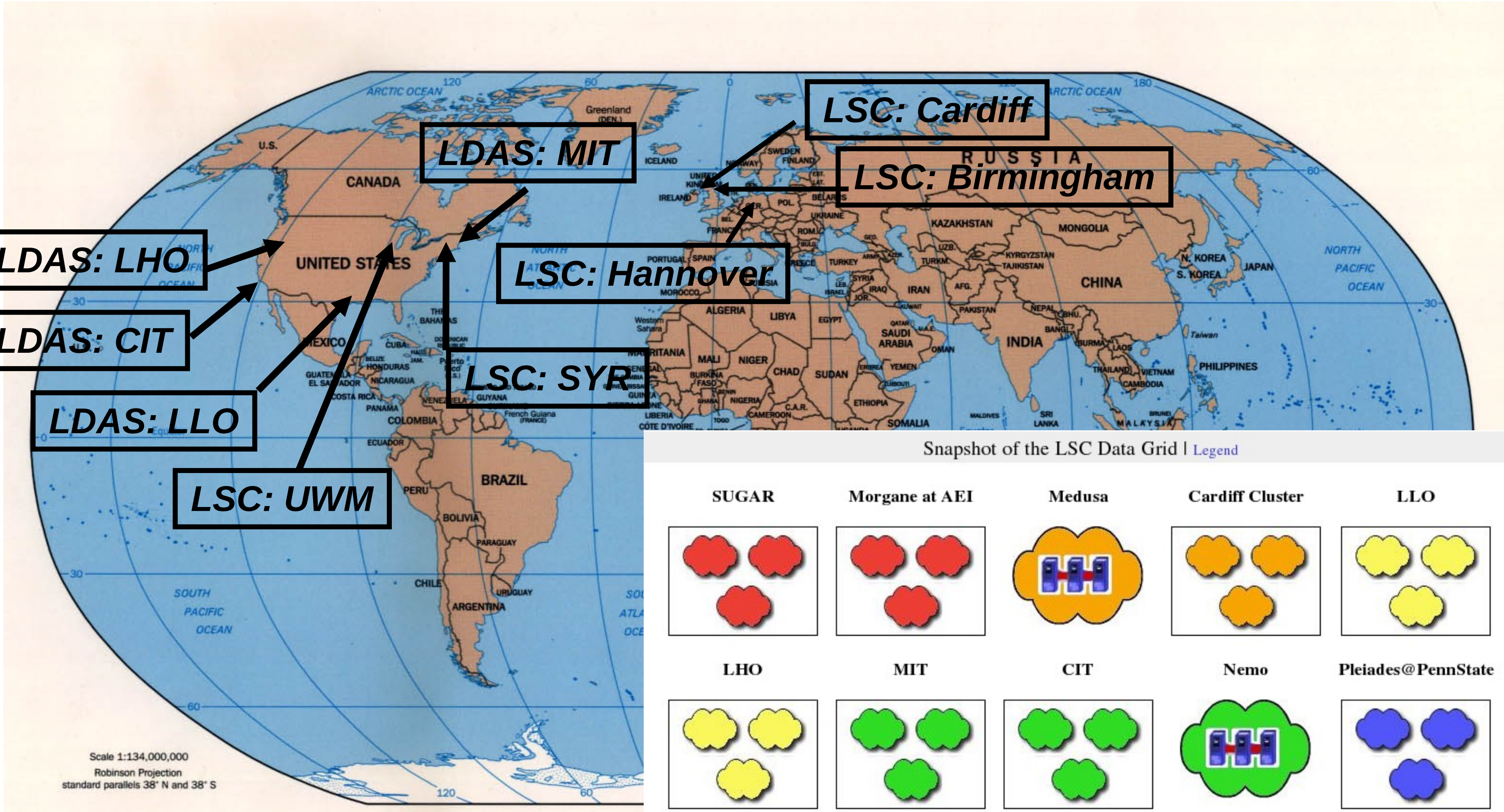
LIGO-G1101145

The LIGO-Virgo network



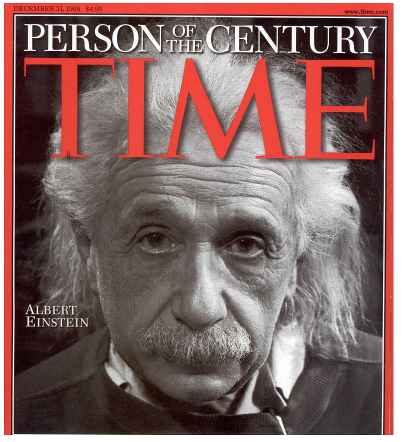
600+ Scientist and Engineers

Worldwide Data Analysis using The LIGO Data Grid (LDG)



23518 cores with a typical CPU speeds of 2.6 GHz

Some Far Out Ideas



- Nothing can go faster than light.
- The faster you go the slower time goes.
- Gravity disappears when you free fall.
- Einstein's General Theory Relativity:
  - Sources of gravity warp space and time.
  - Black holes really are like holes in space.
  - Gravitational Waves = radiation in the gravitational field = ripples in the fabric of spacetime.
  - GW Sources: supernovae, dense stars, black holes, and the big bang.
  - Initial LIGO: searched up to 2010. Advanced LIGO is being installed with 10x the sensitivity.

LIGO

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

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

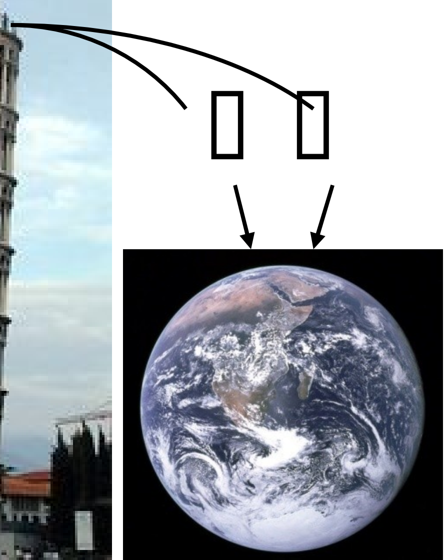


Photo: NASA

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

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

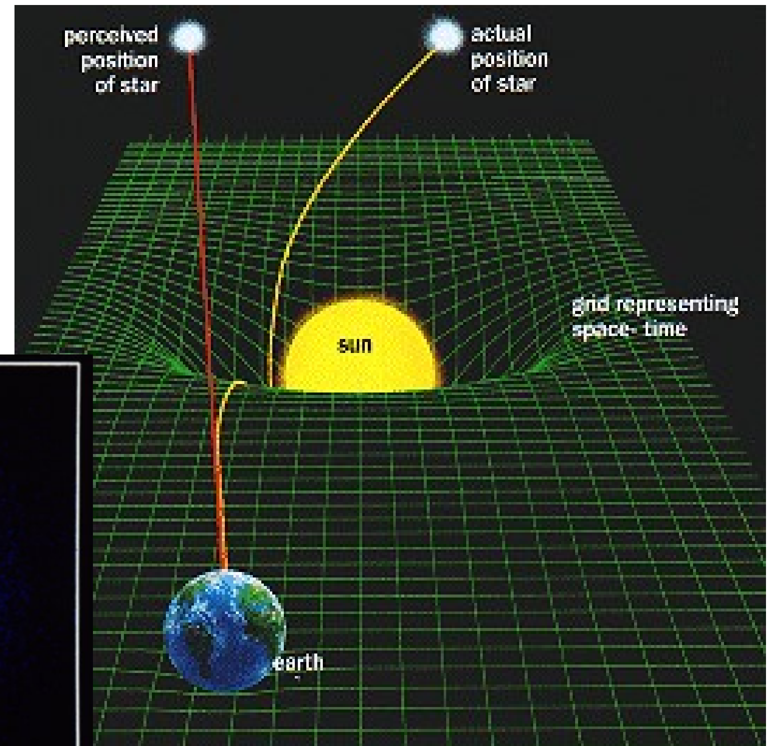
Gravity warps space and time

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

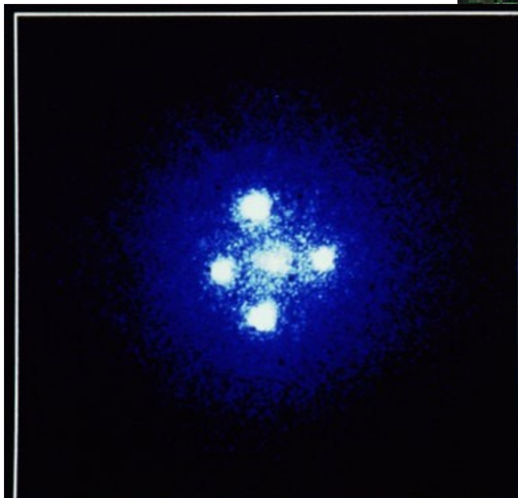
Not only the path of matter, but even the path of light is affected by gravity from massive objects. Gravity is the curvature of space and time!

Figure: Focus Mar95 p30

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



A massive object shifts apparent position of a star



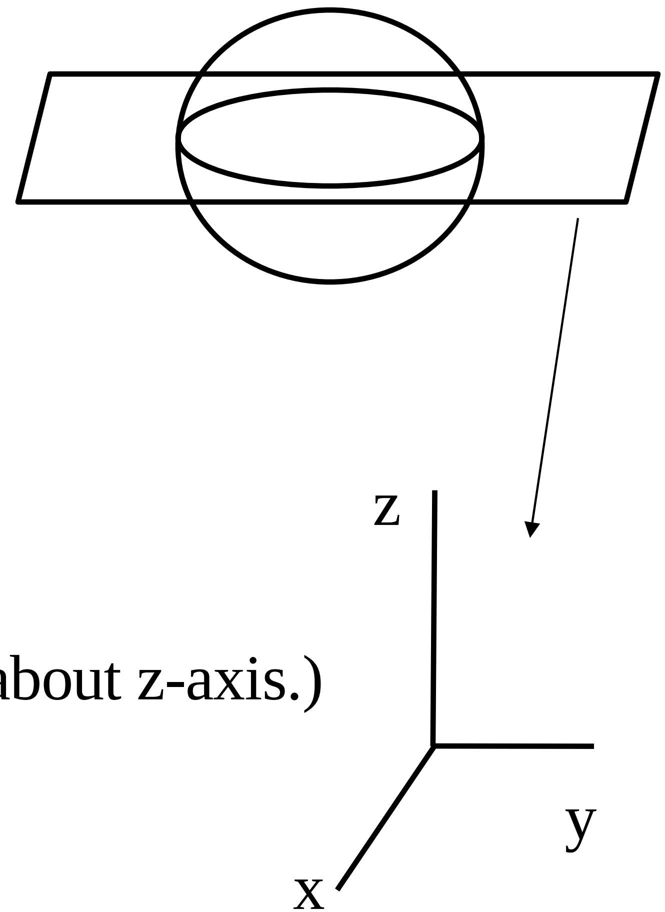
Gravitational Lens G2237+0305

Photo credit: NASA and European Space Agency (ESA)

Embedding Diagram

Schwarzschild for t = 0, θ = π /2:

$$ds^2 = \frac{1}{\left(1 - \frac{2GM}{rc^2}\right)} dr^2 + r^2 d\phi^2$$



Flat space cylindrical coordinates:

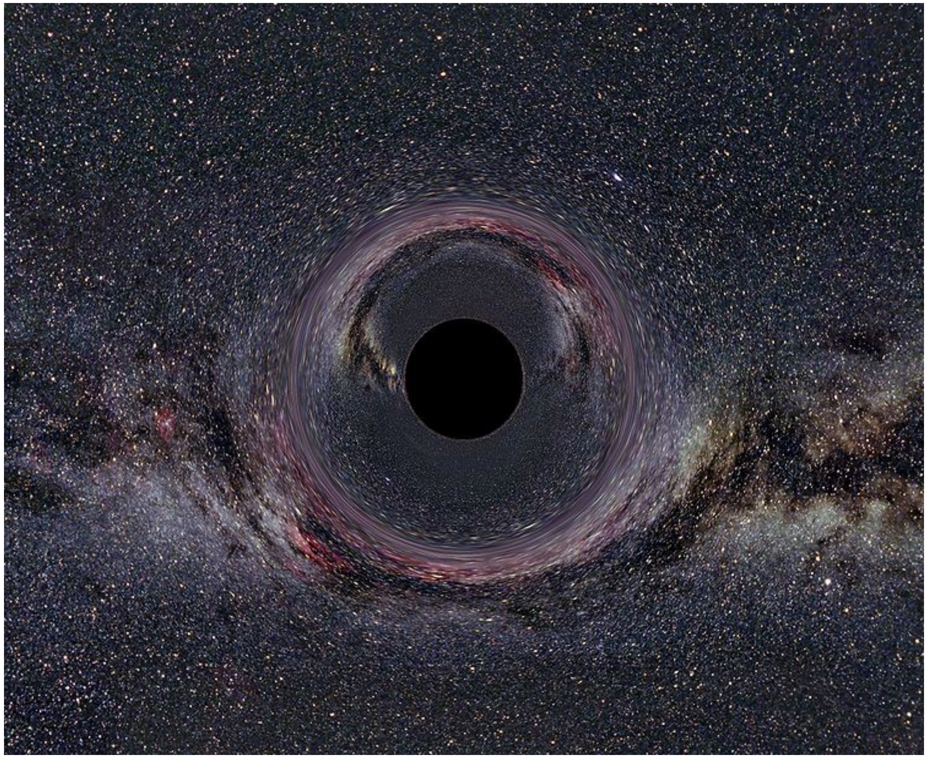
$$ds^2 = dz^2 + dr^2 + r^2 d\phi^2$$

$z = f(r)$ (Surface of revolution about z-axis.)

$$dz = f'(r) dr$$

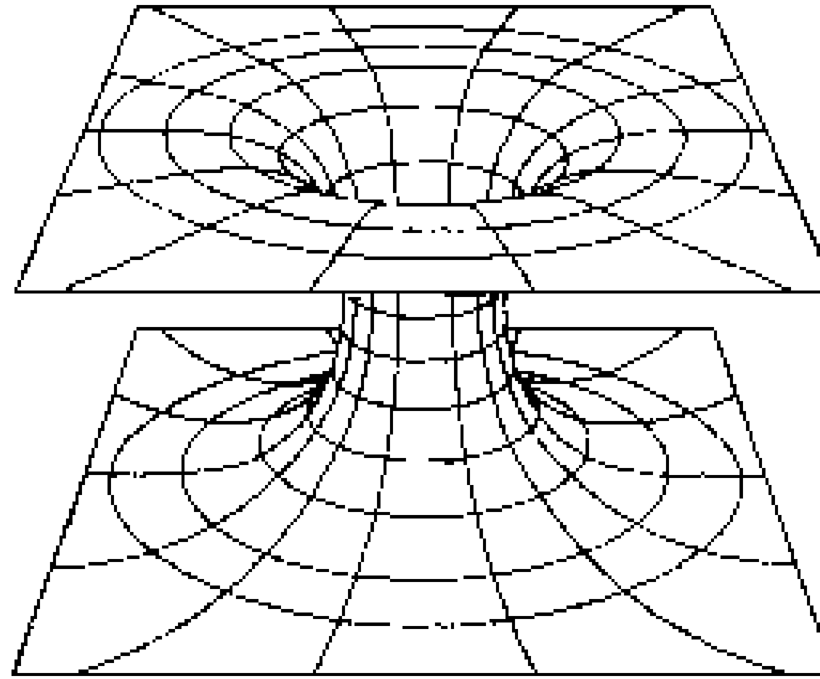
$$ds^2 = [f'(r)^2 + 1] dr^2 + r^2 d\phi^2$$

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

Supernovae

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

Anglo-Australian Observatory, photo by David Malin.

