LIGO and Gravitational Wave Detection Workshop

Gregory Harry
American University

National Society of Black Physicists
February 28, 2015

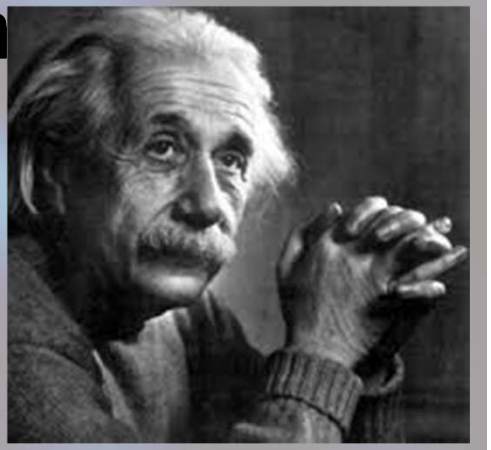
G1500157-v1

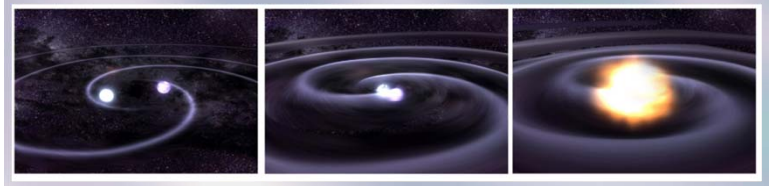
Outline of Workshop

- Technical Overview of LIGO
  - Gravitational Waves
  - Gravitational Wave Detectors
  - Astronomical Sources for LIGO
  - Advanced LIGO Detectors
- Break for Informal Discussions
- Involvement with LIGO and Outreach
  - Joining LIGO
  - Open Data and Joint Data Analysis
  - Programs for Teachers and Students

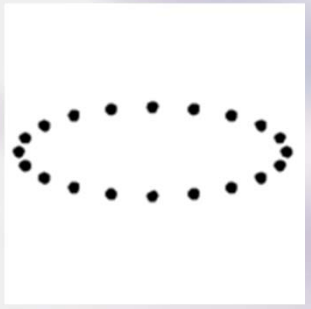
Gravitational Waves

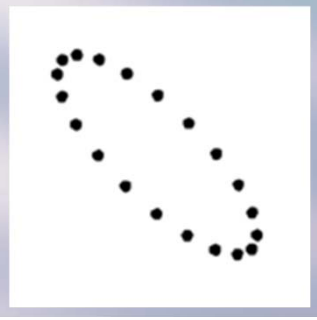
- Gravitational waves are a prediction of Einstein's theory of gravity
- Similar to electromagnetic waves (light) from Maxwell's equations





- Two major differences
- Spin two (tensor) shape
- Much smaller amplitude
  - Strain $\frac{\Delta L}{L} \cong 10^{-22}$
  - Kilometer baseline, subnuclear length changes





General Relativity turns 100; Gravitational Waves turn 99

General Relativity:
Einstein Field Equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The metric: distance in space-time

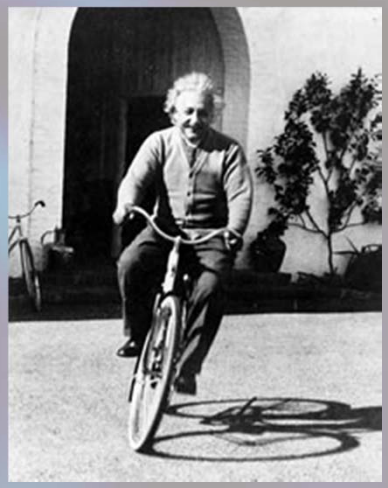
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

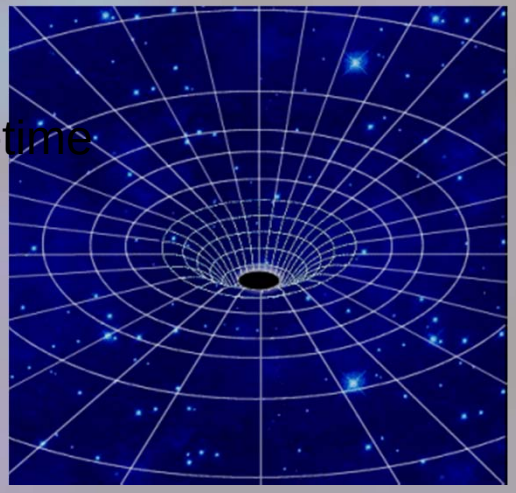
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Weak field approximation: space-time is slightly perturbed from flat space-time

$$\Box h_{\mu\nu} = 0$$

Simple wave equation for the metric perturbation $h_{\mu\nu}$



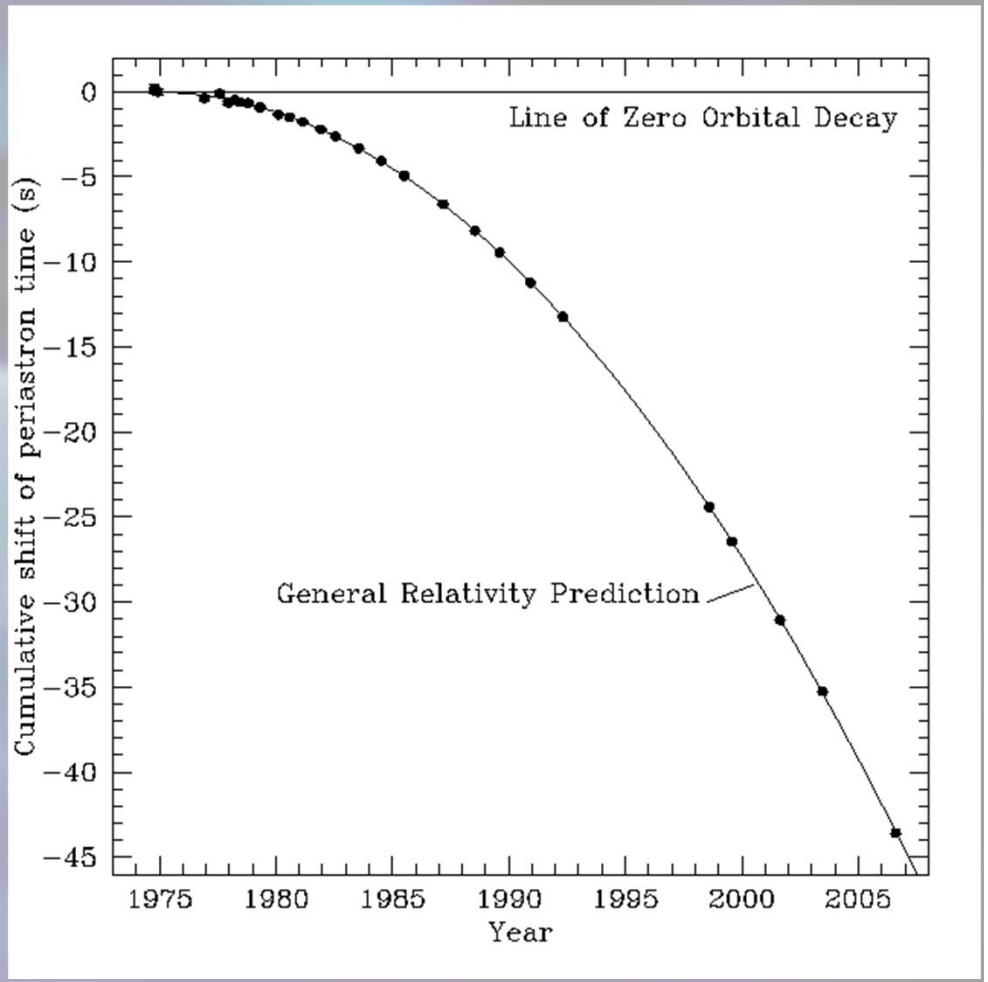


A. Einstein, *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften* (Berlin,1916), 688696; *Sitzungsberichte der Kniglich Preussischen Akademie der Wissenschaften* (Berlin, 1918), 154167.

