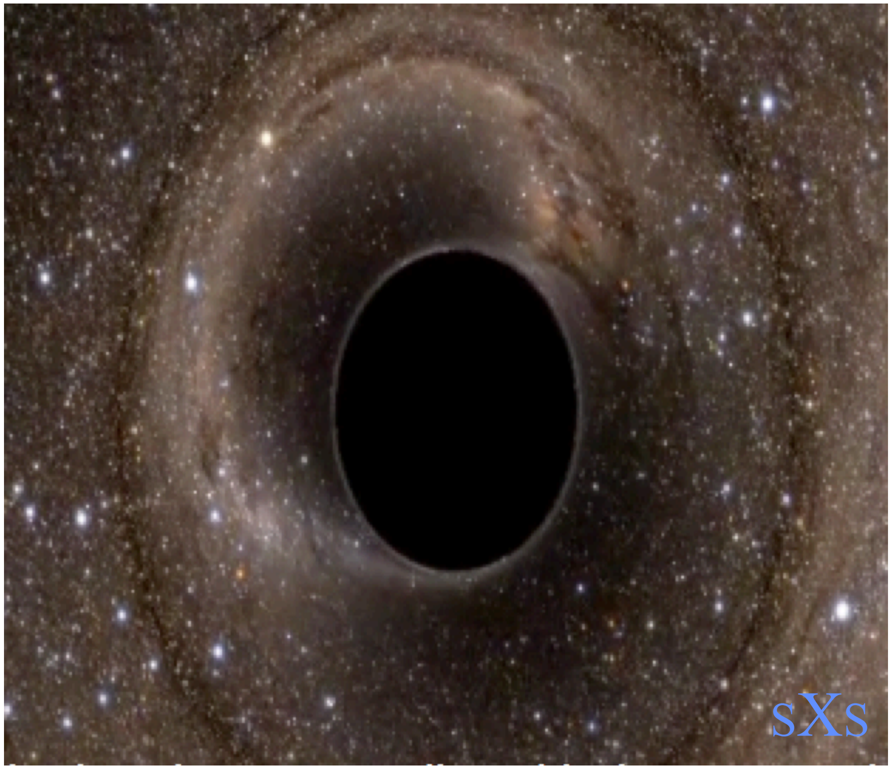
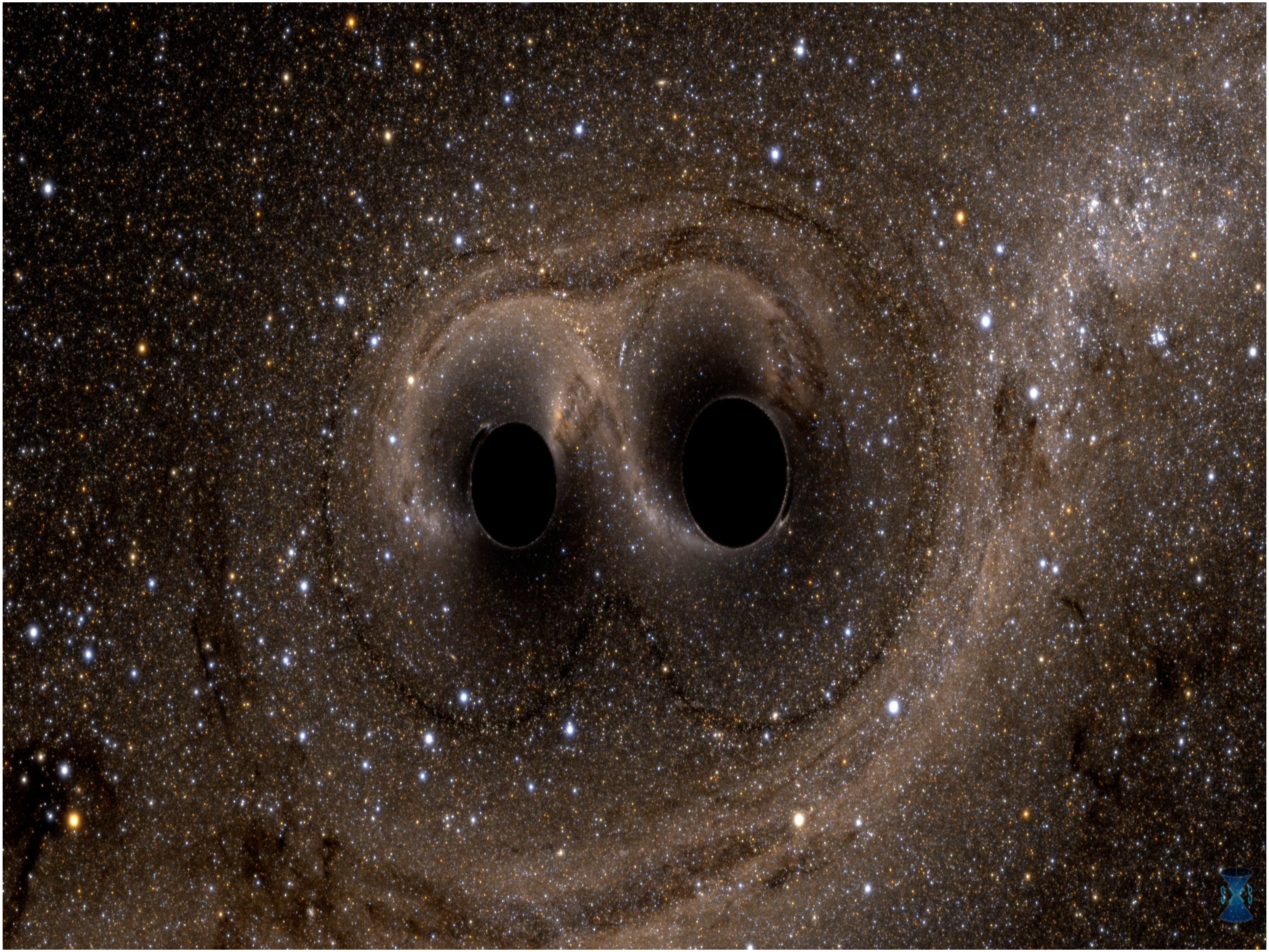
Laser Interferometer Gravitational Wave Observatory (LIGO) : The Inside Story

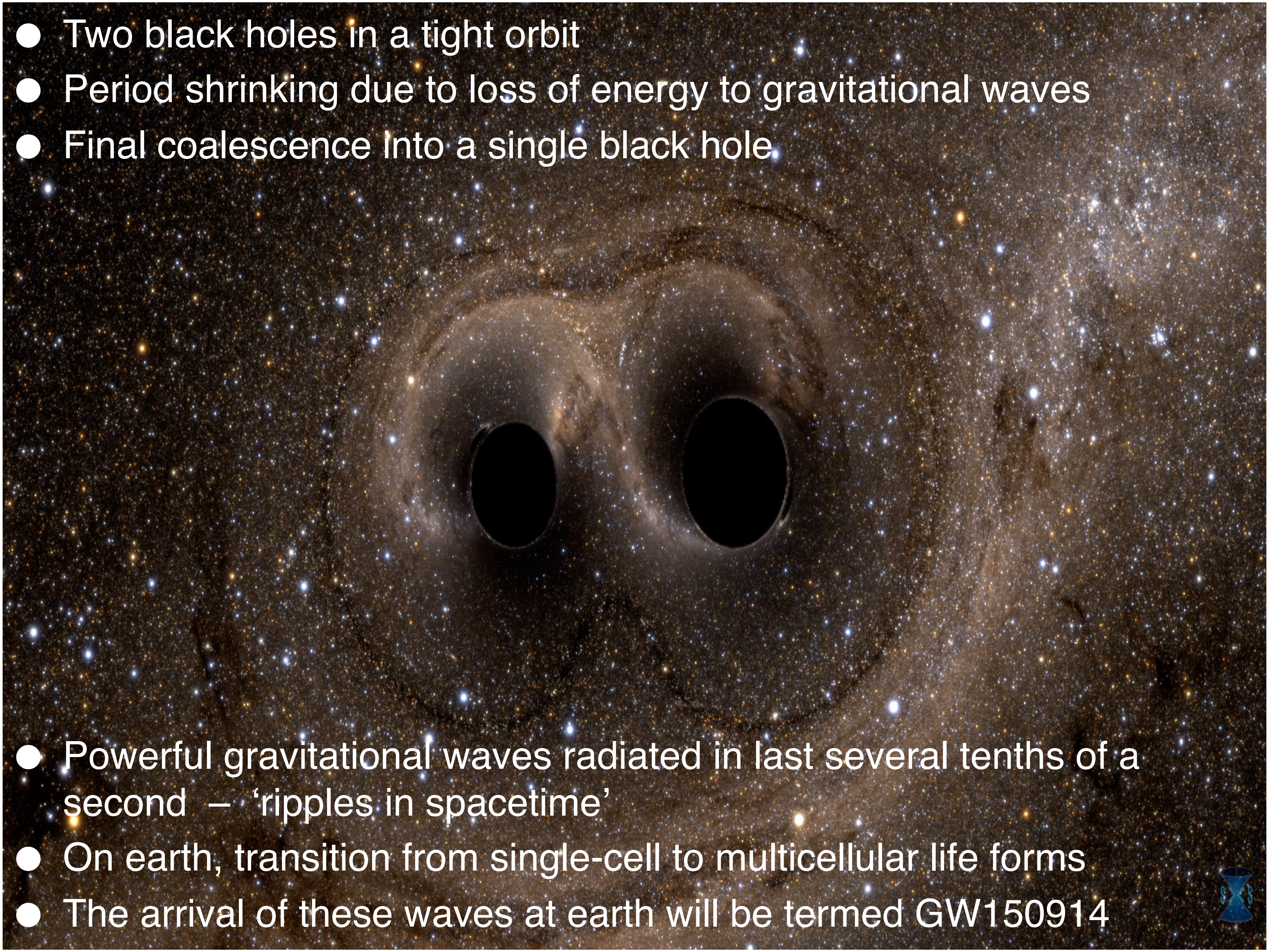


M. Landry
LIGO Hanford Observatory/Caltech
for the LIGO and Virgo Scientific Collaborations

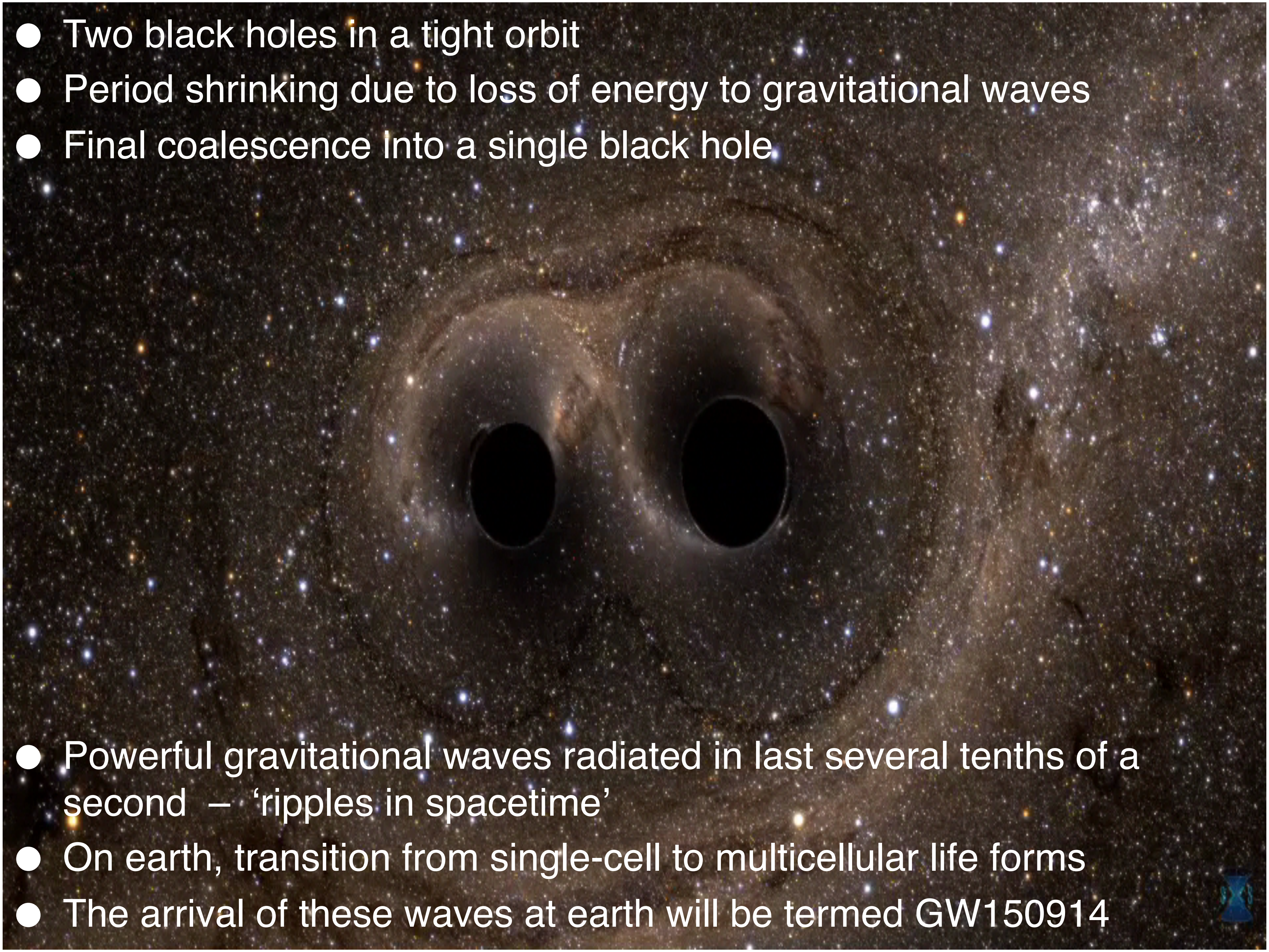
NSF Large Facilities Workshop *24 May 2016*



- Two black holes in a tight orbit
- Period shrinking due to loss of energy to gravitational waves
- Final coalescence into a single black hole



- Powerful gravitational waves radiated in last several tenths of a second – ‘ripples in spacetime’
- On earth, transition from single-cell to multicellular life forms
- The arrival of these waves at earth will be termed GW150914



- Two black holes in a tight orbit
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Outline

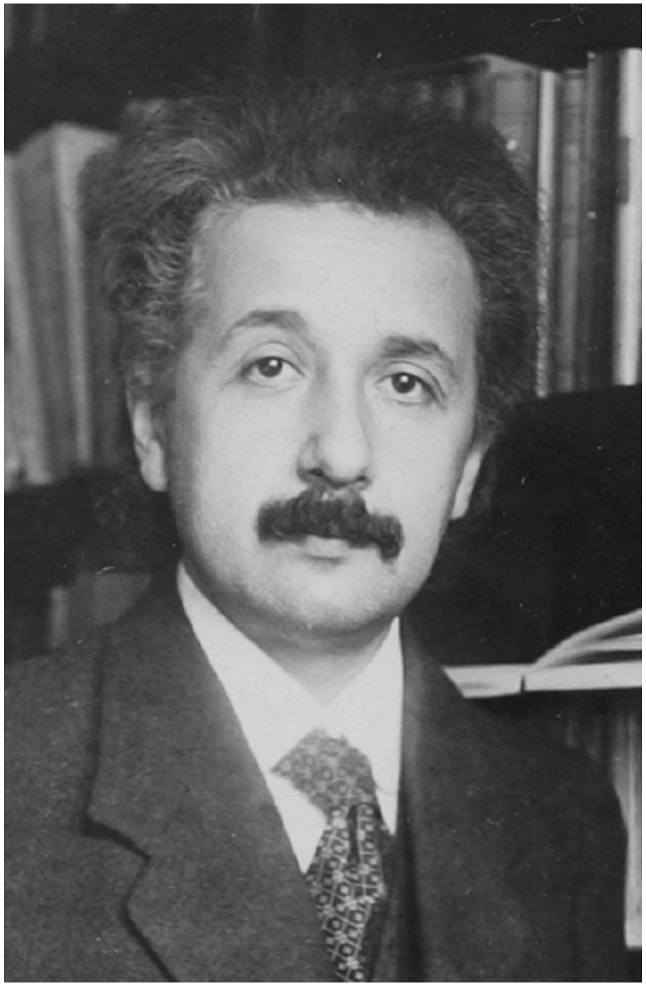
- A timeline of GW150914
- Some history of gravitational waves, and experiments
- Initial LIGO, the Advanced LIGO Project, LIGO Operations
    - The experiments
    - The phases and transitions, some problems and some lessons
- The Event itself, GW150914
- Some results and conclusions

100 years ago

- General Relativity is published in 1915 by former patent clerk, now Professor, A. Einstein
- First paper indicating that gravitational waves (GW) in 1916
  - Contains an algebraic error, leading Einstein to think that no energy is carried by GWs
- Second paper in 1918 corrects this error, but Einstein indicates that the effect is of no practical interest since the effect is too small to be detected

Meanwhile….

- The gravitational waves from the binary black-hole merger cross Gacrux, a star in the Southern Cross

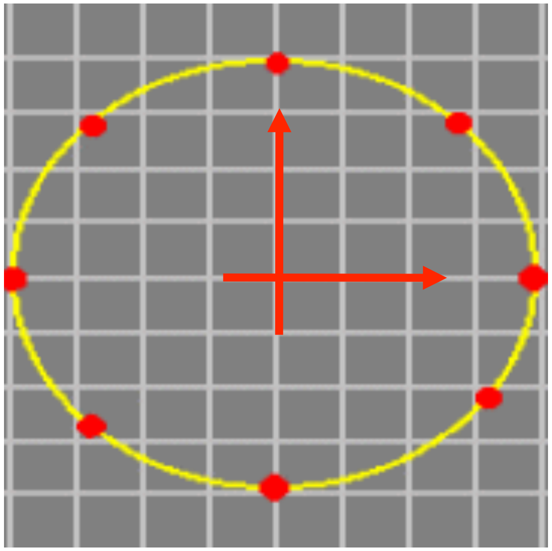


Gravitational waves

- Distortions in space-time, generated by changing quadrupole moments such as in co-orbiting objects, spinning asymmetric objects
- Interact weakly with matter - even densest systems transparent to gravitational waves
- An entirely new phenomenon with which to explore the universe

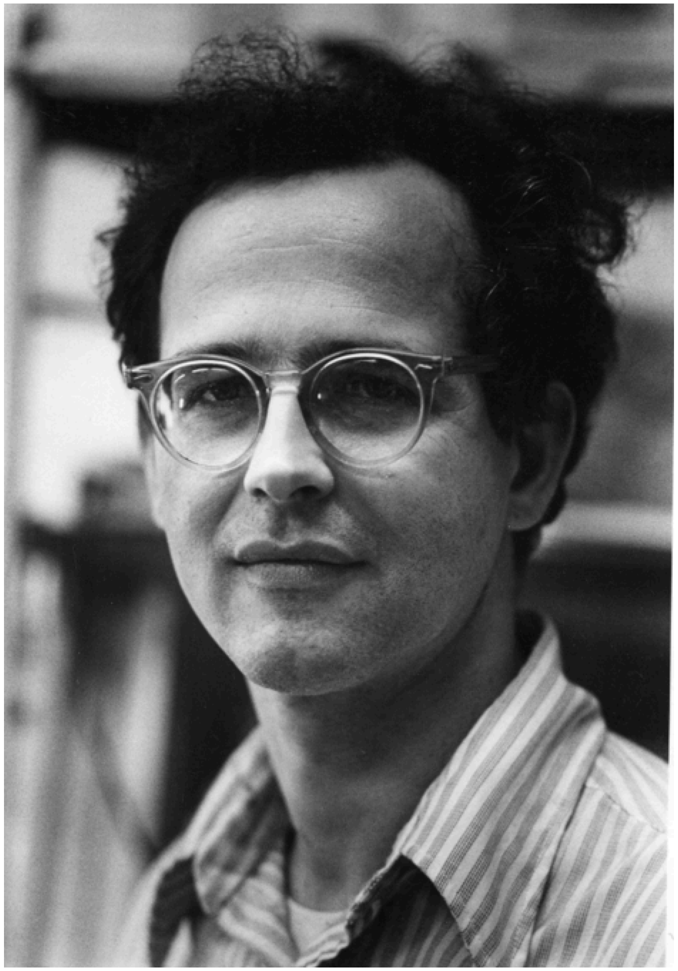
Physically, gravitational waves are *strains*:

$$\boxed{h = \frac{\Delta L(f)}{L}}$$

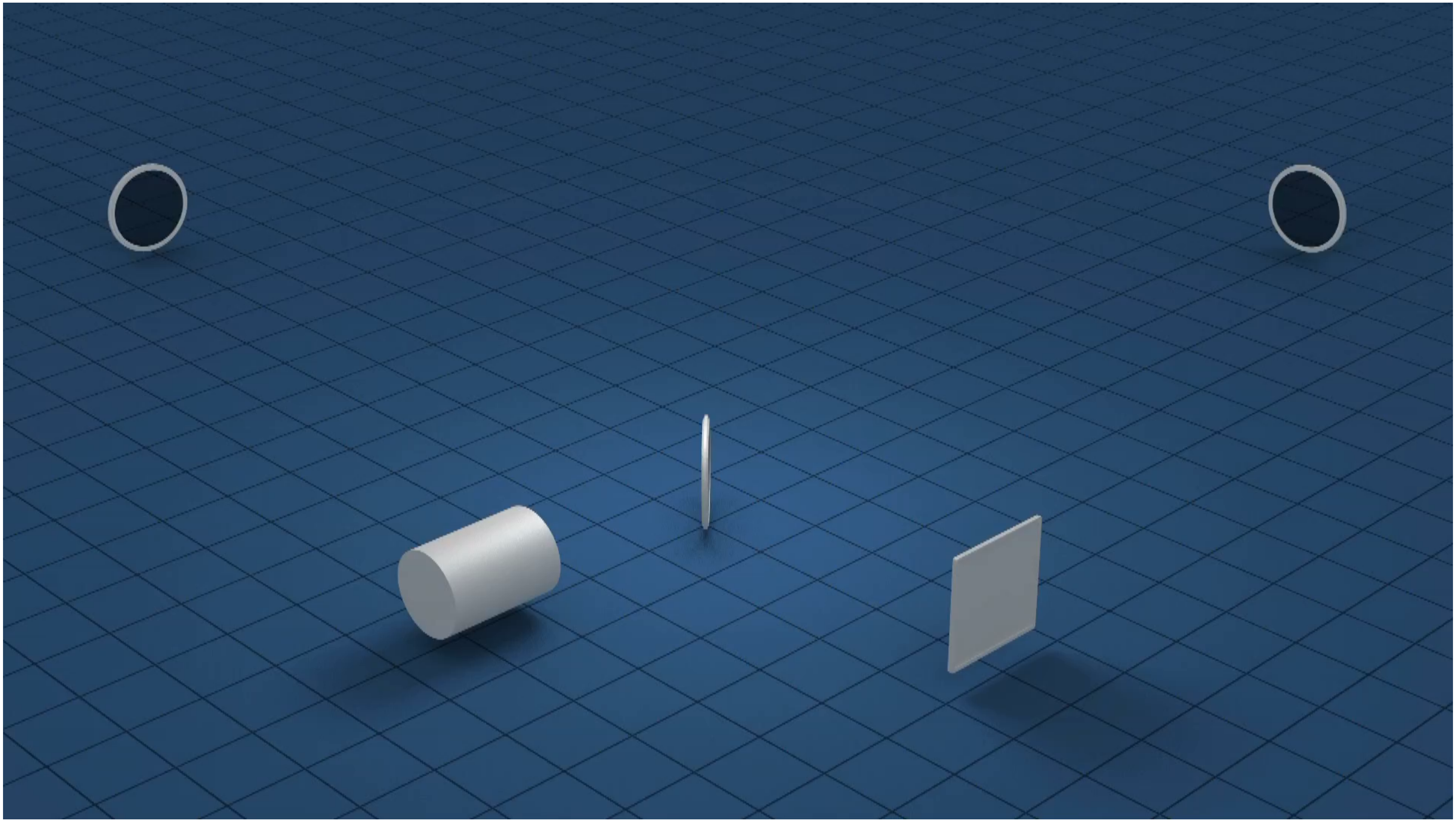


A half-century ago

- Gertsenstein and Pustovoit, 1963: theoretical study of using laser interferometry to detect GWs (Russian)
- Others re-invent the notion – among them Joe Weber, who pioneered experimental searches for GWs, in developing 'acoustic bar' sensors
- In 1972, Rainer Weiss publishes an internal MIT report
  - Sets the concept and scale of LIGO
  - This roadmap contains also noise sources and how to manage them
- Interest grows in Max Planck Garching (Germany), U. Glasgow, Caltech in this interferometric technique
- GW150914 passes HR 2225 in Canis Major