LIGO

Pulsars

Play Me

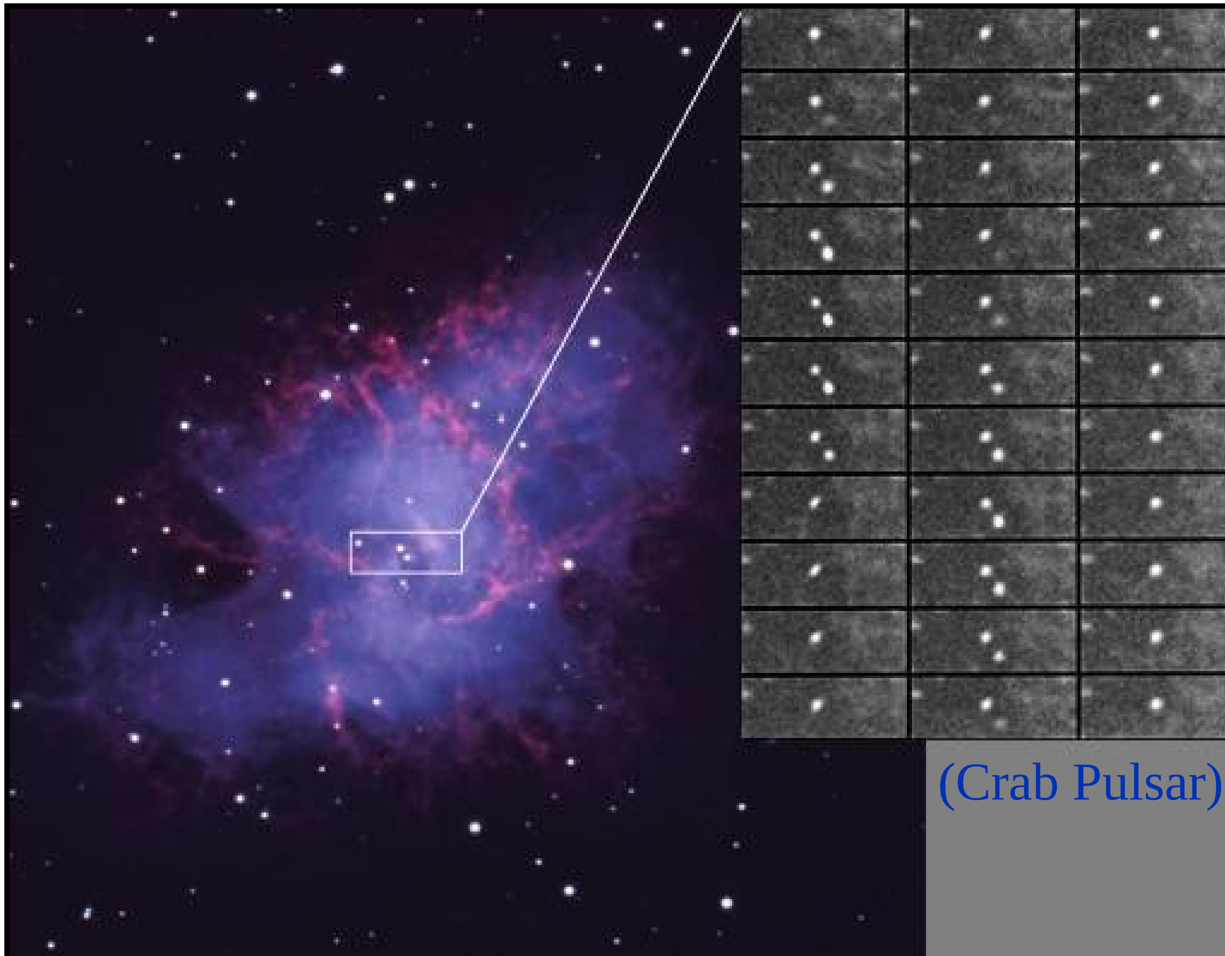
(Vela Pulsar)

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

Jodrell Bank Observatory,

Dept. of Physics & Astronomy,

The University of Manchester

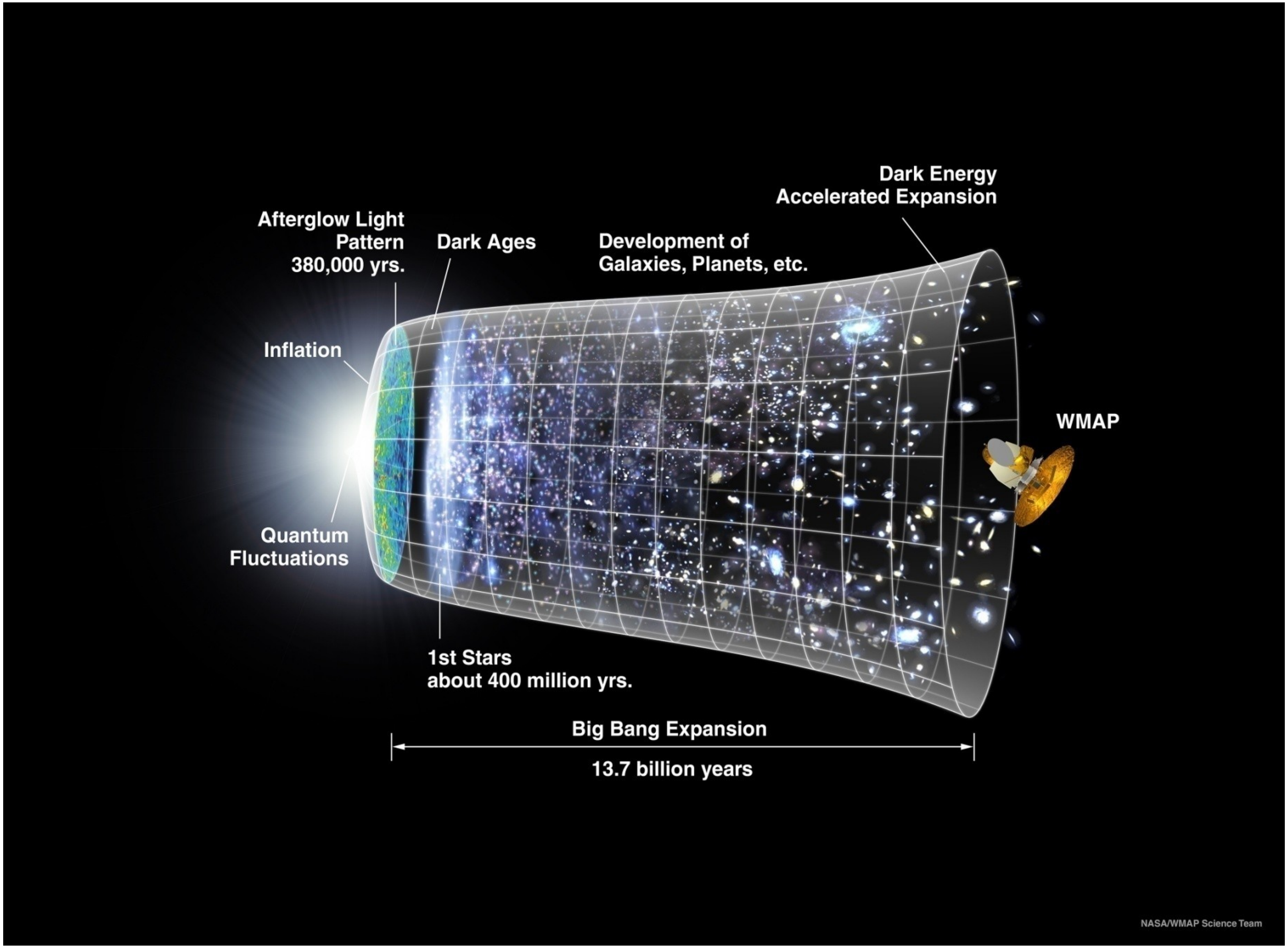


(Crab Pulsar)

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

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

The Big Bang

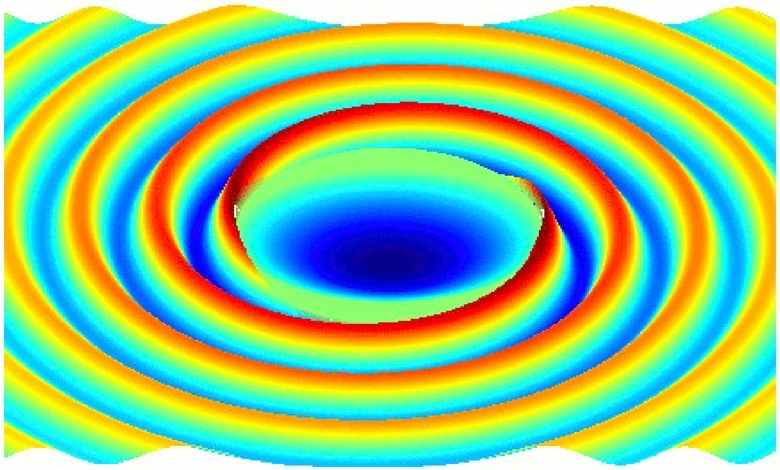


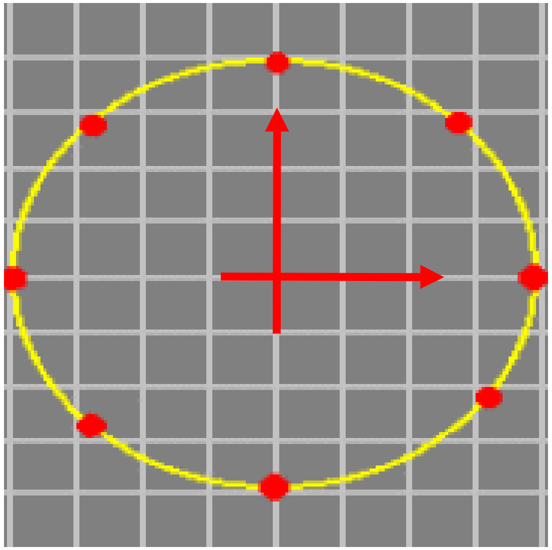
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

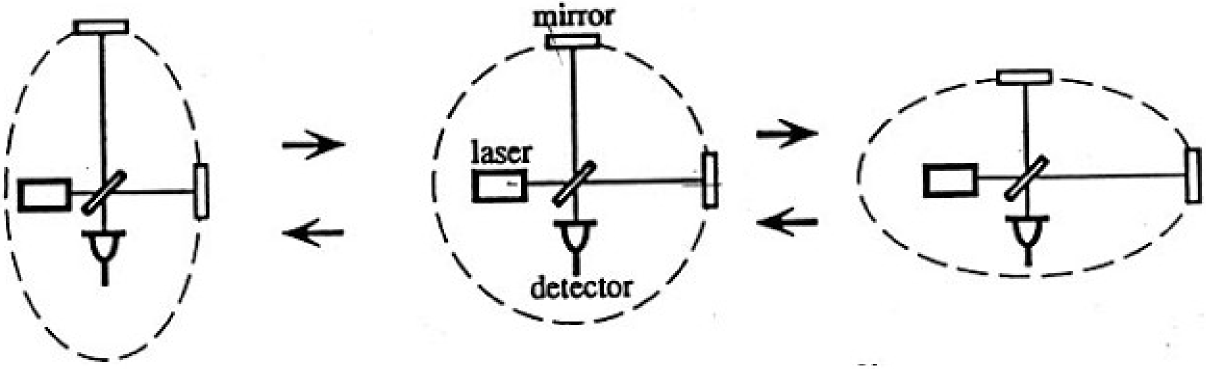
Gravitational Waves

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:







LIGO & Gravitational Waves

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

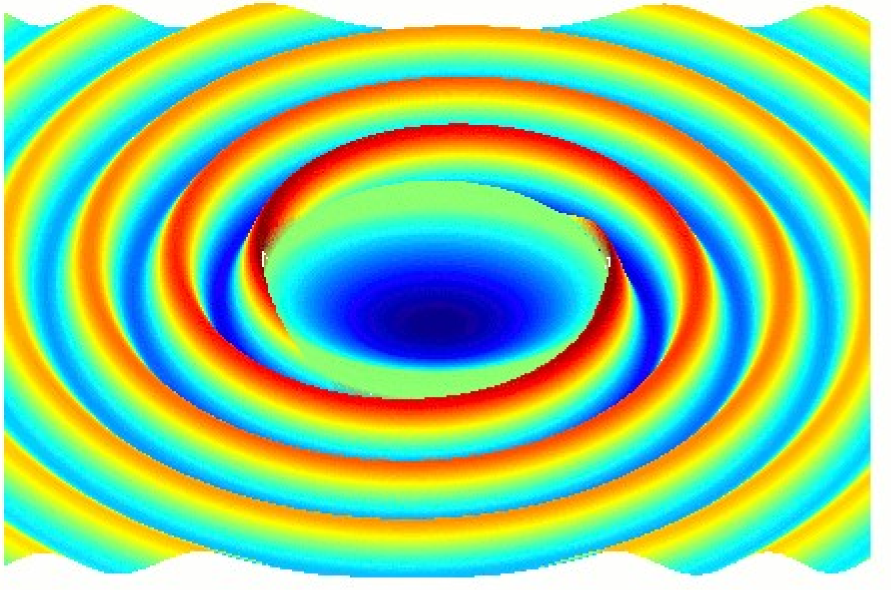
$$dT^2 = g_{\mu\nu} dx^{\mu} dx^{\nu}$$

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

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

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

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



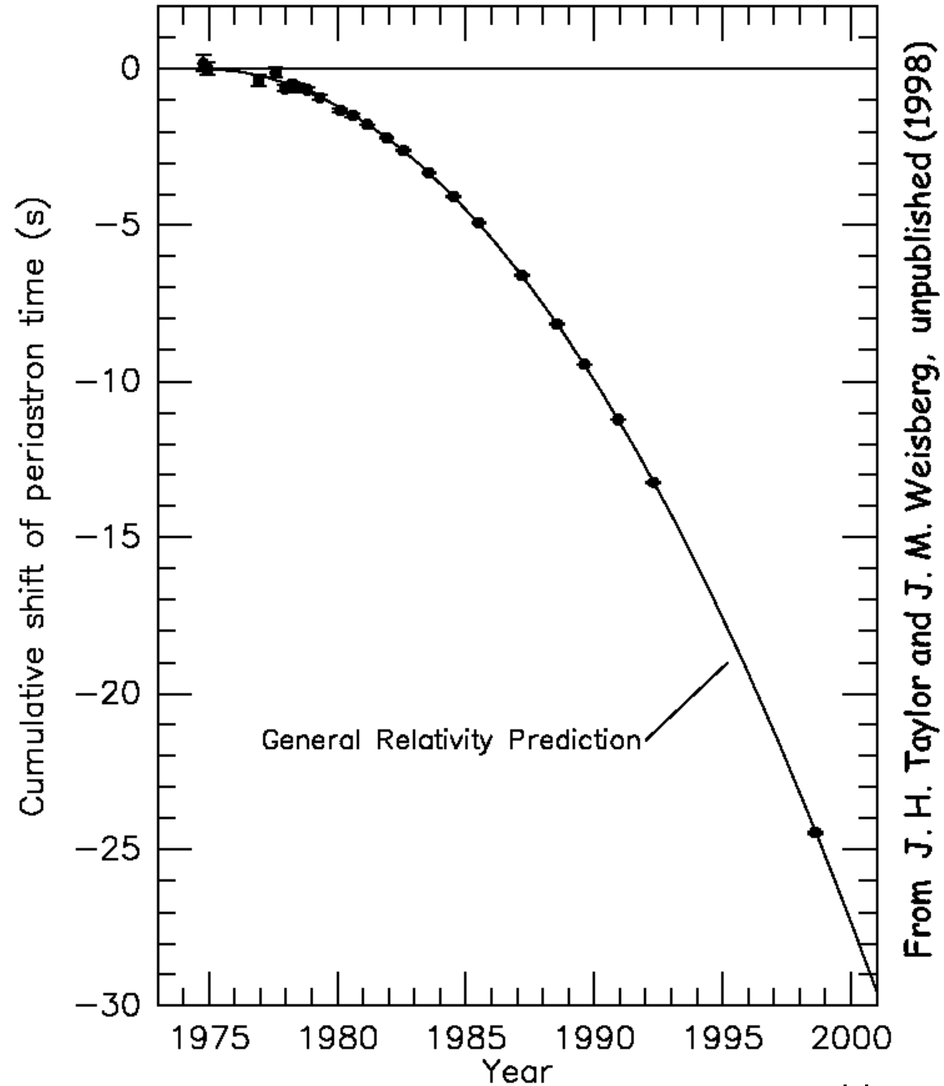
LIGO Do Gravitational Waves Exist?

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

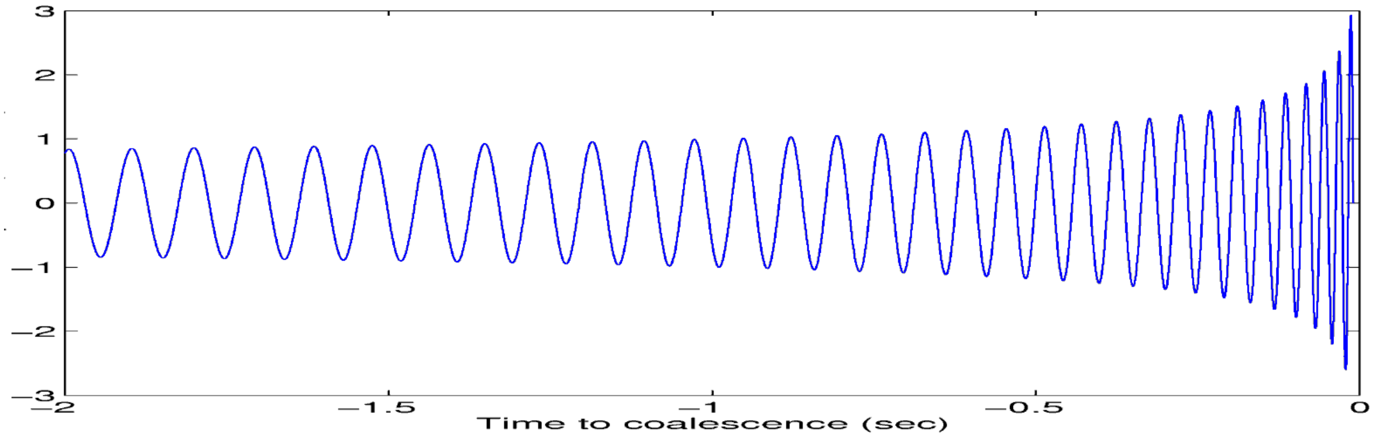
System shows very gradual orbital decay – just as general relativity predicts!

⇒ Very strong indirect evidence for gravitational radiation



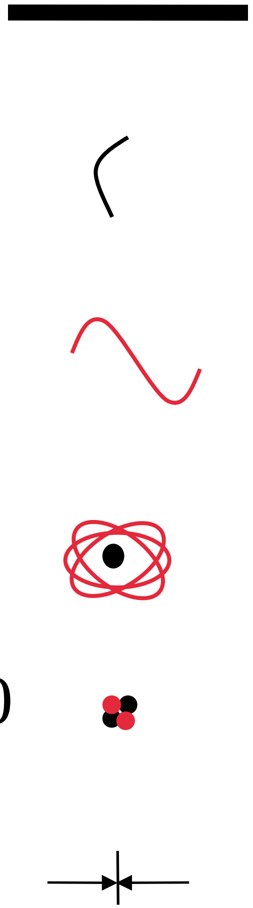
The Fate of B1913+16

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



LIGO

How weak are they?



One meter, about 40 inches

÷10,000 — Human hair, about 100 microns

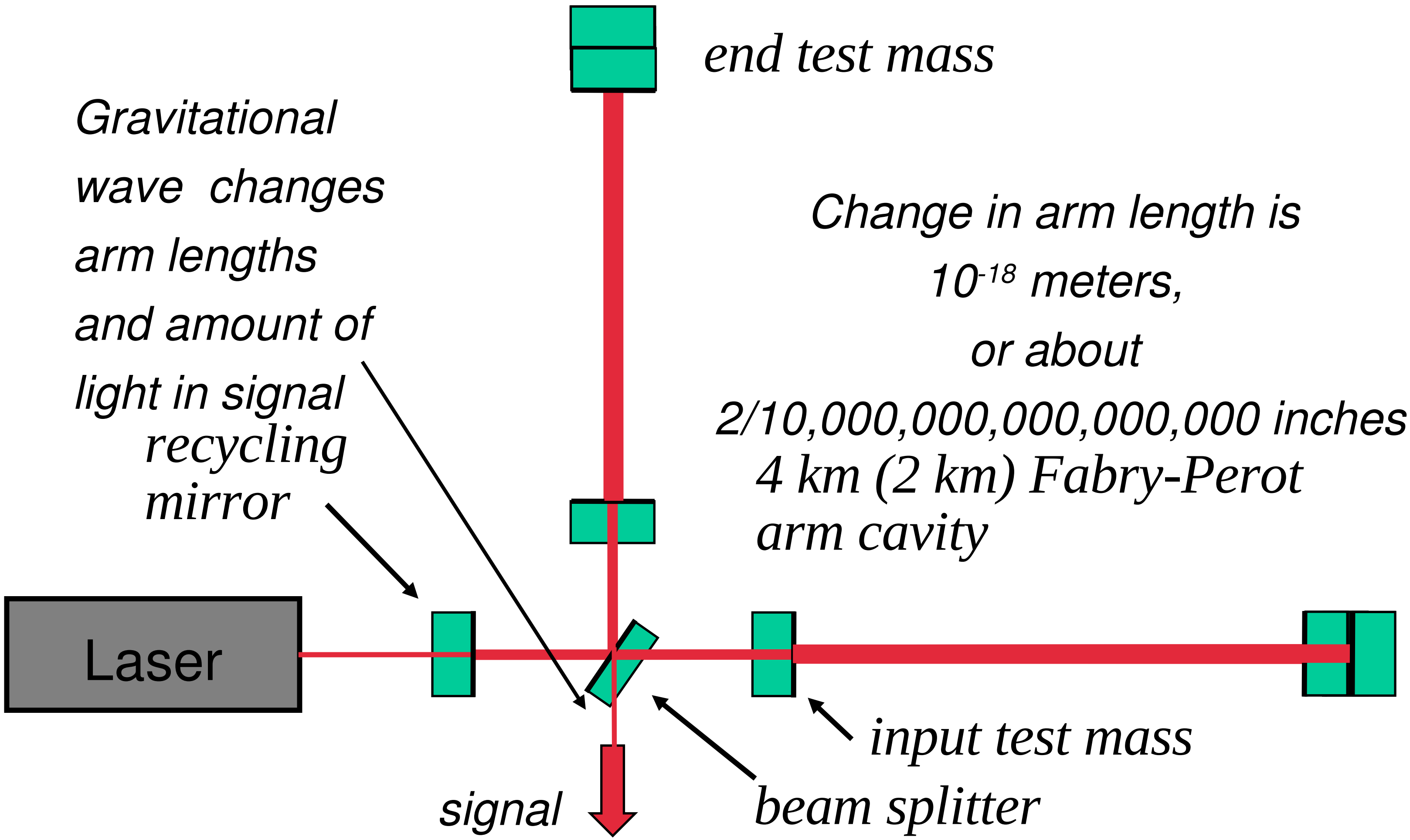
÷100 — Wavelength of light, about 1 micron

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

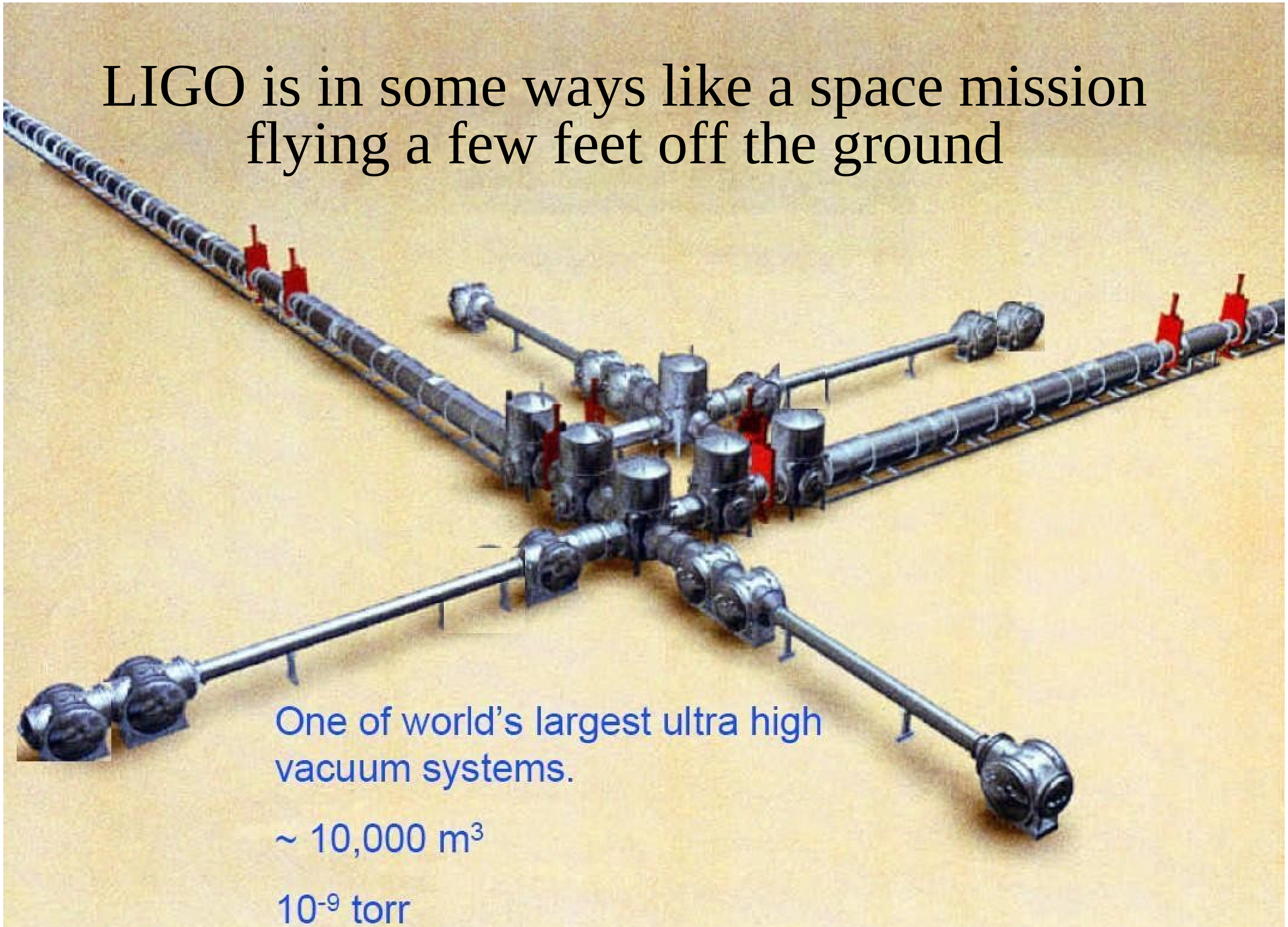
÷100,000 — Nuclear diameter, 10^{-15} meter

