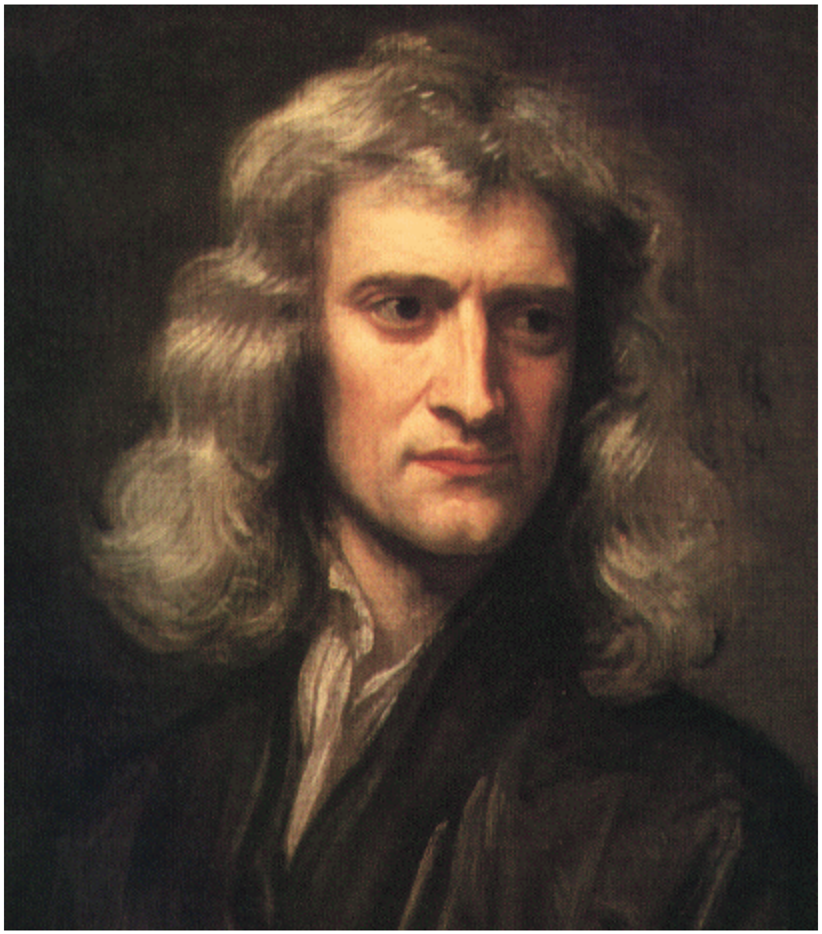
History and status of LIGO
Laser Interferometer
Gravitational Wave Observatory

Hiroaki Yamamoto Caltech/LIGO

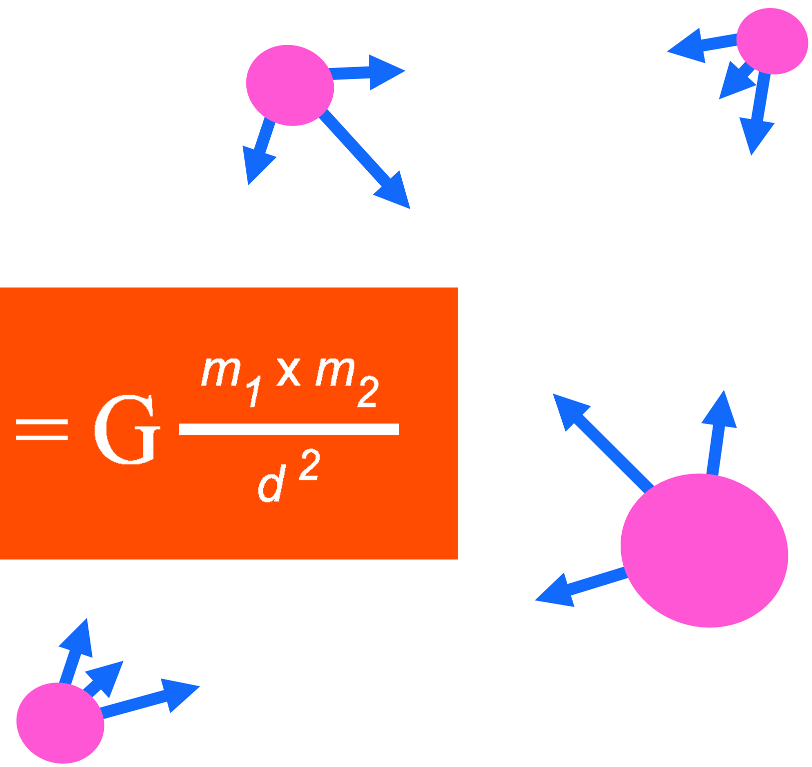
- Introduction
  - » Newton's gravity to Einstein's general relativity
- Gravitational Wave
  - » Source and signal
- Detection of the Gravitational Wave Signal
- Second generation detectors
- Plan toward the first detection of GW

Many items in the presentations are from
"Listening to the Universe through Einstein's Waves" by S. Whitcomb LIGO-G0900456
"Projected Integrated Testing & Operations Commissioning" by P. Fritschel LIGO-G1400628
"ET-aLIGO and beyond" by David Shoemaker LIGO-G14001331

Newton’s Theory of Gravity (1686)



- Equal and opposite forces between pairs of bodies

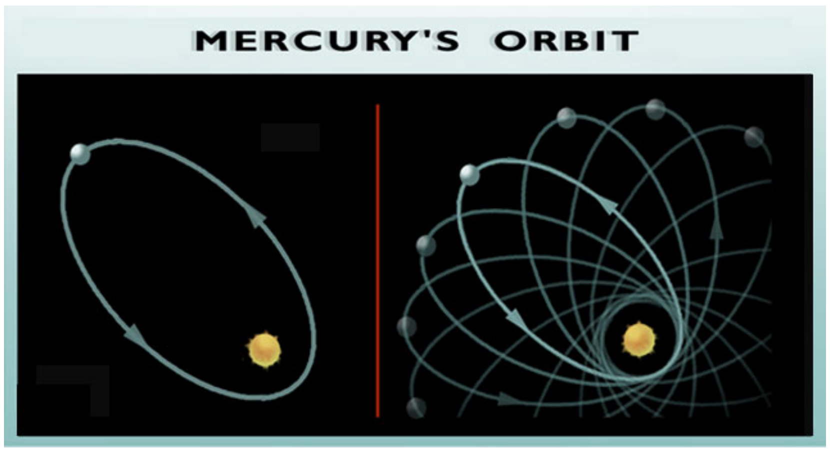


$$F = G\frac{m_1 \times m_2}{d^2}$$

Newton’s Theory of Gravity to Einstein’s General Theory of Relativity

Newton’s Theory of Gravity was very successful

However, One Unexplained Fact and Two Mysteries



Astronomers observed perihelion of Mercury advances by 43”/century compared to Newton’s theory

- **What causes the mysterious force in Newton’s theory ?**
- **How can a body know the instantaneous positions of all the other bodies in the Universe?**