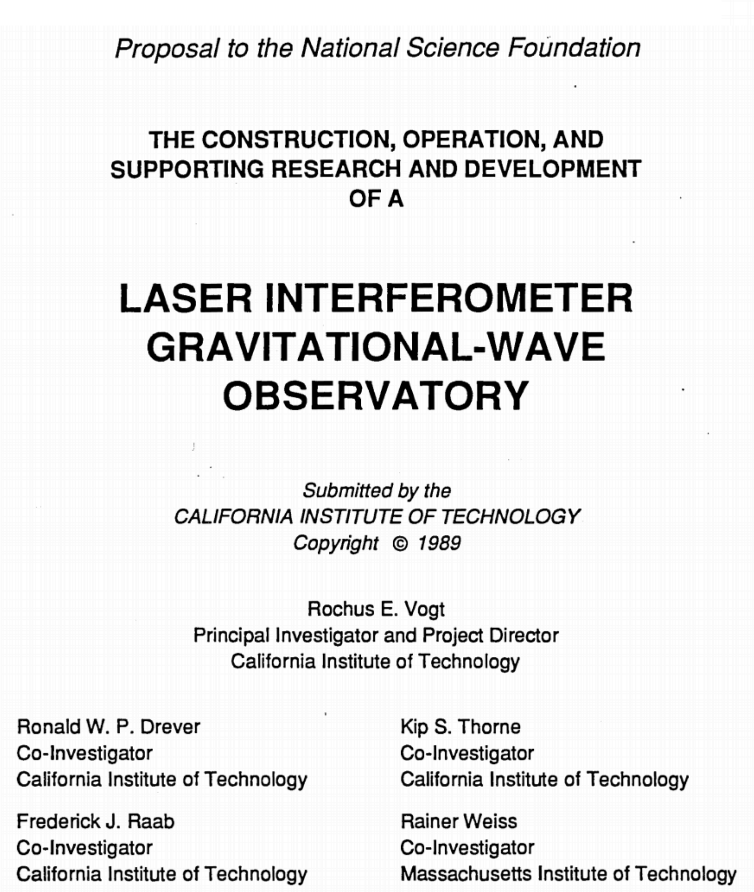

Rainer Weiss

Michelson interfometers



Two decades ago

- Caltech and MIT propose to the NSF to establish Observatories
- Proposal states clearly that the initial detectors only have a chance of detections, and that upgraded detectors must be accommodated and foreseen



Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND
SUPPORTING RESEARCH AND DEVELOPMENT
OF A

LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY
Copyright © 1989

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever Co-Investigator California Institute of Technology	Kip S. Thorne Co-Investigator California Institute of Technology
Frederick J. Raab Co-Investigator California Institute of Technology	Rainer Weiss Co-Investigator Massachusetts Institute of Technology

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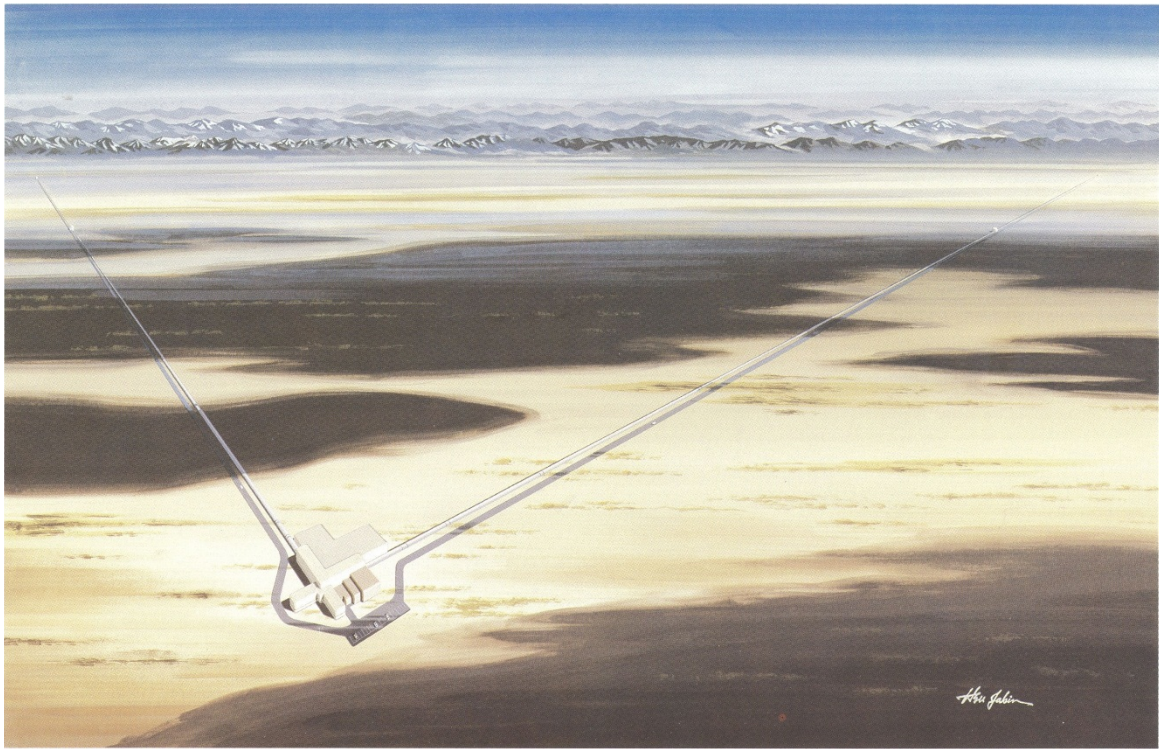
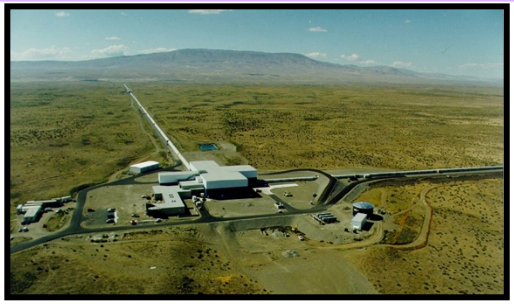
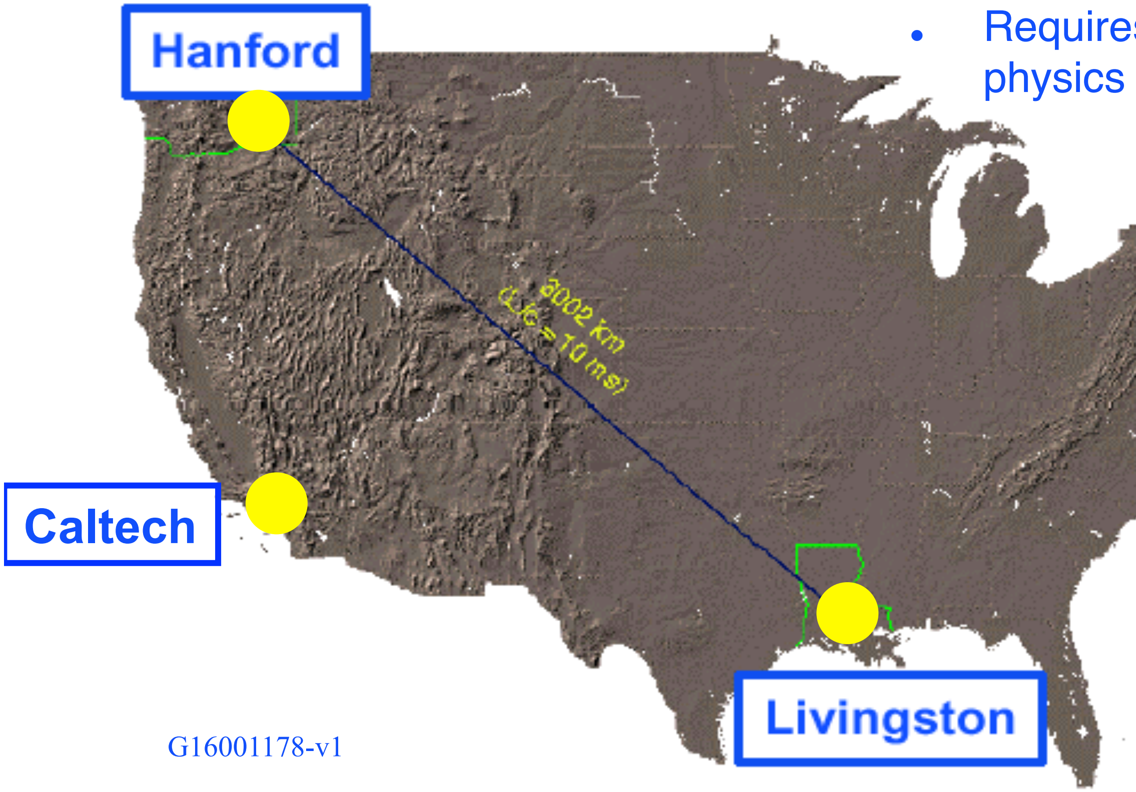


- Artist's conception of what an observatory might look like
- GW150914 passing 82 Eridani…

LIGO Laboratory: two observatories, Caltech and MIT campuses



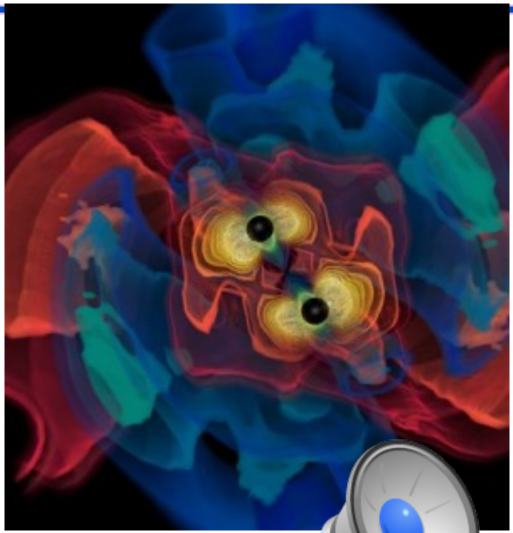
- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



LIGO Scientific Collaboration

- 900+ members, 80+ institutions, 17 countries

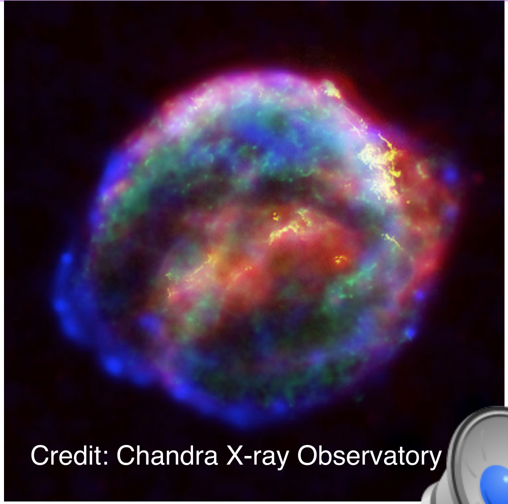
Astrophysical sources of gravitational waves


Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems: *Neutron Star-NS, Black Hole-NS, BH-BH*

- Strong emitters, well-modeled,

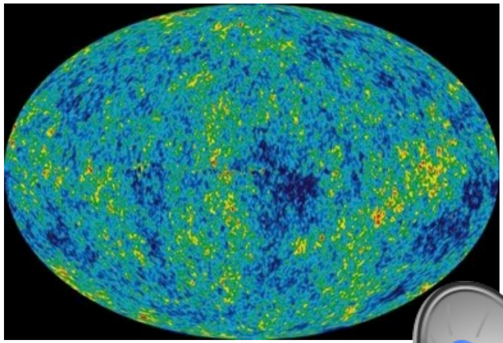
- (effectively) transient


Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled (‘bursts’), transient

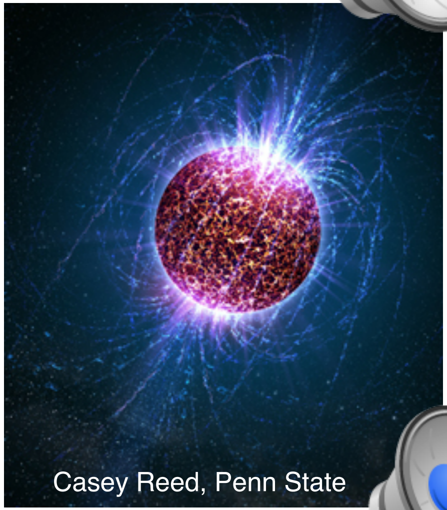
- Also: cosmic strings, SGRs, ulsar glitches


NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang

- Long duration, stochastic background


Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform

- Long duration

Within 10 years

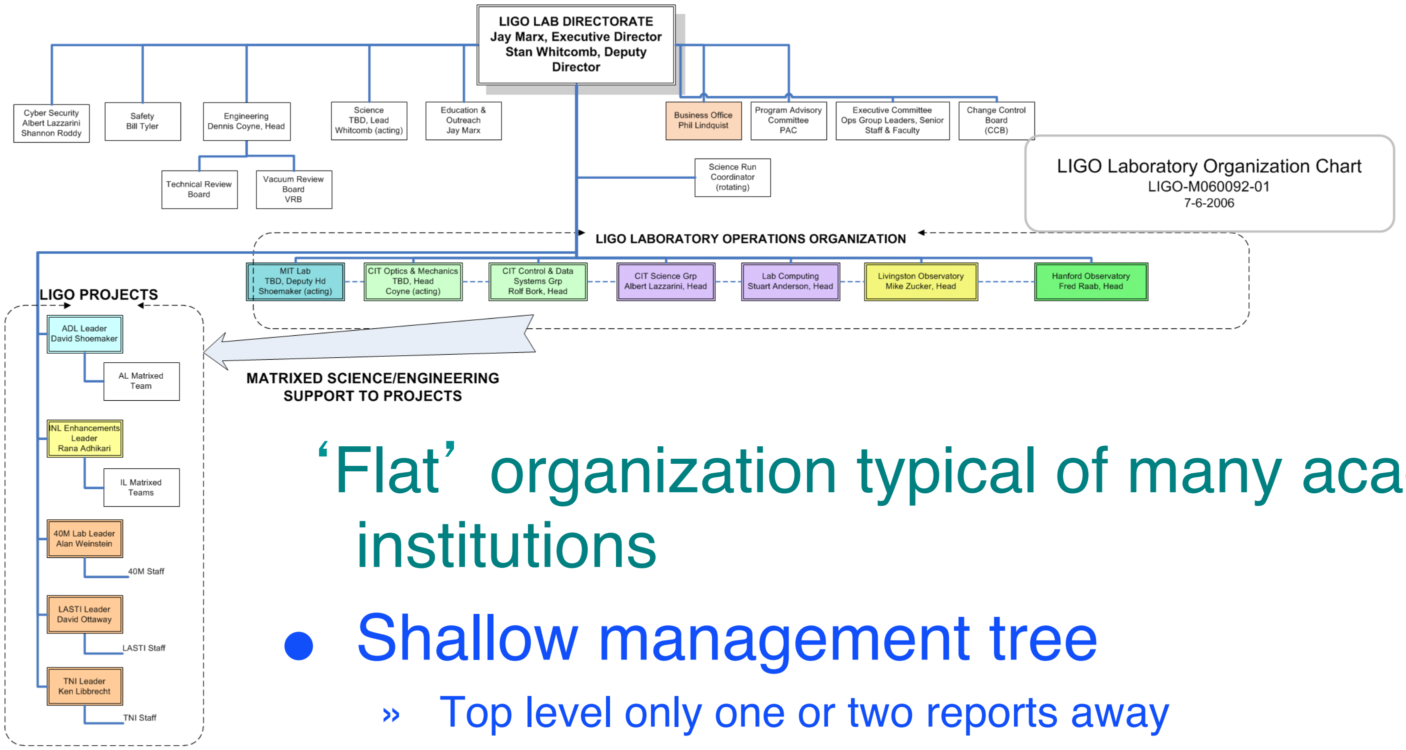
- Advanced LIGO is funded in 2006: an upgrade of all components, 10x better sensitivity

- Initial LIGO deinstallation Oct 20, 2010, installation starts for Advanced LIGO after
  - GWs from the BH-BH cross Alpha Centauri, the closest star, just 4.4 light years away

Advanced LIGO support

- NSF-supported (~$205M MREFC phase)
  - Caltech as awardee, MIT and Caltech sharing responsibility institutionally, organizationally, scientifically, and technically
  - Several US LSC institutions supported on subcontracts from LIGO Lab in Project phase (all US-supported aLIGO work to be on aLIGO MREFC)
- Foreign contributions – from experienced collaborators
  - Germany – Pre-stabilized laser (value ~$14M incl. development)
  - United Kingdom – Test mass suspensions and some test mass optics (value ~$14M incl. development)
  - Australia – alignment sensors, optics, and suspensions (value ~ $1.7M incl. development)

LIGO Pre-Project Organization Structure



LIGO LAB DIRECTORATE
Jay Marx, Executive Director
Stan Whitcomb, Deputy Director

Cyber Security
Albert Lazzarini
Shannon Roddy

Safety
Bill Tyler

Engineering
Dennis Coyne, Head

Technical Review Board

Vacuum Review Board
VRB

Science
TBD, Lead
Whitcomb (acting)

Education & Outreach
Jay Marx

Business Office
Phil Lindquist

Program Advisory Committee
PAC

Executive Committee
Ops Group Leaders, Senior Staff & Faculty

Change Control Board
(CCB)

Science Run Coordinator
(rotating)

LIGO Laboratory Organization Chart
LIGO-M060092-01
7-6-2006

LIGO LABORATORY OPERATIONS ORGANIZATION

MIT Lab
TBD, Deputy Hd
Shoemaker (acting)

CIT Optics & Mechanics
TBD, Head
Coyne (acting)

CIT Control & Data Systems Grp
Rolf Bork, Head

CIT Science Grp
Albert Lazzarini, Head

Lab Computing
Stuart Anderson, Head

Livingston Observatory
Mike Zucker, Head

Hanford Observatory
Fred Raab, Head

LIGO PROJECTS

ADL Leader
David Shoemaker

AL Matrixed Team

INL Enhancements Leader
Rana Adhikari

IL Matrixed Teams

40M Lab Leader
Alan Weinstein

40M Staff

LASTI Leader
David Ottaway

LASTI Staff

TNI Leader
Ken Libbrecht

TNI Staff

MATRIXED SCIENCE/ENGINEERING SUPPORT TO PROJECTS

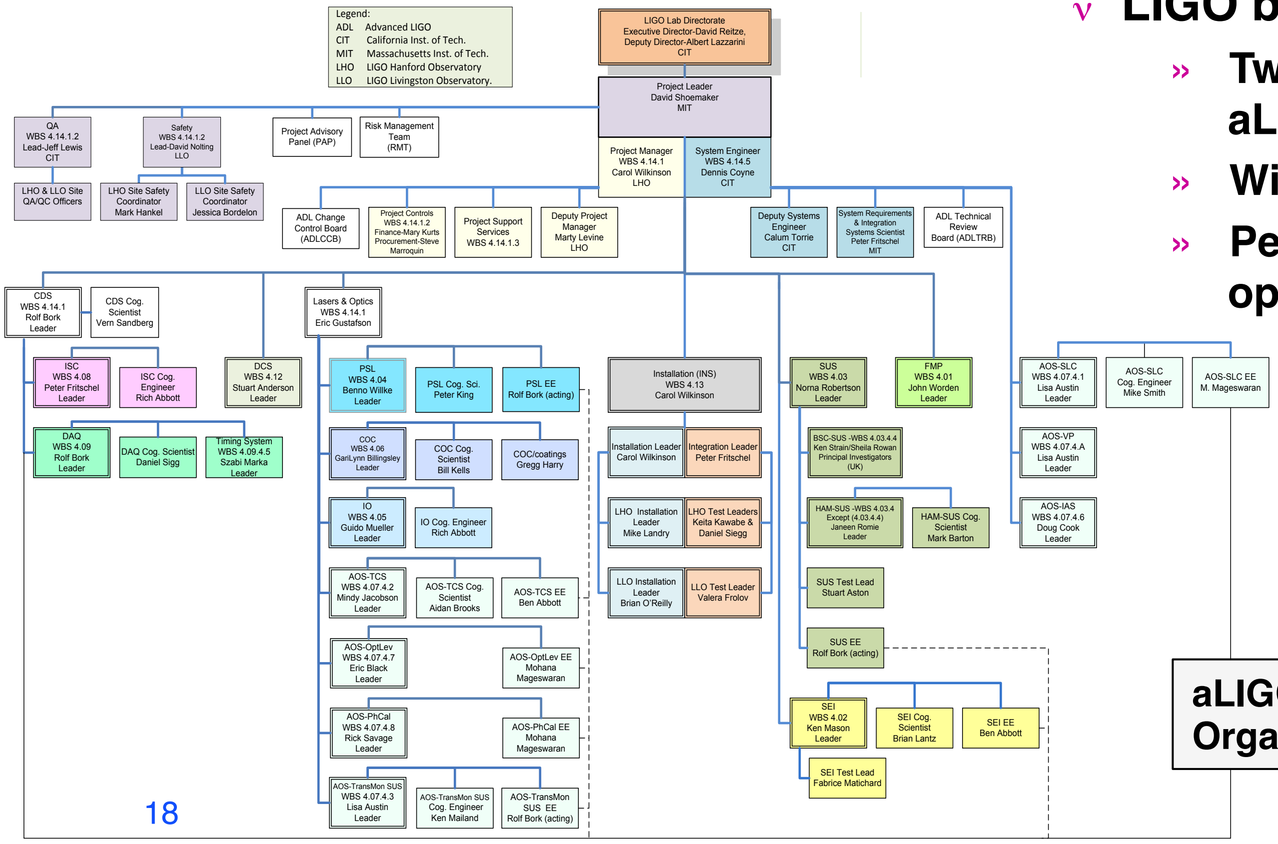
‘Flat’ organization typical of many academic institutions

- Shallow management tree
  - Top level only one or two reports away
  - From 10 to 30+ direct reports per manager (~170 FTE)
- Authority and responsibility held by a few at the top
  - Little delegation of budget, hiring, mission, and priority decisions
  - Technical staff not burdened by bureaucratic responsibilities

aLIGO Project Organization Chart

Project organization is hierarchical, with several tiers of managers

- Authority and responsibility delegated downwards
  - Fewer direct reports
- LIGO becomes strongly matrixed
  - Two thirds of lab staff works on aLIGO project assignments
  - With new hires - 280 employees
  - Permanent staff will return to operations



Legend:
ADL Advanced LIGO
CIT California Inst. of Tech.
MIT Massachusetts Inst. of Tech.
LHO LIGO Hanford Observatory
LLO LIGO Livingston Observatory.

