LIGO: Progress Report

Marco Cavaglià

LIGO Scientific Collaboration
Department of Physics and Astronomy
University of Mississippi

The University of Mississippi

LIGO-G1200673-v1

Background picture from http://cgwp.gravity.psu.edu

Part I

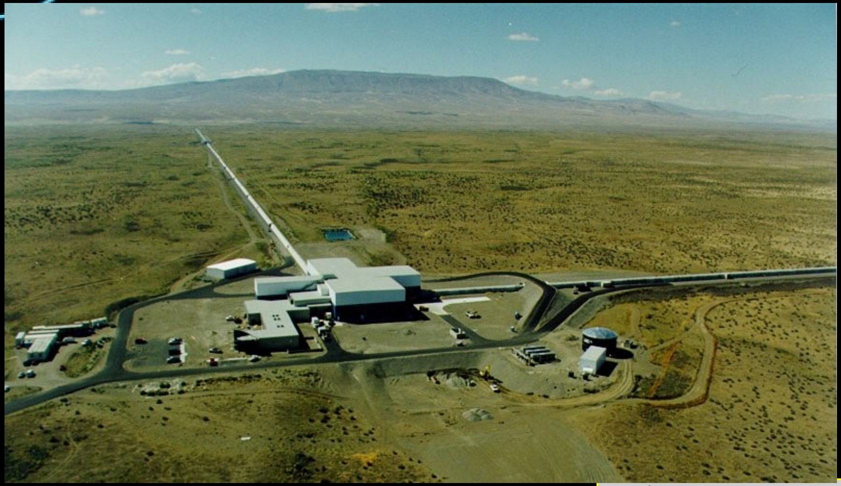
The fellowship of LIGO

The University of Mississippi

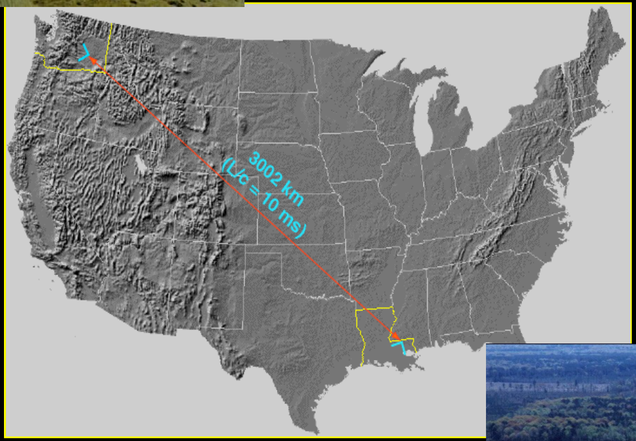
LIGO-G1200673-v1

Background picture from http://cgwp.gravity.psu.edu

Laser Interferometer Gravitational-wave Observatory



Hanford, WA

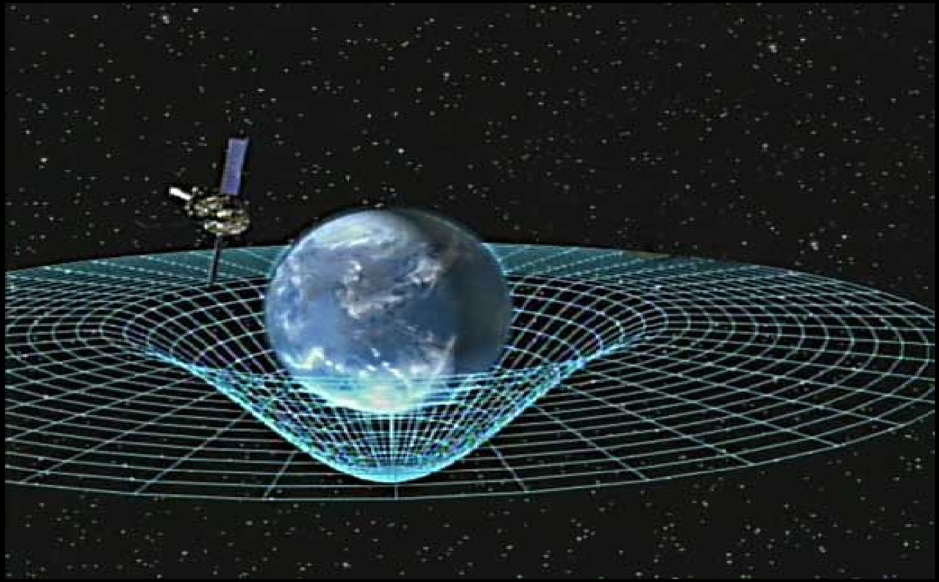


Livingston, LA

The University of Mississippi

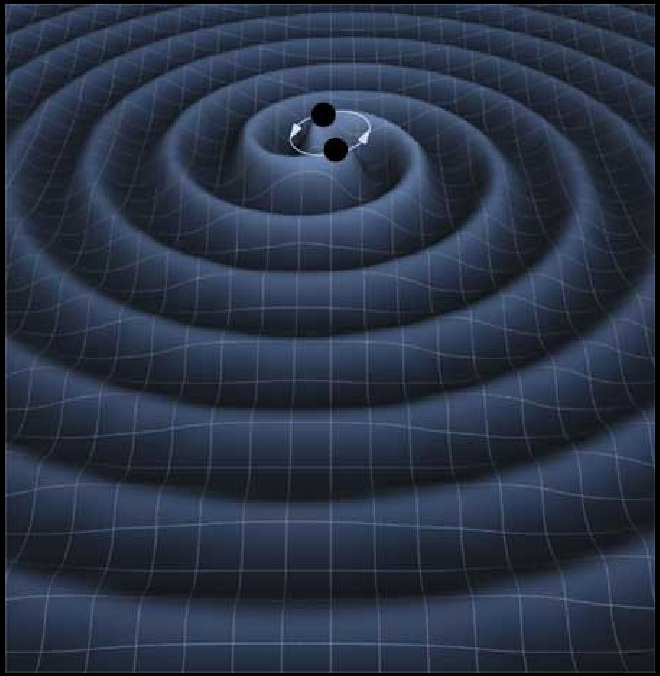
Einstein's General Relativity

The space-time geometry is distorted by the presence of mass (=energy).



A gravitational wave is a propagating disturbance of the spacetime

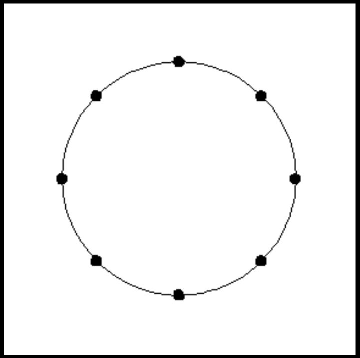
When masses move rapidly, the space-time becomes stirred by their motion: *ripples* start traveling outward with the speed of light



What is the effect of a gravitational wave?

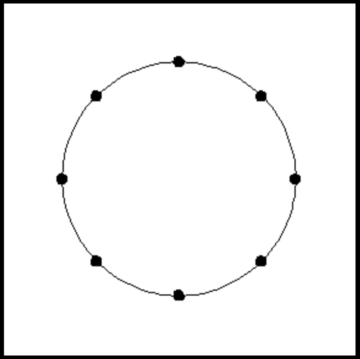
"+" polarization:

$$h_+(t-z) = h_{xx}^{TT} = -h_{yy}^{TT}$$

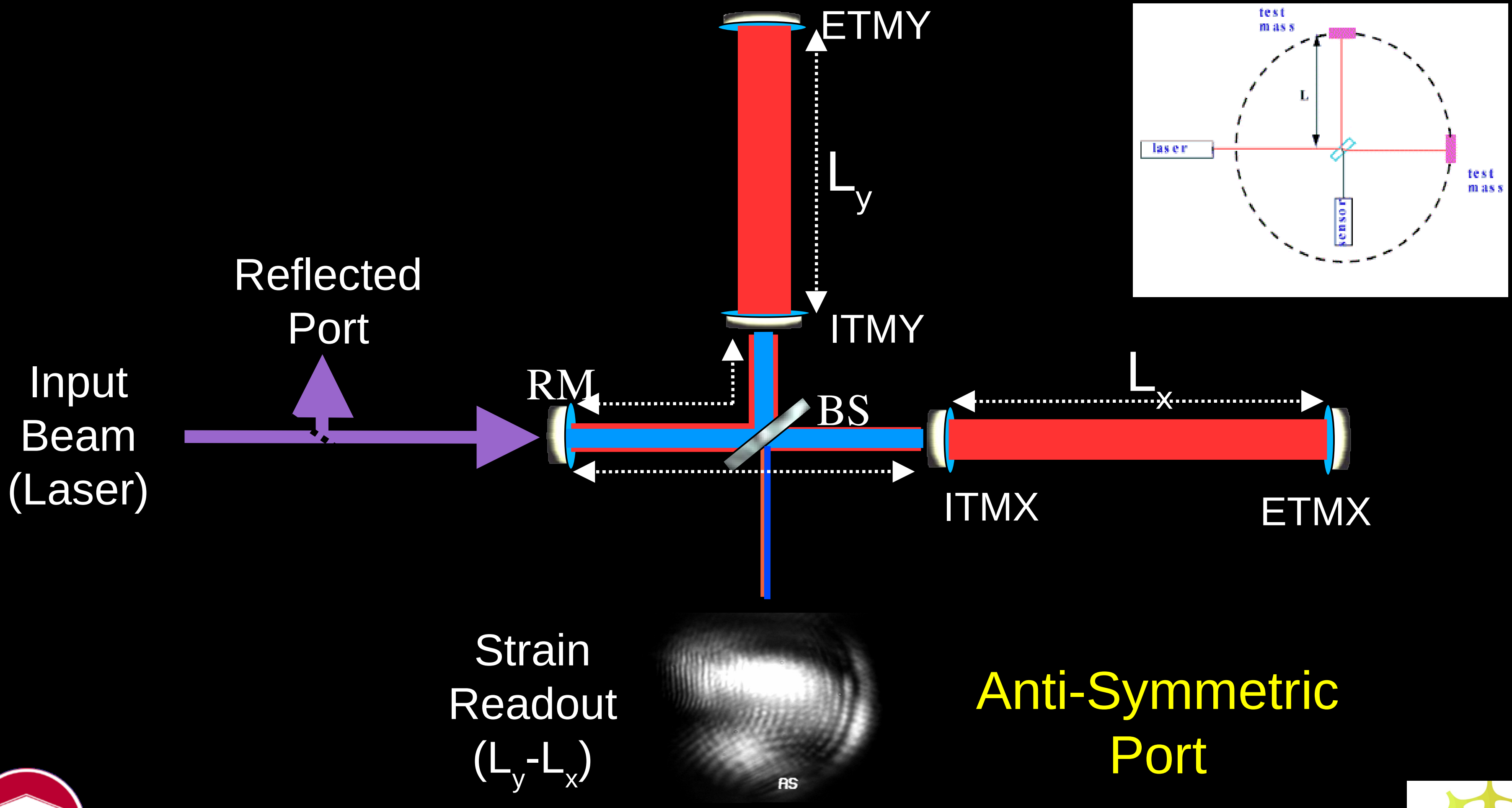


"x" polarization:

$$h_\times(t-z) = h_{xy}^{TT} = h_{yx}^{TT}$$



LIGO instrument



The University of Mississippi

The gravitational strain

Laser light travels on light cones:

$$ds^2 = -c^2 dt^2 + (1 + h_{ij}) dx_i dx_j$$

On the *x*-axis, integrate from $x=0$ to $x=L$

$$\Delta t = h_{11} L/2c$$

Repeat for y-arm. Difference is ($h_{11} = -h_{22} = h$):

$$\Delta t = 2hL/c \xrightarrow[\text{trips}]{N} \Delta t = 2hNL/c$$

The effect of a gravitational wave on one interferometer arm is:

$$\frac{\Delta L}{L} = \frac{h}{2}$$

← "Strain"

We need to calculate h for a typical gravitational wave reaching Earth

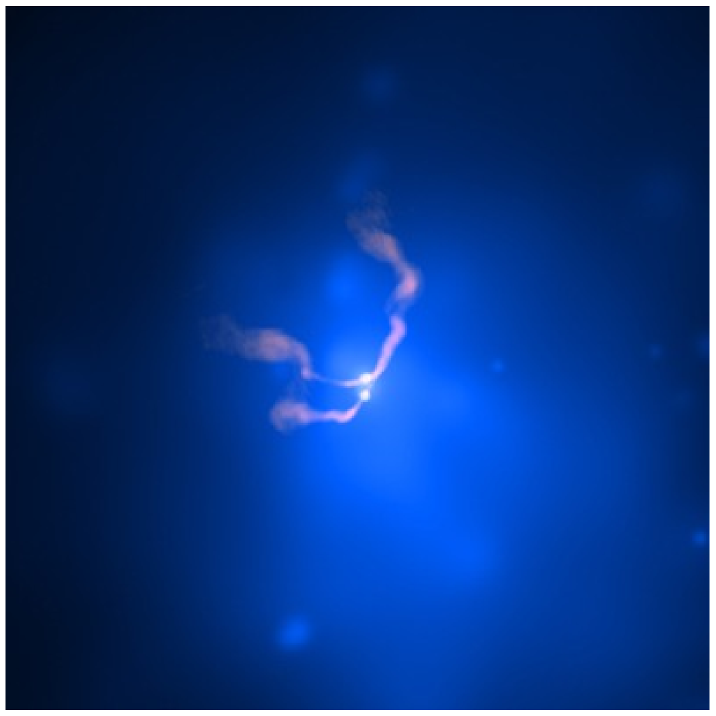
Sources of gravitational waves

- Coalescing binary neutron stars or black holes
- Spinning neutron stars
- Gravitational bursts (e.g. supernovae)
- Big bang gravitational echo

The University of Mississippi

Sources of gravitational waves

- ♦ Coalescing binary neutron stars or black holes
- ♦ Spinning neutron stars
- ♦ Gravitational bursts (e.g. supernovae)
- ♦ Big bang gravitational echo



Picture credit: NASA/CXC/AIfA; NRAO/VLA/NRL

The University of Mississippi

Sources of gravitational waves

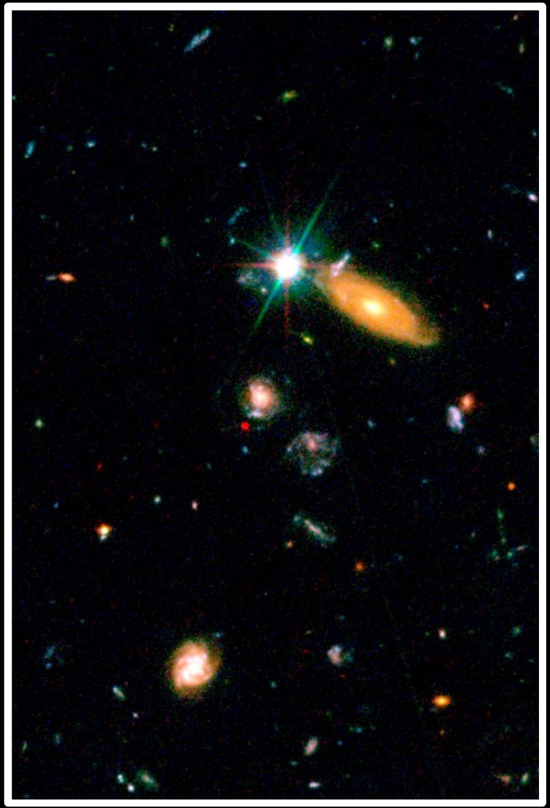
- Coalescing binary neutron stars or black holes
- Spinning neutron stars
- Gravitational bursts (e.g. supernovae)
- Big bang gravitational echo

Picture credit: NASA/HST/STSc

The University of Mississippi

Sources of gravitational waves

- ♦ Coalescing binary neutron stars or black holes
- ♦ Spinning neutron stars
- ♦ Gravitational bursts (e.g. supernovae)
- ♦ Big bang gravitational echo

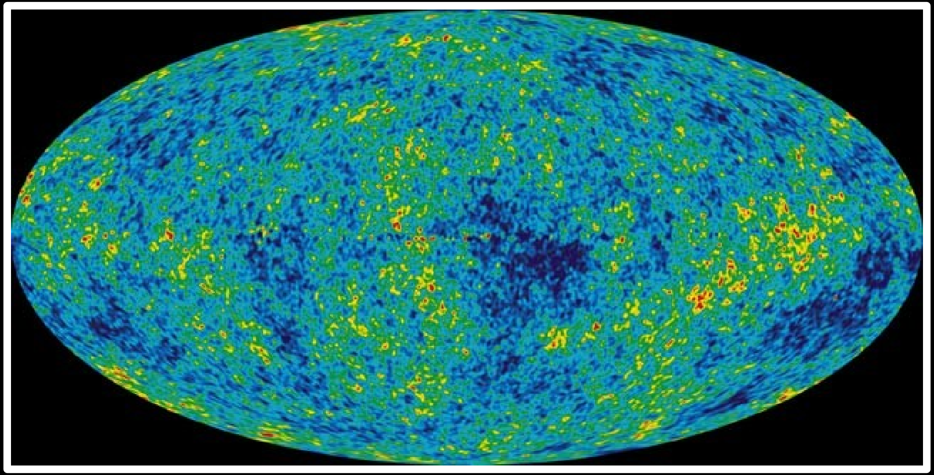


Picture credit: NASA/HST/STScI

The University of Mississippi

Sources of gravitational waves

- ♦ Coalescing binary neutron stars or black holes
- ♦ Spinning neutron stars
- ♦ Gravitational bursts (e.g. supernovae)
- ♦ Big bang gravitational echo



Picture credit: **NASA/WMAP**

The University of Mississippi

1848

Back of the envelope calculation

For a coalescing compact object into a black hole:

$$f \sim \frac{1}{M} \sim 10^4 \text{ Hz} \left(\frac{M_\odot}{M} \right)$$

$$h \sim \epsilon^{1/2} \frac{M}{r} \sim 10^{-21} \left(\frac{\epsilon}{0.01} \right)^{1/2} \left(\frac{M}{M_\odot} \right) \left(\frac{10 \text{ Mpc}}{r} \right)$$

Distance Earth-Sun (1.5 x 10^7 km)….

…stretches by a fraction of an atom!

The University of Mississippi

Required sensitivity for these sources

$$\frac{\Delta L}{L} \sim 10^{-21}$$

Can we reach this precision?

If we look at on/off fringes:

$$\Delta x \sim \lambda \sim 1\,\mu m \longrightarrow \Delta x / L \sim 10^{-11}$$

but...