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

Sensing the Effect of a Gravitational Wave



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



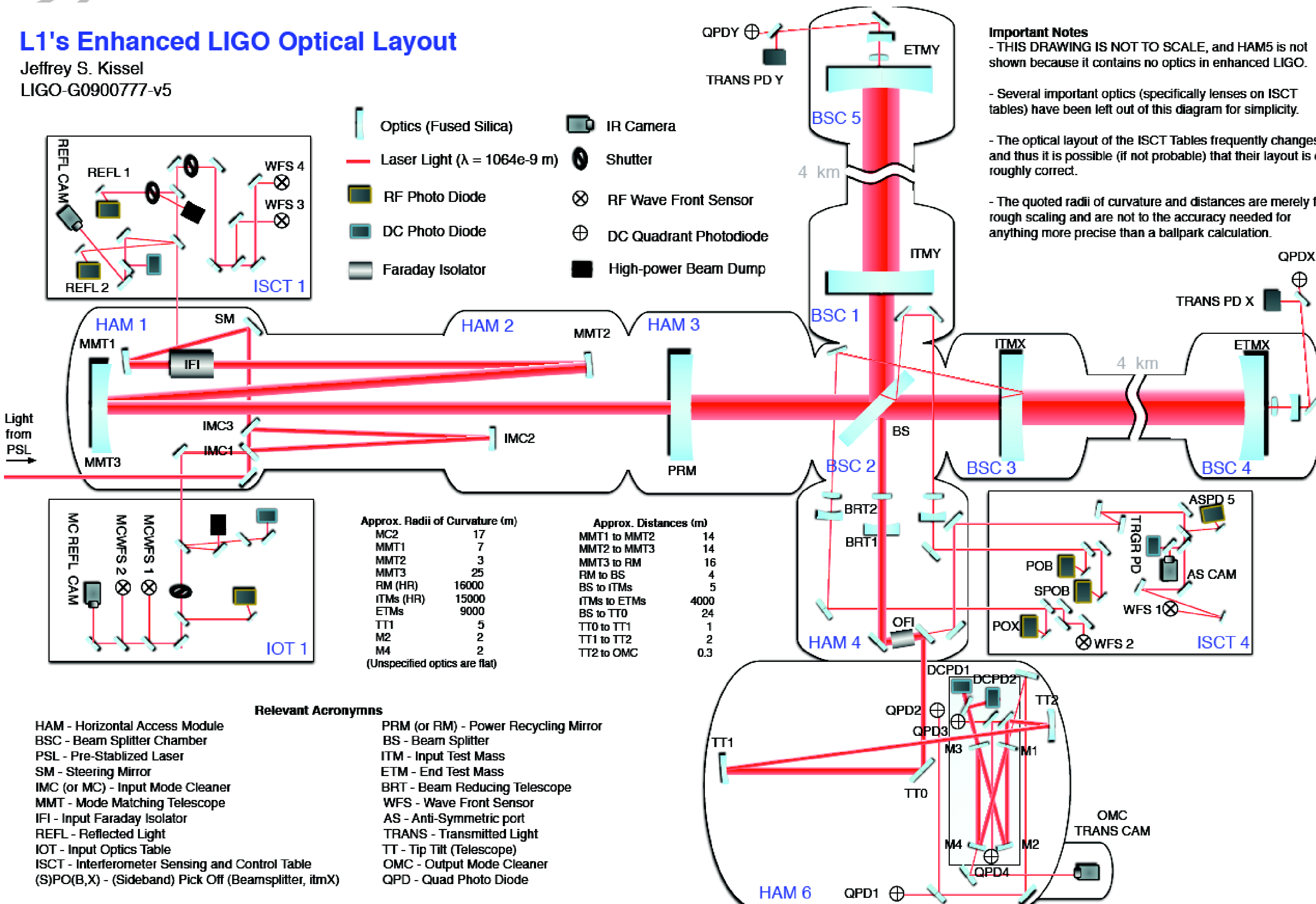
LIGO

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)

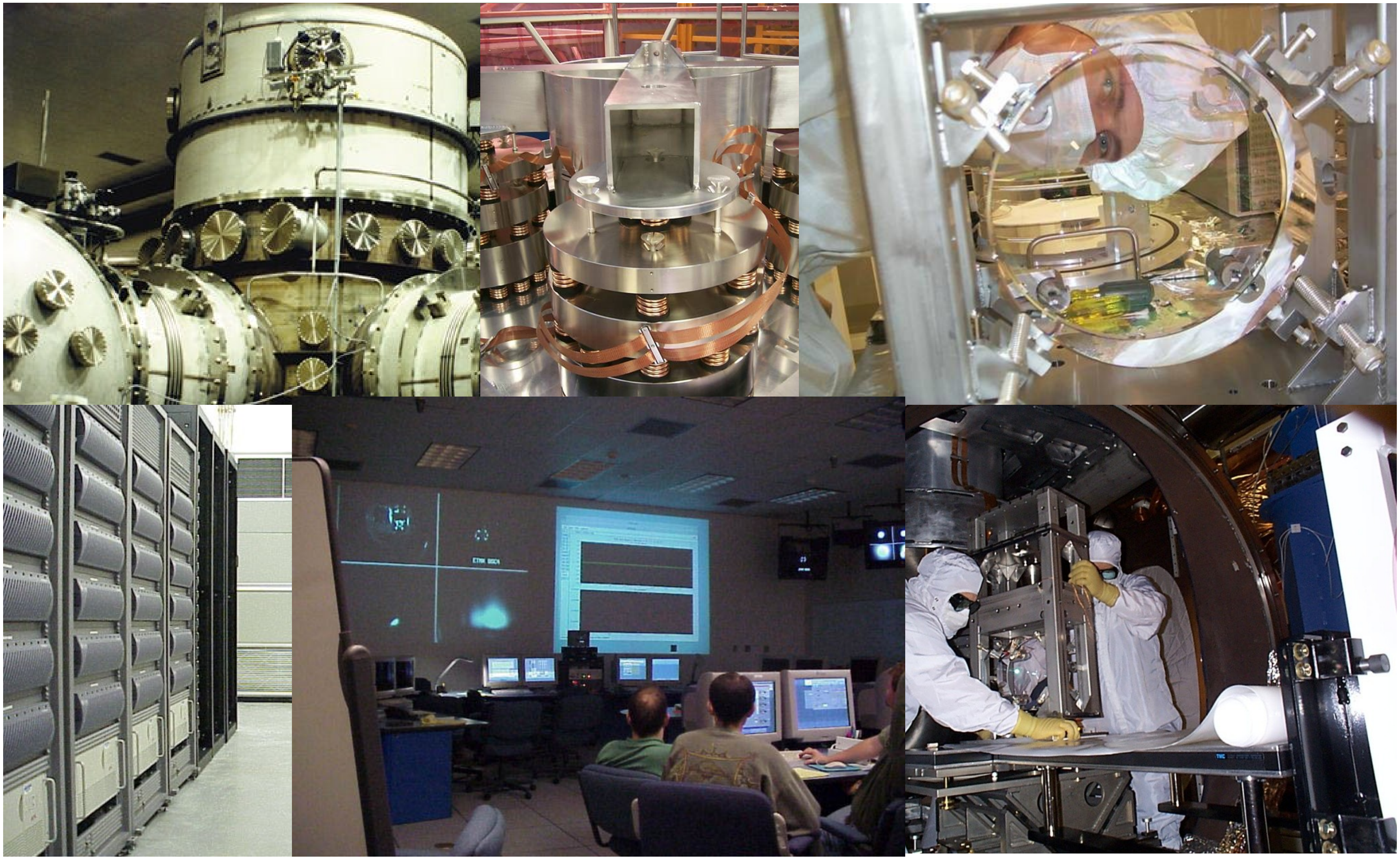
Approx. Distances (m)

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 Acronymns

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

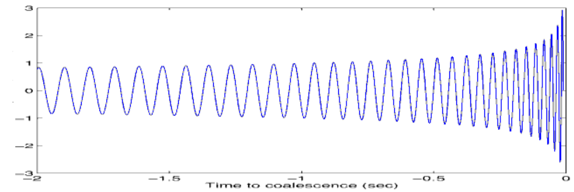
Inside Initial LIGO



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.

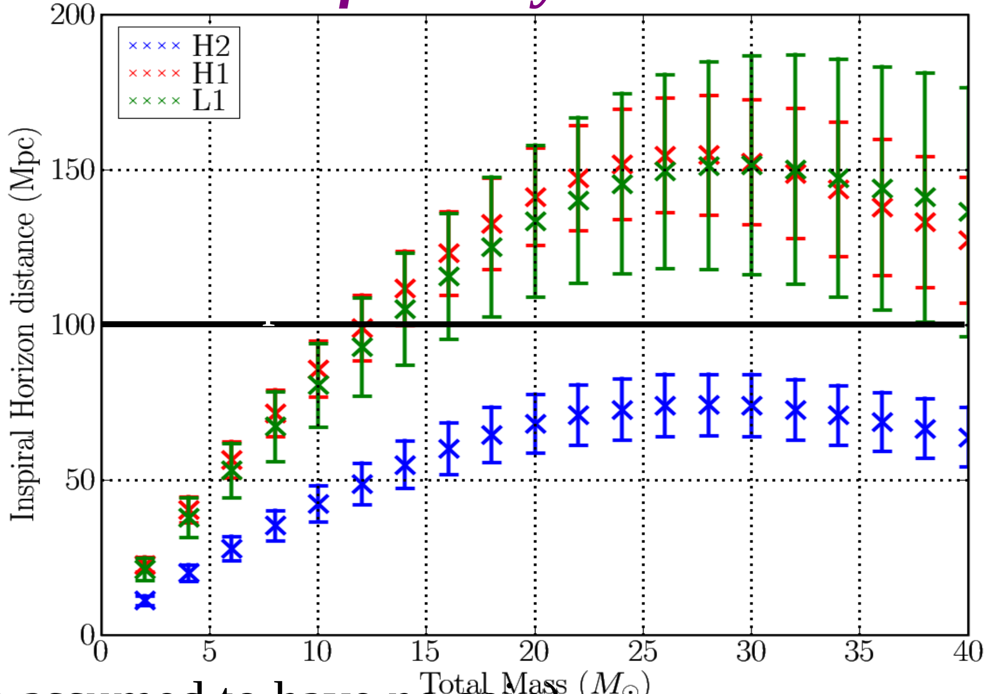
Binary Inspiral Searches



[arXiv:0901.0302]

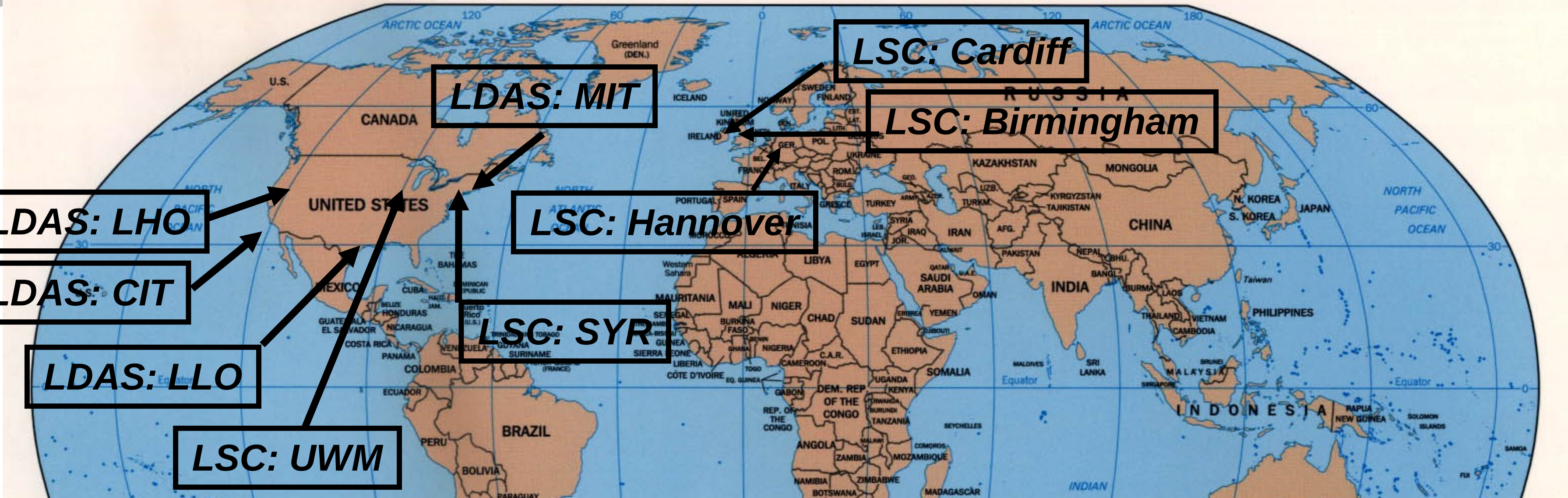
- Recently released result from first year of S5 data
- No inspiral signals detected
- Using population models, calculated 90% confidence limits on coalescence rates:
- For binary neutron stars:
  3.8×10^{-2} per year per L_{10}
- For 5+5 $M_{\odot}$ binary black holes:
  2.8×10^{-3}
- For BH-NS systems: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

How far away can we hear?