Slide from D. Reitze G1500139

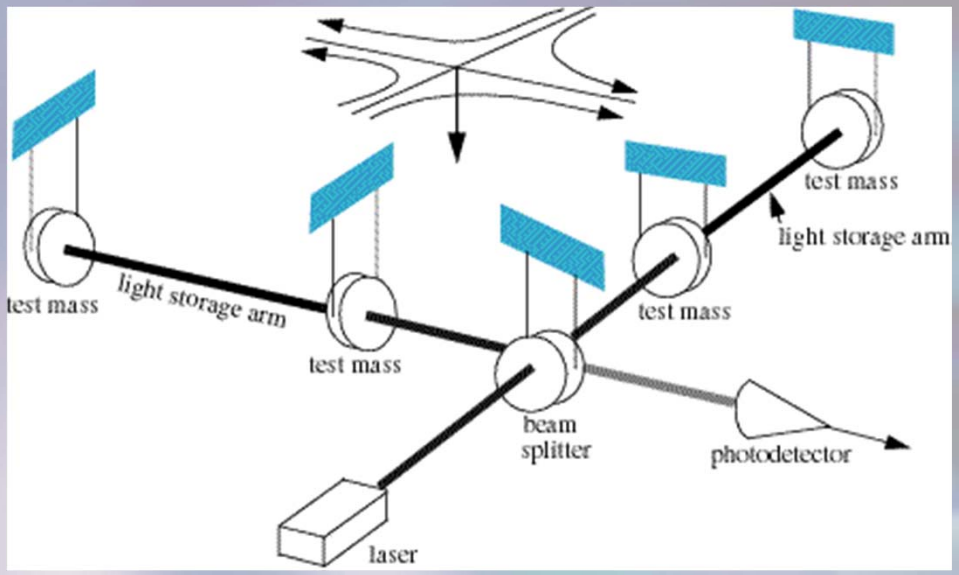
Indirect Evidence for GW

- Known binary neutron star binaries will merge within 100 million years
- Hulse and Taylor observation
  - Change in orbit of neutron star binary
- Orbital period decreases
- Deviation grows as predicted by Einstein
- 1993 Nobel Prize to Taylor and Hulse



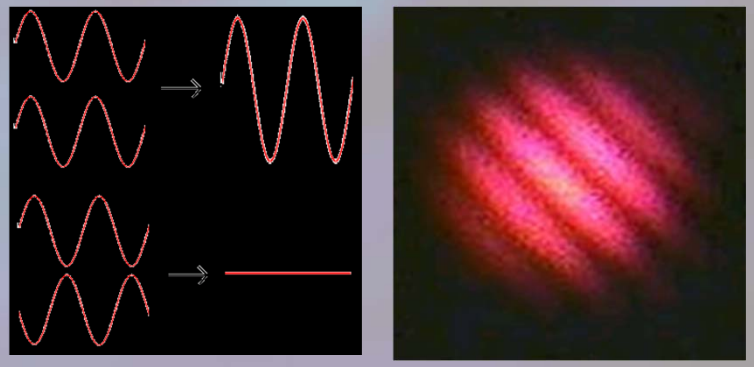
Direct Detection

Interferometers



- Light goes down two perpendicular arms
  - Similar to Michelson-Morley
- Mirrors are free to move
  - Suspended as pendulums
  - Isolated from seismic noise

- Returning light recombines
  - Constructively: equal arm length
  - Destructively: different arm lengths
- Gravitational wave
  - Stretch one arm, shrink other



Interference of Light

LIGO Detectors

- US has two sites
  - Livingston, Louisiana (LLO) and Hanford, Washington (LHO)
- 4 kilometer-long beam tubes
  - Entire 8 km length in vacuum
  - Low seismic noise environment

- Sensitive to strains

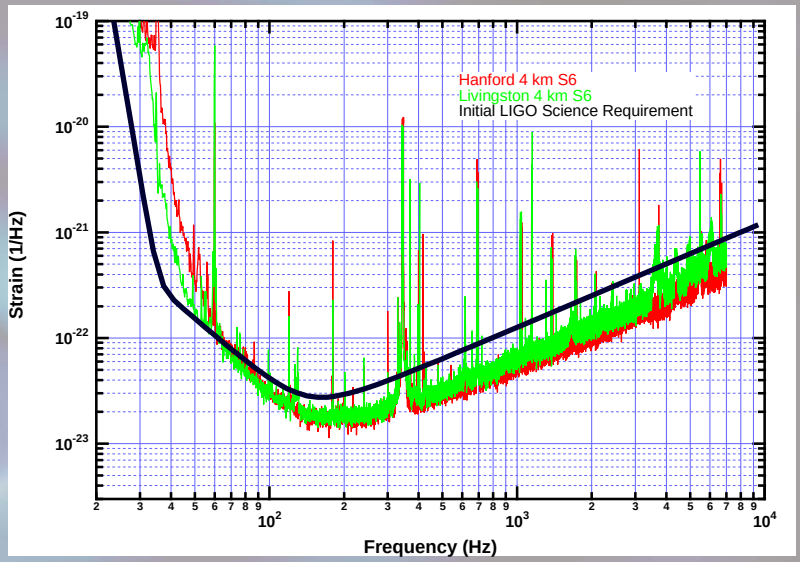
$$h \approx 10^{-21}$$

- $\Delta L = hL \approx 10^{-18}$ m
  - Subnuclear scale

Initial LIGO 2002-10

- More than full year of coincident data
- Bandwidth 40 – 3000 Hz
- Exceeded sensitivity goal

$$\frac{\Delta L}{L} = 2 \times 10^{-22}$$

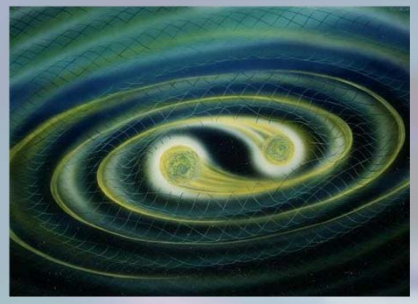


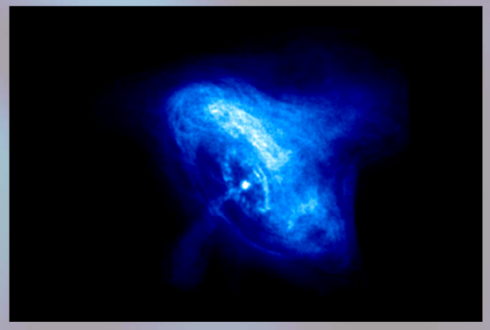
- 3 detectors. 2×4 km/1×2 km
- 20 W Nd:YAG laser
- 10 kg silica optics
- Steel wire suspensions

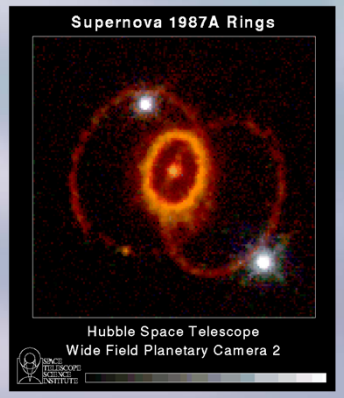
World Network of Detectors

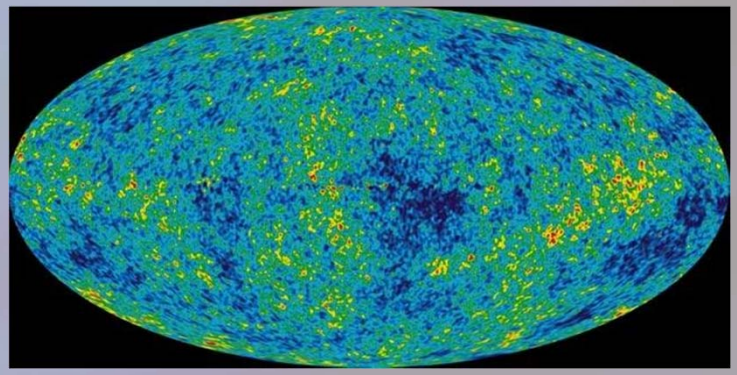
Gravitational Wave Sources

	Short Duration	***Long Duration***
Modeled	Compact Body Inspirals	Periodic Sources
Unmodeled	Bursts	Stochastic Background