Average flux of photons

$$\bar{N} = \frac{\lambda}{2\pi\hbar c} P$$

Fluctuations (shot noise):

$$\Delta N / N = 1/\sqrt{N}$$

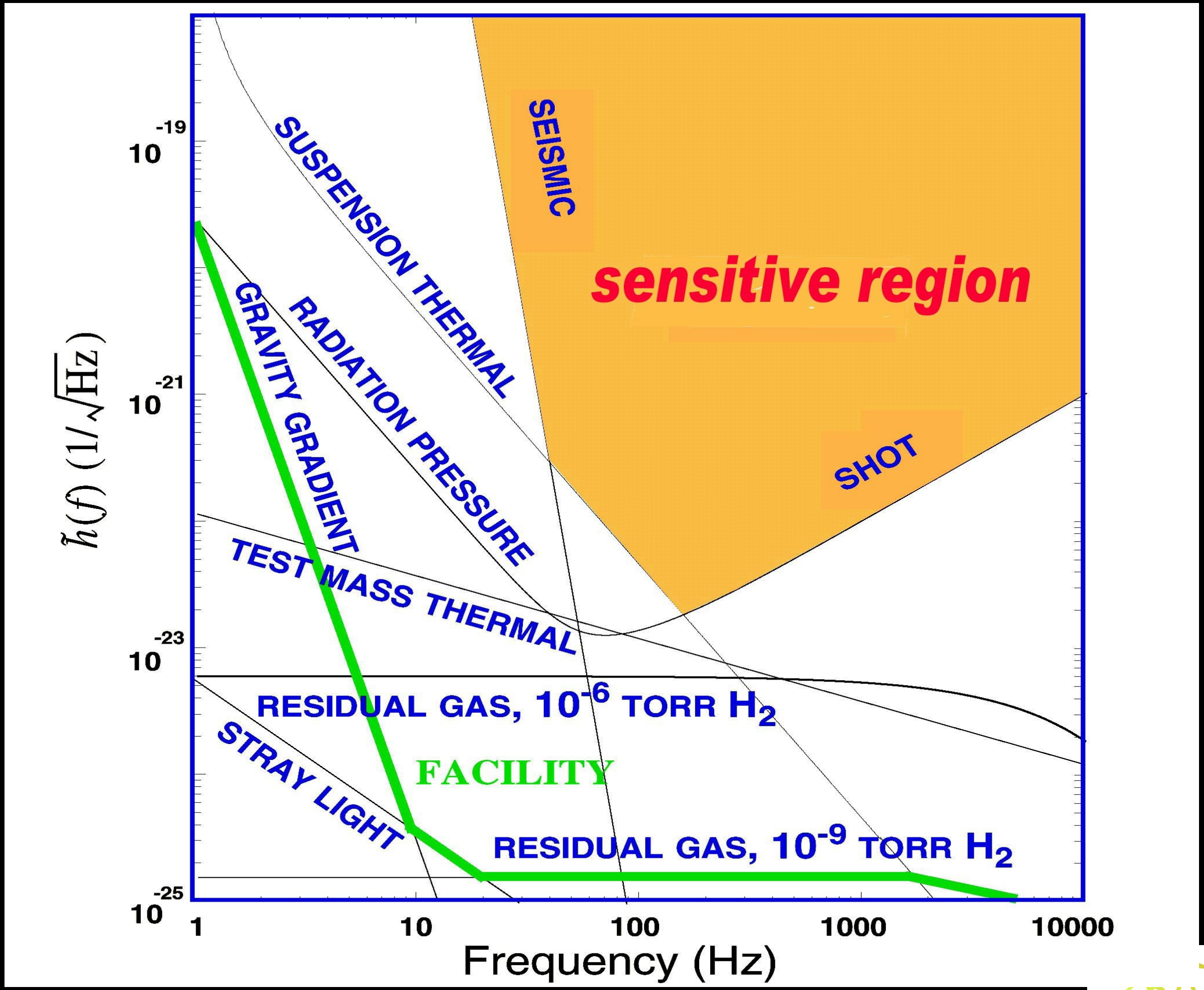
200 W of laser light carries 10^{19} photons per second, giving a sensitivity of

$$\Delta N / N \sim 3 \times 10^{-11} \longrightarrow \frac{\Delta x}{L} \sim \lambda \frac{\Delta N}{N} \sim 3 \times 10^{-22}$$

LIGO phase I design sensitivity

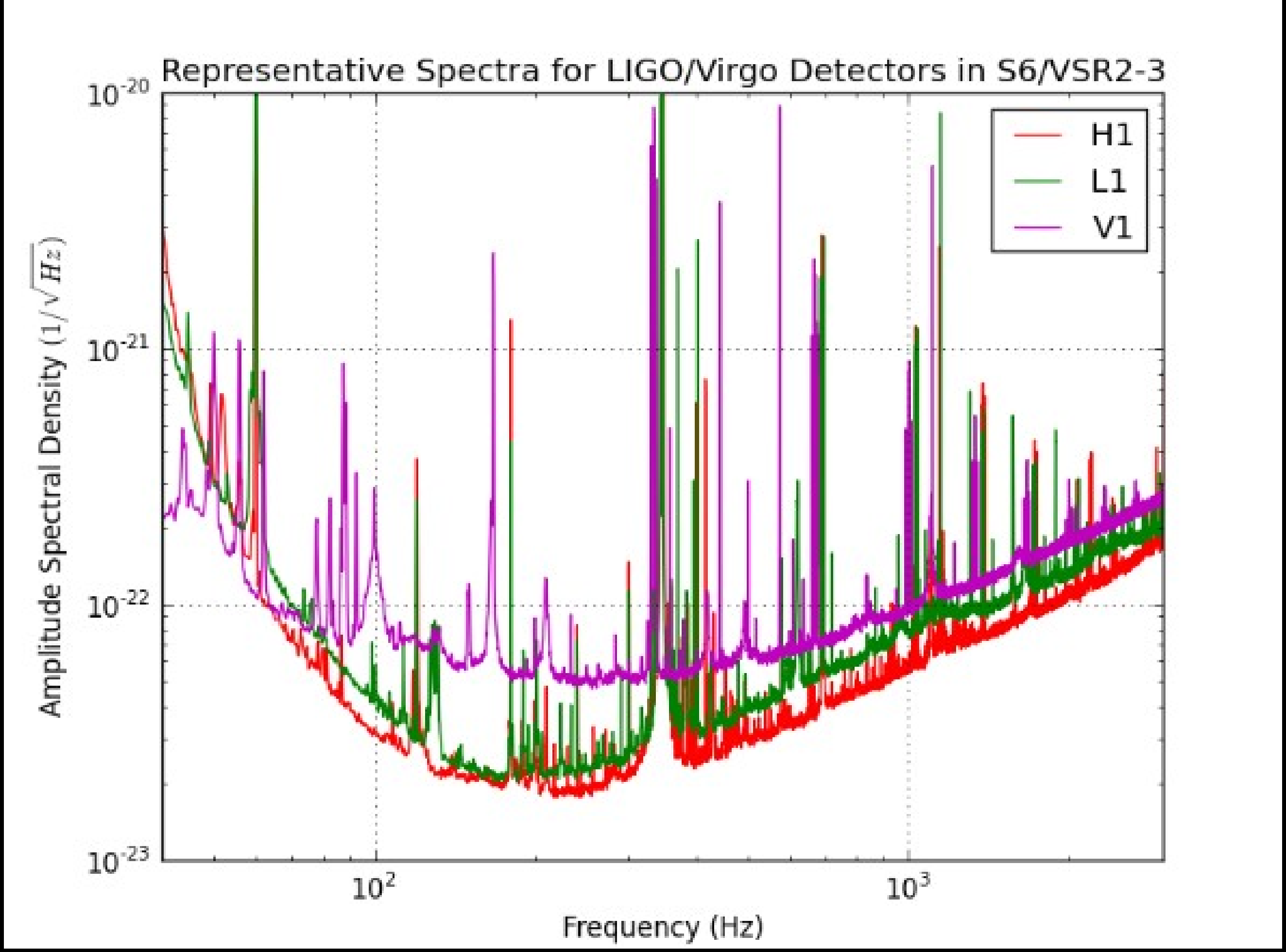
Noise sources:

- ♦ seismic
- ♦ thermal
- ♦ shot
- ♦ etc…



The University of Mississippi

LIGO phase I actual sensitivity



Let's focus on seismic noise...

Amplitude of seismic noise above 10 Hz

$$A_{seis}(f) \sim 10^{-9}\,\mathrm{m/Hz}^{1/2}\,(10\,\mathrm{Hz}/f)^2$$

At ~ 100 Hz:

$$A_{seis}(f = 100) \sim 10^{-11}\,\mathrm{m/Hz}^{1/2}$$

We need 8 orders of magnitude of isolation!

Strategies - I

Mirrors are suspended

→ Simple harmonic oscillator with resonant frequency ~ 1 Hz

→ Frequency response ~ $(1 \text{ Hz} / f)^2$

Good at or above 1000 Hz

The University of Mississippi

Strategies - II

Multiple stages of isolation

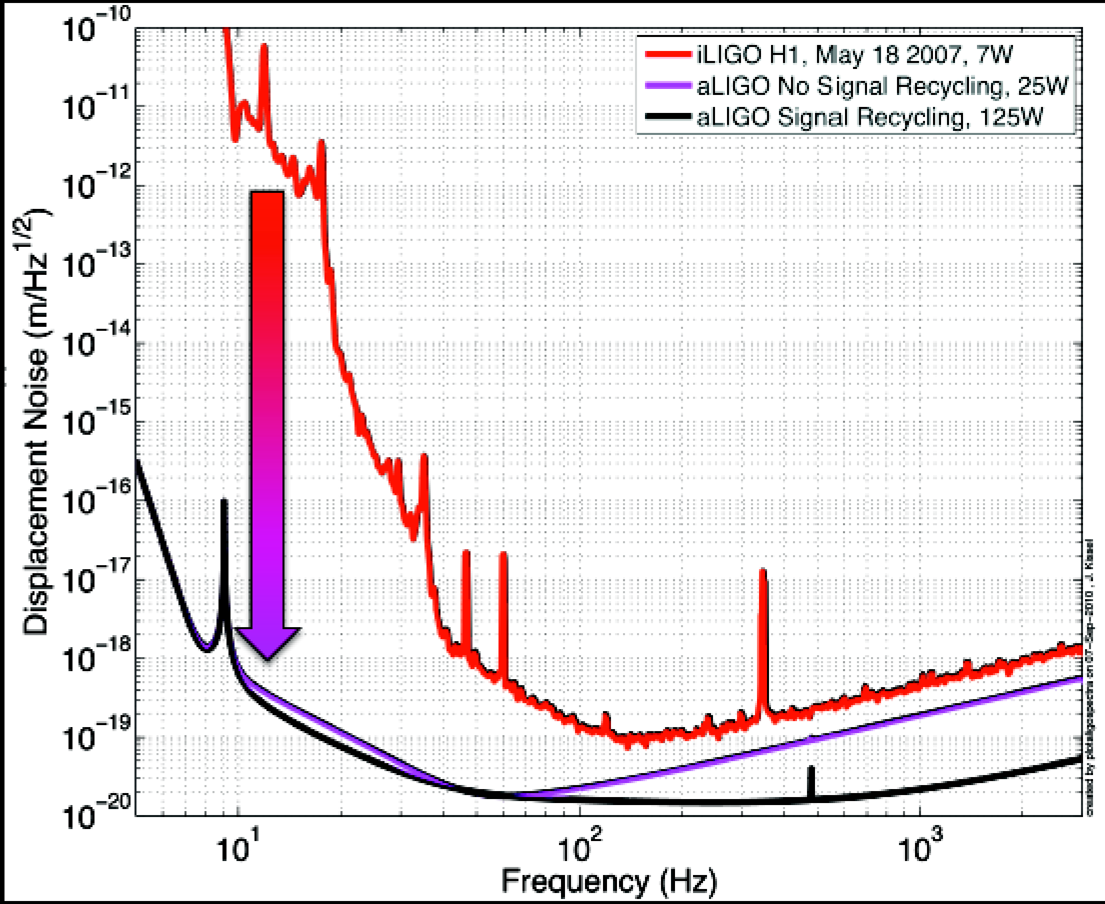
→ Chains of N oscillators (springs) with highest resonance $f_0 \sim$ few Hz

→ Frequency response $\sim (f_0 / f)^{2N}$

With 3 stages, good at ~ few × 10 Hz

The University of Mississippi

Final result



The University of Mississippi

Types of searches

Modelled (match-filtering, low-latency, IMR, low-mass...)