LIGO Lab Directorate
Executive Director-David Reitze,
Deputy Director-Albert Lazzarini
CIT

Project Leader
David Shoemaker
MIT

Project Manager
WBS 4.14.1
Carol Wilkinson
LHO

System Engineer
WBS 4.14.5
Dennis Coyne
CIT

QA
WBS 4.14.1.2
Lead-Jeff Lewis
CIT

LHO & LLO Site
QA/QC Officers

Safety
WBS 4.14.1.2
Lead-David Nolting
LLO

LHO Site Safety
Coordinator
Mark Hankel

LLO Site Safety
Coordinator
Jessica Bordelon

Project Advisory
Panel (PAP)

Risk Management
Team
(RMT)

ADL Change
Control Board
(ADLCCB)

Project Controls
WBS 4.14.1.2
Finance-Mary Kurts
Procurement-Steve
Marroquin

Project Support
Services
WBS 4.14.1.3

Deputy Project
Manager
Marty Levine
LHO

Deputy Systems
Engineer
Calum Torrie
CIT

System Requirements
& Integration
Systems Scientist
Peter Fritschel
MIT

ADL Technical
Review
Board (ADLTRB)

CDS
WBS 4.14.1
Rolf Bork
Leader

CDS Cog.
Scientist
Vern Sandberg

ISC
WBS 4.08
Peter Fritschel
Leader

ISC Cog.
Engineer
Rich Abbott

DAQ
WBS 4.09
Rolf Bork
Leader

DAQ Cog. Scientist
Daniel Sigg

Timing System
WBS 4.09.4.5
Szabi Marka
Leader

DCS
WBS 4.12
Stuart Anderson
Leader

Lasers & Optics
WBS 4.14.1
Eric Gustafson

PSL
WBS 4.04
Benno Willke
Leader

PSL Cog. Sci.
Peter King

PSL EE
Rolf Bork (acting)

COC
WBS 4.06
GariLynn Billingsley
Leader

COC Cog.
Scientist
Bill Kells

COC/coatings
Gregg Harry

IO
WBS 4.05
Guido Mueller
Leader

IO Cog. Engineer
Rich Abbott

AOS-TCS
WBS 4.07.4.2
Mindy Jacobson
Leader

AOS-TCS Cog.
Scientist
Aidan Brooks

AOS-TCS EE
Ben Abbott

AOS-OptLev
WBS 4.07.4.7
Eric Black
Leader

AOS-OptLev EE
Mohana
Mageswaran

AOS-PhCal
WBS 4.07.4.8
Rick Savage
Leader

AOS-PhCal EE
Mohana
Mageswaran

AOS-TransMon SUS
WBS 4.07.4.3
Lisa Austin
Leader

AOS-TransMon SUS
Cog. Engineer
Ken Mailand

AOS-TransMon
SUS EE
Rolf Bork (acting)

Installation (INS)
WBS 4.13
Carol Wilkinson

Installation Leader
Carol Wilkinson

Integration Leader
Peter Fritschel

LHO Installation
Leader
Mike Landry

LHO Test Leaders
Keita Kawabe &
Daniel Siegg

LLO Installation
Leader
Brian O'Reilly

LLO Test Leader
Valera Frolov

SUS
WBS 4.03
Norna Robertson
Leader

BSC-SUS -WBS 4.03.4.4
Ken Strain/Sheila Rowan
Principal Investigators
(UK)

HAM-SUS -WBS 4.03.4
Except (4.03.4.4)
Janeen Romie
Leader

HAM-SUS Cog.
Scientist
Mark Barton

SUS Test Lead
Stuart Aston

SUS EE
Rolf Bork (acting)

SEI
WBS 4.02
Ken Mason
Leader

SEI Cog.
Scientist
Brian Lantz

SEI EE
Ben Abbott

SEI Test Lead
Fabrice Matichard

FMP
WBS 4.01
John Worden
Leader

AOS-SLC
WBS 4.07.4.1
Lisa Austin
Leader

AOS-SLC
Cog. Engineer
Mike Smith

AOS-SLC EE
M. Mageswaran

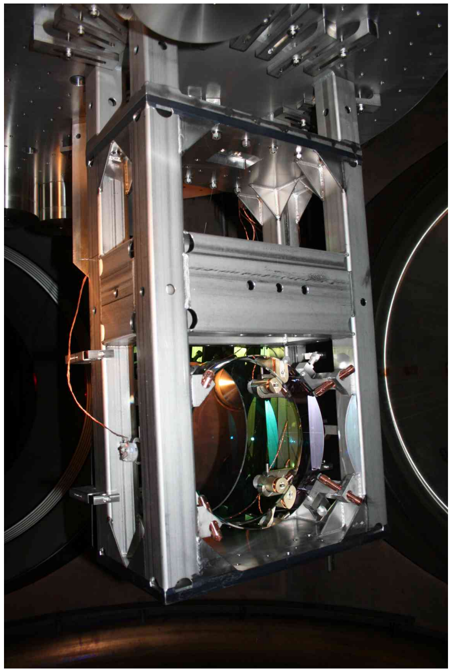
AOS-VP
WBS 4.07.4.A
Lisa Austin
Leader

AOS-IAS
WBS 4.07.4.6
Doug Cook
Leader

aLIGO Project Management Organization Chart

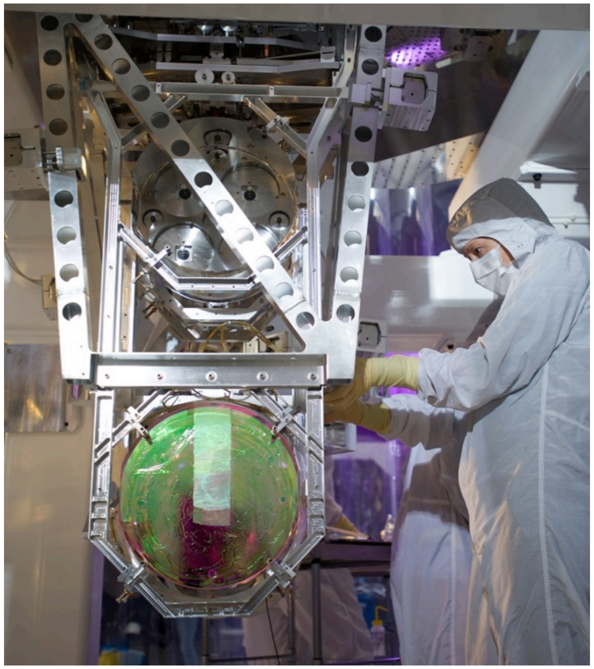
10X more sensitive, >10X harder…

- 14 unique fabricated parts
- 68 fabricated parts total
- 165 total including machined parts and hardware



Test mass suspension
From Initial LIGO

- 188 unique fabricated parts
- 1569 fabricated parts total
- 3575 total including machined parts and hardware



Test mass suspension
From Advanced LIGO

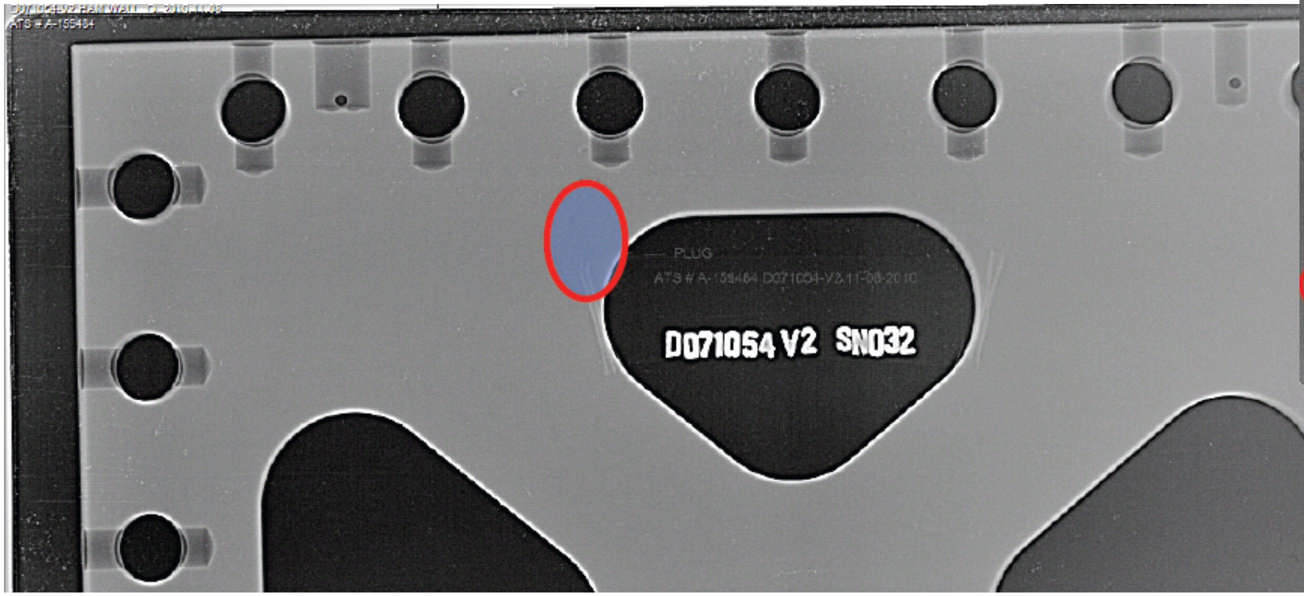
Key Installation elements

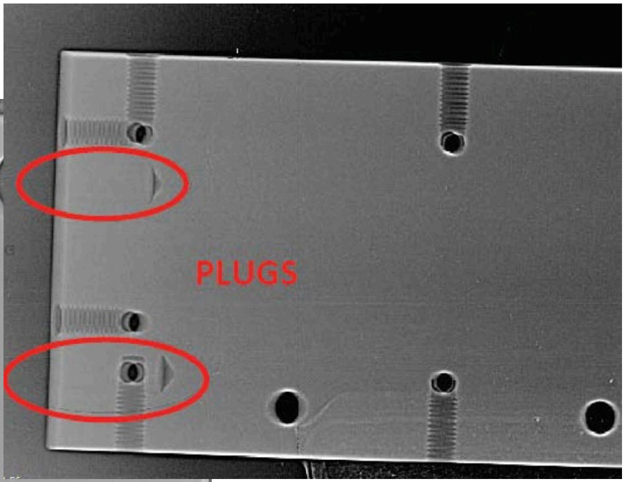
- People
  - Steady state science running: ~40 people at each of the sites. At install peak ~90 people @ LHO, less at LLO
  - Included technicians, engineering, scientists, project controls, facilities, management, i.e. everything
  - Installation staff launched each day with coordination meeting
  - Also includes riggers/millwrights operating under $3.3M time and materials (T&M) contract. Introduced to LIGO science to stress our unique needs (precision and contamination control, vs. speed)
- Safety
  - Checklists
  - Hazard Analyses
  - Stop work

Weld repairs

Assembly issue

- Unauthorized weld repairs detected visually in some seismic plates; underscores need for good QA
- Investigated with contractor and x-rays
- At issue is trapped volumes and virtual leaks
- Concluded new parts were required

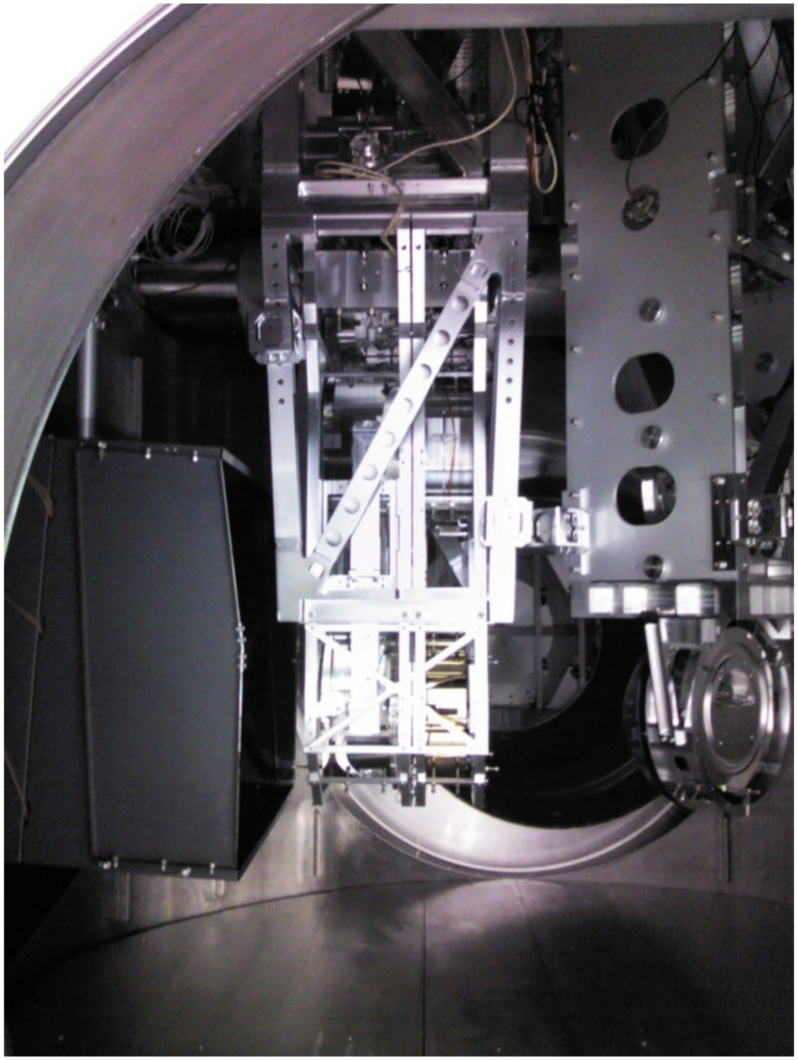


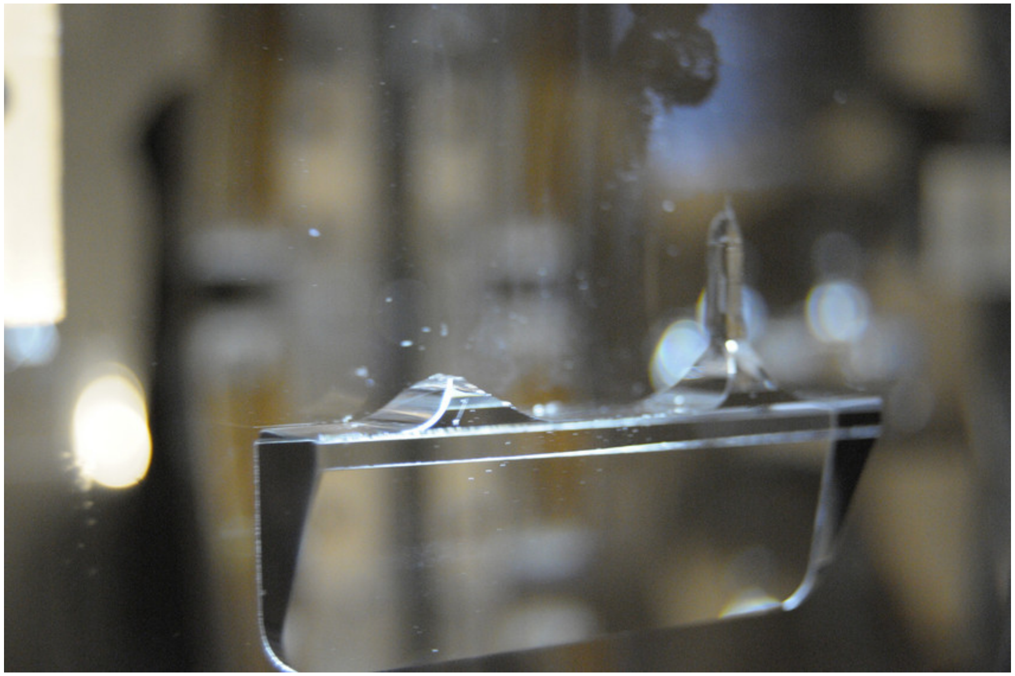


Fiber breakage

Install issue

- ITMY fibers broken in shaking incident induced by code bug
- Stop work called; code fixed/reviewed, testing restarted
- Underscores need for code reviews and testing