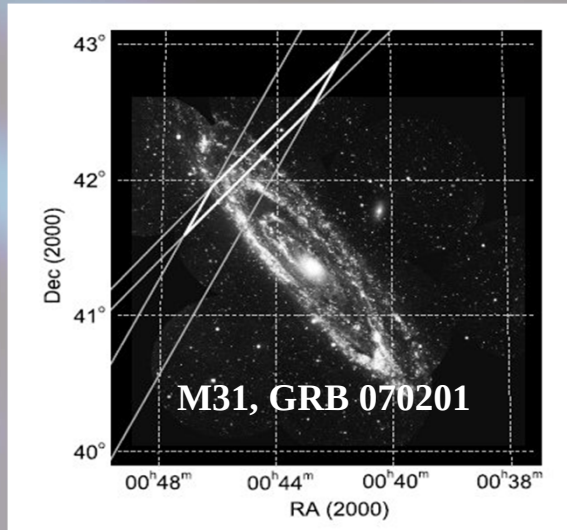


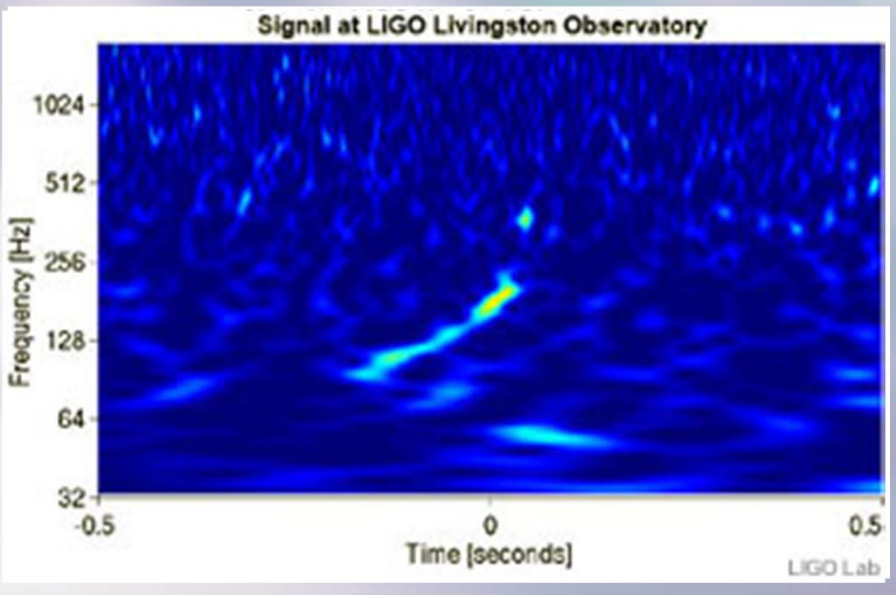




Initial LIGO Astrophysics: Burst and Inspiral Sources

- Gama ray bursts (GRBs) may be compact body inspirals
- Short GRBs 050311 and 070201
  - Locations in galaxies M81 and M31
  - Inspiral excluded at >98%

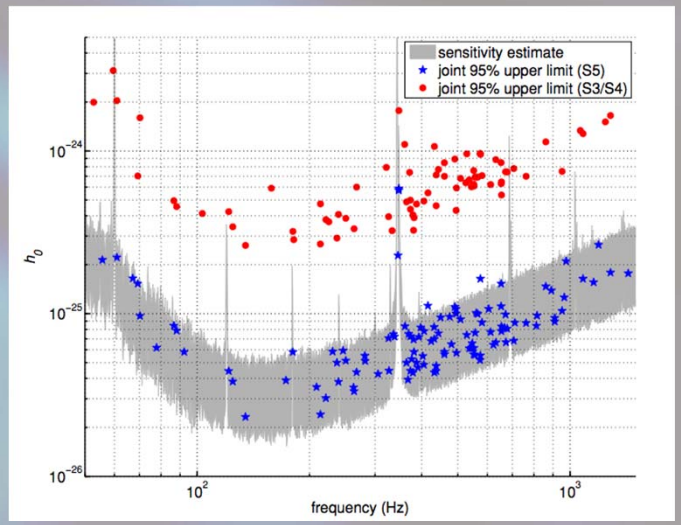


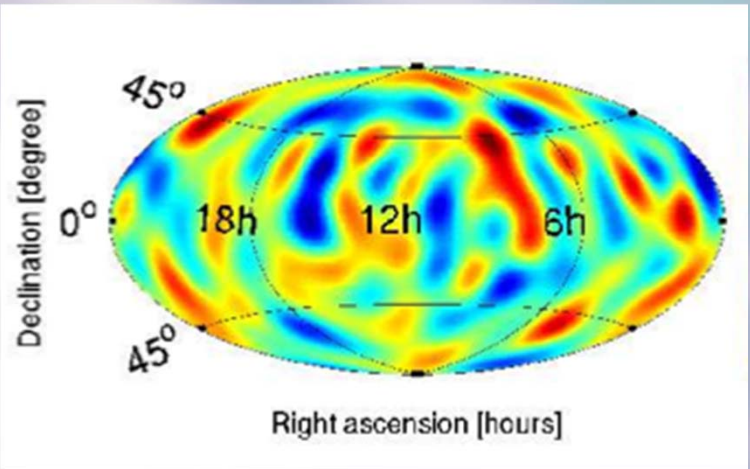


- GW100916
  - Consistent with compact body inspiral
  - Blind injection done to test analysis process

Initial LIGO Astrophysics: Pulsars and Stochastic

- Pulsars can give continuous GW from asymmetric rotation
- Crab pulsar $E_{GW} < 0.02\ E_{total}$
- Ellipticity limit in 116 pulsars
  - Lowest upper limit $\epsilon < 7 \times 10^{-8}$

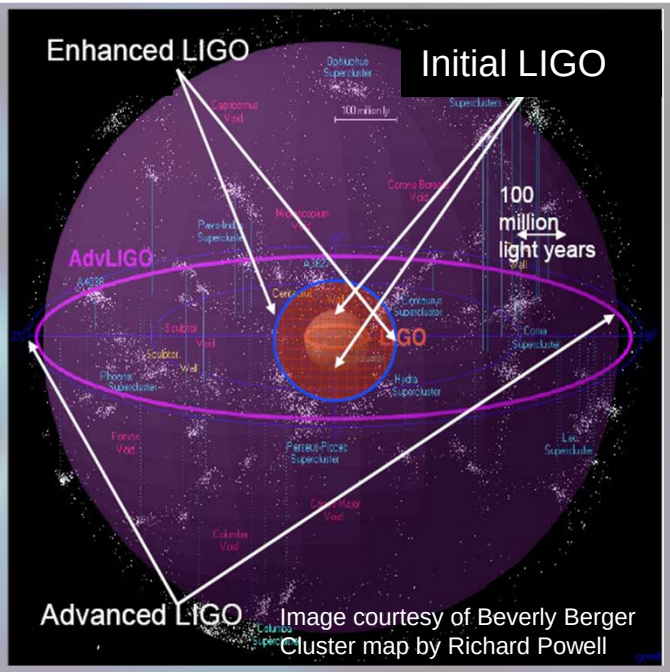




- Stochastic GW from primordial background
- $\Omega_0 < 6.9 \times 10^{-6}$
  - Nucleosynthesis limit 10^{-5}
- Limits on point sources