Unmodelled (burst, coherent...)

Continuous wave signals (narrowband, targeted, E@H...)

Stochastic (isotropic, directional...)

External triggered (neutrinos, EM...)

The University of Mississippi

Modelled searches (CBC)

Phys. Rev. D 85, 082002 (2012) [12 pages]

Search for gravitational waves from low mass compact binary coalescence in LIGO's sixth science run and Virgo's science runs 2 and 3

Abstract | References | No Citing Articles

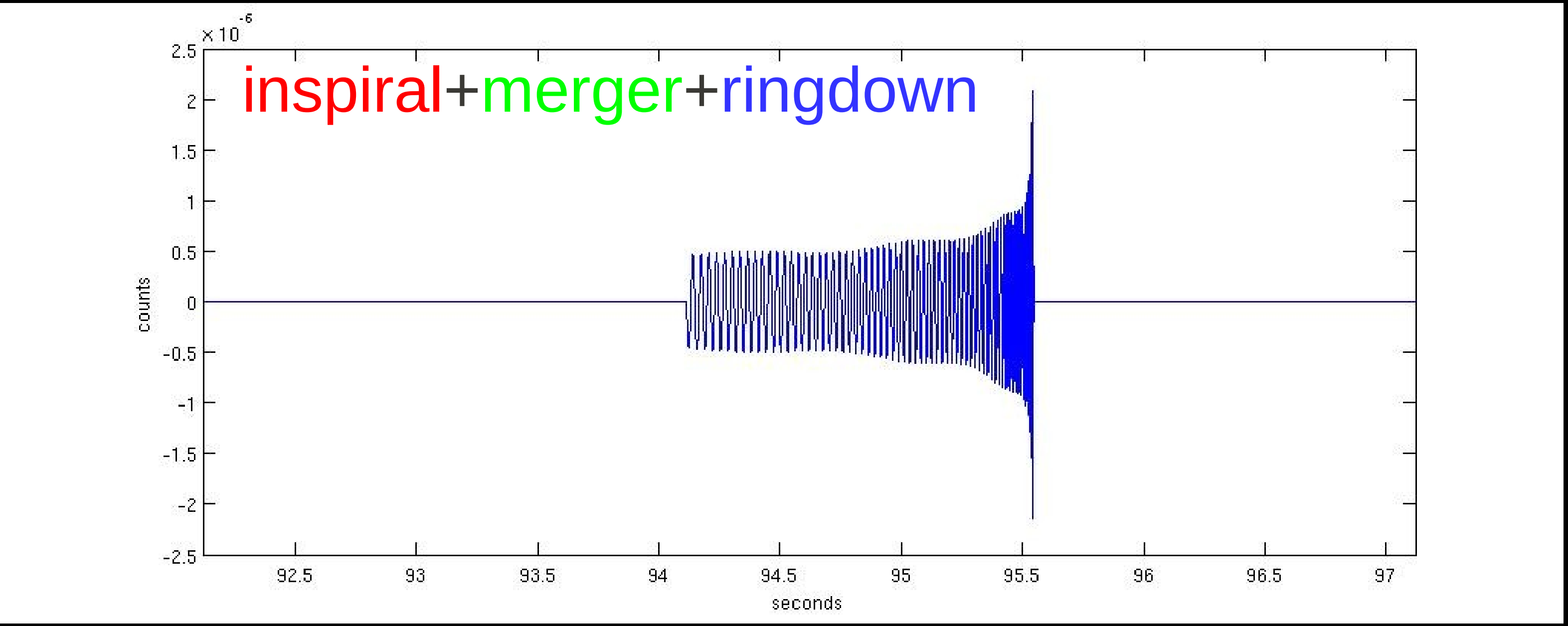
Download: PDF (795 kB) Export: BibTeX or EndNote (RIS)

J. Abadie *et al.* (LIGO Scientific Collaboration, Virgo Collaboration)
Show All Authors/Affiliations

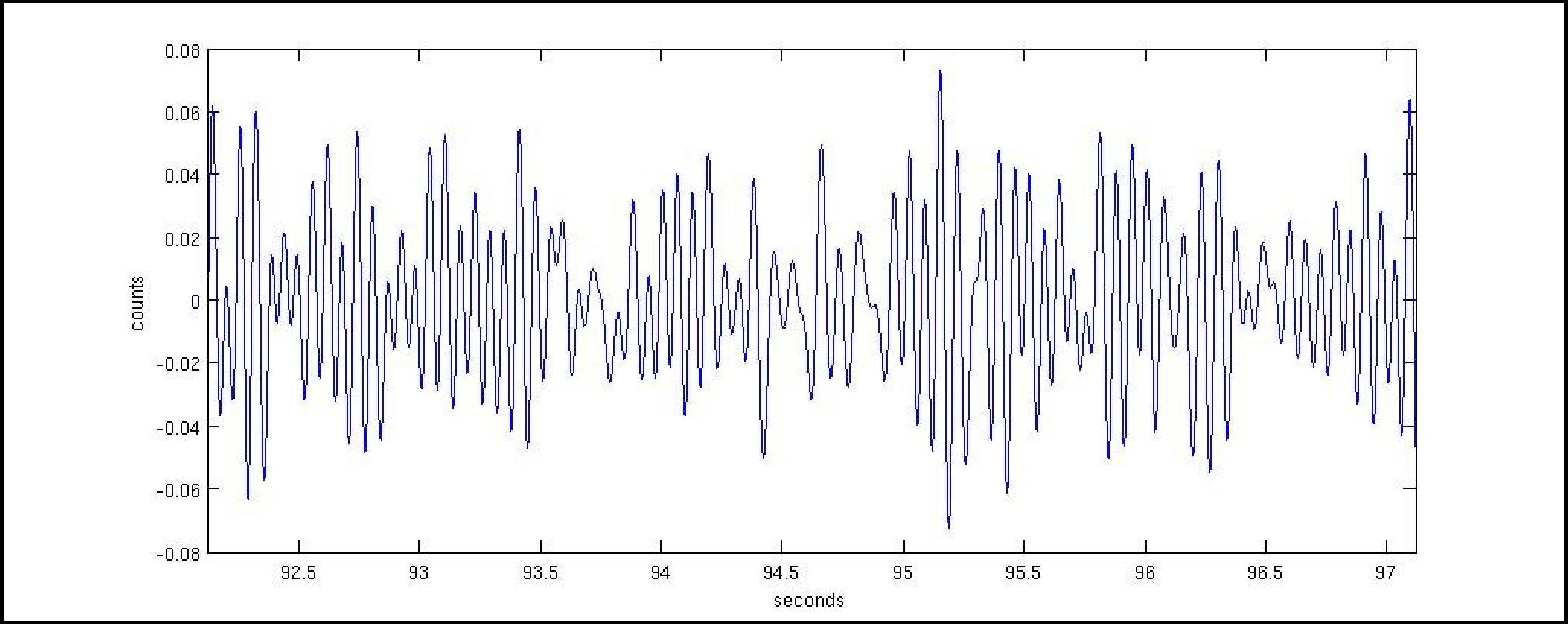
Received 16 December 2011; published 19 April 2012

Phys. Rev. D 85, 082002 (2012)

An IMR signal



A typical signal stretch of data



Matched filtering

Signal-to-noise ratio:

$$\rho(h) = \frac{\langle s, h \rangle}{\sqrt{\langle h, h \rangle}}$$

$$\langle s, h \rangle = 2 \int_{-\infty}^{\infty} \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_h(|f|)} df = 4\Re \int_0^{\infty} \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_h(f)} df$$

$$h(t) = F_+(\theta, \phi, \psi) h_+(t) + F_\times(\theta, \phi, \psi) h_\times(t)$$

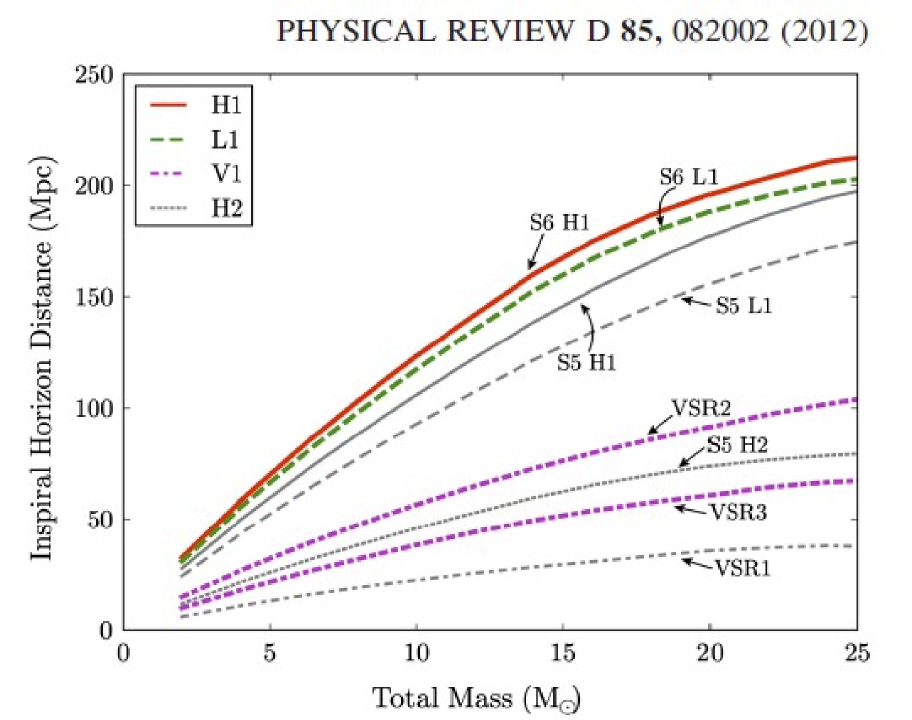
The University of Mississippi

Analysis pipeline (CBC search)