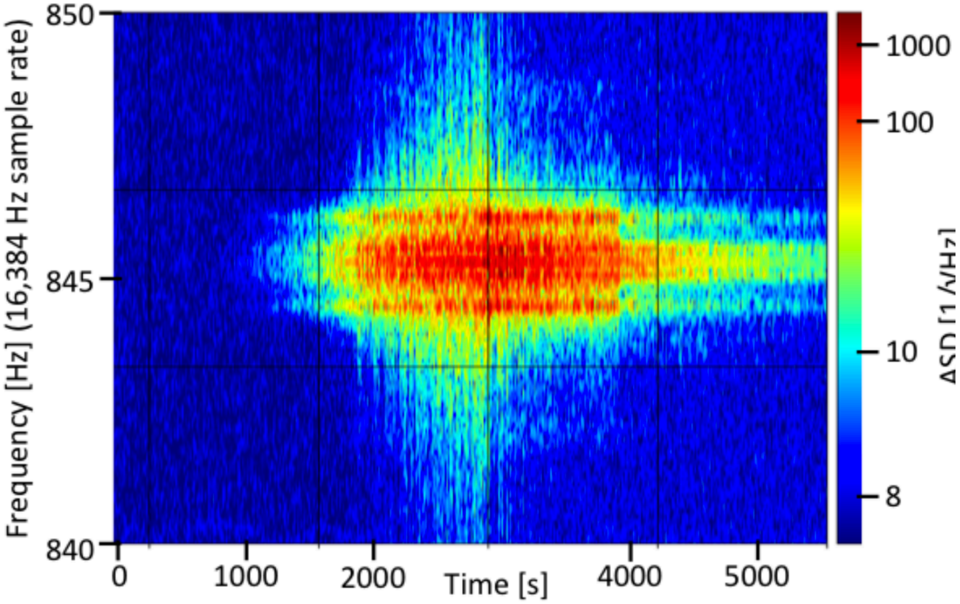


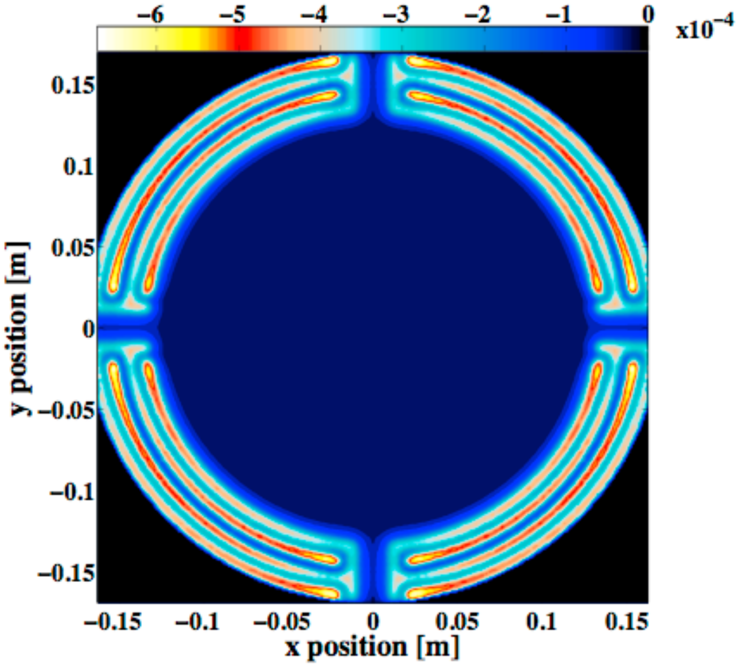


Active acoustic mode damping

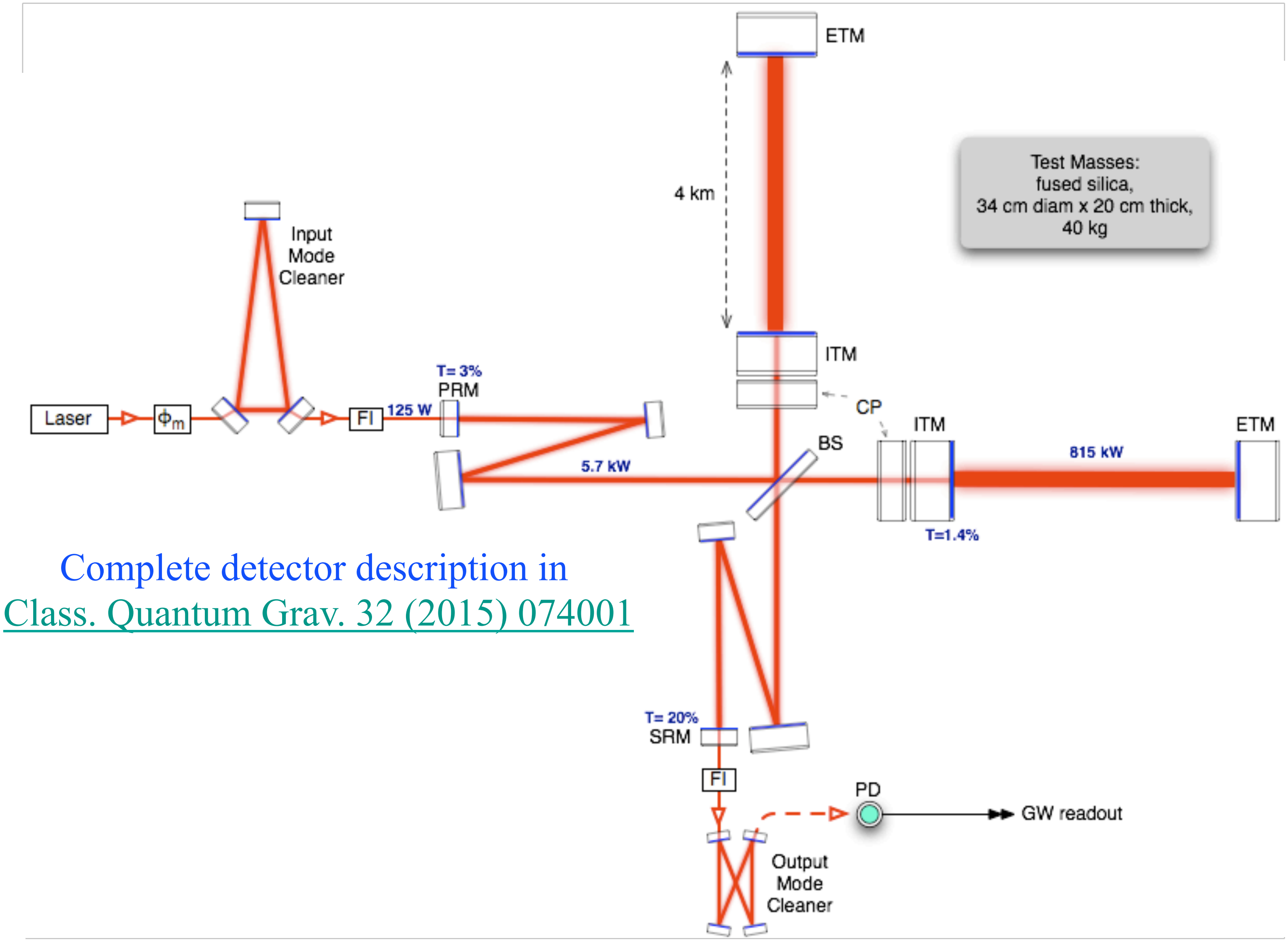
Commissioning issue

- Active damping using the electro-static drive, or ESD on the test masses

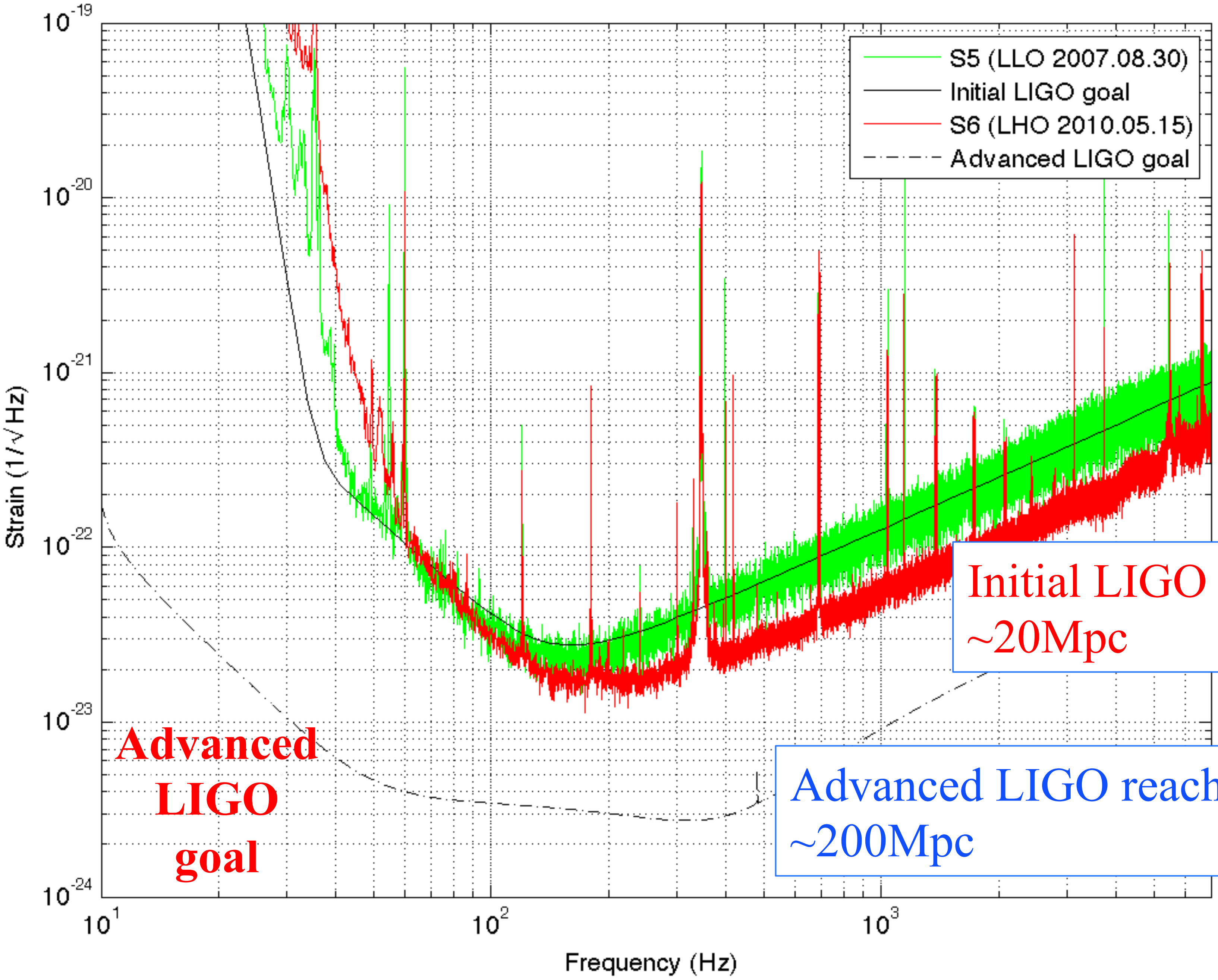



Test mass ESD

Optical configuration



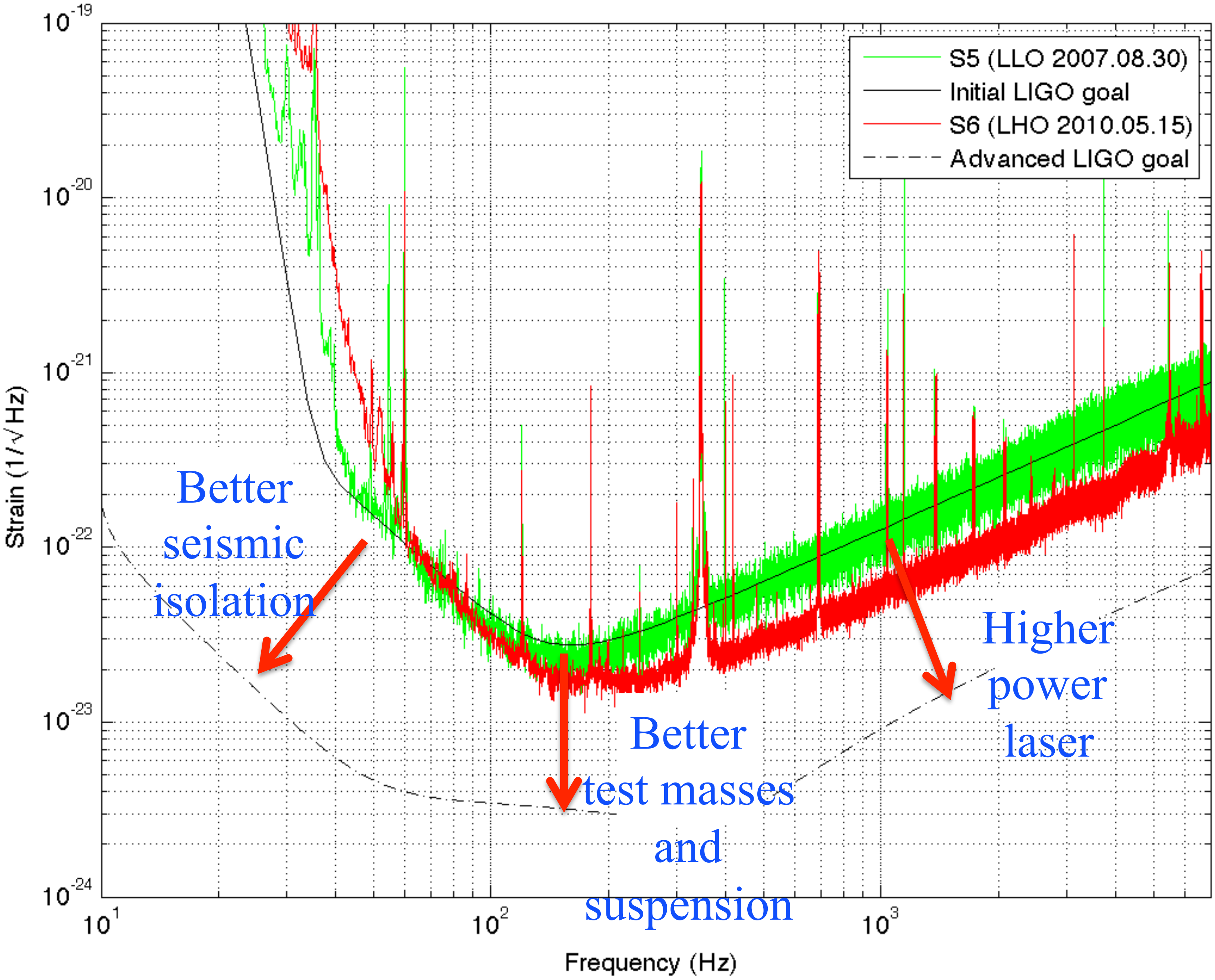
Complete detector description in
Class. Quantum Grav. 32 (2015) 074001



Initial LIGO reach
~20Mpc

Advanced LIGO goal

Advanced LIGO reach
~200Mpc

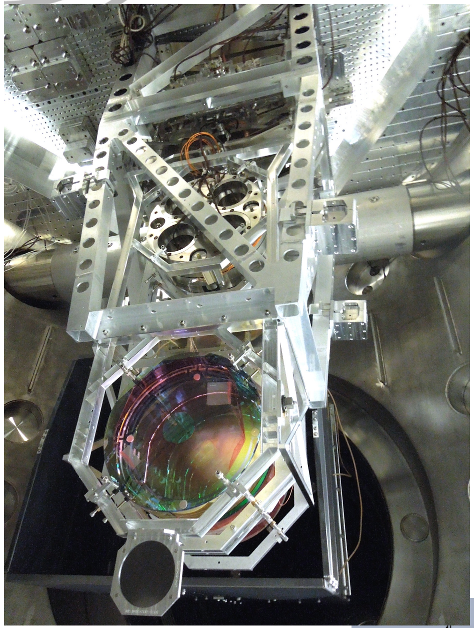


Better seismic isolation

Better test masses and suspension

Higher power laser

Seismic Isolation

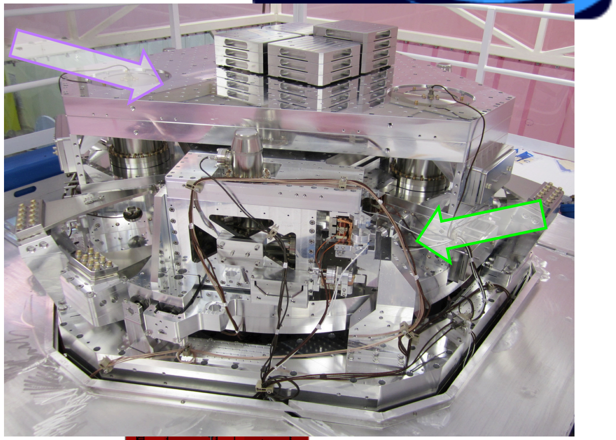


Ground Motion at 10 [Hz] ~ 10^{-9} [m/rtHz]

$$\Delta L = h\ L \sim 10^{-19}\, m / Hz^{1/2}$$

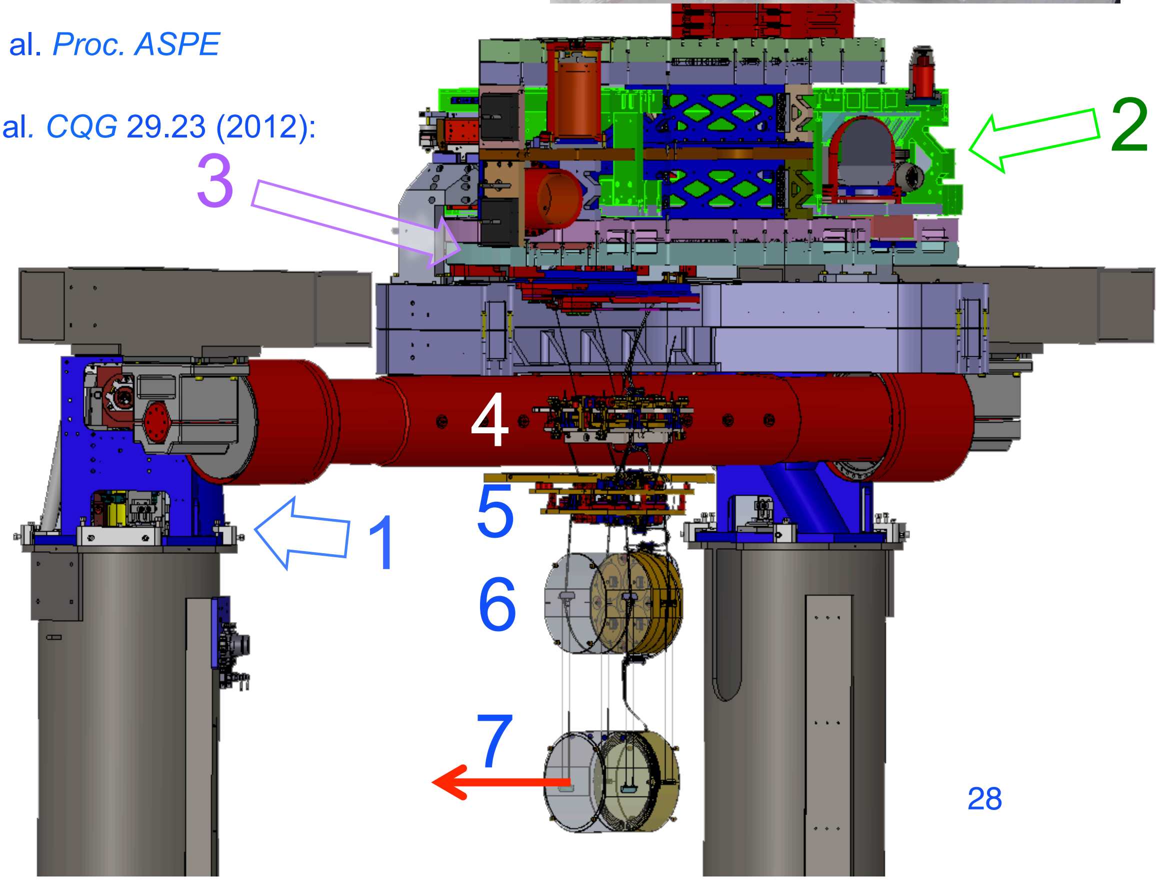
Need 10 orders of magnitude

Test masses are suspended from 7 stages of active and passive vibration isolation

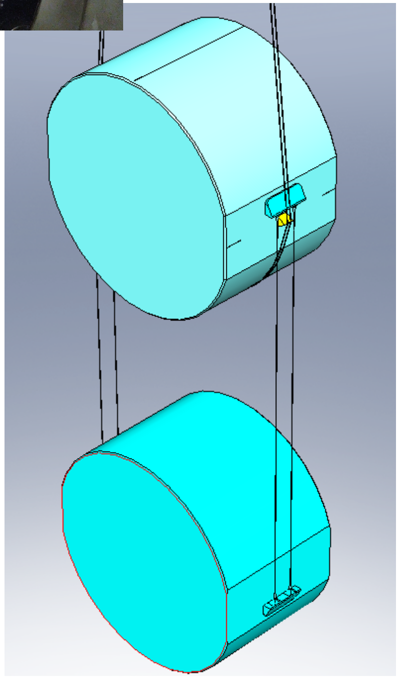


Matichard, F., et al. *Proc. ASPE* (2010)

Aston, S. M., et al. *CQG* 29.23 (2012): 235004.



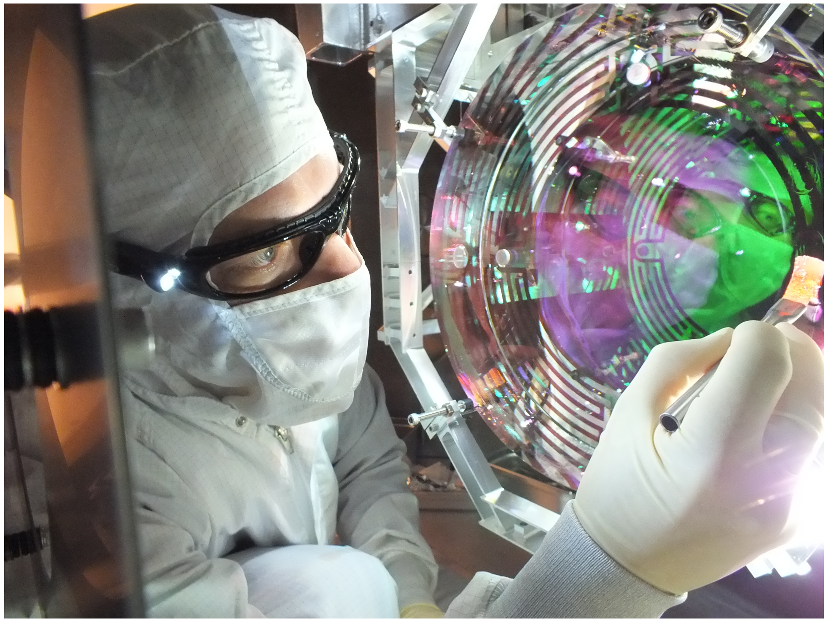
Last two stages are monolithic to improve Brownian noise



Cumming, A. V., et al. *CQG* 29.3 (2012): 035003.

Test Masses

- Heavy Mirrors → Insensitive to photon pressure from high power
- Test mass coating brownian noise dominates strain sensitivity in the most sensitive region (~100 [Hz])
- Larger Mirrors → Increase Spot Size: Average over more surface area

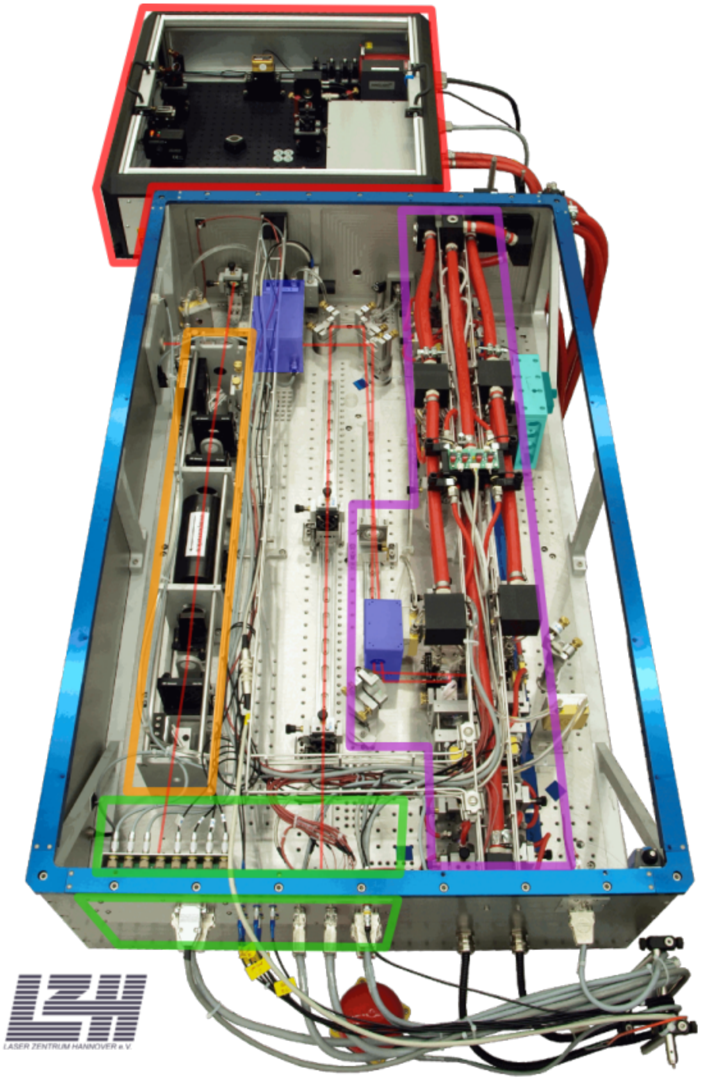


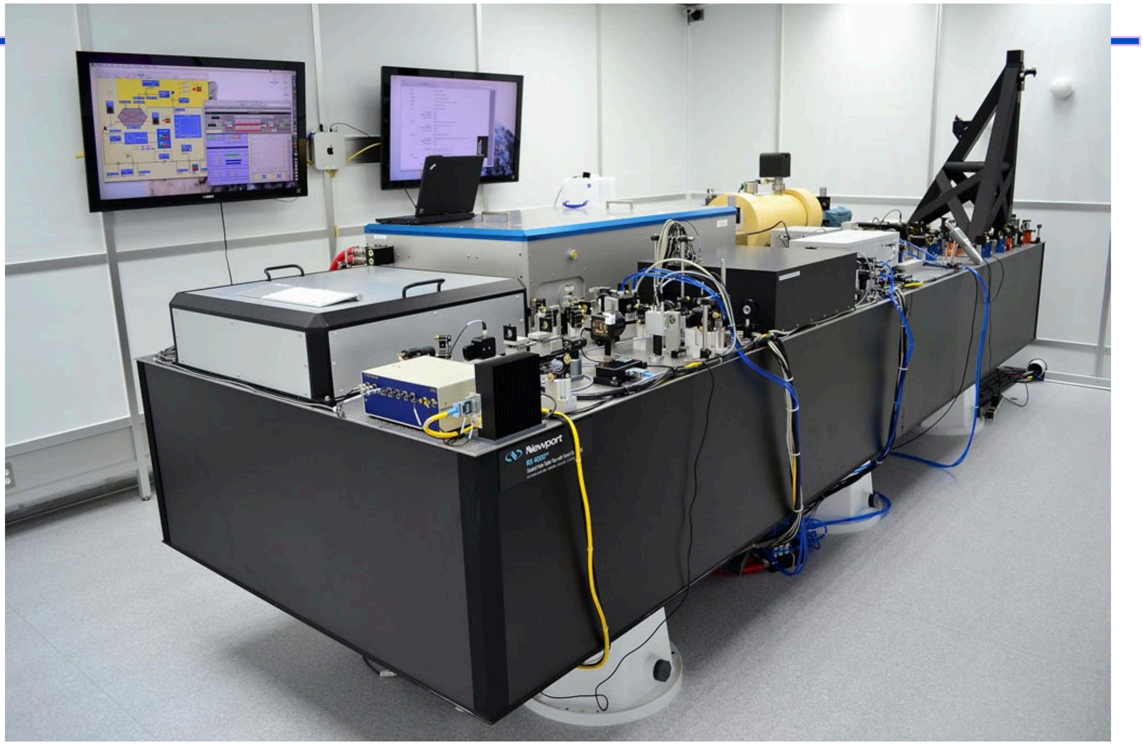
Diameter	**34 cm**
Thickness	**20 cm**
Mass	**40 kg**
$1/e^2$ Beam Size	**5.3-6.2 cm**