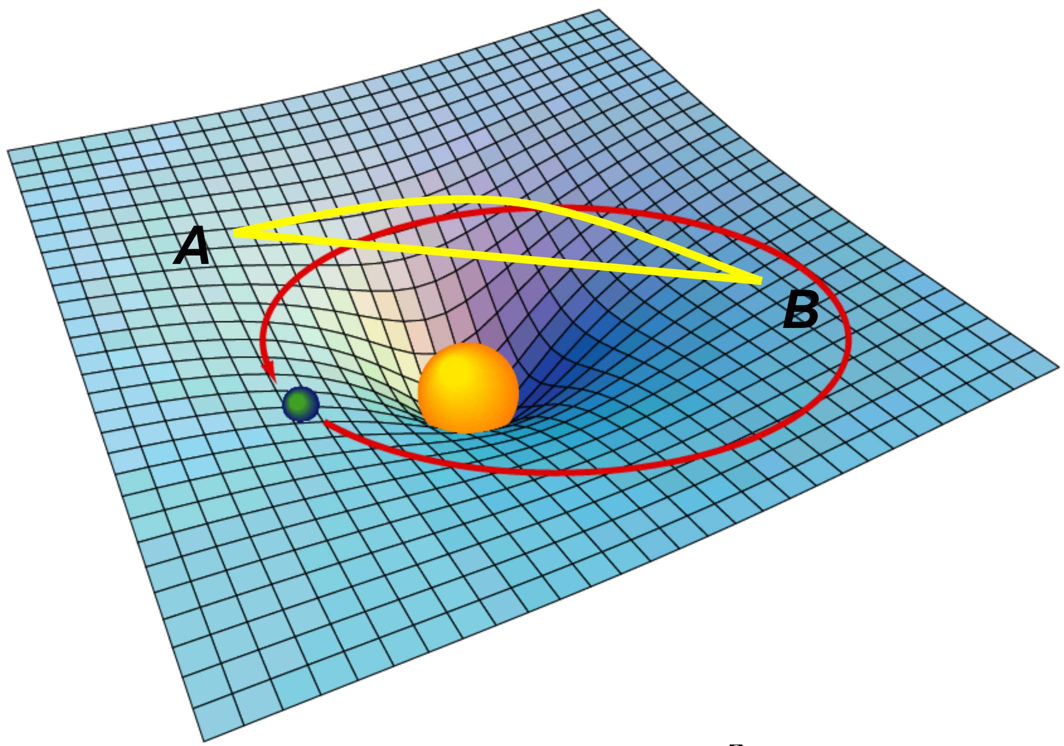
General Relativity
A Radical Idea

- Overthrew the 19th-century concepts of absolute space and time
- Spacetime = 3 spatial dimensions + time
- Perception of space and time is relative

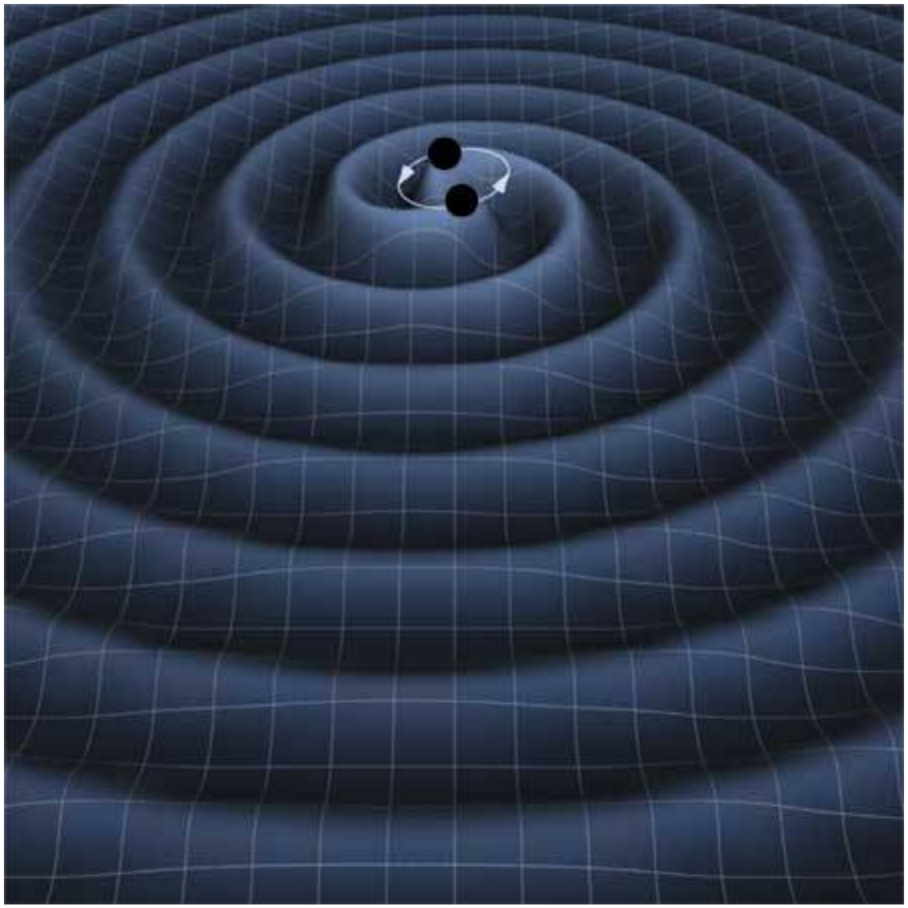
AIP Emilio Segrè Visual Archives

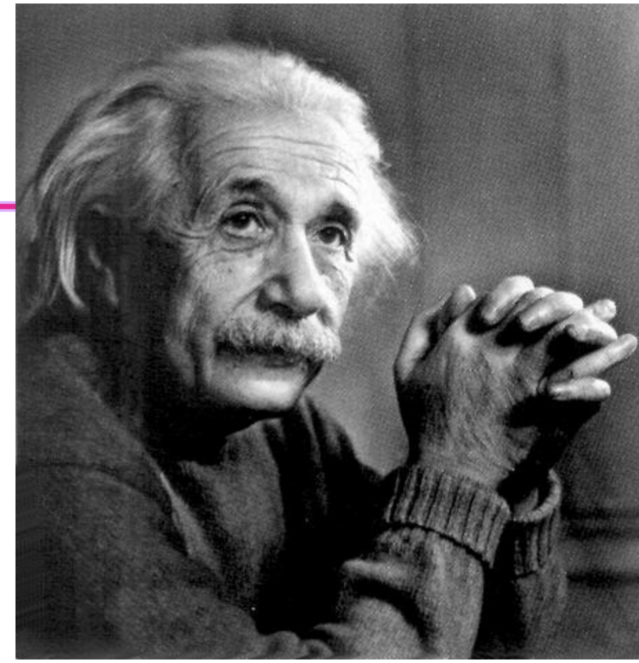
General Relativity
A Radical Idea

- Gravity is not a force, but a property of space & time
- Concentrations of mass or energy distort (warp) spacetime
- Objects follow shortest path through this warped spacetime
- Explained the precession of Mercury



A New Prediction: Gravitational Waves



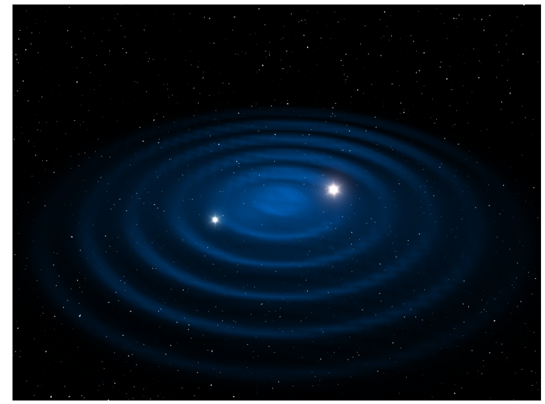


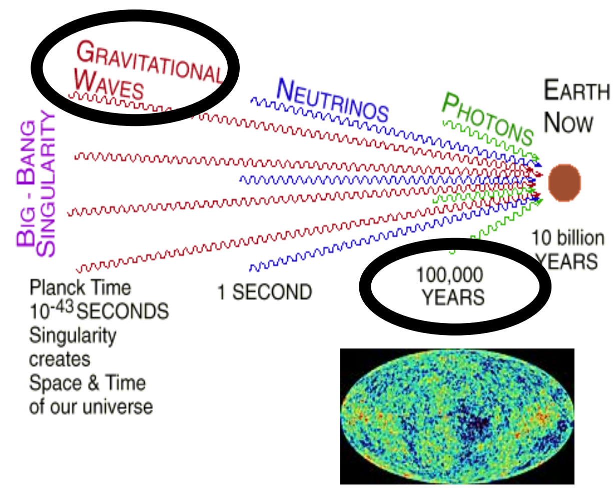
Photograph by Yousuf Karsh of Ottawa, courtesy AIP Emilio Segre Visual Archives