Advanced LIGO

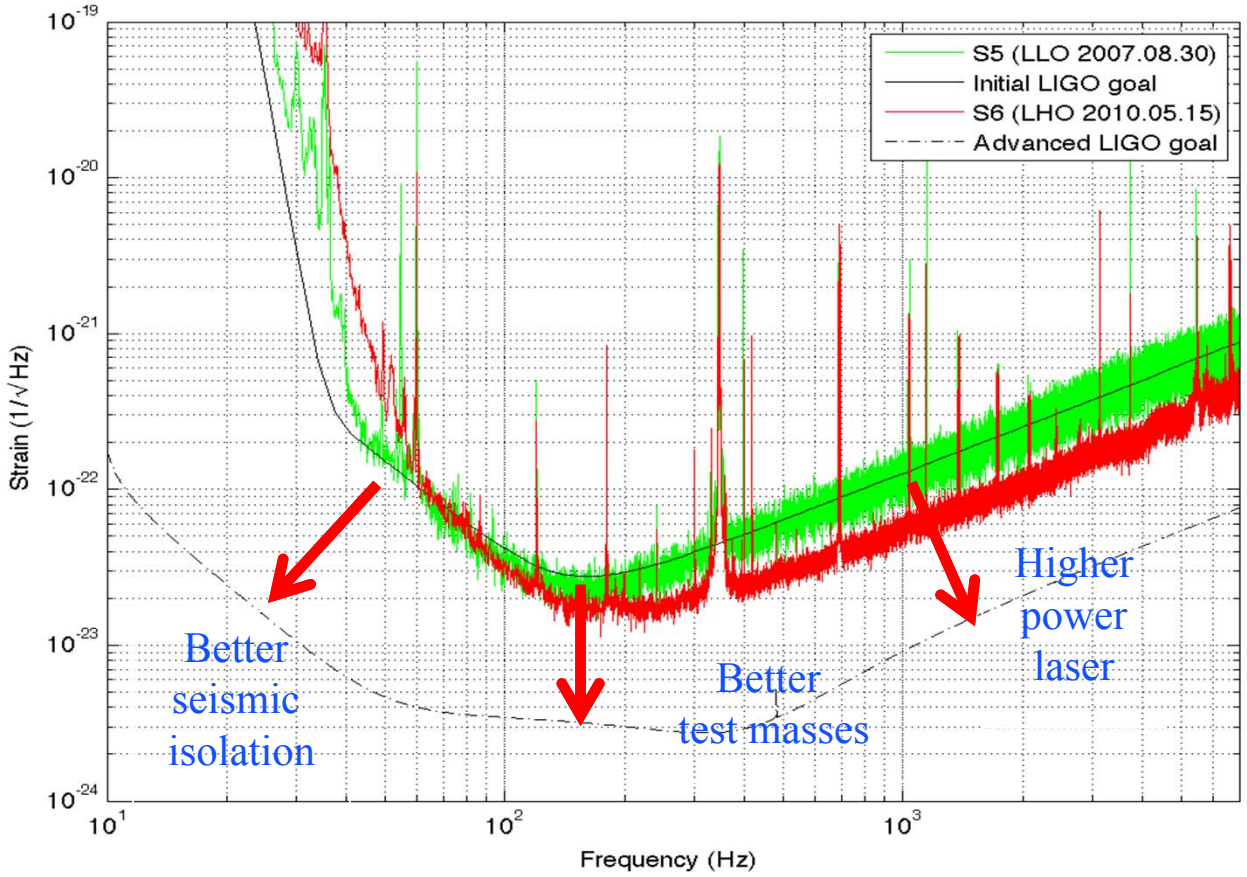
- Goal: 10 X sensitivity
  - 1000 X rate
  - 10 – 5000 Hz, wider range
  - 200 Mpc NS inspiral range
  - Inspirals possible ~ 1/month
  - One day with Advanced LIGO = a few years with initial LIGO



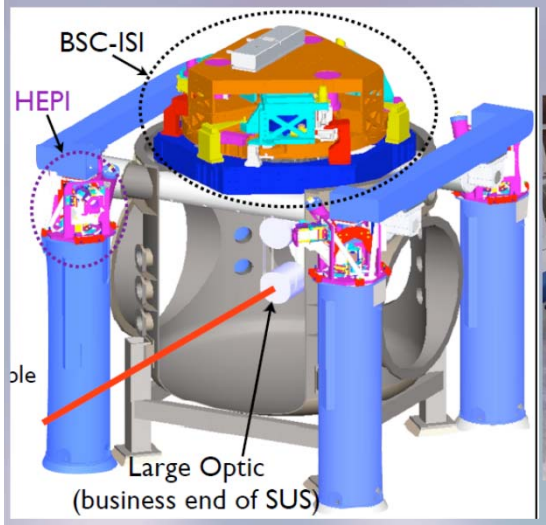
- Construction project complete
  - Budget began in 2008
  - Installation started 2010
  - Building three interferometers
  - Installation finished Feb 2015

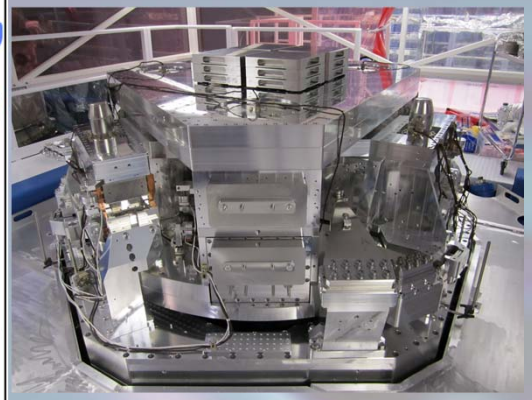
Advanced LIGO Sensitivity

Limited by Earth motion, thermodynamics, and quantum mechanics



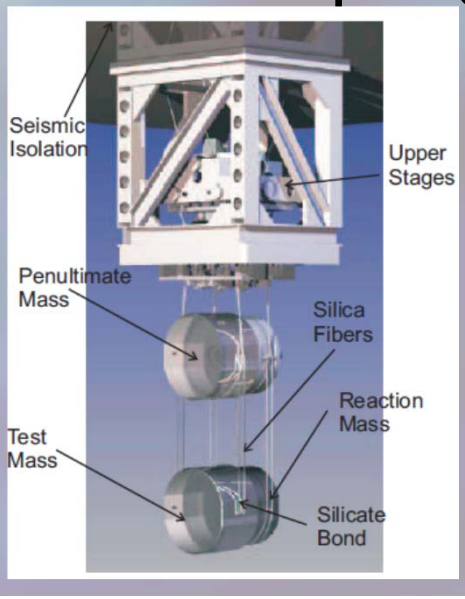
Advanced LIGO Seismic Isolation and Suspension

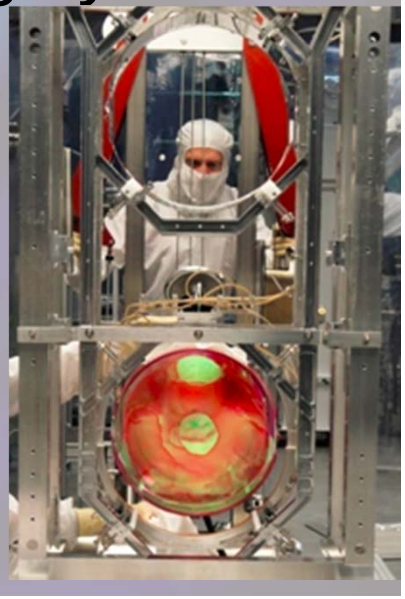




- Seismic isolation
  - Hydraulic preisolator external to vacuum
  - In vacuum, two stage, 6 DOF active mass/spring system