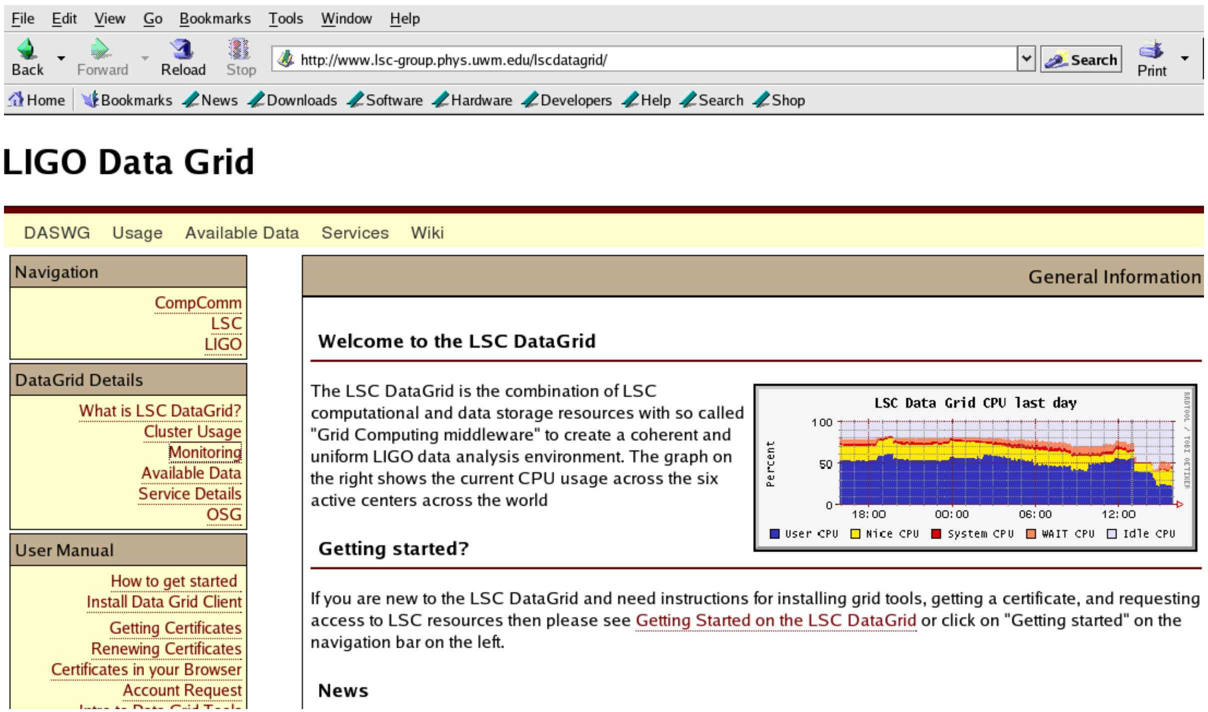
- (Slightly tighter limits if BHs are assumed to have no spin)

Worldwide Data Analysis using The LIGO Data Grid (LDG)



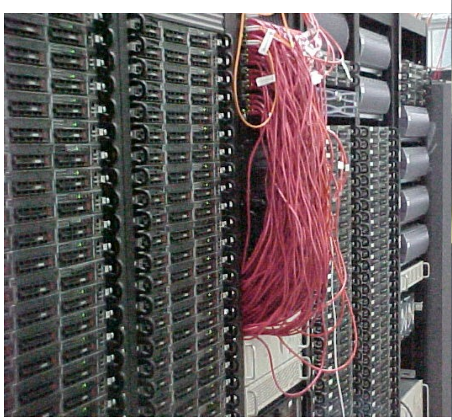
- *Clusters with currently 23518 cores, 10 Tflops per cluster (aLIGO 10x this)*
- *Linux nodes, Solaris Servers; ~500 users with 100 TB of home directory space.*
- *C/C++/python/Matlab analysis libraries; tcl/perl/php; mysql, sqlite databases. Programmers/Sys. Admins provide DAQ, data I/O libraries, reduced data, calibrated data, data archiving, finding, and transfer services.*
- *LIGO produced 1 TB of data per day. (aLIGO 3-10x this)*
- *Stored 2.5 Petabytes of data (100's of TB disk space +tape library systems)*
- *Fiber Channel Storage Area Management Filesystems connect RAID arrays.*
- *For aLIGO all disk storage (with possible deep tape storage)*
- *Shared memory, GigE-10GigE TCP/IP, Data Broadcasters and Servers.*
- *Einstein@Home BOINC*
- *For aLIGO will have web based open data infrastructure after 1st detections.*

The LIGO Data Grid



LDG Client/Server Distribution

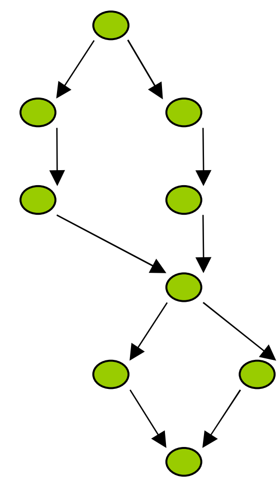
```
packageName( 'Server' )
version( '4.5' )
pacmanVersionGE('3.18.5')
package( 'Server-Environment' )
package( 'VDT_CACHE:Globus' )
package( 'VDT_CACHE:CA-Certificates' )
package( 'VDT_CACHE:CA-Certificates-Updater' )
package( 'VDT_CACHE:Condor' )
package( 'VDT_CACHE:GSIOpenSSH' )
package( 'VDT_CACHE:KX509' )
package( 'VDT_CACHE:MyProxy' )
package( 'VDT_CACHE:UberFTP' )
package( 'VDT_CACHE:EDG-Make-Gridmap' )
package( 'VDT_CACHE:Globus-RLS')
package( 'VDT_CACHE:Globus-Core')
package( 'VDT_CACHE:Globus-Condor-Setup' )
package( 'VDT_CACHE:PyGlobus' )
package( 'VDT_CACHE:PyGlobusURLCopy' )
package( 'VDT_CACHE:Pegasus' )
package( 'VDT_CACHE:VOMS-Client' )
package( 'VDT_CACHE:Globus-WS' )
package( 'VDT_CACHE:Tomcat-5.5' )
package( 'VDT_CACHE:TclGlobus' )
package( 'Server-FixSSH' )
package( 'Server-RLS-Python-Client' )
package( 'Server-Cert-Util' )
package( 'Server-LSC-CA' )
```



Data Analysis on the LDG by the LIGO Scientific Collaboration

Condor
High Throughput Computing

• The LDG clusters use Condor, which handles 10’s of millions of jobs per year running on the LDG, and up to 500k jobs per DAG.



• At Caltech, 30 million jobs processed using 22.8 million CPU hrs. on 1324 CPUs over 2.5 years.

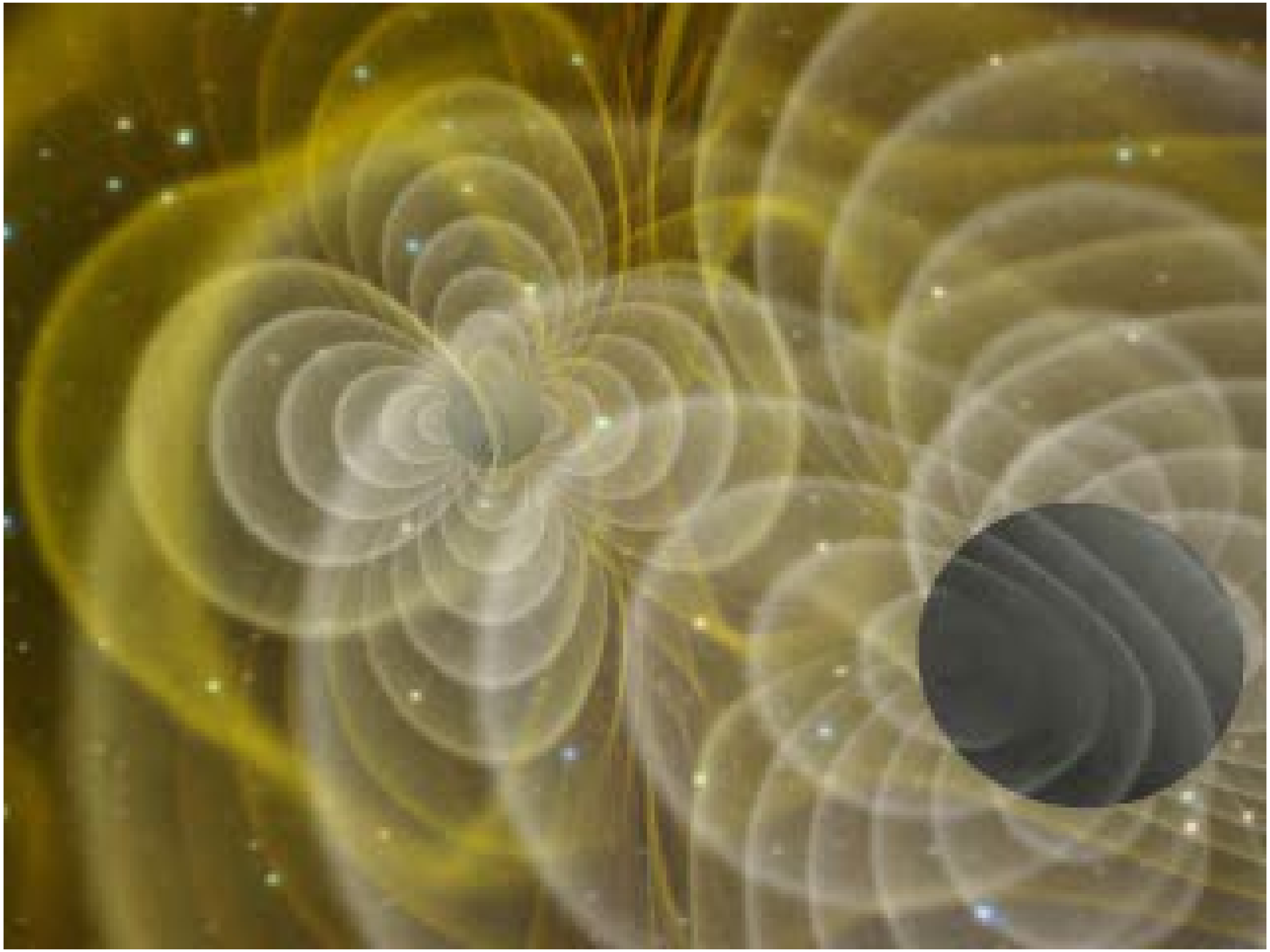
• For example, to search 1 yr. of data for GWs from the inspiral of binary neutron star and black hole systems takes ~2 million jobs, and months to run on several thousand ~2.6 GHz nodes.

• Most pipelines use matched filtering with template banks or look for excess power from averaging FFTs; all Multivariant Statistical Classifier. Trivial to run in parallel. MPI also available for parallel universe jobs.