Ripples in spacetime moving at the speed of light

Source of Gravitational Waves

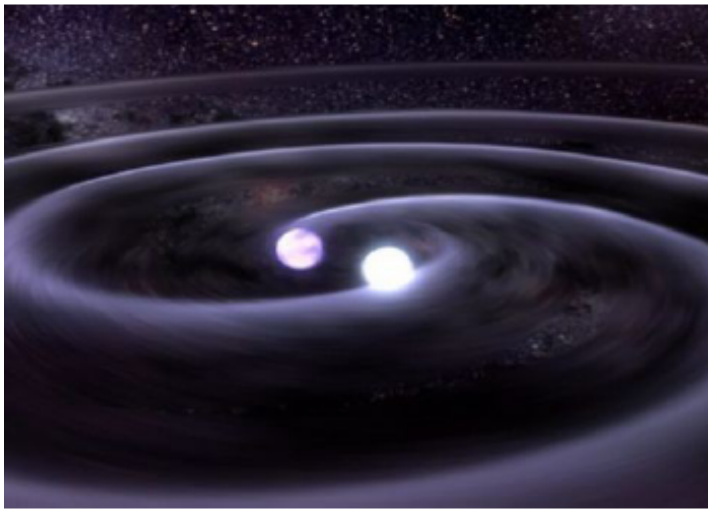
- Any massive objects can radiate GWs
  - » Black Halls, Neutron Stars, Pulsars, Supernova, Big Bang, etc
- Using GW signals, we can investigate sources
- Least unambiguous detectable GW source : coalescence of neutron binary stars