- Data quality cuts
- Matched filtering → **Triggers – level I**
- Time+parameter coincidence
- Refined MF+ signal based vetoes+coincidence
  ↳ **Triggers – level II**
- Coherent SNR for multiple detectors → **Final triggers**
- Careful follow-up of single candidates

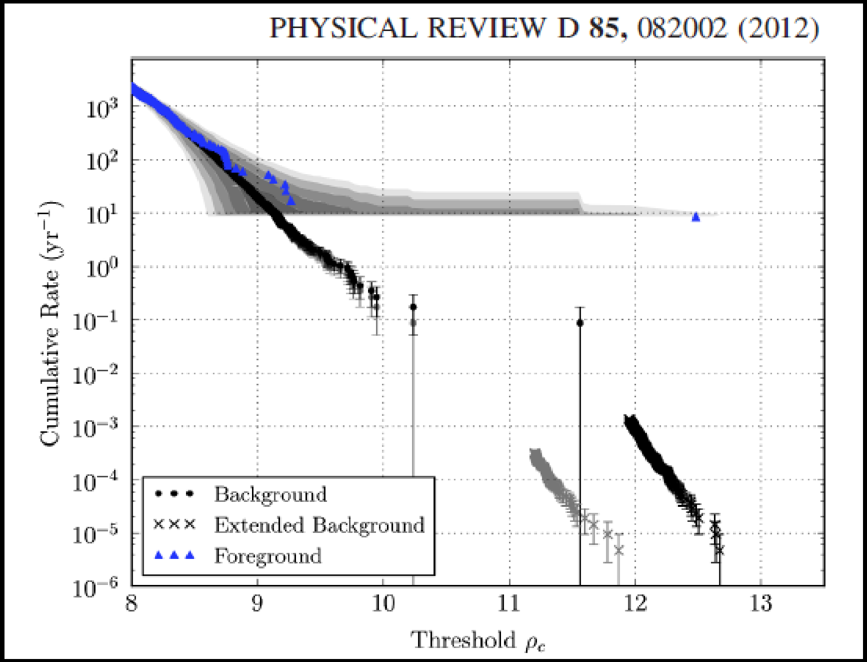
The University of Mississippi

LIGO UMISS LSC



Inspiral reach

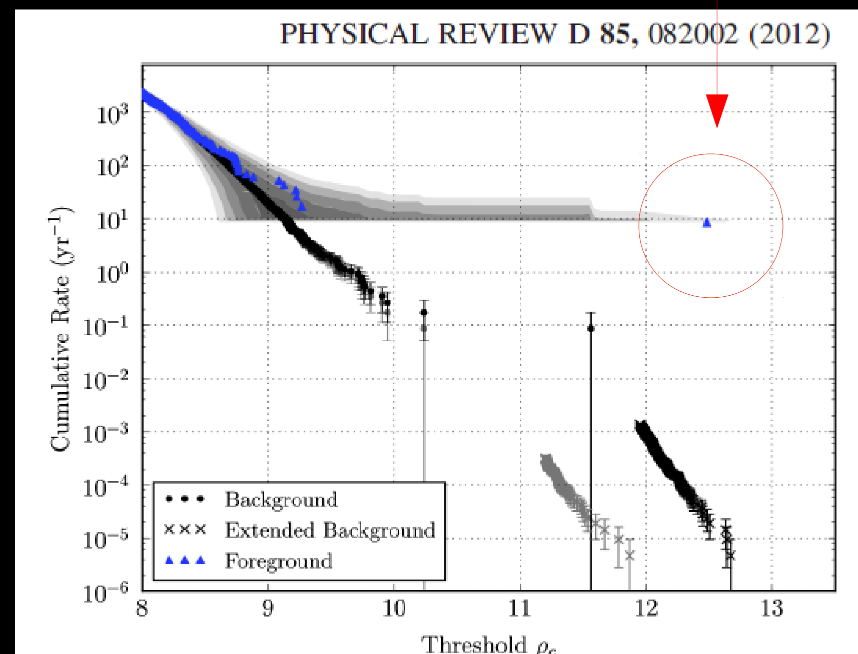
Event rate

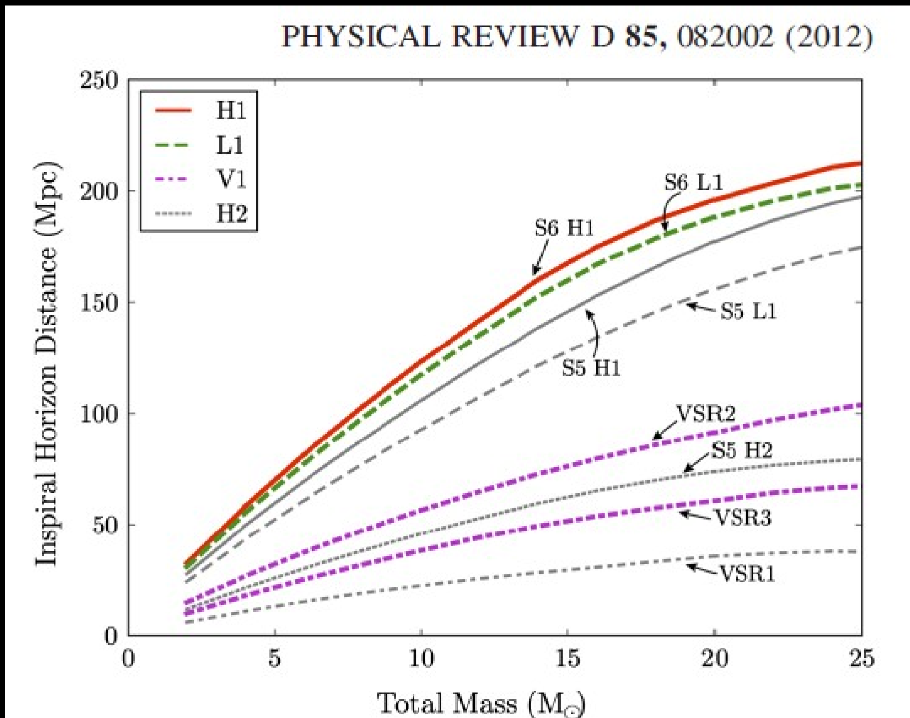


The University of Mississippi

Big Dog!

Event rate





Inspiral reach

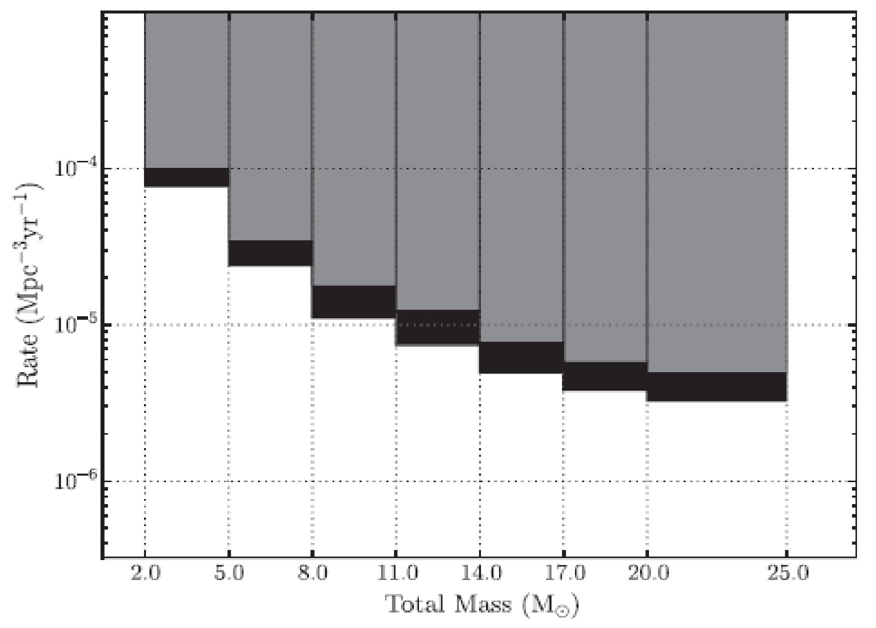
LIGO UMISS LSC

TABLE I. Rate upper limits of BNS, NSBH, and BBH coalescence, assuming canonical mass distributions. D_{horizon} is the horizon distance averaged over the time of the search. The sensitive distance averaged over all sky locations and binary orientations is $D_{\mathrm{avg}} \simeq D_{\mathrm{horizon}}/2.26$ [35]. The first set of upper limits is those obtained for binaries with nonspinning components. The second set of upper limits is produced using black holes with a spin uniformly distributed between zero and the maximal value of Gm^2/c.