Harry, G. M., *et al.* CQG 27.8 (2010) 084006

200W Nd:YAG laser

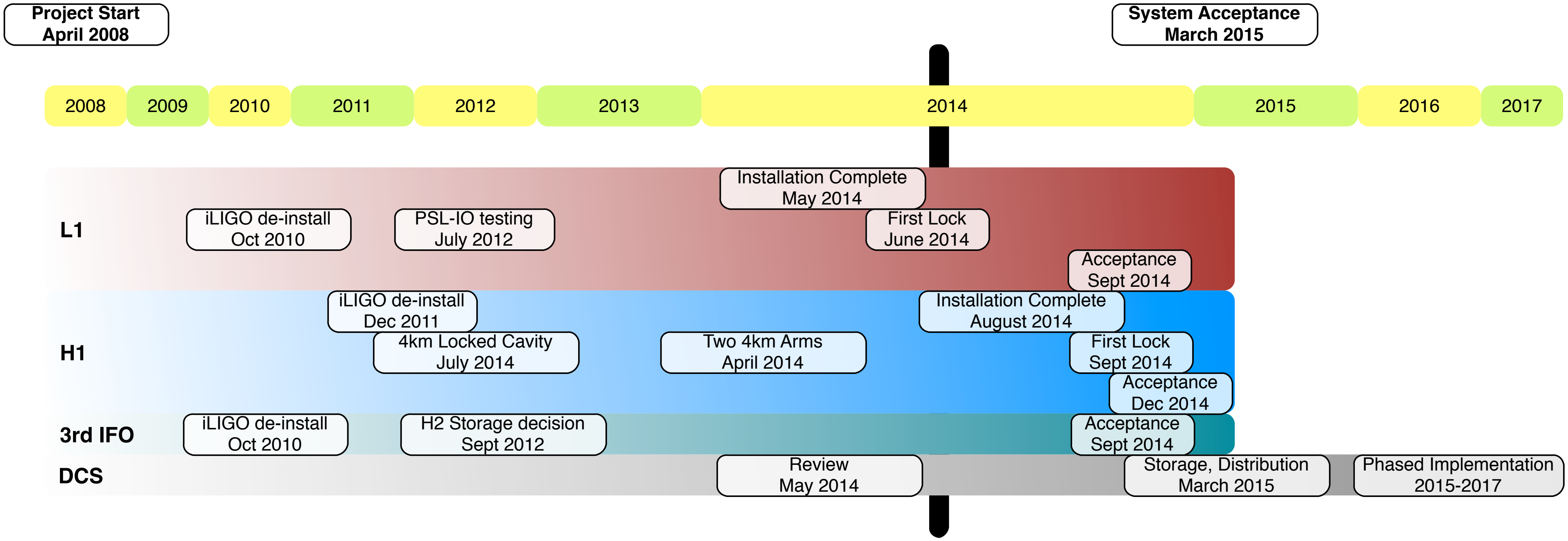
Designed and contributed by Max Planck Albert Einstein Institute





- Stabilized in power and frequency – using techniques developed for time references
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
- Delivers the required shot-noise limited fringe resolution

Project Schedule Highlights



Project Start
April 2008

System Acceptance
March 2015

2008 2009 2010 2011 2012 2013 2014 2015 2016 2017

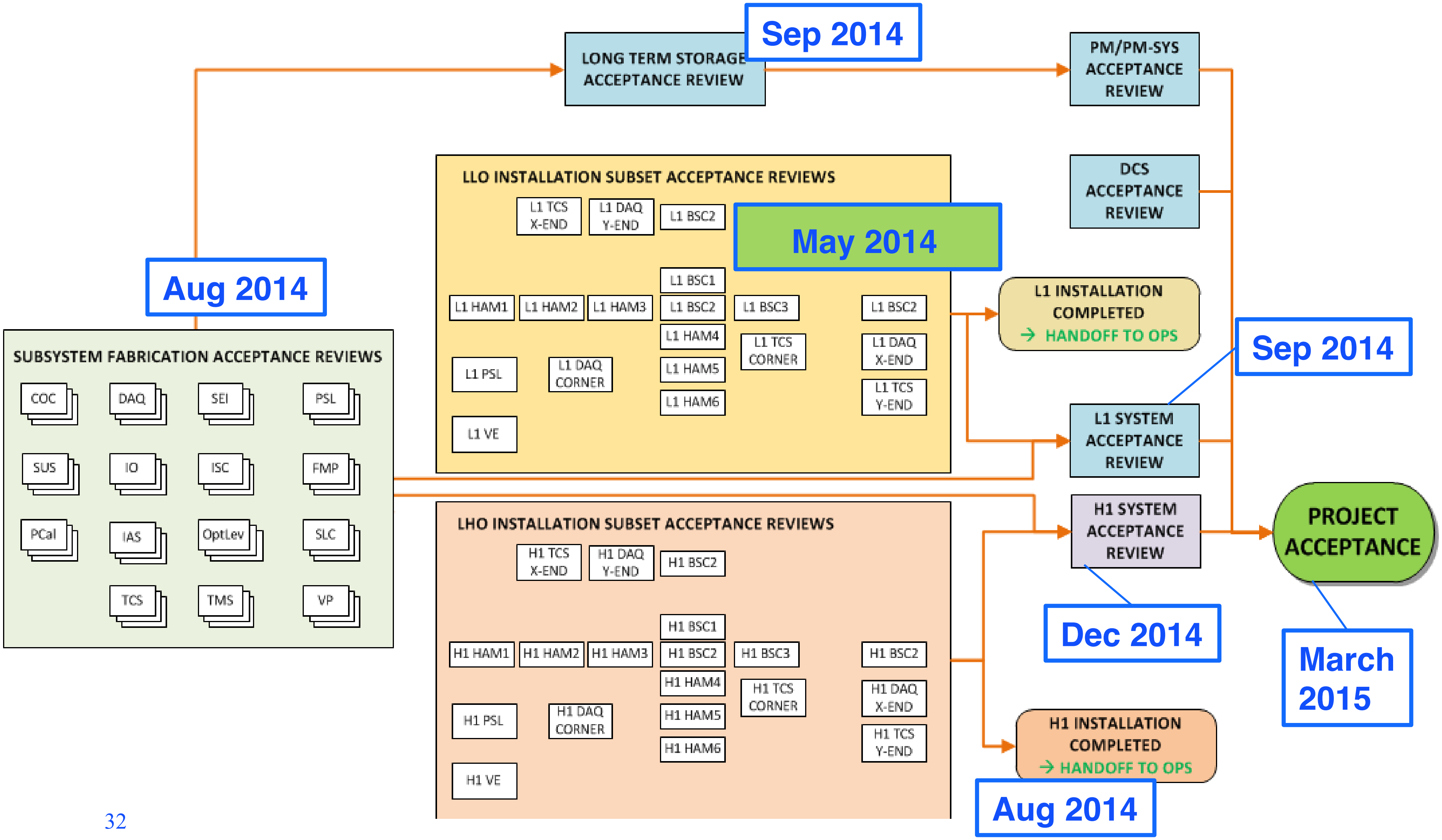
L1
- iLIGO de-install Oct 2010
- PSL-IO testing July 2012
- Installation Complete May 2014
- First Lock June 2014
- Acceptance Sept 2014

H1
- iLIGO de-install Dec 2011
- 4km Locked Cavity July 2014
- Two 4km Arms April 2014
- Installation Complete August 2014
- First Lock Sept 2014
- Acceptance Dec 2014

3rd IFO
- iLIGO de-install Oct 2010
- H2 Storage decision Sept 2012
- Acceptance Sept 2014

DCS
- Review May 2014
- Storage, Distribution March 2015
- Phased Implementation 2015-2017

Acceptance



LONG TERM STORAGE ACCEPTANCE REVIEW

Sep 2014

PM/PM-SYS ACCEPTANCE REVIEW

DCS ACCEPTANCE REVIEW

LLO INSTALLATION SUBSET ACCEPTANCE REVIEWS

L1 TCS X-END
L1 DAQ Y-END
L1 BSC2
L1 BSC1
L1 HAM1
L1 HAM2
L1 HAM3
L1 BSC2
L1 BSC3
L1 BSC2
L1 HAM4
L1 TCS CORNER
L1 DAQ X-END
L1 PSL
L1 DAQ CORNER
L1 HAM5
L1 HAM6
L1 TCS Y-END
L1 VE

May 2014

L1 INSTALLATION COMPLETED
→ HANDOFF TO OPS

Sep 2014

L1 SYSTEM ACCEPTANCE REVIEW

Aug 2014

SUBSYSTEM FABRICATION ACCEPTANCE REVIEWS

COC
DAQ
SEI
PSL
SUS
IO
ISC
FMP
PCal
IAS
OptLev
SLC
TCS
TMS
VP

H1 SYSTEM ACCEPTANCE REVIEW

PROJECT ACCEPTANCE

LHO INSTALLATION SUBSET ACCEPTANCE REVIEWS

H1 TCS X-END
H1 DAQ Y-END
H1 BSC2
H1 BSC1
H1 HAM1
H1 HAM2
H1 HAM3
H1 BSC2
H1 BSC3
H1 BSC2
H1 HAM4
H1 TCS CORNER
H1 DAQ X-END
H1 PSL
H1 DAQ CORNER
H1 HAM5
H1 HAM6
H1 TCS Y-END
H1 VE

Dec 2014

March 2015

H1 INSTALLATION COMPLETED
→ HANDOFF TO OPS

Aug 2014

Transition to operations

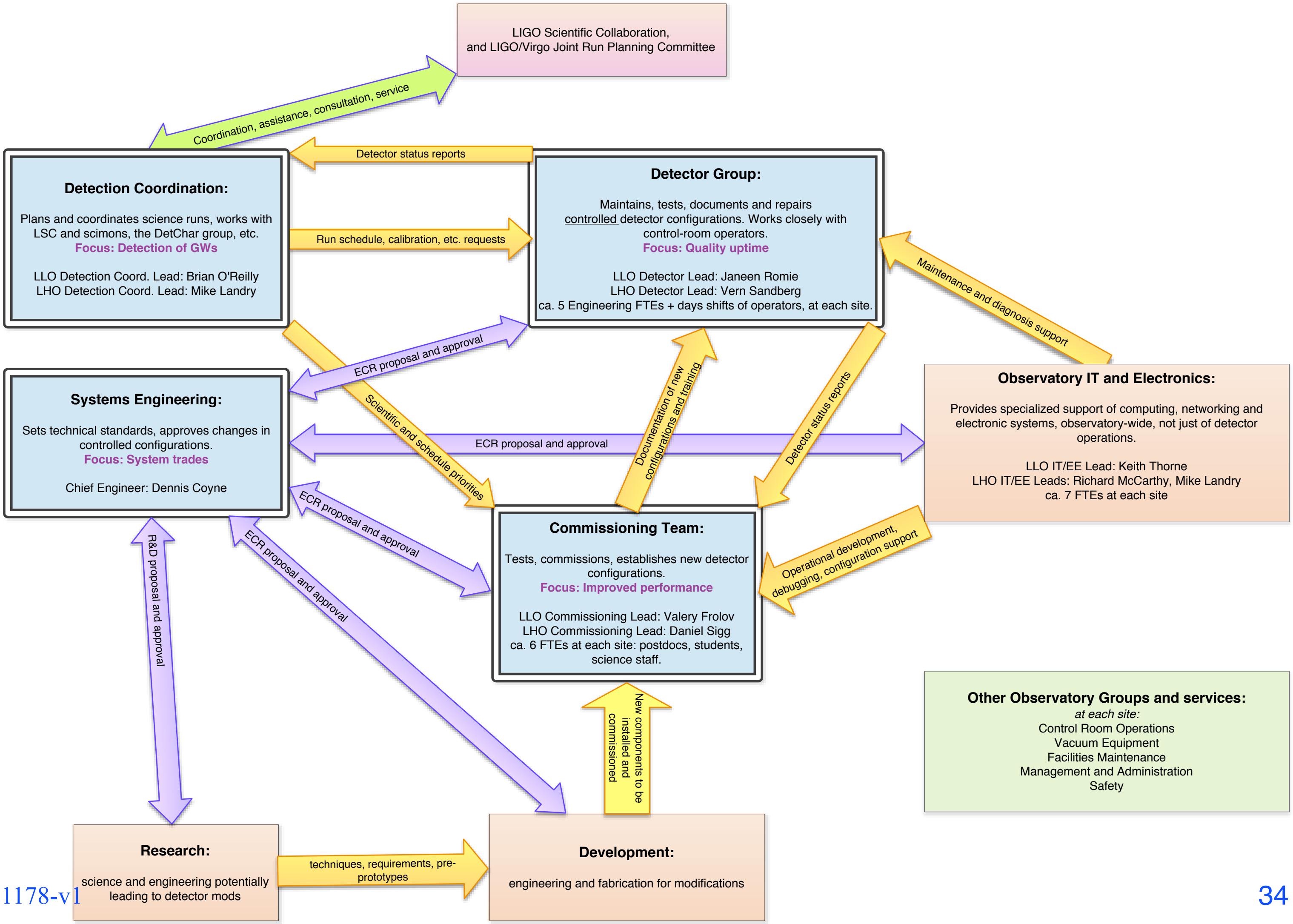
aLIGO Project:

- Subsystem installation and testing.
- Integrated testing, leading to locked whole detector, ready for Ops acceptance.
- Data computing and storage installation.
- Training and documentation.

Operations:

- Assembling of new teams and groups.
- Adapting and inventing operations and maintenance plans.
- Maintenance of detector components after installation complete.
- Commissioning detectors that are accepted.

OPS functional groups



LIGO Scientific Collaboration,
and LIGO/Virgo Joint Run Planning Committee

Detection Coordination:

Plans and coordinates science runs, works with LSC and scimons, the DetChar group, etc.
Focus: Detection of GWs

LLO Detection Coord. Lead: Brian O'Reilly
LHO Detection Coord. Lead: Mike Landry

Detector Group:

Maintains, tests, documents and repairs controlled detector configurations. Works closely with control-room operators.
Focus: Quality uptime

LLO Detector Lead: Janeen Romie
LHO Detector Lead: Vern Sandberg
ca. 5 Engineering FTEs + days shifts of operators, at each site.

Systems Engineering:

Sets technical standards, approves changes in controlled configurations.
Focus: System trades

Chief Engineer: Dennis Coyne

Observatory IT and Electronics:

Provides specialized support of computing, networking and electronic systems, observatory-wide, not just of detector operations.

LLO IT/EE Lead: Keith Thorne
LHO IT/EE Leads: Richard McCarthy, Mike Landry
ca. 7 FTEs at each site

Commissioning Team:

Tests, commissions, establishes new detector configurations.
Focus: Improved performance

LLO Commissioning Lead: Valery Frolov
LHO Commissioning Lead: Daniel Sigg
ca. 6 FTEs at each site: postdocs, students, science staff.

Other Observatory Groups and services:
at each site:
Control Room Operations
Vacuum Equipment
Facilities Maintenance
Management and Administration
Safety

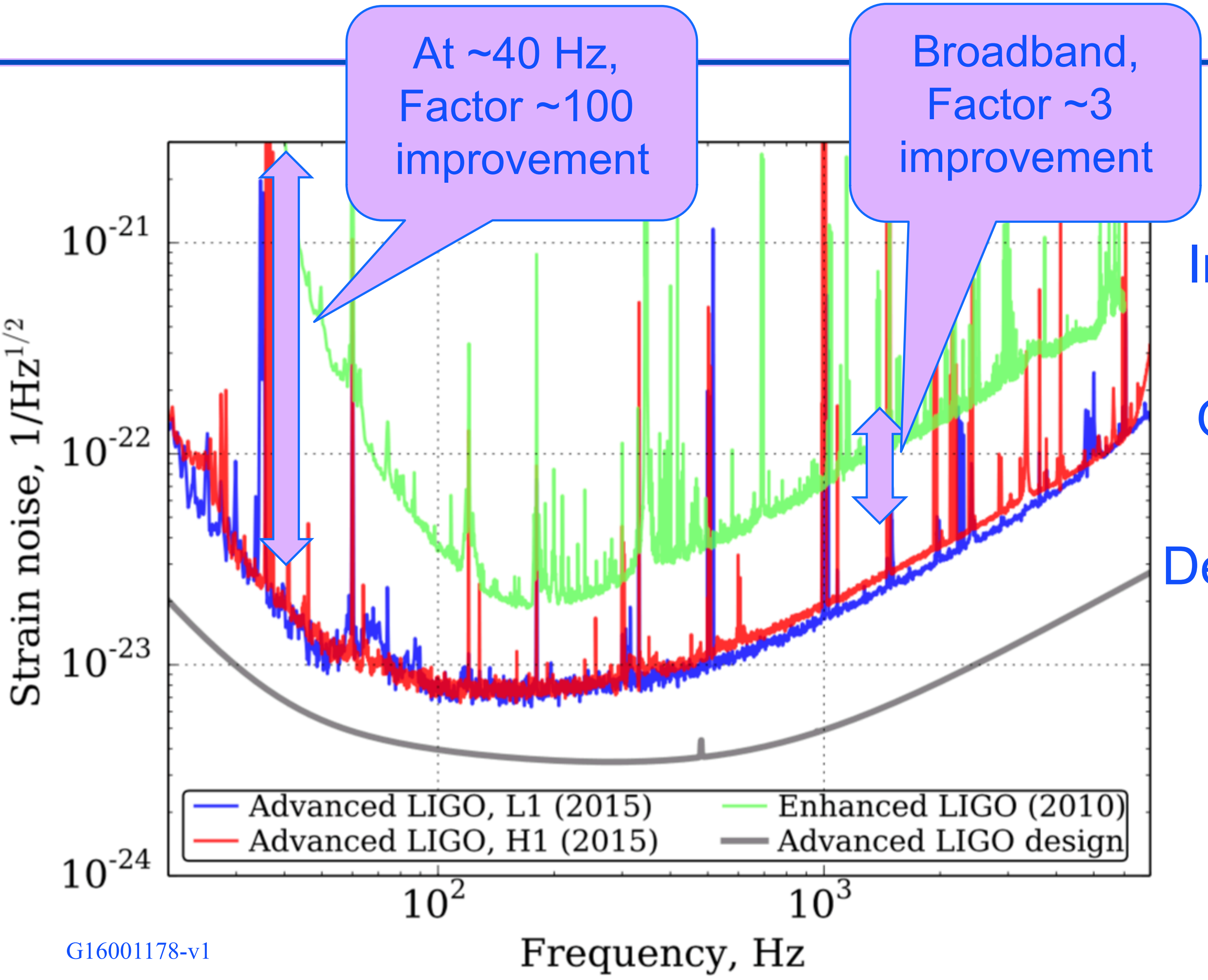
Research:

science and engineering potentially leading to detector mods

Development:

engineering and fabrication for modifications

Sensitivity for first Observing run O1



At ~40 Hz, Factor ~100 improvement

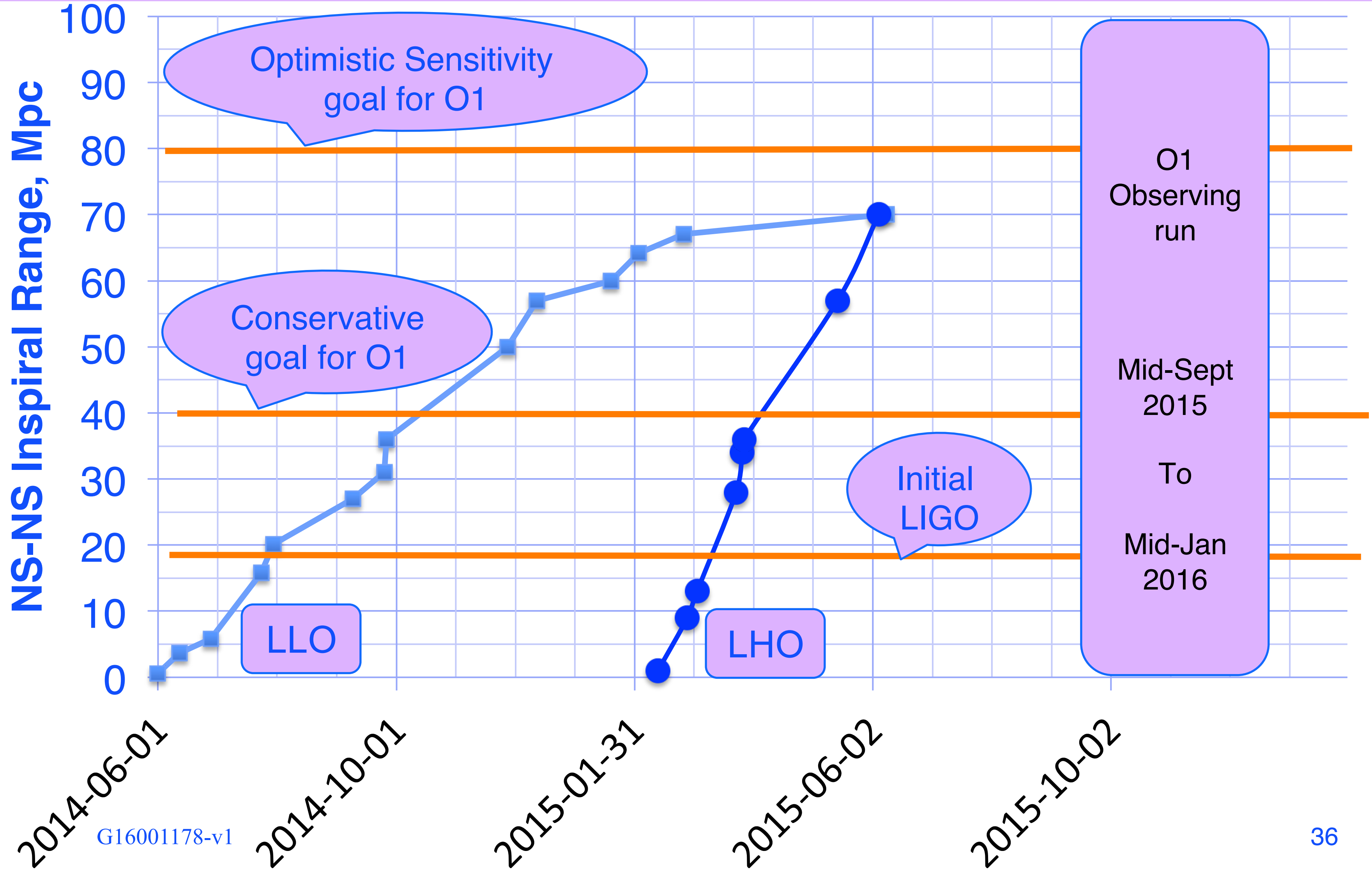
Broadband, Factor ~3 improvement

Initial LIGO

O1 aLIGO

Design aLIGO

Sensitivity Commissioning of aLIGO after completion of installation

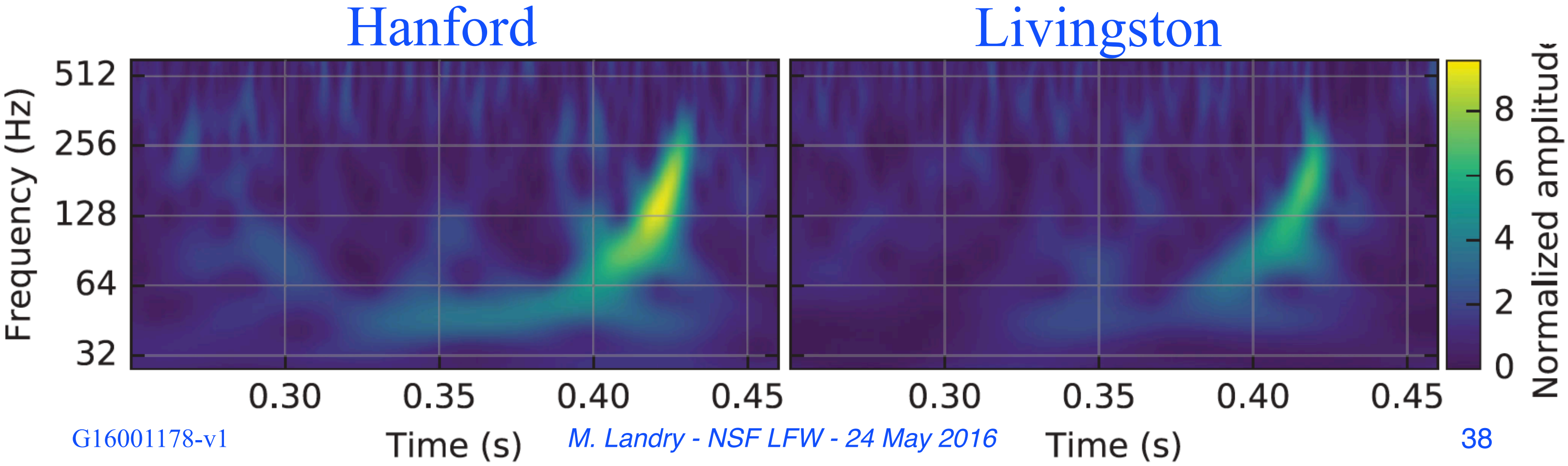


GW150914

- Early morning of Sep 14, at each LIGO site, only an operator and a couple of scientists are present
- Scientists and grad students make final electronic logs and leave site