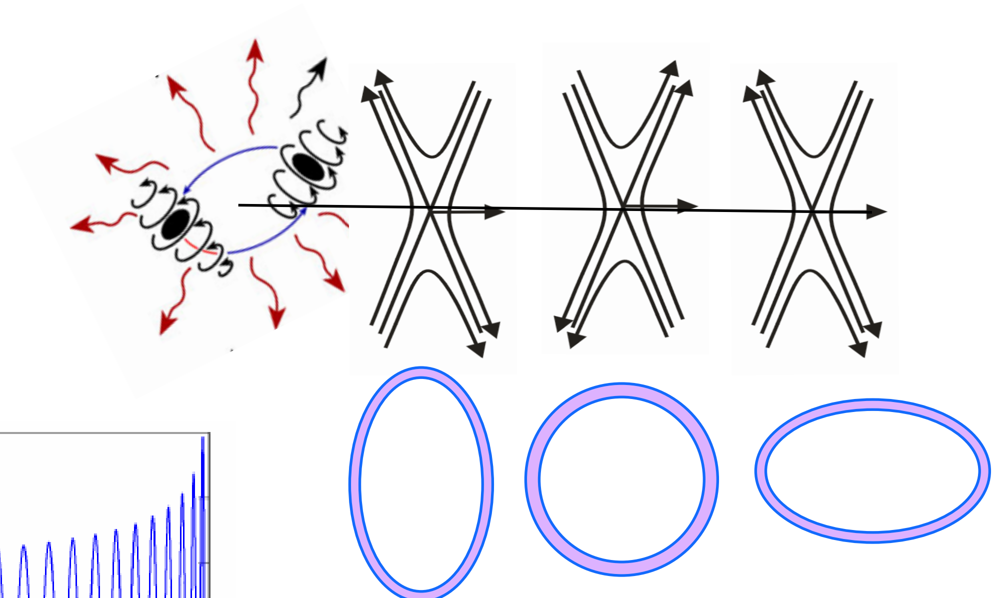


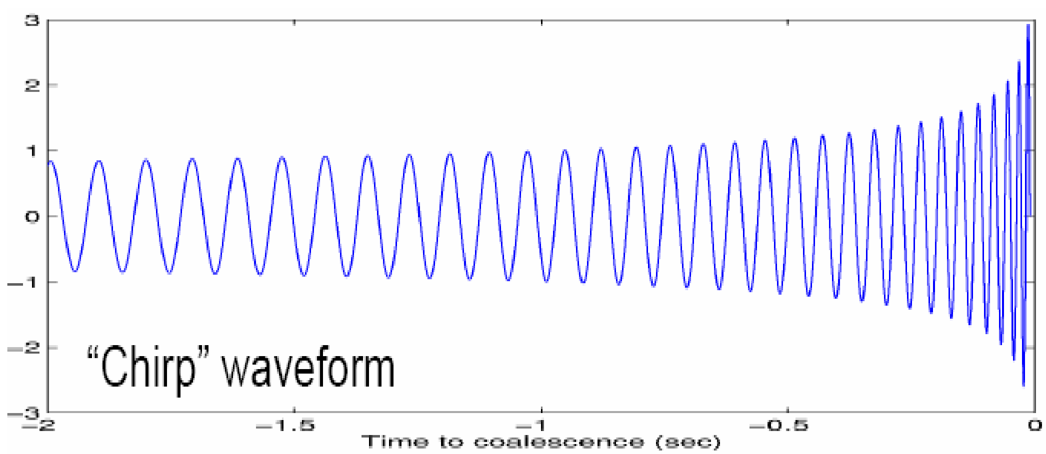


Cosmic microwave background

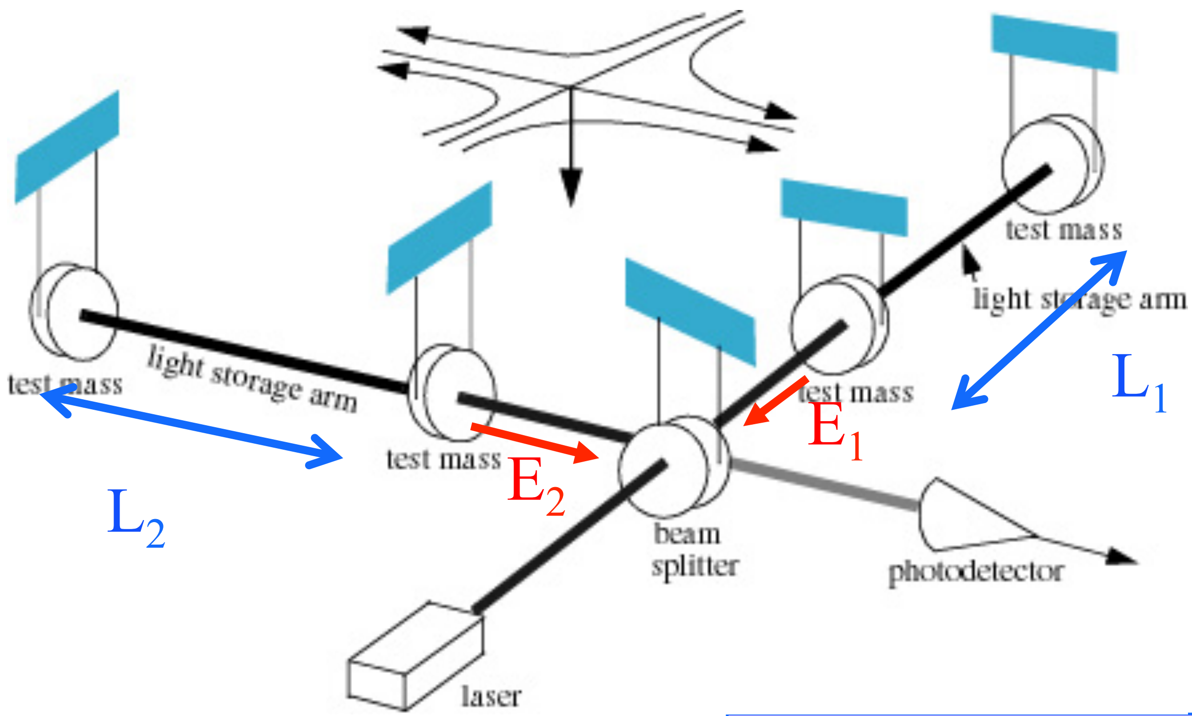
Propagation of Gravitational waves







Direct Detection of Gravitational Waves



$E_1 - E_2 \propto L_1 - L_2$

$$h = \frac{L_1 - L_2}{L_1 + L_2}$$

$h \sim 10^{-23}$

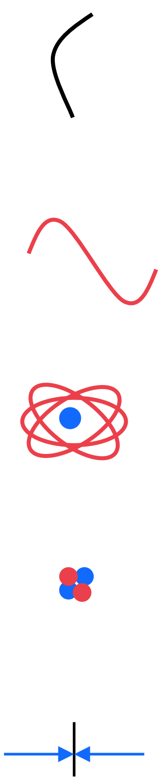
$L_1 - L_2 \sim 10^{-19}$m

LIGO-G1401342

Hiro Yamamoto Salerno on November 27, 2014

How Small is 10^{-19} Meter?

One meter



÷10,000	*Human hair ~ 100 microns*
÷100	*Wavelength of light ~ 1 micron*
÷10,000	*Atomic diameter 10^{-10} m*
÷100,000	*Nuclear diameter 10^{-15} m*
÷10,000	*GW detector 10^{-19} m*

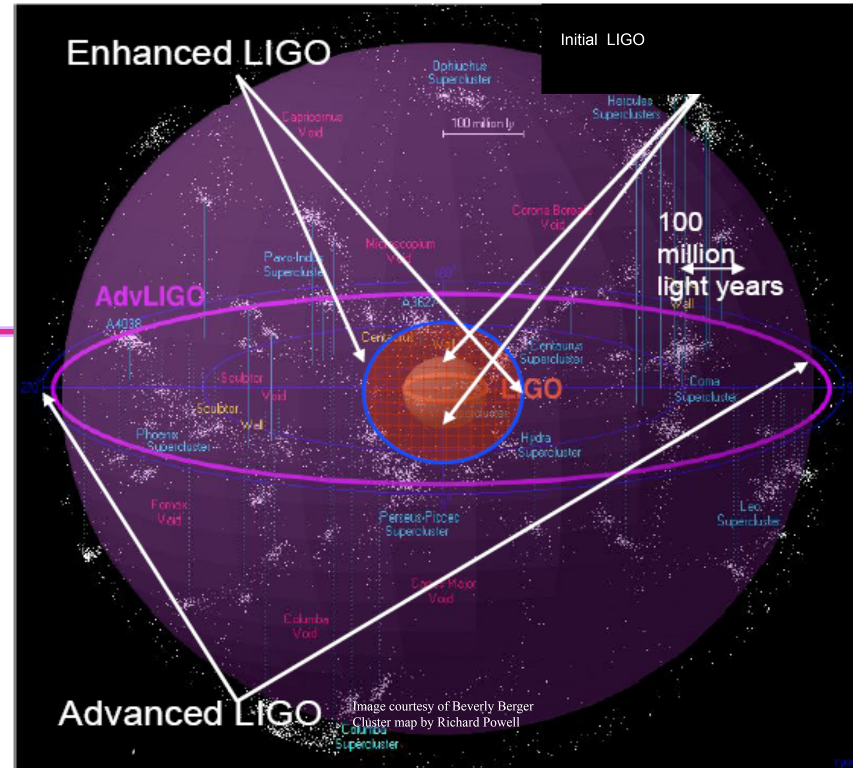
GW detector sensitivity or Listening to the GW songs

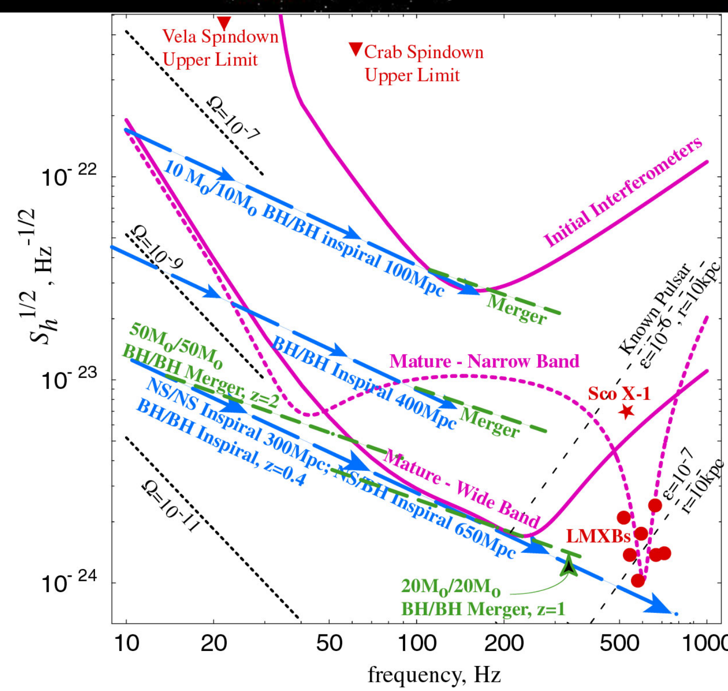
First generation detector
Too noisy and hard to hear

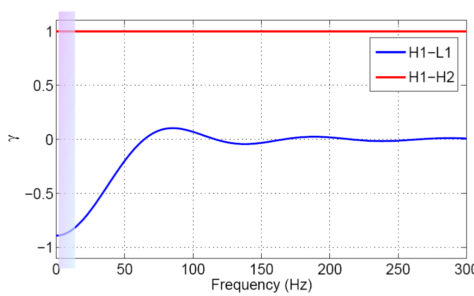
Second generation detector
Low noise and enjoy music

Advanced LIGO Scope and Deliverables

- Factor 10 better amplitude sensitivity
  - » $(\text{Reach})^3$ = rate
- Factor 4 lower frequency bound
- Tunable for various sources
- NS Binaries: for three interferometers,
  - » Initial LIGO: ~20 Mpc
  - » Adv LIGO: ~300 Mpc, expect one event/week or so
- BH Binaries:
  - » Initial LIGO: 10 M_o, 100 Mpc
  - » Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - » Initial LIGO: Ω~3e-6
  - » Adv LIGO ~3e-9

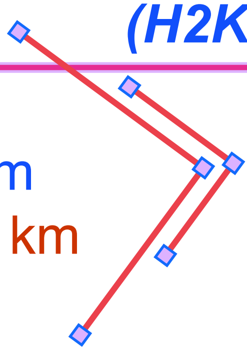






LIGO sites

Hanford Observatory (H2K and H4K)



Hanford, WA (LHO)