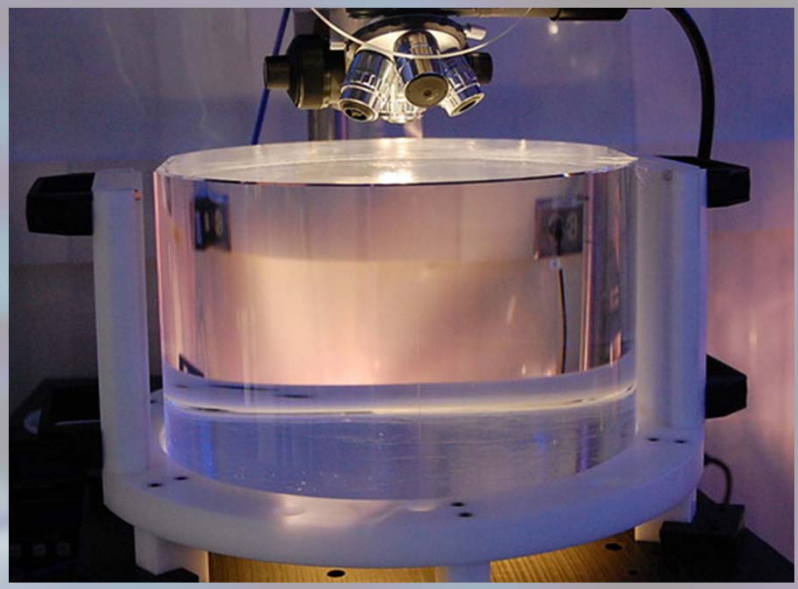
- Quadruple suspension
  - Based on GEO600 triples
  - Seismic noise reduction $1/f^8$ above pendulum f
  - Final stage silica fibers to reduce thermal noise

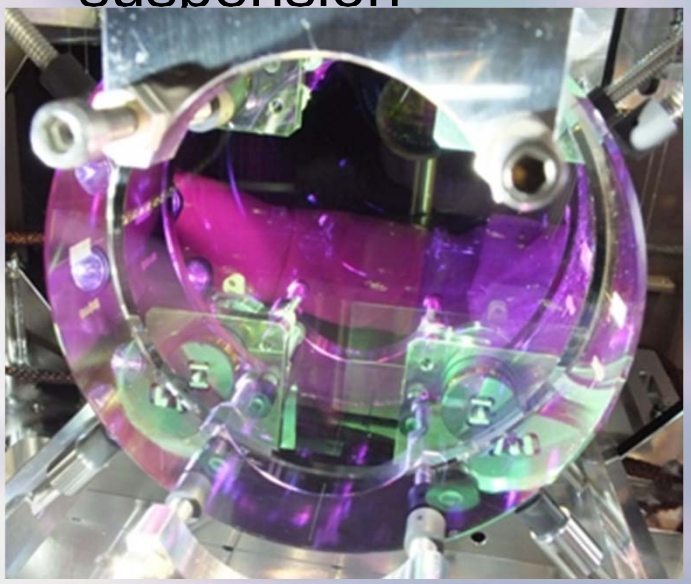




Advanced LIGO Mirrors and Coatings

- Fused silica optics
  - 40 kilograms
  - Very low absorption
  - < 0.2 nm rms polish
  - Monolithic connection to suspension



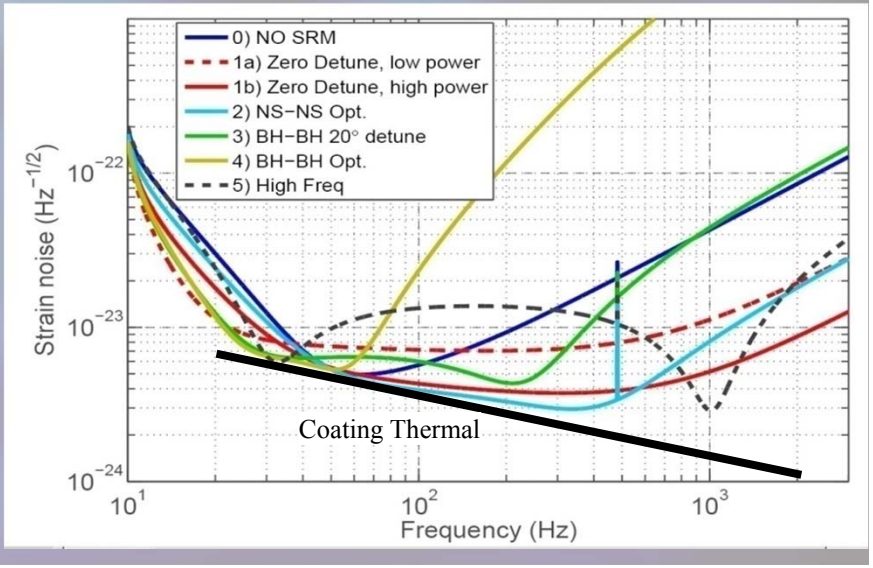


- Optical coatings
  - 34 centimeter diameter
  - 5-6 cm beam spot
  - Very low absorption
  - Titania-doped tantala for low thermal noise

Advanced LIGO Laser and Interferometry

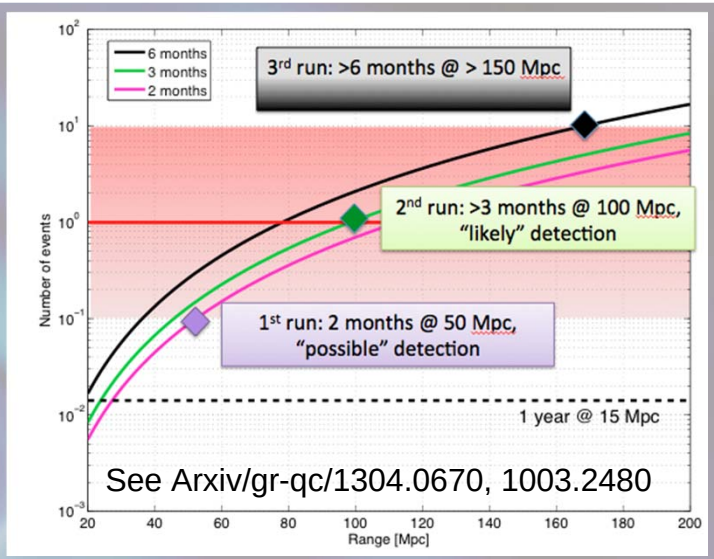
- Laser
  - Nd:YAG 1064 nm
  - Three stage NPRO
  - 180 Watts
  - Shot noise limited

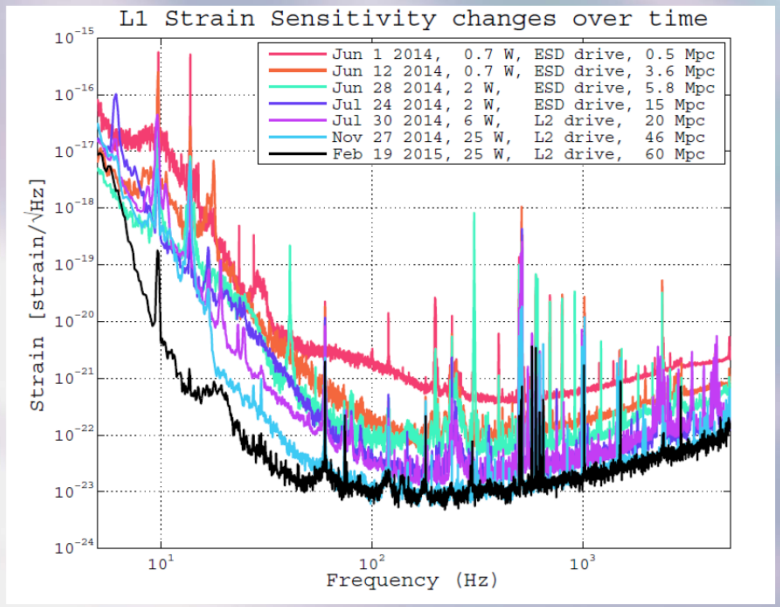
- Interferometry
  - Power recycling increases arm power to 800 kW
  - Signal recycling to tune sensitivity curve