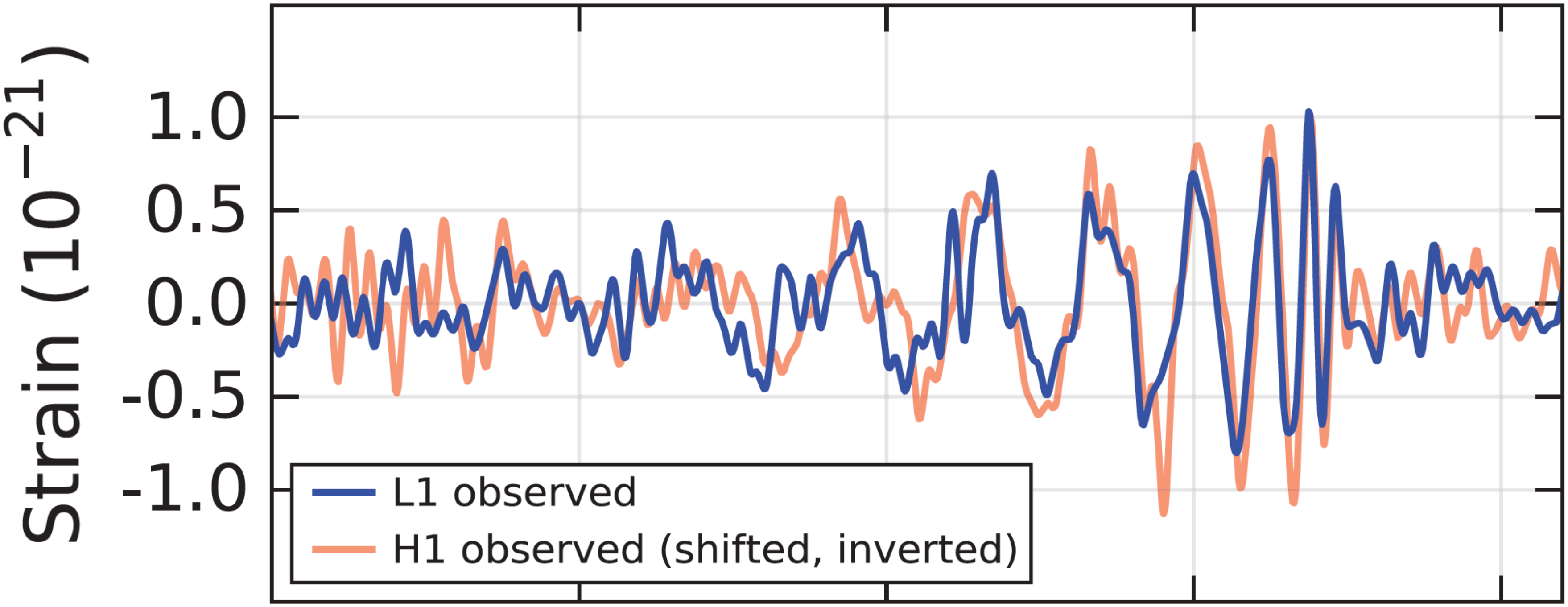
GW150914

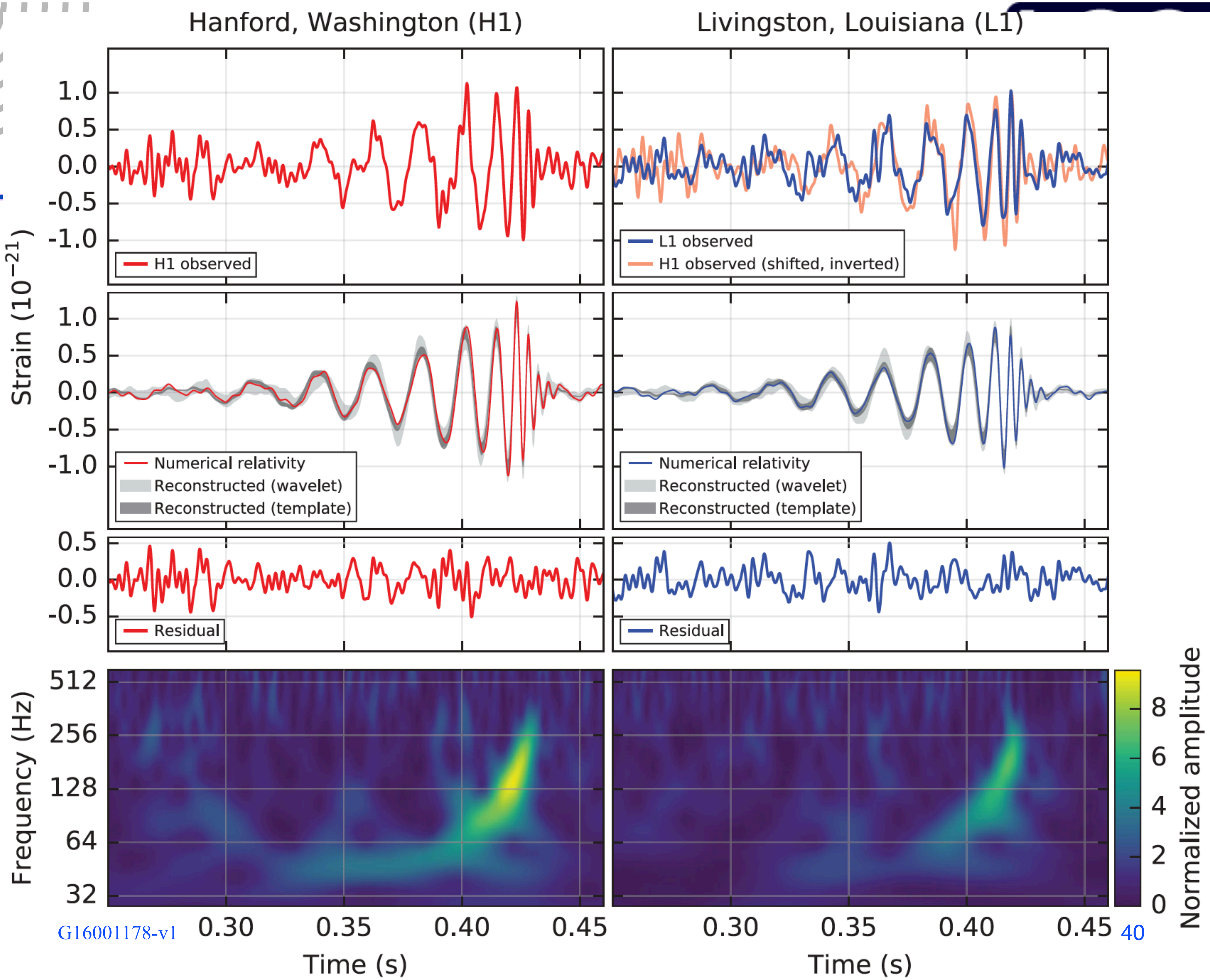
- Early morning of Sep 14, at each LIGO site, only an operator and a couple of scientists are present
- Scientists and grad students make final electronic logs and leave site
- GW150914 passes through Livingston site at 09:50:45 UTC, and 6.9ms later, through the Hanford site (02:50:45 Pacific time)
- Within 3 minutes it is detected by online search codes

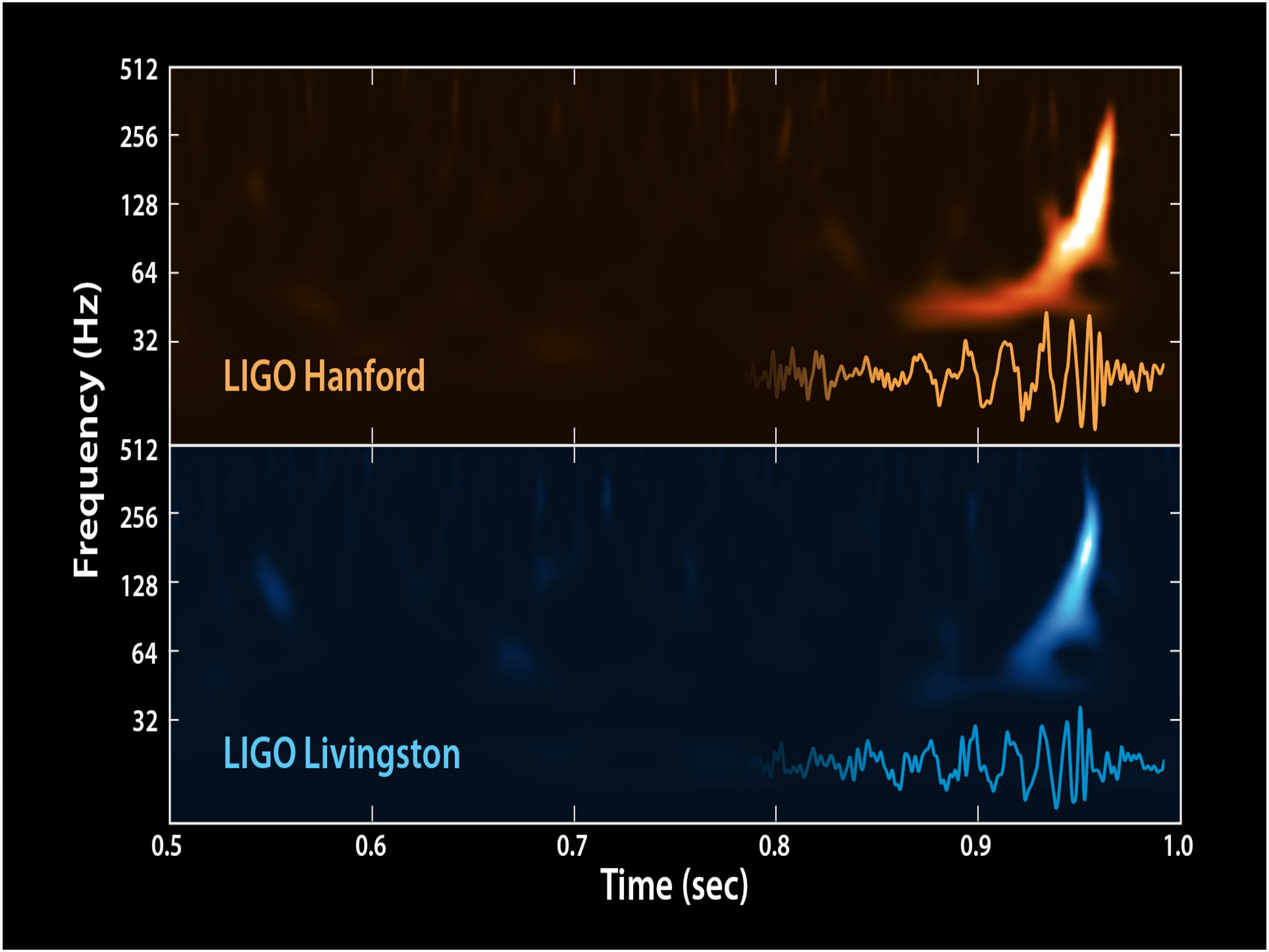


Time series

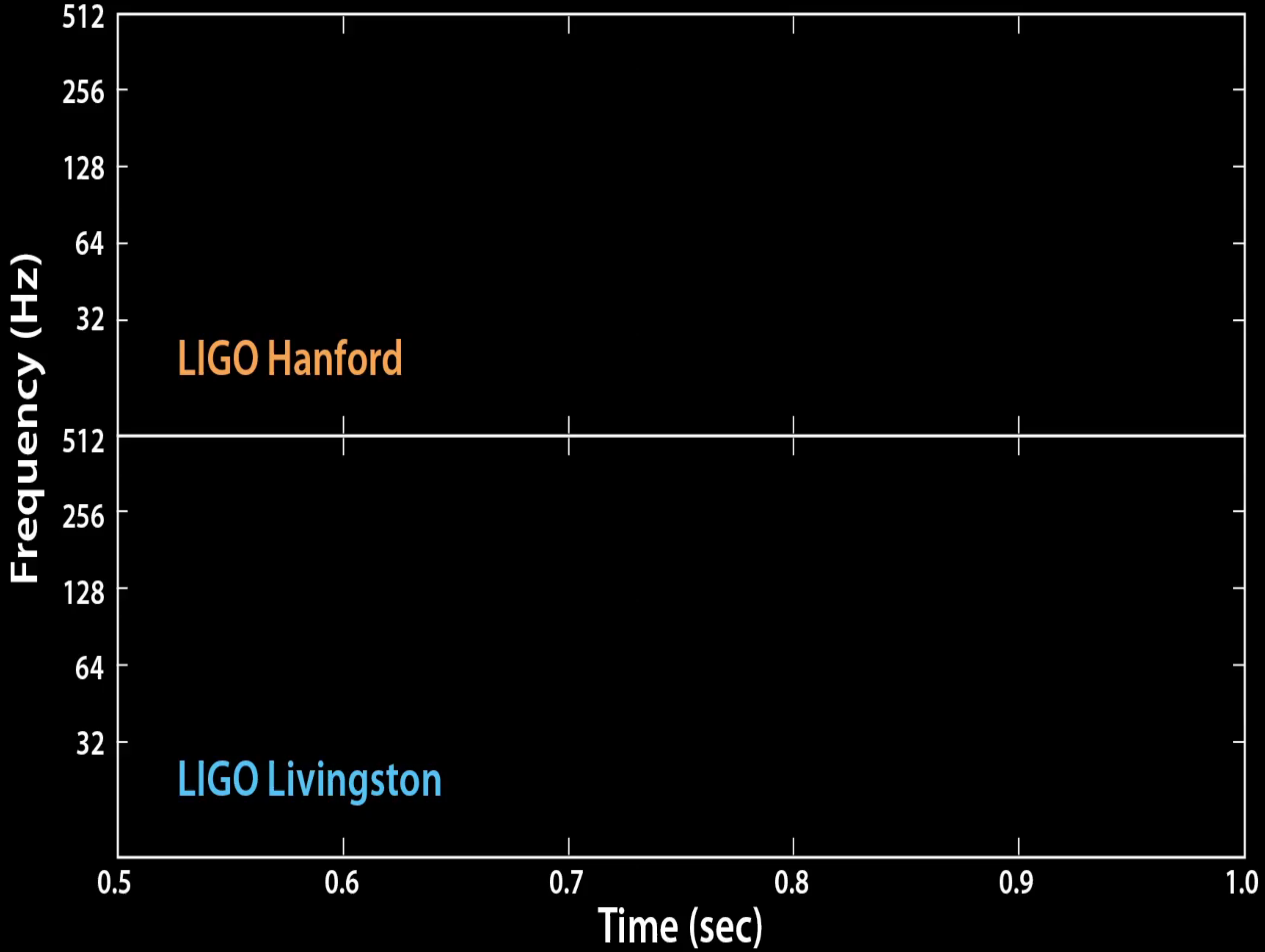
- Within ~15m, postdocs at AEI see the trigger in our GW database, suspect it is either a signal or an injection
- By 9am Pacific we know it is not a blind injection: we freeze the sites for a month, poll the sites, begin accumulating background data…




Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

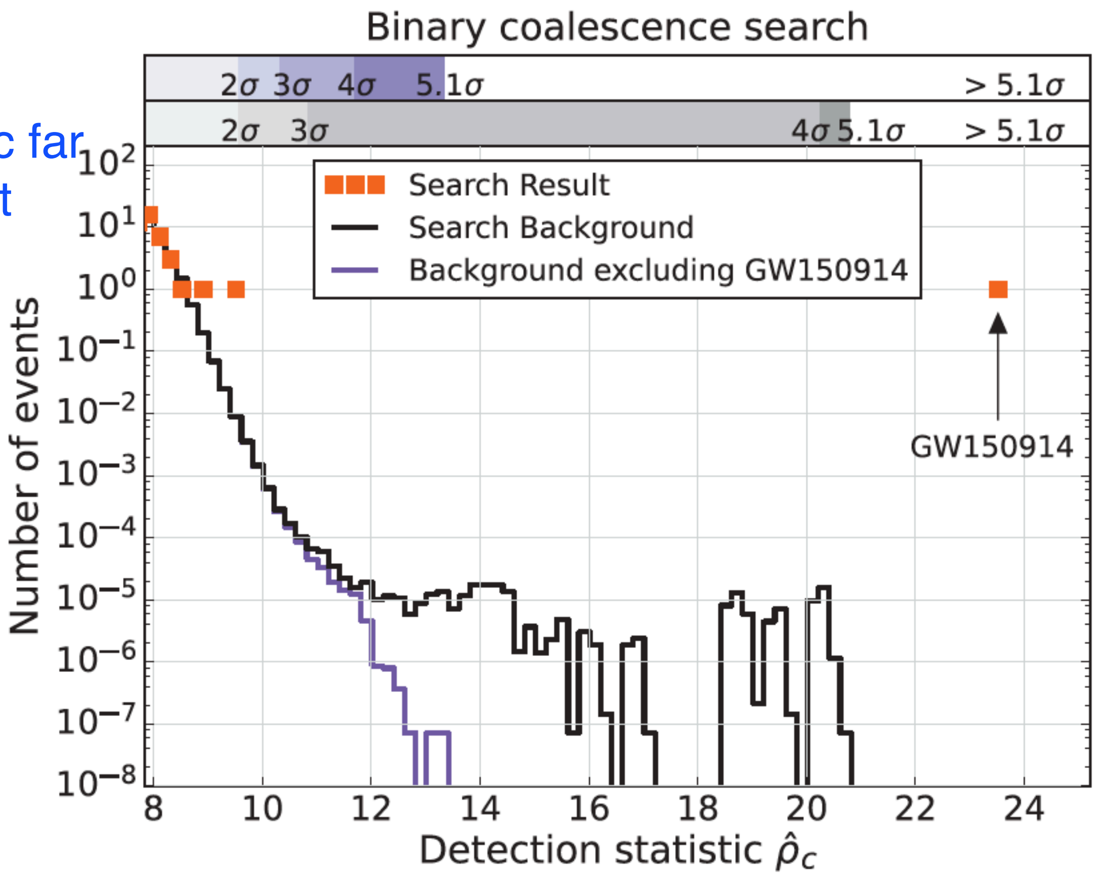


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

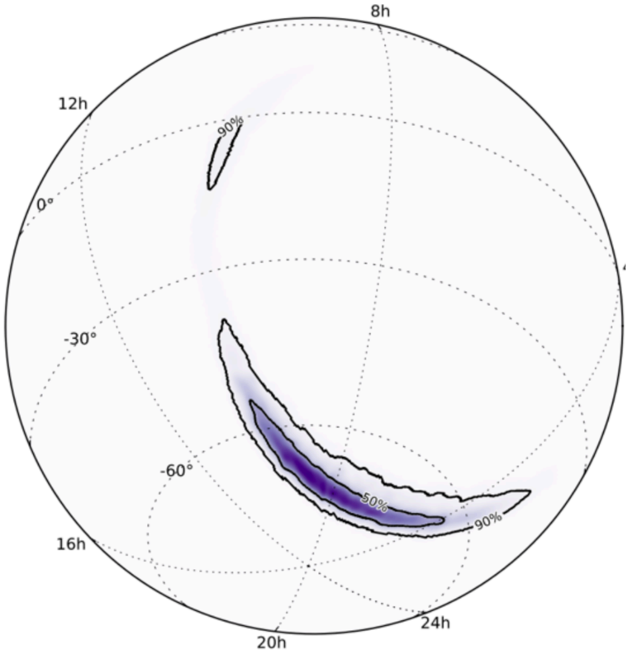
Detection confidence

- First seen with a ‘burst’ on-line detection system, but best statistical confidence measure obtained with a template search based on GR, and numerical solutions
- ‘Off-source’ background built up using non-physical time slides (>10 msec)
- Equivalent of 600,000 years of background used
- GW150914 had detection statistic far larger than any background event
- False Alarm rate <1/203,000 years, corresponding to 5.1σ.
- A very large SNR in quiet data.



Source characteristics

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



- 3 $M_\odot$ radiated in GWs;
  36 + 29 = 62....+3
- Degeneracy in position and distance (only 2 detectors… need Virgo!)
  - In the Southern Hemisphere, an annulus with some preference in angle
- Alerted EM partners, a group of over 60 telescope collaborations for follow-up
- Can determine a rich set of conclusions due to
  - ‘time trace’ of amplitude of strain,
  - Absolute calibration of the instrument in strain, and
  - Excellent match to GR

The New York Times

New England Edition

Today, sunshine mixing with some clouds, cold, high 26. **Tonight,** cloudy, a flurry or heavier squall late, low 17. **Tomorrow,** windy, frigid, high 18. Weather map, Page A18.