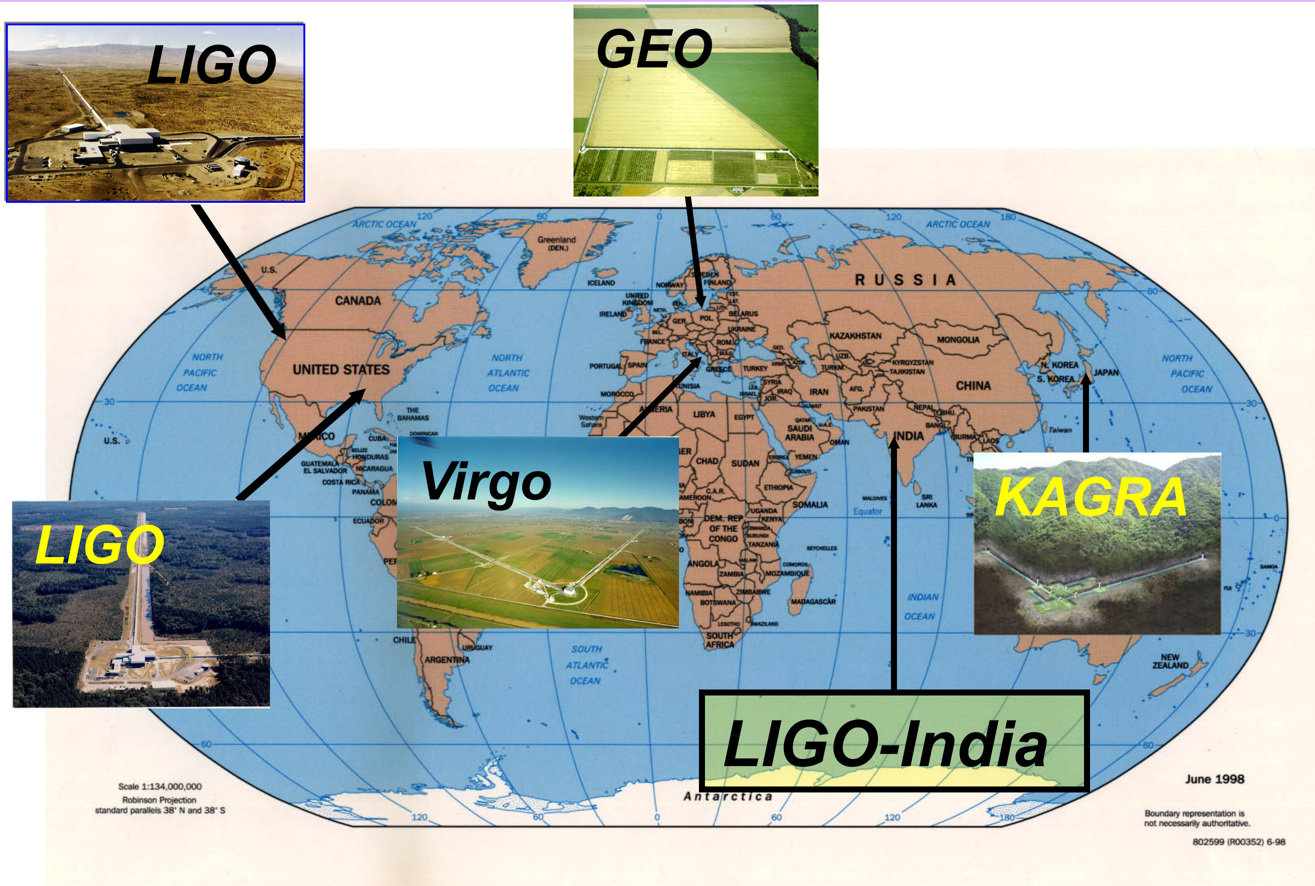
- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA
- **Two IFOs: H2K and H4K -> 4k LHO + 4k India**

Livingston, LA (LLO)

- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA
- **One 4K IFO**

Livingston Observatory (L4K)

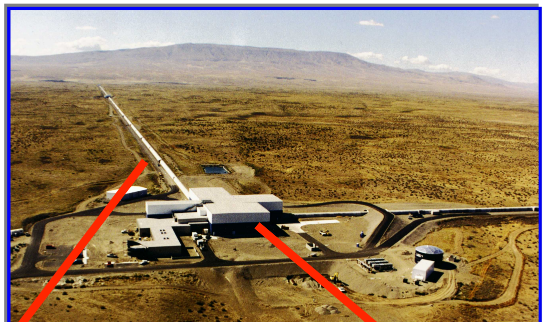
International network



- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- Open up a new field of astrophysics!

LIGO Large vacuum enclosures

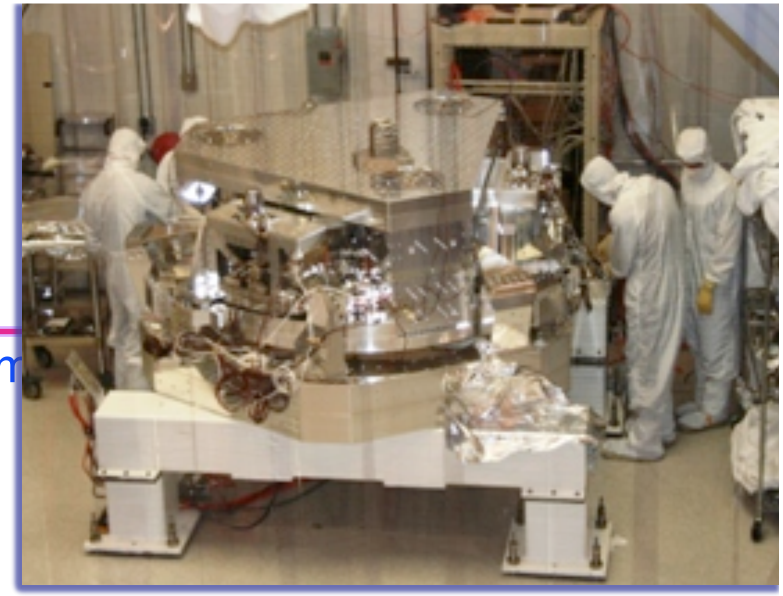
Beam light path must be high vacuum, to minimize "phase noise"



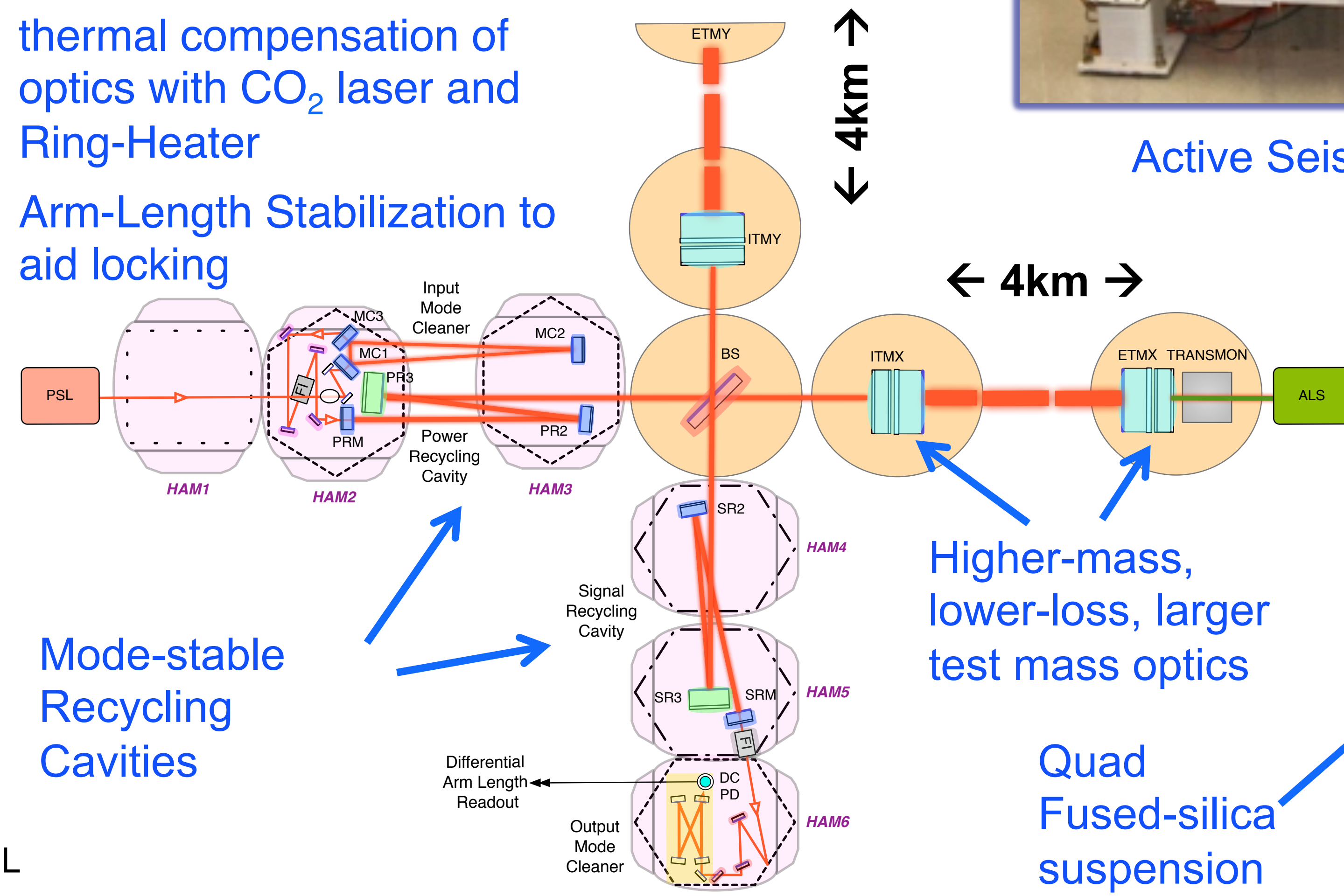
All optical components must be in high vacuum, so mirrors are not "knocked around" by gas pressure