Status and Science Plans

- Installation complete
- Remaining activities
  - Noise reduction at both LLO and LHO
  - Computer procurement

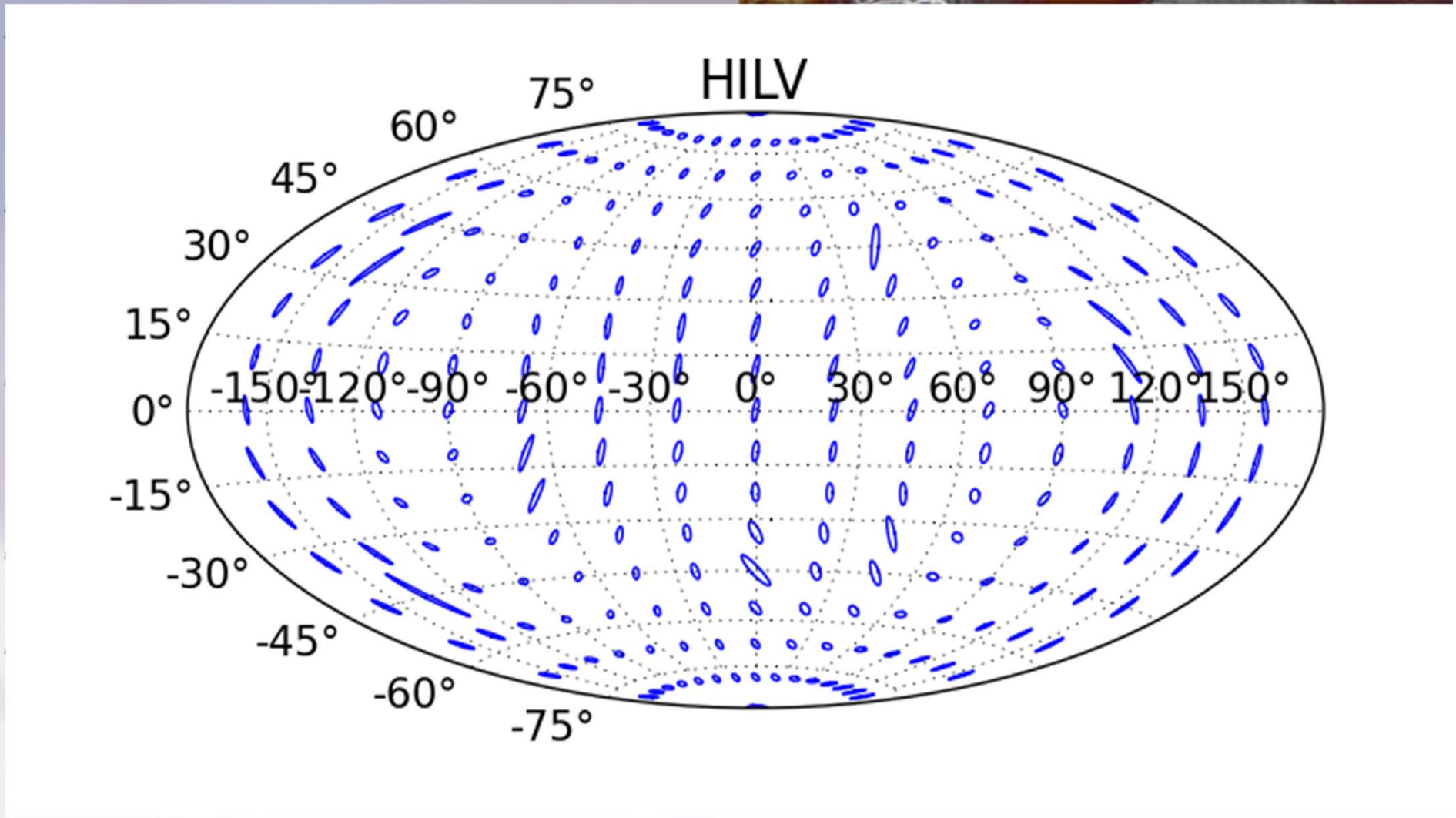




Goal: Direct detection century after Einstein's 1916 GW paper

Date	Length	Sensitivity
Summer 2015	3 months	40-80 Mpc
2016/2017	6 months	80-120 Mpc
2017/2018	9 months	120-170 Mpc
2019	Full year	200 Mpc

LIGO India

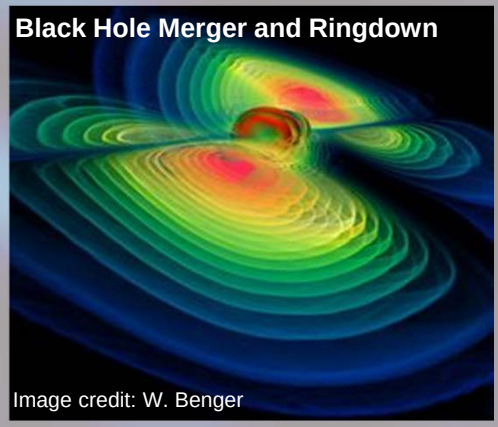

HILV
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°

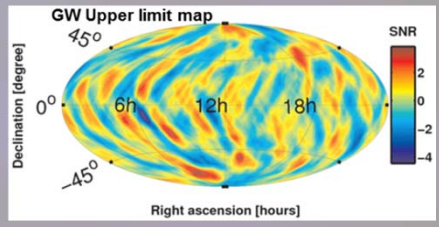
Gravitational Wave Sources for Advanced LIGO

- Compact body coalescence
  - Neutron stars and black holes
  - Inspiral, merger, and ringdown phases
- Stellar core collapse
- Gamma ray bursts
  - Kilonova
- Millisecond pulsars
  - Known and unknown
- Stochastic background
  - Cacophony of above sources
  - Cosmological origin (?)