System	BNS	NSBH	BBH
Component masses ($M_\odot$)	1.35/1.35	1.35/5.0	5.0/5.0
D_{horizon} (Mpc)	40	80	90
Nonspinning upper limit ($\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$)	1.3×10^{-4}	3.1×10^{-5}	6.4×10^{-6}
Spinning upper limit ($\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$)	⋯	3.6×10^{-5}	7.4×10^{-6}

Marginalized upper limits

PHYSICAL REVIEW D 85, 082002 (2012)

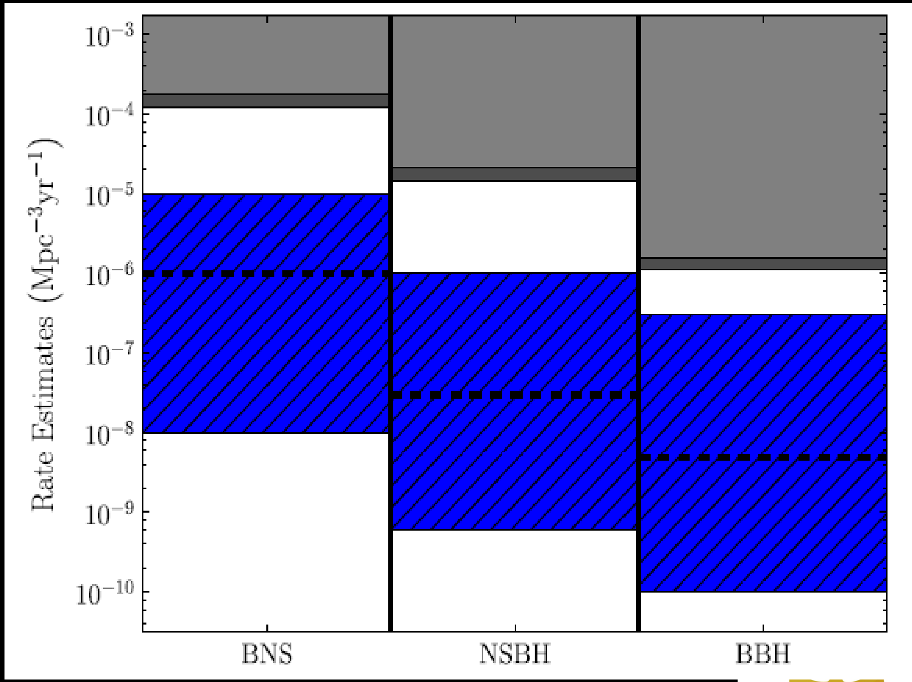


The University of Mississippi
1848

TABLE I. Rate upper limits of BNS, NSBH, and BBH coalescence, assuming canonical mass distributions. $D_{\rm horizon}$ is the horizon distance averaged over the time of the search. The sensitive distance averaged over all sky locations and binary orientations is $D_{\rm avg} \simeq D_{\rm horizon}/2.26$ [35]. The first set of upper limits is those obtained for binaries with nonspinning components. The second set of upper limits is produced using black holes with a spin uniformly distributed between zero and the maximal value of Gm^2/c.

System	BNS	NSBH	BBH
Component masses ($M_\odot$)	1.35/1.35	1.35/5.0	5.0/5.0
$D_{\rm horizon}$ (Mpc)	40	80	90
Nonspinning upper limit ($\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$)	1.3×10^{-4}	3.1×10^{-5}	6.4×10^{-6}
Spinning upper limit ($\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$)	···	3.6×10^{-5}	7.4×10^{-6}

Marginalized upper limits



The University of Mississippi

LIGO UMISS LSC

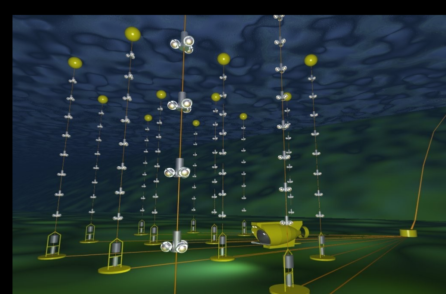
Neutrino-triggered search

A First Search for coincident Gravitational Waves and High Energy Neutrinos using LIGO, Virgo and ANTARES data from 2007

The ANTARES Collaboration, the LIGO Scientific Collaboration, the Virgo Collaboration. THE ANTARES COLLABORATION: S. Adrián-Martínez, I. Al Samarai, A. Albert, M. André, M. Anghinolfi, G. Anton, S. Anvar, M. Ardid, T. Astraatmadja, J-J. Aubert, B. Baret, S. Basa, V. Bertin, S. Biagi, C. Bigongiari, C. Bogazzi, M. Bou-Cabo, B. Bouhou, M.C. Bouwhuis, J. Brunner, J. Busto, A. Capone, C. Cârloganu, J. Carr, S. Cecchini, Z. Charif, Ph. Charvis, T. Chiarusi, M. Circella, R. Coniglione, L. Core, H. Costantini, P. Coyle, A. Creusot, C. Curtil, G. De Bonis, M.P. Decowski, I. Dekeyser, A. Deschamps, C. Distefano, C. Donzaud, D. Dornic, Q. Dorosti, D. Drouhin, T. Eberl, U. Emanuele, A. Enzenhöfer, J-P. Ernenwein, S. Escoffier, K. Fehn, P. Fermani, M. Ferri, S. Ferry, V. Flaminio, et al. (905 additional authors not shown)