LIGO Design Overview

- Signal- and Power-recycled Fabry-Perot interferom
- 180 W 1064 nm laser
- thermal compensation of optics with CO_2 laser and Ring-Heater
- Arm-Length Stabilization to aid locking



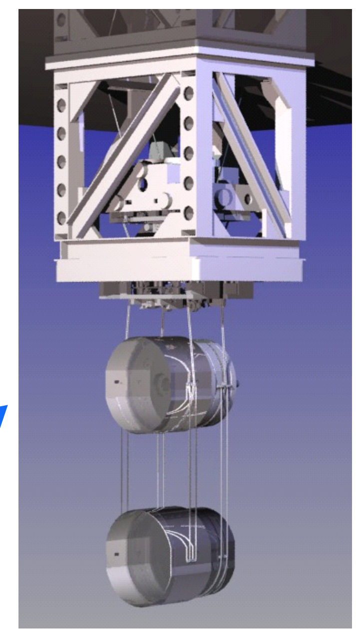
Active Seismic Isolation



Mode-stable Recycling Cavities

Higher-mass, lower-loss, larger test mass optics

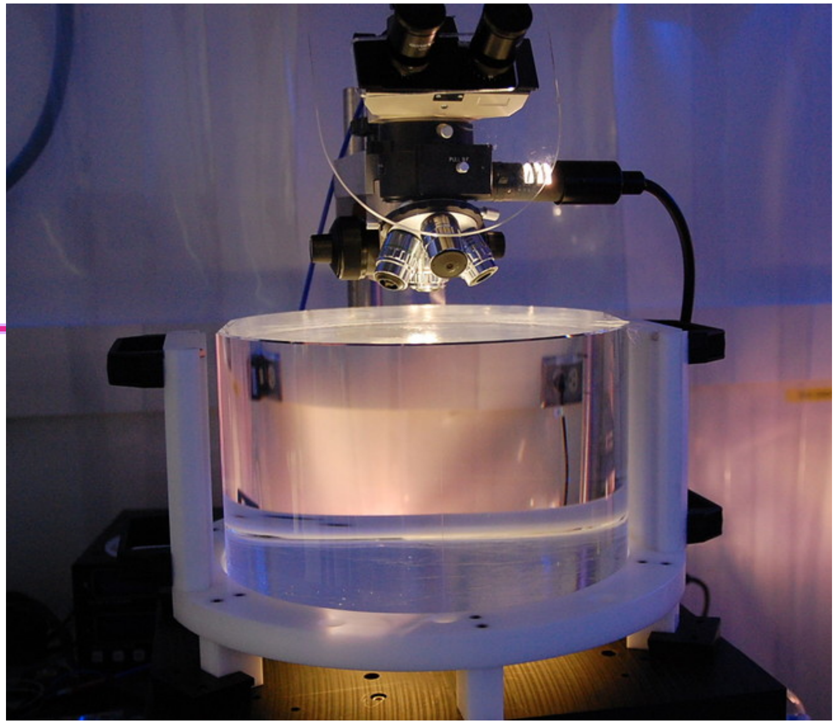
Quad Fused-silica suspension

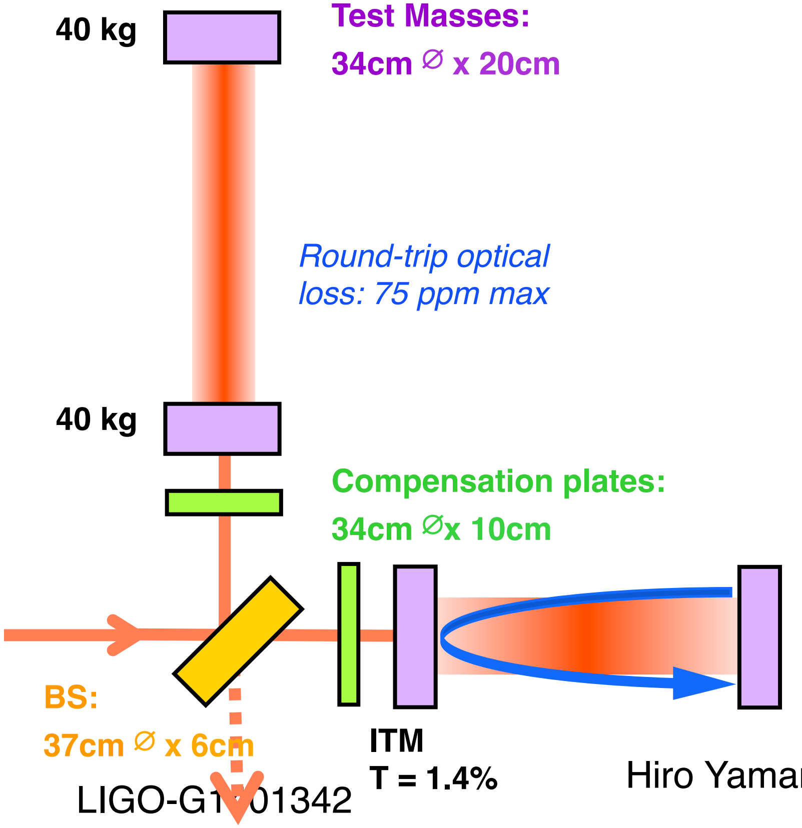


L

aLIGO Test Masses

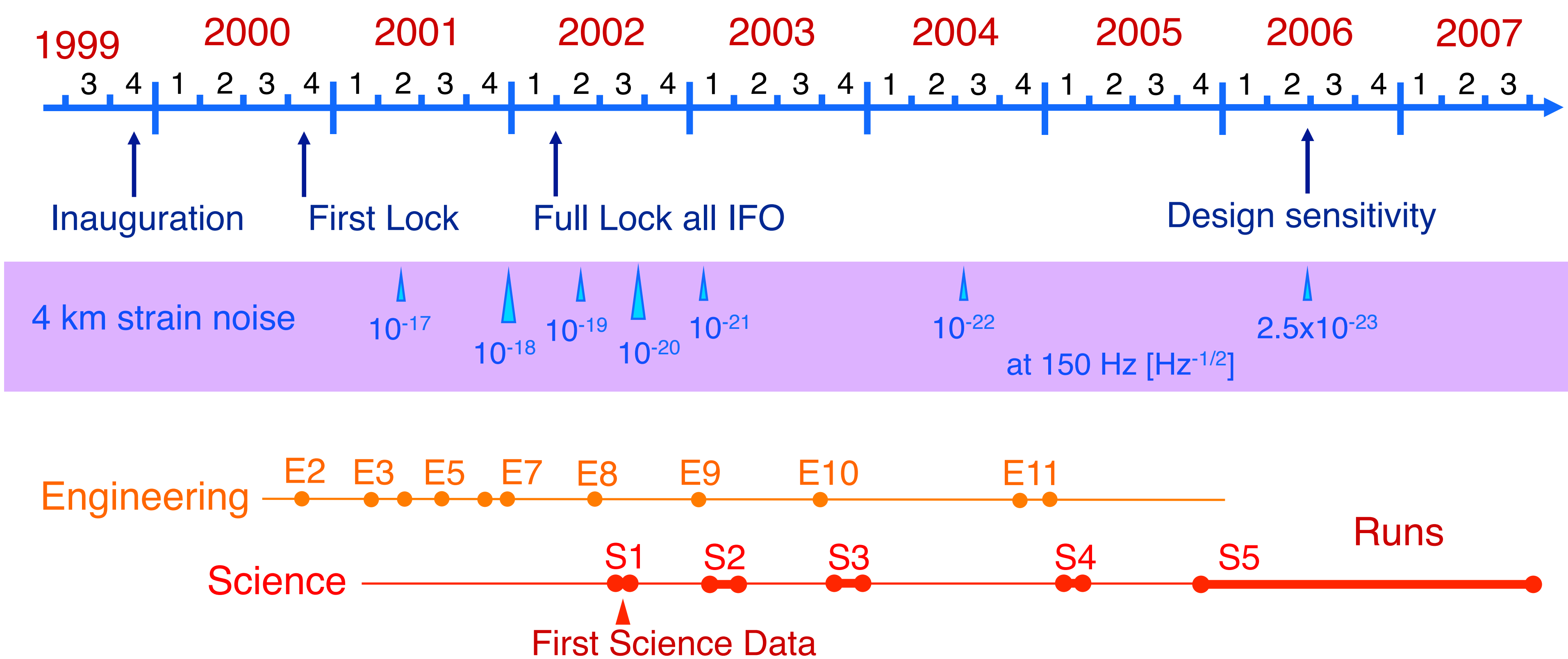