Physics and Astronomy with Advanced LIGO

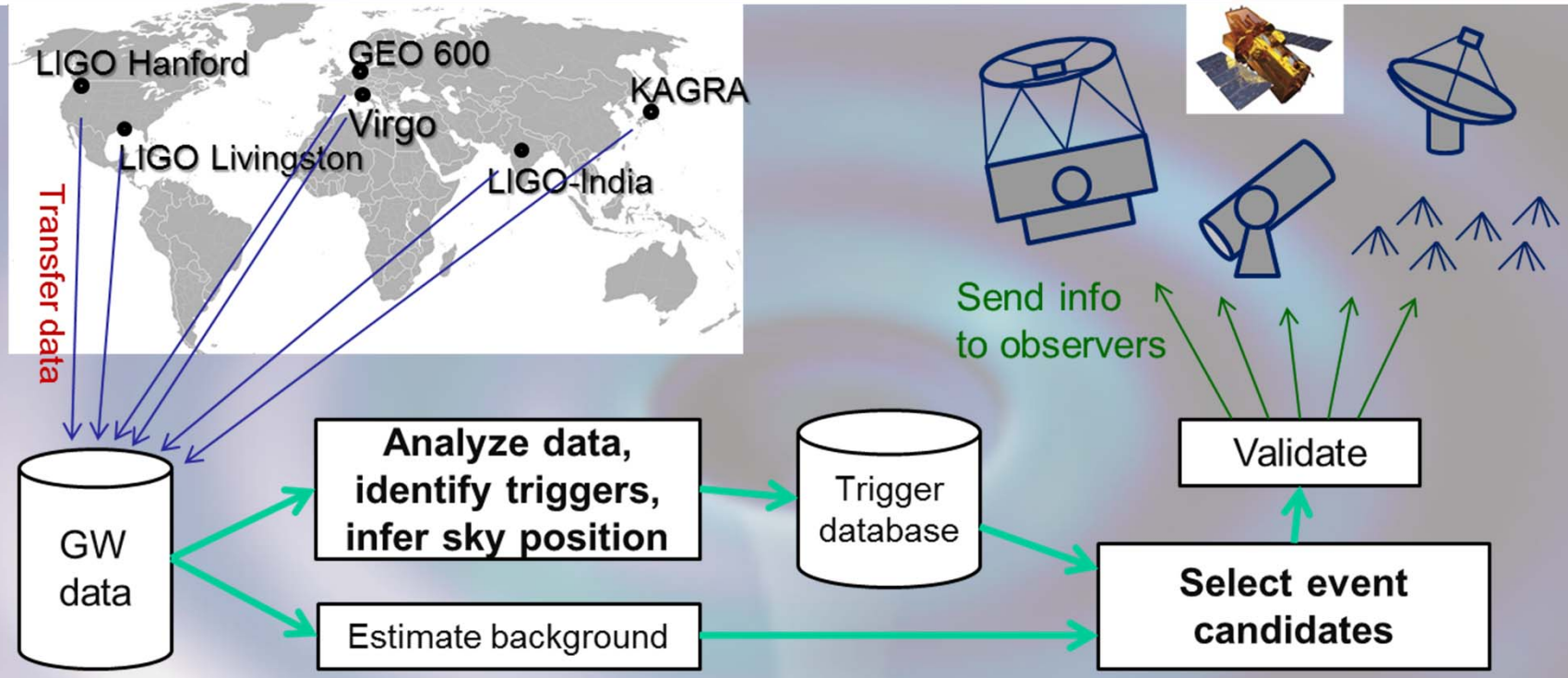
- Fundamental Physics
  - Is General Relativity the correct theory of gravity?
  - How does matter behave under extreme conditions?
  - What equation of state describes a neutron star?
  - Are black holes truly bald?
- Astrophysics, Astronomy, Cosmology
  - Do compact binary mergers cause GRBs?
  - What is the supernova mechanism in core-collapse of stars?
  - How many low mass black holes are there in the universe?
  - Do intermediate mass black holes exist?
  - How bumpy are neutron stars?
  - Is there a primordial gravitational-wave residue?
  - Can we observe populations of weak gravitational wave sources?
  - Can binary inspirals be used as “standard sirens” to measure the local Hubble parameter?





Slide from Dave Reitze

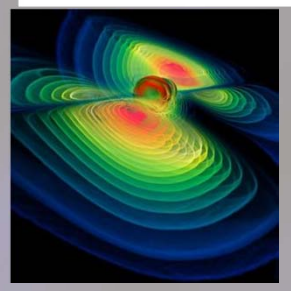
Multimessenger Astronomy



- Low latency data analysis happening as data comes in → Generate triggers
- Increase confidence in GW detection
- More precise sky location, better understanding

LIGO in the Audience

- Gregory Harry – Faculty, American University
  - LIGO hardware, optics, thermal noise
- Jedidah Isler – Faculty, Syracuse University
  - Astrophysics
- Jaysin Lord – Grad student, Syracuse University
  - Neutron star and black hole searches
- Amber Lenon – Grad student, Syracuse
  - Gravitational wave astrophysics
- Corey Gray – Operator, LIGO Hanford Observatory
  - LIGO interferometer status and operation
- Martha Casquette – Faculty, Texas Southmost College
  - LIGO outreach



Hanford Observatory

Research with LIGO and Outreach

- LIGO Scientific Collaboration
- Open data and joint analysis
- LIGO programs for teachers
  - Community college
  - High school teacher training
- Programs for students
- Outreach to the general public
- LIGO online

LIGO Scientific Collaboration

- Nearly 1000 members from over 80 institutions in 16 countries for the LIGO Scientific Collaboration (LSC)
- Large and small departments, graduate and undergraduate institutions, academic and research laboratories
  - Several members serving under-represented groups
  - Southern University, a Historically Black University
- Most US groups supported by single investigator NSF grants
  - LIGO Laboratory (Caltech, MIT, Observatories) supported by MRFC from NSF
- LSC and LIGO Laboratory make up “LIGO”
  - Mission “The LIGO Scientific Collaboration (LSC) is a self-governing collaboration seeking to detect gravitational waves, use them to explore the fundamental physics of gravity, and develop gravitational wave observations as a tool of astronomical discovery”

LSC Organization

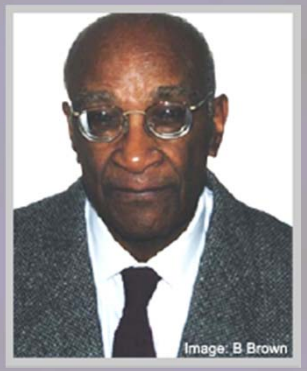
- Working groups organize LIGO activities
  - Hardware groups: Suspensions and Seismic Isolation, Optics, Quantum Noise, Advanced Interferometer Configurations, Detector Characterization
  - Data analysis groups: Bursts, Compact body coalescence, Continuous waves, Stochastic
- Other groups and committees
  - Education and public outreach, Diversity, Academic advisory, Joint running (with Virgo), Software
- LIGO Collaboration Meetings
  - Joint meetings with Virgo
  - Currently twice yearly; Caltech March 2015

Joining the LSC

- Anyone willing and able to contribute to LIGO's mission may apply for membership
  - Contributions to one or more of analysis of LIGO data, operation and characterization of current detectors, and development of future detectors
  - Contact LIGO Spokesperson Gabriela Gonzalez (gonzalez@lsu.edu)
- Must be approved by 2/3 vote of current members
- Sign a Memorandum of Understanding with LIGO
  - Evaluated by working groups and resigned annually
- LIGO Beginner's Guide available at
  - dcc.ligo.org/public/0112/P1400033/005/FinalDocumentAug2014%289%29.pdf

LIGO Diversity Initiatives

- LIGO commitment to diversity
  - As members of the LIGO Scientific Collaboration, we recognize the importance of diversity to enrich our research and scholarship.
  - dcc.ligo.org/public/0107/M1300484/001/LSC-diversity-statement.pdf
  - As international collaboration, focus on gender issues over race or ethnicity
- Sponsor Undergraduate Research Fellowships for underrepresented minorities
- With NSBP - Carl Albert Rouse Fellowship
- With National Society of Hispanic Physicists - Victor M. Blanco Fellowship



Joint Analysis with Astronomers

- LIGO has Memorandum of Understanding with astronomers to do multimessenger astronomy
- High Energy Neutrinos: ANTARES and IceCube
  - Short GRBs, SGRs
- Low Energy Neutrinos: Super-K, LVD, Borexino
  - Core collapse supernova
- Gamma Rays: SWIFT
  - Short GRBs, galactic supernova
  - Low latency
- Optical and IR: ROTSE a,b,c,d; TAROT N,S SkyMapper, QUEST, PTF/ZTF, Pi of the Sky, Zadko, Quest, DECam, BlackGEM
  - GRB afterglows, galactic supernova
- Radio: LOFAR, ETA, NRAO Green Bank, ARECIBO
  - BNS mergers, GRB radio afterglows, pulsar glitches