Preliminary

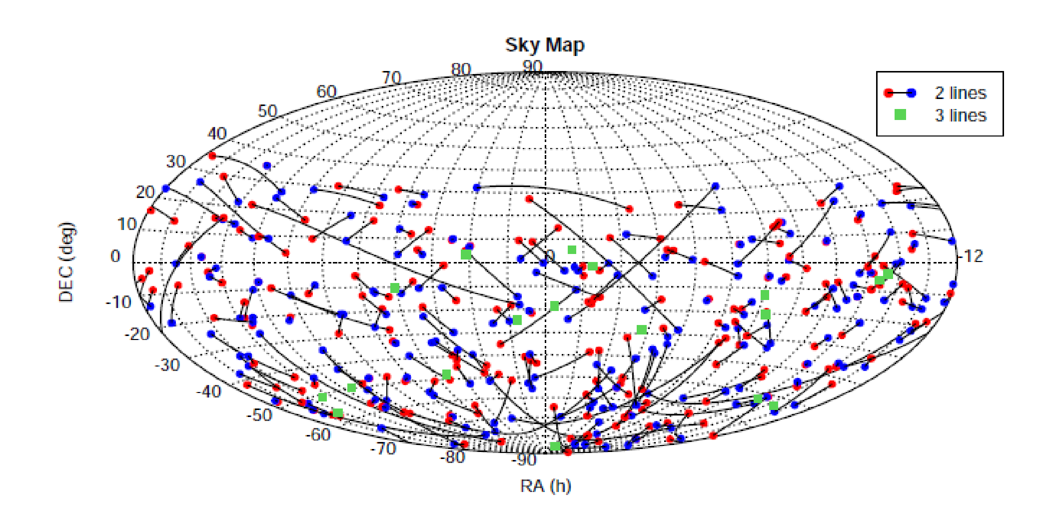
arXiv:1205.3018



The University of Mississippi 1848

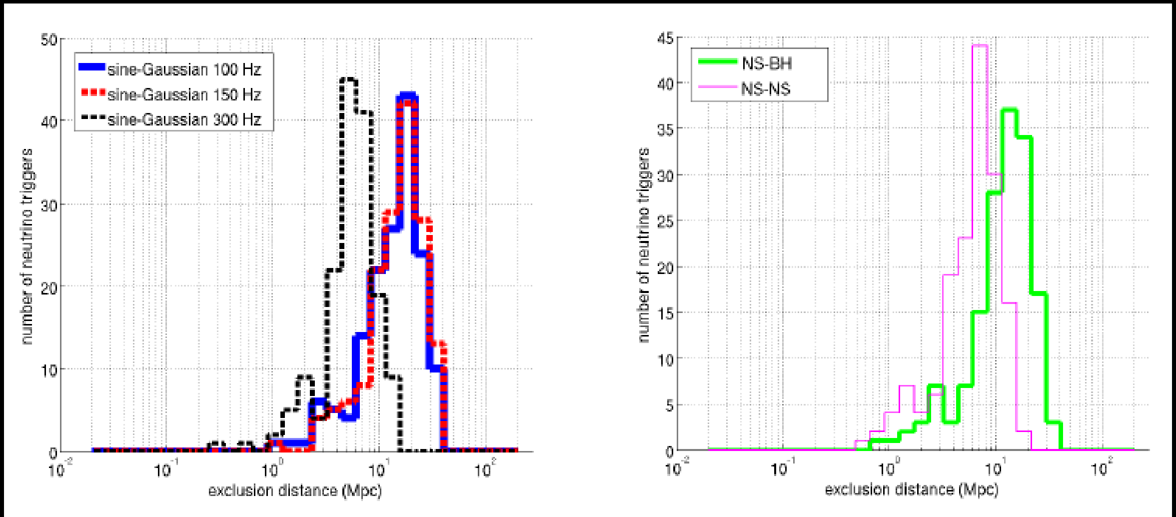
LIGO-G1200673-v1

NSF



Triggers

Exclusion distances

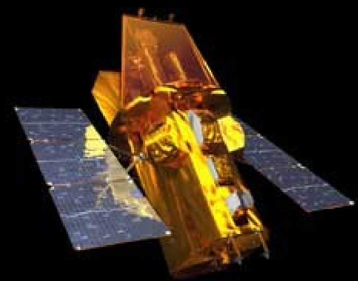


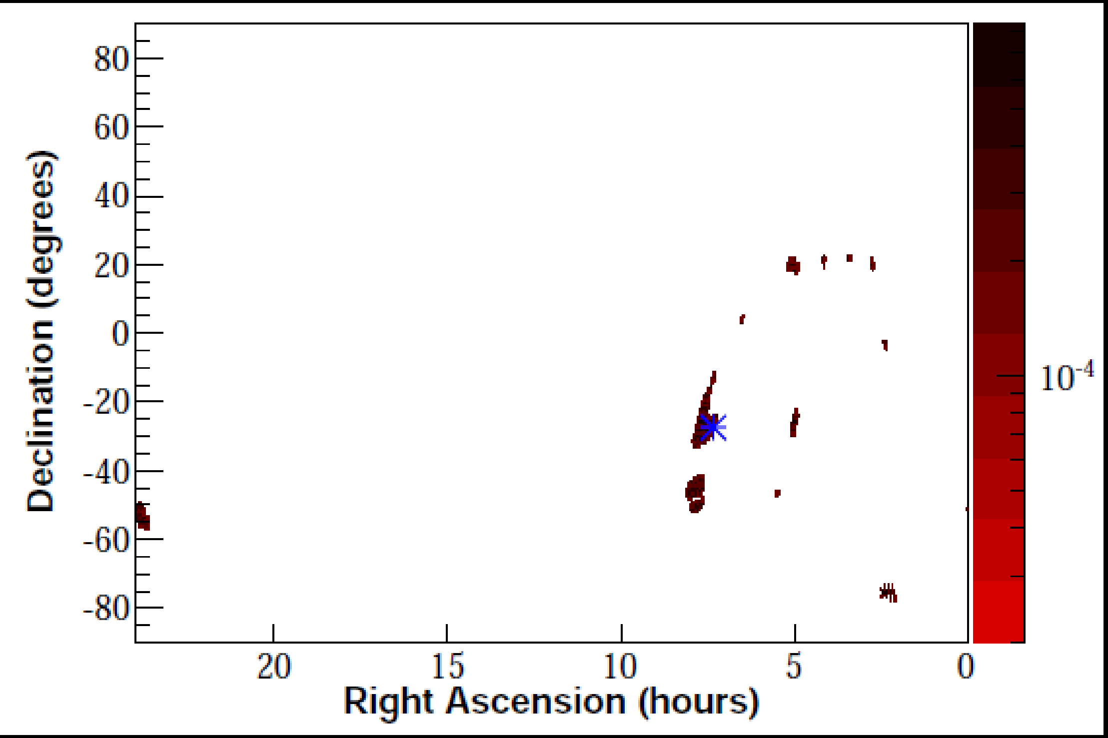
EM-triggered search

Swift follow-up observations of candidate gravitational-wave transient events

P. A. Evans, J. K. Fridriksson, N. Gehrels, J. Homan, J. P. Osborne, M. Siegel, A. Beardmore, P. Handbauer, J. Gelbord, J. A. Kennea, M. Smith, Q. Zhu, The LIGO Scientific Collaboration, Virgo Collaboration J. Aasi, J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese ac, C. Adams, T. Adams, P. Addesso, R. Adhikari, C. Affeldt, M. Agathos, K. Agatsuma, P. Ajith, B. Allen, A. Allocca ac, E. Amador Ceron, D. Amariutei, S. B. Anderson, W. G. Anderson, K. Arai, M. C. Araya, S. Ast, S. M. Aston, P. Astone, D. Atkinson, P. Aufmuth, C. Aulbert, B. E. Aylott, S. Babak, P. Baker, G. Ballardin, S. Ballmer, Y. Bao, J. C. B. Barayoga, D. Barker, F. Barone ac, B. Barr, L. Barsotti, M. Barsuglia, M. A. Barton, I. Bartos, R. Bassiri, M. Bastarrika, A. Basti ab, J. Batch, et al. (756 additional authors not shown)

arXiv:1205.1124





Probability sky map

Swift data

THE REDUCED-THRESHOLD DETECTIONS IN THE X-RAY DATA FOR THE JANUARY EVENT.

Source #	Right ascension (RA) (J2000)	Declination (dec) (J2000)	Position Error ($''$ 90% conf.)	Count Rate (0.3–10 keV, ks^{-1})	N_s [1]	Variability [2] significance (σ)
1	05h 55m 1.00s	-40°58′ 00.8″	4.5	$5.9^{+1.5}_{-1.2}$	0.9	2.05
2	05h 57m 4.80s	-40°54′ 45.4″	4.3	$5.9^{+2.1}_{-1.6}$	0.9	0.26
3	05h 54m 12.72s	-40°44′ 05.8″	4.3	$4.6^{+1.5}_{-1.2}$	1.3	0.45
4	05h 54m 59.29s	-40°54′ 19.6″	4.5	$3.2^{+1.3}_{-1.0}$	2.4	0.75
5	05h 51m 57.66s	-40°46′ 10.9″	5.6	$2.8^{+1.8}_{-1.1}$	2.9	1.10
6	05h 51m 41.12s	-40°44′ 46.4″	5.5	$1.4^{+1.1}_{-0.7}$	7.5	0.74
7	05h 52m 6.29s	-40°59′ 14.3″	6.5	$2.3^{+1.2}_{-0.8}$	3.9	0.91
8	05h 52m 55.88s	-40°46′ 14.9″	5.2	$2.9^{+1.7}_{-1.2}$	2.8	2.00

[a] N_s is the number of 2XMMi-DR3 sources which are at least as bright as the Swift source, which are expected in a single Swift field.

Part II

The two detectors

The University of Mississippi

LIGO-G1200673-v1

Background picture from http://cgwp.gravity.psu.edu

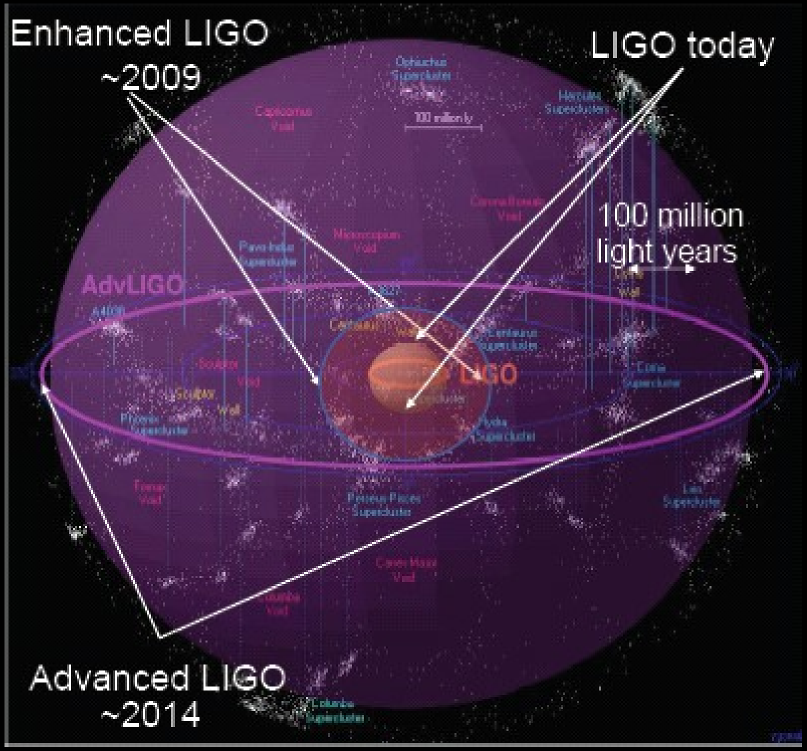
Advanced LIGO

Factor of 10 improvement in sensitivity (event rate x 1000)

Install started in 2011 - online in 2014

Binary neutron star range:

- ♦ Now -Thousands of galaxies
- ♦ AdL - Millions of galaxies!



Vacuum equipment

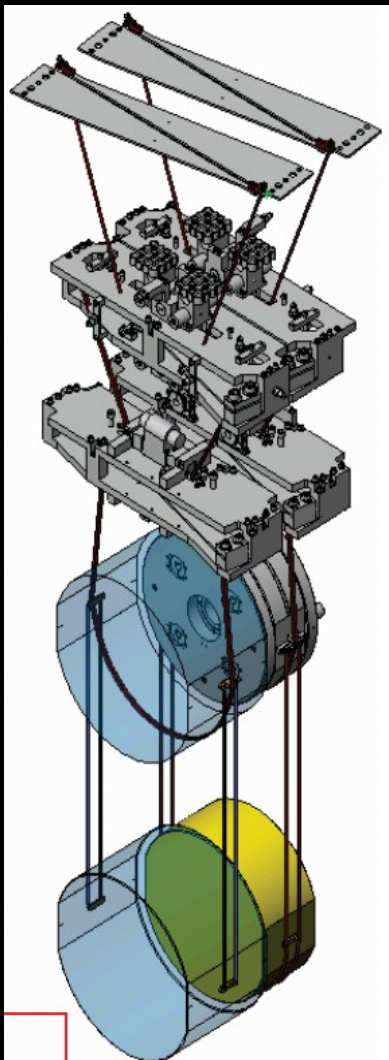
The University of Mississippi

Initial LIGO vs Advanced LIGO

	Initial LIGO	Advanced LIGO
Input laser power	10 W	180 W
Laser power in arm Cavities	~10 kW	850 kW
Beam size	4 cm	6cm
Mirror mass	11 kg	40 kg
Mirror diameter	25 cm	34 cm
Mirror suspensions	Single Pendulum, steel wire	Quadruple pendulum, fused silica
Seismic isolation system	5 stage passive	3 stage active, 4 stage passive

Core optics

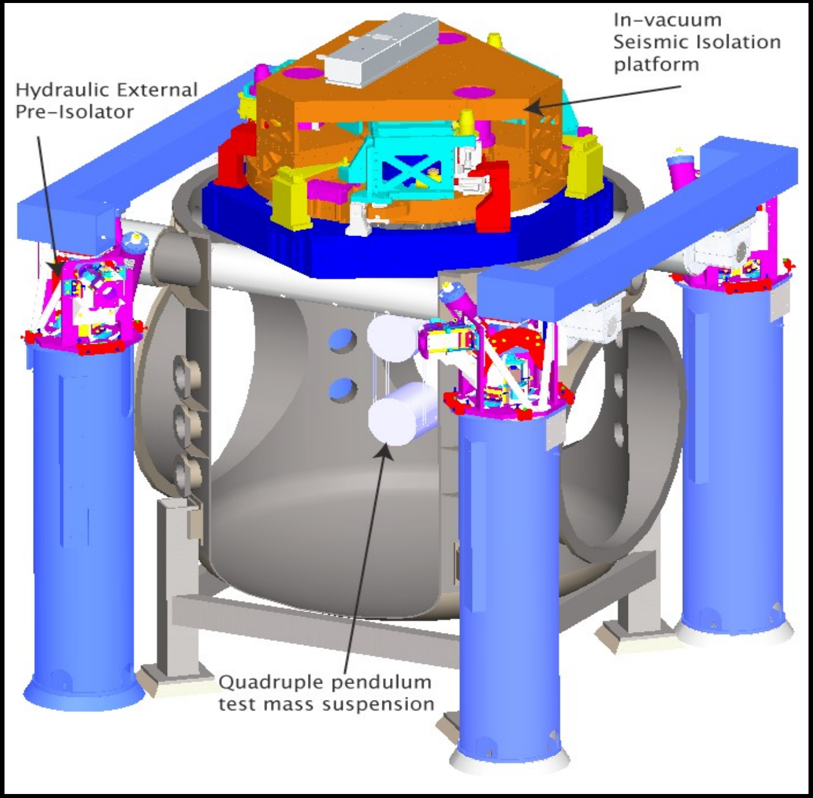
Low absorption fused silica (surface < 0.7 nm RMS, micro-roughness < 0.2 nm RMS, 34 cm diameter 20 cm thickness, 40 kg mass)