- Requires the state of the art in substrates, polishing, coating
- Both the physical test mass – a free point in space-time – and a crucial optical element





- Half-nm flatness over 300mm diameter
- 0.2 ppm absorption at 1064nm
- Coating specs for 1064 and 532 nm
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency

Historical perspective: Initial LIGO commissioning

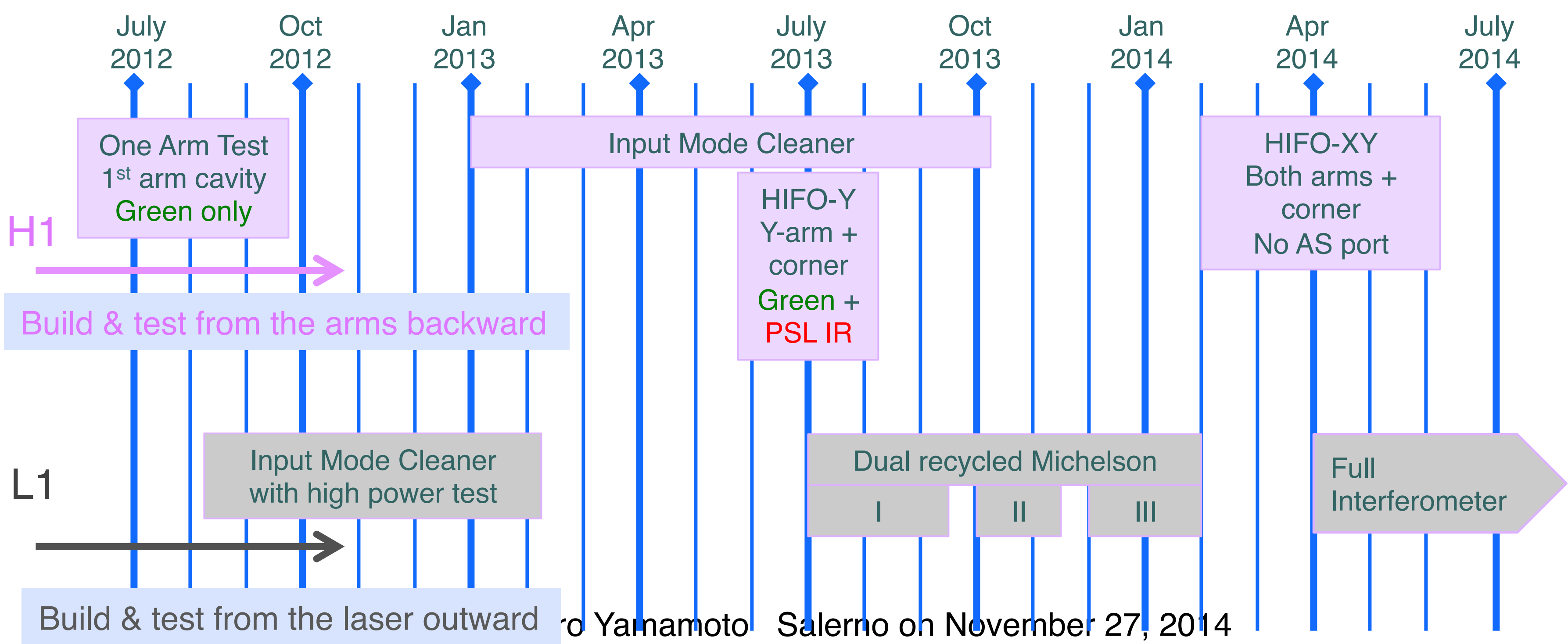


Overall, 4-5 years from locking to design sensitivity

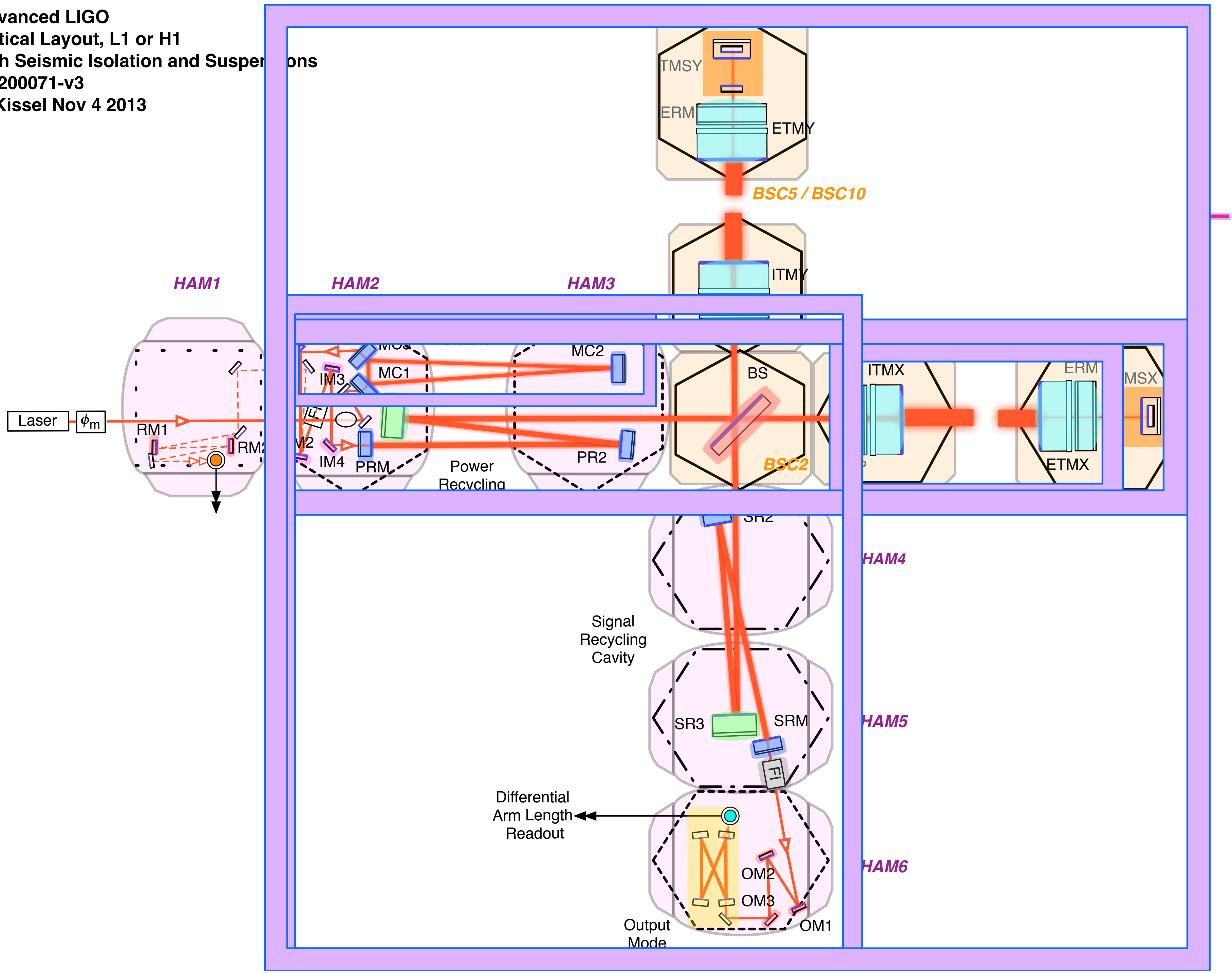
Hiro Yamamoto Salerno on November 27, 2014