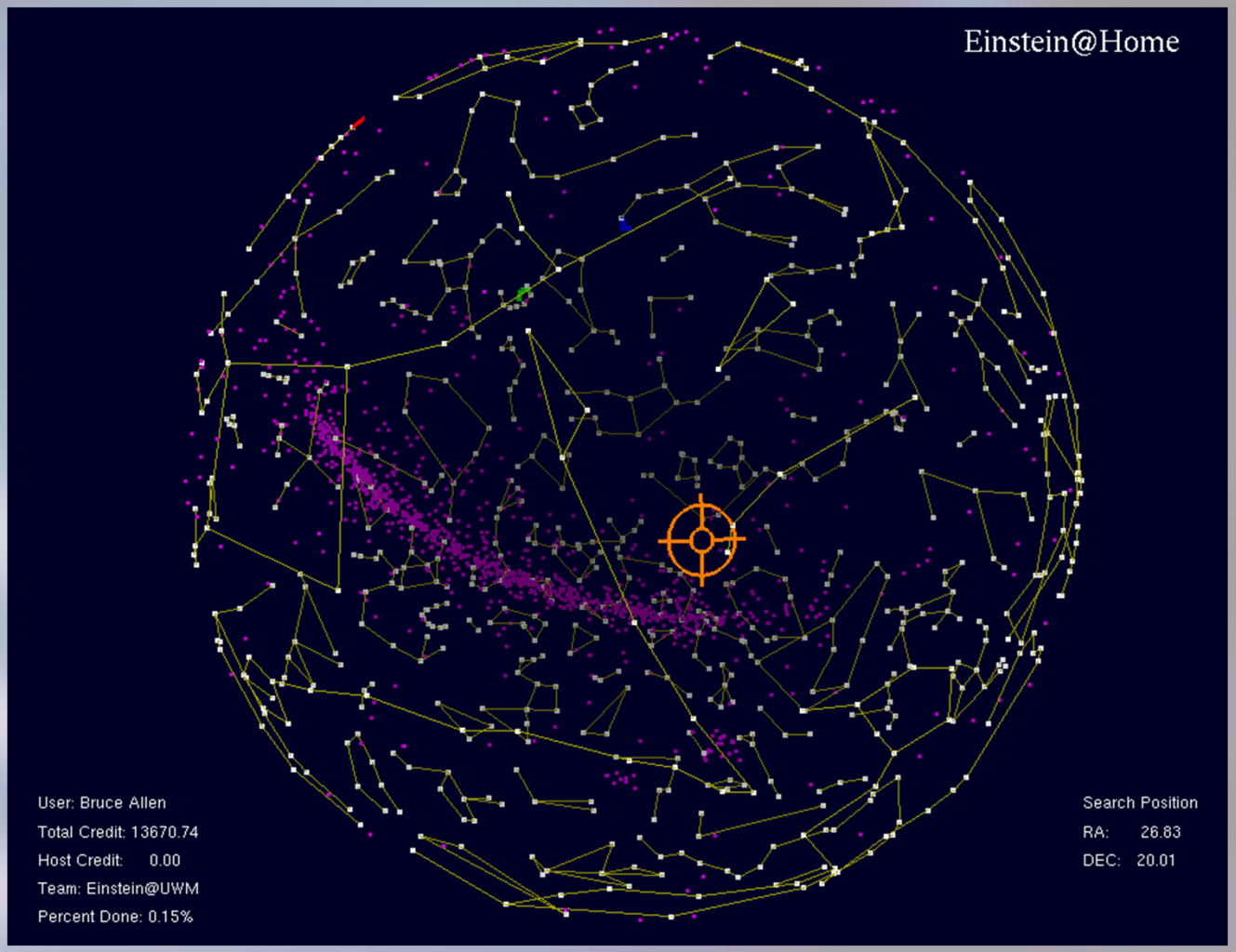
LIGO Open Data

- LIGO data available online to anyone interested: losc.ligo.org/about
  - Also documentation, tutorials, and tools
  - losc.ligo.org/tutorials/
- Most recent data from 2005-2007 S5
- Will release 2009-2010 S6
- Used for student projects and outreach as well losc.ligo.org/projects/

Einstein @ Home

http://einstein.phys.uwm.edu/

- Based on SETI@Home
- Searching for unknown pulsars
- Operating systems:
  - Windows
  - Mac
  - OSX
  - Linux
- More computing power
- Low cost



LIGO Community College Teachers

- Two-unit online courses for community college teachers about LIGO science and technology
  - LIGO Science course starts July 2015
- Coming soon, March 16, 2015

  epo.sonoma.edu/projects/ligo/

Secondary School Teachers

- LIGO Livingston observatory in Louisiana partners with regional organizations to provide teacher training

  www.ligo-la.caltech.edu/SEC.html
- LIGO Hanford observatory in Washington state offers stand alone summer workshops for teachers

  www.ligo-wa.caltech.edu/prof_dev.html
- LIGO participates in remote workshops for teachers by invitation from organizers
- Hanford observatory also provides summer teacher internships through the STAR teacher program

  www.ligo-wa.caltech.edu/internships.html
- Contact William Katzman (wkatzman@ligo-la.caltech.edu) and Dale Ingram (ingram_d@ligo-wa.caltech.edu)

K12 Education Projects

- Hanford participates in IU2U to make LIGO seismometer data available to students for research

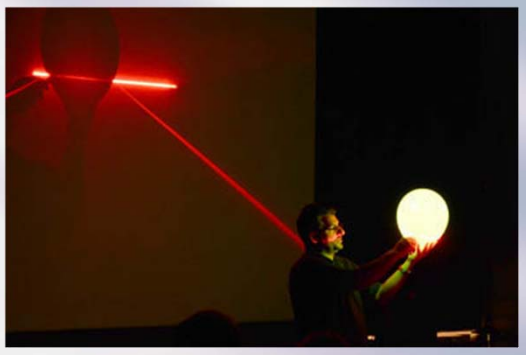
  www.i2u2.opg/elab/ligo/home/projects.jsp
- LIGO science classroom activities

  www.ligo-wa.caltech.edu/activities.html

  www.einsteinsmessengers.org
- Kids corner has LIGO games, activities, etc.
  - www.ligo-wa.caltech.edu/kids_corner.html

AU Optics Olympiad

- LIGO group at American University in Washington DC starting an Optics Olympiad for DC high school students
- Day of individual and group competition in optics, physics, and science



- Organizing now, looking for volunteers to help with all aspects
  - Panel speakers, demonstration development, teacher recruitment, day of volunteers, etc.
  - See me after the workshop if you are interested in participating in any way

Opportunities for Undergraduates

- LSC research experiences for undergraduates
  - International through U Florida
    www.phys.edu/ireu/index.html
  - Other LSC institutions
    www.ligo.org/students.php
- LIGO Laboratory SURF program
  www.ligo.caltech.edu/LIGO_web/students/SURF/

Opportunities for Graduate Students and Postdocs

- Many LSC institutions have graduate programs in LIGO science

  wiki.ligo.org/LAAC/UndergraduateResources

  wiki.ligo.org/LAAC/StudentOpportunities
- LIGO on Linkedin
  www.linkedin.com/groups?gid=2626910
- From the LIGO Academic Affairs Committee

  “It doesn't hurt to drop the head of a group an email expressing your interest, even if they have not advertised. They will see you are keen and most likely email you if money becomes available. I know people within the LSC who have secured a position this way, or the groups have found money for the right person.”

Outreach to the General Public

- Summaries of LIGO publications

  www.ligo.org/science/outreach.php
- Public festivals, fairs, and events
  - Traveling exhibit
  - US Science and Engineering Festival
  - World Science Festival
  - National Astronomy Night on the Mall

LIGO Online

- On the web

www.ligo.caltech.edu

www.ligo.org

- On Facebook

www.facebook.com/LigoScientificCollaboration

- On Twitter

twitter.com/LIGO

- On Youtube
  - LIGO Generations www.youtube.com/watch?v=3xVUmmSFxXu
  - LIGO, A Passion for Understanding www.youtube.com/watch?v=_OPTo1kPJI
- LIGO Magazine

  www.ligo.org/magazine.php