Core optic suspensions

Suspended by fused silica tapered fibers attached with hydroxy-catalysis bonds

Seismic isolation system



Hydraulic external (to the vacuum) pre-isolator stage and in-vacuum 2-stage active seismic isolation platform give horizontal attenuation > 10^{-10} at 10 Hz

Part III

The return of the outreach (I could not come up with a better title)

The LSC EPO group

Almost six year old

~40 members from LSC institutions + LIGO Lab
(mostly volunteers)

31 LSC institutions (~60%)
are active in EPO

LSC-EPO mission statement

As a frontier physics effort, a core mission of the LSC is to harness the excitement and enthusiasm generated by gravitational wave research to inspire and educate students and the general public in astronomy and fundamental science, thus raising standards of science literacy and education. LSC's researchers and students believe that the opportunity to discover the beauty of the cosmos should not be limited by age, culture or abode. The LSC EPO working group aims to communicate the vision and benefits of gravitational wave detection to the public at large throughout the world. By combining different ideas and approaches across participating institutions, the LSC EPO network is able to create outreach programs which are far more effective than they would be if LSC member institutions worked independently.

Broader goals

- Improving science literacy in the general population
- Increasing participation in science, especially among under-represented and underserved groups
- Helping to reduce existing disparities in the access to educational resources
- Advocating the intellectual and social / socio-economic benefits of careers in science
- Recruiting future generations of scientists and engineers, to our own collaboration and to the wider scientific community
- Providing and coordinating resources for the design and delivery of outreach and education activities by others within the collaboration
- Improving understanding by the citizenry of frontier science and large scientific projects

Day-to-day activities

Events at the observatory outreach centers, on-site tours and visits
Public events and lectures, projects in local communities
Development of printed materials, hand-outs, internet-based activities, games, multimedia...
Use of new social media, Twitter, Facebook
Formal education programs, classroom lessons, curriculum development
Professional development
Diversity initiatives
Participation at conferences, science fairs, and exhibits

LIGO Lab

School field trips

Special interest programs
(Cub Scout astronomy pin

Initial LIGO artifacts
now going on display

Public events

Off-site activities

LIGO Lab outreach continues to focus on the general public, school groups, school teachers and university students

Social networking

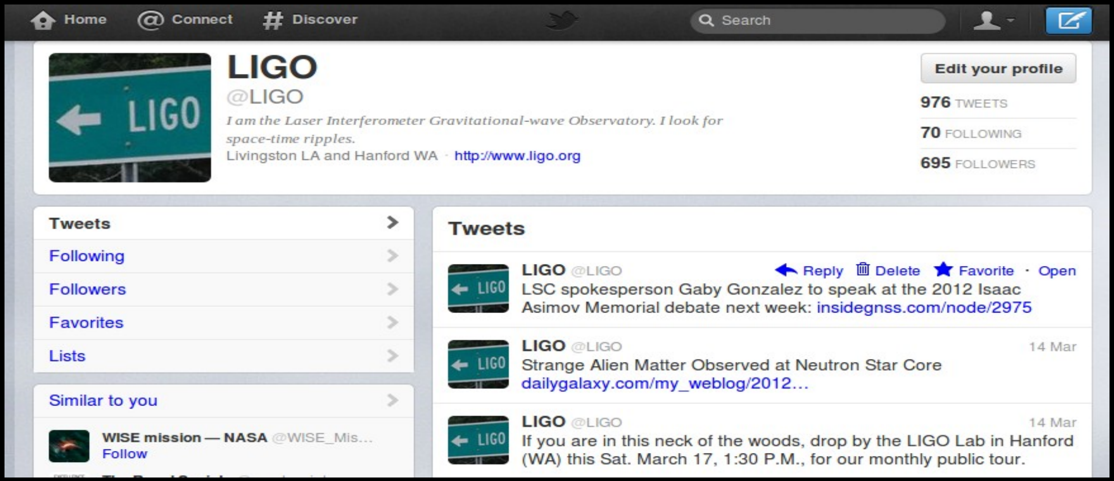
LIGO Scientific Collaboration + Lab pages

http://www.facebook.com/ligo.collaboration

https://www.facebook.com/pages/LIGO-Hanford-Observatory/238772419225

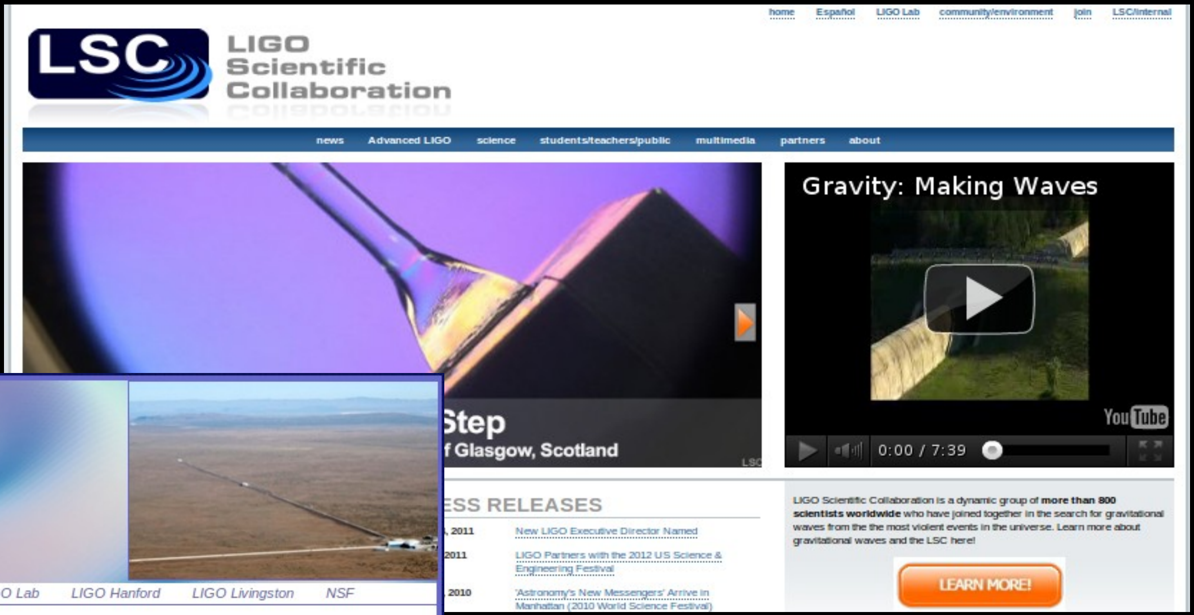
https://www.facebook.com/LIGOLivingston

~800 followers and growing



Web sites

www.ligo.org



www.advancedligo.mit.edu

Science summaries

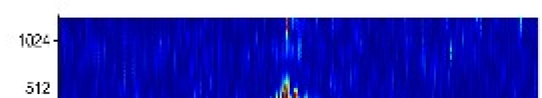
SUMMARIES OF LSC SCIENTIFIC PUBLICATIONS

We now feature, for each new research article, a summary written for the general public. Summaries are listed in reverse chronological order.

Mar 14, 2012	Sensitivity of LIGO and Virgo Gravitational Wave Detectors to Compact Binary Inspirals
Feb 15, 2012	Listening for gravitational-waves with "ears wide open"
Feb 06, 2012	Optical, X-ray, and Radio Telescopes Seek Explosive Sources of Gravitational Waves
Jan 31, 2012	Search for Gravitational Waves from Intermediate Mass Binary Black Holes
Jan 23, 2012	Implications for the origin of GRB 051103 from LIGO observations
Jan 11, 2012	First Low-Latency LIGO+Virgo Search for Binary Inspirals and their Electromagnetic Counterparts
Jan 03, 2012	Directional limits on persistent gravitational waves using LIGO S5 science data
Dec 21, 2011	Upper limits on a stochastic GW background using LIGO and Virgo interferometers at 600-1000 Hz
Dec 01, 2011	A search for gravitational waves from inspiraling neutron stars and black holes

VIRGO DATA CHARACTERIZATION AND IMPACT ON GRAVITATIONAL WAVE SEARCHES

Several kilometric interferometers (LIGO, Virgo, GEO) in the world have been designed and operated to search for gravitational waves (GW) emitted by astrophysical sources. Those complex instruments are very sensitive to tiny displacements theoretically induced by gravitational waves but are limited by various fundamental *noises*. Seismic, acoustic and electromagnetic



LIGO on Tour

Currently in: Texas

Next stop: Wisconsin

Games

www.gwoptics.org

Space Time Quest

Black Hole Pong

`Ebook' on GRWs in English, Spanish, Chinese, German, Italian. Russian, Catalan soon.

More info in...

The LSC White Paper on Education and Public Outreach

Goals, Status and Plans, Priorities (2011 edition)

Circulation Restricted to LVC Members

EPO group of the LSC[1]

June 16, 2011

http://dcc.ligo.org

The University of Mississippi

LIGO-G1200673-v1

Obrigado!