. 57,140 © 2016 The New York Times FRIDAY, FEBRUARY 12, 2016 $2.50

CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most fore-

Long in Clinton's Corner, Blacks Notice Sanders

Courted Hard in South Carolina, Loyalists

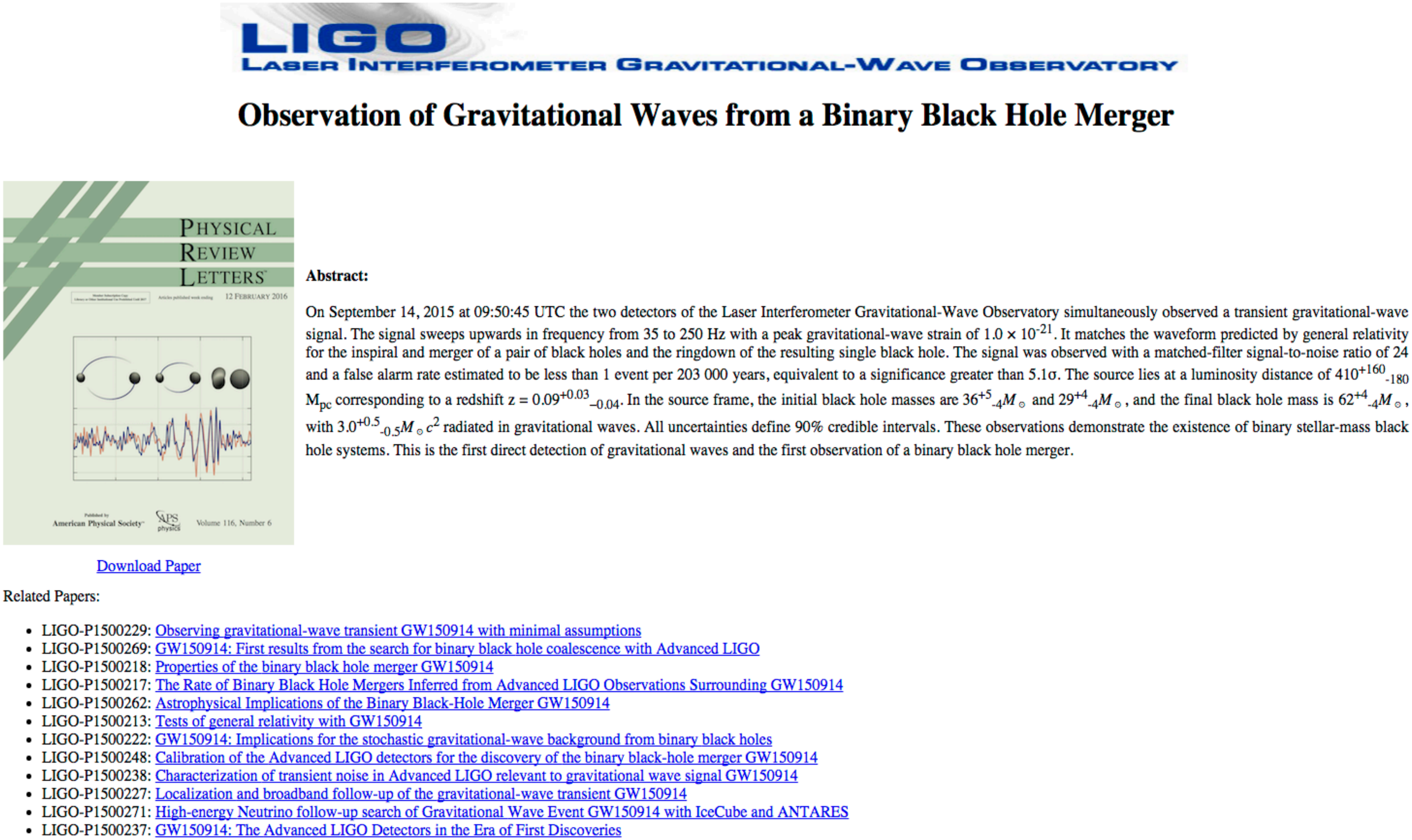
By RICHARD FAUSSET

ORANGEBURG, S.C. — When Helen Duley was asked whom

candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an un-

Last Occupier Is Coaxed From Oregon Refuge

More info: papers.ligo.org



Observation of Gravitational Waves from a Binary Black Hole Merger

Download Paper

Abstract:

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} M_{pc} corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

Related Papers:

- LIGO-P1500229: Observing gravitational-wave transient GW150914 with minimal assumptions
- LIGO-P1500269: GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
- LIGO-P1500218: Properties of the binary black hole merger GW150914
- LIGO-P1500217: The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
- LIGO-P1500262: Astrophysical Implications of the Binary Black-Hole Merger GW150914
- LIGO-P1500213: Tests of general relativity with GW150914
- LIGO-P1500222: GW150914: Implications for the stochastic gravitational-wave background from binary black holes
- LIGO-P1500248: Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
- LIGO-P1500238: Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
- LIGO-P1500227: Localization and broadband follow-up of the gravitational-wave transient GW150914
- LIGO-P1500271: High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
- LIGO-P1500237: GW150914: The Advanced LIGO Detectors in the Era of First Discoveries

Analyses in companion papers

- Effects due to GR-violations in GW150914 are limited to less than 4% (see the Tests of GR paper)
- Electromagnetic followup made by astronomy partners (see Localization & Follow-up paper)
- Expected rate of BBH mergers (see the Rates paper)
  - 2-400 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- Limit on the mass of the graviton (Testing GR):

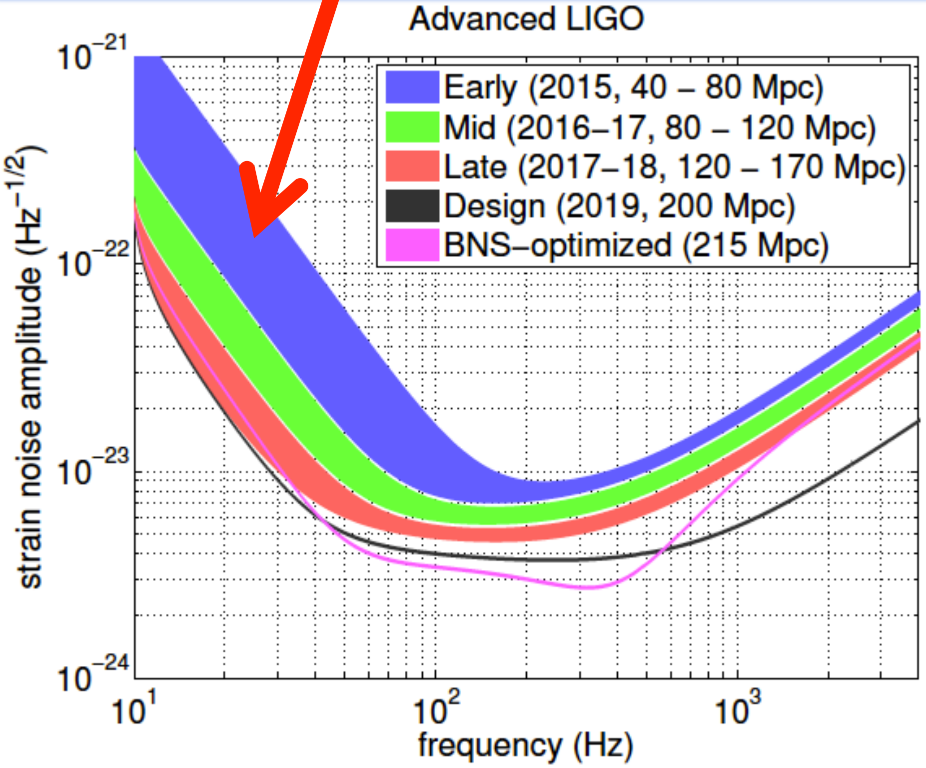
$$m_g \leq 1.2 \times 10^{-22} \text{ eV/c}^2 \text{ at } 90\% \text{ confidence}$$

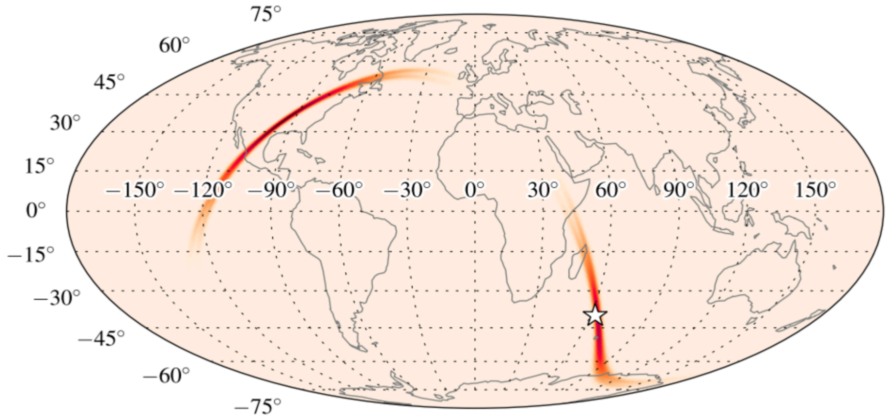
- GW150914 demonstrates heavy stellar mass black holes can form in binaries and merge within a Hubble time; requires weak massive-star winds, possible in low metalicity environments (see the Astrophysical implications paper)

LIGO Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670

Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	$E_{\rm GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) Virgo	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within $5\,\mathrm{deg}^2$	% BNS Localized within $20\,\mathrm{deg}^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48



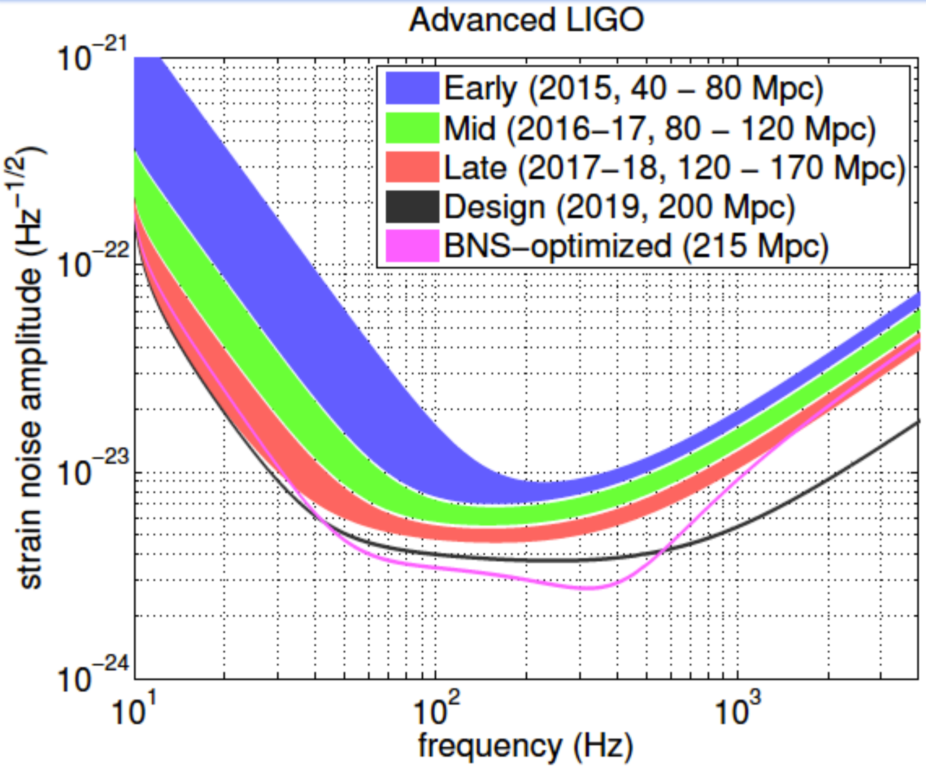


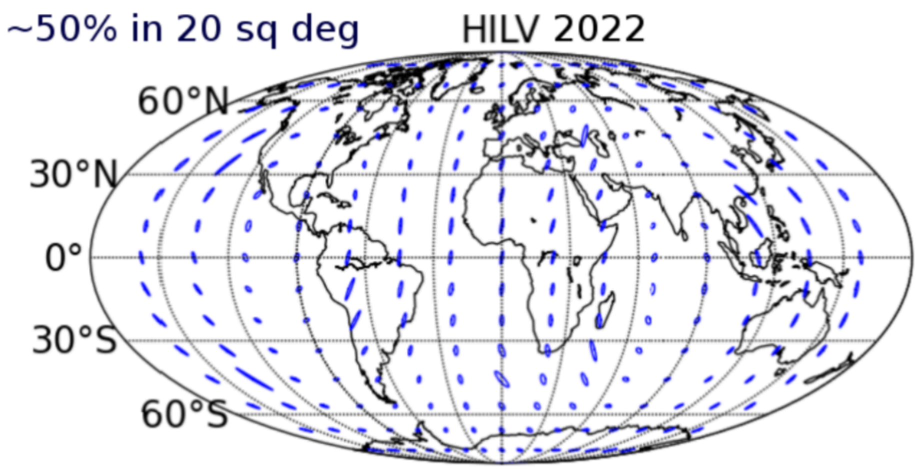
Localization of source,
Hanford and Livingston LIGO detectors,
First science run at end 2015

Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670

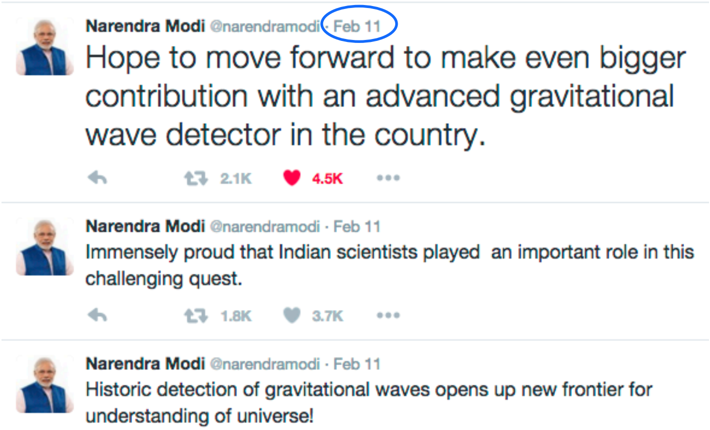
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48





Localization of source,
Hanford, Livingston, Virgo, India detectors,
Observing 2022

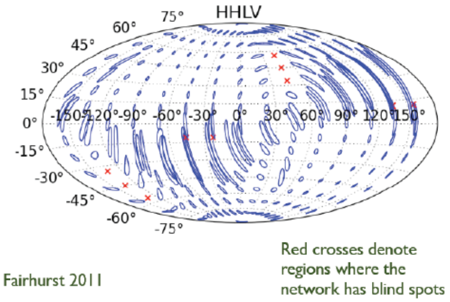
LIGO India is a GO,
after several years of delay



Narendra Modi @narendramodi · Feb 11
Hope to move forward to make even bigger contribution with an advanced gravitational wave detector in the country.

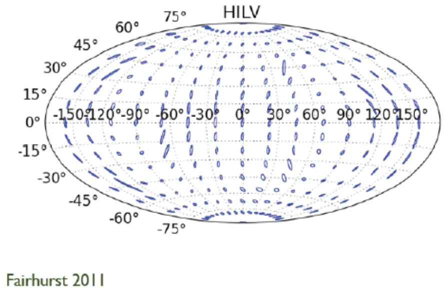
Narendra Modi @narendramodi · Feb 11
Immensely proud that Indian scientists played an important role in this challenging quest.

Narendra Modi @narendramodi · Feb 11
Historic detection of gravitational waves opens up new frontier for understanding of universe!



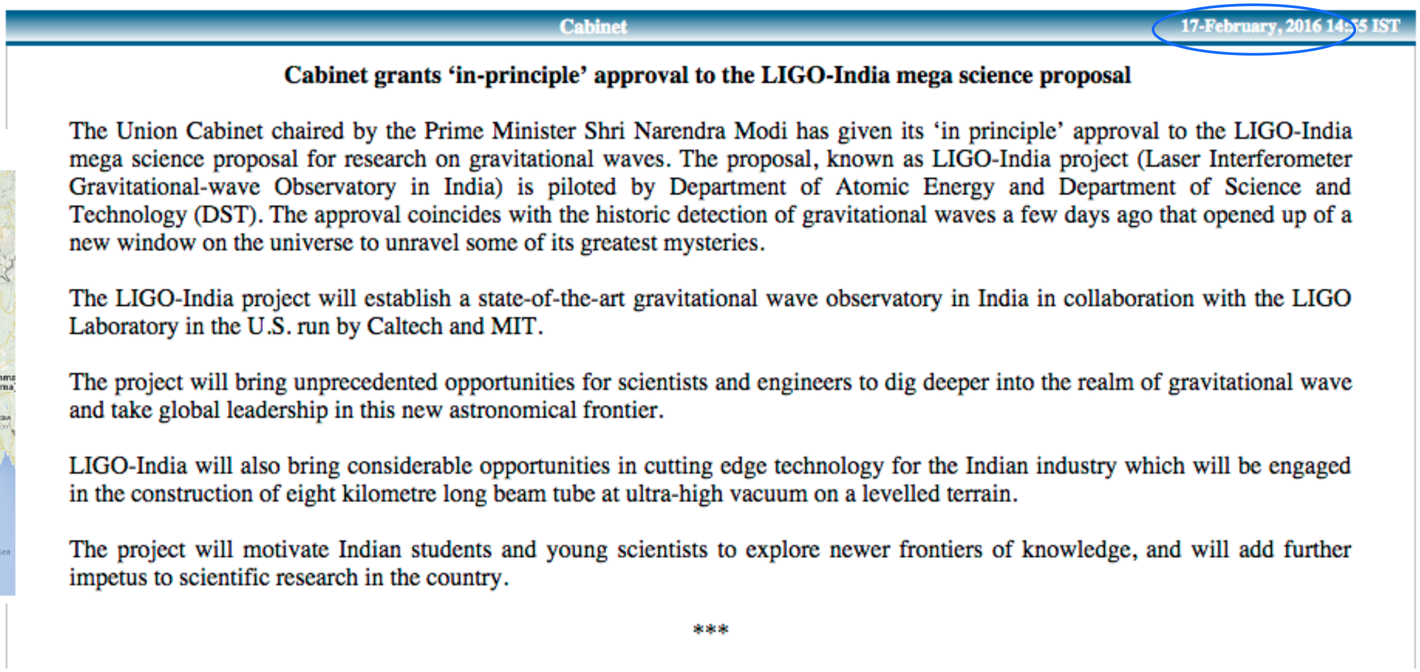
Fairhurst 2011

LIGO+Virgo only



Fairhurst 2011

With LIGO-India



Cabinet 17-February, 2016 14:55 IST

Cabinet grants 'in-principle' approval to the LIGO-India mega science proposal

The Union Cabinet chaired by the Prime Minister Shri Narendra Modi has given its 'in principle' approval to the LIGO-India mega science proposal for research on gravitational waves. The proposal, known as LIGO-India project (Laser Interferometer Gravitational-wave Observatory in India) is piloted by Department of Atomic Energy and Department of Science and Technology (DST). The approval coincides with the historic detection of gravitational waves a few days ago that opened up of a new window on the universe to unravel some of its greatest mysteries.

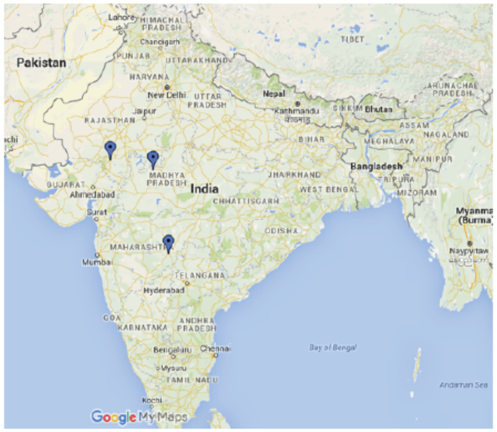
The LIGO-India project will establish a state-of-the-art gravitational wave observatory in India in collaboration with the LIGO Laboratory in the U.S. run by Caltech and MIT.

The project will bring unprecedented opportunities for scientists and engineers to dig deeper into the realm of gravitational wave and take global leadership in this new astronomical frontier.

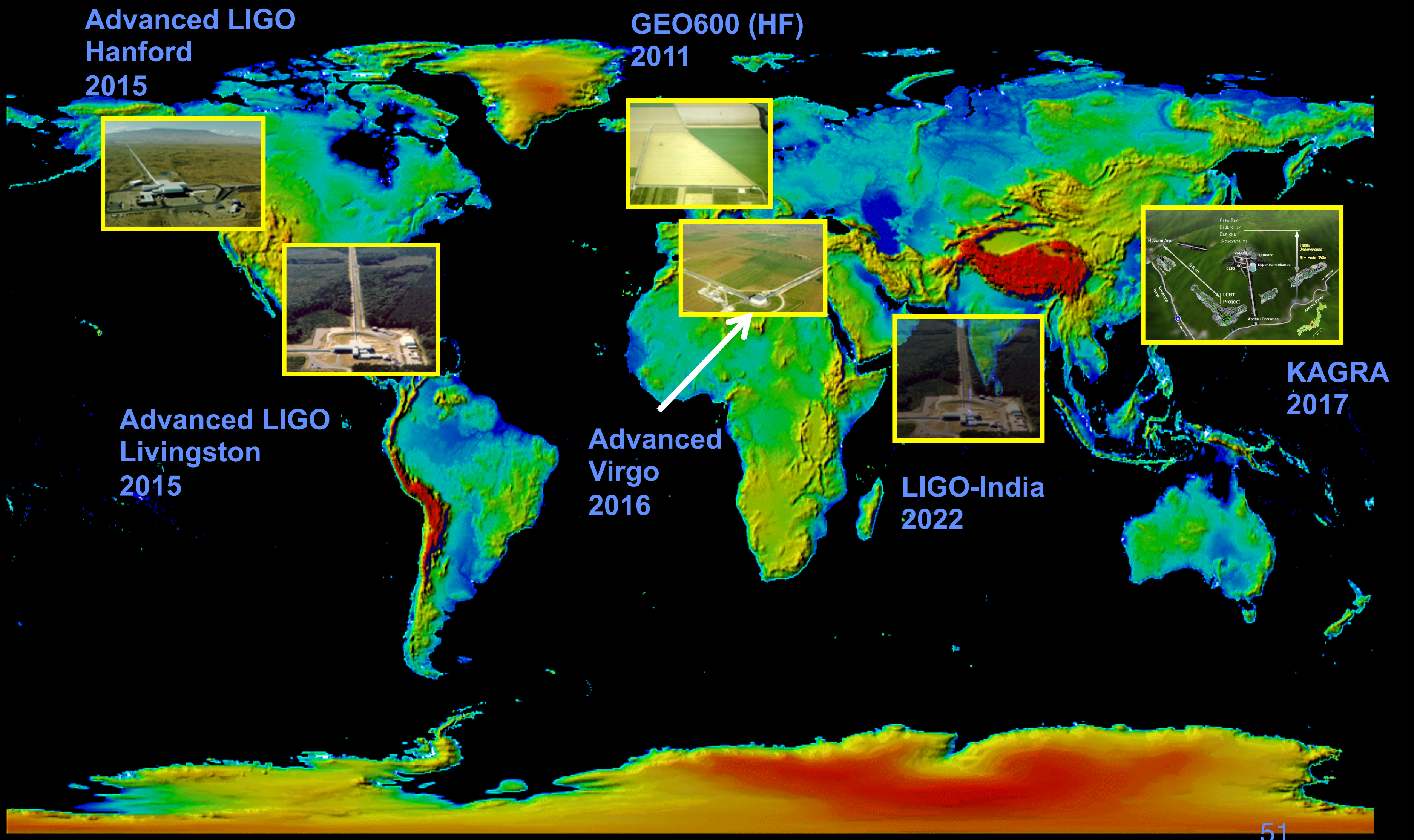
LIGO-India will also bring considerable opportunities in cutting edge technology for the Indian industry which will be engaged in the construction of eight kilometre long beam tube at ultra-high vacuum on a levelled terrain.

The project will motivate Indian students and young scientists to explore newer frontiers of knowledge, and will add further impetus to scientific research in the country.