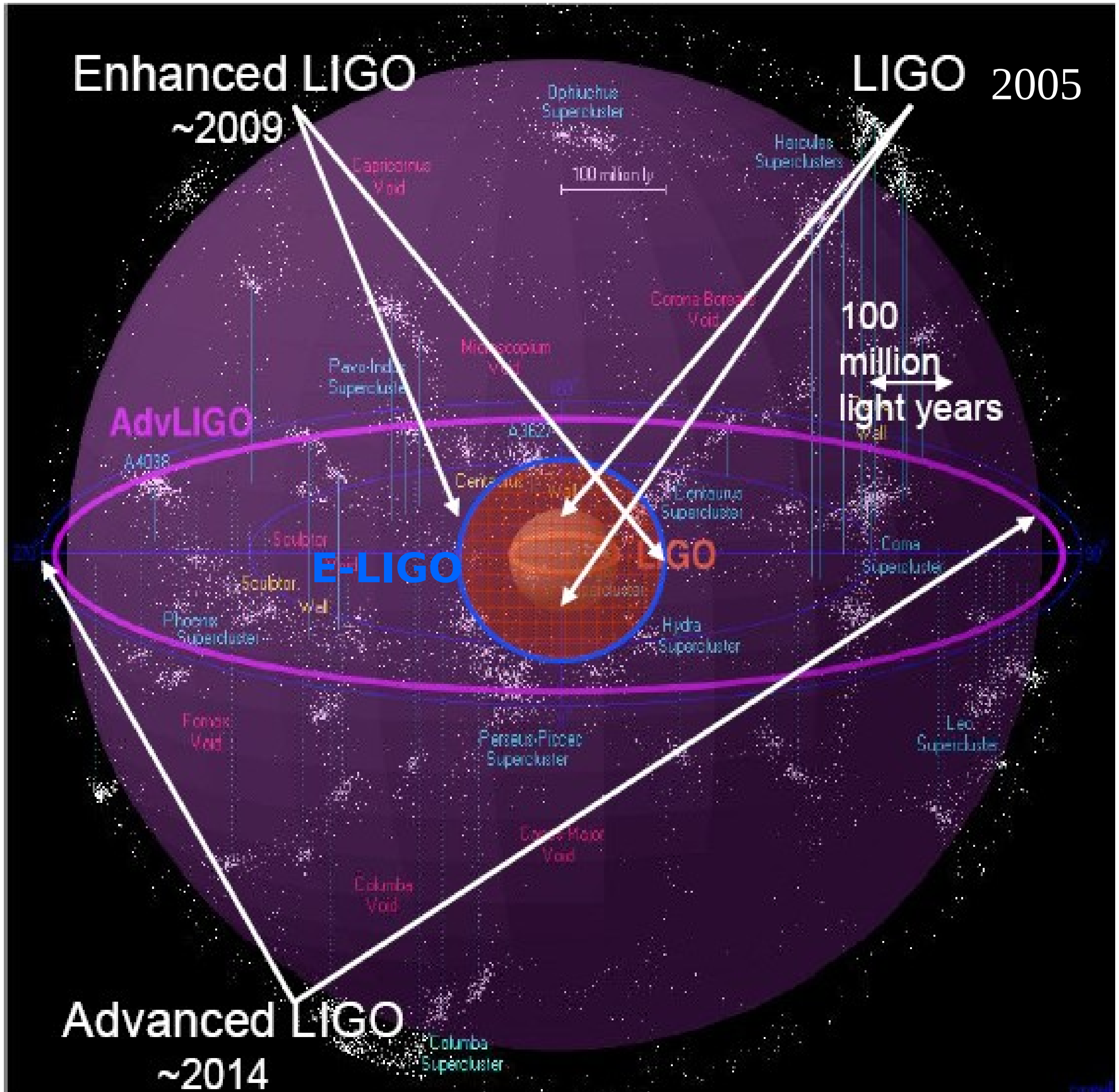
Hanford Cluster Installation 2009


LIGO And Numerical Relativity

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



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

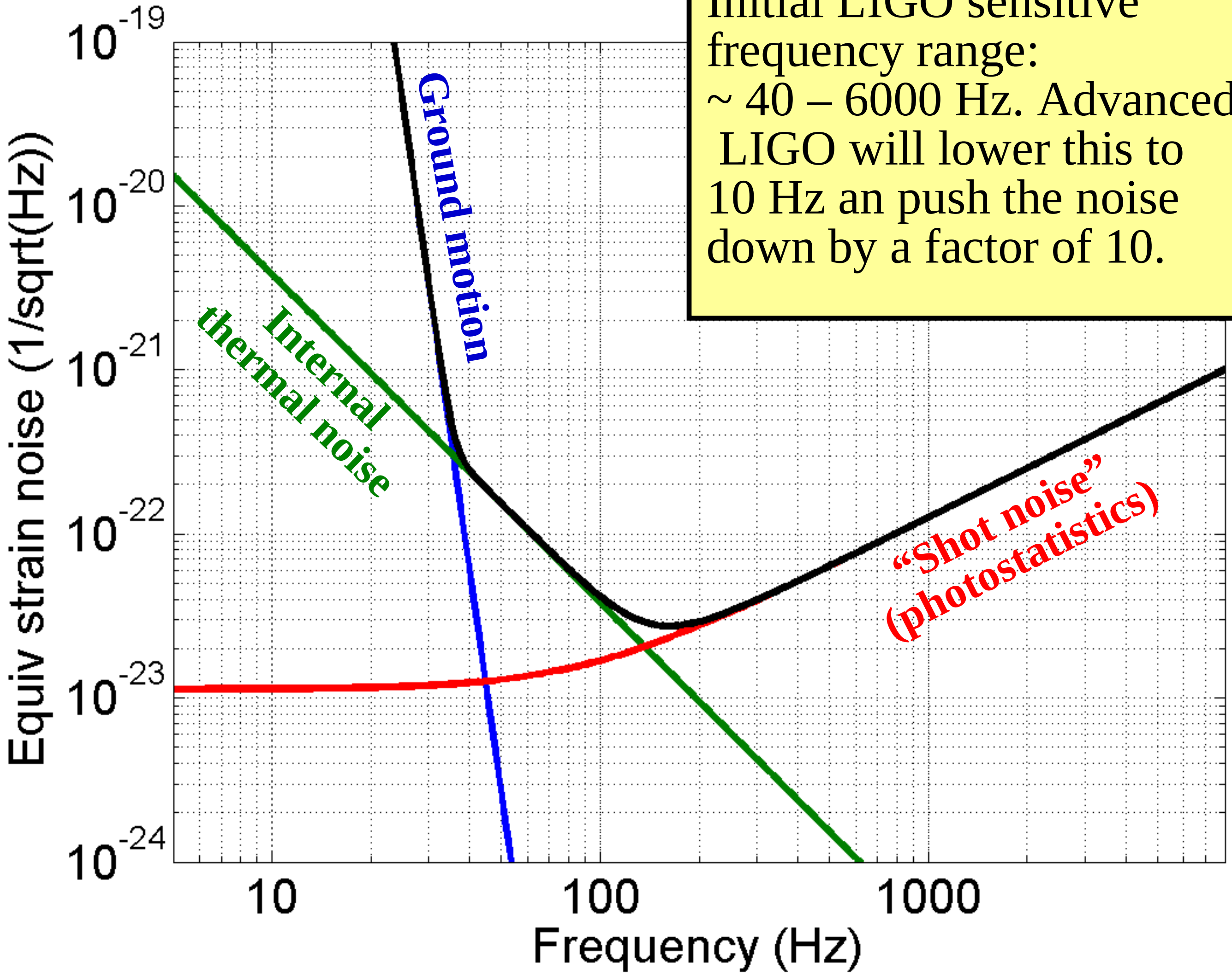
CW signals from pulsars, LMXBs, or unseen NSs

Stellar core collapse

Transient or stochastic signal from cosmic strings

etc…

Limiting Sources of Noise



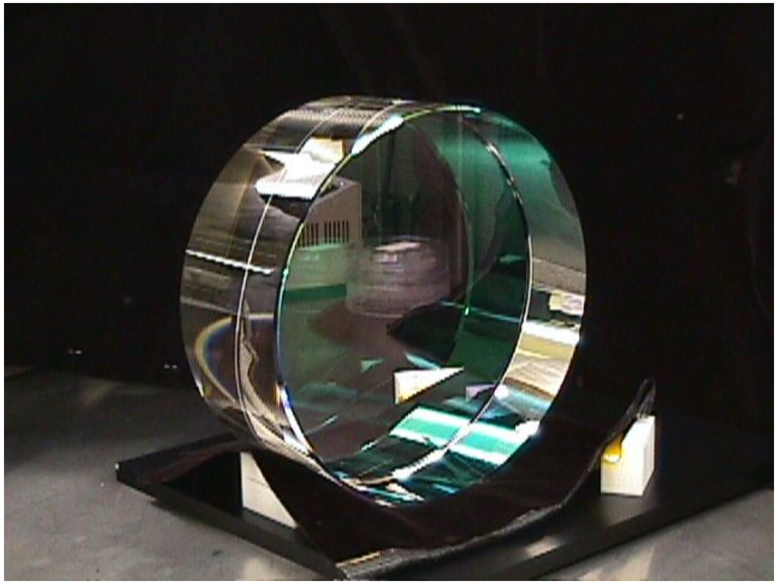
Initial LIGO sensitive frequency range: ~ 40 – 6000 Hz. Advanced LIGO will lower this to 10 Hz an push the noise down by a factor of 10.

LIGO

Advanced LIGO Assembly Area

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)

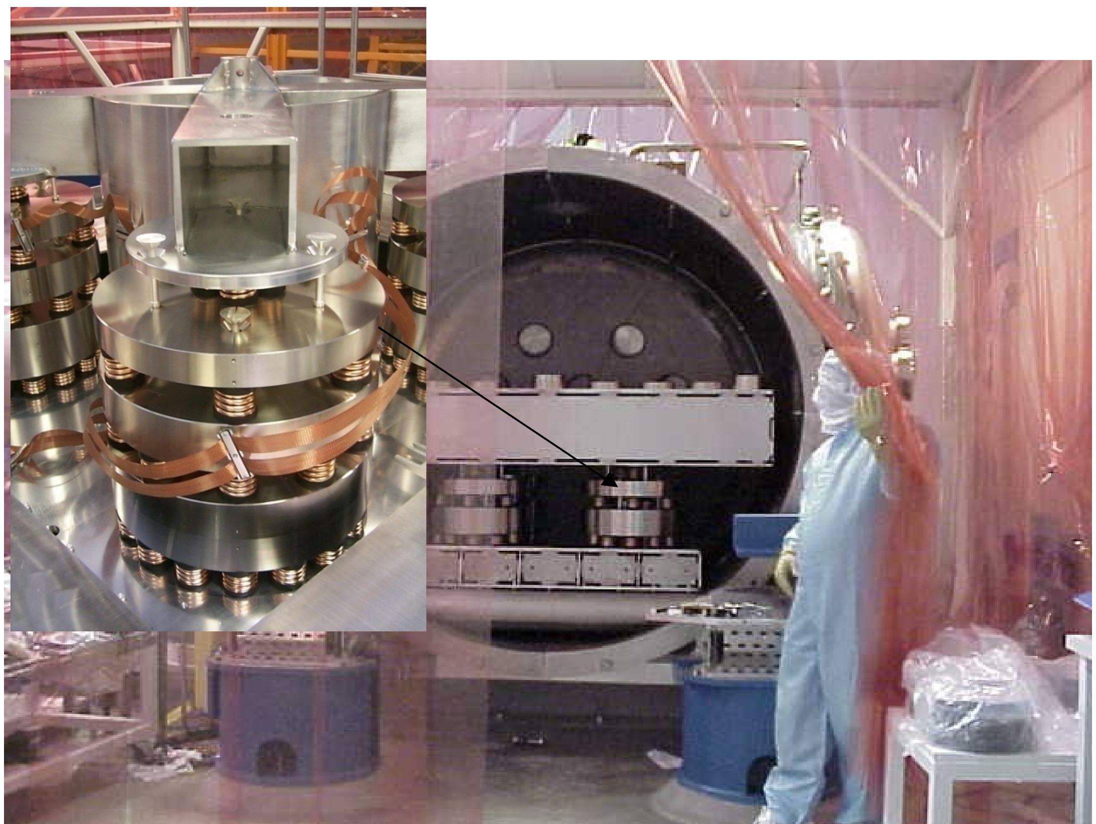
- A bigger mass (and larger beam size) means less thermal noise amd radiation pressure, which means better sensitivity.