Project Integrated Testing Plan

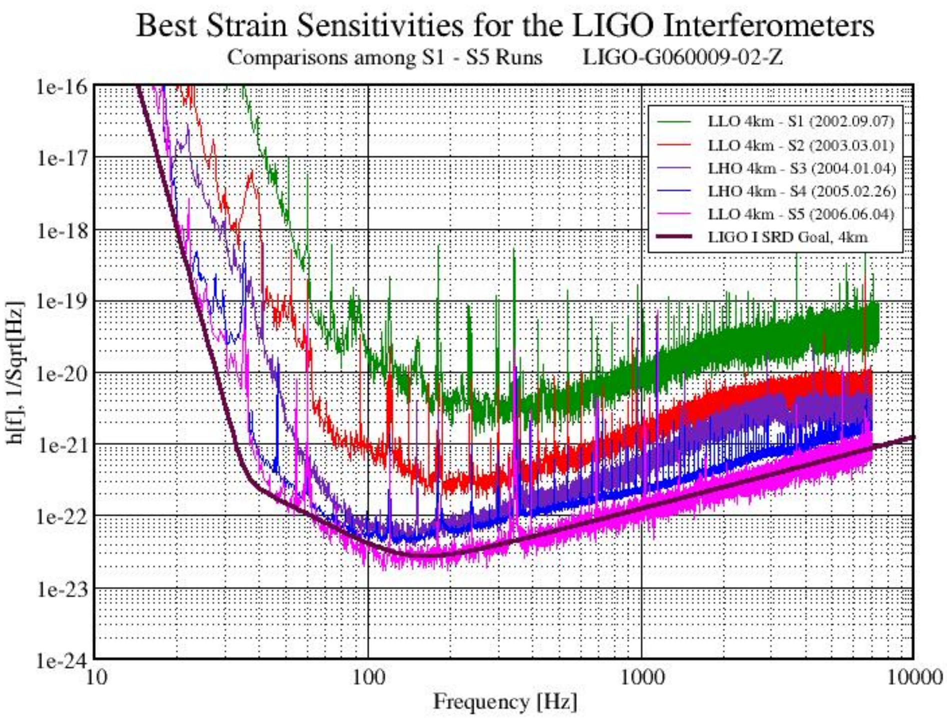
- Integrated testing phases interleaved with installation
- Complementary division between LHO and LLO
  - » Designed to address biggest areas of risk as soon as possible
  - » H1 focused on long arm cavities; L1 worked outward from the vertex

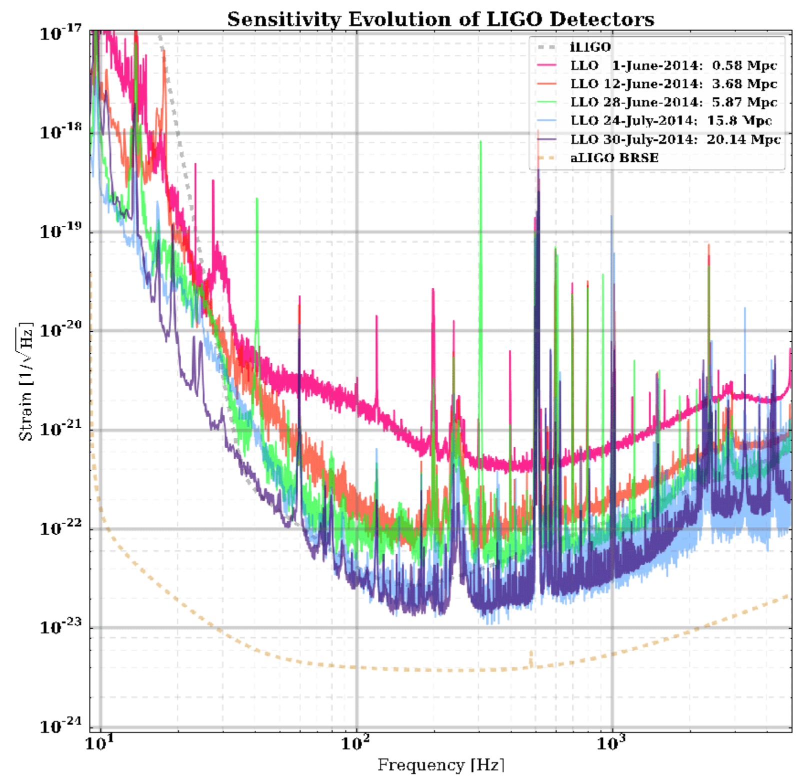


Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013



Improving sensitivities





LLO Project scope finished

- **The full interferometer lock was achieved on May 26, 2014**
- **L1 formally met the aLIGO goal of a 2h stable lock**
- The IFO has been locked for as long as 7.5h
- Initial alignment and the lock acquisition are mostly automated
- Currently recovering from some in-vacuum work
- (Need to complete System Acceptance/ documentation)

LHO installation complete

- Now under vacuum at all stations. Dual-recycled Michelson test underway; arms lockable with green Arm Length Stabilization, working toward full lock
- Accomplished with huge help from LLO, CIT and MIT
- Next: installation acceptance, and get to two-hour-lock milestone
- Also, responsibility for 3rd ifo (India) is at Hanford – non-trivial task.

Targeting the first observations

- ER6 slated for start December 8th, 2014
  - » L1 expected to be locked for multiple-hour intervals, although not at peak sensitivity; H1 not locking yet
  - » Significant discussion in Joint Run Planning Committee on ER6 readiness (throughout the LSC), start date, calibration/freeze/run durations, and impact on commissioning
- O1 observation run slated for as early as mid-July 2015; an evolving discussion as commissioning progress is understood
- Important point: we want **Both** LIGO instruments working at **comparable sensitivity** for the first observing run
  - » Catch-up needed at LHO – integrated testing starting ~6 months later than LLO, and e.g., operator/detector support training just getting going; lessons learned will help, but only so much
  - » Still 'all hands on deck' from LLO, MIT, CIT and of course LHO to reach that goal, but with competing needs to complete aLIGO hardware and documentation, work on BeamTube leak repair

Advanced LIGO: anticipated science runs