***



The advanced GW detector network: 2015-2025



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

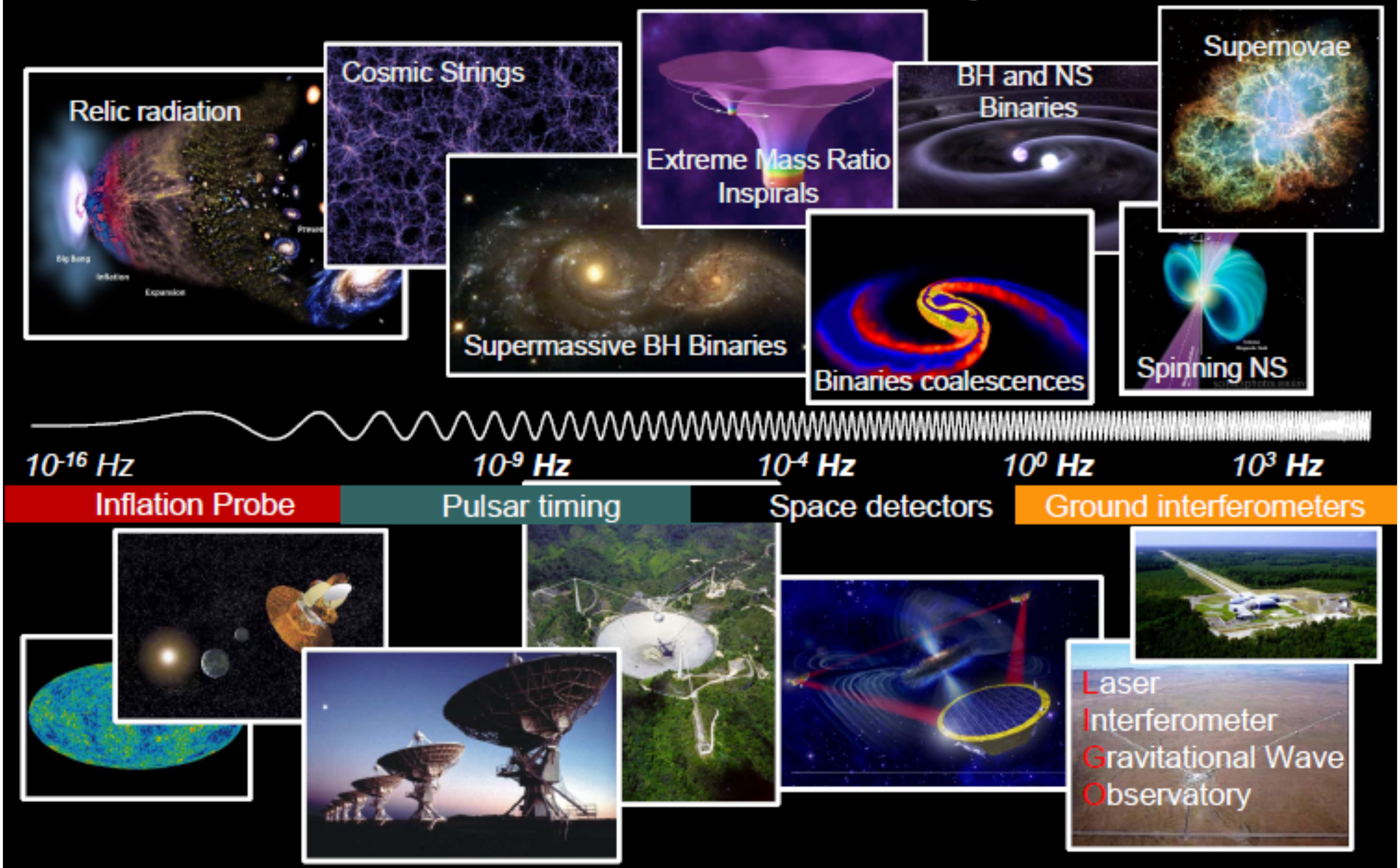
KAGRA
2017

Advanced LIGO
Livingston
2015

Advanced
Virgo
2016

LIGO-India
2022

The Gravitational Wave Spectrum



LIGO

LIGO Scientific Collaboration

LSC

TRINITY UNIVERSITY

UNIVERSITY OF MARYLAND

Andrews University

WASHINGTON STATE UNIVERSITY

CALIFORNIA STATE UNIVERSITY FULLERTON

indigo

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

SEAL OF TEXAS TECH UNIVERSITY

R·I·T

ICTP SAIFR

MONTANA STATE UNIVERSITY

SONOMA STATE UNIVERSITY

AMERICAN UNIVERSITY WASHINGTON, DC

UNIVERSITY OF THE WEST of SCOTLAND UWS

MONTCLAIR STATE UNIVERSITY

清華大學 Tsinghua University

WHITMAN COLLEGE

LSU

UNIVERSITY OF STRATHCLYDE

MICHIGAN

CITA–ICAT

UNIVERSITY of GLASGOW

1754

NASA GODDARD SPACE FLIGHT CENTER

LELAND STANFORD JUNIOR UNIVERSITY

THE UNIVERSITY OF WESTERN AUSTRALIA

ПАН

ACU

UNIVERSITAS SCIENTIARUM SZEGEDIENSIS

CALIFORNIA INSTITUTE OF TECHNOLOGY

UNIVERSITY OF MINNESOTA

The University of Mississippi

UTB TSC

UNIVERSITY OF CAMBRIDGE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SOUTHERN UNIVERSITY Agricultural & Mechanical College

THE UNIVERSITY OF ADELAIDE AUSTRALIA

THE UNIVERSITY OF MELBOURNE

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA

UNIVERSITY OF WASHINGTON

NORTHWESTERN UNIVERSITY

GEO 600

CARDIFF UNIVERSITY

Universitat de les Illes Balears

COLL: CARLETON

Georgia Tech

SYRACUSE UNIVERSITY

CHARLES STURT UNIVERSITY

UNIVERSITY of WISCONSIN UWMILWAUKEE

UNIVERSITAT HAMBURG

TSINGHUA UNIVERSITY

ACIGA

University of Southampton

Korean Gravitational-Wave Group

PENNSTATE 1855

HOBART COLLEGE

WILLIAM SMITH COLLEGE

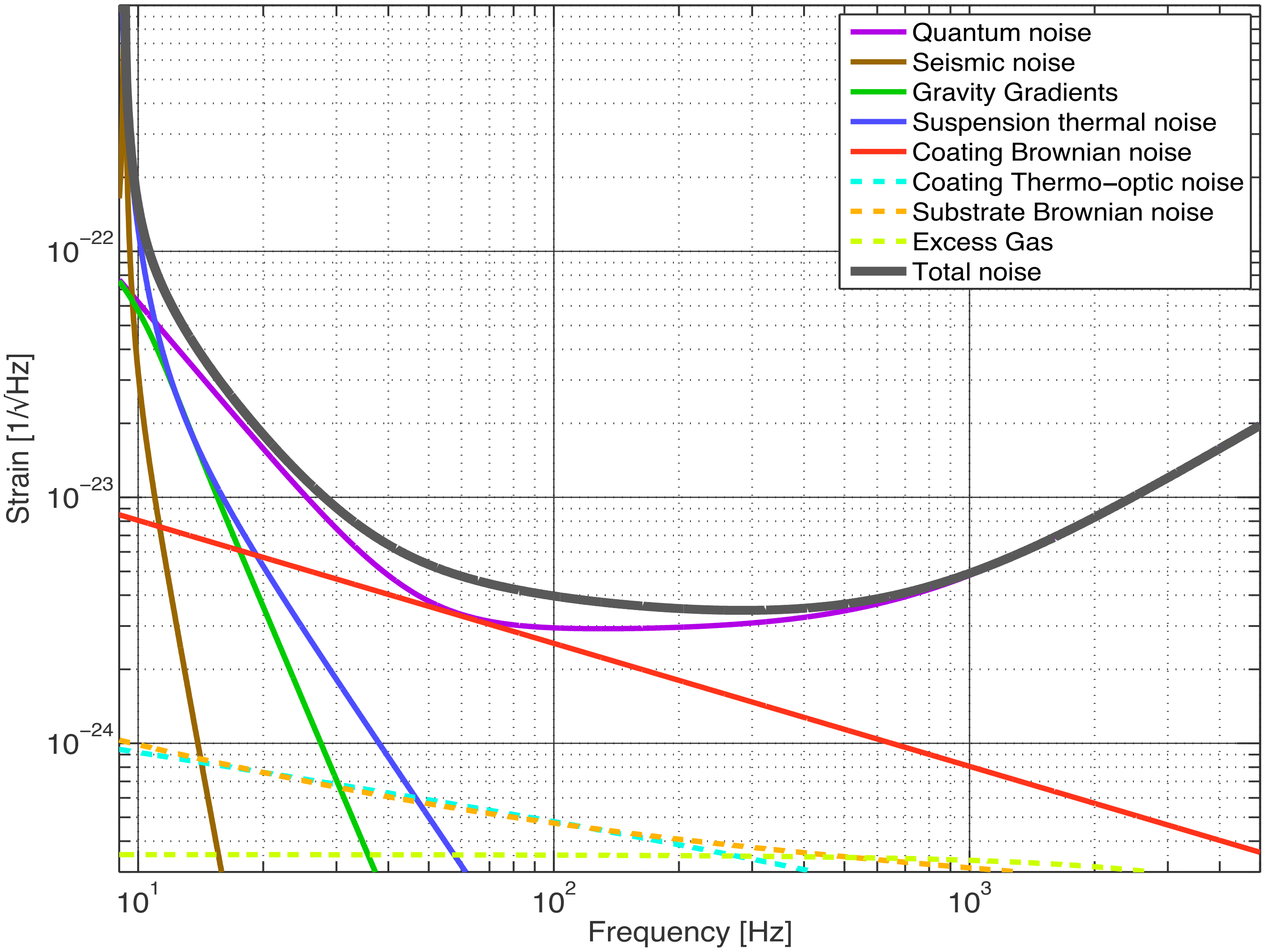
UNIVERSITY OF ROCHESTER

Leibniz Universität Hannover

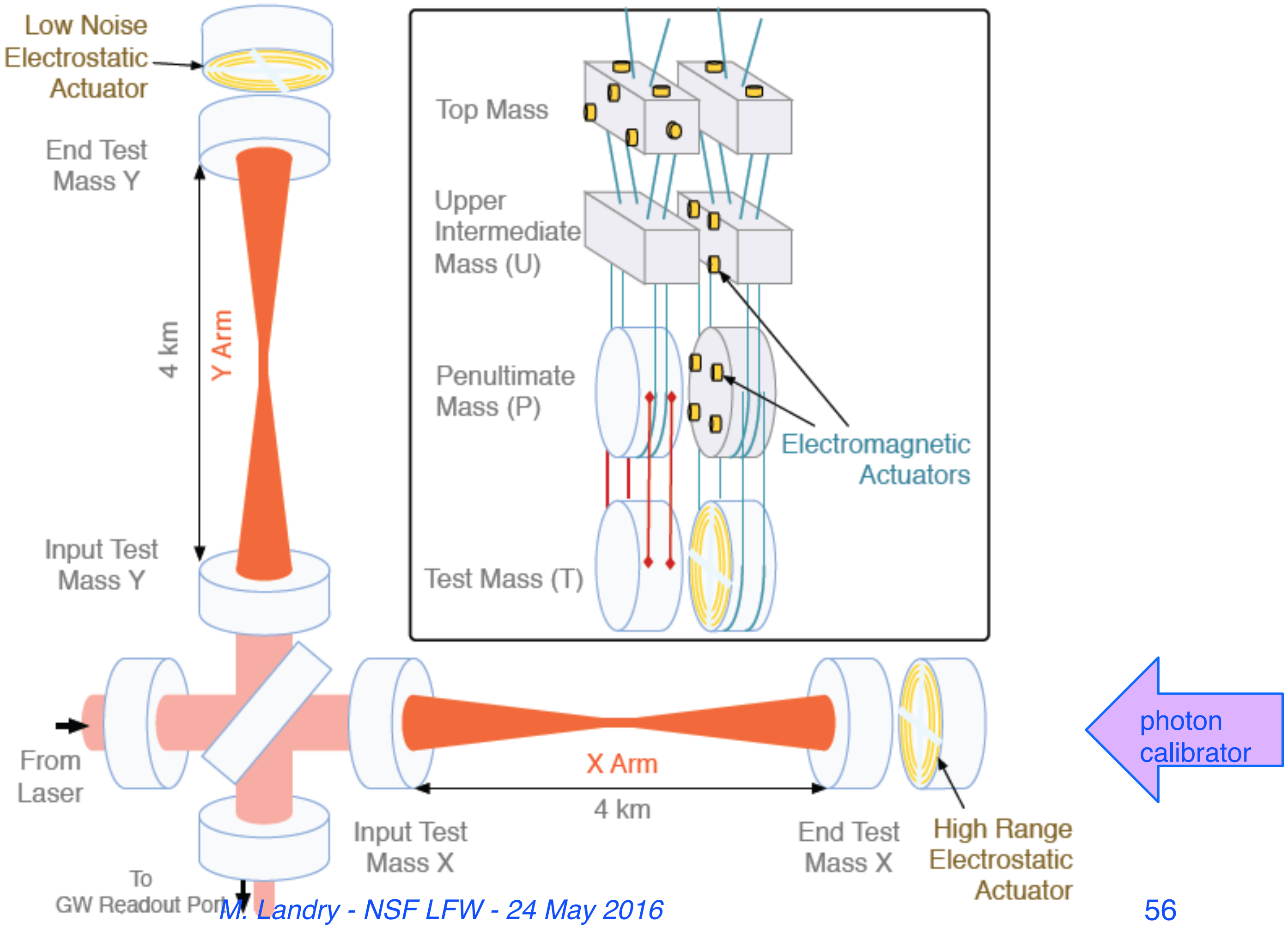
Science & Technology Facilities Council Rutherford Appleton Laboratory

Extra slides

Principal noise terms



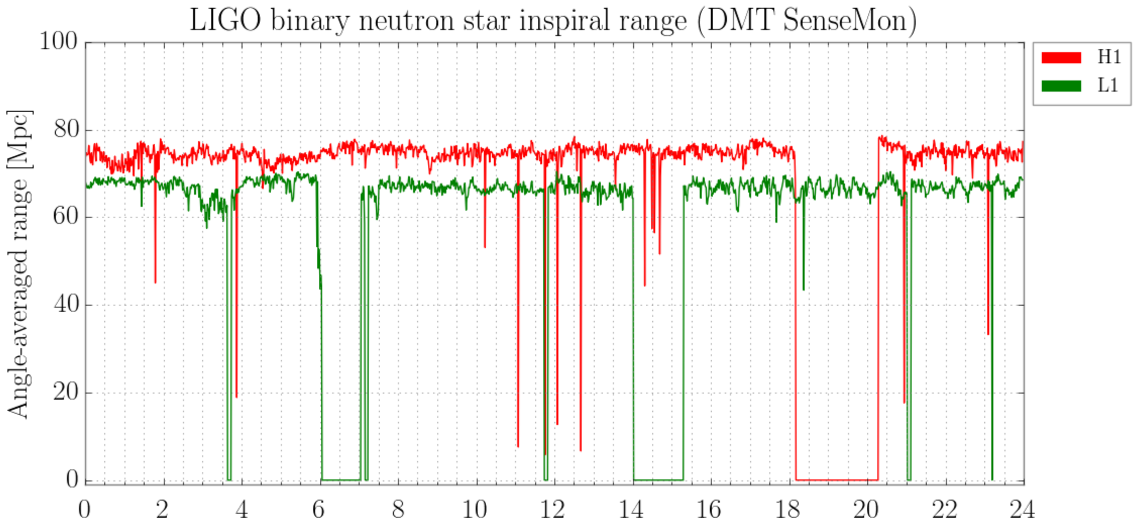
End mirror (“test mass”) quadruple-pendulum suspensions

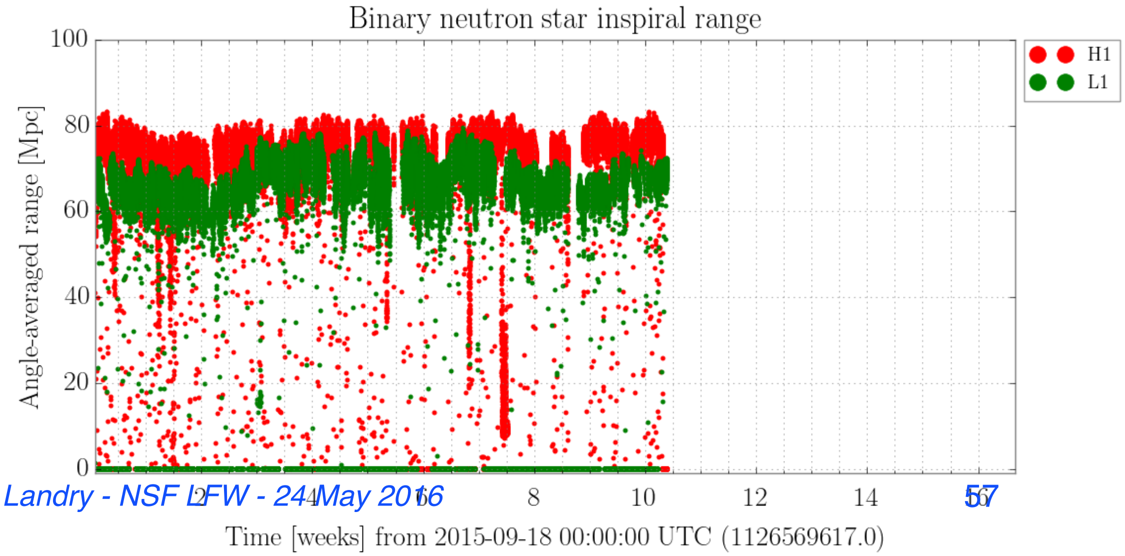


https://dcc.ligo.org/LIGO-P1500248/public/main

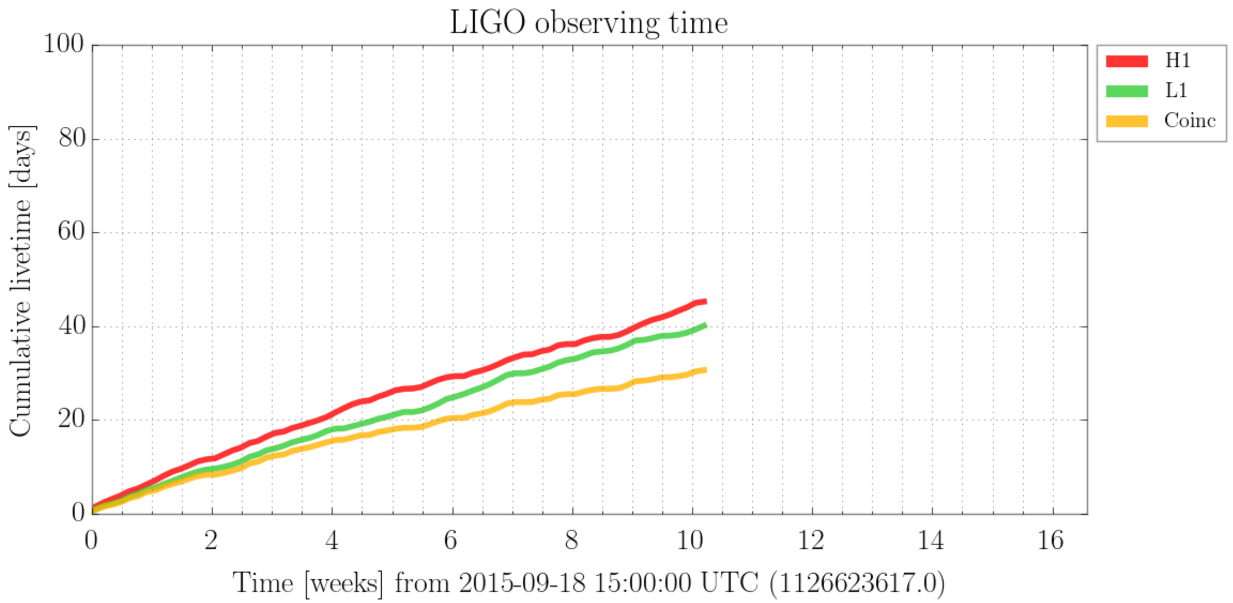
LIGO range

LIGO range into space for binary neutron star coalescence (Mpc)


LIGO binary neutron star inspiral range (DMT SenseMon)


Binary neutron star inspiral range

LIGO up time



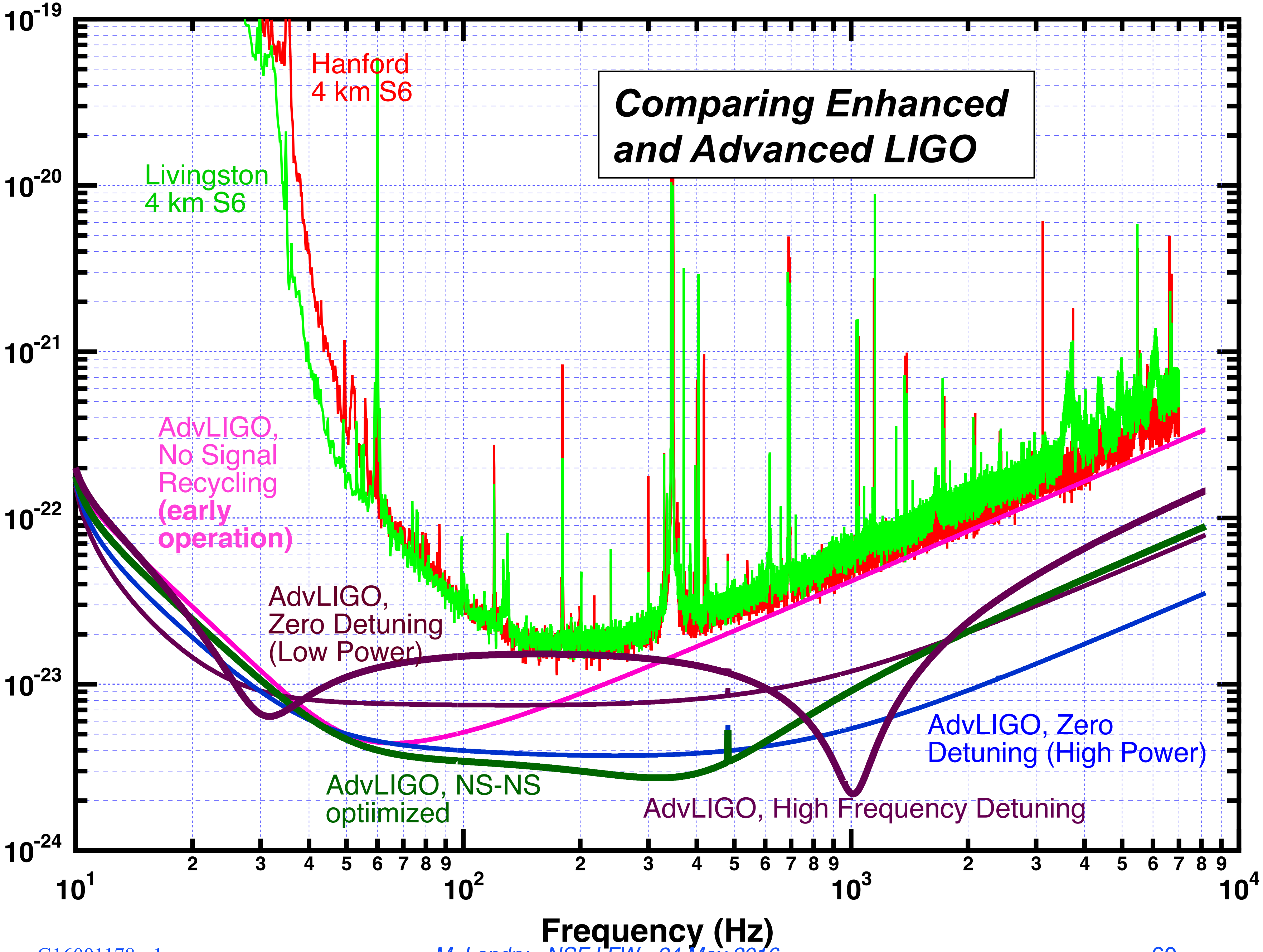
LIGO network duty factor

- 🟧 Double interferometer [42.6%]
- 🟦 Single interferometer [33.4%]
- ⬛ No interferometer [24.0%]

Expected data rates

- LIGO will produce, in raw science frames, ~ 10 MB/s ~ 840 TB/day ~ 300 TB/year per IFO.
- For 2 IFOs, with trend and RDS data included, we will generate on the order of 1 Petabyte of data per year total, per copy. (And we'll keep dual copies of all data, with one copy at the observatories and one copy at Caltech.)

Comparing Enhanced and Advanced LIGO



Staff

- Steady state science running: ~40 people at each of the sites
- At the peak of Advanced LIGO install ~90 people @ LHO, fewer at LLO owing to single interferometer
- Includes technicians for assembly and clean and bake, engineering, scientists, project controls, facilities, management, i.e. everything
- Also includes riggers/millwrights operating under $3.3M time and materials (T&M) contract. Expertise in rigging, pipefitting, sheet metal, etc. Flexibility in numbers (currently 4 at LHO, 2-3 part time at LLO)
- Visitors: Lab and LSC visitors to sites. LSC on sub-contract