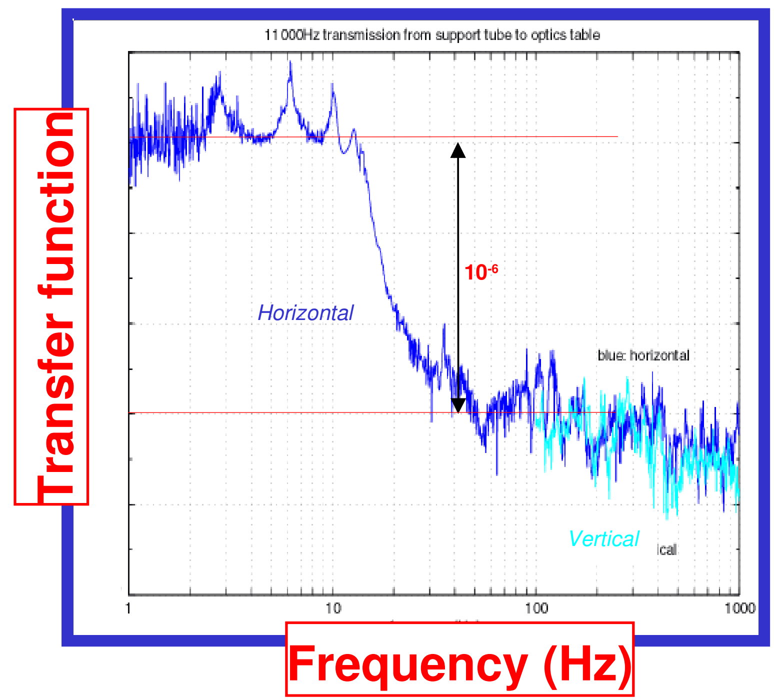
LIGO

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

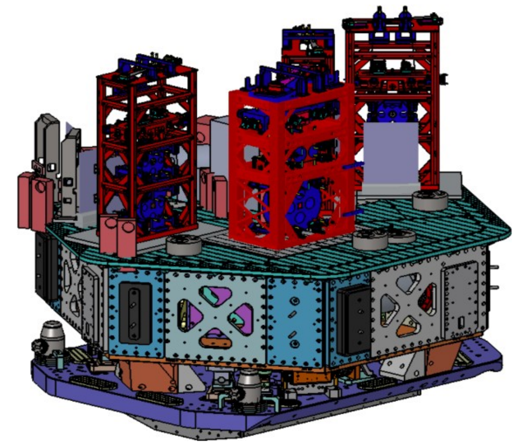


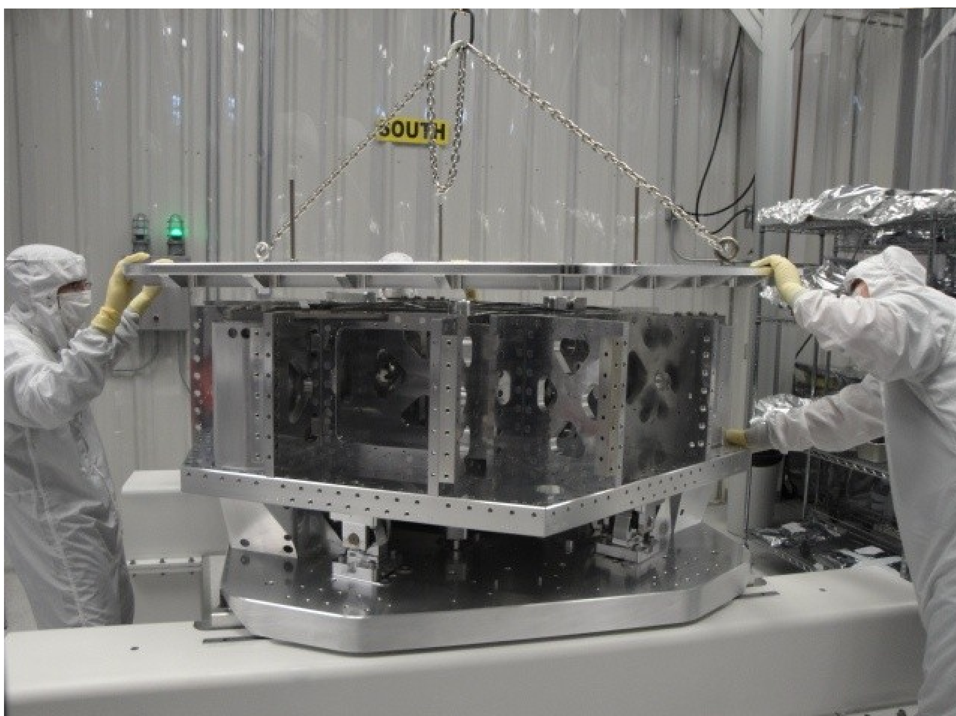


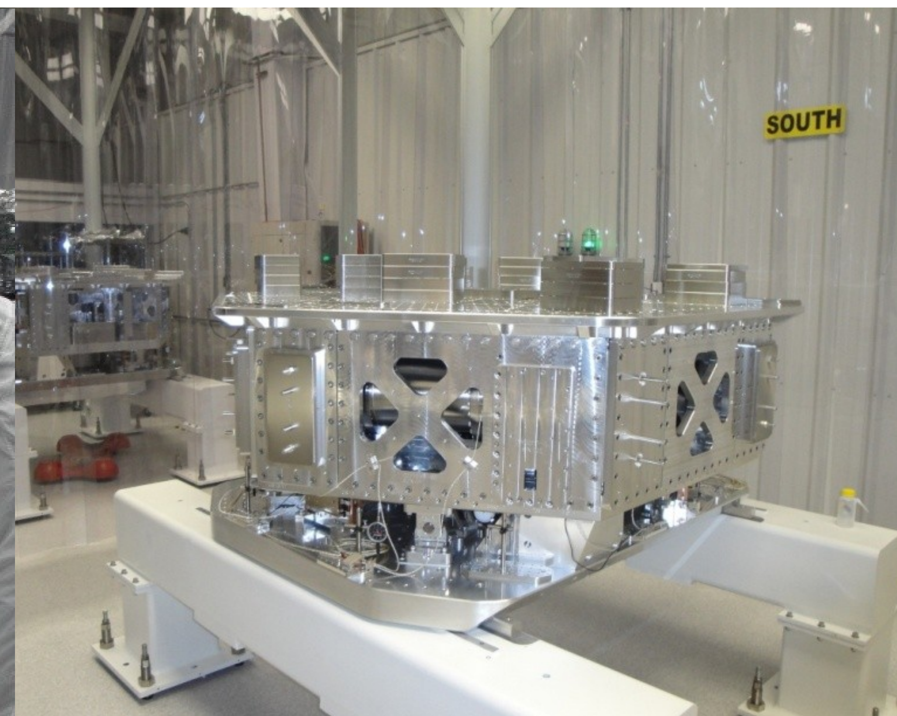
LIGO

Advanced LIGO Seismic Isolation

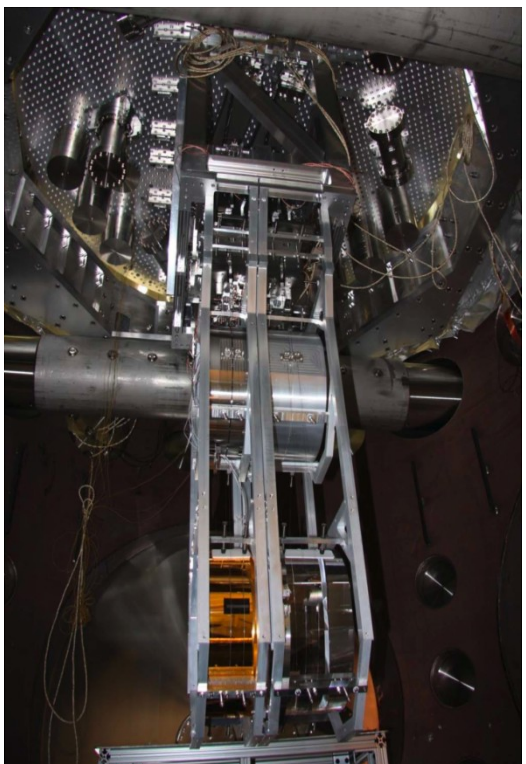
- Assembly of the Horizontal Access Module stacks is in full swing at both observatories.
- Active feedback control will be used.
- One assembly already used in current Enhanced LIGO configuration.

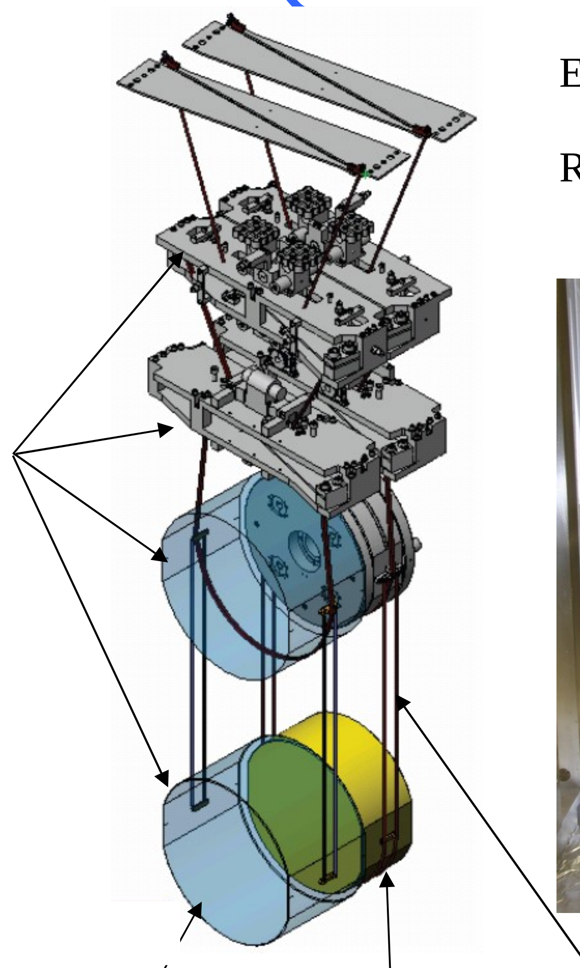




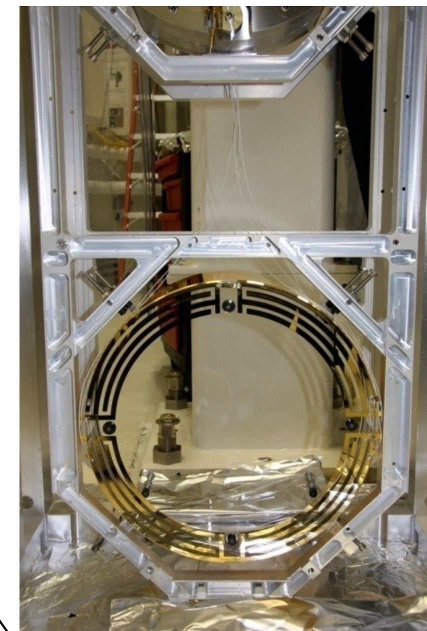


Suspension Systems
Initial Single vs. Advanced Quad Pendulum



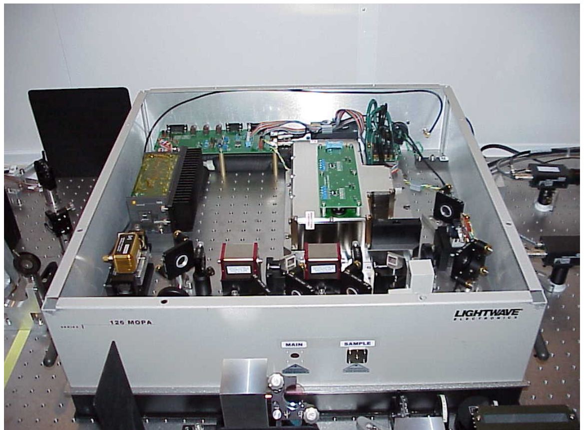


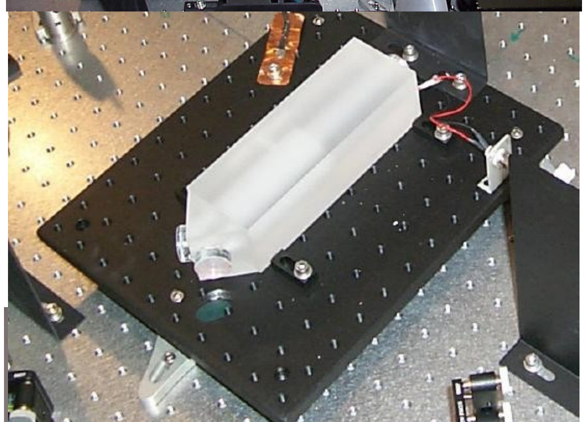
Electro Static Drive (ESD) on last stage:
Reduces noise from electromagnets

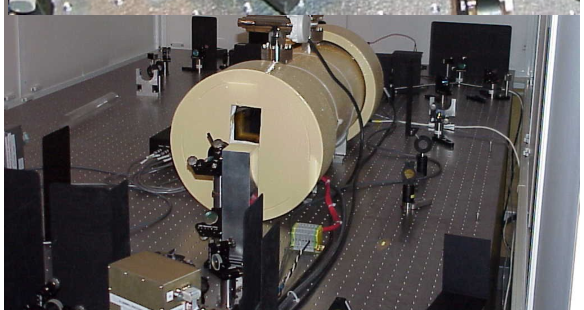


LIGO

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.

The End

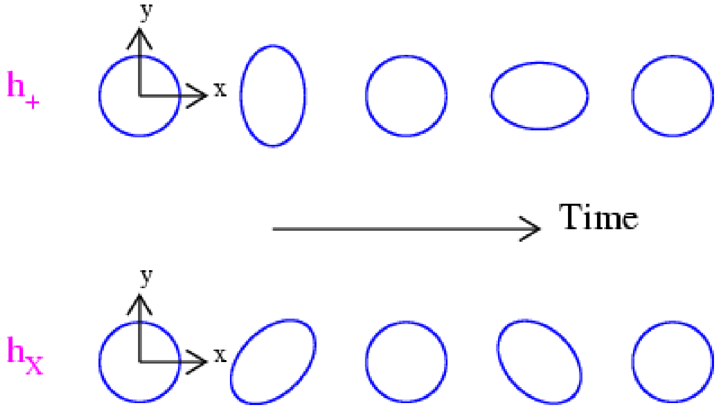
What is the observable effect?

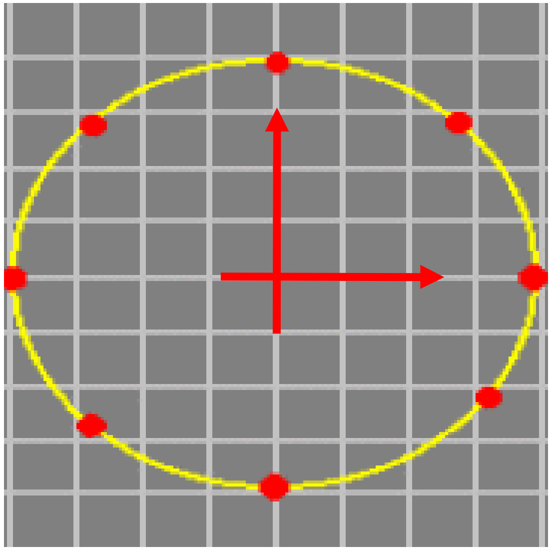
Example:

Ring of test masses

responding to wave

propagating along z

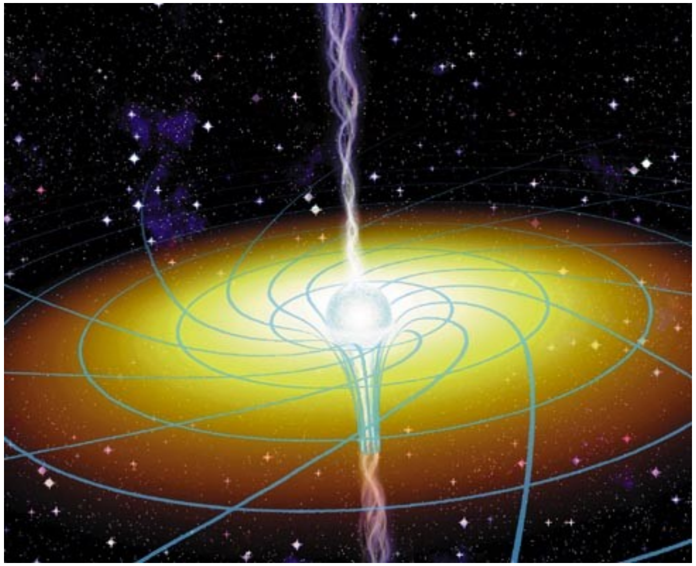




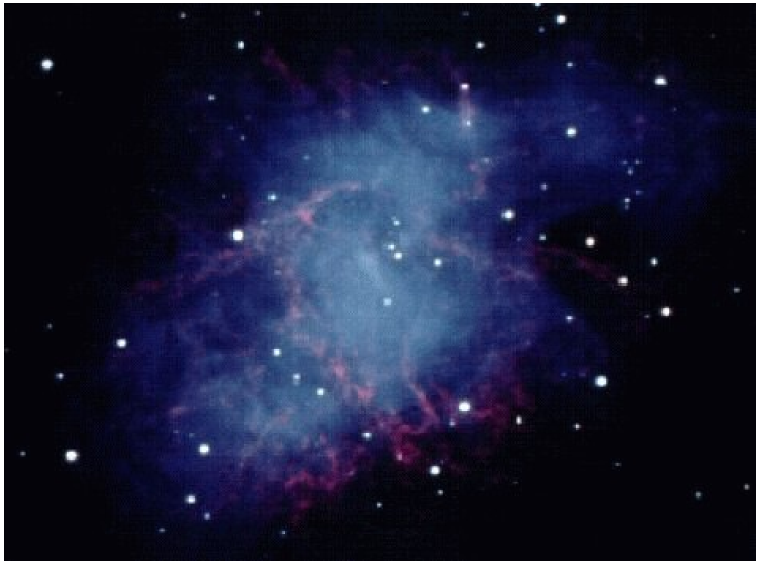
Amplitude parameterized by (tiny) dimensionless strain h:

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

Astrophysical Sources

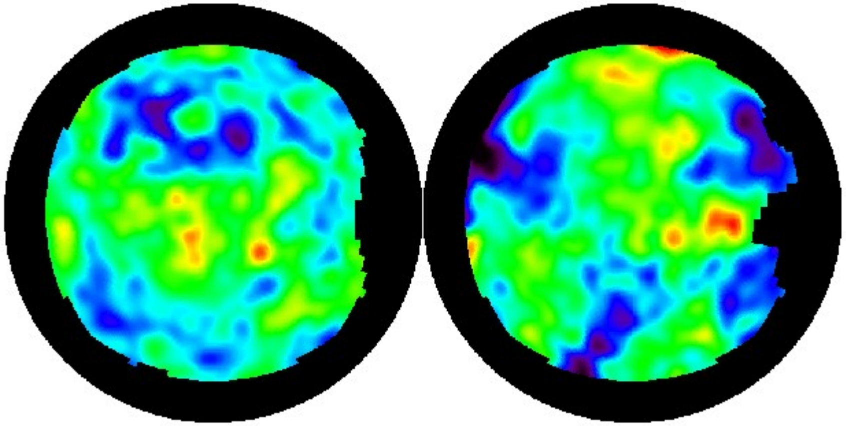


Black Holes



Dense Stars

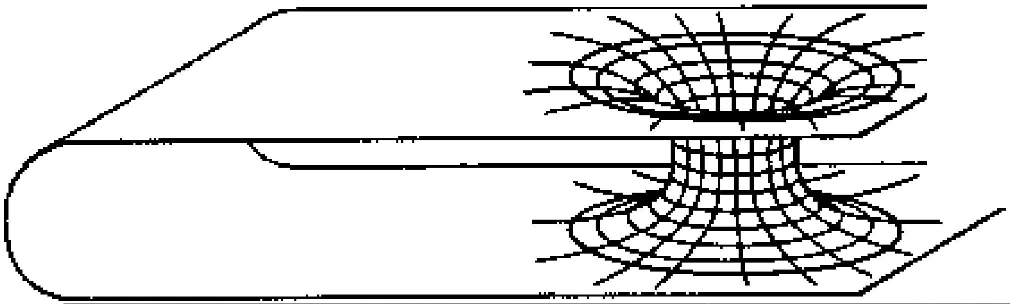
Supernovae



Stochastic Background

Photos: http://antwrp.gsfc.nasa.gov; http://imagine.gsfc.nasa.gov *http://www.astrosociety.org/education/publications/tnl/24/24.html*

Worm Holes
Time Travel & All That



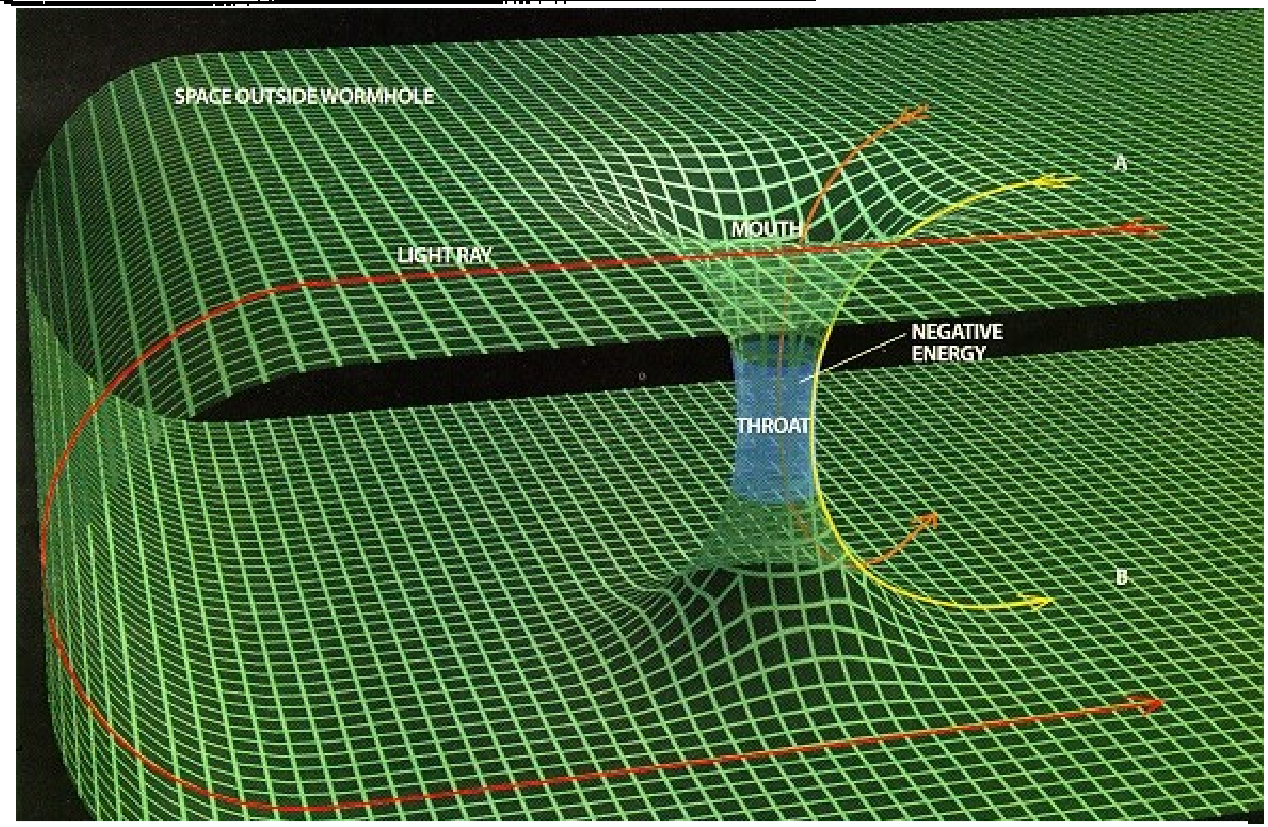
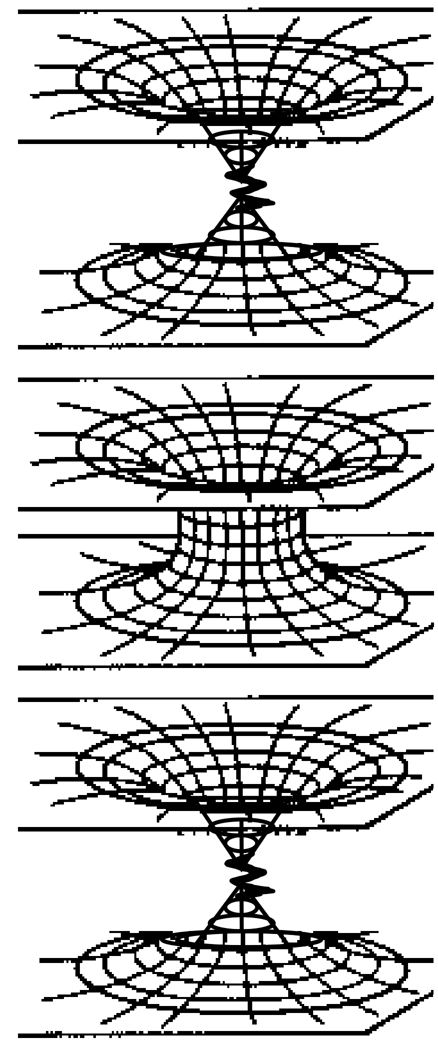


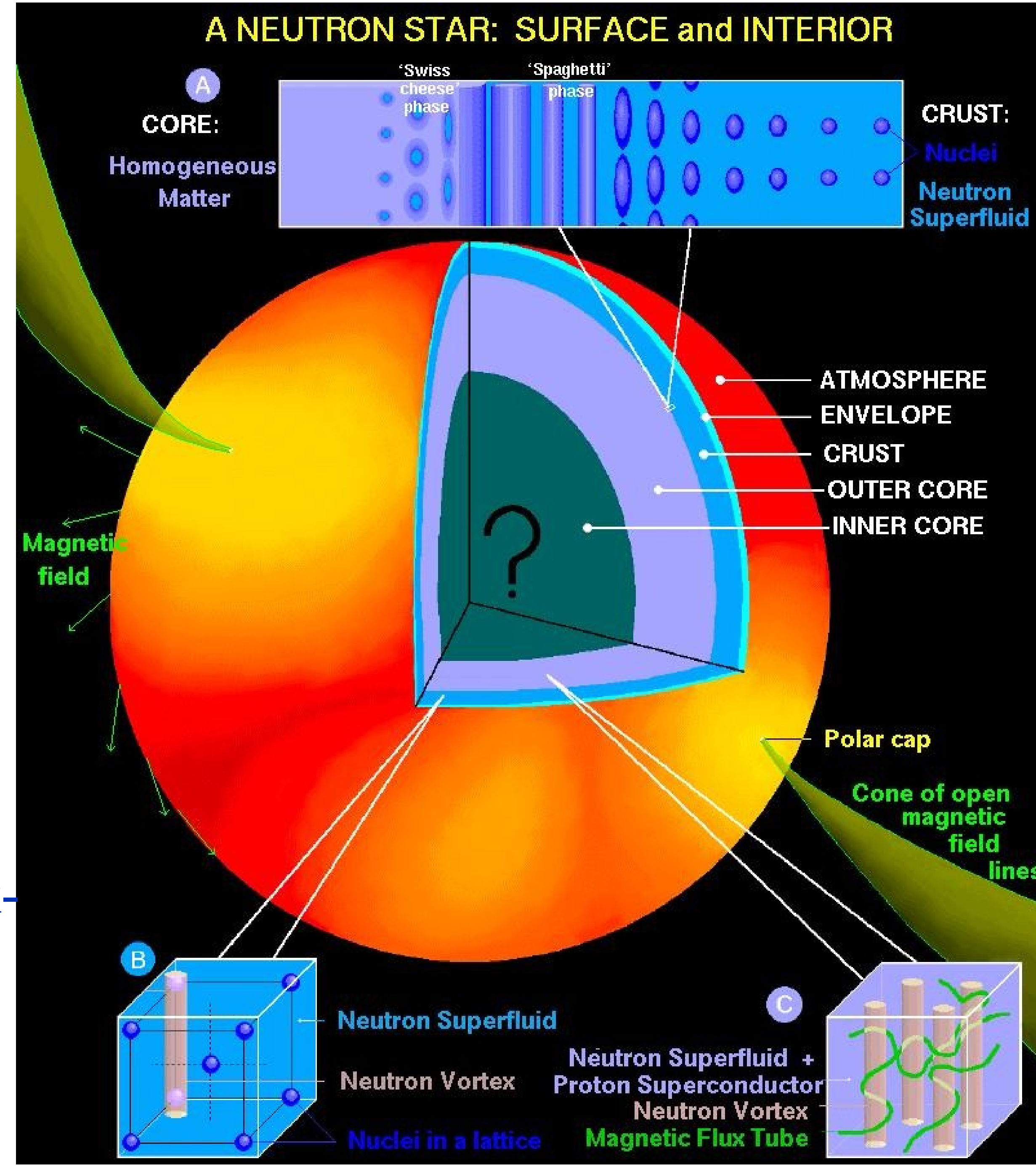
Figure: http://en.wikipedia.org/wiki/Worm_hole. Created by by Benji64 and originally uploaded to English Wikipedia (19:08, 4 March 2006). Made in 3D isis draw. Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License, Version 1.2 or any 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

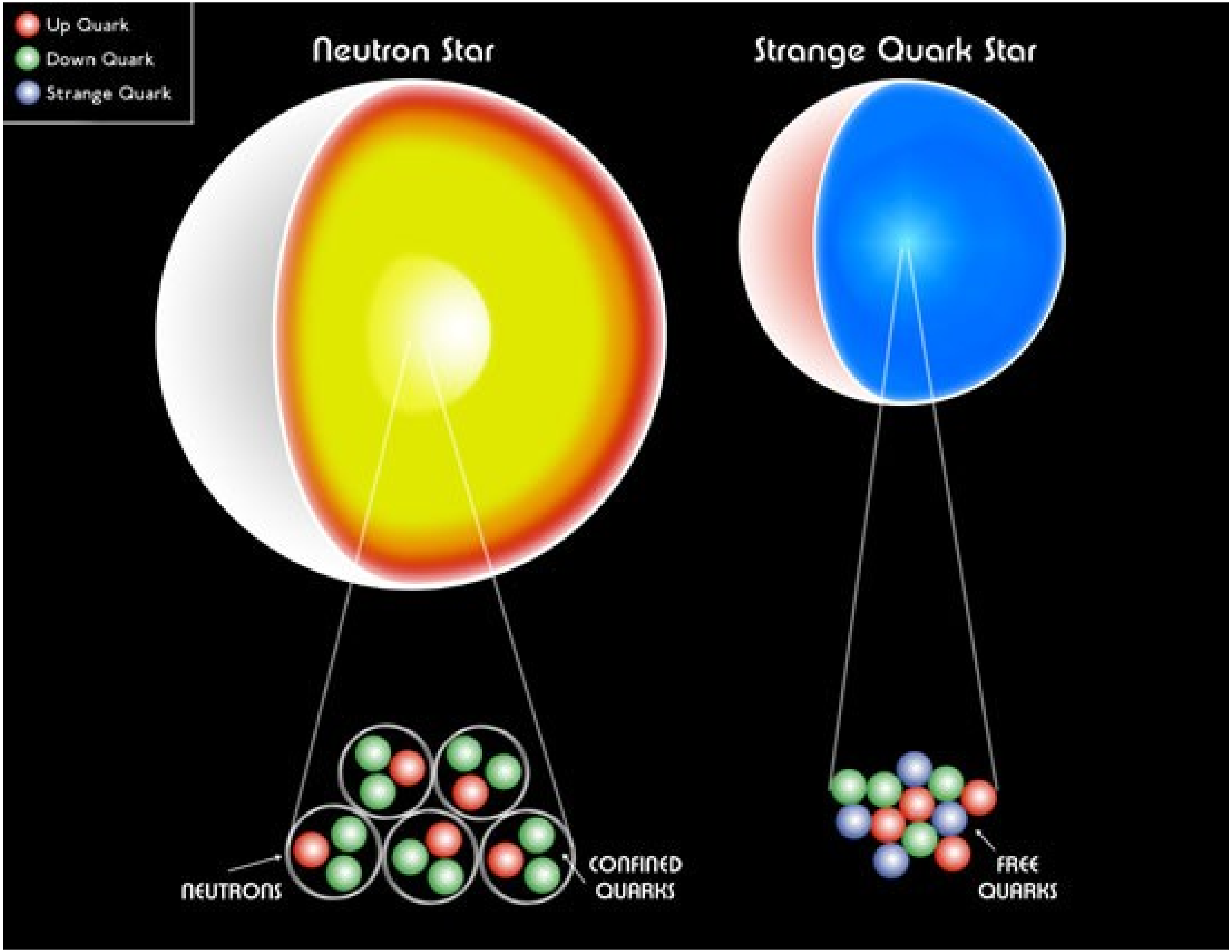
Getting dense…

- 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